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Late Quaternary alluvial sequence and uplift-driven incision of the Urumqi River in the north front of the Tian Shan, northwestern China

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ABSTRACT

This work focuses on the driving force behind the late Quaternary river incision and terrace formation of the Urumqi River in the north piedmont of the Tian Shan, northwestern China. Field investigations on geomorphic surfaces, terrace deposits, and its underlying bedrock identify four most significant features, which creates a local applicable framework for subdivision of the late Quaternary terrace sequence in the study area. Nine stepped river terraces are defined and designated as T_1 to T_9 increasing systematically in elevation. Morphologically, the highest T_9 correlates with the oldest alluvial fan F_1 of the Urumqi River. River incision and the resultant abandonment of fan F_1 are chronologically constrained at ca. 550 ka. The stratigraphic geometry of the Saerqiaoke anticline, a structure developing at the fan end of F_1, reveals the existence of growth strata, implying continuous growth of this fold when the F_1 alluvial sediments were deposited. In the range front of the Urumqi River, growth of the Saerqiaoke anticline has derived tectonically from uplift and basinward thrusting of the Tian Shan range. Such thrusting and basinward extension of the range are expected to force rock uplift of the headwater of the Urumqi River with respect to the Chaiwopu basin to the north and thus river incision occurring at ca. 550 ka. During the subsequent period, several younger terraces have been formed in response to the further uplift of the Saerqiaoke anticline as well as climate changes during glacial–interglacial transitions. In the present study area, the total incision during Quaternary comes close to 400 m, with about 85% contribution likely attributed to rock uplift of the Saerqiaoke anticline.

1. Introduction

For an active orogenic belt, the topographic evolution derives from the interactions of tectonics and surface processes (Burbank and Pinter, 1999; Burbank, 2005; Burbank and Anderson, 2011; D'Arcy and Whittaker, 2014). Among the geomorphic systems, fluvial terrace is particularly sensitive to allogenic factors (such as tectonism and climate) (Blum and Törnqvist, 2000; Westaway et al., 2006; Daniels, 2008; Burbank and Anderson, 2011; Zhang et al., 2014), which makes the study of fluvial landforms fundamental for reconstructing the history of regional environmental evolution (e.g., Avouac and Peltzer, 1993; Li et al., 1999; Bridgland, 2000; Sun, 2005; Hanson et al., 2006; Lu et al., 2010a; Macklin et al., 2013; Pan et al., 2013; Gong et al., 2014). However, the relative role of tectonism and climate in the recent topographic evolution, especially terrace formation, remains an issue of debate (e.g., Pan et al., 2000, 2003; Starkel, 2003; Bridgland and Westaway, 2008; Daniels, 2008; Lu et al., 2010a). The Tian Shan and its surrounding area provide such an excellent natural laboratory to probe this scientific question.

The modern Tian Shan has been built largely by basinward thrusting along range-bounding faults (Fig. 1A) (Avouac et al., 1993; Deng et al., 2000; Lu et al., 2010b). As a result, the present topography in both the northern and southern Tian Shan foreland basins is characterized by several fold-and-thrust belts roughly parallel to the trend of the range (Fig. 1) (Avouac et al., 1993; Deng et al., 2000; Zhang, 2004). Transverse rivers emanating from the high range of the Tian Shan across the piedmonts incise into the anticlines roughly perpendicular to their strike (Fig. 1). We focus on the range front of the Urumqi River, where a small-scale anticline (here referred to as the Saerqiaoke anticline) develops at the fan end of the oldest alluvial fan of the river (the area covered by the lower Pleistocene strata in Fig. 2). Well-developed terrace staircase and alluvial fans display along the course in the range front (Fig. 2). Previous studies have analyzed the effect of Quaternary glaciation on the piedmont alluviation in this area (e.g., Yang and Qiu, 1965; Zhou et al., 2002), whereas relatively few studies have focused on the geomorphic processes forcing river incision and terrace formation (e.g., Zhou et al., 2002). In order to better understand the driving force behind river incision and terrace generation in the range front of the Urumqi River, we have measured five terrace cross sections and defined the types and distributions of terraces and their correlations with alluvial fans. From these, we have dated five samples using optically

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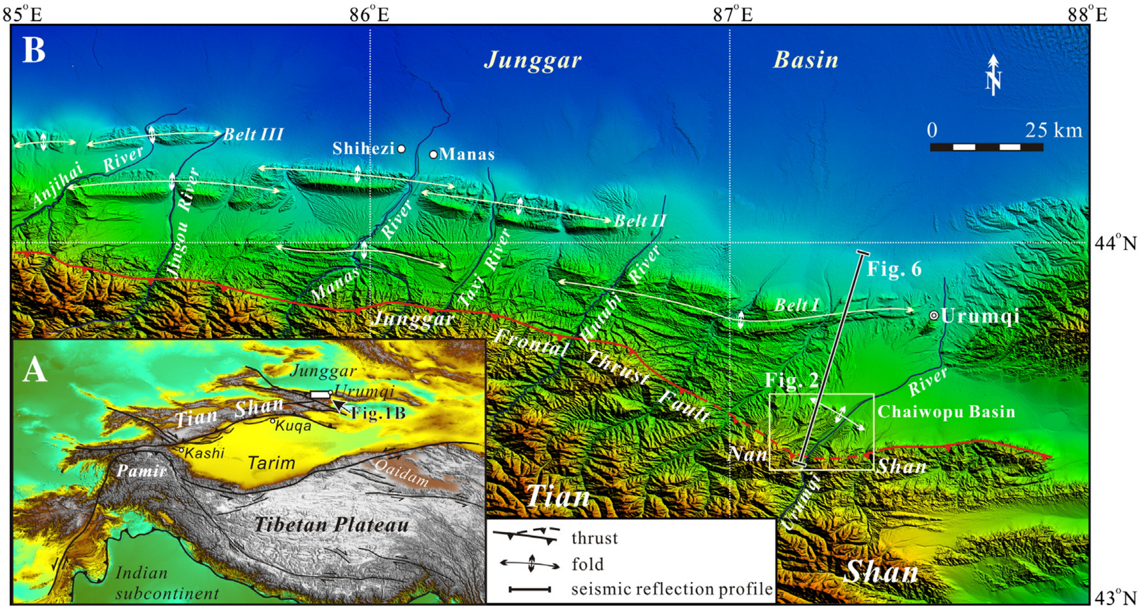

Fig. 1. (A) Map shows overall topographical pattern and tectonic setting of the interior of Asia. (B) Digital elevation model (DEM) of the northern Tian Shan foreland, where three fold-and-thrust belts (belt I, II, and III) characterize the regional topography (Deng et al., 2000; Zhang, 2004).

