

Editorial

Cretaceous to Cenozoic Magmatic and Crustal Evolution of the Pamir-West Kunlun Orogenic Belt

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0 INTRODUCTION

Orogenic belts are commonly built by multiple-stage processes involving oceanic subduction and continental collisions that result in the generation of magma with distinct geochemical compositions, as exemplified by Central Asian Orogenic Belts (e.g., Wang et al., 2024; Yin et al., 2024; Xiao et al., 2005) and the Tethyan tectonic domains (e.g., Chen et al., 2024; Li et al., 2024; Tao et al., 2024a; Gehrels et al., 2011; Yin and Harrison, 2000). Therefore, identifying the transition from subduction to collision in convergent orogenic belts is critical for constructing the geodynamic framework of orogenic evolution, and providing further constraints on the crustal and mantle evolution (Liu et al., 2022). Several geochemical proxies have been used to trace this transition due to the significant changes in crustal thickness as well as upper mantle geometry from convergence to post-collisional extension: (1) The transition in magma compositions from calc-alkaline to alkaline can provide a maximum estimate of the timing of collision at ancient convergent margins (e.g., Zhao et al., 2023; Liu et al., 2022); (2) Variations in oxygen fugacity and fluid fluxes can be used to identify magmatism related to different tectonic events (e.g., Xue et al., 2023; Zhang et al., 2020); (3) The onset of collision is also marked by isotopic perturbation, such as whole-rock $\epsilon_{\text{Nd}}(t)$ and zircon Hf-O values, due to increased assimilation of continental crust (e.g., Moghadam et al., 2022). These geochemical variations are direct manifestations of crustal and mantle dynamic processes, and contribute to a better understanding of continental crust formation, reworking, and long-term evolution.

The Pamir-West Kunlun Orogenic Belt (PWKOB) underwent prolonged subduction of the Neo-Tethyan oceanic lithosphere during the Cretaceous, followed by India-Asia collision and subsequent continental lithospheric

subduction during the Cenozoic. Thus, PWKOB offers a valuable natural laboratory to investigate the tectono-magmatic transition from oceanic subduction to continent-continent collision. Numerous studies have addressed aspects of the precise timings of Neo-Tethys Oceanic closure and initial India-Asia collision in the Tibetan Himalaya (e.g., An et al., 2021; DeCelles et al., 2014; Yin and Harrison, 2000), but there is a lack of research to assess how magmatism changed over geologically short time scales in the PWKOB. In addition, the processes governing continental crust evolution during this critical period are still poorly constrained. It is also unclear whether the PWKOB mantle source remained persistently enriched due to successive metasomatic events associated with the subducted Neo-Tethyan slab and the continental lithosphere of India and/or Asia. Some authors propose that the lithospheric mantle had been long-term enriched since the Cretaceous (e.g., Ke et al., 2016), while others suggest that there was a change in the nature of the mantle from enrichment to depletion during the Late Cretaceous (e.g., Chapman et al., 2018a). To address these issues, this study presents a comprehensive compilation of geochronological and geochemical data on Cretaceous – Cenozoic magmatic rocks from the PWKOB, to assess the nature and timing of the transition from oceanic subduction to continent-continent collision. Based on systematic temporal geochemical trends, we further propose that the Cretaceous–Cenozoic magmatism in the PWKOB coincided with significant crustal growth and thickening, highlighting its geodynamic significance during the transition from oceanic subduction to continental collision.

1 GEOLOGICAL SETTING

The PWKOB, situated in the northwestern part of the Tibetan Plateau and bounded by the South Tianshan to the north and the Tarim Basin to the northwest (Figure 1a), records a prolonged tectonic history. It experienced successive subduction-accretion and collisional events associated with the evolution of the Proto-Tethyan, Paleo-Tethyan, and Neo-Tethyan oceans from the Early Paleozoic to the Mesozoic, and was subsequently affected by Cenozoic crustal shortening and structural overprinting

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(e.g., Rutte et al., 2017; Robinson, 2015; Xiao et al., 2005; Schwab et al., 2004).

