Quaternary Climate Change and the Formation of River Terraces across Growing Anticlines on the North Flank of the Tien Shan, China

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ABSTRACT

Nested stream terraces, warped upward over actively growing anticlines along the north flank of the Tien Shan in western China, appear to record alternating phases of valley widening and incision. Differences of relative heights between remnants of four separate strath terraces along one river and between two such terraces along another reach 100 to 120 m over the crests of the anticlines. We infer that this spacing is due to alternating stages of valley widening and rapid incision associated with climate changes with a periodicity of 100 kyr. The crests of the anticlines appear to emerge from the aggrading flanks of the anticlines at an average rate of about 1 mm/a. The maximum heights of 25 and 35 (±10) m for the lowest terraces above their projected initial profiles imply ages of roughly 25 kyr and 35 kyr (±10 kyr). Hence, they suggest that flood plains, which were abandoned to form the terraces, developed adjacent to active stream beds during the last glacial period, when climates were relatively cold and dry. We presume that they were incised during deglacial periods when discharges and stream power increased. Apparent durations of exposure, obtained from Be in quartz cobbles lying on the surface of the lower terrace from one anticline, concur with abandonment and deep (~150 m) incision of the flood plain during the last global deglaciation (ca. 20 to 13 kyr B.P.). A minimum carbon-14 date of 33.9 kyr B.P. from deposits on the lowest terrace sequence from the other anticline, however, implies that such abandonment and incision of this flood plain occurred before the most recent global glacial maximum, about 20 kyr B.P. We infer that incision of this second anticline’s floodplain began during an earlier deglacial epoch within the last glacial period (between about 70 and 20 kyr, and perhaps near 35 kyr B.P.).

Introduction

If both sedimentation and erosion, including regional denudation and river incision, occurred as steady-state processes, features such as river terraces and V-shaped valleys sharply incised into gentle landscapes would be rare. Their existence virtually guarantees temporal variations in rates of erosion and sedimentation, or in rates of degradation and aggradation of river beds. Over and above land use, two basic classes of environmental change are likely to instigate regional variations in erosion or deposition rates. First, tectonic processes create elevated terrains, which are eroded and incised, as well as some of the adjacent basins in which sediment accumulates. Despite its being rejected by most geomorphologists, the Davisian concept of landscape evolution—from youth, to maturity, to old age—has led many geologists commonly to assign tectonic processes as the cause of both sharply incised landscapes and rapid deposition of coarse sediment. However, climate changes can also alter rates at which rivers and glaciers erode and transport material. Tectonic processes commonly persist over millions of years and obviously profoundly affect the landscapes of mountain ranges. Fluvial systems, in contrast, respond in tens to hundreds of years to disruptions of what otherwise is equilibrium [e.g., Merritts and Vincent 1989, Williams and Wolman 1984]. Thus cli-
climate changes, cyclic on time scales of thousands to tens of thousands of years, should lead to alternating styles of landform development on scales smaller than those spanning mountain ranges.

In this paper we examine terraces across two growing anticlines along the northern flank of the Tien Shan Mountains, China (figures 1 and 2) (e.g., Avouac et al. 1993; Burchfiel et al. unpub. data; Deng et al. 1991a; Feng et al. 1991). The two anticlines have different structural cross sections, apparently different ages of initiation of folding, and were incised by rivers with quite different discharges. Despite the active tectonic forces, we will present evidence that terrace formation and abandonment across both anticlines were climatically, rather than tectonically, controlled.

**Regional Geology**

The Tien Shan constitutes an easterly trending, intracontinental mountain belt with peaks higher than 7000 m and with many large earthquakes (e.g., Tapponnier and Molnar 1979). The range has been built largely by the thrusting on relatively steep thrust faults (dips of 30–60°) within pre-Mesozoic basement rock. Nevertheless, thin-skinned fold-and-thrust belts flank the Tien Shan along much of its length, where Mesozoic and C-
nozoic sedimentary rocks have been detached from the underlying pre-Mesozoic rock and folded into a series of E-W trending anticlines and synclines.

**Active Folding on the Northern Margin of the Tien Shan.** Three parallel rows of anticlines extend for some 300 km along the northern edge of the pre-Mesozoic core of the Tien Shan (figure 2). Those in the row closest to the Tien Shan expose the oldest rock, commonly Mesozoic but in some places late Paleozoic; sedimentary and volcanic rocks with rare evidence of intrusives (Avouac et al. 1993; Burchfiel et al. unpub. data; Feng et al. 1991). Others expose rock no older than the Tertiary. Some of the northernmost anticlines are only barely discernible as gentle warps of the earth’s surface.

The geometry of folding varies from one anticline to another. In some, a large part of the warping is concentrated near the northern edge of the anticline, where a southward-dipping thrust fault approaches, if it does not reach, the surface (e.g., Avouac et al. 1993; Deng et al. 1991a, 1991b; Feng et al. 1991). In nearly all anticlines, deformation also occurs within the anticline, both by long wavelength (λ ~10 km) folding and in some places by faulting.

River valleys, originating high in the Tien Shan or on its northern flank, expose cross sections through the anticlines. Cenozoic sedimentary rock crops out in the cores of each. Mapping of the structure along these river valleys has allowed the construction of balanced cross sections and inferences of deeper structure (Burchfiel et al. unpub. data; Deng et al. 1991a).

Some of the differences between anticlines, such as the age of the oldest rock exposed in the core or the magnitude of folding, surely result from different ages of initiation of folding, different depths of décollement, and possibly different rates of shortening among them. Other differences, such as in the widths of the valleys and of the exposed terraces, appear to depend on the discharges of rivers that have cut the valleys.

Both our examinations of the anticlines (Feng et al. 1991) and descriptions by Avouac et al. (1993) indicate that the geologic structure and ages of the anticlines are similar to one another along strike. All have formed on the flank of a wide piedmont whose surface slopes gently at 15–25 m/km from the high pre-Mesozoic rock on the Tien Shan toward the Dzhungarian Basin to its north. The anticlines of the middle and northern rows emerge from this gently northward-sloping surface, with southward-facing dip-slopes on their south sides.

**General Characteristics of the Region.** Whereas the pre-Mesozoic rock cropping out within the high, axial part of the Tien Shan seems to be very resistant to erosion, relatively weak, younger sedimentary rock has been detached from older, stronger rock and folded into the anticlines on the flanks. Thus, sufficiently rapid erosion has prevented the anticlines from forming high topography, compared with that of the axial part of the range, despite the higher part’s having been subject to erosion for a much longer period than the anticlines themselves. Northerly flowing perennial rivers emanating from the axial part of the Tien Shan cross the anticlines and in many cases have cut deep valleys through them. Much of the dissection of the anticlinal crests, however, has been effected by ephemeral streams flowing east and west from the cores of the anticlines into these trunk streams.