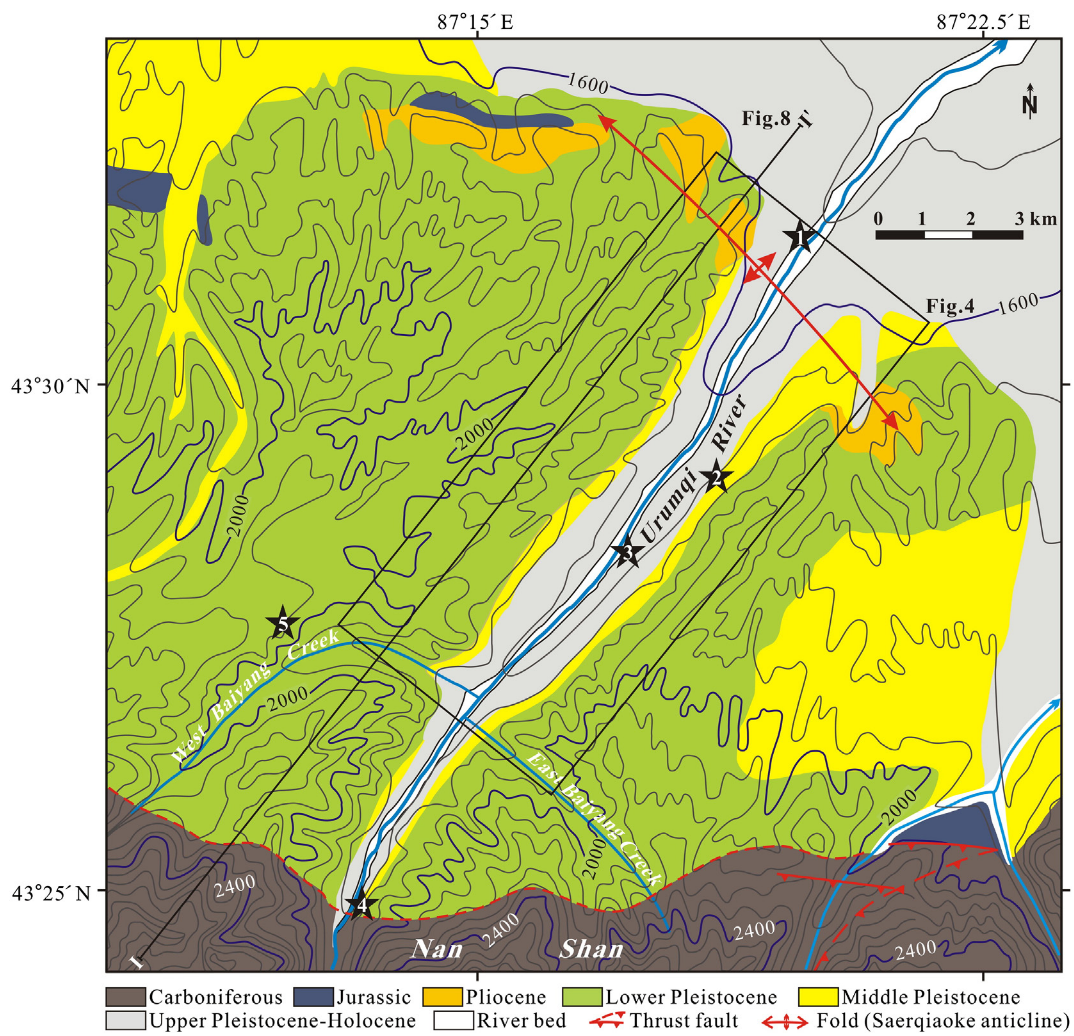

Fig. 2. Geological map (based on 1:50,000 geological map) in the range front of the Urumqi River, where intense incision exposes thick Quaternary alluvium as well as Jurassic and Pliocene strata. Stars show the sampling sites for ESR, OSL, and AMS ^{14}C dating, as reported in Table 1.

stimulated luminescence (OSL), electron spin resonance (ESR), and AMS radiocarbon (^{14}C) dating methods. Also we have characterized the stratigraphic geometry of the Saerqiaoke anticline by measuring the stratigraphic dips of the limbs in order to reveal the growth history of this structure and thus understand the local tectonic setting. The goals of this paper are (i) to describe the sequence and distribution of fluvial features, and (ii) to evaluate the possible contribution of tectonic uplift and/or climate change to river incision and terrace formation. Our results suggest that favorable tectonic conditions (first-order), rather than climate, promoted the river incision and the formation of late Quaternary fluvial terraces (especially several high terraces) in the range front of the Urumqi River.

2. General settings

The EW-trending Tian Shan is one of the largest and most active mountain ranges in central Asia, which comprises many individual ranges exhibiting high current seismicity and rapid rates of late Cenozoic deformation (Abdrakhmatov et al., 1996; Reigber et al., 2001). The average elevation of ridges along the Tian Shan is ~4000 m above sea level (asl), whereas the highest peak Tuomer exceeds 7400 m asl. The ancestral Tian Shan was formed during the Permian after experiencing two collisions and amalgamations of blocks during the Late Devonian–Early Carboniferous and Late Carboniferous–Early Permian (Windley et al., 1990). The subsequent Mesozoic deformation of the Tian Shan is characterized by three distinguishable episodes in response to successive accretion onto the south Asian margin of the Qiangtang block in the Late Triassic, the Lhasa block in the Latest Jurassic–Early Cretaceous, and the Kohistan–Dras arc complex in the Late Cretaceous periods (Hendrix et al., 1992; Dumitru et al., 2001; Lu et al., 2010b). During the Latest Mesozoic and Paleogene, the relative tectonic stability was prevailing within the Tian Shan range, resulting in the beveling of topography and thus creating several widespread regional unconformities (Allen et al., 1991; Bullen et al., 2003). Hendrix et al.'s (1992) result shows that, however, the Tian Shan has existed as a positive physiographical feature separating the Junggar basin to the north from the Tarim basin to the south throughout the Mesozoic times. In response to the India–Asia collision during the early Cenozoic (Najman et al., 2001), the Tian Shan has been tectonically reactivated and uplifted and intensely encroached into its foreland basins (Zhang, 2004; Lu et al., 2010b, 2013a). As a result, both the northern and southern Tian Shan foreland depressions (such as the Urumqi depression, Kuqa depression, and Kashi depression) have developed several fold-and-thrust belts (Fig. 1A) (Deng et al., 2000; Fu et al., 2003; Zhang, 2004). In the Urumqi depression, three fold-and-thrust belts (belts I to III) stretch from the mountain front sequentially towards the foreland basin and characterize the regional topography (Fig. 1B).

In the easternmost Urumqi depression (i.e., the southern Chaiwopu basin), such a fold, i.e., the Saerqiaoke anticline, is located in the range front (Figs. 1 and 2). The deformation history (timing and process) of the Saerqiaoke anticline, however, is still unclear. The NE-flowing Urumqi River has sliced through this fold, thus displaying well-exposed outcrops of the Pliocene and Pleistocene strata in the river valley. The Urumqi River originates from active glaciers in the axial part of the Tian Shan range, and thus the fluvial water supply depends on glacier melt besides precipitation. After experiencing a process of progressively enhancing aridification since at least about 6 Ma (Lu et al., 2013b), modern climate in the Urumqi region is characterized by semiarid to arid environment. The annual precipitation in this region is about 650 mm, controlled largely by the mid-latitude Westerly circulation (Xu et al., 2010). Substantial coarse clastics were carried by the Urumqi River from the range into the Chaiwopu basin and were deposited as the Quaternary alluvial fans (Figs. 1 and 2). Pleistocene aeolian loess extensively mantles several high terrace surfaces developed by this piedmont fluvial system (Yang and Qiu, 1965; Zhang, 1981; Zhou et al., 2002).

3. Methods

In order to examine the factors that drive river incision and terrace formation in the range front of the Urumqi River, it is important to define the Quaternary fluvial sequence and its temporal framework and understand the local tectonic setting. Thus, our analysis comprises two principal facets: geomorphologic classification and local tectonic analysis. Instead, the regional climate history is from previous studies on the Quaternary glaciation of the Urumuqi River catchment (e.g., Yi et al., 2004; Zhao et al., 2006; Xu et al., 2010).

3.1. Fluvial geomorphologic classification

A three-step process is used to define the fluvial geomorphic sequence in the present study area. First, for each geomorphic feature, field observations define the geomorphic surface's characteristics (elevation, continuity, and extent of dissection), the bedrock beneath it, and the thickness of capping gravels and overlying loess (if any). Second, we utilize field investigations and geomorphologic mapping based on Google Earth and 1:50,000 topographic maps to identify the most significant features, which are used as the geomorphic framework for the terrace classification in the range front of the Urumqi River. Third, based on the topographic continuity, the surface characteristics of fluvial features, and the ages of those surfaces, we classify nine river terraces (T_1 to T_9 from youngest to oldest).

