Differential structural and geomorphic mountain-front evolution in an active continental collision zone: The northwest Pamir, southern Kyrgyzstan

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ABSTRACT

Western, central, and eastern segments of the Trans Alai mountain front in the northern Pamir of Kyrgyzstan have accommodated varying degrees of approachment of the Pamir orogen with respect to the Tien Shan (Shan = Mountains) to the north. Ongoing collision between the northwestern corner of the Indian indenter and Eurasia has resulted in closure of the intramontane Alai Valley, which separates the Tien Shan and Trans Alai (Pamir) ranges. The different segments highlight the processes of shaping tectonically active mountain fronts in a semiarid environment. In this study, we have characterized this variation in processes with compilations of regional tectonic information, detailed geologic and geomorphic maps, topographic analyses, and interpretation of seismic reflection data. Along the sinuous western segment of the mountain front, dextrally oblique thrusting has created a wide (>500 m) zone of highly erodible fault gouge. This fault zone impinges on the southern Tien Shan, but complete basin closure is prevented by erosion due to the westward-flowing Kyzilsu River; the Kyzilsu valley forms the only outlet and is the vestige of a formerly contiguous sedimentary basin linking the Tarim Basin of China with the Tadjik Depression in the west. Numerous large landslides rooted in the fault zone have covered the active fault, which is partially undercut by the Kyzilsu River. Older, large landslides in this setting are associated with different levels of fluvial terraces of the former or present course of the Kyzilsu River, suggesting a causative relationship between lateral fluvial scouring, failure of mechanically weak mountain fronts, ongoing faulting, and mass transfer. Along the linear central segment, deformation is confined to a narrow single south-dipping thrust fault that juxtaposes Pliocene–Pleistocene and Holocene conglomerates. In this sector, the mountain front has numerous Holocene offsets. This prevailing structural style and the long-term deformation are underscored by multiple flights of gently sloping pediments and glaciogenic terrace surfaces that abruptly terminate at the steep mountain front, which also forms the boundary with the wide regraded piedmont. In contrast, closure between the Pamir and Tien Shan is complete along the eastern segment. The eroded and sinuous mountain front has been tectonically inactive during late Quaternary time. Small drainage-basin areas and low stream power apparently were not conducive to maintaining an eastern outlet to the Tarim Basin. Active deformation has stepped back into the orogen and now is concentrated along the Markansu Fault and within the Tien Shan to the north. The large drainage-basin area of the Kyzilsu River and the constant, glacially fed runoff guarantee that an effective interplay between tectonic uplift and erosion is maintained. Therefore, the geomorphically different mountain-front segments highlight the relationships between tectonic uplift and geomorphic processes, which in turn are controlled by lithology, topography, and the history of sediment routing throughout the landscape.

Keywords: drainage basin, Main Pamir Thrust, mass movements, neotectonics, orogenic belts, Pamir.

INTRODUCTION

Studies of mountain fronts along extensional basins in arid to semiarid regions have demonstrated that changes in fault geometries and slip rates divide the mountain fronts into geomorphic and tectonic segments, characterized by different surface processes and earthquake behavior over time scales of 10–1000 k.y. These segments may act as semi-independent rupture zones during earthquakes and often represent morphotectonic segments with sustained localized deformation and erosional processes. This concept has improved our understanding of the complex interplay among topography, tectonic deformation, inherent lithologic variation, and superposed climate-controlled sediment transport processes in these environments (e.g., Bull and McFadden, 1977; Gawthorpe and Hurst, 1993; Jackson and Leeder, 1994; Allen and Hovius, 1998; Gupta et al., 1999; Allen and Densmore,

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GSA Bulletin; February 2003; v. 115; no. 2; p. 166–181; 10 figures.

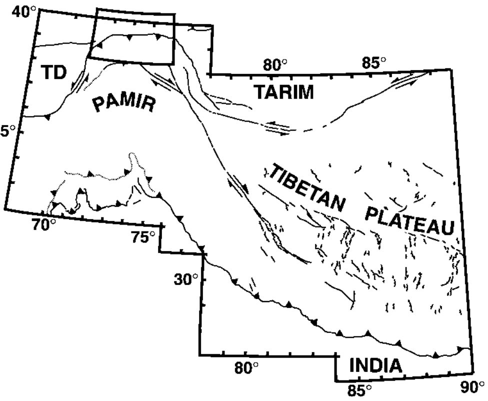

Figure 1. Location map with major late Cenozoic faults of the Pamir orogen in the northwestern sector of the collision zone between India and Eurasia. TD—Tadjik Depression. Rectangle outlines area covered by Figure 2. Modified from Tapponnier et al. (1981), Armijo et al. (1986), Frisch et al. (1994) and Arrowsmith and Strecker (1999).

2000). What is important to note is that geometry and slip-rate changes along faults clearly influence topography in these regions. These factors may vary along the total length of a fault-bounded range front; however, segments typically 10–50 km long exist where these factors remain relatively constant (e.g., Schwartz and Coppersmith, 1984).

Geomorphically and structurally prominent mountain-front segments in areas undergoing shortening deformation such as the Trans Alai Range of Kyrgyzstan are analogous to segmented mountain fronts in extensional settings (Figs. 1–4). The Trans Alai constitutes the northern part of the Pamir orogen, located in the collision zone between India and Eurasia (e.g., Burtman and Molnar, 1993). West of long. 73°30′ E, the Trans Alai range front is delineated by the Main Pamir Thrust, which can be divided into three distinct morphotectonic segments, hereafter referred to as the western, central, and eastern segments (Figs. 5 and 6). Individual fault segments are separated from each other by complex en echelon transfer zones with dextral strike-slip and oblique thrust faults, up to 20 km wide (Strecker et al., 1995; Arrowsmith and Strecker, 1999). These structures thus represent analogues of the intra- and interbasin transfer structures typical of extensional environments (e.g., Gawthorpe and Hurst, 1993). Along strike, the mountain-front segments have accommodated varying degrees of northward displacement of the Pamir orogen with respect to the southern mountain front of the Tien Shan (Shan = Mountains) (Nikonov et al., 1983; Burtman and Molnar, 1993; Arrowsmith and Strecker, 1999) (Figs. 2 and 3). This variation in displacement has resulted in a progression of closure of the intramontane Alai Valley, which separates the Tien Shan and Trans Alai (Burtman and Molnar, 1993; Pavlis et al., 1997; Arrowsmith and Strecker, 1999; Coutand et al., 2002). We hypothesize that the morphology of the range front and the degree of basin closure are dependent on the kinematics of the collision, the rock types exposed at the surface and the structural damage they have sustained, and the distribution of surface processes in the landscape. The latter may depend on stream power, climate, and regional geomorphic history. Because each of these factors apparently varies between the morphotectonic segments, each segment may represent a different stage in the advance of the Pamir mountain front and basin closure. Therefore, this area presents an excellent opportunity to evaluate the role and progression of different surficial and tectonic processes in range-front development.

In this paper, we describe the structural setting of the Trans Alai region and analyze its relationship with the differential geomorphic evolution of individual mountain-front segments along the convex northern perimeter of the orogen. We characterize and integrate the topography, geomorphology, and geology of the region from topographic maps, satellite imagery, published geologic mapping, and our own field studies. We evaluate the interplay between Quaternary climate change and tectonism by examining terrace formation in the hanging walls of active mountain fronts. In addition, digital elevation models based on 1:50,000 topographic maps are used to assess the magnitude of excavation and the dominance of different transport processes along structurally contrasting mountain-front segments. Our results show that the geometry and history of the thrust system depend on the rates and processes of removal of material from the mountain range and its subsequent routing through the landscape. Removal rates are largely controlled by stream power along the main drainage system of the region. In areas with low removal rates, convergence is no longer accommodated at the major mountain front, but rather along faults bounding intramontane basins to the north and south. In areas with moderate removal rates and wider separation between the Trans Alai and the Tien Shan, incomplete exhumation of a recently uplifted pediment provides sediment that is moved down the broad piedmont to the major trunk stream. Thrust faulting is localized at the piedmont and mountain-front junction. Finally, where stream power is high and closure of the intervening basin nearly complete, sediment is removed from a cataclasite zone at the mountain front via landslides and delivered almost immediately to the constricted trunk stream.

METHODS

We used CORONA declassified satellite photography and Kyrgyz 1:50,000- and 1:200,000-scale topographic maps as a base for intensive geologic and geomorphic mapping in two field seasons of five weeks each during July–August of 1996 and 1999 (Figs. 5 and 6). These data were rectified and/or geographically referenced with Arc/Info Geographic Information System and Erdas Imagine remote sensing software. In addition, stereo aerial photography of the Alai Valley (1:50,000) aided in the assessment of geologic and geomorphic features. We also interpreted a petroleum industry-style seismic reflection section along a north-south line to define the subsurface structure.

To construct high-resolution topographic profiles of terraces and piedmont surfaces, we used a laser theodolite to gather surveyed data. Digital elevation models (DEMs) of parts of the range fronts were produced from the geographically referenced 1:50,000 maps. Supervised autotracing of 20–40-m-interval contour maps and, in places, stream networks, were used to construct three high-resolution (30 m) DEMs (e.g., Hutchinson, 1989; Tarboton, 1997). Shaded-relief maps exemplifying the morphology of the range front were created from these data. In addition, volume-removal calculations from geomorphic surfaces were performed by (1) fitting a plane to the points belonging to each geomorphic surface; (2) requiring this surface to contain the line representing the orientation of the average trunk-stream gradient and direction; (3) where

