

Article

Sediment Recycling as a Major Source of the Qigequan and Shizigou Formations in the Qigequan Area, Western Qaidam Basin: Evidence from Quantitative Detrital Zircon U-Pb Analysis

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Abstract

Situated between the Altyn Tagh and Eastern Kunlun ranges, the western Qaidam Basin records Cenozoic sediment-routing changes associated with the growth of the northern Tibetan Plateau. However, the provenance of post-Miocene strata in this region remains debated, and the role of sediment recycling has not yet been quantitatively constrained. Here, we integrate field observations, sandstone petrography, quantitative detrital zircon U-Pb analysis, and inverse Monte Carlo modeling to compare Late Cenozoic strata in the Qigequan area with nearby Mesozoic strata and basement sources in the Altyn Tagh and Eastern Kunlun ranges, thereby assessing direct versus recycled sediment supply. Sandstones of the Qigequan and Shizigou formations are poorly sorted and contain angular to subangular quartz and feldspar grains and identifiable sandstone and mudstone lithic fragments, indicating erosion of pre-existing sedimentary rocks. Their detrital zircon age spectra are dominated by 300–600 Ma grains (57.9%–69.0%), followed by subordinate < 300 Ma grains (18.4%–21.1%) and minor 600–1000 Ma (6.9%–13.2%), 1000–1500 Ma (1.3%–3.9%), and >1500 Ma (1.3%–3.9%) components. Similarity metrics and multidimensional scaling (MDS) analyses show that the Cenozoic age distributions are substantially more similar to the composite Mesozoic proxy than to the Altyn Tagh or Eastern Kunlun basement endmembers. Inverse Monte Carlo modeling further shows that a three-endmember model incorporating the composite Mesozoic proxy provides a better fit than the two-endmember Altyn Tagh–Eastern Kunlun model. Across the three optimization metrics, the composite Mesozoic proxy contributes approximately 36%–68% and 61%–72% to the modeled detrital zircon age distributions of the Shizigou and Qigequan formations, respectively. Together, these results support a substantial role for recycled Mesozoic material in the Late Cenozoic sediment-routing system of the western Qaidam Basin, providing new provenance constraints on basin–range coupling along the northwestern margin of the Tibetan Plateau.

Keywords: Qaidam Basin; provenance analysis; sediment recycling; detrital zircon U-Pb geochronology; Altyn Tagh Fault; inverse Monte Carlo modeling

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1. Introduction

The Qaidam Basin, located in northern Tibet, is one of the largest Mesozoic–Cenozoic continental sedimentary basins in the interior of the Tibetan Plateau [1–3]. The basin preserves a >10 km thick Cenozoic clastic sedimentary succession and constitutes a key sedimentary archive for investigating the growth of the northern Tibetan Plateau and intracontinental deformation processes since the India–Asia collision [4–6]. However, considerable debate persists regarding the Cenozoic evolution of the Qaidam Basin and its basin–range coupling [6–9], which has hindered a full understanding of tectonic expansion mechanisms along the northern margin of the Tibetan Plateau.

Provenance analysis links detrital material preserved in sedimentary basins to surrounding potential source regions and therefore provides direct constraints on basin-filling processes and the tectonic evolution of source terranes [10–12]. A variety of methods are available for provenance analysis, ranging from field-based observations, such as stratigraphic relationships and paleocurrent indicators, to petrographic, mineralogical, geochemical, palynological, and geochronological analyses [13–15]. Each method has its own advantages and limitations, and its effectiveness depends on the geological context [16]. For example, petrographic, heavy-mineral, geochemical, and single-grain mineral-chemical data can provide complementary information on source rock composition and sedimentary modification, but these signals may be variably affected by grain-size sorting, weathering, transport, and diagenesis [14]. In this context, detrital zircon U–Pb geochronology has become one of the most widely used tools because zircon age spectra record magmatic and metamorphic events in source regions and can therefore be used to correlate sediments with potential source areas [17–19]. Recent studies have further shown that integrated provenance approaches combining field relationships, stratigraphy, sedimentology, petrography, geochemistry, and detrital zircon geochronology can provide a more complete reconstruction of sediment-routing systems in tectonically active basins [20,21]. Nevertheless, in regions where multiple source terranes share similar tectono-magmatic histories, qualitative comparisons based solely on zircon age peaks may lead to non-unique provenance interpretations. In recent years, quantitative approaches, including similarity metrics, multidimensional scaling (MDS), and inverse Monte Carlo modeling, have therefore been increasingly introduced into detrital zircon provenance studies to more objectively evaluate age spectrum similarity and relative contributions of different source endmembers to detrital zircon age distributions [22–24]. When combined with conventional geological evidence, these quantitative detrital zircon approaches can provide a more robust framework for reconstructing sediment-routing systems and evaluating the role of sediment recycling [25,26].

The western Qaidam Basin is bounded by the Altyn Tagh Range to the northwest and the Eastern Kunlun Range to the south [3,6,27]. Understanding sediment provenance and routing in this setting is important for reconstructing Cenozoic basin–range evolution and evaluating its hydrocarbon and sandstone-hosted uranium resource potential [28–30]. Numerous provenance studies have been conducted in this region [6,28,30–33], but the provenance of post-Miocene strata remains controversial. Previous studies have commonly interpreted Cenozoic sediments in the western Qaidam Basin as being derived from the Altyn Tagh Range, the Eastern Kunlun Range, or a mixture of both [6,28,30]. However, two issues remain unresolved. First, most existing provenance interpretations are largely qualitative and lack quantitative evaluation of relative source contributions. Second, the widespread exposure of older sedimentary strata along the basin margin and regional evidence for their reworking into younger deposits identify sediment recycling as a plausible but poorly quantified alternative [6]. Because recycled sedimentary rocks can inherit zircon age spectra from earlier source regions, detrital zircon age spectra in young basin fills may not directly record first-cycle erosion of adjacent basement rocks but

may instead represent mixtures of first-cycle detritus and multi-cycle recycled sediment [34,35]. Ignoring such recycled sedimentary endmembers may lead to overestimation of direct basement-derived input and bias source-to-sink reconstructions. Evaluating the contribution of recycled sedimentary material is therefore essential for distinguishing multi-cycle sediment supply from direct basement-derived input and for more reliably reconstructing the source-to-sink system of the western Qaidam Basin [26,31].

Recent provenance studies of Cenozoic strata along the Qilian Shan piedmont on the northern margin of the Qaidam Basin have demonstrated the importance of sediment recycling [36–38]. Exposed Mesozoic and even early Cenozoic sedimentary strata along the northern basin margin may have served as important sediment sources for younger strata deposited during later stages of basin evolution. These findings indicate that sediment recycling may be a widespread process in the Qaidam Basin rather than a local phenomenon. However, the relative importance of recycled sedimentary components to Late Cenozoic strata in the western Qaidam Basin remains poorly quantified. In particular, it remains unclear whether the Qigequan and Shizigou formations in the Qigequan area were supplied mainly by direct erosion of the Altyn Tagh and Eastern Kunlun basement rocks or whether recycled Mesozoic strata along the basin margin constituted a major sediment source.

To address these issues, this study integrates field observations, sandstone petrography, detrital zircon U-Pb geochronology, quantitative age spectrum comparison, MDS analysis, and inverse Monte Carlo provenance modeling of samples from the Qigequan and nearby Caishiling areas. Unlike previous studies that mainly emphasized direct sediment supply from the Altyn Tagh Range and/or the Eastern Kunlun Range, we explicitly include recycled Mesozoic sedimentary rocks as a potential source endmember. To our knowledge, this provides the first quantitative age spectrum-based evaluation of recycled Mesozoic sedimentary input to the Late Cenozoic Qigequan and Shizigou formations in the western Qaidam Basin, thereby offering new constraints on sediment recycling and basin–range coupling along the northwestern margin of the Tibetan Plateau.

2. Geological Setting

2.1. Qaidam Basin

The Qaidam Basin, located in the northern Tibetan Plateau, is one of the largest intermontane sedimentary basins within the plateau (Figure 1a). It is bounded by orogenic belts, including the Altyn Tagh Range to the northwest, the Eastern Kunlun Range to the south, and the Qilian Shan to the northeast, forming a typical basin–range tectonic system along the northern margin of the Tibetan Plateau (Figure 1b,c) [1,39]. The basin comprises crystalline basement and sedimentary cover. The basement is mainly composed of Neoproterozoic, Early Paleozoic, and Late Paleozoic metamorphic and igneous rocks [40]. Recent studies indicate that basement rocks in the Qaidam Basin have geochemical and geochronological characteristics similar to those of the surrounding orogenic belts [40]. The sedimentary cover mainly comprises Mesozoic (Jurassic–Cretaceous) and Cenozoic continental sedimentary rocks (Figure 1d). Cenozoic strata are exposed throughout the basin, locally exceeding 10 km in thickness, with an average thickness of 6–8 km [2,3,5]. The Cenozoic strata of the Qaidam Basin are generally divided, from bottom to top, into the Lulehe Formation (E_{1+2l}), Lower Ganchaigou Formation (E_{3xg}), Upper Ganchaigou Formation (N_{1sg}), Lower Youshashan Formation (N_{2^1xy}), Upper Youshashan Formation (N_{2^2sy}), Shizigou Formation (N_{2^3s}), and Qigequan Formation (Q_{1q}) [6]. The chronological framework of the Cenozoic succession in the Qaidam Basin remains debated, especially regarding the depositional onset of the basal Lulehe Formation. Traditional age models suggest that the Lulehe Formation began to accumulate during the Early Eocene (~52 Ma) [41,42]. However, recent magnetostratigraphic studies [43,44] and carbonate U-Pb dating

results [45] have challenged the traditional age model and proposed that deposition of the Lulehe Formation began in the Late Oligocene. For consistency, this study follows the traditional age model.

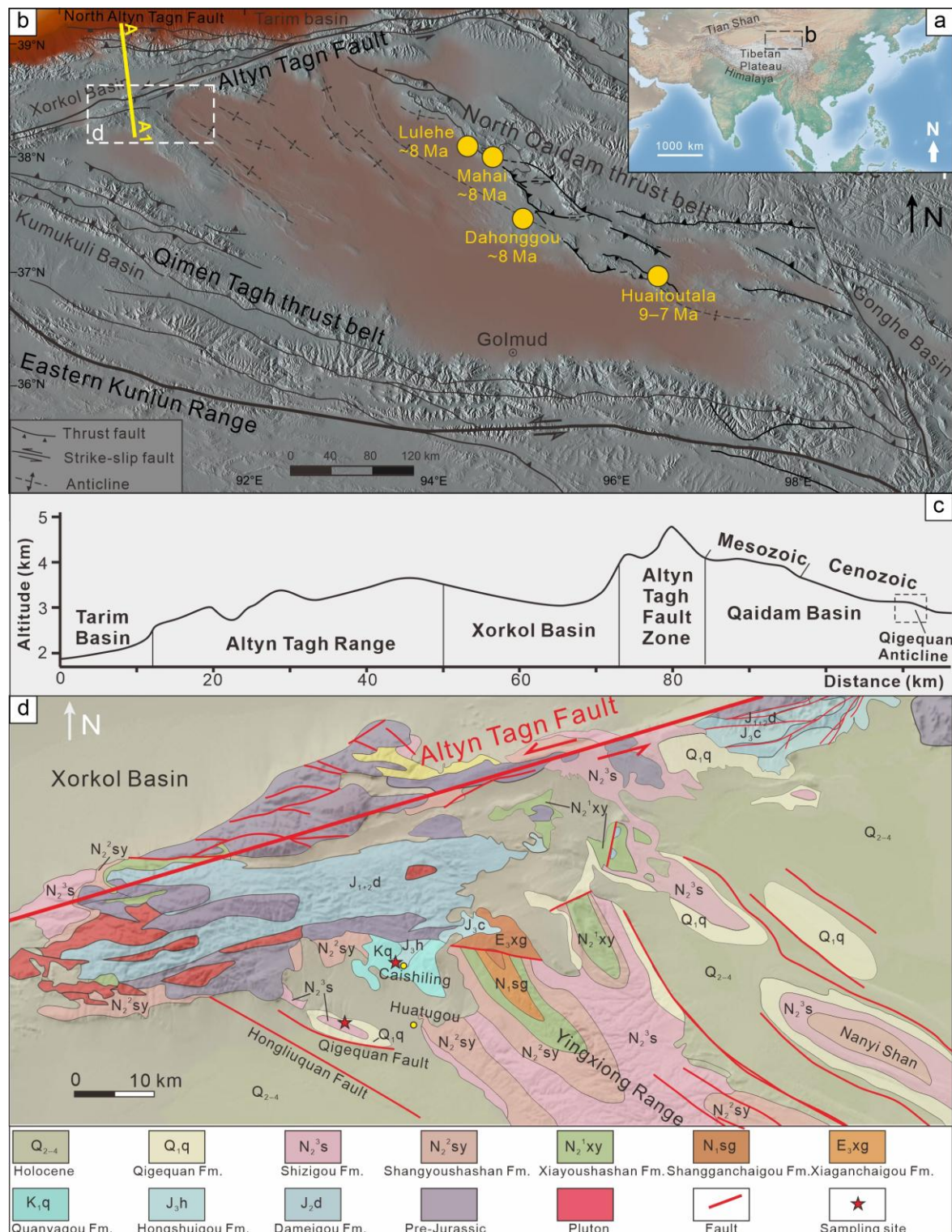


Figure 1. (a) Map showing the location of the Qaidam Basin in the Tibetan Plateau; (b) tectonic framework of the Qaidam Basin and adjacent regions (modified after [46]), superimposed on an SRTM-based digital topographic map. Yellow circles mark locations within the Qaidam Basin where sediment recycling has been documented, including the Huaitoutala section [47], the Lulehe and Dahonggou sections [36], and the Mahai section [38]; (c) nearly north-south topographic profile from the southern margin of the Tarim Basin (A) to the area south of Qigequan, Qaidam Basin (A1).

The profile location is shown by the yellow solid line in Figure 1b; (d) simplified geological map of the northwestern margin of the Qaidam Basin, modified after [48].

The Mesozoic strata of the Qaidam Basin are dominated by Jurassic and Cretaceous continental clastic rocks, which are mainly distributed along the northern and northeastern margins of the basin, with well-exposed outcrops also occurring along the western margin [49–51]. The Jurassic succession generally includes, from bottom to top, the Lower Jurassic Xiaomeigou Formation (J_{1x}), Middle Jurassic Dameigou Formation (J_{2d}), Upper Jurassic Caishiling Formation (J_{3c}), and Hongshuigou Formation (J_{3h}), whereas the Cretaceous succession is represented mainly by continental clastic deposits such as the Lower Cretaceous Quanyagou Formation (K_{1q}) [51,52]. Jurassic sedimentary rocks mainly comprise alluvial-fan, braided-river, braided-river delta, and lacustrine deposits, with lithologies including sandstone, conglomerate, mudstone, shale, and coal-bearing strata. These deposits record fault-controlled lacustrine basin evolution under an intracontinental extensional setting during the Mesozoic [50]. In terms of sedimentary architecture, Early Jurassic deposition was largely restricted to small, isolated fault-controlled depressions along the western and northern basin margins. By the Late Jurassic, deposition had expanded substantially, and the basin had evolved into a more unified lacustrine system, with the Eastern Kunlun Range acting as a persistent sediment source region [50]. The importance of the Altyn Tagh Range as a sediment source progressively increased during the Jurassic and became dominant by the late Early Cretaceous [49].