Although the orography of the region permits sufficient rainfall to maintain forests and pastures within the axial part of the Tien Shan, the lower region where the anticlines lie is arid. With annual rainfall less than 25 mm/a (Fullard 1968), little vegetation grows on the slopes of the anticlines or on the piedmont above the incised northerly flowing trunk streams. Vegetation is common only within the high range, along the perennial streams, and north of the anticlines where irrigation allows farming. Difficulties in finding buried organic material suitable for radiocarbon dating suggests that the climate has been arid through glacial periods, as Kukla et al. (1988) have documented for China 1000 km farther east. Most of the trunk streams emanate from active glaciers in the axial parts of the Tien Shan. Hsieh (1973, p. 25) stated that much of western China is “so dry that it depends for its water supply on the melting of snow on top of the flanks of the Tien Shan”; hence discharge probably varies dramatically during the year. At present, however, most of these streams are dammed for power or irrigation; thus discharge and sediment transport have been severely modified in the last few years. Presumably discharge and sediment transport were very different in glacial and interglacial periods.

Late Quaternary loess, whose precise age is unknown, caps the dissected anticlines in many places. Its presence suggests periods of dry climate, presumably during glacial periods. The thickness of the loess varies widely, but exceeds 10 m in some places (see figures 6, 12, 13, 14, and 17). In some areas, the loess has clearly been reworked, for it contains cobbles and pebbles. In others (e.g., figures 6 and 17), loess is interbedded with alluvial deposits.
Figure 3. The Huoerguosi anticline where the Jinggou He crosses it (figure 2), showing beds dipping south along the eastern side of the Jinggou He valley anticline and terraces incised by the river. Terrace in the foreground was probably abandoned since (or during) the last glacial period, subsequently, about 30 m of downcutting has occurred. Higher on the eastern margin of the valley remnants of an older terrace can be seen. The southerly dip of the bedrock prevails across nearly all of the anticline. Only near the northern edge, where bedrock dips south, does the anticlinal structure become apparent.

Terraces

Surfaces cut in the weak Mesozoic and Cenozoic sedimentary bedrock define strath terraces exposed in the flanks of the valleys crossing the anticlines. Along some anticlines, terraces are virtually continuous along the valleys that have cut the anticlines (figure 3), but in others only sparse remnants of separate eroded terraces remain. These strath terraces are overlain by roughly 2–3 m to as many as 10–20 m of gravel, and then by loess above the gravel. On the flanks of the anticlines, the straths are deeply buried, and only the gravel-loess interface can be mapped. This variation in thickness implies that, as the anticlines have grown and while the streams flowed over them, deposition has occurred at a much more rapid rate on the flanks than on the crests. We presume that the streams maintained grade as they crossed the anticlines. In doing so, they eroded the weak bedrock and cut the straths.

A key feature is the warping of river terraces during the growth of the anticlines, which demonstrates continued anticline growth. Both strath and fill terraces emerge from the northerly sloping piedmont and have been incised by the present stream valleys. Where flights of terraces can be seen, their ages must increase with elevation. The youngest terraces slope northward throughout their lengths. The older terraces have been warped sufficiently that they slope southward on the south flanks of the anticlines.

Our study concentrates on strath terraces cut across two anticlines, one from the middle row and the other, the most developed of those in the northern row of anticlines. These terraces and anticlines are not unusual for the region; similar terraces are found along the Jinggou He (figure 2) where it crosses the Huoerguosi anticline (figure 3) and along the Taxi He where it crosses the eastern part of the Tugulu anticline. Our field work was not directed toward a thorough understanding of the geomorphology, but on using the warping of the terraces to constrain rates of deformation (Burchfiel et al. unpub. data), thus we did not trace the terraces far north or south of the anticlines.

Dushanzi Anticline and Kuitu He Terraces

The Dushanzi anticline, the best developed of the northern row of anticlines west of Urumqi (figure 2), exposes Pliocene and Quaternary sedimentary rock in its core (figures 4, 5, and 6). Although this rock is indurated and forms steep cliffs, it is not especially resistant to erosion. Most of this rock dips southward at about 30°, but near the northern flank the beds are sharply folded. The dip becomes steeply northward and locally overturned (Burchfiel et al. unpub. data; Deng et al. 1991a). Fault-propagation folding has resulted from slip on a ramp dipping approximately 15° southward to a depth of about 6 km below its surface (about 5 km below sea level), where décollement seems to occur on a nearly flat surface (see also Avouac et al. [1993]). A steeper thrust fault has broken through the axial surface of the fold and modified it somewhat. The amplitude of the fold, from crest to trough, is 2.1 km (figure 6). An unpublished seismic profile across the anticline by the Ministry of Petroleum is consistent with the cross section in figure 6.

This folding appears to be middle to late Quaternary in age. Both Neogene and Quaternary deposits have been folded. The Tertiary Dushanzi Formation (N3 of figure 6) of mudstone, sandstone, and conglomerate is exposed in the core of the anticline. Fossils of cervids, giraffids, and Hipparion
Liu et al., 1988] define its age. Fossil remains of a Plio-Pleistocene horse, Equus sanmeniensis, were found at the base of the overlying thick sequence of coarse material [Liu et al. 1988; Wang and Wang 1991]. The age range of Equus sanmeniensis, between 2.5 and about 1 Ma, constrains the age of this sequence, the Xiyu Formation, sometimes called the "Xiaxiyu moraine" (Q1 in figure 6). Poorly sorted gravel with dimensions of clasts commonly of 1 to 20 cm, and rarely 50 cm, infilled with muddy sand characterizes the Xiyu Formation, which commonly is interpreted as marking the inception of glaciation. From a detailed geologic cross section across the anticline, we estimate the thickness of the Xiyu Formation on the south limb of the Dushanzi anticline to be at least 1.5 m. It appears to exceed 2 km farther south [figure 6]. Although its age is commonly given as Quaternary, Chinese geologists have traditionally treated the Pliocene Epoch as spanning 7 to 2.5 Ma and

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**Figure 4.** Block-diagram of the geometry of the Dushanzi terraces and anticline from the NW. Topography does not reflect an accurate image of the valleys, ridges or heights. The Kuitun He, in the center, has cut a deep gorge through an earlier flood plain and through the anticline. The recently abandoned wide flood plain is mildly folded over the anticline with most of the warping near the northern margin where a thrust fault approaches the surface. The widths of the remnant of this flood plain and of the present valley where it crosses the anticline are both about 1 km. Warped traces of an earlier terrace can be seen along the east side of the valley. From this vantage traces of the upper terrace on the west side are obscured.

**Figure 6.** Hand-balanced cross section across the Dushanzi anticline showing limits of surface data. Outside these points dipping strata are covered by horizontally bedded strata. Within the anticline are the Lower Quaternary Xiyu F. (Q1) and the Pliocene Dushanzi F. (N1). Position of older units are unknown. Based on our mapping farther south, the level of detachment would be within Cretaceous or late Jurassic rock. Here and for the Tugulu anticline [figure 11], we have adopted the simplest interpretations that fit the observed strikes and dips of units within the anticline. Shortening was calculated for the thin black level within N2. Two possible geometries are shown in the footwall where shortening was calculated: black units (2.35 km)—footwall beds become vertical below the fault; the dotted line (2.12 km)—gentle anticline in the footwall. South is on left.

