Late Cenozoic tectonic development of the intramontane Alai Valley, (Pamir-Tien Shan region, central Asia): An example of intracontinental deformation due to the Indo-Eurasia collision

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[1] The Pamir indentor of the northwestern Himalayan syntaxis is a first-order feature demonstrating partly the northward extent of deformation due to the Cenozoic Indo-Eurasia collision. The Alai Valley of Kyrgyzstan at the northern end of the indentor is a strategically positioned, E-W trending intramontane basin that constrains the timing and extent of crustal deformation in this area of the collision zone. To quantify the convergence accommodated across the Alai Valley during the Late Cenozoic, we collected structural and stratigraphic field data, reviewed existing Soviet literature, and analyzed migrated seismic reflection profiles to construct and restore two regional sections crosscutting the basin. Our study suggests that the development, progressive closure, and conversion of this formerly marine basin into a terrestrial intramontane basin result from two main deformation events: (1) Distributed north-south contraction took place during the late Oligocene–early Miocene, accommodated one third to half of the total shortening and was followed by the formation of a regional erosion surface; and (2) N-S shortening resumed in the mid-Miocene and continues today. During this second episode the thrust front migrated southward, localized along the Trans Alai ranges, and failed to reactivate earlier Neogene structures. Horizontal shortening of about 35% across the Alai Valley implies relatively low strain rates and displacement rates of about $4.18-4.69 \times 10^{-16}\ s^{-1}$ and $0.66-0.78\ mm\ yr^{-1}$, respectively, for the last 25 Myr. Our study confirms other regional observations indicating that contractional deformation occurred far in the interior of the Asian continent as early as the late Oligocene. *INDEX TERMS:* 9604 Information Related to Geologic Time: Cenozoic; 5475 Planetology: Solid Surface Planets: Tectonics (8149); 8102 Tectonophysics: Continental contractional orogenic belts; 8105 Tectonophysics: Continental margins and sedimentary basins; 9320 Information Related to Geographic Region: Asia; *KEYWORDS:* Intramontane basin, central Asia, continental deformation, India-Eurasia collision. **Citation:** Coutand, I., M. R. Strecker, J. R. Arrowsmith, G. Hilley, R. C. Thiede, A. Korjenkov, and M. Omuraliev, Late Cenozoic tectonic development of the intramontane Alai Valley, (Pamir-Tien Shan region, central Asia): An example of intra-continental deformation due to the Indo-Eurasia collision, *Tectonics*, *21*(6), 1053, doi:10.1029/2002TC001358, 2002.

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1. Introduction

[2] The collision of India with the southern margin of Asia about 55 Myr ago [*Patriat and Achache*, 1984; *Searle et al.*, 1987], has produced one of the most spectacular mountain belts on Earth that accommodates ~2000–2500 km of convergence [*Cobbold and Davy*, 1988; *Dewey et al.*, 1989]. Whereas deformation has apparently propagated northward from the Indus-Tsangpo suture [*Burchfiel and Royden*, 1991; *Harrison et al.*, 1992] causing extensive intracontinental deformation in Asia [e.g., *Molnar and Tapponnier*, 1975], preexisting zones of lithospheric weakness may have caused synchronous deformation far in the Asian interior (e.g., Tien Shan mountains [*Burtman*, 1975; *Hendrix et al.*, 1992]). A clear picture of the complex spatial and temporal distribution of crustal deformation in the Asian continent is required, in order to make realistic inferences about the processes driving this mountain building. Within the northwestern Himalayan syntaxis (Figure 1), the southern edge of the Pamir indentor has moved northward by at least 600–650 km during the Cenozoic with respect to stable Eurasia [e.g., *Burtman and Molnar*, 1993] and this makes it a first-order feature of the Indo-Eurasian collision.

[3] Within the central Pamir, north of the Rushan-Pshart zone (Figure 1), apatite fission track data suggest rapid exhumation of amphibolite-grade metamorphic domes associated with 31 Ma old granites [*Schwab et al.*, 2000]. These domes are perhaps due to gravitational collapse of the over-thickened indentor, implying pre-Miocene shortening in the area [*Schwab et al.*, 2000]. In addition, 210 Ma old granitic intrusions in the northern Pamir have yielded Paleocene to

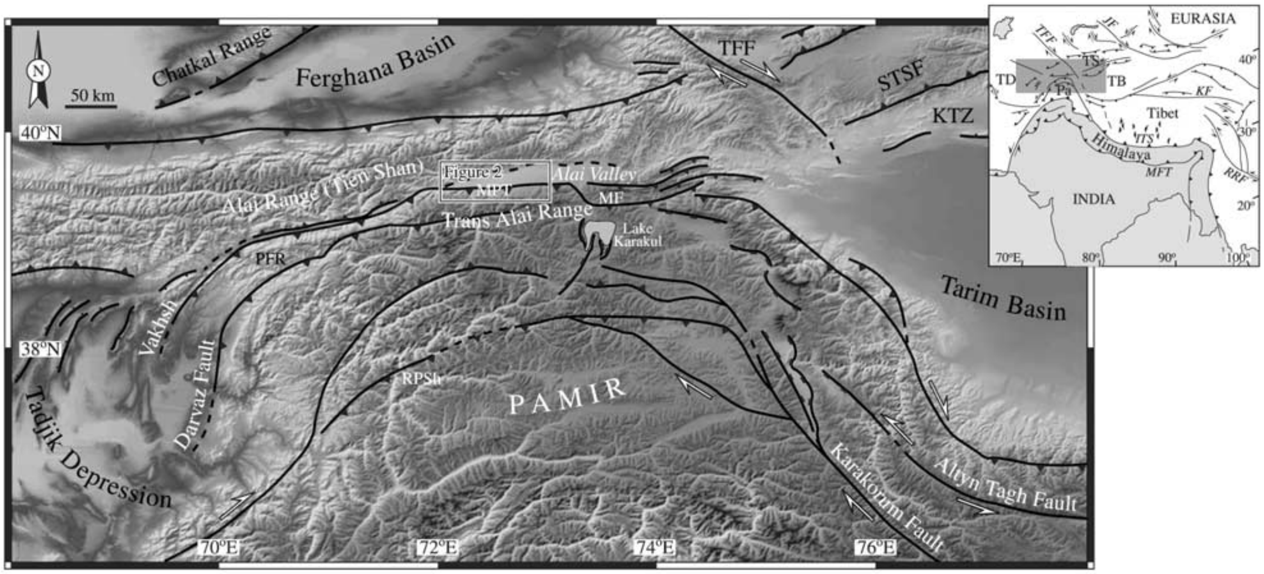


Figure 1. Major Cenozoic faults of the Pamir and adjacent areas showing the situation of the Alai Valley, between the Pamir and the Tien Shan [modified after *Burtman and Molnar*, 1993; *Strecker et al.*, 1995]. The Alai Valley is a remnant of the once continuous early Cenozoic basin connecting the Tadjik depression and the western Tarim. Figure 3 covers the boxed area. The shaded box in inset shows the area covered by digital topography and depicts major structural features of the Himalaya-Tibet region (modified after *Allen et al.* [1999]). Topography is from the U.S. Geological Survey. Abbreviations are ITS: Indus-Tsangpo Suture, JF: Junggar Fault, KF: Kunlun Fault, KTZ: Kepingtage Thrust Zone, MF: Markansu Fault, MFT, Main Frontal Thrust, MPT: Main Pamir Thrust, Pa: Pamir, PFR: Peter the First Range, RPSh: Rushan Pshart Zone, RRF: Red River Fault, STSF: South Tien Shan Fault, TB: Tarim basin, TD: Tadjik Depression, TFF: Talas Ferghana Fault. See color version of this figure at back of this issue.

Miocene apatite fission track cooling ages [*Schwab et al.*, 2000]. However, along the northern periphery of the Pamir, folding and regional uplift are thought to have started in the Quaternary [*Belousov*, 1976; *Yermilin and Chigarev*, 1981; *Nikonov et al.*, 1983; *Burtman and Molnar*, 1993]. The spatial and temporal patterns of deformation in this region remain poorly known, but may potentially be resolved by studies combining field observations and analysis of seismic reflection and borehole data.

[4] Intramontane basins preserve stratigraphic and structural information that records deformation in the upper levels of the continental lithosphere during orogeny. One such basin is the Alai Valley, which is located along the northern periphery of the Trans Alai range of the Pamir (Figure 1). The apparently deep basin exposes key lithologic and tectonic units along its northern and southern margins, and motivated geophysical exploration in the late 1980s. Thus, the basin is strategically placed for constraining and quantifying episodes of tectonic activity due to the Indo-Eurasia collision. We collected structural and stratigraphic data during 1999 fieldwork, reviewed existing Soviet literature and analyzed migrated seismic reflection profiles made available by the Kyrgyz Geological Survey. We also used lithologic information from an exploratory well located in the Trans Alai piedmont, restored two regional sections crossing the Alai basin, and calculated the strain and displacement rates for this region during the Late Cenozoic. This allowed us to investigate the development and progressive closure of this formerly marine basin and its conversion into a terrestrial collisional basin during the last ~25 Myr. We infer that the Alai Valley is an asymmetric intramontane basin whose development and progressive annihilation result from a two-stage tectonic history beginning in the late Oligocene and continuing until the present. Horizontal shortening estimates across the valley are about 35% and yield average strain and displacement rates that are rather small (on the order of $4.18-4.69 \times 10^{-16}$ s^{-1} and $0.66-0.78$ mm yr^{-1}, respectively, for the last 25 Myr).

2. Geological Setting of the Northern Pamir and Adjacent Regions

[5] North of the Pamir indentor, the Tien Shan Range (Figure 1) extends broadly E-W to ENE-WSW for more than 2500 km across central Asia and records multiple transpressive deformation during late Paleozoic and Mesozoic time [*Korolyov*, 1961; *Knauf*, 1966; *Windley et al.*, 1990; *Allen et al.*, 1993; *Carroll et al.*, 1995; *Hendrix et al.*, 1992]. During the late Cenozoic it was reactivated as a result of the India-Eurasia collision [*Tapponnier and Molnar*, 1979]. In the southern Tien Shan, Paleozoic crystalline reverse-fault bounded basement ranges alternate with Cenozoic intramontane basins [*Molnar and Tapponnier*, 1975; *Sengör*,

