Late Cenozoic slip on the Talas-Ferghana fault, the Tien Shan, central Asia

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ABSTRACT

Although Cenozoic crustal shortening and thickening by thrust faulting have built the present Tien Shan, active right-lateral shear on the northwest-trending Talas-Ferghana fault appears to be the most rapid localized deformation in the belt. Ephemeral stream valleys have been offset right-laterally tens of metres. New and published radiocarbon dates of organic material deposited in depressions blocked by offset ridges place upper bounds on the average Holocene slip rate at 18 localities. Uncertainties allow 14 upper bounds to overlap the range of 8–16 mm/yr, and 95% confidence limits on such bounds at 11 sites are entirely within this range. We infer that the rate of ≈10 mm/yr is not simply an upper bound, but applies to the late Holocene Epoch. Although the bounds on rates permit more rapid slip in the northwest than the southeast, they do not place a useful constraint on variations in slip rate along the fault. Offsets of Paleozoic facies boundaries imply a total right-lateral shear of 180–250 km, but Early Cretaceous sedimentary rock appears to have been offset only 60 ± 10 km. Published paleomagnetic declinations of Cretaceous– Miocene rock demonstrate 20°–30° of counterclockwise rotation of the Ferghana Valley, which lies just west of the Talas-Ferghana fault, with respect to stable parts of Eurasia and 20° ± 11° with respect to the central Tien Shan east of the fault. These declinations are consistent with a maximum northwestward translation of 70–210 km of the Ferghana Valley at the Talas-Ferghana fault and, therefore, with a similar maximum horizontal shortening across the Chatkal Ranges, which lie between the Ferghana Valley and the Kazakh platform. Estimates of crustal thickness beneath the Chatkal Ranges, however, permit only 60–100 km of Cenozoic shortening. If <100 km of slip on the Talas-Ferghana fault accumulated at a constant rate of 10 mm/yr, it would imply an initiation of slip more recently than ca. 10 Ma, long after India collided with the rest of Eurasia.

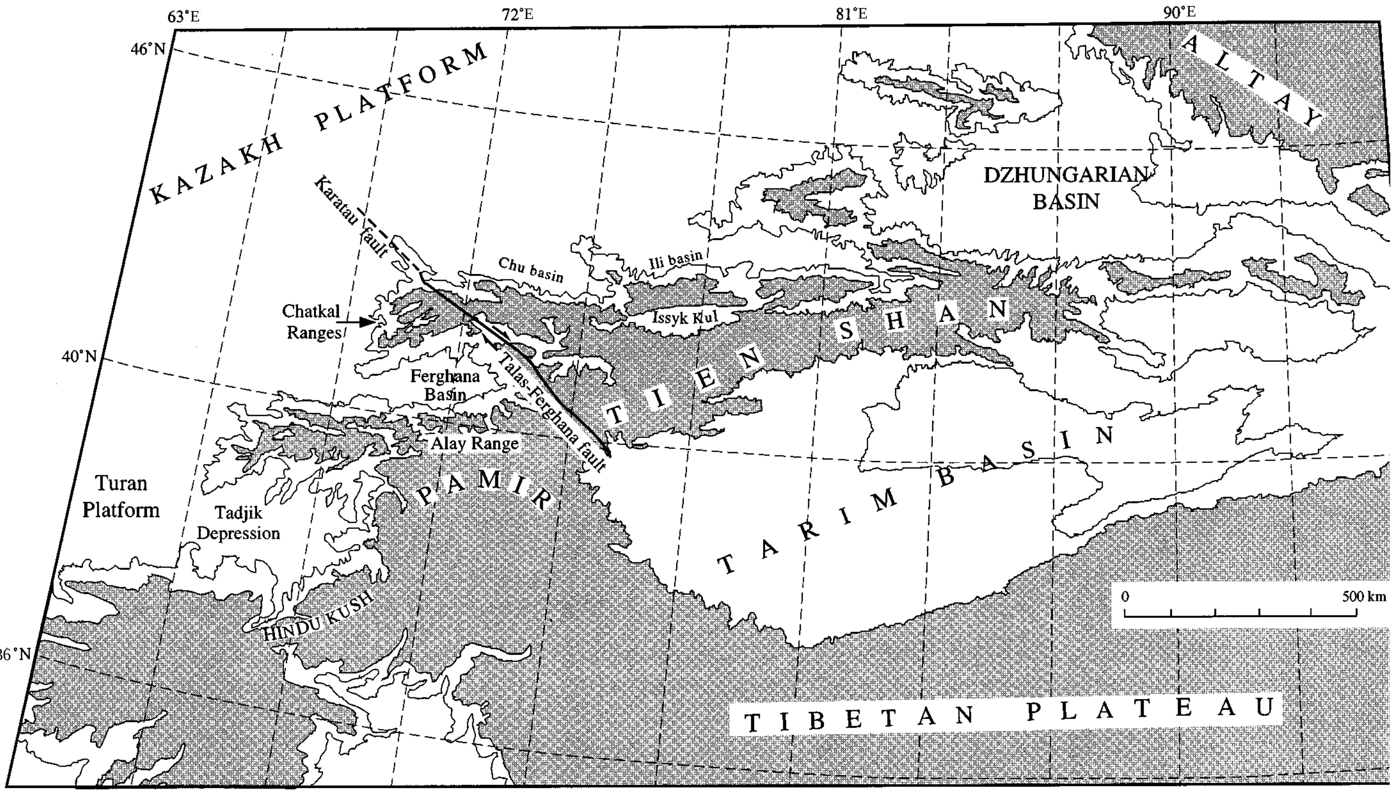

Figure 1. Map of the central Asia showing the Tien Shan and its surroundings and the position of the active trace of the Talas-Ferghana fault. Simplified from Avouac et al. (1993).

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INTRODUCTION

Mountain building generally includes significant crustal shortening by thrust faulting and by folding, but for whatever reasons, inhomogeneities in the deformation field require some strike-slip faulting to link thrust faults separating different ranges within the belts. The Talas-Ferghana fault in the western part of the Tien Shan in central Asia is one of the world's most prominent strike-slip faults (Fig. 1). As illustrated elsewhere (e.g., Burtman and Molnar, 1993; Davis and Burchfiel, 1973; Wernicke et al., 1982), the quantification of slip on intracontinental strike-slip faults places bounds on the rates of regional shortening or regional extension. Correspondingly, an appreciation for the rate of slip along the Talas-Ferghana fault is vital for quantifying active deformation within the Tien Shan. Given the preeminence of the Tien Shan as an active intracontinental mountain belt, similar to the Rocky Mountains of the western United States in Late Cretaceous time, the quantification of its deformation should provide a step toward understanding intracontinental deformation in general.

The Tien Shan forms part of the high terrain north of India that developed following India's collision with the rest of Eurasia. Ascribing the ongoing crustal shortening to India's penetration is logical; Cenozoic deformation in the Tien Shan is consistent with the strain field expected from India's movement, and the Cenozoic age of deformation allows such a cause and effect relationship (e.g., Molnar and Tapponnier, 1975). Whereas deformation in the Himalaya apparently began immediately after the collision, that within the Tien Shan may be significantly younger.

Our main purpose is to present objective data that bound the present-day rate of slip on the Talas-Ferghana fault. A secondary objective is to review evidence that suggests 60–100 km of slip in Cenozoic time. We then use the present-day slip rate to suggest a date when this phase of Cenozoic slip began.

TECTONIC SETTING OF THE TALAS-FERGHANA FAULT

The Talas-Ferghana fault forms the obliquely oriented boundary between the central Tien Shan, east of the fault, and the western Tien Shan, which includes the Ferghana Valley, the Chatkal Ranges, and the Alay Range (Fig. 1). The central (and eastern) Tien Shan comprises a wide belt of east-west–trending ranges that separate parallel intermontane basins between the Tarim basin and the Kazakh platform. Cenozoic warping and thrusting of crustal blocks over the basins have built the individual ranges within the Tien Shan (e.g., Makarov, 1977; Sadybakasov, 1990). The associated crustal shortening has created a relatively thick crust (≈60 km), which buoys up the belt. The Ferghana basin, within the western Tien Shan, has formed in Cenozoic time as the Chatkal and Alay Ranges have been thrust onto the basin and as material eroded from these elevated areas has filled the low area between them.

Talas-Ferghana Fault in Late Paleozoic Time

Although the present mean topography of the Tien Shan results largely from Cenozoic crustal movements, intense tectonic activity occurred in this area in the late Paleozoic Era. Nappes and more open folds formed during the Late Carboniferous and Early Permian periods as a result of the closing of roughly east-west–trending ocean basins (Fig. 2) (e.g., Burtman, 1964, 1975). Tectonic activity apparently diminished in the Permian Period. The study of Paleozoic tectonic structures, igneous intrusions, and sedimentary facies zones shows that Paleozoic rocks have been displaced right-laterally along the Talas-Ferghana fault ≈180 km (Fig. 3). Including continuous deformation—shearing or bending about vertical axes—of units adjacent to the fault, the displacement of Paleozoic rock reaches 250 km (Burtman, 1964, 1975, 1976, 1980).

The active trace of the Talas-Ferghana fault, ≈500 km in length, appears to delimit only a fraction of the strike-slip fault active in late Paleozoic time. Another segment, sometimes called the Karatau fault, marks a northwest continuation for at least another 300 km. Orientations of folds in Paleozoic rock to the strike of the Karatau fault attest to right-lateral slip on this fault, but the amount of slip cannot be determined (Burtman, 1964). Presumably, the entire Karatau-Ferghana fault system was active in late Paleozoic time. Moreover, its combined length of 800 km may be a minimum for this zone; the Karatau fault is buried under Quaternary sediment

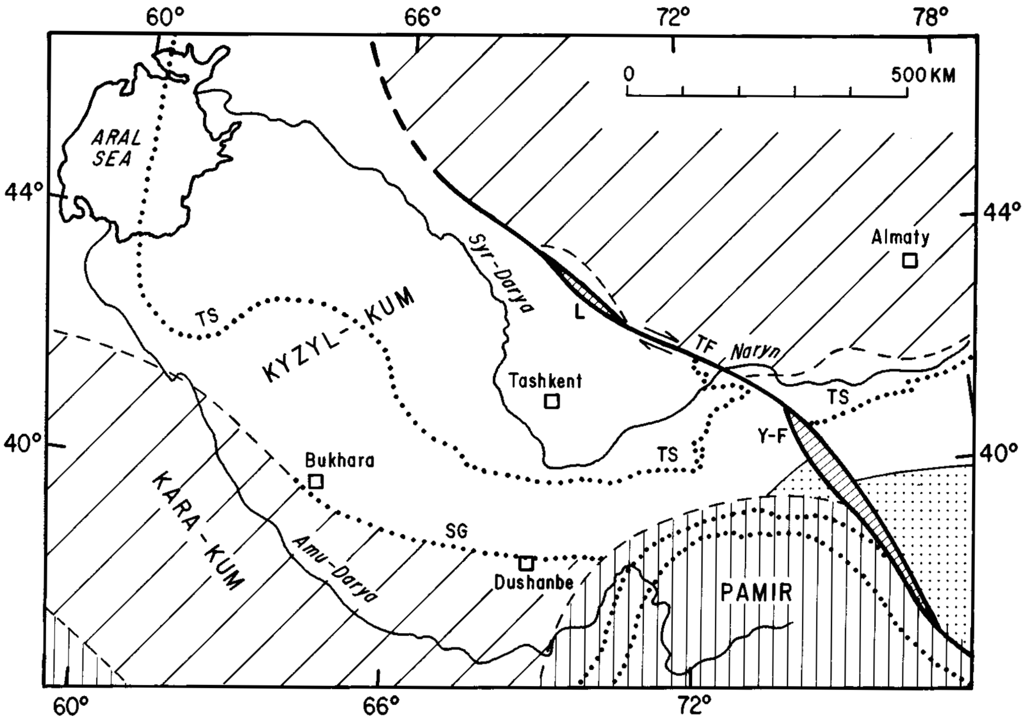


Figure 2. The Talas-Ferghana fault and Paleozoic structure of the western part of central Asia. Abbreviations for sutures of Paleozoic ocean basins: TS—Turkestan, SG—South Gissar. F-T denotes the Talas-Ferghana fault. Fine diagonal lines mark two Jurassic basins that are along the Talas-Ferghana fault: L—Leont'yev basin, Y-F—Yarkand-Ferghana basin. Vertical lines indicate the area of Cenozoic folding and faulting in the Pamir and adjacent regions. Wide diagonal lines show areas of widespread folding in early Paleozoic time. Dotted area is the Tarim platform.