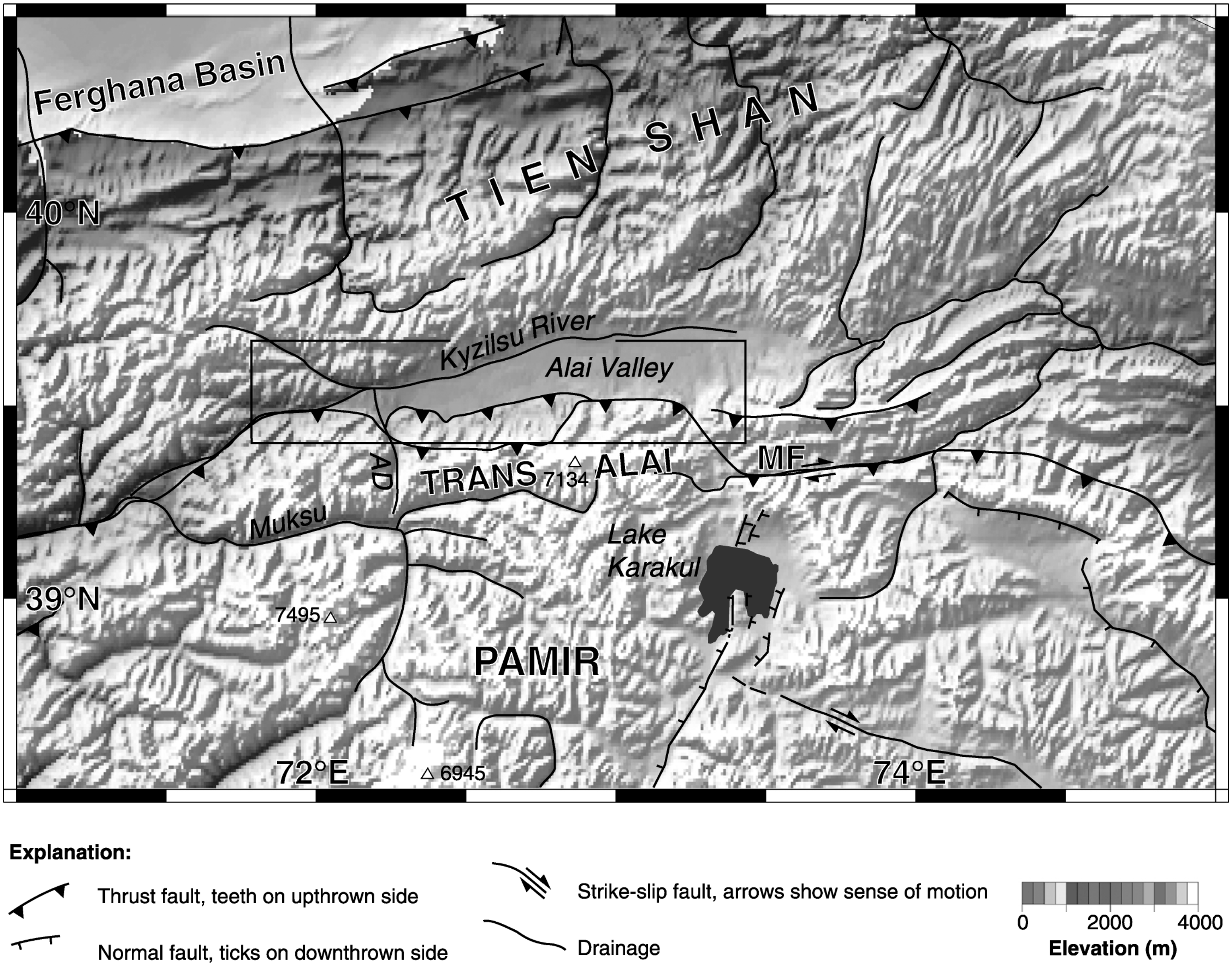

Figure 2. Digital topography (GTOPO30 1 km data set from the U.S. Geological Survey), rivers, and major neotectonic faults of the Pamir and Tien Shan regions. The spot elevations of 7134, 7495, and 6945 m mark the locations of Pik Lenin, Pik Communism, and Pik Revolution, respectively. MF—Markansu Fault, AD—Altyndara River. Pik Lenin is the highest peak of the Trans Alai range. The course of the westward-flowing Kyzilsu River marks the boundary between the Trans Alai and Tien Shan piedmonts. The Alai Valley is a distinctive intramontane depression with a floor at 2.5–3 km elevation, whereas the surrounding ranges reach elevations of >7 km. The Alai Valley is bounded to the south by the Main Pamir Thrust fault (fault trace with teeth on upthrown side). The area covered by Figure 3 is indicated by the outlined rectangle.

appropriate, calculating the volume removal adjusted for the fault dip and horizontal component of displacement; and (4) calculating the distribution of exhumation by subtracting the best-fit surface planes from the current topography. In addition, we used a modified version of the hydrologically corrected version of the GTOPO30 global elevation data set (HYDRO1K DEM; http://edcdaac.usgs.gov/gtopo30/hydro/index.html, 2002) to perform regional-scale geomorphic analysis. To ensure that water is correctly routed into the channel network, stream networks from the data set were modified by using the geographically referenced 1:50,000 scale topographic maps. These data were contoured at a 200 m interval, and artifacts were manually removed after inspection of the 1:50,000 topographic maps. The contour map and stream network were used to create a new, hydrologically correct version of the HYDRO1K data set for the area. From this, we derived the local slope, source area (e.g., Tarboton, 1997), and stream power index (source area times local slope; e.g., Montgomery et al., 2001) for each point in the DEM to understand the distribution of erosional capacity in the landscape and its relationship to deformation.

REGIONAL TECTONICS AND GEOLOGIC FRAMEWORK

The Alai Valley between Trans Alai and Tien Shan is the vestige of a formerly contiguous Cenozoic sedimentary basin, which once linked the Tadjik Depression and parts of the

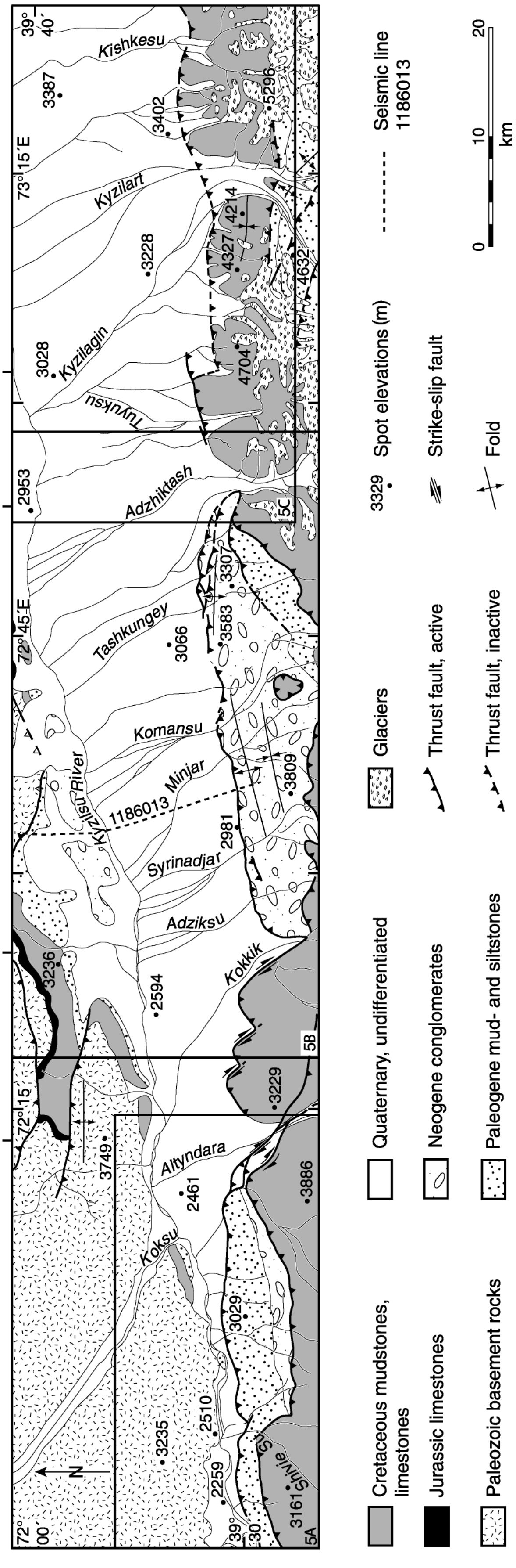

Figure 3. Generalized geologic map of the Alai Valley and northern Trans Alai and southern Tien Shan piedmonts. Based on field, aerial photograph, and CORONA image mapping in 1997 and 1999 and compilation from map sheets of the Geologic Map of the Kyrgize Republic (1964a, 1964b, 1964c), Nikonov et al. (1983), Burtman and Molnar (1993), Arrowsmith and Strecker (1999). The three boxes outline the approximate locations of Figures 5A, 5B, and 5C. The stippled north-south line at Minsar River corresponds to the seismic reflection line in Figure 4.

Tarim Basin in the west and east (Figs. 1 and 2), respectively (Davidzon et al., 1982; Burtman, 2000). The thrust front of the Trans Alai corresponds to an area where Eurasian lithosphere is interpreted to subduct southward and causes numerous earthquakes (Hamburger et al., 1992; Burtman and Molnar, 1993) (Figs. 2 and 3). Well-preserved fault scarps and uplifted and deformed landforms document ongoing tectonism (Nikonov et al., 1983; Burtman and Molnar, 1993; Arrowsmith and Strecker, 1999; Arrowsmith et al., 1999). Holocene geologic data show that the thrust-dominated northern range front of the Trans Alai accommodates at least 6 mm/yr of the 40–50 mm/yr total convergence between India and Eurasia (Burtman and Molnar, 1993; Arrowsmith and Strecker, 1999), and Reigber et al. (2001) reported 23 ± 3 mm/yr of differential movement between the central Pamir, Tien Shan, and regions farther north, based on space geodetic measurements.

Trans Alai, Alai Valley, and Tien Shan

Stratigraphy

The external parts of the western and central segments of the Trans Alai investigated here are mainly characterized by Neogene conglomerates and sandstones, which unconformably overlie Paleogene sandstones and siltstones with intercalated gypsum (Geologic map of the Kyrgize Republic, 1964a, 1964b; Davidzon et al., 1982; Burtman, 2000). The eastern mountain-front sectors comprise Cretaceous red beds and limestones and Paleogene units (Fig. 3). The lower Neogene sedimentary rocks consist of >3-km-thick cross-bedded red sandstones, conglomeratic sandstones, and mudstones that form steep-walled escarpments in the western part of the range. These units grade into upper Neogene gray, blocky to coarse conglomerates, at least 1000 m thick (Coutand et al., 1999). The adjacent Tien Shan is characterized by Devonian limestones and Carboniferous metasedimentary rocks that are overlain by Jurassic conglomerates and sandstone (Geologic map of the Kyrgize Republic, 1964a, 1964b). These units are covered by Cretaceous conglomerates, sandstone, and gypsum that are conformable with Paleogene dolostones and gypsum layers (Czassny et al., 1999; Burtman, 2000). In the piedmont, these strata are unconformably overlain by lower Neogene conglomerates. Quaternary conglomeratic piedmont deposits (Qt$_{1,2}$), terrace and alluvial-fan gravels, and glacial tills (Qm$_1$–Qm$_3$) overlie the Tertiary units in the Trans Alai region with an angular unconformity. Owing to tectonically

