Segmentation of the Kepingtage thrust fault based on paleoearthquake ruptures, southwestern Tianshan, China

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Abstract

Decreasing deformation rates across the southern Tianshan have led to different seismogenic mechanisms and different proposed models to explain the orogen-scale fault kinematics. In this study, we focus on the segmentation of the Kepingtage fault by studying variations in the total offset and shortening rates of the Kepingtage fault along the southern front of the Tianshan. We used fault scarp mapping and trench excavations to assess fault segmentation and deformation on the Kepingtage fault. Our results indicate there are different shortening rates on the western (2.5–2.7 mm/year) versus the eastern segments (~0.3 mm/year), which are separated by the Piqiang tear fault. The decrease in shortening rates is not gradual; instead, it decreases sharply from west to east at the Piqiang fault. These segmentation boundaries are also supported by geodetic data and balanced structural restorations. Our data support a model where strike-slip faults accommodate step-changes in the deformation rates and the earthquake risks from west to east across the Tianshan.

Keywords Fault segmentation · Paleoearthquake rupture · Shortening rate · Kepingtage fault · Tianshan

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1 Introduction

The Kepingtage fault, the frontal fault of the Kalpin thrust zone, is more than 220 km long. The fault is active, and paleoearthquakes along the Kepingtage fault have ruptured alluvial fans and created several fault scarps at the foot of Kepingtage Mountain. Moreover, a series of earthquakes have occurred on the west Kalpin thrust zone. The largest event, the Atushi Mw 7.7 earthquake, occurred near the western part of the Kalpin thrust in 1902 (Kulikova and Krüger 2017). Especially in the past 20 years or so, many earthquakes occurred frequently. An earthquake swarm that included three earthquakes larger than Mw 6.0 and dozens of Mw 5.0 earthquakes occurred from 1997 to 1998. Subsequently, an Mw 6.3 earthquake and several Mw 5.0 earthquakes shocked the same region in 2003. More recently, a destructive Mw 6.0 Jiashi earthquake occurred on January 19, 2020 (Fig. 1).

In the Tianshan Mountains, observations appear to show a decrease in the shortening rates from west to east (Avouac et al. 1993). The current global positioning system (GPS) velocities also show that the southern Tianshan Mountains are shortening at a rate of ~10 mm/year in the western region and ~2 mm/year in the eastern part (Zubovich et al. 2010). The Kalpin thrust is located between the Kashi and Kuqa depressions in front of the southern Tianshan Mountains in a transition zone between areas with shortening rates of 6–9 mm/year in the Kashi region (Thompson Jobe et al. 2017) and ~2 mm/year in the Kuqa region (Li et al. 2012; Zhang et al. 2014; Saint-Carlier et al. 2016) (Fig. 2). The long-term shortening rate of 1–1.5 mm/year since 25 Ma is based on a 4 km detachment depth and the ~35 km of total shortening of the western part (Allen et al. 1999) and 21–23 km of shortening of the eastern part (Yin et al. 1998), where crustal shortening was observed the significant difference on both sides of the Piquiang fault (Fig. 3). However,

Fig. 1 Simplified Cenozoic tectonic map of the Tianshan in Central Asia. *TFF* Talas–Fergana fault, *NZF* Naiman–Zhalair fault, *DF* Dzhungarian fault, *KF* Karakoram fault, *SF* Selibuya fault, *MF* Mazatage fault, *ATF* Atlyn Tagh fault, *KLF* Kunlun fault, *MPT* Main Pamir Thrust. Earthquake locations are from the U.S. Geological Survey earthquake catalog

Fig. 2 **a** Satellite image and **b** geologic map of the southern Tianshan and Kalpin thrust structure. F1: east Kepingtage fault; F2: west Kepingtage fault; F3: Saergantage fault; F4: Aozitage fault; F5: Tuokesan fault; F6: Piqiang fault; F7: Mangute fault; F8: Kalabukesai fault

such comparisons are difficult because the rates are measured over different time scales. Therefore, rates from the Quaternary to Recent are essential to compare with geologic and geodetic shortening rates along the front of the southern Tianshan.

In this study, we explore the late Quaternary rupture characteristics of the Kepingtage fault along the southern front of the Kalpin thrust structure using field-based fault scarp mapping and paleoseismic trenching. To characterize the fault displacement, we surveyed the topography of the faulted alluvial fans. We rely on previously published in situ cosmogenic ^{10}Be depth profiles and surface sample ages, (Xu et al. 2019) to constrain the timing of the abandonment of the alluvial fans and determine shortening rates. We focused on the segmentation features of the Kepingtage fault and the significance of the Piqiang fault deformation reflected by the segmentation features. Our results improve the understanding of the deformation of the Kalpin structure and the Piqiang fault, which is a tear fault (Turner et al. 2011). This structure transfers crustal shortening to strike-slip that results in the different shortening rates of the western and eastern segments.

