Rate of left-lateral movement along the easternmost segment of the Altyn Tagh fault, east of 96°E (China)

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SUMMARY

Field work carried out in Gansu province and complemented with analysis of SPOT panchromatic scenes allows us to characterize the deformations along the eastern segment of the Altyn Tagh fault and to place bounds on its Holocene left slip rate. East of 96°E, the long-term, left-lateral offset of stream channels, alluvial fans, and terrace edges is about 50 m. These offsets are most probably of Holocene age (12 ± 2 ka) and imply that the corresponding derived slip rate is 4 ± 2 mm yr⁻¹. This observation is consistent with a north-eastward along-strike decreasing slip rate on the Altyn fault due to partitioning of slip on multiple, more easterly trending splays.

Key words: Altyn Tagh fault, fault slip, Tibet.

INTRODUCTION

The Altyn Tagh fault follows the north-western edge of Tibet and has long been recognized as the most outstanding active strike-slip fault system within Eurasia (Molnar & Tapponnier 1975). Approximately 2000 km long, this fault zone has been interpreted as a major left-lateral strike-slip fault permitting the eastward movement of the Tibet Plateau relative to the Tarim basin (e.g. Molnar & Tapponnier 1975; Tapponnier & Molnar 1977; Armijo, Tapponnier & Tonglin 1989).

Recent work, based on measurements of long-term offsets on SPOT satellite images, distinguished several segments with different slip rates (Peltzer et al. 1989; Fig. 1). The western segment, the Karakax fault, trends N100°E and forms the south-western edge of the Tarim basin. Eastwards from 82°E, the junction between the western segment and the southern Ghoza fault marks the beginning of the central segment of the Altyn Tagh fault. The central segment extends linearly as far as 92°E. The geometry of the eastern segment is more complicated; the fault zone is made of two main strands remaining parallel up to 94°E. East of 94°E, several more easterly trending faults splay from the two main parallel faults (Fig. 1). The southern strand splays into two segments, each one running approximately NW–SE, at the base of 5500–6000 m high relief: the Tang He Nan Shan (94°30'E, 39°20'N) and the Ta Xueh Shan (95°E, 39°30'N). Two segments splay from the northern strand that remains linear (Fig. 1). The first splay corresponds to the Chang Ma fault zone (95°E, 39°30'N), and the second to the thrust fault bounding the Qilian Shan front (95°45'E, 39°45'N) (Fig. 2). Eastwards from the junction with the Qilian frontal thrust, the eastern segment of the Altyn Tagh fault forms the NW border of an anticlinorium of Cenozoic sediments corresponding to a broad push-up within a left en échelon stepover about 20 km wide. Finally, east of 98°E, the trace of the Altyn Tagh fault vanishes into the Gobi desert.

By analysing long-term cumulative horizontal offsets of the late Quaternary morphology on SPOT panchromatic scenes, and taking into account the most plausible last deglaciation morpho-climatic history, Peltzer et al. (1989) obtained Holocene slip rates of 20 and 30 mm yr⁻¹ for the eastern and central segments, respectively. East of 94°E, they suggested that the slip rate is partitioned, with each splay accounting for about 5 mm yr⁻¹ of left slip. This sketch implies that the remaining left slip rate on the Altyn Tagh fault, east of these fault bifurcations, must be of the order of a few mm yr⁻¹. This attractive sketch, however, needs to be compared with precise field observations.

In this paper, we present detailed SPOT image analysis complemented by field observations that allow us to estimate the slip rate along the north-eastern end of the Altyn Tagh fault. We analyse long-term horizontal offsets of late Quaternary morphological features and deposits along the easternmost segment of the fault, east of 96°E, in between the Chang Ma fault zone and Qilian front splays. We describe the deformations at five sites, four of which allow estimates of recent left-lateral offsets. Some of these offsets clearly postdate the last glaciation and give access to the first even rough
estimate of slip rate along the eastern end of the Altyn Tagh fault.