2.2. Surrounding Ranges

The major mountain ranges surrounding the Qaidam Basin include the Eastern Kunlun Range, the Altyn Tagh Range, and the Qilian Shan, which together constitute the main potential provenance regions for basin sediments (Figure 1b). The Eastern Kunlun Range lies along the southern margin of the Qaidam Basin and trends approximately east–west. It is an important tectono-geomorphic boundary separating the Qaidam Basin from the Hoh Xil Basin. The basement of this orogenic belt is mainly composed of Proterozoic–Paleozoic metamorphic rocks, overlain by Paleozoic–Mesozoic strata and extensively intruded by Paleozoic and Permian–Triassic igneous rocks [4,40]. Cambrian, Mississippian, and Permian–Triassic ophiolite belts are also exposed in the region, reflecting complex processes of paleo-ocean closure and continental amalgamation. A prominent feature of detrital zircon age spectra from the Eastern Kunlun Range is the relatively small proportion of Precambrian ages and the pronounced Early Paleozoic and Late Paleozoic–Early Mesozoic age populations [53]. The ca. 430 Ma age peak is commonly associated with Early Paleozoic metamorphic rocks and Ordovician–Silurian tectonic amalgamation, whereas the 300–200 Ma age population corresponds to Permian–Triassic closure of the Paleo-Tethys Ocean and post-collisional magmatism [54,55]. This population is an important provenance signature that distinguishes the Eastern Kunlun Range from the Altyn Tagh Range and the Qilian Shan [54–56]. In addition, local Cretaceous magmatism and Miocene–Quaternary volcanism have also been recorded [57].

The Altyn Tagh Range is located along the northwestern margin of the basin and evolved primarily under the control of the Altyn Tagh fault system. The range separates the Qaidam Basin from the Tarim Basin, and the Late Cenozoic Xorkol Basin developed within the range. Specifically, the Altyn Tagh Fault separates the Qaidam Basin from the Xorkol Basin, whereas the North Altyn Tagh Fault separates the Tarim Basin from the Xorkol Basin (Figure 1b) [58,59]. Although the Altyn Tagh Fault is widely regarded as a large-displacement, multi-stage sinistral strike-slip fault, the timing of its activity, evolutionary stages, and displacement remain highly debated [10,31–33,58,60–62]. In the Altyn Tagh Range, Archean and Proterozoic crystalline basement rocks and Paleozoic intrusive

rocks are widely exposed. Existing zircon U-Pb geochronological data show abundant Archean–Proterozoic age populations in the Altyn Tagh basement, with Archean ages of ca. 3.6–2.6 Ga and Proterozoic ages of ca. 2.4 Ga–650 Ma. Among these, Early Neoproterozoic ages of 1050–650 Ma, especially the ca. 850–1000 Ma population, represent a key feature for identifying Altyn Tagh Range provenance [63,64]. In addition, Paleozoic igneous rocks with ages of 550–400 Ma are widespread in the Altyn Tagh Range [65–69]. Late Paleozoic igneous rocks with ages of 300–260 Ma or 330–270 Ma occur locally, but they constitute only a small proportion of the overall age spectrum [70,71].

The Qilian Shan lies along the northeastern margin of the Qaidam Basin and consists mainly of Early Paleozoic flysch, island-arc assemblages, low- to high-grade metamorphic rocks, and Proterozoic passive-margin sedimentary–metamorphic sequences. Previous geochronological studies have documented several major zircon age components in the Qilian Shan. Late Archean–Early Proterozoic orthogneisses yield zircon ages of ca. 2.6–1.75 Ga [72–75], whereas Late Proterozoic metamorphic and ultramafic rocks yield ages of ca. 1.0 Ga and ca. 800 Ma, respectively, forming a prominent 1050–700 Ma age population [76]. Early Paleozoic granitic bodies intruding the Proterozoic basement are widespread, with zircon U-Pb ages mainly between 550 and 400 Ma. The region also experienced Devonian metamorphism at 400–360 Ma, and peak metamorphism of the North Qaidam ultrahigh-pressure metamorphic belt occurred at ca. 440–423 Ma [77,78]. In contrast, Permian–Triassic igneous rocks are only sporadically distributed in the Qilian Shan, with ages of ca. 270–210 Ma, and do not form a major age population. Therefore, the Qilian Shan provenance signal is characterized mainly by Early Paleozoic and Precambrian age components, making it broadly comparable to the Altyn Tagh Range but distinct from the Eastern Kunlun Range, which contains more abundant Permian–Triassic magmatic age signals.

3. Samples and Methods

We first conducted detailed field geological investigations in the Qigequan and Caishiling areas of the western Qaidam Basin to characterize sedimentary facies and structural deformation features. On this basis, six sandstone samples were collected from the two areas for petrographic observations and detrital zircon U-Pb geochronological analysis (Figures 1d and 2; Table 1). In the Qigequan section (Figure 2a), samples QGQ03-1 and QGQ08-1 were collected from the upper and middle parts of the Pleistocene Qigequan Formation, respectively, whereas sample QGQ07-1 was collected from the upper part of the Pliocene Shizigou Formation. In the Caishiling section (Figure 2b), sample CSL09-1 was collected from the lower part of the Early Cretaceous Quanyagou Formation, and samples CSL01-1 and CSL07-1 were collected from the upper and middle parts of the Upper Jurassic Hongshuigou Formation, respectively. In addition, published data for sample E122 from the upper part of the Early–Middle Jurassic Dameigou Formation were compiled from Cheng et al. [31]. The lithology, sampling coordinates, relative stratigraphic positions, detrital zircon age ranges, age peaks, and numbers of accepted analyses are summarized in Table 1.

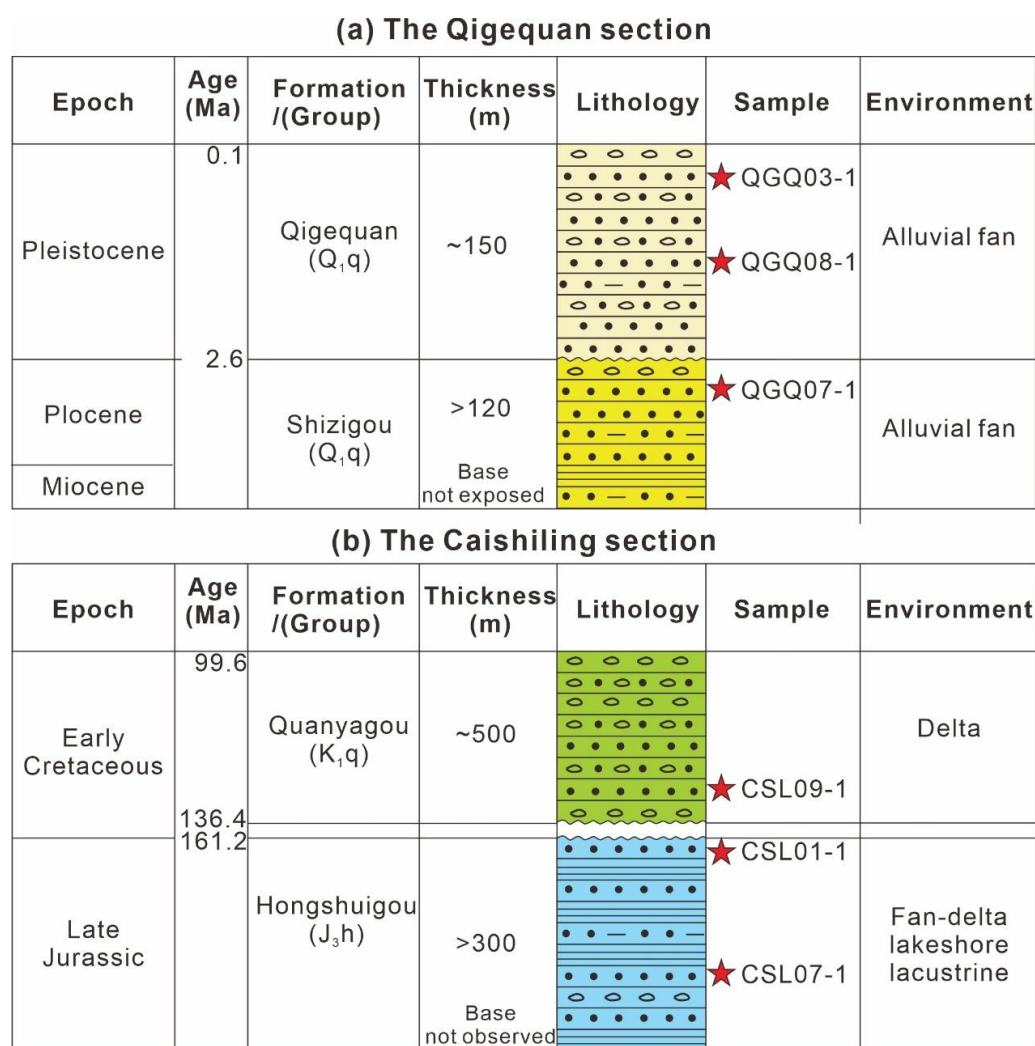


Figure 2. Lithostratigraphic columns showing the exposed portions of the Qigequan (a) and Caishiling (b) sections and the corresponding sampling positions (red stars along the columns).

Table 1. Summary of lithological characteristics, sampling information, and detrital zircon U-Pb geochronological data for sandstone samples analyzed and compiled in this study.

Sample Name	Epoch	Formation (Fm.)	Position in Succession	Lithology	Sampling Location	Detrital Zircon Age Range (Ma)	Detrital Zircon Peaks (Ma)	Number of Accepted Analyses	<300 Ma	300–600 Ma	600–1000 Ma	1000–1500 Ma	>1500 Ma
QGQ03-1	Pleistocene	Qigequan Fm.	Upper	Gray-white sandstone	38°21'28.5" N, 90°39'54.3" E	216–1837	ca. 428 ca. 239 ca. 923	76	21%	58%	13%	4%	4%
QGQ08-1	Pleistocene	Qigequan Fm.	Middle	Yellow sandstone	38°20'05.8" N, 90°39'50.0" E	229–1721	ca. 445 ca. 258 ca. 934	76	21%	68%	8%	1%	1%
QGQ07-1	Pliocene	Shizigou Fm.	Upper	Yellow sandstone	38°20'29.6" N, 90°39'52.2" E	212–1731	ca. 434 ca. 232 ca. 882	87	18%	69%	7%	3%	2%
CSL09-1	Early Cretaceous	Quanyagou Fm.	Lower	Gray-green sandstone	38°26'05.4" N, 90°44'16.0" E	212–1555	ca. 257 ca. 421 ca. 221	79	43%	56%	0%	0%	1%

CSL01-1	Late Jurassic	Hongshuigou Fm.	Upper	Brown sandstone	38°26′24.0″ N, 90°44′05.7″ E	227–2450	ca. 437 ca. 235 ca. 878	72	21%	62%	10%	0%	7%
CSL07-1	Late Jurassic	Hongshuigou Fm.	Middle	Gray-green sandstone	38°27′42.0″ N, 90°44′02.7″ E	217–2581	ca. 430 ca. 259 ca. 809	74	36%	38%	12%	5%	8%
E122	Early–Middle Jurassic	Dameigou Fm.	Upper	Gray-white sandstone	—	246–1951	ca. 422 ca. 255	79	15%	72%	9%	0%	4%

3.1. Zircon U-Pb Dating

Sandstone samples were processed using conventional mineral-separation procedures, including crushing, washing, heavy-liquid separation, and magnetic separation, to obtain zircon grains. To minimize selection bias, the separated zircon concentrates were thoroughly mixed, and zircon grains were randomly selected under a binocular microscope without preference for grain size, shape, color, transparency, or degree of abrasion. The selected grains were mounted in epoxy resin. The mounts were then ground and polished to expose internal grain structures. Zircon grains were examined using transmitted-light, reflected-light, and cathodoluminescence images to identify internal zoning, fractures, inclusions, and suitable analytical spots.

Zircon picking, transmitted- and reflected-light imaging, cathodoluminescence imaging, and U-Pb isotope analyses were performed at Wuhan SampleSolution Analytical Technology Co., Ltd., Wuhan, China. Detailed instrumental parameters and analytical procedures are described by Zong et al. [79]. Laser sampling was performed using a GeolasPro (MicroLas Lasersystem GmbH, Göttingen, Germany) laser ablation system consisting of a COMPexPro 102 ArF excimer laser (Coherent, Göttingen, Germany) (wavelength of 193 nm and maximum energy of 200 mJ) and a MicroLas optical system (MicroLas Lasersystem GmbH, Göttingen, Germany). An Agilent 7900 ICP-MS instrument (Agilent Technologies, Santa Clara, CA, USA) was used to acquire ion-signal intensities. Helium was used as the carrier gas. Argon was used as the make-up gas and mixed with the carrier gas via a T-connector before entering the ICP. A “wire” signal-smoothing device was incorporated into this laser ablation system [80]. The laser spot diameter and repetition rate were 32 µm and 5 Hz, respectively. Tanz zircon and NIST610 glass were used as external standards for U-Pb dating and trace-element calibration, respectively [81]. Each analysis incorporated a background acquisition of approximately 20–30 s, followed by 50 s of data acquisition from the sample. The Excel-based software ICPMSDataCal was used for offline selection and integration of background and sample signals, time-drift correction, and quantitative calibration for trace-element analysis and U-Pb dating [82,83]. U-Pb age concordance was calculated in ICPMSDataCal (version 10.9) as $100 \times [1 - \text{abs}((^{206}\text{Pb}/^{238}\text{U})_{\text{Age}} - ^{207}\text{Pb}/^{235}\text{U})_{\text{Age}}) / ((^{206}\text{Pb}/^{238}\text{U})_{\text{Age}})]$, and discordance was defined as 100% minus concordance [82,83]. Analyses with concordance $\geq 95\%$ were retained, whereas analyses with concordance $< 95\%$ were excluded from all subsequent analyses; analytical uncertainties are reported at 1σ . All accepted U-Pb age data were re-evaluated using IsoplotR (version 6.8), including the generation of concordia diagrams and weighted mean ages for the calculation of maximum depositional ages [84]. Ages younger than ca. 1000 Ma are based on common-Pb-corrected $^{206}\text{Pb}/^{238}\text{U}$ ratios, whereas ages older than ca. 1000 Ma are based on common-Pb-corrected $^{207}\text{Pb}/^{206}\text{Pb}$ ratios. Detrital zircon age distributions were primarily visualized and evaluated using kernel density estimate (KDE) and cumulative distribution function (CDF) plots generated in DZstats [24]. KDE plots do not incorporate analytical uncertainties and reduce distortions associated with probability-density-plot peak

shapes [85]. CDF plots allow direct, distribution-level comparison among samples. Probability density plots (PDPs) are retained only as a secondary visual reference and were not used in the quantitative similarity analyses or provenance interpretation.