Fig. 3 The three balanced profiles (a, a', b, b', and c, c') were reconstructed by our group, Yin et al. (1998), and Allen et al. (1999). The seismic interpretation profile d-d' shows the depth features of the Piqiang fault and the Mangute fault (Qu et al. 2003). Profile locations are shown in Fig. 2b

2 Regional background

The Tianshan orogen reactivated during the Cenozoic in response to the ongoing Indo-Eurasian collision (Molnar and Tapponnier 1975; Tapponnier and Molnar 1979; Avouac et al. 1993; Burbank et al. 1999; Burchfiel et al. 1999). Cenozoic deformation began ~25 Ma ago and has progressed from south to north across the range (Hendrix et al. 1994; Sobel and Dumitru 1997).

The Kalpin thrust, located on the northwest margin of the Tarim basin and the southern Tian Shan, includes several thrust faults that converge to the same detachment at depth. The Kalpin region deposited the Permian through the Quaternary strata and has a significant stratigraphic gap between the Permian and the Paleogene clastic rocks (Allen et al. 1999). Near the Kalpin thrust, the thrust sheets generally verge southward toward the interior of the Tarim basin (Yeats et al. 1997; Allen et al. 1999; Xu et al. 2006). Strata crop out in elongated ridges along the hanging wall of each thrust, and the spacing between these ridges is typically ~10–20 km (Fig. 2). Notably, there is a major stratigraphic gap between the Permian and Paleogene clastic rocks.

Seismic reflection data show that the detachment is ~4 km deep, and the faults dip NNW at ~30° in the Kalpin thrust structure (Yang et al. 2010). Three balanced sections across the Kalpin thrust indicate 20–28% shortening, which is equivalent to 21–23 km on the eastern side of the Piqiang fault and ~35 km on the western side of the Piqiang fault (Fig. 3) (Yin et al. 1998; Allen et al. 1999). This shortening results in an average slip rate of 1–1.5 mm/year assuming that the deformation began circa 20–25 Ma across the entire Kalpin thrust (Yin et al. 1998; Allen et al. 1999).

3 Methods

3.1 Surveying

We mapped fault scarps at the front of Kepingtage Mountain and surveyed the heights of fault scarps using the Laser handheld range finder with an accuracy of 10 cm. Moreover, we surveyed the heights and distributions of fault scarps at the front of Kepingtage Mountain in well-preserved alluvial fans at two study sites using a high-precision, real-time kinematic differential GPS (dGPS). Site A was located 3.5 km east of Xikeer, and site B was located 13.7 km west of Sanchakou (Fig. 2). We also used these dGPS surveys to quantify the heights of different alluvial fans above the channels. All topographic maps and surface profiles were derived using the dGPS survey data with an accuracy of 2 cm horizontally and 5 cm vertically.

3.2 Shortening rate calculations

By using the height distribution of fault scarps, segmentation boundaries of the Kepingtage fault were estimated via the lengths and heights of the fault scarps. The shortening rates of fault segments were calculated with measurements of the fault scarps and the heights of the alluvial fans above the channels. We used the approach developed by Thompson et al. (2002) to calculate the fault slip from regression parameters fitted to the survey points along with the hanging wall tread, scarp face, and footwall tread on the T3–T5 fans. Then, we converted the slip rate to the shortening rate based on assumptions of fault dip. Xu et al. (2019) discussed the long-term incision rate of the Kapin region kept consistent in the Late Quaternary. Therefore, for the T1 and T2 alluvial fans, we calculated the uplift rate of the hanging wall, which includes the vertical rate of faulting and the incision rate of the channel. The average incision rate of the channel was substituted by the average incision rate of the T3, T4, and T5 fans via the height of these alluvial fans above the channel divided by the age of these alluvial fans. Then, we calculate the vertical rate of the fault using the uplift rate of T1 and T2 fans after subtracting the average incision rate. And final, we convert the vertical rate to a shortening rate using an estimate of the fault dip.

Monte Carlo simulations were used to estimate the uncertainty associated with the calculated values for all the parameters, such as offset, shortening rate, and slip rate. The Monte Carlo simulations incorporated the uncertainties on individual variables characterized by either uniform distribution or normal distribution functions (Thompson et al. 2002; Davis et al. 2005; Amos et al. 2010; Thompson Jobe et al. 2017). In each calculation, the Monte Carlo simulation associated with each input variable was used in over 50,000 trials to generate a histogram of the calculated parameter for the shortening rate. The reported values for each output parameter reflect the mode and the 95% confidence interval of the resulting frequency distributions.

3.3 Paleoseismic trenching

We selected two sites on preexisting scarps on the well-preserved alluvial fans for paleoseismic trenching to evaluate the earthquake history. At each location, we excavated trenches roughly perpendicular to the fault trace, photographed and logged the trench, and

described the stratigraphy. Offsets in the stratigraphy and colluvial wedge packages were used to interpret the number and relative sequence of paleoearthquakes along the Kepingtage fault.

