A 900 k.y. record of strath terrace formation during glacial-interglacial transitions in northwest China

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ABSTRACT

The timing of the development of strath terraces with respect to climatic variability remains equivocal. Previous studies attribute strath-terrace formation to glacial or interglacial climates or to variations in sediment and water fluxes that cause lateral erosion followed by vertical incision. A chronology of strath-terrace formation spanning ~900 k.y. has been generated on the basis of loess-paleosol couplets and paleomagnetic, thermoluminescence, and radiocarbon dating of strath terraces in the Qilian Shan of northeastern Tibet. Repetitive stratigraphic and geomorphic patterns on each terrace indicate that they formed during glacial-interglacial transitions. Long-term bedrock incision rates and inferred rock uplift rates appear steady and unrelated to strath formation over the past 900 k.y.

Keywords: climatic control, strath, terrace, chronology, Tibetan Plateau.

CONTROLS ON FLUVIAL TERRACES

In their revolutionary study of Alpine glaciations, Penck and Brückner (1909) concluded that river terraces in the Alpine foreland correlated to glacial moraines in the Alps. They thereby inferred a link between changing climate and the formation of fluvial terraces. Over the intervening decades, the character of large-scale climatic oscillations has become well established (Martinson et al., 1987; Karner et al., 2002). Nonetheless, the timing of terrace formation with respect to those cycles remains controversial. Do terraces form during peak glaciations, deglaciations, or interglaciations? Whereas both aggradational (fill) and bedrock (strath) terraces may occur in a single river network, it is usually unknown whether they formed synchronously. Strath terraces are most commonly preserved in the mountains, whereas fill terraces are preserved in the lowlands: such spatial separation typically renders physical correlation impractical.

Perhaps the greatest obstacle to resolving these issues is that of chronology, because ages can define a terrace's position with respect to the glacial-interglacial climatic record, enable temporal comparisons among strath and fill terraces, and facilitate correlations to documented climatic or tectonic events. Paired river terraces are most relevant to these issues, because unpaired terraces can form due to autocyclic fluvial processes that are unrelated to tectonics or climate. Hence, we restrict this study to paired terraces.

Due to a reliance on radiocarbon dating, most previous chronological studies have utilized dates on organic matter preserved either within an aggradational fill or in the veneer of gravels that commonly mantles strath terraces. Even for many dated terraces <50 k.y. old, however, correlations with major climatic cycles are commonly ambiguous. Fill and strath terraces have been interpreted to correlate with peak glacial advances (Molnar et al., 1994; Penck and Brückner, 1909; Pinter et al., 1994), with deglacial transitions (Bull, 1991; Formento-Trigilio et al., 2003), and with nonglacial phenomena, such as monsoon intensification (Pratt et al., 2002) or migrating sediment waves (Weldon, 1986).

Longer records, extending through multiple glacial cycles, should help to clarify whether a consistent timing of terrace formation exists vis-à-vis climatic cycles. Developing the requisite chronologic control, however, is commonly difficult. Radiocarbon dating is widely applied to both fill and strath terraces, but its usefulness typically extends no farther back than 45 ka—insufficient to create long-term records. Strath terraces, by definition, are cut on bedrock, where the beveled surface is commonly mantled with a thin veneer of gravel or colluvium. Even when dated, such materials only provide minimum limiting ages for strath formation. Furthermore, for gravels or bedrock surfaces >50 k.y. old, most dating techniques, such as uranium series on pedogenic cements (Ku, 2000) or cosmogenic nuclide exposure dating of clasts or bedrock straths (Anderson et al., 1996; Bierman, 1994), have sufficiently large uncertainties (>5–10%) that detailed comparisons with climate or tectonic records are precluded, given the frequency of climatic oscillations (Karner et al., 2002). Consequently, long-term chronologies require different dating approaches that still have sufficient accuracy to compare terrace, climate, and tectonic records.

In this study we present a new chronology that extends through at least eight glacial-interglacial cycles in an actively deforming region of northeastern Tibet. Using a combination of paleomagnetism, thermoluminescence dating, paleosol-loess stratigraphy, and radiocarbon dating, we develop sufficient time control on a succession of paired strath terraces to demonstrate that long-term rates of tectonic forcing and river downcutting are steady throughout this interval and that strath formation is repeatedly correlated with deglacial transitions. Hence, we conclude that specific climatic conditions, independent of tectonics, promote strath formation.