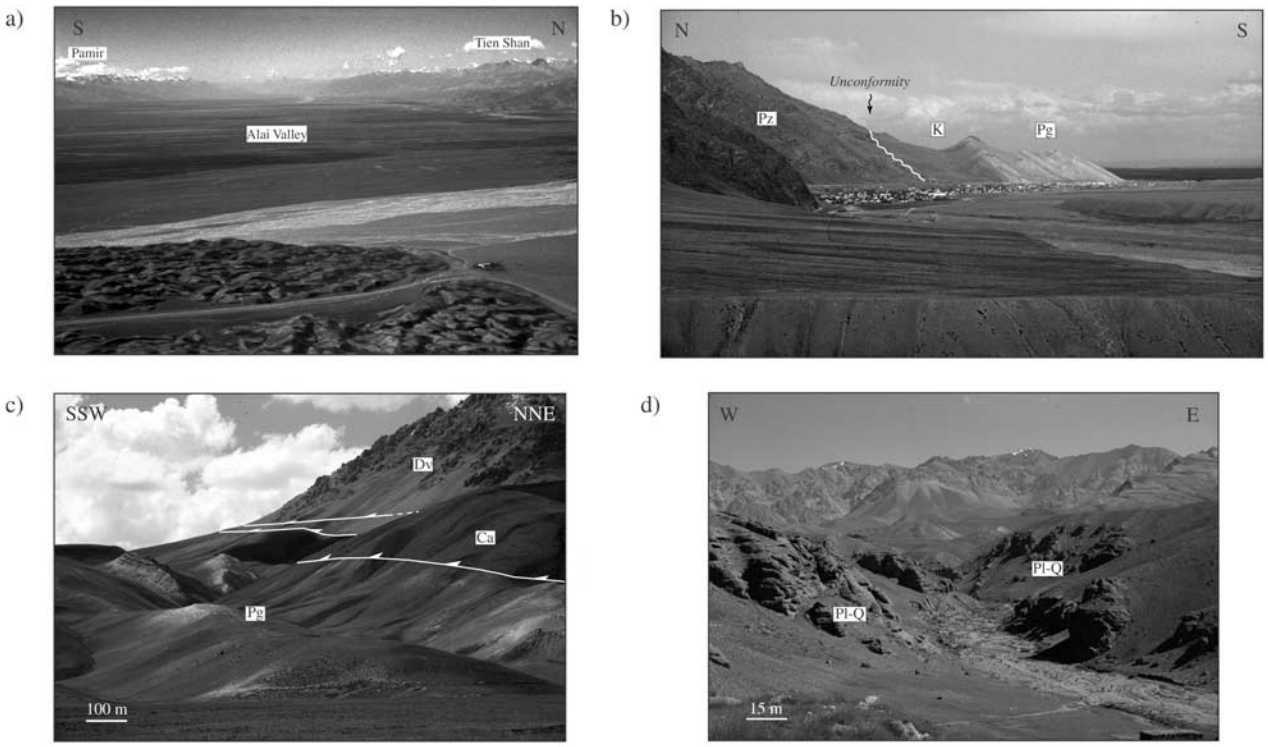


Figure 2. (a) The present southern Alai Valley mainly comprises north sloping coalesced alluvial fans at an average elevation of ~2700 m, surrounded by high mountains of the Alai Range (Tien Shan) to the north, and the Trans Alai Range (Pamir) to the south reaching elevations >7000 m (Pik Lenin, 7134 m; see Figures 1 and 3). Hummocky topography in front is due to ground moraine deposits of extensive piedmont glaciers. The valley closes westward where both ranges meet, ~80 km west of the point at which the photograph was taken (view due west). (b) Unconformity between Paleozoic basement (Pz) and Early Cretaceous red beds (K) and Late Cretaceous-early Paleogene white carbonates (Pg) in the southern limb of a drape fold, east of the intersection between Kyzylsu and Altyndara drainages, NW Alai Valley (view to east; for location, see Figures 3 and 9c). In the foreground is an incised pediment of the southern Tien Shan. Houses for scale. (c) South vergent thrust fault, which successively juxtaposes Devonian marbles (Dv; rocky slope above) on Carboniferous metasediments (Ca), and Paleogene strata (Pg; smooth lower slopes). Thrusts run along breaks in slope (view to northwest, for location, see Figure 9a). (d) Plio (?)-Quaternary conglomerates (Pl-Q) cropping out within Kyzylunkur drainage are flat-lying and undeformed (view to the north; for location, see Figure 3).

1984; *Chedia*, 1986; *Sadybakasov*, 1990; *Cobbold et al.*, 1994; *Burbank et al.*, 1999]. However, differential motions between the eastern and western portions of this mountain belt lead to varying range morphology along strike. The right-lateral Talas-Ferghana strike-slip fault (TFF) accommodates this differential motion, creating a series of narrow ranges to the west [*Burov and Molnar*, 1998], in contrast to a larger single belt to the east (Figure 1).

[6] South of the western Tien Shan is the Alai Valley, an E-W trending almond-shaped topographic depression at an average elevation of 2700 m (Figures 1 and 2a). It lies on the southern margin of Eurasia, extending ~180 km from Tadjikistan in the west to China in the east (Figures 1 and 3). The Alai Valley is a vestige of the Mesozoic to early Cenozoic Afghan-Kashgar basin, that linked the Tadjik depression in the west and parts of the Tarim basin in the east (Figure 1) [*Leith*, 1982; *Sengör*, 1984; *Burtman and Molnar*, 1993; *Burtman*, 2000].

[7] South of the Alai Valley is the leading edge of the convex-northward arc of the northern Pamir (Figures 1 and 3). The Pamir is a mosaic of Paleozoic and Mesozoic blocks that were successively accreted to southern Eurasia [e.g., *Burtman and Molnar*, 1993]. Deflection of structural belts [*Burtman and Molnar*, 1993], paleomagnetic rotations and reconstructions [*Bazhenov and Burtman*, 1986; *Thomas et al.*, 1993], and offset facies in adjacent basins [*Suvorov*, 1968; *Burtman and Molnar*, 1993] suggest that the Pamir was bent and displaced northward by ~300 km onto the southern Tien Shan domain [*Burtman and Molnar*, 1993; *Bourgeois et al.*, 1997]. In addition, large amounts of internal crustal shortening were accommodated, as much as 300 km [*Burtman and Molnar*, 1993]. Areas with largest amounts of shortening coincide with the highest elevations (>7000 m), immediately south of the Alai Valley in the Trans Alai range (Figure 1) [*Burtman and Molnar*, 1993], implying that the southern edge of the Pamir has moved northward by at least 600 km during

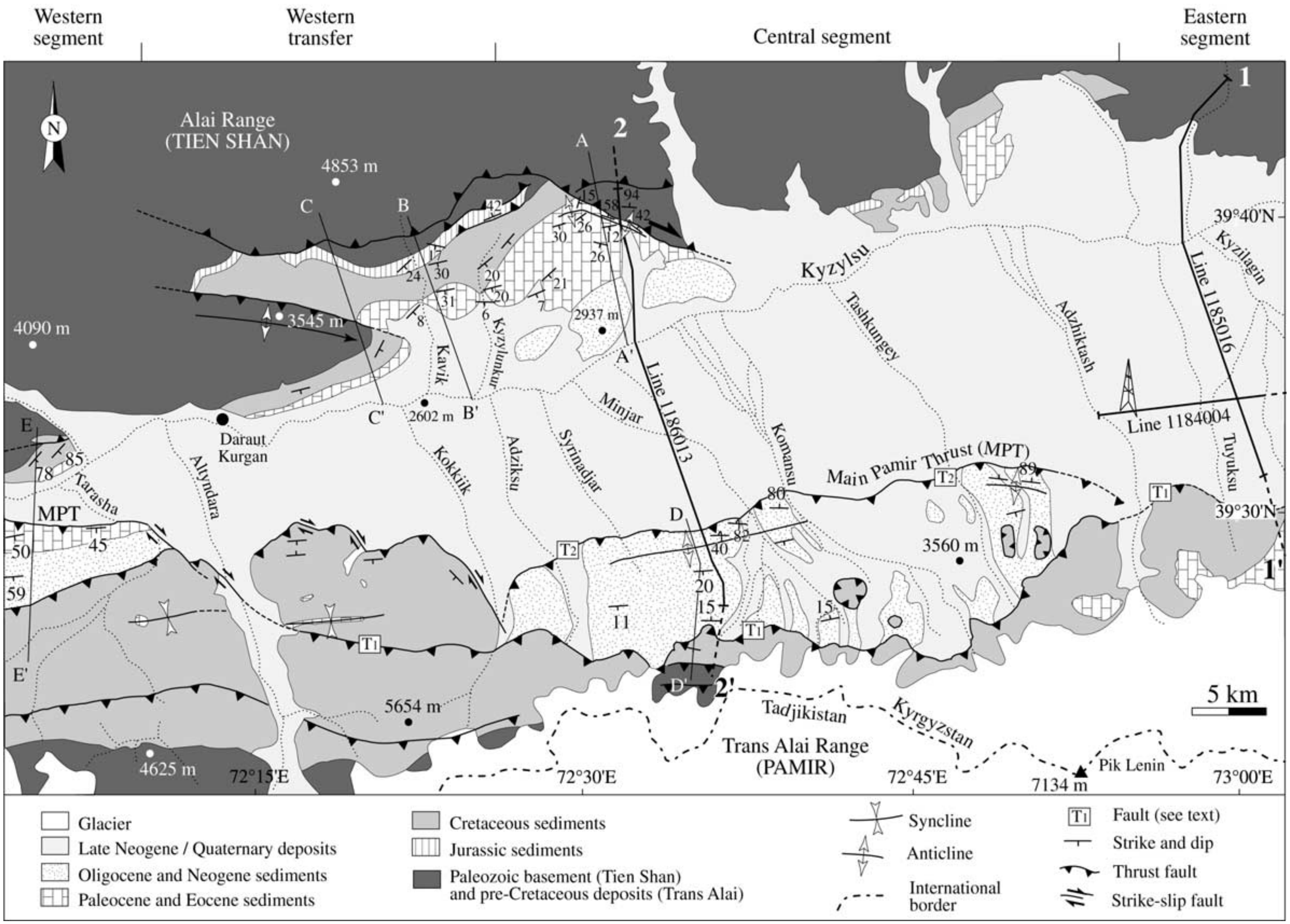


Figure 3. Geologic map of the Alai Valley partly based on field observations and published data. Modified after *Kozlov and Artemov* [1964], *Razvalyaev et al.* [1964], and *Arrowsmith and Strecker* [1999]. Along southern basin margin, the north vergent thrust faults of the Main Pamir thrust system progressively close the valley. Short lines indicate locations of detailed cross sections AA′, BB′, CC′, DD′ and EE′ along the borders of the valley (Figures 9 and 10). Symbols T_1 and T_2 refer to the main faults of the external part of the thrust belt. Long bold lines indicate locations of seismic profiles 1186016, 1185013, and 1184004 (Figures 5 and 6). The drilling-rig symbol indicates the location of well 1P-Alai. Dashed lines indicate regional cross sections 1-1′ and 2-2′ used for restoration (Figures 7 and 8).

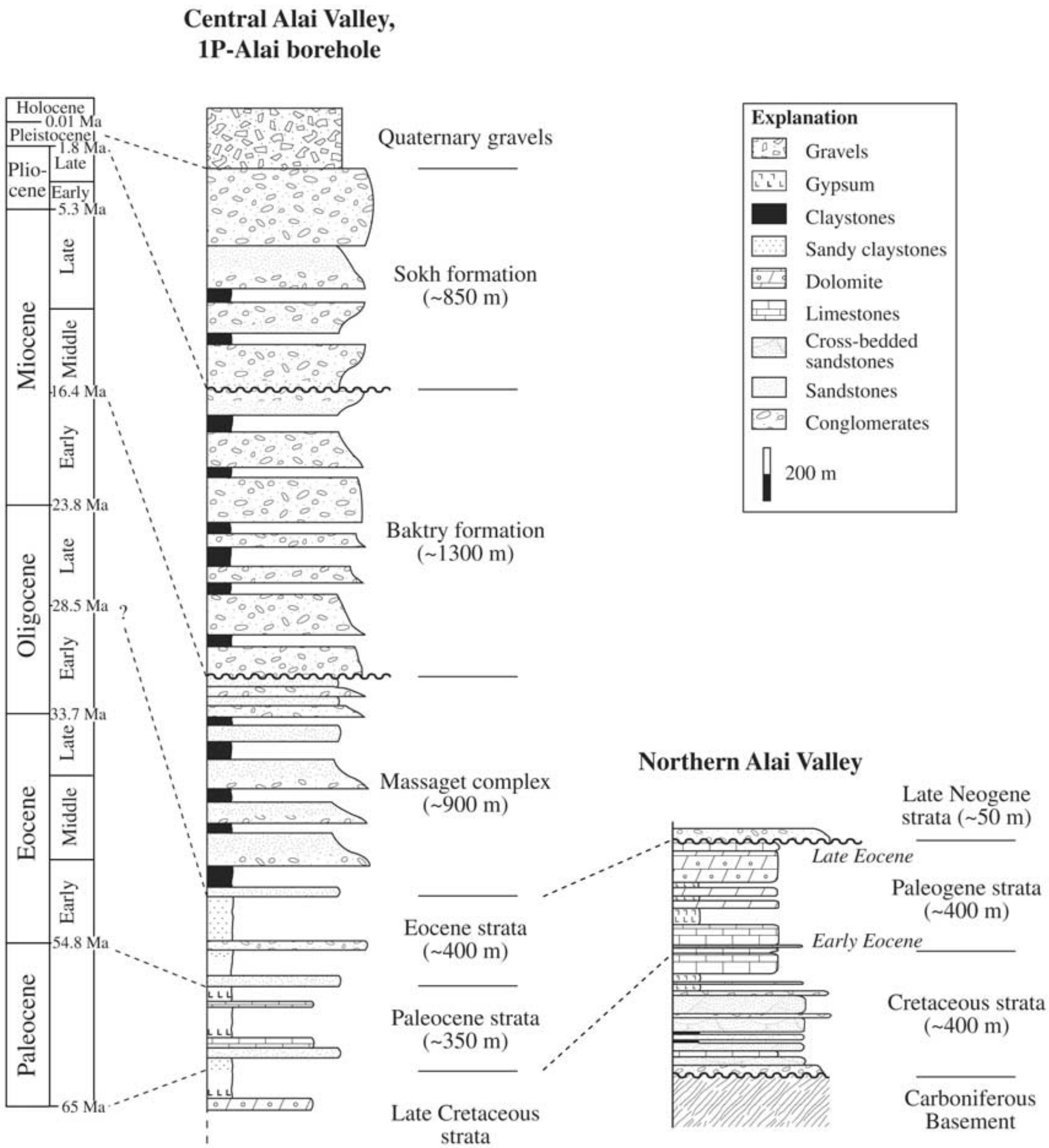


Figure 4. Cenozoic stratigraphic columns for the Alai Valley (modified after *Czassny et al.* [1999] and L. S. Ovsyannikov and F. S. Nakonechny, unpublished report, 1993). A Mesozoic section with transgressive pattern, and a late Paleogene-Neogene continental clastic package on top unconformably overlie Paleozoic basement. Data from the central Alai Valley are from 1P-Alai borehole (Ovsyannikov and Nakonechny, unpublished report, 1993), data from the northern Alai Valley were logged east of Kavik drainage [*Czassny et al.*, 1999]. For locations, see Figure 3. Ages reported in the scale are from the 1999 Geological Time Scale (GSA).