4 Results

Numerous fault scarps cross the alluvial fans along the trace of the Kepingtage fault. We surveyed totals 183 heights of fault scarp on these alluvial fans (Appendix A of Electronic Supplementary Material). We analyzed the heights and distributions of the fault scarps at the front of the Kepingtage Mountain (Fig. 4). dGPS profiles of the fault scarps were used to measure the fault shortening rate, and two paleoseismic trenches were excavated at study sites A and B. Based on these results, we defined two paleoseismic rupture segments of the Kepingtage fault, separated by the Piqiang fault (Fig. 4). Moreover, the fault scarp heights change across the Piqiang fault. Below, we first describe the heights of the fault scarps, then the observations and interpretations from the paleoseismic trenches.

4.1 Stages and datings of alluvial fans

The southern Tianshan is an arid region with temperatures that range from 20 to 30 °C in July to 10–20 °C in January; average annual precipitation is 50–80 mm on the edge of the basin (Chen et al. 2006). In such arid and alluvium-dominated piedmonts, most streams are ephemeral and flow only during heavy rains and times of meltwater discharge from higher locations within the mountains. This climate and environment have led to the creation of alluvial fans that flank the southern Tianshan, which form useful markers for assessing the late Quaternary tectonic activity. Five alluvial surfaces were distinguished by their height above the channel and relative degree of erosion and

Fig. 4 Fault scarp height along the front edge of Kepingtage Mountain. Major scarp heights were measured by using a TruPulse 200 Laser Rangefinder, and minor ones were measured by using the dGPS survey data. Different gray points show the heights of fault scarps on T2–T5 alluvial fans

Fig. 5 Geomorphic surface of study sites B in the Kepingtage fault. **a** Satellite image and **b** field photograph of the alluvial fans (view to the east). Location of photograph is shown in (a). T1–T5 are the alluvial fans surfaces from oldest to youngest

dissection of the surface (Fig. 5). The oldest and highest alluvial fans, T1, were preserved only at the mouths of channels and were 30–50 m high above channels on the hanging wall of the Kepingtage fault. Most of the T2 alluvial fans were preserved at the mouths of channels, 20–30 m high above channels on the hanging wall. Most of the T3–T5 alluvial fans are maintained well on the hanging wall and footwall of the Kepingtage fault and kept fault scarps in their original state.

The rupture trace of the Kepingtage fault crosses T3–T5 alluvial fans (and a few T2 fans in the east segment), and therefore, we were able to measure the height of the fault scarps on these alluvial fans. The majority of T3 fans are ~10 m higher than the channels on the hanging wall, and subgullies have eroded these on the original surface. By using terrestrial cosmogenic nuclide (TCN) ^{10}Be exposure dating methods, the T1 to T5 alluvial fans respectively formed at $63.7^{+5.9}_{-5.9}$ ka, $36.2^{+3.4}_{-3.4}$ to $40.9^{+3.8}_{-3.8}$ ka, $22.1^{+5.1}_{-4.7}$ ka, $5.8^{+1.5}_{-1.2}$ ka and $1.5^{+0.8}_{-0.6}$ ka (Xu et al. 2019). We use these ages (Table 1) to calculate the shortening rate of the Kepingtage fault.

Table 1 ^{10}Be exposure ages of alluvial fans

Site	Fans	Height (m)	^{10}Be age (ka)
<i>Site A: Xikeer (Latitude: 39.817°N, Longitude: 77.400° E)</i>			
	xT2	1190.9	$36.2^{+3.4}_{-3.4}$ ka
	xT4	1150.1	$5.1^{+0.7}_{-1.9}$ ka
<i>Site B: Sanchakou (Latitude: 39.993°N, Longitude: 78.267° E)</i>			
	sT1	1326.8	$63.7^{+5.9}_{-5.9}$ ka
	sT2	1311.0	$40.9^{+3.8}_{-3.8}$ ka
	sT3	1303.8	$22.1^{+5.1}_{-4.2}$ ka
	sT4	1295.3 m	$5.8^{+1.5}_{-1.2}$ ka
	sT5	1287.1 m	$1.5^{+0.8}_{-0.6}$ ka

The alluvial fans are named in accordance with the initials of the sites. The dating ages of alluvial fans were published in Xu et al. (2019)

4.2 Fault scarps of the Kepingtage fault

We measured fault scarp heights at the Kepingtage mountain front locations, both east and west of the Piqiang fault. The maximum scarp height of the western segment is higher than that of the eastern segment on the younger T3, T4, and T5 alluvial fans (Table 2).

In the western segment, the highest fault scarp, 5.5 m, occurs near Wujianfang on the T3 fan, and the lowest ~0.5 m fault scarp occurs on the T5 fan near the Piqiang fault. Alluvial fan deposits are offset by a low dip angle fault of 12–25° observed in outcrop (Fig. 6).

