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Morphological response to Quaternary deformation at an intermontane basin piedmont, the northern Tien Shan, Kyrghyzstan

Dan Bowman^{a,*}, Andrey Korjenkov^b, Naomi Porat^c, Birka Czassny^d

^aBen-Gurion University of the Negev, Beer Sheva 84105, Israel ^bInstitute of Seismology NAS, Asanbay 52/1, Bishkek 720060, Kyrgyzstan ^cGeological Survey of Israel, 30 Malchei Yisrael Street, Jerusalem 95501, Israel ^dInstitute of Geosciences, Potsdam University, Postfach 60 15 53, D-14415 Potsdam, Germany

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Abstract

The Tien Shan is a most active intracontinental mountain-building range with abundant Quaternary fault-related folding. In order to improve our understanding of Quaternary intermontane basin deformation, we investigated the intermontane Issyk-Kul Lake area, an anticline that was up-warped through the piedmont cover, causing partitioning of the alluvial fan veneer. To follow the morphological scenario during the warping process, we relied on surface-exposed and trenched structures and on alluvial fans and bajadas as reference surfaces. We used air photos and satellite images to analyze the spatial-temporal morphological record and determined the age of near surface sediments by luminescence dating.

We demonstrate that the up-warped Ak-Teke hills are a thrust-generated subdued anticline with strong morphological asymmetry which results from the coupling of the competing processes of up-warp and erosional feedback. The active creeks across the up-warped anticline indicate that the antecedent drainage system kept pace with the rate of uplift. The rivers which once sourced the piedmont, like the Toru-Aygyr, Kultor and the Dyuresu, became deeply entrenched and gradually transformed the study area into an abandoned morphological surface. The up-warp caused local lateral drainage diversion in front of the northern backlimb and triggered the formation of a dendritic drainage pattern upfan. Luminescence dating suggest that the period of up-warp and antecedent entrenchment started after 157 ka. The morphologically mature study area demonstrates the response of fluvial systems to growing folds on piedmont areas, induced by a propagating frontal fold at a thrust belt edge, following shortening.

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1. Introduction

* Corresponding author.

E-mail address: dbowman@bgumail.bgu.ac.il (D. Bowman).

The Tien Shan (Fig. 1) is a very active intracontinental mountain belt that was formed as a post-

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Fig. 1. Location of the study area and its structural setting.

collisional deformation in response to the India– Eurasia convergence (Molnar and Tapponier, 1975, 1980; Pavlis et al., 1997; Burchfiel et al., 2000) and provides an excellent field laboratory for studying young tectonic morphology. The Tien Shan is composed of a Paleozoic crystalline basement with intervening intermontane basins which are infilled by Cenozoic sediments (Chediya, 1972, 1986; Skobelev, 1977; Sengor, 1984; Korjenkov, 1990, 1991). From Late Palaeozoic through Mesozoic to the Paleogene era, the area was an epi-Hercynian stable continental platform, with very little sedimentation (Petrushevski, 1955). At the end of the mid-Oligocene the Tien Shan area was part of a vast peneplain which is indicative of the pre-orogenic Tien-Shan stage. Mountain building did not begin until Late Paleogene (Chediya, 1986).

The region of Lake Issyk-Kul in northern Kyrghysztan (Fig. 1), centered around long. 76° 26', lat. 42° 35', is a tectonic ramp depression, measuring about 250 by 110 km, bordered by thrust faults (Chediya, 1993) that dip in opposite directions. The Issyk-Kul depression (Fig. 1) is bordered on the north by a set of en-echelon thrust faults, i.e., the West Toguz-Bulak, Kultor, the northern Aksu and



Fig. 2. Simplified geological map of the study area following Korjenkov (1988, 2000). For cross section A-B see Fig. 5.

the Taldy-Bulak faults. In the south, the Terskey ridge borders the depression along the southern pre-Terskey fault zone which exhibits a 4000 m maximal vertical separation and a 7000 m strike slip (Chediya and Trofimov, 1978). The infilling of the Issyk-Kul by the fine sandy-silty Kirgiz formation, up to a thickness of 1500 m (Fortuna, 1993), started in the Oligocene-Miocene and is the first manifestation of continuous lacustrine deposition. The Issyk-Kul intermountain basin was occupied by lakes from the early Neogene (Voskresenskaya, 1983). The Miocene-Pliocene marks an era of intensive orogenic uplift as shown by the coarsening-upward of the 3000 m thick, sandy-gravelly Issyk-Kul Formation. Orogenic uplift is further reflected in the coarsening of the Lower Pleistocene Sharpyldak Formation, up to 200 m thick (Fortuna, 1993). Coarsening of the Quaternary syncline fill continues into the Holocene. The Palaeozoic basement below the Issyk-Kul depression is downwarped 4.5 km below the present-day lake level. In the surrounding mountains, the basement is uplifted to 5 km, amounting to a vertical separation of almost 10 km.

The morphology of piedmont areas following Quaternary deformation has not been the focus of neotectonic research in the Tien Shan. Our aims are to reveal the spatial-temporal morphological development in the peripheral foreland of the compressional Issyk-Kul basin and reconstruct its links to the structural evolution. The Toru-Aygyr study area was chosen as an example of geomorphic surfaces and hydrographic networks interacting with evolving Quaternary deformation. The results are expected to improve our understanding of the relation of tectonics to the erosional history at Quaternary thrust belts in the piedmont areas of intermontane basins.

