Slip Rate Variation Along the Main Pamir Thrust in the Pamir-Alai Region of Southern Kyrgyzstan from Geodesy, Paleoseismology, Geomorphology, and Geology

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Abstract

In progress.

Introduction

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deformation of margin
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The India-Eurasian collision has resulted in 200-2500 km of convergence across the mountain belt (Patriat and Achache, 1984; Searle, et al., 1987; Dewey, et al., 1989). About one half of the contraction is accommodated along the Himalayan thrust systems (refs), while the rest is accommodated in the interior of deforming southeastern Eurasia (refs). In the east, much of the deformation is accommodated by strike-slip faulting, while in the east, it is accommodate more by thrusting (could be somewhat incorrect). In this latter area, pre-existing zones of lithospheric weakness may have localized deformation (e.g., Tien Shan Mountains; Burtman and Molnar, 1993; Hendrix, et al., 1992). One major zone of convergence away from the Himalayan front in the NW portion of the orogen is in Pamir-Tien Shan mountain belts. This convergence zone apparently has migrated northward in an arcuate geometry (refs) due the northward penetration of crustal blocks of the southern Eurasian margin possibly along a mechanically weak zone. This Pamir indentor may have moved northward by at least 600-650 km during the Cenozoic with respect to stable Eurasia (Burtman and Molnar, 1993). This large-scale shortening and the presence of a southward dipping zone of intermediate depth earthquakes whose projection coincides with large scale north vergent thrust faults led Burtman and Molnar (1993) to suggest that continental crust of Eurasia was and continues to be subducted southward as the southern blocks move northward. In this case, the area at and around the zone of convergence records this continental subduction and hence measurement of the kinematic evolution of this area provides a direct test of this continental subduction hypothesis.

The Alai Valley in southern Kyrgyzstan lies directly in this convergence zone. The northern margin of the valley that is flanked by the Kyrgyz Tien shan is separated from the southern bounding range, the Trans Alai by the Main Pamir Thrust (Burtman and Molnar, 1993; Figures 1, 2). Deformation related to this continental subduction should therefore be recorded by this structure, possibly those within the Tien Shan (Burtman and Molnar, 1993). To test the feasibility of continental subduction in this area, we conducted field studies in 1996 and 1999 aimed at quantifying total deformation and deformation rates over paleoseismic ($10^2-10^4$ yr), geomorphic ($10^5$ yr – Myr), and geologic (1–25 Myr) timescales.

In this paper, we report the results of our paleoseismic investigations along the MPT and compile the geodetic (Reigber, et al., 2001), geomorphic (Arrowsmith and Strecker, 1999; Strecker, et al., in press), and geologic (Coutand, et al., in press) horizontal and vertical offset and displacement data to infer total slip and slip rates along the MPT over these timescales. We find that when considering the uncertainties in each method, total slip released over the last 1-10 kyr, 100 kyr–2 Myr, and 15 Myr are on the order of 1–40 m, 305–611 m, and 8.7–13 km respectively. The implied slip rates along the MPT over these timescales are 0.46–6.31 m/kyr; 0.17 m/kyr, and 0.58–m/kyr, respectively. The geodetically inferred slip accumulation rate along the MPT is between 0.8 and 16.7 m/kyr. While the slip rates are all self-consistent within the errors of the measurements, taken together, they may suggest an acceleration of slip along the structure over the Quaternary. Our findings imply two important conclusions: First, shortening in the region over lithospheric (geomorphic-geologic) is insufficient to accommodate wholesale continental subduction to 250 km depth. If the continental subduction hypothesis is correct, additional shortening must be taken up within the southern Tien Shan via mid-crustal detachment that surfaces along the northern margin of the Tien Shan. Second, geodetic measures of displacement accumulation are significantly large than those recorded
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Therefore, at least in this area, extrapolation of current GPS rates to long-term geologic rates results in large misestimates of the rates and shortening over these timescales.

Pamir-Alai region study area

The Alai Valley is bordered on its northern and southern margins by the Southern Tien Shan and Trans Alai ranges respectively. The eastern end of the valley is topographically truncated by the northward advancing mountain front, hydrologically isolating the Valley from the Tarim Basin to the east. In the west, incision of the axial Kyzilsu River maintains a hydrologic connection between the Valley and the Tadjik Depression to the west. Along the western portion of the Valley, the northward advance of the Trans Alai constricts the channel and progressively closes the Alai depression to the west. Paleogene sediments within the Alai Valley indicate that it formed a connection between the Tarim and Tadjik basins to the east and west, respectively, during that time. Sediments within the valley and exposed along its flanks record deformation and deposition since 25 Ma (COoutand, et al., in press), that likely results as deformation from the convergence of the Pamir northward. These strata extend in age through the early Pleistocene, after which time, deformation is recorded in a number of deformed geomorphic surfaces. Along the northern margin of the Valley, these surfaces are uninterrupted, indicating tectonic quiescence there since the time of their formation. NEED REFERENCING. In contrast, uplifted paleo-piedment (?) surfaces along the southern valley margin demonstrate the activity of those associated structures. Young terraces offset along the central portion of the southern Valley margin indicate that these structures are currently active; however undisrupted glacial morain and fluvial terraces along the eastern portion indicate the rangefront there is currently tectonically inactive. Active seismicity along this margin includes the 1975 M5.9 Za Alai earthquake and the 1978 M7 Markansu earthquake. Finally, resurveyed monuments using GPS indicate that there are high velocity differences (xx-xx mm/yr) over the southern edge of the Valley.

Detailed studies of this active southern margin indicate that shortening in the area is primarily taken up along the MPT (Arrowsmith and Strecker, etc). Based on field geologic and geomorphic mapping, and kinematic measurements, Arrowsmith and Strecker (1999) outlined three major segments of this structure (Western, central, and eastern). Along the western segment, northward advance of the MPT juxtaposes the Trans Alai rangefront with that of the southern Tien Shan. To the east, the MPT steps southward into the central segment and slip is transferred between the two segments through a right lateral strike-slip fault. Finally, the lack of offset of late Quaternary landforms (Strecker, et al., in press) along the eastern segment coincides with a major change in bedrock geology and structure (Strecker, et al., Kyrgyz mapping agency). In addition, active microseismicity apparently migrates southward to the Markansu fault, suggesting Quaternary activity of this southerly structure. In this case, slip may be transferred to this fault through a right-lateral strike-slip fault.

Along the Trans Alai mountain front, numerous fluvial terraces, landslides, and moraines emanate from the range and are offset by splays of the MPT. These tectonic landforms were noted by Nikonov, et al., 1983; and further investigated by Strecker, et al., 1995; Arrowsmith and Strecker, 1999; and Strecker,
et al., in press. A major effort in our work was the geological mapping summarized in Strecker, et al., in press. We identified several paired moraine and fluvio-glacial outwash sequences that are relatively dated by topographic position, cross-cutting relationships, and degree of soil development and surficial modification. The unit designations are Qt_n for the terraces and Qm_n for the moraines. The subscripted number (n) increases with younger units (i.e., Qt_4 is younger than Qt_3).