STUDY AREA AND METHODS

The Qilian Shan are actively shortening ranges (Tapponnier, 2001; Yin and Harrison, 2000) defining the northeastern margin of the Tibetan Plateau. Rivers flowing northeastward off this margin display well-developed terrace sequences (Chen et al., 1998; Jia et al., 1994; Li et al., 1999), but few ages have been previously obtained for these loess-mantled terraces. Moreover, little agreement exists among the ages of terraces that have been dated (Jia et al., 1994; Li et al., 1999).

This study focuses on the Shagou River, an intermittent river of ~50 km length (Fig. 1), which originates at ~3500 m in the currently unglaciated parts of the Qilian Shan. The Shagou River flows between the uplifted foreland-basin fill in its upper reaches and actively aggrading alluvial fans in its lower reaches in the Hexi Corridor. A succession of five strath terraces is incised into the foreland deposits of the uplands. Each strath grades downstream to

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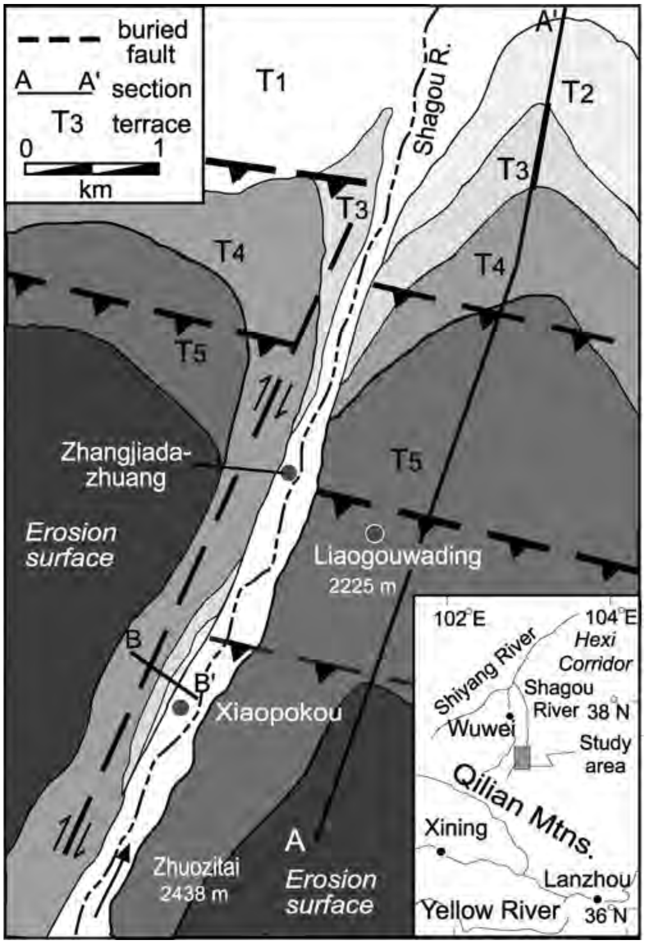

Figure 1. Distribution of terraces and conglomerate fans in lower reaches of Shagou River in eastern Qilian Shan, northeastern Tibet. Inset depicts regional setting of Shagou River. Line A-A′ defines longitudinal geomorphic profile (Fig. 2), and line B-B′ defines valley section (see Fig. 3).