The paper presents the Issyk-Kul basin and the basic morphology of the discrete Toru-Aygyr study

area. We proceed by demonstrating the Ak-Teke hills as a thrust-generated anticline between Quaternary alluvial veneers. Next we focus on the response of the drainage system to the up-warp of the Ak-Teke. We conclude by dating and temporally constraining the history of this Quaternary deformation.

2. Study area

The study area is in the northwestern part of the intermountain Issyk-Kul depression, within the Cenozoic sedimentary fill surrounding Lake Issyk-Kul, crossed by the Toru-Aygyr and the Dyuresu–Kultor rivers (Figs. 1 and 3). The area was initially studied by Chediya and Trofimov (1978), Chediya (1993) and by Korjenkov (1986, 1988, 2000).

The study area is a peripheral foreland in the form of an alluvial piedmont, composed of fans and bajadas, at an altitude of 1700–2100 m, extending from 100 to 500 m above the Issyk-Kul Lake level. Mean annual precipitation in the study area is 300–400 mm (Adyshev, 1987).

The alluvium in the study area was subdivided into: Lower Pleistocene, Mid Pleistocene, Late Pleistocene and Holocene deposits (Naperstkin et al., 1967). Three morphologic units stand out: 1-The northern bajada composed of coalescing fans, sourced by the paleo-Kultor and the paleo-Toru-Aygyr rivers, which traverse the Kyzyl-Kultor granitic core (Figs. 2, 3 and 4). 2-The Ak-Teke ("White Goat")-a well defined belt of hills some 15 km long and 3 km wide (Figs. 2 and 3). The hills range between 1844 and 2041 m in altitude, rising higher toward the north and the Chon-Dyobyo hill (Fig. 4), from where the area slopes eastwards and westwards. 3-The southern bajada, which lies south of the Ak-Teke (Figs. 3 and 4) is a smooth alluvial surface that slopes towards Lake Issyk-Kul.

Fig. 3. The study area shown by Landsat Multi-Spectral Scanner (MSS), Path 161, Row 30 (8 August 1976). The main surficial units are: 1 northern bajada; 2—Ak-Teke Hills; 3—southern bajada; 4—Toru-Aygyr river; 5—Confluence of Dyuresu and Kultor rivers; 6—Kyzyl-Kultor hills; 7—shoreline of lake Issyk-Kul. Note the dense vegetation along the Toru-Aygyr stream bed where it crosses the the Ak-Teke Hills (8), the Tekren anticline (9) and along the Dyuresu river (10). The Kungey ridge (11) closes the Issyk-Kul basin to the north. Dots indicate trench locations. Note that the Ak-Teke is a local phenomenon and does not grow laterally beyond the area shown in this picture. The image was processed, geocoded and printed by Kirk Haselton at the Institut fur Geowissenschaften, Universitate Potsdam. North is towards the top.



3. Methods

3.1. Field study

All former Soviet and Kyrghyzstan research, related to the study area, was examined, including former mapping and seismic profiling. Morphological traverses were measured by level along selected stretches of terrain, in addition to topographic crosssections based on local detailed maps. The structure was recorded along outcrops of the Issyk-Kul formation. Field work was supplemented by interpretation of declassified US intelligence air photography, satellite images and standard air photos. Two trenches were logged perpendicular to the southern boundary of the Ak-Teke Hills (Figs. 3 and 4). A third exposure



Fig. 4. The study area in detail including the sites of the trenches and of the dated samples. Contours are shown selectively to delineate the general topography.

was logged along a creek bank, on the northern flank of the Ak-Teke. The evolution of the drainage network was studied by analysis of the drainage patterns, catchment areas and the relief.

3.2. Luminescence dating

To reconstruct the morphological evolution, sediment samples taken from the geomorphic surfaces and from the trenches were dated by the luminescence methods (Aitken, 1998). These methods date the last exposure of mineral grains to sunlight, using signals that accumulate in the minerals as a result of natural ionizing radiation, and which are zeroed by exposure to sunlight. After each resetting and burial, the signals start to accumulate and their intensity is a function of elapsed time and environmental radiation. Therefore they can be used to estimate the time elapsed since the mineral was last deposited.

The samples were collected under a black tarp, from holes dug into the sediments and were immediately placed in black light-proof bags. All further laboratory processing was carried out under subdued orange light. The laboratory procedures roughly follow those described by Porat et al. (1999). Sand-size (150–177 μ m) alkali feldspars (KF) of specific weight less than 2.58 g/cm³ were extracted from the sand by heavy-liquid separation, following sieving and dissolution of carbonates with 10% HCl. Aliquots of ~ 5 mg of extracted KF were deposited on 10-mm aluminum discs using silicon spray as an adhesive. All measurements were carried out on a Risø DA-12 reader, equipped with an array of infrared diodes and a ⁹⁰Sr β irradiator (Bøtter-Jensen et al., 1991). Equivalent doses of the younger samples were determined by the infrared stimulated luminescence (IRSL) signal and the single aliquot added dose protocol (Duller, 1994). For the older samples the multiple aliquot added dose protocol was used (Aitken, 1998), using mainly the IRSL signal.