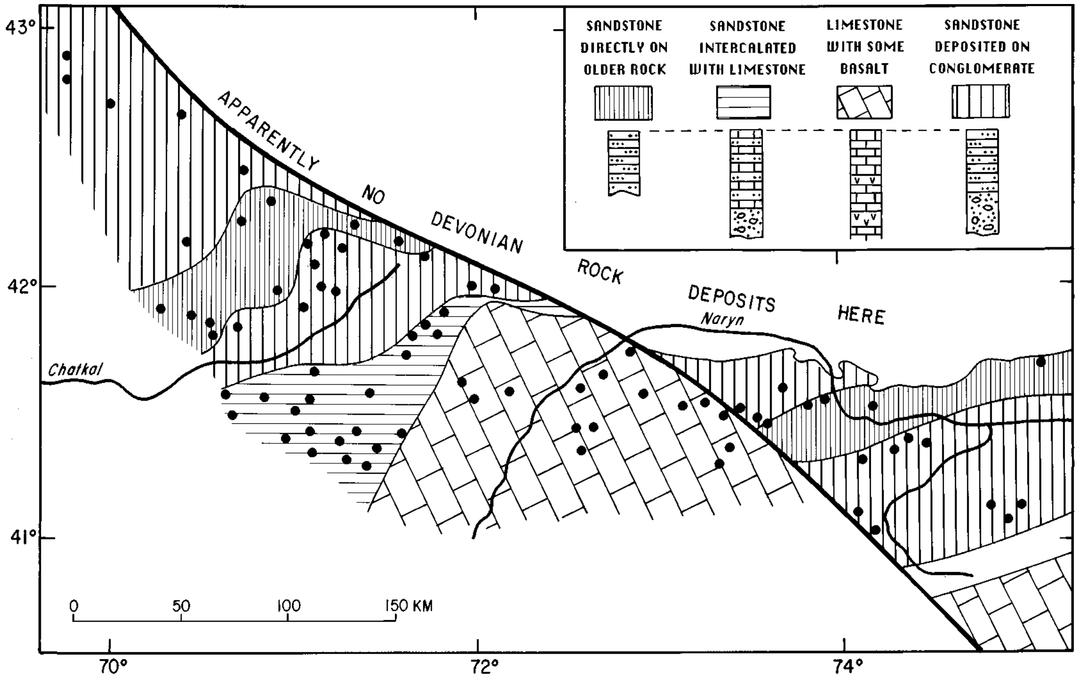


Figure 3. Map of facies zones for Devonian deposits in the Tien Shan along the Talas-Ferghana fault (shown by the dark line). Only rock older than Devonian crops out, and Devonian sediments do not appear to have accumulated in the white areas north of the fault. Black dots show the locations of measured stratigraphic sections. Redrawn from Burtman (1964, 1980).

farther northwest. Afanas'yeva et al. (1983) reported that from satellite imagery they could trace unspecified features, collectively termed a "lineament" and presumed to be a northwestward continuation of the Karatau-Talas-Ferghana fault, to the Ural Mountains, >1000 km to the northwest. At the edge of the Tarim basin, the currently active Talas-Ferghana fault seems to split into several branches that curve to the east and into east-west–trending thrust faults (Afanas'yeva and Faradzhev, 1978). In the late Paleozoic and Mesozoic Eras, however, the Talas-Ferghana fault may have continued southeast as a strike-slip fault. Thus, the currently active fault seems to be only a part of a much longer zone with a history that apparently began before the Cenozoic Era.

The rock units clearly offset by the Talas-Ferghana fault lie in the Chatkal Ranges west of the fault and farther south on the east side, in the interior of the central Tien Shan (Fig. 3). Because essentially all offset rocks are Paleozoic, an important question is, How much of the 180–250 km offset occurred in Cenozoic time?

Tien Shan in Mesozoic and Cenozoic Time

Two Jurassic sedimentary basins are aligned with the Talas-Ferghana fault and Karatau faults: the Leont'yev basin in the northwest and the Yarkand-Ferghana basin in the southeast (Fig. 2) (Burtman, 1964, 1980). Defined by thick Jurassic sedimentary rock, the basins follow segments of the fault zone where the local strike is northwest and separated by a west-northwest–trending segment. The geometric relationship of the basins to the fault concurs with right-lateral slip and with the basins being pull-apart basins, but we are aware of no reliable estimate of the amount of slip in this period.

In Early Cretaceous time, broad intracontinental sedimentary basins formed over much of Central Asia. Sediment with both fresh-water and salt-water fauna were deposited in shallow water to the west of the Talas-Ferghana fault, in the Ferghana basin, the Tadjik depression, and the Alay Range (Fig. 1). Early Cretaceous sedimentary rocks include conglomerate, sandstone, clay, and limestone, but limestone is not widespread. The upper parts of these deposits contain thin layers of gypsum. Alluvial deposits mark the peripheries of lakes. The thickness of Early Cretaceous deposits exceeds 500 m in some places.

Early Cretaceous deposits have not been reported east of the Talas-Ferghana fault, except possibly on the southern foothills of the Akshirak Range (Figs. 4 and 5). Verzilin (1968) described deposits overlying Paleozoic rock in the Akshirak Range east of the fault, having lithologic features resembling those of the Early Cretaceous rock in the Ferghana basin (Fig. 4). In the eastern Ferghana basin, Early Cretaceous sedimentary rock can be separated into two facies zones distinguished by significantly different stratigraphy and by different compositions of clasts in the basal conglomerate (Fig. 4). Conglomerate clasts in the Akshirak Range east of the Talas-Ferghana fault appear to correlate with those west of the fault and 60 km to the northwest (Fig. 4). The relative positions of these facies zones suggest right-lateral slip of 60 (±10) km after Early Cretaceous time. Unfortunately, the inference of an Early Cretaceous age for the sequence in the Akshirak Range is based only on the lithologic and petrographic resemblance to Early Cretaceous rock from the Ferghana basin, and not on local fossil control.

At the beginning of Late Cretaceous time, a lake covering a part of the western Tien Shan was transformed into a shallow intracontinental sea with lagoons. From Late Cretaceous to Eocene time, marine and lagoonal deposits accumulated in the Ferghana basin, in the Tadjik depression, and what is now the Alay Range. Maximum transgressions occurred during Campanian and middle Eocene time. Later in Paleogene time, the sea retreated. Oligocene conditions in the Ferghana Valley changed from marine to lagoonal and then to continental. The thickness of the Cretaceous–Eocene sequence exceeds 2000 m.

East of the Ferghana Valley, Late Cretaceous and Paleocene sedimentary rock is absent; continental sediment began to accumulate in Eocene time. Clay, siltstone, and sandstone with interbedded layers of limestone, marl, gypsum, and conglomerate and containing freshwater fauna and mammal bones accumulated in isolated or interconnected basins throughout the Tien Shan in Oligocene and Miocene time. Thicknesses of these deposits vary

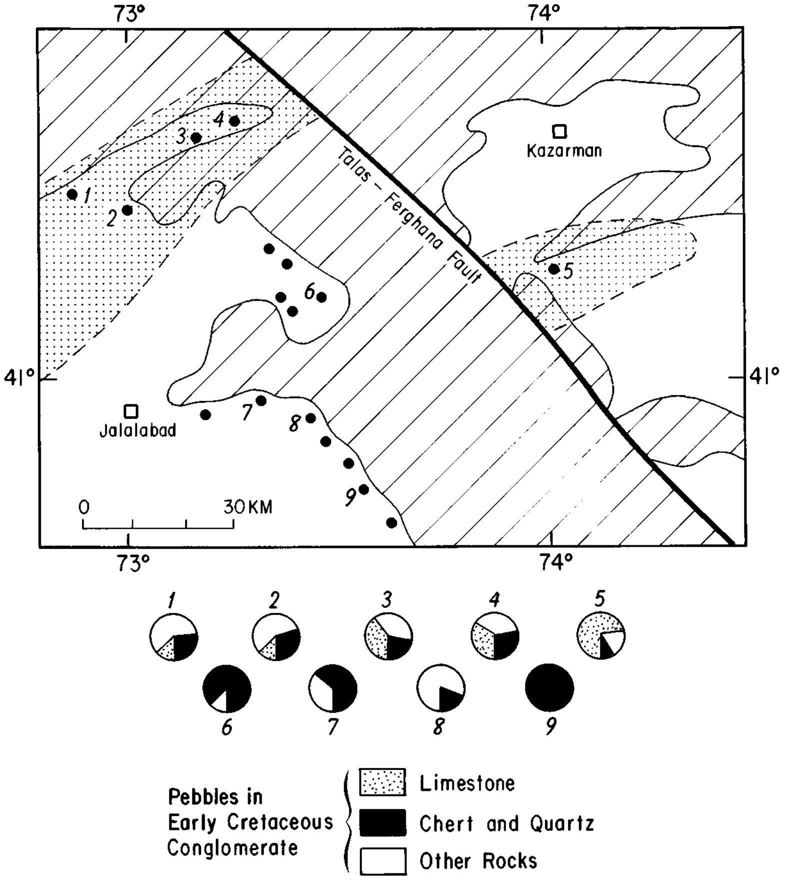


Figure 4. Cretaceous facies zone, mapped by Verzilin (1968), apparently offset by slip along the Talas-Ferghana fault. Large dots show localities where Verzilin (1968) measured Early Cretaceous stratigraphic sections. The ruled area shows Jurassic and older rocks. Dotted areas show the zone where limestone pebbles are found in Early Cretaceous conglomerate. Pie diagrams below show the relative amounts of limestone in pebbles within the basal conglomerate at selected sites denoted by the numbers on the map. The separation between the areas of similar Early Cretaceous rock east and west of the fault is 60 ± 10 km.

from tens of metres in some basins to kilometres in others, reaching >4000 m. Coarse-grained facies including conglomerate on the peripheries of lake-filled basins attest to the presence of relief surrounding the basins.

LATE QUATERNARY OFFSETS AND BOUNDS ON THE SLIP RATE

We examined several segments of the Talas-Ferghana fault where offset topographic features are clear on aerial photos and where datable material might allow bounds to be placed on the slip rate on the fault. Where it seemed promising, we dug pits in search of organic material for radiocarbon dating, mostly in topographic lows that are now dry, but that apparently were once sag ponds. In all cases, material had been deposited since the initiation of incision of the gullies that had been offset. In addition, Burtman et al. (1987) and Trifonov et al. (1990, 1992) reported similar measurements and dates for other offsets. Because the material was deposited after the formation of a gully or ridge subsequently offset, radiocarbon dates, corrected for variations in cosmic radiation (Table 1) (Bard et al., 1990; Pearson and Stuiver, 1986; Stuiver and Pearson, 1986), provide lower bounds on the time intervals over which these features have been offset. Hence, ratios of measured offsets to corrected dates place upper bounds on average rates of slip since these dates.

Jilangach Region

Numerous offsets of ≈30–70 m can be seen along much of the segment between the Jilangach and Pchan Rivers (Figs. 5–8) (see also Burtman, 1964, Fig. 3, p. 12–14). We did not work southeast of this area.

With a tape measure, we measured offsets between 5 and ≈50 m near Jilangach Pass; most were near 40–50 m (Figs. 8 and 9). Except for two relatively small offsets of 5 and 12 m, we saw no clear evidence of a surface rupture from a major earthquake. Along most of this zone, the southwest side has moved up a few metres with respect to the northeast side to form shutter ridges that have dammed the upstream reaches of the gullies at the fault. Although now dry, the dammed areas contain organic material, presumably ponded in occasionally and temporarily flooded basins. The numerous 30–50 m offsets suggests that a change in the rate incision of gullies occurred within the past several thousand years.

Radiocarbon dates obtained from the southeasternmost gully at Jilangach Pass (Fig. 6) yield a bound on the slip rate of 13–15 mm/yr. A shutter ridge seems to have temporarily dammed the gully to form a sag pond, now dry, on the northeast side of the scarp. At the base of the upstream reach of the gully a pit to a depth of 1.28 m reached poorly sorted cobbles (Fig. 10), the composition and texture of which resemble those of colluvial material currently on the hillside. Black soil rich in organic material at depths between 0.63 and 0.69 m and between 0.70 and 0.78 m, with flecks of charcoal at the shallower level seems to have been deposited in a swampy environment behind the shutter ridge. The ratio of 40 ± 3 m to the oldest age range of 2777–2934 yr B.P., taken from the deeper soil, yields an upper bound on the slip rate of 13–15 mm/yr (site 2, Table 1, Fig. 6). Scattered colluvium begins at a depth of 1 m in the pit. If the sedimentation rate of the overlying material were constant, the age of deposits at the base of the pit might be 30% greater, reducing the bound on the slip rate by 30% to 9–11 mm/yr.

A similar procedure was applied to another gully to the northwest, offset 45 m (Fig. 8). We dug a shallow pit on the northeast side of the shutter ridge near its northwest end. This locality presumably was separated

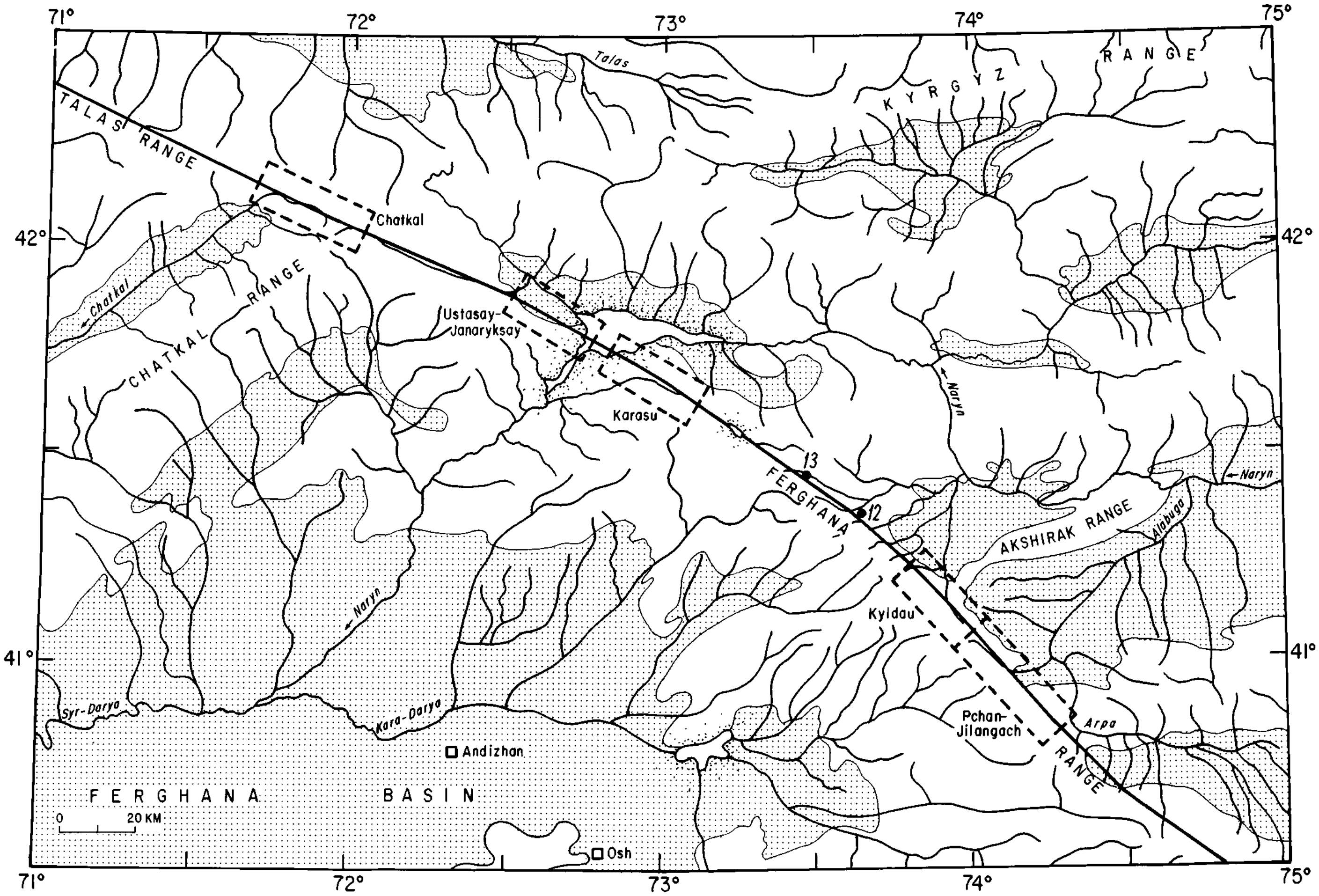


Figure 5. Map of the Talas-Ferghana fault trace and its surroundings. Dashed rectangles show the segments of the fault that we studied and that are discussed in detail. Sedimentary basins are shown by the regularly spaced dotted pattern. Random dotted patterns outline large lakes and reservoirs. Numbers along the fault trace show the positions of sites 12 and 13 (Table 1).

