Detrital muscovite ^{40}Ar/^{39}Ar geochronology and provenance of Cenozoic deposits in the Qaidam basin, northern Tibetan Plateau and comparison with detrital zircon and apatite records

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ABSTRACT

The single-grain detrital multi-mineral dating techniques are powerful tools for tracing sediment provenance. However, natural biases in sediment source-to-sink systems may lead to heterogeneous sink signals based on detrital single-grain ages. Differing provenance interpretations may arise from detrital multi-mineral geochronologic data because of the potentially diverse origins and transport behaviors of the analyzed detrital minerals. To test this hypothesis, we present new single-grain detrital muscovite ^{40}Ar/^{39}Ar dating results from the Cenozoic Qaidam basin and compile published detrital muscovite ^{40}Ar/^{39}Ar, detrital zircon U-Pb, and detrital apatite fission track age data to interpret muscovite provenance and to explore the potential inconsistencies among multi-dating results and related controlling mechanisms. Our results indicate that detrital muscovite grains from most Cenozoic deposits have a similar, dominated 300–400 Ma age range, with subordinate 200–300 Ma and 400–500 Ma. The new and compiled ^{40}Ar/^{39}Ar age data demonstrate that detrital muscovite records from the Cenozoic Qaidam basin are stratigraphically variable. Samples from middle fine-grained deposits-dominated strata, representing the paleo-megalake period, exhibit a relatively wider age range compared to those from lower and upper coarse-grained deposits-dominated strata, indicating a probable control of sedimentary environments. Comparisons of detrital muscovite, zircon, and apatite records indicate that the detrital zircon age spectra have the oldest ages, the widest age ranges, and the largest number of age groups. Detrital zircon and apatite age spectra exhibit higher spatial variations than detrital muscovite records, likely due to the distinct source-to-sink behaviors of these minerals. The magmatic, metamorphic, and uplift history of source terranes, along with system closure temperatures, originally determine detrital mineral age records, i.e., high-temperature systems yield older ages, and vice versa. Parent-rock types, mineral fertility, and weathering resistance control the numbers and probabilities of the detrital age clusters. Differences in mineral shape, density, and transport and depositional processes (i.e., different transport loads of light, platy minerals vs. heavy, granular minerals) may cause variations in age spectra. These differences in detrital mineral behaviors warrant more attention in multi-mineral dating-based sediment provenance studies. Additionally, ^{40}Ar/^{39}Ar age data compilation based on global Cenozoic sedimentary basins and modern rivers indicates that detrital muscovite records have potentials to determine tectonic settings, but climate-induced exhumation signals need to be distinguished before interpretation.

1. Introduction

Detrital single-grain dating (i.e., detrital geochronology and thermochronology) is a powerful tool for sediment provenance studies and is crucial for addressing various geoscience issues. These include tracing sediment provenance and dispersal patterns, understanding sediment recycling (e.g., Andersen, 2005; Carrapa, 2010; Dickinson and Gehrels, 2008, 2009a, 2009b; Caracciolo et al., 2015; Moecher et al., 2019), assessing the timing of tectonic processes such as the onset and kinematic history of mountain building (e.g., Carrapa, 2010; DeCelles et al.,

2004; Gehrels, 2014; Najman et al., 1997; White et al., 2002), determining the maximum depositional age of otherwise undatable sedimentary units (e.g., Carrapa, 2010; Copeland, 2020; Dickinson and Gehrels, 2009b; Najman et al., 1997, 2001), evaluating source-sedimentary basin evolution (e.g., Carrapa, 2010; Fildani et al., 2009; Rahl et al., 2003), analyzing sediment lag-times and transfer rates (e.g., Najman et al., 2003, 2009, 2019; Stockli and Najman, 2020), and assessing post-depositional burial heating (e.g., Stockli and Najman, 2020). Unlike traditional petrography (e.g., Jian et al., 2013a; Critelli and Martín-Martín, 2022, 2024; Criniti et al., 2023), which focuses on sand or sandstone framework grain composition (Critelli et al., 2018, 2021, 2023; Critelli and Criniti, 2021), single-grain dating primarily targets accessory minerals (such as zircon, apatite, rutile, and muscovite) through radiometric isotopes or fission track analysis (Carrapa, 2010; Chew et al., 2020; von Eynatten and Dunkl, 2012).

Zircon is the most widely used accessory mineral for geochronological and thermochronological studies. Magmatic crystallization processes are commonly dated using zircon U-Pb isotopes, which have a high closure temperature of >900 °C (Carrapa, 2010; Cherniak and Watson, 2001; Dahl, 1997; Mezger and Krogstad, 1997). Cooling and exhumation processes are dated using zircon fission-track (ZFT) and (U-Th)/He (ZHe) techniques, with closure temperatures of around 210 ± 20 °C (Carrapa, 2010; Zaun and Wagner, 1985) and 171–196 °C (average 183 °C; Reiners, 2005; Reiners et al., 2002, 2004), respectively. Zircon's high durability during sedimentary processes allows it to survive multiple sedimentary cycles (Garzanti, 2016; von Eynatten and Dunkl, 2012), making it an important and widely-used target for sedimentary provenance studies (e.g., Cawood and Nemchin, 2000; Dickinson and Gehrels, 2008, 2009a; Jian et al., 2020, 2024). Apatite is another common accessory mineral in magmatic, metamorphic, and clastic sedimentary rocks and is frequently used in low-temperature thermochronology studies (e.g., Chew et al., 2020; Jian et al., 2018; Mark et al., 2016; von Eynatten and Dunkl, 2012; Wang et al., 2022a; Wang et al., 2017). Similar to zircon, apatite U-Pb, fission track (FT), and (U-Th)/He (AHe) techniques elucidate cooling and exhumation processes with closure temperatures of ca. 400–500 °C (Chamberlain and Bowring, 2001), ca. 60–120 °C (Green et al., 1989), and ca. 60–80 °C (Carrapa et al., 2009; Farley, 2000), respectively. Multiple dating, i.e., U-Pb, FT, and (U-Th)/He dating on the same crystals (both zircon and apatite), has a high potential to reveal the entire cooling history of rock from crystallization to near-surface exhumation (Carrapa, 2010; Danišík et al., 2010). However, these techniques do not resolve mid-temperature (ca. 300–400 °C) geological processes. The $^{40}Ar/^{39}Ar$ dating of K-bearing minerals (such as muscovite, biotite, amphibole, and feldspar) may fill this gap and muscovite is the most commonly used K-bearing mineral (Hodges et al., 2005; Stuart, 2002). With the Ar isotope closure temperature of ca. 350–400 °C (Stuart, 2002), muscovite $^{40}Ar/^{39}Ar$ ages document the time when a rock mass passed through 8–10 km beneath actively eroding mountain belts (Hames and Bowring, 1994; Stuart, 2002).

Natural environmental bias (e.g., various parent rocks and sedimentary environments) may cause detrital single-grain ages to indicate different sources (Malusà and Garzanti, 2019; Chew et al., 2020; Criniti et al., 2024). Studies based on different detrital minerals (such as heavy and light minerals with different shapes) may provide dissimilar provenance interpretations due to various origins and different transport-depositional behaviors (Chew et al., 2020; Malusà et al., 2013, 2016; Malusà and Garzanti, 2019). Although combining geochronologic data from several detrital mineral species (multi-dating) is beneficial to better understand sedimentary provenance and basin-range evolution (e.g., Carrapa et al., 2009; Danišík et al., 2010; Kirkland et al., 2020; Xu et al., 2017), how to treat different provenance interpretations, if any, is usually a troublesome issue. To discuss the potential biases of single-grain dating and inconsistencies among multi-dating results, and to explore the underlying mechanisms, we focus on detrital muscovite, zircon, and apatite records from the Cenozic Qaidam basin in the

northern Tibetan Plateau (Fig. 1). The Qaidam basin contains an unusually thick (3–16 km) Cenozoic sedimentary sequence, i.e., 3 km for margin and 16 km for the center (the center is in the western part of the basin). These Cenozoic deposits are thought to be mainly derived from the surrounding mountain ranges (Cheng et al., 2015, 2016, 2019a, 2019b, 2021; Jian et al., 2013a, 2013b, 2018, 2024; Lu et al., 2018, 2022b; Rieser et al., 2006b; Wu et al., 2012b) Wu et al., 2012a. The Qilian, Altun, and Eastern Kunlun Mountains are considered as the source areas for the Cenozoic Qaidam basin and contain kinds of metamorphic sedimentary rocks, especially the Qilian Mountains, (Gehrels et al., 2003a, 2003b; Rieser et al., 2005; Jian et al., 2013a, 2018, 2024; Cheng et al., 2015, 2016; Fu et al., 2022; Wang et al., 2023) which may have high muscovite fertility. Previous studies have shown relatively high detrital muscovite contents in some Ceonozoic Qaidam basin sandstones (Fig. 2; Jian et al., 2013a; Rieser et al., 2005, 2006a, 2006b). Numerous detrital zircon and apatite age data from the Cenozoic deposits have been published (e.g., Cheng et al., 2019a; He et al., 2020, 2021a, 2021b; Jian et al., 2018, 2024 and reference therein; Wang et al., 2017, 2022a). These conditions make the Cenozoic Qaidam basin an ideal place to discuss the source-to-sink behaviors and mechanisms of detrital muscovite, zircon, and apatite grains and to verify potential dissimilar provenance interpretations based on single-grain dating results.
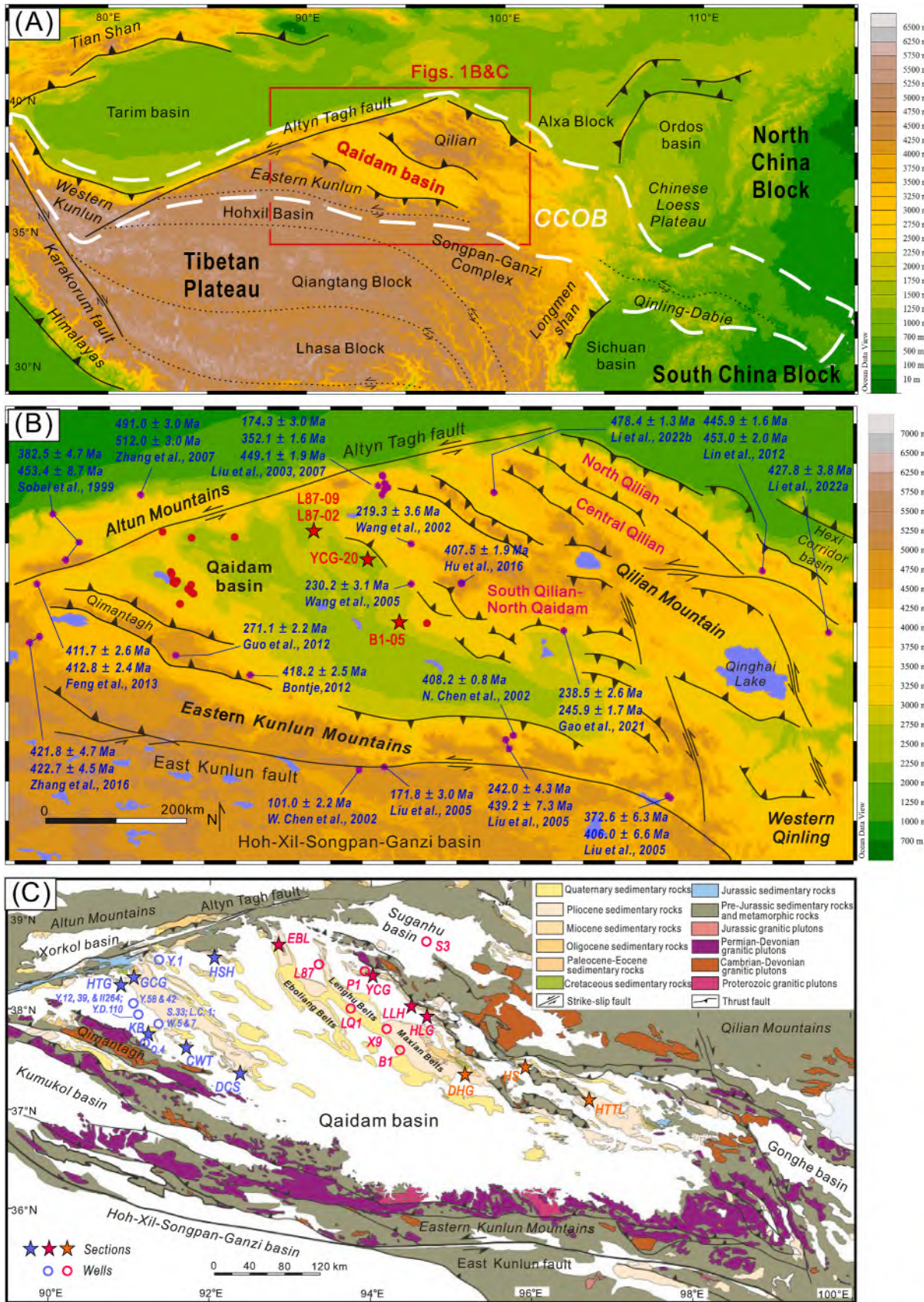
In this study, we present new sandstone (involving borehole and outcrop samples) detrital muscovite $^{40}Ar/^{39}Ar$ dating data (n = 194) from the northern Qaidam basin. We also compile published detrital muscovite $^{40}Ar/^{39}Ar$ ages from other regions of the Qaidam basin (n = 520), other Cenozoic sedimentary basins (n = 5583), and modern river basins (n = 8058) worldwide. Published detrital zircon U-Pb age data (n = 12978) and detrital apatite fission track (AFT) data (n = 3364) from the Cenozoic Qaidam basin are also compiled in this contribution. All the involved dating data are shown in the supplemental materials (Tables S1–S9 in Appendix A). The aims are to: 1) clarify the spatial and stratigraphic distributions of the Qaidam basin detrital muscovite $^{40}Ar/^{39}Ar$ age records, and explore related controlling mechanisms; 2) investigate detrital muscovite, zircon, and apatite age responses to their potentially different source-to-sink behaviors, and discuss the role of detrital muscovite in provenance analysis; 3) analyze the relationship between tectonic setting and detrital muscovite $^{40}Ar/^{39}Ar$ age spectra on a global scale.