**GEOLOGICAL SETTING**

East of 96°E, the Altyn Tagh fault separates 3500 m high relief to the south from a broad, gently north-dipping sedimentary apron to the north (Figs 2 and 3). This piedmont bajada is composed of recent sediments eroded from adjacent relief and deposited by heavily loaded streams that emerge from the mountains to vanish into the southern border of the Tarim basin (Figs 2 and 3). The basement crops out extensively to the south of the fault trace, except in the Shi Bao Cheng basin, which is filled with Neogene to Quaternary sediments (Fig. 3). The basement consists mainly of Lower Palaeozoic rocks (Fig. 3). North-dipping schistozed volcanodetritic rocks of Cambro-Ordovician age are overthrust by an ultrabasic unit made of highly deformed and metamorphosed pillow lavas, with their associated radiolarian red cherts. Fine limestones of Upper Devonian age form sharp crests in the morphology,
and outcrops of Siluro-Devonian flysch are scarce in this area. Cambro-Ordovician rocks probably represent an old dismembered oceanic crust that may have been obducted to the north during the early Palaeozoic suturing of the southern Qaidam block with the northern Gobi block. Upper Palaeozoic granites intrude the volcano-sedimentary units and are surrounded by a metamorphic contact aureole.

North of the Altyn Tagh fault, basement outcrops are scarce (Fig. 3). On the other hand, Quaternary sediments crop out extensively and have been deposited by the rivers that drain the gently north-dipping sedimentary piedmont. Between the Ta Shi and Su Lo rivers, which drain the Shi Bao Cheng and Chang Ma basins respectively, smaller gullies actively feed the local sedimentation. The late Quaternary formations deposited by these gullies are made of numerous coalescent alluvial fans, over-run or re-incised by braided channelized flows. While all of them are of late Quaternary age, they are not coeval. On the SPOT images and in the field, it is possible to distinguish three formations and to infer their relative ages (e.g. a3, younger than a2, itself younger than a1; Fig. 3) from their relative elevation and the degree to which they have been incised by active channels (for an extended description of such late Quaternary formations and a discussion of their relative age, see Meyer 1991). Dark linear areas (formation a3) correspond to main river flood plains of contemporary drainage systems that incise from 50 cm to a few metres deep into the coalescent alluvial fan (formation a2) covering the main land surface north of the fault. These two alluvial formations cross-cut more localized and less abundant outcrops of an older fan system (formation a1) that has been more incised by rivers.

SITES DESCRIPTION

At site 1, one of the few large outcrops of basement that lies north of the fault bounds the sediments of the Shi Bao Cheng basin (Figs 2, 3a,a' and 4a,b). The Ta Shi river, the main collector of the many streams that flow out of the Ta Xueh Shan mountain, drains the Shi Bao Cheng basin and finally vanishes in the southern Tarim desertic basin (Fig. 2). The Ta Shi river crosses the Altyn Tagh fault at a right-angle, without any apparent lateral offset. A detailed analysis of the network geometry and most plausible history, however, allow us to describe evidence of kilometric horizontal displacements. North of and downstream from the Altyn Tagh fault trace, the Ta Shi river course has incised the bedrock and now flows into entrenched meanders (Figs 3a,a' and 4a,b). Immediately to the north of the fault trace and to the west of the present-day Ta Shi river course, two meanders whose bottom floors are made of strongly indurated conglomerates capped by recent conglomerates are recognizable on the SPOT image. The orientation of the pebbles within the conglomerates that crop out on the eastern edge of the largest and westernmost meander indicates a northward palaeocurrent direction (Fig. 4c). These meanders are now occupied by rivers whose sizes are obviously too small to account for the formation of such large (≈300 m) meanders and whose direction of flow is sometimes nearly opposite the palaeocurrent direction. In the Shi Bao Cheng basin, the only river to have been able to dig such meanders is the Ta Shi river. These abandoned meanders are most probably ancient river beds of the Ta Shi He, suggesting that its river course has been particularly unstable north of the fault. Situated east of the active channel, such basement-entrenched abandoned meanders are only found close to the fault trace (Figs 3a,a') and are most probably of tectonic origin. Their position measured relative to the active Ta Shi river floodplain indicates large recent left-lateral offset along the Altyn Tagh fault. Restoration of the offset that could have been responsible for the abandonment of these meanders yields left-lateral displacements of about 1320 and 840 m for the western and eastern meanders respectively (Fig. 4d).