3.2. Composite Dataset Construction and Quantitative Analysis of Zircon U-Pb Data

For both source and sink datasets, composite detrital zircon age distributions were constructed where multiple samples were used to represent a broader stratigraphic or source unit [86–88]. This treatment increases the total number of zircon grains in the endmember and reduces the influence of stochastic variability or local depositional bias associated with individual samples. In these cases, the samples were combined after applying the same data-screening criteria. Because the numbers of valid zircon analyses are comparable among the combined samples, direct pooling of the grain-age data produces a result close to an equal-sample-weighted composite and avoids overrepresentation by any single sample.

For the Qigequan Formation, samples QGQ03-1 and QGQ08-1 were combined to obtain a formation-level detrital zircon age distribution for provenance modeling. This combined result is intended to represent the average zircon age signal of the Qigequan Formation in the study area, rather than the signal of either individual sample alone.

Similarly, the four Mesozoic samples (CSL09-1, CSL01-1, CSL07-1, and E122) were combined to construct a composite Mesozoic sedimentary-cover source proxy, hereafter referred to as the composite Mesozoic proxy. This composite Mesozoic proxy does not imply that the individual Mesozoic formations have identical detrital zircon age spectra. Rather, it is used as a first-order representation of the broader zircon age signal of Mesozoic sedimentary units exposed in the potential source regions.

In addition to the composite datasets constructed in this study, the Altyn Tagh Range and Eastern Kunlun Range endmembers were defined using the regional zircon U-Pb age compilation of Cheng et al. [6], which summarizes published ages from basement and magmatic rocks around the Qaidam Basin. The two datasets include 152 ages from the Altyn Tagh Range and 195 ages from the Eastern Kunlun Range, mainly representing crystalline basement rocks, granitoid plutons, metamorphic rocks, and related igneous units. The locations of the compiled ages are shown in Figure DR1 of Cheng et al. [6], and the individual ages are summarized in Table S1. Because these endmember datasets were compiled from published studies, the raw isotopic data and original screening procedures are not uniformly available for all analyses. We therefore used the accepted compiled ages reported by Cheng et al. [6] without applying an additional re-screening procedure. These two datasets are considered representative of the first-order zircon U-Pb age signatures of the Altyn Tagh Range and Eastern Kunlun Range source regions [6,31].

3.2.1. Metrics Describing Sample Similarity in Zircon U-Pb Data

To quantitatively compare detrital zircon U-Pb age spectra among samples, this study employed age spectrum similarity metrics (the cross-correlation and similarity coefficients) and nonparametric statistics (the Kolmogorov-Smirnov D and Kuiper V values). All metrics were calculated using DZstats (version 2.30) [24].

(1) Cross-correlation coefficient

The cross-correlation coefficient is the coefficient of determination (R^2) from a cross-plot of KDEs for two samples over the same age intervals [88,89]. It reflects the presence and shapes of age peaks and the similarity of their relative intensities [88]. The value ranges from 0 to 1, with values closer to 1 indicating greater similarity between two age spectra.

(2) Similarity coefficient

The similarity coefficient measures the degree of overlap between age peaks and their relative proportions in two age probability distributions. It is commonly defined as the sum of the square roots of the products of corresponding probability values in two KDE curves [24]. The value also ranges from 0 to 1. Values closer to 1 indicate more similar age distributions, whereas values closer to 0 indicate that the samples share almost no age peaks.

(3) Kolmogorov-Smirnov (K-S) Test

The K-S test D value represents the maximum difference between the empirical cumulative distribution functions of two samples and is used to evaluate the overall difference between two age distributions. Smaller D values indicate more similar age distributions [89].

(4) Kuiper Test

The Kuiper V value is the sum of the maximum positive and negative differences between two cumulative distribution functions. Compared with the K-S test, it has more uniform sensitivity across all parts of the cumulative distribution function and avoids the lower sensitivity of the K-S test in the distribution tails. Smaller V values likewise indicate greater similarity between two age spectra.

3.2.2. 2D/3D Multidimensional Scaling (MDS) Analysis

Although the quantitative methods described above measure similarity or dissimilarity between pairs of samples, they are less intuitive for comparing multiple samples simultaneously. To more clearly visualize the overall relationships among detrital zircon age spectra of multiple samples, this study used MDS to reduce the dimensionality of the sample dissimilarity matrix [22]. MDS converts differences in age spectra, based on R^2 values from the cross-correlation coefficient, D values from the K-S test, or V values from the Kuiper test, into spatial distances while preserving the original dissimilarity relationships as closely as possible in two- or three-dimensional space. Therefore, in MDS diagrams, samples located close to each other generally have more similar detrital zircon age spectra, whereas samples farther apart represent greater age spectrum differences. The reliability of MDS diagrams can be evaluated using the stress function, a commonly used loss function, and Shepard plots [90]. Lower stress values or points closer to the 1:1 line in Shepard plots indicate a better-fitting MDS configuration. In this study, 2D and 3D MDS diagrams were generated based on R^2 values, K-S test D values, and Kuiper test V values, and the solution with the lowest stress value was retained for interpretation. MDS diagrams, Shepard plots, and stress values were generated using DZmds (version 1.10) [23].

3.2.3. Inverse Monte Carlo Modeling

Inverse Monte Carlo mixture modeling was performed using DZmix (version 1.21) [23] to quantitatively fit the detrital zircon U-Pb age distributions of the Qigequan and Shizigou formations. In this approach, each sink age distribution is treated as a mixture of age distributions from selected source endmembers. The model randomly generates non-negative source mixing coefficients that sum to one, constructs weighted model age distributions, compares them with the observed sink distribution, and retains the combinations that provide the best fits.

Three goodness-of-fit metrics were used to evaluate and cross-check the modeling results: Kolmogorov-Smirnov (K-S) D values and Kuiper V values based on cumulative distribution functions (CDFs), and cross-correlation coefficients (R^2) based on kernel density estimates (KDEs). Lower D and V values, or an R^2 value closer to 1, indicate a better model fit. For each sink dataset, 100,000 Monte Carlo trials were performed, and the best-fitting 1% of trials were retained for analysis. Following the DZmix output format and the

approach of Sundell and Saylor [23], the retained trials for each optimization metric were summarized as mean relative mixing coefficients ± 1 standard deviation (SD). Because the identifiability of mixture-model solutions depends on the degree of separation among source age distributions, similarities among endmembers may result in non-unique mixing coefficients, with different endmember combinations producing comparably good fits. The reported ± 1 SD values characterize the dispersion among retained trials for each optimization metric but do not include the structural uncertainty associated with endmember similarity.

Two modeling scenarios were tested: (1) a two-endmember model including only the Altyn Tagh Range and Eastern Kunlun Range, and (2) a three-endmember model including the Altyn Tagh Range, Eastern Kunlun Range, and the composite Mesozoic proxy. The two scenarios were compared using the D, V, and R^2 values, together with geological constraints such as sedimentary and structural characteristics.

It should be noted that the modeled source contributions represent the relative mixing coefficients required to reproduce the detrital zircon U-Pb age distributions of the sink samples. They should not be interpreted as actual mass proportions of each source in the total sediment. This distinction is important because zircon fertility, grain-size sorting, hydraulic transport, sediment recycling, and other sedimentary processes may decouple the zircon age distribution from the bulk sediment composition. Therefore, the Monte Carlo results are used here to evaluate relative source affinity and the importance of different zircon age components, rather than to calculate exact sediment-flux or bulk mass proportions.

3.3. Maximum Depositional Age Estimation

Maximum depositional ages were evaluated using the youngest single-grain age (YSG) and the weighted mean age of the youngest cluster comprising at least three analyses overlapping within 2σ uncertainty, $YC2\sigma(3+)$ [35]. The YSG was defined as the youngest accepted preferred U-Pb age in each sample. For the $YC2\sigma(3+)$ calculation, analyses were sorted according to age plus 2σ uncertainty, and the youngest contiguous cluster containing at least three mutually overlapping analyses was selected. The cluster age was calculated as an inverse-variance-weighted mean using the reported 1σ analytical uncertainties in IsoplotR (version 6.8) [84], and the uncertainty of the weighted mean is reported at the 2σ level.

4. Results

4.1. Field Sedimentary and Structural Characteristics

(1) Qigequan area

The Qigequan area is located in the northwestern Qaidam Basin and is an important hydrocarbon-producing and uranium-mineralized area in the western Qaidam Basin [28]. Regional structures are dominated by the Qigequan Fault and a fault-related anticline, both of which trend NW–SE. The northeastern limb is relatively steep, whereas the southwestern limb is gentler (Figure 1c). Topography generally decreases from north to south. Previous studies indicate that the Qigequan Fault was strongly active from deposition of the Upper Youshashan Formation through that of the Qigequan Formation [8]. The Qigequan area preserves a relatively complete Cenozoic succession from the Lulehe Formation to the Qigequan Formation, with both the Shizigou and Qigequan formations exposed (Figure 2a). Field observations show that the Qigequan Formation is mainly composed of grayish-white to yellow medium- to coarse-grained sandstones, pebbly sandstones, and conglomerates. Locally developed erosional surfaces, lenticular gravelly layers, and cross-bedding indicate high-energy depositional conditions (Figure 3a,b). The

Shizigou Formation is dominated by yellow to grayish-yellow fine- to medium-grained sandstone, argillaceous sandstone, and silty mudstone, with well-developed bedding (Figure 3c,d). The Qigequan Formation overlies the Shizigou Formation with a pronounced angular unconformity (Figure 3c), indicating that the study area experienced significant tectonic uplift and erosion after deposition of the Shizigou Formation and before deposition of the Qigequan Formation. In terms of sedimentary assemblages, both the Shizigou and Qigequan formations form part of a large alluvial-fan system and are mainly composed of debris-flow deposits, incised channel-fill deposits, and sheetflood deposits [91].

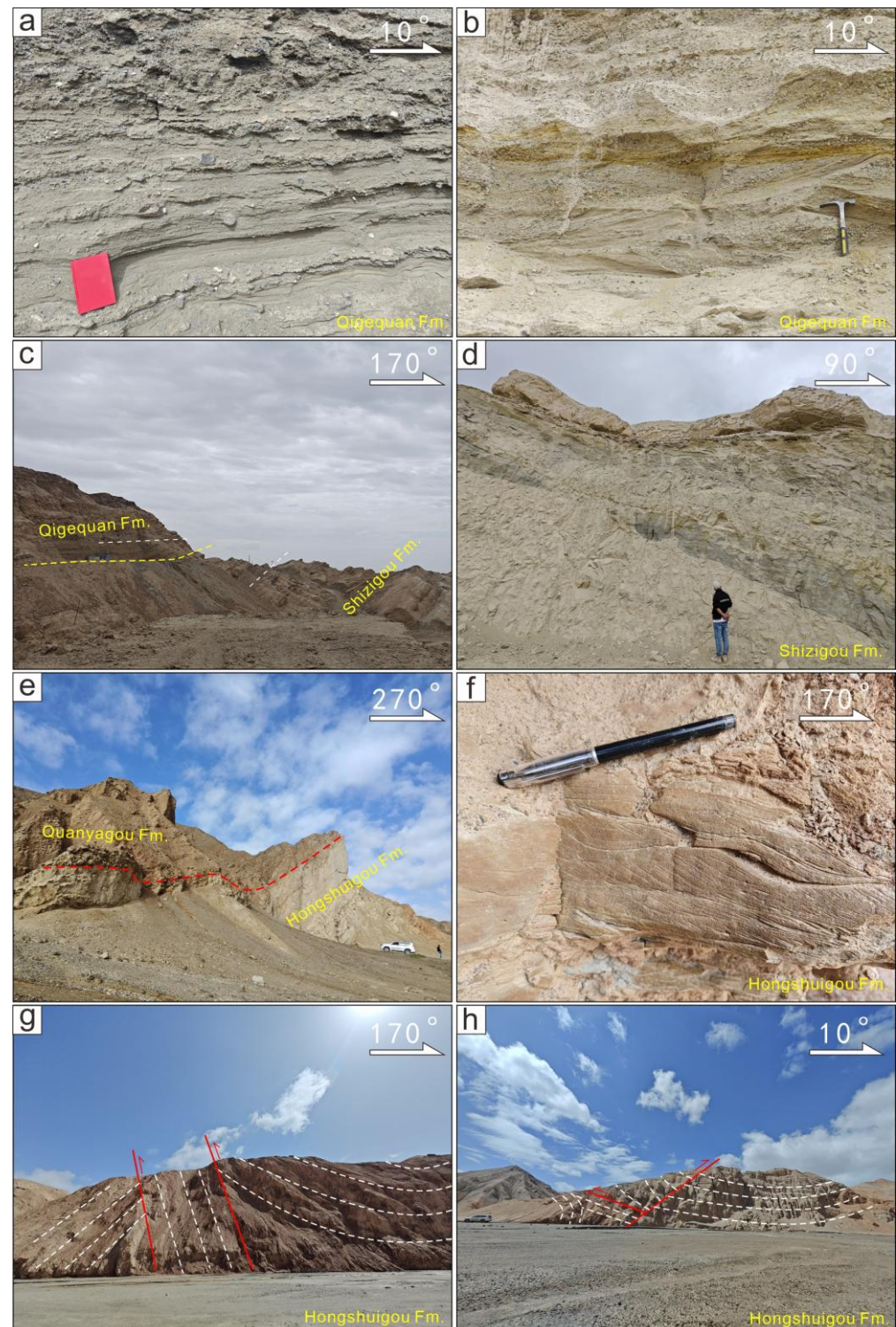


Figure 3. Representative field photographs showing sedimentary and structural features in the Qigequan area (a–d) and the Caishiling area (e–h). (a) Gray conglomerate interbedded with fine-grained sandstone in the Qigequan Formation; (b) yellowish-green pebbly coarse-grained sandstone with well-developed cross-bedding in the Qigequan Formation; (c) the Qigequan Formation unconformably overlies the Shizigou Formation; (d) steeply dipping and deformed sandstone beds of the Shizigou Formation. (e) The Quanyagou Formation unconformably overlies the Hongshuigou Formation; (f) cross-bedding in sandstone of the Hongshuigou Formation. (g,h) Strongly folded and faulted strata of the Hongshuigou Formation.

(2) Caishiling area

The Caishiling area is located approximately 10 km northwest of the Qigequan area, in the piedmont zone of the Altyn Tagh Range along the western basin margin. The area mainly exposes the Lower Cretaceous Quanyagou Formation and the Upper Jurassic Hongshuigou Formation, with the former unconformably overlying the latter (Figures 2b and 3e). The Quanyagou Formation mainly consists of brown conglomerates interbedded with brown mudstone, whereas the Hongshuigou Formation is dominated by reddish-brown mudstone, argillaceous siltstone, siltstone, and fine-grained sandstone, with thin conglomerate beds. Cross-bedding is locally visible in the fine-grained sandstone (Figure 3f). In terms of sedimentary facies, the Quanyagou Formation mainly represents deltaic deposits, whereas the Hongshuigou Formation was deposited in fan-delta, lakeshore, and shallow-lacustrine environments [33]. Field observations indicate that the Mesozoic strata underwent intense tectonic deformation and developed a series of thrust faults and related folds, forming a typical contractional structural style (Figure 3g,h). The fault architecture includes imbricate fault systems and back-thrust fault systems (Figure 3g,h). Deformation intensifies northward toward the Altyn Tagh Range.