In the eastern segment, the scarp extends from the east side of the Piqiang fault to the site of Yijianfang. The heights of fault scarps range from ~0.5 m on T5 fans to 1–1.5 m on T4 fans and 2–3 m on T3 fans in the eastern segment. The highest fault scarp, which measures ~5 m, occurs on the T2 alluvial fans. Many of the smallest fault scarps that are 0.5–0.7 m high are preserved near the Piqiang fault. Where observed in outcrops, the fault dips 17°–20° (Fig. 7).

4.3 Paleoseismic trenches

We chose two sites to excavate trenches and survey topographic landforms to determine the paleoearthquake history and shortening rate. Study site A, located in the western

Table 2 Statistic results of fault scarp surveying

Segment	Alluvial fan	Quantity	Max height (m)	Min height (m)	Average height (m)	Std
Western	T5	25	1.75	0.5	0.95	0.30
	T4	18	2.75	1.25	2.03	0.51
	T3	7	5.5	1.75	3.36	1.26
Eastern	T5	17	0.85	0.4	0.58	0.13
	T4	57	1.75	0.6	1.18	0.31
	T3	45	3.25	1.5	2.40	0.42
	T2	6	5.0	3.25	3.83	0.55

Fig. 6 Photographs of the western segment. **a** A 0.5-m-high fault scarp near the Piquang fault, view to the north. **b** A 1–1.5-m-high fault scarp on the eastern side of Xikeer, view to the north. **c** A fault scarp in the T5 alluvial fan, view to the west. **d** Fault scarps in T3 alluvial fans, view to the east. **e** ~1.5-m-high fault scarp in the T4 alluvial fans, view to the north, and **f** the fault has offset alluvial fan deposits, view to the west. Photograph locations are shown in Fig. 2b

segment, was ~3.5 km east of Xikeer, and study site B, located in the eastern segment, was ~13.7 km northwest of Sanchakou (Fig. 2).

4.3.1 Paleoseismic site A

At site A, there are four alluvial fans, which we named xT2 to xT5. The xT5 fan is the youngest alluvial fan and has almost the same elevation as the channel. The height of the xT4 fan is ~1 m above the channel on the footwall. The fault scarp on the xT4 fan has a height of ~2.5 m. The older xT2 fan is only preserved in the western part of the channel mouth (Fig. 8). The heights of the xT3 and xT2 fans above the channel are 9.8 ± 0.1 m (Fig. 8f) and 37.7 ± 0.1 m (Fig. 8d), respectively, on the hanging wall. These heights include the vertical offset from the fault and the incision of the channel.

Fig. 7 Photographs of the eastern segment. **a** A 0.5–0.7-m-high fault scarp near the Piquang fault, view to the northeast. **b** A 1–1.5-m-high fault scarp in the T4 alluvial fan, view to the north. **c** Multiple subparallel fault scarps in the T3 alluvial fan, view to the north. **d** Cambrian limestone thrust over alluvial fan deposits. **e** The fault offset alluvial fan deposits, view to the east. **f** The fault offset alluvial fan deposits at the site shown in **a**, view to the west. Photograph locations are shown in Fig. 2b

We excavated the Tc1 trench and measured a topographic profile of the fault scarp at site A (Fig. 8). The Tc1 trench is located on xT4 and exposes five geological units that appear cut by three faults and records two paleoearthquake events (Fig. 9). We first describe the stratigraphy from the base to the top of the trench and then discuss evidence of paleoearthquake events.

At the base of the trench, unit 1 (U1) is a graded coarse gravel layer with a thickness of more than 2 m. The sub-angular gravel diameter at the bottom is ~10 cm and fines upwards to a diameter of ~3–5 cm with a higher coarse sand percentage; additionally, there is more clearly horizontal bedding at the top than at the bottom of U1. The next unit, U2, is a fine gravel layer with a thickness of 1.5 m separated from U1 by a wavy, undulated contact. The basal gravels in U2 are ~3–5 cm in diameter and gradually decrease toward a diameter of ~1–2 cm with a higher fine and medium sand matrix composed at the top of U2. Three 10-cm-thick fine sandy lenses are offset in

Fig. 8 Topographic surveying for site A near Xikeer on the western Kepingtage segment. **a** Google Earth image of the fault scarp crossing alluvial fans. **b** High-resolution DEM of the alluvial fans created with dGPS data at site A. Contour intervals are 2 m. **c** Field photograph of the alluvial fans at site A (view to the north). Location of photograph is shown in (a). **d** Height of xT2 surface above the modern channel. The modern channel elevation extracted from high-resolution DEM. **e** and **f** are topographic profiles of the fault scarp across the xT3 and xT4 fan surfaces. Location of site A is shown in Fig. 2b

the U2 (Highlighted by yellow, purple, and Brown in Fig. 9b). Unit 3 (U3) is separated from U2 by a relatively planar contact. U3 contains a few 50–80 cm diameter boulders within a coarse sand matrix. The boulders are sub-angular. Gully incision has led to a lack of U3 near the fault on the footwall. However, we found some boulders similar to those of U3 in the hanging wall on the surface of the footwall (Fig. 9d). U4 is a small wedge of unsorted gravels with a coarse sand matrix located near the base of the scarp and is separated from U3 with an angular unconformity contact at the hanging wall and separated from U2 with a relatively planar contact at the footwall. Covering U4, another small wedge of gravels, U5 is present at the base of the scarp. The material is loose, and no other sediments cover on U5. In addition, we observed three faults that offset the stratigraphy with dip $\sim 17^\circ$ N. All three faults appear to offset U1–U3, and Fault F3 also offsets U4.