from its upslope continuation shortly after the gully began to incise. At a depth of 0.55 m, basal gravel consisting of limestone cobbles underlies clay and sand with organic soil at depths between 0.45 and 0.5 m (Fig. 10). The organic material did not form a layer and could have been material deposited in a burrow hole. The upper bound on the slip rate is 24–31 mm/yr (site 3, Table 1). We suspect that this age is significantly younger than incision of the gully offset in this locality.

Northwest of Jilangach Pass, a stream has dissected the fault zone. Evidence of recent slip is sparse for ≈5 km, but just southeast of where the Pchan River crosses the Talas-Ferghana fault (Fig. 6), recent offsets are clear. The fault follows the southwest side of a hill between the Pchan and Birguzy Rivers (Fig. 11). Among several offsets ranging from 35 to 70 m, the clearest is that at the northwestern edge of the area shown in Figure 11A, where a shutter ridge displaced 35 ± 5 m blocks the drainage (Fig. 11B). The sequence, including sod at the top, in the dry sag pond consists of 0.27 m of black and brown soil, ≈0.5 m of sand and gravel apparently deposited by an alluvial regime, a thin layer (0.03 m) of organic sediment with charcoal, and more gravel (Fig. 10). The upper bound on the slip rate is 9–13 mm/yr (site 5, Table 1).

On the opposite (northeast) side of the hill shown in Figure 11A, a secondary trace emanates from the main trace and curves east-southeast. This splay can be traced clearly for ≈2 km southeast on the northeast side of the hill until the topography becomes steep. Displacement seems to include both right-lateral (≈3 m) and vertical (1–2 m) components, such that the lower northeast side has moved up, relative to the ridge to the southwest. The topography associated with offset features suggests oblique normal faulting, despite the geometrical relationships calling for reverse faulting. We saw clearer examples of such splays farther northwest along the Pchan River.

Pchan River

For ≈6 km southeast of where the Pchan River approaches the fault from the southwest (Figs. 5 and 6), late Quaternary faulting is almost as spectacular as in the Jilangach region (Figs. 12 and 13). Roughly 30 m offsets of valleys and ridges are common, but the most interesting features might be clearly active splays that curve east-southeast from the main trace.

Northwest of the Korumdy River, a main tributary to the Pchan River, a shutter ridge has dammed a small perennial stream, and there is an offset of 21–24 m between the upstream and downstream reaches of the stream (Figs. 12 and 13A). Although the "sag pond" is currently drained, the flat surface northeast of the shutter ridge and at the southwest end of the upstream reach attests to recent ponding of material. Approximately 2 m northeast of the scarp and along the southwesterly projection of the upstream reach of the displaced stream, a pit to a depth of 1.14 m revealed

TABLE 1. RADIOCARBON AGES AND CORRECTED AGE RANGES OF SAMPLES FROM OFFSET STREAMS AND BOUNDS ON THE SLIP RATE ALONG THE TALAS-FERGHANA FAULT

Site	River valley or segment	Offset (m)	Radiocarbon age (yr)	Corrected age range* (yr)	Apparent slip rate† (mm/yr)	Sample number
1	Jilangach	19	3970 ± 40	4410–4460	4	1§
2	Jilangach	40 ± 3	1940 ± 50	1847–1943	(19–25)	7055 GIN92
		40 ± 3	2630 ± 70	2730–2815	(13–16)	Beta-47553
		40 ± 3	2740 ± 70	2777–2934	13–15	Beta-47552
3	Jilangach	45 ± 3	1720 ± 70	1545–1717	24–31	Beta-47551
4	Chitty-west	40	4590 ± 100	4400–4800	8–9	2§
		40	15800 ± 1300	17000–19000	(2.1–2.4)	3§
5	Birguzy	35 ± 5	3030 ± 90	3070–3360	9–13	Beta-47554
6	Birguzy	27	3740 ± 600	3370–4570	6–8	4§
7	Pchan	90 ± 3	3150 ± 40	3359–3426	25–28	5§
8	Pchan	21–24	2180 ± 120	(2050–2340)	9–12	7052 GIN92
		21–24	2280 ± 70	(2306–2350)	9–10	Beta-47550
		21–24	2540 ± 70	2540–2752	8–9	Beta-47549
9	Pchan	25 ± 1	2640 ± 600	1980–3450	7–13	6§
10	Kyldau	23–24	2320 ±40	2336–2351	10	7§
11	Kyldau	125 ±25	3670 ± 80	3962–4132	(24–38)	Beta-47555
		60 ± 25#	3670 ± 80	3962–4132	8–21	
12	Urumbash	17–20	1510 ± 60	1330–1550	11–15	8§
13	Keklikbel	10–12	1240 ± 60	1060–1220	8–11	9§
14	Janaryksay	14 ± 2	1440 ± 30	1311–1361	9–12	7054 GIN92
15	Chatkal	17–20	1450 ± 40	1306–1373	12–15	4300 GIN85
16	Chatkal	20	1350 ± 60	1264–1308	15–16	4301 GIN85
		40	1350 ± 60	1264–1308	(31–32)	
17	Chatkal	20	1150 ± 40	988–1143	(17–20)	4302 GIN85
		20	2020 ± 50	1928–2030	10	
		40	2020 ± 50	1928–2030	(20–21)	
18	Chatkal	20	1220 ± 50	1064–1250	16–19	4304 GIN85
		40	1220 ± 50	1064–1250	(32–38)	

*Calendar years. Age ranges are those given by Pearson and Stuiver (1986) and by Stuiver and Pearson (1986) for radiocarbon dates less than 3700 yr B.P. and by Bard et al. (1990) for greater dates.

†Rates in parentheses seem less reliable than those without parentheses for reasons discussed in the text.

§Offsets and ^{14}C dates from Trifonov et al. (1990, 1992).

#Here we consider the possibility that the ^{14}C date applies only to roughly half of the total offset (see text).

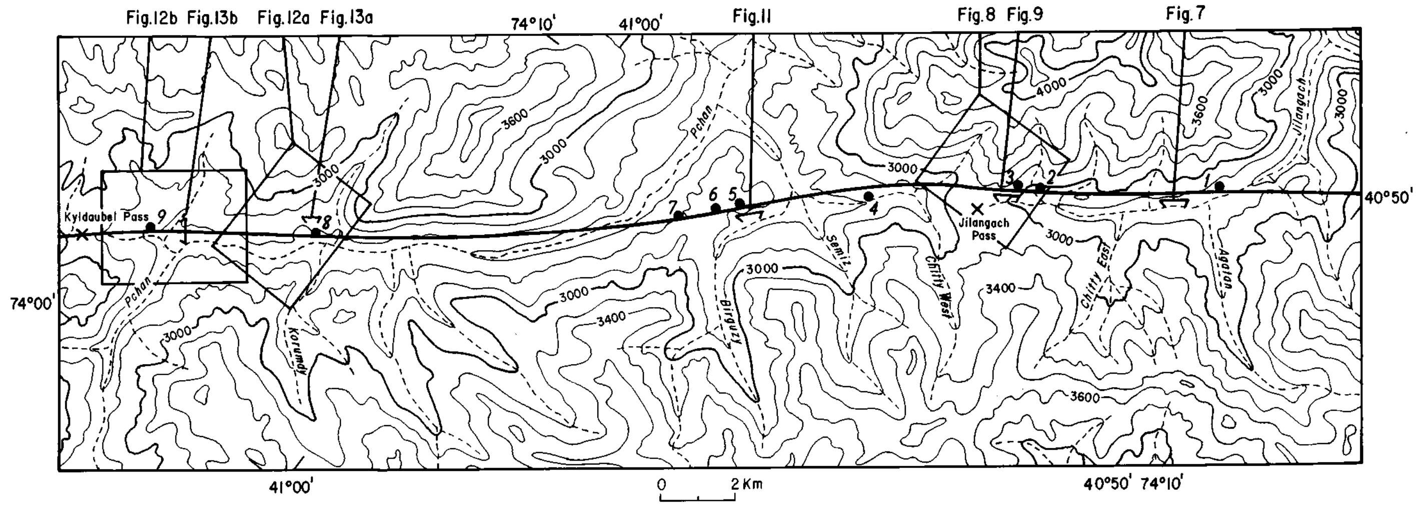


Figure 6. Topographic map of the segment of the Talas-Ferghana fault between the Pchan and Jilangach Rivers. Dark line shows the trace of the Talas-Ferghana fault. Numbers show the locations of sites 1–9 and of photos in Figures 7–13. Contour interval = 200 m.

0.24 m of top soil, a 0.6-m-thick layer of clay with a thin layer of dark, organic rich soil within it, another layer of organic rich soil 0.2 m in thickness, and 0.1 m of clay mixed with gravel (Fig. 10). Samples from the deeper layer of the organic rich material, taken at heights of 0.25–0.3 m and 0.1–0.15 m above the bottom of the pit, yield consistent dates. The oldest age yields an upper bound for the slip rate of 8–9 mm/yr (site 8, Table 1).

Northwest of this area, the fault is perched high on the left bank of the Pchan River. Offsets of 20–30 m can be seen along the fault northeast of where the upper, northeasterly flowing reach of the Pchan River turns and

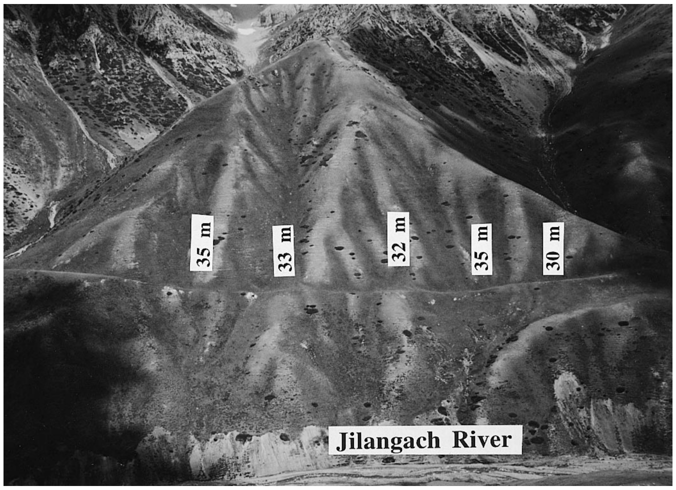


Figure 7. Photograph, using a lens with a focal length of 20 mm, looking northeast at the trace of the Talas-Ferghana fault on the hillside across the Jilangach River. After measuring one distance with a tape measure, we estimated the offsets shown by scaling them by eye. Most offsets are estimated to be ≈30–35 m. This area is ≈5.5 km southeast of Jilangach Pass.

Figure 9. Photograph looking northeast across the Jilangach River at some of the offset gullies shown in Figure 8.

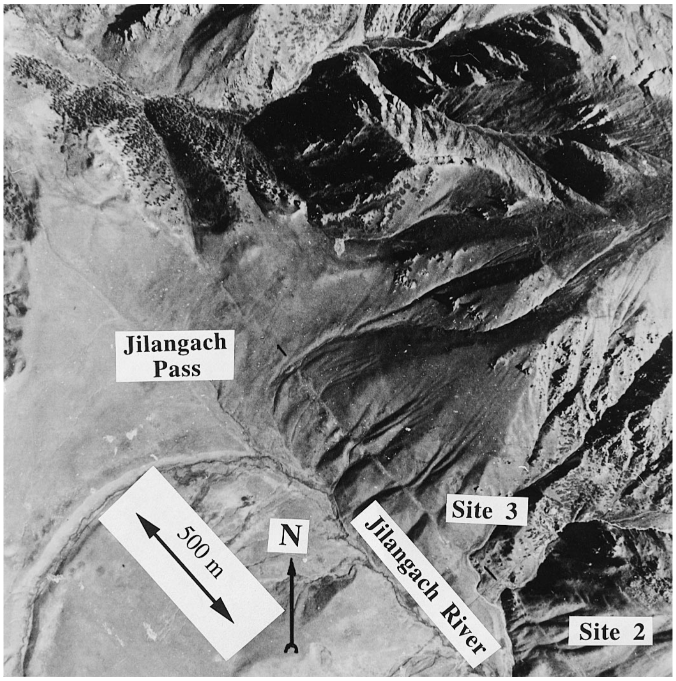


Figure 8. Aerial photograph (M-945 28/VIII 59-20526) showing the offset gullies at Jilangach Pass and locations of sites 2 and 3. Modified from Burtman (1963, Fig. 7; 1964, Fig. 4; 1980, Plate A), Tapponnier and Molnar (1979, Fig. 4), and Trifonov et al. (1992, Fig. 4).

flows southeast (Figs. 12B and 13B). Farther northwest, large sag ponds mark the trace.