4.2. Petrographic Characteristics of the Samples

Samples QGQ03-1 and QGQ08-1, collected from the upper and middle parts of the Qigequan Formation, respectively, are poorly sorted, medium-grained lithic feldspathic sandstones composed mainly of quartz, feldspar, and lithic fragments, with subordinate dark matrix and calcite cement (Figure 4a–f). The framework grains are predominantly angular to subangular, with only a small proportion of subrounded grains, indicating low textural maturity. Quartz occurs mainly as monocrystalline grains, whereas feldspar is represented by both plagioclase and K-feldspar, some of which show varying degrees of alteration. Minor hornblende is also present.

Lithic fragments are visually estimated to constitute approximately 10–15 vol.% of the framework grains in samples QGQ03-1 and QGQ08-1. They are dominated by sedimentary lithic fragments, particularly sandstone fragments, with subordinate quartzite, mudstone, and granitic fragments. The sandstone lithic fragments are generally irregular, elliptical, or locally elongated and consist internally of fine quartz and feldspar grains embedded in a fine-grained matrix (Figure 4b,c,e,f). These internal granular textures distinguish them from single mineral grains and demonstrate that they are fragments of pre-existing clastic rocks. Quartzite lithic fragments are characterized by tightly interlocking quartz aggregates and locally sutured grain boundaries (Figure 4b,e). Mudstone lithic fragments are finer grained and more homogeneous, whereas granitic lithic fragments contain intergrown quartz and feldspar. Dark clay-rich matrix occupies part of the intergranular space, and calcite occurs as pore-filling cement and locally surrounds or partly replaces framework grains and lithic fragments.

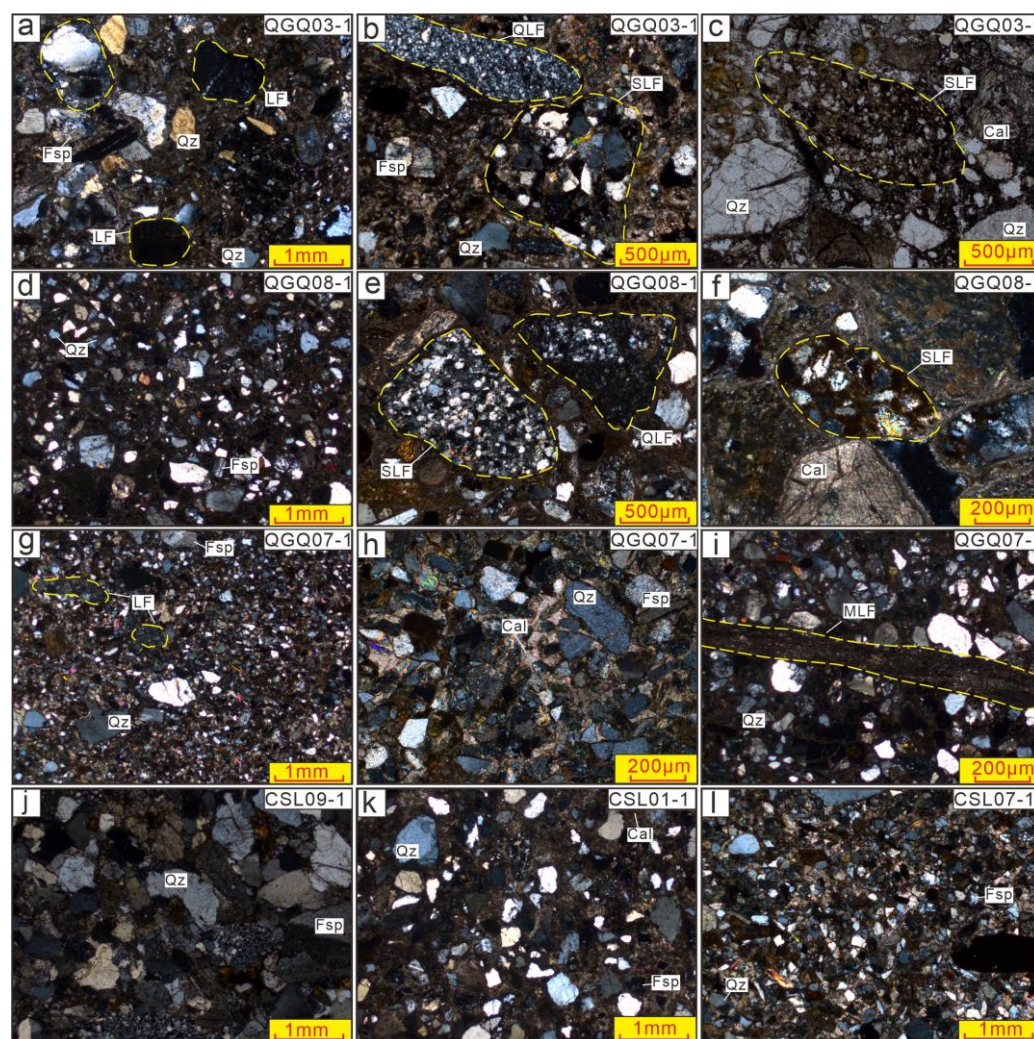


Figure 4. Representative photomicrographs of sandstone samples from the Qigequan area (a–i) and the Caishiling area (j–l). (a) Poorly sorted, medium-grained sandstone of sample QGQ03-1, composed mainly of angular to subangular quartz, feldspar, and lithic fragments. (b) Sandstone and quartzite lithic fragments in QGQ03-1; the sandstone lithic fragment preserves an internal fine-grained clastic texture. (c) An elongated sandstone lithic fragment in QGQ03-1, characterized by fine-grained internal components. (d) Poorly sorted sandstone of sample QGQ08-1 containing angular to subangular quartz and feldspar grains. (e) Sandstone and quartzite lithic fragments in QGQ08-1; the sandstone lithic fragment retains a fine-grained granular texture. (f) A sandstone lithic fragment in QGQ08-1. (g) Poorly sorted sandstone of sample QGQ07-1 containing quartz, feldspar, and scattered lithic fragments. (h) Intergranular calcite cement among quartz and feldspar grains in QGQ07-1. (i) An elongated mudstone lithic fragment in QGQ07-1, showing a homogeneous fine-grained internal texture. (j) Medium- to coarse-grained quartz-feldspar sandstone of sample CSL09-1. (k) Poorly sorted quartz-feldspar sandstone of sample CSL01-1 with intergranular calcite cement. (l) Fine-grained sandstone of sample CSL07-1, composed mainly of angular to subangular quartz and feldspar grains. Yellow dashed lines outline representative lithic fragments. Abbreviations: Qz, quartz; Fsp, feldspar; Cal, calcite; LF, lithic fragment; SLF, sandstone lithic fragment; QLF, quartzite lithic fragment; MLF, mudstone lithic fragment.

Sample QGQ07-1, collected from the upper part of the Shizigou Formation, is a poorly sorted, fine-grained feldspathic sandstone and is distinctly finer grained than the Qigequan Formation samples (Figure 4g–i). The framework grains consist mainly of angular to subangular quartz and feldspar, accompanied by fewer lithic fragments, visually estimated at approximately 5 vol.%. The lithic fragments include scattered sedimentary

rock fragments and minor other rock fragments (Figure 4g). A representative elongated mudstone lithic fragment displays a homogeneous, very fine-grained internal texture and a well-defined boundary against the surrounding quartz and feldspar grains (Figure 4i). Calcite cement is more abundant than in the Qigequan Formation samples, accounting for approximately 10–15 vol.% of the rock and occurring mainly as intergranular pore-filling cement (Figure 4h). Dark matrix is also present locally. The poor sorting, angular to subangular grain shapes, preservation of unstable feldspar and sedimentary lithic fragments, and relatively abundant matrix and cement collectively indicate low textural and compositional maturity.

Sample CSL09–1, collected from the lower part of the Quanyagou Formation, is a medium- to coarse-grained quartz-feldspar sandstone (Figure 4j). It is moderately to poorly sorted and displays a broad grain-size range. Quartz and feldspar constitute the dominant framework components, whereas granitic and other lithic fragments are minor, together accounting for less than approximately 5 vol.%. Quartz grains are mostly subangular to subrounded, and several grains exhibit prominent intragranular fractures. Feldspar grains are common and locally show sericitization or other alteration. The intergranular material consists of subordinate dark matrix and minor calcite cement.

Samples CSL01-1 and CSL07-1, collected from the upper and middle parts of the Hongshuigou Formation, respectively, are quartz-feldspar sandstones with low textural maturity. Sample CSL01-1 is medium grained and moderately to poorly sorted (Figure 4k). Its framework is dominated by angular to subangular quartz and feldspar grains, with only minor lithic fragments. Dark matrix and calcite cement occupy part of the intergranular space, and the calcite locally fills pores and replaces grain margins. Sample CSL07-1 is finer grained and more poorly sorted than CSL01-1 (Figure 4l). It consists mainly of angular to subangular quartz and feldspar grains dispersed within a fine-grained matrix and subordinate calcite cement. Lithic fragments are uncommon in both samples compared with the Qigequan Formation sandstones.

Overall, the Cenozoic Qigequan and Shizigou sandstones contain identifiable sandstone and mudstone lithic fragments, some of which retain internal fine-grained clastic or homogeneous mud-rich textures. These petrographic observations directly document the incorporation of fragments derived from pre-existing sedimentary rocks, although the stratigraphic age of those source rocks cannot be determined from petrography alone.

4.3. Detrital Zircon U-Pb Geochronology

The morphological and internal-textural characteristics of detrital zircons, together with their Th/U ratio statistics, are summarized in Table S2. Detrital zircons from all sandstone samples are predominantly euhedral to subhedral and are mainly short- to long-prismatic crystals. CL images show that most zircons display well-developed oscillatory zoning, whereas a small number of grains show weak zoning, core–rim structures, or irregular internal textures (Figure 5). Most analyzed zircons have Th/U ratios greater than 0.1, which, together with their oscillatory zoning, is broadly consistent with a predominantly magmatic origin. However, Th/U ratios alone are not used here to distinguish magmatic from metamorphic zircon or to infer source rock affinity. The provenance interpretations in this study are based primarily on detrital zircon U-Pb age spectra, age-population proportions, similarity metrics, MDS analysis, and inverse Monte Carlo modeling.

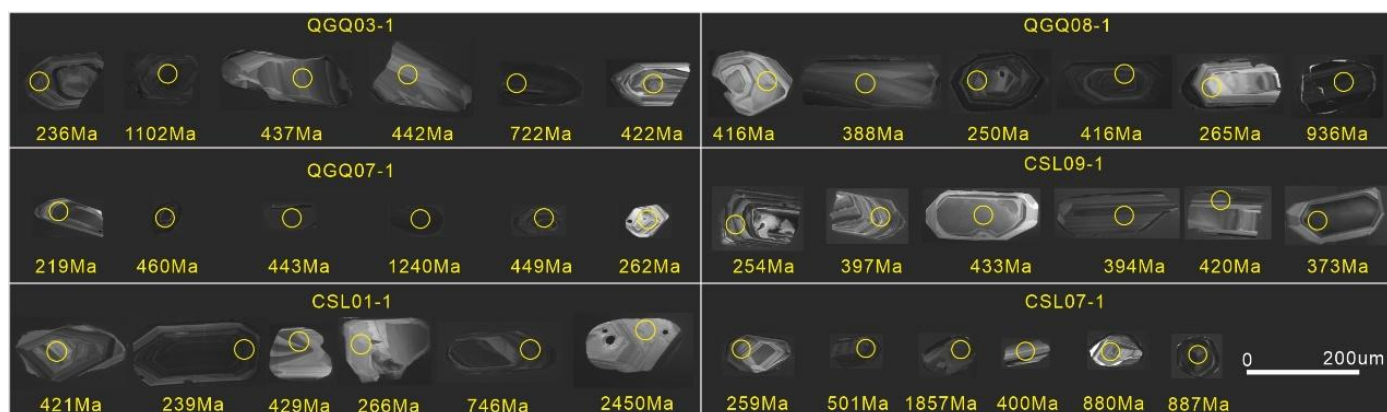


Figure 5. Representative cathodoluminescence (CL) images of detrital zircons from the six sandstone samples. The yellow circles show the locations of the U-Pb analysis spots.

After data processing, Wetherill concordia diagrams were generated in IsoplotR (version 6.8) for all six newly analyzed samples using analyses with concordance $\geq 95\%$ (Figure 6). Most accepted analyses plot on or close to the concordia curve, indicating generally limited discordance. A total of 4, 11, 10, 7, 11, and 7 analyses with concordance $< 95\%$ were excluded from QGQ03-1, QGQ08-1, QGQ07-1, CSL09-1, CSL01-1, and CSL07-1, respectively. The final numbers of accepted analyses were 76, 76, 87, 79, 72, and 74, respectively. The compiled E122 dataset contains 79 analyses that satisfy the same criterion. All isotopic data from the six newly analyzed samples are provided in Table S3.

