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**Petrogenesis of Late Miocene high Ba-Sr granitoids in eastern Pamir,
northwest Tibetan Plateau: Insights into lithospheric mantle evolution and
geodynamic processes during India-Asia bidirectional subduction**

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ABSTRACT

Cenozoic crustal thickening and surface uplift in Pamir, northwest Tibetan Plateau is controlled by India-Asia continental convergence and post-collisional subduction processes. However, the nature and evolution of post-collisional subducted lithosphere and the associated deep dynamic processes remain unclear. In this study, we report new geochemistry, mineral chemistry and geochronology for three plutons (Kuzigan, Karibasheng and Zankan) in eastern Central Pamir, to constrain their petrogenesis and help understand the associated post-collisional geodynamic processes. LA-ICP-MS U-Pb zircon dating indicates that the Kuzigan and Karibasheng plutons were emplaced in the Late Miocene (ca. 11.2–10.7 Ma). Whole-rock compositions are characterized by high Ba (1890–7550 ppm) and Sr (1050–3570 ppm) as well as crust-like Sr-Nd-Pb-Hf-O isotopic compositions, thus with a marked affinity to high Ba-Sr granitoids. Mafic to intermediate syenites have moderate $Mg^\#$ values (up to 55) as well as Cr (up to 104 ppm) and Ni (up to 59 ppm) contents, indicative of a mantle source. They have negative $\epsilon_{Nd}(t)$ (-9.22 to -8.87) and $\epsilon_{Hf}(t)$ (-11.8 to -6.49), combined with high $(^{87}Sr/^{86}Sr)_i$ (0.7099–0.7109) and $\delta^{18}O_{Zrn}$ (+9.99‰ to +10.9‰), as well as enrichment in large ion lithophile elements (LILEs, e.g. Ba, U, Th and K) and depletion in high field strength elements (HFSEs, e.g. Nb, Ta, P and Ti). These features suggest an origin from enriched lithospheric mantle, modified by subduction-related melts. Sr-Nd-Pb isotope modelling indicates contributions from both the Indian plate (~20–30%) and the Asian plate (~1–3%). Associated syenogranites exhibit a mineral assemblage and isotopic compositions similar to the syenites, as well as parallel trace-element patterns, indicating a common magma source. Their geochemical variability likely reflects fractional crystallization of clinopyroxene, biotite, rutile, feldspars and accessory phases (titanite, zircon, apatite and allanite). The Karibasheng monzogranites, by contrast, have uniformly high SiO_2 (70.9–72.5 wt.%) but lower MgO (0.36–0.48 wt.%) compared to the syenitic rocks. Their low $\epsilon_{Nd}(t)$ (-7.46 to -6.88) and $\epsilon_{Hf}(t)$ (-11.9 to -5.80), along with high $(^{87}Sr/^{86}Sr)_i$ (0.7091–0.7092) and $\delta^{18}O_{Zrn}$ (+8.75‰ to +10.7‰), point to derivation from the remelting of ancient metasedimentary rocks. Combining these data with regional geochronology and previous geophysical studies, we propose a west-to-east magmatic migration in the Central Pamir and a gradual delamination model to explain the origin of

Miocene magmas. Blocked by the subducting Indian plate, continental crust foundered resulting in asthenosphere upwelling and subsequent melting of the lithosphere, producing high Ba-Sr syenites. Given the spatial-temporal distribution of Pamir magmatism and the associated regional geology, we suggest that the deep geodynamic evolution of the lithosphere was the primary driver of Late Cenozoic tectonic uplift in the Pamir. This study highlights the deep link between continental delamination, mantle processes and generation of Miocene magmas in Central Pamir and provides new insights into episodic uplift of Pamir.

Keywords: Continental delamination; Central Pamir; high Ba-Sr granitoids; Sub-continental lithospheric mantle; Mantle metasomatism

INTRODUCTION

As originally defined by Tarney & Jones (1994), high Ba-Sr granitoids are characterized by specific geochemical features, such as high Ba (>500 ppm), Sr (>300 ppm) and light rare earth elements (LREEs), and low Rb, Nb, Ta and heavy rare earth elements (HREEs). They are thus distinct from traditional I-, S- and A-type granites (e.g., Whalen *et al.*, 1987; Chappell & White, 1992). High Ba-Sr granitoids are widespread in Archean to present-day collisional belts and mainly occur in post-collisional extensional settings (e.g., Jiang *et al.*, 2012; Lara *et al.*, 2017; de Lima *et al.*, 2021). However, their petrogenesis and magma source(s) are highly controversial (e.g. Qian *et al.*, 2003; Zhang *et al.*, 2015; Wang *et al.*, 2018). Several petrogenetic models have been proposed for their formation, including: (1) partial melting of subducted oceanic islands or plateaus (Tarney & Jones, 1994); (2) partial melting of lower crust (Ye *et al.*, 2008; Lara *et al.*, 2017; de Lima *et al.*, 2021; Lin *et al.*, 2024); (3) mixing/mingling of crustal- and mantle-derived melts (Zhang *et al.*, 2015; Wang *et al.*, 2018; Xie *et al.*, 2022; Hao *et al.*, 2024); (4) fractional crystallization of magmas derived from or partial melting from metasomatized sub-continental lithospheric mantle (SCLM) (Fowler *et al.*, 2001, 2008; Qian *et al.*, 2003; Jiang *et al.*, 2012; Ren *et al.*, 2018; Zhang *et al.*, 2019; Zhu *et al.*, 2024). One of the most striking features of these rocks is their crust-like isotopic compositions (e.g. Fowler *et al.*, 2001, 2008; Peng *et al.*, 2013) coupled with their enrichment in trace elements (Tarney & Jones, 1994). The focus of the debate on magma sources for these rocks is the origin of enriched

components and of the felsic rocks. The potential sources include fluids or melts derived from subducted oceanic slab, sediments or ancient continental crust (e.g. Jiang *et al.*, 2012; Lara *et al.*, 2017; Zhang *et al.*, 2019). Therefore, high Ba-Sr granitoids contain key information on crust-mantle interactions and are critically important in understanding post-collisional geodynamic processes (e.g. Qian *et al.*, 2003; Zhang *et al.*, 2015, 2019; Nardi *et al.*, 2021; Xie *et al.*, 2022). Furthermore, high Ba-Sr granitoids have been regarded as equivalents of Archean sanukitoids, and thus they may provide key information on the crustal growth and evolution (e.g. Fowler & Rollinson, 2012; Lin *et al.*, 2024; Zhu *et al.*, 2024).

Cenozoic collision and convergence between India and Asia have resulted in subduction of the Indian continental lithosphere since the closure of Neo-Tethys Ocean and formation of the Pamir-Tibetan Plateau (e.g. Burtman & Molnar, 1993; Yin & Harrison, 2000; Replumaz *et al.*, 2014). Based on geophysical data, some authors have proposed that the southward-dipping Asian plate subducted beneath the Pamir-Tibetan Plateau at its northern boundary (e.g. Negredo *et al.*, 2007; Zhao *et al.*, 2010; Sobel *et al.*, 2013). Thus, the Pamir-Tibetan Plateau is an ideal place to study continent-continent collision and post-collisional geodynamic processes.

The Cenozoic subduction history beneath the Pamir-Tibetan Plateau remains controversial (e.g. Schneider *et al.*, 2013; Kufner *et al.*, 2016). In response to the subduction of Cenozoic plates, voluminous and near-continuous magmatism was produced from 50 Ma to the present (e.g. Turner *et al.*, 1996; Chapman *et al.*, 2018; Guo & Wilson, 2019). Several geodynamic models have been proposed to explain the formation of these magmas, such as lithospheric delamination (e.g. Turner *et al.*, 1996; Chapman *et al.*, 2018; Li *et al.*, 2023), single (Indian) continental subduction (e.g. Jiang *et al.*, 2012) and India-Asia bidirectional subduction with related plate break-off or roll-back (e.g. Zhao *et al.*, 2009; Guo *et al.*, 2014; Guo & Wilson, 2019; Tang *et al.*, 2022a). Additional data are clearly needed which may help constrain the Cenozoic geological evolution of the region, particularly crust-mantle interaction and crustal reworking processes (e.g. Mahéo *et al.*, 2009; Zhang *et al.*, 2014; Tang *et al.*, 2022b) – precisely those recorded by high Ba-Sr magmatism.

Cenozoic post-collisional magmatic rocks are widely distributed in South and Central Pamir in the NW Tibetan Plateau (e.g. Schwab *et al.*, 2004; Chapman *et al.*, 2018) (Fig. 1A). Among them, crustal magmas occurred in the Eocene and Miocene, derived from partial

melting of juvenile lower crust to ancient middle-lower crustal materials (e.g. Tang *et al.*, 2024), and mantle-derived magmas record subduction evolution of the Neo-Tethys oceanic slab and post-collisional continental plates since the Cenozoic (e.g. Khan *et al.*, 2004; Mahéo *et al.*, 2009; Chapman *et al.*, 2018; Tang *et al.*, 2023). The Miocene (ca. 11 Ma) Taxkorgan complex (including high Ba-Sr granitoids in the Kuzigan and Karibasheng plutons) and Zankan pluton in eastern Central Pamir (e.g. Jiang *et al.*, 2012; Ke *et al.*, 2016) belong to this suite of post-collisional rocks. The petrogenesis of these plutons has been debated, with a range of models invoking partial melting of sub-continental lithospheric mantle (Jiang *et al.*, 2012; Ke *et al.*, 2016), magma mixing (Wang *et al.*, 2013) and partial melting of thickened lower crust (Yuan *et al.*, 2020a), reflecting the ongoing discussion of the petrogenesis of high Ba-Sr granites in general. In addition, there are four Cenozoic uplift events in Pamir (e.g. Robinson *et al.*, 2004, 2007; Liu *et al.*, 2017; Meng *et al.*, 2023), including the initial uplift in the Early Cenozoic (ca. 50-40 Ma), several in the Late Cenozoic (ca. 25-17 and ca. 11-7 Ma) with the final uplift after the Pliocene (<5 Ma). The relationship of these uplift events with deep lithospheric processes is however, still unclear.

In this contribution, we present new geochemical data and in situ zircon U-Pb ages, along with zircon Hf-O isotopes and whole-rock Sr-Nd-Pb isotopic data from the high Ba-Sr Kuzigan, Karibasheng and Zankan plutons. Combined with previously published data, we refine the magmatic age and further elucidate the association between magmatism and uplift. Additionally, we investigate the magma sources and melting mechanisms, and develop a robust model that provides new insights on Late Cenozoic tectonic evolution and plateau uplift in Pamir.

GEOLOGICAL SETTING AND SAMPLING

Geological setting

Pamir, at the western end of the India-Asia collision zone, is divided into three tectonic units (i.e. the North, Central and South Pamir) by the Paleozoic Tanyamas and Mesozoic Rushan-Pshart sutures (Fig. 1B; Burtman & Molnar, 1993; Schwab *et al.*, 2004; Angiolini *et al.*, 2013; Robinson, 2015). The region experienced long-term accretion and collision during the Early Paleozoic-Mesozoic and suffered Cenozoic deformation and structural overprinting to form its present-day spectacular landscape (Robinson *et al.*, 2012; Robinson, 2015; Rutte *et*

149 *al.*, 2017). North Pamir is a Paleozoic accretionary complex (Schwab *et al.*, 2004; Robinson *et*
150 *al.*, 2012), broadly correlative to the West Kunlun Terrane (Fig. 1B; Burtman & Molnar, 1993).
151 Central and South Pamir rifted from the northern margin of Gondwana during the Late
152 Carboniferous to Early Permian (Burtman & Molnar, 1993; Angiolini *et al.*, 2013) and are
153 laterally equivalent to the Qiangtang Terrane in Tibet (Fig. 1B, Robinson *et al.*, 2012). South
154 Pamir is geologically connected to the SW-Hindu Kush and SE-Karakorum terranes, which are
155 further subdivided by a system of Cenozoic extensional detachments and separated from the
156 Kohistan-Ladakh arc by the Shyok suture (Angiolini *et al.*, 2013) (Fig. 1B). Pamir moved
157 approximately 300 km northward relative to Tibet during the Cenozoic (Fig. 1A; e.g. Robinson
158 *et al.*, 2007; Sobel *et al.*, 2011, 2013). This relative displacement was mostly accommodated
159 along east-west thrust and strike-slip faults (i.e. Karakoram fault and Kashgar-Yecheng transfer
160 system) within the orogenic flanks (Fig. 1B; e.g. Molnar & Tapponnier, 1975; Cowgill, 2010).

161 Northward subduction of the Neo-Tethys oceanic slab continued through the Late Triassic
162 and Late Cretaceous in Pamir (Jiang *et al.*, 2014; Zhu *et al.*, 2015; Chapman *et al.*, 2018; Yang
163 *et al.*, 2024). Final closure of the Neo-Tethys Ocean and initial India-Asia collision are
164 generally considered to occur at ca. 65-50 Ma (DeCelles *et al.*, 2014; An *et al.*, 2021; van
165 Hinsbergen, 2022). Subsequently, the Indian continental lithosphere began to subduct
166 northward, and slab break-off of the Indian lithosphere beneath Pamir and the Tibetan Plateau
167 occurred at ca. 25 Ma (e.g. Mahéo *et al.*, 2002; Williams *et al.*, 2004; Kufner *et al.*, 2016). Since
168 then, the Indian lithosphere has been subducting continuously to the present-day at a relatively
169 shallow angle. The northward underthrusting of the Indian plate to the present-day
170 progressively decreases from west to east at different locations (i.e., Hindu Kush-Karakorum
171 in Pamir and Bangong-Nujiang suture in Tibet (Burtman & Molnar, 1993; Yin & Harrison,
172 2000; Negredo *et al.*, 2007). To the north, the deep geodynamic evolution of the Asian
173 continental lithosphere is still controversial. Geological and geophysical evidence suggests that
174 the Asian continental lithosphere has been subducting southward beneath Pamir and northern
175 Tibet since ca. 25 Ma (e.g. Negredo *et al.*, 2007; Zhao *et al.*, 2010; Sobel *et al.*, 2013). However,
176 other researchers propose that the south-dipping slab represents delaminated Pamir lower crust,
177 rather than intracontinental subduction of the Asian lithosphere (e.g. Chapman *et al.*, 2018;
178 Schneider *et al.*, 2019; Li *et al.*, 2023).