2. Geological setting

2.1. The Qaidam basin and the surrounding mountain ranges

The Qaidam basin covers ca. 120,000 km^2 and is situated at an elevation of ca. 2.7–3.0 km above sea level (Fig. 1B). It is bounded by the Qilian Mountains to the northeast, the Altun Mountains to the northwest, and the Eastern Kunlun Mountains to the south. These mountain ranges are significant components of the Central China Orogenic Belt (CCOB; Fig. 1A; Dong et al., 2021).

The Qilian Mountains are mainly composed of various types of metamorphic rocks, volcanic rocks, marine sedimentary strata, and ophiolite associations (Fig. 1C; Dong et al., 2021; Fu et al., 2022; Jian et al., 2013a; Rieser et al., 2005; Wang et al., 2023). The Qilian orogen is thought to have formed through the breakup of the supercontinent Rodinia, followed by subduction and collision involving the Alxa-North China, Central Qilian, and Qaidam Blocks during the Neoproterozoic to late Paleozoic (>ca. 550–415 Ma; Dong et al., 2021; Jian et al., 2018, 2024; Li et al., 2020). These blocks experienced a magmatic lull from the late Paleozoic to the Triassic and underwent extension from the Jurassic to the Cretaceous likely due to the Lhasa-Qiangtang collision (Chen et al., 2021; Li et al., 2020; Lin et al., 2019; Tong et al., 2020; Zuza et al., 2018). The early Cenozoic witnessed the reactivation of the Qilian orogen, influenced by the far-field effect of the India-Asian collision (Chen et al., 2021; Li et al., 2020; Lin et al., 2019; Tong et al., 2020; Zuza
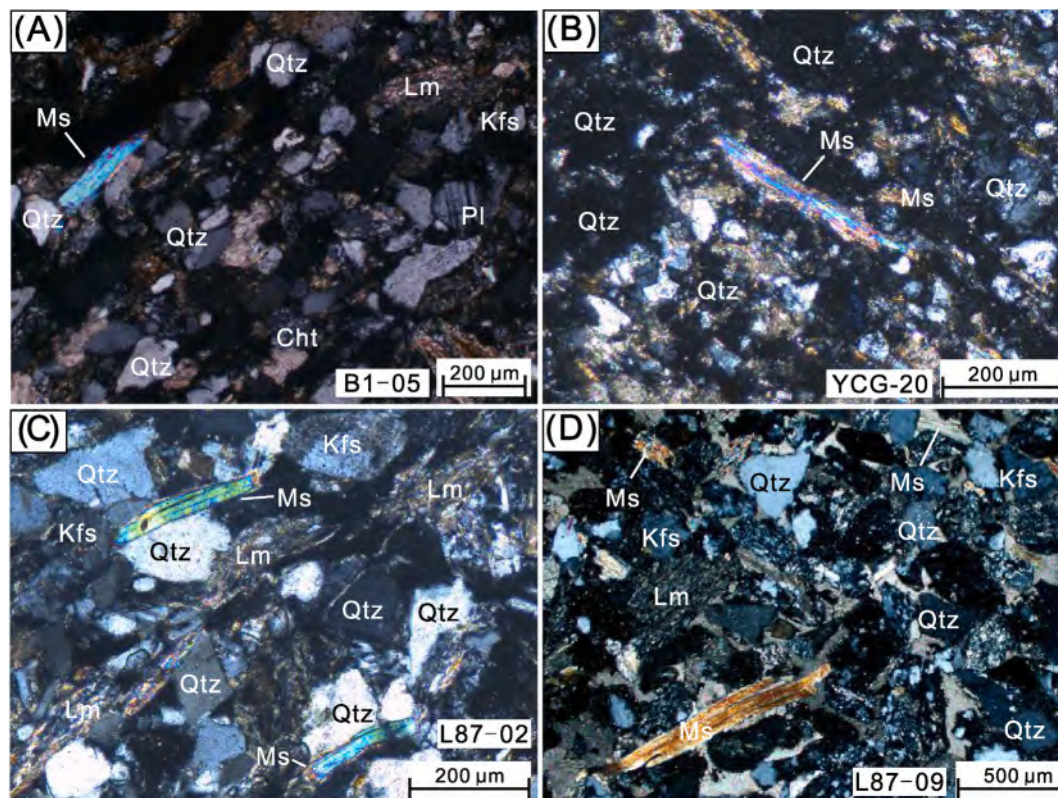
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Fig. 2. Photomicrographs of sample B1-05 (A), sample YCG-20 (B), sample L87-02 (C), and sample L87-09 (D). Notice the high concentration of detrital muscovite. Photomicrographs modify from Jian et al. (2013a). Qtz: quartz; Kfs: K-feldspar; Pl: plagioclase; Ms: muscovite; Lm: metamorphic lithic; Cht: Chert.

et al., 2018; Li et al., 2022).

The Altun Mountains are renowned for their ultra-high pressure (UHP) metamorphism and the Mesozoic–Cenozoic sinistral strike-slip tectonic settings (Dong et al., 2021, Fig. 1B). This orogen consists mainly of Archean-Proterozoic basement rocks and marine sedimentary strata, Paleozoic metamorphic and magmatic rocks, and Mesozoic sedimentary strata (Fig. 1C; Allen et al., 2023; Dong et al., 2021; Gehrels et al., 2003a; Jian et al., 2018). It shares a similar Paleozoic tectonic history with the Qilian Orogen (>ca. 520–385 Ma; Dong et al., 2021; Sobel and Arnaud, 1999; Sobel et al., 2001). Muti-stage displacements of the Altyn-Tagh fault from the Mesozoic to the Cenozoic resulted in several cooling and exhumation events in the Altun Mountains (Dong et al., 2021; Shi et al., 2018; Sobel et al., 2001; Wu et al., 2012b).

The Eastern Kunlun Mountains are geographically separated from the Kunlun Orogen by the Altyn-Tagh fault (Fig. 1A). This orogen is mainly composed of Early Cambrian to Early Devonian and Late Permian to Triassic magmatic rocks, Devonian to Early Triassic marine sedimentary rocks, and Jurassic and Cenozoic non-marine rocks (Allen et al., 2023; Dai et al., 2013; Dong et al., 2021; Jian et al., 2018). The Eastern Kunlun Mountains record a prolonged history of subduction and accretion related to the Proto-Tethys and Paleo-Tethys oceans during the Paleozoic to early Mesozoic (>485–220 Ma; Dong et al., 2021; Jian et al., 2024; Jian et al., 2018; Wang et al., 2023). Exhumation events in the Eastern Kunlun regions are regarded to be associated with the Qiangtang-Kunlun collision in the Early Jurassic, the Lhasa-Qiangtang collision from the Late Jurassic to Cretaceous, and the India-Asia collision since the early Cenozoic (Dai et al., 2013; Staisch et al., 2020; Tian et al., 2020; Wang et al., 2018; Wu et al., 2019a; Yuan et al., 2006).

2.2. Cenozoic stratigraphy, lithology, and sedimentary environments

The Cenozoic succession in the Qaidam basin is regularly divided into seven stratigraphic units: 1) Lulehe Formation (E_{1+2}), 2) Xiaganchaigou Formation (E_3), 3) Shangganchaigou Formation (N_1), 4) Xiayoushashan Formation (N_2^1), 5) Shangyoushashan Formation (N_2^2), 6) Shizigou Formation (N_2^3), and 7) Qigequan Formation (Q_{1+2}) (Fig. 3; Ji

Era	Formation	Abbr.	Lithology SW	Lithology NW	Lithology N&NE	Samples	Sedimentary Environment & Lithologic Description
Cenozoic		Q_{3+4}					Alluvial fan and salt lake environments, consisting of conglomerates, sandstones, and evaporites.
	Qigequan Fm.	Q_{1+2}					
	Shizigou Fm.	N_2^3					Alluvial fan and occasionally fluvio-lacustrine environments, the sediments consist of conglomerates, sandstones, occasionally mudstones, and evaporites.
	Shang youshashan Fm.	N_2^2				B1-05	
	Xia youshashan Fm.	N_2^1					Fluvial, deltaic, and lacustrine environments. Predominantly consisting of fine-grained sandstones and mudstones with subordinate carbonate and evaporite layers in northern-northeastern regions, and mixed carbonate-siliciclastic deposits (with evaporite layers) in western regions.
	Shang ganchaigou Fm.	N_1				L87-09 YCG-20	
	Xia ganchaigou Fm.	E_3				L87-02	
	Lulehe Fm.	E_{1+2}					Alluvial fan, plain, and marginal lacustrine environments. The sediments consist of red, basin-margin facies conglomerates with minor sandstones and mudstones.
							Lack of sediments, unconformity with Mesozoic strata or pre-Mesozoic basements.

Legend: mudstone; evaporite-mudstone; marlstone; algal limestone; oolitic limestone; sandstone; evaporite-sandstone; siltstone/sandstone; conglomerate; evaporite-conglomerate.
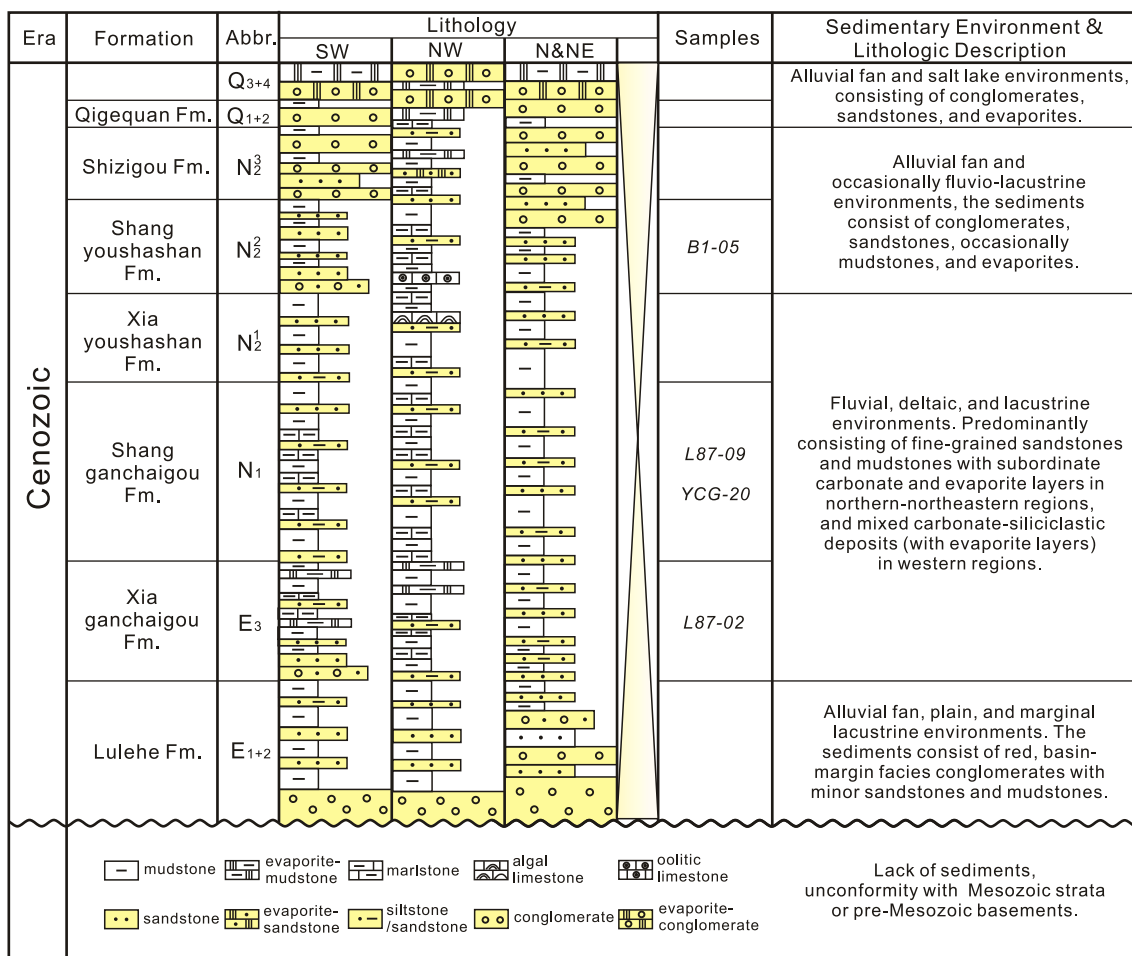
Fig. 3. Cenozoic stratigraphic framework, sedimentary environment, and lithological description of the Qaidam basin in northern Tibet, modified from Wang et al. (2023).

et al., 2017; Xing et al., 2023). There is ongoing debate about the depositional ages of these Cenozoic strata (Cheng et al., 2019a, 2019b, 2021; Jian et al., 2023). An "old age model" suggests that the initial deposition of the Lulehe Formation occurred in the early Eocene (ca. 43.5–54 Ma; Fang et al., 2007, 2019; Chang et al., 2015; Ji et al., 2017; Xing et al., 2023). In contrast, a "young age model" proposes an Oligocene initial deposition for the Cenozoic strata (ca. 20–25 Ma; Wang et al., 2017, 2022a; Nie et al., 2019; Duan et al., 2022; Lu et al., 2022a, 2022b). The "old age model" is supported by vertebrate fossils, ostracods, spore, and pollen assemblages, (detrital) thermochronological data, and regional lithostratigraphic correlations (Cheng et al., 2021 and references therein). Additionally, biostratigraphy based on Charophyte assemblages (Xing et al., 2023) correlates with the high-resolution magnetostratigraphy of the Paleogene–Neogene sequence (ca. 52–7 Ma; Ji et al., 2017) at the Dahonggou (DHG) Section (Fig. 1C). Recently, carbonate U-Pb dating of syntectonic deposits in the pull-apart East Xorkol basin (Fig. 1C, western Qaidam basin) yielded an age of 58.9 ± 1.29 Ma, providing compelling evidence that the Altyn-Tagh fault initiated its strike-slip motion during the Paleocene–early Eocene (Yi et al., 2024). Additional support for the Eocene initiation viewpoint comes from stable isotope records and long-chain n-alkanes from the DHG section, the ages of interbedded volcanic and tuff rocks from several Eocene sedimentary basins in the northern and eastern Tibetan Plateau, and low-temperature thermochronology results of the Qilian, Altun, and Eastern Kunlun Mountains (Jian et al., 2023, and references therein). The "young age model" is supported by vertebrate fossils, magnetostratigraphy control by mammal fossil assemblages, detrital

zircon geochronologic and detrital apatite thermochronological data (Wang et al., 2017, 2022a; Nie et al., 2019; Duan et al., 2022; Lu et al., 2022a, 2022b). Detailed reviews and comparison analyses of these two age models have been provided by Cheng et al. (2018, 2021, 2023)and Wang et al. (2022b). Although the depositional age of the Cenozoic strata in the Qaidam basin requires further detailed study, this study applies the "old age model" where needed.

