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1 Background

Rivers play a dominant role in the earth surface process system on the continents, providing the major pathways for both the water and sediment fluxes, causing material transport from land to ocean. In response to changes in discharge, slope and sediment load, a river can incise or aggrade. The related evolution of river systems is controlled by internal processes and external forces induced by climate change, tectonic movements and anthropogenic influences. Unravelling the relative contributions of these factors is one of the most challenging goals of fluvial geomorphological research (Schumm, 1965; Vandenberghe, 1995a; Bridgland *et al.*, 2000; Bridgland and Westaway 2008; Wang *et al.*, 2015; Cordier *et al.*, 2017; Rits *et al.*, 2017). Alternations of aggradation and incision, and the formation of fluvial terraces may reflect the different impacts of individual driving forces (e.g. Mather *et al.*, 2017).

As concerns climate forcing, morphological cyclicity in temperate and cold regions has generally been attributed to cold (glacial)-warm (interglacial) alternations in settings with a background tectonic uplift (e.g., Büdel, 1977; Vandenberghe, 1993, 1995b; Van den Berg, 1996; Maddy *et al.*, 2001; Starkel., 2003; Lewin and Gibbard, 2010; Bridgland *et al.*, 2017). But, similar climate-driven terrace staircases do exist also in other climatic environments (e.g., Bridgland and Westaway,2008; Pan *et al.*, 2009; Wang *et al.*, 2013; 2015; Gao *et al.*, 2016; Jia *et al.*, 2017).

The climate-driven model fails to explain the progressive Quaternary valley incision, which is suggested to be the result of fluvial system adjustment to long-term regional uplift. The degree of regional uplift is a key issue in the generation and subsequent preservation of terrace flights (Maddy *et al.*, 2001; Bridgland and Westaway, 2008; Wang *et al.*, 2014, 2015), as it can force a river system to incise during each climate cycle to separate terrace levels adequately. Terraces can be generated only when the regional uplift rate is sufficiently high (e.g., Pan *et al.*, 2009). Based on the assumption that terrace surfaces record net incision driven by tectonic uplift, the vertical separation and the longitudinal profiles of terrace surfaces have widely been used to infer tectonic uplift rate (e.g., Van Balen *et al.*, 2000; Maddy *et al.*, 2001; Van den Berg and Van Hoof, 2001; Peters and Van Balen, 2007; Demoulin *et al.*, 2017).

In contrast to large-scale tectonic movements, tectonic differentiation at small scale may lead to a variegated fluvial morphology. For example, in the Huangshui catchment (Northeastern Tibetan Plateau) areas of fluvial incision and aggradation spatially alternate and erosion and accumulation terraces simultaneously develop at relatively short distances indicating effects of relative uplift and subsidence on relatively small spatial scales (Wang *et al.*, 2010, 2014; Vandenberghe *et al.*, 2011).

The relation between forcing intensity by climate and tectonics and fluvial response is not linear due to the preponderant role of delay effects and thresholds (Schumm, 1979; Knox, 1972; Vandenberghe, 2002; Veldkamp *et al.*, 2017). For instance, fluvial incision may lag behind uplift as the river may be dependent on a climatic change to enable incision to take place (Maddy *et al.*, 2001). Tectonic movements and climate are independent forcing factors and their interplay may result in conflicting, or at least complex, effects on the fluvial morphology (Wang *et al.*, 2015; Van Balen *et al.*, 2016). Until now, both forcing factors have been approached as separate as possible. However, it is challenging to investigate the complex result of their interference.

The Northeastern Tibetan Plateau (NETP) (Figure 1) is one of the tectonically most active regions in the world. However, it also experienced drastic climate changes. For example, during the LGM mean annual temperatures were at least 7° less than at present leading to the expansion of glaciers and the initiation of periglacial processes (Wang *et al*., 2013). Thus, geological and geomorphological records of river evolution in the NETP are ideal for studying the impacts of the coupled effects of tectonic motions and climate changes on fluvial processes. At here we review the studies of the fluvial morphological development and the resulting sedimentary architecture of fluvial deposits in the NETP, mainly based on the case of the Huangshui catchment.