Quartz was extracted for some samples following the procedure outlined in Zilberman et al. (2000). However, the optically stimulated luminescence (OSL) signal was very weak, resulting in very large errors on the equivalent dose values. Therefore this mineral was not pursued any further.

External γ and cosmic dose rates were measured in the field in the same holes dug for sample collection, using a calibrated portable Rotem P-11 γ scintillator with a 2-in. sodium iodide crystal (Porat and Halicz, 1996). The concentrations of U and Th in the sediment were measured using Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) and the K contents in the sediment and extracted KF was measured by ICP-Emission Spectroscopy (ICP-AES).

External α and β dose rates were derived from the concentrations of the radioelements in the sediment and the internal β dose rates were determined from the

Table 1 Field and laboratory data for luminescence dating samples

Sample	Depth	De (Gy)	Water	Technique	K KF	Κ	U	Th	Int.	Ext.	Ext.	Ext.	Total dose	Age (ka)
	(m)		(%)		(%)	(%)	(ppm)	(ppm)	β	α	β	$\gamma + \cos \theta$		
TAR-1	1.3	67 ± 6	15	SA	5.3	2.0	2.4	6.5	243	263	1638	1850	3993 ± 240	16.8 ± 1.9
TAR-2	0	4.8 ± 0.8		SA		2.7	2	6.4					~ 4000	1.2
TAR-3	1.5	88 ± 12	15	SA	5.5	2.3	2.4	6.8	251	265	1827	1787	4130 ± 243	21.4 ± 3.1
TAR-6	1	425 ± 29	10	MA	6.47	2.32	2.26	9.47	297	335	2017	1778	4426 ± 256	96.0 ± 8.6
TAR-7	1	279 ± 26	10	MA	4.98	2.16	1.90	8.66	228	295	1851	2001	4376 ± 260	63.8 ± 7.1
TAR-8	0.6	6.2 ± 0.9	10	SA	6.72	2.57	2.17	9.54	308	330	2177	1894	4709 ± 269	1.32 ± 0.21
TAR-9	0.9	66.1 ± 5.4	10	SA	7.72	3.32	1.90	9.17	354	306	2644	2159	5463 ± 306	11.6 ± 1.2
TAR-11	1.1	803 ± 73	10	MA	5.0	2.66	2.53	15.76	299	478	2408	2014	5128 ± 266	157 ± 16
TAR-12	0.85	24.6 ± 2.0	10	SA	5.06	2.66	1.63	5.84	232	222	2100	1646	4199 ± 236	5.86 ± 0.58
TAR-14	0	20.7 ± 7.5											~ 4000	5.1
TAR-15	0.75	27.9 ± 2.0	10	SA	4.98	2.57	1.44	5.62	228	205	2013	1613	4059 ± 228	6.62 ± 0.55
TAR-16	1	354 ± 23	10	MA	5.89	2.57	1.99	8.88	270	306	2143	1613	4331 ± 246	81.7 ± 7.1

De: measured using infrared stimulated luminescence on alkali feldspars. SA: single aliquot added dose protocol.

MA: multiple aliquot added dose protocol. Grain size for all samples: $149-177 \mu m$. Water contents are estimated at either $10 \pm 5\%$ or $15 \pm 5\%$, depending on the sediment. All dose rates are in μ Gy/year. γ dose rates measured in the field. Depth is from the river bed.

K contents of the extracted KF. An a-value of 0.2 ± 0.05 was used for α -efficiency corrections (Mejdahl, 1987; Rendell et al., 1993). Water contents were estimated at $10 \pm 5\%$. Table 1 lists all field and laboratory measurements and the dose rate calculations. Errors on individual dates are based on errors from all laboratory and field measurements and include analytical and random errors resulting from inhomogeneities in the sediments.

The luminescence ages in this study (Table 1) should be considered as minimum ages, particularly ages greater than 20 ka, for the following reasons: Dose rates are very high (4-5.5 Gy/1000 years) therefore the luminescence signal grew rapidly and may have reached an early saturation (Aitken, 1998) and signal fading may have occurred (Huntley and Lamothe, 2001).

4. The thrust-generated anticlinal Ak-Teke Hills

The structure of the Ak-Teke Hills was described by Schmidt (1983) as a Neogene anticline of Mid-Issyk-Kul Formation. The sedimentary section underlying the Ak-Teke was studied by Naperstkin et al. (1967). The Issyk-Kul Formation exposed in the Ak-Teke Hills displays cyclic alternations of hard and well-bedded platy sandstones with pebbles; brownreddish siltstone and clay; fine and coarse sand and clast-supported conglomerates. No boulders are found in the Issyk-Kul Formation, which is a useful field criterion for differentiating it from the younger Quaternary gravel veneer capping the hills. The Issyk-Kul formation represents a fan environment along the margins of the Issyk-Kul depression, and is dated by ostracods and pollen to the Late Pliocene (Grigina and Fortuna, 1981; Fortuna, 1993). The asymmetry of the Ak-Teke structure was realized by Korjenkov (1988, 2000) and Streltzov et al. (1994) who discussed the genetic fold-fault relations, although without invoking the latest fold and thrust concepts. These concepts are also not displayed in the geological section across the study area (Fig. 5).