Methods

We focused our studies along the central segment because of the geologic shortening estimates, presence of uplifted geomorphic markers, clear morphologic expressions, and resurveyed geodetic monuments in the area.

Compilation of published data

Estimation of fault geometry

Calculation of displacements and rates via other people’s work

Friedrich diagrams

In addition, Digital Elevation Models (DEMs) of portions of the range fronts were produced from the georeferenced 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) DEM’s (e.g., Hutchinson, 1989; Tarboton, 1997). From those data we produced profiles of a mapped offset high level paleo-pediment surface in our estimations of slip along the MPT.

Earthquake geology investigation

To determine the earthquake history and deformation rates along the MPT over paleoseismic time scales, we chose sites along the central and western segments to maximize exposure of the near surface fault zone and stratigraphy to identify paleoearthquakes, collect materials to bracket their ages, and determine the slip in each, if possible. We made excavations into an offset terrace on the Central Segment (Figure 5) and in an offset fan-terrace complex along the Western Segment (Figure 6). At each site, we made numerous topographic profiles across the prominent fault scarps and across terrace risers nearby (Figures 7 and 8). At Komansu, excavated two trenches across the north-facing main scarp (~20 m long x 5 m wide x 2–4 m deep) and across an small backthrust and south-facing scarp (~15 m long x 3 m wide x 2 m deep). The western segment site (Shivie Su) was manually excavated across a north-facing scarp (~10 m long x 2 m wide x 1–2 m deep). In both trenches, the walls were cleaned by scraping and brushing, and gridded with 0.5 cm intervals. We logged one wall of each trench on which relationships were clearest and mapped silts, sands, and clasts; sedimentary, pedogenic, and tectonic structures and dated sample locations (see next section) at 1:20 scale. We also photographed the logged wall from a constant distance and orthogonal
orientation using a 20 mm rectilinear lens fitted to a camera. The logs were compiled and redrafted, and the photographs scanned and mosaicked and are presented below.

**Geochronology**

We collected charcoal fragments from exposures for $^{14}$C-dating. Analytical parameters are presented in Table 2. The samples were processed by Beta Analytic, Inc. where they were pretreated them with acid/alkali/acid washes and measured for $^{13}$C/$^{14}$C Accelerator Mass Spectometry (AMS). We converted the radiocarbon ages to calendar years using the program OxCal (Bronk Ramsey, 1995), applying the INTCAL calibration curve (Stuiver, et al., 1998).

In addition to $^{14}$C-dating, we collected materials for Infrared Stimulated Luminescence age dating (See Table 1). Samples were collected after excavating several cm into the exposure walls, inserting a 20-cm-long x 2.5 cm diameter PVC tube into the wall, capping the outer end of the tube, and removing and capping the inner end. The tubes were sealed with several layers of duct tape to prevent light contamination that may alter the age. The luminescence analyses were completed on the 4-11 μm polynminerl fraction. The resultant blue emission is isolated by 5-58 and GG400 Corning filters and measured by a standard photomultiplier tube. The total bleach–multiple aliquot additive dose (MAAD) method was used with the residual response level defined by 2-hour sunlight exposure. An exponential or linear fit were used to model the additive dose response with the interpolation to the residual level <20% of the highest applied beta dose. The equivalent dose was calculated for 3 to 90 seconds after initial exposure to infrared excitation (880 ± 80 nm). The precision of analysis is very good, with dispersion in additive dose response usually ≤10%. Dose rate estimate was calculated from alpha counting to determine U and Th content (assuming secular equilibrium) and elemental analyses to provide for $^{40}$K component. Moisture contents were assumed to be 10±3 % in the final age calculation.

**Displacement accumulation and release along the Main Pamir Thrust**

**Geodetic Constraints on MPT Displacement Accumulation Rates on the $10^1$ yr Timescale**

Seven sites in the Pamir-Alai region were surveyed at least twice between 1992 and 1998 using high-precision GPS (Reigber, et al., 2001). Reigber, et al. (2001) processed these repeated geodetic measurements to determine station velocities with respect to stable Eurasia. We plotted the seven sites in the Pamir-Alai region in Figure 2a and projected them and their errors to 350°-perpendicular to the MPT strike (see line on Figure 2b and Figure 4) to examine the horizonatal velocities in the direction of convergence across the region. The highest velocity is south of the MPT and the normal and strike-slip faults of the Pamir Plateau (Strecker, et al., 1995; and Blisniuk and Strecker, 1997). Velocities decrease northward and no major
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Discontinuity is evident across the MPT. We do not consider point SK in our displacement accumulation rate estimations because it is nested within a complex zone of normal and strike-slip faults that appear linked with the oblique-slip Markansu fault of the Eastern segment and the grabens of the eastern Pamir. Therefore, this site’s motion not only records the displacements accumulating across the central MPT, but also those related to these second order tectonic features. Curiously, stations AD and DK (in the hanging- and footwall of the MPT, respectively) show relatively similar velocities, whereas those to the north (18, 13, 29) show significant velocity differences with respect to those to the south. The lack of neotectonic activity within and along the northern margin of the basin indicates that strain accumulating in the basin interior is released along the MPT or structures farther north in the Tien Shan. Therefore displacement accumulation along the central MPT is likely recorded by the motion of station AK in the hanging wall and stations 13, 18, and 29 in the footwall. The largest velocity differences between the hanging wall and footwall stations are 0.7 and 13.7 mm/yr bracketed by the 1σ minimum velocity at KA and the 1σ maximum velocity of station 29, and the 1σ maximum velocity of KA and the 1σ minimum velocity of station 13. Comparing the two velocities closest to the projection line (KA and station 18), velocity differences across the area range between 6.1 and 11.6 m/kyr.

To calculate the displacement rate that results from shortening recorded across the valley by GPS measurements, we assume that all displacements accumulating across the region are released along the MPT. Thus, these displacement rates provide a maximum bound on the displacement rate along the MPT. Fluvial cuts into the MPT expose a 28°±30° dipping fault plane, and so we consider a conservative range for the fault dip to be 25°±35°. In addition, uplifted fluvial terraces in the hangingwall of the thrust show no warping that would be expected from changes in downdip fault geometry. Using the horizontal velocities determined from the GPS measurements and this range of fault dips for the MPT, we estimate the displacement accumulation rate to be between 0.8–16.7 m/kyr along this structure.