Previous studies (e.g., Yang and Qiu, 1965; Zhou et al., 2002) have suggested that the formation ages of several high terrace surfaces in the present study area lie beyond the typical range of conventional radiocarbon (^{14}C) and also optical stimulated luminescence (OSL) dating. Our age control for these geomorphologic units is, therefore, based primarily on electron spin resonance (ESR) dating. For the lower terraces, the formation ages are dated by OSL and AMS ^{14}C dating methods. The ESR and OSL samples were collected from homogeneous fluvial sediments comprising silt or very fine sand. When sampling, a 20-cm-long, 5-cm-diameter steel pipe with one end covered with opaque materials was driven into the sampled layer using a plastic hammer. In order to ensure maximal shielding, we analyzed only the middle part of each sample. Following the procedures of Lin et al. (2005), ESR dates were determined in the State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration. The OSL dates were determined in the Institute of Crustal Dynamics of China Earthquake Administration according to the procedures of Rees-Jones (1995) and Wang (2006). The AMS ^{14}C dating was performed in the Beta Analytic Lab.

3.2. Local tectonic setting analysis

We revealed the local tectonic setting by characterizing the strata of the Saerqiaoke anticline and analyzing the seismic reflection profile crossing through this fold. We measured the attitude of stratum and described the lithofacies. Although the topographic expression of the Saerqiaoke anticline is not very clear, the exposed strata along the river valley clearly display the asymmetric structure of this fold. The systematic change in stratigraphic dip in the south and north limbs of the Saerqiaoke anticline is regarded as indicative of growth strata, which is causally associated with the continuous growth and deformation of a structure (e.g., Suppe et al., 1992; Burbank et al., 1996). Also we characterized the deformed terraces in the range front of the Urumqi River. All these field investigations on stratigraphy and terrace indicate the Quaternary continuous tectonic deformation of the Saerqiaoke anticline.

4. The staircase of nine terraces

Based on our field investigations as well as the previous studies (e.g., Yang and Qiu, 1965; Zhou et al., 2002), nine terraces (T_1 to T_9) are identified in the study area, increasing systematically in elevation (Figs. 3, 4, and 5). In comparison to the area beyond the Saerqiaoke anticline, more terraces are preserved within this structure (Figs. 4 and 5), which is likely owing to rock uplift caused by growth of this fold. According to our field investigations, terraces T_4, T_5, T_7, and T_9 are the most significant features in the range front of the Urumqi River.

The highest terrace (T_9) surface is morphologically the surface of the oldest alluvial fan F_1, covering an area of ~180 km^2 with the longitudinal length of ~12 km (Fig. 2). At the fan end, the surface merges northward with the younger and much gentler fan (designated as F_2, morphologically corresponding to the lower terrace T_4) (Figs. 2 and 4). The alluvium of fan F_1 is comprised of gray cobbly conglomerates with the thickness of about 400 m at the fanhead (Zhou et al., 2002). Here we refer to the alluvial conglomerates of F_1 as Saerqiaoke gravel after Zhou et al. (2002). The elevation difference between the current riverbed and the surface of F_1 reaches almost 400 m (Figs. 2 and 5A). This implies that the river has likely cut through the alluvial deposits of F_1, especially near the Saerqiaoke anticline when considering the intense rock uplift of this structure. This inference is consistent with the filed observation that the underlying reddish–yellow Pliocene strata were exposed in the river valley within this fold (Figs. 3B, C, and 5). The present surface of fan F_1 (terrace T_9) exists as heavily dissected and undulating terrain owing to continuous post-deposition incision caused mainly by longitudinal gullies on the surface (Fig. 4). Some gullies with the length of more than 10 km have eroded headward to the fanhead (Figs. 2 and 4). Considering the relatively slow development process of a piedmont gully in the semiarid and arid area, the above observations on the F_1 surface are thus considered to imply the relatively early timing of the stabilization of this surface. An ESR dating sample taken from the depth of ~5.1 m in the fan F_1 sediments (see Fig. 2 for the sampling location) was dated at 559 ± 55 ka (Table 1), implying the abandonment (i.e., stabilization) of this fan at about 550 ka.

Terrace T_7 is another best-expressed feature in the range front of the Urumqi River, where it is preserved on the eastern bank of the river (Figs. 3 and 4). Terrace T_7 commonly lies about 140–160 m above the modern riverbed (Fig. 5). Although dissected by transverse gullies, this

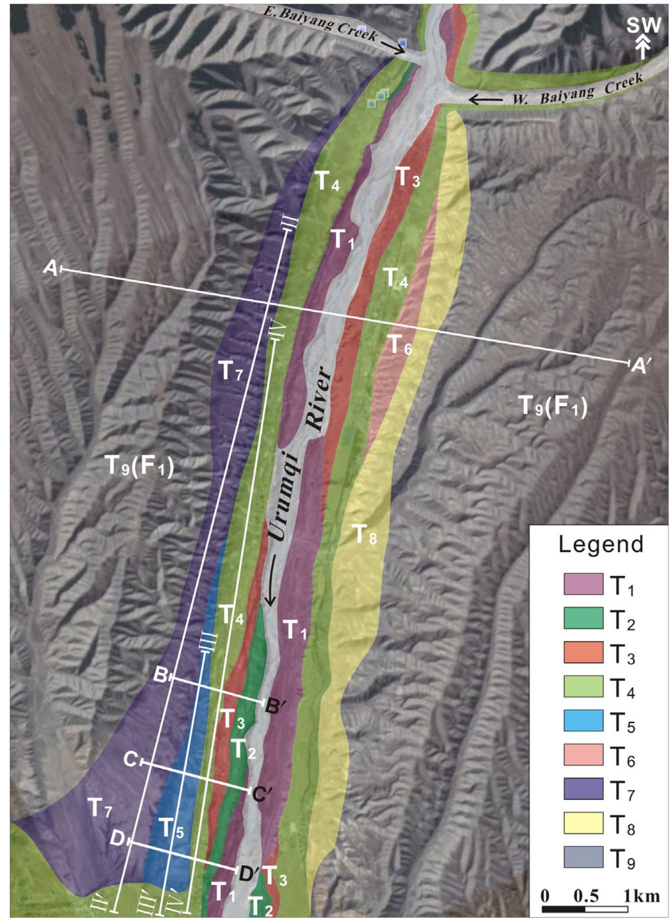

Fig. 4. Distribution of nine river terraces in the range front of the Urumqi River based on Google Earth image and field investigations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