the Cenozoic, with respect to stable Eurasia [*Burtman and Molnar*, 1993]. The relative northward motion of the Pamir is accommodated by radial thrust faulting, sinistral and dextral strike-slip faulting along the northern, western and eastern margins, respectively [e.g., *Frisch et al.*, 1994]. Slip rates along the western (left-lateral) Darvaz fault and the northern (thrust) faults of the Peter the First and Trans Alai ranges are estimated to be 10–15 mm yr^{-1}, 10–15 mm yr^{-1}, and $\sim$20 mm yr^{-1}, respectively [*Hamburger et al.*, 1992; *Burtman and Molnar*, 1993]. However, slip along the Trans Alai ranges was recently determined to be $\geq$6 mm yr^{-1} [*Arrowsmith and Strecker*, 1999]. Shortening has thickened the crust up to 70–75 km over the Pamir [*Beloussov et al.*, 1980; *Brandon and Romanowicz*, 1986], and gravity measurements indicate local isostatic equilibrium [*Burov et al.*, 1990]. Seismicity [*Hamburger et al.*, 1992; *Lukk et al.*, 1995; *Nelson et al.*, 1987], geodetic studies [*Guseva et al.*, 1983; *Lukk and Schevchenko*, 1988; *Burtman and Molnar*, 1993], and geomorphological

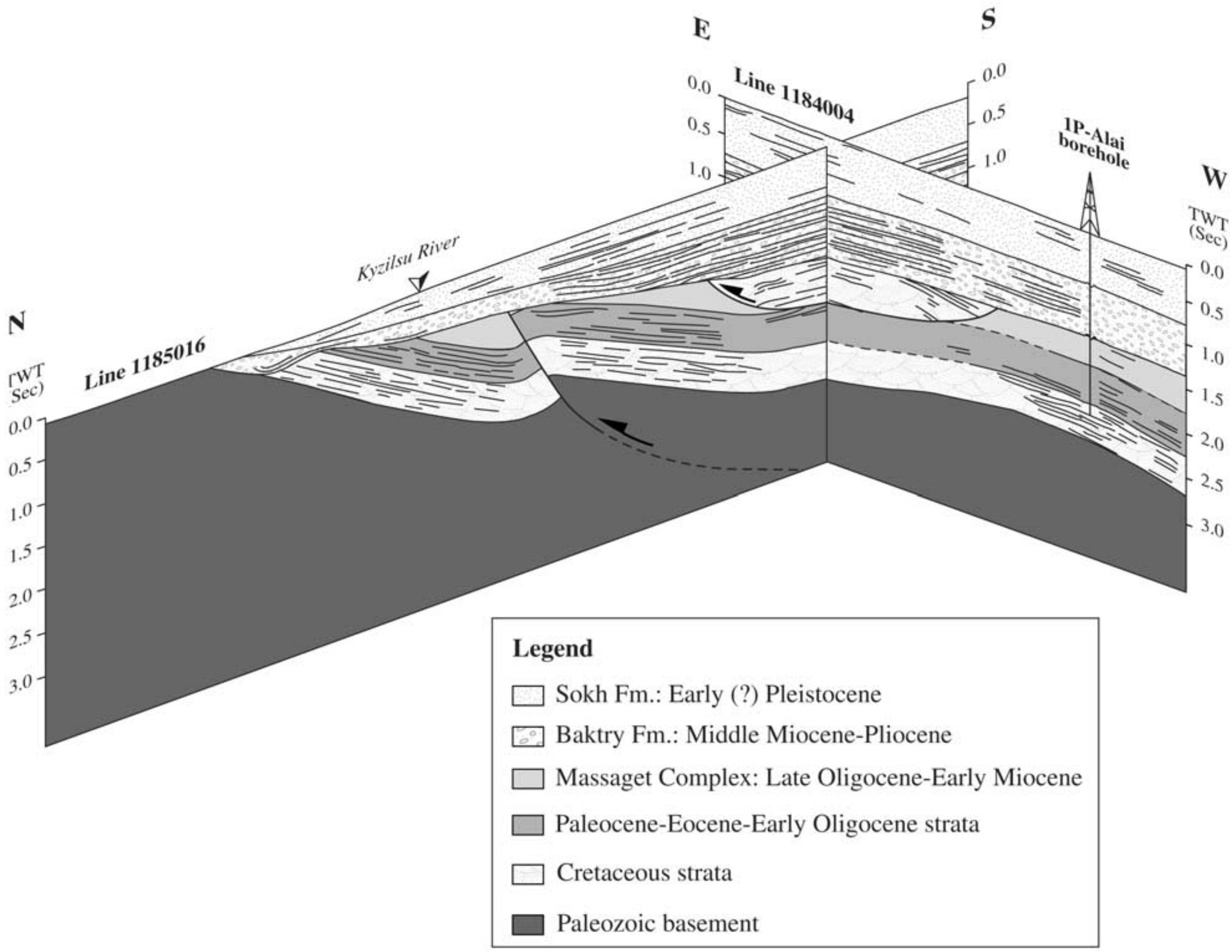


Figure 5. Interpreted seismic reflection profiles and cross sections showing the location along E-W trending line 1184004 of the 4.5-km-deep 1P-Alai borehole, penetrating Quaternary, Neogene, Paleogene and the upper part of Late Cretaceous strata. Line 1184004 cuts N-S trending profile 1185016 allowing stratigraphic correlations along profiles crossing the Alai Valley. For location, see Figure 3.

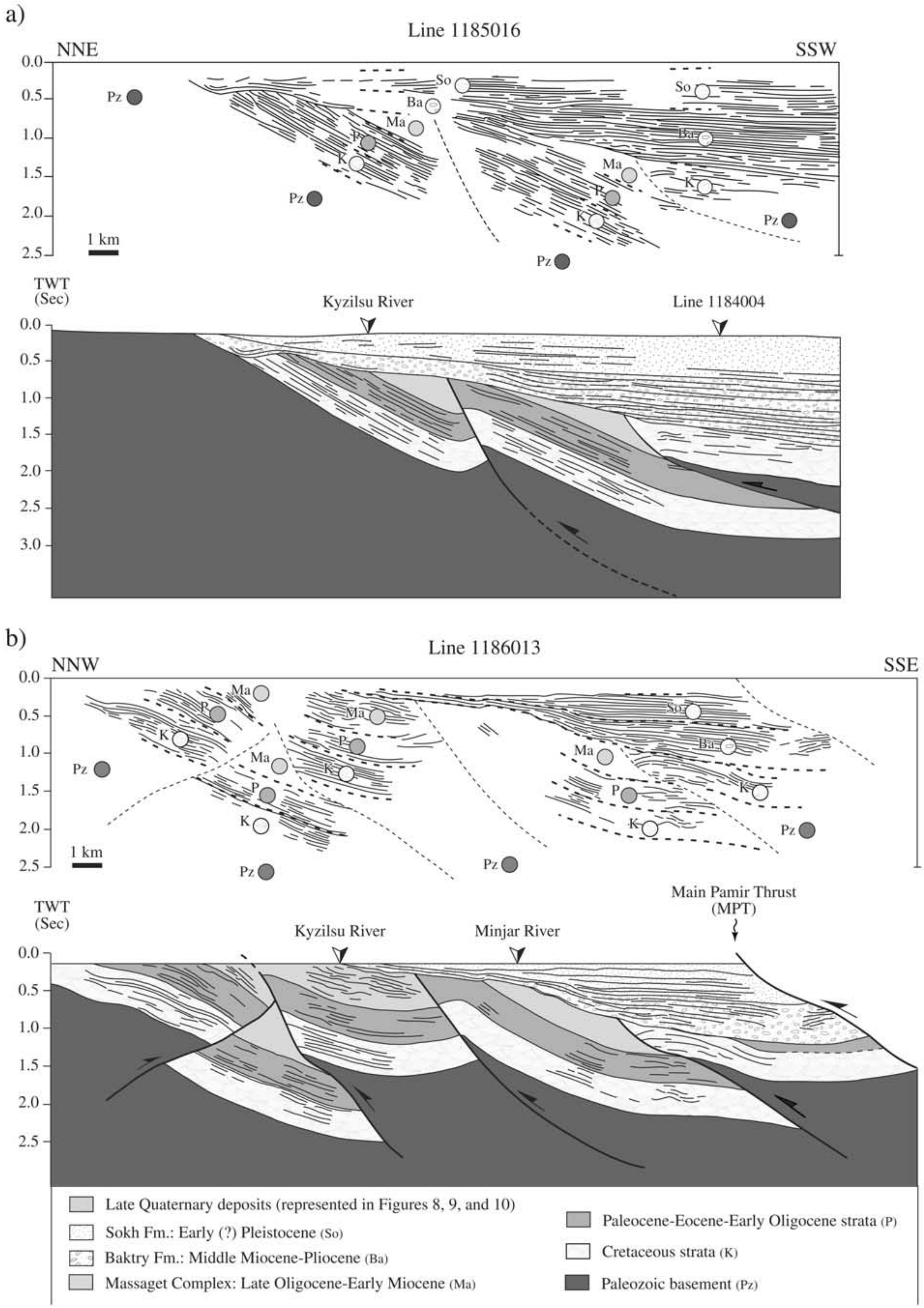
observations [e.g., *Nikonov et al.*, 1983; *Strecker et al.*, 1995; *Arrowsmith and Strecker*, 1999] suggest that in the Pamir-Alai region, convergence between India and Eurasia is currently absorbed near the outer margin of the Pamir along the Darvaz fault to the west, the Trans Alai thrust system within the Alai Valley, and dextral splays of the Karakorum in the east (Figure 1). Earthquakes along the Trans Alai front predominantly indicate thrust faulting and are approximately normal to the traces of the major thrust belts [*Burtman and Molnar*, 1993; *Fan et al.*, 1994; *Strecker et al.*, 1995]. The high slip rates and seismicity patterns suggest that the fault zone along the Trans Alai is part of a major intracontinental convergent boundary between the Pamir and Eurasia [*Hamburger et al.*, 1992; *Burtman and Molnar*, 1993]. In fact, the Alai Valley coincides with the surface intercept of a steeply southward dipping seismic zone, visible to depths down to 250 km, that has been interpreted to reflect either intracontinental subduction of Eurasian lithosphere under the Pamirs [*Hamburger et al.*, 1992; *Burtman and Molnar*, 1993; *Fan et al.*, 1994] or an overturned northward subducting Indian slab in response to mantle drag [*Pegler and Das*, 1998; *Pavlis and Das*, 2000].

3. Methodology

3.1. Stratigraphy Description

[8] Our lithologic description and stratigraphy are based on published Soviet literature [*Kozlov and Artemov*, 1964; *Razvalyaev et al.*, 1964; *Nikonov et al.*, 1983] (L. S.