Paleoseismic interpretations of MPT Displacement release over $10^3$–$10^4$ yr Timescales

Syrindjar

Offset terraces along the Central Segment constrain the displacement along the MPT since the terraces’ formation. In particular, Arrowsmith and Strecker (1999) documented an 18 m vertical offset of their mapped Qt1 surface adjacent to the Syrinadjar drainage (Figure 3). Along this drainage, incision has exposed the active fault plane which dips 27° towards the south. Using this fault dip and vertical offset, they calculated a total dip-slip of 40 m along the MPT since the abandonement of the surface. In addition, Nikonov, et al., 1983 studied the wite and noted the large scarp, and in the right bank where Arrowsmith and Strecker (1999) examined the fault zone, they excavated a cultural layer with Stone age artifacts (flakes and microscrapers). The layer was about 25 cm thick, 5 m in extent horizontally, and were apparently about 5 m below the terrace surface interbedded with the fluvial deposits. They reported horizontal amplitude of overthrusting of 12–15 m (possibly 25 m). along the fault zone of
Komansu

Our paleoseismic investigations at Komansu along the central segment of the Trans Alai range front focused on profiling and excavating a 5-m-high 080° trending north-facing scarp (Figures 3, 5, 7, and 10). Here, the scarp is developed in terraces adjacent to and about 30 m above the active channel. We mapped a 6.5 m-high east-facing terrace riser about 50-100 m west of the cliff at the edge of the active channel (K2 and K3 profiles in 7). Downstream, the riser becomes less distinct and shorter (K1 profile). By regional correlation with the Quaternary chronosequence developed by Arrowsmith and Strecker, 1999 and Strecker, et al., in press, we infer that the higher surface may be Qt3, while the lower is Qt4. Without much more extensive numerical age control, these correlations are only constrained by our geological map designations and their confidence limited. The scarp is mostly north-facing but a 0.5-1 m-high south-facing scarp parallels the main scarp about 50 m to the south. It is developed in both terrace surfaces. Topographic profiles over the scarp indicate offsets on the Qt3 of about 6.4 m and on Qt4 of 4.6 to 5.2 m, once the offset due to the back thrust is removed. The vertical cliff face formed by the 30 of incision of the active channel exposes offset and folded gravels below the scarp (Figure 7d). In this cut, the main fault dips 33° to the south and is intersected by a 31°-north dipping back thrust. Between the two faults, the gravels are folded into a north-facing monocline. Near the bottom of the exposure the main thrust offsets a gravel layer by 4.9 m—lending confidence to the fault location and surface offset determinations.

Mechanical excavation exposed deformed gravels and retransported loess in both trenches at Komansu. We exposed the major S-dipping thrust fault and N-facing monocline (main or northern trench) and a minor N-dipping backthrust (south trench) (Figures 11 and 12). The northern excavation contains more direct information about the history of ground rupture at the site. In it, the layers on the north portion of the exposure show the undeformed situation: horizontally and discontinuously bedded fluvial gravels with CaCO3 coatings (in black) capped by retransported loess (silt-matrix supported pebbles). The vegetation here is predominantly grass and some annual plants with root systems 0.5-1 m deep. To the south, the layering is still evident, but the monocline is manifest by north dips. Layer attitude is indicated by the discontinuous bedding as well as the gross pattern of the CaCO3 coatings (crude paleohorizontal indicator). In the middle of the exposure, the fault zone is manifest where the bedding attitudes are discontinuous, clasts are broken, and sometimes upside down over a zone of about 10 cm width (shown in red on Figure 11). Below and to the north of the fault, three wedges of poorly sorted sand and silt with both fine pebbles and medium to coarse gravels are preserved with gentle north inclinations. They are distinctly different from the fluvial gravels. The layering within them is not well developed, but where evident is defined by variations in the clast/matrix ratio and sizes of clasts. These deposits have clear relative age relationships with the southernmost and lowest being oldest. The wedges thicken to the south and the older two are truncated to the south. All three merge northward with the retransported loess cover of the terrace.

The retransported loess in the northern trench is an acceptable material for the application of IRSL numerical dating. We dated 5 IRSL samples collected from various positions within the wedge materials (Figure 11 and Table 1). We targeted the most well sorted fine sand and silt zones. The lowermost and southernmost sample (99KOM-NTL7) is 10.12±0.72 ka. 99KOM-NTL3 was intended to date the
retransported loess cover of the originally undeformed terrace surface (3.20±0.22). 99KOM-NTL4 and 99KOM-NTL5 provide ages in the middle wedge of 1.51±0.10 ka and 3.20±0.26 ka respectively. 99KOM-NTL2 is 1.43±0.10 ka and provides an age for the youngest wedge.

The southern trench over the back thrust also shows deformation of the fluvial gravels and capping retransported loess. In this exposure, a 34° north-dipping 20–30 cm-wide zone of rotated pebbles and cobbles marks the location of the backthrust. Bedded clast-supported pebbles are overlain by poorly sorted clast-supported pebbles and cobbles at a depth of about 0.25 m. To the south, a potentially correlative transition upsection from bedded to poorly sorted clast-supported pebbles and cobbles is evident at a depth of about 1.5 m implying a vertical offset of about 1.25 m (similar to the maximum scarp height above). This would be a minimum offset because otherwise no correlation is visible indicating that some erosion occurred on the hanging wall because of the difference in thickness of gravels across the fault zone. The retransported loess is only 10–20 cm thick and the poorly sorted materials are massive on the north side of the fault. To the south, the retransported loess is almost 1 m thick and shows variation in sedimentary structures from massive and fairly clast free especially in the south to two clast-rich matrix-supported pebbly wedges at depths of 40 and 80 cm. These wedges are within the matrix-dominated retransported loess and are 2–3 m long and up to 25 cm thick at the fault. These wedges of pebbly fine sand grades laterally into the massive matrix supported retransported loess to the south. Two faults bound the shear zone. The lower one is buried, while the other cuts nearly to the surface. The lower fault zone (denoted as I) in Figure 12 cuts the lower wedge, but is buried by retransported loess which is in turn overlain by the upper wedge. Fault zone II cuts through all of the gravels. There is little evidence that it cuts above into the retransported loess.

In the southern excavation, we recovered charcoal from the retransported loess in the southern portion of the trench. The lower sample came from the base of the retransported loess and is 770BC–400BC (8-4-99-9) while the upper is 50BC–250AD (8-4-99-11; Table 2). To provide local control for our IRSL numerical ages, we collected one IRSL sample (99KOM-STL2) adjacent to the 8-4-99-11 and dated it to 1.87±0.14 ka (Table 1). The correct stratigraphic ordering of the 14C dates and the similarity in the upper ages (2.01–1.73 ka for IRSL versus 2.05–1.75 ka for 14C) lends confidence to the IRSL dates from the northern trench.

Our interpretation of the northern exposure is that each of the wedge-shaped gravel deposits represents colluvial deposition from the erosion of the surface rupture of a major thrust earthquake. Offset of the ground surface increases the scarp height and slope and material subsequently is eroded from the scarp face, transported downslope and deposited at the base of the scarp. The earliest event is indicated by a wedge that is truncated by a 30° S-dipping fault. The fault dip is horizontal above the second wedge. The youngest wedge is not faulted. The thrust fault in the last 2 m of extent up dip actually dips 10 degrees to the north and indicates that in the last earthquake the rupture displaced the hanging wall downhill over the pre-existing scarp. The decrease in dip forms a monocline in the hanging wall. Flattening of the dips as the ruptures move out over the horizontal to north sloping topography is also indicated by the cut off fault tip above the oldest wedge (tan). Following the penultimate earthquake, the “nose” of the hanging wall stopped there, but in the most recent earthquake, a more favorable fault orientation cut the nose off,
transferring the material to the hanging wall. Offset of a distinctive “pea gravel” in the last earthquake was 1.6 m (Figure 11). The shape and size of the three wedges suggests that the events that preceded their formation had similar dip slip.