Vertical offsets coeval with the former horizontal offsets are more difficult to estimate. Indeed, hydrographic networks are known to record horizontal offsets much better than vertical ones (e.g. Peltzer et al. 1988). Moreover, vertical throw can only be obtained by comparing the elevation of identical morphological structures that have been displaced by the fault. Although the abandoned meanders are restricted to the north of the fault, the fact that the active river course incision is greater to the north rather than to the south of the fault may suggest a relative uplift of the northern block. The difference between the elevation of abandoned meanders (2120 and 2100 m for western and eastern meanders respectively, R.P.C. topographic maps) and the elevation of the active Ta Shi river course (about 2075 m near the fault, R.P.C. topographic maps) is due to both average incision rate and average vertical throw rate on the fault. One can simply write

\[ E - h = (V + I)t, \]

where \( E \) and \( h \) are the elevations of abandoned meander and active river bed respectively, \( V \) is the average vertical throw rate, \( I \) is the average incision rate, and \( t \) is the elapsed time since the abandonment of the meander. The horizontal offset \( H \) of the abandoned meander is also linked to the rate of left slip \( S \) on the fault by

\[ H = St. \]

Combining (1) and (2) for the western (w) and eastern (e) meanders leads to

\[ (E_w - h)/(E_e - h) = H_w/H_e. \]

Finally, the fact that the calculated value of \( h (2065 \text{ m}) \) is close to that given by R.P.C. topographic maps (2075 m) may be taken to imply that the hypotheses made were reasonable, and that the palaeomeanders correspond to the ancient watercourse of the Ta Shi river. If we assume that the average rate of incision was much less than the average rate of faulting during the time span that led to the abandonment of the western meander and to the formation of the eastern meander, the comparison between elevations and offsets of these two abandoned meanders may provide preliminary information. The difference between the elevations of the western and eastern meanders (≈20 m) is 24 times less than the horizontal offset responsible for the abandonment of the western meander (480 m, stage III–stage II in Fig. 4d), suggesting that horizontal and vertical throw rates are in the same ratio. In any case, without a reliable estimate of the average rate of incision, the small vertical offsets coeval with the horizontal displacements of 840 and 1320 m cannot be estimated precisely.

At site 2, one can recognize the late Quaternary formations a1–3 that have been deposited north of the N70°E-striking fault trace (Figs 3b–b', 5a–c). Patches of the oldest fan system (formation a1) are scarce and mainly located north of and close to the fault. They lie nearly opposite smooth basement

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Figure 3. (a), (b) and (c): detail of 12/11/1987 KJ 239–270 and KJ 240–270 SPOT scenes. 3(a'), (b') and (c'): sketches of Figs 3(a,b,c). Boxes show locations of Figs 4(a), 5(a) and 9(a). Prequaternary geological units are from field observations and a geological map of Gansu province (Gansu geological bureau 1975). Late quaternary units are from field observations and satellite and air photo interpretation. The relative ages of recent alluvial fan surface are indicated (darker when older).
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Relative age of quaternary alluvial formation

QUATERNARY
- Active formation a3
- Intermediate formation a2
- Older formation a1

ANTEQUATERNARY
- Neogene
- Cretaceous
- Upper Paleozoic Granites
- Siluro Devonian flysch
- Metamorphic aureole

Ordovician Limestone
Volcano Detritic Cambro Ordovician
Cambro Ordovician Oceanic Crust
Precambrian