The Cenozoic strata in the Qaidam basin consist of evaporite, carbonate, and siliciclastic deposits, predominantly deposited in fluvial-lacustrine sedimentary environments (Jian et al., 2013a, 2013b). Previous studies demonstrate that the Qaidam sedimentary depocenters shifted eastward during the Cenozoic (Bao et al., 2017; Yin et al., 2008), likely due to the uplift of the Eastern Kunlun Mountains (Bao et al., 2017). This results in significant spatial and stratigraphic variations in the Cenozoic lithology (Fig. 3; Jian et al., 2024). The northern and eastern regions of the Qaidam basin are dominated by siliciclastic sedimentary rocks (Fu et al., 2022; Jian et al., 2023; Zhuang et al., 2011), whereas carbonate rocks, evaporite rocks, and mixed carbonate-siliciclastic deposits are common in the western Qaidam basin (Guo et al., 2017; Jian et al., 2014; Zhang et al., 2018). Stratigraphically, the Cenozoic sedimentary succession generally transitions from coarse-grained deposits at the base (E_{1+2}) to relatively fine-grained deposits (E_3, N_1, N_2^1, and N_2^2), and then back to coarse-grained deposits (N_2^3 and Q_{1+2}) in most areas of the basin (Fig. 3). The coarse-grained strata (E_{1+2}, N_2^3, and Q_{1+2}) are interpreted as being dominated by alluvial fan, plain, and marginal lacustrine facies, while the fine-grained strata (E_3, N_1, N_2^1, and N_2^2) are associated with fluvial, deltaic, and

lacustrine environments (Fig. 3).

3. Samples and methods

Four sandstone samples (Figs. 1B and 5) were selected for detrital muscovite $^{40}Ar/^{39}Ar$ geochronological analysis. Borehole samples L87–02 and L87-09 (Fig. 4) are classified as medium-fine-grained lithic feldspar sandstone, whereas borehole sample B1-05 and outcrop sample YCG-20 (Fig. 4) are fine-grained lithic sandstone. These samples had previously been analyzed for petrographic and heavy mineral compositions as well as detrital zircon U-Pb analyses (Jian et al., 2013a, 2023, 2024, Fig. 5). Additionally, samples B1-05 and L87-09 were analyzed for detrital garnet geochemistry (Hong et al., 2020; Jian et al., 2013a), while samples B1-05 and YCG-20 were employed in detrital AFT analyses (Jian et al., 2018, Fig. 5). The detrital framework grains in these samples are angular to subangular and are poorly to moderately sorted (Fig. 2). Quartz and lithic fragments dominate the detrital framework grains, with the lithic fragments primarily consisting of metasedimentary lithic fragments (Jian et al., 2013a). The heavy mineral assemblage includes garnet, epidote, zircon, tourmaline, and apatite, indicating a significant derivation from metamorphic rocks (Jian et al., 2013a).

In preparation for $^{40}Ar/^{39}Ar$ isotopic analysis, detrital muscovite grains of 180–280 μm were separated from sandstone samples, cleaned with deionized water, and dried. About 50–60 grains of muscovite were separated from each sample. The muscovite samples, along with standard ZBH-25 biotite (132.9 ± 1.3 Ma; Sang et al., 2006) used for neutron monitoring, and K_2SO_4 and CaF_2 used for K and Ca isotopic revising were packaged together by aluminum foil, sealed in a vacuum quartz bottle and then irradiated in the B4 canal of the 49-2 nuclear reactor at Chinese Institute of Atomic Energy (CIAE), Beijing. Muscovite laser

$^{40}Ar/^{39}Ar$ analyses were conducted at the Key Laboratory of Orogenic Belts and Crustal Evolution, Peking University. After irradiation, the samples were analyzed by using the automatic high-precision and high-resolution laser microprobe $^{40}Ar/^{39}Ar$ dating system (Zhou et al., 2008; Xu et al., 2013). The muscovite samples and monitors were degassed and fused by a New Wave CO_2 laser. The argon isotopes were measured by using a VG5400 mass spectrometer. About 50 unknown grains were analyzed per sample. The $^{40}Ar/^{39}Ar$ ages were calculated based on the argon isotopic ratios measured after corrections for mass discrimination, interfering nuclear reactions, procedural blanks, and atmospheric Ar contamination. The procedures for isotopic analyses and age calculations were controlled by MassSpec software (Deino, 2010).

4. Results

In total, we report 194 new detrital single-grain muscovite $^{40}Ar/^{39}Ar$ ages from the four samples. The ages range from 210 Ma to 490 Ma and have a major age group of 300–400 Ma and minor groups of 250–270 Ma and ca. 500 Ma (Fig. 6). Specifically, sample L87-02 from the E_3 strata yields detrital muscovite ages range from 210 Ma to 430 Ma, with a major age group of 280–410 Ma (Fig. 6E). Ages of the N_1 sample YCG-20 are distributed between 250 Ma and 460 Ma with a major age group of 280–430 Ma (Fig. 6D). The N_1 sample L87-09 yields an age distribution from 290 Ma to 390 Ma, with a major age group of 320–390 Ma (Fig. 6C). Ages of sample B1-05 from the N_2^2 strata covers a range from 250 Ma to 490 Ma, with a major age group of 380–410 Ma (Fig. 6B).

The compilation indicates that detrital muscovite grains from the Lulehe (LLH) Section (Fig. 1C) in the northern Qaidam basin yield a uniform Permian $^{40}Ar/^{39}Ar$ age group of 250–279 Ma (Fig. 7; Rieser et al., 2006a). In the western Qaidam basin, detrital muscovite $^{40}Ar/^{39}Ar$ dating reveals several age groups, including ca. 350–450 Ma and ca.
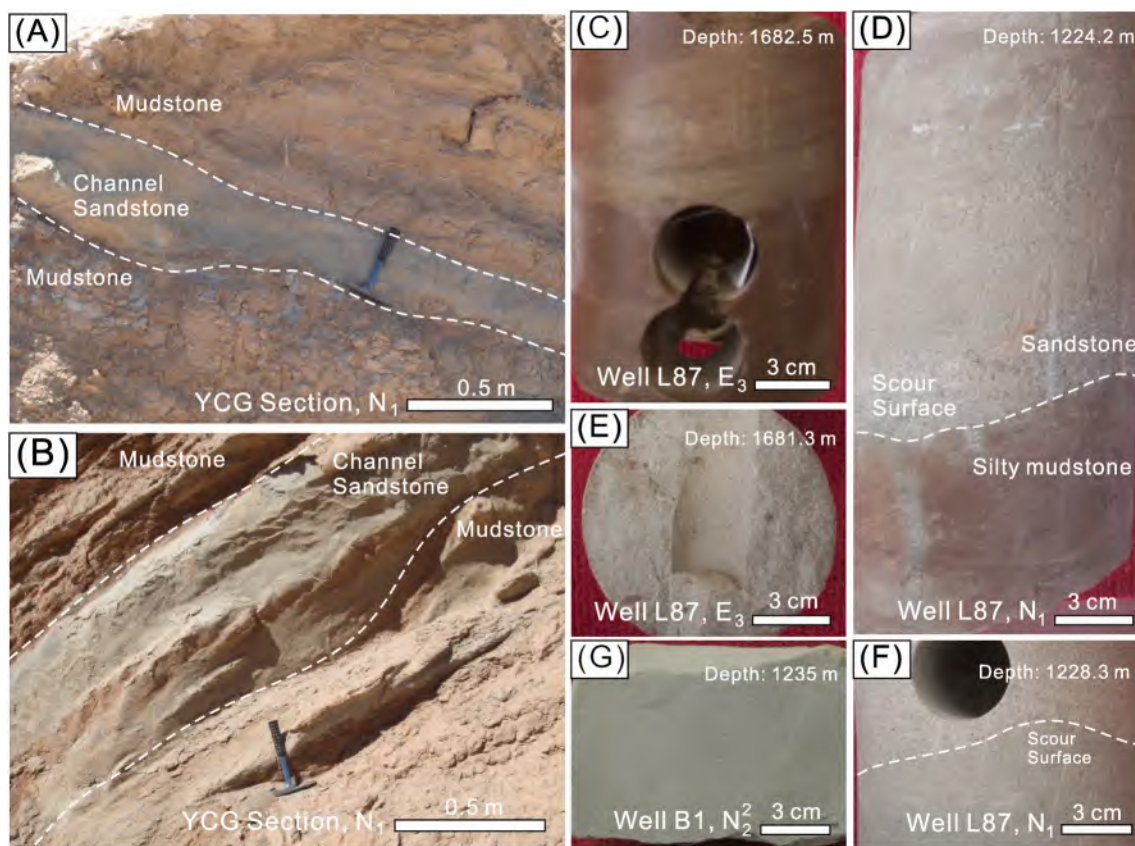

Fig. 4. Representative photographs of sedimentary rocks of the Xiaganchaigou Fm. (E_3), Shangganchaigou Fm. (N_1), and Shangyoushashan Fm. at the YCG Section and wells L87 and B1 in the northern Qaidam basin (locations see Fig. 1C). (A–B) YCG Section; (C–F) well L87; (G) well B1.
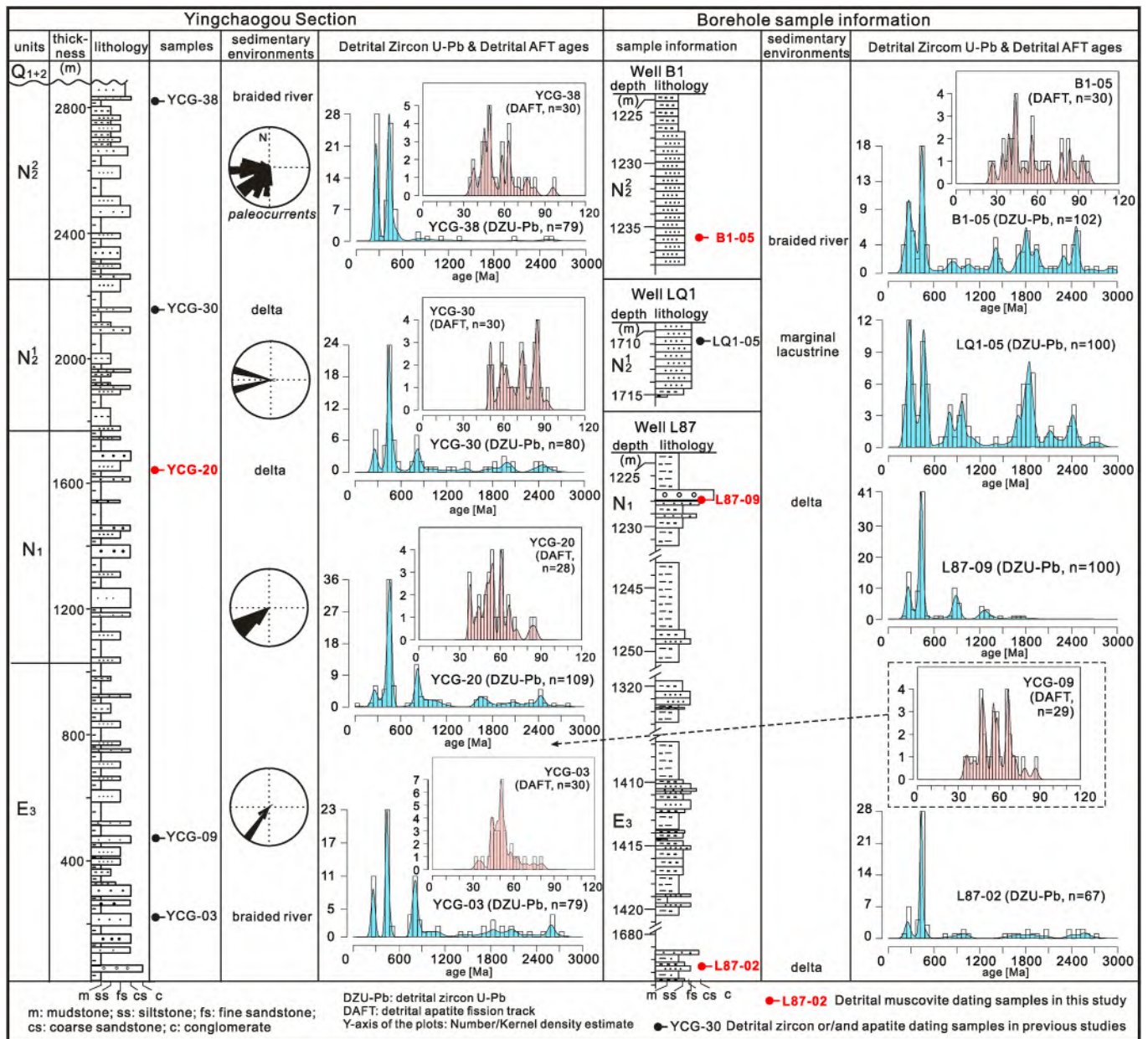
Fig. 5. Stratigraphic columns of the analyzed outcrop section and drilling cores and previously published data, modified from Jian et al. (2024). The samples marked as red names were selected for detrital muscovite $^{40}Ar/^{39}Ar$ geochronology in this study. Detrital zircon U-Pb results are from Jian et al. (2024). Paleocurrent data and detrital apatite fission track results are from Jian et al. (2018).