Fig. 9 Paleoseismic trench site A in the western Kepingtage segment. **a** Merged photomosaic of the east side of trench wall. **b** Interpretation of the stratigraphy and faults within the trench. Units are described in text. **c** Detailed photograph of the fault and the faulted colluvial wedge. Photograph shows a fragment of U3, which was **d** eroded by subgullies on the footwall

We interpret U1–U3 as fluvial-alluvial units deposited by the channel during the formation of the alluvial fans. U4 and U5 are interpreted as colluvial wedges based on their geometries and position located at the base of the scarp and their relationship with the faults.

We interpret that the trench records two paleoseismic events. First, Fault F1 and F2 offset U1, U2, and U3, creating the U4 colluvial wedge during the penultimate event A. Fault F3 then offsets the U4 colluvial wedge during the most recent event B and created the U5 colluvial wedge. Using three marker sand lenses in the U2, we measured ~2.5 m of vertical displacement of the fault similar to the scarp height measured from the surface.

4.3.2 Paleoseismic site B

At site B, there are five alluvial fans, which we named sT1 to sT5 in accordance with the initials of Sanchakou. The fault scarp is preserved in the sT3, sT4, and sT5 fans. We surveyed scarp heights (Fig. 10d–f) of 3.0 ± 0.1 m, 1.3 ± 0.1 m, and 0.6 ± 0.1 m on the sT3, sT4, and sT5 fans, respectively. Additionally, we also surveyed the height of every alluvial fan above the channels on the hanging wall (Fig. 10).

We excavated the Tc2 trench and measured a topographic profile of the fault scarp at site B (Fig. 10). The Tc1 trench is located on sT3 and exposes five units and two faults and records three paleoearthquake events (Fig. 11). We first describe the stratigraphy from the base to the top of the trench and then discuss evidence and interpretation of paleoearthquake events.

At the base of the trench, unit 1 (U1) is a ~ 2 m thickness coarse gravel layer with clearly horizontal bedding and well cemented. The sub-angular gravel diameter at the U1 is ~ 5 – 10 cm and a few of ~ 10 – 20 cm diameter; additional, there is a higher coarse sand percentage at the U1. At the top of U1, there is a maker sub-angular gravel layer with a thickness of ~ 20 cm and a diameter of ~ 5 cm. The layer thickens near the fault at the hanging wall. The next unit, U2, is a fine ~ 3 – 5 cm diameter gravel layer with a medium sand matrix separated from U1 by a wavy, undulating depositional contact on the top of the maker gravel layer. There is more

Fig. 10 Topographic survey of the alluvial fan surfaces and fault scarp at site B in the eastern segment. **a** High-resolution DEM of the alluvial fans created with dGPS data at site B. **b** Heights of sT1 and **c** sT2 alluvial fans above the modern channel respectively. Topographic profiles of fault scarps and heights above the modern channel on the **d** T3, **e** T4, and **f** T5 fans. The modern channel elevation extracted from High-resolution DEM. Location of site B is shown in Fig. 2b

Fig. 11 Paleoseismic trench of site B in the western Kepingtage segment. **a** Merged photomosaic of the southwest trench wall. **b** Interpretation of the stratigraphy and faults within the trench. Units are described in text. **c** Detailed photograph of the fault and the faulted colluvial wedges related to the three interpreted events

clearly horizontal bedding at the footwall and slightly dip at the hanging wall by fold deformation. At the top of U2, gravels fine upwards to a diameter of ~1–2 cm with a higher fine sand percentage and slight salinization. U3 is a wedge-shaped unit overlying U2 in an unconformity. It is reserved only at the footwall. U3 includes two sub-units: U3-1 is an unsorted gravel wedge with a coarse sand matrix and a thickness of ~1 m, and U3-2 is a medium sand unit with slight salinization and thickness of ~50 cm deposited on the top of this wedge. The color of U3-2 is darker than the U3-1. Unconformably above U3, unit 4 (U4) is also a colluvial wedge-shaped unit with two sub-units. U4-1 is a colluvium with unsorted sub-angular gravel

and a thickness of ~1 m. U4-2 is a fine gravel layer with a fine sand matrix which has a degree of soil development and has experienced salinization during stability.