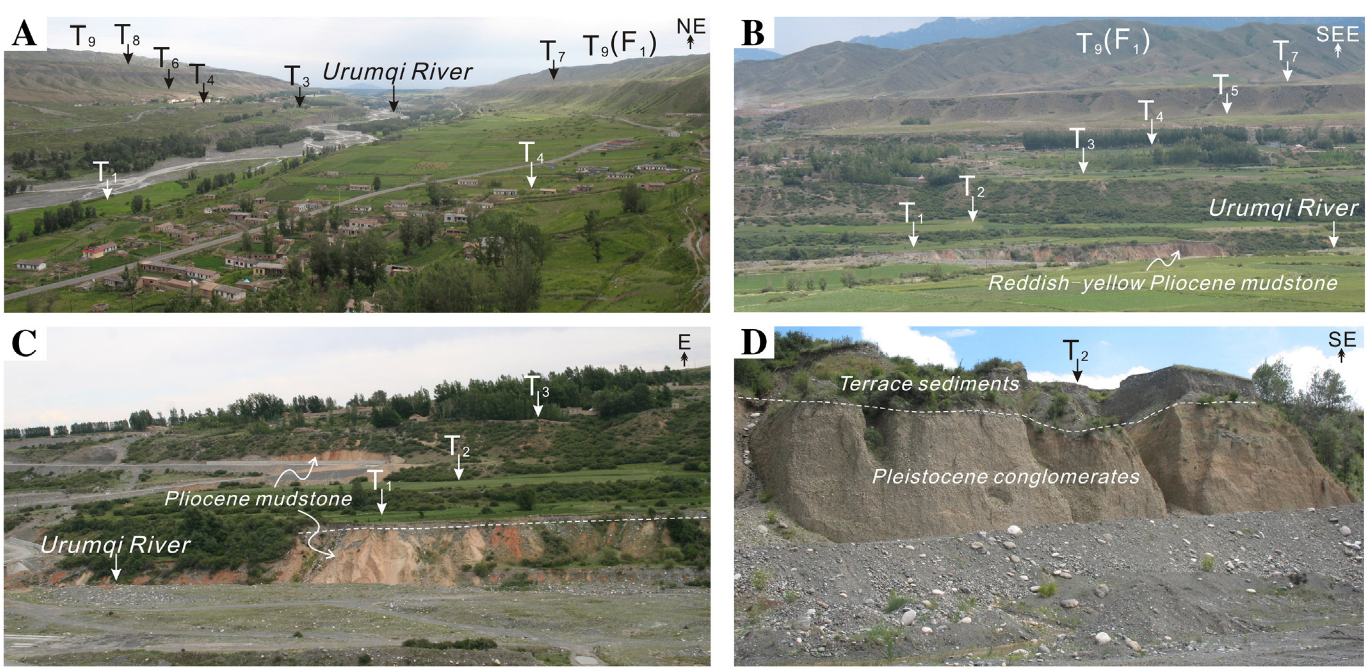

Fig. 3. (A) Photo showing the staircase of nine terraces well-developed along the course in the range front of the Urumqi River. The river flows northeastward. (B) and (C) Photos show that strath terraces are clearly presented at the fan end of the oldest alluvial fan (F_1) on the east bank of the river. The reddish yellow Pliocene mudstone is exposed as the underlying bedrock for the terrace deposits. (D) About 5 km southward, the underlying bedrock of the terrace deposits changes to the lower Pleistocene alluvial conglomerates.

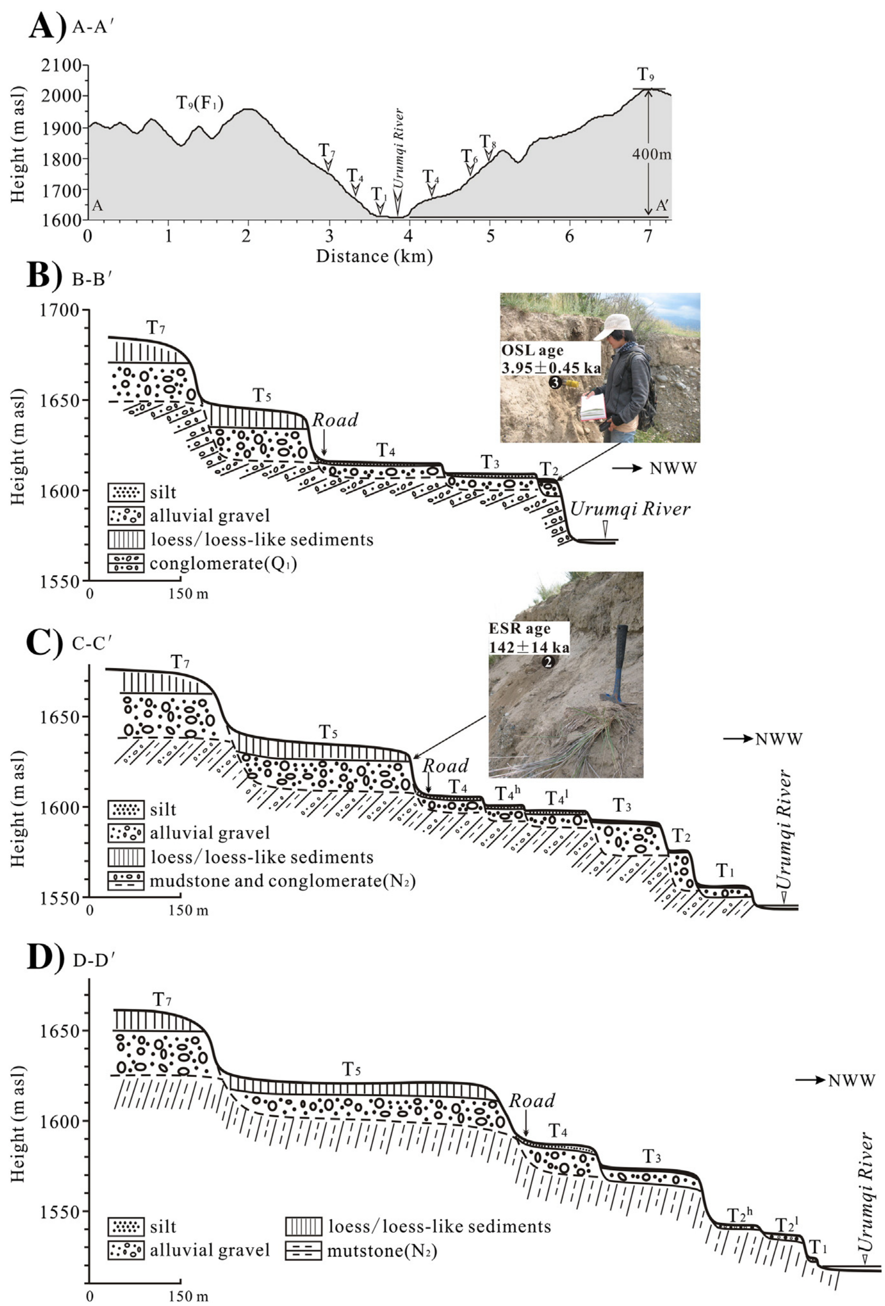

Fig. 5. Terrace-to-river cross sections of the Urumqi River. A–A′ cross section was extracted from Google Earth showing the cumulative incision of ~400 m in the range front of the Urumqi River. The other three cross sections are based on the field investigations. See Fig. 4 for the locations of these cross sections.

terrace surface is less incised than terrace T_9 (fan F_1) and thus is relatively more continuous and planar (Figs. 3B and 4). The thickness of the terrace deposits (blackish gray gravel) was not determined in the field owing to lack of the outcrop of the underlying bedrock. The overlying loess (or loess-like) deposits are commonly several meters in thickness: a feature in striking contrast with the oldest terrace T_9/fan F_1. Our ESR dating data constrains the depositional age of terrace T_7 at 255 ± 25 ka (Table 1). Similar to terrace T_7, terrace T_5 is also relatively planar, covered by about 10-m-thick loess sediments near the Saerqiaoke anticline. The surface of terrace T_5 stands about 30–40 m below that of

Table 1
Calculated value of equivalent doses, annual doses, and ages[a].

Sample no.	Sampled layer	Dating material	Dating method	Equivalent doses (Gy)	Annual doses (Gy/ky)	Age (ka)[b]
1	The base of ~120-cm-thick silt above the terrace gravels of T_2	Charcoal	AMS ^{14}C	–	–	3.52 ± 0.04
2	The base of ~80-cm-thick floodplain sediments of T_5	Silt	ESR	478 ± 47	3.35	142 ± 14
3	The depth of 55 cm in the 90-cm-thick floodplain deposits of T_2	Silt	OSL	17.06 ± 0.94	4.32	3.95 ± 0.45
4	The base of terrace deposits of T_7	Silt	ESR	855 ± 85	3.35	255 ± 25
5	The depth of 5.1 m in the F_1/T_9 alluvial sediments	Silt	ESR	2131 ± 213	3.81	559 ± 55

[a] Locations of dating samples are shown with stars in Fig. 2.
[b] The age uncertainty is 1 σ.

terrace T_7. According to the ESR age of 142 ± 14 ka for one sample taken from the base of ~80-cm-thick floodplain sediments of T_5 (Table 1), this terrace is estimated to have been formed during the latest middle Pleistocene. Terrace T_4 is another best expressed feature in the study area, which is well developed on both the eastern and western banks of the river (Figs. 3A and 4). To the north of the Saerqiaoke anticline, this terrace grades downstream to alluvial fan F_2 (Fig. 4). The surface of terrace T_4 lies about 60–70 m above the river level. Unlike the above two older terraces (T_7 and T_5), terrace T_4 is not covered by thick loess deposits but thin silt sediments (commonly several decimeters). Terraces T_8 and T_6 are preserved on the western bank of the Urumqi River (Figs. 3A and 4), where these two terraces are intensively remade owing to surface processes such as debris flow as well as human activity. The other terraces (T_3, T_2, and T_1) comprise a strath that is overlain by several meters of fluvial gravels and that are, in turn, capped by thin silt deposits (Figs. 3B, C, D and 5). The abandonment age of terrace T_2 is dated at about 3.5–3.9 ka based on the OSL and AMS ^{14}C dating data (Table 1).