Just northwest of site 8, the main strand trends more south-southeasterly than it does either to the northwest or southeast (Fig. 12A). Splays branch from it and curve into east-southeasterly (115°) trends. These splays are especially clear on the ground (Fig. 14). Components of displacement are right lateral and vertical, and the southern side is up. This sense of slip is opposite that of the regional topography and suggests a component of normal faulting and extension across the faults. Magnitudes of vertical components range from 2 m to 4–5 m; consistently larger right-lateral components are commonly between 10 and 20 m (Fig. 14). The smooth surface traces across the landscape (Fig. 12) imply steep dips (>60°). For a dip of 63° horizontal components perpendicular to the strike would be half of the vertical components. Thus, slip vectors must be nearly parallel to the surface traces and indicate primarily strike-slip faulting.

The Talas-Ferghana fault defines the western boundary of an area undergoing crustal shortening by thrust faulting. These thrust faults must terminate at or near the Talas-Ferghana fault, and hence rates of strike slip must vary along that fault. Moreover, the angle between its strike and that of the thrust faults should change with time (e.g., McKenzie and Jackson, 1983, 1986), leading to relative rotation of the thrust blocks with respect to the Talas-Ferghana fault. These splays, which curve eastward toward the southeast, might therefore be manifestations of evolving deformation where long east-west blocks intersect the northwest-trending Talas-Ferghana fault. These splays, however, do not seem to mark faults that curve into the thrust faults between the blocks. The vertical components seem to indicate normal instead of thrust faulting, and the right-lateral strike-slip offsets are clearly not the conjugate left-lateral slip that might be expected between the east-west blocks. The kinematic relationship of these splays to the main fault suggests that the active Talas-Ferghana fault zone is wide in this area, a few kilometres, apparently with deformation that is more complex than that expected from the regional strain field.

Kyldau Valley

A segment ≈5 km farther northwest of the Pchan Valley reveals a spectrum of right-lateral offsets ranging from 12 m for a small gully to 125

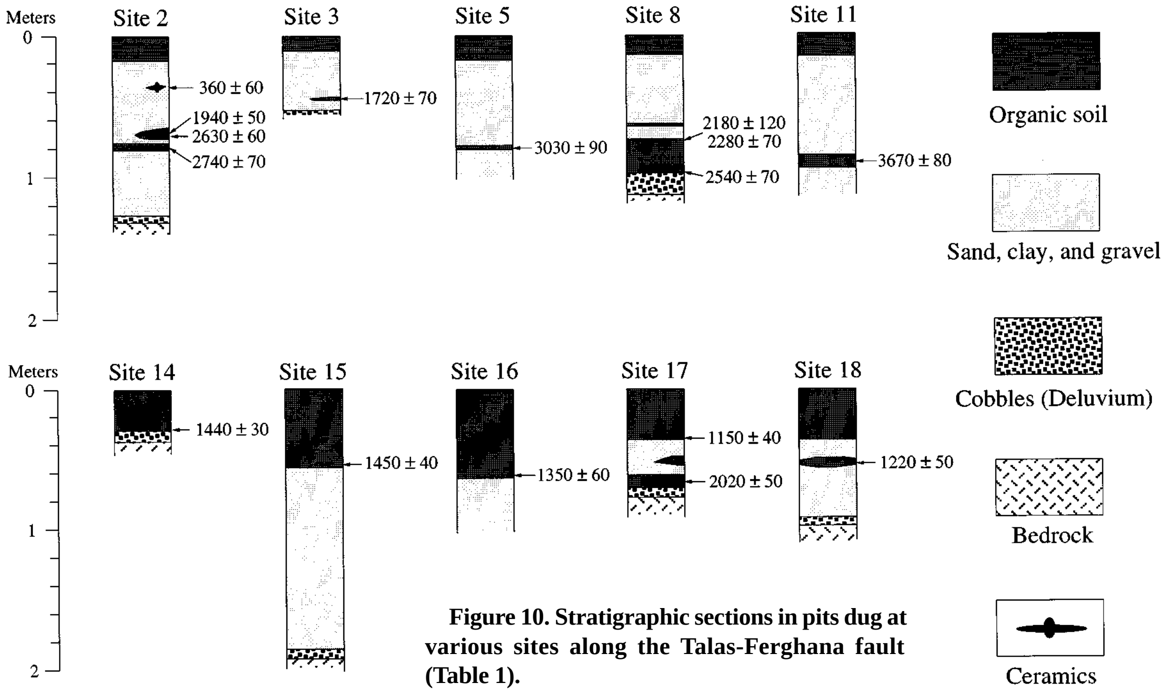
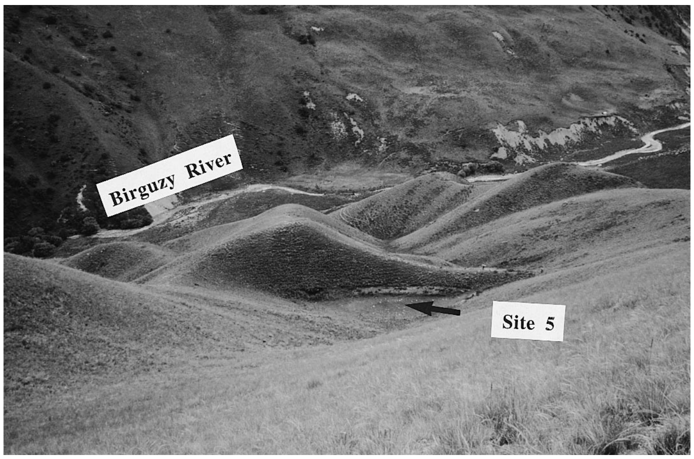


Figure 10. Stratigraphic sections in pits dug at various sites along the Talas-Ferghana fault (Table 1).

A



B

(±25) m for the nose of a ridge (Figs. 5, 15, and 16). In a pit on the northwest side of the nose displaced 125 (±25) m and on the northeast side of the fault trace (Fig. 17), a layer of black soil ≈0.3 m thick overlies brown soil ≈0.6 m thick, which in turn overlies clay and sand (Fig. 10). The interface separating brown soil and clay from sand slopes northeast at ≈20°. The corrected radiocarbon age range of 3962–4132 yr B.P. (site 11, Table 1) is the oldest for the samples that we obtained.

This locality is not ideal for bounding the rate of slip. A few metres northwest of our pit, a spring provides a constant source of water to the area near the fault. Water emanating from this spring currently flows downhill to the northeast and does not affect the site of the pit, but the flow of such water could have affected it when the displacement on the fault was a few metres smaller. The locality lies roughly in the middle of the 125 m offset. Thus, if the organic material was deposited when the spur southwest of the fault first provided a scarp that ponded water and sediment, this ponding occurred only after ≈60 m of displacement had occurred. In addition, the organic material is not flat, but overlies a surface dipping northeast. Either there has been subsequent tilting or, more likely, this material was deposited on colluvium slumping from the scarp downward toward the northeast. In the latter case, the material was deposited not only after ≈65 m of offset had occurred, but after sufficient offset had occurred to create a scarp from which material could slump. Roughly 100 m northwest of this site, the trace crosses a relatively flat fan, and a small scarp ≈0.5 m high faces northeast. This vertical component, how-

Figure 11. Photographs of the section along the Birguzy River (Fig. 6). (A) View northeast at the Talas-Ferghana fault where it follows a hillside (with a 20 mm lens). (B) View southwest where southwesterly flowing drainage has been dammed by a shutter ridge. The arrow points toward where we dug a pit for organic material.

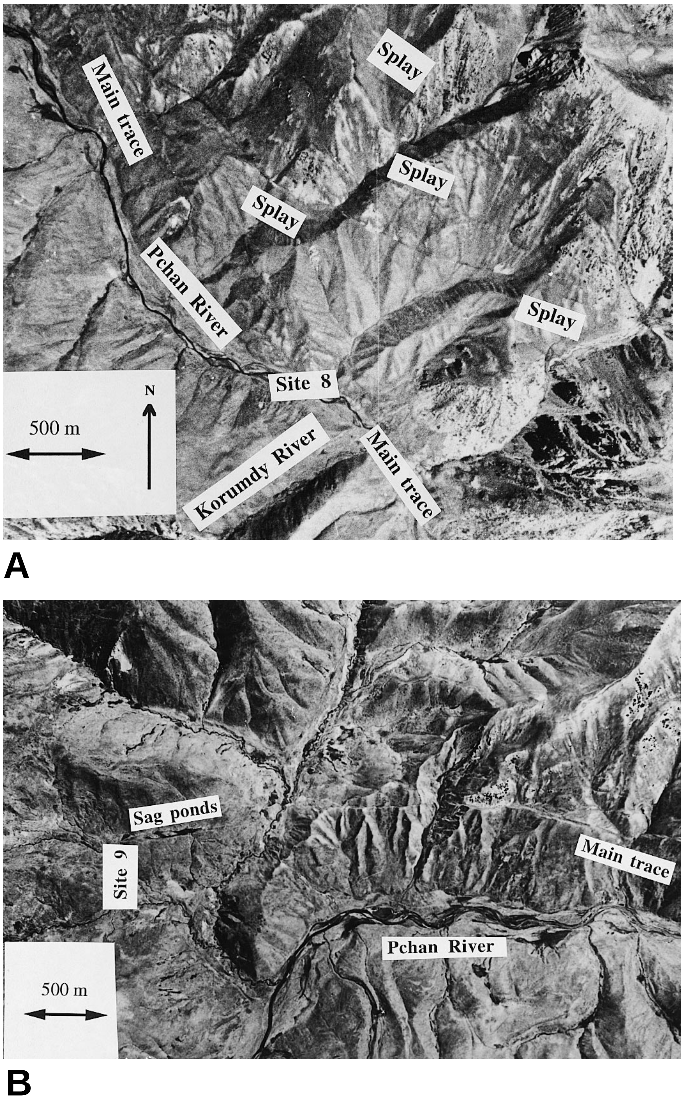


Figure 12. Aerial photographs of the Pchan segment. (A) A part of the Pchan segment that we studied, showing the location of site 8 and the oblique splays that emanate from the main trace farther to the northwest. (B) The area northwest of that in (A). The trace enters the photo on the left as a sharp feature and passes through wide dark sag ponds. Site 9 (Table 1) studied by Trifonov et al. (1990, 1992) is also shown.

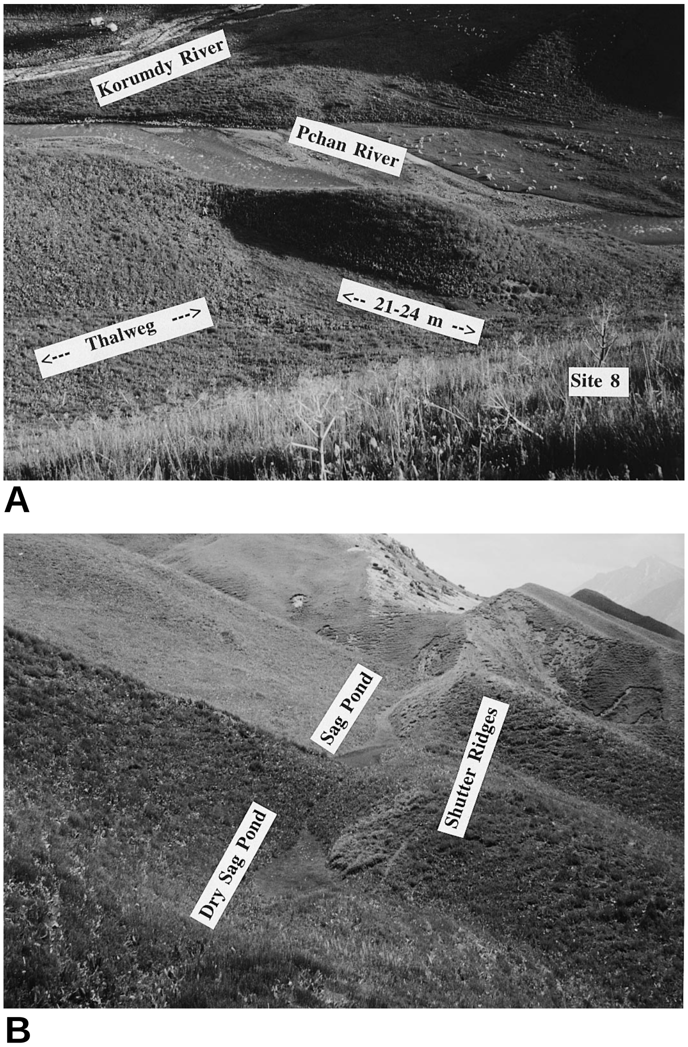


Figure 13. Photographs of the Talas-Ferghana fault in the Pchan segment. (A) View looking south-southwest across the main strand of the Talas-Ferghana fault and the Pchan River near where the Korumdy Stream enters the Pchan (see Fig. 12A). A shutter ridge casts a shadow in the afternoon light. The flat area to its left is an abandoned sag pond, dammed by the shutter ridge. The offset between the upstream reach and downstream is 21–24 m. (B) View looking southeast along the Talas-Ferghana fault in the segment just northeast of the area where the northeast-flowing reach of the Pchan River turns and flows southeast (see Fig. 12B). Notice the clear fault zone with a right-lateral component and a vertical component with the southwest side up. Shutter ridges have dammed sag ponds, one of which is wet.

ever, is too small to have provided the relief from which the material slumped or was carried downslope (by whatever means).