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Figure 4. (a) Detail of 21/09/87 KJ 238–270 SPOT scene. (b) Sketch of Fig. (a). Palaeomeanders of Ta Shi He are offset by the Altyn Tagh fault, whose trace is particularly clear. (c) Palaeocurrent direction given by inclination of pebbles within conglomeratic layers. (d) Plausible reconstruction of displacement if palaeomeanders are from tectonic origin only (see text for discussion).
Figure 5. (a) Detail of 12/11/87 KJ 239-270 SPOT scene. (b) Reconstruction of the inferred original fan shape after subtracting 50 m of left-lateral fault motion. (c) Sketch of (a). Relative ages of alluvial fan surface are indicated (darker when older). B shows the position of the theodolite. The photograph in Fig. 6(a) is taken from B, looking south-west. R refers to rivers, u and d to upstream and downstream channels. R1 is indicated in Fig. 6(b). The box shows the location of Fig. 6(c).
ridges separated by flat depressions whose bottom floors are occupied by channels of the active network. Coalescent fans of formation a2, located north of the fault between remnants of formation a1, crop out nearly opposite to the flat depressions. Formation a2 has been reincised by the active network (formation a3) that appears as black linear zones on the SPOT image. North of the fault, the eastern and western edges of alluvial fan a2 are not exactly opposite to their corresponding edges south of the fault (Figs 5a–c), as if they have been displaced in a left-lateral sense. The reconstruction of the initial fan shape, which makes the eastern and western fan edges fall into line, indicates that the left-lateral offset is 50±20 m [Fig. 5b, errors are taken to be ±2 pixels as in Peltzer et al. (1989); pixel sizes are 10 m for panchromatic images].

In the field, the surface of the alluvial fan a2 has been incised a few metres deep by streams and intermittent rills (Figs 6a,b). The N70°E fault clearly cuts and offsets both the intermittent rills and the intervening isolated patches of fan surface a2 (Figs 6a,b). Because there is no significant vertical offset of the

Figure 6. (a) South-looking view of the alluvial fan surface offset. (b) Sketch of (a): f, fan surface; fs, fault scarp; r, seasonal rills. Thin dark line are levelling profiles and numbers with dots refer to specific levelling points. (c) Map of levelling profile and estimation of left-lateral offset of seasonal stream banks. The locations of river R1 and seasonal rill r are indicated. (d) Longitudinal profiles measured north and south of the fault are projected on a N70°E vertical plane; the vertical exaggeration is 10. Dots and crosses are measured points; numbers refer to specific levelling points as in Figs 6(b)–(c). Black squares and italicized numbers are the projection of corresponding levelling points belonging to river bank profiles onto the N70°E vertical plane. (e) As (d). The northern profile has been displaced so that its general shape fits best with that of the southern one. Corresponding apparent horizontal and vertical offsets are 23.5 and 0.8 m, respectively. (f) Schematic sketch illustrating differences between apparent offsets and real offsets. H and Ha are the horizontal and apparent horizontal offsets respectively. V and Va are the vertical and apparent vertical offsets respectively. W is the width between longitudinal profiles; δ is the angle between fault and terrace riser azimuths and β is the regional slope angle.
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Apart from the fault scarp, the slip vector is mainly horizontal. To estimate the vertical and horizontal offsets, we measured several topographic profiles:

1. two profiles parallel to the fault, south and north of it (profiles I and II, Fig. 6b);
2. four profiles following the edges of small terraces displaced by the fault (profiles III, IV, III', IV', Fig. 6b).

We first estimate the horizontal offset by aligning the edges of terraces III and IV of the upstream southern block with the edges of terraces III' and IV' of the downstream northern block (Figs 6b,c). This yields horizontal offsets between 50 and 56 m in a N70°E direction (Fig. 6c). These values are compatible with that obtained directly by reconstruction of the inferred original fan shape on the SPOT image. Because the terraces, which extend only a few tens of metres upstream and downstream from the fault, cannot be followed across long distances, we also tried to constrain both horizontal and vertical offsets of the whole fanglomerate surface using vertical projection of the longitudinal profiles (Fig. 6c).