Above another angular unconformity, the uppermost unit, U5, is also a discontinuous fine gravel wedge-shaped unit with a thickness of ~30 cm and a length of ~4–5 m preserved at the base of the scarp. The material is loose, and no other sediments cover U5. Besides, we observed two faults dipping ~20° N, which offset the stratigraphy and merge to a single fault near the surface. These faults offset U1–U3, before merging to a single fault that offsets U4.

We interpret U1 and U2 as fluvial-alluvial units deposited by the channel during the formation of the alluvial fans. The high fine sand matrix and slight salinization at the top of U2 are interpreted as a paleo-surface of the T3 alluvial fan. U3, U4, and U5 are interpreted as colluvial wedges based on their geometries and position located at the base of the scarp and their stratigraphic relationship with the faults.

We interpret that the trench records three paleoearthquake events. The first event created the colluvial wedge U3, and the faults offset U1 and U2. Following the first event, the U3 wedge was eroded completely from the hanging wall. Next, the U4 is the colluvial wedge formed during the penultimate earthquake, which cut the colluvial wedge U3. Finally, the most recent event offset colluvial wedge U4 and created colluvial wedge U5. We estimated U2 is vertically offset by ~3.0 m, which is similar to the scarp height in the sT3 fan, suggesting that this trench exposes all events since sT3 formed.

4.4 Shortening rates of the sites

We calculated shortening rates at the two sites using exposure ages of alluvial fan published in Xu et al. (2019). At site A, the ^{10}Be exposure age, derived from depth profile dating of the xT4 fan, is $5.1^{+0.7}_{-0.9}$ ka (Xu et al. 2019). The ^{10}Be exposure age of the oldest xT2 fan is $36.2^{+3.4}_{-3.4}$ ka based on 50–80 surficial amalgamated-gravel samples by terrestrial cosmogenic nuclide (TCN) dating (Xu et al. 2019). A horizontal shortening rate of $2.5^{+2.6}_{-1.3}$ mm/year was calculated based on the surveyed height of the fault scarp and a $17^\circ \pm 3^\circ$ fault dip on the xT4 fan (Fig. 12a). A horizontal shortening rate of $2.7^{+3.5}_{-1.0}$ mm/year was estimated based on the height of the oldest xT2 fan above the channel (Fig. 12b). Thus, the shortening rate of the west segment remained ~2.5–2.7 mm/year in the late Pleistocene.

At site B, the ^{10}Be exposure age of sT3 is $22.1^{+5.1}_{-4.2}$ ka based on a depth profile (Xu et al. 2019). Combining the age of this surface with the 3.0-m-high scarp and a $20^\circ \pm 3^\circ$ fault dip results in a horizontal shortening rate of $0.3^{+0.2}_{-0.2}$ mm/year (Fig. 12c). In addition, a horizontal shortening rate of $0.3^{+1.2}_{-0.3}$ mm/year was approximated via the 37.2 ± 0.3 m height of the sT1 fan above the modern channel, a $20^\circ \pm 3^\circ$ fault dip and the surface age of 62.3 ± 11.6 ka (Xu et al. 2019) (Fig. 12d). Thus, the shortening rate of the east segment remained ~0.3 mm/year in the late Pleistocene, and difference with the shortening rate of the west segment.

5 Discussion

5.1 Comparison with geodetic and seismic data

Our results of fault scarps show a distinct change where the Piqiang fault intersects the Kepingtage fault. We suggest this change is present in multiple datasets that span time-scales of millions of years to the present. Below we discuss evidence to support the interpretation that the Piqiang fault is a vital fault boundary.

Fig. 12 Insets show the results of the Monte Carlo simulations. **a** Shortening rate of the western Kepingtage fault (Site A) and **c** shortening rate of the eastern Kepingtage fault (Site B), based on measurements from fault scarps. Average shortening rates based on the height of the oldest alluvial fan above the channel for **b** Site A and **d** Site B. Locations of profiles are shown in Figs. 8 and 10

The vertical velocity (uplift) rate rapidly decreases from ~ 2 mm/year (Bufe et al. 2017) in the western segment to < 1 mm/year to the east of the Piqiang fault (Qiao et al. 2017) based on geodetic data. The vertical rate based on the Interferometric Synthetic Aperture Radar (InSAR) results of Qiao et al. (2017) shows a different uplift region for the Kalpin thrust zone. Compared with the vertical rate in the eastern profile (Fig. 13c), the curve of the vertical rate shows a significant steep near the site of faults in the western profile (Fig. 13b). In addition, GPS velocities, referenced to the stable Eurasian reference frame and resolved in a 345° direction (the approximate trend of the Piqiang fault and direction of horizontal shortening), show different horizontal shortening rates on the two sides of the Piqiang fault. The GPS velocities are $17.8\text{--}19.3$ mm/year on the south side of the Kepingtage fault (Vc in Appendix B of Electronic Supplementary Material) but decrease by 4.5 ± 1.8 mm/year to $13\text{--}15.1$ mm/year across the western segment, but only by 1.0 ± 1.0 mm/year to $17.3\text{--}18.2$ mm/year across the eastern segment (Fig. 13). In particular, the velocity at the I393 and NJ27 stations is 13.0 mm/year and 17.2 mm/year, respectively, despite a separation of only a few kilometers across the Piqiang fault.