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**Figure 5.** The higher terrace on east side of the Kuitun He. The smooth foreground comprises the eastern part of the lower terrace. Southward-dipping bedding in the cliff face is abruptly truncated, and a smooth strath terrace is cut into it. Overlying this terrace is a layer of dark gravel, roughly 2–3 m thick, covered by light-colored, mostly reworked loess, which dips west toward the present stream.
the beginning of loess deposition in eastern China as the beginning of the Quaternary Period. Heller and Liu (1982, 1984) confirmed that loess deposition began at about 2.4 Ma. Thus, regardless of how one defines this geologic age, global climate changed dramatically and continental glaciation became important in the northern hemisphere at 2.4 Ma (e.g., Shackleton et al. 1984). Accordingly, we suspect that the onset of deposition of conglomerate resulted from such a climate change, and that Quaternary conglomeratic sediment accumulated at an average rate of approximately 1 mm/a.

From the balanced cross section (figure 6), we infer that roughly half of the conglomeratic sequence has been folded coherently. Thus, if folding began at about 1 Ma, and the 2.1-km amplitude of the anticline would have grown at an average rate of roughly 2 mm/a.

A major river, the Kuitun He, has cut a deep valley into the core of the anticline and some 150 m below a wide, gently north-dipping river terrace (figures 4 and 7). At the level of this terrace, the width of the present river valley is about 1 km, but its flanks are defined by steep cliffs in many places (figures 5 and 7). The width of this terrace remnant is also about 1 km, so that at the level of this terrace surface, the width of the valley in the anticline is 2 km (figure 4).

Remnants of an older terrace can be traced along both flanks of the wide valley above this surface (figures 5 and 7). This terrace is defined by a sharp, unconformable contact between the Plio-Quaternary bedrock and younger stream gravel. The thickness of the gravel varies from place to place, but where we could measure it near the crest of the anticline, it is between 10 and 20 m. A relatively thick layer of loess interbedded with gravel overlies this basal gravel layer. The strath terrace emerges from beneath the south flank of the anticline, but erosion of the north flank has erased unequivocal remnants of it there. On the east side, the strath is continuous for 5 km. On the west side, most of the strath terrace is either buried or eroded; remnants can be seen only near the crest for a distance of about 2 km. Measured heights of remnants of this warped strath terrace on opposite sides of the valley, although 2 km apart, agree with one another (figures 8 and 9). Heights of the depositional surfaces above this strath and below the loess on opposite sides of the valley also agree with one another at localities between the crest and the south flank of the anticline. Farther south, where the terrace has not been folded, however, the measured heights differ by about 10 m, with the higher of these on the west side (figures 8 and 9).

We were not all granted permission to visit this upper surface. Moreover, the two of us (D. Q. and
Both the wide smooth abandoned terrace, which forms the western part of the valley, and the higher terrace are fluvial in origin. Traces of braided channels form the only significant relief (1 to 2 m) on the wide terrace. Fluvial erosion and deposition also created the sharp contact between the beveled surface of the folded Late Cenozoic sedimentary rock and the thin overlying layer of coarse gravel, marking the upper terrace (figures 5 and 7).

We measured the heights of points along the lower terrace (figures 8 and 9) using a combined theodolite and distance-measuring device (total station). We used a reflector to measure distances and heights with errors of 0.1 m or less. Such errors are much smaller than the variability in heights of 1–2 m due to abandoned braided channels over the surface. One of us (L. J.) also carried the reflector to all but one of the points on the depositional surface of the upper terrace on the west side of the valley and to the one locality where the underlying strath terrace could be reached easily (figure 8).

None of the measured points on the east side of the valley could be reached safely (see figure 5). To estimate their heights, as well as the other four measured heights of the strath terrace on the west side, we triangulated on selected points at distances of between 1 and 5 km from pairs of reference points on the lower terrace. We measured directly the distances between pairs of reference points, roughly 1 km apart. Then with horizontal angles from each, we determined locations of the targeted sites, and with vertical angles we estimated heights of each targeted site from each reference point (figure 9). The common agreement within 2 m of the two measured heights of the same target point suggests a precision of a meter or two. The biggest source of error arose from choosing target sites that could be confidently identified after moving to a new reference point and seen from a different vantage. In a few cases large errors in horizontal positions of such points implied that we had not sighted on the same target point, and we discarded the heights.

The plotted heights suggest that both terraces have been warped (figure 9). This warping is most clearly seen in reference to a regionally northward-sloping surface. The average slope of the undissected piedmont surface extending 5 km south of the anticline, measured from a topographic map with a scale of 1:50,000, is 21 m/km, which agrees with the average slope between end points of the profile in figure 9. Subtracting heights defining a plane with such a slope from the measured heights yields a profile of differences in height (figure 10) that approximates the uplift of surveyed terraces with respect to the flanks of the anticline. Extrapo-
Figure 10. Terrace height profiles for the lower and upper Kuitun He terraces [figure 9], with a slope of 21 m/km removed, thus giving the difference in heights between those measured and that calculated assuming a constant grade. Symbols as in figure 8.

lating a planar surface across the entire profile some 10 km long, however, need not approximate well the initial cross sectional profiles of the terraces, which might have been concave upward or downward before they were incised. Accordingly, we arbitrarily assigned an uncertainty of 10 m to the maximum height of the lower terrace above its flanks.

The asymmetry of the lower terrace is clear. The maximum warping above the flanks is about 25 \(\pm 10\) m with more than half of it localized near the northern edge of the anticline, where the underlying thrust fault approaches, if it does not reach, the surface.

The upper terrace is not sufficiently continuous for us to trace it across the entire anticline. Moreover, we cannot be certain that the measured remnants of the terrace define a surface that was planar when a stream flowed on it. Drainage perpendicular to the valley, from the crest of the anticline and toward the river valleys, cut down to the level of the trunk stream [figures 4 and 5]. Upstream in such transverse valleys, the elevations of the river beds incised into the bedrock would have been higher than the strath cut by the trunk stream. The interlayers of gravel and loess on the ridges seen in figure 5 (on the east side of the valley) show westward-sloping surfaces that attest to transverse drainage. We presume that straths, which were cut by such drainage before the deposition of the loess and interbedded gravel, also sloped into the trunk stream. The variations of the thickness of gravel within the upper terrace and the irregularity of its surface across the anticline [figures 8, 9, and 10] suggest that such drainage may have introduced a scatter of about 10 m in measured heights of this terrace. Whatever the source of the scatter, the maximum height of the upper terrace is about 125 \(\pm 10\) m above the lower one and about 150 \(\pm 20\) m above the inferred profile before the terraces formed.