The northernmost slopes and peaks of the Ak-Teke Hills are partially capped by Pleistocene fluvio-glacial bajada deposits, predating the up warp of the Ak-Teke. This veneer includes large granite boulders which could not have been derived from the Issyk Kul formation. The veneer is best preserved at the northeastern peaks of the Ak-Teke and tapers southwards due to intensive stripping.

Three structural cross-Ak-Teke sections (Figs. 4 and 6) were unified into one (Fig. 7) which reveals an asymmetric anticline with a steep and overturned southern forelimb. Dips exposed along the Chon Dyobyo creek across the northen Ak-Teke Hills (Fig. 8) similarly reveal a northward gently dipping $(2-6^{\circ})$ backlimb which changes into an abrupt plunge $(22-31^{\circ})$, demarcating the sharp bounding zone along the northern bajada.

Additionally, we have found in a river bank outcrop located north of the backlimb of the Ak-Teke Anticline (N in Fig. 4), an onlapping wedge system (Fig. 9) with units 2, 3, 4 showing a gradual increase of the dip northward. We infer a progressive drag of the up-warping backlimb and transformation of the contacts between the onlapping units, which are partly erosional, into a set of progressively steepening syntectonic, angular unconformities. The up-warp caused formation of local sag ponds, shown in the log by the brown-red, massive, gravel-free silty wedge (Fig. 9, unit 4). The reversed fanning of the dips northwards and the 8-10° southward slope of the overlying alluvium (unit 5) indicate renewal of the downfan drainage. Asymmetric folds with steep or overturned front limbs are commonly associated with thrusting and fault-propagation folds (Strecker et al., 1995).

In the south the plunge of the Ak-Teke Hills is observed along the eastern valley wall of the Toru-Aygyr river. Here the Issyk-Kul Formation dips 45-73° N212 E. Along the contact of the Ak-Teke Hills with the southern bajada, exposures of the Issyk-Kul Formation also show subvertical to overturned positions, with dips up to 45-56°N 359E. In the southern trench, the Issyk-Kul Formation is upthrown and overturned, dipping $47-54^{\circ}$ to the north (Fig. 10, unit 1), indicating a thrust fault that dips away from the basin. The southern border of the Ak-Teke Hills has no hydrographic expression. Its surface trace, however, forms a very sharp line between the 30-40 m hilly relief of the intensively incised Ak-Teke and the smooth surface of the southern bajada (Fig. 3). Small alluvial fans bridge this sharp morphostructural boundary, which is also observed as a fault in the Toru-Aygyr valley bed (Fig. 11).



Fig. 5. Geological section across the study area after the Hydrogeological Department of the Geological Survey, Bishkek (Streltsov et al., 1994), based on surface exposures, boreholes, electric resistivity and seismic reflection profiles. For location see Fig. 2. Note the clear demarcation of the Ak-Teke and the Tekren anticlines. No structural asymmetry is shown.



Fig. 6. Topographic and structural sections (for location see Fig. 4): section A-A' crosses the entire Ak-Teke anticline. Section B-B' crosses the anticline-southern bajada boundary and section C-C' crosses the northern bajada-anticline boundary. Dips in the Issyk-Kul Formation are indicated, each is based on 1-4 measurements.

Westwards, beyond the Toru-Aygyr valley the Ak-Teke anticline plunges below the Quaternary veneer.

An embryonic up-warp is detectable on the southern bajada, named the Tekren anticline (Fig. 5), based on geoelectrical data and on drillings (Streltzov et al., 1994). The structure is also clearly visible on Landsat imagery supported by an anonymous referee. It shows on the surface of the bajada as a series of low (<5 m) hills, which do not yet offset the drainage. The northern flank of the Tekren up-warp is shown along the wall exposures of the Toru-Aygyr valley as a 6° northwards plunging limb. Sharpyldak conglomerates



Fig. 7. Reconstruction of the Ak-Teke as a thrust hanging-wall anticline, based on dips measured in the field and shown on Fig. 6. The oversteepened southern fold limb is interpreted from the overturned dips in the southern trench (Fig. 10). Note that the morphology bears no relation to the structure.

fill the syncline between the Ak-teke and the Tekren. The Tekren structure indicates a frontal thrust migration towards the Issyk-Kul basin.

Schmidt (1983) has suggested that the Ak-teke and the Tekren anticline structures cause subterranean damming of the ground water. The dense vegetation along the Toru-Aygyr stream bed by the Ak-Teke (Fig. 3, no. 8), west to the Tekren up warp (no. 9) and along the Dyuresu river (no. 10) seem to provide the surficial evidence for such ground water barriers.

5. Quaternary bajada sediments

The structural warp of the Ak-Teke Hills stands out against the more planar appearance of the



bed rock: Issyk-Kul formation

Fig. 8. The structure along the Chon Dyobyo creek at the crossing from the northern bajada southwards across the backlimb of the Ak-Teke (for location see Fig. 4 by trench N). Chon Dyobyo hill and the bajada are correctly located in the background, but not to scale. The dips exposed at sites 1-7 along the valley bed (N-M), which is entrenched by the active creek, demonstrate the structure: Site 7 reveals undisturbed alluvium of the northern bajada dipping to the south. Station 5 records the dragged alluvium dipping to the north, shown in detail in Fig. 9. Stations 1-4 demonstrate exposures in the Issyk-Kul Formation starting with mild northwards-dipping (Station 1) and gradually steepening towards the backlimb (Stations 2–4).