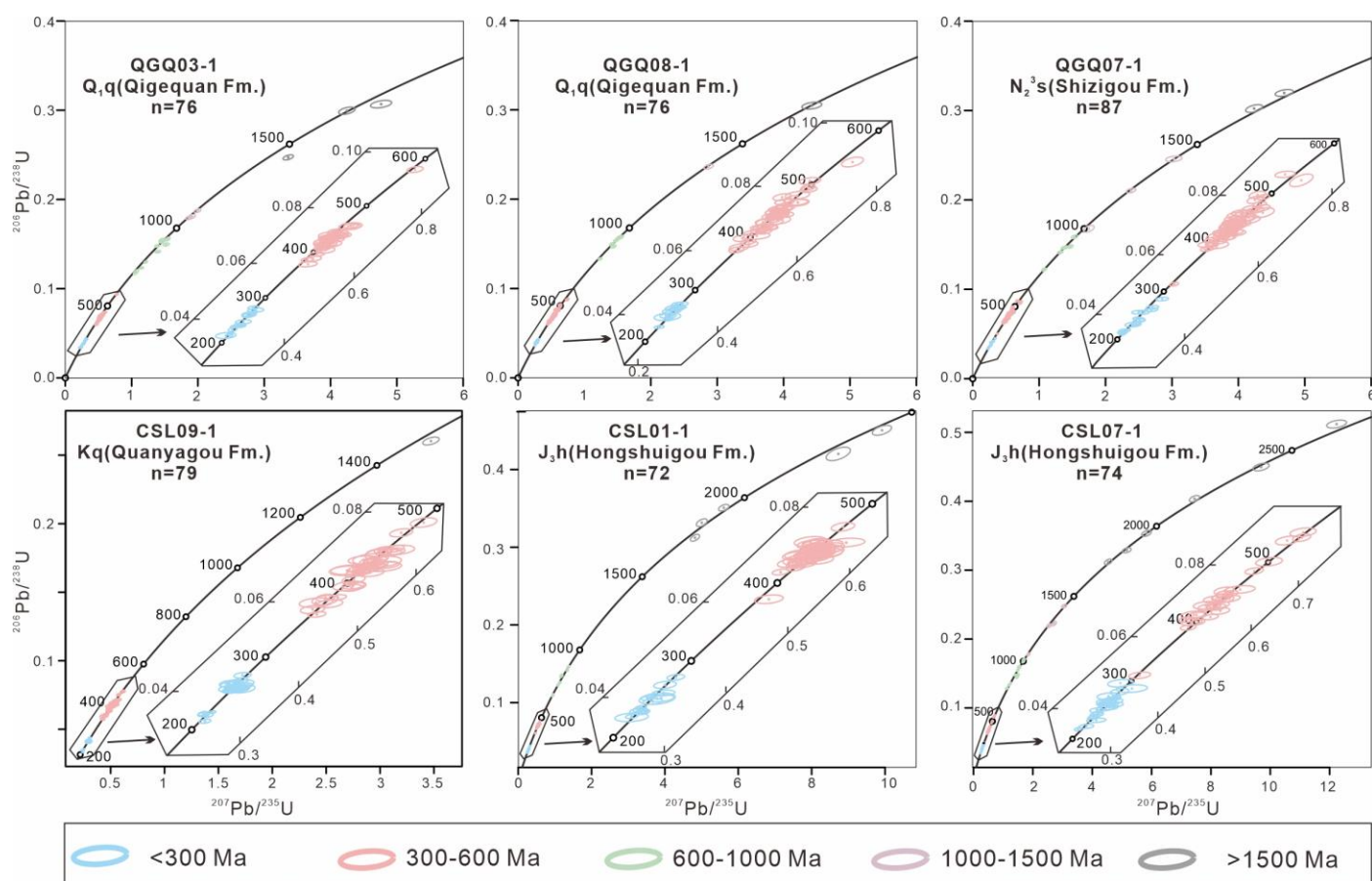


Figure 6. Wetherill U-Pb concordia diagrams of detrital zircons from the six sandstone samples. Only analyses with concordance $\geq 95\%$ are shown.

Based on the five provenance-related age intervals used throughout this study (<300 Ma, 300–600 Ma, 600–1000 Ma, 1000–1500 Ma, and >1500 Ma), the Cenozoic samples from the Qigequan area are consistently dominated by 300–600 Ma zircons, which account for 58%–69% of the accepted analyses. The <300 Ma population forms a subordinate but stable component of 18%–21%, whereas the 600–1000 Ma, 1000–1500 Ma, and >1500 Ma populations account for 7%–13%, 1%–4%, and 1%–4%, respectively (Figure 7a–c; Table 1). The Mesozoic samples show greater internal variability (Figure 7d–g; Table 1). Sample CSL09-1 contains 43% <300 Ma and 56% 300–600 Ma zircons, no 600–1000 Ma or 1000–1500 Ma grains, and 1% >1500 Ma grains. Sample CSL01-1 contains 21% <300 Ma, 62% 300–600 Ma, 10% 600–1000 Ma, no 1000–1500 Ma grains, and 7% >1500 Ma grains. Sample CSL07-1 contains 36% <300 Ma and 38% 300–600 Ma zircons, together with 600–1000 Ma (12%), 1000–1500 Ma (5%), and >1500 Ma (8%) components. The published Dameigou Formation sample E122 is characterized by 15% <300 Ma, 72% 300–600 Ma, 9% 600–1000 Ma, no 1000–1500 Ma grains, and 4% >1500 Ma zircons. These age-population characteristics are consistent with the principal KDE peaks at ca. 421–445 Ma and ca. 221–259 Ma, which represent the dominant Early Paleozoic and Late Paleozoic–Early Mesozoic components, respectively.

Comparison with the surrounding basement source regions reveals both similarities and important differences. The Eastern Kunlun Range is also dominated by 300–600 Ma zircons (59%) and contains a substantial <300 Ma component (33%), but the proportion of <300 Ma grains is higher than that in the Cenozoic samples from the Qigequan area (18–21%; Figure 7i). Its 600–1000 Ma, 1000–1500 Ma, and >1500 Ma components account for 4%, 1%, and 3%, respectively. In contrast, the Altyn Tagh Range contains a similarly high proportion of 300–600 Ma zircons (58%) but only 3% <300 Ma grains (Figure 7h), together with much larger 600–1000 Ma and >1500 Ma components (20% and 17%, respectively) and a minor 1000–1500 Ma component (2%).

4.4. Maximum Depositional Ages

The YSG and $YC2\sigma(3+)$ results for the six newly analyzed samples and the published sample E122 are summarized in Table S4. The Qigequan Formation samples QGQ03-1 and QGQ08-1 yield YSG ages of 215.5 ± 4.4 Ma and 228.6 ± 4.3 Ma, respectively, with corresponding $YC2\sigma(3+)$ ages of 217.7 ± 2.8 Ma and 246.1 ± 2.1 Ma. Sample QGQ07-1 from the Shizigou Formation yields a YSG age of 211.6 ± 3.1 Ma and a $YC2\sigma(3+)$ age of 213.6 ± 2.0 Ma.

The Mesozoic samples CSL09-1, CSL01-1, and CSL07-1 yield YSG ages of 212.1 ± 4.1 Ma, 226.7 ± 7.7 Ma, and 217.1 ± 3.4 Ma, respectively, with corresponding $YC2\sigma(3+)$ ages of 222.4 ± 1.5 Ma, 232.4 ± 1.8 Ma, and 237.6 ± 2.2 Ma. The published Dameigou Formation sample E122 yields a YSG age of 246.0 ± 8.0 Ma and a $YC2\sigma(3+)$ age of 253.1 ± 2.7 Ma.

All zircon-derived maximum depositional ages are older than the independently constrained depositional ages of the corresponding formations. The discrepancy is particularly large for the Pliocene–Pleistocene Shizigou and Qigequan formations, whose youngest zircon constraints remain Mesozoic in age. These values therefore provide only loose maximum depositional constraints and should not be interpreted as estimates of the actual depositional ages. The absence of syndepositional Cenozoic zircon is consistent with sediment supply dominated by older basement and recycled Mesozoic sedimentary rocks, although the maximum depositional ages alone cannot distinguish between these two sediment-routing pathways.

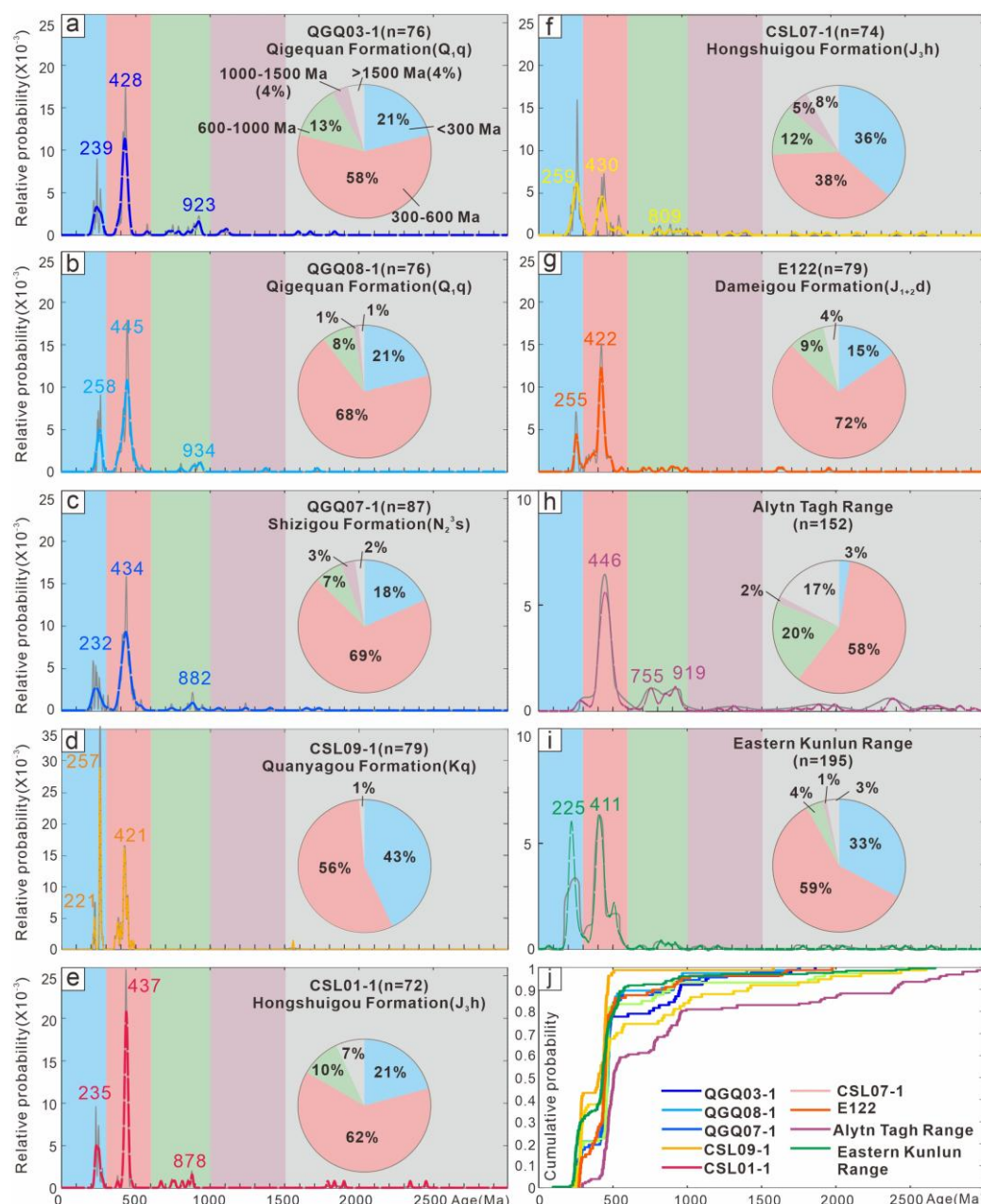


Figure 7. Kernel density estimate (KDE) plots (colored dashed lines) and probability density plots (PDPs; gray solid lines) of detrital zircon U-Pb ages from Cenozoic strata (a–c), Mesozoic strata (d–g), the Altyn Tagh Range (h), and the Eastern Kunlun Range (i). (j) Cumulative distribution function (CDF) plots of zircon U-Pb ages from all samples and basement rocks of the Altyn Tagh Range and Eastern Kunlun Range. The pie charts show the relative proportions of five age groups, using the same color scheme as Figure 6: <300 Ma, 300–600 Ma, 600–1000 Ma, 1000–1500 Ma, and >1500 Ma. The PDP curves are retained only as a secondary visual reference and were not used in the quantitative similarity analyses, MDS, inverse Monte Carlo modeling, or provenance interpretation. Data for sample E122 are from [31], whereas zircon U-Pb age data for the Altyn Tagh Range and Eastern Kunlun Range are from [6] and references therein.

4.5. Quantitative Comparison of Detrital Zircon Geochronology

4.5.1. Results of Sample Similarity Metrics

Quantitative pairwise comparisons further clarify the relationships among the detrital zircon age spectra (Figure 8). In the color-coded matrices, warmer red tones correspond to greater age spectrum similarity, represented by higher cross-correlation and similarity

coefficients or lower K-S D and Kuiper V values, whereas cooler blue tones indicate greater dissimilarity. Because these metrics emphasize different features of the distributions (Section 3.2.1), their values need not covary exactly.

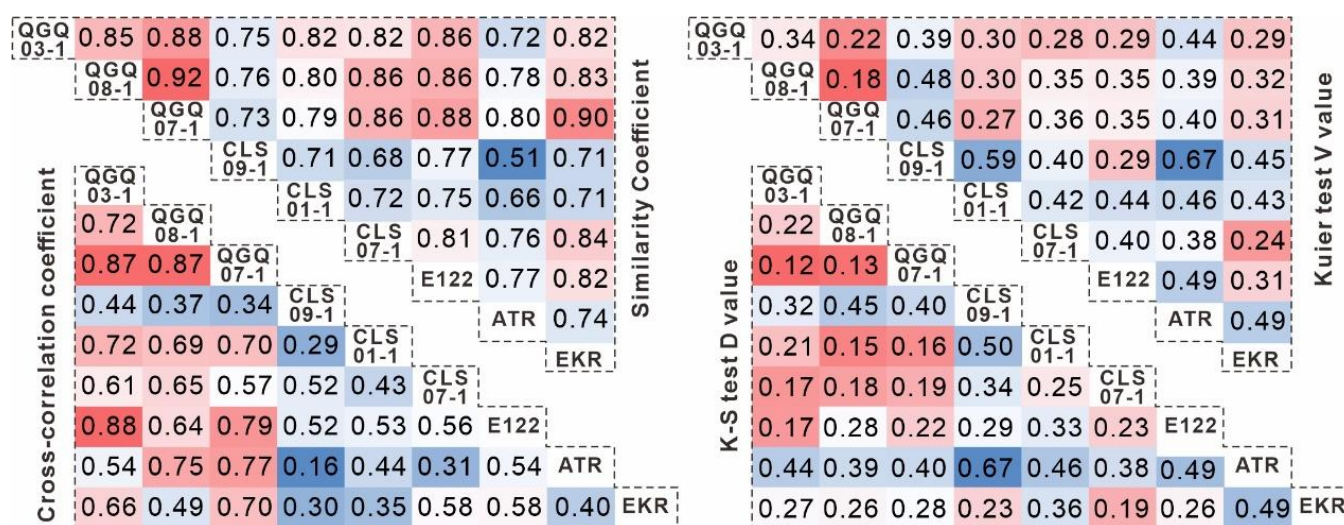


Figure 8. Color-coded pairwise comparison matrices of detrital zircon age spectra based on cross-correlation coefficient, similarity coefficient, K-S test D value, and Kuiper test V value. Warmer colors indicate greater similarity, corresponding to higher cross-correlation and similarity coefficients or lower D and V values. ATR: Altyn Tagh Range; EKR: Eastern Kunlun Range.

The three Cenozoic samples from the Qigequan area show consistently high mutual affinity. Their pairwise cross-correlation coefficients range from 0.72 to 0.87, similarity coefficients from 0.85 to 0.92, K-S D values from 0.12 to 0.22, and Kuiper V values from 0.18 to 0.34. QGQ08-1 and QGQ07-1 yield the highest similarity coefficient (0.92) and the lowest Kuiper V value (0.18), whereas QGQ03-1 and QGQ07-1 yield the lowest K-S D value (0.12); both pairs have cross-correlation coefficients of 0.87. These results confirm the overall consistency of the detrital zircon age spectra within the Cenozoic succession.