Cenozoic magmatism has constructed two distinct magmatic belts: one in the Central Pamir-to-West Kunlun terrane and the other in the Karakorum-to-Lhasa terrane (Tang *et al.*, 2023) (Fig. 1B). The southern Karakorum-to-Lhasa terrane belt is related to the break-off of the Indian continental lithosphere and records an eastward migration of magmatism since ca. 25 Ma (Mahéo *et al.*, 2002, 2009; Stearns *et al.*, 2015; Tang *et al.*, 2023). Abundant Eocene-Miocene igneous rocks are observed in the Central Pamir Cenozoic gneiss domes (Chapman *et al.*, 2018; Tang *et al.*, 2024). Notably, Eocene magmatism (ca. 46-33 Ma) is sporadically distributed in the Yazgulom, Sarez and Muskol gneiss domes (Stearns *et al.*, 2015; Hacker *et al.*, 2017; Chapman *et al.*, 2018). This magmatism was followed by a magmatic lull during the Oligocene in northern Pamir (Chapman *et al.*, 2018), which was subsequently terminated by Miocene (ca. 22-10 Ma) magmatism, including leucogranite plutons, dikes and sills (Fig. 1B) (Stearns *et al.*, 2015; Chapman *et al.*, 2018; Tang *et al.*, 2024). Additionally, a series of intrusive complexes (Taxkorgan, Zankan, and Dunkeldik complex) was emplaced during this time (Fig. 1C) (e.g. Hacker *et al.*, 2005; Jiang *et al.*, 2012; Chapman *et al.*, 2018). Finally, K-rich magmatic rocks, formed from ca. 8 Ma to the present, are found in the West Kunlun and eastern Pamir regions (e.g. Guo *et al.*, 2014; Yuan *et al.*, 2020b; Tang *et al.*, 2022a; Wang *et al.*, 2023). Along with Miocene magmatism in Central Pamir, these rocks suggest the formation of a magmatic belt extending from western Central Pamir to West Kunlun over the past 20 m.y. (Fig. 1B).

Sampling and descriptions

Several Miocene plutons (including Kuzigan, Karibasheng and Zankan plutons), distributed parallel to the Karakoram fault (KKF) along the eastern margin of Central Pamir (Figs. 1B-1C; Lin *et al.*, 2006), are intruded into Permian strata and Proterozoic metasediments. The Kuzigan and Zankan plutons are mostly comprised of syenites and syenogranites, that exhibit gradual contacts without distinct boundaries (Ke *et al.*, 2006, 2016; Tang *et al.*, 2022b), while monzogranites are mainly found in the Karibasheng pluton. Previous studies have demonstrated that these all have similar crystallization ages, indicating synchronous magmatic activity (Jiang *et al.*, 2012; Ke *et al.*, 2016; Tang *et al.*, 2022b). In addition to the new data presented here, we also summarize published geochemical data to constrain their genesis (Table

S3, Ke *et al.*, 2006; Jiang *et al.*, 2012; Wang *et al.*, 2013; Yuan *et al.*, 2020a; Tang *et al.*, 2022b; Liu *et al.*, 2024). Additionally, the geochemically-similar Dunkeldik complex, located the west of the Taxkorgan complex (Fig. 1C), contains alkali basalt, trachyte, syenite and carbonatite, along with xenoliths from the deep crust and lithospheric mantle (Hacker *et al.*, 2005; Gordon *et al.*, 2012; Hong *et al.*, 2019).

A total of twenty-one samples was collected from the east Central Pamir, including 6 syenites from Kuzigan, 2 syenites from Zankan, 4 syenogranites from Kuzigan, and 9 monzogranites from Karibasheng (Fig. 1C). They all exhibit massive and fine- to medium-grained granitic textures (Fig. 2). The syenite samples (WK1604 and WK2303) and syenogranites (WK1604) share the same mineral assemblage of K-feldspar, quartz, plagioclase, minor biotite and clinopyroxene with accessory titanite, apatite, zircon, and allanite (Figs. 2A-2B and 2D-2F), but with different modes, e.g. clinopyroxene is more abundant in syenites (10–25 vol.%) than in the syenogranites (~3–5 vol.%). The monzogranite (WK1605 and WK2301) consists of plagioclase (35–45 vol.%), K-feldspar (30–35 vol.%), quartz (20–25 vol.%) and biotite (~5 vol.%) with accessory apatite, zircon, titanite, and allanite (Fig. 2C and 2G-2H). Plagioclase in these rocks occurs as euhedral to subhedral laths and is characterized by polysynthetic twinning. K-feldspars are euhedral to subhedral with plagioclase and biotite inclusions. The subhedral clinopyroxenes in the syenites and syenogranites are green to dark green, with 0.2-2.0 mm in length, and sometimes contain inclusions of biotite (Figs. 2D-2F).

RESULTS

Analytical methods for zircon U–Pb and Hf–O isotope ratios, plus whole-rock and mineral geochemistry are given in the Text S1.

Zircon U-Pb geochronology

Four representative samples (WK1603, WK1604, WK1605, and WK2301) from Kuzigan and Karibasheng plutons were selected for zircon LA-ICP-MS and results are presented in Table S1. All zircon crystals are generally euhedral, and are prismatic, transparent, and colorless with length/width ratios of 3:1 to 3:2. They display well-developed concentric oscillatory zoning in cathodoluminescence (CL) images and high Th/U ratios (typically > 0.2)

(Fig. 3), indicative of a magmatic origin (Belousova *et al.*, 2002).

Seventeen zircon analyses from the syenogranite sample WK1603 yielded concordant $^{206}\text{Pb}/^{238}\text{U}$ ages of 9.6 to 11.7 Ma, with a weighted mean age of 10.7 ± 0.3 Ma (MSWD = 0.82) (Fig. 3B). Seventeen zircon analyses from syenite sample WK1604 yielded concordant $^{206}\text{Pb}/^{238}\text{U}$ ages of 9.9 to 12.7 Ma with a weighted mean age of 11.0 ± 0.4 Ma (MSWD = 1.07) (Fig. 3A). Twenty concordant analyses of zircons from monzogranite sample WK1605 yielded a weighted mean age of 11.2 ± 0.2 Ma (MSWD = 0.83) (Fig. 3C). Eighteen spots from monzogranite sample WK2301 yielded concordant ages between 10.5–11.4 Ma, with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 11.0 ± 0.1 Ma (Fig. 3D). Combined with published geochronological data (e.g. Ke *et al.*, 2006, 2016; Jiang *et al.*, 2012; Wang *et al.*, 2013; Yuan *et al.*, 2020a; Tang *et al.*, 2022; Liu *et al.*, 2024), these results indicate that the major lithologies of the Kuzigan, Karibasheng and Zankan plutons were emplaced during the Late Miocene at ca. 11 Ma.

Mineral compositions

Major oxide data for clinopyroxene, plagioclase, K-feldspar and biotite are listed in Table S2.

Clinopyroxene

Clinopyroxene occurs in both syenites and syenogranites, typically with K-feldspar rims (Figs. 2D–2F). They mostly plot within the hedenbergite-diopside field, with $\text{En}_{17-36}\text{Fs}_{13-33}\text{Wo}_{42-48}$ (Fig. 4A). These clinopyroxenes are characterized by consistently low SiO_2 (49.6–52.5 wt.%) and Al_2O_3 (0.24–2.06 wt.%) along with relatively high CaO (20.8–23.7 wt.%). From core to rim, they show decreasing $\text{Mg}^\#$, MgO and CaO, while FeO^T increases (Fig. 4B; Table S2). To estimate the potential temperature and pressure, the thermobarometer calculations using the clinopyroxene-melt compositions from Putirka (2008) was applied, yielding temperatures ranging from 767–1222 °C and pressures from 1.90–19.9 kbar (Table S2).

Biotite

Biotite from the syenites and monzogranites is predominantly Mg-biotite (Fig. 4C), characterized by low Al_2O_3 (11.8–13.3 wt.%) and a low Al-saturation index (A/CNK of 1.16–

1.17). Combined with high MgO (13.5–17.3 wt.%) and FeO^{T} (14.7–18.9 wt.%), this indicates that relatively low Al and high Mg in the corresponding melt. CaO contents are typically very low, while $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$ ratios remain consistent (0.66 to 0.69 in monzogranites and 0.59 to 0.70 in the syenites), indicating that the biotite is primary and has not undergone significant chloritisation by post-magmatic deuteric alteration or meteoric fluid circulation (Kumar & Pathak, 2010). Crystallization temperature and pressure were estimated using the machine learning based geothermometer and geobarometer developed by Li & Zhang (2022) (Table S2). The syenites yielded temperatures of 1023–1074 °C and pressures of 8.48–10.8 kbar, while the monzogranites exhibited considerably lower estimates of 832–842 °C and 3.30–3.80 kbar.

Feldspar

Representative plagioclase and K-feldspar from syenites and granitoids were analyzed from core to rim (Table S2). The plagioclase comprises albite and oligoclase, with variable end-members compositions ($\text{An} = 5.5\text{--}27.7$ mol.%, $\text{Ab} = 70.4\text{--}93.6$ mol.% and $\text{Or} = 0.9\text{--}5.2$ mol.%), whereas the alkali-feldspar is sanidine with more limited compositional ranges of $\text{Or} = 82.6\text{--}93.4$ mol.%, $\text{Ab} = 6.4\text{--}17.3$ mol.% and $\text{An} = 0\text{--}0.3$ mol.% (Fig. 4D; Table S2). For granitoids, plagioclase grains typically show a decrease in An from core to rim, while those of syenite show more consistent compositions (Fig. 4D).

Major and trace element geochemistry

Twenty-one representative samples from the Kuzigan, Karibasheng and Zankan plutons were selected for whole-rock major and trace element analyses. The results, along with previously published data (Ke *et al.*, 2006; Jiang *et al.*, 2012; Wang *et al.*, 2013; Yuan *et al.*, 2020a; Tang *et al.*, 2022; Liu *et al.*, 2024) are listed in Table S3.

The syenites display a wide compositional range from mafic to felsic, with SiO_2 varying from 49.9 to 70.3 wt.%, Fig. 5A). They have consistently high K_2O (6.04–9.45 wt.%) and total alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O} = 9.58\text{--}13.2$ wt.%). All samples exhibit high $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios (1.71–6.33) and plot in the shoshonite series (Fig. 5B). The syenites also display variable Al_2O_3 (13.0–16.4 wt.%), MgO (0.30–4.46 wt.%), $\text{Fe}_2\text{O}_3^{\text{T}}$ (2.02–7.09 wt.%), CaO (1.62–7.85 wt.%) and TiO_2 (0.33–1.26 wt.%), with variable $\text{Mg}^{\#}$ (20–55). Their A/CNK values (0.57–0.98) indicate a

peraluminous-peralkaline affinity (Fig. 5C). The granites, in contrast, are more felsic, with higher SiO₂ (70.6–72.5 wt.%), Al₂O₃ (13.7–15.5 wt.%) and total alkalis (Na₂O + K₂O = 8.34–10.5 wt.%), but lower TiO₂ (0.18–0.32 wt.%), Fe₂O₃^T (1.31–1.66 wt.%), MgO (0.21–0.48 wt.%) and CaO (1.28–1.84 wt.%). They are high-K calc-alkaline to shoshonitic (Fig. 5B) and exhibit metaluminous to weakly peraluminous affinity with A/CNK ratios of 0.87–1.13 (Fig. 5C). Combined with published data, all the Miocene samples exhibit extremely high Ba (701–15570 ppm) and Sr (503–6582 ppm), analogous to those of high Ba-Sr granitoids (Fig. 5D; Tarney & Jones, 1994; Fowler *et al.*, 2008; Peng *et al.*, 2013). Both syenites and granites display near parallel trace-element patterns (Fig. 6), characterized by enrichment of LREEs ((La/Yb)_N = 26–129) and relatively flat HREEs ((Gd/Yb)_N = 2.92–4.80), with weak negative Eu anomalies (Eu/Eu* (Eu_N/√(Sm_N × Gd_N)) = 0.70–0.92) (Fig. 6A). On a primitive-mantle normalized diagram, these samples show consistent patterns with marked enrichment of large ion lithophile elements (LILEs; such as Ba, Th, Rb, U, and K) relative to high field strength elements (HFSEs) and HREE, along with pronounced negative Ta, Nb, P and Ti anomalies (Fig. 6B).

Whole-rock Sr-Nd-Pb isotopes

The whole-rock Sr-Nd-Pb isotopic compositions are provided in Table S3. Initial Sr-Nd-Pb isotopic values are calculated using a crystallization age of 10 Ma. All samples exhibit similar, highly enriched initial ⁸⁷Sr/⁸⁶Sr isotopic ratios (0.7091–0.7109; Fig. 7A) and radiogenic Pb isotopic compositions ((²⁰⁶Pb/²⁰⁴Pb)_i = 18.32–18.59; (²⁰⁷Pb/²⁰⁴Pb)_i = 15.67–15.70; (²⁰⁸Pb/²⁰⁴Pb)_i = 39.02–39.31), which plot to the left side of the Northern Hemisphere reference line (NHRL) (Figs. 7C–7D). The syenites and syenogranites display comparable Nd isotopic signatures (ε_{Nd}(*t*) = -9.22 to -8.87), which are slightly more negative than those of the monzogranites (ε_{Nd}(*t*) = -6.88 to -7.46) (Figs. 7A–7B). Furthermore, the syenites and syenogranites have Sr-Nd-Pb isotopic compositions similar to those of the Dunkeldik complex (including syenites and carbonatites), but distinct from those of the Western Kunlun potassic and ultrapotassic rocks (Figs. 7A and 7C–7D).

Zircon Hf-O isotopic compositions

Zircon Lu-Hf and O isotopic compositions are given in Table S4. Initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios and Hf model ages are calculated using individual crystallization ages. All samples are characterized by negative $\varepsilon_{\text{Hf}}(t)$ (-5.4 to -12.0) and old Hf model ages ($T_{2\text{DM}} = 1.85\text{--}1.43$ Ga) (Fig. 8A). They have similar zircon $\delta^{18}\text{O}$ (i.e., 9.99‰–10.9‰, 8.35‰–10.2‰, and 8.75‰–10.7‰, for syenite, syenogranite and monzogranite respectively), which are higher than those of igneous-origin zircons in equilibrium with mantle-derived magmas ($5.3 \pm 0.6\text{‰}$, 2SD; Valley *et al.*, 1998) (Figs. 8B–8C).

DISCUSSION

Petrogenetic models for high Ba-Sr granitoids

High Ba-Sr granitoids worldwide exhibit consistent geochemical features: (1) enrichment in LILEs (such as Ba, Sr, K_2O and LREEs) and depletion in Nb, Ta, and HREE; and (2) crust-like isotopic compositions (Tarney & Jones, 1994; Peng *et al.*, 2013). In general, high Ba-Sr granitoids that are derived from partial melting of subducted oceanic islands, plateaus or mafic lower crust, have adakitic characteristics, since they form under high-pressure conditions (Fig. 9A; Tarney & Jones, 1994; Wang *et al.*, 2014; de Lima *et al.*, 2021). These rocks typically have low MgO or $\text{Mg}^\#$ values, plotting within the field of experimental melts for meta-basalts and eclogites (Fig. 9B; Rapp *et al.*, 1999; Martin *et al.*, 2005). Additionally, those derived from crustal melting are characterized by high Na_2O contents (3.3–5.6 wt.%) and low $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios (0.7–1.8, with an average ratio of 1.0) (Fig. 9C; Ye *et al.*, 2008; Wang *et al.*, 2014; Lara *et al.*, 2017; de Lima *et al.*, 2021). Although, regional studies indicate the absence of a subducting oceanic slab or plateau beneath the Pamir region (e.g. Burtman & Molnar, 1993), the Karibasheng monzogranites exhibit geochemical features consistent with crust-derived high Ba-Sr granitoids, as discussed below.