The schematic map of this site is given in Fig. 6(c). The projection of longitudinal profiles I and II onto a N70°E vertical plane, parallel to the fault strike, emphasizes the offset of the rivers (Fig. 6d). Upstream (profile I), the sporadic rills denoted by points 3 and 6 are shuttered by the fault. On the other hand, the gully denoted upstream by point 2 and downstream by point 9 appears to cross the fault without any significant offset. This may be due to the entrenchment of this river, which shifts laterally through reincision, erosion of its right bank and progressive abandonment of both its left bank and its older bed, whose remnants could be materialized at point 10. The different in elevations between points 2 and 9 on the one hand and points 3, 11, 5, 12, 6, and 13 on the other hand, which corresponds to ≈5 m of entrenchment, favours this hypothesis. This deepening was probably made easier both because the river flows close to the eastern edge of the fan and because the east-dipping slope of the fan surface favours such a migration. This rather simple explanation is also strengthened by the fact that downstream, even for the rivers whose course is perturbed close to the fault, the right banks are much steeper than the left banks. Indeed, downstream from the fault, the
left-lateral offset of a river bed induces a more efficient erosion of right than left banks (and vice versa for a right-lateral offset). This observation has also been made for active strike-slip faults cross-cutting submarine turbidity current channels seaward of the Oregon convergent margin (e.g. Figs 6, 7 and 8 in Appelgate et al. 1992). In addition, because the two upstream river banks are symmetrical (profile I), the observed asymmetry of the two downstream river banks (profile II) is most probably the result of an interaction between erosion and tectonics.

Two different hypotheses may explain why the active river course R1 does not appear to have been displaced by the fault (see points 5 and 12 in Fig. 6d). First, either this river has been superimposed and/or is the result of a stream piracy after the offset of the fan. Second, the high rate of erosion within the stream channel does not allow the lateral offset to be detected between two longitudinal profiles only 20 m apart, the upstream and downstream river bed being only deflected in a left-lateral sense (e.g. Gaudemer et al. 1989). A more convenient spacing of longitudinal profiles to detect cumulative horizontal offsets of such river beds appears to be close to 200–300 m (e.g. Peltzer et al. 1988). The small amount of local entrenchment of R1, close to that observed between points 9 and 10 for a gully thought to be coeval with the offset of the fan surface, favours the hypothesis of recent superimposition. Moreover, after reconstruction of the inferred original fan shape, the upstream channel R1u falls into line with the channel R2, whose size agrees better than that of R1d with the wide upstream channel R1u of river R1 (Fig. 5c). Thus, the downstream channel R1d might have been superimposed by regressive erosion, and might have caught the upstream channel R1u, formerly the upstream channel of R2, as suggested in Fig. 5(b).

The two longitudinal profiles parallel to the fault trace corresponding to the initial stage before displacement are indicated in Fig. 6(e) (profiles I and II’). The change from the initial shape of the alluvial fan to its present-day configuration is tied to a large amount of left-lateral displacement and a small relative uplift of the northern block. The restoration of the initial fanglomerate shape agrees with the main rules that govern the structure and evolution of alluvial fans:

1) the general shape of the alluvial fan is indeed convex upward;
2) all the rivers flow downhill from the apex to the toe of the fan.