**Tugulu Anticline and Quergou He Terraces**

This anticline, called Qiu Er Gou by Avouac et al. (1993), differs from the Dushanzi anticline in several respects. First, the rock on the north flank dips north and reveals no evidence for a fault bounding this flank [figure 11]. Slip on a major south-dipping reverse fault has displaced sedimentary rock units in the core of the anticline [figure 11], but this fault does not appear to cut the lowest terraces along the Quergou He valley; hence this segment of the fault does not appear to be active. The present growth of the anticline must be due to slip on an blind thrust fault [Burchfiel et al. unpub. data]. Both to the east and west, the continuation of the inactive reverse fault bounds the continuation of the Tugulu anticline on its north side, and in these areas, it seems to reach the surface as an active fault [e.g., Avouac et al. 1993; Feng et al. 1991]. The terraces that we measured, however, do not seem to cross any active fault scarps.

Second, the core of the Tugulu anticline reveals much older sedimentary rock, assigned an Eocene age where the Quergou He crosses it and Cretaceous farther west, than that exposed in the Dushanzi anticline. The entire Tertiary sequence seems to be folded coherently. The Pleistocene sequence is identified on the basis of its lithologic similarity to the Xiyou formation, whose key fossil was found 100 km to the west. The thickness of the Pleistocene sequence, inferred from a balanced cross section, again is roughly 2 \(\pm 0.5\) km, implying a sedimentation rate of about 1 mm/a.

Third, the balanced cross section [Burchfiel et al. unpub. data] shows that the projected height of units in the crest would stand roughly 5.5 km above their continuations on the flanks of the anticline [figure 11]. This greater amplitude of folding than for the Dushanzi anticline suggests either that it began to form earlier than the Dushanzi anticline, or that the rate of convergence is greater. If folding began at 2.5 Ma, after deposition of the
a gorge that is an obstacle to east-west travel, as does the Kuitun He. Moreover, at its narrowest, the Quergou Valley is only about 200–300 m wide, not 1000 m as with the Kuitun Valley. The Quergou He has cut a valley neither as deep, nor as wide as that cut by the Kuitun He.

Flanking the Quergou He are discontinuous remnants of several terraces. In all cases, they seem to be strath terraces, cut into bedrock and capped by only 2–3 m of coarse gravel. The gravel is covered by loess (figure 15), whose precise age we do not know. Some of the loess has been reworked and mixed with cobbles. Layers of reworked loess commonly dip eastward or westward toward the Quergou Valley and therefore seem to have been deposited by transversely oriented tributaries (figure 12). We studied only the strath terraces and the thin overlying gravel layers that seem to have been cut and deposited by the Quergou He itself, and not by transverse drainage.

We again measured the heights of terraces using a total station (figures 13 and 14). One of us (L. J.) carried the reflector to all measured points except the four points on the highest terrace on the south side and the two southernmost points. Most relative heights are uncertain by less than 0.1 m. We only tentatively associate the two southernmost heights in figures 13 and 14 with terraces, and we do not use them in our interpretation.

The lowest terrace level is the clearest for the longest segments of the valley through the anticline (figures 12–15). Near the axis of the anticline, this terrace level actually consists of a series of three neighboring straths roughly 2–5 m above one another (figure 15). These three straths are not continuous over long distances from the center of the anticline, in part because they are obscured by a dam in this area. Elsewhere, one or two, if not all three, straths have been eroded or buried. Because of a lack of mappable continuity of the three straths, the lowest surveyed terrace on the north side is the middle of these three straths, but the one on the south side appears to be the highest of the three. Mapping of different straths results in a 3-m offset in measured heights of what is plotted in figures 13 and 14 as the lowest terrace level.

Again the warping of the terraces is clearer when their heights are corrected for a regional slope (figure 13). The difference in heights of the end points of the measured profile, which extends both north and south of the anticline, gives a regional slope of 15 m/km. As inferred from the contour map at a scale of 1:50,000, this slope continues
Figure 12. The lower terrace across the south side of Tugulu anticline W-NW across the present Quergou Valley and along its western margin. The terrace is marked by discontinuous dark bands of gravel above less dark (red) Tertiary sedimentary rock and below white loess.

Figure 13. Terrace height profiles for remnants of different terraces along the Quergou He. Different symbols are used for the strath terrace, between the bedrock and the gravel, for the top of the gravel and its contact with the loess, or air in the case of the lower terrace, and for the present flood plain. We interpret the relatively steep northern front of the lowest terrace as erosional where the river debouches into this wide flood plain north of the anticline.

Figure 14. Terrace height profiles for remnants of different terraces along the Quergou He, with a slope of 15 m/km removed. As in figure 10, heights shown here give differences in heights between those measured and those calculated assuming a constant grade. Symbols as in figure 13.
southward for about 2 km, where the terrain is interrupted by a small anticline. To the north, the regional slope is much smaller across a broad flat cultivated flood plain.

Subtracting the regional slope of 16 m/km from the measured heights yields a height of about 35 m for the lowest terrace above the flanks of the anticline (figure 14). As for Dushanzi, we assign an arbitrary uncertainty of 10 m to the difference between this height and that of the initial profile. Given that there is more than one strath, the error in the height difference might be a little greater than for the lower Dushanzi terrace.

Only sparse remnants of higher terraces remain. Nevertheless, the second principal terrace over the crest of the anticline is continuous for several kilometers, and remnants of it are easily correlated (figures 13, 14, and 16). Similarly, the highest terrace on the north flank is also continuous for several kilometers (figures 13, 14). The highest terrace seen on the south flank, however, was visible on only one hill (figure 17).

Correlating such sparse, widely spaced remnants or differentiating them would be impossible were it not for one remarkable feature. In the two places where remnants of three terraces nearly overlap, the spacing between adjacent terraces is approximately an integral multiple of the height difference between the two lowest terraces (figures 13 and 14). On the south flank, the height (120–130 m) of the highest terrace (figure 17) above the lowest is roughly twice that (60–65 m) of the second above the lowest. On the north flank, the height (200–210 m) of the highest terrace above the lowest is roughly three times that (70 m) between the two lowest in this area. Because of this spacing, we infer that the high terrace on the south side is the third major terrace and projects to a position below the highest terrace on the north side (figure 14). Assuming such a correlation and the symmetry of the lowest terrace level, the maximum difference in heights of adjacent terraces is about 100 (±20) m (figure 14).

Inferred Ages of Terraces and Their Suggested Relationship to Climate Change

We estimated ages of terraces using three techniques: (1) radiocarbon dating of charcoal sampled above one strath in the lowest Tugulu terrace sequence; (2) measurements of the concentrations of $^{10}$Be, due to exposure to cosmic rays, in samples from the Dushanzi terrace surfaces; and (3) correlations of maximum terrace heights with periodic changes in global climate.