Comparisons with the Mesozoic samples reveal variable affinities, some of which are strong. The published Dameigou Formation sample E122 shows generally high similarity to the three Cenozoic samples, with cross-correlation coefficients of 0.64–0.88, similarity coefficients of 0.86–0.88, K-S D values of 0.17–0.28, and Kuiper V values of 0.28–0.35. Sample CSL01-1 also shows moderate to high affinity with the Cenozoic samples, with cross-correlation coefficients of 0.69–0.72, similarity coefficients of 0.82–0.86, K-S D values of 0.15–0.21, and Kuiper V values of 0.28–0.35. These results indicate that E122 and CSL01-1 broadly resemble the Cenozoic samples in their overall age-population structure, although the correspondence in the relative amplitudes of individual age peaks varies among samples.

Comparisons with the basement-source endmembers yield contrasting results. The Altyn Tagh Range yields moderate cross-correlation coefficients (0.54–0.77) and similarity coefficients (0.72–0.80) with the Cenozoic samples, reflecting the presence of some shared major age components. However, its higher K-S D values (0.39–0.44) and Kuiper V values (0.39–0.44) indicate substantial differences in the relative proportions of these age populations. The Eastern Kunlun Range shows higher similarity coefficients (0.82–0.90) and lower K-S D (0.26–0.28) and Kuiper V (0.29–0.32) values, although its cross-correlation coefficients range from 0.49 to 0.70.

4.5.2. Results of 2D/3D MDS Analysis

The two- and three-dimensional MDS configurations were constructed from pairwise K-S D values, such that shorter distances between points represent greater similarity between detrital zircon age distributions (Figure 9). In both the 2D and 3D configurations, the three Cenozoic samples from the Qigequan area form a compact cluster, confirming their highly similar age spectra (Figure 9). In the configurations excluding the composite Mesozoic proxy, the Cenozoic samples plot closer to the Eastern Kunlun Range than to the Altyn Tagh Range, although neither basement endmember closely overlaps the sample cluster (Figure 9a,b). When the composite Mesozoic proxy is included (Figure 9c,d), it plots close to the Cenozoic cluster, particularly to QGQ03-1 and QGQ07-1, whereas the Altyn Tagh and Eastern Kunlun endmembers remain farther from the cluster.

In the corresponding Shepard plots, the fitted MDS distances closely follow the original K-S D dissimilarities, as indicated by the concentration of points near the 1:1 line. The stress values (0.0079–0.1320) indicate acceptable reproduction of the original dissimilarity relationships, with the 3D configurations yielding especially low stress. Together, these results indicate that the Qigequan and Shizigou samples have a stronger age spectrum affinity with the composite Mesozoic proxy than with either basement endmember.

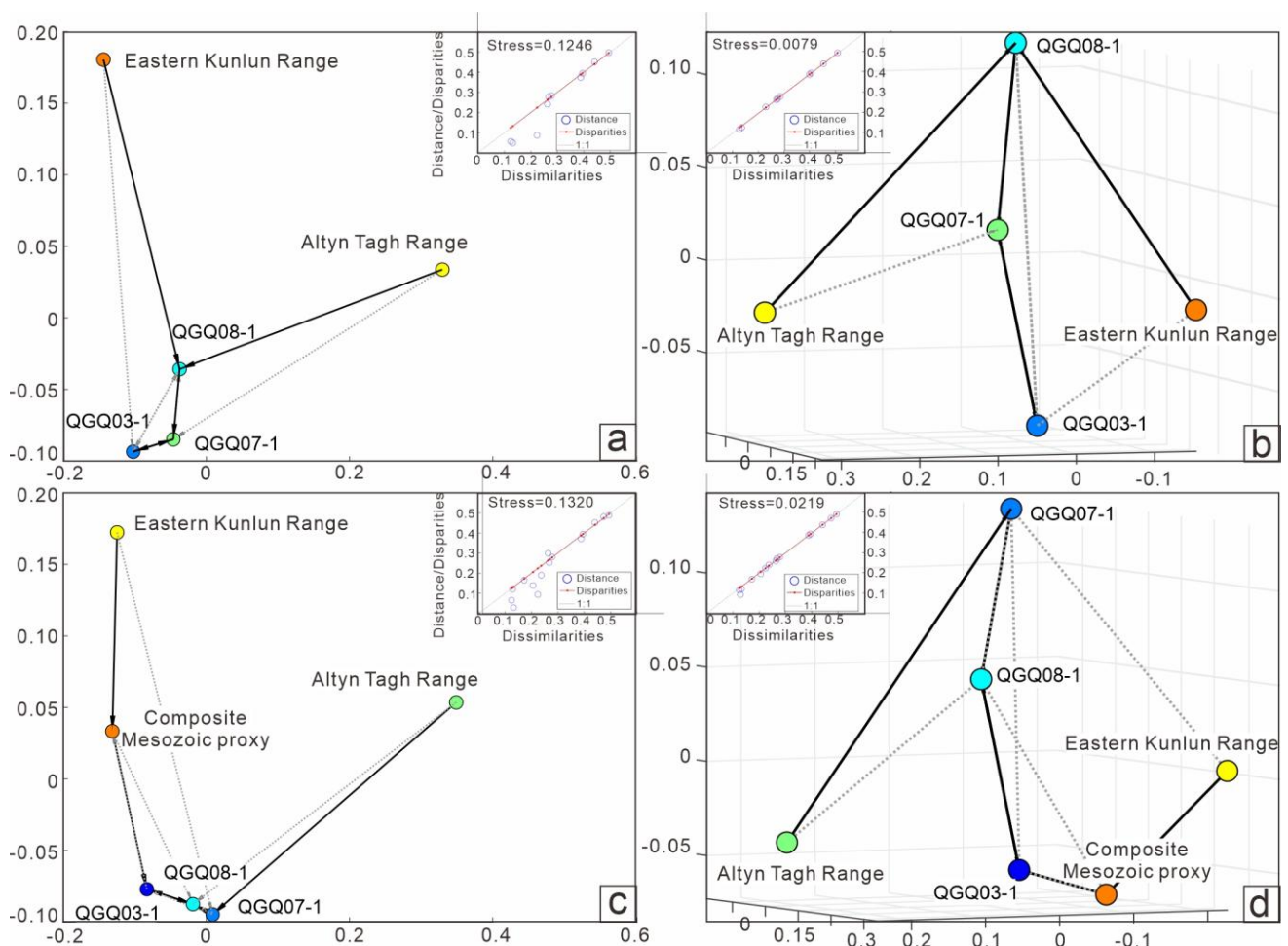


Figure 9. Multidimensional scaling plots of zircon U-Pb age distributions for the analyzed samples and basement-source endmembers from the Altyn Tagh and Eastern Kunlun ranges, with corresponding Shepard plots and stress values shown. (a) 2D MDS plot without inclusion of the composite Mesozoic proxy; (b) 3D MDS plot without inclusion of the composite Mesozoic proxy; (c) 2D MDS plot including the composite Mesozoic proxy; (d) 3D MDS plot including the composite Mesozoic proxy. All MDS plots are based on K-S test D values because this configuration yields the lowest stress values and the Shepard plots with data points closest to the 1:1 line. Distances between

points in the MDS plots represent dissimilarities derived from pairwise K-S D values; shorter distances indicate more similar detrital zircon age distributions. The composite Mesozoic proxy includes zircon U-Pb age data from samples CSL09-1, CSL01-1, CSL07-1, and E122. Solid and dashed lines connect each sample to its closest and second-closest neighbors, respectively.

4.5.3. Results of Inverse Monte Carlo Modeling

Inverse Monte Carlo modeling was conducted using two scenarios: a two-endmember model including the Altyn Tagh and Eastern Kunlun ranges, and a three-endmember model additionally incorporating the composite Mesozoic proxy. The goodness of fit for the two scenarios was evaluated using the K-S D, Kuiper V, and cross-correlation R^2 values (Figures 10 and 11).

(1) The two-endmember model involving the Altyn Tagh Range and Eastern Kunlun Range

When only the Altyn Tagh and Eastern Kunlun ranges are considered as potential source endmembers, the modeled age distribution provides only a moderate fit to the Qigeguan Formation data. The cross-correlation-based coefficient of determination is $R^2 = 0.857$, whereas the K-S D and Kuiper V values are 0.126 and 0.250, respectively (Figure 10a–c). The modeled source mixing coefficients vary substantially among the three optimization metrics. The R^2 -based solution assigns modeled mixing coefficients of 59% to the Altyn Tagh Range and 41% to the Eastern Kunlun Range, whereas the D- and V-based solutions assign mixing coefficients of approximately 30% to the Altyn Tagh Range and 70% to the Eastern Kunlun Range (Figure 12a).

The two-endmember model yields a comparable fit for the Shizigou Formation, with $R^2 = 0.911$, $D = 0.133$, and $V = 0.244$ (Figure 10d–f). However, the modeled source mixing coefficients remain metric-dependent: the modeled Altyn Tagh mixing coefficient ranges from approximately 32% to 58%, whereas the modeled Eastern Kunlun mixing coefficient ranges from approximately 42% to 68% (Figure 12a).

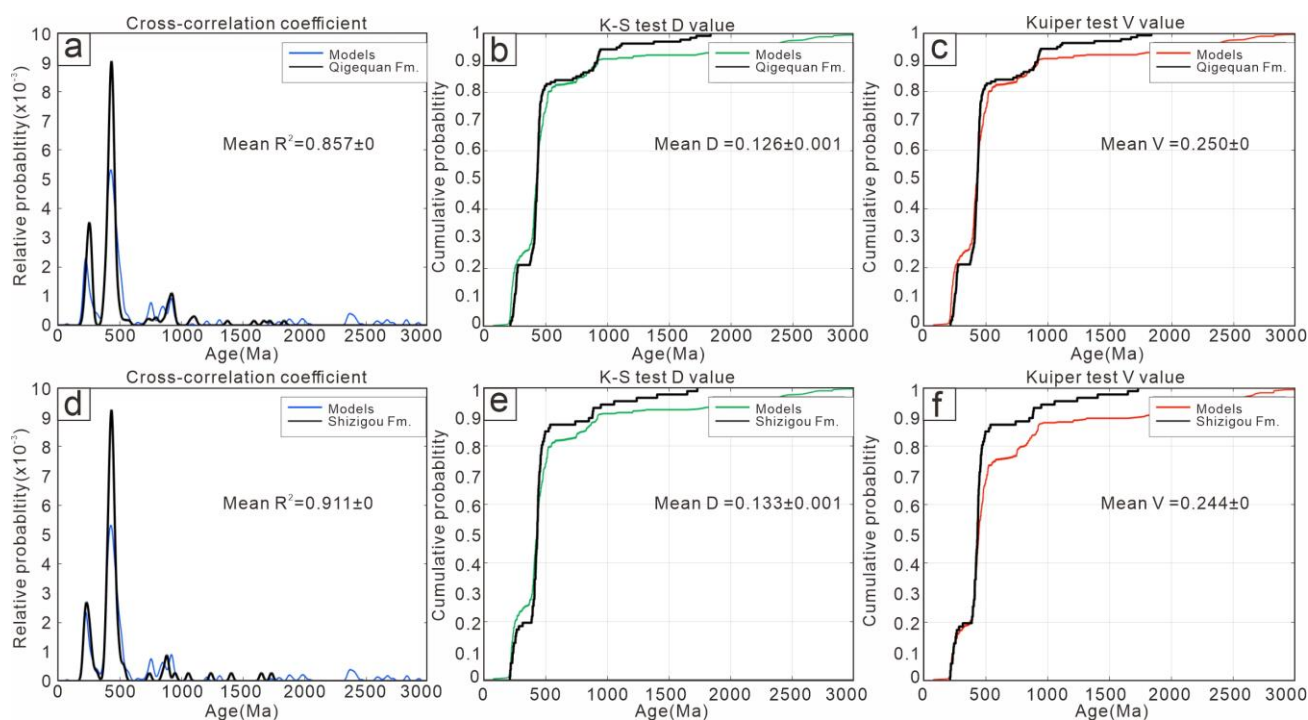


Figure 10. Results of the two-endmember inverse Monte Carlo provenance model involving the Altyn Tagh Range and Eastern Kunlun Range for the Qigeguan Formation (a–c) and Shizigou Formation (d–f), using KDE-based cross-correlation (blue) and CDF-based K-S D (green) and Kuiper V

(red) statistics. Black lines represent the observed detrital zircon age distributions of the Qigequan or Shizigou Formation, whereas the colored lines represent the corresponding best-fit modeled mixtures. Model fit is evaluated using the cross-correlation-based R^2 , K-S D, and Kuiper V statistics; higher R^2 and lower D and V values indicate closer agreement between the observed and modeled distributions.

(2) The three-endmember model involving the Altyn Tagh Range, Eastern Kunlun Range, and the composite Mesozoic proxy

After inclusion of the composite Mesozoic proxy, all three goodness-of-fit metrics improve for the Qigequan Formation. The R^2 value increases from 0.857 to 0.977, whereas D decreases from 0.126 to 0.065 and V decreases from 0.250 to 0.122 (Figures 10a–c and 11a–c). In all three solutions, the composite Mesozoic proxy yields the largest modeled contribution to the zircon age distribution, accounting for approximately 61%–72% of the modeled mixture. The Altyn Tagh mixing coefficient is approximately 22%–36%, whereas the Eastern Kunlun mixing coefficient is approximately 3%–6% (Figure 12b). These proportions should be interpreted as model-dependent mixing coefficients rather than unique source proportions; the dominant contribution of the composite Mesozoic proxy indicates that its inclusion substantially improves the representation of the observed Qigequan age distribution.

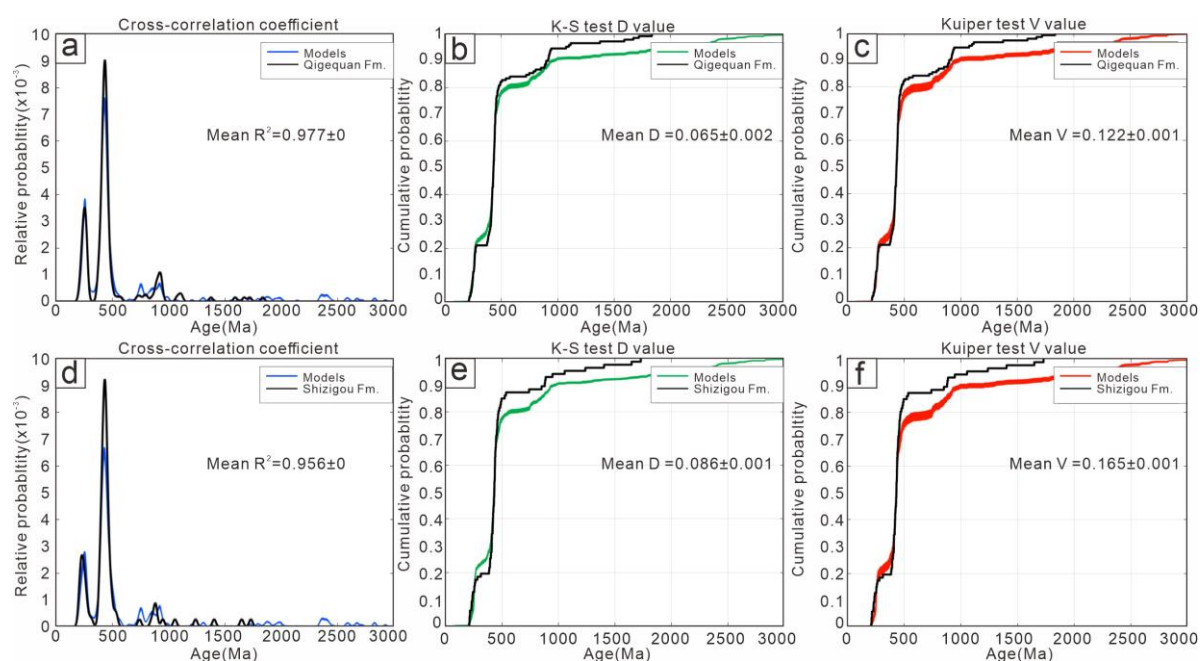


Figure 11. Results of the three-endmember inverse Monte Carlo provenance model involving the Altyn Tagh Range, Eastern Kunlun Range, and the composite Mesozoic proxy for the Qigequan Formation (a–c) and Shizigou Formation (d–f), using KDE-based cross-correlation (blue) and CDF-based K-S D (green) and Kuiper V (red) statistics. Black lines represent the observed detrital zircon age distributions of the Qigequan or Shizigou Formation, whereas the colored lines represent the corresponding best-fit modeled mixtures. Model fit is evaluated using the cross-correlation-based R^2 , K-S D, and Kuiper V statistics; higher R^2 and lower D and V values indicate closer agreement between the observed and modeled distributions.