Magmatic activity in the PWKOB is closely linked to these tectonic events and can be divided into four major episodes: Early Paleozoic, Triassic–Jurassic, Cretaceous and Cenozoic (e.g., Tao et al., 2024a, b; Yin et al., 2020; Chapman et al., 2018a; Schwab et al., 2004). The Early Paleozoic and Triassic–Jurassic magmatism are mainly distributed in the North Pamir and South Kunlun terrane, and are related to the subduction of Proto-Tethyan and Paleo-Tethyan Oceans, respectively (e.g., Tao et al., 2024a; Xiao et al., 2005; Schwab et al., 2004). The third magmatic episode, occurring during the Cretaceous in South Pamir, has been attributed to the subduction of the Neo-Tethyan oceanic slab (Figure 1; Ma, 2024; Yang et al., 2024; Chapman et al., 2018a). Following the closure of Neo-Tethyan Ocean, the Cenozoic Indian and Asian collision has led to continued convergence and bidirectional lithospheric subduction involving both the Indian and Asian plates (e.g., Chen and Chen, 2020; Replumaz et al., 2014; Sobel et al., 2013; Zhao et al., 2010; Negredo et al., 2007), which played a key role in generating Cenozoic post-collision magmatism.

2 DATASET

To investigate the spatial and temporal distribution of magmatic rocks and the tectonic transition from Cretaceous to Cenozoic, we compiled comprehensive geochronological and geochemical datasets from the PWKOB. The dataset includes 285 geochronological ages (including U-Pb, K-Ar, and Ar-Ar dating methods) across these regions (Figure 1 and Table S1). Additionally, we compiled the geographic coordinates, lithological characteristics, geochemical data, including whole-rock major- and trace-elements, as well as Nd-Hf-O isotopic data. We excluded the whole-rock Sr isotopes due to alteration, which can lead to elevated Sr isotopic ratios in magmatic rocks (White, 1993). To better investigate the shift of lithospheric mantle nature and tectonic evolution in the PWKOB, we have divided these magmatic rocks into mantle-derived and crustal-derived rocks based on their lithology and petrogenesis from the corresponding references. Among them, the mantle-derived magmatic rocks underwent limit crustal contamination (e.g., Yang et al., 2025, 2024; Ma, 2024), and thus their isotopic changes can represent the mantle evolution processes.