Recent studies suggest that some high Ba-Sr granitoids can form by magma mixing (Zhang *et al.*, 2015; Wang *et al.*, 2018; Hao *et al.*, 2024). In this scenario, mafic magma injection into a felsic magma chamber induces melting of lower crustal materials, which along with mantle-derived materials, contribute to the high Ba-Sr source (Zhang *et al.*, 2015). These high Ba-Sr granitoids typically display both crustal- and mantle-like features, including variable $\text{Mg}^\#$ values, and high Na_2O contents (Figs. 9B–9C). Magma mixing often produces linear arrays in

element ratio diagrams and generates disequilibrium textures and mineral compositions in intermediate rocks (Zhang *et al.*, 2015; Wang *et al.*, 2018). However, the petrological and geochemical characteristics of the rocks in the present study are inconsistent with those expected from magma mixing. Moreover, the absence of mafic microgranular enclaves further suggests that magma mixing did not play a significant role (Frey & Prinz, 1978). Thus, we conclude that magma mixing was negligible in the formation of these rocks.

Several lines of evidence indicate that the syenites and syenogranites from Kuzigan and Zankan plutons were derived from similar sources contemporaneously. Firstly, these rocks show comparable crystallization ages (ca. 11 Ma; Jiang *et al.*, 2012; Ke *et al.*, 2016; Tang *et al.*, 2022b). Secondly, they form a continuous compositional spectrum with SiO₂ ranging from 48.9 to 74.8 wt.% (Fig. 5A), and exhibit near parallel trace-element patterns (Fig. 6). Thirdly, they show close similarities in zircon Hf-O isotopic compositions and whole-rock Sr-Nd-Pb isotopic compositions (Figs. 7, 8 and 9C-9D). Their mineral assemblages are also compositionally similar, albeit with different proportions (Fig. 2), further suggesting a petrogenetic link. The compositional difference between silica-undersaturated and silica-saturated samples may reflect variations in the degrees of partial melting, source heterogeneity, or fractional crystallization of cogenetic magmas (e.g. Riishuus *et al.*, 2008; Nandedkar *et al.*, 2014; Xu *et al.*, 2021; Qi *et al.*, 2022). However, the La/Sm versus La diagram suggests that fractional crystallization, rather than partial melting, played a dominant role in formation of the high Ba-Sr syenites and syenogranites (Fig. 9E). In contrast, the Karibasheng silica-saturated monzogranites, which have higher SiO₂ contents and more radiogenic Nd isotopes, represent a distinct source (Fig. 9E). Their consistent La contents but variable La/Sm ratios (Fig. 9F) further suggest that these rocks formed via partial melting of a different magma source.

Petrogenesis of the high Ba-Sr syenite-syenogranites

Assimilation and fractional crystallization (AFC) effect

In addition to the nature of magma sources, the compositions of continental magmas may be influenced by various factors, including the conditions of partial melting, shallow-level fractional crystallization and crustal contamination (e.g. DePaolo, 1981). As noted above, the Miocene plutons (including Kuzigan, Karibasheng and Zankan plutons) exhibit high Ba-Sr

affinities. Previous studies have shown that AFC processes may play a significant role in the petrogenesis of high Ba-Sr granitoids, modifying their elemental and isotopic compositions (e.g. Fowler *et al.*, 2001, 2008). Thus, it is crucial to evaluate the relative roles of crustal contamination and fractional crystallization before constraining the nature of the magma sources.

All the high Ba-Sr granitoids exhibit negative Nb-Ta-Ti anomalies in multi-element mantle-normalized plots (Fig. 6B), which is consistent with a subduction-related origin but can also arise from crustal contamination (Rudnick & Gao, 2003). Typically, crustal contamination of such elementally-enriched rocks would dilute LILEs and LREEs contents (Rudnick & Fountain, 1995; Taylor & McLennan, 1995). Additionally, crustal assimilation during magma ascent or emplacement tends to increase $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ratios and decrease $\epsilon_{\text{Nd}}(t)$ values with increasing SiO_2 (e.g. Rudnick & Fountain, 1995; Fowler *et al.* 2001, 2008). However, the studied high Ba-Sr granitoids exhibit consistent trace element distribution patterns (Fig. 6). Their incompatible elements (e.g. Ba = 701-15570 ppm, Sr = 503-6582 ppm) far exceed those of average continental crust (Ba = 390 ppm, Sr = 325 ppm; Rudnick & Fountain, 1995). Moreover, the whole-rock Sr-Nd isotope compositions of these high Ba-Sr granitoids from the Pamir region are poorly correlated with SiO_2 , indicating limited evidence for crustal interaction (Figs. 9D-9C). The $\delta^{18}\text{O}$ values of the local wall rock (gneissic granites, $\delta^{18}\text{O} = 8.5\text{‰}$; Ke *et al.*, 2016) are lower than those of the high Ba-Sr granitoids (Fig. 8B), further suggesting that significant crustal contamination or assimilation is unlikely.

Given the limited evidence for crustal contamination, the variable but coherent major and trace element compositions suggest that fractional crystallization likely played a significant role in the petrogenesis of these rocks (Fig. 10). Mantle-derived primary melts typically have high Ni (>300 ppm), Cr (> 750 ppm) and $\text{Mg}^\#$ (>68) values (Herzberg & O'Hara, 2002). In contrast, the syenites have lower Cr (<104 ppm), Ni (<59 ppm) and $\text{Mg}^\#$ (12-68) values, indicating early olivine and clinopyroxene fractionation. The trends in major element compositions (i.e. MgO versus FeO^T) from core to rim within clinopyroxene further support clinopyroxene fractionation in syenites and syenogranites (Figs. 4B). Negative correlations between SiO_2 and other major oxides (e.g. Fe_2O_3^T , MgO , CaO , and TiO_2) strongly indicate the fractionation of mafic minerals (e.g. clinopyroxene and biotite) and Ti-

containing minerals (rutile) during magma evolution (Figs. 10A-10D). Additionally, the decreasing clinopyroxene and rutile contents from syenites to syenogranites (Jiang *et al.*, 2012; Ke *et al.*, 2016) are also consistent with this scenario. The negative relationship between P_2O_5 and SiO_2 also supports the fractionation of apatite under phosphorus-saturated conditions (Fig. 10G). Biotite fractionation is further suggested by the V–Th correlation (Fig. 10H; Bea *et al.*, 1994). This mineral fractionation process is corroborated by the negative Cr–Ni correlation (Fig. 10J), indicating that the removal of mafic minerals, rutile and apatite resulted in lower concentrations of $Fe_2O_3^T$, MgO, CaO, TiO_2 and P_2O_5 in the silica-rich melts.

Several lines of evidence suggest that plagioclase was not involved in the early stages of magma evolution but became a significant fractionating phase later in the process. The increase in Al_2O_3 , Na_2O and $(K_2O + Na_2O)$ at low SiO_2 , followed by decrease with an inflection at ca. 64 wt.% SiO_2 (Figs. 10E-10F and 5A) suggests late-stage plagioclase fractionation. This is further confirmed by the absence or weak expression of Eu anomalies in rocks with $SiO_2 < 64$ wt.%, compared to more pronounced negative Eu anomalies in the more silicic rocks (Fig. 10I). K-feldspar crystal fractionation towards the end of the differentiation processes accounts for the relatively low Ba and Sr contents in the high-silica rocks (Fig. 10L). Accessory minerals such as titanite, zircon, apatite and allanite strongly partition Ce (and other REEs) and Nb (Fig. 10K), which could explain the differences in ΣREE between analyzed syenites and granitoids (Fig. 6; Bea, 1996). Thermobarometry calculations based on clinopyroxene compositions indicate two pressure ranges: 15.5–19.9 kbar (52–66 km) and 1.90–8.65 kbar (10–31 km) (Table S2). Pressure (kbar) was converted to depth (km) using a regression fit based on PREM (depth (km) = $14.6 + 29 \cdot P(GPa) - 0.157 \cdot [P(GPa) - 8.4]^2$; Anderson, 1989). Hence, it is inferred that the first stage of fractional crystallization occurred within a shallow magma chamber, while the second stage took place during magma ascent and lateral propagation (Tang *et al.*, 2022b).

Constraints on the mantle sources of the high Ba-Sr syenites

Metasomatism and mantle mineralogy

The Pamir high Ba-Sr syenites, characterized by low SiO_2 and moderate MgO with elevated-Mg[#] values along with moderate Cr and Ni concentrations, are inferred to be mantle-derived. A distinctive geochemical feature of these rocks is their significant enrichment in

incompatible elements (Ba, Sr, K, and LREEs; Fig. 6A), coupled with notable depletions in Nb, Ta, and Ti (Fig. 6B). The syenites also display enriched Sr-Nd-Pb and zircon Hf-O isotopic compositions (Figs. 7 and 8). Their low Nb/U (0.65-9.37) and Ce/Pb (0.16-21.1, with an exception of 73.4 for sample 019H) ratios, in comparison with oceanic basalts (MORB & OIB: Nb/U=47±10; Ce/Pb=25±5) (Hofmann *et al.*, 1986), suggest that these rocks are not derived from typical asthenospheric mantle. Instead, these geochemical features point to an enriched sub-continental lithospheric mantle (SCLM), metasomatized by subduction-related processes, such as fluids or melt inputs from subducted continental or oceanic crust and/or sediments (e.g. Pearce, 1982; Hawkesworth *et al.* 1997). Subduction-related hydrous melts from the continental crust or sediment are particularly effective in transporting HFSEs (e.g. LREEs, Nb and Th) to the mantle (e.g. Plank, 2005). In contrast, the enrichment in LILEs such as K, Ba, Rb, and Sr, along with fluid-mobile trace elements (e.g. U and Pb), is typically attributed to aqueous fluids (e.g. Hawkesworth *et al.*, 1997; Hermann *et al.*, 2006). Thus, fluid-mobile/immobile trace element ratios, and incompatible element signatures (e.g. LILE/LREE and $(La/Sm)_N$) effectively reflect subduction-related metasomatic imprints on the mantle source (Class *et al.*, 2000; Woodhead *et al.*, 2001). For the high Ba-Sr syenites, low Sr/Th and Rb/Nb ratios, coupled with high $(La/Sm)_N$ and Th/Yb ratios (Figs. 11A-11B), suggest that subduction-related sediment melts were the primary agents of mantle metasomatism. Two distinct types of subducted sediments (e.g. pelagic vs. terrigenous) can be distinguished based on their elemental characteristics (Garçon *et al.*, 2013; Chauvel *et al.*, 2014; Zhao *et al.*, 2019; Wang *et al.*, 2023). Coarser-grained terrigenous sediments generally contain more zircons compared to finer-grained pelagic sediments, which are typically dominated by finer-grained clay. This results in pelagic sediments having higher Lu/Hf ratios and developing more radiogenic Hf over time (Garçon *et al.*, 2013; Wang *et al.*, 2023). In contrast, coarser-grained continental detritus is enriched in Th, leading to elevated Th/REE ratios (Plank, 2005). The high Th/La (0.12–0.98) and Th/Yb (13–139) ratios for the studied Ba-Sr syenites, along with low Lu/Hf (0.01–0.11) values, indicate that terrigenous sediments, rather than pelagic sediments, contributed significantly to the enrichment of the mantle source.

When high-pressure silicate liquids from the subducted crust interact with overlying mantle rocks, hybrid silicate-carbonate melts may form, contributing to metasomatized

domains rich in hydrous phases such as phlogopite (Foley, 1992; Soder & Romer, 2018). The high Rb/Sr and low Ba/Rb ratios in these syenites support the involvement of phlogopite in their source region (Fig. 11C; Furman & Graham, 1999) and trace element modeling suggests that the enriched mantle underwent low-degree partial melting to produce these syenites (Fig. 11D). Phlogopite, a common K-rich and volatile-bearing phase in metasomatized mantle, is responsible for the elevated K_2O contents and K_2O/Na_2O ratios of the rocks. Incongruent melting of phlogopite in the metasomatized domains likely caused a slight increase in alkali/aluminum ratios in the granites relative to the syenites (Fig. 5D; Soder & Romer, 2018). In addition, reactions between carbonate-rich melts and peridotite would generate lherzolites and wehrlites (e.g. Qi *et al.*, 2022), equilibrating with aluminous minerals such as plagioclase, spinel and garnet (Wyllie, 1979; Lambart *et al.*, 2012; Müntener & Ulmer, 2018). The minor to absent Eu anomalies (Fig. 6C) and low HREEs contents ($(La/Yb)_N = 26.1-139$), high Al_2O_3 (9.46-15.4 wt.%) contents and MREE/HREE ratios ($Dy/Yb = 2.01-5.65$) of the syenites suggest that the source mantle contained residual garnet and/or spinel rather plagioclase. A La/Yb versus Dy/Yb diagram (Fig. 11D) indicates that the syenites formed through low-degrees (ca. 3-5%) partial melting of spinel-garnet lherzolite with more garnet contribution to the melting process (Fig. 11D).

The high Ba-Sr syenites show variable Nb/Ta (11.6-46.5) and Zr/Hf (23.3-52.1) ratios, exceeding those of chondrites, Bulk Silicate Earth, and MORB (Sun & McDonough, 1989; Workman & Hart, 2005; Pfänder *et al.*, 2007). Zr/Hf ratios decrease from low- to high-SiO₂ end-members (Fig. 11E), suggesting garnet fractionation during solid-liquid interactions in the mantle (Rubatto & Hermann, 2007). On a Th/Yb versus Nb/Yb plot, these syenites overlap with the fields of continental basement (Fig. 12F), indicating that enriched continental crustal components likely contributed to the mantle source. High $\delta^{18}O$ values and enriched Pb isotopic compositions (e.g. high $(^{207}Pb/^{206}Pb)_i$ and $(^{208}Pb/^{206}Pb)_i$) point to old continental crust as the source of these enriched Pb isotopic signatures (Figs. 7C-7D). Thus, the high Nb/Ta ratios in the syenites likely reflect the influence of sub-continental lithospheric mantle metasomatized by ancient continental crust (Aulbach *et al.*, 2008).

In conclusion, the high Ba-Sr syenites likely formed through low-degrees partial melting of spinel-garnet lherzolite in the lithospheric mantle. The silica-saturated high Ba-Sr syenites

and syenogranites are interpreted to result from varying degrees of fractional crystallization of their syenitic parental magmas.

Sources of subducted sediment

The tectonic evolution of Pamir and Tibetan Plateau suggests that the lithospheric mantle was likely influenced by the northward subduction of the Neo-Tethys oceanic plate since the Mesozoic (e.g. Ding *et al.*, 2003; Jiang *et al.*, 2014; Yang *et al.*, 2024). Other researchers argue that post-collisional subduction of continental lithosphere also played a significant role (e.g. Mahéo *et al.*, 2002; Guo & Wilson, 2019; Tang *et al.*, 2022a). As discussed above, the parental high Ba-Sr syenites were derived from lithospheric mantle infused with subducted sediment. However, the specific origin of the subducted sediments remains a key question, with potential contributors being the Neo-Tethys oceanic slab and the Indian and/or Asian continental lithosphere.