The three-endmember model also improves the fit for the Shizigou Formation. The R^2 value increases from 0.911 to 0.956, whereas D decreases from 0.133 to 0.086 and V decreases from 0.244 to 0.165 (Figures 10d–f and 11d–f). Across the three optimization metrics, the composite Mesozoic proxy accounts for approximately 36%–68% of the

modeled mixture, the Altyn Tagh Range for approximately 25%–44%, and the Eastern Kunlun Range for approximately 3%–20% (Figure 12b). The D- and V-based solutions assign approximately 67%–68% to the composite Mesozoic proxy, whereas the R²-based solution assigns a larger contribution to the Altyn Tagh Range and a smaller contribution to the composite Mesozoic proxy. Because the three endmembers share prominent ca. 450 Ma and ca. 260 Ma zircon populations, this inverse variation indicates a trade-off between the overlapping Altyn Tagh and composite Mesozoic signals, particularly for the Shizigou Formation, and demonstrates the sensitivity of the modeled coefficients to the selected optimization metric.

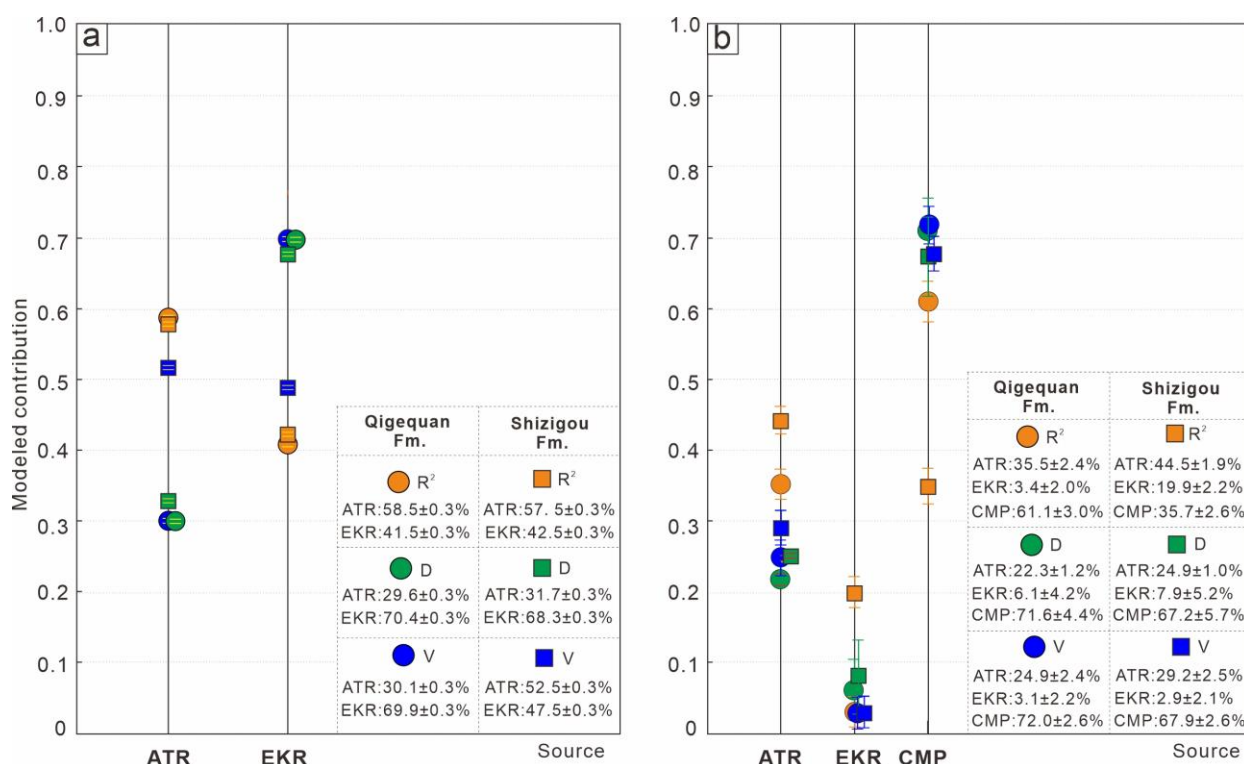


Figure 12. Monte Carlo unmixing results for the Qigequan and Shizigou formations. (a) Two-source model using the Altyn Tagh Range (ATR) and Eastern Kunlun Range (EKR) as potential sources. (b) Three-source model including the Altyn Tagh Range (ATR), Eastern Kunlun Range (EKR), and composite Mesozoic proxy (CMP). Circles represent the Qigequan Formation, and squares represent the Shizigou Formation. Orange, green, and blue symbols represent results optimized using the cross-correlation coefficient (R²), K-S D statistic, and Kuiper V statistic, respectively. Values in the inset tables are reported as mean ± 1 standard deviation of the retained best-fitting 1% Monte Carlo trials. Error bars indicate ±1 standard deviation. Relative contributions represent modeled contributions to the detrital zircon U-Pb age distributions.

5. Discussion

5.1. Provenance Analysis of the Qigequan and Shizigou Formations in the Qigequan Area

The Qigequan area, located along the northwestern margin of the western Qaidam Basin, is a key region for investigating Late Cenozoic source-to-sink processes and basin-range coupling in the Qaidam Basin. Previous studies have applied detrital zircon U-Pb geochronology, petrography, geochemistry, and sedimentology in the Qigequan area and adjacent regions, such as the Ganchaigou and Yuejin areas, and have generally attributed these sediments to erosion of surrounding orogenic belts [6,9,28,30–32]. For example, based on bimodal detrital zircon age spectra with peaks at ca. 450 Ma and ca. 260 Ma in sandstones of the Shizigou Formation, Huang et al. [28] suggested that the Qimantagh

area of the Eastern Kunlun Range was the principal source. Zhang et al. [92] proposed that zircon ages in sandstones of the Shizigou Formation from the Qigequan area are mainly concentrated at 343–542 Ma and 200–285 Ma, indicating provenance from both the Altyn Tagh and Eastern Kunlun ranges and emphasizing an important contribution from the Altyn Tagh Range. These interpretations demonstrate that direct basement-derived input from the surrounding ranges is plausible. However, peak matching alone is non-unique because the two basement source regions and the Mesozoic sedimentary rocks exposed along the basin margin contain overlapping Early Paleozoic and Late Paleozoic–Early Mesozoic zircon populations. In addition, recycled sedimentary rocks may inherit zircon age signatures from their original source terranes and subsequently transfer them into younger basin fills. Therefore, the two principal age peaks alone cannot distinguish direct basement erosion from sediment recycling. Although some earlier studies proposed that the provenance of Late Cenozoic strata in adjacent areas, such as the Huatugou area, may have been partly sourced from Early Cenozoic or Mesozoic strata [6,31], this possibility and its specific contribution have not been systematically evaluated.

5.1.1. Petrographic and Geological Evidence for Sedimentary Recycling

Petrographic observations provide direct evidence that fragments of pre-existing sedimentary rocks were incorporated into the Cenozoic basin fill. In samples QGQ03-1 and QGQ08-1, lithic fragments are visually estimated to constitute approximately 10–15 vol.% of the framework grains and are dominated by sandstone fragments, with subordinate mudstone, quartzite, and granitic fragments. The sandstone lithic fragments are irregular to elliptical and consist internally of fine quartz and feldspar grains embedded in a fine-grained matrix, thereby preserving recognizable clastic textures (Figure 4b,c,e,f). Sample QGQ07-1 contains fewer lithic fragments (approximately 5 vol.%), but an elongated mudstone fragment retains a homogeneous, very fine-grained internal texture (Figure 4i). Together with poor sorting, predominantly angular to subangular framework grains, preserved feldspar, and locally abundant matrix and calcite cement, these features indicate low textural and compositional maturity and are consistent with erosion and relatively short-distance transport of pre-existing sedimentary rocks. These observations provide direct petrographic evidence for sedimentary recycling, although petrography alone cannot determine the stratigraphic age of the recycled source rocks.

The field relationships provide the geological context needed to identify a plausible recycled sedimentary source. In the Caishiling area, the Quanyagou, Hongshuigou, and Dameigou formations are exposed along the basin margin, occur at relatively high elevations, and are strongly folded and faulted. Their present structural position shows that Mesozoic sedimentary rocks are exposed and constitute a physically available source along the northwestern basin margin. The coexistence of these Mesozoic clastic successions and sedimentary lithic fragments in the Cenozoic sandstones establishes a plausible recycling pathway. However, the field relationships alone do not determine when uplift and erosion began, and the contribution of the Mesozoic strata during deposition of the Qigequan and Shizigou formations is therefore evaluated below using detrital zircon age distributions.

5.1.2. Detrital Zircon Evidence for Recycling Through Mesozoic Strata

Because petrography alone cannot determine the stratigraphic age of the recycled source rocks, the possible Mesozoic origin of the recycled component was further evaluated using detrital zircon age distributions. Individual detrital zircon grains generally do not retain an unambiguous petrographic marker of sedimentary recycling because zircon can survive weathering, transport, burial, uplift, and redeposition while preserving its original crystallization age. Recycling must therefore be evaluated at the population level

rather than inferred from a diagnostic feature of a single grain. In this study, the relevant evidence is provided by the combined positions and relative proportions of the principal age populations, the complete age-distribution patterns, and their statistical relationships to the Mesozoic sedimentary and surrounding basement endmembers.

The age-population proportions provide a first-order constraint on these alternative interpretations. The three Cenozoic samples from the Qigequan area are consistently dominated by 300–600 Ma zircons, which account for 58%–69% of the accepted analyses, followed by a subordinate but stable <300 Ma component of 18%–21%. The 600–1000 Ma, 1000–1500 Ma, and >1500 Ma populations are minor, accounting for 7%–13%, 1%–4%, and 1%–4%, respectively (Figure 7a–c; Table 1). This combination is closely matched by the Early–Middle Jurassic Dameigou Formation sample E122 (Figure 7g), which contains 72% 300–600 Ma, 15% <300 Ma, 9% 600–1000 Ma, no 1000–1500 Ma grains, and 4% >1500 Ma zircons, and is also broadly comparable to sample CSL01-1. By contrast, the Altyn Tagh Range contains a similarly abundant 300–600 Ma population (58%) but only 3% <300 Ma zircons, together with comparatively large 600–1000 Ma and >1500 Ma components (20% and 17%, respectively) and a minor 1000–1500 Ma component (2%; Figure 7h). The Eastern Kunlun Range contains 59% 300–600 Ma zircons but a higher proportion of <300 Ma grains (33%) and only minor 600–1000 Ma, 1000–1500 Ma, and >1500 Ma components (4%, 1%, and 3%, respectively; Figure 7i). Thus, neither basement endmember alone reproduces the stable combination of dominant 300–600 Ma grains, subordinate <300 Ma grains, and minor Precambrian components observed in the Qigequan and Shizigou formations.

The quantitative age spectrum comparisons independently support this interpretation. The three Cenozoic samples display consistently high mutual similarity in the pairwise comparison matrices and form a compact cluster in the MDS configurations (Figures 8 and 9). Among the Mesozoic samples, E122 shows the most consistent affinity with the Cenozoic samples across the cross-correlation, similarity, K-S, and Kuiper metrics, whereas CSL01-1 shows moderate to high affinity. The MDS configurations based on K-S D values also place the composite Mesozoic proxy close to the Cenozoic sample cluster, whereas the Altyn Tagh and Eastern Kunlun basement endmembers remain farther from the cluster (Figure 9).

The significance of these similarities lies not simply in the recurrence of the ca. 450 Ma and ca. 260 Ma peaks because both peaks also occur in the surrounding basement source regions. Rather, the Cenozoic samples reproduce the broader Mesozoic sedimentary signature, including the dominance of the 300–600 Ma population, the stable subordinate <300 Ma component, and the limited Precambrian contribution. The same relationship is recovered by several independent distribution-based metrics and by the MDS configurations. This population-level correspondence is consistent with zircon grains having been transferred from their original basement sources into Mesozoic sedimentary successions and subsequently recycled into the Late Cenozoic basin fill. Thus, the detrital zircon data do not identify recycling from a single-grain feature; they support it through reproducible similarity between the complete Cenozoic and Mesozoic age distributions.

5.1.3. Quantitative Mixture Modeling and Integrated Provenance Interpretation

The inverse Monte Carlo results further test whether inclusion of the composite Mesozoic proxy improves the representation of the observed age distributions. In the two-endmember model, the Qigequan Formation yields $R^2 = 0.857$, $D = 0.126$, and $V = 0.250$, and the modeled Altyn Tagh and Eastern Kunlun contributions to the zircon age distributions vary substantially among the three optimization metrics. The Shizigou Formation yields a comparable fit ($R^2 = 0.911$, $D = 0.133$, and $V = 0.244$), but the modeled source mixing coefficients also remain metric-dependent. These results indicate that the two basement

endmembers reproduce some principal age components but do not provide stable mixing coefficient estimates.