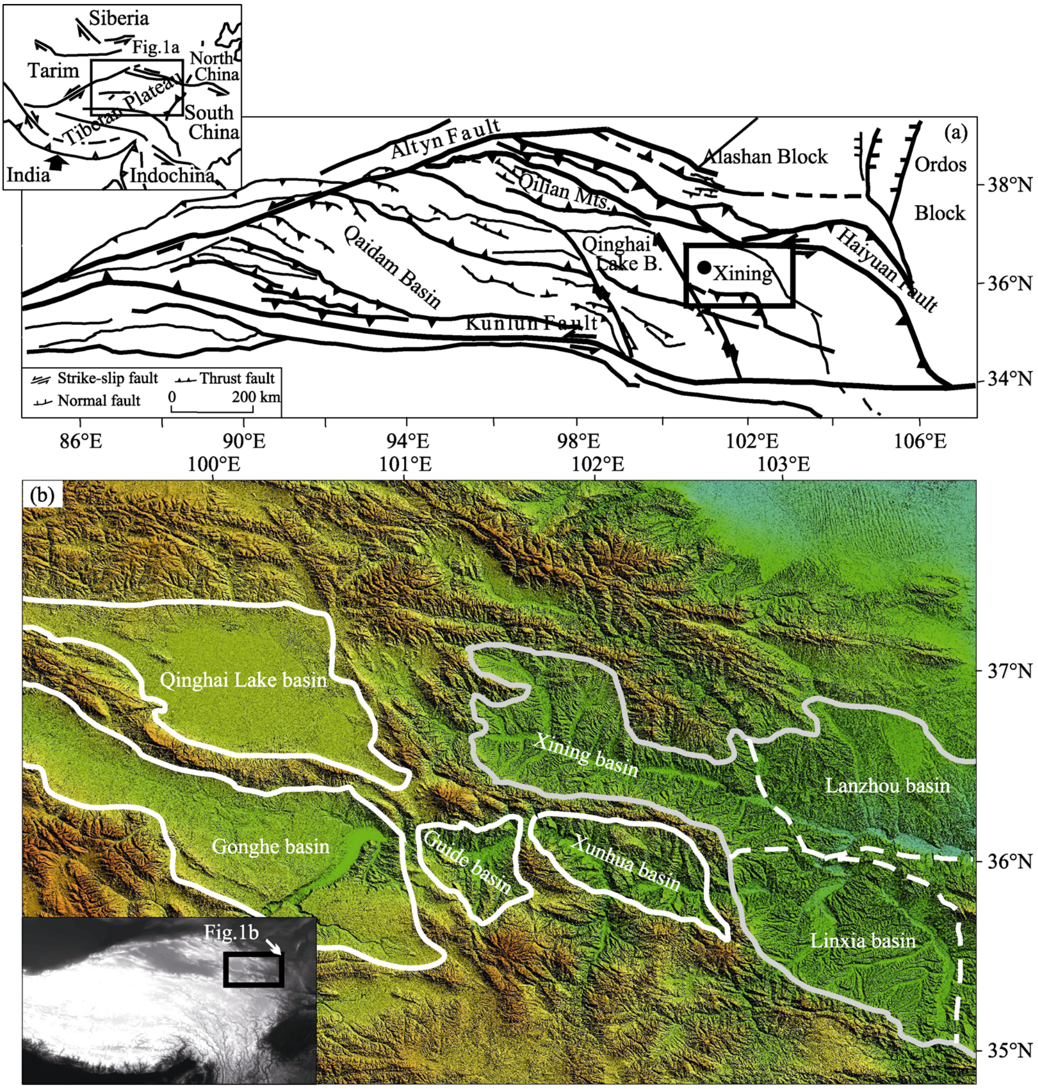

Figure 1 (a) Simplified map of major tectonic boundaries and Tertiary faults in the Northeastern Tibetan Plateau (after Dai *et al*., 2006); (b) Morphologic characteristics of the NETP derived from Aster Global Digital Elevation Model data

2 Geological and geomorphological background

The NETP, undergoes coeval crustal shortening and left-lateral strike-slip faulting, related to the northeastward growth of the plateau margin as a result of the collision of the Indian and

Asian plates. The crustal deformation primarily due to these relative plate motions is expressed by folding and faulting of the Paleozoic to Cenozoic bedrock (Figure 1). Within the NETP, also syn-orogenic basins were formed, such as the Gonghe basin (Craddock *et al*., 2010), Linxia basin (Li *et al*., 1997), Baode basin (Pan *et al*., 2010; Hu *et al*., 2017) and Xining basin (Figure 1). The basins have been filled with thick continental clastic red beds, while simultaneously the surrounding highs were bevelled (as in the areas surrounding the Xining basin, see further discussion below). Subsequently, the area was incised by rivers in response to regional tectonic uplift of the Tibetan Plateau and local deformation affecting even the red basin fills, probably during the Pliocene and Pleistocene (Li, 1997; Fang *et al*., 2005; Gao *et al*., 2008; Stroeven *et al*., 2009; Craddock *et al*., 2010; Hu *et al*., 2017).

The deformation in the study area was controlled by two major large sinistral strike-slip faults, the Altyn-Haiyuan Fault in the north and the Kunlun Fault in the south (Figure 1; Tapponnier *et al*., 2001; Dai *et al*., 2006). The offset along these faults decreases gradually in eastward direction, which is accommodated by internal compressive deformation (Tapponnier *et al*., 2001; Dai *et al*., 2006). This deformation has resulted in a tectonic mosaic, consisting of open folds, and reverse and normal, dextral- and sinistral strike-slip faults, leading to the formation of alternating subsided and uplifted blocks of more limited extent than the large Mesozoic-Early Cenozoic basins, resulting in a fragmentation and compartmentalization of the former basins and inter-basin areas (Figure 1).

The Yellow River and its tributary, such as Huangshui River which is the focus of the study, follows a series of those uplifted and subsided blocks that resulted from the fragmentation of the Xining and other basins. The basement of the Xining Basin consists of Proterozoic gneisses and schists, Cambrian gray limestones and green basalts and Mesozoic clastic sediments (QBGMR, 1991; Dai *et al*., 2006). Cenozoic successions of playa to fluvio-lacustrine environments, concordantly overlying the Cretaceous clastic sediments or discordantly older basement rocks, have been subdivided into the Xining and Guide Groups. In addition, 'fanglomeratic' rocks unconformably overlie the Guide Group (QBGMR, 1991; Dai *et al*., 2006). The Huangshui cut ~600 m into the Cenozoic strata and the Proterozoic-Mesozoic basement rocks, and meanwhile built a well-shaped staircase of terraces in the Xining basin (Figure 2) (Lu *et al*., 2004a; Vandenberghe *et al*., 2011). The youngest deposits consist of aeolian sediments that blanket the landscape.

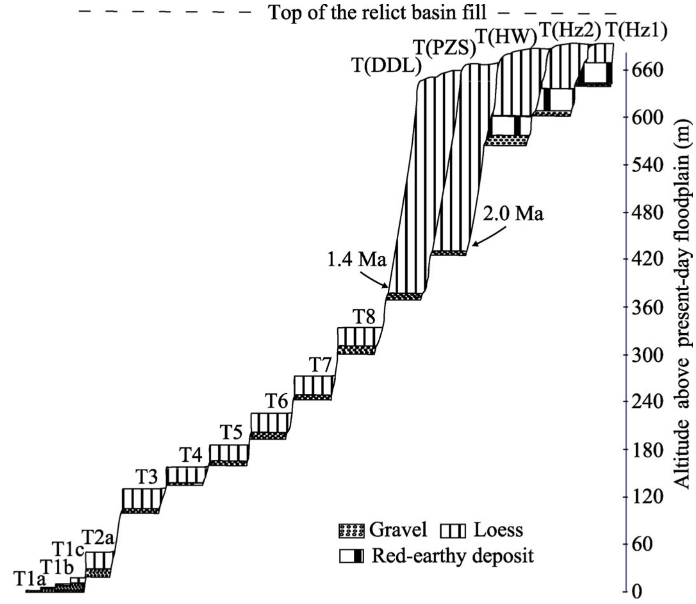

Figure 2 Terrace sequence along a schematic section in the Xining basin (modified after Lu *et al*., 2004a, and Vandenberghe *et al*., 2011)

3 Quartz Optically Stimulated Luminescence (OSL) dating of fluvial sediments in the NETP

Datings are the prerequisite to unravel the details of the relationship between the fluvial events (as terrace formation, processes of erosion and deposition) and climate changes, and they are also significant to examine the neo-tectonic process in the NETP. It is difficult to establish a reliable chronological control by ^{14}C dating for the last-glacial events in the study region because of the dating limit (<45 ka) and the lack of suitable dating materials in this arid and cold area. The typical fluvial channel sands, floodloam sediments, outwash fans and glacial- and fluvio-glacial sediments were successfully dated using quartz optically stimulated luminescence (OSL) with the single aliquot regenerative-dose (SAR) protocol (Wang *et al*., 2013, 2014, 2015).