Prior to the India-Asia continental collision (ca. 60-55 Ma), subduction of the Neo-Tethys oceanic slab persisted through the Early Cretaceous-Early Eocene (Ding *et al.*, 2003; Jiang *et al.*, 2014; Yang *et al.*, 2024). However, the majority of Neo-Tethys-related igneous rocks are found in the southern Pamir and the Lhasa Terrane (Khan *et al.*, 2004; Mo *et al.*, 2008), and these rocks generally display more depleted Sr-Nd isotopic compositions compared to the high Ba-Sr syenites in this study (Fig. 7A; Turner *et al.*, 1996; Miller *et al.*, 1999; Mo *et al.*, 2007, 2008; Ma *et al.*, 2021). This suggests that there was a shift towards depleted mantle isotopic compositions during the Late Cretaceous-Eocene (Chapman *et al.*, 2018; Wang *et al.*, 2023).

Following the India-Asia collision, the Indian plate continued to subduct northwards (Bouilhol *et al.*, 2013; DeCelles *et al.*, 2014; van Hinsbergen, 2022), eventually breaking off around 25 Ma (Mahéo *et al.*, 2002; Williams *et al.*, 2004; Amidon & Hynek, 2010). Subsequently, the Asian continental lithosphere began subducting southwards beneath the Pamir-Tibetan Plateau (Mahéo *et al.*, 2002; Sobel *et al.*, 2013). Therefore, a significant question regarding Cenozoic magmatism in the Pamir-Tibetan Plateau is whether the subducted Asian continental crust has contributed to mantle enrichment (e.g. Guo *et al.*, 2014; Tang *et al.*, 2022a). Indian and Asian basement rocks have distinct Sr-Nd isotope signatures (Fig. 7A) and the high Ba-Sr syenites exhibit Sr-Nd isotopic compositions that lie close to the intersection of the Indian

and Asian continental reservoirs with a mantle component (Figs. 7A and 12). This isotopic signature is similar to that of the Dunkeldik complex (ca. 11 Ma; Li & Liu, 2023) and K-rich rocks from the West Kunlun (ca. 8 Ma to A.D. 1951; Guo *et al.*, 2014; Wang *et al.*, 2023) (Fig. 7A). However, the high Ba-Sr syenites have distinct radiogenic Pb isotopic compositions compared to the potassic-ultrapotassic lavas of the West Kunlun (Figs. 7C-7D), which originated from SCLM modified by Indian continental crust (e.g. Tang *et al.*, 2022a; Wang *et al.*, 2023). Furthermore, Pb isotopic data (Figures 7C-7D) demonstrate that Indian subducted crust and depleted mantle (DMM) cannot explain the Pb isotopic compositions of high Ba-Sr granitoids through simple binary mixing. Instead, a three-component mixing model involving DMM, Asian and Indian subducted crusts (Figs. 7A, 7C-7D) is necessary. This is consistent with the location of these rocks at the deep convergence between the Indian and Asian subducting plates (Kumar *et al.*, 2005; Zhao *et al.*, 2010; Schneider *et al.*, 2013). Therefore, both Indian and Asian continental materials likely contributed to the source of the high Ba-Sr syenites.

The presence of two distinct continental crust-derived metasomatic signatures within the lithospheric mantle, which are spatially separated, suggests the mantle enrichment occurred during two stages of subduction. In the first stage, the depleted mantle was metasomatized by materials from the subducting Indian plate. Sr-Nd-Pb isotopic mixing calculations suggest that binary mixing (ca. 20-30%) between DMM and the Indian basement can explain the mantle source of the potassic and ultrapotassic rocks from West Kunlun (Fig. 14) (Tang *et al.*, 2022a; Wang *et al.*, 2023). In the second stage, the Asian plate (ca. 1-3%) further modified the same mantle volume (Fig. 14). Consequently, both Indian and Asian subducted plates are significant contributors to the lithospheric mantle metasomatism in the Pamir during the Miocene, including the high Ba-Sr syenites and the Dunkeldik complex (Fig. 14). As part of this model, the high Ba-Sr signature would develop as complex, possibly long-term metasomatic transfers from the subducting oceanic slabs plus the Indian and Asian basement blocks (Pearce & Stern, 2006). It has been argued above that this involved a stage of melt-related element transfer, on the basis of the relationships between fluid-mobile and melt-mobile elements (Fig. 11A and B). During both fluid- and melt-related metasomatism from oceanic or continental subducting slabs, HFSEs (e.g. Nb, Ta, Ti) are retained in residual rutile and/or Fe-Ti oxides, thus accounting for

the characteristic negative Nb, Ta and Ti on mantle-normalized diagrams (Fig. 6B).

Petrogenesis and source of Karibasheng monzogranites

The Karibasheng high Ba-Sr monzogranites exhibit uniformly high SiO₂ (68.5-72.5 wt.%) contents, low MgO (0.26-0.81 wt.%), CaO (1.19-2.43 wt.%), TiO₂ (0.17-0.45 wt.%), Cr (3.46-14.2 ppm) and Ni (1.14-3.97), displaying high-K calc-alkaline to shoshonitic and peraluminous to weakly metaluminous affinities (Figs. 5B-5C). Compared to syenogranites derived from syenite fractionation, these monzogranites have higher Mg[#] (23-40), $\epsilon_{\text{Nd}}(t)$ (-8.0 to -6.7) values and Sr/Y (47.8-117) ratios, alongside lower K₂O/Na₂O (1.05-1.55) and Nb/Ta (11.3-18.2) (Figs. 9A-9C and 11E), suggesting distinct magma sources. The relatively low zircon saturation temperatures ($T_{\text{Zr}} = 733\text{-}847\text{ }^{\circ}\text{C}$; Supplementary Table 3) further differentiate them from typical A-type granites (Whalen *et al.*, 1987; Chappell & White, 1992). Their geochemical characteristics, such as high $\delta^{18}\text{O}$ (8.75-10.7‰) values (Fig. 8B) and low (CaO+FeO^T+MgO+TiO₂) contents (Fig. 13A), indicate a metasedimentary source (Patiño Douce, 1999).

Partial melting of the crustal materials is influenced by both the composition of metasedimentary rocks (i.e. clay-rich metapelite versus clay-poor metagreywacke; Sylvester, 1998) and the extent and mechanism of melting (Patiño Douce & Harris, 1998; Patiño Douce, 1999; Hopkinson *et al.*, 2017). The studied high Ba-Sr monzogranites have low Rb/Ba (0.03-0.12) and Rb/Sr (0.08-0.29) ratios suggest a clay-poor metagreywacke-source rather than metapelite (Sylvester, 1998), supported by the experimental petrology (Figs. 13B-13D). Water distribution also plays a critical role in monzogranite generation (e.g. Sylvester, 1998; Clemens & Stevens, 2012). Although H₂O-fluxed melting of metagreywackes typically results in higher CaO (1.4–3.9 wt.%) and lower K₂O/Na₂O ratios (0.3–1.0), the Karibasheng monzogranites exhibit relatively low CaO (1.19–2.43 wt.%) and high K₂O/Na₂O (1.05–1.55), implying fluid-absent muscovite dehydration melting (Inger & Harris, 1993; Figs. 13E–13F).

These monzogranites have low Y (9.1-25 ppm) and Yb (0.7-2.0 ppm), with high Sr/Y (48-117) and (La/Yb)_N (21-129) ratios, thus showing geochemical affinities to adakitic rocks (Defant & Drummond, 1990; Martin *et al.*, 2005). Studies of Dunkeldik granulite xenoliths suggest that during the Miocene, crustal thickness in the Central Pamir reached ~70 km (Li *et*

al., 2023). We therefore infer that these monzogranites originated from the thickened lower crust (e.g. Ye *et al.*, 2008; Lara *et al.*, 2017; Yin *et al.*, 2020). Biotites in the monzogranites occur as late-stage interstitial phases (Figs. 2E-2F), with pressure estimates of 3.3-3.8 kbar, with an average of 3.6 kbar, corresponding to a depth of 14.9 km and temperatures of 832-842 °C, with an average of 837 °C. Therefore, the Karibasheng monzogranites are interpreted as products of fluid-absent muscovite dehydration melting from metagreywacke within the Pamir thickened lower crust.

Geodynamic and tectonic implications

Spatial and temporal distribution of the Cenozoic magmatism in the Central Pamir

The Cenozoic magmatism in the Central Pamir can be divided into two distinct stages, the Eocene (ca. 46-26 Ma) and Miocene (ca. 22-10 Ma) (Fig. 14A; Table S5). Eocene magmatism, associated with the India-Asia collision, is concentrated in the Yazgulom, Sarez and Muskol gneiss domes (Figs. 1B and 14A). These magmas, characterized by high $\varepsilon_{\text{Hf}}(t)$ and variable $\delta^{18}\text{O}$ values, are interpreted as having originated from juvenile lower crust with contributions from ancient crustal components (Chapman *et al.*, 2018; Tang *et al.*, 2024). A series of mantle drips or delamination events, driven by the negative buoyancy of the thickened mantle lithosphere, led to asthenosphere upwelling, which subsequently heated the lower crust, triggering magma generation (Chapman *et al.*, 2018).

In contrast, Miocene magmatism, along with (ultra)potassic rocks of the West Kunlun (from 8 Ma to A.D. 1951), migrated from west-to-east between ca. 20 Ma to present (Figs. 1B and 14A-14B; Table S5) (Chapman *et al.*, 2018; Tang *et al.*, 2023, 2024; Wang *et al.*, 2023). Previous studies have suggested that lithospheric delamination triggered crustal anataxis and syn-extensional decompression melting, resulting in the formation of the Vanj and Sarez leucogranites (Chapman *et al.*, 2018; Tang *et al.*, 2024). Other studies argue that slab break-off or near-vertical subduction of the Indian continental plate was responsible for the generation of Miocene magmatism and K-rich rocks to the east (Jiang *et al.*, 2012; Guo *et al.*, 2014). After the Indian plate break-off at ca. 25 Ma, it underthrust northwards in a sub-horizontal fashion, reaching the Hindu Kush, Karakoram, and Bangong-Nujiang suture regions (Fig. 14B; Negredo *et al.*, 2007; Zhao *et al.*, 2010; Replumaz *et al.*, 2010, 2014). This low-angle subduction led to

the metasomatism of the Indian subducted lithosphere, influencing the formation of high Ba-Sr and K-rich rocks, and creating a short-term magmatic hiatus in the Pamir (Chapman *et al.*, 2018). We suggest that the Miocene magmas were primarily influenced by the delaminated Pamir lower crust and mantle lithosphere, based on the following observations:

(1) Compared to the mantle-derived West Kunlun lavas (ca. 8 Ma to A.D. 1951), the high Ba-Sr syenitic rocks in the eastern Central Pamir (ca. 11 Ma; Kuzigan, Zankan plutons and Dunkeldik complex) exhibit similar incorporation of Indian basement materials, suggesting a stabilizing influence of the Indian plate on deep mantle metasomatism (Fig. 12). However, their higher $^{206}\text{Pb}/^{204}\text{Pb}$ ratios indicate variations in the subduction processes and evolution of the Asian plate (Fig. 12).

(2) The Dunkeldik xenoliths from the southwestern Taxkorgan complex have been interpreted as (ultra)high pressure lower crustal materials (Hacker *et al.*, 2005, 2017). Thermodynamic calculations suggest that these xenoliths originated from Pamir deep lithospheric materials at depths of ca. 70 km (granulite xenoliths) and ca. 100-140 km (eclogite and pyroxenite xenoliths), representing Pamir thickened lower crust and delaminated lower crust, respectively (Li *et al.*, 2023).

(3) Low-temperature thermochronological studies indicate that deformation and metamorphic events during Late Miocene (ca. 12-9 Ma) coincided with magmatic activity, marking a significant phase in Pamir formation (Robinson *et al.*, 2004; Cao *et al.*, 2013a, b; Meng *et al.*, 2023). The widespread thrust faulting in the northwestern Pamir during this period absorbed crustal compression and shortening within the collisional zone, resulting in crustal thickening and plateau uplifting (Robinson *et al.*, 2004, 2007; Chapman *et al.*, 2017; Liu *et al.*, 2017; Rutte *et al.*, 2017). Geophysical studies further support the idea that Asian continental materials were shortened and incorporated into the Pamir crust beneath the eastern Central Pamir (Sippl *et al.*, 2013; Mechie *et al.*, 2019). Since ca. 25 Ma, the Asian continental lithosphere has been subducting southward at a shallow angle, forming a bidirectional subduction pattern (Negredo *et al.*, 2007; Zhao *et al.*, 2010; Sobel *et al.*, 2013). During the continuous plate convergence, there is a southerly dipping and increasingly subvertical slab below the Pamir, forming a double Moho structure (Sippl *et al.*, 2013; Schneider *et al.*, 2019). The south-dipping slab was regarded to likely represent the delaminated Pamir lower crust and

mantle lithosphere (Schneider *et al.*, 2019).

The India-Asia collision caused progressive thickening of the Asian lithosphere from ca. 50-25 Ma (Najman *et al.*, 2010), with high-pressure eclogitization reducing the buoyancy of the lithosphere beneath the Pamir (Ducea *et al.*, 2003; Hacker *et al.*, 2005). The delamination of the Pamir plate may have been driven by the transformation of the lower crust into eclogite, reversing its buoyancy and facilitating foundering (Molnar & Gray, 1979; Krystopowicz & Currie, 2013). Rayleigh-Taylor-type instability has also been proposed as a mechanism for this delamination (Chapman *et al.*, 2018; Molnar & Bendick, 2019). Following the ca. 25 Ma break-off of Indian plate beneath the Karakoram terrane and Lhasa terrane, the Indian lithosphere converged towards Asian lithosphere at a rate of ca. 34 mm/year (Molnar & Stock, 2009), leading to the eventual collision of the Indian and Asian lithospheres during the late Miocene (Kumar *et al.*, 2005; Zhao *et al.*, 2010; Sippl *et al.*, 2013; Kufner *et al.*, 2016). The Miocene west-to-east magmatic migration in the Central Pamir likely reflects this collision and subsequent delamination at different times (Fig. 14B). As the Pamir plate foundered, upwelling asthenospheric mantle heated the enriched SCLM, generating large volumes of mantle-derived magmatism (Fig. 14C) (Humphreys *et al.*, 2003). These mantle-derived magmas underplated the crust, acting as heat sources for crustal melting and producing high Ba-Sr monzogranites. Tang *et al.* (2022b) proposed that these syenitic magmas propagate laterally due to crustal rigidity differences and topography-induced pressure gradients, explaining why syenites crystallized slightly later than the monzogranites (Fig. 14A). Additionally, strike-slip faults, such as the Karakorum strike-slip fault, may have served as conduits for the emplacement of these Miocene magmas, including the Dunkeldik and Taxkorgan complexes (Fig. 14C; Hong *et al.*, 2019).