220–280 Ma, with subordinate clusters of ca. 122–140 Ma and a minor group ca. 500 Ma. The age range between 350 and 450 Ma is the most common and dominant (Fig. 8; Rieser et al., 2006b, 2007). Another study on detrital muscovite $^{40}Ar/^{39}Ar$ dating for the E_3 and N_1 stata of the Hongsanhan (HSH) Section (Fig. 1C) in the western Qaidam presents a major age group of ca. 30–340 Ma (Wang, 2023).

5. Discussion

5.1. Provenance of the Cenozoic deposits in the Qaidam basin: A review

Studies from distinct target perspectives, such as bed load, suspended load, and dissolved load, focus on different mediums and may draw diverse conclusions on the provenance of the Cenozoic Qaidam basin. From the perspective of relatively coarse grains which are commonly transported by bed loads, petrographic analyses show that most of the

Cenozoic sandstones are relatively immature in both texture and composition. Specifically, detrital grains in most sandstones are mainly angular to subangular, poorly to moderately sorted, and contain abundant lithic fragments (Fig. 2; Rieser et al., 2005; Jian et al., 2013a; Bush et al., 2016; McRivette et al., 2019; Sun et al., 2020a). This indicates that the sandstones were mainly derived from nearby source terranes (Jian et al., 2013a; Rieser et al., 2005). The sandstone point-count modal data suggest predominant recycled-orogeny and collisional sutures & fold-thrust belt sources (Rieser et al., 2005; Jian et al., 2013a; Bush et al., 2016; McRivette et al., 2019; Lu et al., 2018; Fu et al., 2022). The framework grain compositions exhibit slight spatial variation in the northern Qaidam basin (Jian et al., 2013a) and minor changes over time in the western Qaidam basin (Rieser et al., 2005). Heavy minerals are dominated by zircon, tourmaline, rutile, apatite, epidote, garnet, hornblende, hematite, and magnetite, indicating that the source terranes comprise intermediate-acidic igneous rocks and medium-to low-grade
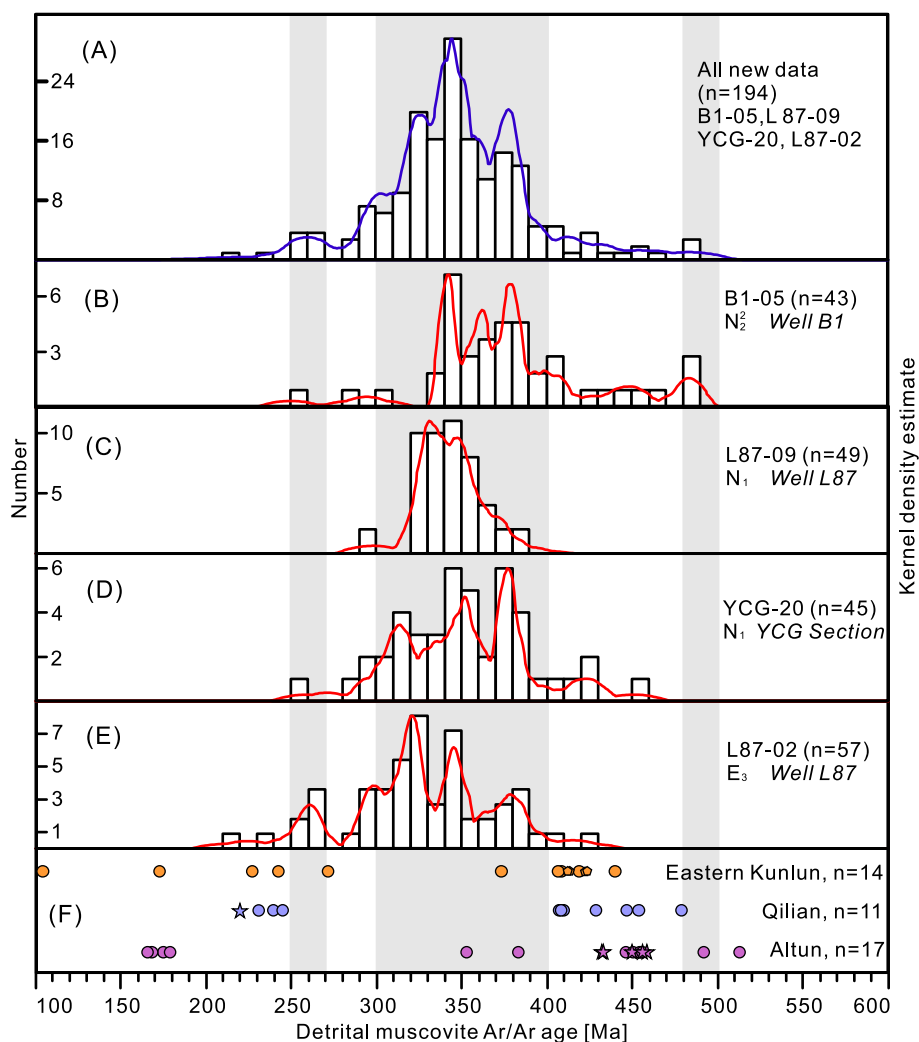
Fig. 6. Kernel density estimate (KDE) curves and histograms for detrital muscovite $^{40}Ar/^{39}Ar$ geochronologic results of the Cenozoic sandstone samples from the northern Qaidam basin. (A) KDE curves and histograms for all our new data. (B) KDE curves and histograms for sample B1-05. (C) KDE curves and histograms for sample L87-09. (D) KDE curves and histograms for sample YCG-20. (E) KDE curves and histograms for sample L87-02. (F) Muscovite $^{40}Ar/^{39}Ar$ ages of potential source terranes. The circle represents metamorphic rocks, the pentagon represents dike rocks, and the pentagram represents magmatic rocks. Shaded bars point out the 250–270 Ma, the 300–400 Ma, and the ca. 500 Ma intervals. References and locations of ages in three mountain ranges see Fig. 1B.

metamorphic rocks or slightly metamorphic clastic rocks (Jian et al., 2013a; Zhu et al., 2017; Zhou et al., 2018; Nie et al., 2019; Ding et al., 2022). Detrital zircon U-Pb age signatures of the western basin are characterized by 400–480 Ma and 220–280 Ma with minor Precambrian signals, indicating major contributions from the neighboring Altun and Eastern Kunlun ranges (Fig. 10; e.g., Bush et al., 2016; Cheng et al., 2016; Wang et al., 2017, 2022a; Jian et al., 2024 and references therein). However, detrital zircon records in the northern and eastern basin display prominent early Paleozoic U-Pb ages with relatively significant Paleoproterozoic, Neoproterozoic, and Permian–Triassic signals in some samples (Fig. 10; e.g., Bush et al., 2016; Cheng et al., 2016; Wang et al., 2017, 2022a; Jian et al., 2024 and references therein). The observed different temporal variation trends in detrital zircon records from the northern basin are thought to be due to variable zircon supply from different micro-terranes in the Qilian Mountains (Fig. 10; e.g., Bush et al., 2016; Cheng et al., 2016; Wang et al., 2017, 2022a; Jian et al., 2024 and references therein). Detrital AFT ages of previously analyzed sandstones also display high spatial variations (Fig. 11; e.g., Wang et al., 2017, 2022a; Jian et al., 2018; He et al., 2021a, 2021b). The northern Qaidam basin indicates two kinds of detrital AFT age distributions: ca. 20 Ma to ca. 100 Ma in the western region and ca. 5 Ma to ca. 200 Ma in the eastern region and the ages of the western Qaidam basin range from

ca. 20 Ma to ca. 160 Ma (Wang, 2023).

Mudstone and siltstone analyses may provide valuable insights into the provenance of fine grains that are commonly transported by suspended loads. Geochemical studies on mudstone indicate that sediments were primarily derived from a source area dominated by acidic-intermediate rocks (Jian et al., 2013b; Bao et al., 2019; Sun et al., 2020b; Li et al., 2021). The $^{87}Sr/^{86}Sr$ ratios and $^{143}Nd/^{144}Nd$ ratios of mudstone silicate fractions from the Cenozoic strata in the northern Qaidam basin indicate that the fine-grained sediments were primarily derived from the Qilian Mountains (Yan et al., 2024). Furthermore, fine-grained sediments may be affected by sediment transport pathways and water dynamics, such as lake currents, especially in paleo-megalakes. This results in well-mixed composition of sediments from various source terranes (Ren et al., 2019; Wang et al., 2023). Paleowater solute Sr isotope studies, based on authigenic carbonate fractions, provide insights into dissolved load (Yang et al., 2016, 2022; Liu et al., 2022, 2023; Yan et al., 2024). The $^{87}Sr/^{86}Sr$ ratios in paleo-water solutes from the northern Qaidam basin have been remarkably high since ca. 54 Ma, suggesting a Qilian-dominated source (Liu et al., 2023; Yan et al., 2024). Given that the $^{87}Sr/^{86}Sr$ ratios in Eastern Kunlun Mountains are significantly lower (Yang et al., 2022; Liu et al., 2023; Yan et al., 2024), the relatively low paleowater solute $^{87}Sr/^{86}Sr$ ratios
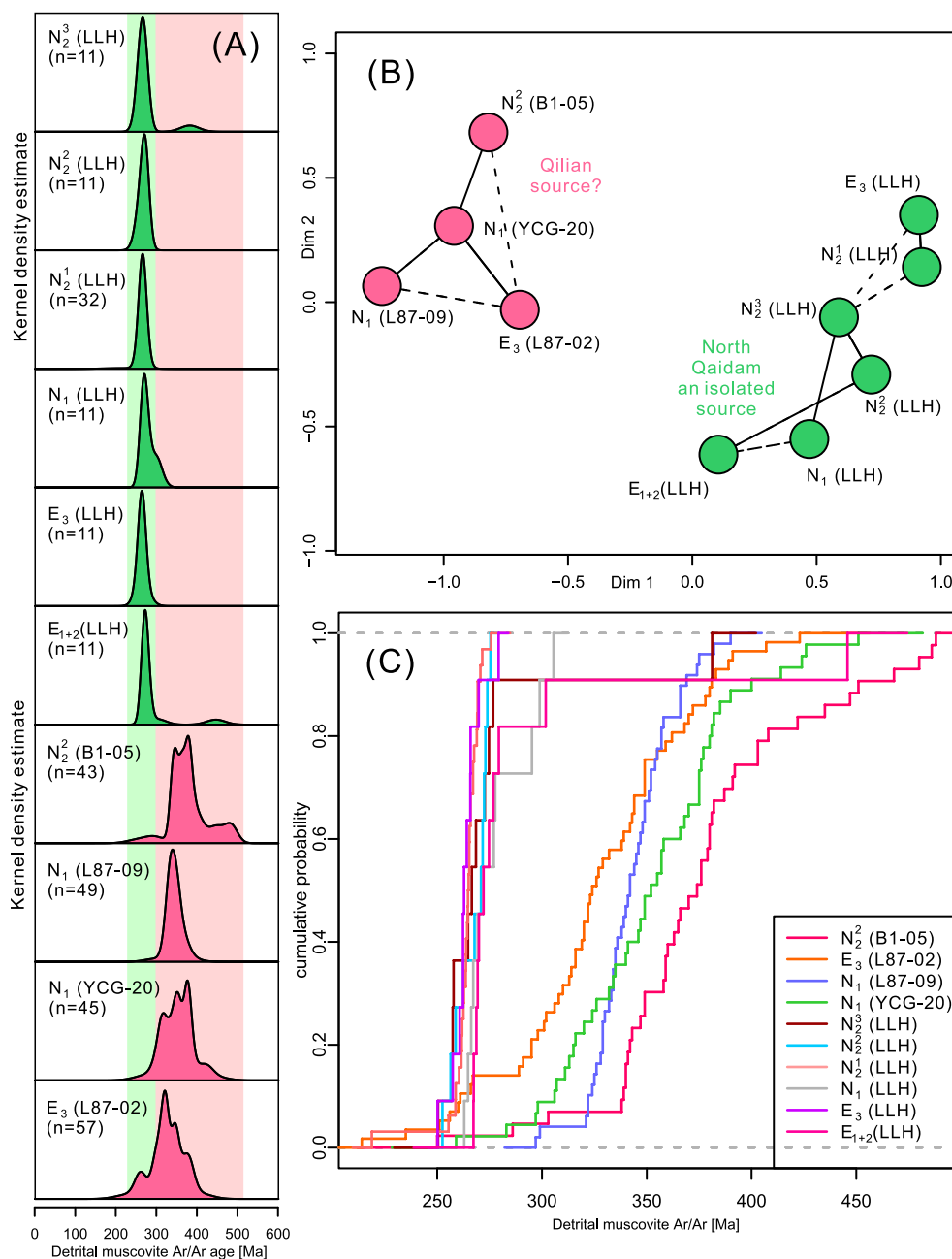
Fig. 7. KDE curves (A), non-metric multidimensional scaling (MDS) plots (B), and Cumulative probability plots (C) for detrital muscovite ^{40}Ar/^{39}Ar ages from the northern Qaidam basin. LLH, Lulehe Section. Data of the LLH Section are from Rieser et al. (2006a). The R programming language-based Provenance software (Vermeesch et al., 2016) was employed for the illustrations.

during the paleo-megalake periods (ca. 44.5 to ca. 32 Ma and after ca. 16 Ma; Liu et al., 2023) likely indicate the well-mixing of materials derived from both the Qilian and Eastern Kunlun Mountains (Liu et al., 2023).

In summary, the above-mentioned analysis of sedimentary samples combined with paleo-flow direction measurement results (Zhuang et al., 2011; Wu et al., 2012b; Bush et al., 2016; Xia et al., 2020; Lu et al., 2022b) suggests that the expansive northern and eastern regions of the Qaidam basin were primarily fed by the Qilian Mountains. In contrast, the Altun and Eastern Mountains were the major sources of the Cenozoic sedimentary rocks in relatively limited western Qaidam regions (Rieser et al., 2005, 2006a, 2006b; Zhuang et al., 2011; Jian et al., 2013a, 2024; Liu et al., 2022, 2023). During the paleo-megalake periods, fine-grained sediments and solute materials from these different source terranes may have mixed through lake currents or other water dynamics (Liu et al.,

2022, 2023; Wang et al., 2023). Additionally, tectonic evolutions of the surrounding mountains, climate change, and variations in the sediment source-to-sink system contributed to the high spatiotemporal variability in detrital compositions within the Cenozoic Qaidam basin (Cheng et al., 2021; Jian et al., 2024). This variability indicates that the Cenozoic provenance of the Qaidam basin still needs to be rigorously inspected.