A small but sufficient amount of fine-sand quartz could be extracted to permit standard SAR-OSL analysis. The measurements using small aliquots (or single grains) might be the best to assess the degree of partial bleaching and date glacial and glacio-fluvial sediments, as they are likely to suffer from poor or inhomogeneous bleaching. However, the measurements show that OSL signals of most samples in the Tibetan Plateau were not bright and that their luminescence sensitivity was low (Wang *et al*., 2013). The results of the measurements using small aliquots for selected relatively bright samples show the distributions of the equivalent doses are broad, with relative standard deviations in the range of ~16% to 26%, and display little or no asymmetry (Figure 3) (Wang *et al*., 2013). In addition, the un-weighted average De's using small aliquots are not different from the values obtained using large aliquots. These results indicate a well-bleached nature of glacial- and fluvial sediments in the NETP, and do not hint at incomplete resetting as a significant source of error. Also, it has been ar-

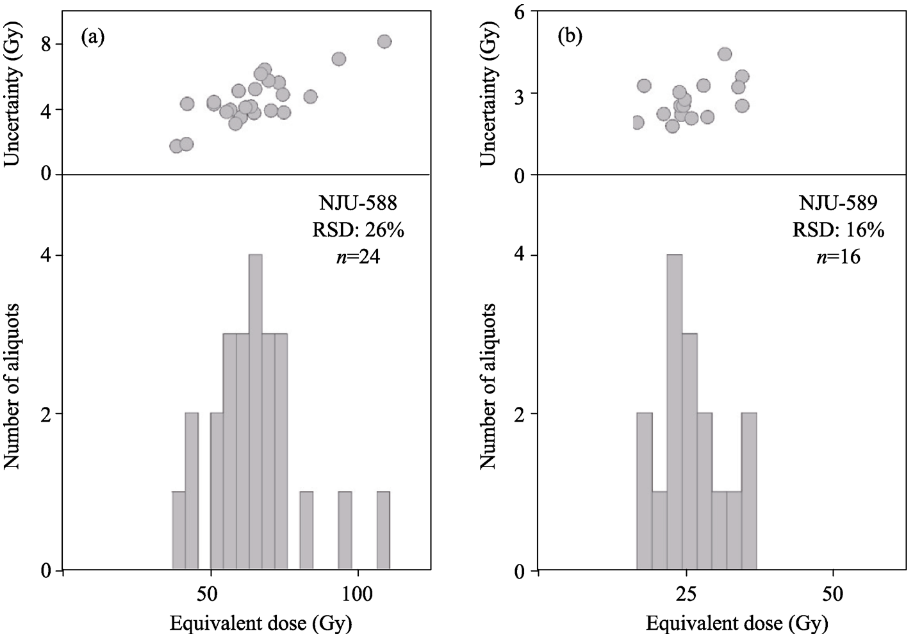

Figure 3 Histogram of De distribution for typical samples in Menyuan basin using small aliquots (after Wang *et al*., 2013)

gued (see e.g. Murray and Olley, 2002; Jain *et al*., 2003) that incomplete resetting is unlikely to give rise to significant age overestimations for samples older than a few ka, even in glacio-fluvial environments. Thus the Quartz-based ASR-OSL analysis could provide robust age control for glacial and fluvial terrace deposits in the NETP, although they should, at least in principle, be considered as maximum ages.

4 Morpho-tectonic and geomorphological evolution of the NETP

Several stages can be discriminated in the geomorphological evolution of the Huangshui catchment, inferred from basin filling, planation and fluvial terraces in the Huangshui catchment (Vandengerghe *et al*., 2011; Wang *et al*., 2012). During the first stage, the landscape consisted of mountains and filled-up basins that were leveled synchronously, ultimately resulting in the formation of a peneplain (Figure 4). This peneplain thus consists partly of a bedrock surface and partly of the eroded top of the basin fills. This kind of surface has also been documented at several other places besides in Huangshui catchment (e.g., Clark *et al*.,