Correlations of Terrace Heights with Global Cli-
**Figure 16.** The second Qiurgou He terrace, roughly 100 m above the lowest one, along the N-NE on the south side of the anticline. The foreground slopes west toward the lowest terrace. The line across the hill in the background marks the contacts of a thin layer of dark gravel with bedrock and with overlying light colored loess. Points were measured to define the heights of this terrace on the south side of the anticline crest.

**mate Changes.** The apparently uniform spacing of the terraces across the Tugulu anticline reaches a maximum difference in elevation of about 100 m, comparable with the maximum (~125 m) spacing between the two terraces across the Dushanzi anticline. This spatial periodicity suggests that the processes that first created the flood plains and then abandoned them to leave terraces have been periodic in time. We consider the possibility of periodic growth of the anticlines due to tectonic processes to be absurdly remote. We assume that the anticlines have grown steadily, at least for times averaged over 1000 years or more, with a constant growth rate. Amplitudes of folds that form with constant rates of convergence should not increase at constant rates (Rockwell et al. 1988). For the dimensions of the folds studied here and for the depth of detachment of the folding rock, however, the decrease in growth rate during 150 m (Dushanzi) or 350 m (Tugulu) of growth should be only 10% or less, which is small compared with the errors in heights and inferred rates. Moreover, eventually, when the thrust fault reaches the surface, the rate of vertical slip should be proportional to the slip rate on the underlying surface of décollement, and the growth rate should be constant. We

**Figure 17.** The highest Qiurgou He terrace south of the Tugulu anticline, north view. The clear flat surface at the lower contact of about 2 m of dark gravel with the underlying bedrock and at the upper contact with light colored loess defines the highest terrace level on the south side of the anticline.
Figure 18. Oxygen isotopes measured from marine organisms in sediment deposited during the past 500,000 years [Imbrie et al. 1984]. Negative values of δ^18O indicate relatively warm periods with relatively little sea water contained in continental ice sheets.

suppose that this relatively uniform spacing of terrace heights seen for Tugulu and the nearly equal spacing between the two Dushanzi terraces are governed by periodic changes in erosion and deposition. We assume further that only climate changes could impose such a periodicity. The most pronounced variations in global climate since about 600 kyr B.P. have occurred with a period of about 100 kyr (e.g., Imbrie et al. 1984). Accordingly, each terrace would be roughly 100 kyr younger than the one overlying it.

A periodicity of 100 kyr in regional climate is strongly implied by the widespread evidence for such a periodicity in sea-surface temperature and in continental ice-sheet development (figure 18) (e.g., Hays et al. 1977; Imbrie et al., 1984). Similarly, the periodic changes in moist and dry climates in China some 1000 km farther east of these anticlines are clearly synchronized with these changes in temperature and continental ice sheet development (Kukla et al. 1988). Evidence suggesting a 100-kyr periodicity in the development of landforms, either depositional or erosional, is less definitive than that for sea-surface temperature. Nevertheless, others have inferred patterns of terrace development (e.g., Palmquist 1994; Porter et al. 1992; Reheis et al. 1991), stream incision (Winter et al. 1993), and deposition of coarse sediment (e.g., Koltermann and Gorelick 1992) with the same 100-kyr periodicity.

A simple argument based on the tectonics of the Tien Shan lends qualitative support to the inference that the ages of the adjacent terraces differ by about 100 kyr. The spacing of maximum heights of about 100 m between nested terraces and the inference of 100-kyr periodicity implies that the crests of the anticlines emerge from the flanks at a rate of about 1 mm/a. With an average net sedimentation rate of about 1 mm/a on the flanks of the anticlines, noted above, the bedrock of the anticlinal crests should rise above that in the flanking synclines at about 2 mm/a (figure 19). This rate equals the average growth rate inferred from amplitudes of the folds and their ages: 2 km since about 1 Ma for Dushanzi and 5 km since 2.5 Ma for Tugulu. For shortening at a constant rate, the uplift of the crest with respect to the flanks of a symmetric fold should decrease with time (Rockwell et al. 1988). For fold-propagation folds, however, in which the crest of the fold migrates with respect to the undeformed rock, the amplitude increases at a nearly constant rate. Thus, variations in time of average rates measured over folds as gentle as those studied here will be smaller than the uncertainties in the rates that we infer. Although this test of a 100-kyr periodicity is not definitive, the agreement in average rates over 100 kyr and 1 Myr is noteworthy.

The 1-mm/a difference between a growth rate of 2 mm/a and a sedimentation rate of 1 mm/a on the aggrading flanks yields estimates for the ages of the youngest terraces in the Dushanzi and Tugulu anticlines: approximately 25 kyr for Dushanzi and 35 kyr for Tugulu. Uncertainties are at least 10 kyr, given the assumed uncertainties in the inferred uplifts of terraces above the flanks of the anticlines. With these uncertainties, the abandonment of the lower Dushanzi terrace could have occurred since the last deglaciation, which began about 20 kyr B.P. (Bard et al. 1990), if not since the most recent global warming and melting about 13–15 kyr B.P. (Fairbanks 1990; Lehman and Keigwin 1992; Veum et al. 1992). The lowest Tugulu terrace level, however, seems to have formed before the last global glacial maximum about 20 kyr B.P.

**Durations of Exposure of Samples from the Dushanzi Terraces.** We measured concentrations of ^10^Be in 13 rock samples to determine durations that the surfaces of the Dushanzi terraces have been exposed to cosmic radiation. Cosmogenic nuclides, like ^10^Be, are produced in situ from interactions between secondary cosmic rays (mostly neutrons) and material exposed at the earth's surface. Because production rates of cosmogenic nuclides decrease exponentially with depth in rock, with a characteristic length of 0.5–0.6 m (or about 150 g/cm²) for ^10^Be (Brown et al. 1992; Kurz 1986), their concentrations are directly linked to the rock's exposure at the surface. The number of atoms of a cosmogenic nuclide at time t may be represented as a function of production rate, radioactive decay, and erosional loss:
Figure 19. Cartoon profiles of development of strath and fill terraces across the anticlines. Deposition occurs on the flanks as the anticlines emerge from this material. All profiles are vertically exaggerated. (a) Profile across partially eroded anticline showing position of river course at time $t_n$. (b) Profile along river shortly later, at $t_n + \Delta t$, after the river has rapidly incised into the anticline and the deposits upstream and downstream from it. Here $\Delta t$ is a time short compared to 100 kyr. Above the new river profile is an abandoned flood plain. The background relief of the anticline in (a) has been omitted. (c) Profile at $t_{n+1}$, approximately one cycle of river incision after $t_n$. The strath terrace over the anticline and abandoned between $t_n$ and $t_n + \Delta t$ has been warped up. The abandoned fill terraces on the flanks of the anticline have been buried. In the next short period of duration roughly $\Delta t$, the river will incise again to the level shown by the dashed line. (d) Profile at time $t_{n+2}$, approximately two cycles of river incision after $t_n$. Both strath terraces have been warped up over the anticline, and both fill terraces have been buried. Sediment accumulates on the flanks, while the strath terraces across the anticline emerge from the accumulating regions. The emergence rate is the ratio of the height of the crest of a terrace above the flanks. The growth rate of the anticline is the rate that crest of the anticline rises relative to the rock on the stable flanks. Thus, the growth rate equals the emergence rate plus the sedimentation rate on the flanks.

