Switching Extensional and Contractional Tectonics in the West Kunlun Mountains During Jurassic: Responses to the Neo-Tethyan Geodynamics along the Eurasian Margin

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Submitted to: Solid Earth

Abstract: The Tethyan Orogenic Belt records a long-lived geological cycle involving subduction and collision along the southern margin of the Eurasian continent. The West Kunlun Mountains, located at the junction between the Tibetan and ~~Western Asian~~Pamir orogens within the Tethyan realm, records multiple orogenic events from the Paleozoic to the Cenozoic that shape the northwestern Tibetan Plateau. However, deciphering the complex Mesozoic contractional and extensional tectonics to interpret the broader Tethyan geodynamics remains challenging. To address the tectonic transition following the early Cimmerian (Late Triassic) collision, this study investigates the newly identified Jurassic sedimentary strata and volcanic rocks in the West Kunlun Mountains. Zircon geochronological results of basalts and sandstones reveal that this ~ 2.5-km-thick package was deposited at ca. 178 Ma, rather than the previously reported Neoproterozoic age. The alkaline basalts at the top of the formation exhibit chemical compositions similar to oceanic island basalts, consistent with the intracontinental extension environment revealed by the upward-fining sedimentary pattern. Provenance analysis, including~~integrating~~ conglomerate clast lithologies ~~with~~ and detrital zircons, suggests a substantial contribution from adjacent basement sources, likely influenced by the normal faulting during initial rift stage. These findings indicate that the West Kunlun Mountains rapidly transitioned into an extensional setting after suturing with Cimmerian terranes. The regional structure, stratigraphy and magmatism suggest that ~~this~~ the Early~~-~~–Middle Jurassic southwestern Tarim basin was subsequently inverted during the Late Jurassic and earliest Cretaceous. We propose that the Mesozoic deformational history in the West Kunlun Mountains was related to the northward subduction of the Neo-Tethys Ocean, as it transitioned from southward retreat to northward flat-slab advancement. Comparing with the entire strike-length of the Eurasian Tethyan orogen, we find that the subduction mode varied from the west to the east, reflecting the broad geodynamic changes to, or initial conditions of, the Neo-Tethyan system.

Keywords: Tethyan Orogenic Belt; West Kunlun Mountains; Jurassic ~~volcanics~~basalts; Basin evolution; Subduction retreating and advancing.

1 Introduction

The Tethyan Orogenic Belt is an over 15,000 km trans-Eurasian orogenic system with a series of mountain chains and orogenic plateaus.~~The Tethyan Orogenic Belt, a trans-Eurasian mountain system spanning an east-west strike-length of over 15,000 km, is characterized by a series of mountain chains and orogenic plateaus along its latitudinal extent~~ (Fig. 1a; Şengör, 1987; Metcalfe, 2013; Wu et al., 2020). The evolution of the Tethyan Orogenic Belt involved multiple phases of ocean basin opening and closure~~closing~~ (i.e., the Proto-, Paleo-, and Neo-Tethys oceans) throughout the Phanerozoic era, which resulted in the development of multiple orogenic belts across the Eurasian continent (Stampfli, 2000; Wan et al., 2019; Metcalfe, 2021). The complex history of accretionary and collisional orogenesis in the Tethyan realm is intricately linked to the breakup and formation of~~ the~~ two mega-landmasses, Gondwana and Laurasia (Şengör et al, 1988; Stampfli and Borel, 2002; Zuza and Yin, 2017; Li et al., 2018; Wang et al., 2018). Documenting the mode and nature of the accretionary and collisional events in the Mesozoic history of the Tethyan orogenic system is, therefore, important for understanding the continental dynamics of Eurasia.

The Mesozoic Tethyan Orogenic Belt involved~~ a protracted phase of~~ orogenesis, rifting, and basin evolution, associated with the convergence between the southern Asian margin and Cimmerian terranes derived from Gondwana (e.g., Kazmin, 1991; Stampfli and Borel, 2002; Angiolini et al., 2013; Robinson, 2015). The Mesozoic tectonic evolution of the Tethyan realm ~~during the Mesozoic~~ exhibits significant variations from the west to the east (Şengör, 1984; Zhu et al., 2022). In the Western Asian section of the Tethyan Orogenic

Belt, geochronological and geochemical data from different~~diverse~~ magmatic ~~rocks ~~rock assemblages suggest a northwestward-propagating~~propagating~~ continental rift system ~~in ~~along the southern margin of the Central Iran Block during the Early Jurassic to Early Cretaceous (Hunziker et al., 2015; Lechmann et al., 2018; Azizi and Stern, 2019). This process is envisioned to have been associated with subduction geodynamics involving multiple intraoceanic subduction zones, slab tearing, and alternating slab rollback and advance within Neo-Tethys (Zhang et al., 2018; Jafari et al., 2023). Conversely, in the Eastern Asian section of the Tethyan Orogenic Belt (i.e. Tibetan sector), an Andean-type orogeny along the southern margin of Eurasia from the Early Jurassic to the Early Cretaceous has been proposed to explain deformation and sedimentation patterns in the southern Tibetan Plateau (Kapp et al., 2007; Zhang et al., 2012; Xie and Dilek, 2023). This process was punctuated by Toarcian-Aalenian back-arc rifting event resulting from retreat of the subducting Neo-Tethyan seafloor (Hou et al., 2015; Wei et al., 2017).

The West Kunlun Mountains, stretching from the northern Pamir to northwestern Tibetan Plateau, occupy a critical position at the junction between the western and eastern Tethyan Orogenic Belts (Fig. 1b; Şengör, 1984; Wu et al., 2016). The West Kunlun Mountains involved the closure of the Paleo-Tethyan Ocean in the Triassic-Jurassic, followed by Cenozoic deformation and uplift during the Himalayan orogeny (Mattern and Schneider, 2000; Cao et al., 2015; Li et al., 2019; Xiao et al., 2002). Hence, the Mesozoic geology of the West Kunlun Mountains documents the plate tectonic history of the junction region within the Tethyan realm, providing pivotal insights into the formation of this extensive orogenic system. In particular, the Cimmerian Orogeny in the

West Kunlun region critically ~~represents~~ records the collision between the Gondwana- derived continental fragments and the southern Eurasian margin in the latest Triassic to late Jurassic (e.g., Şengör, 1979), but the timing and duration of this orogen remains equivocal. Existing interpretations of the Jurassic palaeogeography and evolution vary, ranging from syn-orogenic (Cao et al., 2015), post-orogenic (Wu et al., 2021), to transtensional (Sobel, 1999), because of the scarcity of the relevant geological record from this period. Significant challenges also persist in understanding the Mesozoic evolution of the Pamir terranes (Angiolini et al., 2013), including the timing of suturing and exact kinematics of related deformation (Robinson, 2015). The Cenozoic contractional deformation episodes, due the northward subduction of the Neo-Tethyan Ocean and the collision of India with Eurasia, further complicates our understanding in this remote region (Burtman and Molnar, 1993; Cowgill, 2010). The limited knowledge of the Jurassic and Cretaceous evolution of the Pamir interior has been preliminarily deduced from the timing and nature of regional magmatic activities (Chapman et al., 2018) that are challenged by the information derived from the surrounding, fragmented sedimentary basins (Leith, 1985; Wu et al., 2021).

To better understand the regional evolution and tectono-magmatic processes in the West Kunlun Mountains, we have undertaken a systematic geochronological and geochemical study and detailed analyses of sedimentary provenance of volcaniclastic rock suites in ~~a~~ the Jurassic Kyzyltau-Kandilik basin. By integrating these new results with existing data from the adjacent region, this study provides further constraints on the Mesozoic tectonic history of the central junction of the Tethyan Orogenic Belt~~,~~ and ~~probing~~ probes the preceding processes that cause the formation of the broad plateau in central Asia.