The southern excavation provides an earthquake history that also depends on the formation and offset of colluvial wedge packages. However, in the southern trench, the fault is more planar and the offsets are smaller. If we assume that the wedges of colluvial material observed in that trench represent ground rupture, the lower one would thus record the oldest event. It is cut by the subsequent earthquake and then the offset was buried (see tip of fault zone I; Figure 12). The next rupture apparently broke along a parallel fault zone (II) 40 cm north and from which a scarp was eroded to produce the upper wedge. That upper wedge was cut in the last earthquake and the capping reworked loess deposited.

Although they are limited, the numerical ages from both trenches and geologic correlation provide constraints on the timing of events at Komansu. Arrowsmith and Strecker, 1999 reported two 14C dates they associated with the Qt3 surface (Table 2). The broadest age range from both samples is 6.34–7.99 ka. Our geological mapping correlates the units along the central segment of the Trans Alai such that the terrace we excavated at Komansu should be younger (Qt4). The oldest IRSL age, 99KOM-NTL7, is an outlier with respect to the other IRSL dates and is older than the correlatively older Qt4 date from the Syrinadjar area. The similarity in ages between 99KOM-NTL3 and 99KOM-NTL5 (~3.2 ka) implies that they may provide some age for the middle wedge and the cover retransported loess, while 99KOM-NTL4 may have been disturbed in the last earthquake or just prior to it given its proximity to the inferred paleo ground surface and thus it is similar to the age of 99KOM-NTL2 and possibly the most recent earthquake (~1.5 ka). The most recent earthquake would thus be bracketed between 1.51±0.10 ka (99KOM-NTL4) and 1.43±0.10 ka (99KOM-NTL2). The record from the southern excavation indicates that two earthquakes occurred before 770BC–400BC (8-4-99-9) and after the deposition of the gravel, and two more events occurred after 50BC–250AD (8-4-99-11 and 99KOM-STL2). The interpretation of events in the southern trench is less confident because it relies on the simple assumption that following an earthquake the colluvial wedge forms. We have no other evidence for the events except that there are two wedges and both are cut and the younger one cannot have formed as a result of the same earthquake as that which offset the lower one. For a conservative interpretation, we might infer that the wedges are not directly associated with earthquakes and it is just the buried tips of fault zones I and II that each record one earthquake. Without much more extensive numerical age control, these correlations are only constrained by our geological map designations and their confidence limited. Furthermore, with only six IRSL and three 14C dates at this site, our numerical age control only provides a crude sketch of the event timing.

Information from the northern excavation and the surface and gravel offsets at Komansu in combination with the numerical ages there provide several slip rate estimates (Table 3). We emphasize the results from the northern trench. The most recent earthquake slipped 1.6 m. If we assume that the time between it and possibly the penultimate event (1.43±0.10–99KOM-NTL2 and 3.20±0.26–99KOM-NTL5) are representative of a recurrence interval, we estimate 0.46–1.20 m/kyr. In our slip rate calculations for the terrace offset at Komansu, we used two maximum ages for the events at Komansu: 6.34–7.99 ka by correlation and
10.12\pm 0.72\text{ ka (99KOM-NTL7). The minimum age was the same because the surface should be older than 99KOM-NTL3 and 99KOM-NTL5 (3.20\pm 0.26\text{ ka). The vertical offsets of 4.6–5.2 m convert to slip of 8.4–9.5 m using the observed dip of 33°. Slip rates range thus from 1.05–3.24 m/kyr. Using the alternative maximum age of 10.12\pm 0.72\text{ ka, the minimum slip rate is 0.78 m/kyr.}

**Shivie Su**

Along the western range front of the Trans Alai, the proximity of the main drainage of the Alai region (the Kyzyl Su) to the mountain front along with relatively greater erodibility of the rocks with respect to the central segment makes the surface trace of the active MPT less pronounced (Strecker, et al., in press). In many places the mountain front is cut by the Kyzyl Su, promoting landsliding which covers the fault traces. Strecker, et al., in press map an inferred thrust fault along the south edge of the Kyzyl Su. At Shivie Su we found well preserved fault scarps cutting an alluvial terrace (Figures 3, 6, and 8). The causative fault is 1–2 km south of the trace of the inferred or buried thrust, so either this is the sole active manifestation of shortening at this longitude, or results from here are minima because we have no slip rate information about the inferred structure.

The terrace was abandoned as the Shivie Su down cut. This terrace is Qt\textsubscript{4} within the chronosequence developed by Arrowsmith and Strecker, 1999 and refined by Strecker, et al., in press who mapped the site. However, regional correlation with limited geochronologic control limits confidence in this assignment. Overlying the terrace in places is younger alluvial fan and landslide debris. As the drainages incised, younger terraces were developed (Qt\textsubscript{5}). Topographic profiles of the terrace riser between Qt\textsubscript{4} and Qt\textsubscript{5} show incision of about 7 m between the two surfaces (Figure 8c). Topographic profiles of the active channel clearly show that it is unaffected by faulting, but the Qt\textsubscript{4} surface above has a 3.2–5.9 m high scarp developed on it. The Qt\textsubscript{5} surface does not appear to be faulted (Strecker, et al., in press). The scarp is an assymetric hump with a northwest trend and taller northeast side (in the direction of inferred vergence of the thrusting). The scarp form may result from some folding in addition to surface rupture. The minimum height measures only the offset of the Qt\textsubscript{4} surface, while the maximum includes the inferred folding. On the top of the scarp is a shallow and steep-walled trough that we interpret as an irrigation canal (Figure 8b).

Our excavation across the fault scarp at Shivie Su exposed medium to coarse-grained fluvial gravels with stage I-II CaCO\textsubscript{3} soil development manifest as mm-thick carbonate coatings on the lower portions of most clasts. Original fluvial sedimentary fabrics are preserved in the upper and lower portions of the logs by well sorted pebbly and sandy horizons. In the middle of the exposure, the sedimentary fabrics are not evident and we infer have been destroyed by distributed deformation in the fault zone. If the bedding on the hanging wall and footwall are the same, the vertical offset is about 2 m along a 28° S-dipping thrust fault. The footwall is capped by a tan-brown matrix-supported gravel unit that merges to the north with retransported loess that covers the terrace and thickens to 60 cm toward the south where it is overridden by the footwall. The matrix-supported unit’s texture and wedge form may have resulted from colluvial deposition in front of a fault scarp developed in the penultimate earthquake (and possibly earlier ones) at this site and then cut in the last event. Thus we infer that at least two earthquakes ruptured the surface
at this location since the formation of the terrace with 4.7–6.8 m total dip slip. The lower estimate comes from the possible bedding offset observed in the trench, while the larger one uses the vertical offset of the terrace surface measured from the topographic profiles (3.2 m).