Figure 6. (opposite) Line drawings and interpreted seismic profiles 1185016 and 1186013. Circles symbolize rock units identified from outcrop or borehole correlations. Associated reflector packages are delimited by dashed lines. Vertical scales are in TWT (seconds).


a)
Line 1185016
NNE
SSW
TWT
(Sec)
1 km
So
Ba
Ma
P
K
Pz
Kyzilsu River
Line 1184004
b)
Line 1186013
NNW
SSE
Kyzilsu River
Minjar River
Main Pamir Thrust
(MPT)
Late Quaternary deposits (represented in Figures 8, 9, and 10)
Sokh Fm.: Early (?) Pleistocene (So)
Baktry Fm.: Middle Miocene-Pliocene (Ba)
Massaget Complex: Late Oligocene-Early Miocene (Ma)
Paleocene-Eocene-Early Oligocene strata (P)
Cretaceous strata (K)
Paleozoic basement (Pz)

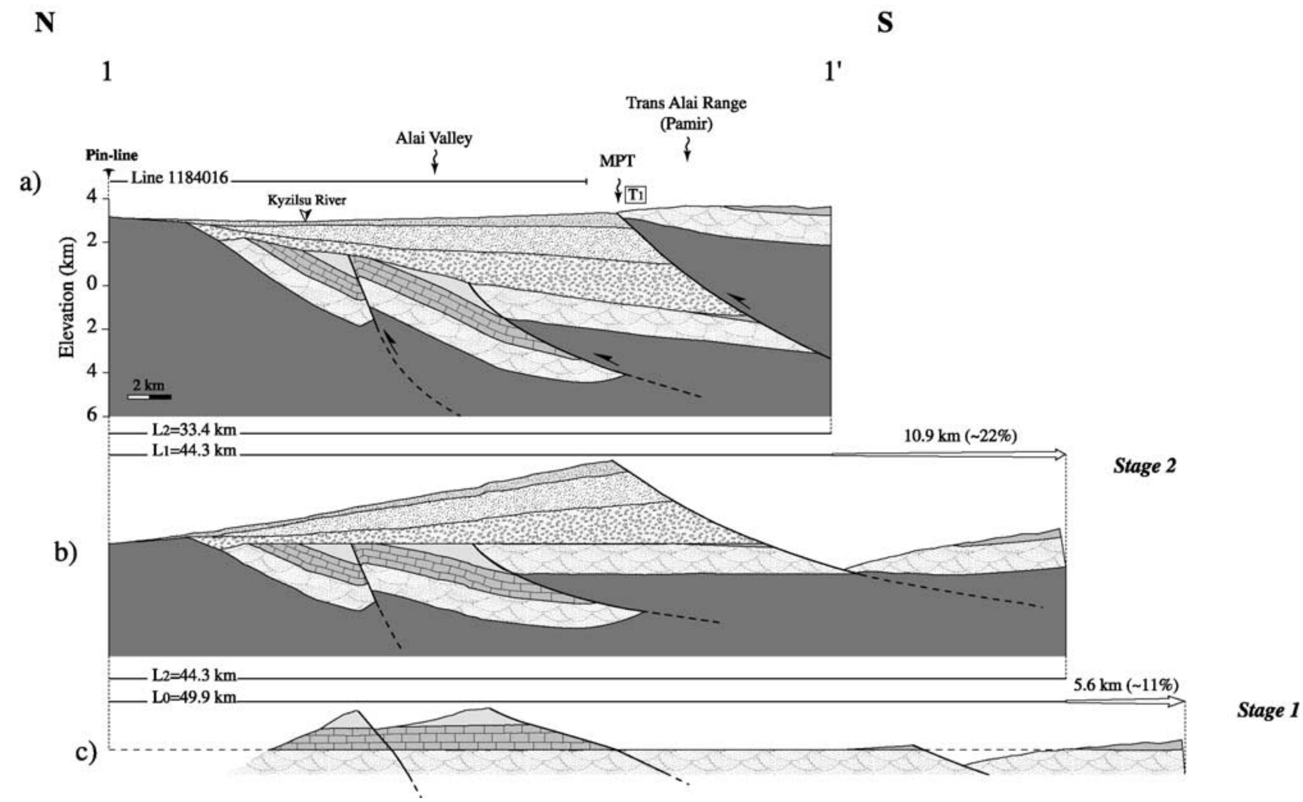


Figure 7. (a) Cross section 1-1′ through the Alai basin (eastern segment) based on our field observations and seismic reflection line 1184016. TWT seismic profile was converted to depth using Geosec2D Software, standard average velocities were assigned for each stratigraphic unit. The section was restored in two steps corresponding to (b) the middle Miocene to Quaternary growth of the asymmetric clastic wedge (Stage 2) and (c) the early Miocene episode of shortening (Stage 1). Unit patterns as in Figure 6.

Ovsyannikov and F. S. Nakonechny, Trans Alai GGSP, State Committee on Geology, Using and Protection of the Earth interiors of Kyrgyz Republic, Bishkek, Kyrgyzstan, unpublished report, 1993, hereinafter referred to as Ovsyannikov and Nakonechny, unpublished report, 1993, hereinafter referred to as Ovsyannikov and Nakonechny, unpublished report, 1993), previous work along the northern side of the valley (Figure 3) [e.g., *Czassny et al.*, 1999], and inspection in the field. In addition, the 4.5-km-deep 1P-Alai borehole (drilled in 1989 by the Saratov Oil and Geophysics Company), located in the Trans Alai piedmont (Figures 3 and 4) penetrates Quaternary, Neogene, Paleogene, and upper Late Cretaceous strata and provides stratigraphic control, resistivity, and acoustic data (Ovsyannikov and Nakonechny, unpublished report, 1993).

3.2. Seismic Reflection Data

[9] We obtained two N-S trending dip lines (profiles 1186013 and 1185016) and one strike line (profile 1184004) of a seismic reflection survey carried out in 1989 by the Saratov Oil and Geophysics Company using a multiple coverage survey (for location, see Figure 3). The stacking method used during processing is unknown. Using Geosec2D software, two-way-travel (TWT) time (seconds) profiles were converted to depth using velocities for each stratigraphic unit obtained by Vertical Seismic Profiling (VPS) along the 1P-Alai borehole (Ovsyannikov and Nakonechny, unpublished report, 1993). Borehole logging (Ovsyannikov and Nakonechny, unpublished report, 1993) allowed us to define seismic facies and make stratigraphic correlations along N-S trending profiles (Figure 5). Identification of stratigraphic units at depth was furthermore based on outcrop correlations. Time-migrated seismic reflection profiles are not shown for reasons of confidentiality; however, we provide line drawings for each profile (Figures 6a and 6b).

3.3. Restoration

[10] We used the method of balanced cross sections for restoring deformation [*Dahlstrom*, 1969; *Hossack*, 1979; *De Paor*, 1988; *Geiser et al.*, 1988]. Combining field data, observations from Landsat images, and depth-converted seismic reflection profiles, we constructed two regional NNW-SSE trending sections (sections 1-1′ and 2-2′; Figures 3, 7a, and 8a), to estimate the amount of Cenozoic shortening across the Alai depression. Sections were restored by bed length balancing using Geosec2D Software (Figures 7 and 8). This method relies on three assumptions: (1) Lengths of competent layers or surface areas of the layers in cross section

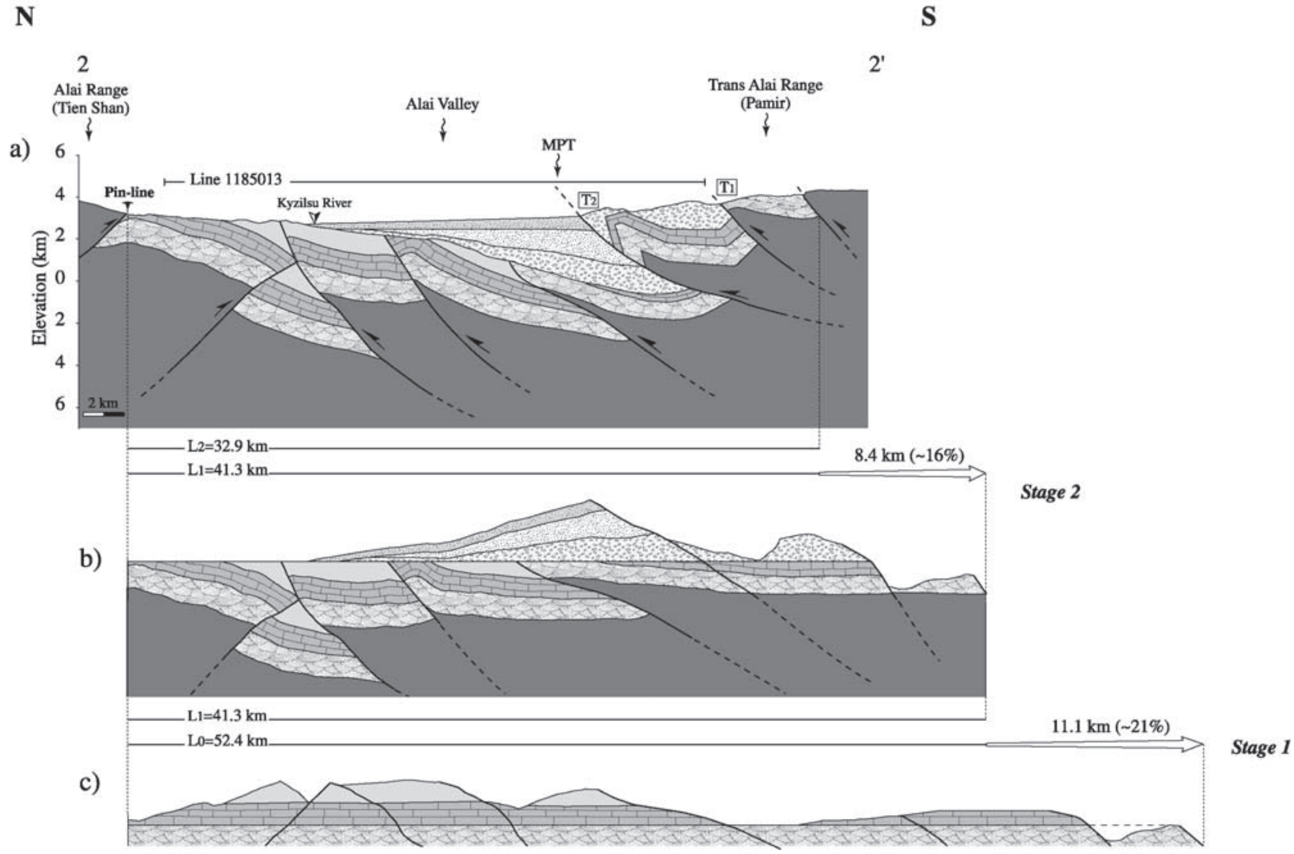


Figure 8. Cross section 2-2′ through the Alai basin (western segment) and section restoration. Depth conversion as in Figure 7. Unit patterns as in Figure 6.

are conserved, (2) before deformation, reference layers are horizontal and of even thickness, and (3) at one of its ends, the section carries a vertical pin line, which remains fixed during deformation.

4. Stratigraphy of the Alai Valley

4.1. Paleozoic Basement

[11] Basement rocks in the area consist of Paleozoic low-grade metasediments [*Burtman*, 1975], including Silurian terrigenous deposits, Devonian to middle Carboniferous limestones and marbles (1–2.5 km thick) and middle Carboniferous flysch units, ≤500 m thick [*Kyrgize Geologic Agency*, 1979]. All units were pervasively deformed during the Hercynian orogeny [*Burtman*, 1975]. These units are unconformably overlain by Jurassic to Quaternary sediments with a total thickness of ~7000 m in the southeastern part of the basin, east of the Tuyuksu drainage (Figure 3). These sediments are only partially exposed along the northern and southern margins of the valley and are buried under the valley floor in the rest of the basin (Figure 2a).

4.2. Jurassic Strata

[12] Jurassic deposits are partially exposed within a narrow strip along the northern side of the valley (Figure 3) and unconformably overlie Paleozoic units. They comprise coarse-grained sandstones and light green to white pebble quartzitic conglomerates, interbedded with claystones containing gypsum and coal lenses. Total thickness of this unit is unknown but it probably does not exceed 300 m along the northern side of the Alai Valley, based on surface outcrops. Jurassic and Cretaceous strata are unconformable (section B-B′; Figures 3 and 9b). The attitude of Jurassic strata implies that they are rapidly beveled at depth and are crosscut by the erosional base of the Cretaceous sequence. Their absence at structurally deeper levels (section C-C′; Figure 9c) supports this inference. These sediments were deposited under terrestrial conditions at the periphery of the marine domain of the Tadjik Sea [*Akramhodjaev et al.*, 1971].