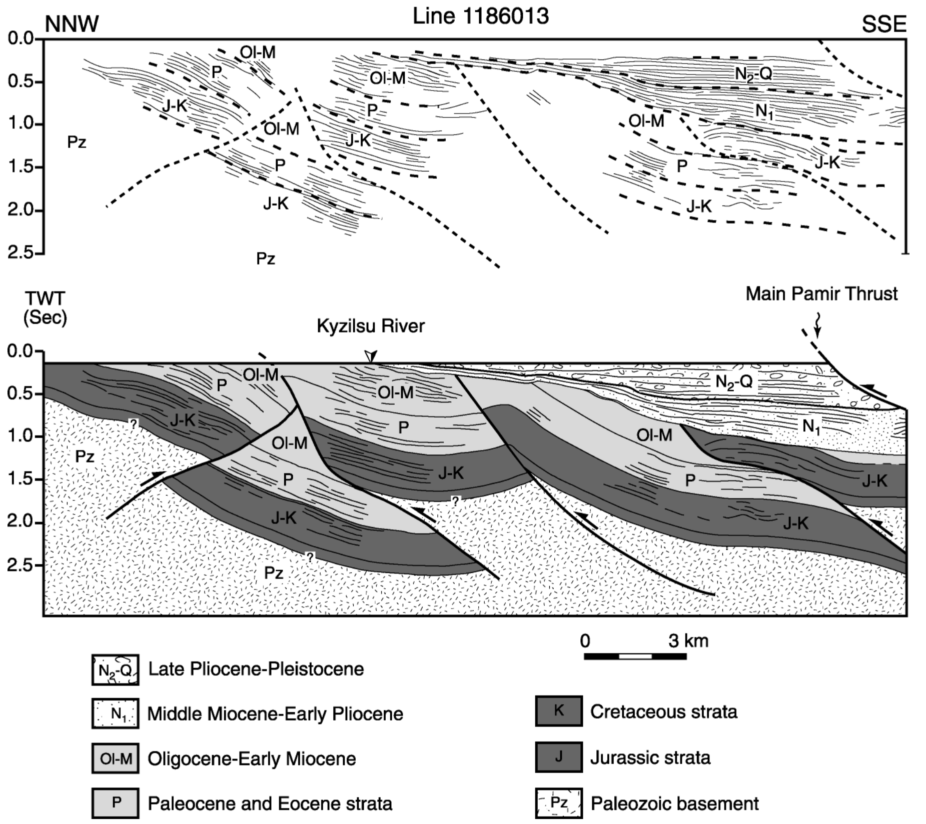

Figure 4. Line drawing of a representative reprocessed north-northwest–oriented seismic reflection line from the central section of the Alai Valley (line 1186013). This section shows a broader early Tertiary thrust system, such as the one that preceded localization of the Main Pamir Thrust to the south, and deposition and deformation of the Neogene units. See center of Figure 3 for location. The interpretation of the different lithologic units is based on a correlation by Ovsyannikov and Nakonechny (1993) and Coutand et al. (2002) with a strike line that crosses a 4-km-deep borehole in the vicinity of the Adzhiktash River. Owing to the minor thickness of Neogene units north of the Kyzilsu River, corresponding sediments are not shown on the interpreted line drawing. The section illustrates the two-stage tectonic evolution of the central Trans Alai and the associated development of Neogene sedimentary wedges (N_1, N_2–Q).

controlled incision, increasingly younger deposits are located at successively lower elevations in the central segment (Figs. 6A and 6B). Extensive mass-movement deposits are located along the western parts of the range front (Fig. 6B); sturzstrom deposits exist in the transition between the central and eastern segments (Fig. 6C) and are interpreted to have been caused by cliff collapse at Pik Lenin (Minina, 1987; Arrowsmith and Strecker, 1999).

It is difficult to ascertain the age of terrace and moraine deposits because of the sparse chronologic information on climatically controlled surface processes in this region. Regional stratigraphic relationships and paleoclimate information suggest, however, that the extensive Qm_1 and Qm_2 piedmont-moraine systems in the Trans Alai may correlate with early Wisconsinan (early Weichselian) stadials or two major glaciations separated by the Sangamon (Eemian) interglacial. Dramatically reduced moisture availability during the Last Glacial Maximum has been documented for this part of central Asia and adjacent regions (Nöth, 1932; Nikonov et al., 1979; Borisov and Minina, 1987) in contrast to more humid conditions during early Wisconsinan (Weichselian) time (Thompson et al., 1997; Frenzel and Gliemeroth, 1998). It is therefore unlikely that the younger piedmont glaciation (Qm_2 deposits) could be related to the Last Glacial Maximum. In the headwaters of the Koksu River, a tributary of the Kyzilsu in the Tien Shan (Fig. 3), Zech et al. (2000) showed that moraines associated with the Last Glacial Maximum are postdated by three additional, small moraine sequences that are correlated with Younger Dryas and Neoglacial ice advances.

Two of the Holocene fluvial terraces in the central and western segments were radiometrically dated by the radiocarbon method. Arrowsmith and Strecker (1999) reported maximum ages of 7–6 ka for a well-developed, extensive terrace surface (Qt_3 gravels) in the uplifted central segment. The age of the Qt_4 gravels west of the Shivie Su River in the western segment is 3.3 ka. The Qt_3 surface is always in erosional or depositional contact over Qm_2 deposits and abuts the Qm_3 terminal moraines. The terrace is thus related to the Qm_3 glaciation; this glaciation was probably an early Holocene (Younger Dryas?) event, or alternatively, it represents the Last Glacial Maximum, whereas the terrace deposits in front of it record a prolonged history of deposition and regrading.

Structural Characteristics

The Trans Alai is bounded by south-dipping thrust faults that generally strike east-northeast (Fig. 3). This thrust system commonly forms along Paleogene gypsum layers and displaces Paleozoic on Cretaceous units (Nikonov et al., 1983). In the western and central parts of the range, these units overthrust folded Neogene and faulted Pleistocene conglomerates (Figs. 6A and 6B), which are in turn juxtaposed against Holocene alluvial-fan sediments along thrust faults that dip 25° to 40° south (Arrowsmith and Strecker, 1999).

Progressive basin closure of the Alai Valley is recorded by dip sections of seismic reflection profiles (Ovsyannikov and Nakonechny, 1993; Coutand et al., 1999; 2002; Fig. 4). The profiles show that the Quaternary alluvial-fan gravels in the piedmont are part of two wedge-shaped basin-fill units that correlate with Neogene–Quaternary strata (N_1, N_2–Q) that were penetrated in a borehole in the Alai Valley (Ovsyannikov and Nakonechny, 1993; Coutand et al., 2002). The lower wedge (N_1) is cut by the Main Pamir Thrust where these rocks now form the hanging wall, whereas the upper wedge (N_2–Q) thickens toward the Main Pamir Thrust and is overridden by it (Fig. 4), demonstrating the structural involvement of increasingly younger gravels in the piedmont, a process that may ultimately terminate the Alai Valley as an active depocenter.

Internal deformation of the Neogene–Quaternary thrust sheet between the Kokkik and Adzhiktash Rivers (Fig. 3) is characterized by paired distal folds; the southern fold limbs dip gently toward the south, whereas near the mountain front, the northern limbs are either steeply dipping, overturned or locally

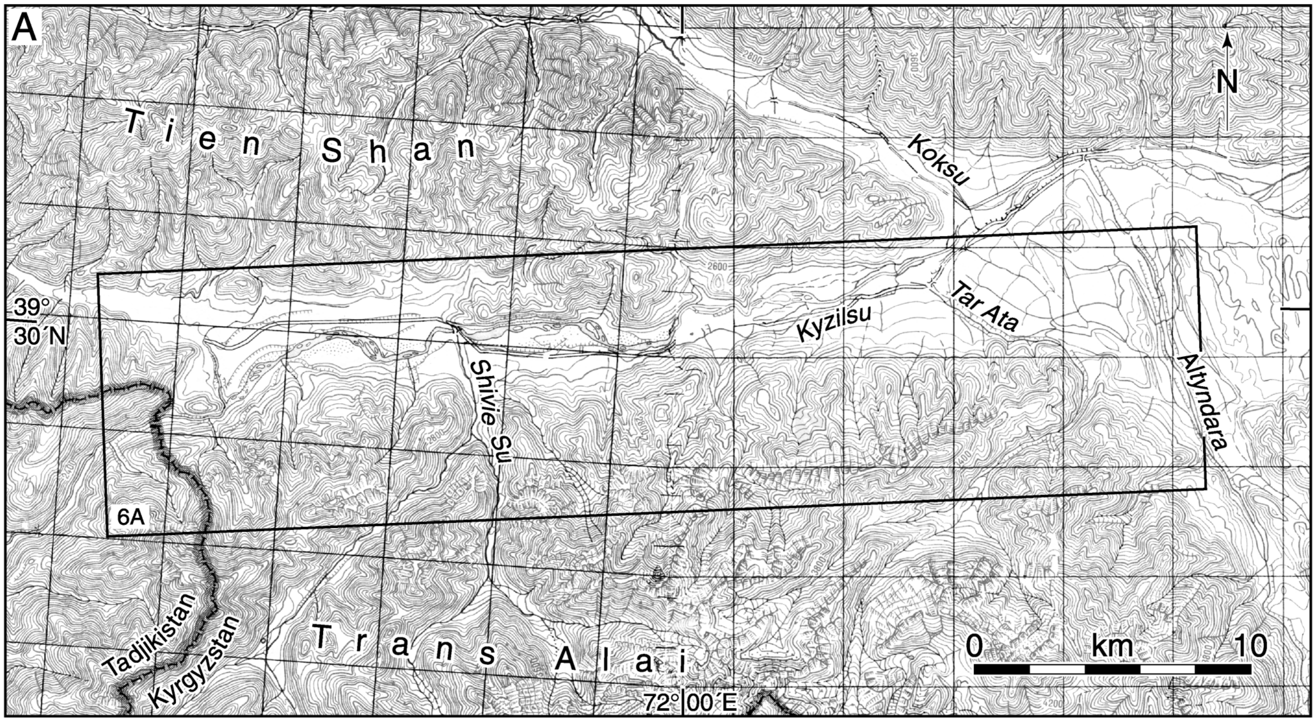

Figure 5. Annotated topographic maps of the (A) western, (B) central, and (C) eastern range-front segments and adjacent areas in the Alai Valley. Note the clear depiction of the narrow gorge of the Kyzilsu River and the large Altyndara drainage in A, the broad piedmont abruptly bounded to the south by the uplifted Trans Alai piedmont and to the north by the Kyzilsu River in B, and the broad hummocky (from the extensive moraine deposits) piedmont with a smooth transition to the Trans Alai in C. Original map scale of 1:200,000. Modified after map sheets J-43-I, J-43-II, and J-43-VII of the Kyrgize Geodetic and Cartographic Agency (1978). See Figure 3 for approximate location of the three maps. Black rectangles indicate approximate outlines of corresponding maps in Figure 6.

cut by back thrusts (Fig. 6B). The throw of the frontal thrust diminishes toward the eastern boundary of this segment, also marked by the closure of an east-plunging anticline in the Neogene conglomerates (Fig. 6B). In contrast, Cretaceous units in the eastern segment are in contact with regraded Quaternary alluvial-fan gravels (Fig. 6C), and the mountain-bounding fault has offset upper Pleistocene deposits only in a 6-km-long sector east of the Adzhiktash River. Other Quaternary deformation along this part of the mountain front was not found.

The western segment is characterized by active thrusts and small-scale transfer faults (Fig. 6A). Cretaceous limestones are thrust over a thick Tertiary sequence of conglomerates and conglomeratic sandstones that are also in thrust contact with Holocene terrace and alluvial-fan conglomerates, which in turn are offset by thrust faulting. The thrust front of the Trans Alai impinges on the cover and basement rocks of the southern Tien Shan (Figs. 3 and 6A), documenting nearly completed closure of the basin. The Tertiary units strike approximately due east and dip between 30° and 40°S; closer to the mountain front, the dip increases to 70°S, and individual strata are replaced by a shear fabric dipping between 80°S and 90° and indicating dextrally oblique thrusting and strike-slip faulting. This zone defines a 0.6–2-km-wide area of intensely cataclastically deformed Paleogene strata (Fig. 6A).