The age of the deformed surface (Qt_4) at Shivie Su is poorly constrained. Central segment numerical ages for Qt_3 at Syrinadjar are 6.34 to 7.99 ka and ages for the probable Qt_4 surface at Komansu are probably 3.2 ±0.26 ka, but possibly as old as 10.12 ± 0.72 ka. The Qt_4 gravels west of Shivie Su in the western segment are 3.4–3.7 ka as reported by Strecker, et al., in press. Thus, if we accept the correlation of the Quaternary mapping, the deformation documented at Shivie Su has occurred since 3.4–3.7 ka. Converting the offsets from the trench and the surface to slip using the observed 28° dip, slip rates range from 1.27 to 1.84 m/kyr.

Displacement along the MPT over Geomorphic (10^5–10^6 yr) Timescales

Displacements along the MPT over the Quaternary are recorded by an uplifted pediment surface (Qt_1; Figure 14) in the hangingwall of the thrust (Strecker, et al., in press). This geomorphic marker was formed by simultaneous fault displacement and continuous erosion of the hangingwall piedmont that created a gravel veneered bevelled bedrock surface. It was progressively dissected after its abandonment, leading to the preserved remnants recorded in the Quaternary deposits and topography currently observed (Strecker, et al., in press).

We constrained the total uplift of this surface using the high resolution DEMs produced as part of our research in the region. Figure 14 shows a topographic and geologic profile in the vicinity of the Komansu excavation site. We bracketed the maximum and minimum elevations of the Qt_1 surface at the MPT by assuming an initially flat, and a sloping surface that connects all remnants of the eroded surface, respectively (Figure 14). The proximity of the early Pleistocene Sokh Formation to the surface (Coutand, et al., in press) and the fact that sediment is likely efficiently routed from the mountain front to the valley’s axial drainage indicate that accumulation of sediment in the footwall of the thrust has been small since the uplift of the Qt_1 surface (Strecker, et al., in press). Therefore, the difference in elevation between the projected Qt_1 surface and the MPT constrain its total uplift after abandonment as 193–276 m.

We inferred the amount of fault displacement along the MPT between paleoseismic timescales and the abandonment of the Qt_1 surface. First, the relatively younger Qt_3 terrace studied by Arrowsmith and Strecker, 1999 at Syrinadjar is cut into Qt_1. The amount of vertical uplift experienced by Qt_3 is 18 m; therefore, between the abandonment of Qt_1 and the formation of Qt_3, Qt_1 has been uplifted a minimum and maximum of 175 and 258 m, respectively. The dip of the MPT near the surface is between 25° and 35° Arrowsmith and Strecker, 1999. These dips are likely consistent down-dip, as terraces in the hangingwall of the MPT do not show warping that result from changes in the downdip geometry of the thrust. Using this range of fault dips, the offset of Qt_1 was produced by between 305 and 611 m of dip-slip along the MPT.

The timing of the abandonment of the Qt_1 surface is constrained by cross-cutting relations between moraines and Pliocene units in the area. Two sets of glacial till deposits are sculpted into Qt_1. These units are thought to be produced early in the Wisconsinan/Weichselian stadial or by two glaciations separated...
by the Sangamon/Eem interglacial period (Strecker, et al., in press). We consider a minimum age for these moraine units to be Wisconsinan/Weichselian (~115 ka); thus, the Qt₁ surface is older than 115 ka. Finally, geologic cross-cutting relations show that the surface is younger than the early Pleistocene Sokh Formation (Coutand, et al., in press), constraining the maximum age of the surface to be the early Quaternary (~1.8 Ma). The total time between abandonment of the Qt₁ and establishment of the 6-10 ka Qt₃ surface (see previous section) is 105–1794 kyr. Using these bounds for the timing of motion and offset along the MPT between abandonment of Qt₁ and establishment of Qt₃ yields fault slip rates between 5.8 and 0.17 mm/yr during this time.

Displacement along the MPT over Geologic (10⁶–10⁷ yr) Timescales

Deformed sedimentary strata in the Alai Valley document deformation since 25 Ma. Surface outcrops, interpretation of seismic stratigraphic data, and drill cores constrain the nature and deformation of stratigraphic units exposed at the surface and buried beneath the Valley (Coutand, et al., in press). Coutand, et al., in press correlated units within the Alai Valley to those in the adjacent Tadjik and Tarim basins to estimate the ages of these strata. In addition, paleontologic studies within units exposed along the northern margin of the Valley provided additional age control for these units (Czassny, et al., 1999). Coutand, et al., in press used line-balancing methods (Dahlstrom, 1969; Hossack, 1979; De Paor, 1988; Geiser et al., 1988) to retro-deform the strata and constructed a two-stage deformation history in which distributed shortening across the width of the Valley (25–15 Ma) was followed by localization of deformation along its southern margin.

We focused our analysis on the second stage of deformation in which shortening was localized along the southern margin of the Valley and calculated slip along the MPT and equivalent structures since 15 Ma. First, Coutand, et al., in press found that deformation migrated from a fault south of the MPT to the current location of the MPT between the deposition of the early Pleistocene Sokh Formation and the abandonment of Qt₁. Therefore, our calculations of the displacement along the MPT fault system (MPTFS) include the currently active MPT and the thrust to the south. Second, strata of the middle Miocene Baktry and Pliocene–Pleistocene Sokh Formations were apparently deposited as syndeformational strata ahead of the advancing MPTFS and show no obvious unconformities that reflect changing shortening rates (Coutand, et al., in press). Therefore, deformation has accrued more or less continuously since the middle Miocene. Since this time, 10.9 and 8.4 km of horizontal displacement of India with respect to Eurasia has been accommodated along the MPTFS (Coutand, et al., in press). We estimated the dip of faults in the MPTFS to be between 25° and 35°. These fault geometries and horizontal displacements yield a minimum and maximum slip of 9.268 and 13.306 m of displacement along the MPT zone, respectively, since 15 Ma. To estimate the range of dip-slip along the MPT fault system between 15 Ma and the abandonment of the Qt₁ surface, we subtracted offsets that uplifted this surface from the cumulative offset recorded geologically. Therefore, between 15 Ma and the abandonment of Qt₁, a minimum and maximum of 8,657 and 13,001 m of dip-slip has accumulated along the MPTFS. This yields average dip-slip rates between 0.58 and 0.98 mm/yr along the MPTFS during this time.
Discussion

Variation in slip along the Main Pamir Thrust

Geodetic, paleoseismologic, geomorphic, and geologic offsets spanning timescales of 6 to 15,000,000 years yield slip rates and thus displacement release rates along the MPT of 0.17 to 6.31 m/kyr (Table 3). The highest rates come from the offsets at Syrindjar and the maximum rate from the offset pediment (5.31–6.31 m/kyr). These are for moderate offset magnitudes (10s–100s of m) and ages (~10s–100s of ka). In contrast, the minimum rates result from analysis of the largest offset and ages from the geology (0.62 m/kyr), from assumption of large age (1800 ka) and low offset (175 m) of the pediment (0.17 m/kyr—the lowest rate in this study), and from the single earthquake offset and inferred maximum recurrence interval at Komansu (0.46 m/kyr for 1.6 m in 3.46 kyr). The mean and standard deviation in slip rate for all of the determinations is 2.2±2.1 m/kyr. If that is meaningful, it assumes that all of the differences are due to natural variation and normally distributed errors in the observations and measurements. On the other hand, the distribution of rates is skewed toward the lower end and not normally distributed.