Implications for plateau uplift and crustal growth

Low-temperature thermochronology, magnetostratigraphy and re-calculated block rotations reveal four Cenozoic episodic uplift events in the Pamir Plateau (see Amidon & Hynek, 2010; Sobel *et al.*, 2011; Cao *et al.*, 2013b; Clift *et al.*, 2017). The initial uplift occurred between ca. 50-40 Ma, directly linked to the India-Asia continental collision (Leech *et al.*, 2005; Amidon & Hynek, 2010). Thermochronologic evidence suggests that the second tectonic uplift of the

western Pamir, affecting the Muskol and western Sarez domes, occurred during ca. 25-16 Ma (Amidon & Hynek, 2010; Sobel *et al.*, 2011; Cao *et al.*, 2013b; Clift *et al.*, 2017). Regional exhumation indicates a third uplift event at ca. 11 Ma, related to thrust fault activity (Robinson *et al.*, 2007; Cao *et al.*, 2013b; Rutte *et al.*, 2017; Chen *et al.*, 2023). If our model accurately describes the lithospheric dynamics of the Miocene rocks, the second and third uplift events may be linked to the Indian plate break-off and the subsequent delamination of the Pamir lithosphere. We propose that the continued India-Asia plate convergence in the deep mantle led to compression absorption through back-thrusting along the foundering Pamir lithosphere, facilitating both magma migration and plateau uplift. The final uplift event occurred after the Pliocene (<5 Ma) in the northeastern Pamir, resulting from continued convergence between Pamir and Tian Shan (Liu *et al.*, 2017; Chen *et al.*, 2023). This model provides a plausible explanation for the mechanism of the plateau uplift, magma migration, and deep rock exhumation during the late Cenozoic.

Finally, high Ba-Sr granitoids have been regarded as compositional equivalents of Archean sanukitoids, representing a mantle contribution to crustal growth over some 3 billion years of Earth history (Fowler & Rollinson, 2012; Peng *et al.*, 2013; Lin *et al.*, 2024; Zhu *et al.*, 2024). The mantle-derived high Ba-Sr magmas incorporated pre-existing crust by a variety of mechanisms, ultimately forming large igneous bodies. Such post-collisional batholiths represent juvenile injections to the continental crust, resulting in crustal growth (Gómez-Frutos *et al.*, 2023). Therefore, we suggest that the addition of mantle-derived magmas has made an important contribution to crustal evolution in the Pamir during the Miocene.

CONCLUSIONS

The petrological, geochemical, and geochronological analyses of high Ba-Sr granitoids from Kuzigan and Karibasheng plutons in east Pamir presented in this study lead to the following conclusions:

- (1) LA-ICP-MS zircon dating indicates that the high Ba-Sr granitoids formed at ca. 11 Ma.
- (2) The high Ba-Sr syenites originated from enriched subcontinental lithospheric mantle modified by subduction-related sediments from both the Indian plate (~20–30%) and the Asian plate (~1–3%), and the syenogranites are differentiated products of the syenites.

(3) The delamination of Asian plate induced asthenosphere upwelling providing heat to melt the lithospheric mantle source. With the underplating and lateral propagation of the syenitic magmas, the high Ba-Sr monzogranites were generated by muscovite-dehydration melting from metagreywacke under middle-upper crustal conditions.

(4) Differences in the timing of delamination of the Pamir lithosphere resulted in magma migration in Central Pamir as well as episodic plateau uplift.

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Data Availability Statement

The data in the manuscript are available in Mendeley Data repository (<https://data.mendeley.com/drafts/sjxkn582yt>).

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FIGURE CAPTIONS

Figure 1. (A) Regional tectonic map, showing the geographic location of Pamir-West Kunlun. (B) Simplified geological map of Pamir, showing major faults and terrane boundaries as well as exposures of magmatic rocks (after Tang *et al.*, 2024). (C) Geological map of the Kuzigan, Karibasheng, Zankan plutons and Cenozoic Dunkeldik complex (Tajikistan). ATS—Akbaytal-Tanymas suture; JS—Jinsha suture; KKF—Karakoram fault; KS—Kudi suture; MKS—Mazar-Kangxiwa suture; MPT—Main Pamir thrust; RPS—Rushan-Pshart suture.

Figure 2. Field photographs (A-C) and photomicrographs (D-H) of the Miocene intrusive rocks in the eastern Pamir. (A) Syenite in the Zankan plutons. (B) Syenogranite in the Kuzigan pluton. (C) Monzogranite in the Karibasheng pluton. (D), (F), (G) and (H) are under crossed polarizers. (E) is under plane polarized light. Bt—biotite; Kfs—K-feldspar; Cpx—clinopyroxene; Pl—plagioclase; Qz—quartz.

Figure 3. Weighted-mean ages and concordia diagrams of zircon U-Pb data from (A) syenite WK1604 and (B) syenogranite WK1603 from Kuzigan pluton; (C) monzogranite WK1605 and (D) monzogranite WK2301 from Karibasheng pluton. Cathodoluminescence images of representative zircon grains are shown. MSWD—mean square of weighted deviates.

Figure 4. Mineral compositions and classification of the Zankan, Kuzigan and Karibasheng rocks. (A) Clinopyroxene classification diagram showing clinopyroxene are diopside to hedenbergite (modified after Morimoto, 1988). (B) Elemental composition diagrams of clinopyroxene, documenting decreasing MgO with increasing FeO^T from core to rim. (C) Mica classification diagram of Foster (1960). Clinopyroxene and biotite data of previous studies are from Jiang *et al.* (2012) and Yuan *et al.* (2020a). (D) Or–Ab–An classification diagram for feldspar (modified after Deer *et al.*, 1992). Or = orthoclase, Ab = albite, An = anorthite, Ol = oligoclase, And = andesine, La = labradorite, By = bytownite.

Figure 5. Classification and major geochemical features for the Miocene intrusive rocks in the eastern Pamir. (A) TAS classification diagram (Middlemost, 1994); (B) K_2O versus Na_2O diagram (Rollinson, 1993); (C) A/NK versus A/CNK (Maniar & Piccoli, 1989). (D) Sr-Rb-Ba plot for the studied syenites and granitoids (after Tarney & Jones, 1994). Fields of high Ba-Sr and low Ba-Sr granites are based on data from Fowler & Henney (1996) and Fowler *et al.* (2001). Fields of adakites are from Peng *et al.* (2013). Data from previous studies (Table S3) is from Ke *et al.* (2006, 2016), Jiang *et al.* (2012), Wang *et al.* (2013), Yuan *et al.* (2020a), Tang *et al.* (2022b) and Liu *et al.* (2024).

Figure 6. Chondrite-normalized REE patterns and primitive mantle-normalized multi-element patterns for the Miocene intrusive rocks in the eastern Pamir (A-B). Chondrite and primitive mantle values are from Sun & McDonough (1989). The cited data for comparison are given in Fig. 5.

Figure 7. (A) $\epsilon_{Nd}(t)$ versus $(^{87}Sr/^{86}Sr)_i$, (B) $\epsilon_{Hf}(t)$ versus $\epsilon_{Nd}(t)$ (Vervoort *et al.*, 1999), (C) $(^{207}Pb/^{204}Pb)_i$ versus $(^{206}Pb/^{204}Pb)_i$, and (D) $(^{208}Pb/^{204}Pb)_i$ versus $(^{206}Pb/^{204}Pb)_i$ diagrams for the Miocene intrusive rocks in the eastern Pamir. The Tethyan subduction-related rocks and Indian subduction trend in figure (A) are from Zhao *et al.* (2009). Potassic and ultrapotassic rocks from the West Kunlun (Li, 2008; Wang & Zhang, 2011; Guo *et al.*, 2014; Wei, 2018; Yuan *et al.*, 2020b; Wang *et al.*, 2023) and southern Tibet (Zhao *et al.*, 2009) are shown for comparison. The Dunkeldik complex (including syenites and carbonatite) are from Li & Liu (2023). The depleted MORB-source mantle (DMM) and Indian crustal basement shown are from Wang *et al.* (2023) and Tian *et al.* (2017), respectively). Due to the lack of Pb isotopes from Pamir, we assume the Pb isotopic compositions are similar to the Asian crustal basement (Zhang *et al.*, 2016). The Higher Himalayan Crystalline Sequence (HHCS) are from Wang *et al.* (2023). The Northern Hemisphere Reference Line (NHRL) is from Hart, (1984). The enriched mantle I (EMI) and enriched mantle II (EMII) are from Tian *et al.* (2017). Data from

previous studies are given in Fig. 5.

Figure 8. (A-B) Correlation plots between ages and Hf-O isotopic data for the studied high Ba-Sr granitoids. (C) In-situ zircon $\delta^{18}\text{O}$ versus zircon Hf isotope. The gray fields in (B) and (C) of mantle-derived zircon ($5.3 \pm 0.6\text{‰}$, 2SD; Valley *et al.*, 1998) and dotted line of wall rock (gneissic granites) adjacent to the Kuzigan pluton (Ke *et al.*, 2016) are shown for comparison. The West Kunlun K-rich rocks in figure (C) are from Wang *et al.* (2023).

Figure 9. (A) Sr/Y versus Y (after Defant & Drummond, 1990), (B) $\text{Mg}^\#$ versus SiO_2 (after Rapp *et al.*, 1999; Martin *et al.*, 2005), and (C) $\text{K}_2\text{O}/\text{Na}_2\text{O}$ versus SiO_2 , showing geochemical differences of crust-derived high Ba-Sr granitoids (Ye *et al.*, 2008; Wang *et al.*, 2014; Lara *et al.*, 2017; de Lima *et al.*, 2021) and mixing of crust-mantle derived high Ba-Sr granitoids (Wang *et al.*, 2018; Zhang *et al.*, 2015; Hao *et al.*, 2024). SiO_2 versus $(^{87}\text{Sr}/^{86}\text{Sr})_i$ (D) and $\epsilon_{\text{Nd}}(t)$ (E), and La versus La/Sm (F) diagrams for the high Ba-Sr granitoids. Data sources are given in Fig. 5. Amp—amphibole; Cpx—clinopyroxene.

Figure 10. (A-G) SiO_2 versus selected major element oxides for the studied high Ba-Sr granitoids; (H) V versus Th (after Bea *et al.*, 1994); (I) δEu versus SiO_2 , showing the plagioclase (Pl) fractionation. (J) Cr versus Ni, (K) Ce versus Nb and (L) Ba versus Sr (after Fowler *et al.*, 2008). Data sources are given in Fig. 5. Aln—allanite; Amp—amphibole; Ap—apatite; Bt—biotite; Cpx—clinopyroxene; Kfs—K-feldspar; Pl—plagioclase; Rfm—rock-forming minerals; Ttn—titanite; Zrn—zircon.

Figure 11. Sr/Th versus $(\text{La}/\text{Sm})_{\text{N}}$ (A) and Rb/Nb versus Th/Yb (B) diagrams, showing that melt-related materials play an important role in the generation of the high Ba-Sr syenites. (C) Rb/Sr versus Ba/Rb (after Furman & Graham, 1999). (D) Dy/Yb versus La/Yb, showing trace-element modeling results for nonmodal batch melting of lherzolite. To constrain the mantle mineralogy, we analyzed the high Ba-Sr syenites

with low SiO₂ (<55 wt.%) and moderate Mg[#] (46-68) values, which were influenced by limited fractional crystallization. For spinel lherzolite source, modal composition is 57.8% olivine + 27% orthopyroxene + 11.9% clinopyroxene + 3.3% spinel (Özdemir & Güleç, 2013); melting mode is 10% olivine + 27% orthopyroxene + 50% clinopyroxene + 13% spinel; Source composition is 2.36 ppm La, 0.34 ppm Dy, and 0.22 ppm Yb (Huang et al. 2013). For garnet lherzolite source, modal composition is 59.8% olivine + 21.1% orthopyroxene + 7.6% clinopyroxene + 11.5% garnet (Özdemir & Güleç, 2013); melting mode is 5% olivine + 20% orthopyroxene + 30% clinopyroxene + 45% garnet; Source composition is 2.42 ppm La, 0.37 ppm Dy, and 0.16 ppm Yb (Huang et al. 2013). Nb/Ta versus Zr/Hf (E) and Th/Yb versus Nb/Yb (F) diagrams for the high Ba-Sr granitoids. MORB (Pfänder *et al.*, 2007; Sun & McDonough, 1989; Workman & Hart, 2005), Chondritic, BSE (bulk silicate Earth), and the silicate fractionation trend (Münker *et al.*, 2003) in (E) are shown for comparison. Continental basements (Indian and Asian continents) in (F) are from Tian *et al.* (2017) and Zhang *et al.* (2017).

Figure 12. Sr-Nd-Pb isotopic compositions mixing model. (⁸⁷Sr/⁸⁶Sr)_i versus (²⁰⁶Pb/²⁰⁴Pb)_i (A) and (¹⁴³Nd/¹⁴⁴Nd)_i versus (²⁰⁶Pb/²⁰⁴Pb)_i (B) of the high Ba-Sr granitoids. The isotopic data for the high Ba-Sr granitoids can be simulated by mixing between an average value of Indian basement and a DMM component (black solid lines with tick marks), followed by mixing with an average value of Asian basement (black dotted lines with tick marks). The Indian basement, (HHCS: Higher Himalayan Crystalline Sequence, Wang *et al.*, 2023): Sr = 135 ppm; Nd = 29.9 ppm; Pb = 5 ppm; ⁸⁷Sr/⁸⁶Sr = 0.742983; ¹⁴³Nd/¹⁴⁴Nd = 0.511737; ²⁰⁶Pb/²⁰⁷Pb = 18.8644. The Asian basement (Zhang *et al.*, 2016): Sr = 693 ppm; Nd = 30.6 ppm; Pb = 11.16 ppm; ⁸⁷Sr/⁸⁶Sr = 0.714090; ¹⁴³Nd/¹⁴⁴Nd = 0.511459; ²⁰⁶Pb/²⁰⁷Pb = 16.91775. DMM (Tethys MORB ophiolite, Wang *et al.*, 2023): Sr = 206 ppm; Nd = 5.28 ppm; Pb = 0.57 ppm; ⁸⁷Sr/⁸⁶Sr = 0.703401; ¹⁴³Nd/¹⁴⁴Nd = 0.513122, ²⁰⁶Pb/²⁰⁷Pb = 18.412. The numbers in per cent shown on the curves denote the proportions of addition to Indian basement and Asian basement. Data sources are given in Figs. 5.