The Variscan-age Tien Shan (Figs. 2 and 3) was reactivated during Cenozoic time, causing uplifted and tilted basement surfaces, often >5000 m high (Burtman, 1975). This deformation placed Paleozoic metasedimentary rocks and limestones over Mesozoic–Cenozoic cover rocks and resulted in the deposition of blocky and coarse conglomerates in the early Neogene (Coutand et al., 2002). In the southwestern Alai Valley where the rocks of the Tien Shan are in immediate proximity with the Kyzilsu River, shortening resulted in the formation of south-dipping faults and associated east-plunging drape folds over Carboniferous basement rocks (Geologic map of the Kyrgize Republic, 1964a, 1964b; Czassny et al., 1999) (Fig. 3). In the Tien Shan piedmont, later-formed gravel-covered pediment and inset terrace sequences cover Neogene units unconformably and are essentially undeformed, indicating tectonic quiescence since their deposition. The tectonic inactivity of the southwestern Tien Shan thus contrasts drastically with the Trans Alai range front and other sectors of the Tien Shan farther north (e.g., Arrowsmith and Strecker, 1999; Burbank et al., 1999).

STRUCTURAL STYLE AND GEOMORPHIC EVOLUTION OF THE TRANS ALAI FAULT SEGMENTS

In the following sections, we discuss the results from analysis of topographic maps, CORONA images, and new geologic mapping with an emphasis on Quaternary deposits. Figures 5A–5C are annotated topographic maps of the western, central, and eastern Alai Valley from original 1:200,000 scale maps. They illustrate the topographic relationships among the ranges, piedmonts, and drainages as arrayed along the east-west Kyzilsu trunk-stream axis. Figure 6 shows new, detailed, geologic field mapping and compiled information from Kyrgyz sources that provide important geologic constraints on the timing and

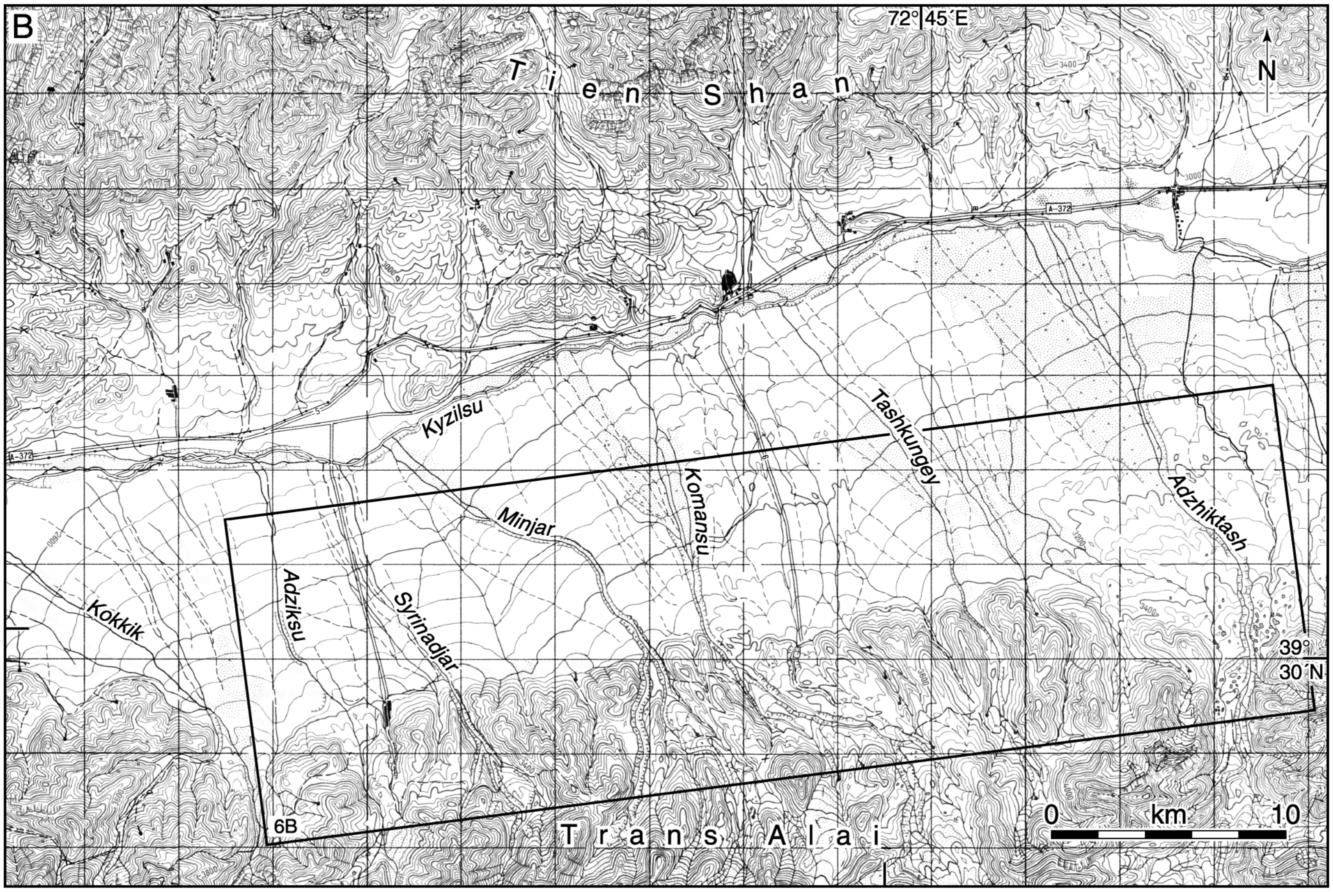

Figure 5. (*Continued*).

processes by which range-front morphology has developed.

Western Segment

Along the sinuous western segment (Fig. 6A), young fault traces can be readily observed in river cuts. Where the Alai Valley narrows to a width of <3 km, remnants of old fluvial terraces that correlate with tributary terraces and alluvial-fan surfaces exist. One prominent terrace-surface remnant is defined by the 3.3 ka terrace at the Shivie Su River, which stands ~14 m above the Kyzilsu River, and is offset 2 m by a thrust fault (Fig. 6A). Embedded in these incised terrace deposits are two younger fill terraces at lower elevations, however, that are not faulted (Fig. 6A). Other offset Holocene units underscore the importance of recent fault motion, although the surface trace of the mountain-bounding fault within interfluves is often covered by landslip and landslide deposits that originate in the highly erodible cataclasites of the mountain front; the reduced strength of this zone results in pervasive mass movements. Mass-movement deposits consistently overlie fluvial terraces and alluvial fans adjusted to higher base levels or occur where the present course of the Kyzilsu River lies in immediate proximity to the range front. This association of range-front mass movements, covered terrace levels, and mass movements terminating in the present channel suggests a causative relationship between lateral fluvial scouring, truncations, failure of highly erodible mountain fronts, and sustained faulting in the narrow remnant of the Alai Valley. This setting is thus analogous to the Peter the First Range in the westernmost Pamir (e.g., Hamburger et al., 1992; Pavlis et al., 1997).

Extensive glacial deposits occur in the transition to the central segment in the lower Altyndara Valley and belong to the oldest tills (Qm_1) in the region. In contrast to the tills in the other segments and younger tills in the upper Altyndara Valley, these deposits are characterized by sillimanite gneiss, a rock type that does not exist in the present Altyndara catchment (Nöth, 1932). Sillimanite gneiss is typical for the Pik Communism (7495 m) and Pik Revolution (6945 m) regions in the central Pamir and is found in gravels of the Muksu River and the Fedchenko ice stream to the south (M. Omuraliev, personal commun., 1999; Nöth, 1932). The upper Altyndara Valley terminates in a wind gap and is separated abruptly from the Muksu Valley by a precipitous 800 m drop in elevation, suggesting an important stream-capture event in Pleistocene time.

Central Segment

Uplifted and deformed Pliocene–Pleistocene conglomerates and geomorphic surfaces are juxtaposed against undeformed, gently sloping alluvial fans in the straight central segment between the Kokkik and Adzhiktash Rivers; the deformed rocks outcrop in interfluve areas and are unconformably covered by younger piedmont conglomerates (Fig. 6B). In places, these piedmont gravels ($Qt_{1,2}$) are overlain by glacial tills (Qm_1). Together with the glacial tills in the lower Altyndara Valley (Fig. 6A) they constitute the oldest glacial deposits in the valley. Eroded glacial deposits in the piedmont northwest and northeast of the Adzhik-

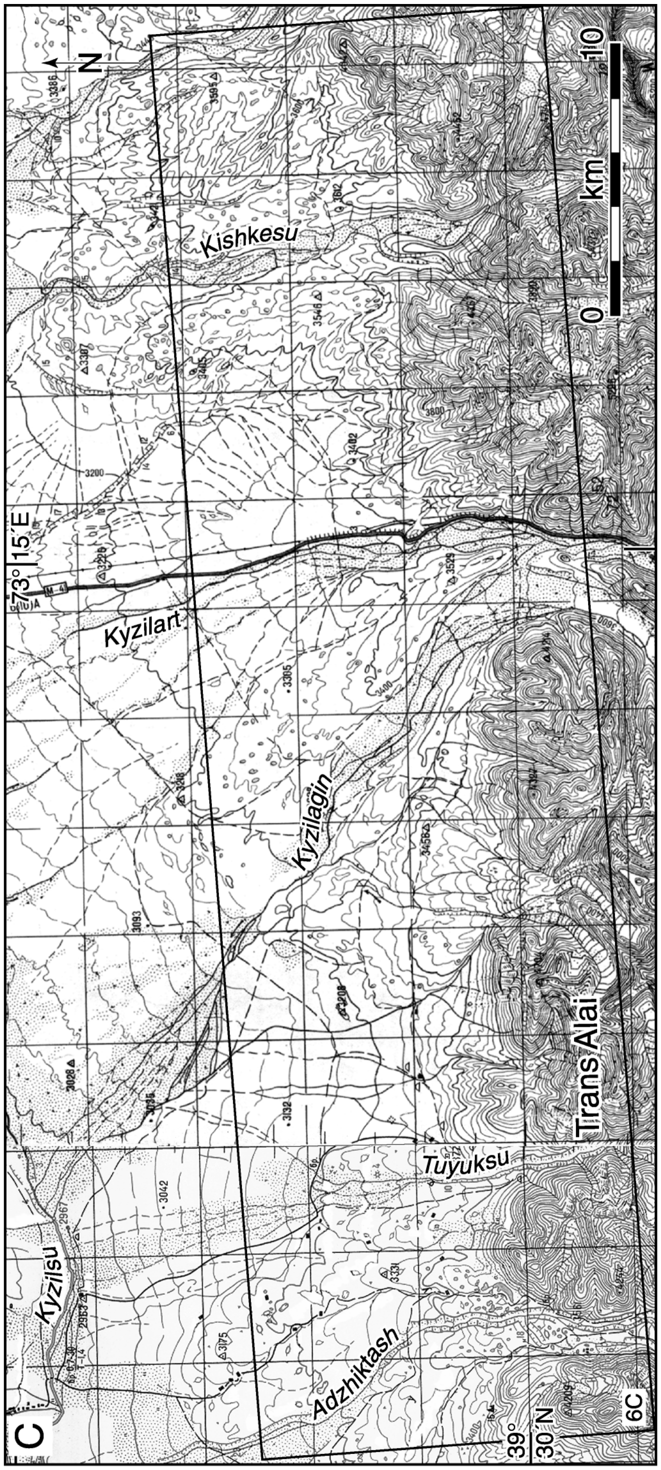

Figure 5. (*Continued*).

tash and Komansu Rivers, respectively, may also belong to this older glaciation (Nöth, 1932). In contrast to the older moraines, Qm_2 moraines are characterized by innumerable water-filled kettle holes. Both groups of tills were deposited by piedmont glaciers that extended >10 km northward from the Trans Alai. Owing to activity along the present mountain-bounding fault, Qm_1 tills were uplifted and have primarily been preserved in interfluves between incising hanging-wall streams. Subsequently, incised valleys hosted renewed glacial advances during the Qm_2 piedmont glaciation, and younger, more restricted glacial advances created at least two additional separate till and moraine generations (Qm_3) nested in other deposits.