5. Discussion

As shown above, nine terraces (T_1 to T_9) are defined in the range front of the Urumqi River (Figs. 3, 4, and 5), and the oldest terrace T_9 (morphologically equivalent to alluvial fan F_1) was abandoned at about 550 ka. This age is younger than Zhou et al.'s result (2002), which constrained chronologically the abandonment of F_1 at about 1.2 Ma based on an ESR age of 1148.2 ka for a sample taken from the top of the fan F_1 deposits. Unfortunately, Zhou et al. (2002) did not show the sampling site and assign any uncertainties for this ESR dating sample, which makes it difficult to assess the validity of this age and to compare it with other dating results.

Further considering two following lines of evidence, we prefer the abandonment age of about 550 ka of the oldest alluvial fan F_1 of the Urumqi River. Firstly, the upper boundary of Urumqi gravel, deposited in the northern Chaiwopu basin as part of the gravelly basin infill (thick Quaternary fluviatile gravelly sediments), is considered to stand slightly above the B/M boundary based on the vertebrate fauna *Equus sanmeniensis* (horse) and the preliminary paleomagnetic investigations (Gao, 2004). This gravel unit stratigraphically corresponds to Saerqiaoke gravel (the fan F_1 conglomeratic deposits) in the southern Chaiwopu basin. Secondly, our previous work on the river systems in the north piedmont of the Tian Shan indicates that abandonment of the oldest alluvial fan and subsequent formation of the highest river terrace surface occurred at about 530 ka constrained by the loess/paleosol stratigraphic correlation and ESR dating data (Lu et al., 2010a). Given the similar climatic and tectonic setting in this area (Xinjiang Institute of Geography, 1986; Deng et al., 2000; Xu et al., 2010), these piedmont fluvial systems are expected to develop comparable geomorphic features. A recent study on the Manas River (Gong et al., 2014) reported an age of about 20 ka for the oldest terrace preserved within the Manas anticline of belt II in the same area, much younger than formation age of the oldest alluvial feature (F_1/T_9) of the Urumqi River in this study. According to our previous study, however, the highest terrace within the Manas anticline is likely preserved about 2.5 km east of the current riverbed (see Fig. 8 of Lu et al., 2010a). Based on the fluvial sequence and its chronological data presented above, we examine the factors that drive river incision and terrace formation in the range front of the Urumqi River. To make the following analysis easier, we at first review briefly several possible driving forces commonly considered.

5.1. Uplift, climate change, river incision, and terrace formation

River terraces are fluvial landforms developed along the river course in various climatic settings (Yang and Li, 2005). Terrace formation is largely associated with the transition in the mode of operation of a river system between aggradation and degradation in response to tectonic and climatic perturbations (Bull, 1990, 1991; Maddy et al., 2000; Starkel, 2003; Bridgland and Westaway, 2008; Lu et al., 2010a; D'Arcy and Whittaker, 2014), although other factors such as lithology and base level may also play a role in terrace formation (Yang and Li, 2005; Daniels, 2008). Further considering that base level is controlled mainly by vertical movement and/or climatic fluctuation (Yang and Li, 2005), we thus stress the potential effects of tectonism and climate on river incision and terrace formation here.

River networks are particularly sensitive to vertical movements (Schumm et al., 2000; Burbank and Anderson, 2011). A river terrace commonly represents a paleo-floodplain that has been abandoned owing to vertical incision by a river in response to tectonic uplift (Yang and Li, 2005). Such incision will cease when the river reaches a new equilibrium at a lower base level. When a renewed uplift event occurs, the further vertical river incision can be expected. In this way, a river terrace staircase is formed at different elevations above the current riverbed. As the other style of vertical movement, however, subsidence will cause intense sedimentation thus burying previous terrace surfaces (e.g., Molnar et al., 1994; Vandenberghe et al., 2011). Besides tectonism, climatic fluctuations during glacial–interglacial transitions can also be a driving force of river terrace formation: Episodes of aggradation occur late in the glacial cycles, and the subsequent incision causing terrace formation occurs near to glacial–interglacial transitions (Bridgland, 2000; Pan et al., 2003; Bridgland and Westaway, 2008; Lu et al., 2010a). However, if no uplift event occurs, the river might not be able to incise considerably downward (Vandenberghe et al., 2011) and thus form generally minor aggradational terraces (fill-cut terraces) with relatively small height above the river level (Bull, 1991; Pan et al., 2000).

5.2. Uplift-driven incision and terrace generation in the range front of the Urumqi River

Based on the local tectonic setting revealed by the following geological and geomorphic evidence, we propose tectonic uplift as the first-order forcing mechanism of the late Quaternary river incision and thus terrace formation in the range front of the Urumqi River. The field investigations reveal the process of growth and deformation of the Saerqiaoke anticline, a structure developing at the fan end of F_1 in the range front of the Urumqi River (Fig. 2). The deep seismic reflection profile stretching from the Nan Shan ((shan) means (mountain) in Chinese) northward to the West Shan in Urumqi (Figs. 1 and 6; Liu et al., 2007) indicates that growth and deformation of the Saerqiaoke anticline are tectonically associated with basinward thrusting of the Nan Shan along the range-bounding thrust fault (i.e., Junggar frontal thrust fault, JFT) (Fig. 6). The observed stratigraphic geometry of the Saerqiaoke anticline in the field characterizes the growth process of this fold (Fig. 7). On the western bank of the Urumqi River, the Pliocene strata in the south limb dips to the southwest at an angle >30° near the fan end of F_1 (Fig. 7A). The attitude of the overlying Pleistocene conglomerates is similar to that of the Pliocene strata here. About 4 km southward, the dip angle of the Pleistocene conglomerate strata in the river valley decreases to <10° (Fig. 7B). Wherever these two strata composing the Saerqiaoke anticline are juxtaposed (near the core of the anticline), the dips of the Pleistocene alluvial conglomerate strata gradually decrease upward from ~90° in the river valley (Fig. 7C) to ~45° at the ditch on the western bank of the Urumqi River (Fig. 7D). This observed change in the dips of the lower Pleistocene strata is in coincidence with the characteristics of growth strata (Fig. 8), syntectonic sedimentation causally associated with fold growth (Suppe et al., 1992; Burbank et al., 1996; Chen et al., 2007; Sun et al., 2009; Lu et al., 2010b). This interpretation of growth strata suggests the commencement of growth of the Saerqiaoke anticline since at least the time when the thick alluvial conglomeratic sediments of fan F_1 deposited. The cessation of aggradation of this alluvial fan is constrained chronologically around 550 ka. We thus propose that growth of the Saerqiaoke anticline continued at least till this age. In the absence of high-resolution