$$N(t) = \frac{P}{\epsilon / L + \lambda} [1 - e^{-t(\epsilon / L + \lambda)}] + N(0) e^{-t\lambda}$$  \hspace{1cm} (1)$$

where $P$ is the production rate per unit mass at the earth's surface, $\epsilon$ is the erosion rate, measured as a mass per unit area per unit time, $N(0)$ is the concentration of the nuclide at the beginning of the present episode of exposure, $\lambda$ is the radioactive decay constant, and $L$ is the characteristic attenuation length for production of the nuclide, expressed as a mass per unit area. The production rate of cosmogenic nuclides in a rock depends upon the altitude and the geomagnetic latitude and is subject to variability associated with changes in the primary cosmic ray flux, the earth's geomagnetic field, and solar activity. Assuming $N(0)$ to be negligible, the duration, $t$, of exposure of a rock may be expressed in terms of the concentration of a cosmogenic nuclide by

$$t = \frac{-ln[1 - N(\epsilon / L + \lambda)/P]}{\epsilon / L + \lambda}$$  \hspace{1cm} (2)$$
See Brown et al. (1991) and Lal (1988, 1991) for further discussion of this. For samples exposed for short periods (compared with the half-life of the radionuclide, which for $^{10}$Be is 1.5 My), and for reasonable erosion rates ($\epsilon/L \ll t$), equation (2) can be simplified to

$$t = N/P$$  \hspace{1cm} (3)

The application of cosmic ray exposure dating to the formation of these terraces requires the following assumptions. (1) At the initiation of the present period of exposure, the rocks were exhumed rapidly from depths and thus contained negligible concentrations of cosmogenic nuclides. (2) The rocks were deposited shortly before the flood plains were incised to leave the terraces from which they were sampled. (3) The rocks have been at the surface since they were deposited. We thus presume that concentrations of $^{10}$Be date the time when the flood plain ceased to be a surface over which the river flowed and on which material was deposited. We give arguments supporting (1) below. The assumptions (2) and (3), which if in error would render the measured dates too large or too small, respectively, are more difficult to justify. In any case, complex histories of exposure of samples might lead to significant scatter of inferred dates of samples from a single surface.

We gathered quartz-rich cobbles from the surfaces of both terraces on the west side of the Kuitun He. All of our samples were taken from the surfaces of terraces where they are relatively flat and far from steep topography that might obstruct cosmic radiation or shed younger material. Samples were cleaned and dissolved following previously reported methods (Brown et al. 1991). Measurements of $^{10}$Be were carried out at the Tandetron accelerator mass spectrometer (AMS) facility at Gif-sur-Yvette, France (Raisbeck et al. 1987). Reported uncertainties in both concentrations and durations of exposure are based on the analytical errors associated with counting statistics and with machine stability.

An important step in cosmic ray exposure dating is in the selection of an appropriate production rate for the latitude and altitude of exposure (e.g., Brook and Kurz 1993). At the latitude of our samples, the polygonal curve fits of Lal (1991) yield altitude-dependent production rates ranging from 9.9 to 10.8 at/g yr. Because these production rates were calibrated with results representing the average over approximately the last 10 kyr (Nishiizumi et al. 1989), they may be unrepresentative of production rates during earlier periods. In fact, the atmospheric $^{14}$C production curves of Bard et al. (1990) and Mazzaud et al. (1991) suggest that the 10-kyr average production rate is lower than the 30 to 50 kyr average. Analogous variability might be expected for the ground level cosmic ray flux as well. Should this be the case, durations of exposure calculated using production rates calibrated to 10 kyr could potentially be overestimated by as much as 25% for samples 15 kyr. These uncertainties will be reduced with improved knowledge of past variations in ground level cosmic ray fluxes.

The assumption that the rocks contained negligible quantities of $^{10}$Be at the initiation of their current exposure is supported by two lines of reasoning. First, the systematically lower concentrations of $^{10}$Be samples from the lowest terrace, than from those from the upper terrace (table 1), imply a shorter duration of exposure. The general coherence between relative dates expected from terrace positions and the experimental results provides qualitative evidence that “inherited” $^{10}$Be is not a major component. A second, more quantitative, argument is based on a calculated upper limit for the $^{10}$Be in rocks eroding from nearby mountains. The steady-state concentration of $^{10}$Be (equation 1 at $t$ approaches infinity) in rock exposed at 3000 m and subject to an erosion rate of 1 mm/a (reasonable values for the source rocks of this region),

### Table 1. $^{10}$Be Concentrations and Inferred Durations of Exposure of Samples from the Dushanjæz terraces

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Concentration ($\times 10^3$ atoms/g)</th>
<th>Duration of exposure (kyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Terrace, South limb, Southern section</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TS-91-1</td>
<td>4.5 ± 0.4</td>
<td>44 ± 4</td>
</tr>
<tr>
<td>TS-91-7a</td>
<td>1.5 ± 0.2</td>
<td>14 ± 2</td>
</tr>
<tr>
<td>TS-91-9a</td>
<td>2.7 ± 0.3</td>
<td>26 ± 3</td>
</tr>
<tr>
<td>TS-91-9b</td>
<td>3.0 ± 0.4</td>
<td>29 ± 3</td>
</tr>
<tr>
<td>Upper Terrace, South limb, Northern section</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TS-91-4</td>
<td>4.1 ± 0.4</td>
<td>41 ± 4</td>
</tr>
<tr>
<td>TS-91-5</td>
<td>17. ± 1.4</td>
<td>180 ± 15</td>
</tr>
<tr>
<td>TS-91-6a</td>
<td>7.2 ± 0.6</td>
<td>73 ± 7</td>
</tr>
<tr>
<td>TS-91-8</td>
<td>5.8 ± 0.7</td>
<td>59 ± 7</td>
</tr>
<tr>
<td>Lower Terrace</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TS-91-2</td>
<td>0.86 ± 0.16</td>
<td>8.4 ± 1.6</td>
</tr>
<tr>
<td>TS-91-3</td>
<td>1.1 ± 0.2</td>
<td>11. ± 2</td>
</tr>
<tr>
<td>TS-91-10c</td>
<td>1.5 ± 0.2</td>
<td>16. ± 2</td>
</tr>
<tr>
<td>TS-91-11b</td>
<td>1.4 ± 0.2</td>
<td>14. ± 2</td>
</tr>
<tr>
<td>TS-91-11d</td>
<td>2.1 ± 0.4</td>
<td>22. ± 4</td>
</tr>
</tbody>
</table>

Note. Durations of exposure are based on the altitude-dependent production rates with no temporal variation given by Lal (1991). Uncertainties are based solely on analytical uncertainties. Poor constraints on average production rates permit a maximum additional systematic error of about 30%.
would be 25,000 at/g. This maximum value is considerably smaller than those measured in the terrace deposits, providing an additional argument that "inherited" $^{10}$Be has not introduced an important error in inferred durations of exposure of these samples. Nevertheless, this hypothetical initial concentration is comparable to the scatter among the five measured concentrations. Therefore the magnitude of the scatter may reflect a variety of durations that the samples were exposed before being deposited. For instance, the sample dated at 22 kyr B.P. could easily have spent several thousand years accumulating $^{10}$Be while in a moraine, before being transported to the flood plain at 10–15 kyr B.P.