5.2. Cenozoic Qaidam basin detrital muscovite ^{40}Ar/^{39}Ar age distributions, controls, and muscovite provenance interpretations

The compilation results of detrital muscovite ^{40}Ar/^{39}Ar ages, including our new data, reveal that the Cenozoic deposits from the Qaidam basin (excluding the LLH section) are predominantly characterized by ages of 300–400 Ma, with minor groups of 200–300 Ma and sparse occurrences of 400–500 Ma (Figs. 7 and 8).
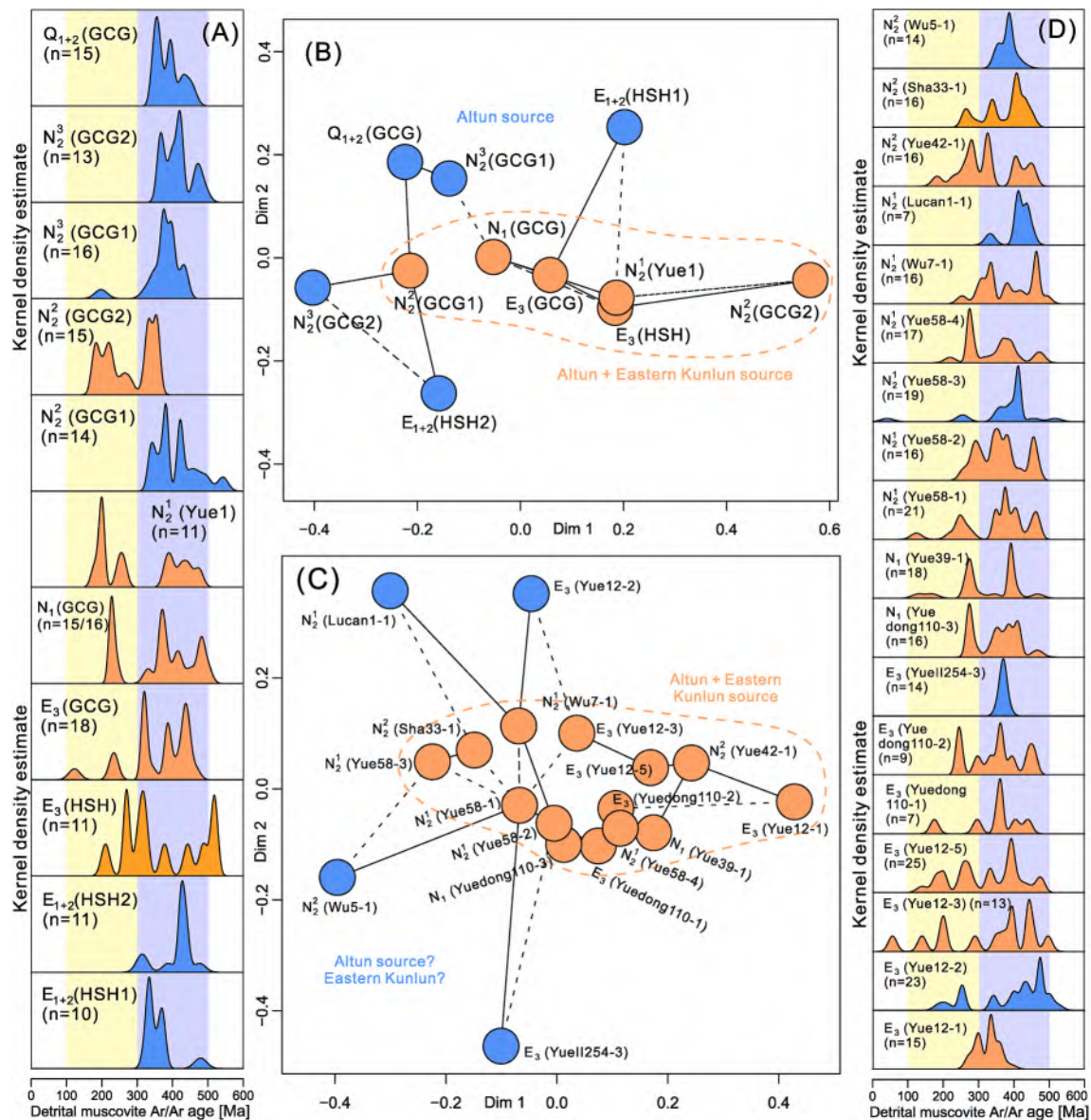
Fig. 8. KDE curves (A) and MDS plots (B) for detrital muscovite ^{40}Ar/^{39}Ar ages from GCG and HSH Sections and drilling well Yue1. MDS plots (C) and KDE curves (D) for detrital muscovite ^{40}Ar/^{39}Ar ages from drilling wells located in the western Qaidam basin. Data are from Rieser et al. (2006b, 2007, 2010). The R programming language-based Provenance software (Vermeesch et al., 2016) was employed for the illustrations.

Our new samples from the northern Qaidam basin show a dominant detrital muscovite age group of 300–400 Ma (Figs. 6 and 7). As mentioned above, the Qilian Orogen has been thought to be the main source of the northern Qaidam basin deposits (Rieser et al., 2005, 2006a; Zhuang et al., 2011; Jian et al., 2013a, 2024; Liu et al., 2022, 2023). It contains abundant metamorphic sedimentary rocks (Fu et al., 2022; Gehrels et al., 2003a, 2003b; Jian et al., 2013a, 2018, 2024; Rieser et al., 2005; Wang et al., 2023) and may have high muscovite fertility. Consequently, the detrital muscovite grains of our samples in the northern basin were likely derived from the Qilian Orogen and may be related to the Devonian–Carboniferous cooling history of the North Qaidam orogenic belt (Song et al., 2005). However, there is a lack of muscovite ^{40}Ar/^{39}Ar records with 300–400 Ma from the potential source areas (Figs. 1A and 6F), and modern river sediments in the north margin of the Qaidam basin show only a few grains with these ages (Genser et al., 2010). This discrepancy may be due to the limited application of muscovite ^{40}Ar/^{39}Ar dating in the North Qaidam region, hindering a direct comparison between source (Qilian Orogen) and sink (Cenozoic Qaidam basin). Samples from the LLH Section, in the northern Qaidam

basin, display a unique detrital muscovite age range of 250–279 Ma (Fig. 7; Rieser et al., 2006a), which is dramatically different from the others. The Cenozoic lithology of the LLH section (Jian et al., 2013a), isopach maps of the Cenozoic strata (Bao et al., 2017; Cheng et al., 2021), and the paleogeography of the LLH area (Li, 2022) suggest that the LLH area was located far away from the depocenter and was dominated by the alluvial fan, fluvial, and delta sedimentary environments during the Cenozoic. This means that detrital muscovite grains in the LLH area may be derived from a solitary proximal source terrane with Permian–Triassic muscovite ^{40}Ar/^{39}Ar ages in the Qilian Orogen.

Two major detrital muscovite age groups have been identified in the western Qaidam basin, namely, 200–300 Ma and 300–500 Ma (Fig. 8). The Altun and Qimantagh Orogens are considered the primary Cenozoic sources for this region (Rieser et al., 2006b; Zhu et al., 2017, 2019; Cheng et al., 2015, 2016, 2021). Muscovites with ages of ca. 270 and 400 Ma have been reported in the Qimantagh Orogens (Fig. 1B; Feng et al., 2013; Bontje, 2015; Guo et al., 2012; Zheng et al., 2016), and ages between 350 and 500 Ma and ca. 170 Ma have been found in the Altun Orogens (Figs. 1B and 6F; Sobel and Arnaud, 1999; Liu et al., 2003,
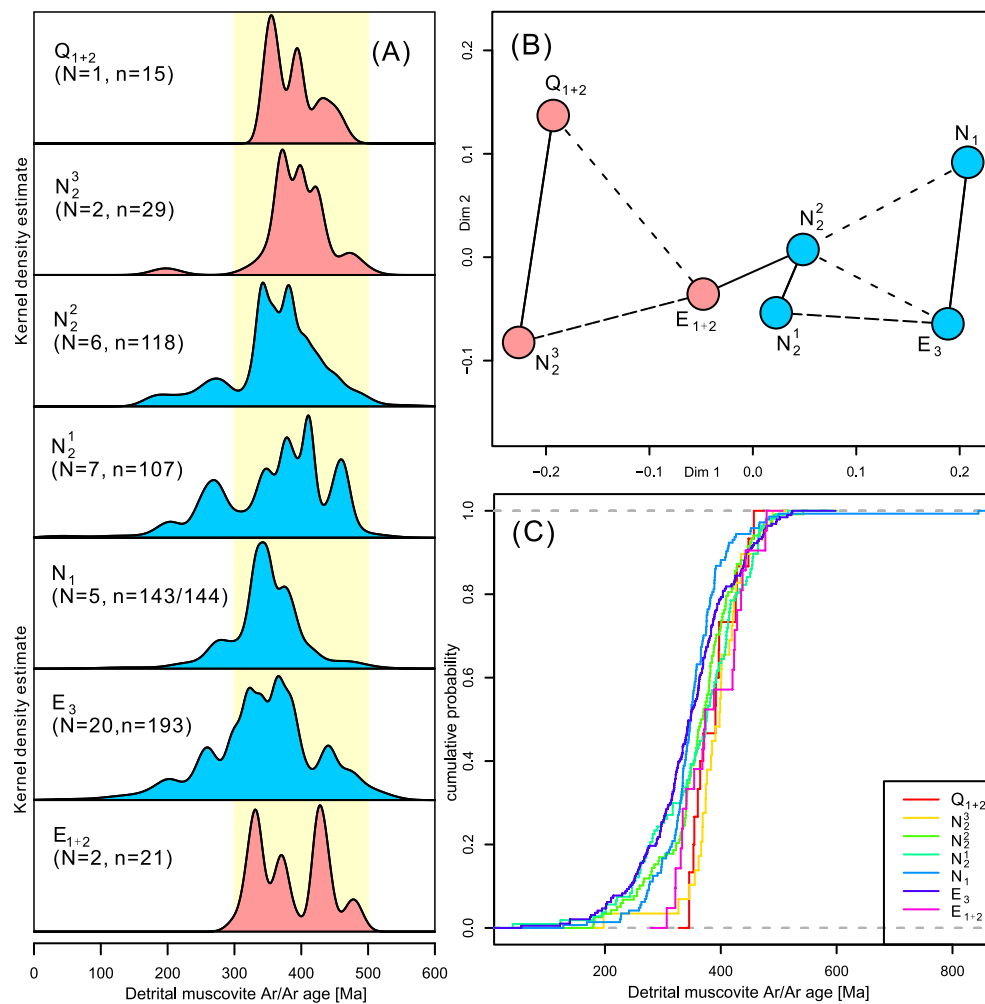
Fig. 9. KDE curves (A), MDS plots (B), and cumulative probability plots (C) of detrital muscovite $^{40}Ar/^{39}Ar$ age from different Cenozoic strata of the Cenozoic Qaidam basin. N, number of samples; n, number of dated detrital muscovite grains. Data are from Rieser et al. (2006b, 2007, 2010) and this study. The R programming language-based Provenance software (Vermeesch et al., 2016) was employed for the illustrations. We realize that the numbers of the combined ages of the E_3, N_1, N_2^1, and N_2^2 strata are much more than those of the E_{1+2}, N_2^3, and Q_{1+2} strata. Here, we employed sensitivity analyses to test the geological meaning of these relatively wide age ranges (see Appendix B for details). The results show that for each formation, almost all the samples have similar sensitivity to the age ranges of combined data (Figs. S4–S7). The combined data exhibits a wider age range because most of the samples have wide age ranges, rather than large sample sizes.

2007; Zhang et al., 2007). The locations of the HSH and the GCG Sections and the drilling well Yue1 are close to the Altun Orogen (Fig. 1B and C). Therefore, the detrital muscovite grains with ages of 300–500 Ma in these areas may be derived from the Altun Orogen (Fig. 8A and B). These ages may be related to the Paleozoic subduction-collisional and subsequent cooling process of this orogen. The detrital muscovite grains with 200–300 Ma ages in these areas may be provided by the Qimantagh Orogen and documented late Paleozoic to early Mesozoic subduction-collisional and subsequent cooling processes. Samples with age groups of 200–340 Ma from the HSH Section (the E_3 and N_1 strata; Wang, 2023) may be also associated with these tectonic events. Samples from drilling wells located in the Qimantagh foreland, the western Qaidam basin (Fig. 1C) show a wider age range (Fig. 8C and D), indicating a broader mixing of detrital muscovite grains from both the Altun and Qimantagh Orogens.