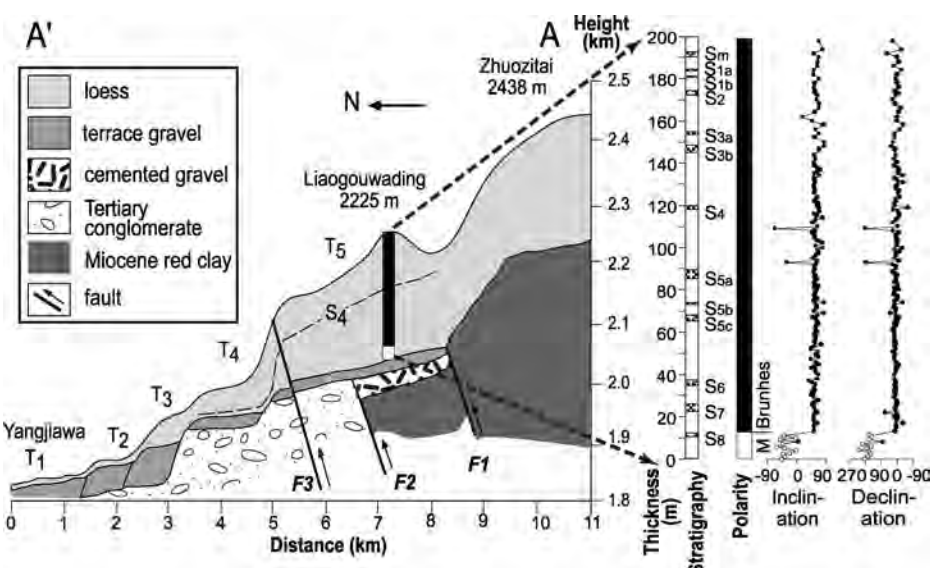

Figure 2. Schematic longitudinal section of terraces and loess cover along Shagou River. Strath terraces are incised into Miocene red clay or uplifted foreland conglomerates. Paleosol S_4 is shown for reference. Highest terrace (T_5) is cut by small-displacement faults. Magnetostratigraphy on T_5 terrace (shown on right) of 200-m-thick loess sequence (with numbered paleosols correlative to those in Loess Plateau: Liu, 1987) records Brunhes-Matuyama boundary and indicates strath formed before 845 ka. See Figure 1 for profile location.

an alluvial fan surface and is capped with a thin veneer of gravel, which is in turn overlain by as much as 200 m of loess.

As in much of northwestern China, the loess succession comprises couplets of thick, largely unaltered loess alternating with thin paleosols (Liu, 1987). Previous studies show that paleosols form during interglacial times characterized by reduced loess influxes (Kukla et al., 1988; Liu, 1987). The loess succession in northwestern China has been successfully correlated to the oxygen isotopic record of Quaternary climate change (Ding et al., 1995; Kukla et al., 1988), thereby providing a chronology of Quaternary climate change. Beginning with Holocene soils (S_0), the paleosols are sequentially numbered and assigned to successively older interglaciations (Fig. 2).

For each terrace, field observations define the strath's elevation, the bedrock beneath it, the thickness of capping gravels and overlying loess, and the sequence of paleosols (if any) within the loess. A chronology of the terrace succession was developed using radiocarbon dates on organic debris, paleosol stratigraphy, and thermoluminescence (TL) dates of loess-bounding paleosols.

On the highest terrace, a 200-m-thick loess and paleosol sequence provides an age estimate for the underlying strath. Paleomagnetic sites (3 samples/site) were collected every 1–2 m. The samples were progressively demagnetized to 600 °C or to 600 Oe. Similar to previous results (Burbank and Li, 1985), secondary magnetizations are effectively removed by 250–300 °C or 300 Oe, such that the characteristic remanence directions are clearly identifiable at temperatures >300 °C or alternating field strengths of 300 Oe. The results shown here follow demagnetization in a peak field of 350 Oe.

TIMING OF STRATH FORMATION

All of the pre-Holocene straths are beveled across a Miocene red clay unit (Guo et al., 2002) that is widely recognized around the Loess Plateau. The highest strath (T_5, Figs. 2 and 3) is overlain by a 5-m-thick cemented conglomerate capped by a 10-m-thick sand-gravel unit. The basal 13 m of the loess sequence above the gravel is reversely magnetized and is capped by a paleosol, whereas the remaining 186 m of loess is normally magnetized and contains numerous paleosols (Fig. 2). The magnetic reversal is correlated to the Brunhes-Matuyama boundary, thereby indicating an age of 790 ka at a height of 13 m above the strath. If the average accumulation rate (~24 cm/k.y.) within the Brunhes chron is extrapolated downward, it indicates that loess accumulated after ca. 845 ka (during marine isotopic glacial stage 20; Karner et al.,