1366

1367 **Figure 13.** Plots of (A) $\text{CaO} + \text{FeO}^{\text{T}} + \text{MgO} + \text{TiO}_2$ versus $\text{CaO}/(\text{FeO}^{\text{T}} + \text{MgO} + \text{TiO}_2)$;
 1368 (B) $\text{Al}_2\text{O}_3 + \text{MgO} + \text{FeO}^{\text{T}} + \text{TiO}_2$ versus $\text{Al}_2\text{O}_3/(\text{MgO} + \text{FeO}^{\text{T}} + \text{TiO}_2)$; (C) $\text{Na}_2\text{O}/\text{K}_2\text{O}$
 1369 versus FeO^{T} ; and (D) $\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{FeO}^{\text{T}} + \text{MgO} + \text{TiO}_2$ versus $(\text{Na}_2\text{O} + \text{K}_2\text{O})/(\text{FeO}^{\text{T}}$
 1370 $+ \text{MgO} + \text{TiO}_2)$. Parts B-D are after Patiño Douce, 1999. (E, F) Plots of Rb/Sr ratios
 1371 versus Sr (ppm) and Ba (ppm), respectively (after Inger & Harris, 1993). Data sources
 1372 are given in Figs. 5.

1373

1374 **Figure 14.** (A) Age versus distance diagram of the Central Pamir. The crystallization
 1375 ages in (A) are shown in Table S5. (B) Plate tectonic evolutionary model of the Pamir
 1376 during ca. 25-11 Ma. This model shows collision of the India-Asia subduction plates,
 1377 resulting in the delamination of the Pamir lithosphere. (C) An evolutionary model of
 1378 the Pamir showing the mantle metasomatism and crustal remelting accompanied with
 1379 plateau uplifting. ATS—Akbaytal-Tanyamas suture; KKF—Karakoram fault; MPT—
 1380 Main Pamir thrust; RPS—Rushan-Pshart suture.

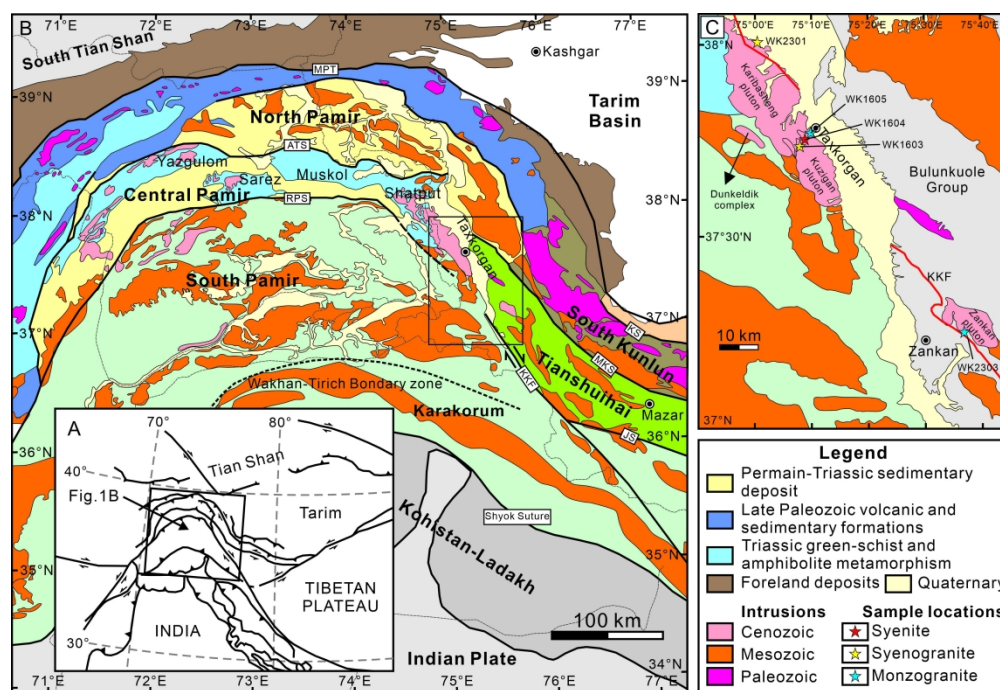


Fig.1

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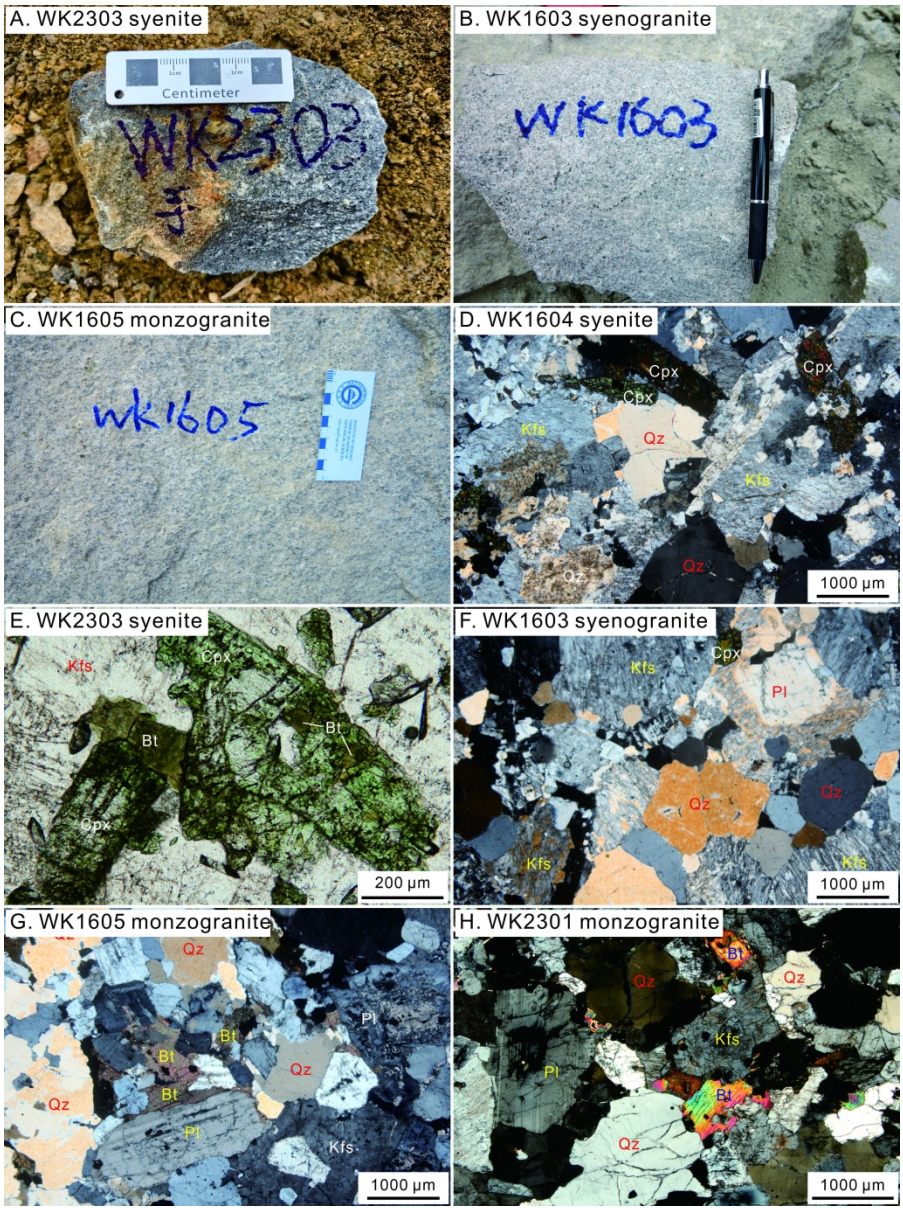


Figure 2

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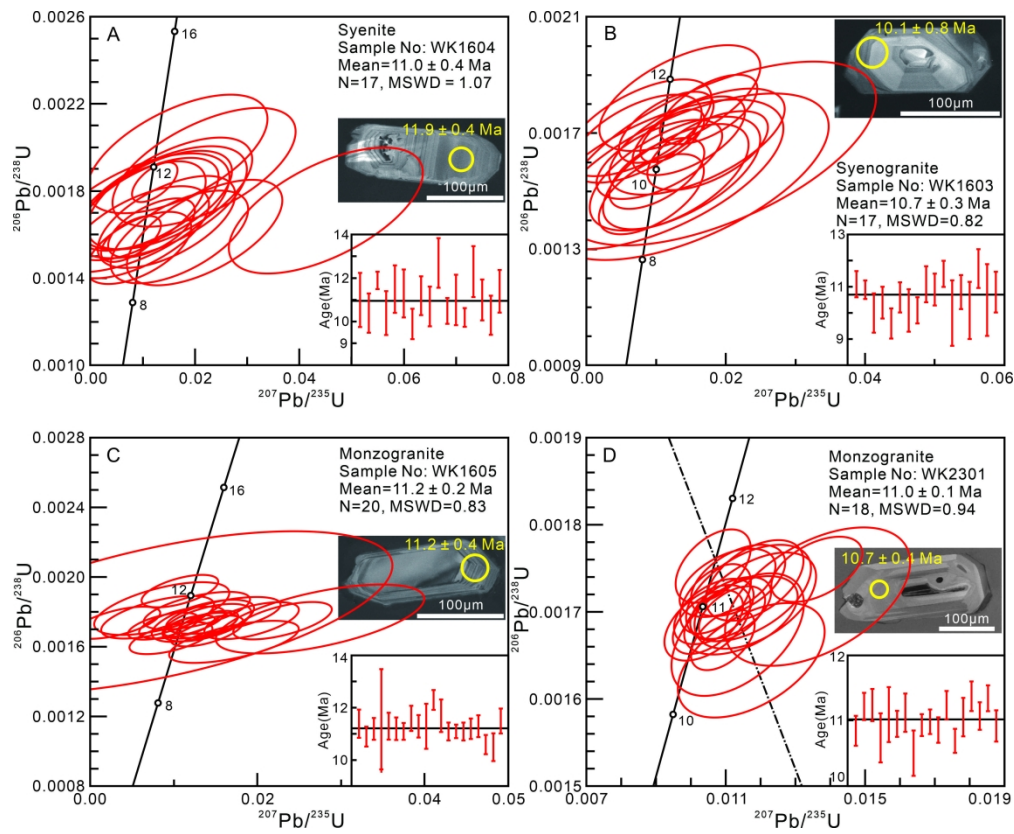


Figure 3

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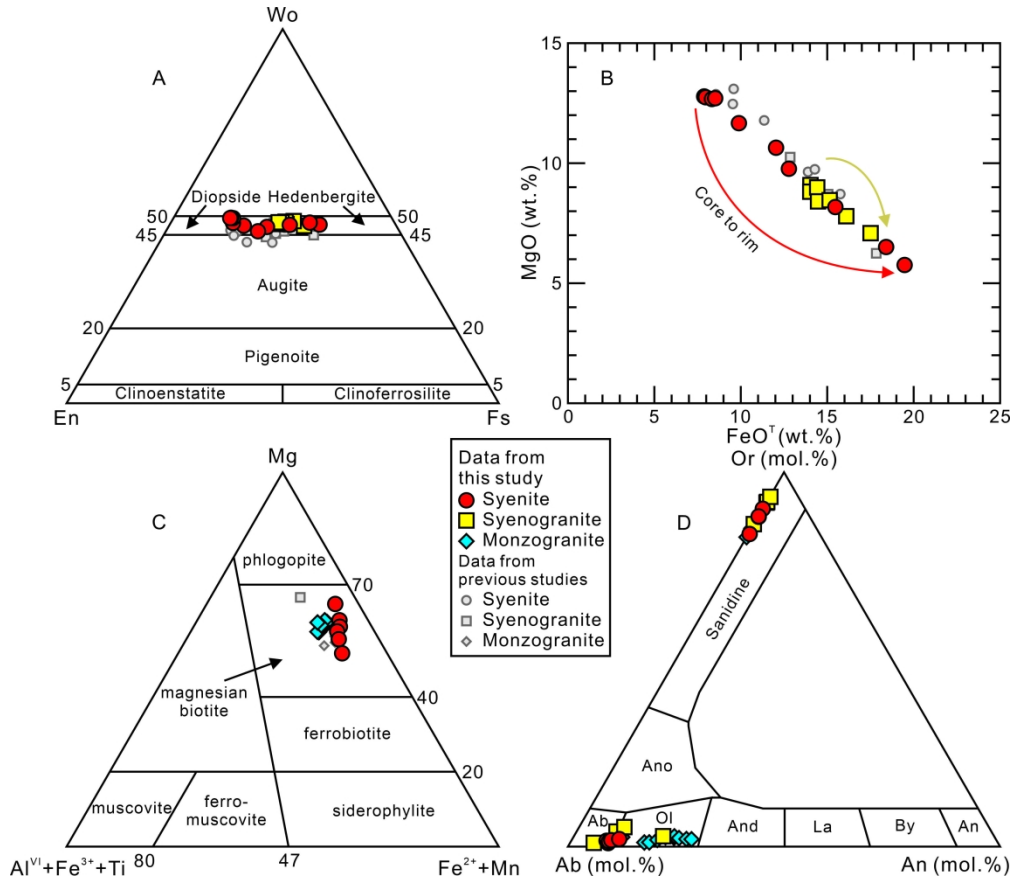


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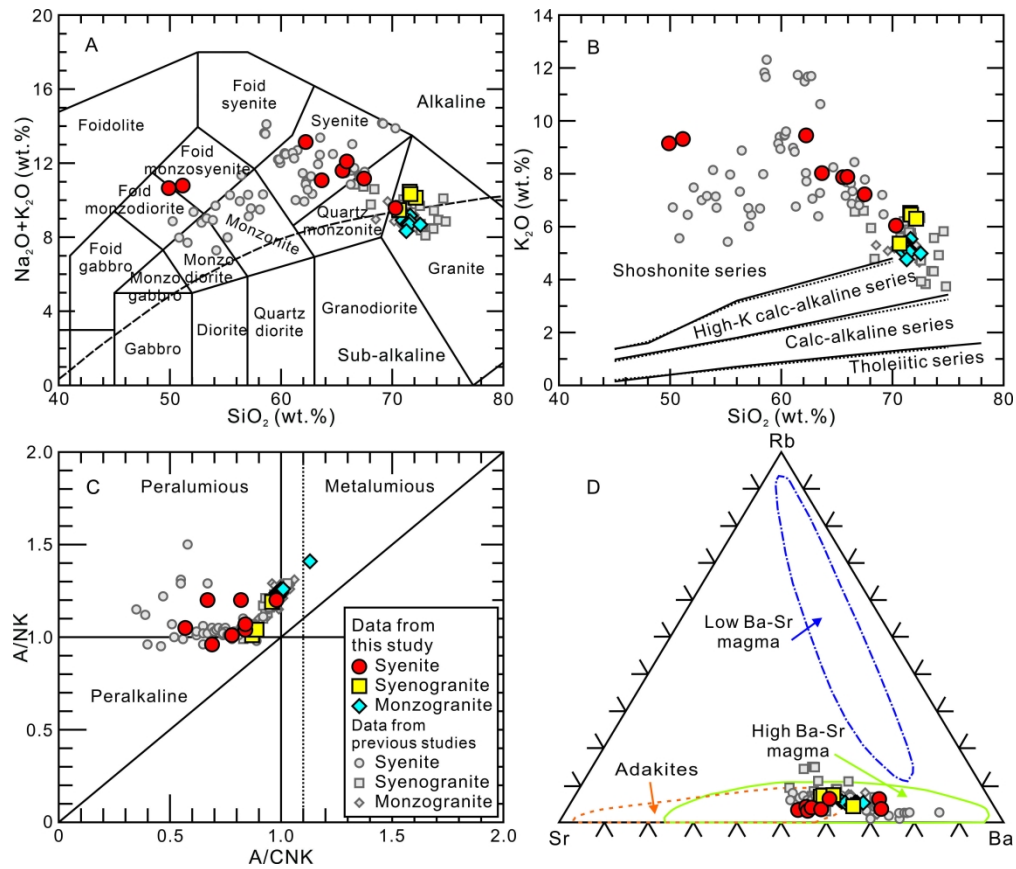