To examine whether the displacement release rate varies with time and to compare it with that accumulated, we plotted the data from along the entire MPT in a displacement accumulation-release plot (Figure 15). We assume that spatial variation is unimportant, despite the obvious segmentation of the thrust belt (Figures 2 and 3). Given the better constraints on the most recent earthquake, and to limit the analysis to data from the central segment, we do not include the Shivie Su results. The left column of this figure shows the displacement released as presented in Table 3. We work back in time (increasing ka) and assume that the displacement release is additive. The most recent release is the most recent earthquake which occurred conservatively between 1.43±0.10 ka and 3.20±0.26 ka. Prior to that, maximum fault slip of 1.6–9.52 m displaced the terrace and gravel at Komansu between 3.46 and 7.99 ka. Assuming that the Komansu slip is representative for later slip, 40–9.52 m accumulated between 6.34 and 7.99 or 10.84 ka at Syrinadjar. The pediment offset is an order of magnitude greater than the Syrindjar determination, and it is measured over 1 to 3 orders of magnitude greater time. Thus the range of displacement release prior to that measured by Syrinadjar is broad (Figure 15a). We change the plotting scale in Figure 15b to show the displacement accumulation from the pediment bounds to the geologic shortening. The geologic results are plotted with a maximum age of 15000 ka and slip 9268–13306 m. Because there are growth strata in the Alai Valley associated with continued slip along the MPT, we assume that the slip accumulated steadily to the Quaternary.

rate variation: real or within error? - Tien shan GPS

B and M implications - Decoupling between upper and lower crust required to have continental subduction - Pegler and Das - something else
Conclusions

Acknowledgments

This work was supported by Deutsche Forschungsgemeinschaft (D.F.G.) granted to M. Strecker, and an INTAS grant by the EC to M. Strecker and K. Haselton, and National Science Foundation grant EAR-9805319 to R. Arrowsmith. We thank A. and O. Korjenkov, A. Konykov, E. Mamyrov, and M. Omaruliev for field and logistical support, and I. Coutand, B. Czassny, R. Thiede, and E. Young for assistance in the field. E. Mamyrov provided the KIS seismicity data plotted in Figure 2. We are indebted to B. Fabian, A. Landgraf, N. Stahlberg, and A. Roy (Universität Potsdam), and M. Baillie, S. Holloway, and S. Selkirk (Arizona State University) for helping with digitizing and drafting tasks. We benefitted from discussions with P. Blisniuk, M. Meghraoui, and E. Sobel. Figure 2 was created using GMT (Wessel and Smith, 1995).

References


Blisniuk, P. M., Strecker, M. R., 1997, Quaternary oblique normal faulting in the Lake Karakul area, northern Pamir (Tajikistan); transfer of lateral escape along the Karakorum and Altyn Tagh faults? GSA Abstracts with Programs, 29, 6, A-470.


Table 1: Infrared Stimulated Luminescence ages by the multiple aliquot additive dose method on fine-grained polymineral extracts. All errors are 1σ. Analyses were performed by S. L. Forman at the Luminescence Dating Research Laboratory University of Illinois at Chicago.

<table>
<thead>
<tr>
<th>Field #</th>
<th>Laboratory #</th>
<th>Equivalent Dose (Gy)</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>K₂O %</th>
<th>Dose rate (Gy/ky)</th>
<th>IRSL Age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>99KOM-STL2</td>
<td>UIC775</td>
<td>8.126±0.025</td>
<td>2.67±0.46</td>
<td>9.60±1.28</td>
<td>2.77±0.02</td>
<td>4.34±0.33</td>
<td>1.87±0.14</td>
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<tr>
<td>99KOM-NTL2</td>
<td>UIC780</td>
<td>5.505±0.039</td>
<td>2.66±0.37</td>
<td>6.84±1.00</td>
<td>2.40±0.02</td>
<td>3.85±0.29</td>
<td>1.43±0.10</td>
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<tr>
<td>99KOM-NTL3</td>
<td>UIC777</td>
<td>11.08±0.021</td>
<td>1.91±0.30</td>
<td>6.48±0.80</td>
<td>2.47±0.02</td>
<td>3.46±0.21</td>
<td>3.20±0.22</td>
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<tr>
<td>99KOM-NTL4</td>
<td>UIC774</td>
<td>6.073±0.017</td>
<td>2.87±0.34</td>
<td>6.90±0.87</td>
<td>2.64±0.03</td>
<td>4.02±0.30</td>
<td>1.51±0.10</td>
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<tr>
<td>99KOM-NTL5</td>
<td>UIC776</td>
<td>8.836±0.032</td>
<td>1.91±0.30</td>
<td>6.48±0.80</td>
<td>1.75±0.02</td>
<td>2.76±0.18</td>
<td>3.20±0.26</td>
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<tr>
<td>99KMO-NTL7</td>
<td>UIC779</td>
<td>24.806±0.06</td>
<td>1.90±0.26</td>
<td>5.21±0.69</td>
<td>1.54±0.02</td>
<td>2.45±0.15</td>
<td>10.12±0.72</td>
</tr>
</tbody>
</table>

Table 2: ¹⁴C data. Samples were all charred material and had acid/alkali/acid pretreatment. All analyses are standard AMS dates from Beta Analytic Radiocarbon Dating Laboratory. All errors are 1σ; except calibrated age which is 2σ. BP is years before 1950.

<table>
<thead>
<tr>
<th>Field Sample Number</th>
<th>Lab Sample Number</th>
<th>Measured radiocarbon age</th>
<th>¹³C/¹²C ratio (o/oo)</th>
<th>Conventional radiocarbon age</th>
<th>2σ calibrated age* (cal AD)</th>
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</thead>
<tbody>
<tr>
<td>A4-1</td>
<td>Beta-96219</td>
<td>5610±50 BP</td>
<td>-25.2</td>
<td>5610±50 BP</td>
<td>4540BC–4340BC (95.4%)</td>
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<tr>
<td>A5-2</td>
<td>Beta-96221</td>
<td>6160±60 BP</td>
<td>-24.9</td>
<td>6160±60 BP</td>
<td>5300BC–4930BC (94.4%)</td>
</tr>
<tr>
<td>7-27-1</td>
<td>Beta-134700</td>
<td>3280±50 BP</td>
<td>-26.3</td>
<td>3260±50 BP</td>
<td>4870BC–4850BC (1.0%)</td>
</tr>
<tr>
<td>8-4-99-9</td>
<td>Beta-134705</td>
<td>2480±40 BP</td>
<td>-25.4</td>
<td>2470±40 BP</td>
<td>1690BC–1420BC (95.4%)</td>
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<tr>
<td>8-4-99-11</td>
<td>Beta-134706</td>
<td>1910±60 BP</td>
<td>-25.9</td>
<td>1900±60 BP</td>
<td>770BC–400BC (95.4%)</td>
</tr>
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</table>