Four of five samples from the lower Dushanzi terrace yield dates suggesting exposure of this surface since the last global glacial maximum about 20 kyr B.P. Only by allowing for a conspiracy in both statistical errors, reported in table 1, and systematic errors of 30% associated with poor constraints on production rates, could the date of more than one sample be greater than 20 kyr. As noted above, the use of average production rates calibrated to 10 kyr to infer ages of samples exposed for longer than 15 kyr may have overestimated durations of exposure. Uncertainties in all dates permit them to be consistent with the terrace having been abandoned during or following the rapid warming about 13 kyr B.P. [e.g., Fairbanks 1990; Lehman and Keigwin 1992; Veum et al. 1992], especially if allowance is made for possible initial concentrations of $^{10}$Be.

Suppose the age of this terrace is 15 ± 5 kyr. Assuming steady growth of the fold, the ratio of heights of the lower and upper terrace above their projected initial profiles yields an estimate for the age of the upper terrace. Heights of the lower and upper terraces of 25 ± 10 m and 150 ± 20 m, respectively, suggest an age of 90 kyr. If all uncertainties are independent of one another, the uncertainty in that age is about 50 kyr.

Concentrations of $^{10}$Be from samples deposited on the upper terrace are the more difficult to interpret. Samples were collected from two sections of the southern limb of the anticline, where we could not measure the thickness of the gravel layer overlaying the sharply defined strath terrace in the crest of the anticline. With one exception, the dates of samples in the southern section, where the upper and lower terraces are parallel and undeformed, are smaller than those from the more northern section. Those from the southern section are younger than about 45 kyr, but those from the northern group, on the gentle south flank of the anticline, are somewhat older, ranging in age from about 40 to 180 kyr (figure 8, table 1).

The greatest date of 178 kyr B.P. is consistent with the suggestion made above that this upper terrace was an active flood plain during the penultimate glaciation, between about 200 and 135 kyr B.P. The use of this apparent age is supported by comparisons of the distributions of concentrations of $^{10}$Be in the two terraces. The relatively tight distribution of $^{10}$Be concentrations in the lower terrace suggests that the cobbles had fairly uniform concentrations when deposited, and therefore that the scatter for samples from the upper terrace must be due to post-depositional burial and re-exposure. Such processes could have shielded the cobbles from cosmic radiation for a portion of their exposure histories. In fact, reworked loess has been deposited over much of this terrace [Zhang Peizhen, pers. commun. 1993], suggesting that many of these dates may underestimate duration since deposition of the cobbles. Clearly, however, one date and the disclaimers for seven others cannot provide the basis for the assignment of an age of 135 kyr or greater to the upper terrace.

**Carbon-14 Date from the Lowest Tugulu Terrace Level.** We obtained charcoal from sand directly overlying the gravel on the middle strath of the lowest terrace sequence from the Tugulu anticline (figure 15). Abandonment of this strath occurred since the charcoal was deposited. In the area where this sample was found, there is an older strath about 2–3 m higher and a younger one about 5 m lower (figure 15). The date, determined by Beta Analytic, Inc. in Coral Gables, Florida (sample Beta-45800), is >33,900 radiocarbon years and hence does not allow an upper limit to be placed on the age of the terrace. (A correction for variations in cosmic radiation might make the age in calendar years 10% greater [Bard et al. 1990].) Because this date applies to the middle strath of the sequence, it permits a younger formation of the lowest strath. For the reasons given above, we presume that the age of the top strath is not as great as 100 kyr. Most importantly, this date of >33,900 years is consistent with the inference that the incision of the flood plains began during the glacial period between about 20 kyr and 60 kyr B.P. and before the last deglaciation and subsequent warming.

**Implications for the Development of Pleistocene Alluvial Terraces**

The nested terraces, with maximum differences in heights of roughly 100 m, are consistent with their
formation being roughly synchronized to the 100-kyr periodicity of global climate change. The heights of the lowest terrace levels suggest: [1] that the wide flood plains defined by these terraces formed during the last glacial period between about 60 kyr and 20 kyr B.P. and [2] that they were abandoned during or since the glacial period. This disagrees with the interpretation of Avouac et al. [1993] that both the widening of the valleys and their subsequent incision occurred during melting following the last glacial maximum. We studied different stream valleys, however, and we do agree that the lower Dushanzi terrace was an active flood plain at the beginning of the last deglaciation. We also agree that all of the low terraces are younger than the interglacial period between roughly 135 kyr and 110 kyr B.P.

Both the height and the concentrations of \(^{10}\)Be in samples from the lower terrace at Dushanzi suggest that it formed during the last deglaciation or in the transition from glacial to deglacial periods since roughly 20 kyr B.P. [Avouac et al. 1993]. A reasonable interpretation is that this flood plain was abandoned during the global warming about 12–13 kyr B.P. [Fairbanks 1990; Lehman and Keigwin 1992; Veum et al. 1992], when melting of alpine glaciers in the Tien Shan might have been rapid.

The heights of the lowest terrace level over the Tugulu anticline imply that the flood plains in this region not only formed, but also were abandoned, during the last glacial period between roughly 70 kyr and 20 kyr B.P. Because three separate straths, at least in the middle of the anticline, define the lowest Tugulu terrace level, the abandoning of the lowest of the three straths could have occurred more recently than 35 kyr B.P. Clearly, however, the height of the lowest strath above its projected initial level, of about 30 m, makes it very unlikely that the flood plain across the Tugulu anticline persisted as such a feature after the last global glacial maximum roughly 20 kyr B.P. [e.g., Bard et al. 1990]. The radiocarbon date exceeding 33.9 kyr also requires that the middle strath be older than the last global glacial maximum.