The uplifted piedmont, terraces, and moraines suggest a two-step tectonic evolution of this mountain front. First, Pliocene conglomerates at the present mountain front were folded and overturned, whereas strata to the south were folded more gently. Piedmont remnants and terraces, however, are not deformed and compose surfaces inclined between 2° and 4° toward the Alai Valley. They represent the uplifted paleopiedmont in front of the formerly active thrusts involving Cretaceous rocks in the south (Fig. 3). In addition, these remnants must have formed behind a system of older blind thrusts farther north or above the tips of the up-dip, propagating, range-bounding faults that caused the folds in the Pliocene conglomerates as they propagated to the surface. However, erosional processes probably were strong enough to have constantly regraded the actively deforming piedmont, routing sediment from the mountain front to the axial stream.

After this earlier phase of concatenated, balanced deformation and erosion, the second phase of mountain-front evolution was characterized by uplift at the present mountain front above an inferred blind thrust. This deformation uplifted a 5–7-km-wide (perpendicular to the thrust strike) part of the former upper piedmont. Later-formed inset fill terraces (Qt_3–Qt_5) at lower elevations parallel to the streams document sustained uplift and superposed alluviation and erosion. These effects can be seen along virtually all major rivers in the central segment. Longitudinal river and terrace profiles in the hanging wall are parallel to one another, no knickpoints exist, and the Qt_3 and older terraces terminate abruptly at the frontal thrust (Fig. 7) (Arrowsmith and Strecker, 1999). Qt_4–Qt_5 terraces and the modern channel document late Holocene incision throughout the piedmont system.

Field and topographic laser-theodolite surveying showed that the gently inclined fluvial

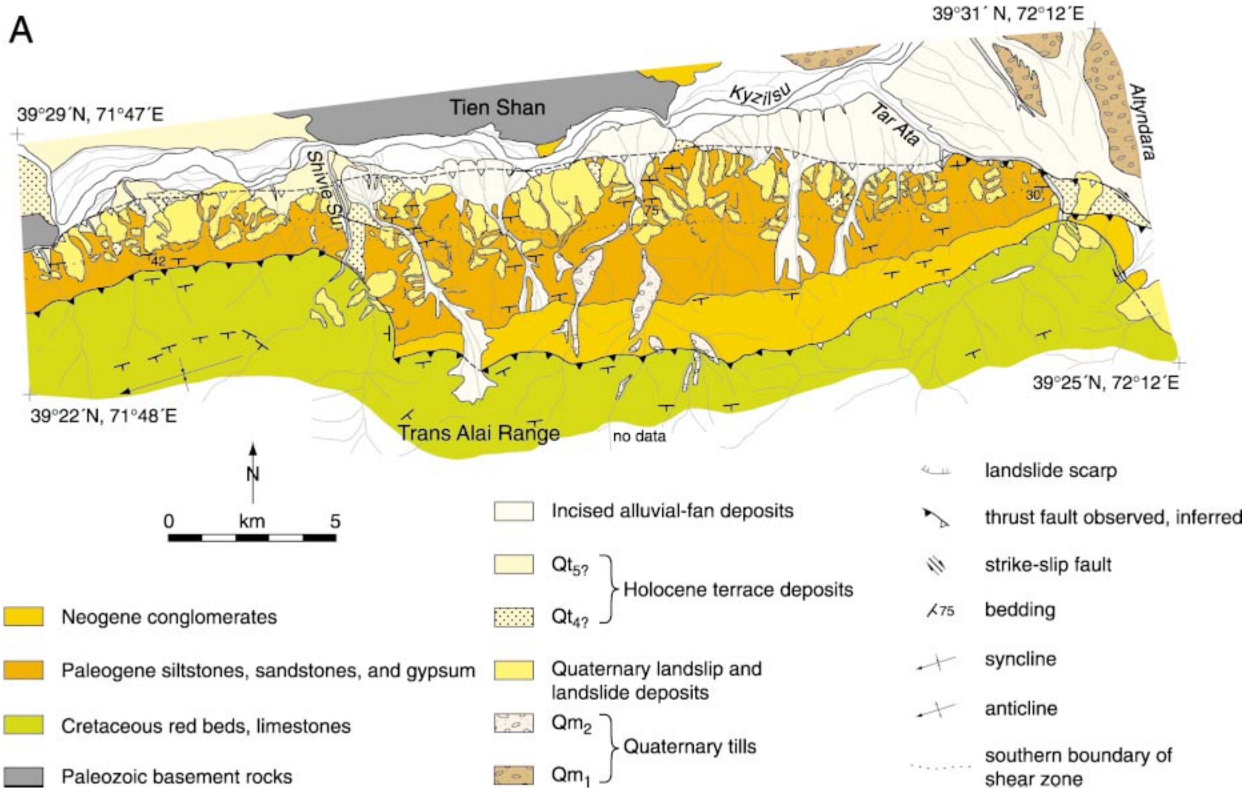

Figure 6. Detailed geologic maps of the (A) western, (B) central, and (C) eastern mountain-front segments of the Trans Alai range. For locations, see Figures 3 and 5. The maps, based on field and aerial-photographic mapping, depict tectonically active structures, bedrock geology, and most important upper Cenozoic deposits and associated landforms. Additional information in the central and eastern segments from 1:50,000 geologic map sheets J-43-14-B and J-43-14-A from the Kyrgize Geologic Agency (1991) and Minina (1987). Map bases are monochromatic CORONA images and topographic maps at a scale of 1:50,000 from the Kyrgize Geodetic and Cartographic Agency. In valleys, active channels with pronounced incision are shown in white. The dotted line south of the concealed range-bounding fault in A defines the width of a cataclasite zone.

terraces appear to have formed as the valley glaciers began to retreat within the incising hanging wall (Figs. 6B and 7). In the Komansu Valley, for example, the Qt_3 terrace terminates at the mountain-bounding fault, whereas upstream it abuts the Qm_3 terminal moraine (Fig. 7). In the other valleys, this prominent terrace has an identical relationship to the Qm_3 moraines, which are always unconformable and in erosional contact with the much more extensive Qm_1 and Qm_2 moraines.

Eastern Segment

In the broad transfer zone between the eastern and central segments, Qm_1 and Qm_2 deposits are offset by thrust faults only in the vicinity of the Tuyuksu River (Fig. 6C). Farther east along the mountain front, such manifestations of Quaternary tectonic activity were not observed, and the position of the mountain front becomes diffuse because of numerous old faults and folds in the Tertiary and Mesozoic units between the Trans Alai and the Tien Shan. In addition, east of 73°15′ E, the region between the two ranges is covered with glacial deposits related to the Qm_1 to Qm_3 glacial advances that extended as far as the Tien Shan piedmont. The lack of recent tectonic activity in this region is well illustrated by the smooth, unfaulted alluvial-fan surfaces that unconformably overlie the glacial deposits in the piedmont and the eroded Cretaceous hanging-wall rocks (Figs. 5C and 6C). Similar to the unfaulted piedmont region of the central segment, erosive contacts between the fan surfaces and the Qm_1 and Qm_2 moraines demonstrate that the fans were constantly regraded with respect to the Kyzilsu River during repeated glacial advances and deposition. The eastern segment thus lacks a well-developed and morphologically clear mountain-bounding fault zone. The drainage divide between the Tarim Basin and the Alai Valley lies east of the valley (Fig. 2). Widespread deformation in this area has completely segregated these two formerly contiguous basins (e.g., Burtman and Molnar, 1993). Where the glaciation did not affect parts of the sedimentary rocks within the collision zone, such as in the areas west of 73°20′ E, a sinuous mountain front in Cretaceous to Paleogene rocks abuts alluvial fans (Geologic Map of the Kyrgize Republic, 1964c).

Quaternary deformation in the eastern segment apparently shifted southward from the mountain front to the active Markansu Fault ~26 km to the south and northward to areas within the Tien Shan. The Markansu Fault defines the boundary between Paleozoic and Mesozoic to Cenozoic cover rocks within the Pamir; offset alluvial fans and river terraces observed on CORONA images and pronounced seismic activity (e.g., Jackson et al., 1979; Burtman and Molnar, 1993; Fan et al., 1994) along this intramontane fault identify it as active and probably connected to the northwestern mountain front via a diffuse dextral transfer zone (Fig. 2).