2 Geological framework and sampling

2.1 Tethyan history

The Tethyan Orogenic Belt~~ is a vast, east-west-extending mountain system that~~ separates the main Eurasian cratons and stable platforms in the north from Gondwana - derived continental terranes in the south (e.g., Şengör et al, 1988; Stampfli et al., 1991). The development of the Tethyan Orogenic Belt involves the evolution of multiple ocean basins and their seaways, including the Proto-Tethys, Paleo-Tethys, and Neo-Tethys (Stampfli, 2000; Metcalfe, 2021). These ancient ocean basins overlapped in time but closed successively as the Gondwana - derived ribbon continents (i.e., Apulia, Pelagonia, Sakarya, Tauride, South Qiangtang and North Qiangtang and Lhasa) accreted to the southern margin of Eurasia, creating several sub-parallel suture zones stretching from the circum-Mediterranean region, Caucasus, Iranian Plateau, and continuing eastward into the Tibetan Plateau and Southeast Asia (Fig. 1a; Dilek and Moores, 1990; Wu et al., 2020; Metcalfe, 2021).

The Cenozoic indentation of the Pamirs fundamentally affected the deformation pattern of the Tethyan Orogenic Belt and geographically divided the belt into western and eastern sectors (Tapponnier et al., 1981). The history of the Proto-Tethys was linked to the breakup of the Rodinia supercontinent (Zhao et al., 2018). The western segment of the Proto-Tethys has been defined as a Cambrian-Silurian ocean existing between Baltica and Gondwana, whereas the eastern Proto-Tethys appears to have been closed earlier in the

Early Silurian, as a series of Asian blocks collided onto the northern margin of Gondwana (e.g., Stampfli and Borel, 2002). The opening of the Paleo- and Neo-Tethyan ocean basins was related to slab pull forces that caused the detachment of the Hun (including the Tarim, North and South China) and Cimmerian terrane ribbons from the northern margin of Gondwanaland, respectively (Stampfli and Borel, 2002; Ruban et al., 2007). These terranes were successively transferred northward to the Eurasian continent, causing the closure of these internal seaways during the Cimmerian and Himalayan orogenies at the end of the Triassic and the beginning of the Cenozoic, respectively (Dilek and Furnes, 2019; Wan et al., 2019).

The final demise of the Paleo-Tethyan Ocean and the initiation of subduction in the Neo-Tethyan Ocean occurred simultaneously in the Triassic - earliest Jurassic, which is of vital importance for comprehension of the cyclical Tethyan evolution (Wan et al., 2019). The West Kunlun Mountains, situated to the north of the Pamir syntaxis, forms the western extent of the Tibetan Plateau (Fig. 1b-c). They constitute an important spatial link between the western and eastern domains of the Tethyan Orogenic Belt. The formation of the West and East Kunlun Mountains, involved accretionary and collisional orogeneses during the closure of the Proto-Tethys and Paleo-Tethys oceans (Mattern and Schneider, 2000; Xiao et al., 2005; Dong et al., 2018). The East Kunlun Mountains are displaced~~deflected~~ to the north relative to the West Kunlun Mountains by the dextral Altyn-Tagh strike-slip fault (Fig. 1b). During the Early Paleozoic, the closure of the Proto-Tethys Ocean led to the collision of the Tarim Craton (North Kunlun) and the South Kunlun terrane along the Kudi suture zone (Fig. 1c; Zhang et al., 2019a). After splitting from eastern Gondwana in the

Devonian - Carboniferous, the Tianshuihai - Qiangtang blocks travelled northward towards the Tarim Craton because of the subduction of the Paleo-Tethyan Ocean~~ floor~~. These blocks ultimately collided with the Tarim Craton at the latest Triassic, forming the Mazar - Kangxiwa suture zone (Fig. 1c; Xiao et al., 2005; Metcalfe, 2021). The Pamir terranes (including the Central Pamir, South Pamir, and Karakoram), commonly regarded as the western counterpart of the Qiangtang block, rifted from Gondwana ~~much later, ~~during the Permian (Robinson, 2015; Angiolini et al., 2015). The major Cimmerian orogenic unconformity between the Lower Jurassic and the deformed Upper Triassic strata is generally considered to mark the timing of the amalgamation~~integration~~ of these Pamir terranes onto the Eurasian margin (Angiolini et al., 2013; Li et al., 2022b).

The mid-Mesozoic tectonic evolution of the West Kunlun Mountains and Pamir is somewhat enigmatic, as the first-order geodynamic mechanisms for widespread ~~observed ~~deformation remain unclear. Several major exhumation events, including the Late Triassic and Early Jurassic, Middle-Late Jurassic, Early Cretaceous, and Late Cretaceous, are documented by low-temperature thermochronology in the mountain ranges and surrounding basins (Sobel, 2013; Cao et al., 2015; Li et al., 2019, 2023). Mid-Cretaceous granitoids~~ plutons~~ are widespread in the South Pamir and Karakoram. A~~ polymetamorphic~~ Jurassic ~~and ~~to Cretaceous polymetamorphic history~~ of the mountains~~ is also displayed by monazite ages (Faisal et al., 2014). The basement cooling as well as magmatic, and metamorphic ~~events ~~activities have previously been interpreted as associated with far-field stress effects of collisional events (Yang et al., 2017) or ~~a ~~retro-arc contraction~~high-flux event~~ during an Andean-type subduction of the Neo-Tethyan Ocean (Chapman et al., 2018). These Mesozoic structures within the orogenic belts were intensely reworked by the Cenozoic deformation during the Himalayan orogeny (Burtman and Molnar, 1993).

2.2 Regional geology and sampling strategy

This study focused on the central and southern parts of the northwest-trending Jurassic basin within the West Kunlun Mountains (Fig. 1c). The Kyzyltau region, situated in the central part of this Jurassic basin, preserves ~~the~~ thick~~est~~ Early-Middle Jurassic strata. It mainly comprises the Lower Jurassic Shalitashi and Kangsu formations, and the Middle Jurassic Yangye and Taerga formations (Fig. 2a). The Shalitashi Formation comprises a massive, thick conglomerate that overlies the deformed Carboniferous and Permian shallow marine clastic rocks and limestones along an angular unconformity (Fig. 3a). The poorly sorted textures and lateral thickness variations in the conglomerate indicate that its clastic material originated from alluvial fans (Sobel, 1999; Fig. 3b-e). The Kangsu and Yangye formations form the main part of the Jurassic strata (Fig. 2a), with total stratigraphic thickness exceeding 1800 meters. The Kangsu Formation mainly comprises stacked greywackes interbedded with coal layers. The Yangye Formation consists mainly of interbedded sandstones and shales exhibiting typical Bouma sequences, indicative of turbidite deposits in a deepwater environment (Wu et al., 2021). The Middle Jurassic Taerga Formation is only exposed in the northeastern side of the region and consists of thinly-bedded shales and siltstones. The Lower to Middle Jurassic stratigraphy forms an upward-fining sequence, indicating the expanding and deepening of the basin over time. Structurally, the Jurassic strata exhibit strong deformation, forming a northwest-trending synclinorium (Fig. 2a). The Cenozoic contraction in the region extensively deformed the coal-bearing strata, resulting in the formation of multi-scale folds and thrusts (Fig. 3f and 3g). Regionally, the Early-Middle Jurassic strata are unconformably overlain by the Late Jurassic Kuzigongsu Formation and the Cretaceous Kezilesu Group, which are characterized by oxidation-colored, massive conglomerate and sandstones (Fig. 3h). Synchronous unconformities also exist in the South Qiangtang and Bangong-Nujiang suture zones (Ma et al., 2017, 2018).~~ This event was generally interpreted to have been linked to the Middle - Late Jurassic, large-scale contraction and aridification across central Asia (Hendrix et al., 1992; Yang et al., 2017).~~