4.3. Cretaceous Strata

[13] Early Cretaceous deposits unconformably overlie Jurassic and Paleozoic rocks along the northern margin of the valley (Figures 2b, 3, and 9c). In the Trans Alai, they are widely exposed at elevations between 3500–5500 m (Figure 3). The lowest part of this section is composed of a 200–300 m [*Djalilov et al.*, 1971; *Czassny et al.*, 1999] and 800-m-thick red-colored medium to coarse-grained sandstone interbedded with mudstone [*Davidzon et al.*, 1982] in the southern Tien Shan and Trans Alai ranges, respectively. Along

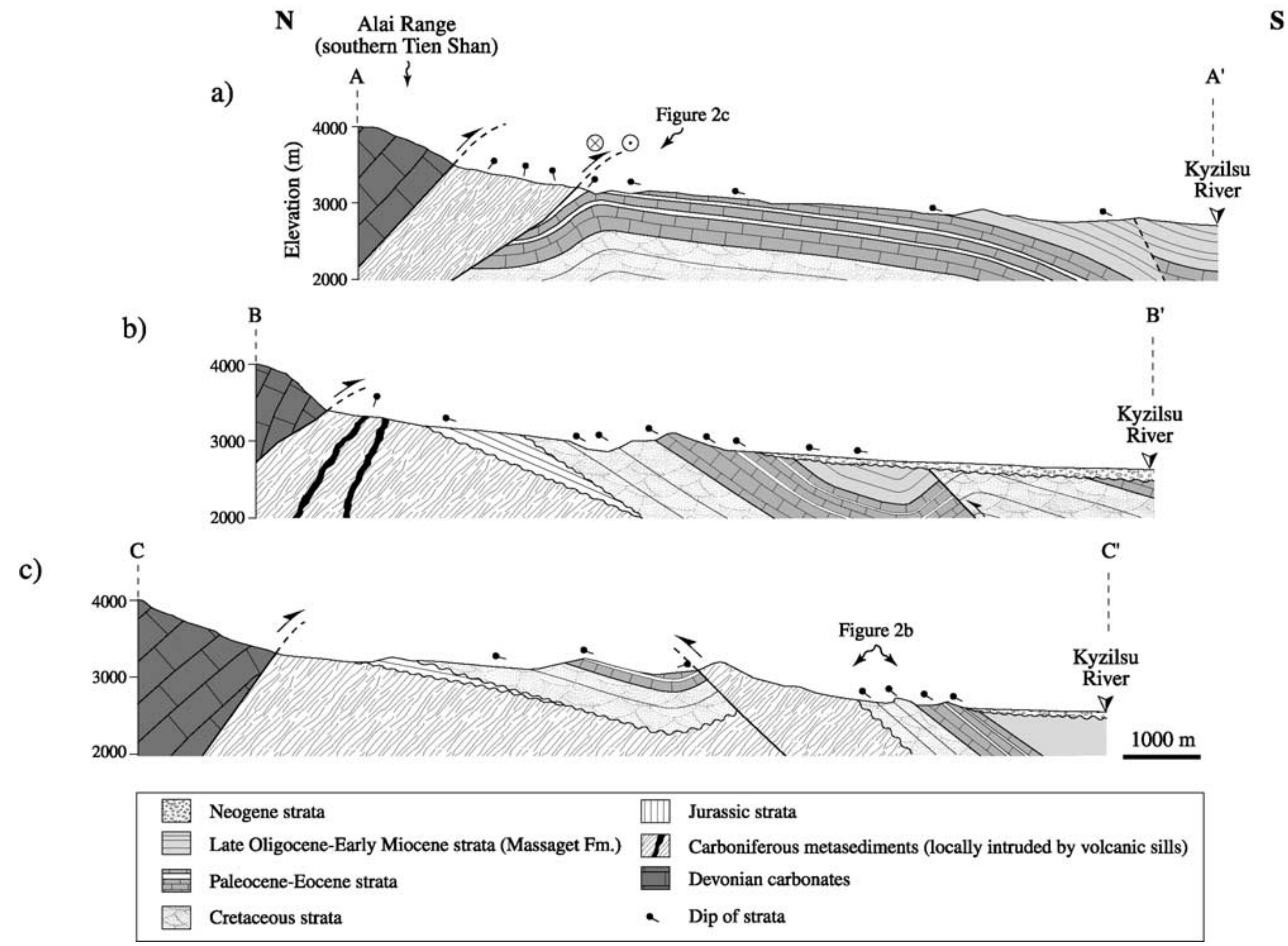


Figure 9. Detailed structural and geological sections AA′, BB′ and CC′ (east to west) across the northern edge of the Alai Valley. CC′ was modified after *Czassny et al.* [1999]. Successive sections illustrate the evolution of structures along the external southern flank of the Alai Range. From east to west, Mesozoic and Cenozoic deposits are increasingly deformed and eroded. This is accompanied by larger exhumation of Paleozoic rocks toward the west. For locations, see Figure 3.

the northern edge of the Alai Valley, (Figures 3 and 9c), a lower Cretaceous package of conglomerates, conglomeratic sandstones and siltstones, 300 to 400 m thick, grades upward into cross-bedded sandstones interbedded with argillite and conglomerate-filled paleochannels [*Czassny et al.*, 1999] (Figure 4). These deposits, interpreted as representing coarse distal alluvial fan and braid plain sediments derived from the highlands of the present Tien Shan [*Czassny et al.*, 1999], attest to Early Cretaceous denudation north of the Alai Valley [*Burtman and Molnar*, 1993].

[14] Limestones, marls, claystones, and gypsum 400 m thick form a Late Cretaceous sequence [*Pojarkova*, 1969]. Along the northern flank of the valley, Late Cretaceous gypsiferous siltstones and gypsum capped by massive fossiliferous limestones do not exceed 100 m [*Czassny et al.*, 1999]. Starting in the late Cenomanian, a series of marine transgressions from the Tadjik depression to the west reached the western Tarim basin, through the Alai Valley [*Hao and Zeng*, 1984], causing a transition from continental to lagoonal and shallow marine conditions [*Sochava*, 1965; *Akramhodjaev et al.*, 1971; *Czassny et al.*, 1999].

4.4. Paleocene to Early Oligocene Strata

[15] Paleocene and Eocene units [*Gubin*, 1960; *Skobelev*, 1977; *Burtman and Molnar*, 1993] $\sim$400 m thick, include fossiliferous limestones, dolomites, marls and mudstones containing gypsum layers, up to 750 m thick in the vicinity of the 1P-Alai borehole (Figures 3 and 4) (Ovsyannikov and Nakonechny, unpublished report, 1993). Early Paleogene deposits include Eocene strata only in the north of the valley, east of the Kavik drainage (Figures 3 and 4) [e.g., *Czassny et al.*, 1999]. These strata document shallow marine sedimentation with water depths above the wave base, as suggested by the presence of oyster beds and tempestites [*Czassny et al.*, 1999]. The last marine transgression in the western Alai

Valley is attributed to the late Oligocene [*Burtman*, 2000]. Since then, terrestrial sedimentation has prevailed.

4.5. Late Oligocene to Quaternary Strata

[16] Late Paleogene and Neogene strata consist of a coarsening-upward section of conglomerates and sandstones interbedded with claystones. Earlier workers subdivided the sequence based on stratigraphic correlations with neighboring basins; however, little direct local evidence exists to constrain the age of these strata [*Kozlov and Artemov*, 1964; *Razvalyaev et al.*, 1964; *Nikonov et al.*, 1983; Ovsyannikov and Nakonechny, unpublished report, 1993]. To resolve these timing uncertainties, we correlated dated facies packages from a neighboring area in China where direct age data were available [e.g., *Sobel*, 1995], with the units in the Alai Valley. Although this is a crude attempt, the resulting chronology appears reasonable.

[17] The oldest Cenozoic continental clastic rocks in the Alai Valley region are late Oligocene–early Miocene strata (Massaget formation) composed of conglomerates and sandstones interbedded with thin claystone layers, up to 900 m thick in the vicinity of the Adzhiktash drainage (Figures 3 and 4). Seismic reflection data (see below, section 6.1) and borehole data reveal a conformable contact with older Paleogene strata (Figures 3 and 4) (Ovsyannikov and Nakonechny, unpublished report, 1993). This predominantly buried unit is possibly exposed along the northern margin, and consists of poorly sorted south dipping blocky conglomerates (Figures 3 and 9a).

[18] Middle Miocene to Pliocene deposits (Baktry formation) consist of westwardly thinning (2150 m east of Tuyuksu drainage to 1350 m along profile 1186013; Figure 3), massive conglomeratic strata interbedded with thin layers of siltstones (Figure 4). This thickness change is partly due to the exhumation of the thickest (southern) part of this unit in the central segment of the valley (Figures 3, 4, and 10a). The base of the Baktry formation is poorly exposed but crops out between the Kokkiik and Adzhiktash drainages, in the hanging wall of the Main Pamir thrust (MPT; Figures 3 and 10). This unit lies unconformably on Cretaceous and Paleogene strata.

[19] The mostly covered early Pleistocene strata (Sokh formation) consist of westwardly thinning (1600 m north of the MPT at Tuyuksu drainage to 1250 m along line 1186013; see below; Figure 3) gravel to blocky conglomerates and coarse-grained sandstones interbedded with siltstones (Figure 4) that onlap the Baktry formation. Middle Pleistocene to recent deposits consist of coarse pediment-cover gravels, glaciofluvial terraces and alluvial-fan gravels, landslide deposits and glacial tills that unconformably overlie Tertiary strata [*Arrowsmith and Strecker*, 1999; *Strecker et al.*, 2002]. The late Neogene and Quaternary units are interpreted as a molasse deposited in front of the northward advancing Pamir thrust system [*Burtman and Molnar*, 1993].

5. Cenozoic Structural Evolution of the Southern Tien Shan and Northern Pamir

[20] We characterized the style of deformation (geometry and kinematics of structures) from structural fieldwork and Landsat image analysis on the margins of the Alai Valley. This was combined with subsurface data (see section 6) to construct and, where possible, retrodeform synthetic structural cross sections to quantify timing and magnitude of deformation.

5.1. Northern Margin of the Alai Valley

[21] The unconformity between Paleozoic units of the southern Tien Shan and the Mesozoic strata is mostly well preserved and tilted southward on the northern basin margin (Figures 2b, 3, 9b, and 9c). Also, pervasive thrust faulting and folding in the southern Tien Shan affect Paleozoic through early Cenozoic units in the area (Figures 3 and 9a). The range front at about 3400 m coincides with a major south vergent thrust fault that places Devonian massive limestones and marbles on less competent Carboniferous metasediments (Figures 2c, 9a, 9b and 9c).

[22] In the sector to the north of the Kyzilsu river, between the Komansu and Altyndara drainages, ENE-WSW striking and generally south dipping thrusts place Carboniferous metasediments over Mesozoic and early Cenozoic deposits (Figures 3 and 9a). Along section AA′, an oblique NW-SE striking right-lateral tranpressive fault within early Paleogene gypsum-rich layers accommodates N-S shortening (Figures 2c, 3, and 9a). An asymmetric anticline in the footwall of the thrust (Figure 2c) rotates clockwise, from a NE-SW to E-W trending axis in the vicinity of the fault (Figure 3), consistent with right-lateral oblique slip. To the west, Cretaceous and Paleogene units are increasingly folded into a ramp anticline. The fault driving this deformation ruptures the surface west of the Kavik drainage (Figures 3, 9b, and 9c) [*Czassny et al.*, 1999]. Further west, the valley narrows dramatically and Mesozoic and Cenozoic sediments are absent as Paleozoic basement is being increasingly exhumed (Figures 3 and 10b). West of the study area, the southern flank of the Tien Shan consists only of Paleozoic metasediments and crystalline rocks [*Hamburger et al.*, 1992].