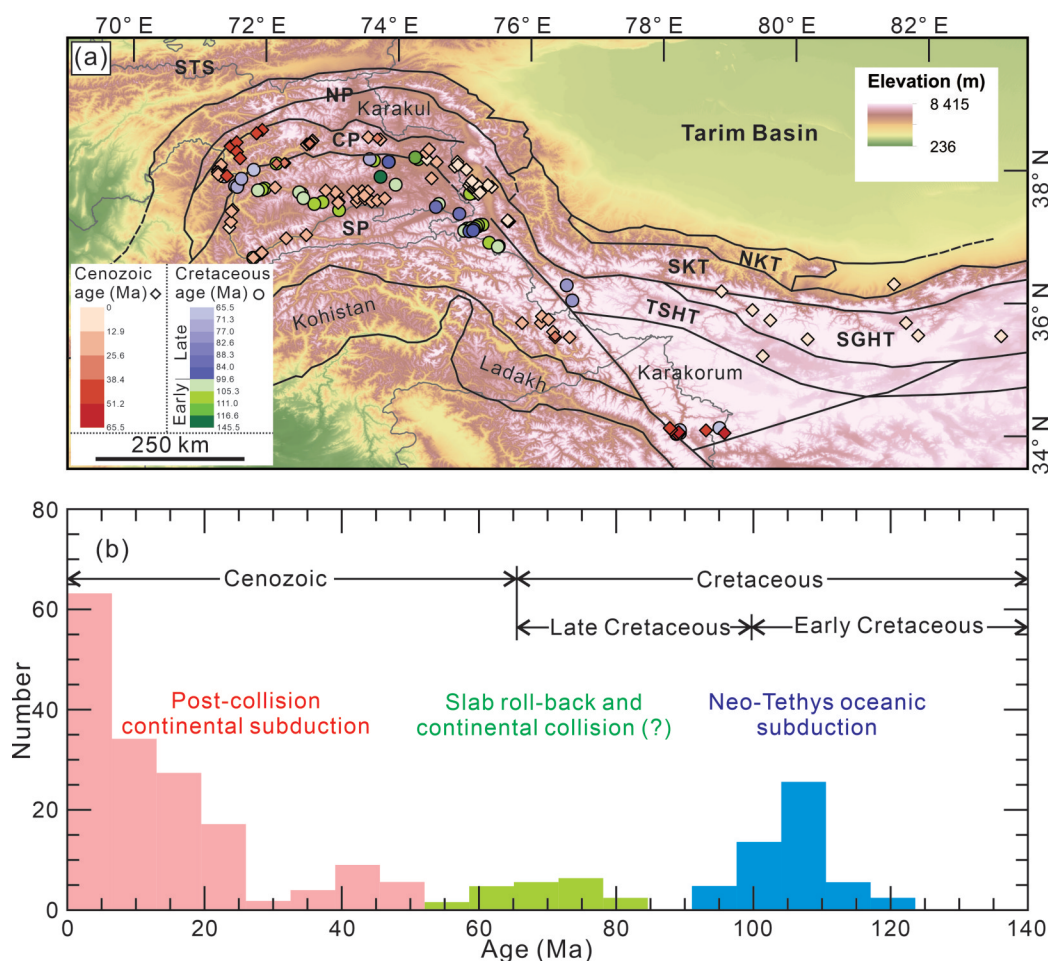


Figure 1. (a) Simplified topographic map of PWKOB, showing location of geochronological data during Cretaceous to Cenozoic; (b) histogram of Cretaceous to Cenozoic ages of PWKOB. The published geochronological data are shown in Table S1. CP. Central Pamir; NKT. North Kunlun terrane; NP. North Pamir; SGHT. Songpan-Ganze-Hoxlin terrane; SKT. South Kunlun terrane; SP. South Pamir; TSHT. Tianshuihai terrane; STS. South Tianshan.

3 DISCUSSION

3.1 Spatial and Temporal Variations of Magmatism in the PWKOB

The compilation of published geochronological data (Table S1) reveals that the PWKOB has experienced prolonged magmatism, with two principal magmatic periods, i.e., Early Cretaceous and Miocene (Figure 1b). During the Cretaceous (ca. 122–90 Ma), northward flat-slab subduction of the Neo-Tethyan oceanic slab played an important role in the generating Andean-type continental arc magmatism (Yang et al., 2024). The Early Cretaceous magmatic rocks predominantly occurred in the Shakh-dara-Aliqiu, Tashbulak-Beik and Wakhan Corridor (Southern Pamir), and exhibit a peak at ca. 106 Ma (Figure 1; e.g., Ma, 2024; Yang et al., 2024; Aminov et al., 2017). Following this period, magmatism during the Late Cretaceous–Early Cenozoic (ca. 90–50 Ma) is interpreted to correspond to roll-back of the Neo-Tethyan oceanic slab and the initiation of India-Asia continental collision. This phase of magmatism is predominantly localized in the Southern Pamir, Tianshuihai, and Karakoram terranes (Figure 1; Chapman et al., 2018a). In the Eocene–Oligocene (ca. 46–26 Ma), magmatism is concentrated in the gneiss domes and western central Pamir (Figure 1a), likely driven by mantle drips or delamination events (Tang et al., 2024; Chapman et al., 2018a). The Miocene magmatism is characterized by two distinct magmatic belts: (1) the northern belt (ca. 22–0 Ma), where magmatism migrated from the central Pamir to the WKOB; (2) the southern belt (ca. 26–8 Ma), where magmatism propagated from the southern Pamir to the Lhasa terrane (Figure 1a; Yang et al., 2025; Tang et al., 2023, 2024). These post-collisional magmatic rocks are attributed to the bidirectional subduction of the Indian-Asian lithospheres since the break-off of the Indian Plate at ca. 25 Ma (e.g., Yang et al., 2025; Wang et al., 2023; Sobel et al., 2013).