The available data demonstrate that the Cenozoic deposits exhibit stratigraphically various detrital muscovite age ranges (Fig. 9). Most samples from the E_3, N_1, N_2^1, and N_2^2 strata have relatively wider age ranges compared to those from the E_{1+2}, N_2^3, and Q_{1+2} strata (Fig. 8; Rieser et al., 2006b). Although the number of the available detrital muscovite $^{40}Ar/^{39}Ar$ dating grains varies significantly among these stratigraphic units, sensitivity analysis results (Figs. S4–S7 in Appendix

B) indicate that these differences in detrital muscovite records are not due to sample sizes and the number of analyzed grains. We recognize that the E_{1+2}, N_2^3, and Q_{1+2} strata in the Qaidam basin are mainly composed of relatively coarse-grained deposits, while the E_3–N_2^2 strata are dominated by fine-grained deposits, indicative of alluvial-fluvial and deltaic-lacustrine sedimentary environments, respectively (Fig. 3). It is also observed that detrital muscovite grains are likely to transport with silt and mud by suspended loads (Jiří, 2009; Stuart, 2002; Malusà and Garzanti, 2019), suggesting that their transport pathways may be more complex than those of sandy sediments within the same sedimentary depocenter (Malusà and Garzanti, 2019; Shen et al., 2021; Wang et al., 2023). Consequently, we advocate that various transport processes in distinct sedimentary environments likely control the detrital muscovite age distributions over time. This interpretation is reinforced by the mega-lake proposition (Liu et al., 2022, 2023; Wang et al., 2023), which suggests that fine-grained sediments (transported by suspended loads, such as clay minerals and detrital muscovite grains) from different source terranes may be transported through lake currents and thoroughly mixed (Fig. 13), resulting relatively wide detrital muscovite age ranges in the fine-grained deposits (Figs. 8 and 9). Furthermore, our four samples (Fig. 7) and several previous samples (Fig. 8; Rieser et al., 2006b) from the fine-grained deposits exhibit narrower age ranges than
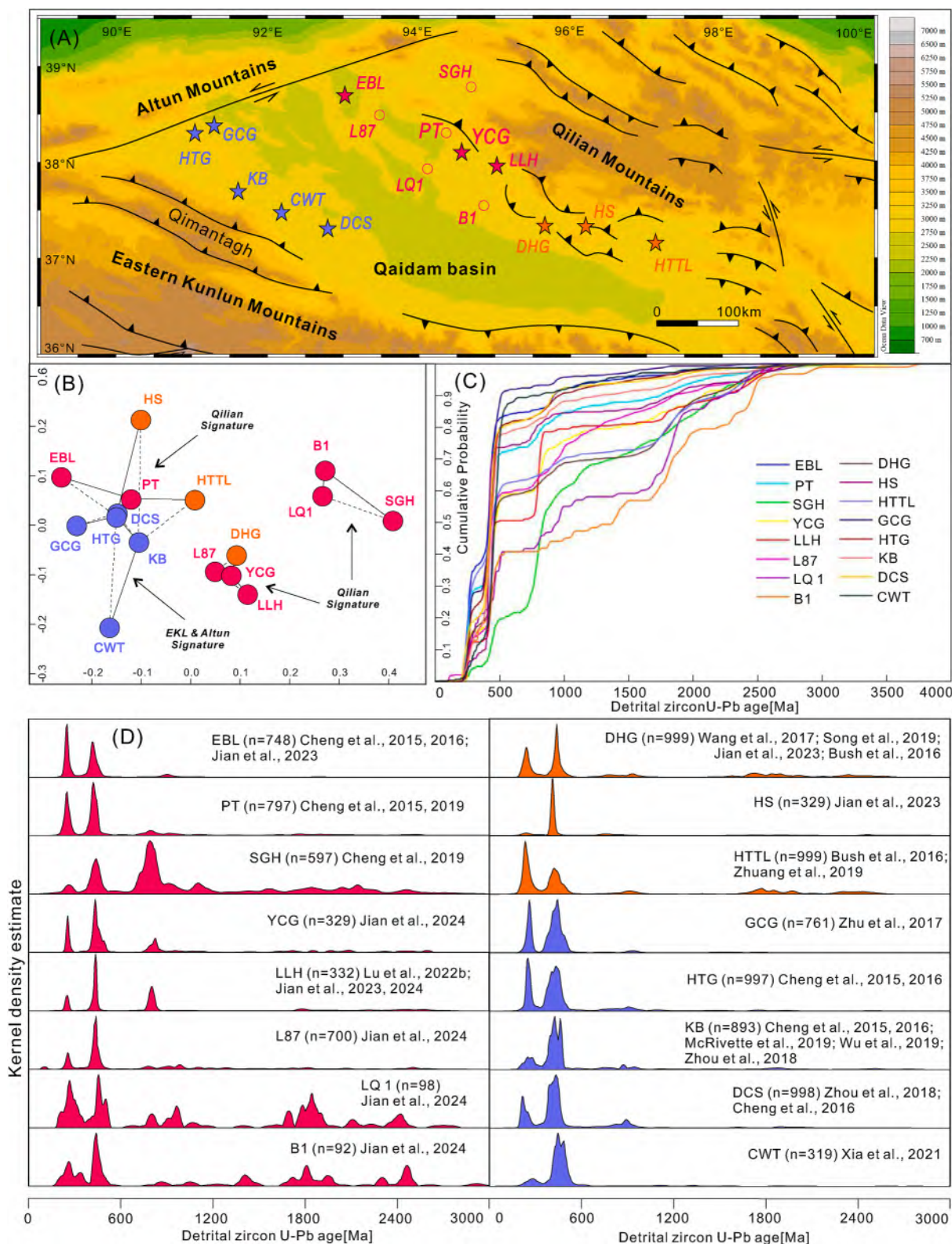
Fig. 10. (A) Topographic map of the Qaidam basin with locations of published detrital zircon studies. (B) MDS plots for published detrital zircon U-Pb age of the Cenozoic Qaidam basin. (C) Published detrital zircon U-Pb age cumulative probability curves of the Cenozoic Qaidam basin. (D) KDE curves for published detrital zircon U-Pb age of the Cenozoic Qaidam basin. Ages <1000 Ma are based on initial-Pb corrected ^{206}Pb/^{238}U ratios, whereas ages >1000 Ma are based on initial-Pb corrected ^{206}Pb/^{207}Pb ratios. Data are from Bush et al. (2016); Cheng et al. (2015, 2016, 2019b); Jian et al. (2023, 2024); Li et al. (2021); Lu et al. (2022b); McRivette et al. (2019); Pullen et al. (2011); Sun et al. (2020a); Wang et al. (2017); Wu et al. (2019b); Xia et al. (2020); Yin et al. (2020); Zhou et al. (2018); Zhu et al. (2017, 2019); Zhuang et al. (2019). The R programming language-based Provenance software (Vermeesch et al., 2016) was employed for the illustrations.
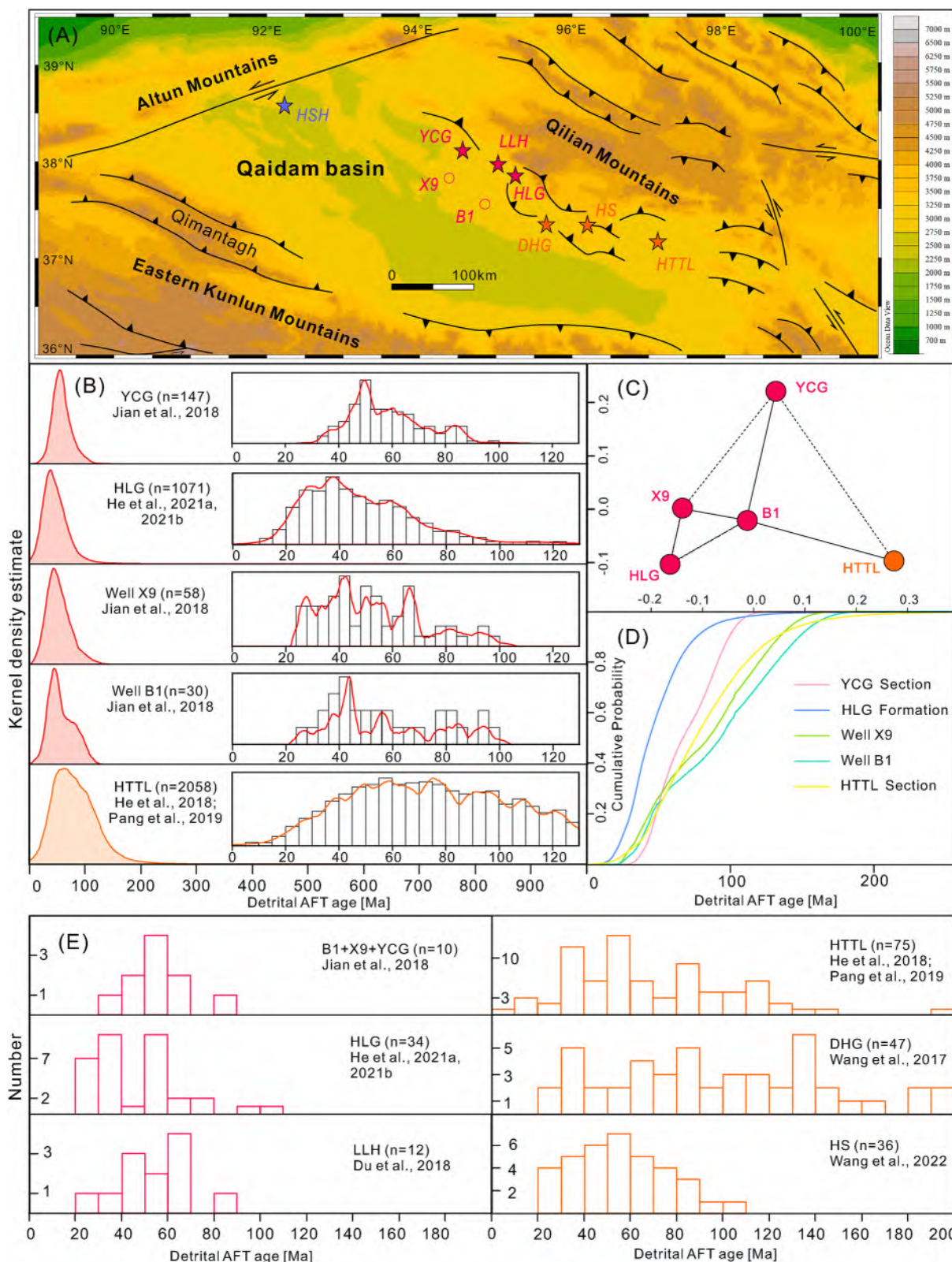
Fig. 11. (A) Topographic map of the Qaidam basin with locations of published detrital apatite studies. (B) KDE curves and histograms for published detrital apatite studies of the Cenozoic Qaidam basin. (C) MDS plot for published detrital apatite fission track (AFT) age of the Cenozoic Qaidam basin. (D) Published detrital AFT age cumulative probability curves of the Cenozoic Qaidam basin. (E) Histograms for published detrital AFT peak ages. Data are from Du et al. (2018); He et al. (2018, 2021a, 2021b); Jian et al. (2018); Lu et al. (2022a); Pang et al. (2019); Wang et al. (2017); Yin et al. (2002). The R programming language-based Provenance software (Vermeesch et al., 2016) was employed for the illustrations.

others (Figs. 7 and 8; Figs. S1 and S2 in Appendix B). We observed that our samples are fine-to medium-grained sandstones (Fig. 2 and Fig. S2); the samples from the E₃, N₁, N₂¹, and N₂² strata in the GCG section are siltstones (Rieser et al., 2007); and samples from the N₂³, and Q₁₊₂ strata in the HSH and the GCG sections are medium-grained sandstones (Fig. S2; Rieser et al., 2007). This indicates that samples (host clastic rocks) with coarser grain sizes may have narrower detrital muscovite age ranges compared to samples with finer grain sizes.

5.3. Comparison of the Cenozoic Qaidam basin detrital muscovite, apatite, and zircon records and their source-to-sink behaviors