The late Quaternary histories of these terraces share some but not all similarities with terraces in other areas. Bull [1990, 1991] suggested that terraces can be classified into three categories: "tectonic," "climatic," and "complex response," where in most cases, strath terraces are tectonic and fill terraces are climatic. He associated tectonic terraces with terrains that rise steadily with respect to base-level and noted that in the absence of environmental changes, terraces should not form. Bull [1990, p. 357] envisioned climatic terraces to "represent brief reversals of long-term trends of tectonically induced downcutting," in which "climate-change induced aggradation" buried the strath terraces. Complex-response terraces are those not easily ascribed to major tectonic processes or significant climate changes. They can vary along the courses of streams because of feedback upstream and downstream among sediment supply, sediment transport, and changes in grade [e.g., Womack and Schumm 1977]. Bull [1990, 1991, p. 26] considered such terraces to be minor, compared with those associated more directly with tectonic and climatic processes.

Stream terraces along rivers in several alpine settings concur with glacial periods being characterized by aggradation. Bull [1990, 1991] reported this for the Charwell River in New Zealand. Reheis et al. [1991] and Palboquist [1994] suggested that fluvo-glacial processes built terraces near glaciers in the Rocky Mountains valleys. During deglacial periods, these terraces were incised. Similarly, Porter et al. [1992] associated glacial periods with aggradation along rivers emanating from the high terrain along the eastern margin of Tibet and deglacial periods with incision of them. To the best of our knowledge, the only well-studied set of terraces whose formation seems synchronized to global climate changes, but with a notably different phase, is from the American River in California. Shlemon [1972] argued that these terraces were affected as much by sea level changes as by variations in discharge and sediment supply. Clearly sea level changes ought not to have affected the terraces near the internally drained Tien Shan.

Whereas in tectonically relatively quiet areas, glacial periods are associated with aggradation of flood plains, they seem to be associated with widening of the valleys cut into bedrock across the actively growing anticlines in the Tien Shan. Bull [1990, p. 355] stated that "when rates of tectonically induced downcutting equal rates of uplift" [of rock relative to sea level], "erosional widening of valley floors in bedrock is the main process." It appears that this balance operated during cold, glacial periods north of the Tien Shan.

Because glacial periods were dry, at least in China 1000 km east of the anticlines [Kukla et al. 1988], the discharge in rivers probably was relatively low. During glacial maxima, however, alpine glaciers excavated valleys within the Tien Shan and provided debris to streams below them. Presumably, glacial periods were also characterized by aggradation upstream and downstream of the
anticlines. The accumulation south of the anticlines of roughly 2000 m of conglomeratic debris assigned a Quaternary age attests to relatively rapid sedimentation during the period when glaciation was frequent and widespread. Accordingly, material would have been either deposited before reaching the anticlines or transported beyond them. Aggradation could not occur on the river beds across the growing anticlines, and degradation was sufficiently rapid to keep pace with the growth of the anticlines.

During brief interglacial periods, melting of ice should have enhanced discharges in the rivers and probably sediment transport as well. One can imagine two possible extreme consequences of melting on the piedmont flanking the high range downstream: incision of the piedmont because of increased stream power [e.g., Bagnold 1966; Bull 1979], or rapid deposition resulting from greater sediment supply provided by the exposure of moraines and till. From the observations and inferences given above for the anticlines north of the Tien Shan and for tectonically inactive regions elsewhere, we infer that incision resulted from the concomitant increase in stream power. Whatever the increase in sediment transport during such intervals, the incision of the valleys into the old flood plains implies that such rivers eroded. The young age of the wide, flat lower Dushanzi terrace high above the present gorge, in particular, implies deep incision into the piedmont between the anticline and the pre-Mesozoic core of the Tien Shan since the last global glacial maximum.

The thick Quaternary deposits south of the anticlines imply that the development of terraces across the anticlines does not characterize the geomorphic evolution of the entire drainage basin. A few studies have demonstrated that aggradation or degradation need not occur synchronously along rivers [Bull 1991, p. 218–225; Reheis 1992; Reheis et al. 1991; Weldon 1986; Womack and Schumm 1977]. Because of the small dimensions of the anticlines, however, such temporal variations along the Tien Shan rivers probably have not contaminated the development of the segments of terraces across the anticlines.

The important difference between the terraces that we studied and those elsewhere is caused by the growth of the anticlines, which prevented significant aggradation across them [figure 19]. For this reason, the strath terraces across the anticlines on the north flank of the Tien Shan may not be typical of the more common aggradational terraces of tectonically more stable regions. The absence of widespread deposition and the dominance of erosion by rivers crossing the anticlines may make our results atypical for river terraces in most of the world, at least where active tectonics are mild or insignificant.

Regardless of how typical these terraces are, the apparent maintenance of streams near, if not at, grade during relatively dry global glacial maxima, without any obvious deep incision, suggests that gradual flood plain development can occur during periods of low discharge. Such flood plains can develop either by aggradation, as Bull [1990], Porter et al. [1992], and Reheis et al. [1991] noted, or by valley widening in bedrock. The rapid incision, apparently during periods when alpine glaciers melted, implies that abruptly increased discharge and stream power are responsible for the incision and abandoning of the flood plains. In the initial stages of melting, high sediment supply from the melting glaciers and from erosion of their moraines might make this period one of deposition, as Avouac et al. [1993] suggested, but there seems no escaping eventual deep incision during this period.

The correlation of river terraces, such as those north of the Tien Shan, with the roughly 100-kyr periodicity of climate change suggests that such geomorphic features can, at least in some situations, provide a useful clock for studying tectonic processes in tectonically active regions. Roughly equally spaced landforms, like terraces, have sometimes been assigned ages, from bottom to top, of Holocene, Late Pleistocene, Middle Pleistocene, etc., or Q4, Q3, etc. The results presented above, together with those of Koltermann and Gorelick [1992], Porter et al. [1992], Reheis et al. [1991], and Winter et al. [1993], suggest that such evenly spaced features might be assigned more precise ages of 20 \(\pm 10\) kyr, 140 \(\pm 20\) kyr, 260 \(\pm 30\) kyr, 340 \(\pm 30\) kyr, etc., corresponding to glacial maxima [figure 18] [e.g., Imbrie et al. 1984], or perhaps to systematically, somewhat earlier times, as the data from Tugulu imply. The spatial periodicity in the terrace heights and the proposed correlation with global climate changes suggest that orbitally controlled climate changes may offer a possible "quartz crystal" for a geomorphic clock in the study of tectonic processes.

An understanding for how river terraces, and other geomorphic features, form is vital for tuning such a clock. The incision of 150 m of the flood plain to form the most recent Dushanzi terrace apparently occurred during the most recent deglaciation and suggest synchronism with global climate change. The inference that the abandonment of flood plains to form the most recent Tugulu terrace did not occur during the most recent deglaciation,
however, suggests that not all alpine glaciers and/or fluvial systems in high altitude terrains follow precisely the same clock that sets the pace of continental glaciations. The most important alpine deglaciation in parts of the Tien Shan since 100 kyr B.P. might have been earlier than the most recent global deglaciation, as others have suggested for alpine glaciation: in the Sierra Nevada (Gillespie et al. 1984), the Vosges of France (Seret et al. 1990), and the French Alps (Montjuvent and Nicoud 1988).

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