~~Documentation and study of the Mesozoic stratigraphy in the southernmost part of the Jurassic basin have been relatively insufficient.~~ In the Kandilik region, geological mapping identified a coal-bearing formation, known as the Lower - Middle Jurassic Yarkant Formation, and a massive conglomerate classified as the Upper Jurassic Kuzigongsu Formation (Fig. 2b). These Jurassic strata were strongly deformed and laterally bounded by a mylonitic shear zone to the west and thrust faults to the east. A stratigraphic unit consisting of gray-black ~~slate~~ mudstone,~~interbedded with~~ siltstone, and fine sandstone~~s and siltstones~~ is exposed to the east of the Yarkant Formation, with a thickness exceeding 3500 meters (Ma et al., 1991). Abundant mafic dykes intruded into the lower part of the strata (Fig. 3i), causing local contact metamorphism. A suite of volcanic strata composed of several basalt layers are juxtaposed with the thick clastic package along a steeply-dipping fault. Several eruptive episodes are identified within this unit based on alternating volcanic horizons, including volcanic breccia (Fig. 3j), amygdaloidal basalts, and massive basalts (Fig. 3k). These volcanic rocks belong to the part of upper member deposited above the thick clastic strata (Ma et al., 1991). Due to the lack of reliable constraints from chronological results, this stratigraphic unit has long been thought as Precambrian in age (Ma et al., 1991). Structurally, the strata were intensely deformed by regional Kashgar-Yecheng transfer faults (Fig. 2) and bedding dips steeply to the northeast (Fig. 3l).

In the Kandilik region, one basalt sample (AYBL09) was collected near the thrust fault for geochronological dating (Fig. 2b). Six fresh, undeformed basalt samples were also obtained away from faults for geochemical analysis. These basaltic rock samples consist primarily of plagioclase with a fine columnar texture and anhedral Ti-Fe oxides (Fig. 3m). Plagioclase is locally altered into chlorite. Additionally, one quartz-lithic sandstone sample (AYBL13) was collected for detrital zircon age analysis. This sample exhibits poor sorting and is composed mainly of quartz (~ 30%) with angular shapes, feldspar (<10%), and lithic fragments (> 60%) (Fig. 3n). For regional comparison, two sandstone samples were collected from the Kangsu (KZLT1601) and Yangye formations (KZLT1602) in the Kyzyltau region (Fig. 2a). These sandstones show similar textures and compositions to the clastic sample from the Kandilik region (Fig. 3o).

3 Methodology

One basalt sample (AYBL09) was collected from the Kandilik ~~region~~ section (Fig. 2b) for zircon U - Pb geochronology and in-situ trace element analysis. Zircon separation and cathodoluminescence (CL) imaging were done at Yuheng Rock & Mineral Technology Service Co., LTD., Langfang, China. Zircons were analyzed for U‐Pb geochronology using an Agilent 8900 ICP-QQQ equipped with an ESI New Wave NWR 193UC (Two Vol2) laser ablation system at Beijing Quick-Thermo Science & Technology Co., Ltd, China. Concordia plots were constructed using IsoplotR (Vermeesch, 2018).

To analyze the petrogenesis and tectonic setting of magmatism, six fresh basalt rocks were collected from the same section for determining their major and trace element chemistry. Samples were first crushed, and powdered in an agate mill. Elemental analyses were conducted at Wuhan SampleSolution Analytical Technology Co., Ltd. Major-element analyses were performed by X-ray fluorescence spectrometry (ZSXPrimusII), with analytical uncertainties generally better than 1%. Trace-element contents were determined using an Agilent 7700e ICP-MS.

To compare the detrital age patterns and sedimentary provenance, we have conducted zircon U-Pb dating on two sandstones (KZLT1601 and KZLT1602) exposed in the Kyzyltau section, and one sandstone (AYBL13) exposed in the Kandilik section (Fig. 2B). Zircons from samples KZLT1601 and KZLT1602 were analyzed for U‐Pb geochronology using a Thermofisher iCAP RQ ICP-MS equipped with a Cetea Analyte HE laser ablation system at School of Earth Sciences, Zhejiang University. Zircons from sample AYBL13 were analyzed for U‐Pb geochronology using an Agilent 8900 ICP-QQQ equipped with an ESI New Wave NWR 193UC (Two Vol2) laser ablation system at Beijing Quick-Thermo Science & Technology Co., Ltd. The Common Pb was corrected with the method proposed by (Andersen, 2002). Concordia plots and Kernel Density Estimate (KDE) plots were constructed using IsoplotR (Vermeesch, 2018) and

Density Plotter 8.5 (Vermeesch, 2012), respectively.

The details of the analytical procedures and the information of the analytical methodologies, as explained above, are presented in Table S1.

The data from the conglomerate in the Shalitashi Formation were collected at eight different sections. Analysis of conglomerate clasts was conducted within a designated 1 square meter area. Our focus was on documenting the lithological compositions of the clasts, with at least one hundred gravels randomly counted at each site.

4 Analytical Results

4.1 Morphology and geochronology of zircons from basalt sample~~s~~

The results of zircon U-Pb dating of the basalt sample are presented in Table S2. Approximately one hundred and seventy zircon grains have been successfully separated from the basalt sample. Zircon crystals are mostly transparent and colorless, displaying varying lengths ranging between 50-200 μm with elongation ratios of 1:1-5:1 (Fig. 4). Upon examination of their cathodoluminescence (CL) images, we have sub-categorized these zircons into two groups based on the presence of oscillatory zoning. The grains showing well-defined growth zoning (type 1) are generally sub-euhedral in shape (no.3 in Fig. 4), which imply their magmatic origin (Fig. 4; Hoskin and Schaltegger, 2003). Another type (type 2) of zircon displays inconspicuous zoning texture (no.4 in Fig. 4) or yields only faintly visible zoning patterns (no.15 in Fig. 4). Morphological analysis of these zircons reveals a range from needle-shaped and elongated crystals (no.13 in Fig. 4) to stubby and equant forms (no.12 in Fig. 4). A common feature of these varying grains is their subrounded external appearance. This may result from moderate resorption either during the evolution of the magma chamber when the magma is oversaturated with respect to zircon or a certain degree of metamorphism (Corfu et al., 2003). In addition to their "polished" shape, these zircons commonly display nebulous or patchy-zoned centers, without distinct core-rim structures (no.11-13 in Fig. 4).

We have conducted a total of thirty-six spot analyses on various types of zircons (Fig. 4), resulting in thirty-three analyses with a > 90% concordance (Fig. 5a). The Th/U ratios of all tested zircons range from 0.04 to 1.52 (Fig. 5d). We cannot assert that all of them are primary crystals without modification simply based on the evaluation of Th/U ratios. However, all of these results yielded concordant ages spanning a broad range from the Early Neoproterozoic to the Jurassic. Type 1 zircon grains have Th/U ratios ranging from 0.38 to 1.44, while type 2 zircon grains exhibit a wider range. Based on the classification and statistical analysis of zircon characteristics, we found that type 1 zircons, which commonly exhibit clear oscillatory zoning, have older ^{206}Pb/^{238}U ages ranging from 405 Ma to 911 Ma, whereas type 2 zircons display uniform ages between 168 Ma and 193 Ma (Table S2). Twenty youngest zircons with the concordant ages define a weighted mean ^{206}Pb/^{238}U age of 178±2 Ma (MSWD = 0.99) (Fig. 5b). We interpret this Toarcian age as the crystallization age of ~~the zircons in~~ this rock sample. The remaining older zircons yield primarily middle Paleozoic and Neoproterozoic ages, which we interpret as inherited from the country rock.