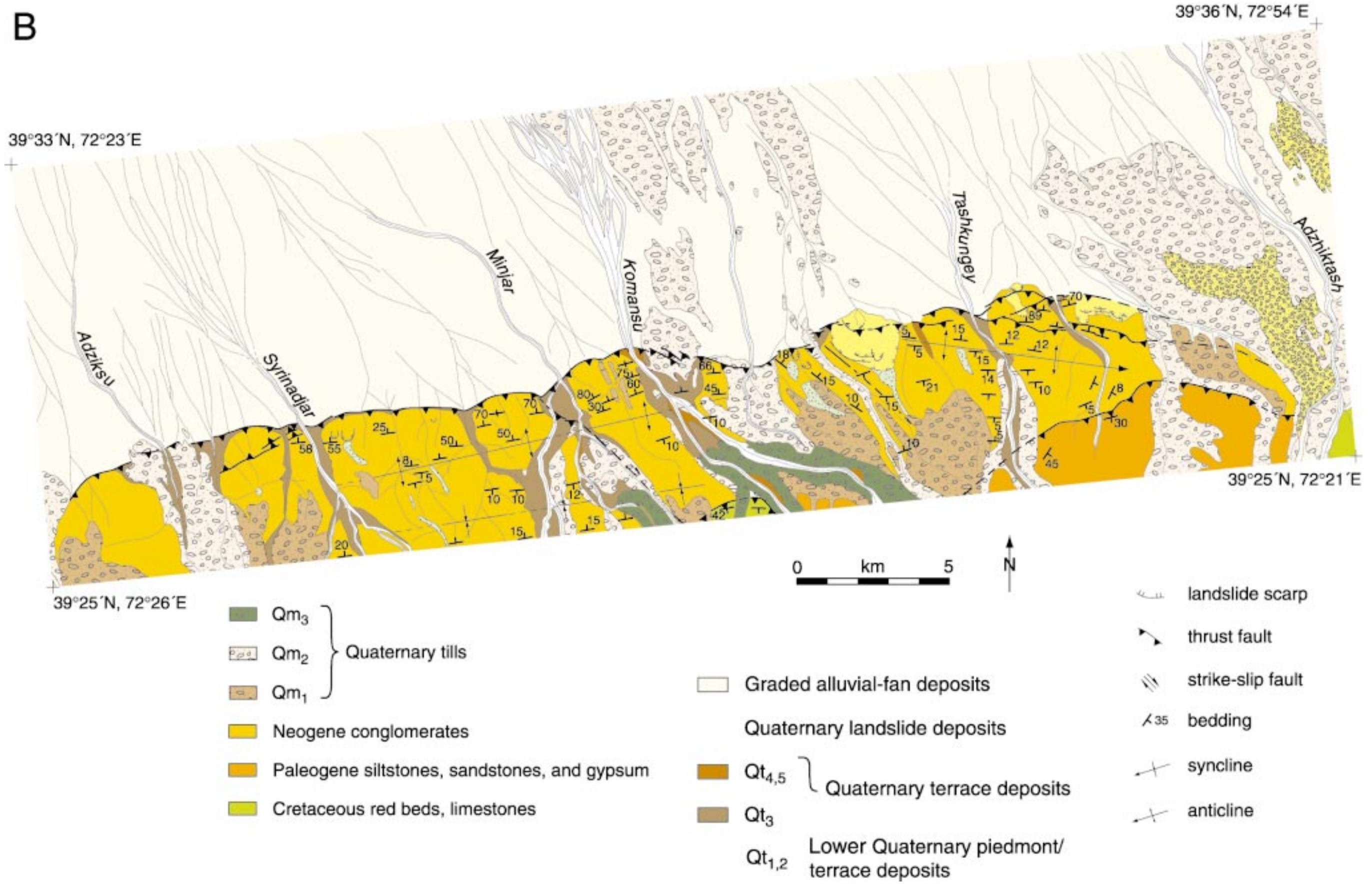

Figure 6. (***Continued***).

EROSIONAL CAPACITY IN THE DIFFERENT MORPHOTECTONIC SEGMENTS AND EXCAVATION OF THE MOUNTAIN FRONT ALONG THE CENTRAL SEGMENT

We calculated the source area, local slope, and stream power index (SPI, defined as the source area times local slope) for each point in the modified HYDRO1K DEM to infer the location of high transport capacity in the basins draining the Alai Valley (Fig. 8). In general, small source area and low SPI correspond to areas along the hillslopes; larger values are obtained along the trunk stream of the valley. The analysis demonstrates systematic differences in source area and SPI between the eastern, central, and western mountain-front segments. The eastern Alai Valley is the headwater region for the trunk stream, and the small source area results in low erosional capacity, as demonstrated both by the source area and SPI plots (Figs. 8B and 8C). Small source areas and low SPI values correlate with areas where deformation has completely closed the Alai Valley and isolated it from the Tarim Basin to the east. Farther west (in the central segment), the main trunk stream (Kyzilsu River) gains source area, and SPI values increase; however, the tributary channels in the Kyzilsu source areas are one to two orders of magnitude smaller than the channel of this large trunk stream (Fig. 8D). Finally, in the western segment, tributaries draining perpendicular to the range front accrue little source area and erosional capacity; the upstream source area of the Kyzilsu River results in high source area and SPI adjacent to the constricted western range front, where steep slopes, lateral scouring, landsliding, and proximity of the thrust front contribute to effective exhumation.

The uplifted piedmont surfaces along the central segment of the Trans Alai range front provide a marker with which to gauge the amount of uplift and incision in this area through the use of the high-resolution DEM (Fig. 9). We assume that the gradient of the trunk-stream channel has not changed significantly between the creation of the uplifted piedmont surface and today. Therefore, the best-fit plane to the points mapped as part of a piedmont surface had to include a line defining the active trunk-stream orientation. The orientation of the piedmont surface as an idealized plane was calculated to be 239°/1.59° N (strike and dip). This surface was combined with the current topography to reconstruct the approximate topography at the time of piedmont formation in front of the then-active mountain front defined by the Cretaceous–Neogene thrust contact (Figs. 3, 5B, and 6B). Finally, total incision was calculated by subtracting the current topography from the topography of the reconstructed Qt_1 surface. We account for the removal of material that was translated by horizontal motion by assuming a fault dip of 30°. Such horizontal translation involved ~3.0 km^3 of material along the central segment. This value was added to the exhumation of material calculated based on pure uplift. We estimated the error in our ability to locate the elevations of the piedmont-surface remnants to be ±10 m. The errors reported in our volume calculations represent this uncer-

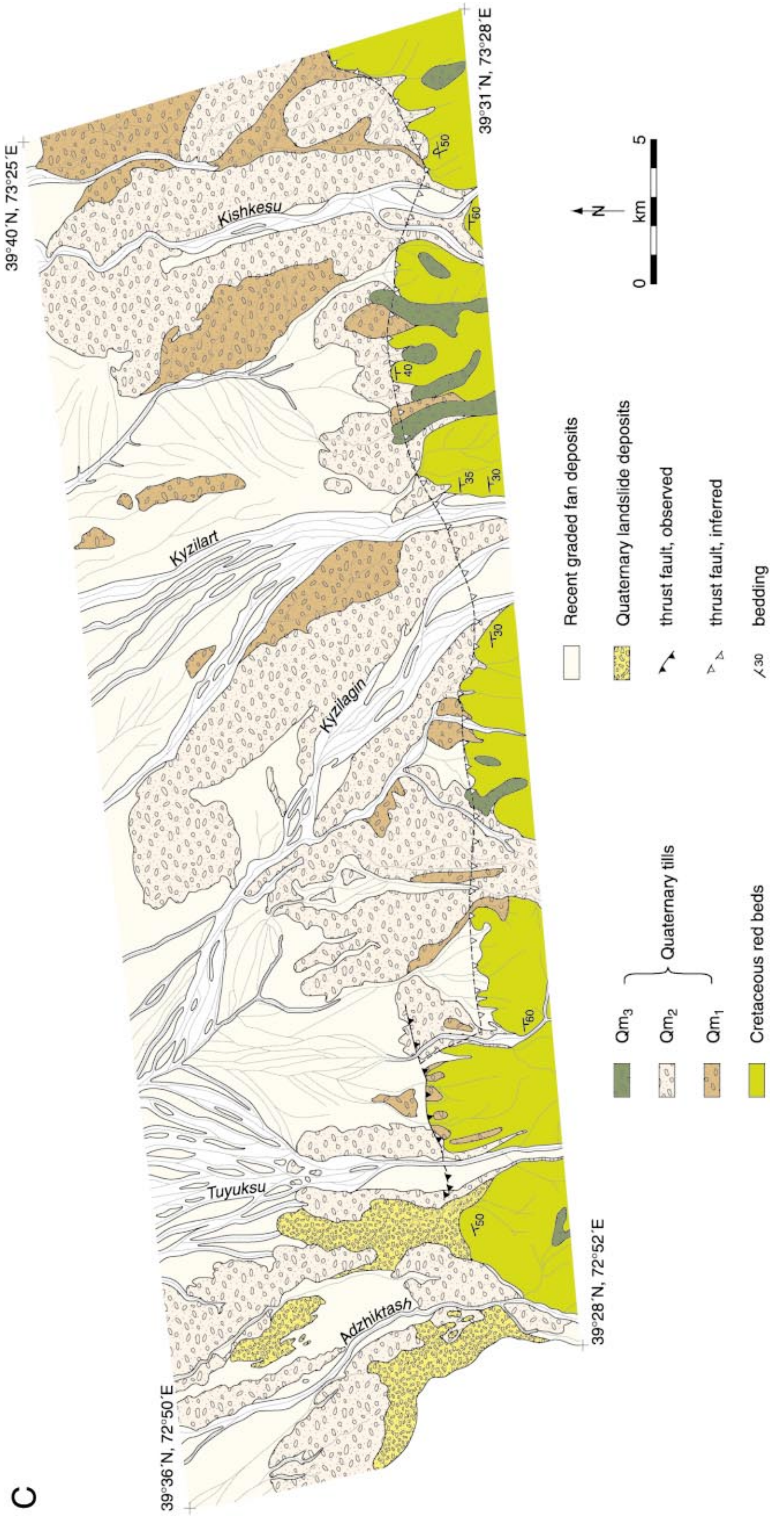

Figure 6. (*Continued*).

tainty. Thus, a total of 19.8 ± 0.7 km^3 of material has been eroded from the former piedmont surface by incision. In contrast, the total volume of material uplifted since abandonment and incision of this surface is 93.8 ± 3.2 km^3 in the absence of erosion. Therefore, only ~21% of material uplifted by tectonics has been removed by geomorphic processes. This result is compatible with the moderate erosional capacity in this mountain-front sector. In contrast, in the western segment, volume calculations using old geomorphic surfaces in uplifted piedmont regions cannot be performed. The dynamics of this range front do not allow for preservation of such landforms, and the areally limited fluvial terraces are below the resolution of the DEM needed to provide mass-transfer rates.

DISCUSSION

Tectonism, Quaternary Climate Change, and Fluvial Terraces in the Trans Alai

Rupture propagation during recent earthquakes (e.g., Nikonov et al., 1983) and, in particular, the deformation history of the Qt_3 terrace (e.g., Arrowsmith and Strecker, 1999) provide evidence that the central segment of the western Trans Alai is a semi-independent structural element of the range front that profoundly influences geomorphic processes in this sector. Uplifted piedmont surfaces and remnants of piedmont glaciers, as well as several inset hanging-wall terraces, markedly contrast with the smooth alluvial-fan surfaces in the present piedmont. In addition, young tectonic scarps and lack of knickpoints in the longitudinal stream profiles demonstrate active range-front uplift and concomitant incision in the hanging wall; this trend was only episodically modified by terrace building.

The interplay between tectonic activity at the mountain front, phases of alluviation, and subsequent formation of multiple terraces is reminiscent of marine terraces along segmented island arcs (e.g., Bloom et al., 1974). Such terraces are controlled by eustatic sea-level changes and active coastal uplift. With sustained high uplift rates, subsequent sea-level highstands do not reach previously formed terraces. Eventually, this leads to a coastal staircase morphology of reefs or erosional terraces, emphasizing recurrent climate-controlled terrace-forming episodes superposed on the long-term uplift process (e.g., Bloom and Yonekura, 1985; Merritts et al. 1994).