Moreover, this operation makes the ends of the upstream and downstream watercourse of rills that flow at points 3, 11 and 6, 13 or that were flowing at points 10 and 2 before over deepening took place, meet exactly. On the other hand, the active river bed (R1) appears to be displaced in a right-lateral sense (points 5 and 12, Fig. 6e). The values of the apparent horizontal and vertical offsets are 23.5 and 0.8 m, respectively. Because the N30°E-striking terraces are not exactly perpendicular to the direction (N70°E) onto which the two longitudinal profiles were projected, and because of the distance that separates the two profiles, the apparent horizontal offset must be corrected (Fig. 6f). The angle between fault and rills azimuths is 40° (70°–30°), and the average distance between profiles I and II is 15 m; the apparent horizontal offset is then increased by 15 cot(40°). The true left-lateral offset is 41 m. The small apparent vertical offset (0.8 m) must also be corrected because it slightly underestimates the true vertical offset. With an average distance between profiles I and II of about 15 m and an average north-dipping regional slope angle of about 1.7°, the apparent vertical offset is increased by 15 tan (1.7°), and the real vertical offset of the northern uplifted block is 1.25 m (Fig. 6f). In summary, the northern downstream side of this alluvial fan has been left-laterally displaced by 41 m and uplifted by 1.25 m. The ratio between horizontal and vertical offsets (≈33) for this recent alluvial fan agrees with that of ≈24 inferred for the abandoned meanders at site 1. The discrepancy may represent the influence of the incision rate I of eq. (1), which we neglected for the meanders of site 1, overestimating vertical offsets and thus underestimating the ratio between horizontal and vertical offsets. The closeness of these two values, however, indicates that the slip vector on the Altyn Tagh fault has remained relatively constant, at least since the time when the Ta Shi He dug the meanders; these high values also indicate that the slip vector is nearly horizontal and confirm that this segment of the Altyn Tagh fault is mostly strike-slip.

The 41 m of left-lateral offset we obtained by running topographic profiles is close to but less than the ≈50 m we get when using a direct measurement on the SPOT image, and than the 50 to 56 m we get by aligning the edges of terraces III and IV with the edges of terraces III’ and IV’ (Figs 6b,c). This difference may arise from the fact that river banks of small intermittent channels are passive markers, while re-incision of main river floodplains could modify the fan shape, particularly on its borders. In any case, the three different estimates we used to measure the left-lateral offset of this recent alluvial fan are compatible and the offset may be confidently taken to be 50 ±20 m.

At site 3, farther east, the clear fault trace cuts across fan surface a2 and merges with a small camel trail (site 3, Figs 3b and 7). The disturbance of both river flows and saturation level sheet floods by faulting induces the formation of resurgence, ponds and backwaters, and does not allow a precise analysis of fault scarp. At site 4 (Fig. 3b), a river entrenched in the alluvial deposits of fan surface a2 is displaced by the fault. The profile following the edge of this terrace allows us to constrain the left-lateral offset of this riverbed to be ≈60 m (Fig. 8).

At site 5, a few kilometres east of site 4 and north of a prominent calcareous Ordovician bar, the geometry of the fault zone defines a pull-apart basin (site 5, Figs 3b–b’ and 9a,b). Several N55°E-striking normal fault scarps bound the small depression within the two overlapping south-western and north-eastern strike-slip strands (Figs 9a,b). These normal fault scarps cross-cut and offset a succession of three imbricated terraces, the inner one (I) corresponding to the main river floodplain of active drainage network (formation a3). Two north-facing normal fault scarps S1 and S2, offset down to the north of the three terrace levels (Fig. 9a). To determine the amount of vertical offset of each terrace, we levelled several topographic profiles across fault scarps S1 and S2. The southward view of scarp S2 (Figs 9c,d) and the profiles of scarp S1 and S2 (Fig. 9e) emphasize the fact that the older the terraces are, the higher the scarp is. Average amounts of vertical displacement, 0.85, 2.3, and 3.25 m, have been recorded since the emplacement of the lower, middle, and upper terraces respectively. The vertical offset of the lower terrace (I) is
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Figure 7. Altyn Tagh fault trace across the alluvial fan corresponding to alluvial formation a2. A small camel trail used by desert convoys outlines the fault trace.