4.42 Whole-rock major and trace elements of basalts

The chemical compositions of the basalt samples from the Kandilik section are provided in Table S~~5~~4. Except for one sample (AYBL11D), the majority of our samples displays similar geochemical compositions, characterized by low SiO_2 (45.7-51.0 wt.%) and MgO (4.78-7.18 wt.%) contents, and Mg#s ranging between 45 and 52. These samples possess high TiO_2 (2.42-3.34 wt.%) and total alkali (Na_2O+ K_2O = 5.17-6.35 wt.%) contents, and exhibit moderate Al_2O_3 contents ranging from 11.1 to 14.4 wt.% and total Fe_2O_3 ranging from 12.6 to 13.7 wt.%. In comparison, the sample AYBL11D displays relatively high contents of SiO_2 (55.5 wt.%) and TiO_2 (4.76 wt.%) with a low total alkali content (4.80 wt.%). All basalt samples fall within the alkaline series field as depicted in the total alkali-silica diagram (Fig. ~~7~~6a). However, it is worth noting that all analyzed samples exhibit varying Loss-on-Ignition (LOI = 1.51-9.81 wt.%) values, attributed to weathering and alteration effects, with the presence of chlorite and calcite (Fig. 3m). Hence, it is crucial to assess the alteration effects on the chemical compositions of the analyzed samples. The high-field-strength elements (HFSE, such as Nb, Ta, Ti, and Hf) and rare earth elements (REE) are typically immobile during alteration. This is supported by the consistent elemental variations against the most immobile element Zr, as shown in the Fig. S1. Additionally, Cr (25.4–108 ppm) and Ni (27.4–61.2 ppm) in these samples (except AYBL11D) also demonstrate strong correlations with Zr, suggesting that these elements were essentially immobile during alteration. Based on the Nb/Y vs. Zr/TiO_2 diagram proposed by Winchester and Floyd (1977), all samples plot in the alkaline series (Fig. ~~7~~6b). Therefore, we posit that these rocks are best classified as alkaline basalt.

All analyzed samples display consistent chondrite-normalized rare earth element patterns (Fig. ~~7~~6c), characterized by an enrichment of LREE relative to HREE, with $(La/Yb)_N$ ratios ranging from 6.24 to 7.96. Moreover, their REE patterns exhibit slight negative Eu anomalies (δEu = 0.7-1.0). The primitive mantle-normalized multi-element diagram illustrates that the analyzed samples are characterized by the enrichment of highly incompatible trace elements relative to low incompatible elements (Fig. ~~7~~6d). The samples present significant depletion of Sr and slight enrichment in Zr and Hf. No negative Zr-Hf-Ti anomalies are observed in any of the analyzed basalts.

4.~~2~~ 3 Detrital zircon U–Pb ages from Jurassic sandstones

The zircon U-Pb geochronological dataset for the detrital zircons is presented in Table S2. A total of 101 spot analyses were conducted on zircon grains from sample AYBL13. After filtering grains with greater than 10%~~ age~~ discordance, 98 of them met the criteria for inclusion in the Kernel Density Estimate (KDE) visualization (Fig. ~~6a~~7a). The analyzed results reveal that the Th/U ratios of most effective zircons range between 0.12 and 2.61, with only four zircons yielding extremely low values below 0.1 (Fig. 5d). The results suggest that most detrital zircons from sample AYBL13 are of igneous origin (Belousova et al., 2002). The youngest zircon grain from this sandstone yielded an apparent ^{206}Pb/^{223}U age of 429 ± 5Ma, whereas the oldest grain has ~~revealed~~ an apparent ^{206}Pb/^{207}Pb age of 3080 ± 22 Ma. The KDE plot reveals four main age populations with peaks at approximately 446 Ma, 820-955 Ma, 1553 Ma, and 2484 Ma (Fig. ~~6b~~7b).

For analyzing~~ regional detrital~~ provenance, two Jurassic samples from Kyzyltau were analyzed for age comparison. The Early Jurassic sample KZLT1601 underwent one hundred spot analyses on randomly selected zircon grains. These measured grains exhibit Th/U ratios ranging from 0.09 to 1.49

(Fig. 5d), consistent with an igneous origin. Eighty-nine zircon ages were plotted on or near the concordant curve (Fig. ~~6c~~7c), providing zircon ages ranging from 369 ± 6 Ma to 3314 ± 15 Ma. The detrital age spectrum was obtained using the KDE method and revealed similar peaks at approximately 444 Ma, 807 Ma, 1823 Ma, and 2566 Ma (Fig. ~~6d~~7d).

Similarly, one hundred zircon grains from the Middle Jurassic sample KZLT1602 exhibit characteristics indicative of a magmatic origin, with high Th/U ratios ranging between 0.11 and 2.63 (Fig. 5d). Ninety - eight concordant results display consistent age population with the sample KZLT1601, ranging from 345 ± 4 Ma to 3029 ± 15 Ma (Fig. ~~6e~~7e). These age populations on the KDE plot also display four main peaks at approximately 435 Ma, 782-988 Ma, 1829 Ma, and 2480 Ma (Fig. ~~6f~~7f).

4.~~3~~ 4 Analysis of Jurassic conglomerate clast lithologies

The field provenance analysis of the Lower Jurassic conglomerate (Shalitashi Formation) reveals significant variations in composition across different sections. In the Kangsu and Wulagen sections, located in the northernmost region of the West Kunlun Range, clasts are composed predominantly of green-colored sandstone~~s~~ (80-51%) and low-grade metamorphic rocks like schist (0-46%), with minor occurrences of light-colored siliceous rock (14-3%) and granitoid (6-0%). In the northwestern sector of the Pamir, ~~a variegated~~ sandstone (22-46%) and ~~a~~ recycled siliceous rock (29-46%) predominantly constitute major clasts in the Oytag and Gaizi sections, respectively (Fig. 3b and 3c). Additionally, minor limestone (11-2%) and diverse igneous rocks (38-6%), including granitoid~~s~~, rhyolite, and basalt~~s~~ occur characteristically in the same stratigraphic horizon. In the Kyzyltau section (Fig. 3d), the clasts of the Jurassic conglomerate are dominated by green-colored sandstone (28%) and granite~~s~~ (50%) with subordinate schist (13%) and siliceous rock (9%). To the south of Kyzyltau, the Tamu and Qimugen sections present a provenance source dominated by sedimentary rocks. Clasts of limestone (Fig. 3e) and green-colored sandstone account for 85% and 61% in the neighboring sections, respectively. The proportion of reddish sandstone in the Qimugen section (33%) surpasses that in the Tamu section (15%). The Kusilafu section, located to the north of the Kandilik region, exhibits similar clast lithologies in the conglomerate to the Qimugen section, with a predominance of green-colored sandstone (34%) and recycled siliceous rock (45%), along with minor occurrences of reddish sandstone (16%). Detailed clast lithologies and counting results are presented in the Table ~~S4~~S5.