Fig. 9. Log of the eastern bank of Chon Dyobyou creek at the backlimb of the Ak-Teke Hills (Fig. 4, N): 1—Pebbly–cobbley unit, with few boulders, poorly sorted, matrix- to clast-supported. 2—Coarse gravelly unit up to boulder size, clast-supported, subangular, poorly sorted, dipping $10-20^{\circ}$ northward. 3—Poorly sorted, clast-supported pebbles, dipping $22-33^{\circ}$ northwards. 4—Wedge-like, reddish, massive silt with very coarse yellow–brownish sand, almost gravel-free, dipping $32-36^{\circ}$ northward. Units 1-4 show a gradual steepening northwards and final erosional truncation. The truncation plan dips 2.5° S to 6° to the north. 5—Poorly bedded and medium-sorted loose grit, granules and pebbles up to cobble size with imbrication and subhorizontal bedding indicating post-deformational deposits. The alluvial surface at the top is the first terrace above the active creek, sloping $8-10^{\circ}$ southwards. Its age is 11.6+/-1.2 ka (TAR 9, Table 1). Main lithology of the gravel is granite, diorite and granodiorite.

sloping bajadas (Fig. 3). The surface roughness, which denotes drainage density and reflects the resistance to erosion, clearly differentiates the southern and northern bajadas from the densely eroded, sandy Ak-Teke anticline with its typically long spur crests.

The northern bajada is composed of discrete fans (Fig. 4), filling a backlimb low and suggesting that fan-coalescence has not been completed. The southern bajada is very different: it is a flatter alluvial surface topping a forelimb basin.

Earlier studies (Naperstkin et al., 1967; Trofimov and Grigina, 1978; Streltzov et al., 1994) defined four Quaternary bajada units, related to different moraine stages:

Q1—Sharpyldak Formation: these are the oldest Quaternary fans. In the study area the Sharpyldak Formation is mostly buried. It is composed of coarse, well-sorted and medium to well-rounded gravel and conglomerates. Its thickness, estimated from boreholes, ranges from 30 to 300 m, and its age is Early to Middle Pleistocene.

Q2 is composed of coarse pebbles to boulders of fluvio-glacial origin and could have been derived only from the higher peaks north of the study area.

Ν



Fig. 10. Log of the eastern wall in the southern trench (for location see Fig. 4, S): upthrown hanging wall of Issyk-Kul Formation (unit 1) dipping $47-54^{\circ}$ to the north and composed of fine to coarse sand and siltstones alternating with a well-cemented pebble conglomearte containing granodiorite, granite, gneiss and aplite. The thrust fault almost approaches the surface. Footwall beds (unit 2) are dragged along the fault, dipping $38-27^{\circ}$ southward. Both units are truncated and covered by loose sandy–gravelly alluvium containing pebbles of quartzdiorite, granodiorite and granite (unit 3).

This unit forms the main surface of the northern bajada and is sharply dragged and warped in front and on top of the northern peaks of the Ak-Teke Hills (Figs. 12 and 13). Its age is Middle Pleistocene and it predates the warping of the Ak-Teke Hills.

Q3 forms the main surface of the southern bajada as well as the sediments deposited in the valleys



Fig. 11. Log of the western wall in the Toru-Aygyr trench, located across the southern trace of the front limb of the Ak-Teke anticline (Fig. 4, T). The sandy-clay on top the gravel is floodplain deposit. Tar-8 was sampled outside the trench, on a surface upthrusted 1.5 m above the flood plain. It indicates the youngest tectonic event we have observed and dated within the study area -1.3+/-0.2 ka (Table 1).



Fig. 12. View toward the contact zone between the Ak-Teke anticline at the Chon-Dyobyo hill (1) and the northern bajada (2) indicated by a sharply entrenched subsequent creek (B). At middle distance a smooth bajada surface (A) is dragged up along the backlimb of the Ak-Teke (shown as type A in Fig. 13).

entrenched in the northern bajada and in the Toru-Aygyr and Kultor valleys. Its age is Late Pleistocene. The Ak-Teke anticline formed between deposition of Q2 and Q3. Q4 forms the youngest and the lowest terrace along the creeks in the study area, including the flood plain and the active bed. Its age is Holocene.



Fig. 13. Sketch map, based on air photos and field observations, demonstrating the contact zone of the northern bajada with the Ak-Teke anticline (contact between zones 1 and 2 in Fig. 3). Selected topographic and drainage features are shown. Segment A is the well-preserved bajada surface dragged up along the backlimb. Segments B show subsequent creeks that trigger the headward dendritic entrenchment.

The Quaternary chronostratigraphy in the intermontane basins in the Tien Shan is based on magnetostratigraphic data (Chen, 1994), correlation of glacial periods (Shi et al., 1984) and absolute ages (Feng, 1997). Accordingly, Q1 is dated: 2.92 to 1 Ma; Q2—1 Ma to 120 ky, Q3—120 ky to 12 ky and Q4—12 ky to present. Other time scales define Q1—500–1800 ky and Q2—120–500 ky.

The contact zone of the northern bajada with the backlimb of the Ak-Teke exhibits two types of morphologies which indicate different stages in the erosional stripping: Type A (Figs. 12 and 13)—the Q2 bajada climbs over the backlimb of the Ak-Teke Hills uninterrupted by any subsequent drainage. Type B (Figs. 8 and 13)—a subsequent gully system develops along the contact zone and marks a sharp boundary between the bajada and the backlimb.