Figure 8. Left-lateral offset of terrace riser. Blacks circles denote points where measurements are taken.

recent, because this terrace corresponds to the present-day bottom floor of the contemporary main river floodplain. The small average height (0.85 m) of the scarp of the lower terrace (lt) is probably historical and could therefore be related to the topographic offset of a single seismic event. The clear slope break (Profile 6, Fig. 9e) within scarp S2 in the upper terrace (ut) may correspond to the reactivation coeval with the last event and favours the inference that the total scarp height results from the addition of incremental throws. The vertical offsets recorded by the upper and middle terraces would then correspond to the cumulative displacements of three and four earthquakes respectively. Unfortunately, we could not spend more than a couple of hours at that site, obviously too short a time to dig trenches to look for radiocarbon-datable materials or to run the numerous long topographic profiles needed to carry out the diffusion analysis. It would be of great interest to date these terraces. This could be done either directly by geochronologic methods or by diffusion degradation methods (e.g. Andrews & Hanks 1985; Hanks & Wallace 1985; Avouac 1993), and this would provide the recurrence interval of earthquakes linked to the formation of such a pull-apart. Let us, however, assume that the vertical offset of the upper terrace (ut) would have been rapidly erased by cryoplanation and erosion during the Würm glacial stage. If so, incremental vertical offsets of the upper terrace (ut) produced prior to the last deglaciation—i.e. 12±2 ka ago; see the discussion section—would have been removed and no cumulative offsets would have been preserved. Thus, assuming that the four events responsible for the vertical offset of the upper terrace have occurred since the onset of Holocene global warming, we deduce an average earthquake recurrence interval of about 2.5–3.5 ka. This estimate is of the same order of magnitude as the recurrence interval of earthquakes in the same region (e.g. Peltzer et al. 1988; Tapponnier et al. 1990; Meyer et al. 1991; Gaudemer et al. 1995) or within other regions of Asia, such as the Tien Shan (e.g. Avouac et al. 1993) or within Mediterranean intracontinental actively deforming regions (e.g. Armijo et al. 1991).

The average vertical offset of the upper terrace is 3.25 m for scarps S1 and S2. If the five normal faults within that pull-apart basin had experienced the same amount of displacement at depth since the time when the upper terrace was emplaced, the total amount of vertical displacement would have been 16.5 m. During that period, and if we take 50° fault dips, which...
Figure 9. (a) Detail of 12/11/87 KJ 239–270 SPOT scene; incipient pull-apart basin along the Altyn Tagh fault. (b) Sketch of (a). Three imbricate terraces are offset by several normal fault scarps. Numbers on small arrows show the locations of profiles in (d). The photograph in (c) was taken from the eastern end of scarp S1 looking towards scarp S2. The lower left corner inset is a sketch linking the horizontal displacement S and net extension e within the pull-apart basin. V is the sum of cumulative normal throw; z is the normal fault dip, taken to be 50°. (c) View to SE of inner terraces displaced along S2 fault scarp. ut, mt and lt for upper, middle and lower terraces respectively. (d) Sketch of (c). (e) Profiles across fault scarps S1 and S2, see location in (b). (f) Schematic sketch of the interaction between erosion and tectonics. The offset of inner terraces increases with the age of terraces.
is close to that measured for normal faults in Tibet, this vertical displacement corresponds to a N145°E net extension \( e \) of 13.6 m (inset Fig. 9b). This net extension \( e \) is due to a total left-lateral slip \( S \) of 53 m, partitioned between the two strike-slip strands that overlap (inset Fig. 9b). Space and time relationships between offsets of faulted inset terraces, however, need to be carefully examined. On the one hand, an active alluvial formation may record horizontal offset, but it could not preserve vertical offset because of the erosion of its substratum or deposition of alluvium on it (e.g. Peltzer et al. 1988; Fig. 9f). On the other hand, terraces that result from the entrenching of rivers into alluvium, where the terraces were previously deposited by active alluvial surfaces, are much less eroded, and therefore preserve vertical offsets. We may thus assume that the cumulative vertical offset of the upper terrace \((ut)\), formerly alluvial formation \((a1)\), started to be recorded when the alluvial formation \((a2)\) was emplaced (Fig. 9f). The 16.5 m of cumulative vertical offset that could have been recorded since the emplacement of the upper terrace \((ut)\) is coeval with 53 m of horizontal displacement and postdates the emplacement of alluvial formation \(a2\).