~~4.4 Whole-rock major and trace elements of basalts~~

~~The chemical compositions of the basalt samples from the Kandilik section are provided in Table S5. Except for one sample (AYBL11D), the majority of our samples displays similar geochemical compositions, characterized by low SiO_2 (45.7-51.0 wt.%) and MgO (4.78-7.18 wt.%) contents, and Mg#s ranging between 45 and 52. These samples possess high TiO_2 (2.42-3.34 wt.%) and total alkali (Na_2O+ K_2O = 5.17-6.35 wt.%) contents, exhibit moderate Al_2O_3 contents ranging from 11.1 to 14.4 wt.% and total Fe_2O_3 ranging from 12.6 to 13.7 wt.%. In comparison, the sample AYBL11D displays relatively high contents of SiO_2 (55.5 wt.%) and TiO_2 (4.76 wt.%) with a low total alkali content (4.80 wt.%). All basalt samples fall within the alkaline series field as depicted in~~

~~the total alkali-silica diagram (Fig. 7a). However, it is worth noting that all analyzed samples exhibit varying Loss-on-Ignition (LOI = 1.51-9.81 wt.%) values, attributed to weathering and alteration effects, with the presence of chlorite and calcite (Fig. 3m). Hence, it is crucial to assess the alteration effects on the chemical compositions of the analyzed samples. The high-field-strength elements (HFSE, such as Nb, Ta, Ti, and Hf) and rare earth elements (REE) are typically immobile during alteration. This is supported by the consistent elemental variations against the most immobile element Zr, as shown in the Fig. S1. Additionally, Cr and Ni in these samples (except AYBL11D) also demonstrate strong correlations with Zr, suggesting that these elements were essentially immobile during alteration. Based on the Nb/Y vs. Zr/TiO_2 diagram proposed by Winchester and Floyd (1977), all samples plot in the alkaline series (Fig. 7b). Therefore, we posit that these rocks are best classified as alkaline basalt.~~

~~All analyzed samples display consistent chondrite-normalized rare earth element patterns (Fig. 7c), characterized by an enrichment of LREE relative to HREE, with $(La/Yb)_N$ ratios ranging from 6.24 to 7.96. Moreover, their REE patterns exhibit slight negative Eu anomalies (δEu = 0.7-1.0). The primitive mantle-normalized multi-element diagram illustrates that the analyzed samples are characterized by the enrichment of highly incompatible trace elements relative to low incompatible elements (Fig. 7d). The samples present significant depletion of Sr and slight enrichment in Zr and Hf. No negative Zr-Hf-Ti anomalies are observed in any of the analyzed basalts.~~

5 Identification and age constraints for the Lower Jurassic strata

~~Identified~~ Jurassic strata are largely exposed in the eastern edge of the West Kunlun Mountains and on the southern side along the Talas-Fergana Fault (Fig. 1c). The Jurassic sequences are comprised of coal-bearing siliciclastic rocks with variable thicknesses (Wu et al., 2021). Jurassic volcanic strata have not been previously identified in the West Kunlun Mountains, although a Jurassic tuffaceous succession and Upper Triassic - Lower Jurassic volcanic rocks crop out in the Hindu Kush along the western edge of the Pamir (Brookfield and Hashmat, 2001). Our study has focused on a package of thick clastic rocks intercalated with basaltic lavas, ~~are~~ exposed in the southernmost part of the Jurassic Kyzyltau syncline (Fig. 2). This stratigraphic package was previously considered to be of Mesoproterozoic or Neoproterozoic age due to the lack of fossil records and the presence of low-degree metamorphism (Ma et al., 1991). Lithologically, the ~~monotonous~~ clastic member is composed primarily of gray-black ~~slate~~ mudstone and fine - grained sandstone to siltstone, rich in iron and carbonaceous components (Ma et al., 1991). The overlying basalts vary significantly in their thickness and lithological composition~~makeup~~, composed primarily of basaltic volcanic breccia, amygdaloidal, and massive layers (Fig.3j and 3k).

Our new results of zircon U-Pb dating of basalts and sandstones suggest that this rock assemblage is not Precambrian in age, given the widespread appearance of Phanerozoic ages. We suggest that the weighted mean $^{206}Pb/^{238}U$ age (~178 Ma) ~~of the youngest group of zircons separated~~ from the basalt sample could define the eruptive age of this magmatic episode based on the following lines of evidence. First, these zircons exhibit similar morphological and CL imaging characteristics (Fig. 4), with the majority of the analyzed grains displaying Th/U ratios indicating their igneous origin (Fig. 5d). Secondly, the results of our in-situ trace elemental composition of the zircons (Table S3) indicate that the chondrite-normalized rare earth elements consistently exhibit left-sloping pattern with positive anomalies in Ce and Sm, and negative anomalies in Eu, similar to those of typical igneous zircons (Fig. 5c; Hoskin and Schaltegger, 2003). Thirdly, according to the Y vs. Yb/Sm plot proposed by Belousova et al. (2002), these Jurassic zircons are consistent with the basic or ultrabasic igneous origin (Fig. 5e). Thus, we posit that the crystallization age of the basalt is Toarcian.

To refine the depositional age of the clastic member of the stratigraphy, we have compared the detrital zircon results from the feldspar lithic sandstones with those from the Lower and Middle Jurassic strata~~, exposed~~ in the Kyzyltau region. The sandstone collected from the Kangsu Formation displayed similar texture and composition to the rocks from the Kandilik region, both composed of immature and poorly sorted quartz and lithic fragments (Fig. 3n and 3o). The age patterns of detrital zircons display remarkably similar populations with Early Silurian (~440 Ma) and Tonian (~800-950 Ma)~~ dominated~~ peaks, indicating that sediments of the two investigated areas shared a common~~ exhumed~~ provenance. The Lower and Middle Jurassic sedimentary rocks were previously suggested to have been deposited within~~ structural~~ half grabens and mostly sourced from the West Kunlun Mountains (Chen et al., 2018). This interpretation aligns~~is~~ ~~consistent~~ with our findings, which~~. Furthermore, we infer~~ indicate that this stratigraphic package comprises thick sequences of laminated mudstone and siltstone, ~~resembles~~ resembling ~~a turbidite~~rift-related deposits~~sequence,~~ formed in a ~~exhibiting~~ relatively proximal, ~~deep-~~

~~water~~rapidly filling depositional ~~features~~environment.

Accordingly, we propose reassigning this thick package of clastic rocks to the Early - Middle Jurassic age. ~~Hereon, w~~We demonstrate the structural compatibility of this new stratigraphic scheme. The Lower ~~-~~to Middle Jurassic strata of the Yarkant Formation in the ~~studied~~ study ~~region~~ area ~~comprise~~ consist of a lacustrine ~~association~~ sequence rich in coal beds, structurally ~~and it delineated structurally~~ bounded to the west by a mylonite zone ~~to its west~~ (Fig. 2b). The redefined stratigraphic sequence~~s~~ ~~are~~ is similarly rich in carbonaceous material~~components~~ and is thrusted beneath the~~are closely bounded by Jurassic~~ coal-bearing strata of the Yarkant Formation along an east-verging~~several~~ thrust~~reverse~~ fault~~s~~. These ~~two~~ units ~~successfully~~ could extend into the NW-SE-striking Jurassic graben, which surprisingly narrows rapidly towards the south without any obvious facies transition (Fig. 1c). The basin-ward dipping of ~~the~~ strata constituted the western limb of the Jurassic syncline, which has a comparable thickness that may extend into the southern area of the Kyzyltau syncline (Fig. 2).