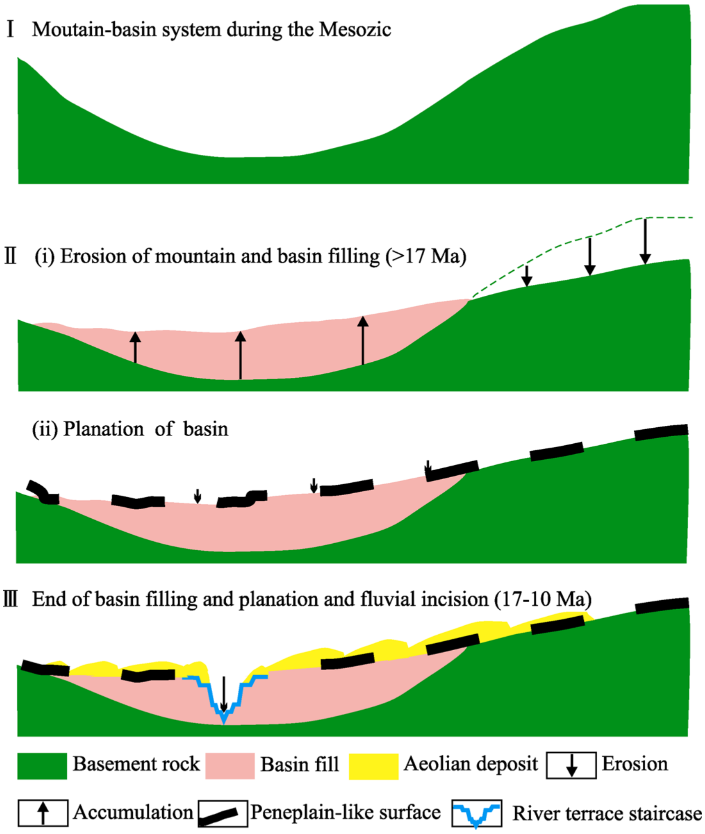

Figure 4 Schematic diagram illustrating the geomorphologyical evolution of the Xining basin and the formation of the relict surface (modified after Wang *et al*., 2012). Firstly, the tectonic basin was formed before the Mesozoic (I). Then, the surrounding mountains eroded and the basin was filled (II,i). As a last stage in this step, limited and very local erosion in the basin might have slightly lowered the surface formed in II (i), ultimately resulting in the formation of a peneplain surface (II, ii). Finally, tectonic uplift caused the Huangshui to incise vertically into the surface, producing a terrace sequence (III).

2006; Pan *et al*., 2007; 2010, 2012; Craddock *et al*., 2010; Hu *et al*., 2017). Indeed, two planation surfaces on the top of folded strata from the eastern Qilian Mountains, around one hundred km north of the Huangshui catchment have been reported by Pan *et al*. (2007): an older ‘main surface’ and a younger ‘erosion surface’ (1.4 Ma). According to its age (Wang *et al*., 2012), the peneplain-like surface in the Huangshui catchment might be equivalent to the 'main surface' in the eastern Qilian Mountain. During the second stage, the Huangshui incised into the peneplain surface, producing a terrace sequence (Figure 4). The transition from peneplain formation to incision in the study region was dated as older than 10–6 Ma using the biochronology of micromammalian assemblages from fluvial terraces. In addition, it is should be younger than the final filling of the tectonic basins, that is around 17 Ma according to Dai *et al*. (2006).

Erosion surfaces have served as important markers of tectonic uplift and deformation (e.g., Epis and Chapin, 1975; Spotila and Sieh, 2000; Clark *et al*., 2004). The combination of rapid fluvial incision into bedrock and relict geomorphic surfaces have been interpreted to reflect a tectonic uplift on the southern Tibetan Plateau margin with a magnitude equal to the incision depth (Burbank *et al*., 1996). At the southeastern margin of the Tibetan Plateau, relatively flat and highly elevated surfaces of postulated pre-uplift age were also reported, which were heavily dissected, creating steep fluvial valleys, and indicating the relative lowering of base levels due to tectonic uplift (Clark *et al*., 2004, 2006; Schoebohm *et al*., 2004, 2006). Thus, the end of basin filling and the start of the incision in the Huangshui catchment may thus be attributed to an important uplift event starting at around 10–17 Ma (Lu *et al*., 2004a; Wang *et al*., 2012).

The entrenchment rate of the Huangshui was not stable. It accelerated for instance from 2 cm/ka to 19.5 cm/ka at around 2 Ma (Vandenberghe *et al*., 2011; Wang *et al*., 2012), indicating a specific phase of accelerated uplift (Lu *et al*., 2004a; Miao *et al*., 2008; Vandenberghe *et al*., 2011; Wang *et al*., 2012).

Previous studies near the Huangshui catchment, by Pan *et al*. (2010, 2012), Hu *et al*. (2017) and Craddock *et al*. (2010), show that rivers started entrenching from a beveled (erosional) surface at much younger ages, c. 3.7 Ma and 1.8 Ma along the Yellow River. The discrepancy may be explained in several ways. First, the older landscapes at the other sites may not have been preserved; they might have been eroded. Secondly, the relict beveled surfaces may have experienced a complex history with different ages of development in different areas (Clark *et al*., 2006). The late entrenching of the relict surface reported by the former authors could have been caused by the headward erosion of rivers flowing at a lower level and not by a river properly flowing on top of the peneplain, like in the Huangshui catchment. Thus, a certain lag is possible because of time needed by the headward erosion. In our opinion, the infilling of the large tectonic basins and the peneplain formation should have occurred largely in the same time period on the NETP. But, the effective duration of these different processes, and thus their time of termination, may have been different at different locations. In addition, it was argued that the drainage basin integration, and related excavation of Tertiary–Quaternary sedimentary basins along the Yellow River, led to isostatic uplift, and the development of an internally drained basin in the NETP (Zhang *et al*., 2014).

5 Fluvial morphology and sedimentology response to small-scaled tectonic movements

The general uplift at 10–17 Ma caused local fragmentation of the Huangshui catchment into blocks of small extent, demonstrated as gorges and depressions (scale of kilometers or maximally, a few tens of kilometers), respectively (Wang *et al*., 2010; Vandenberghe *et al*., 2011). These blocks might have undergone relative subsidence and/or uplift (Wang *et al*., 2010, 2014; Vandenberghe *et al*., 2011). It has been suggested that the inferred tectonic motions are related to the transpression movements in the NETP as a result of the collision of the Indian and Asian plates (Vandenberghe *et al*., 2011; Wang *et al*., 2012). In contrast with the generally persisting uplift of the NETP, at the scale of individual blocks uplift sometimes alternated with relative subsidence, leading to laterally alternating accumulation terraces and erosion terraces (Figure 5) in those blocks (Fluvial deposition (>30 m thick) in the subsided blocks, resulting in accumulation terraces, contrasts with entrenching (resulting in erosional terraces with thin fluvial deposits, i.e., strath terraces) and formation of gorges (where terraces are rare or completely absent) in the uplifted blocks (Figure 6) (Wang *et al*., 2010). The different rates of uplift and subsidence in the individual blocks resulted in the simultaneous development of erosion and accumulation terraces in different blocks within the same catchment (Figure 6) (Wang *et al*., 2010; Vandenberghe *et al*., 2011). In other words, fluvial aggradation may have occurred in specific blocks at the same time rivers incised in other (adjacent) blocks.