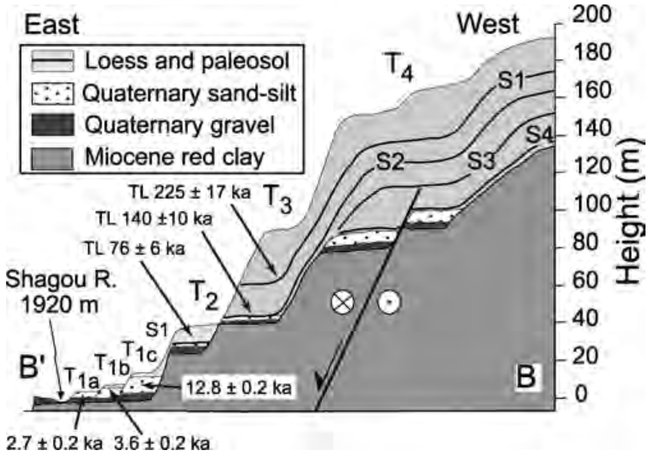

Figure 3. Cross-valley profile of lower four terraces along Shagou River near Xiaopokou. Strath surfaces are visible beneath all except youngest (T_1) terrace. T_4 is displaced by oblique-slip fault and covered with ~70 m of loess. Soil S_4 at base of T_4 terrace cover formed ca. 425 ka based on stratigraphic comparison with marine isotopic record (Karner et al., 2002) and paleosols in Loess Plateau (Liu, 1987). On terrace T_3, soil S_2, with thermoluminescence (TL) age of 225 ± 17 ka, correlates with isotope stage 7 (200–220 ka) interglaciation. On terrace T_2, soil S_1 is bracketed by TL ages of >78 ± 7 ka and <140 ± 10 ka, placing it in last interglaciation. On lowest terrace, ^{14}C dates in fluvial sediment mantling underlying strath indicate that strath was formed before 13 ka. See Figure 1 for profile location.

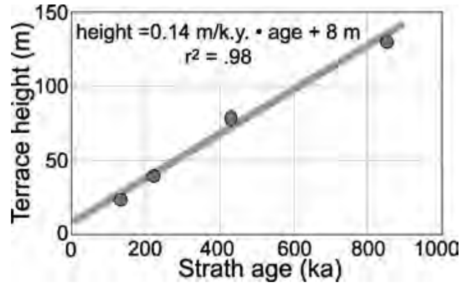

Figure 4. Reconstructed bedrock incision based on strath heights and ages, Shagou River. Long-term rate of bedrock incision is ~0.14 mm/yr over past 870 k.y.

2002). The basal cemented conglomerate suggests an earlier, initial interval of slow accumulation and perhaps pedogenesis after the strath was created. If so, the strath formed just prior to isotope stage 21 ca. 870 ka.

There are no direct dates for the fourth terrace (T_4, Fig. 3). The strath is offset ~10 m by a tear fault and is overlain by ~10 m of gravels and floodplain silt and sand. The ~70 m of loess overlying the strath contains 4 suites of paleosols, the oldest of which is developed on the basal 1–3 m of the loess sequence. By correlation of the paleosol succession with the marine isotope record (Karner et al., 2002), the basal paleosol can be assigned an age of ca. 420 ka.

The T_3 strath is mantled by 2 m of gravel capped by 2 m of silt. The overlying loess sequence is ~50 m thick and contains 2 paleosols. As with the fourth terrace, the basal paleosol (S_2) is at the base of the loess section (Fig. 3). A TL date on that paleosol indicates an age of 225 ± 17 ka, whereas the overlying paleosol (S_1) yields a TL date of 140 ± 10 ka. Given that paleosols are known to form during interglaciations (Kukla et al., 1988), paleosols S_1 and S_2 should correlate with marine isotope stages 5 and 7, respectively.

The T_2 terrace reveals 2–3 m of gravel and ~2 m of silt above its strath (Fig. 3). The overlying loess attains ~30 m thickness. At its base, the loess contains one paleosol, for which a TL date indicates that the paleosol formed before 78 ± 7 ka. When combined with the date on the correlative paleosol on T_3, these TL dates confirm formation of S_1 during the penultimate interglacial stage.

The lowest terrace (T_1; Fig. 3) actually consists of three latest Pleistocene–Holocene fill terraces. A bedrock strath underlies the fill, but is typically unexposed. Radiocarbon dates indicate that aggradation was ongoing ca. 12.8 ka, 3.6 ka, and 2.7 ka, respectively, on the three terraces. The age of the oldest fill indicates that the youngest strath formed prior to 13 ka, but after the loess accumulation during the last glaciation.

The height of each strath above the modern river level (Table 1) and its age define a long-term rate of bedrock incision of ~0.14 m/k.y. (Fig. 4), and, within uncertainty, the rate has been steady for the past 850 k.y. Although faults displace several terraces, the net slip is small (<10%) compared to the magnitude of downcutting. The simplest interpretation is that episodic tectonic deformation has not influenced specific events of terrace creation. Instead, tectonism may have driven relatively steady rock uplift of the headwaters of the Shagou River with respect to the Hexi Corridor and thereby caused overall incision in response to a steepened gradient.

DISCUSSION

Do strath terraces form primarily during glacial-interglacial transitions, irrespective of tectonic forcing? This is a two-part process; i.e., creation of a strath followed by abandonment due to vertical channel incision. Only after abandonment do nonfluvial processes, such as loess accumulation or paleosol formation, occur on top of the strath.