The ratio of 125 ± 25 m to the corrected age implies that the slip rate must be <≈40 mm/yr, an upper bound of little use. If, as suggested here, this age dated only half of the 125 m offset (60 ± 25 m), the estimated bound on the rate would be only 8–21 mm/yr (site 11, Table 1). Clearly, the age and possible offset cannot place a tight constraint on the slip rate. The important facts are that the largest apparent offset we studied is associated with the oldest radiocarbon age, and that, with the various uncertainties, a rate of 10 mm/yr is clearly possible.

Northwest of the Kyldau segment, the Talas-Ferghana fault crosses high terrain. The trace can be seen clearly both on aerial photographs and on the ground. In one locality, a moraine has been offset ≈30 m (Burtman, 1964, p. 16).

Karasu Valley to the Toktogul Reservoir

Farther northwest, the Karasu River has excavated the fault zone (Figs. 5 and 18), but clear offsets of tens of metres can be seen where the trace lies on the southwest or northeast side of the valley (Figs. 19 and 20). Ridges and valleys have been displaced from ≈40 to 225 m (Figs. 19 and 20), and >2 km (Fig. 18). Near the Kokbel Pass, where the main road from the Ferghana Valley in the west crosses into the Ketmen Tube basin, now occupied by the Toktogul Reservoir, the trace steps right ≈300 m. On the

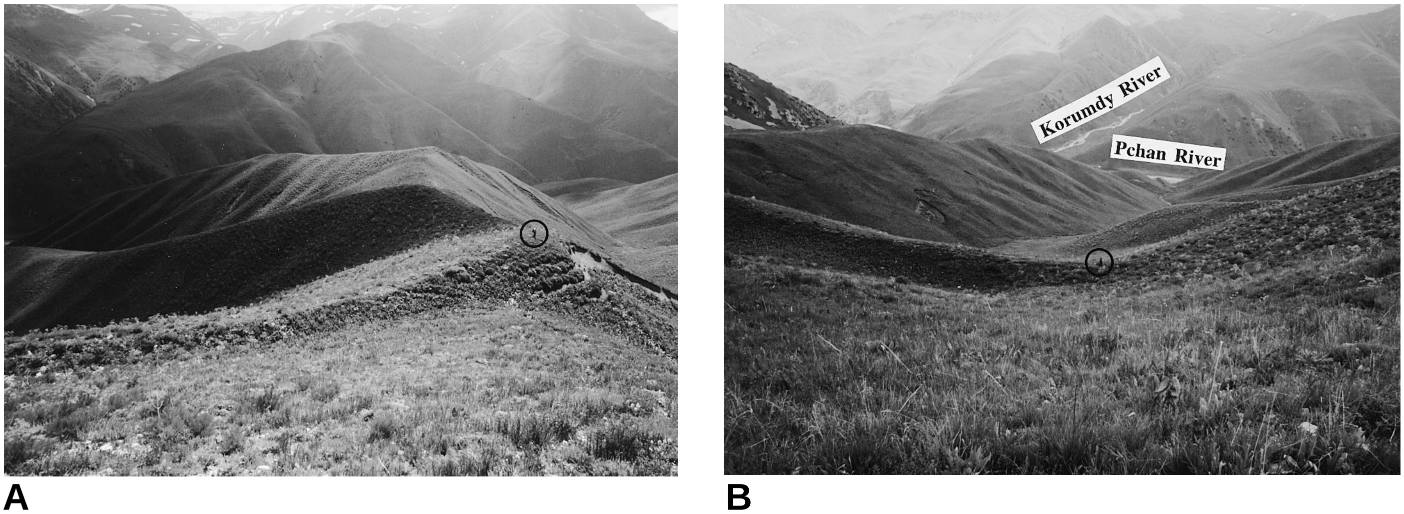


Figure 14. Photographs looking southwest of splays that branches from the Talas-Ferghana fault near the Pchan River (see Fig. 12A). In each, a circle surrounds one of us (Burtman) on the scarp. (A) View west-southwest along a ridge offset by a splay from the main strand. The scarp faces northeast, toward the photographer. (B) View southwest across a scarp on the same splay as in (A), but farther southeast. The shutter ridge at site 8 (Table 1) can be seen in the background near the Pchan and the Korumdy Rivers.

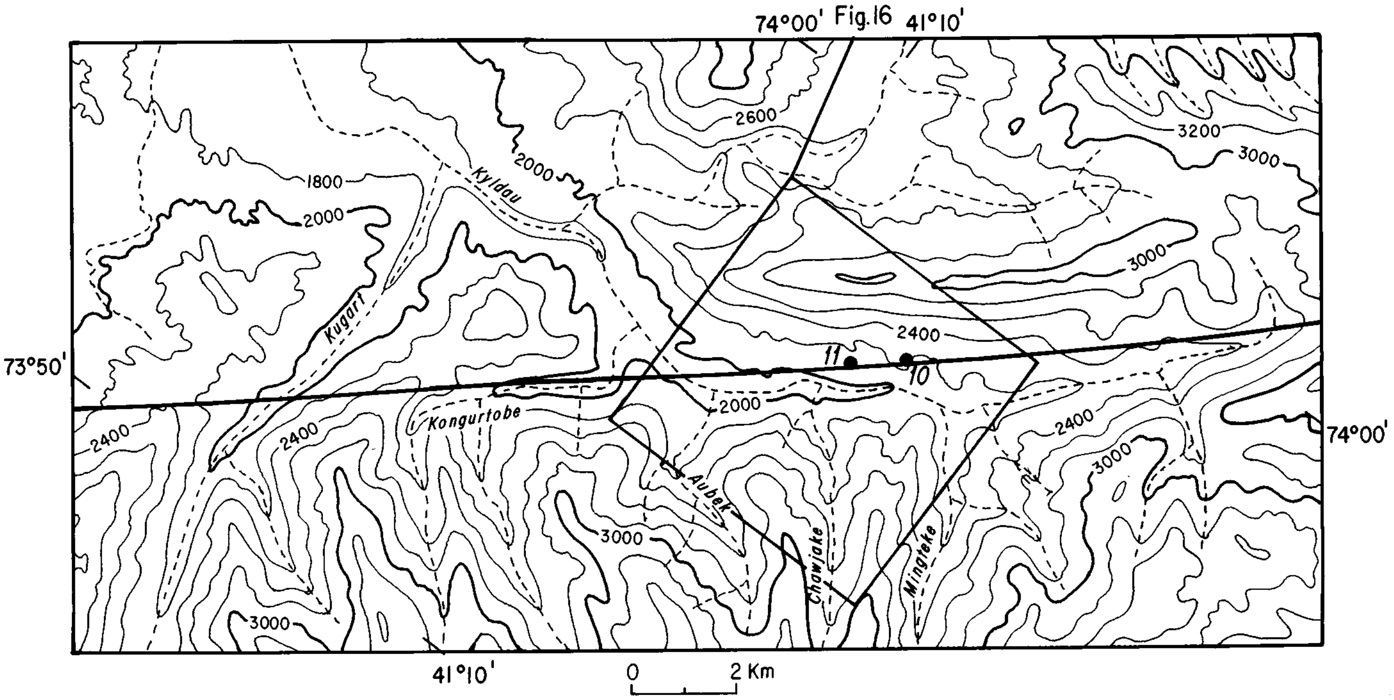


Figure 15. Topographic map of the segment of the Talas-Ferghana fault along the Kyldau River. Dark line shows the trace of the Talas-Ferghana fault. Numbers show the locations of sites 10 and 11, and the square shows the area in Figure 16. Contour interval = 200 m.

southwest side of a dry valley aligned parallel to the fault trace (Fig. 18), the trace is especially clear (Fig. 21). Unfortunately, we did not find areas that seemed worth digging for datable material.

Ustasay-Janaryksay Region

Northwest of the Toktogul Reservoir, the Talas-Ferghana fault follows the northeast slope of gentle topography. The overall strike of the fault measured from the Ustasay-Janaryksay segment across the Toktogul Reservoir to the trace near the Karasu River is 121° ± 2°, somewhat more east-west than that farther southeast.

Although the trace is less clear than to the southeast or farther northwest, and measurable offsets are sparse, evidence of right-lateral slip is clear (Figs. 5, 22, and 23). A ridge and valley pair in the left of the photo in Figure 23, where the orientation of the trace is 120°, is offset 110 ± 10 m.

We measured a displacement of a small gully 14 ± 2 m at locality 14

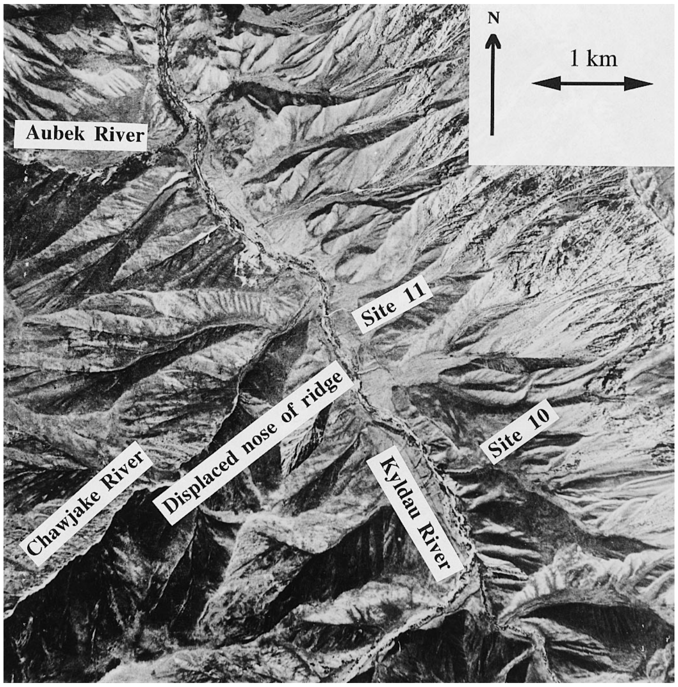


Figure 16. Aerial photograph (T-52 24/VIII 60-5880) of the Kyldau segment, showing localities with measured offsets.

Figure 17. Photograph taken looking west at section where we measured an offset of 125 (±25) m. A minibus provides a scale. Note the low scarp to the right of it. The fault trace passes southeast of the offset nose of the ridge (see Fig. 16) where the road curves left on the left side of the photo.

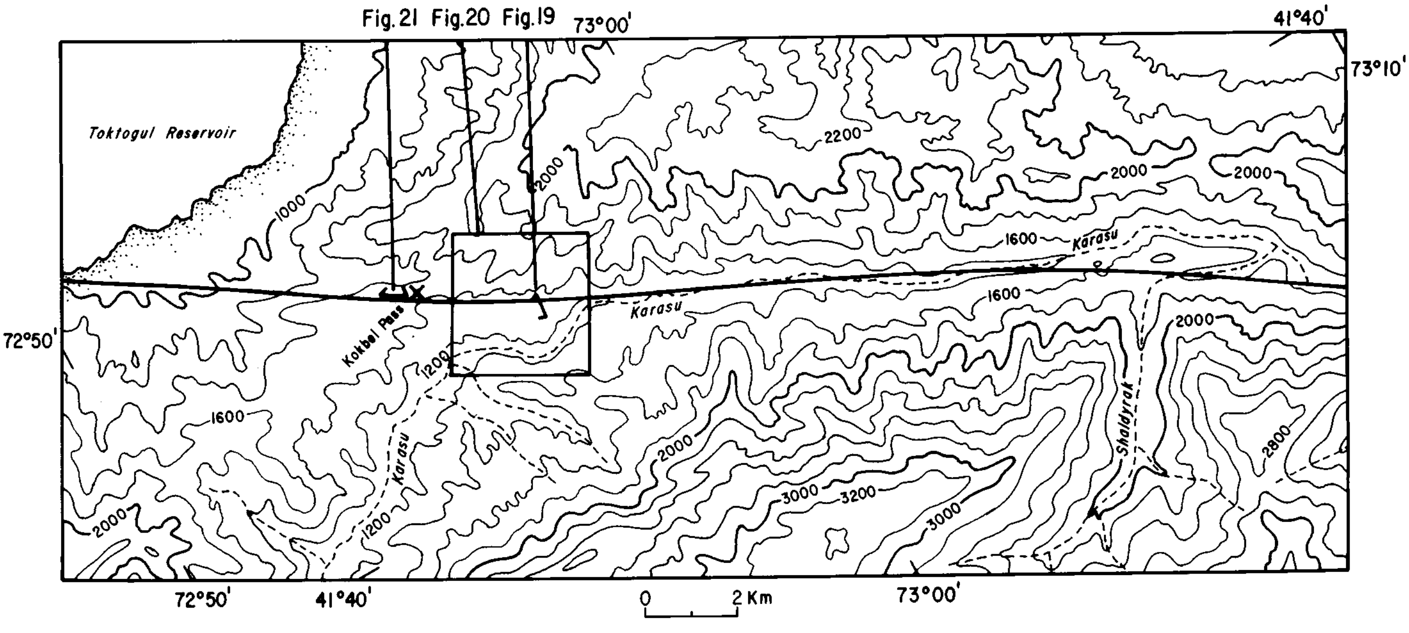


Figure 18. Topographic map of the segment of the Talas-Ferghana fault along the Karasu River. Dark line shows the trace of the fault, and locations of Figures 19–21 are shown. Contour interval = 200 m.

(Figs. 22 and 23). A pit in the upper segment of the gully near the fault trace reached hard rock at a depth of 0.50 m, beneath 0.45 m of soil (Fig. 10). Organic soil from the basal 0.10 m of this layer (depth = 0.35–0.45 m) yields an upper bound for the slip rate of 9–12 mm/yr.