**INFERRED SLIP RATES AND IMPLICATIONS**

We lack absolute dates of the displaced morphological markers to be used to obtain a direct assessment of the fault slip rate.
However, a regional correlation of the formations a1–3 described above plus geomorphologic reasoning supported by an absolute date allow us to place bounds on the slip rate. The formations a1–3 that lie along the Alty Tagh fault zone have the same aspect in the field and a similar signature on both SPOT images and topographic maps to recent sediments cropping out throughout the whole region, as far as the Yumushan foreland 400 km towards the east (Tapponnier et al. 1990). Such late Quaternary formations, widely distributed along the entire north-eastern border of Tibet have been regionally correlated and, for the two youngest ones at least, their emplacement has been linked to the Holocene warming.
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Figure 10. Left-lateral offsets versus inferred age for the eastern Altyn Tagh fault segment. The rate of left-lateral movement is $4 \pm 2$ mm yr$^{-1}$.

Table 1. Values of late Quaternary offsets with their inferred age.

<table>
<thead>
<tr>
<th>Horizontal Offset</th>
<th>Morphological Inferred age</th>
</tr>
</thead>
<tbody>
<tr>
<td>in m</td>
<td>in ka</td>
</tr>
<tr>
<td>site 1</td>
<td>1320</td>
</tr>
<tr>
<td>site 2</td>
<td>840</td>
</tr>
<tr>
<td>site 4</td>
<td>50 ± 20</td>
</tr>
<tr>
<td>site 5</td>
<td>59</td>
</tr>
<tr>
<td>Su Lo He</td>
<td>5000</td>
</tr>
</tbody>
</table>

*Does not correspond to a direct measurement.

During the Holocene stage, around 6 ka B.P. Since the alluvial formation a2 covers extensive areas of the main piedmont ranges (e.g. Altyn Tagh relief, Figs 3 a,b,c; Qilian shan and Ta xueh Shan, Meyer 1991), we assume it was deposited at the very onset of the Holocene as a result of increased run-off in the piedmonts. We thus assign to a2 an age of 12 ± 2 ka. The offsets and ages used to derive the slip rate are listed in Table 1. These offsets and inferred ages provide a rate of left-lateral slip of between 2 and 6 mm yr$^{-1}$ (Fig. 10). The ages of the approximately kilometric and multikilometric horizontal offsets of Ta Shi He and Su Lo He, respectively, are much more difficult to estimate than that of the postglacial alluvial formations. If the slip rate ($4 \pm 2$ mm yr$^{-1}$) had remained constant since at least the early Quaternary, as suggested by a constant ratio of horizontal to vertical offsets for different magnitudes of displacements, the offset of the Ta shi He meanders would have formed mainly during the Riss glacial stage, and the entire Su Lo He outlet would have formed during the Quaternary.

However, careful and detailed studies of fault slip should be carried out along the entire eastern segment of the Altyn Tagh fault, specifically between 92°E and 96°E—the small value of fault slip derived here supports the idea of a north-eastward decreasing slip rate on the Altyn Tagh fault (Burchfiel et al. 1989; Peltzer et al. 1989; Meyer 1991, Fig. 1). The $\approx 25$ mm yr$^{-1}$ difference between the slip on the central segment ($\approx 30$ mm yr$^{-1}$, Peltzer et al. 1989) and that on the eastern end of the eastern segment ($4 \pm 2$ mm yr$^{-1}$, this study) has been absorbed between 93°E and 98°E, probably by the four main splays of the Altyn Tagh fault. Kinematic models of the active tectonics of NE Tibet should take into account or predict a fault slip rate compatible with the former observations. The precise way that fault slip has been absorbed and/or transferred between the Altyn Tagh and Qinling faults (Gaudemer et al. 1995; Meyer et al. 1995; Zhang, Vergely & Mercier 1995), however, remains an important challenge to

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the improvement of our understanding of the India–Asia collision over the last ten million years.

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REFERENCES


R.P.C. topographic map, scale 1/100,000, Shi Bao Cheng sheet.