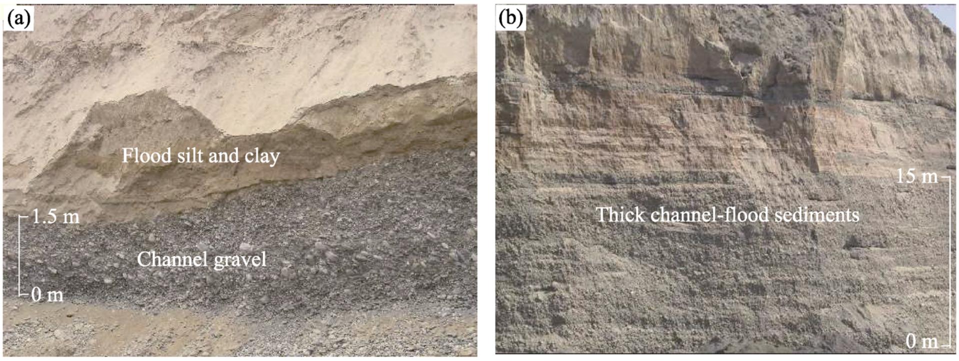

Figure 5 Sedimentologic character of the erosion terrace (a) and the accumulation terrace (b) in the Huangshui catchment

In the confluence region of the Huangshui and Huanghe rivers, from the Minhe depression to the west Lanzhou depression, the average river incision rate since –70 ka was much higher than in the up- and down-stream blocks, indicating relative uplift of the confluence region (Wang *et al*., 2014). At a smaller time scale, somewhere between 20 and 70 ka, two accumulation terraces with thick stacked fluvial deposits (>18 m) indicate two phases of subsidence in the confluence region relative to the up- and down-stream blocks (Wang *et al*., 2014). This could point to relatively short phases of tectonic stability or even subsidence during a period of general tectonic uplift.

The lateral transition between the very erosion-resistant Palaeozoic rocks of the uplifted block to the much younger and less resistant Tertiary clastic sediments in the depression, such as between Laoya gorge and Minhe depression (Figure 7), normaly corresponds with a very prominent, almost vertical escarpment in the topography (Figure 8), and this morphological escarpment may be interpreted as a fault. The vertical erosion (with formation of the strath terraces) obviously was always the main fluvial activity in the exit of the Laoya gorge, NW of the Huangshui, as a result of the regional tectonic uplift, while in part of the Minhe depression, SE of the Huangshui vertical erosion was interrupted by accumulation at specific periods as a result of local subsidence (Figure 9) (Vandenberghe *et al*., 2011). It was deduced that different tectonic backgroud caused by faults between the gorge and the depression lead to different fluvial response, a series of erosion terraces and steep cliff formed in the hard bedrock of the Laoya block north of the Huangshui as the general uplift, where erosion and accumulation terraces developed response to general uplift and relatively subsidence, in the Minhe depression, SE of the Huangshui (Figure 9) (Vandenberghe *et al*., 2011).

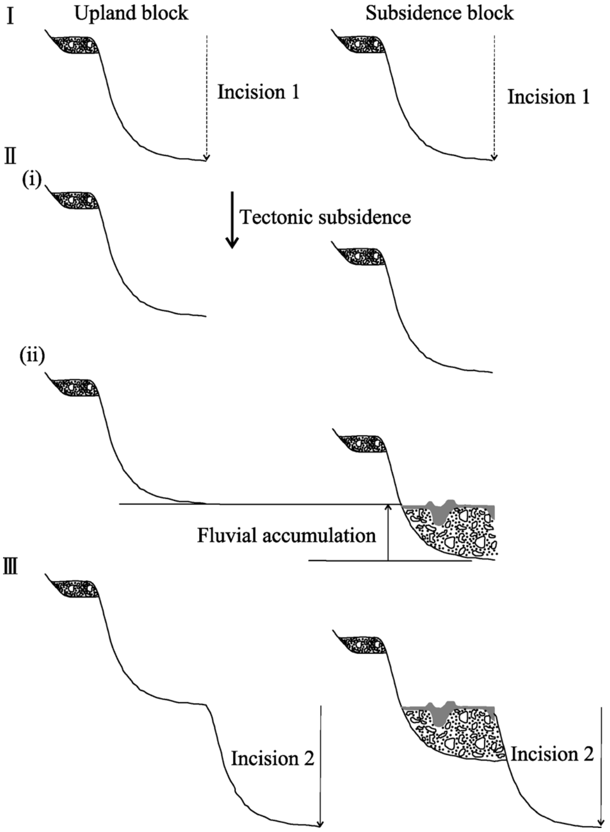

Figure 6 The formation model of the terrace in Huangshui catchment (modified after Wang *et al*., 2010). Firstly, the fluvial balance state is crossed because of climatic change or tectonic and the river incisions, until reaching to a new balance state; Secondly, the tectonic subsidence happens in the blocks, and an intensified erosion in upstream while a huge volume of sediments supplied deposit quickly in the subsidence depression. Finally, the river incises in the whole catchment, caused by climatic changes such as increasing of the precipitation and the reducing of the sediment load caused by the relevant development of the vegetation cover or tectonic uplift, and the accumulation terraces are formed in the subsidence depressions while the erosion terraces or no terrace are formed in upstream blocks.

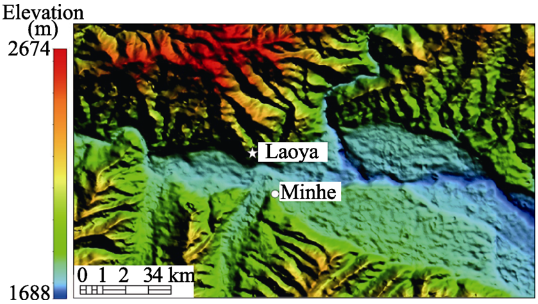

Figure 7 DEM of the Minhe subsided block with the transition to the Laoya gorge in the left upper corner

Figure 8 Fault scarp at the boundary between the Laoya block composed of hard rock and the Minhe depression underlain by soft sediments