These GPS velocities are measured across the region, which has three faults (including the western segment of the Kepingtage fault, the Aozitage fault, and the Tokesan fault), in the western segment of the whole Kalpin thrust structure (Fig. 2). Shortening rates of these

Fig. 13 Geodetic data and focal mechanisms near the Kalpin thrust structure. **a** Earthquake focal mechanisms since 1976 and the GPS velocities near the Kalpin thrust structure. **b** InSAR vertical rate and the GPS horizontal rate in the 345° direction in the western segment of the Kalpin structure. The location of the transect is shown in (a). **c** InSAR vertical rate and the GPS horizontal rate in the 345° direction in the eastern segment of the Kalpin structure. The location of the transect is shown in (b). The yellow curve is the vertical rate of the InSAR (Qiao et al. 2017), and blue circles are the GPS horizontal rates. The gray-shaded area in the profiles represents the topography. Profiles **b** and **c** were modified based on Qiao et al. (2017) and the GPS results of Yang et al. (2008b), Zubovich et al. (2010), and Ischuk et al. (2013)

faults have been estimated as ~ 0.9 mm/year for the Aozitage fault and ~ 0.3 mm/year for the Tokesan fault (Li et al. 2016). Therefore, the total shortening rate of the western segment of the Kalpin thrust can be estimated as $3.7^{+2.6}_{-1.3}$ mm/year and $3.9^{+3.5}_{-1.0}$ mm/year by including the 2.5–2.7 mm/year rate for the western Kepingtage fault in this study and the rates of ~ 0.9 mm/year for the Aozitage fault and ~ 0.3 mm/year for the Tokesan fault. We estimated values of $1.0^{+0.2}_{-0.2}$ mm/year and $1.0^{+1.2}_{-0.3}$ mm/year for the shortening rate in the eastern part of the Kalpin structure based on our shortening rate of ~ 0.3 mm/year across the eastern Kepingtage fault, a shortening rate of ~ 0.4 mm/year for the Saerganawu fault, and a similar rate for the Kalabukesai fault (Li et al. 2011). Turner et al. (2011) obtained similar results for the Piqiang fault. Although the Piqiang fault likely did not initiate by differential strain rates across the Kalpin structure, the Piqiang fault in the current strain regime forms a tear fault in the Kalpin thrust structure.

Comparing geodetic shortening rates, paleoearthquake displacements, fault scarps, and balanced structural restorations allow an interpretation of the temporal variability of shortening rates (Fig. 14a). The average rate of 1.4–1.7 mm/year across the western segment is almost twice that of the eastern segment (0.8–1.1 mm/year) since the early Miocene (21–25 Ma), determined via balanced cross sections (Fig. 3) (Yin et al. 1998; Allen et al. 1999). However, based on our results, the shortening rate has increased in the late Pleistocene to ~ 4 mm/year for the western segment. At present, the GPS shortening rates, which are 4.5 ± 1.8 mm/year for the western segment and 1.0 ± 1.0 mm/year for the eastern segment, are relatively consistent with those since the late Pleistocene. The shortening rate appears to have been a steady ~ 1 mm/year since the middle Cenozoic in the eastern segment of the Kalpin thrust structure. In the western segment, the shortening rate has significantly increased in the Late Pleistocene and Holocene. In addition, GPS data and

Fig. 14 Comparison of the shortening rates on the Kalpin Thrust and along the southern Tianshan. **a** Shortening rates of the Kalpin structure during different periods based on the current crustal deformation from GPS and InSAR data (Yang et al. 2008b; Zubovich et al. 2010; Ischuk et al. 2013; Qiao et al. 2017), late Quaternary geomorphic data (this study), and balanced structural restorations from the Cenozoic (Yin et al. 1998; Allen et al. 1999). Circles represent the western segment of the Kalpin structure data, and squares represent the eastern segment of the Kalpin structure data. **b** The shortening rate of the same faults and folds at different distances from the Piqiang fault along the southern Tianshan. Black long ellipses show the shortening rate of the structures in front of the South Tianshan Mountain. Shortening rates from Scharer et al. (2004), Hubert-Ferrari et al. (2005), Li et al. (2013, 2015), Zhang et al. (2014), Saint-Carlier et al. (2016), Tian et al. (2016), Thompson Jobe et al. (2017, 2018)

frequent earthquakes reveal high rates of tectonic activity. While the timing of the initiation of the rate increase remains uncertain, the shortening rates have increased since the late Quaternary.