[23] Along the southern Tien Shan, in the Kyzylunkur and Kavik drainages, polymictic poorly sorted conglomerates of Paleozoic granodiorites and metasediments, Devonian carbonates, black Carboniferous carbonates, and early Cretaceous red sandstones from the Tien Shan, unconformably overlie older Mesozoic and Cenozoic strata (Figures 2d, 3, 9b, and 9c). These units are undeformed and flat-lying to gently southward dipping (up to $6°–8°$); they were deposited in paleo-valleys cut into deformed Cretaceous, Paleogene and early Neogene strata (Figures 2d, 3, 9b, and 9c). The Tien Shan piedmont bevels both deformed and undeformed units and includes several sets of inset fluvial terraces, with locally derived gravels and $\leq 2°$ southward inclination (Figure 11a). Importantly, late Neogene gravels, Quaternary pediments and terraces are undeformed, suggesting that this range front has been tectonically inactive for most of the Quaternary. This observation contrasts strongly with the southern margin of the valley, where the thrust system associated with the Tran Alai range front is propagating northward, the active MPT currently accommodating ≥ 6 mm yr^{-1} of the total convergence between

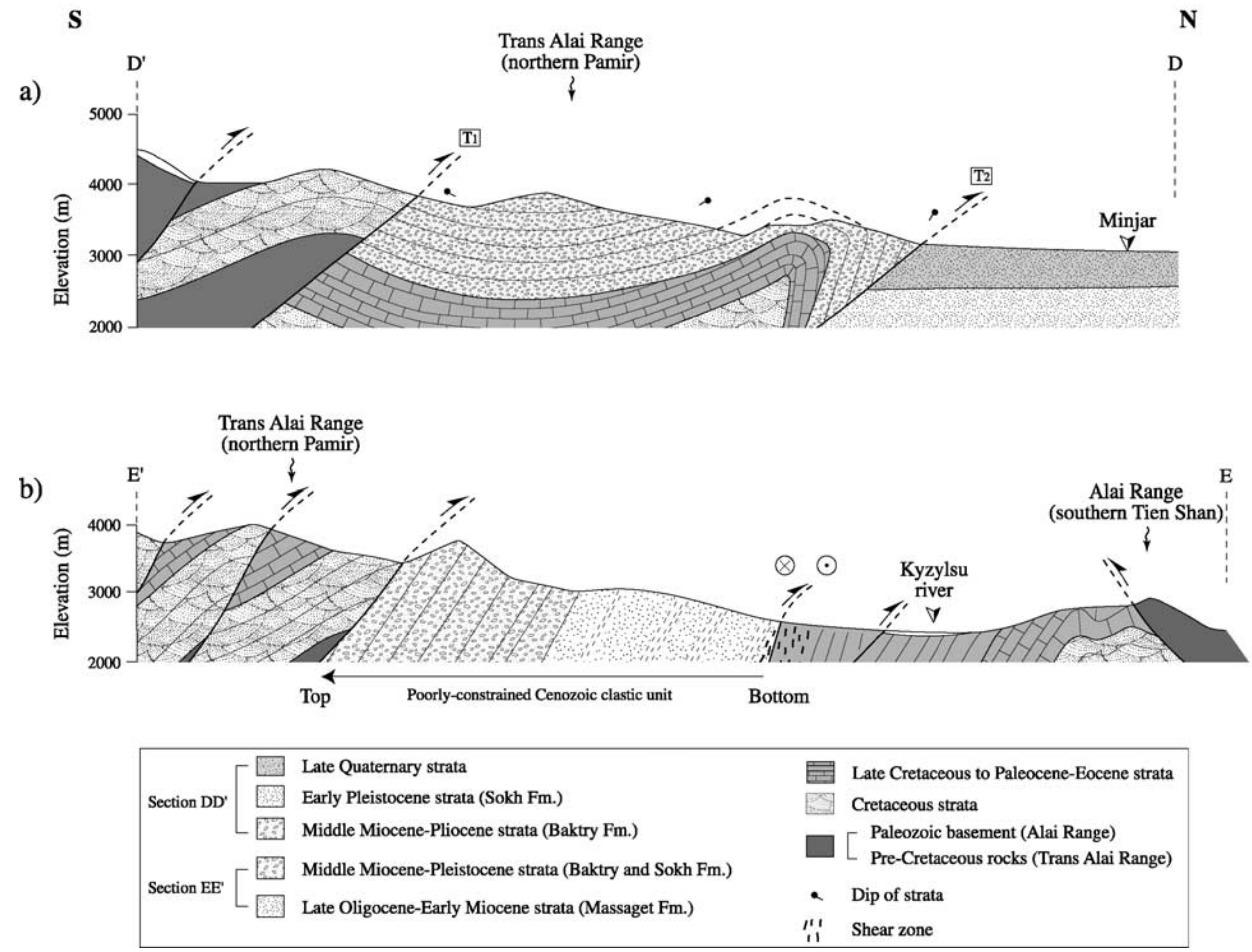


Figure 10. Detailed structural and geological sections DD′ and EE′ across the southern edge and the western closure of the Alai Valley, respectively, constructed from data collected in the field. (a) Along the central segment, internal deformation within the exhumed Neogene conglomerates (Baktry formation) is expressed by tight asymmetric fault propagation folds with northern limbs overturned and cut by the MPT against Holocene alluvial fan gravels. (b) At the western end of the Alai Valley, the external Trans Alai comprises a stack of steeply dipping imbricated thrust sheets involving Cretaceous to Quaternary strata. In this area, the Trans Alai impinges on the southern Tien Shan. For locations, see Figure 3.

India and Eurasia (Figures 1 and 3) [*Arrowsmith and Strecker*, 1999].

5.2. Southern Margin of the Alai Valley

[24] The larger thrust on the southern margin of the valley is the north vergent MPT (Figures 1 and 3), which can be divided into three morphotectonic segments (Figure 3): eastern, central, and western [*Arrowsmith and Strecker*, 1999; *Strecker et al.*, 2002]. Obliquely striking transfer zones along which deformation is transferred basinward from east to west, comprise reverse and right-lateral oblique slip faults [*Arrowsmith and Strecker*, 1999; *Strecker et al.*, 2002].

[25] Along the eastern mountain front, Early Cretaceous red beds and Late Cretaceous to early Paleogene tan shales and light brown carbonates are unconformably overlain by Quaternary alluvial-fan gravels and tills (Figure 3). Thrust faulting east of the Adzhiktash river offsets late Pleistocene units [*Strecker et al.*, 2002]. However, these faults fail to offset Holocene deposits, suggesting that deformation may have recently moved ~26 km southward to the Markansu fault [*Jackson et al.*, 1979; *Strecker et al.*, 2002]. The Mesozoic-early Cenozoic units are cut by southward dipping thrusts. A box fold (Figure 11b) [*Arrowsmith and Strecker*, 1999] that formed above a north vergent thrust, places Early Cretaceous red beds over the late Paleogene–early Neogene Massaget formation. Farther south, exposure is limited by glaciers (Figure 3).

[26] The central and western segments of the Trans Alai range front contain a series of southward dipping imbricate thrust sheets that involve younger strata to the north (Figure 3). Specifically, Triassic and Cretaceous strata [*Razvalyaev et al.*, 1964] are thrust over Paleogene, Neogene, and

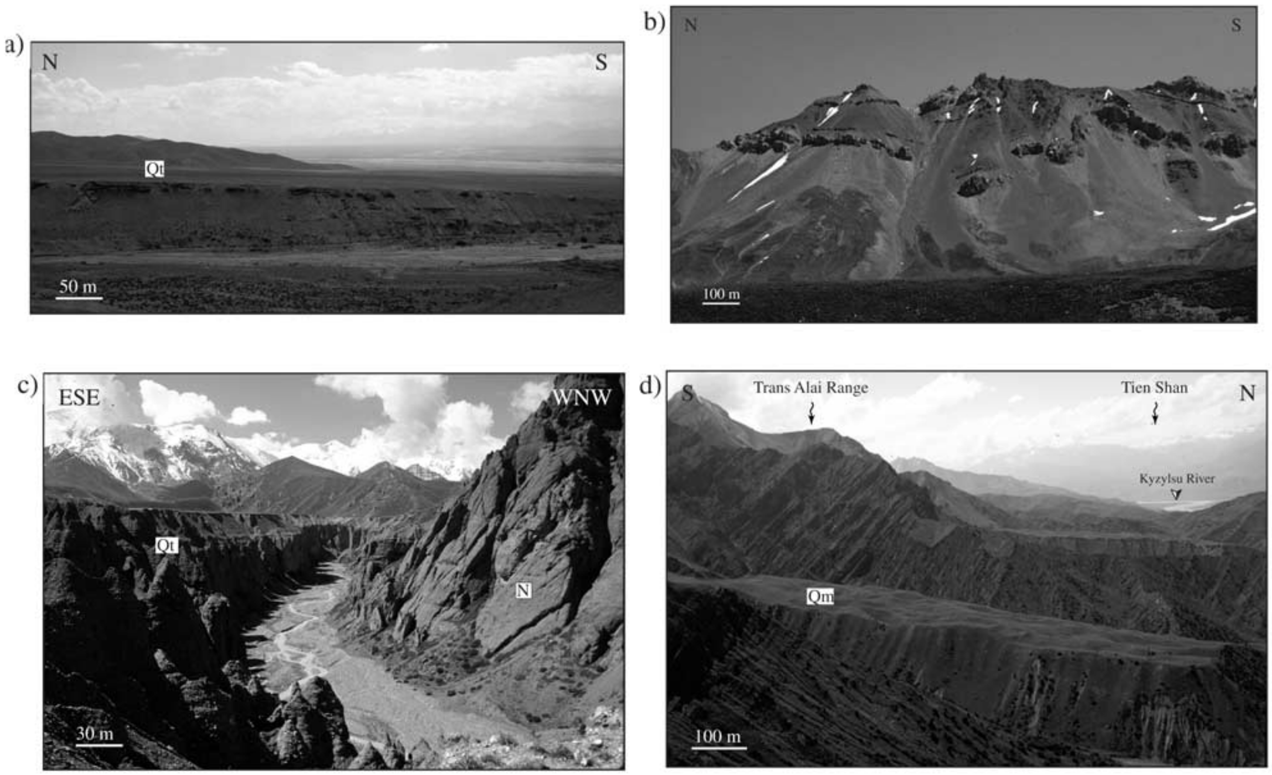


Figure 11. (a) Undeformed incised pediment surface (Qt) along the Kyzylunkur drainage (view to east; for location, see Figure 3). (b) 100-m-scale box fold developed within alternating late Cretaceous shales and carbonates, southern Alai Valley, Tashkungey drainage (view to east; for location, see Figure 3). (c) Late Pleistocene fluvial terrace deposits (Qt) unconformably overlying late Neogene folded conglomerates (N: Baktry formation) and uplifted in the hanging wall of the MPT along Minjar drainage, southern Alai Valley, (view to south-southwest, for location, see Figure 3). (d) Poorly defined coarse clastic succession uniformly tilted southward along the Trans Alai thrust front west of Tarasha drainage (view to west; for location, see Figures 3 and 10b). Gently inclined fluvial terraces with moraine deposits (Qm) preserved hummocky geomorphic surface that was originally adjusted to the Kyzyksu river. Note the proximity of the Tien Shan in the background.

Pleistocene strata (Figures 3 and 10). These are in turn faulted against Holocene alluvial-fan sediments [*Arrowsmith and Strecker*, 1999; *Strecker et al.*, 2002].

[27] Within the western transfer zone and the central segment, the trace of ~75 km long southward dipping thrust fault (T_1 in Figure 3) is bounded by the Altyndara river to the west and connects with thrusts of the eastern segment to the east. The fault trace is sinuous, changing from E-W to NE-SW toward the east (Figure 3). It progressively places Cretaceous over younger strata (Cretaceous, Neogene, and Quaternary) toward the east (Figure 3). The current fault trace suggests that this thrust is not planar and that differential heave has occurred along-strike, the displacement gradient increasing toward the east. Within the central segment, this gradient was compensated by the nucleation of the active MPT (T_2 in Figure 3; also see Figure 10a) that exposes the Baktry formation. Internal deformation within this unit includes tight asymmetric E-W striking fault propagation folds. The northern limbs are steeply dipping, vertical or even overturned and locally cut by the MPT, while southern limbs are open symmetrical synclines (Figures 3 and 10a). Undeformed late Pleistocene pediment gravels and terraces are inclined gently to the north, unconformably overlying deformed late Neogene strata, and likely represent an uplifted paleo-piedmont in front of the formerly active thrust involving Cretaceous rocks in the south (Figure 11c) [*Strecker et al.*, 2002]. The MPT has thrusted these units over Holocene gravels, indicating recent fault motion [*Arrowsmith and Strecker*, 1999; *Arrowsmith et al.*, 1999; *Strecker et al.*, 2002].

[28] To the west, the northward displacement of the Pamir toward the Tien Shan is relayed and transmitted to the western segment through a 25 km wide right-lateral en echelon transfer zone located between the Kokkiik and Tarasha rivers, involving Cretaceous and Quaternary units (Figure 3) [e.g., *Arrowsmith and Strecker*, 1999].