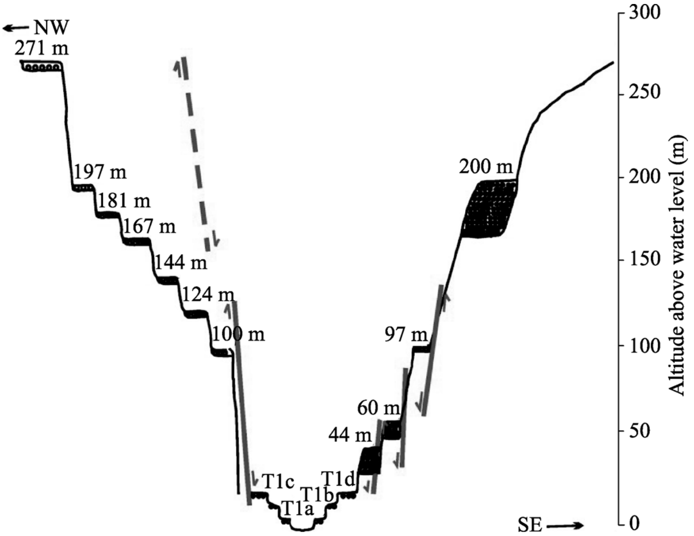

Figure 9 Terrace sequence at the exit of the Laoya gorge and the transition to the western most part of the Minhe basin, and the relation to fault activities (modified after Vandenberghe *et al.*, 2011). Firstly, incision occurred from 271 to 197 m, due to regional tectonic uplift. Secondly, uplift continued in the Laoya block, while the Minhe block subsided, leading to the accumulation of 30 m gravel (terrace at +200 m). Subsequently, uplift was dominant everywhere, resulting in the formation of a series of erosion terraces in the Laoya block between +197 and 100 m; while only one erosional terrace was preserved in the tectonic depression at +100 m. Finally, the recent fault activity, resulted in sharp vertical erosion in Laoya block, while subsidence prevailed in Minhe depression, leading to the formation of two accumulation terraces at 60 and 44 m.

6 Fluvial sediment process and terrace staircases as a response to climatic change

Incision into the former peneplain was not continuous but a staircase of terraces (consisting of at maximum 15 to 20 individual levels in some blocks), developed as a result of climatic influences (Figure 4) (Lu *et al.*, 2004a; Vandenberghe *et al.*, 2011; Wang *et al.*, 2012) . The sedimentary series of the different terraces are similar (Vandenberghe *et al.*, 2011; Wang *et al.*, 2014, 2015). From bottom to top: fluvial gravels of various thickness, interbedded with lenses of sands, silts, and clays, and finally topped by a horizontally laminated silt, occasionally containing gravel strings of limited extent (Figure 10). The lowest part of the gravel deposits consists of massive gravel (Gm) representing channel bedload, grading towards the top into finer-grained, coarsely planar bedding (Gp) (Figure 10). The latter deposits frequently show imbrication and small-scaled cross-bedding, which indicate deposition in lateral and longitudinal bars. Small and shallow channels occur with increasing frequency towards the top of the terrace deposits; they are filled with cross-bedded fine gravel or sands (planar to low-angle trough cross-bedding) (Figure 10). The upper laminated silts are interpreted as flood-loam deposits that complete the fluvial sequence prior to or simultaneously with the abandonment of the floodplain as a result of renewed river incision. These sedimentary characteristics of the fluvial gravel-sand deposits, dominated by varying (often cyclic) assemblages of gravel traction-current deposits, clearly point to the shallow gravel-bed braided river systems (Miall, 1996; Lewin and Gibbard, 2010) that contrast with the present-day wandering or meandering pattern of the Huangshui. At several locations, soil formation has been recognized at the top of fluvial depositional sequences, although not being well developed (Vandenberghe *et* *al*., 2011; Wang *et al*., 2014). Mostly, a gradual transition from flood loam to loess is present and the flood loams are often red-colored, pointing to upstream removal or local reworking of soil material.

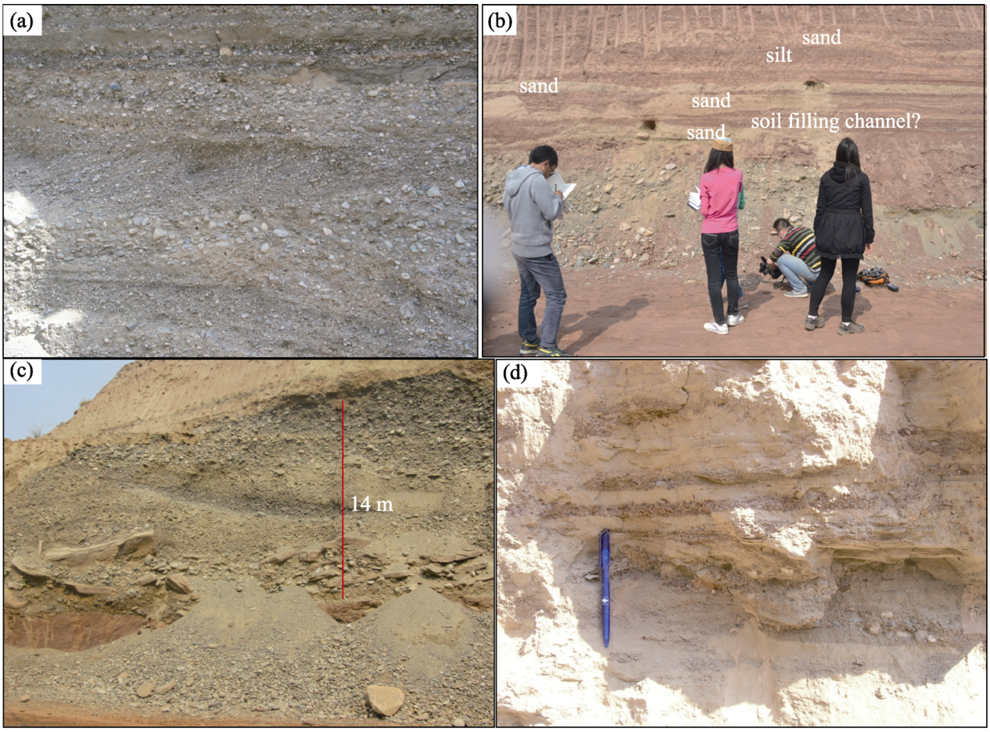

Figure 10 Characteristic sedimentary sequences of terraces: (a) Planar sheets of gravel alternating with finer grained, shallow, trough cross-bedded channels of 44 m terrace above present floodplain in Ledu basin; (b) inter-bedded layers of horizontally-laminated silt reworked soil filling shallow channels; (c) aggradation sequence of –40 m terrace above present floodplain in the eastern part of the Minhe depression; (d) horizontally laminated silts occasionally containing gravel strings of limited extent of 22 m terrace above preset floodplain at east Minhe depression