6 Discussion

6.1 ~~Generation and geological~~Tectonic setting of the Early Jurassic volcanism

The ~~basalt samples are characterized by~~ varying SiO$_2$ ~~(45.7-55.5 wt.%)~~ contents and low Mg# values ~~(45-52), suggesting~~ of the basalt samples suggest that they were not derived from ~~the~~ primary magmas~~,~~ ~~and~~but ~~that they~~ likely ~~experienced~~ underwent crustal assimilation and fractional crystallization (AFC) processes. Generally, mantle~~-~~derived magmas suffer various degrees of crust contamination en-route from magma chambers to the surface (Aitcheson and Forrest, 1994). The presence of inherited Paleozoic and Neoproterozoic zircons in these basalts suggests the potential interactions between the ascending magmas and the country rocks (Fig. 5a). However, these basaltic rocks exhibit no negative anomalies of Nb, Ta, and Ti, which are typically depleted in the crust (Fig. ~~7d~~6d). They exhibit low La/Nb ratios (0.53 - 1.15) and mostly have high Nb/U ratios (37 - 45), similar to the range of oceanic lavas (La/Nb <1.2 and Nb/U >39; Krienitz et al., 2006). Additionally, all basalt samples exhibit low Th/Nb ratios (0.09-0.15), plotting along the MORB−OIB array of oceanic basalts within the Th/Yb-Nb/Yb diagram (Fig. ~~7e~~6e; Pearce, 2008). These signatures, with little indication of crustal components, suggest that these basalts experienced negligible crustal contamination ~~during their journey to the surface~~. They show ~~are characterized by~~ extremely low Ni and Cr concentrations ~~of Ni (27.4–61.2 ppm) and Cr (25.4–108 ppm). They also exhibit~~ and slight~~ly~~ negative Eu and Sr ~~negative~~ anomalies ~~of Eu and Sr on the whole-rock normalized REE patterns and spider diagram~~ (Fig. ~~7c~~ 6c~~-and 7d~~d)~~. These features could be~~, likely resulting from~~caused by varying degrees of~~ fractional crystallization ~~processes involving~~of olivine, clinopyroxene, and plagioclase.

The Early Jurassic episode (178 Ma) of volcanism in the West Kunlun Mountains temporally followed the Cimmerian Orogeny. ~~Regionally, t~~The eruption of the Early Jurassic basalts ~~at 178 Ma~~ was slightly later than the peak metamorphism of high-pressure granulite facies that has been proposed to have occurred between 200 and 185 Ma (Qu et al., 2021). Collisional orogeny commonly transitions from syn-collisional metamorphism to post-collisional unroofing (Dilek and Altunkaynak, 2007, 2010; Zheng et al., 2019). The unroofing phase could generate geochemically varying granitoids ~~with~~ and ~~extrusion of~~ mafic magmatic rocks (Harris et al., 1986; Zhou et al., 2021). ~~However, distinguishing post-collisional from syn-collisional magmatism may present challenges, because the post-collisional mafic rocks could inherit whole-rock geochemical fingerprints from the preceding subducted materials (Zhao et al., 2013). Conversely, intraplate magmas are typically dominated by low-degree partial melting and silica-unsaturated alkaline magmas, which is distinct from syn- and post-collisional igneous rocks (Dilek and Altunkaynak, 2010; Xu et al., 2020).~~

The Jurassic alkali basalts exhibit enrichment of LREE and HSFEs without obvious crustal signatures (~~e.g., Nb-Ta depletion;~~ Fig. ~~7c~~6c-d), different from the syn~~-- and~~/post-collisional mafic intrusions and ~~magmas~~ granitoids in the West Kunlun Mountains (Liao et al., 2012; Chen et al., 2021). Their compositions display high Th/Yb and Nb/Yb ratios, ~~resemble~~ similar to~~those of~~ intraplate OIBs (Fig. 6e). Melt curve modeling of La/Sm vs. La ~~and~~ suggests they were likely~~could have been~~ generated by low-degree partial melting (~5%) of a garnet lherzolite mantle source (Fig. 7~~e-~~f). This aligns with the Zr-Nb-Y and Zr-Y-Ti triangular plots proposed by Meschede (1986), indicating a within-plate affinity for the studied Jurassic basalts (Fig. 8a-b). They also have high Ti-Zr contents and Ti/V ratios (48-77), consistent with the characteristics of within-plate alkali basalts or OIBs (Fig. 8d-e).~~All tectonic discrimination plots using immobile trace elements indicate that the Jurassic basalts formed within an intraplate setting (Fig. 8).~~

The generation of these magmas can be attributed to one of two mechanisms. The first explanation is that the North Kunlun region experienced rapid orogenic collapse after Late Triassic collisional orogeny, during which intra-plate collapse-related volcanism generate the observed basalt flows. We do not find this hypothesis plausible given the implied rapid transition from peak collisional orogeny, including ca. 185 Ma prograde metamorphism (Qu et al., 2021), to collapse and volcanism recorded at ca. ~~175~~ 178 Ma ~~(Wu et al., 2021)~~. Many arc-continent or continent-continent collisional orogens, evolving from peak orogenic metamorphism, to orogenic collapse, to intraplate stage, collectively persist for tens of millions of years (Dewey, 2005; Weller et al., 2021). Conversely, Early-Middle Jurassic graben and half-graben structures are widely identified by seismic profiles in the southwestern and southeastern Tarim Basin, and Qaidam Basin (Cheng et al., 2019; Zhao et al., 2020; Wu et al., 2021; Xia et al., 2024). Jurassic extensional faults have been reported in the eastern Altyn Tagh Range (Chen et al., 2003). ~~a~~ A broad plate-boundary extensional process may have impacted ~~this~~ these orogenic belts and ~~its~~ their hinterland regions ~~in the Early Jurassic~~. Support for this model also includes the expansive extensional rifts developed across the marginal and interior Eurasia during the Early-Middle Jurassic (e.g., Amu–Dar’ya, Afghan–Tajik and Fergana basins; Otto, 1997; Golonka, 2004).

6.2 Jurassic basin formation and implications for sedimentary provenance

The Late Triassic closure of the Paleo-Tethyan Ocean led to collision of the Cimmerian terranes with Eurasia that caused the uplift of the West Kunlun Mountains (Cao et al., 2015). The Triassic stratum is completely absent in the North Kunlun region and western Tarim Basin (Wu et al., 2021).~~development of~~

~~a regional unconformity across the central Asia during the Triassic to Early Jurassic (Gaetani et al., 1993; Schwab et al., 2004; Fürsich et al., 2017).~~ In the ~~studied~~ study area, the deformed Upper Paleozoic strata are unconformably overlain by~~ a~~ Lower Jurassic conglomerates (Fig. 9).

The Kyzyltau basin preserves the most comprehensive record of the formation and evolution of a post-Cimmerian rift, spanning from its initiation in the Early Jurassic to its inversion in the Late Jurassic (Wu et al., 2021). The basement of this basin varies along-strike~~ its lateral extent~~, indicating its strong tectonic reworking prior to Jurassic deposition. It comprises four subdivisions from the north to the southeast: (1) an Early Devonian metasedimentary rock terrane in the Kashgar depression (1-4 in Fig. 9), (2) the Carboniferous island-arc crust and Permian back-arc basin successions in the NW segment of the West Kunlun (5-6 in Fig. 9), (3) an Upper Carboniferous to Middle Permian platform successions in the middle segment (7-11 in Fig. 9), and (4) an Upper Permian clastic formation in the southern part (12-17 in Fig. 9)~~.~~.