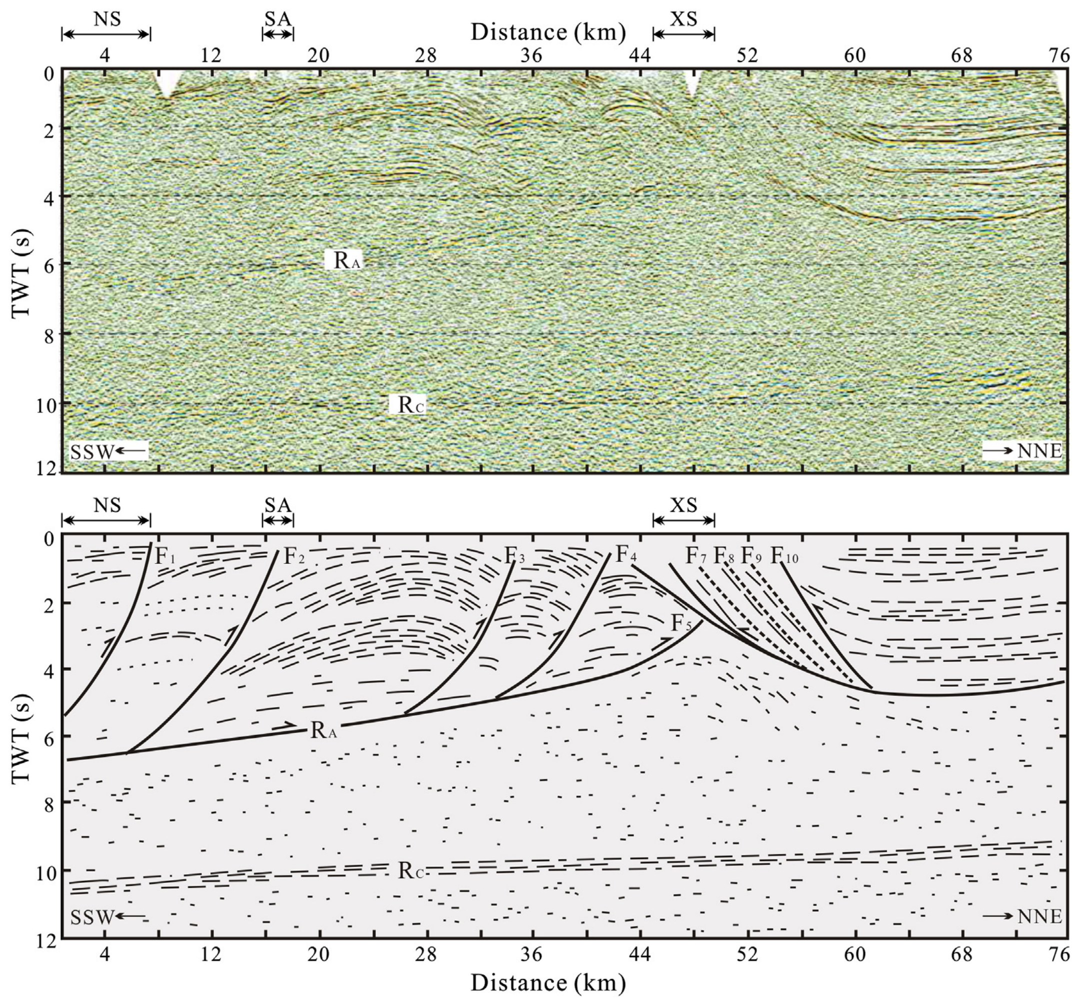

Fig. 6. Deep seismic reflection profile of stretching from the Nan Shan northward the West Shan of Urumqi and the geological interpretation (modified from Liu et al., 2007), showing tectonic style in the range front of the Urumqi River. See Fig. 1 for the location of this seismic reflection profile. F_1 to F_{10} are the interpreted faults, and F_1 to F_5 converge successively southward with the dipping-southward detachment horizon R_A, which is located at a depth of ~17–18 km at the left end of the seismic profile (Liu et al., 2007). These five faults and R_A compose a typical thrust noppe. R_C is a deeper detachment horizon gently dipping southward. F_1 is the south branch of Southern Chaiwopu fault (SSCF), i.e., the east segment of Junggar frontal thrust fault (JFT) (see Fig. 1), and F_2 is the north branch of Southern Chaiwopu fault (NSCF), controlling growth of the Saerqiaoke anticline. NS: Nan Shan; SA: Saerqiaoke anticline; XS: Xi Shan.

seismic data to illuminate stratal geometries in the subsurface, we note that our interpretation of growth strata is based on the bedding-dip relationships described above. The lack of subsurface data for this fold precludes a truly unambiguous interpretation.

The further deformation of the Saerqiaoke anticline is revealed by geomorphic evidence (Fig. 9). The longitudinal profiles of terraces T_7, T_5, and T_4 display obvious folding deformation just at the fan end of F_1 caused by growth of the Saerqiaoke anticline (Fig. 9). With respect to uplift within the Saerqiaoke anticline, the area to the north of this fold is characterized by relative subsidence, which has caused the river to deposit continuously fluvial sediments of considerable thickness (Molnar et al., 1994; Vandenberghe et al., 2011) and thus to bury previous terraces (here they are T_7 and T_5) (Fig. 9). Therefore we cannot define the magnitude of deformation of these two terraces (T_7 and T_5). Clearly, however, the magnitude of deformation for terraces T_7, T_5, and T_4 sequentially decreases (Fig. 9). This implies the continuous deformation of the Saerqiaoke anticline since the surfaces of these terraces were abandoned owing to river incision. Two ESR samples taken from terraces T_7 and T_5 were dated at 255 ± 25 and 142 ± 14 ka, respectively (Table 1). Combined with an ESR age of 114 ka for the sample from the unfolded terrace T_3 (Zhou et al., 2002), we conclude that tectonic deformation of the Saerqiaoke anticline likely continued until at least about the late middle Pleistocene. In comparison with the area to the north of the Saerqiaoke anticline, however, the occurrence of more and lower terraces within this fold (Figs. 4 and 5) seems to imply the subsequent rock uplift, but we have no other field evidence.

The above geological and geomorphic evidence (Figs. 7, 8, and 9) indicate that growth and deformation of the Saerqiaoke anticline commenced since at least the early Quaternary when the F_1 alluvial conglomeratic sediments continuously deposited. As shown by the deep seismic reflection profile (Fig. 6), the Saerqiaoke anticline has causally derived from intense uplift and basinward encroachment of the Tian Shan range. Such basinward thrusting of the range might have caused rock uplift of the headwaters of the Urumqi River with respect to the Chaiwopu basin to the north, thus enhancing erosion in the hinterland and creating more sedimentary accommodation space in the range front. As a result, thick alluvial conglomeratic sediments are deposited in the present study area (PHASE 1, Fig. 10), exhibiting the observed stratigraphic geometry indicative of syntectonic sedimentation (Figs. 7 and 8). This intense alluviation ceased around 550 ka when the river began to incise in response to the significant rock uplift of the Saerqiaoke anticline resulting from northward thrusting of the range into the southern Chaiwopu basin. The fan F_1 aggradational surface was subsequently abandoned as the surface of terrace T_9 (the oldest terrace) (PHASE 2, Fig. 10). During a relatively long period, the river incised and formed several terraces owing to the subsequent growth of the Saerqiaoke anticline (PHASE 3, Fig. 10). The unpaired staircase of river terraces (Fig. 4) is likely owing to the lateral beveling by the