6. The drainage system

The Ak-Teke Hills are morphologically strongly asymmetric in the N–S direction (Fig. 7). The water divide migrated to the northern boundary of the Ak-Teke anticline (Fig. 13), leaving, out of 2.5–4.0 km of its total width, only a very narrow zone of 100–300 m to drain northwards. No significant northward-draining catchments have yet evolved and thus no alluvial fans are fed from the backlimb of the anticline.

The strong asymmetric morphology, with the higher and steeper relief in the north, does not fit the asymmetric thrust fold structure of the Ak-Teke with its broad and flat crestal zone, moderately inclined backlimb and the overturned, southern front limb (Fig. 7). There is no asymmetric orographic precipitation pattern (Beaumont et al., 1992) which could have caused strong spatial erosional variations. The greatest elevations on the Ak-Teke do not correspond to the region of the greatest uplift which is adjacent to the forelimb. The recent morphology does also not fit the model of a steep forelimb with short catchments suggested by Burbank and Anderson (2001).

The morphological asymmetry results from the competing processes of up-warping and erosional feedback (Jackson et al., 1966). The asymmetry of the Ak-Teke anticline reflects the increase in the shear stress and erosion as a negative feedback to the

steepening of the southern limb. The increase in the sediment flux towards the southern bajada and the upslope migration of the drainage divide made the Ak-Teke anticline a deeply incised and exhumed fold, with a southward decrease in the residual relief. Such trends are well demonstrated by additional studies (Willemin, 1984) and by numerical models of coupled tectonic uplift and erosion (Anderson, 1994; Willett, 1999).

The Ak-Teke anticline strikes $100-105^{\circ}$ oblique to the piedmont contour lines (Figs. 3 and 4). The main drainage routes cross the anticline almost perpendicular to the axis. Downstream from their exit to the southern bajada, the creeks gradually return to a somewhat more N–S direction, thereby responding to the initial, pre-Ak-Teke, regional piedmont slope. Wind gaps were observed only at the



Fig. 14. The catchment areas of the main rivers, the Dyuresu and the Toru-Aygyr which initially sourced the study area and later deeply incised the up-warping Ak-Teke anticline. The study area transformed into an abandoned alluvial terrace, disconnected from the rivers. Note the relative small area of the northern bajada (N.B.). Also shown are the main northern peaks on the Ak-Teke anticline.

northeastern backlimb of the anticline. They are indicative of defeat at an earlier stage (Korjenkov et al., 1999; Burbank and Anderson, 2001).

In the pre-Ak-Teke period, the entire study area was a planar, smoothly sloping piedmont, controlled by the Toru-Aygyr, Kultor and the Dyuresu river systems, with drainage basins of 134 and 90 km², respectively (Fig. 14). These rivers, which are typical hinterland systems with large catchments within the higher eroding parts of the orogen, up to an altitude of 3833 m, provided the water needed to source the pre-Ak-Teke fans and bajadas.

The water gaps across the Ak-Teke (Fig. 15) reach a maximum valley depth of 60-70 m and



Fig. 15. The recent drainage basins of the antecedent creeks that cross the Ak-Teke. Note the long and narrow shape of each catchment and their very small area in front of the water gap.



Fig. 16. View westwards: the Toru-Aygyr river and its lowest terrace slope southwards towards the basin, across the Ak-Teke anticline (green arrow), indicating the antecedent drainage. The higher surface (red arrow) is an up-warped terrace sloping northwards demonstrating the reversed direction.

indicate the competence of the initial antecedent drainage system to breach and match the rate of uplift. The Ak-Teke did not become a shutter ridge like the Wheeler Ridge (Burbank and Verges, 1994) or like the Chet-Korumdy Ridge (Korjenkov et al., 1999). No major ponding, in the form of piggyback fill, could develop under such well-drained conditions. The transverse valleys, with their relatively narrow hydraulic geometry, became efficient conduits for carrying the discharge through the Ak-Teke anticline. Each channel maintained its drainage gap across the growing structure. Unlike comparable cases of interrupted piedmont drainage in the Precordillera of the Andes (Jordan et al., 1993) or in the pre-Himalaya (Gupta, 1997), no single point-sourced larger-fan was formed on the southern bajada in response to the up-warp of the Ak-Teke. Instead, a line-source dispersal system with regularly spaced outlets through the Ak-Teke anticline (Fig. 15) formed the relative smooth surface of the southern bajada. With time, the Toru-Aygyr and the Dyuresu rivers gradually became deeply entrenched and the Ak-Teke and bajadas transformed into a raised, inactive morphological surface, which is disconnected from the deeply incised hydrographic system (Fig. 14). The present-day drainage basins sourcing the creeks which cross the northern bajada and the Ak-Teke through water gaps, are completely disconnected from the main drainage systems with the extensive hinterland catchments and are extremely small (Figs. 14 and 15), 0.9-6.4 km². Altogether they form only a 12 km² catchment area, which is one order of magnitude smaller than each of the drainage basins of the Toru-Aygyr and the Dyuresu rivers. They are narrow, linear, local catchments (Fig. 15) and carry a significantly smaller discharge and sediment load. With such a small sourcing area the creeks seem underfit, indicating insufficient stream power to have entrenched the water gaps across the rising Ak-Teke Hills. Similar underfit conditions are often displayed by streams with extremely small drainage basins which appear to have accomplished a disproportionally great labor (Boudiaf et al., 1998; Hsieh and Knuepfer, 2001).