Chatkal Segment

The northwesternmost segment that we consider here lies within the Chatkal Ranges (Figs. 5 and 24). Burtman et al. (1987) measured 26 right-lateral offsets between 17 and 55 m along a segment ≈17 km in length

Figure 19. Photograph looking due east across the Talas-Ferghana fault trace along the Karasu Valley. From the aerial photo in Figure 20, we estimated 225 m of right-lateral offset.

Figure 21. Photograph looking southwest at the Talas-Ferghana fault trace above a dry valley that descends toward the Ketmen Tube basin.

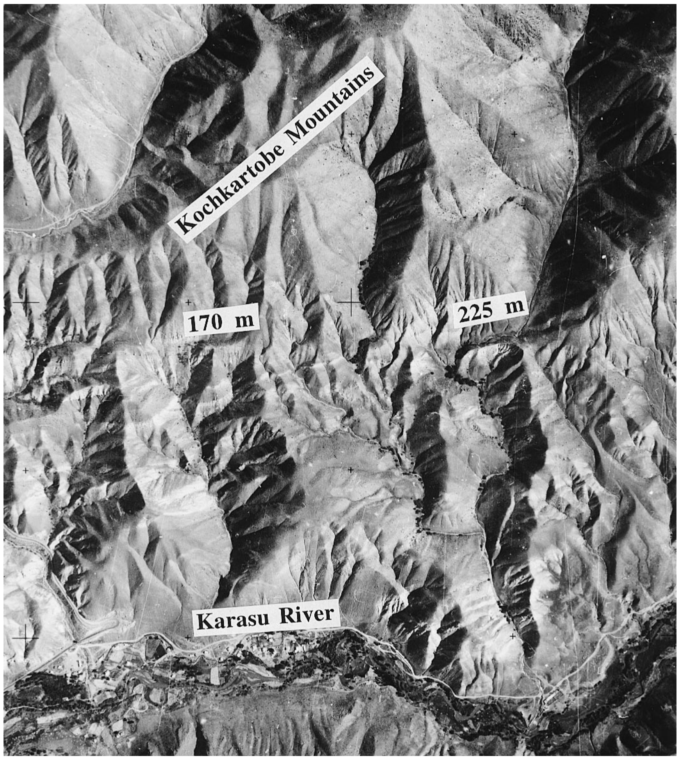


Figure 20. Aerial photograph of the Talas-Ferghana fault near the Karasu River. Two offsets, one of ≈225 m (see Fig. 19) and another of 170 m, are marked.

(Figs. 25 and 26). They obtained organic material from four swampy areas, dammed by the fault scarp. Three of these sites are from localities where an offset could not be measured, and hence the relationships of the dates to the offsets along the fault are less direct than those described herein.

A clear scarp marks the center of this 17-km-long segment, where a shutter ridge up to 4–5 m high has dammed drainage flowing northeast. Swamps along a zone ≈2 km in length are common. A pit to basement at a depth of 1.8 m between two gullies 400 m apart and offset 20 m and 17 m (Figs. 24 and 25) contains 1.3 m of clay with pebbles, overlain by 0.5 m of peat (site 15, Fig. 10). If the sample from the base of the peat dates the 17 m and 20 m offsets, it suggests a rate of 12–15 mm/yr (site 15, Table 1).

Three other pits were dug in swampy areas southwest of the scarp farther northwest. From site 16, ≈1.3 km northwest of site 15 (Figs. 24 and 25), ≈0.5 m of peat overlay clay and pebbles. Approximately 200 m farther northwest (site 17), peat from a depth of 0.2 m and plant remains from 0.5 m yielded dates (Table 1). Another 300 m farther northwest (site 18), peat at 0.3 m overlay basement at a depth of 0.6 m (Table 1). If the age ranges date offsets of 20 m, which characterize the scarp that dams the swamps, then they suggest upper bounds on slip rates of 15–16 mm/yr (site 16), 10 mm/yr (site 17), and 16–19 mm/yr (site 18, Table 1). Because of the proximity of organic material to bedrock at the bottom of the pit at site 17, it seems to give the most reliable bound on the rate.

Burtman et al. (1987) found two offsets of 40 m ≈4 km west of the swamps and a third of 55 m another 2.5 km farther northwest. Given the many offsets of 40 m throughout the Chatkal segment, the dates might apply to such offsets, permitting rates twice as high as those suggested above (Table 1).

The evidence from the Chatkal region shows that the Talas-Ferghana fault is active. The range of possible slip rates overlaps with ranges from the areas farther southeast, but the uncertainties are too large to demonstrate a higher rate in the Chatkal region than farther southeast.

Offsets and Dates of Trifonov et al.

Trifonov et al. (1990, 1992) carried out a study of the Talas-Ferghana fault similar to ours. They reported ^{14}C dates of organic material and offsets of features presumed to be of the same age (Table 1). Here we comment briefly on what they reported.

Trifonov et al. (1990, 1992) noted a relatively small offset of 19 m for the area southeast of both Jilangach Pass and where we visited in 1991 (Fig. 6) and obtained a ^{14}C date for material near the base of ≈0.55 m of organic soil and just above gravel (site 1, Table 1). If the 19 m offset occurred after the gravel was deposited, the upper bound on the slip rate would be 4 mm/yr.

Trifonov et al. (1990, 1992) measured an offset of 40 m along a satellite trace of the fault ≈100 m from it and northwest of the Jilangach Pass

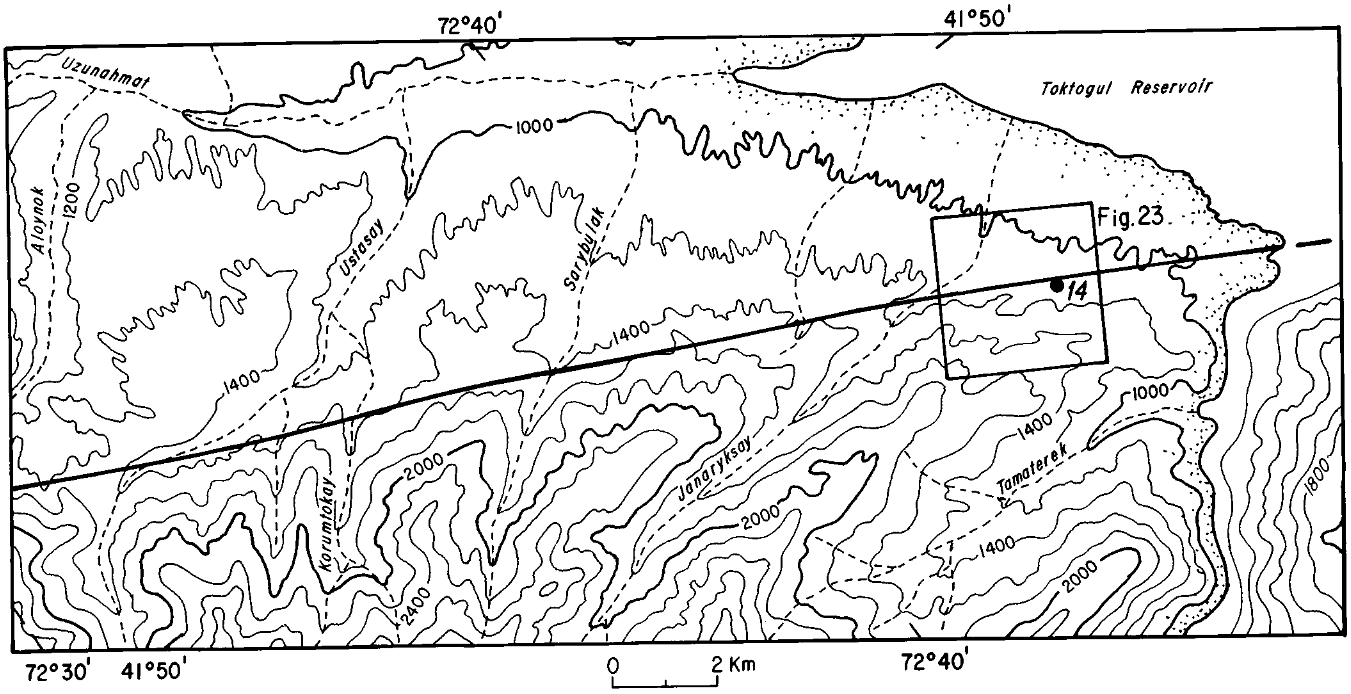


Figure 22. Topographic map of the segment of the Talas-Ferghana fault in the region of the Ustasay and Janaryksay Rivers. Dark line shows the trace of the Talas-Ferghana fault. The locations of site 14 and Figure 23 are shown. Contour interval = 200 m.

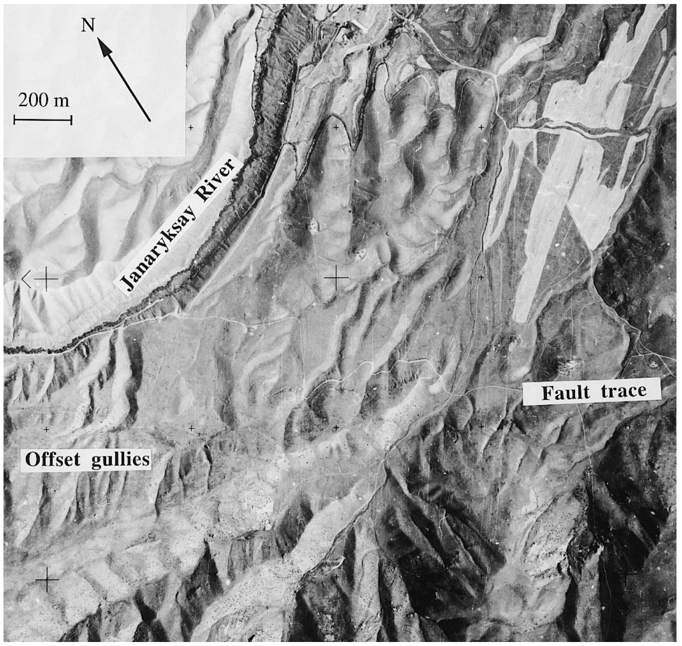


Figure 23. Aerial photograph showing a portion of the Talas-Ferghana fault in the Ustasay-Janaryksay segment. Valleys offset right-laterally 110 ± 10 m are shown on the left side of the photo, and site 14 on the right.

(site 4, Fig. 6). They reported ^{14}C dates of 4590 and 15 800 radiocarbon years from organic material within pods of “clay and loamy soil” that both underlie and overlie layers of gravel. Because of the relationship of this offset to the main trace, its possible slip rates (Table 1) cannot be interpreted unambiguously.

Trifonov et al. (1990, 1992) reported an offset of 27 m along the Birguzy River, northwest of the segment where we worked (Figs. 6 and 11). Their ^{14}C date from organic soil beneath ≈0.35 m of “clay and loamy soil” and directly above gravel yields a range of maximum slip rates of 6–8 mm/yr (site 6, Table 1).

Near the Birguzy River, 1 km northwest of this locality, Trifonov et al. measured an offset of 90 ± 3 m, and northwest of where we worked along the Pchan Valley, they measured an offset of 25 ± 1 m (Fig. 6). For each, they dated organic material in soil ≈0.3 m thick, but their pits apparently did not penetrate below the base of the soil. Thus, the dates are clear minima for deposition in the ponded depressions. The corresponding upper bounds on rates of 25–28 mm/yr and 7–13 mm/yr (sites 7 and 9, Table 1) could be gross overestimates, if significantly older soil lies below the bottoms of their pits.

From the upper reaches of the Kyldau River, Trifonov et al. (1990, 1992) reported an offset of 23–24 m (Fig. 15). A sample of organic material at the base of “clay and loamy soil,” ≈0.45 m below the Earth’s surface, and above 0.4 m of sand overlying basement (site 10, Table 1) yields an upper bound on the slip rate of 10 mm/yr. A few kilometres northwest of where the Kyldau River turns northeast from the Talas-Ferghana fault zone, they found a terrace adjacent to a ravine offset 17–20 m (site 12, Fig. 5, Table 1). Organic material at the base of 0.7 m of silt and overlying gravel yields an upper bound on the slip rate of 11–15 mm/yr.

Along the Kekhlikbel River, between the Kyldau and Karasu Rivers (site 13, Fig. 5), Trifonov et al. (1990, 1992) found peat deposited in ponds adjacent to the fault where it crosses a late Quaternary moraine. Trifonov et al. (1990, 1992) did not report a clear offset of the moraine, but northwest of it they observed several offsets with a “predominant magnitude” of 10–12 m. Assuming that the peat was deposited since the formation of these offsets, the upper bound on the slip rate is 8–11 mm/yr (site 13, Table 1).