3.2 Shift of Lithospheric Mantle Nature in the PWKOB

To investigate the shifts of mantle nature beneath the PWKOB, we used zircon Hf-O and whole-rock Nd isotope data from the mantle-derived magmatic rocks (Table S1). In the first period (122–90 Ma), northward flat-subduction of Neo-Tethyan oceanic slab had migrated landward and foundered beneath the PWKOB, leading to significant flare-up of mantle-derived magmas (Yang et al., 2024; Ma et al., 2023). These magmatic rocks exhibit negative zircon Hf ($\epsilon_{\text{Hf}}(t) = -16.9$ – -2.0) and whole-rock Nd ($\epsilon_{\text{Nd}}(t) = -10.4$ – -0.9) isotopic compositions as well as high zircon O isotopes ($\delta^{18}\text{O} = 7.7\text{‰}$ – 8.2‰) (Figure 2). They generally show the geochemical signatures expected for melts generated above subduction zones, i.e., depletion in high field strength elements (HFSEs; i.e., Nb, Ta, Zr and Hf) and enrichment in large ion lithophile elements (LILEs; e.g., K, Sr and Ba) (Ma, 2024; Zhang et al., 2022; Liu et al., 2020). These features suggest an origin from enriched lithospheric mantle, modified by subduction-related melts (e.g., Yang et al., 2024). Another

high-flux eruption period of mantle-derived magmas in the Miocene (Figure 2) also have enriched Nd-Hf-O isotopes (Figure 2; $\epsilon_{\text{Hf}}(t) = -8.7$ – -3.7 ; $\delta^{18}\text{O} = 8.2\text{‰}$ – 11.2‰ ; $\epsilon_{\text{Nd}}(t) = -13.9$ – -3.0), and arc-related fingerprints (e.g., Yang et al., 2025; Wang et al., 2023; Guo et al., 2014). Such compositions are interpreted to have resulted from the incorporation of continental Indian and/or Asian lithosphere-derived materials into their mantle sources, related to opposing north-direction and south-direction continental subduction during the Cenozoic (Yang et al., 2025; Guo and Wilson, 2019).

However, there is prominent shift to more isotopically juvenile isotopic compositions at ca. 90 Ma (Figure 2), which is consistent with the observation of $\epsilon_{\text{Hf}}(t)$ values from regional detrital zircon (Figure 2a). During this period, mantle-derived magmatic rocks mostly show positive Nd-Hf and mantle-like O isotopic compositions (Figure 2; $\epsilon_{\text{Hf}}(t) = 0.4$ – 7.6 ; $\delta^{18}\text{O} = 5.1\text{‰}$ – 7.5‰ ; $\epsilon_{\text{Nd}}(t) = -3.1$ – 3.5). These rocks have been interpreted to originate from partial melting of a mixed mantle source composed of ~80% asthenospheric and ~20% lithospheric mantle (Ma, 2024). Similar to the Na-rich magmas in the Lhasa terrane, southern Tibetan Plateau, they were derived from asthenosphere-lithosphere interaction due to asthenospheric upwelling resulting from the roll-back of subducted Neo-Tethyan oceanic slab (e.g., Lu et al., 2022; Ma et al., 2013). In addition, the younger trend of magmatic rocks from north to south in the eastern part of the South Pamir further illustrates southward migration of magmatism during ca. 90–50 Ma (Figure 1a). In this scenario, upwelling asthenospheric mantle would have undergone decompression melting and induced partial melting of overlying lithospheric mantle (Ma et al., 2013). This process also led to the extension in the Karakoram terrane and Kohistan intra-arc (e.g., Chapman et al., 2018a).

In summary, we suggest the nature of mantle beneath the PWKOB exhibits transitions from enrichment to depletion to re-enrichment.