Our data compilation indicates that the detrital zircon U-Pb age spectra have the oldest ages, the widest age ranges, and the largest number of age groups, followed by the detrital muscovite ^{40}Ar/^{39}Ar and AFT age spectra (Fig. 12). This can be explained by the tectonic history of source terranes, closure temperature, and mineral weathering resistance (Figs. 12 and 13; Carrapa, 2010; Hodges et al., 2005; Stuart, 2002). The inheritance of detrital zircon is well known and has been broadly involved in detrital zircon provenance interpretations. Due to the high closure temperature of the U-Pb isotopic system and its strong
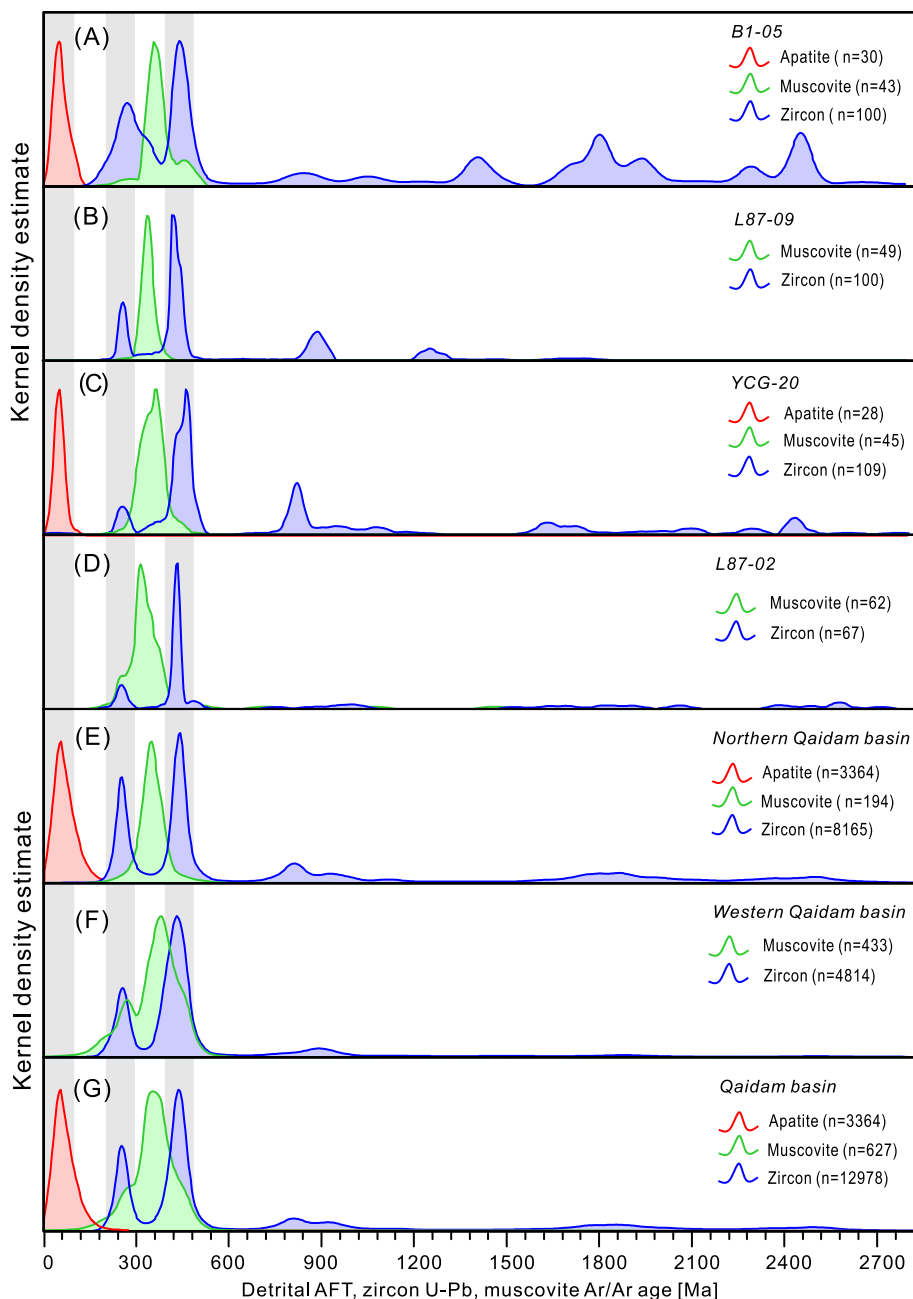
Fig. 12. (A) KDE curves for detrital muscovite ^{40}Ar/^{39}Ar, detrital zircon U-Pb, and detrital AFT ages of sample B1-05. (B) KDE curves for detrital muscovite ^{40}Ar/^{39}Ar and detrital zircon U-Pb ages of sample L87-09. (C) KDE curves for detrital muscovite ^{40}Ar/^{39}Ar, detrital zircon U-Pb, and detrital AFT ages of sample YCG-20. (D) KDE curves for detrital muscovite ^{40}Ar/^{39}Ar and detrital zircon U-Pb ages of sample L87-02. (E) KDE curves for detrital muscovite ^{40}Ar/^{39}Ar, detrital zircon U-Pb, and detrital AFT ages from the northern Qaidam basin. (F) KDE curves for detrital muscovite ^{40}Ar/^{39}Ar, detrital zircon U-Pb, and detrital AFT ages from the western Qaidam basin. (G) KDE curves for all detrital muscovite ^{40}Ar/^{39}Ar, detrital zircon U-Pb, and detrital AFT ages from the Qaidam basin. The R programming language-based Provenance software (Vermeesch et al., 2016) was employed for the illustrations.
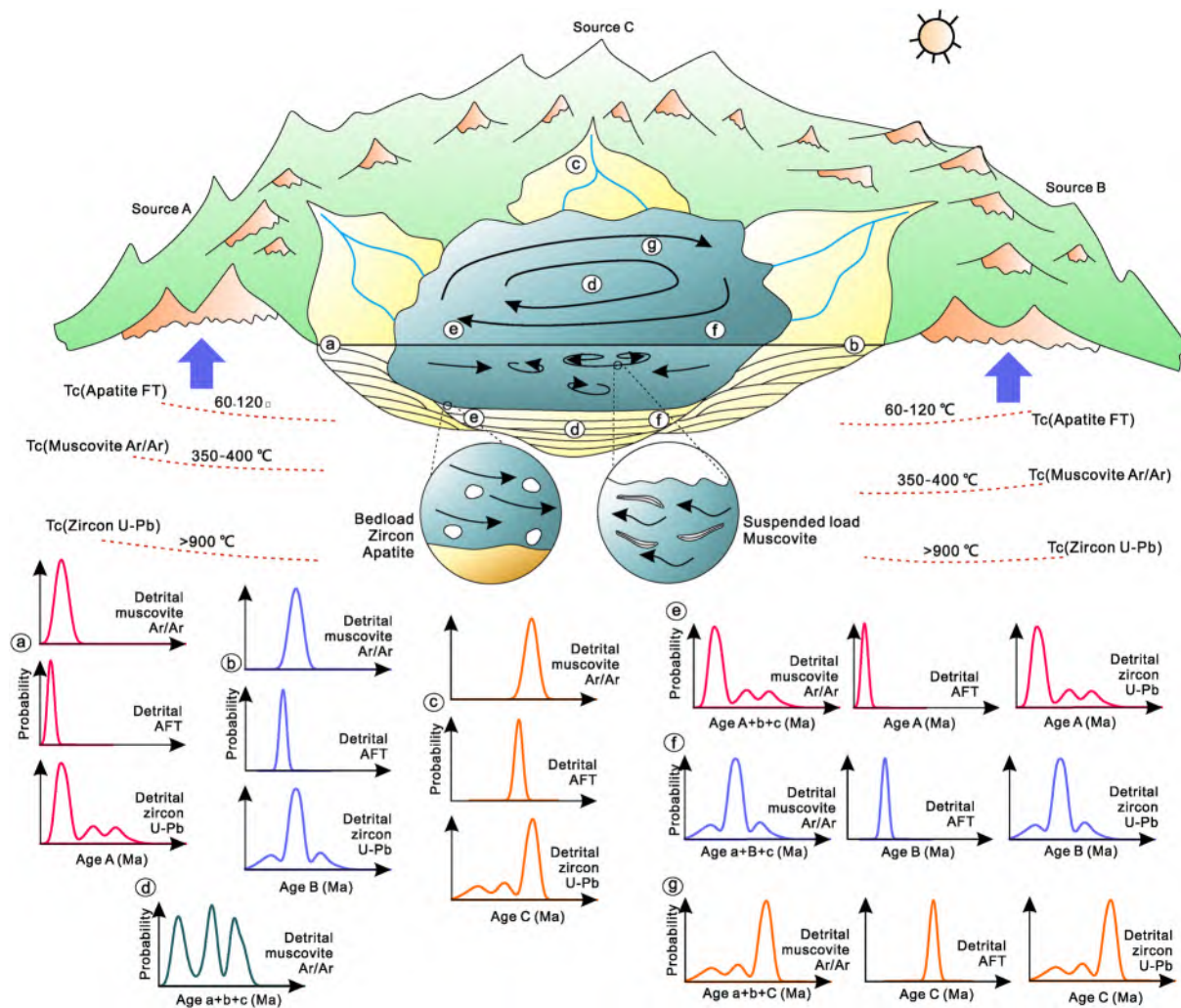
Fig. 13. Schematic model showing the different source-to-sink behaviors of detrital muscovite, zircon, and apatite. Spectra a, b, &, c show the age distributions of proximal and relatively coarse-grained sedimentary environments. Spectrum d shows the remote fine-grained sedimentary environments that accelerate the mixing of detrital muscovites and result in a wide age range with symmetry age groups. The granular-shape detrital zircon and apatite might be absent from the spectra like spectrum d because they would be commonly transported by bed load and likely to deposit proximally. Spectra e, f, &, g of detrital muscovite records show the part mixing of detrital muscovite grains and ages. The muscovites are dominated by the grains that came from nearby source terrane with a few grains from another source terranes. The spectra e, f, &, g of detrital zircon and apatite might be similar to the spectra a, b, &, c for the same reason as the absence of the spectra like spectrum d.

resistance to weathering (Hodges et al., 2005; von Eynatten and Dunkl, 2012), detrital zircon records would not be lost during multiple sedimentary cycles (Dickinson et al., 2009). This means that detrital zircons with distinct age groups associated with different tectonic-magmatic histories may be transported to the same deposition area, producing a wide age range and numerous age groups in detrital zircon records. In contrast, due to their low weathering resistance (relative to zircon) and low closure temperature, the records involving muscovite and apatite grains may only survive from the first or relatively few sedimentary cycles (Stuart, 2002; von Eynatten and Dunkl, 2012).

The 360–540 Ma group of detrital zircons from the Cenozoic Qaidam basin may be associated with the Proto-Tethys Ocean subduction-collision events, which are widely identified in the Altun, Eastern Kunlun, and Qilian Mountains (Dong et al., 2021). The 180–300 Ma group of detrital zircon may be linked with Paleo-Tethys subduction-collision events in this region (Dong et al., 2021). The possible low-angle, north-dipping (current direction) subduction of the Paleo-Tethys resulted in magmatic events from 290 to 230 Ma in the southern Qilian-North Qaidam areas (Jian et al., 2020, 2024; Zhang et al., 2020). The detrital muscovite records are thought to be associated with the post-collisional

thermal relaxation after the closure of the back-arc basin (Zhou et al., 2022). Therefore a detrital zircon age group may be commonly followed by a detrital muscovite age group. The 300–450 Ma group of detrital muscovite grains in the Qiadam basin corresponds to the widespread 360–540 Ma group of detrital zircons. However, the detrital muscovite age data indicate <250 Ma muscovite grains are almost absent in the northern Qaidam basin and are minor in some analyzed samples from the western Qaidam basin (Fig. 12). The decoupling between Triassic–Permian zircon U-Pb ages and muscovite $^{40}Ar/^{39}Ar$ ages might be due to low muscovite fertility of the Triassic–Permian geological records (including magmatic, metamorphic and sedimentary records). The detrital apatite age records in the Cenozoic Qaidam basin may related to the late Mesozoic–Cenozoic uplift history, which is associated with the far-field effects of the Lhasa-Qiangtang and India-Asian collision (Jian et al., 2018; Kapp and DeCelles, 2019). The spatially varied detrital AFT age distributions indicate asynchronous uplift of surrounding mountain ranges or variable source terranes of the Qaidam basin, which may help in understanding the uplifting mechanism of the Tibetan Plateau.

It is worth noting that detrital zircon and apatite age spectra exhibit higher spatial variations compared to detrital muscovite records

(Figs. 10 and 11). This is likely due to the distinct source-to-sink behaviors of these detrital grains. Zircon and apatite are common granular heavy minerals in sandy sediments and sandstones, whereas muscovite is a platy light mineral in relatively fine-grained sediments and sedimentary rocks (e.g., silty or fine sandstones; Fig. 2). The different shapes of detrital muscovite, zircon, and apatite likely play a crucial role in causing the varied age distribution (Malusà and Garzanti, 2019). With their granular shape, detrital zircon and apatite are mainly transported by bed loads, whereas detrital muscovite is mainly transported by a suspended load (Fig. 13; Malusà and Garzanti, 2019). We infer that detrital muscovite grains from different source terranes may be transported over longer distances and mixed more thoroughly than detrital zircons and apatites, resulting in a relatively low age distribution variability (Fig. 13). In addition to transport and depositional processes, the tectonic history, parent rock types, and mineral fertility also significantly influence the age distributions of detrital minerals from the source end (Chew et al., 2020; Malusà and Garzanti, 2019; Malusà et al., 2016; Moecher and Samson, 2006). Muscovite is a common constituent of various lithologies, such as metasediments, and granite, and forms over a large pressure-temperature range (Stuart, 2002). Zircon is widely found in magmatic and metamorphic rocks, especially intermediate to Si-saturated magmatic rocks (Hoskin and Schaltegger, 2003; Chew et al., 2020). Apatite is a common accessory mineral in magmatic and metamorphic rocks (Chew et al., 2020). These three minerals are also prevalent in clastic sedimentary rocks (Chew et al., 2020; Stuart, 2002). This indicates that the rock types of source terranes and potential recycling should be carefully considered while using detrital multi-dating for provenance analyses. Furthermore, deep-burial processes could reset the age of detrital minerals with lower closure temperatures (e.g., apatite) as the depth of burial increases (Jian et al., 2018; Stockli and Najman, 2020).

5.4. The role of detrital muscovite records in revealing tectonic settings and provenance: A brief discussion

Detrital zircon U-Pb age distributions are considered a promising proxy for revealing tectonic settings of sedimentary basins, primarily based on the relationships between zircon crystallization ages and sediment depositional ages (Cawood et al., 2012; Sun et al., 2023). Since muscovite $^{40}Ar/^{39}Ar$ ages document the time when rocks cooled through closure temperatures of ca. 350–400 °C (Hodges et al., 2005; Stuart, 2002), detrital muscovite age spectra of sedimentary rocks are related to regional exhumation rates, which are likely controlled by tectonic settings and climate (Bermúdez et al., 2013; Burbank, 2018; DeCelles and Carrapa, 2023; Georgieva et al., 2016; Pundir et al., 2021; Sobel and Strecker, 2003; Thiede et al., 2004). However, the response of detrital muscovite $^{40}Ar/^{39}Ar$ ages to tectonic settings remains rarely reported, and the potential of detrital muscovite records reflecting tectonic attributes remains unclear. We recognized that the selection of the age model for the Qaidam basin may impact inter-basin comparisons. The Cenozoic Qaidam basin was considered a continental superimposed basin (Yin et al., 2008; Cheng et al., 2021) and its tectonic settings are thought to have not significantly varied since the onset of the Cenozoic deposition. Thus, all the Cenozoic Qaidam basin detrital muscovite age data are combined as a unit for the inter-basin comparisons, rather than using higher stratigraphic resolutions. The collected detrital muscovite $^{40}Ar/^{39}Ar$ data from the worldwide Cenozoic sedimentary basins show that syndepositional detrital muscovite grains are widely present in collision and convergence tectonic settings but absent in intracratonic tectonic settings (Fig. 14; e.g., Benowitz et al., 2019; Carrapa et al., 2009; Liu et al., 2020; Najman et al., 2009; Rahman and Faupl, 2003; Rieser et al., 2007; Stickroth et al., 2019; Uddin et al., 2010). Theoretically, under collision and convergence tectonic settings, source terranes around sedimentary basins may have higher exhumation rates,
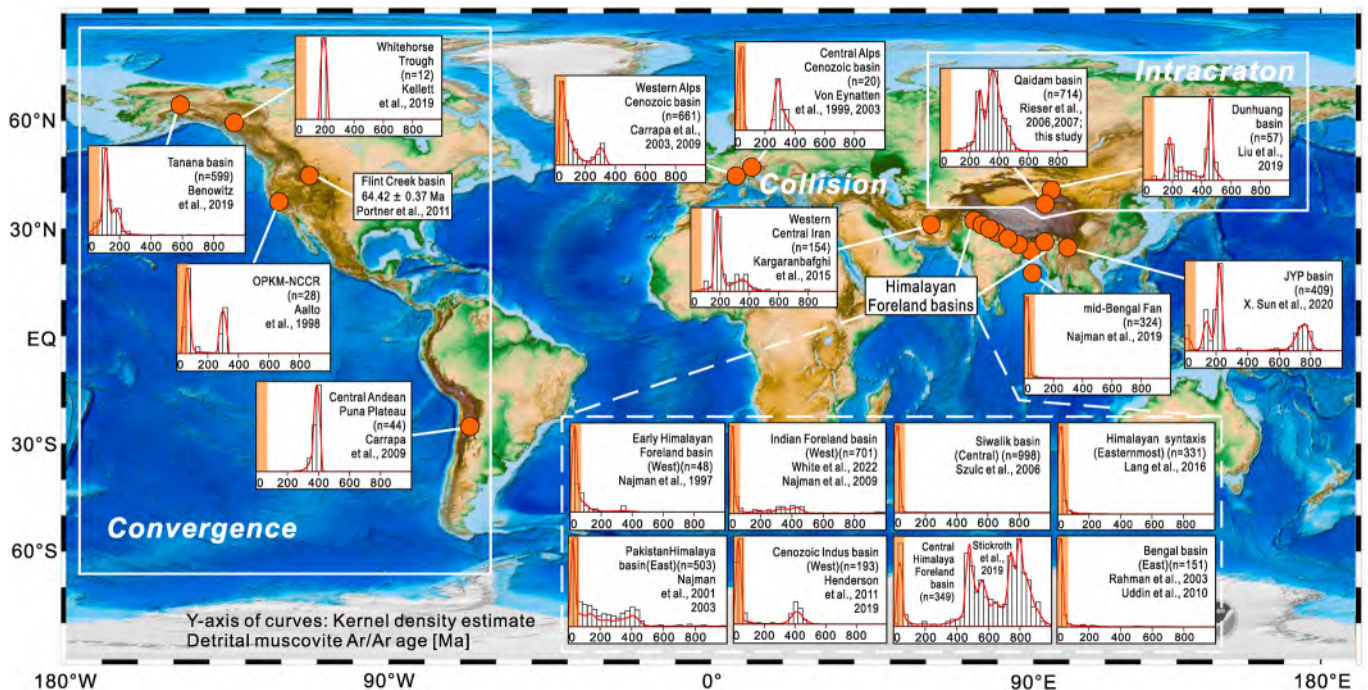