Although age control is poor in this remote region, we consider inset terraces and high piedmont-surface remnants in the hanging

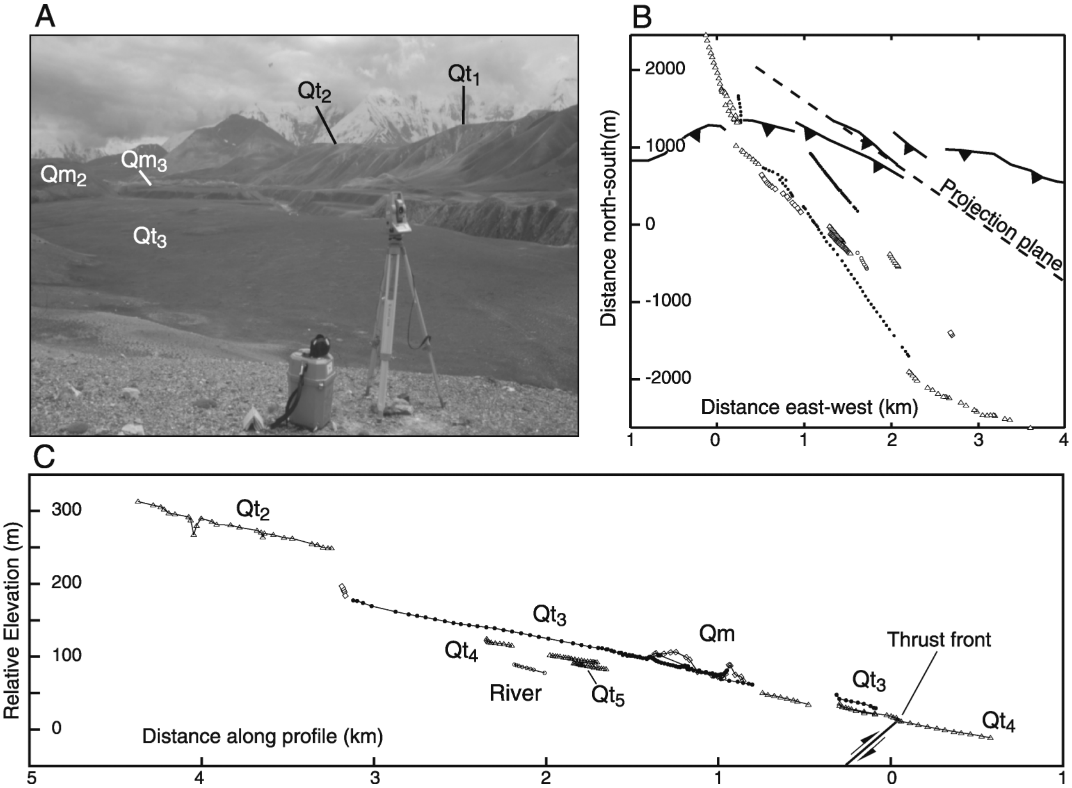

Figure 7. (A) View south of the Komansu River drainage onto the smooth surface of the Qt_2–Qt_3 terraces and terminal Qm_3 moraine. Also visible are remnants of the Qm_2 moraine as well as piedmont surface Qt_1. (B) Map showing position of surveying points on the individual landforms and the plane to which the measurements were projected. The orientation of the plane is approximately parallel to the long axis of the Komansu River drainage. Lines with teeth indicate the approximate location of the major traces of the range-bounding thrust fault. (C) Topographic terrace profiles showing gentle longitudinal profiles and abrupt terrace offsets along the active thrust.

wall of the central Trans Alai to be markers of active uplift and superposed climate change. On the basis of the straightness of the mountain front and the long history of incision, we infer that uplift along the mountain front has been sustained and uplift rates have been relatively constant, when viewed on a time scale of 10–100 k.y. Uplift of the Trans Alai adjacent to the relatively stable course of the Kyzilsu River likely resulted in incision of all tributaries having sources in the uplifting central segment. However, when valley glaciers retreated from their former locations, major volumes of conglomeratic gravel now exposed in the incised hanging-wall valleys must have accumulated in front of receding terminal moraines, choking the drainage systems. Upon climatic amelioration, we interpret the tributaries of the Kyzilsu to have incised and evacuated the formerly filled channels. As in the marine environment, preservation of the terrace gravels may have been effective only where interglacial and interstadial uplift and erosion rates were high enough that downcutting could provide new and successively lower-elevation accommodation space in the hanging wall. Where tectonic activity has been less pronounced, sufficient time for lateral channel migration may regrade piedmonts, terraces, and associated moraines. In addition, different tills and outwash generations may be juxtaposed or regraded, such as along the eastern segment (Qm_1 to Qm_3 moraines between the Tuyuksu and Kishkesu Rivers; Fig. 6C).

The relationships between the various landforms and deposits emphasize the overall low level of tectonism and dominance of glacial deposition and erosion in shaping the mountain front of the eastern segment. However, in the central segment, sustained uplift is the main effect reflected in range-front morphology; superposed climatic cycles define second-order processes of terrace formation and incision that are outpaced by tectonism. In contrast, moraines and terraces are poorly preserved in the western segment, where the combined effects of active tectonism and mass removal are not conducive to their preservation.

Structural Complexity, Drainage-Basin Evolution, and Erosional Capacity

In addition to the differential range-front development in the Trans Alai, this region is further characterized by a close relationship between structural segmentation of the mountain front and drainage-basin evolution. The increasing northwestward approachment of the Trans Alai thrust systems in the central and western segments has led to numerous dextral transfer faults that link individual thrust-fault segments. The most prominent structure is the transition between the central and western segments that hosts the Altyndara River drainage, followed by the broad transfer between the eastern and central segments; smaller examples within the western and central segments also exist (Fig. 10). The unifying characteristic of these transfer-fault zones appears to be their association with drainage basins.

A systematic analysis of drainage-basin areas along the Trans Alai supports these obser-

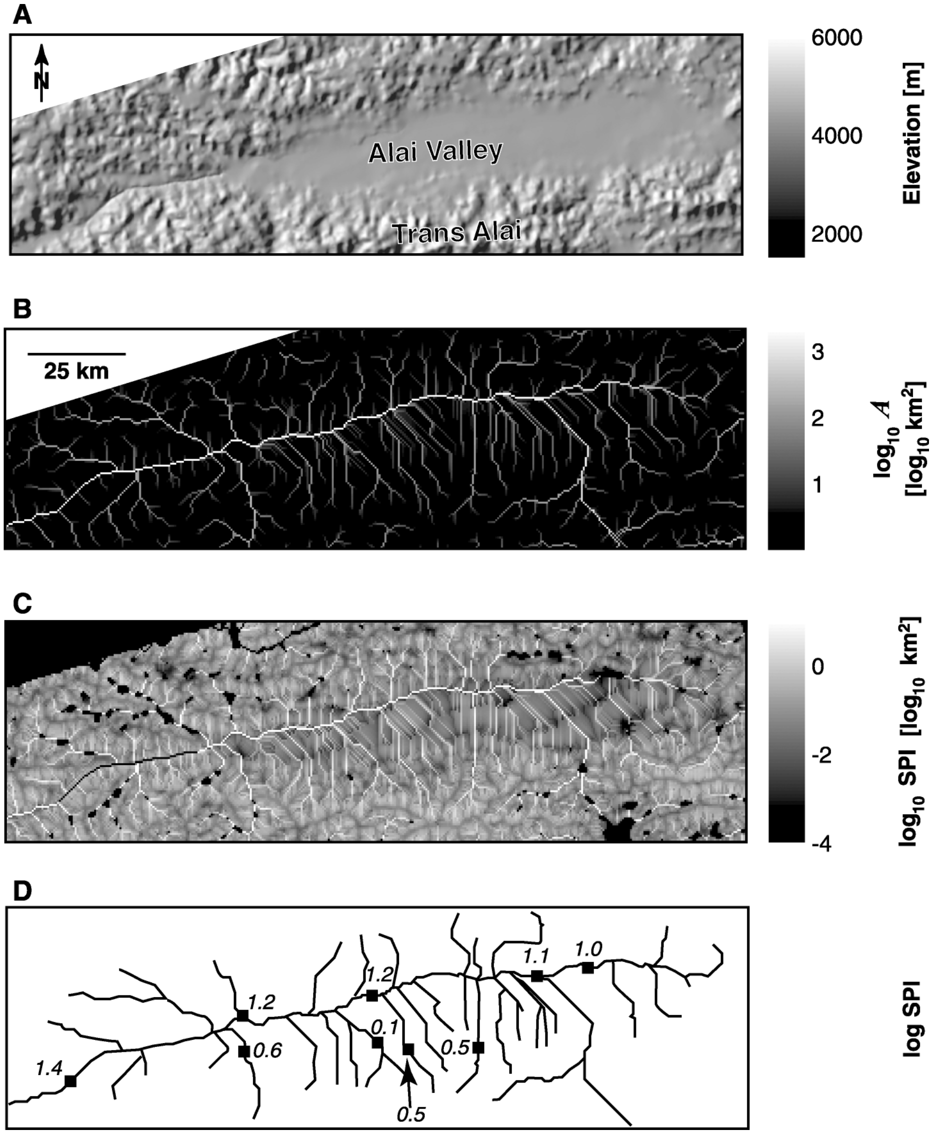

Figure 8. (A) Shaded-relief, (B) source area (*A*, in square kilometers), (C) stream power index (SPI, defined as the source area times local slope), and selected (D) stream power indices for tributaries of the Kyzilsu River. The facts that the headwaters of the trunk stream are in the eastern Alai Valley and that the stream gradients are low result in a low SPI and, hence, low erosional power in the eastern part of the map area. In the western Alai Valley, however, the increase in source area results in larger stream power indices. The stream power index clearly increases downstream along the Kyzilsu and the main and secondary tributaries of the central segment.

vations. The average drainage-basin area along the straight part of the mountain front is on the order of 90 km^2 (Fig. 10). Along thrust-fault–bounded segments, basins are relatively small and typically cover areas of $<$90 km^2. In contrast, rivers that drain into the Alai Valley through the transfer-fault zones have larger catchment areas. For example, the Altyndara River drainage comprises an area of $\sim$400 km^2, whereas the transition between the central and eastern segment is characterized by an area of $\sim$100 km^2. Most of the smaller transfer-fault areas within the central and western segments have larger drainage-basin areas than their structurally homogeneous counterparts, as in the Shivie Su drainage of the western segment (Fig. 10). These observations indicate that obliquely trending transfer structures in mountain belts may cause routing and concentration of drainage systems to a point-source dispersal system similar to transfer zones in extensional environments (e.g., Arrowsmith et al., 2000). The transfer zones are thus analogous to topographic lows between propagating plunging folds as described in the Himalayan foreland (e.g., Gupta, 1997).