3.3 Tectonic and Crustal Evolution

Due to the lack of a Cretaceous-to-Early Cenozoic magmatic record in the WKOB, we mainly discuss the tectonic and crustal evolution of Pamir. The published data reveal systematic geochemical variations from calcic to alkalic during the Early Cretaceous to Cenozoic (Figure 3a), indicating the transition from subduction to collision (Zhao et al., 2023; Liu et al., 2022; Moghadam et al., 2022). Estimating crustal thickness is essential for predicting the timing of continental collision. Some geochemical indexes, such as Sr/Y and (La/Yb)_N ratios, provide key information about the role of pressure-sensitive residual or fractionating minerals (i.e., plagioclase and garnet or amphibole), and serve as first-order constraints on depths of magma generation and fractionation and so indirectly on crustal thicknesses (Lieu and Stern, 2019; Hu et al., 2017; Profeta et al., 2016). In general, Rb and Sr concentrations increase during magma evolution. However, the crystallization of feldspar removes Sr in moderate-

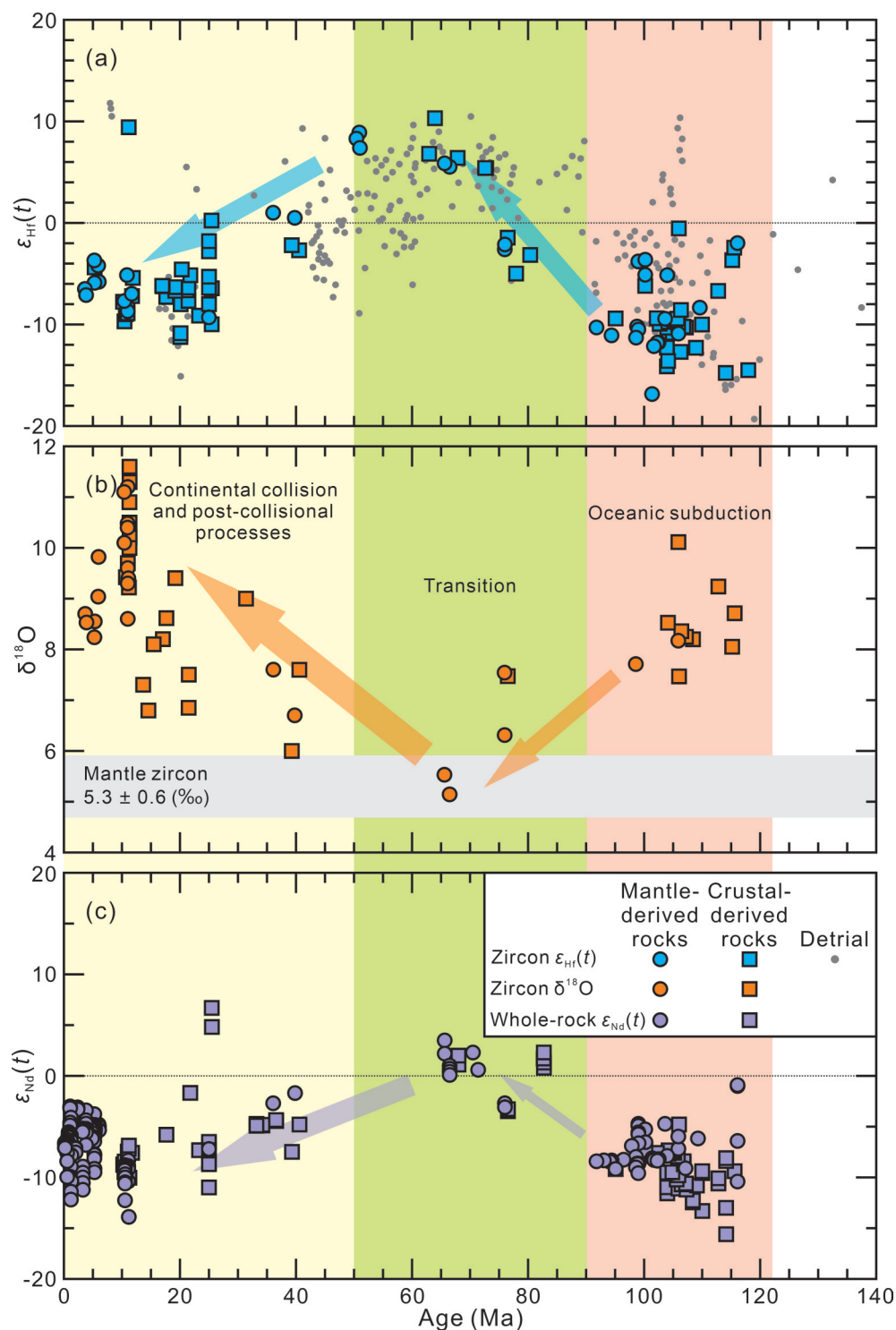


Figure 2. (a) Zircon $\epsilon_{\text{Hf}}(t)$, (b) zircon $\delta^{18}\text{O}$ and (c) whole-rock $\epsilon_{\text{Nd}}(t)$ versus crystallization ages for the magmatic rocks from PWKOB. The detailed data are shown in Table S1. The $\epsilon_{\text{Hf}}(t)$ values for detrital zircons in (a) are shown for comparison (Chapman et al., 2018a; Sun et al., 2016; Carra-pa et al., 2014).

ly fractionated magmas causing Sr/Y to decrease (Chapman et al., 2015; Gelman et al., 2014; Lee and Morton, 2015) whereas Rb remains incompatible. Thus, we employed the calculation formulas from Profeta et al. (2016) (Figures 3b–3c), under the conditions of evolving Rb/Sr (0.01–0.2), Sr/Y (< 80), SiO_2 (55 wt.%–72 wt.%) and MgO (< 6 wt.%). Based on the geochemical changes in

magmatic rocks during Early Cretaceous to Cenozoic, we propose three stages to explain the transition from subduction to collision: (1) a phase dominated by oceanic subduction (ca. 122–90 Ma); (2) a transition phase (ca. 90–50 Ma); (3) an initial collisional phase at ca. 50 Ma with subsequent post-collisional magmatism.

In the first stage, landward flat-subduction of the