Both the TL dates on the paleosols and the ready correlation of the paleosol succession on terrace 5 (paleosols 1–8, Fig. 2) to the well-documented loess-paleosol stratigraphy on the Loess Plateau (Liu, 1987) suggest that no paleosols are missing in the Shagou sections and that they can be reliably used to assign ages to the suprastrath stratigraphy. One key aspect of the loess-paleosol stratigraphy of terraces T_2, T_3, and T_4 is strikingly similar: the basal paleosol on each is typically developed in 1–2 m of loess directly above the straths. This thin loess cover suggests that the straths did not form during full interglacial conditions, because an influx of loess persisted prior to soil formation. Nor were the straths cut and abandoned during full glacial time; otherwise, thicker loess deposits should underlie the paleosols. We conclude that each strath was abandoned during the transition from glacial to interglacial climates, thereby demonstrating a predominant climatic control on strath genesis.

Terrace 5 does not have a paleosol at the base of its loess sequence and does not conform clearly to the glacial-interglacial timing of strath formation. We have no unambiguous explanation for this difference with the other terraces. We note that, in contrast to the other straths, the stratigraphy on this strath is more complicated and includes a cemented, 5-m-thick conglomerate directly overlying the strath. Well-cemented conglomerates can form due to repeated percolation and evaporation during an interval of surface stability; the same conditions under which soils often form.

TABLE 1. CHARACTERISTICS OF SHAGOU RIVER TERRACES

Terrace	Height of strath above water level (m)	Thickness of gravel layer (m)	Thickness of fluvial silt (m)	Thickness of eolian loess (m)	Height above closest lower terrace (m)	Age of incision (ka)
T_1C		0.5	>9	4–5	8.5*	10
T_2	25	2–3	1.5–2	~30	15	135
T_3	40	~2	1.7	53	15	235
T_4	75–85	2.0–2.6	7	66–73	35–45	434
T_5	130	~2.5	3	199	45	~870

*Height above water level of river.

Our proposal, that the cemented conglomerate is climatically analogous to the paleosols developed above the younger, lower straths and could have formed following a glacial-interglacial transition, remains to be tested with a more accurate chronology.

Straths are proposed to form when (1) sediment fluxes are sufficiently high to commonly cover the channel bed, (2) discharge is sufficiently low to be unable to mobilize enough sediment on the bed to expose the bed to erosion, and (3) the resulting rate of lateral erosion is much greater than the rate of vertical incision (Hancock and Anderson, 2002). Enhanced sediment fluxes, as recorded during deglaciation (Church and Slaymaker, 1989), could generate these conditions and promote strath formation. If the bedrock is readily eroded, as is the case with the Miocene red clays in this study, wide straths can be rapidly generated.

When the sediment flux falls below the transport capacity, the bed is reexposed and fluvial incision recommences, thereby transforming the strath to a strath terrace and isolating it from channel processes. During a waning deglacial stage, a thin veneer of loess can accumulate on the strath, providing parent material for subsequent paleosol formation. If renewed incision occurs too late in the deglacial interval, loess deposition may have effectively halted, and any paleosol would form in the terrace gravels, as may be the case for the oldest strath (T_5) in our study. Whereas the data presented here do not directly date strath formation, they indicate that abandonment of formerly active straths and creation of terraces occurred during deglacial time.

Although 8 major deglaciations have occurred since 800 ka, only 5 straths are exposed in the study area. The most recent one is buried beneath the Holocene fill. The other ''missing'' straths may never have formed if the deglacial sediment/water ratio was insufficiently large or sustained, or they could be obscured by younger, but larger sediment influxes that caused the active channel to overtop or reoccupy previously formed straths. Although the strath record may therefore be incomplete, its implications are clear: during at least 5 deglaciations within the past 870 k.y., climatic conditions favored strath formation.

CONCLUSIONS

Even in tectonically active settings, climate variations commonly determine when a strath will be cut and when a river will incise. Tectonic deformation provides a background forcing that can amplify elevation contrasts along a river's course and drive long-term fluvial incision. In northeastern Tibet, a remarkable record of straths and loess accumulation spans the past 870 k.y. and restricts strath formation to a specific climatic interval. Strath formation clearly precedes full interglacial conditions when paleosols are formed. The observation that the oldest paleosol in each terrace sequence is close to the strath surface and is in turn overlain by 10–20 m of loess before a subsequent paleosol is preserved argues that strath terraces do not form during full glacial conditions. Rather, the position of paleosols within the loess sequences indicates that strath terraces form during glacial-interglacial transitions, and that tectonic control on specific intervals of strath formation is negligible.

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