* Calibration performed using OxCal (Bronk Ramsey, 1995) with the INTCAL98 calibration data (Stuiver et al., 1998).
<table>
<thead>
<tr>
<th>Data set</th>
<th>Min. age (ka)</th>
<th>Max. age (ka)</th>
<th>Age comments</th>
<th>Min. dip slip (m)</th>
<th>Max. dip slip (m)</th>
<th>Dip slip rate (m/kyr)</th>
<th>Dip slip rate comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paleoseismic data at Komansu</td>
<td>1.43 ±0.10</td>
<td>3.2 ±0.26</td>
<td>NTL3 and NTL5 defines maximum age for event. NTL2 defines minimum.</td>
<td>1.6</td>
<td>1.6</td>
<td>0.46–1.20</td>
<td>Assuming dip slip over recurrence interval equals dip slip rate.</td>
</tr>
<tr>
<td>Paleoseismic data and terrace offsets at Shivie Su</td>
<td>3.4 ±3.7</td>
<td>6.34 ±0.26</td>
<td>Age for Qt4 surface reported by Strecker et al., in press</td>
<td>4.7</td>
<td>6.8</td>
<td>1.27–1.84</td>
<td></td>
</tr>
<tr>
<td>Terrace offsets at Komansu</td>
<td>3.2 ±7.99</td>
<td>6.34 ±0.99</td>
<td>NTL3 and NTL5 must be younger than surface. Max. age represents correlated QT₄ surface age from ¹⁴C ages (Arrowsmith and Strecker, 1999)–the faulted surface here is mapped as Qt₂ (younger)</td>
<td>8.42</td>
<td>9.52</td>
<td>1.05–3.24</td>
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<tr>
<td>Terrace offsets at Komansu</td>
<td>10.12 ±0.72</td>
<td>10.12 ±0.72</td>
<td>Alternate maximum age from 99KOM-NTL7.</td>
<td>8.42</td>
<td>9.52</td>
<td>0.78</td>
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</table>

Table 3: See table 2 for ¹⁴C ages and table 1 for luminescence ages.
### Displacement release rate, continued

<table>
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<tr>
<th>Data set</th>
<th>Min. age (ka)</th>
<th>Max. age (ka)</th>
<th>Age comments</th>
<th>Min. dip slip (m)</th>
<th>Max. dip slip (m)</th>
<th>Dip slip comments</th>
<th>Dip slip rate (m/kyr)</th>
<th>Dip slip rate comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrace offsets at Syrinadjar</td>
<td>6.34 to 7.99</td>
<td>7.99</td>
<td>Qt₃ surface age from ¹⁴C ages (Arrowsmith and Strecker, 1999). Alternate maximum age is 10.12 ± 0.72 from 99KOM-NTL7.</td>
<td>40</td>
<td>40</td>
<td>Dip slip from offset surface (18 m vertical offset) converted to dip slip using observed 27° dip.</td>
<td>5.01–6.31</td>
<td>Minimum rate from Arrowsmith and Strecker, 1999.</td>
</tr>
<tr>
<td>Pediment surface offset</td>
<td>105 to 1794</td>
<td>1794</td>
<td>Covered by Qm₁ moraines inferred to be early Wisconsin or pre-Sangamon and cut into Pliocene Baktry formation (Strecker, et al., in press and Coutand, et al., in press). Accounts for time up to initiation of offset of Qt₃.</td>
<td>305</td>
<td>611</td>
<td>Vertical surface offset of 193 to 276 m minus 18 m (see above) converted to dip slip with 35°–25° dip for minimum and maximum respectively.</td>
<td>0.17–5.81</td>
<td></td>
</tr>
<tr>
<td>Shortening from balanced cross-section reconstruction</td>
<td>15000</td>
<td>13001</td>
<td>Maximum is from initiation of deformation defined by age of unconformity. Syntectonic deposition on footwall implies continuous dip slip to Quaternary (Coutand, et al., in press).</td>
<td>8657</td>
<td>13001</td>
<td>Horizontal displacements from Coutand, et al., in press converted to dip slip using effective fault dips of 25°–35° and subtracting slip from pediment surface offset.</td>
<td>0.58–0.98</td>
<td>Assume all shortening is accommodated along the MPT.</td>
</tr>
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### Displacement accumulation rate

<table>
<thead>
<tr>
<th>Data set</th>
<th>Min. age (ka)</th>
<th>Max. age (ka)</th>
<th>Age comments</th>
<th>Min. dip slip (m)</th>
<th>Max. dip slip (m)</th>
<th>Dip slip comments</th>
<th>Dip slip rate comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS Geodesy</td>
<td>≤ 6 years of measurement</td>
<td>0.7–13.7 m/kyr horizontal displacement accumulation rate across 100 km-wide aperture projected to 350° (normal to MPT trace). (Reigber, et al., 2001). Converted to minimum and maximum dip slip using a range of dips from 25°–35°.</td>
<td>0.8–16.7</td>
<td>Assumes all interseismic shortening in region is accommodated along Main Pamir Thrust. These are extreme bounds. More reasonable rates are 6.7–14.2 m/kyr.</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
Figure captions

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—Tadzhik Depression. Rectangle outlines area covered by Figure 2. Modified from Armijo et al. (1986), Frisch et al. (1994), Arrowsmith and Strecker (1999), and Strecker, et al., in press.

Figure 2. Geography, major structures, instrumental seismicity, and GPS velocity vectors for the Pamir-Alai region. A) The seismicity in this region is predominantly < 50 km deep and arrayed along the arcuate Main Pamir Thrust (MPT) system cutting the central portion of this map separating the Pamir from the Tien Shan. Harvard CMT focal mechanisms indicate thrusting in the convergence zone between the Tien Shan and Pamir and strike-slip and normal faulting in the Pamirs to the south. Seismicity plotted in black is from the Council of the National Seismic System (CNSS; http://quake.geo.berkeley.edu/cnss/cnss-catalog.html) and ranges in magnitude from M3 to about M7. Kyrgyz Institute of Seismology (KIS) seismicity data for the area indicated by the grey dashed box for which magnitudes range from 2.5 to 6. 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 to 3 km elevation, whereas the surrounding ranges reach elevations of more than 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 black rectangle. Modified from Strecker, et al., in press. B) GPS velocities with respect to stable Eurasia for the southwestern portion of the CATS network (replotted from Reigber, et al., 2001). Velocities generally decrease from south-southeast to north-northwest. The eastward increase in velocity of the northern three stations results from clockwise rotation of the southern Tien Shan and Fergana. We projected these velocities to a line roughly perpendicular to the strike of the central segment of the MPT near the Komansu trench site. The error ellipses denote 95% confidence.

Figure 3. Generalized geologic map of the Alai Valley, northern Trans Alai and southern Tien Shan ranges (from Strecker, et al., in press). The locations of paleoseismic studies at Komansu and Shivie Su are indicated (see Figures 5 and 6).

Figure 4. GPS site velocities projected to 350° line roughly perpendicular to MPT (indicated by vertical dashed line; see Figure 2b). Velocities are with respect to stable Eurasia. Distance is from the NNW (site 18). Velocities and errors are replotted from Reigber, et al., 2001. 13, 18, and 29 are site designations from Reigber, et al., 2001. See text for further explanation.