After inclusion of the composite Mesozoic proxy, all three fit metrics improve. For the Qigequan Formation, R^2 increases from 0.857 to 0.977, whereas D decreases from 0.126 to 0.065 and V decreases from 0.250 to 0.122. The composite Mesozoic proxy yields the largest model-estimated contribution to the zircon age distributions in all three solutions, accounting for approximately 61%–72%, compared with approximately 22%–36% from the Altyn Tagh Range and approximately 3%–6% from the Eastern Kunlun Range (Figures 11 and 12). For the Shizigou Formation, R^2 increases from 0.911 to 0.956, whereas D and V decrease to 0.086 and 0.165, respectively. The discrepancy between the model results and the observed age spectra mainly occurs in the older Precambrian age components. Because only 72–87 accepted analyses were available per sample, the estimated proportions of rare ancient age components may be sensitive to sampling variability. Across the three optimization metrics, the modeled contribution is approximately 36%–68% from the composite Mesozoic proxy, 25%–44% from the Altyn Tagh Range, and 3%–20% from the Eastern Kunlun Range. Among these solutions, the R^2 -based result assigns a larger proportion to the Altyn Tagh Range and a smaller proportion to the composite Mesozoic proxy than the D - and V -based results, indicating that the exact modeled mixing coefficients are sensitive to the selected optimization metric. In addition, because the composite Mesozoic proxy was constructed from samples of different Mesozoic formations, its modeled contribution should be interpreted as the potential input from Mesozoic sedimentary cover as a whole rather than from any specific formation. Accordingly, the modeled percentages are best regarded as ranges of plausible, model-dependent contributions rather than unique or exact source proportions. Nevertheless, despite these uncertainties, the systematic improvement in all three goodness-of-fit metrics demonstrates that a substantial Mesozoic sedimentary component is required to better reproduce the observed Cenozoic detrital zircon age distributions.

Substantial overlap among the endmember age distributions introduces additional uncertainty. All three endmembers contain prominent ca. 450 Ma and ca. 260 Ma zircon populations because Mesozoic strata inherited many zircons from the surrounding basement terranes. Consequently, the model cannot uniquely separate direct basement supply from recycling of same-age zircons, as illustrated by the intermetric trade-off between the Altyn Tagh and composite Mesozoic coefficients for the Shizigou Formation. Minor age populations and the complete distribution patterns provide some discrimination but do not eliminate this non-uniqueness. Accordingly, the consistent improvement in model fit supports the inclusion of a Mesozoic sedimentary component, whereas its exact partitioning from direct basement input remains uncertain and should be evaluated together with the petrographic and geological evidence.

A separate limitation concerns the number and stratigraphic coverage of the analyzed Cenozoic samples. Nevertheless, the samples were collected from representative sandstone intervals within the exposed Qigequan and Shizigou formations in the Qigequan area. The two Qigequan Formation samples are from the middle and upper parts of the formation, whereas the Shizigou Formation sample is from its upper part. These strata belong to a broadly consistent proximal clastic depositional system and display similar zircon age-population patterns (Figures 7 and 9), suggesting that the dominant provenance signal was relatively stable across the sampled intervals. The samples are therefore used to characterize the first-order provenance signal of the sampled intervals, although additional sampling is required to evaluate intra-formational and basin-scale provenance variability.

The modeled source percentages should not be interpreted as unique or exact sediment budgets. Several samples are moderately to poorly sorted, as expected for proximal

alluvial-fan, deltaic, and fan-delta deposits, and hydraulic sorting may modify both framework-grain modes and the relative abundance of zircon populations. Random grain selection reduces operator bias during mount preparation but cannot eliminate sorting imposed during transport and deposition. In addition, the modest number of analyzed grains makes rare age components less stable than the dominant populations. For these reasons, petrographic proportions are treated as qualitative to semi-quantitative evidence, and the modeled zircon age-distribution contributions are interpreted as plausible, model-dependent ranges. The more robust inference is the systematic improvement of all fit metrics when the composite Mesozoic proxy is included.

Taken together, the petrographic evidence documents erosion and recycling of pre-existing sedimentary rocks, whereas the exposure and structural availability of Mesozoic strata along the basin margin, the population-level similarity of the detrital zircon age distributions, the MDS configurations, and the improved mixture-model fits support a Mesozoic affinity for the recycled component. These lines of evidence support a mixed provenance for the Qigequan and Shizigou formations, involving a substantial recycled Mesozoic component, direct supply from the Altyn Tagh Range, and a generally smaller contribution from the Eastern Kunlun Range (Figure 13). This interpretation does not exclude direct Eastern Kunlun input. Instead, it demonstrates that the ca. 214–260 Ma zircon population is not a unique indicator of direct Eastern Kunlun provenance because the same grains may have first accumulated in Mesozoic strata and subsequently been recycled into the Late Cenozoic basin fill. Distinguishing these two sediment-routing pathways is important because they imply different histories of erosion, temporary sediment storage, uplift, and basin–range coupling.

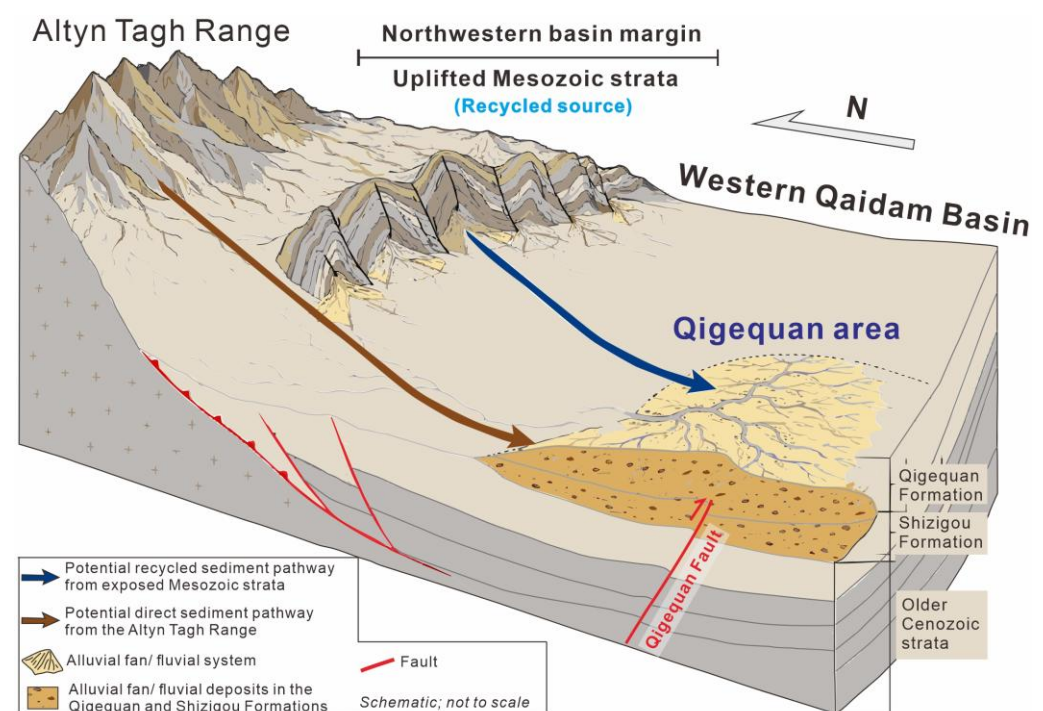


Figure 13. Conceptual provenance and sediment-routing pathways for the Qigequan and Shizigou formations in the western Qaidam Basin. The arrows indicate only possible sediment-routing pathways, and their widths do not represent the source contributions. Metric-dependent mixing coefficient ranges are presented in Figure 12. The Eastern Kunlun Range lies outside the spatial extent of this schematic but remains a potential direct sediment source.

5.2. Regional Context of Late Cenozoic Sediment Recycling in the Qaidam Basin

Sediment recycling refers to the process by which pre-existing sedimentary rocks re-enter a younger depositional system through tectonic uplift, weathering, erosion, and transport [93]. Recycled sediments inherit age signals from earlier source regions, which means that age spectra in sedimentary basins no longer simply reflect first-cycle basement sources but instead record multiple stages of earlier sedimentation, burial, uplift, and re-working. Therefore, in tectonically complex basin–range systems where source age spectra overlap, identifying recycled endmembers is particularly important for reconstructing source-to-sink relationships [11,12,94].

Recent applications of detrital zircon U–Pb geochronology, detrital apatite fission-track analysis, heavy-mineral analysis, sandstone petrography, and sedimentology have substantially advanced understanding of sediment recycling in the Qaidam Basin, especially in the Qilian Shan foreland along the northern margin [36,95,96]. Lu et al. [95] suggested that early Cenozoic deposits such as the Lulehe Formation along the northern Qaidam Basin may not have been derived from the distant Eastern Kunlun Range but instead from proximal sources along the northern Qaidam margin and southern Qilian Shan. Subsequently, Jian et al. [96] integrated paleocurrent, heavy-mineral, and detrital zircon data from the Lulehe Formation and further proposed that early Cenozoic basin filling was strongly localized and segmented, supporting this interpretation. In the piedmont zone of the Altyn Tagh Range along the northwestern margin of the basin, Cheng et al. [31] used detrital zircon data to show that Miocene activity of the Altyn Tagh Fault and rapid uplift of the surrounding mountains disrupted the former regional long-distance transport system, thereby promoting internal sediment recycling within the basin.

Independent regional studies indicate that sediment recycling along the northern margin of the Qaidam Basin intensified during the Late Miocene [36,38,47,97]. Integrated magnetostratigraphic analyses, structural interpretations, and detrital apatite fission-track data reveal an important syntectonic sediment-recycling event: Cenozoic strata along the basin margin have experienced approximately 2–3 km of rapid exhumation since ~8 Ma, causing large volumes of syntectonic sediment to be reworked into the basin [36–38]. Lu et al. [38] showed that this recycling event is recorded in multiple sections along the northern and southwestern basin margins and even in adjacent basins such as the Hexi Corridor, Linxia Basin, and Xining Basin.

Our results indicate that recycled Mesozoic strata along the northwestern basin margin were contributing detritus during deposition of the Shizigou and Qigequan formations. Because the analyzed samples are Pliocene–Pleistocene in age and do not bracket the Late Miocene transition, they do not independently determine the onset of recycling or demonstrate that recycling began synchronously throughout the basin. When placed in the context of previous regional studies [38], our results extend the spatial record of Late Cenozoic sediment recycling to the western Qaidam Basin. Whether recycling began before deposition of the Shizigou Formation, whether older Cenozoic strata were also reworked, and how the magnitude of recycling varied through time require additional stratigraphic, thermochronological, sedimentological, and provenance constraints.

5.3. Implications for Late Cenozoic Basin–Range Coupling and the Altyn Tagh Range

The Qaidam Basin is the largest intermontane basin along the northern margin of the Tibetan Plateau, and its Cenozoic sedimentation records the far-field effects of the India–Asia collision [3,10]. Therefore, the Late Cenozoic provenance changes documented in the Qigequan area can be evaluated within the broader context of Altyn Tagh Range evolution, basin–range coupling, and distributed deformation along the northern margin of the Tibetan Plateau.

The substantial recycling of Mesozoic sedimentary rocks identified in this study indicates that sedimentary cover along the northwestern basin margin was exposed and became an important source during deposition of the Shizigou and Qigequan formations. This provenance change can be evaluated in the context of the Cenozoic evolution of the Altyn Tagh fault system, although its timing, evolutionary stages, and total displacement remain debated [10,31,32,58,60]. Cheng et al. [32] proposed that the Altyn Tagh Fault initiated in the Eocene, with an average strike-slip rate of ~5.0 mm/yr, and accelerated during the Late Miocene to ~12.6 mm/yr. Wu et al. [58] inferred that early Cenozoic displacement was mainly accommodated by the North Altyn Tagh Fault, followed by basinward migration of deformation to the Altyn Tagh Fault at ~16.9 Ma and predominantly strike-slip deformation after ~15.5 Ma. Despite differences in detail, these studies indicate enhanced Miocene activity and basinward redistribution of deformation within the Altyn Tagh fault system. Enhanced activity of the Qigequan, Hongliuquan, and Alaer faults since the Middle Miocene further suggests progressive transfer of deformation into the western Qaidam Basin [8]. Present-day velocity fields also show that strain accumulation is distributed across shear zones more than 100 km wide along several segments of the Altyn Tagh Fault [98]. Together, these structural and geodetic observations indicate that Late Cenozoic deformation became increasingly distributed across basin-margin and intrabasinal structures. Within this regional framework, the recycled Mesozoic input identified here supports the interpretation that deformation and erosion extended from the crystalline range front into basin-margin sedimentary cover, thereby reorganizing the sediment-routing system. These results provide new provenance constraints on the increasing role of distributed shortening and crustal thickening along the northern Tibetan Plateau margin and highlight the importance of recycled zircon age signatures in reconstructing mountain uplift and basin-range coupling.

6. Conclusions

- (1) The Qigequan and Shizigou formations in the Qigequan area are dominated by proximal, texturally immature sandstones containing angular to subangular quartz and feldspar grains, together with identifiable sandstone and mudstone lithic fragments. Some sedimentary lithic fragments preserve internal fine-grained clastic textures, providing direct petrographic evidence for erosion and redeposition of pre-existing sedimentary rocks.
- (2) The detrital zircon age distributions of the Qigequan and Shizigou formations are consistently dominated by 300–600 Ma grains (57.9%–69.0%), followed by subordinate <300 Ma grains (18.4%–21.1%) and minor Precambrian components. The combined proportions of these age populations, together with the similarity metrics and MDS configurations, show a closer affinity to Mesozoic sandstones exposed along the basin margin than to either the Altyn Tagh or Eastern Kunlun basement endmember alone. These population-level zircon signatures, when considered together with the petrographic and field evidence, support substantial recycling through Mesozoic sedimentary strata.
- (3) Inverse Monte Carlo modeling shows that inclusion of the composite Mesozoic proxy systematically improves the fit to the observed Cenozoic zircon age distributions. Across the three optimization metrics, the proxy accounts for approximately 36%–68% and 61%–72% of the modeled age distributions of the Shizigou and Qigequan formations, respectively. Because the zircon age distributions of the Altyn Tagh Range, Eastern Kunlun Range, and composite Mesozoic proxy overlap substantially, the resulting mixing coefficients are model-dependent and non-unique. The more robust inference is that incorporating a Mesozoic sedimentary component better

reproduces the observed age distributions, supporting an important recycled contribution when considered together with the petrographic and geological evidence.

- (4) Recycled Mesozoic sedimentary rocks were an important source during deposition of both the Shizigou and Qigequan formations. This provenance signal is consistent with Late Cenozoic exposure, deformation, and erosion of Mesozoic sedimentary cover along the northwestern margin of the Qaidam Basin, as well as the progressive redistribution of deformation across basin-margin and intrabasinal structures. These results extend evidence for Late Cenozoic sediment recycling to the western Qaidam Basin and provide new provenance constraints on sediment-routing reorganization and basin–range coupling.

Supplementary Materials: The following supporting information can be downloaded at <https://doi.org/10.5281/zenodo.22105153>. Table S1: Zircon U-Pb ages for the Altyn Tagh Range and Eastern Kunlun Range endmembers; Table S2: Morphological and Th/U characteristics of detrital zircons from the analyzed samples; Table S3: U-Pb detrital zircon geochronologic analyses by LA-ICP-MS; Table S4: Maximum depositional age constraints derived from the youngest detrital zircon U-Pb ages.

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Abbreviations

The following abbreviations are used in this manuscript:

ATR	Altyn Tagh Range
EKR	Eastern Kunlun Range
MDS	Multidimensional scaling
CMP	composite Mesozoic proxy
Qz	quartz
Fsp	feldspar
Cal	calcite
LF	lithic fragment
SLF	sandstone lithic fragment
QLF	quartzite lithic fragment
MLF	mudstone lithic fragment

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