[29] Similar to the central segment, the western part of the Trans Alai mountain front consists of a stack of steeply dipping thrust sheets of Cretaceous to Quaternary strata (Figures 3 and 10b). To the south, subvertical to steeply southward dipping imbricate thrust faults are subparallel to the bedding of late Cretaceous gypsum layers. This defor-

mation causes repeated stacking of thrust sheets, progressively involving Early Cretaceous red beds to Late Cretaceous carbonates and gypsum interbeds toward the top (Figure 10b). This package is thrust-faulted against a >3 km thick conformable sedimentary sequence including (1) alternating red sandstones and mudstones which may correspond to the Massaget formation (Figures 3, 10b, and 11d), and are likely conformable with underlying early Paleogene strata in this part of the basin and (2) massive red-colored conglomeratic strata which may correspond to the Sokh and Baktry formations. Along this segment the Trans Alai impinges on the southern Tien Shan, constraining the basin to a narrow outlet, a few hundred meters wide (Figures 3, 10b, and 11d).

6. Seismic Reflection Profiles

6.1. Observations

[30] On the three profiles, the first 0.2 s TWT correspond to poorly consolidated late Quaternary units without seismic reflectivity. Beneath this zone are reflectors (top to bottom) attributed to the Sokh and Baktry formations (Figures 5, 6a, and 6b). Alternating massive sandstone and conglomeratic strata and interlayered mudstones produce well-defined and continuous reflections in these formations (Figures 6a and 6b). The reflectors are closely spaced in the north and progressively diverge southward, defining a wedge-shaped geometry (Figures 6a and 6b). Within the wedge, strata of the Sokh formation apparently onlap the Baktry formation toward the north (Figures 6a and 6b). Reflectors of both units are truncated by the MPT (Figure 6b). The base of these formations is formed by erosional and angular unconformities, Baktry formation reflectors onlapping the underlying strata (Figures 6a and 6b). The underlying Massaget formation strata are seismically transparent when buried (Figures 5, 6a, and 6b) but reflective when near to the surface or exposed (Figure 6b). Below this formation, Early Cretaceous red beds and Late Cretaceous, Paleocene, and Eocene carbonates and mudstones are imaged as less continuous, but well-defined and fairly parallel reflectors. Their thickness is approximately constant along the profiles (Figures 6a and 6b), and the subparallel reflectors suggest that they are conformable (Figures 6a and 6b). Offset and bent reflectors, however, imply that these layers are deformed (Figures 6a and 6b). Finally, the Paleozoic basement of the basin is seismically transparent.

6.2. Interpretation

[31] The seismic data image a southward-thickening wedge composed of middle Miocene to Quaternary continental coarse clastic rocks (Figures 6, 7a, and 8a). It is undeformed and reaches a thickness in the south of ~3450 m along line 1186013 and ~4300 m along line 1185016 in the east (Figures 3, 6a, and 6b). Units below the wedge consist of Mesozoic, Paleogene and early Neogene strata that are faulted and folded (Figures 6a, and 6b).

[32] Late Neogene strata are separated from older units by angular and erosional unconformities dipping gently southward (Figures 6a, 6b, 7a, and 8a). Deformation occurred in several stages (Figure 12). The first deformation involves Mesozoic and early Cenozoic strata by north vergent imbricate thrusts distributed across the entire width of the valley (Figures 6a, 6b, 7a, and 8a). The Massaget formation contains the youngest strata deposited before the second deformation. Syntectonic clastic strata associated with this shortening are absent; instead, a major erosional surface truncates Mesozoic to early Neogene deformed strata and associated folds and thrust faults.

[33] The second stage of contraction is recorded by progressive growth of the clastic wedge. The southward thickening of the wedge units results from deposition in front of the active MPT, whereas the distal part onlaps the rocks of the Tien Shan to the north (Figures 3, 6a, and 6b). Growth of the wedge was variable in space and time. For example, late Neogene sediments were not observed in the hanging wall of the MPT, indicating either that late Neogene strata were deposited and subsequently eroded as the northward vergent thrust sheets near the MPT were activated or that they were not deposited south of this thrust. We assume that early growth of the late Neogene wedge was primarily controlled by displacements along this structure, labeled T_1 in Figure 3. Along the eastern segment, late Neogene to early Quaternary strata are cut by this single thrust (Figure 7a), and growth of the wedge was directly due to its northward propagation, before tectonic activity apparently shifted back into the orogen in the late Quaternary [*Strecker et al.*, 2002]. In contrast, late Neogene strata of the central segment are cut by two thrusts (Figures 3 and 8a). The southern thrust placed Cretaceous sediments over middle Mio-Pliocene strata, and preserved all of the Baktry formation, the basal unit of the clastic wedge. The nucleation of the active MPT to the north (T_2 in Figure 3), led to the exhumation of this basal unit in the hanging wall, and partial erosion of the overlying Cretaceous sediments that lie in fault contact atop the Baktry formation (Figure 3). Therefore the MPT should have formed before the deposition of the early Pleistocene Sokh formation and late Quaternary gravels preserved in the clastic wedge (Figures 3 and 6b). The lack of offsets of the erosional surface (Figures 7a and 8a) indicates that this younger episode of deformation apparently did not reactivate older Cenozoic structures to the south.

7. Shortening Estimates, Strain and Displacement Rates

7.1. Assumptions

[34] We restored the two-stage history of deformation discussed previously. The time recorded by the formation of the erosional unconformity between the late Oligocene–early Miocene and the clastic wedge is uncertain, complicating the calculation of deformation rates. For the older stage (1), we assume that deformation spans the early Miocene (end of deposition of Massaget formation, ~8–10 Myr), providing a maximum estimate of displacement and deformation rates. For the younger stage (2), we use a 15 Myr time interval, spanning from the preservation of the

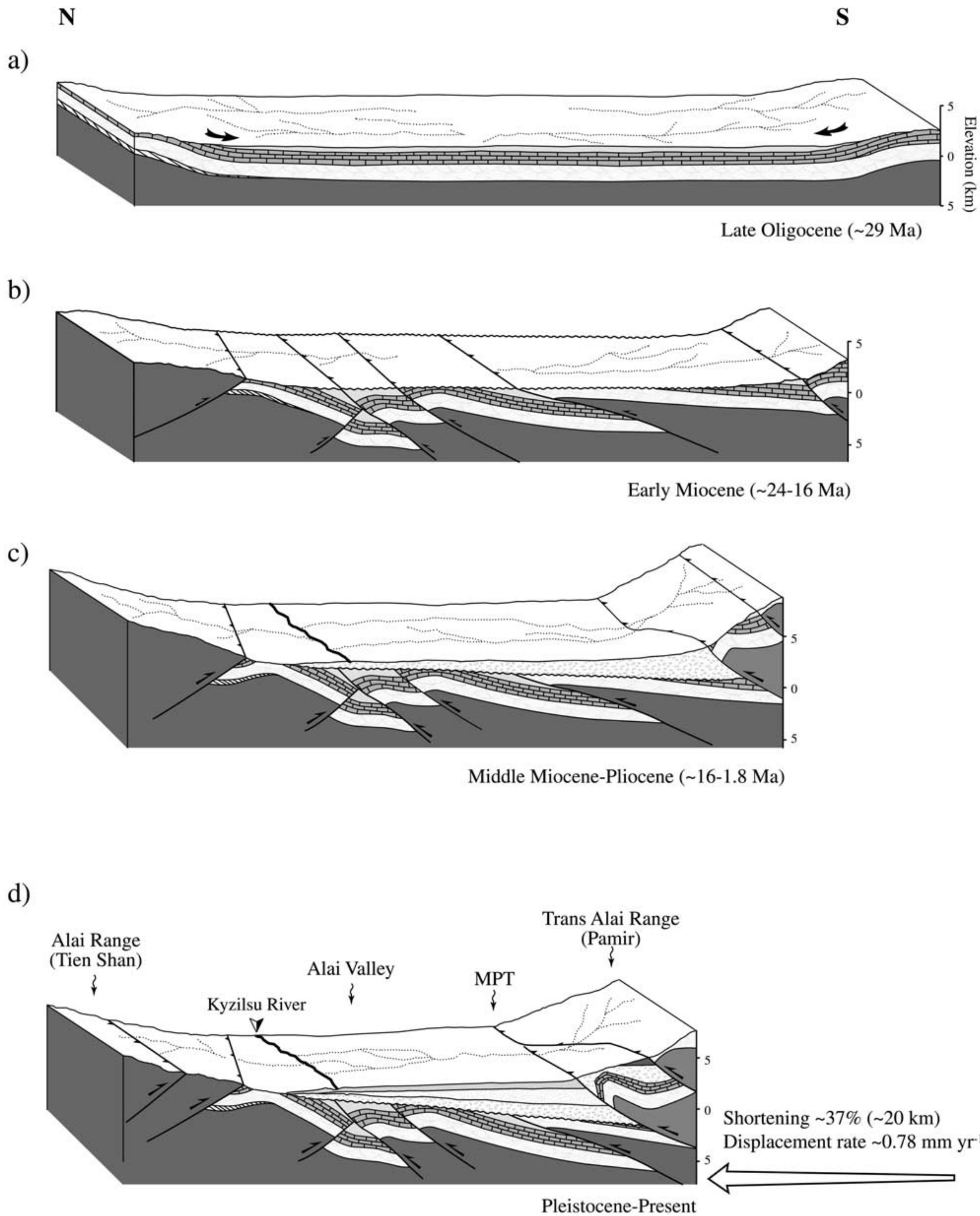


Figure 12. Schematic sections illustrating tectonic development and progressive closure of the Alai Valley intramontane basin in the last ~30 Myr.

Table 1. Calculations of Horizontal Shortening, Strain, and Displacement Rates Over the Last 25 Myr

Stage Duration, Myr	Magnitude of Shortening, %	Strain Rate, s^{-1}	Displacement Rate, mm yr^{-1}
	Section 1-1′		
Stage 1: 10	11	3.49×10^{-16} s^{-1}	0.56
Stage 2: 15	22	4.65×10^{-16} s^{-1}	0.72
Total: 25	33	4.18×10^{-16} s^{-1}	0.66
	Section 2-2′		
Stage 1: 10	21	6.65×10^{-16} s^{-1}	1.1
Stage 2: 15	16	3.38×10^{-16} s^{-1}	0.56
Total: 25	37	4.69×10^{-16} s^{-1}	0.78

Baktry formation (middle Miocene) until present. Thus the total duration of late Cenozoic contractional tectonics along our transects is assumed to be ≤25 Myr.

[35] As a reference surface for deformation stages 1 and 2 we chose the top of the Late Cretaceous shallow marine strata, and the originally subhorizontal erosional surface, respectively. Pin lines were put at the northern ends of the sections (Figures 7 and 8). Sections were constructed approximately parallel to transport direction. We neglected displacements associated with internal deformation or sedimentary compaction as well as possible motion of material into or out of the cross section. In addition, the hanging wall cutoffs of thrusts T_1 and T_2 have been eroded (Figures 7a and 8a), and thus the reference surface for the first stage of restoration was not preserved at the southern ends of both sections. Under these conditions, restoration of our cross sections provides minimum values of horizontal displacements.

7.2. Shortening, Slip and Strain Estimates

[36] Restoration of both cross sections yielded a total minimal amount of Cenozoic shortening on the order of ~35% in a direction subperpendicular to the main thrusts (Figures 7 and 8; Table 1). The incremental restoration indicates that shortening is almost equal between stages 1 and 2 contractional events (Figures 7 and 8; Table 1).

[37] The total amount of shortening observed along the eastern and western sections, is 33% and 37%, respectively, and probably increases toward the west, closing the basin in this same direction (Figures 1 and 3). This was previously suggested by the increasing degree of the northwestward advance of the Trans Alai thrust front from the eastern to the western segment of the valley (Figure 3) [*Pavlis et al.*, 1997; *Arrowsmith and Strecker*, 1999]. The restoration for stage 2 shows westward decreasing shortening (22% to the east versus 16% to the west; see Table 1). This trend is apparently reversed in the earlier event (stage 1), with 21% and 11% of shortening along the western and eastern transects, respectively (Figures 7c and 8c; Table 1). This indicates that (1) amounts of shortening accommodated during stage 1 are significant and account for one third to more than one half of the total shortening documented for sections 1 and 2, respectively (Figures 7 and 8), and (2) the differential closure of the Alai Valley initiated as early as the late Oligocene, through distributed shortening generated during stage 1. Horizontal displacements obtained for stage 2 are comparable along both transects (10.9 km and 8.4 km accommodated along one and two thrusts in section 1-1′ and 2-2′, respectively; Figures 7b and 8b; Table 1). This is consistent with field observations suggesting the heave of thrust T_1 increases toward the eastern segment, while displacement is transferred northward through the nucleation of thrust T_2 (active MPT) in the central segment.