Climate proxies are mostly absent within the Huangshui terrace deposits, which makes it difficult to prove the link between climate and fluvial processes. Nevertheless, in accordance with the reconstructed character of the river morphology as a shallow gravel-bed braided river (Miall, 1996) that contrasts with the Holocene meandering river, the majority of the (coarse grained) fluvial deposits of the terraces seems to date from cold periods. Subsequently, we assume that, in line with the general model of fluvial development derived for temperate and periglacial environments (Vandenberghe, 2008; 2015), the fine-grained sandy gravels and sands near to the top of the sediment series were deposited during the waning of the same glacial period as a result of the beginning incision of the river (possibly in combination with reduced precipitation). Ultimately the fluvial sediments were capped by interglacial soil formation. Rivers incised slightly at the transition from the glacial to the interglacial, due to less peaked river discharge and the reduction of sediment supply to the river. As a consequence of that new, lower position in the next interglacial, the previous coarse grained channel deposits were flooded only during peak discharges resulting in episodic, fine-grained floodplain deposition, while most of the time soil formation took place on the floodplain. Analogous to the present-day river, the interglacial river was probably less energetic and dominantly meandering. Renewed incision took place at the next interglacial-glacial transition, when fluvial energy considerably increased and sediment transport was still limited. At that time, loess covered the former floodplain deposits and soil without any further reworking by the river (Vandenberghe *et al*., 2011)

7 Climate-dependent fluvial architecture and processes on a suborbital timescale in areas of rapid tectonic uplift since the last interglacial

In the confluence region of the Huangshui and Huanghe rivers, from the Minhe depression to the west Lanzhou depression, eight fluvial terraces are present (Figure 11), which are dated at around 129–103 ka (T7), 81–73 ka (T6), 68–51 ka (T5), 42–32 ka (T4), 24–22 ka (T3), and 14–13 ka (T2), respectively, using SAR-OSL analysis (Wang *et al*., 2015). The average river incision rate was 0.87 m ka^{-1} since the last interglacial, which is much larger than in the upstream Huangshui river (around 0.05–0.06 m ka^{-1}, Vandenberghe *et al*., 2011), the downstream Huanghe (around 0.35 m ka^{-1}, Pan *et al*., 2009), and even in most catchments in the world, where long-term average downcutting rates are less than 0.2 m ka^{-1} (Bridgland and Westaway, 2008), indicating relative uplift of the confluence region. This relatively strong uplift gives more space for differentiation within the terrace staircase as a result of climatic changes, leading to 7 terraces formed as a response to small climatic fluctuations (10^3–10^4 year timescale) (Wang *et al*., 2015). Assuming that the OSL-age is reliable, it leads to the striking conclusion that the stronger the tectonic movement the better the climatic imprint is expressed in the terrace development.

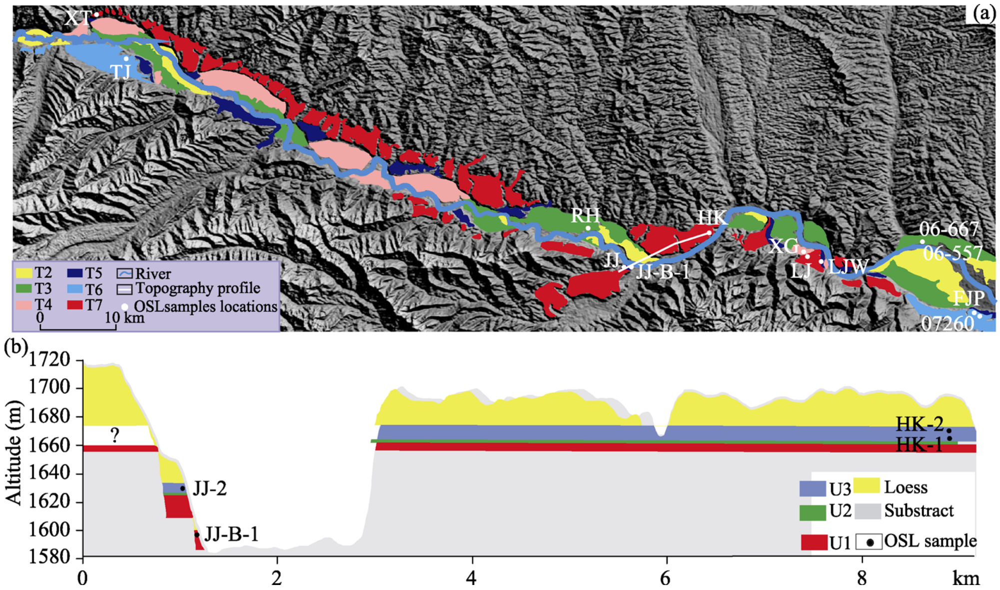

Figure 11 (a) Terrace distribution in the confluence region of the Huangshui and Huanghe rivers (modified after Wang *et al*., 2014). (b) A selected topographic section from Figure 11a, illustrating a typical terrace sedimentary sequence. U1, U2, U3 are the sedimentary units of the terraces (U1: stacked fluvial gravels of varying thickness with inter-bedded sand lenses, U2: cross-stratified sands, U3: inter-bedded layers of horizontally-laminated silt and sands.)