Figure 5. Relationships between landforms, deposits, and structures along the Trans Alai Range front near the Komansu and Minjar Rivers (see Figure 3 for location). The Declassified Intelligence Satellite (CORONA) Photograph on the right shows the relationships that are mapped in the Quaternary geologic map shown on the left. It documents the erosional contact between the Qt3 materials and the Qm3 moraines, and the apparently coeval timing of deposition of Qt3 and Qm3. The earthquake geology topographic profiles and excavations are on the left bank of the Komansu River. Modified from Arrowsmith and Strecker, 1999.

Figure 6. Relationships between landforms, deposits, and structures along the Trans Alai Range front
near the Shivie Su River (see Figure 3 for location). The Declassified Intelligence Satellite (CORONA) Photograph on the right shows the relationships that are mapped in the Quaternary geologic map shown on the left. The earthquake geology topographic profiles and excavations are on an incised alluvial terrace of the Shivie Su River which has cut down along with the main Kyzil Su trunk drainage flowing east to west across the upper portion of the map.

Figure 7. Site map and topographic profiles at Komansu. A) Site map illustrating location of topographic profiles (small dot sequences), excavations (solid polygons), trace of thrust fault (solid line with teeth on upthrown side) and its buried continuation to east (dots)–note the more southerly position due to the 30 m high active river channel cut (west edge of grey area). The active channel surface is shown in grey. B) Scarp and river topographic profiles. Active channel floor is clearly undeformed. The more easterly scarp profile is lower and the offset lower because it is on a surface cut into and thus younger than the surface profiled to the west. Approximate excavation locations are indicated by black polygons. The surveyed topographic points were projected to a 301° plane. C) Terrace riser profiles illustrate the incision indicated by the riser mapped in A. The surveyed topographic points were projected to a 023° plane. D) Photograph from east side of Komansu River looking west along fault at displaced gravels and terrace surface (modified from Arrowsmith and Strecker, 1999). The gravels are offset about 4.9 m and the terrace surface is offset 4.6 to 5.2 m (not including enhanced offset due to dip slip along back thrust). Main fault dips about 33°. Marker layers are indicated with dashed lines; person for scale is inside ellipse, and the boxes show the approximate extent of the excavations which were made just 15 m beyond the cliff edge.

Figure 8. Site map and topographic profiles at Shivie Su. A) Site map illustrating location of topographic profiles (small dot sequences), excavation (solid polygon), trace of thrust fault (solid line with teeth on upthrown side). The active channel surface is shown in grey. B) Scarp and river topographic profiles. Active channel floor is clearly undeformed. The scarp profile shows both the fault-related offset as well as a small notch attributed to a degraded irrigation canal. The surveyed topographic points were projected to a 325° plane. C) Terrace riser profiles illustrate the incision indicated by the riser mapped in A. The terrace profiles are all below the fault scarp. The surveyed topographic points were projected to a 024° plane.

Figure 10. Komansu trench cuts the scarp with resistant vertical Neogene rocks in the middle ground and Pik Lenin in the back. View to the south.

Figure 11. Trench log and photomosaic of the west wall of the Komansu excavation (north trench). A) Log shows fluvial gravels with CaCO₃ coatings (in black), capping retransported loess, and wedges of matrix-supported, northerly inclined, colluvium. Three colluvial wedges inferred to have developed after major earthquakes are colored and the fault zone is shown in red. Offset in the last earthquake is measured by the match between offset portions of a distinctive “pea gravel.” IRSL sample locations and ages are indicated (see also Table 1. B) Photomosaic illustrating sedimentary and fault relationships and the character of the exposure. Mosaic is more extensive than log and clearly shows the undeformed gravels and covering retransported loess to the north and the folded gravels to the south. Note the higher clay content of the colluvial material retains moisture more than the gravels and thus the dark brown zones at the base of the fault zone.
Figure 12. Komansu south trench log and photomosaic (west wall).

Figure 13. Trench log and photomosaic of the east wall of the Shivie Su excavation. A) Log shows fluvial gravels with \( \text{CaCO}_3 \) coatings (in grey) with disrupted layering and in fault contact (above) and depositional contact (below) with matrix supported gravels inferred to be colluvium. The wedge of colluvial material is inferred to have accumulated after the penultimate ground rupture and was then cut in the last earthquake. B) Photomosaic illustrating sedimentary and fault relationships and the character of the exposure.

Figure 14. Geomorphic map and cross section showing the calculation of the offset of Qt surface. Offset of the surface with respect to the MPT is 276–193 m. Moraine deposits are sculpted into the Qt surface, which is in turn cut into the syntectonic Pliocene Bakhtry Formation providing age constraints for the surface. Map modified after Strecker et al., in press.

Figure 15. Summary of inferred and compiled rates of displacement accumulation and release. A (paleoseismic and geomorphic time span) and B (geologic time span) show the observations from this paper and information from Arrowsmith and Strecker, 1999; Strecker, et al., in press; and Coutand, et al., in press. Darker grey implies relatively stronger constraints relative to the areas in medium grey. C and D cover the same time scales, but include information about the regional displacement accumulation rate (Reigber, et al., 2001) and our interpreted displacement release bounds (shown in light grey). The smaller dashes indicate the extreme ranges of geodetically-defined displacement accumulation rates versus the longer dashes which represent more reasonable values. The scales of the plots are such that displacement rates are depicted with constant slopes, so the longer time scale clearly implies a lower displacement release rate (d) with respect to the geodetic, paleoseismologic, and geomorphic rates (c). See table 3 and text for discussion.
Figure 1:
**Figure 2:**

- **A** Ferghana Basin
- **B** 5 mm/yr

**Explanation:**
- Thrust fault, teeth on upthrown side
- Normal fault, ticks on downthrown side
- Strike-slip fault, arrows show sense of motion
- Harvard CMT
- Instrumental seismicity (black = CNSS; grey = KIS in dashed box)

**Sites:**
- AD
- DK
- KA
- SK
Figure 3:
Figure 4:
Figure 5:
Figure 6:
Figure 7:
Slip Rate Variation Along the Main Pamir Thrust

Figure 8:

Figure 9:
Figure 10:
Figure 11:

**Explanation**
- **Fault Zone**
- **Wedge developed after earthquake**
- **Wedge developed after penultimate earthquake**
- **Wedge developed after last earthquake**
- **Offset gravel in last earthquake**
- **IRSL sample location (age in ka)**
- **Silt Lamination**
- **Sand**
- **Pebbles w/o Laminae**
- **Pebbles w/ Laminae**
- **Clast (shading = CaCO3)**
- **Fining Direction**
- **Vegetation (roots) dominates**

**Legend:**
- Red: Fault Zone
- Yellow: Wedge developed after earthquake
- Blue: Wedge developed after penultimate earthquake
- Green: Wedge developed after last earthquake
- Orange: Offset gravel in last earthquake
- **•**: IRSL sample location (age in ka)
- Light blue: Silt Lamination
- Dark blue: Sand
- Light brown: Pebbles w/o Laminae
- Dark brown: Pebbles w/ Laminae
- **↓**: Fining Direction
- **Roots**: Vegetation (roots) dominates

**Figure 11:**