The up-warped area of the Ak-Teke shows no convexity of the longitudinal profiles. N–S sections along the creeks, from the northern to the southern

bajadas through the Ak-Teke Hills, exhibit a perfect regularity. The longitudinal profiles have, however, not yet attained the typical concavity, characteristic of the fan environment. The up-warp of the Ak-Teke is not demonstrated by the active channel network, but by the uplifted tilted morphology, in the form of river terraces sloping northwards, clearly visible in the field (Fig. 16), reflecting the reversed drainage direction.

The drainage pattern across the Ak-Teke is mainly sub-parallel (Figs. 4 and 15), indicating the steep surface slope gradients which are mainly in the $1^{\circ}9'-2^{\circ}3'$ range. The steepest segments are on the northern bajada— $2^{\circ}4'-2^{\circ}8'$. The southern bajada manifests the gentlest slopes $1^{\circ}7'-1^{\circ}8'$.

The drainage pattern on the northern bajada is not the usual downslope diverging braided pattern, typical of fans, but a slightly downfan converging dendritic system which extends and dies out upfan towards the apex (Figs. 17 and 18). Such a pattern forms when a local base level outside an alluvial fan, along its periphery, triggers headward erosion towards the fan apex. In the study area, the subsequent creeks along the northern front of the Ak-Teke operated as such a local base level (Fig. 18) and triggered entrenchment of the dendritic systems headward (Fig. 13, area B). Where no subsequent creeks developed (Fig. 13, area A) upfan entrenchment did



Fig. 17. Looking northwards from the Ak-Teke: the entrenched northern bajada surface. Note the dendritic pattern dying upfan.



Fig. 18. Headward entrenchment of the dendritic drainage pattern on the northern bajada, controlled by subsequent creeks at the backlimb of the Ak-Teke, schematic.

not occur and the bajada surface is still preserved undissected.

7. Chronology

Samples collected for luminescence dating from the alluvial surfaces give ages ranging from 157 ka before the present to 1.3 ka (Table 1). For the reasons mentioned above, these ages should be viewed as minimum ages. Sediments on the northern bajada were dated to 157 ka (TAR-11). The sample taken from a high alluvial terrace incised into the Ak-Teke anticline, west of the Toru-Aygyr valley (TAR-6), was dated to 96 ka. The highest terraces were not dated. The minimum age constraint for the northern bajada is thus 157 to 96 ka, assigning this surface to Mid-Pleistocene. Within this period began the up-warp of the Ak-Teke anticline, accompanied by the uninterrupted response of fluviatile breaching by the Kultor, Dyuresu and Toru-Aygyr rivers.

Naperstkin et al. (1967) noted that in the Lower Quaternary alluvial deposits, estimated to be 700–400 ka according to the old soviet scheme, no red Ordovician granites from the Kyzyl-Kultor granite core (Fig. 4) are observed in the northern bajada. These granites do, however, appear among the northern bajada fan deposits and indicate that the granite core of Kyzyl-Kultor was already uplifted and exposed before at least 157 ka.

The morphological development can be further constrained by samples from within the Toru-Aygyr valley—TAR-16, TAR-7, TAR-3, TAR-1, TAR-15 and TAR-8 (Table 1, Figs. 4 and 11). These samples, which were dated 82 to 1.3 ka, indicate the period of entrenchment of the main rivers to below the surface of the Ak-Teke and the bajadas (Fig. 19) which became an abandoned terrace sourced by a drainage



Fig. 19. Topographic profile ESE–WNW along the northern peaks of the Ak-Teke anticline. The trace of the northern bajada is projected, where the topographic map permitted, to a resolution of 5-10 m, against the backlimb. It is absent between the Chon-Dyobyo creek and the wind gaps, indicating the zone of uninterrupted Quaternary alluvium veneer (Fig. 13). The profile shows the Ak-Teke anticline as a raised terrace-like surface between the deeply entrenched Toru-Aygyr and the Kultor rivers. The water gaps indicate the misfit antecedent valleys across the Ak-Teke.

area several times smaller than the catchments of the Dyuresu and Toru-Aygyr, and thus appear underfit. Had significant up-warping continued under such underfit conditions, drainage offsets would be expected. Absence of evidence for drainage blocking or deflections in the recent underfit valley system of the Ak-Teke suggest that no major uplift continued after the incision of the Toru-Aygyr and the Kultor rivers to below the surface of the Ak-Teke and the bajadas, which occurred not later than 82 ka.

The entrenchment of the Toru-Aygyr and the Kultor rivers partly indicates the transition to a degradational regime induced by a warmer and wetter climate; decrease in the sediment yield and increase in stream discharge and power during the latest Pleistocene (Bull, 1991). In the Chinese Tien Shan, such a transition was related by Molnar et al. (1994) to deglaciation following the last glacial period.