Figure 5

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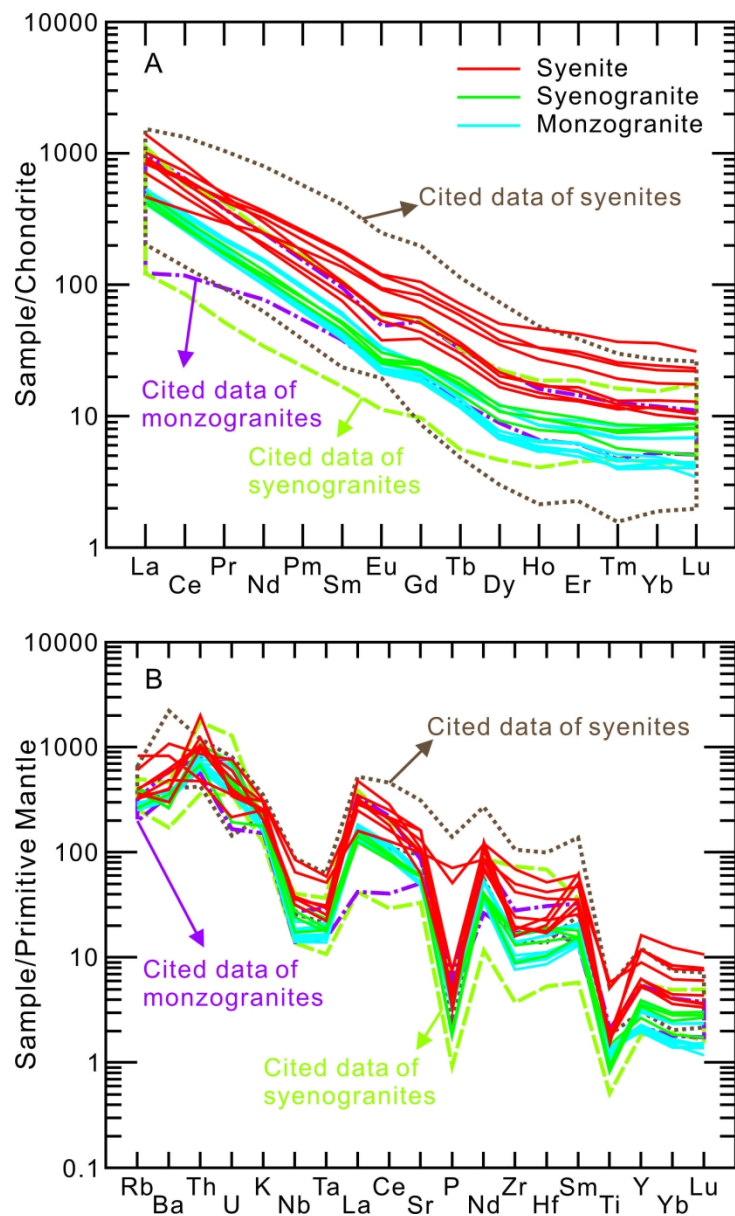


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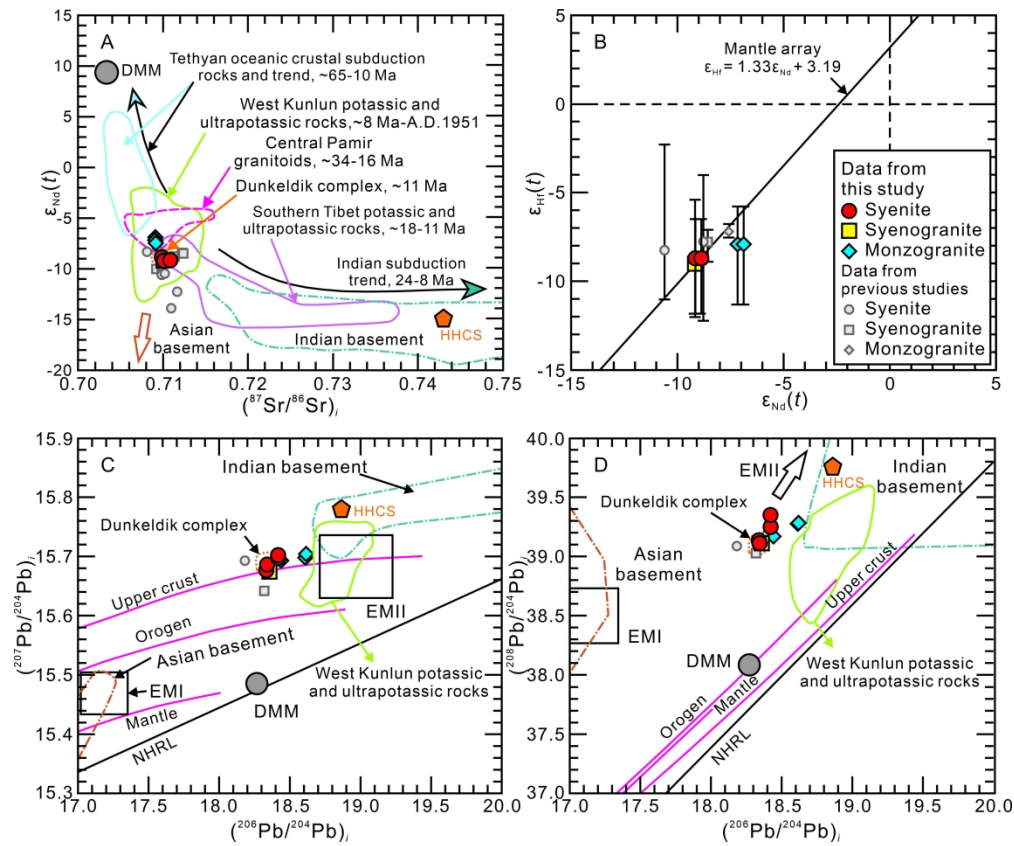


Figure 7

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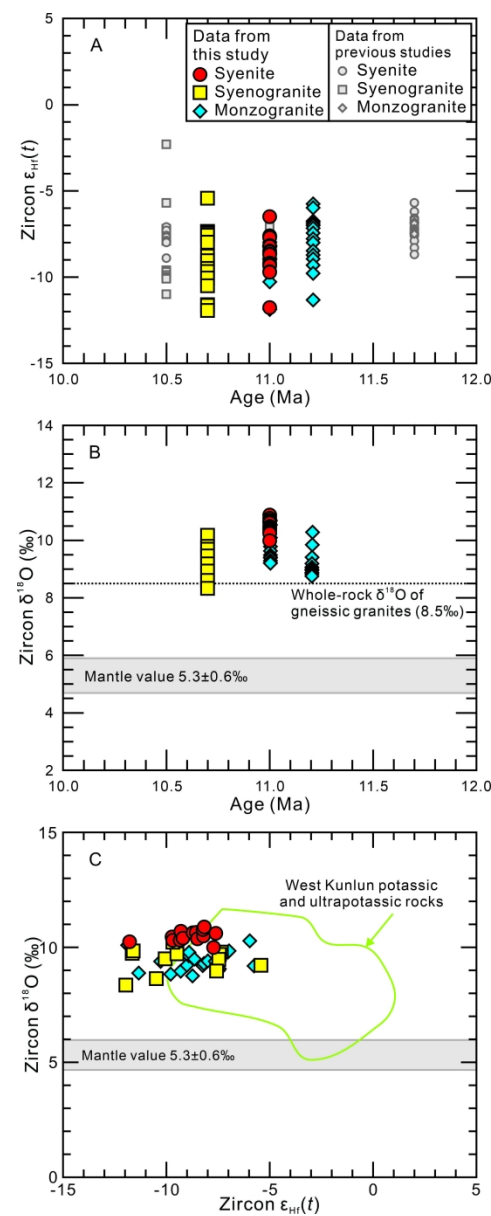


Figure 8

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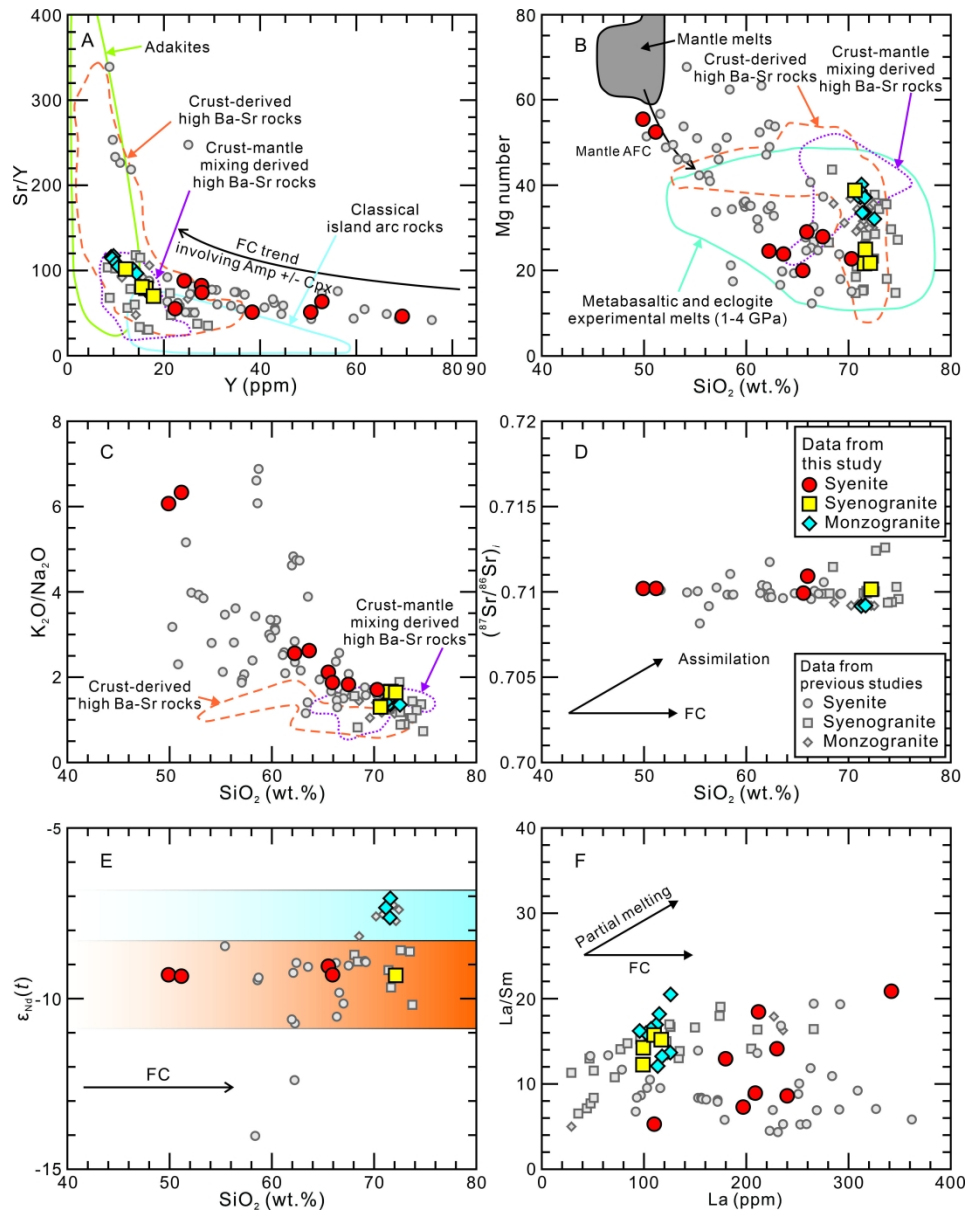


Figure 9

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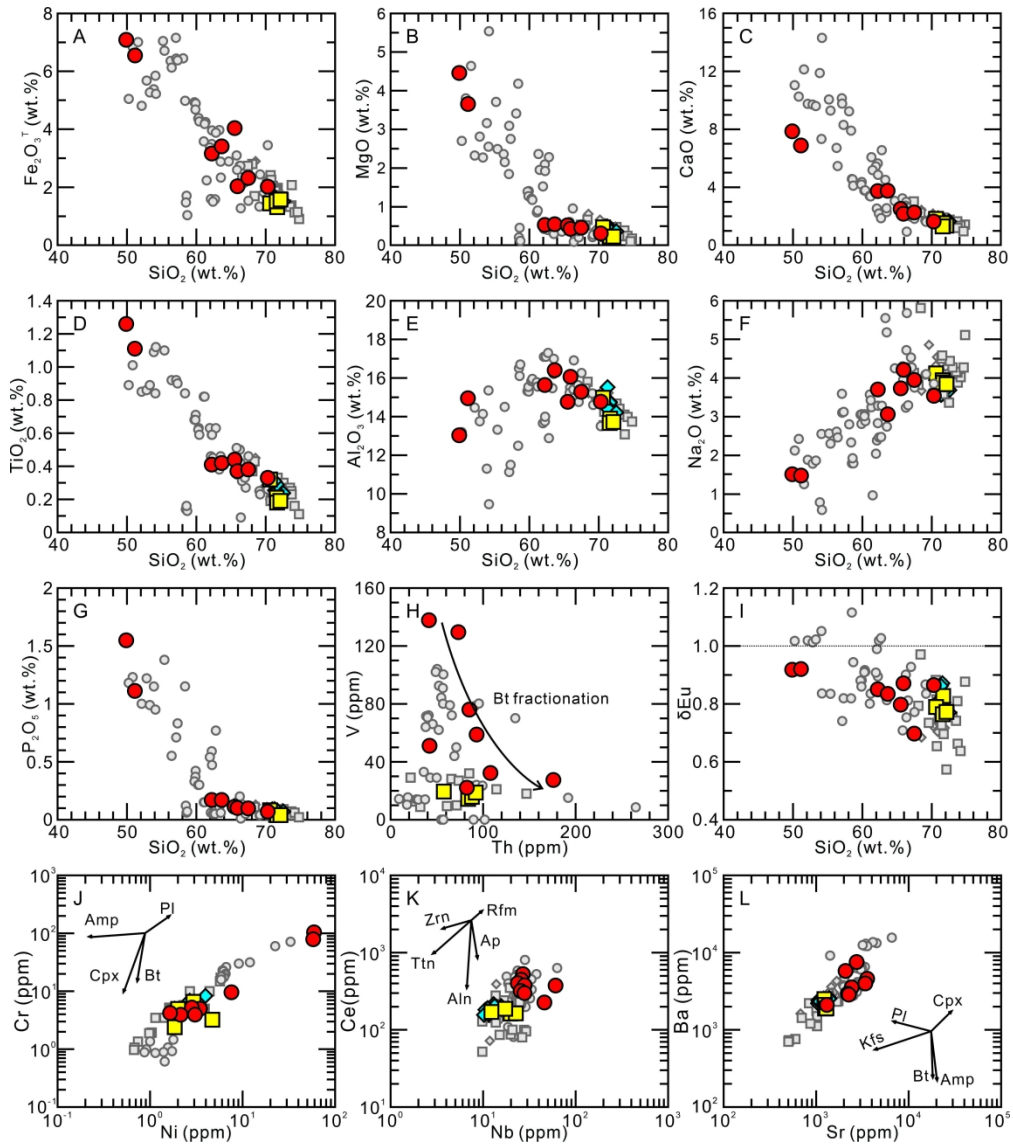