Fig. 14. Published detrital muscovite $^{40}Ar/^{39}Ar$ age studies, KDE curves, and histograms for the detrital muscovite $^{40}Ar/^{39}Ar$ age data of global Cenozoic sedimentary basins. The orange band marks the time frame of the Cenozoic Era. OPKM-NCCR: Olympic Peninsula, Klamath Mountains, and northern California Coast Ranges; JYB basins, Jianchuan and Yuanmou basins. Data are from Aalto et al. (1998); Benowitz et al. (2019); Carrapa et al. (2003, 2016, 2009); Henderson et al. (2010, 2011); Kargaranbafghi et al. (2015); Kellett and Muniz (2019); Lang et al. (2016); Liu et al. (2020); Najman et al. (1997, 2001, 2003, 2009, 2019); Portner et al. (2011); Rahman and Faupl (2003); Rieser et al. (2006a, 2006b, 2007, 2010); Stickroth et al. (2019); Sun et al. (2020); Szulc et al. (2006); Uddin et al. (2010); von Eynatten et al. (1999); von Eynatten and Wijbrans (2003); White et al. (2002). The R programming language-based Provenance software (Vermeesch et al., 2016) was employed for the illustrations.

generating syndepositional detrital muscovite grains and $^{40}Ar/^{39}Ar$ ages close to depositional ages. The relatively older ages which are either prominent or subordinate (Fig. 14), are likely due to early stages of orogenic processes or preceding tectonic cycles. In intracratonic tectonic settings, source terranes with low exhumation rates during the last sedimentary cycle may only generate detrital muscovite grains with older age (Fig. 14). This is reinforced by the available detrital muscovite data from modern river sediments (Fig. 15). Detrital muscovite grains in sediments from rivers draining intracratonic regions show a large number of older ages (Fig. 15), whereas sediments from the rivers with collision and convergence backgrounds have a high abundance of detrital muscovite grains with ages close to the present time (Fig. 15). Several studies have highlighted that detrital muscovite $^{40}Ar/^{39}Ar$ ages may also be controlled by climate-induced exhumation processes in source terranes (Carrapa et al., 2014; Clift, 2017; Clift et al., 2008; Rieser et al., 2010). For example, the detrital muscovite age spectrum of the Pamir drainages is characterized by a dominant younger age group with a minor older age group (Fig. 15). The detrital muscovite age signatures of the rivers draining in the central and southern Pamir, where greater precipitation and higher-magnitude exhumation prevail, are characterized by younger ages than those from the northeastern Pamir (Fig. 15; Carrapa et al., 2014). This means that a more humid climate may lead to higher-magnitude exhumation, generating muscovite grains of younger ages that existed deep under the orogenic belts.

We consider that detrital muscovite $^{40}Ar/^{39}Ar$ age data hold significant promise for addressing various issues in geoscience. However, publications referring to detrital muscovite (or white mica) are far fewer than those referring to detrital zircon and apatite in the past decades (Fig. S3 in Appendix B). Several reasons may account for this discrepancy: 1) Mineral occurrence. Muscovite is a common constituent of metasedimentary rocks and granite as an accessory mineral or a main mineral phase, but zircon occurs in a wider range of rock types (Mark et al., 2016; Spiegel et al., 2004). 2) Transport and deposition. Detrital muscovite grains are generally transported by suspended load (Fig. 13; Malusà and Garzanti, 2019) and tend to be deposited along with other very fine-grained, light grains (e.g., silt and mud detritus) in relatively low-energy sedimentary environments (Jiří, 2009; Stuart, 2002). Consequently, compared with zircon and apatite, muscovite is not a regular target for tracing sand (or sandstone) provenance. 3) Closure temperature. The moderate closure temperature of the muscovite $^{40}Ar/^{39}Ar$ system makes this dating technique mainly useful for addressing exhumation processes at 8–10 km depths for source terranes (Stuart, 2002). In contrast, the high closure temperatures for U-Pb isotopic systems and the low closure temperatures for fission track and (U-Th)/He systems make detrital zircon and apatite dating applicable to a broader range of issues, such as revealing tectonic-magmatic evolution related to plate tectonics and neotectonic events related to geological hazards (Cawood et al., 2012; Stockli and Najman, 2020). Additionally, in-situ zircon and apatite elemental and isotopic analysis techniques are widely used to unravel the petrogenesis of magmatic rocks (Bruand et al., 2017; Sun et al., 2010). 4) Technical complexity and cost. The in-situ single-grain $^{40}Ar/^{39}Ar$ analysis technique is expensive and requires complex, time-consuming operations.

5.5. Implications

Despite the above-mentioned limitations, detrital muscovite $^{40}Ar/^{39}Ar$ dating studies are still beneficial for understanding geological processes in sedimentary source terranes and play a crucial role in ascertaining fine-grained (e.g., muds and silts) sediment source-to-sink systems in some cases. Detrital muscovite grains are commonly present in the loess of the Chinese Loess Plateau (Jeong et al., 2017, Fig. 1A), which is considered to be formed by aeolian transport and mainly comprise silt grains (Pullen et al., 2011; Liu et al., 2016). Understanding loess provenance is fundamental to reconstructing wind patterns during the late Cenozoic (Sun, 2002; Pullen et al., 2011; Wang et al., 2020). Detrital zircon records have been extensively used to unravel the provenance of the Chinese Loess Plateau. Most studies indicate that the Qaidam basin is an important sediment source for the Chinese Loess Plateau (Pullen et al., 2011; Wang et al., 2020). Previous studies
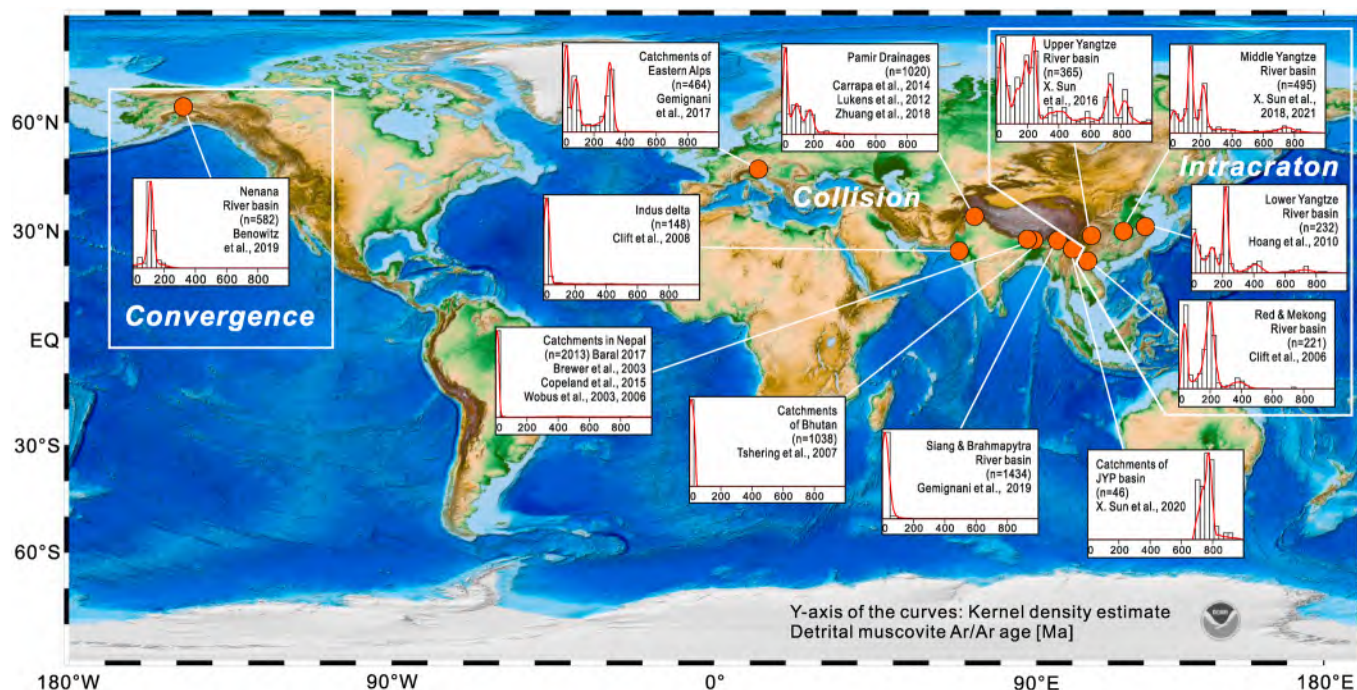
Fig. 15. Published detrital muscovite $^{40}Ar/^{39}Ar$ age studies, KDE curves, and histograms for the detrital muscovite $^{40}Ar/^{39}Ar$ age data of global modern river basins. JYB basins, Jianchuan and Yuanmou basins. Data are from Baral (2017); Benowitz et al. (2019); Brewer et al. (2003); Carrapa et al. (2014); Clift et al. (2006, 2008); Copeland et al. (2015); Gemignani et al. (2017, 2019); Lukens et al. (2012); Sun et al. (2020, 2016, 2018, 2021); Tshering (2007); Van Hoang et al. (2010); Wobus et al. (2003, 2006); Zhuang et al. (2018). The R programming language-based Provenance software (Vermeesch et al., 2016) was employed for the illustrations.

suggest that detrital zircon U-Pb age populations in the Cenozoic Qaidam basin were spatiotemporally diverse (Fig. 10; Jian et al., 2024). However, our findings indicate that detrital muscovite $^{40}Ar/^{39}Ar$ age ranges in the Cenozoic Qaidam basin are spatially similar (Fig. 6). The relatively well-mixed detrital muscovite $^{40}Ar/^{39}Ar$ age signals from the Qaidam basin (as source signals) suggest a high potential of the $^{40}Ar/^{39}Ar$ dating technique in Asian dust provenance studies.

6. Conclusions

Our new detrital muscovite $^{40}Ar/^{39}Ar$ dating results, combined with previously reported data, indicate that most Cenozoic deposits from the Qaidam basin have spatially similar detrital muscovite $^{40}Ar/^{39}Ar$ age ranges. These ages are predominantly 300–400 Ma, with subordinate ranges of 200–300 Ma and 400–500 Ma. This suggests that detrital muscovite records and corresponding provenance signals for the Cenozoic Qaidam basin are well-mixing spatially. However, the available data demonstrate that the Cenozoic deposits exhibit stratigraphically variable detrital muscovite $^{40}Ar/^{39}Ar$ age populations. This variability may be attributed to changes in sedimentary environments over time. Additionally, samples (host clastic rocks) with coarser grain sizes may have narrower detrital muscovite age ranges compared to samples with finer grain sizes. Therefore, it is important to consider natural biases from the source-to-sink systems, such as variations in sedimentary environments and grain sizes, when using the detrital single-grain dating technique for provenance interpretations.

A comparison of detrital muscovite, zircon, and apatite records from the Cenozoic Qaidam basin reveals that the detrital zircon U-Pb age spectra exhibit the oldest ages, the widest age ranges, and the largest number of age groups. Moreover, detrital zircon and apatite age spectra show higher spatial variation compared to detrital muscovite records. These differences can be explained by the distinct source-to-sink behaviors of detrital minerals. The magmatic or high-grade metamorphic history and high closure temperature of the zircon U-Pb system originally determined the oldest ages. The uplift history and relatively low closure temperature of muscovite $^{40}Ar/^{39}Ar$ and AFT systems result in relatively young age records. Parent rock types, mineral fertility, and weathering resistance control the numbers and distribution of the detrital age clusters. Additionally, the shape, density, and transport, depositional processes of minerals (i.e., different transport loads of light, platy minerals, and heavy, granular minerals) contribute to the variation in the age spectra.

The global compilation of detrital muscovite $^{40}Ar/^{39}Ar$ age data reveals that detrital muscovite $^{40}Ar/^{39}Ar$ geochronology has potentials to indicate tectonic settings. However, it is crucial to distinguish climatic signals before tectonic interpretation.

CRediT authorship contribution statement

Shuhuai Ye: Writing – review & editing, Writing – original draft, Investigation, Data curation, Conceptualization. **Xing Jian:** Writing – review & editing, Supervision, Resources, Funding acquisition, Data curation, Conceptualization. **Ling Fu:** Resources, Investigation. **Wei Zhang:** Writing – review & editing, Resources, Project administration. **Xiaotian Shen:** Writing – review & editing, Formal analysis. **Ping Guan:** Resources, Investigation.

Declaration of competing interest

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

Data availability

I have shared the link to my data at the Attach file step.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpetgeo.2024.107068.

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