The youngest sample in the Toru-Aygyr valley was taken from an uplifted floodplain surface (TAR-8). It gave an age of 1.3 ka and indicates the last recorded tectonic pulse of the Ak-Teke. The faulting of flood plain deposits in the Toru-Aygyr valley (Fig. 11), on the trace of the southern forelimb (Fig. 4), indicates a historic tectonic pulse and suggests that tectonic activity along the southern Ak-Teke fault is continuing today.

8. Summary and conclusions

From the overturned forelimb of the Ak-Teke we infer a fault propagation fold (Suppe and Medwedeff, 1984) which caused the partitioning of the foothills into the northern and southern bajadas. The very gentle Tekren warp, which was traced by Mikolaichuk (2000) from the eastern end of the Issyk-Kul basin, could, however, result from a low-angle thrust that branches from the Ak-Teke frontal fault. The Ak-Teke Hills are the morphologically mature expression of a frontal fold at a thrust belt edge, propagating from the Kultor thrust and the Kyzyl-Kultor granitic core into the Issyk-Kul basin.

The Ak-Teke hanging-wall anticline accommodated the shortening compressional strain during the Late Pleistocene through Holocene. The tectonic bulge was subsequently truncated by erosion, so that much of the structural relief is not apparent at the surface. Compared to the Wheeler Ridge, California (Medwedeff, 1992) the Ak-Teke anticline was severely deroofed.

The response of fluvial systems to growing folds, as conceived in current models (Burbank et al., 1996a), suggests the following developments in the study area: Before the onset of warping, the study area was a continuous fan and bajada surface, sourced by the Dyuresu, Kultor and Toru-Aygyr rivers through the Kyzyl-Kultor granitic hills. This morphological stage of "alluvial fans of large mountain rivers" has already been documented in prior research (Naperstkin et al., 1967). During the warping of the Ak-Teke, the drainage system was able to keep to its antecedent courses and maintained its channels by incising water gaps through the growing Ak-Teke anticline (Fig. 19). Under such conditions the anticline never became a major barrier to the drainage. In the following stage, the Dyuresu and Toru-Aygyr rivers became gradually entrenched down to 85-125 m below the northern bajada and 71-82 m below the Ak-Teke floor, leaving the study area as a beheaded and abandoned surface, cut off from its former sourcing basins and left with a dramatically smaller discharge. The recent underfit valleys across the Ak-Teke anticline indicate that no major uplift has occurred since their formation.

Following the uplift of the Ak-Teke and its imposed gradient change we could expect some increase in sinuosity of the channels (Holbrook and Schumm, 1999). It is, however, noteworthy that the antecedent drainage across the Ak-Teke does not show such response to the up-warp and tilting. The high rate of stream incision controlled by the steep gradients of the piedmont setting caused the channels not to stay and flow through their own sediments but to incise and become bedrock-confined which impeded their ability to migrate.

Luminescence datings suggest (Fig. 20) that the upwarp of the Ak-Teke started after 157 ka, within the period 157–96 ka. 82 ka marks already the entrenchment below the bajada surface and the formation of the recent Toru-Aygyr valley. The 1.3 ka seismic event indicates the recent continuation of the tectonic activity which, did, however, not propagate up to the surface along the entire southern boundary of the Ak-Teke.

Maximum topographic separation between the uplifted alluvial veneer, on top of the up-warped anticline at the northern front of the Ak-Teke and



Fig. 20. Field relations between the main dated alluvial surfaces, schematic. Sample numbers are indicated.

the in situ elevation of the veneer on the northern bajada surface (Fig. 19) is about 45 m. This is a minimum magnitude, decreased by the erosion which the pristine surface has experienced since abandonment. Maximum depth of the water gaps is greater, about 60-70 m, and indicates the incision which is part of the perpetual accommodation to the low regional base level of Lake Issyk-Kul.

The incision rate which is a proxy for the uplift rate is 0.6 mm/y. This uplift rate falls within the range of 0.4-0.8 mm/y calculated by Korjenkov (1987) for the Middle-Late Pleistocene in the SW Issyk-Kul region and for the Toru-Aygyr river in the Quaternary (Korjenkov, 1988, 2000). These incision rates, are smaller by one order of magnitude when compared to the 5– 10 mm/y high river incision rates in the Himalayan foreland (Lave and Avouac, 2000; Burbank et al., 1996b, Burbank, 2002).

The drainage area of the creeks that breach the Ak-Teke Hills from the northern to the southern bajadas is several times smaller than those of the Dyuresu and Toru-Aygyr rivers. Since a stream catchment area may be substituted in proxy of discharge (Montgomery and Dietrich, 1994), these very small, beheaded catchment areas indicate a low erosive capability, which seems underfit to have breached the Ak-Teke Hills. The structural reconstruction compared to the exhumation of the Ak-Teke anticline indicates that the most deeply truncated area is the forelimb along the southern boundary of the Ak-Teke. Here uplift and exhumation matched most closely. The highest relief gradually migrated towards the northern boundary of the anticline, where the Quartenary gravel veneer is best preserved.

The study area demonstrates localized warping within an otherwise aggradational piedmont environment in an intermontane basin, which is part of a sedimentary basin inversion process. The basinward migration of the thrust is a progressive stage in the basin closure by collision tectonics which led to the uplift and erosion of the former basin fill. The study area demonstrates the morphological response to folding deformation in piedmont areas induced by thrusting following convergence and shortening.

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