Figure 10

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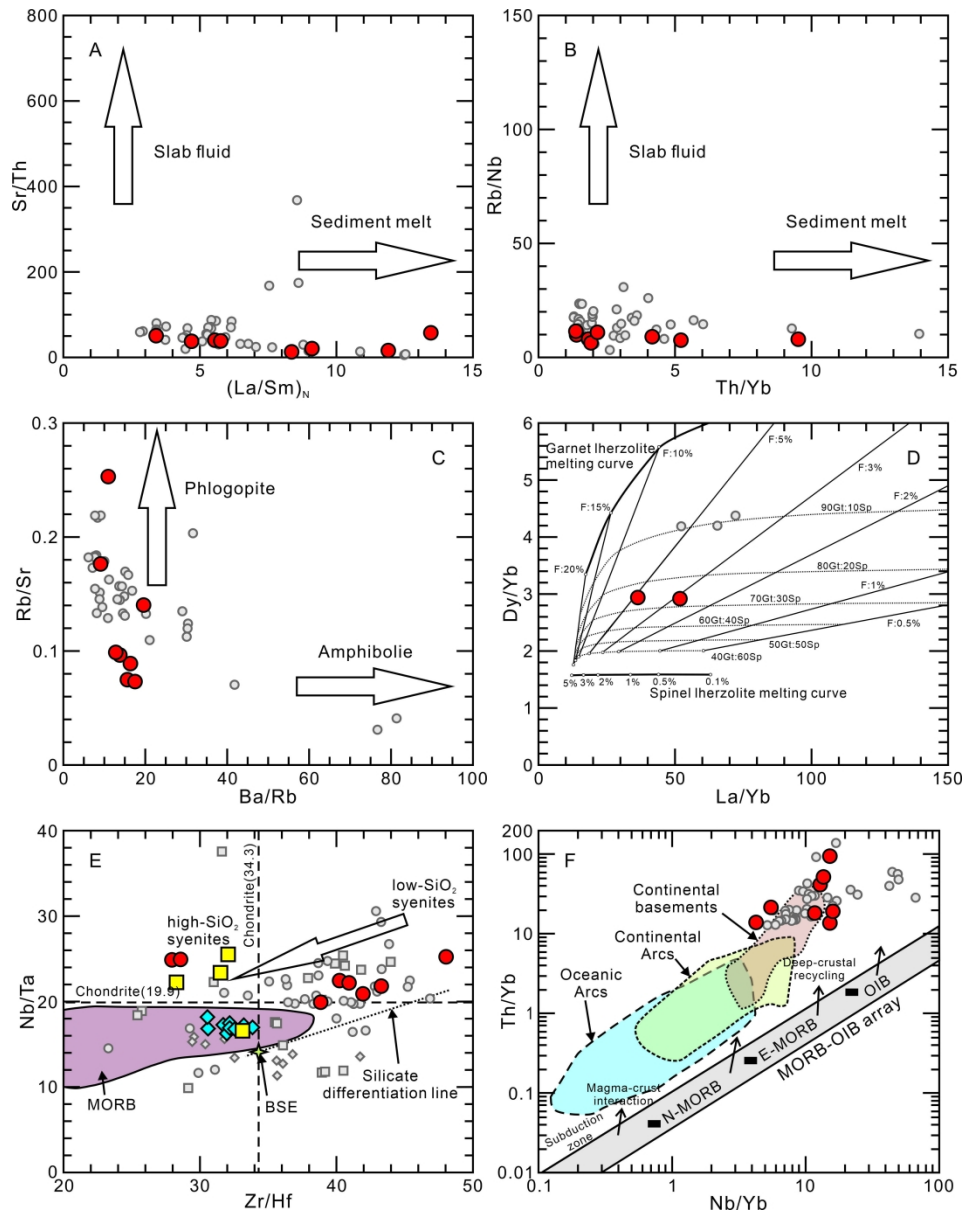


Figure 11

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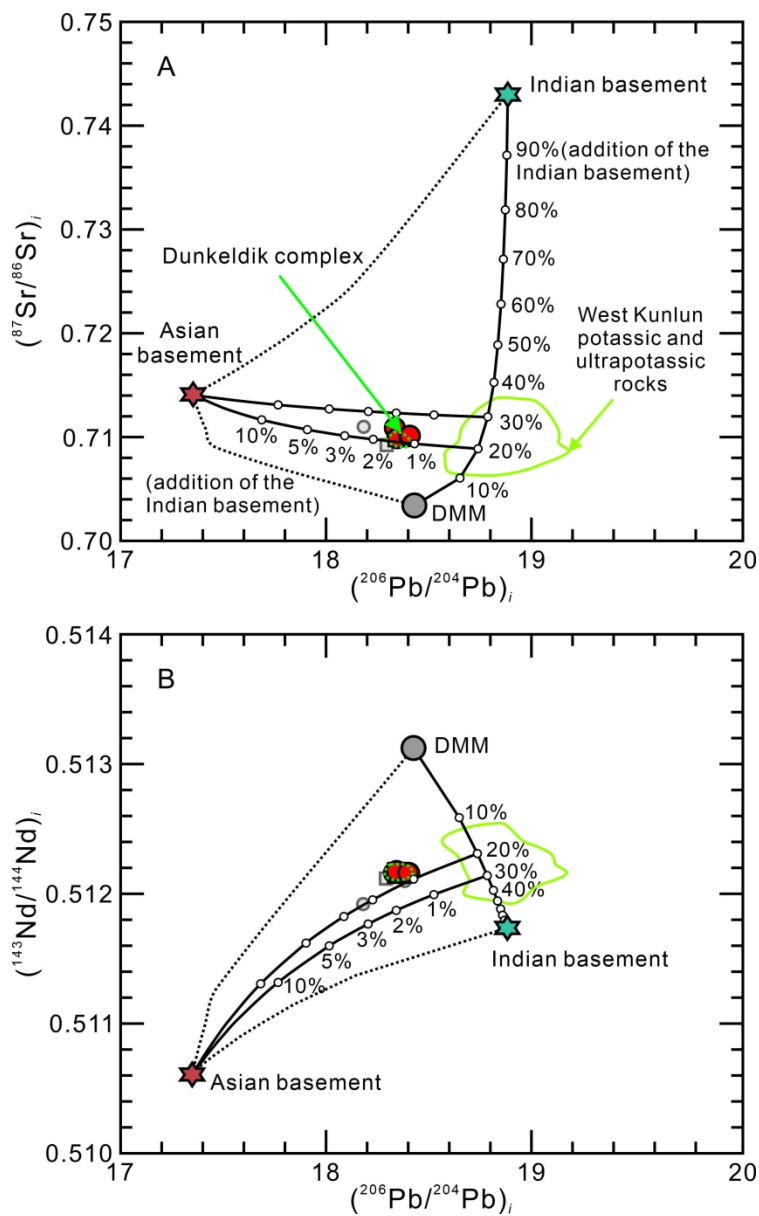


Figure 12

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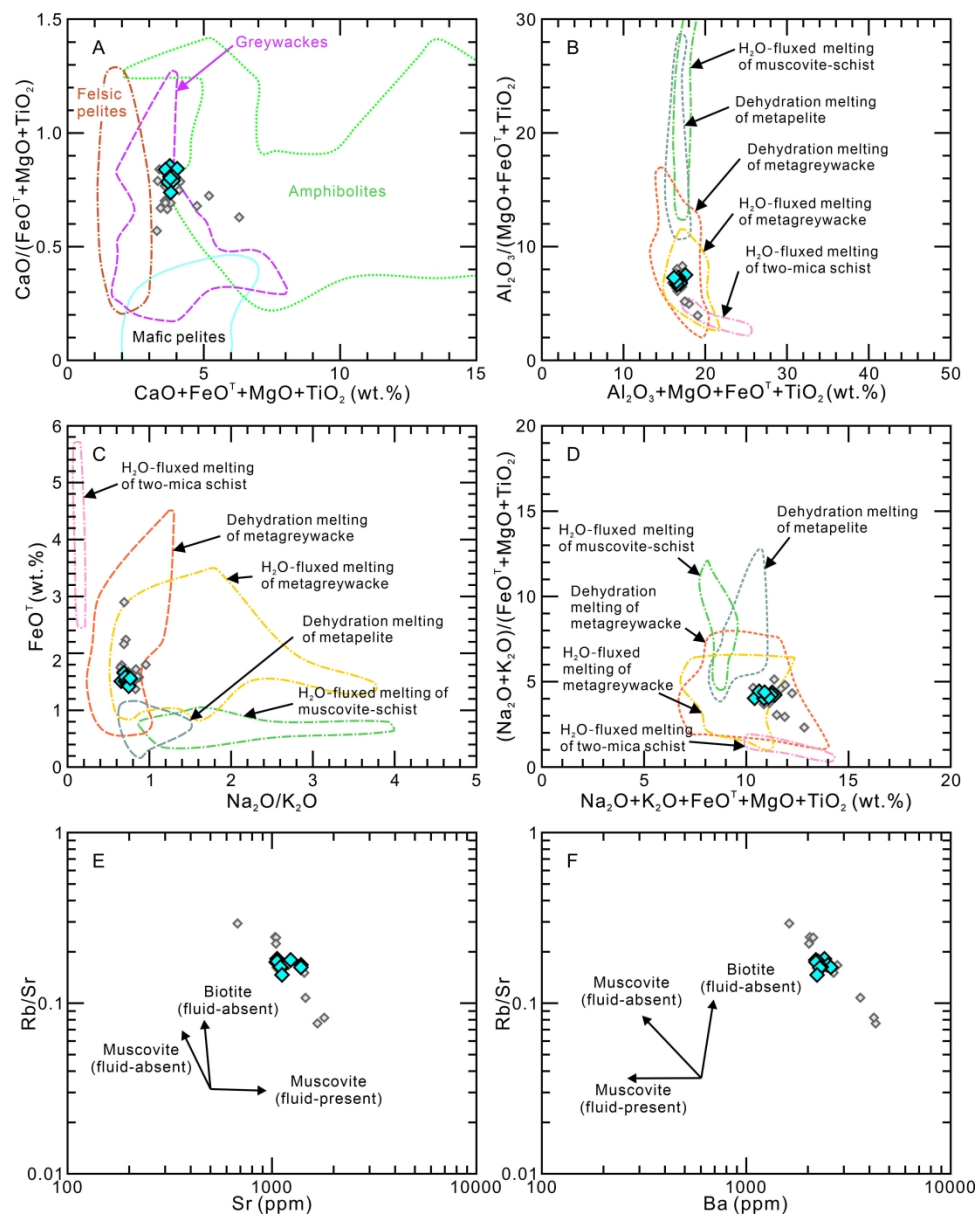


Figure 13

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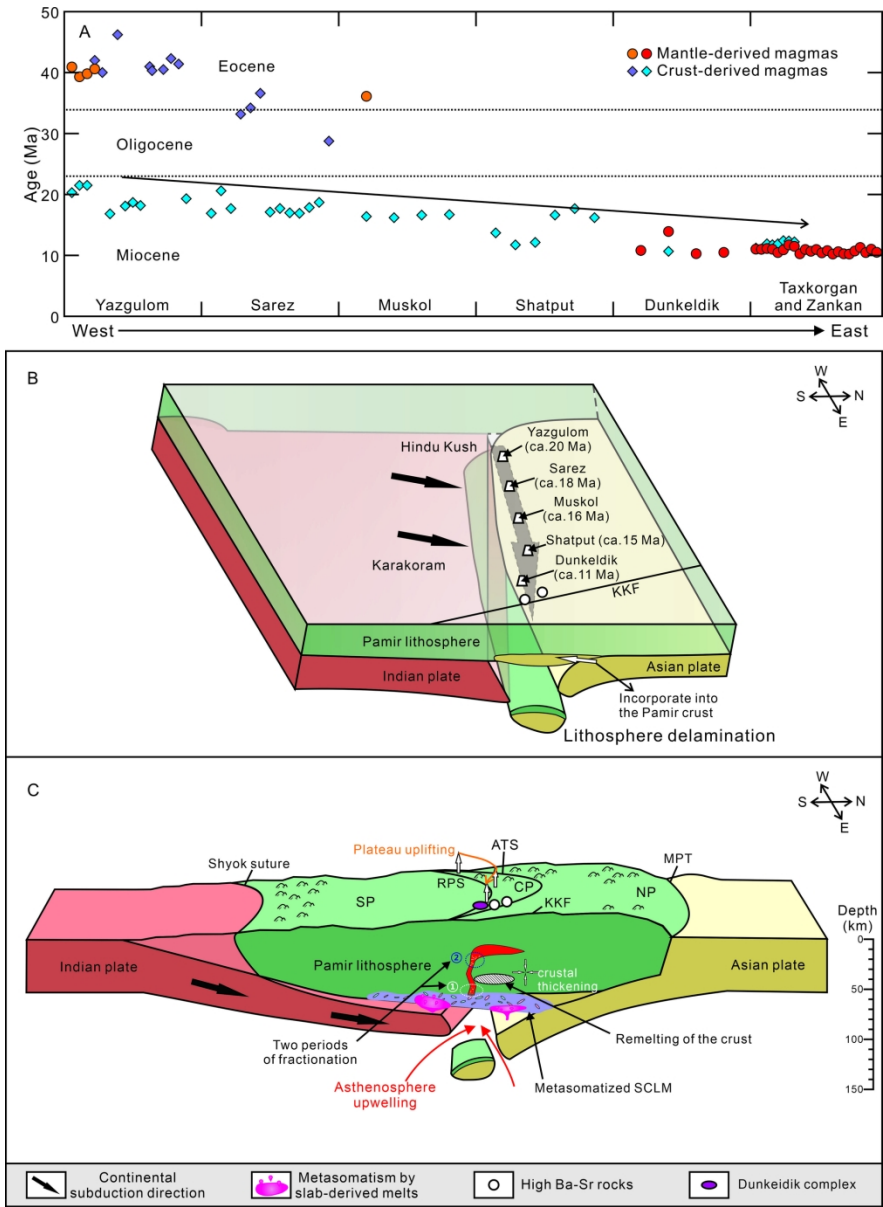


Fig. 14

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