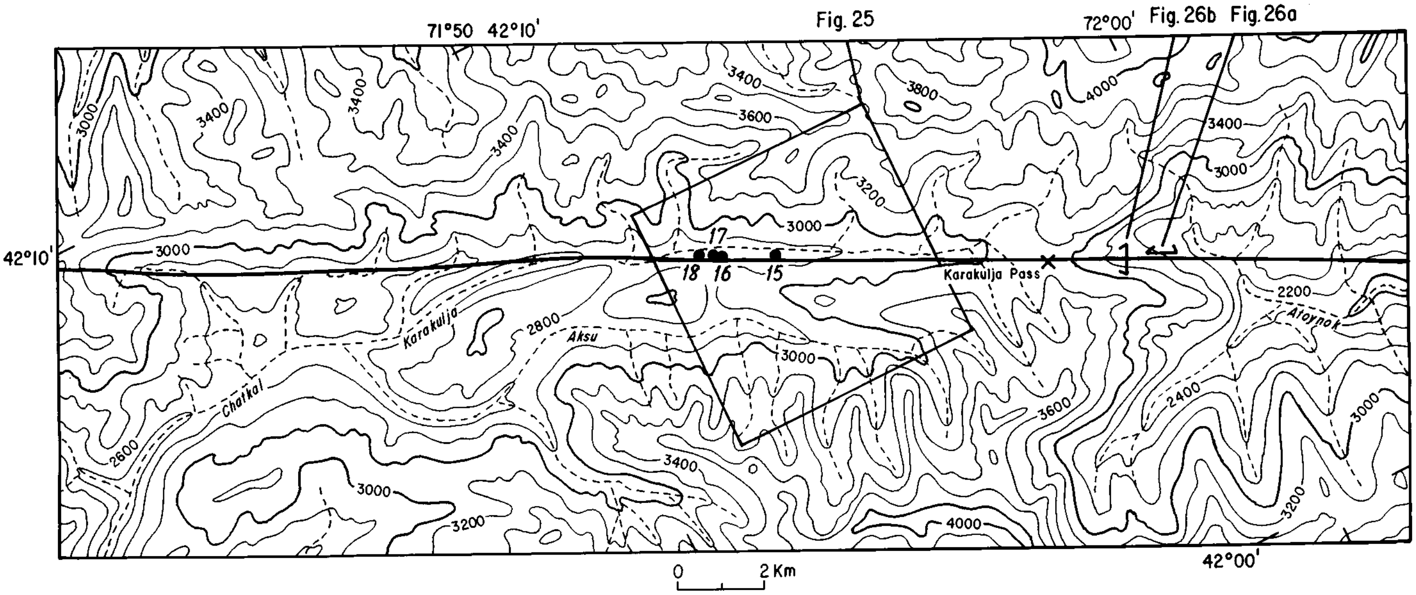


Figure 24. Topographic map of the segment of the Talas-Ferghana fault in the Chatkal Ranges. Dark line shows the trace of the Talas-Ferghana fault. The locations of sites 15–18 and of Figures 25 and 26 are also shown. Contour interval = 200 m.

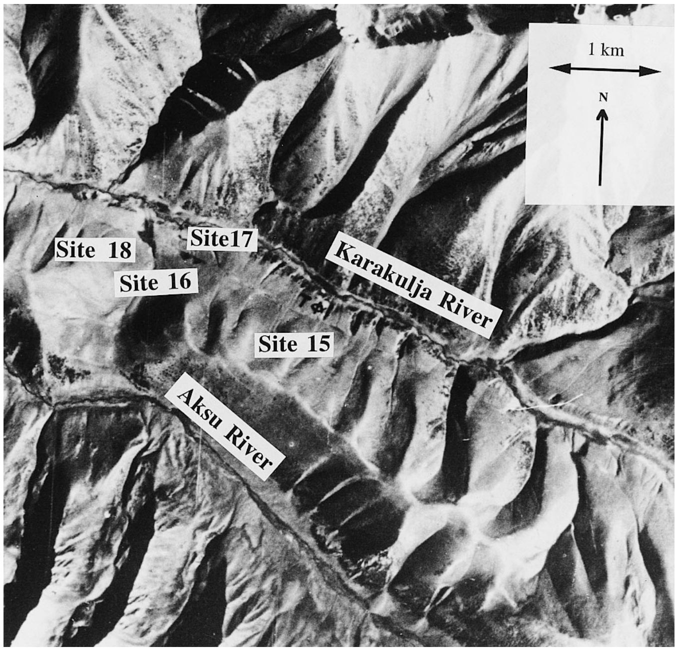


Figure 25. Aerial photograph of the Talas-Ferghana fault in the Chatkal Ranges (see Fig. 24). The trace is clear along the southwest side of the Karakulja River valley. Gullies are consistently offset 20–40 m. Numbered sites (Table 1) show swampy areas filling sag ponds where organic material was found.

Summary of Bounds on Slip Rates

Organic material has been sampled in 18 localities where the fault scarp of the Talas-Ferghana fault has blocked drainage. We obtained organic material from six localities where we could measure offset gullies and ridges that predate the organic material by an unknown, but presumably short, period of time. Four ratios of offset to apparent age yield rates that lie within the range of 8–16 mm/yr. One sample (site 3, Table 1) does not appear to be from a sufficiently deep horizon to be helpful. Another, from the Kyldau segment (site 11, Table 1), requires special consideration of the offset, but with such consideration, it too is consistent with an apparent slip rate in the same range. Similarly, six of eight such ratios presented by Trifonov et al. (1990, 1992) overlap the range of 8–16 mm/yr, though one of these six applies to a satellite trace and may not place a reliable bound on the slip rate. Radiocarbon dates from four localities in the Chatkal Ranges are similar to those elsewhere along the Talas-Ferghana fault, between 1000 and 4000 yr B.P, and most are between 1000 and 2000 yr B.P. If they date nearby features offset ≈20 m, collectively they suggest similar apparent rates, of 10–16 mm/yr.

These apparent slip rates are strictly upper bounds to the late Holocene slip rate. The organic material was deposited after the offset streams had incised the landscape and adjacent ridges had moved to block the drainage. Thus, we can be confident that the slip rate on the fault is no more than ≈15 mm/yr, and apparently no more than 10 mm/yr, except perhaps in the northwesternmost part of the region, adjacent to the Chatkal Ranges. The preponderance (14 of 18) of apparent rates overlapping 8–16 mm/yr, however, suggests that the average slip rate is close to this upper bound, and therefore ≈10 mm/yr.

CONSTRAINTS ON THE CENOZOIC OFFSET

We exploit three constraints on the Cenozoic offset: (1) the tentative correlation of Early Cretaceous sedimentary rock exposed on both sides of the Talas-Ferghana fault and apparently offset along it, discussed herein (Fig. 4), (2) paleomagnetic evidence for the amount of rotation of the Ferghana Valley with respect both to the stable parts of Eurasia farther north and to the central Tien Shan, and (3) bounds on the amount of crust stored in the root of the Chatkal Ranges, which developed by crustal thickening due to slip on thrust faults that abruptly terminate at the Talas-

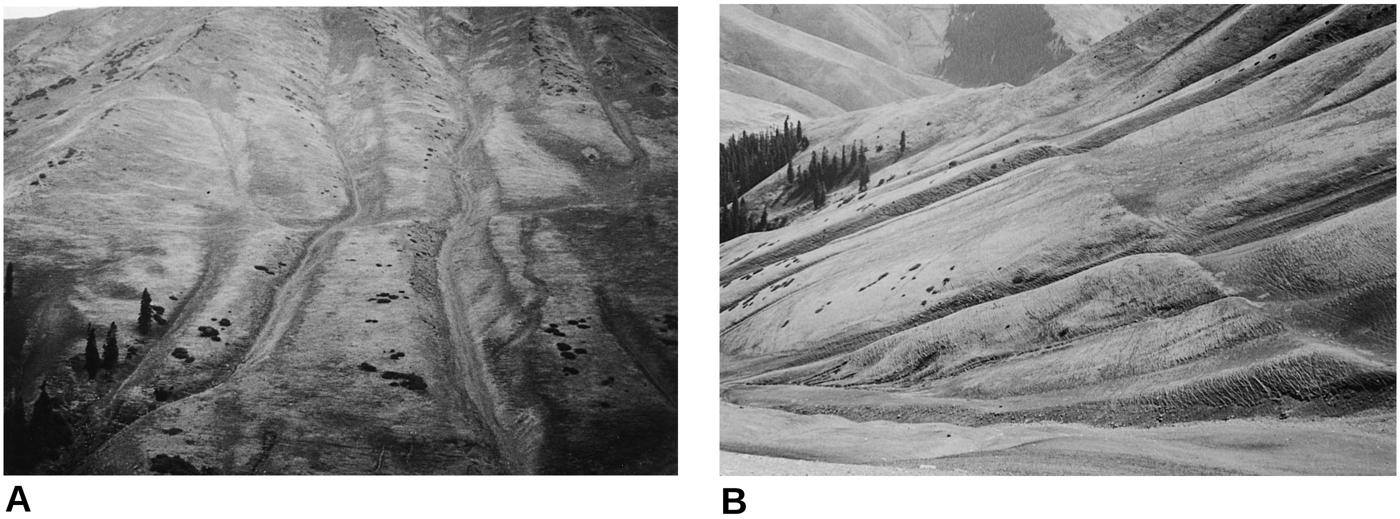


Figure 26. Photographs of offsets along the Talas-Ferghana fault in the Chatkal Ranges segment. (A) Photograph looking southwest across the Atoinok River 2.5 km southeast from the Karakulja Pass (see Fig. 24). Offsets were measured to be from 25 to 30 m. (B) Photograph of the same area, but looking southeast along the trace of the Talas-Ferghana fault.

Ferghana fault (Fig. 1). When convincing, geologically mapped features correlated on both sides of a fault provide the most definitive measures of offset. In our case, however, paleomagnetic data and dimensions of the crust beneath the Chatkal Ranges seem to provide more convincing bounds on horizontal displacement.

To appreciate the significance of the various data that we use and their relationships to slip on the Talas-Ferghana fault requires an appreciation for the role played by the Talas-Ferghana fault in the kinematics of the Tien Shan. This fault, like virtually all intracontinental strike-slip faults (e.g., Davis and Burchfiel, 1973), does not separate two rigid blocks, but rather two areas each of which is undergoing deformation. Thus, both the slip rate and the amount of strike-slip displacement must vary along the fault. Trifonov et al. (1990, 1992) inferred variations in slip rate along the Talas-Ferghana fault, but we found no evidence demonstrating such variations. The currently active Talas-Ferghana fault terminates in the northwest, where slip is transformed into crustal shortening in the Chatkal Ranges. The amount of such shortening places a bound on the amount of strike slip, but the amounts of each need not be equal.

Paleomagnetic Declinations

Paleomagnetic measurements have been made on Cretaceous rock of the Tien Shan west of the Talas-Ferghana fault and on Cenozoic rocks on both sides of the fault (Fig. 27, Table 2). As Bazhenov and Burtman (1990) noted for Cretaceous and early Tertiary rock in the Pamir and Tadjik depression, inclinations of magnetization commonly are gentler than those expected for the pole positions of Eurasia at these times. In some cases, they call for latitudinal movements >1500–2000 km. Because such displacements seem unreasonably large, these inclinations imply that some nontectonic process has contaminated the orientations of the magnetization (e.g., Bazhenov and Burtman, 1990; Thomas et al., 1993). Accordingly, these unexplained gentle inclinations add uncertainty to the interpretations of the measured declinations. We proceed by ignoring this additional uncertainty.

Cretaceous. Bazhenov (1993) investigated Early Cretaceous continental sedimentary rock with Early Cretaceous freshwater mollusks from the foothills of the Ferghana and Alay Ranges, west of the Talas-Ferghana fault, and from the Alay Range. For seven localities from the foothills of adjacent ranges, Bazhenov isolated a component of magnetization that formed before the rock was folded, to which he assigned an Early Cretaceous age (Table 2, Fig. 27). Bazhenov's (1993) mean declination of 353° ± 8° differs from that of 14° ± 8° determined for this part of Eurasia from Besse and Courtillot's (1991) Early Cretaceous pole for Eurasia. Because the paleomagnetic data used to define nearly all poles for Eurasia were obtained from samples in Europe, it is possible that differences between declinations from samples in the Tien Shan from those for Eurasia reflect deformation far from the Tien Shan. We ignore that possibility here, because we cannot quantify it easily. Thus, the difference in declination suggests that rocks from the southeast side of the Ferghana basin, west of the Talas-Ferghana fault, have rotated counterclockwise 21° ± 11° with respect to Eurasia.

Bazhenov (1993) also isolated a secondary component of magnetization from the same samples, which also appears to have formed before the rock was folded (Table 2). He considered the most probable age for this component to be Late Cretaceous, but a younger age cannot be eliminated. A Late Cretaceous age for this magnetization and the average declination of 351° ± 4° for Bazhenov's sites from the Ferghana Valley would imply a counterclockwise rotation of 23° ± 7° of the rock west of the Talas-Ferghana fault with respect to Eurasia, using Besse and Courtillot's (1981) Late Cretaceous reference pole for Eurasia. If the magnetization is younger, the inferred amount of rotation should be smaller, because younger poles for Eurasia lie closer to the present pole.

Paleogene–Miocene. Bazhenov et al. (1993) and Thomas et al. (1993) studied the magnetization in formations ranging in age from Eocene to early Miocene from localities both east and west of the Talas-Ferghana fault (Table 2). Although these formations span a long interval of time, they found no systematic variation with age. Moreover, because the pole for Eurasia moved only a few degrees in this interval, combining the re-

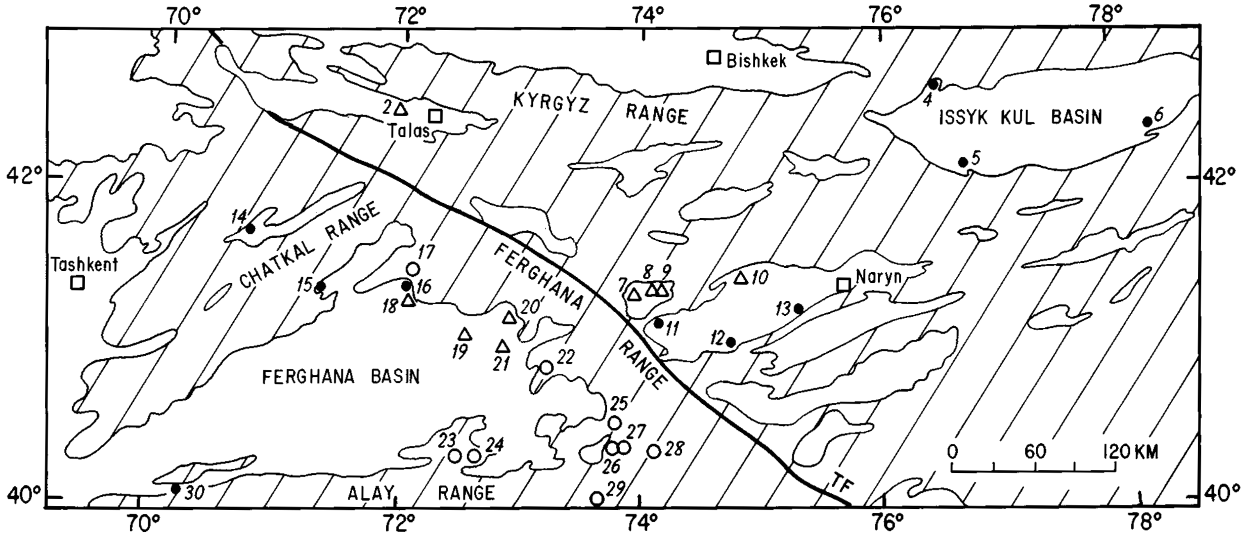


Figure 27. Map of the region surrounding the Talas-Ferghana fault where samples for paleomagnetic measurements were taken. Diagonal ruled areas show outcrops of pre-Cretaceous rock. Triangles, black dots, and open circles show localities or where Lower Cretaceous, Eocene–early Miocene, and Pliocene samples were taken.

sults for different ages introduces a negligible error in declination anomalies. The mean declination from Eocene to early Miocene rock at 14 sites in three localities near Issyk-Kul is 2° ± 9°. That from Eocene rock at 16 sites from 3 localities in the Naryn basin is 5° ± 14°. Compared with an expected declination of 11° ± 6° for a position near 42°N, 75°E and for Besse and Courtillot's (1991) Eurasian poles for 27.9 Ma, these data suggest an insignificant counterclockwise rotation of the area east of the Talas-Ferghana fault.