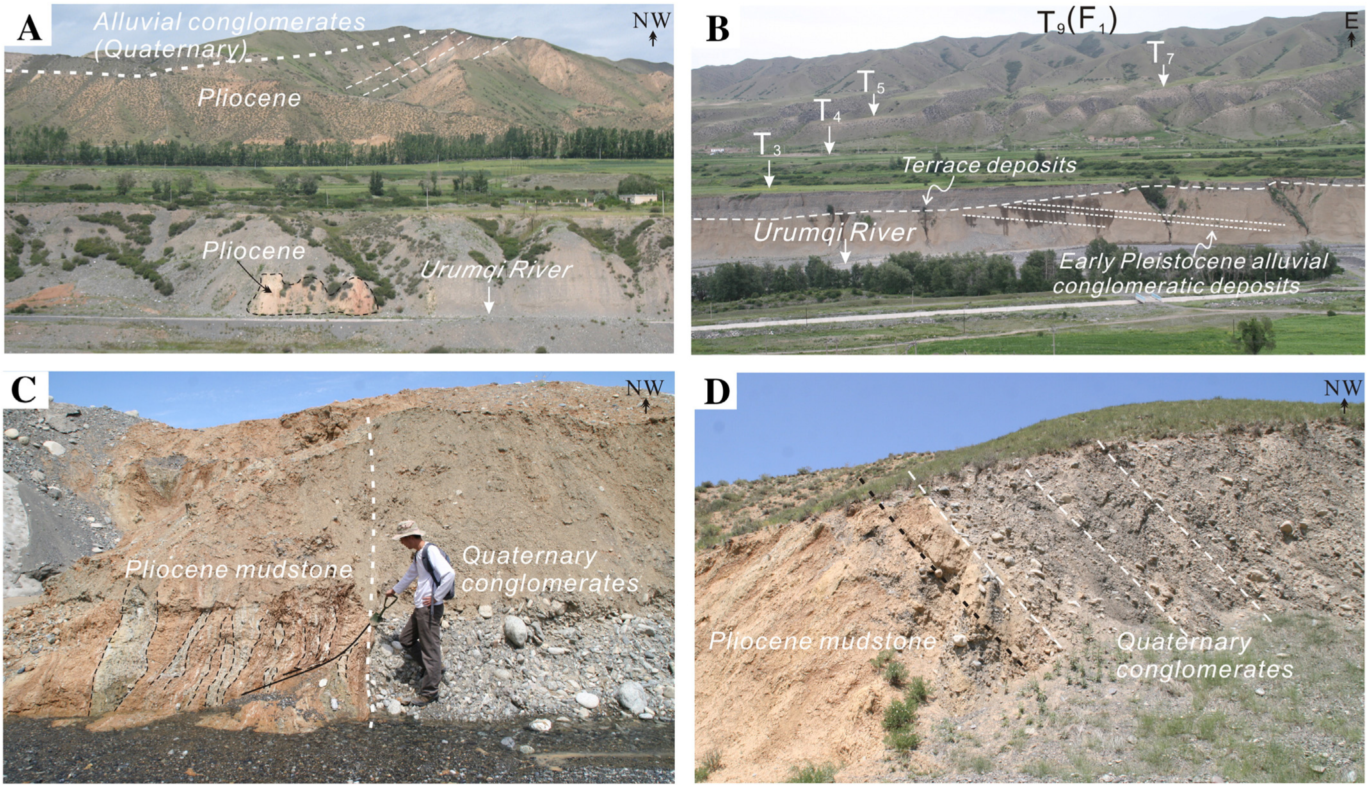

Fig. 7. Photos show the systematic changes in stratigraphic dip of the Saerqiaoke anticline. (A) The Pliocene strata at the south limb dip southwest at an angle >30° near the fan end of F_1 on the western bank of the Urumqi River. (B) About 4 km southward, the dip angle of the Pleistocene conglomerates in the valley is <10°. The upstream end point of terrace T_5 is just at the upper right part of this photo. Wherever the Pliocene and Pleistocene strata are juxtaposed, the dips of the lower Pleistocene alluvial conglomeratic strata gradually decrease upward from ~90° near the river bed (C) to ~45° at the ditch on the western bank of the Urumqi River (D).

Urumqi River. The continuous growth of the Saerqiaoke anticline has already deformed several terraces (Fig. 9). Before ca. 140 ka, significant aggradation formed the terrace deposits of T_4 (PHASE 4, Fig. 10). In response to another significant uplift of the anticline indicated by the deformed T_4 (Fig. 9), the Urumqi River incised and the paleo-floodplain was abandoned as the surface of terrace T_4. The subsequent fluvial process formed several younger terraces (T_3 to T_1). In terms of the contour lines at the F_1 fanhead of the Urumqi River (Fig. 2), the total river incision since ~550 ka is estimated to be about 350–400 m. The above analysis indicates the main contribution of rock uplift of the Saerqiaoke anticline to the river incision. Given the cumulative incision of about 60–70 m since the abandonment of terrace T_4 in the area characterized by relative subsidence to the north of the Saerqiaoke anticline (Figs. 2 and 9), we speculate that about 85% of the river incision in the range front of the Urumqi River is forced by rock uplift of the Saerqiaoke anticline.

5.3. Possible contribution of climate change to terrace formation of the Urumqi River

Undeniably, climate change, especially during the Quaternary rhythmic climatic fluctuations, can also force river incision and thus terrace formation (e.g., Molnar et al., 1994; Bridgland and Westaway, 2008; Li et al., 2012). In the Urumqi River catchment, five sets of Quaternary glacial moraines were deposited within the Daxigou valley, the main tributary of the Urumqi River. The corresponding glacial stages

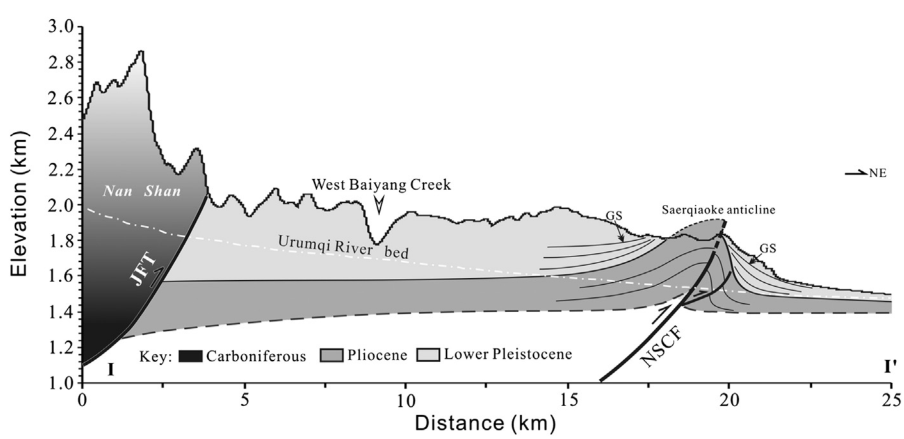

Fig. 8. I–I′ geological cross section in the range front of the Urumqi River. The stratigraphic thickness of the lower Pleistocene conglomerates at the fanhead is ~400 m, but the thickness of the Pliocene strata is not known. JFT (Junggar frontal thrust fault) and NSCF (the north branch of Southern Chaiwopu fault) are characterized according to the interpretation of deep seismic reflection profile shown in Fig. 6. The topography of this cross section is extracted from Google Earth. GS: growth strata. See Fig. 2 for the location of I–I′ section.