[38] Strain rates calculated for the last 25 Myr are 4.18 x 10^{-16} s^{-1} and 4.69 x 10^{-16} s^{-1} for sections 1-1′ and 2-2′, respectively. Equivalent horizontal displacement rates along these sections are 0.66 mm yr^{-1} and 0.78 mm yr^{-1}, respectively (Figures 7 and 8; Table 1).

8. Discussion

8.1. Timing of Regional Deformation

[39] The timing of initial growth of mountain ranges bordering the Alai Valley remains poorly known, and this is mostly due to the difficulty of dating the syntectonic continental sequences preserved in this basin. Stratigraphic correlations and fission track cooling ages obtained in neighboring regions, partly help to solve this problem. In the Tarim basin, the transition from marine to continental deposition occurred between the late Oligocene and early Miocene [*Ye and Huang*, 1990], suggesting onset of crustal thickening and concomitant erosion [*Windley et al.*, 1990; *Allen et al.*, 1991, 1993; *Hendrix et al.*, 1994; *Yin and Nie*, 1996; *Yin et al.*, 1998]. While this period also coincides with a global eustatic regression at ~30 Myr [*Haq et al.*, 1987], apatite fission track analysis of Miocene strata in the western part of the southern Chinese Tien Shan and in the eastern Pamir support a tectonic explanation for the change in sedimentation. *Sobel and Dumitru* [1997] suggested that denudation in this part of the Tien Shan began at the Oligo-Miocene transition (~23–25 Ma) and continued through the mid-Miocene (~13–16 Ma) as a result of tectonically controlled rapid range uplift [*Sobel and Dumitru*, 1997]. The Ferghana basin to the northwest (Figure 1) apparently started to form in the Paleogene (late Oligocene?), deformation intensifying in the Pliocene [*Cobbold et al.*, 1994]. In the Tadjik depression to the west (Figure 1), a late Oligocene shift from marine to continental sedimentation has been attributed to the onset of regional shortening [*Gubin*, 1960; *Thomas et al.*, 1994, 1996]. In the Peter the First Range (PFR) (Figure 1) conformable deposition of Neogene continental coarse clastics took place on Jurassic and Paleogene units [*Gubin*, 1960; *Hamburger et al.*, 1992]; equivalent units occur on basement of the southwestern Tien Shan in the footwall of basement-involved thrusts [*Lukk et al.*, 1995]. These observations suggest late Miocene or even Pliocene deformation in that area [*Pavlis et al.*, 1997]. To date, all available data and the results of our study suggest that significant shortening in the northern Pamir and southern Tien Shan started between late Oligocene and early Miocene time and continued episodically until the present (Figure 12).

8.2. Late Cenozoic Tectonic Development of the Alai Valley Intramontane Basin

[40] The progressive closure of the Alai Valley by the northward advance of thrusting in the Trans Alai exemplifies a four-stage development of an intramontane basin by collision tectonics, from early basin formation to final annihilation (Figure 12).

1. In the late Oligocene, the oldest coarse-grained continental clastic rocks (Massaget formation) were conformably deposited on older Mesozoic and early Cenozoic units (Figure 12a). This event was synchronous with an abrupt shift from marine to continental sedimentation, recorded across the formerly contiguous Afghan-Kashgar basin (Figure 1) [*Leith*, 1982; *Sengör*, 1984; *Burtman and Molnar*, 1993; *Burtman*, 2000]. Terrestrial sedimentation is interpreted to reflect the onset of regional tectonic activity that created the necessary relief and source areas. This assessment is in line with fission track data from the Central Pamir [*Schwab et al.*, 2000] and the Chinese Tien Shan [*Sobel and Dumitru*, 1997].

2. Distributed north-south contraction started in the Alai basin at least during the early Miocene, toward the end of or after deposition of the Massaget formation (Figure 12b). Paleozoic structures may have influenced the location of thrusts during this early episode; however, our knowledge of the geometry and distribution of these preexisting structures is largely unconstrained in the area. Syntectonic deposits due to this stage of deformation are not preserved; instead, a regional erosion surface formed, which was probably related to base-level changes, which may have been caused by regional uplift. About one third to half of the total shortening across the Alai basin occurred during this stage of deformation (Figures 7, 8, and 12). However, significant buildup of topography and exhumation apparently did not take place, as evidenced by the preservation of Mesozoic sediments.

3. After the formation of the post-Massaget erosion surface, a second stage of contraction affected the Alai basin from the middle Miocene onward (Figure 12c). The thrust front stepped southward during this younger episode and was restricted to the southern edge of the Alai Valley. Reverse faults formed during stage 1 were not reactivated as shown by the lack of offset of the erosional surface (Figures 6, 7, 8, and 12). Displacements along the Trans Alai during this time controlled the growth of the clastic wedge. The composition and geometry of the wedge units clearly indicate their origin in the Trans Alai (Figure 12c). The sudden mid-Miocene southward retreat of thrusting together with dormant early Neogene structures within basin may be due either to strain weakening of the MPT during the early Miocene stage of deformation and/or to surficial mass transfer preventing renewed distributed thrusting and reactivation of older faults.

4. The youngest event related to basin closure is the northward migration of the active MPT (Figure 12d). This thrust also displaced and uplifted Pleistocene terraces [*Strecker et al.*, 2002], indicating continued activity. This contrasts with the tectonic quiescence along the southern Tien Shan since at least the Early Quaternary. During these last two stages (3 and 4; mid-Miocene to present), the accommodation space for the sediments deposited in the basin was continuously created by the sustained tectonic loading of the northern Pamir on the southern edge of the Alai Valley.

8.3. Strain and Displacement Rates

[41] On a timescale of $\geq$10 Myr, average strain and horizontal displacement rates are slow (i.e., less than 1 mm yr^{-1}; see Table 1), at least one order of magnitude lower than the 20 mm yr^{-1} previously proposed by *Burtman and Molnar* [1993]. Our results are comparable with long-term rates documented farther east along the southern Chinese Tien Shan, i.e., 1–1.9 mm yr^{-1} in the Kuche basin [*Yin et al.*, 1998] and 1.8 mm yr^{-1} along the Kepingtage thrust zone [*Allen et al.*, 1999]. Low long-term displacement values also contrast with Holocene rates. For instance, Holocene dip slip rates along the MPT are estimated at 6 mm yr^{-1}, equivalent to a horizontal displacement rate $\geq$5.2 mm yr^{-1} [*Arrowsmith and Strecker*, 1999]. A similar rate of 2–4 mm yr^{-1} was determined by *Nikonov et al.* [1983]. Finally, values are considerably larger when considering short-term rates derived from geodetic data. Recent shortening rates of 20 mm yr^{-1} [*Abdrakhmatov et al.*, 1996] and 3.5–12 mm yr^{-1} [*Reigber et al.*, 2001] are proposed for the Tien Shan mountains and the sector between the northern Pamir and the southern Ferghana Valley, respectively. This suggests that displacement rates increase locally over short time periods; these observations also highlight the problem of extrapolating short-term geodetic rates to geological time scales [*Bullen et al.*, 2001].

9. Conclusions

[42] Our study provides new insights on the geometry, kinematics and relative timing of deformation in the frontal part of the northern Pamir. These results show that the Alai Valley is an asymmetric intramontane basin that formed in response to the convergence between India and Eurasia during the late Cenozoic. Its formation and progressive annihilation are the result of two main deformation events. The first took place during the late Oligocene–early Miocene and was accompanied by a change of sedimentary environments from marine to terrestrial conditions, followed by the separation of the Tarim and Tadjik basins in the course of distributed shortening. At least one half of the total horizontal shortening across the Alai basin was accommodated at that time and was accompanied or followed by the development of a regionally extensive erosion surface. The second event shortened and thickened the area starting in the mid-Miocene and continuing through the present. It involved sudden southward migration and localization of deformation along the Trans Alai range front. This deformation event failed to reactivate preexisting structural discontinuities but instead created younger structures at the margin of the basin. This phase is characterized by the progressive approachment between the Pamir and the Tien Shan and will ultimately result in the complete annihilation of the basin. This ultimate stage is already observable in the west and east of the basin. Horizontal shortening of about 35% across the Alai Valley

yields relatively low strain and displacement rates of about $4.18-4.69 \times 10^{-16}\ s^{-1}$ and $0.66-0.78\ mm\ yr^{-1}$ respectively, for the last 25 Myr. Our study agrees with others that show that contractional deformation occurred far in the interior of the Asian continent as early as the late Oligocene.

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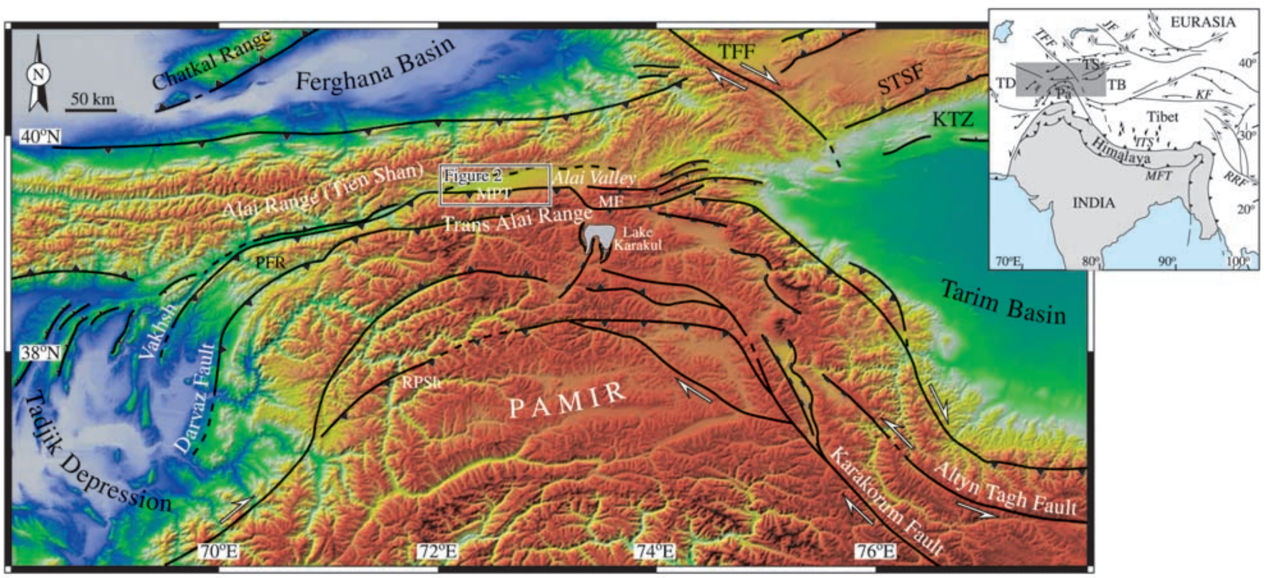

Figure 1. Major Cenozoic faults of the Pamir and adjacent areas showing the situation of the Alai Valley, between the Pamir and the Tien Shan [modified after *Burtman and Molnar*, 1993; *Strecker et al.*, 1995]. The Alai Valley is a remnant of the once continuous early Cenozoic basin connecting the Tadjik depression and the western Tarim. Figure 3 covers the boxed area. The shaded box in inset shows the area covered by digital topography and depicts major structural features of the Himalaya-Tibet region (modified after *Allen et al.* [1999]). Topography is from the U.S. Geological Survey. Abbreviations are ITS: Indus-Tsangpo Suture, JF: Junggar Fault, KF: Kunlun Fault, KTZ: Kepingtage Thrust Zone, MF: Markansu Fault, MFT, Main Frontal Thrust, MPT: Main Pamir Thrust, Pa: Pamir, PFR: Peter the First Range, RPSh: Rushan Pshart Zone, RRF: Red River Fault, STSF: South Tien Shan Fault, TB: Tarim basin, TD: Tadjik Depression, TFF: Talas Ferghana Fault.