The massive conglomerate of the Shalitashi Formation indicates rapid infilling of the Jurassic basin during its initial opening stage. Analysis of conglomerate clast lithologies from different sites suggests significant compositional variations, consistent with the presence of local basement rocks (Fig. 9).~~ For example, the arenaceous gravels in the Kashgar depression are primarily derived from the underlying Devonian (Wulagen) uplift. The gravels from the Oytag and Gaizi contain abundant igneous and siliceous rock fragments, which may have been sourced from the local arc and back-arc basin lithologies. Contrastively, gravels from the Tamu are composed predominately of limestones, implying their origin from the underlying Carboniferous marine~~

~~strata. The Qimugen and Kusilafu share a similar arenaceous source region, located within the Devonian and Permian strata in the core of the Kashgar-Yecheng syncline (Fig. 2a).~~

The Lower Jurassic strata rapidly transition from alluvial fan deposits into fluvial sedimentary environment. During the Middle Jurassic, a sequence of stacked coal-bearing sandstones was deposited (Fig. 9). Extensional faulting across the half-grabens further deepened the basin and facilitated the deposition of a turbidite sequence in the Yangye Formation (Wu et al., 2021). Provenance analysis based on detrital zircons suggests that the source region for these sandstones was dominated by Late Ordovician-Early Silurian (~ 446 - 435 Ma) and Neoproterozoic (~ 980 - 780 Ma) igneous rocks, with minor Neoarchean-Paleoproterozoic and Mesoproterozoic ages (Fig. ~~6~~7). Early Paleozoic (~ 480 - 440 Ma) granitoids, with a peak intrusive event at ~ 440 Ma (Fig. 1c; Tao et al., 2024), are exposed extensively in the South Kunlun terrane. However, the South Kunlun terrane is unlikely to be the source for these Jurassic depositions because the South Kunlun region contains extensive Triassic (~ 240 - 210 Ma) granitoids, intruded into the early Paleozoic rock units (Fig. 1c; Chen et al., 2021). Yet, Triassic detrital zircons are absent in the Lower - Middle Jurassic strata (Fig. ~~6~~7). Therefore, we instead suggest that the potential source area was most likely the North Kunlun terrane, which consists mainly of Paleozoic strata and Precambrian metamorphic basements. A provenance study has revealed that the age patterns of detrital zircons from the Ordovician - Devonian strata contain main age peaks at 430 - 445 Ma, 930 - 800 Ma, and 790 - 760 Ma, with subordinate Neoarchean to Mesoproterozoic ages (Yan, 2022). Our results are consistent with this detrital zircon age information from the Lower Paleozoic sedimentary rocks and with the paleocurrent results of previous studies (Wu et al., 2021).

A Late Jurassic contractional event affected this region, as evidenced by the intense deformation and metamorphism displayed by various formations and rock units in orogen (Robinson et al., 2007; Groppo et al., 2019), and by the uplift and inversion of the earlier basin (Yang et al., 2017). The Middle Jurassic shallow marine sequences in South Qiangtang and SE Pamir were uniformly eroded during this time period (Ma et al., 2023). The Upper Jurassic strata are either entirely absent or locally replaced by conglomerate deposits (Fig. 10). In the Tarim Basin, the Upper Jurassic strata are dominated by brownish reddish conglomerate. Previous studies have suggested that these redbeds may indicate a regional increase in aridity resulting from the uplift of the surrounding mountain belts (Hendrix, 2000). The Late Jurassic uplift event has also been supported by numerous thermochronologic ages (170-155 Ma) within the West Kunlun Mountains and Pamir (Fig.1c; Yang et al., 2017). The uplift event also resulted in significant changes in basin and range patterns, and influenced the potential provenance of sediments. The emergence of juvenile detrital zircons in these Upper Jurassic and Lower Cretaceous deposits indicates the exhumation and erosion of a late Paleozoic to Mesozoic arc system (Fig. 10). The Triassic batholiths were thrust onto the southwestern margin of the Tarim Basin and ~~creating~~ generated~~an~~ elevated topography, which supplied ~~in turn provided~~ ~~abundant~~ igneous clastic material ~~in~~to the Cretaceous depocenters in the region.

In summary, the Early Jurassic basin developed on the deformed Paleozoic basement, separated by ~~a~~ the ~~post-~~Triassic orogenic unconformity.

Provenance analysis indicates that the Early to Middle Jurassic sediments were deposited in a half-graben setting and sourced from the proximal basement of the North Kunlun terrane. This basin was subsequently inverted during the Late Jurassic, driven by the contraction and uplift of the surrounding mountains.

6.3 Switching extensional and contractional tectonics related to the subduction of Neo-Tethys

The Mesozoic era records the transition from the closure of the Paleo-Tethys Ocean to the initiation of subduction within Neo-Tethys (Wan et al., 2019). These processes are influenced by complex plate tectonic conditions, as the evolution of the Paleo- and Neo-Tethys Oceans varies significantly in their time-space patterns. The two Tethyan oceans~~seaways~~ diverge into several branches extending from Iran to Pamir, then eastward into the Tibetan Plateau (Fig. 1a). ~~Deciphering the history of the Pamir Tethyan segment, therefore, improves our knowledge of the geodynamic evolution of the entire Tethyan realm.~~

~~Two major tectonic events profoundly affected the sedimentary patterns of the Mesozoic successions in this region.~~ Episodic collisions along the southern Asian margin in the Late Triassic and then in the Late Jurassic resulted in major deformation in this region (Jolivet, 2017). ~~The regional magmatic history and the results of the provenance studies of the Jurassic basin necessitate a geodynamic scenario to explain the mechanism of an extensional tectonic event between two major contractional events.~~ Although a flat subduction model has recently been proposed to explain the regional Cretaceous magmatism in the Pamir, the mode of Jurassic tectonic processes remains poorly constrained (Chapman et al., 2018). As discussed above, the history of the Neo-Tethyan subduction events significantly varies spatially. The initiation of subduction along the Tibetan margin occurred during the Middle Triassic, leading to volcanic activities in the southern Lhasa (Wang et al., 2016; Xie et al., 2021), whereas the subduction in the Iran sector in the same orogenic belt farther west initiated later in the Early Jurassic (Wan et al., 2023). The extensive Early-Middle arc Jurassic magmatism along both continental margins indicates a synchronous flare-up of continental arcs (Fig. 11a and 11c). The bimodal volcanism (195-174 Ma) in the Gangdese arc was associated with the subsequent opening of a back-arc basin (174-156 Ma) (Fig. 11c; Kapp and DeCelles, 2019). The magmatic arc of the Sanandaj–Sirjan belt (180-140 Ma) in SW Iran was facilitated by a simultaneous progressive back-arc rift (Fig. 11a; Hassanzadeh and Wernicke, 2016; Azizi and Stern, 2019).

By comparison, compiled magmatic detrital zircons in the Pamir segment reveal that Early-Middle Jurassic magmatism was almost absent ~~there ~~(Fig. 11b; Chapman et al., 2018). ~~Available geochronological data indicate that ~~Jurassic igneous rocks surrounding the Pamir are also limited (Fig. ~~6~~7), with only basalts exposed in the North Kunlun (Kandilik) and Tianshuihai regions (Jian et al., 2019) and bimodal volcanic rock suites found in the east of Karakoram (Zhou et al., 2019). ~~Geochemical studies reveal that these ~~These coeval basaltic lavas (178-174 Ma) exhibit distinct features in their major and trace element compositions (Fig. ~~7~~6). Magmas of the basaltic lavas in the North Kunlun were dominated by within-plate~~ basalts that shared similar compositions with typical~~ OIBs (Fig. ~~7 ~~6 and 8). In contrast, basalts in the Tianshuihai to the south were dominated by back-arc MORBs (Fig. 8a-c), characterized by distinct Nb-Ta depletions (Fig. ~~7d~~6d). The scarcity of zircon-rich felsic magmas in this region evidently differs from the conditions in the western and eastern segments of the Eurasian Tethyan margins where arc magmatism developed upon continental basement. To date, the exact timing of the onset of subduction-related magmatism in the Pamir Tethyan margin remains unclear. The geochronological dataset for the Karakoram arc and the Kohistan Ladakh arc indicates that magmatic activity may have occurred as early as the Late Jurassic (Fig. 11b; Jagoutz et al., 2018; Saktura et al., 2023).