Neo-Tethyan oceanic slab resulted in enriched mantle melting, crust-mantle interaction, and ancient crustal remelting (e.g., Yang et al., 2024; Ma et al., 2023). These Early Cretaceous magmatic rocks are calc-alkaline and have higher Sr/Y ratios than in the Late Triassic rocks (average of Sr/Y are 12.7; Ma et al., 2023). From 122 to 100 Ma, the Pamir experienced gradual crustal thickening, with a thickness increase from ~22 to ~35 km (Figures 3a–3b; Profeta et al., 2016). We infer that this period of crustal thickness was mainly caused by vertical accretion due to the segregation, differentiation and preservation of large igneous bodies from the mantle (Yang et al., 2024; Ma et al., 2023; Li et al., 2022). The back-arc compression and crustal shortening (i.e., horizontal accretion) formed by the subduction of Neo-Tethyan oceanic slab, is a secondary cause of crustal thickening (Yang et al., 2024; Robinson, 2015; Robinson et al., 2012, 2004).

The obvious isotopic perturbation occurred at ca. 90 Ma and Nd-Hf-O isotopes of magmatic rocks maintained relatively depleted and stable values during the Late Cretaceous–Early Cenozoic (Figure 2). In addition, research on synorogenic clastic deposits suggests that there is a southward migration of deformation in the Pamir during the Late Cretaceous, consistent with the spatial and temporal variations of magmatism (Figure 1a; Villarreal et al., 2023; Li et al., 2022; Chapman et al., 2018b). Based on these observations, we suggest that the slab roll-back of Neo-Tethyan oceanic slab and upwelling of the asthenosphere began at ca. 90 Ma. Due to the upwelling of depleted materials, the Late Cretaceous crustal-derived magmatic rocks originated from the mixed crust, which contains juvenile and ancient components (e.g., Ma, 2024; Liu L J et al., 2017). Therefore, the isotopic compositions of crustal-derived magmatic rocks also show similar trends with those of mantle-derived magmas (Figure 2). Such slab roll-back also resulted in the back-arc extension and the regional mantle lithospheric thinning (Chapman et al., 2018a), as shown of the extensional magmatism with low Sr/Y and $(La/Yb)_N$ ratios in the central Pamir (Figures 3b–3c; Ma, 2024). As for the southern Pamir, the significant increases in Sr/Y and $(La/Yb)_N$ ratios of magmatic rocks during this period (Figures 3b–3c), indicate that significant crustal thickening occurred over an extensive area before the India-Asia collision. This thickening has been proposed to be caused by regional thrusting, metamorphism and southward deformation as well as crustal shortening during the Late Cretaceous (Villarreal et al., 2023; Li et al., 2022; Chapman et al., 2018b).