The dating results show that for each terrace, the lower coarse-grained sediments (gravel and sand) were deposited during cold periods (such as the LGM, MIS3b, MIS4 and MIS5d) associated with a strong Asian winter monsoon (Figure 12). The coarse

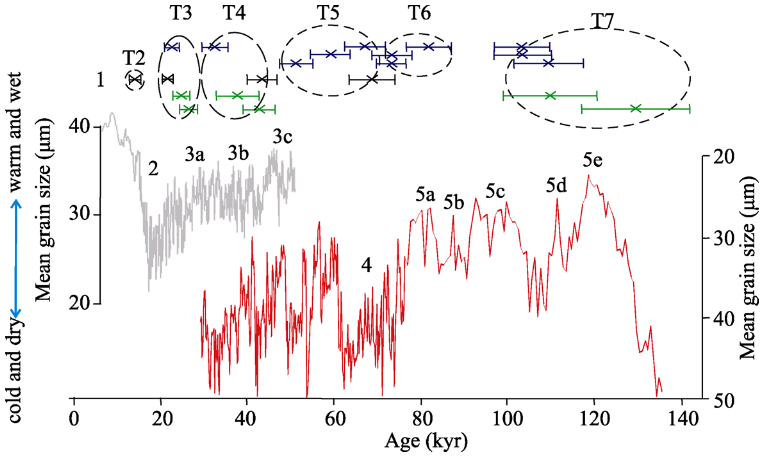

Figure 12 Comparison of the age of terraces (T2, T3, T4, T5, T6 and T7) and periods of fluvial deposition (at top) with climatic evolution recorded by the grain-size record of loess deposits at GL (gray) (Sun *et al*., 2012) and YZ (red) (Lu *et al*., 2004b) in the NETP (modified after Wang *et al*., 2015). Green, black and blue codes of ages and errors (2σ error bars at top) correspond to sedimentary units (U1, U2, and U3, similar to that in Figure 11), respectively. Numbers indicate marine isotope stages and substages. Age of loess deposit sequence is based on 20 OSL datings of GL by Sun *et al*. (2012) and correlation to marine isotope stages in YZ (Lu *et al*., 2004b).

grained cold phase deposits are covered by inter-bedded, horizontally-laminated silt and sand (representing flood sediments that often contain reworked soil material), during the (cold to warm) transitional phases. The floodplain accumulation on the terrace continued during the subsequent warm period. The warm periods (such as MIS3a, MIS3c, and MIS5a) of the climatic cycles are associated with a strong Asian summer monsoon (Figure 12). Pronounced incision took place at the subsequent warm-cold transitions (Figure 13). After this warm-cold transition, aeolian loess accumulated on the abandoned terrace without any further fluvial reworking. It demonstrates that critical thresholds for fluvial response can be crossed at climatic changes on a sub-orbital timescale given conditions of accelerated tectonic uplift in the NETP.

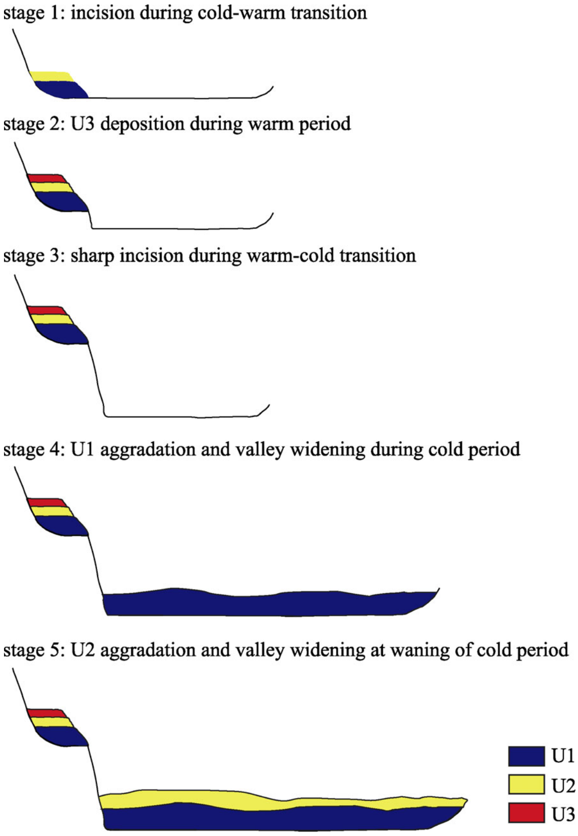

Figure 13 Schematic diagram illustrating the terrace formation in response to climatic change in the confluence of Huangshui and Huanghe. U1, U2, U3 are the sedimentary units of the terraces, similar to that in Figure 11.

8 Conclusions and remarks

The substantial tectonic uplift of the Northeastern Tibetan Plateau (NETP), together with the major climatic changes, provides an opportunity to study the impact of tectonic and climatic changes on the morphological development and sedimentary architecture of fluvial deposits. The effects of these processes are revealed by a terrace staircase, together with the stratigraphy of each individual terrace. A peneplain-like surface and the related landscape transition from basin filling to incision happened at least before the late Miocene in the NETP, which indicates that an intense uplift event with morphological significance happened around 10–17 Ma in the NETP. The general uplift at 10–17 Ma caused local fragmentation of the Huangshui catchment into blocks of small extent, demonstrated as gorges and depression. After that, incision into the former peneplain was not continuous but a staircase of terraces, developed as a result of climatic influences. Since the late Miocene, in spite of generally persisting uplift of the whole region, the neighbouring tectonic blocks had different uplift rates, and the uplift rates could change on a time scale of 10 ka. This tectonic differentiation causes a complicated fluvial response with accumulation terraces alternating with erosion terraces at a small spatial and temporal scale. Fluvial aggradation occurred during cold periods in general. Rivers progressively incised, reaching only sporadically the previous floodplain at the transition warm periods. The resuming vegetation cover reduced sediment supply to the rivers so that. This change in fluvial activity as a response to climatic impact is reflected in the general sedimentary sequence on the terraces from high-energy (braided) channel deposits (at full glacial) to lower-energy deposits of small channels (towards the end of the glacial), mostly separated by a rather sharp boundary from overlying flood-loams (at the glacial-interglacial transition) and overall soil formation (interglacial). Pronounced incision took place at the subsequent warm-cold transitions. In addition, it is hypothesized that in some strongly uplifted blocks energy thresholds could be crossed to allow terrace formation as a response to small climatic fluctuations (10^3–10^4 year timescale).

Although studies of morpho-teconic and geomorphological evolution of the NETP, improve understanding on the impacts of tectonic motions and monsoonal climate changes on fluvial processes, a number of questions remain to be answered and carried out in the future: 1) How far are the peneplain and the related morphological features and can they be correlated over large distances? 2) Morphological features as terraces and peneplains at different blocks have to be dated more precisely to make better correlations and, therefore, firmer hypotheses on morphological evolution and the link in different blocks and/or in different tectonic settings. 3) Can we specify in more detail to what extent and intensity tectonic movements may influence the crossing of climatic thresholds, leading to terrace development?

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