While the spatial continuity of the Tethyan suture zones from Iran into Tibet remains enigmatic, we propose that the regional Early to Middle Jurassic extension ~~expressed~~ across the southern Eurasian continental margin was a consequence of retreating subduction of the Neo-Tethyan Ocean floor. First, the transition from Cimmerian orogenic build-up (200-185 Ma) to large-scale continental extension (178-174 Ma) suggests the involvement of additional external extensional stresses, different from the classic cases of continent - continent collision (Weller et al., 2021). Secondly, the 195 Ma bimodal volcanic rocks in Karakoram and the 174 Ma MORB-like basalts in Tianshuihai have been suggested as associated with the initial opening of a back-arc basin, based on their geochemical signatures of crustal material metasomatism (Jian et al., 2019; Zhou et al., 2019). The magmatism in Pamir and Karakoram was quite similar to the extensional episodes that occurred in the southern margin of the Lhasa block, caused by accelerated slab rollback (Kapp and DeCelles, 2019). Thirdly, deposition of shallow marine carbonates was prevalent in the Pamir and Karakoram during the Middle Jurassic (Fig. 10), indicating an expansive extensional continental platform facing the ocean (Yang et al., 2017). These scenarios are analogous to the active margin of the western Pacific rim, which is characterized by a broad marginal sea with an outboard trench - subduction chain (Fig. 1a). Additionally, the Middle Jurassic extension occurred across the broad hinterlands of central Asia, which cannot be easily explained by the collapse of the Paleo-Tethyan orogenic belt (Otto, 1997).

During the Late Jurassic, this marginal extensional basin started to invert, with extensive contractional deformation of the Lower-Middle Jurassic carbonate strata and the development of a major angular unconformity (Fig. 10; Gaetani et al., 1993; Robinson, 2015). Available basement thermochronological data show widespread exhumation across the West Kunlun Mountains (Fig. 1c), as well as the reactivation of the Paleo-Tethyan sutures within the Pamir terranes (Schwab et al., 2004). The exhumation of the Triassic plutons in the South Kunlun Mountain led to the transport of debris material from the magmatic arc into the Tarim basin through braided fluvial network systems (Fig. 11b). This broad uplift event has been interpreted as retro-arc deformation and shortening related to the advancing subduction of the Neo-Tethyan Ocean (Robinson, 2015).

The subduction style along the broader strike-length of the Tethyan orogen varied from the west to the east in the Late Jurassic - Early Cretaceous. Similar to the West Kunlun Mountains, the Lhasa block to the east experienced basin inversion and contractional deformation starting by ca. 155 Ma and throughout the Early Cretaceous (e.g., Murphy et al., 1997; Ding and Lai, 2003; Kapp and DeCelles, 2019). Geological mapping has documented significant shortening strain (~ 60%) across Lhasa at this time (Murphy et al., 1997). Although the cause of this event has been debated, the magmatic lull since the earliest Cretaceous and subsequent flare-up in the Mid-Cretaceous in both regions imply that they shared a similar geodynamic setting (Fig. 11; Chapman et al., 2018). A major tectonic event involving intense folding and thrusting occurred also around 166 Ma in the South Qiangtang Block, resulting in two phases of southward retreat of the remnant seaway of the Meso-Tethys (Ma et al., 2017a, 2018). A previous study proposed that the development of Jurassic basin inversion in the Tibetan Plateau may be related to the accretion of microcontinents onto the South Qiangtang margin, driven by the northward subduction of the Bangong-Nujiang Ocean (Ma et al., 2023). Conversely, the Iranian segment to the west experienced continuous extension at the same time (Hunziker et al., 2015; Lechmann et al., 2018; Maghdour-Mashhour et al., 2021). These along-strike variations likely reflect broad geodynamic changes to, or initial conditions of, the Tethyan Ocean system that warrant future investigations. For example, variable plate convergence rates related to global tectonic configurations or the oceanic-plate age variations could result in unique tectonic events along the strike-length of the entire Tethyan orogen. Alternatively, the closure of the Bangong-Nujiang Ocean, another branch of the Tethyan system between the Lhasa and Qiangtang blocks, might have also played a significant role in along-strike variations within the Tethyan orogenic belt (Fig. 11; Yang et al., 2017; Kapp and DeCelles, 2019).

7 Conclusion

This study has concentrated on the stratigraphy and provenance of Jurassic strata in the West Kunlun Mountains to better understand the Mesozoic geological evolution of the Eurasian margin within the framework of the Tethyan geodynamics. Our investigations of the Jurassic sedimentary successions, combined with new geochronological and geochemical data from coeval basaltic lava intercalations, led to the following conclusions:

(1) A newly identified, thick sedimentary package with basaltic lava interlayers in the southern end of the Kyzyltau basin bears similarities to the Lower and Middle Jurassic sequences in their clastic compositions and structures. Zircon U-Pb dating results from basaltic lavas suggest an Early Jurassic age (~ 178 Ma) for this stratigraphic member, in contrast to a Precambrian age previously reported. This is a significant change that strongly affects the current tectonic interpretations and models.

(2) Our new geochemical data from the Early Jurassic basaltic extrusive rocks show that magmas of these basalts had typical OIB affinities, and that they lacked crustal contamination. Thus, the related magmatism likely occurred in an intraplate rifting setting and was facilitated by extensional fault systems, which significantly reduced the residence time of the ascending magmas in the crust avoiding contamination.

(3) Provenance analysis, integrating conglomerate clast lithologies with detrital zircons, indicates a significant source contribution from local basements (North Kunlun) for the Early to Middle Jurassic rift basins. In comparison, the Late Jurassic contractional event caused an uplift of the surrounding mountains in the South Kunlun and Pamir, significantly influencing the basin tectonostratigraphy and source- to -sink system.

(4) The Jurassic switching extensional and contractional tectonics in the West Kunlun Mountains and a wider region across the southern Eurasian margin are related to changes in the subduction style of the Neo-Tethyan Ocean floor, transitioning from retreating in Early - Middle Jurassic to advancing in Late

Jurassic - Early Cretaceous. Additionally, the Pamir and West Kunlun regions, as the central junction of the Tethys orogenic belt, share a comparable Mesozoic history of extensional and contractional structures with that of the Tibetan Plateau.

Declaration of Competing Interest

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

Acknowledgement

We gratefully acknowledged the constructive and insightful reviews by two anonymous reviewers and topic editor Yang Chu, and the effective editorial handling of Federico Rossetti ~~and Yang Chu~~. This work was supported by the National Natural Science Foundation of China (Grants No. U22B6002 and 42302231). H.-X. Wu received the funding of Postdoctoral Science Foundation (2023M742979 and 2024T170768).

Author Contributions

Hong-Xiang Wu: Conceptualization, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition; *Han-Lin Chen:* Funding acquisition, Investigation, Project administration; *Andrew V. Zuza: Writing – review & editing; Yildirim Dilek: Writing – review & editing; Du-Wei Qiu:* Investigation, Formal Analysis; *Qi-Ye Lu:* Investigation, Formal Analysis; *Feng-Qi Zhang:* Investigation, Formal Analysis; *Xiao-Gan Cheng:* Investigation*; Xiu-Bin Lin:* Investigation.

Data availability

The data used in this study are available in the references and Supplementary Material, including five tables and one figure.

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Supplementary Materials

Table S1: Analytical methodology.

Table S2: Zircon U-Pb data of Jurassic basalt and sedimentary rocks.

Table S3: Trace element of zircons.

Table S4: Whole rock geochemical results of Jurassic basalts.

Table S5: Jurassic conglomerate clast lithologies.

~~Table S4: Jurassic conglomerate clast lithologies.~~

~~Table S5: Whole rock geochemical results of Jurassic basalts.~~

Fig. S1: Correlations between the trace elements of Jurassic basalts.