Following this thickening, magmatic rocks are generally characterized by alkalic signatures (Figure 3a) with gradually decreasing Nd-Hf and increasing O isotopes (Figure 2). Research on low-temperature thermochronology suggests that rapid exhumation occurred at ca. 50 Ma (e.g., Xia et al., 2025; Liu D L et al., 2017), in response to the “hard” collision between the Indian and Asian continents. We proposed that three persistently geological pro-

cesses in the Cenozoic, i.e., post-collisional lithospheric subduction, subducted plate break-off and bidirectional subduction of continental lithospheres, led to protracted Pamir crustal and mantle melting (Figures 2b–2c). Firstly, previously subducting Neo-Tethyan oceanic slab provided the pulling force for the Indian continental subduction since the India-Asia collision, leading to the northward subduction (An et al., 2021; DeCelles et al., 2014; Replumaz et al., 2014). As a remote response to the collision, crustal thickening and shortening occurred in the North Karakoram and the central Pamir (Rutte et al., 2017; Zanchi and Gaetani, 2011), followed by the lithospheric delamination and asthenosphere upwelling, which triggered partial melting of thickened lower crust to generate the Eocene magmatic rocks (Tang et al., 2024; Chapman et al., 2018a). Secondly, the subducting Indian Plate broke off at ca. 25 Ma (e.g., Rutte et al., 2017), which caused magmatic underplating to generate the juvenile lower crust and the magmatic belts in the South Pamir (Figure 1a; Tang et al., 2023). Finally, geophysical studies suggest that Indian Plate continued to underthrust northward after break-off, and the Asian continental lithosphere started to subduct southwards at ca. 25 Ma (Kufner et al., 2016; Sobel et al., 2013; Zhao et al., 2010). With the deep collision between Indian and Asian plates, the Pamir lithosphere began to delaminate from west to east, which induced northern magmatic migration and drove the overlying Pamir crust from a compressional regime into an extensional regime from ca. 20 Ma (Yang et al., 2025; Kufner et al., 2016). Based on the increasing Sr/Y and $(La/Yb)_N$ ratios, the Cenozoic Pamir crust had significantly thickened by ca. 30 km compared to the Late Cretaceous (Figures 3b–3c). In addition, continuous convergence and continental subduction led to crustal horizontal accretion in the PWKOB during the Cenozoic. Furthermore, the intrusion and differentiation of mantle-derived magma, into the pre-existing continental crust, also resulted in significant vertical growth during this period.

In summary, we propose that Cretaceous-to-Cenozoic was critical period for crustal growth and thickening in the PWKOB.

4 CONCLUSIONS

Based on a compilation of geochronological and geochemical data from previous studies, the following conclusions can be reached regarding the distribution of Cretaceous-to-Cenozoic magmatic history and crustal evolution in PWKOB.

(1) Isotopic changes of mantle-derived magmatic rocks indicate a shift in mantle nature towards depletion during the Late Cretaceous.

(2) Geochemical variations associated with the spatial and temporal changes suggest that the roll-back of Neo-Tethyan oceanic slab and the initial India-Asia collision may occur at ca. 90 Ma and ca. 50 Ma, respectively.