The interactions between tectonic displacements, rock type, local hillslope processes, and fluvial incision play a strong role in controlling the deformation in the Alai Valley. Within the segments, changes in erosional capacity (as gauged by the SPI) may lead to different degrees of exhumation along the orogen. Small source areas in the basins of the eastern segment result in low SPI values. In these Kyzilsu headwater basins, complete removal of uplifted and horizontally translated material may not be possible, ultimately causing basin closure and a halt in hanging-wall advance. In the central segment, higher erosional capacity allows sediment delivered to the trunk stream to be transported westward and out of the basin. However, the presence of a preserved, uplifted piedmont surface, inset fill terraces, and moraines shows that erosional capacity along low-order tributaries that erode the range front has not been sufficient to fully exhume the area (Fig. 6A).

Along the western segment, erosional capacity of the lower Kyzilsu River is high not only because of higher precipitation in the western Alai Valley, but also because of stream capture in the upper Altyndara, which must have resulted in a redistribution of erosional capacity. In addition, the valley constriction places the high erosive capacity of the Kyzilsu River in immediate proximity to the range front. This, in conjunction with the mechanically weak cataclasites, results in direct transport of northward-displaced material into the Kyzilsu via landsliding. Despite the high volume of material generated this way, the Alai Valley remains connected with the Tadjik Depression to the west.

SYNTHESIS AND CONCLUSION

Late Cenozoic tectonic and geomorphic evolution of mountain fronts along the northern perimeter of the Trans Alai of the Pamir takes place within discrete segments with variable tectonic history and seismic activity. This evolution is documented by the disruption of the formerly contiguous Tarim and Tadjik sedimentary basins by a permanent tectonic constriction related to northward-migrating thrust systems in the western Alai Valley, at least since late Neogene or early Pleistocene time.

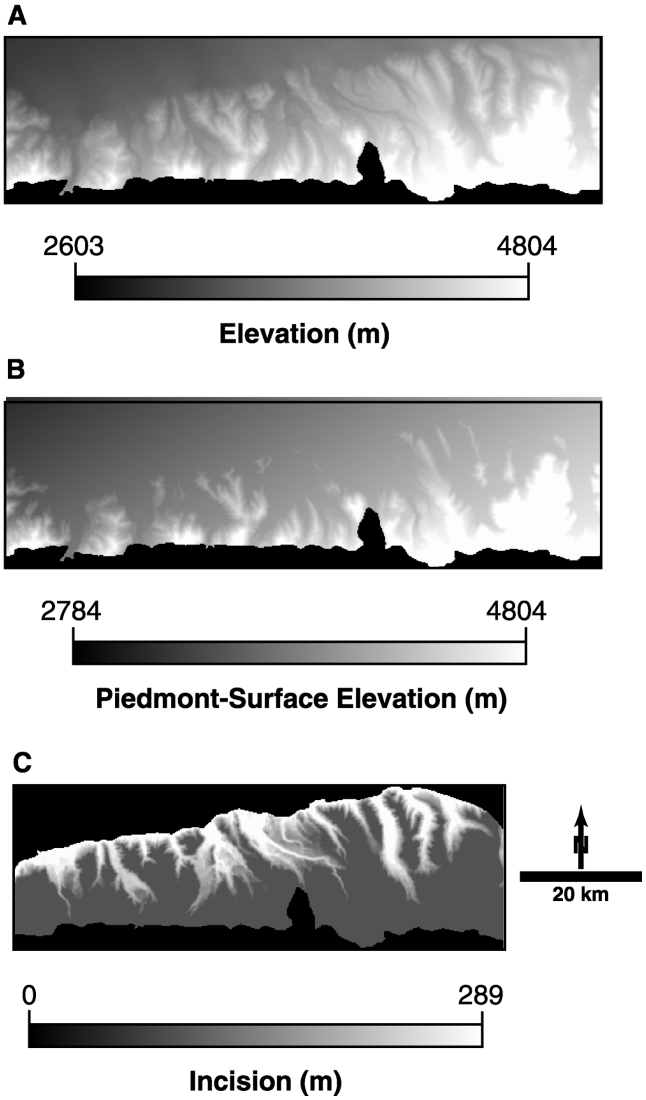

Figure 9. Incision along the central segment. (A) Topography determined from the 1: 50,000 topographic maps. (B) From the topography so determined, points mapped as piedmont surfaces were used with the current geometry of the Kyzilsu River to compute the best-fit plane inferred to represent the piedmont surface at the time of its abandonment. (C) Incision, in meters, calculated along the range front. A total of 93.8 km^3 of material was uplifted by faulting at the range front, of which 19.8 km^3 has since been removed by surface processes. Therefore, only 21% of the topography has been eroded since the abandonment of the piedmont surface.

The confinement of tectonic activity to the mountain fronts is emphasized by the interface between piedmont areas and mountain fronts, which limits the areal extent of tectonically and climatically controlled terrace and piedmont levels. Where basin closure is complete, deformation has migrated elsewhere and is distributed over a wider area. Where this advanced stage of collision has been accomplished in the northern Pamir, the character of deformation resembles that of intramontane basins in the adjacent Tien Shan (e.g., Burbank et al., 1999). When compared to the early history of the Alai Valley (e.g., Coutand et al., 1999), the Quaternary shift of deformation toward the interior of the orogen and regions farther north appears to be a recurring phenomenon in the Cenozoic tectonic evolution of the Pamir region; this behavior might thus be characteristic of the development of other collisional mountain belts as well.

It is intriguing that completed basin closure and redistribution of deformation occur in the eastern, more arid part of the Alai Valley. In contrast, active thrusting continues in those mountain-front sectors where (1) advancing thrusts are still several kilometers away from the Tien Shan, (2) thrusting has displaced the trunk stream in the collision zone, but mass removal is still efficient (e.g., Pavlis et al., 1997), or (3) the advance of the thrusts is counteracted by intense landsliding and lateral scouring by the trunk stream, as in the western segment. Therefore, we speculate that denudation (as influenced by climate and rock type) plays a fundamental role in the longevity of these intramontane basins, the erosional processes that exhume them, and perhaps even the regional accommodation of convergence.

Climate-related processes exert a fundamental and modulating influence on tectonism in this intramontane basin, as highlighted by the DEM and range-front analysis. A high transport-capacity regime in the western Alai Valley exists because of a large drainage-basin area, the narrowing of the valley, and stream capture. The constriction, which is an integral part of the western margin of the orogen, imposes an orographic barrier that causes moisture (>600 mm/yr) derived from the west to precipitate before it reaches the Alai Valley (Atlas of the Kyrgize Soviet Republic, 1987); however, the east-west–oriented valley still allows limited westward penetration of moisture-bearing winds that contribute to maintaining the erosive power necessary to remove the mass influx that is due to thrusting in the western valley segment. The contrast with the closed, arid, eastern end of the valley underscores this point.

ACKNOWLEDGMENTS

This work was supported by a Deutsche Forschungsgemeinschaft (D.F.G.) grant to M. Strecker, an INTAS (International Association for the promotion of cooperation with scientists from the New Independent States of the former Soviet Union) grant by the European Union to M. Strecker and K. Haselton, and National Science Foundation grant EAR-9805319 to R. Arrowsmith. I. Coutand and G. Hilley thank the Alexander von Humboldt Stiftung for supporting their research. We thank A. and O. Korjenkov, A. Konykov, E. Mamyrov, and M. Omuraliev for field and logistical support, and B. Czassny, R. Thiede, and E. Young for assistance in the field. We are indebted to B. Fabian, A. Landgraf, A. Roy, and N. Stahlberg (Universität Potsdam) and M. Baillie, S. Holloway, and S. Selkirk (Arizona State University) for helping with digitizing and drafting tasks. We benefited from discussions with P. Blisniuk, W. Frisch, L. Ratschbacher, and E. Sobel. Figure 2 was created using GMT (Wessel and Smith, 1995). We are grateful to P. Knuepfer, M. Leeder, and D. Merritts for thorough reviews and constructive comments.

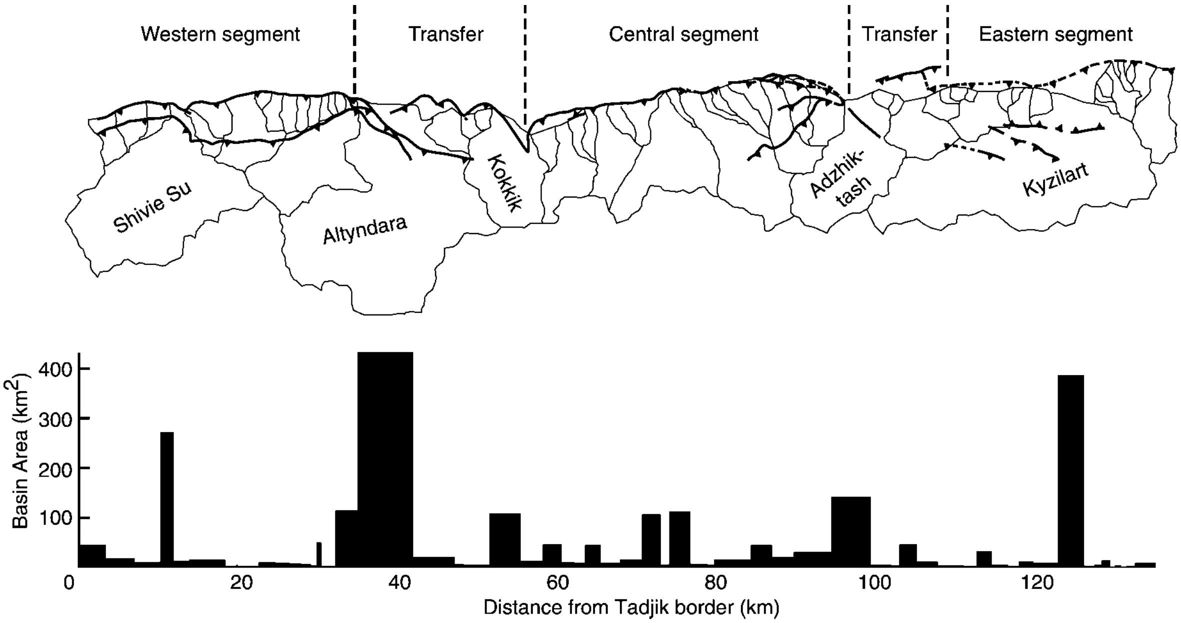

Figure 10. Bar graphs of drainage-basin areas of tributaries of the Kyzilsu River in the Trans Alai, plotted relative to geographic position. Thrust faults bounding the Trans Alai are superposed in map (see Fig. 3 for comparison). Large drainage-basin areas are associated with transfer zones between different mountain-front segments; small drainage-basin areas coincide with the individual mountain-front segments.

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MANUSCRIPT RECEIVED BY THE SOCIETY 15 SEPTEMBER 2001
REVISED MANUSCRIPT RECEIVED 15 APRIL 2002
MANUSCRIPT ACCEPTED 30 APRIL 2002

Printed in the USA