The data from the west side of the Talas-Ferghana fault indicate a mean declination significantly different from those from the east side (Table 2). Samples from the northern and southern edges of the Ferghana basin, taken from Eocene marl and red sandstone and from siltstone with Oligocene–early Miocene freshwater mollusks, indicate a mean declination of 342° ± 11°. This declination suggests that the Ferghana basin rotated counterclockwise 20° ± 16° with respect to the area near Issyk-Kul and 23° ± 18° with respect to the Naryn basin. Compared with an expected declination of 11° ± 6° for a part of Eurasia in this area, the data from west of the Talas-Ferghana fault suggest a counterclockwise rotation of 29° ± 13°. All comparisons suggest an amount of clockwise rotation indistinguishable from that for Cretaceous samples.

Bazhenov et al. (1993) and Thomas et al. (1993) also analyzed samples of Paleogene marl and sandstone from within the Chatkal system of ranges (locality 14 in Fig. 27), which is separated from the Ferghana basin by thrust faults. Thus, relative movement between the basin within the Chatkal Ranges and the Ferghana basin is expected. Their measured declination of 352° ± 12° differs from that of samples from the Ferghana basin by 10° ± 16°. Hence, it is consistent with distributed deformation across the ranges, insofar as convergence is a manifestation of rotation of the Ferghana basin about an axis southwest of the Chatkal Ranges.

Pliocene. Paleomagnetic measurements of Pliocene siltstone and clay were determined from four sites east of the Talas-Ferghana fault and from five sites in the Ferghana basin west of the fault (Table 2) (Khaidarov, 1984; Khramov, 1986). The mean declination from sites east of the fault, 14° ± 12°, differs from that for the sites to the west, 351° ± 13°, suggesting 23° ± 18° of relative rotation. Because the Pliocene magnetic pole is close to the present pole (Table 2), these data suggest rotations of opposite sense on opposite sides of the fault. To estimate an expected Pliocene declination, we used a Eurasian pole of 87.0°N, 149.1°E, half way between that given by Besse and Courtillot (1991) for 7.9 Ma and the present North Pole (Table 3). The differences between measured and expected declinations suggest counterclockwise rotations of 13° ± 13° for the area to the west and 10° ± 14° clockwise rotation of the area to the east, relative to Eurasia.

Summary of Paleomagnetic Results. Paleomagnetic declinations from Early Cretaceous to Miocene rocks suggest that the rock surrounding and including the Ferghana basin has undergone a counterclockwise rotation of 20° ± 11° with respect to the area east of the Talas-Ferghana fault and 20°–30° with respect to the Eurasian plate. Thus, these data suggest that rotation began some time after the Eocene–Miocene sedimentary rock was magnetized, and therefore during or since the Miocene Epoch. The Pliocene magnetization can be taken to suggest less rotation with respect to Eurasia or a comparable amount with respect to the area east of the Talas-Ferghana fault. The data from west of the Talas-Ferghana fault permit an initiation of rotation before the Pliocene Epoch began. With the large uncertainties, however, they also permit either a completion of that rotation before the Pliocene Epoch began or an initiation since it ended.

A counterclockwise rotation of the Ferghana basin and its surroundings relative to Eurasia about an axis near the southwest end of the Chatkal Ranges is consistent with late Cenozoic crustal shortening there (Bazhenov, 1993; Bazhenov et al., 1993; Thomas et al., 1993). Such an axis lies ≈300 (±100) km southwest of the northeast end of the Chatkal Ranges, where they abut the Talas-Ferghana fault trace (Fig. 1). Rotations of 20° or 30° about axes 200–400 km from the Talas-Ferghana fault correspond to maximum amounts of convergence between the eastern part of the Ferghana basin and stable Eurasia that range from as little 70 km to as much as 210 km. For an intermediate rotation of 25° about an axis 300 km from the Talas-Ferghana fault, the maximum convergence is 130 km. The smaller, yet unresolvably, different amount of such rotation of the area within Chatkal Ranges than of areas farther south is consistent with crustal shortening distributed across the Chatkal Ranges and with a diminishing amount of displacement along the Talas-Ferghana fault in this area (Thomas et al., 1993).

TABLE 2. RESULTS OF PALEOMAGNETIC INVESTIGATIONS OF CRETACEOUS AND CENOZOIC ROCKS FROM THE WESTERN AND CENTRAL TIEN SHAN

Region	Location (Fig. 27)	Number of localities	Inclination (°)	Declination (°)	K	α_{95} (°)	Expected declination* (°)
Early Cretaceous, component B (Bazhenov, 1993)							
Ferghana	22–28	7	44	353	77	6	14 ± 8
Early Cretaceous, component A (Bazhenov, 1993)							
Ferghana	17, 22–29	9	56	351	148	4	14 ± 6
Eocene–early Miocene (Bazhenov et al., 1993; Thomas et al., 1993)							
Issyk-Kul	4–6	3	49	2	42	6	11 ± 6
Naryn	11–13	3	37	5	13	11	11 ± 6
Ferghana	15, 16, 30	3	34	342	33	9	11 ± 6
Chatkal	14	(10)	42	352	25	9	11 ± 6
Pliocene (Khaidarov, 1984; Khramov, 1986)							
Talas and Naryn	2, 7–10	5	52	14	77	7	5 ± 5
Ferghana	18–21	4	45	351	57	9	5 ± 5

Note: All measurements have been corrected for tilting and folding of the beds.
*The expected declination is calculated for as site at lat 42°N, long 75°E, from poles given by Besse and Courtillot (1991) for 112.4, 80.7, 27.9, 18.8, 7.9, and 3.9 Ma.

Mass Balance of Crust in the Chatkal Ranges

Assuming that crust is conserved, the amount of crust stored in the root of the Chatkal Ranges provides an independent bound on the amount of convergence across the ranges. Like Ulomov (1974), Chernovskii (1991) reported maximum crustal thicknesses >60 km, but over a larger area than Ulomov showed. Vol'vovskii and Vol'vovskii (1975) reported crustal thicknesses of ≈40 km throughout most of this region except beneath the high ranges, and Ulomov (1974) did not show regions in Central Asia with crust thinner than this value. Assuming that the large crustal thickness beneath the Chatkal Ranges results from thickening of crust initially 40 km thick and approximately in a state of Airy isostatic equilibrium, Ulomov (1974, p. 96–98) estimated crustal shortening across the Chatkal Ranges of ≈50 km. If the initial thickness were 35 km, the estimated shortening would be ≈75 km. Widespread Cenozoic rock within the Chatkal Ranges implies that erosion has not been deep. Thus, its correction to the estimated shortening should be small, no more than a few kilometres. Assuming that shortening results from rotation of the Ferghana Valley about an axis at the southwest end of the Chatkal Ranges, the maximum convergence should be at the Talas-Ferghana fault and consequently 12%–20% larger than the 50–75 km estimate based on Ulomov's (1974) calculation for a cross section west of the fault.

Comparison of Cenozoic Slip on the Talas-Ferghana Fault with the Total Displacement. The problem of accounting for 180 km of total slip on the Talas-Ferghana fault and the corresponding tectonic rotation of the Ferghana Valley cannot be solved by postulating such an amount of Cenozoic shortening in the Chatkal Ranges, at least according to our current knowledge. The eastern boundary of the Ferghana basin and the Chatkal Ranges is the Talas-Ferghana fault. Right-lateral slip on this fault is absorbed, at least in part, by folding and thrust faulting in the Chatkal Ranges (Bakirov, 1969; Chediya, 1986; Cobbold and Davy, 1988; Makarov, 1977, p. 154; Suvorov, 1968, p. 128; Ulomov, 1974, p. 96–101). The maximum displacement along the Talas-Ferghana fault, 180 km, has been determined using Paleozoic rock that crops out on the east side of the fault and in the northern part of the Chatkal Ranges and northwest of them, where Cenozoic deformation is observed to be very weak (Fig. 3) (Burtman, 1964, 1980). Given the low seismicity, low relief, and absence of evidence for Cenozoic deformation northwest of the Chatkal Ranges, Cenozoic accommodation of right-lateral slip does not appear to be hidden there. Consequently, insofar as the upper bound of 60–100 km is correct, Cenozoic shortening within the Chatkal Ranges cannot absorb all of the 180–250 km of right-lateral shear along the Talas-Ferghana fault since Paleozoic time.

The amount of movement of the Ferghana basin with respect to Eurasia and manifested as crustal shortening in the Chatkal Ranges, should, in fact, exceed the amount of Cenozoic right-lateral slip along most of the Talas-Ferghana fault. If the Ferghana basin rotates relative to Eurasia about an axis at the southwest end of the Chatkal Ranges, the direction of movement of the east end of the basin is ≈340°, and *not* parallel to 300°, the strike of the Talas-Ferghana fault. Because the area east of the fault deforms and moves with respect to Eurasia, this fault is not a boundary between the Ferghana basin and Eurasia, and the strike of the fault should not be parallel to the vector displacement of the Ferghana basin with respect to Eurasia. Correspondingly, if all of 180 km, to perhaps 250 km, of slip on the Talas-Ferghana fault had occurred in Cenozoic time, the amount of shortening across the Chatkal Ranges should be yet greater than 180–250 km by an amount approximately equal to the amount of Cenozoic shortening across the Tien Shan northeast of the Talas-Ferghana fault.

Only a combination of errors in measurements and in assumptions allows all of the 180–250 km of right-lateral shear to have occurred in Cenozoic Era following the collision of India with Eurasia. There seems no escaping substantial strike-slip displacement on the Talas-Ferghana fault at the end of the Paleozoic Era and/or in Jurassic time. We find no difficulty accepting the 60 km offset of Cretaceous rock as defining the Cenozoic offset in the central segment of the fault (Fig. 4). If 60 (±10) km of right-lateral slip on the Talas-Ferghana fault reflects movement of the Ferghana basin with respect to the central Tien Shan, it corresponds to counterclockwise rotation of ≈10° of the Ferghana basin with respect to the area east of the fault, about an axis near the southwest end of the Chatkal Ranges. Because the area east of the fault also has moved northward relative to Eurasia, however, 10° must be an underestimate of the rotation. If, for example, the material east of the Talas-Ferghana fault moved north 70 km with respect to Eurasia in Cenozoic time, the corresponding estimated counterclockwise rotation of the Ferghana Valley relative to Eurasia is 25°. Paleomagnetic data for Cretaceous–Miocene rock are consistent with such an amount of rotation.

The late Miocene onsets of east-west extension by normal faulting within Tibet, folding of the Indian plate, and basaltic volcanism within the Tibetan Plateau and the concurrent apparent strengthening of the Indian monsoon have been used to infer a rapid 1–2.5 km increase in the mean height of the Tibetan Plateau ca. 8 Ma (Harrison et al., 1992; Molnar et al., 1993). Such a rise should have substantially increased in the force per unit length that the plateau and the surrounding lower areas must apply to one another. Thus, late Miocene initiation of crustal shortening within the Tien Shan may be a manifestation of this increase in the height of the Tibetan Plateau.

SUMMARY

Among 18 estimated upper bounds on the late Holocene slip rate along the Talas-Ferghana fault, 14 overlap the range of 8–16 mm/yr. Moreover, more than half of these, including the most convincing estimates, are entirely within the range of 8–16 mm/yr. Thus, it appears that this range of upper bounds differs little from the average slip rate, which therefore is ≈10 mm/yr (±2 mm/yr). The uncertainties in estimated rates are too large to demonstrate a variation in slip rate along the fault, which must exist, but a higher rate in the northwestern segments, where the Chatkal Ranges abut against the fault, than in the southeastern segments is permitted.

The combination of (1) published paleomagnetic constraints on amounts of rotation of the Ferghana Valley with respect to Eurasia, (2) estimates of the crustal thickness beneath the Chatkal Ranges, and (3) a tentative correlation of Early Cretaceous rocks across the Talas-Ferghana fault suggest that the amount of Cenozoic right-lateral slip is at least 50 km, but <100 km. If slip has occurred at an average rate of ≈10 (±2) mm/yr, then slip has occurred for only ≈4–12.5 m.y., a small fraction of time since India collided with the rest of Eurasia. Thus, during most of India's penetration into the rest of Eurasia, deformation seems to have been concentrated near India, reaching the Tien Shan much more recently than the collision between India and Eurasia.

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