(3) Continuous emplacement of mantle-derived magma as well as continental convergence indicate that the

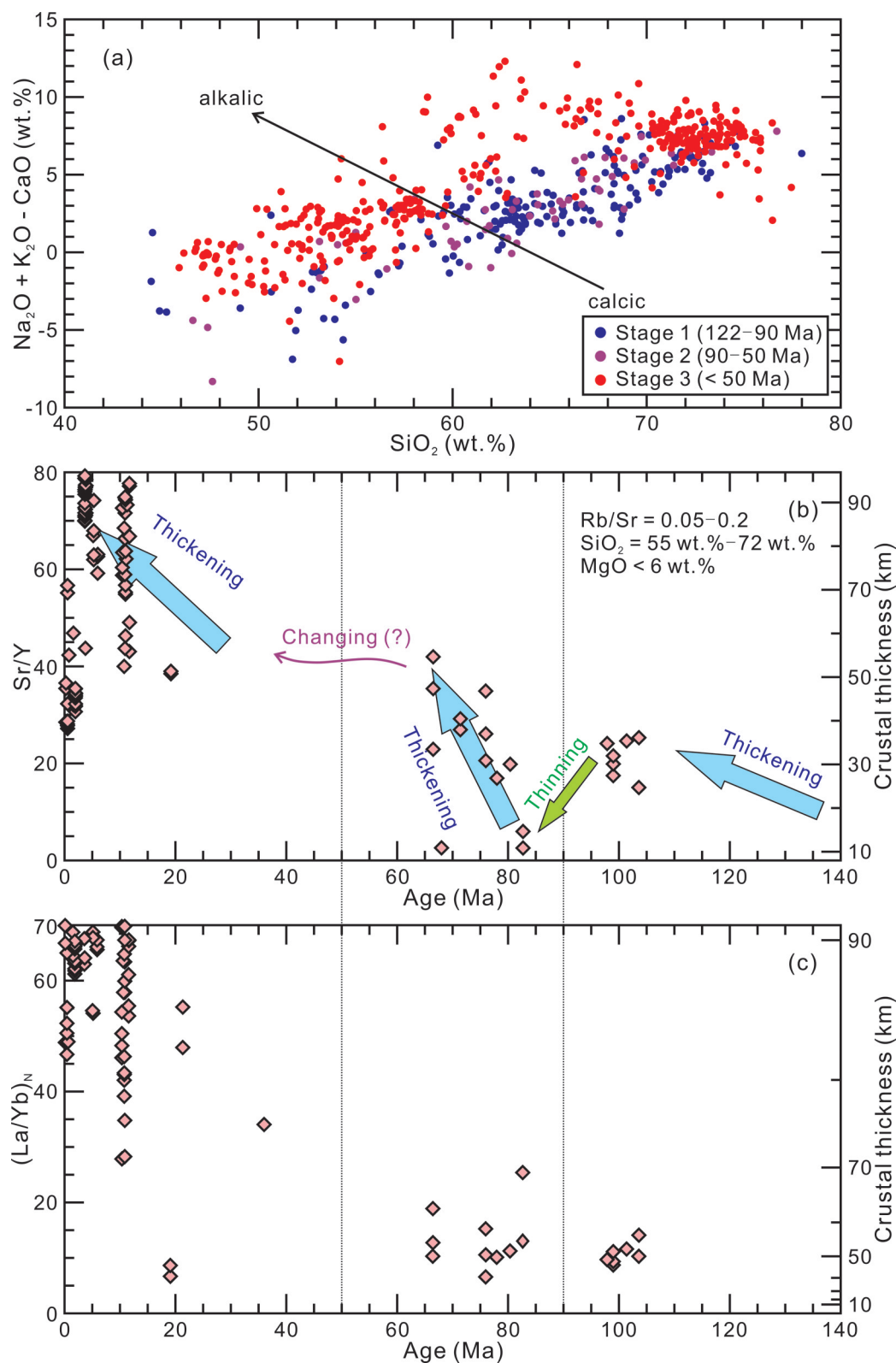


Figure 3. (a) $\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$ versus SiO_2 diagram, showing the trend from calcic to alkalic (Frost et al., 2001); (b) Sr/Y and (c) $(\text{La/Yb})_N$ ratios versus crystallization ages for the magmatic rocks from PWKOB.

Cretaceous-to-Cenozoic was a critical period for PWKOB crustal thickening and growth.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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