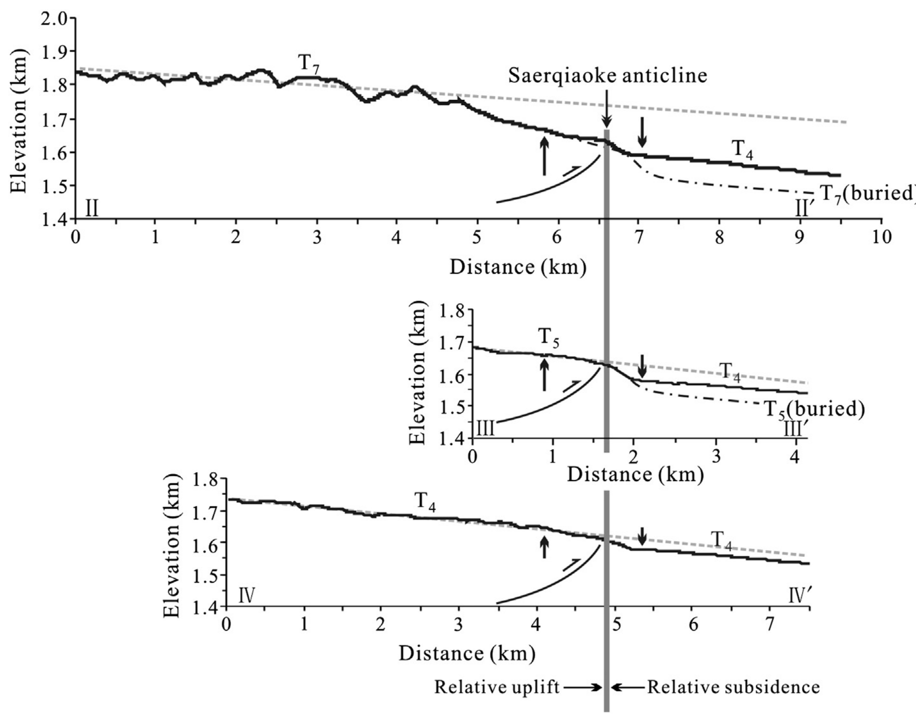

Fig. 9. The longitudinal profiles of terraces T_7, T_5, and T_4 displaying obvious folding at the fan end of F_1. See Fig. 4 for the locations of these terrace longitudinal profiles.

are Little Ice Age (A.D. ~1500–1900; Chen, 1989; Xu et al., 2010), Neoglacial (~4–7 ka; Yi et al., 2004; Xu et al., 2010), Shangwangfeng (~20–40 ka; Zhao et al., 2006; Xu et al., 2010), Xiawangfeng (~60–75 ka for the upper part and ~130–190 ka for the lower part; Zhao et al., 2006; Xu et al., 2010), and Gaowangfeng (~470 ka; Xu et al., 2010), respectively. Clearly, the chronological data of terraces T_9, T_5, and T_2 (Table 1) show approximate synchronicity with the Gaowangfeng stage, the lower part of the Xiawangfeng stage, and the Neoglacial stage,

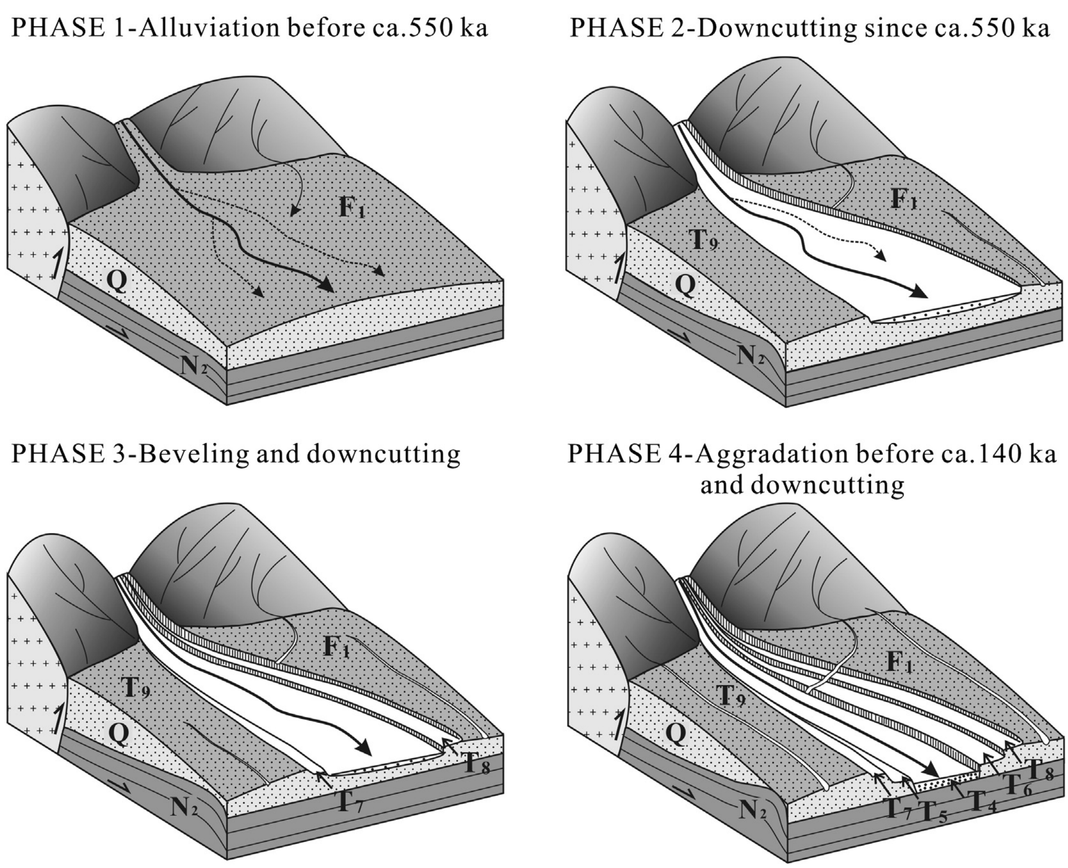

Fig. 10. Cartoons illustrating the late Quaternary geomorphic evolution in the range front of the Urumqi River. See the text for the detailed description. Q: the Quaternary strata; N_2: the Pliocene strata.

respectively. This likely implies the significant contribution of climate change during glacial–interglacial cycles to formation of these three terraces, which has also been seen in terrace formation of the Manas River in the same area (Gong et al., 2014). Given the limited terrace ages here, a more reliable chronological framework for the discussed river terrace staircase is needed in order to further test climate–terrace linkages. In the area to the north of the Saerqiaoke anticline, actually, climate change might have resulted in river incision of about dozens of meters (Figs. 2 and 8). Given the fact that basinward thrusting of the range (Figs. 6 and 8) has caused a more steepened gradient resulting in overall downcutting, we propose that climatically forced incision in the range front of the Urumqi River might be the specific (noise) in a long-term-downcutting regime driven by tectonism, which is in concert with the observations on the other piedmont river systems in the north piedmont of the Tian Shan, NW China (Lu et al., 2010a).

6. Conclusion

The Urumqi River in the northern Tian Shan foreland, Xinjiang, northwestern China incised deeply into the underlying nappe bedrock and basin infill and thus displayed well-developed late Quaternary alluvial sequence in the range front. Based on the evidence from the geomorphic surface, terrace deposits, and its underlying bedrock, we identify four most significant features (terraces T_4, T_5, T_7, and T_9), which create a local applicable framework for subdivision of the Quaternary alluvial sequence in the study area, where nine stepped river terraces are defined. The highest T_9 correlates morphologically with the oldest alluvial fan F_1. River incision and the resultant abandonment of fan F_1 are chronologically constrained around ca. 550 ka. The stratigraphic geometry of the Saerqiaoke anticline, a structure developing at the fan end of F_1, reveals existence of growth strata, implying continuous growth of this fold when the F_1 alluvial sediments deposited. The deep seismic reflection profile indicates that growth of the Saerqiaoke anticline has derived from uplift and basinward thrusting of the Tian Shan range. Therefore, we argue that river incision and terrace formation in the present study have been driven mainly by thrusting and basinward extension of the range. During the period since ~550 ka, several younger terraces have been formed in response to further uplift of the Saerqiaoke anticline as well as climate changes during glacial–interglacial transitions. In the present study area, the total incision during the Quaternary comes close to 400 m, with about 85% contribution attributed to rock uplift of the Saerqiaoke anticline. Given the limited geological evidence (stratigraphic geometry) for growth strata of the Saerqiaoke anticline and the limited dates on the fan F_1 alluvial conglomerates, the future work should focus on magnetostratigraphy of the strata involved in this fold in order to better chronologically constrain its tectonic history.

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