5.2 Geological structure and shortening of the Kalpin thrust structure

The differences of the shortening rate in the southern Tianshan probably led to the significant differences of earthquakes times between the west and east side in the Kalpin thrust zone. The focal mechanisms reveal that most thrust earthquakes with focal depths < 15 km have occurred in the Kalpin thrust structure, a thin-skinned tectonic feature. The newest Mw 6.0 Jiashi earthquake also shows a thrust focal mechanism. However, many strike-slip earthquakes have occurred south of the western segment of the Kepingtage fault (Fig. 13) at depths 30–40 km deeper than the thrust earthquakes (Appendix C of Electronic Supplementary Material). These strike-slip earthquakes might relate to several NW fault by the difference crustal shortening transferring to strike-slip. Seismic reflection profiles show that the interior of the Tarim block has several NW and NWW faults, including the Selibuya and the Mazatag faults, which represent the boundary of the Bachu uplift (Liu et al. 2004; Xiao et al. 2005; Ding et al. 2008; Turner et al. 2011). The Bachu uplift was a major intrabasinal high that partitioned the Tarim basin into two isolated depocenters throughout the Jurassic and Early Cretaceous (Allen et al. 1999; Sobel 1999; Yang and Guo 2003; Yang et al. 2008a; Turner et al. 2011). The NW-trending faults, which formed in

the Mesozoic, likely framed the Kalpin thrust structure. We suggest the Piqiang fault reactivated along with a previous rupture position where a NW-trending fault (possibly linked to the Selibuya fault) was located in the Mesozoic. Different shortening rates have thus been distributed among the different segments of the Kalpin thrust structures throughout the Cenozoic. The Piqiang fault, which is a tear fault, was caused by differential shortening of ~10 km between the ~35 km of shortening of the western part and the 21–23 km of shortening across the eastern part since the Cenozoic (Yin et al. 1998; Allen et al. 1999).

Our study complements several previous analyses that have documented the recent deformation rates across the southern Tianshan region (Brown et al. 1998; Scharer et al. 2004; Hubert-Ferrari et al. 2005; Li et al. 2013, 2015; Saint-Carlier et al. 2016; Thompson Jobe et al. 2017), and thus, the collective findings now provide a comprehensive view of the deformation along the strike of the range (Fig. 14). In the far western end in front of the Pamir, Li et al. (2013, 2015) documented Quaternary shortening rates on Mingyaole and Mushi anticlines that sum to ~6.5 mm/year, and Thompson Jobe et al. (2017, 2018) found a rate of ~6–9 mm/year on a series of faults and folds at the western part of the Kashi region. In the Kashi-Atushi region (including the western segment of the Kalpin structure), Scharer et al. (2004) and Heermance et al. (2008) respectively constrained the average shortening rates of different periods across the Kashi-Atushi anticline to ~5 mm/year since ~1.2 Ma, and 2.25–2.75 mm/year since ~4 Ma, whereas our study estimates a rate of ~4 mm/year in the western part of the Kalpin structure. In the eastern part of the southern Tianshan region (including the eastern segment of the Kalpin structure), Hubert-Ferrari et al. (2005) computed the shortening across the Aksu thrust fault and obtained a shortening rate of 2 ± 0.4 mm/year over the last 12.5 ka. Brown et al. (1998) and Tian et al. (2016) determined a similar shortening rate of ~2 mm/year in the eastern part of Kuqa, which is relatively consistent with the shortening rates of the Yakeng anticline found by Saint-Carlier et al. (2016). Based on magnetostratigraphy and a balanced cross section, the average shortening rate is ~1.4 mm/year in the Kuqa depression since ~2.6 Ma (Zhang et al. 2014). Our estimated rate of ~1 mm/year in the eastern segment of the Kalpin structure is not significantly different than the rates in the Aksu-Kuqa region.

Although the range-front shortening rates vary slightly in each region, the most significant changes in the shortening rate occur across strike-slip faults, including the Talas–Fergana fault (TFF) and Piqiang fault (Fig. 14b). The slip rate of TFF with 2.2–6.3 mm/year (Rizza et al. 2019) consistent with the differences of the shortening rate between the Pamir front and the Kashi-Atushi region. However, these differences may be accommodated on structures within the interior of the Tianshan, where shortening rates have not yet been determined for many faults. Thus, our data support a model where the decreasing shortening rates from west to east across the Tianshan are facilitated by strike-slip faulting.

6 Conclusions

Integrating geomorphic mapping and paleoseismic trenching, we defined two segments of the Kepingtage fault that are separated by the Piqiang tear fault on the southern Tianshan. The west and east segments of the Kepingtage fault, which are separated by the Piqiang fault, have different shortening rates of 2.5–2.7 and ~0.3 mm/year, respectively. These fault segments are also defined by other geomorphic, geodetic, and seismic data, illustrating the segmentation of the fault has persisted for the last hundred thousand years to the present.

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