

Rock uplift increased sensitivity of fluvial response to suborbital climatic fluctuations

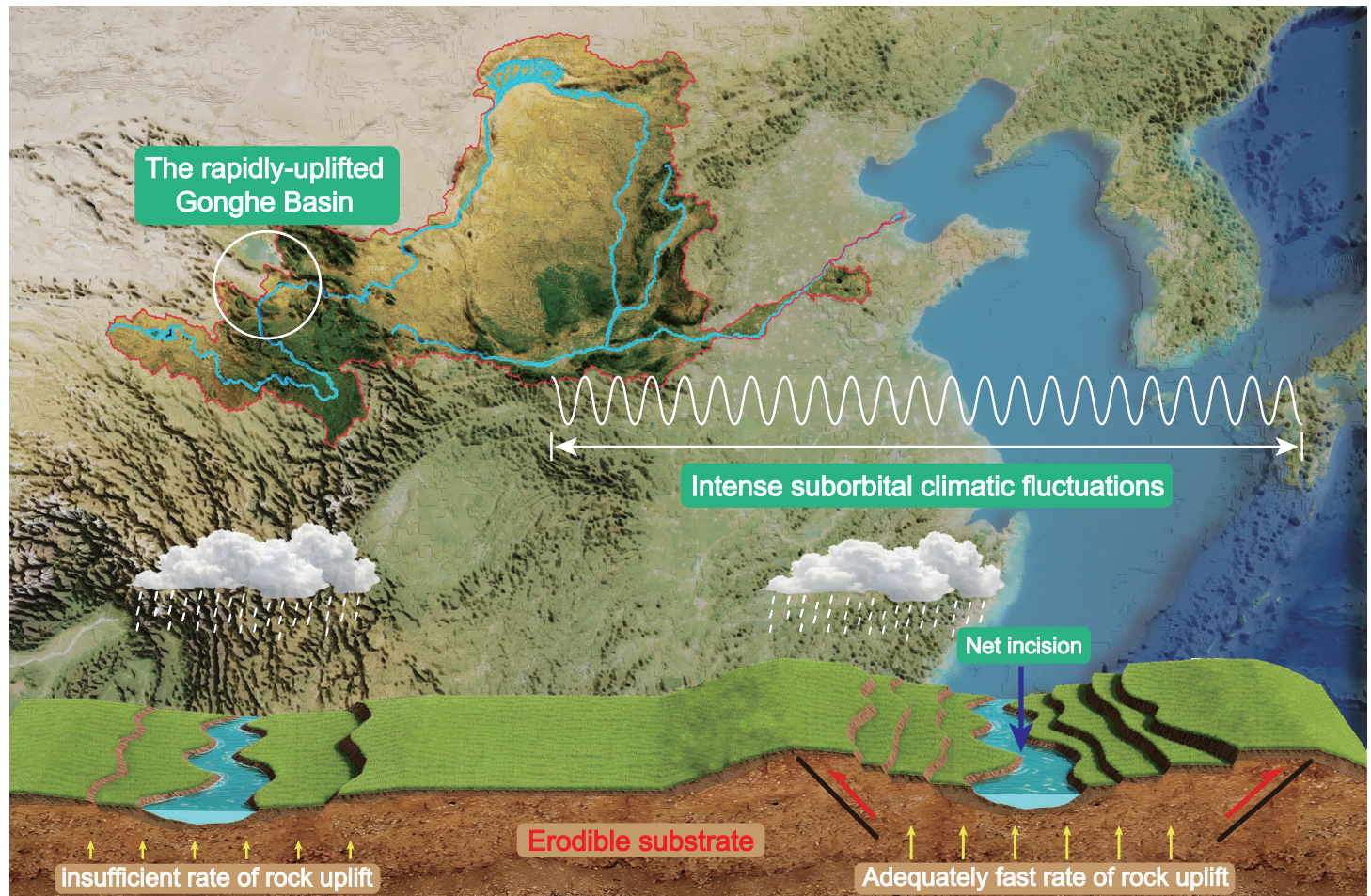
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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- The Yellow River excavated through the Gonghe Basin located in the NE Tibetan Plateau at 238–200 ka.
- The rock uplift over the Gonghe Basin has been rapid, but not uniform since the late Mid-Pleistocene.
- Rapid rock uplift can induce a more sensitive fluvial response to suborbital climatic fluctuations.

Rock uplift increased sensitivity of fluvial response to suborbital climatic fluctuations

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Terrace formation ages in a river system reveal that incision of large rivers is unevenly distributed, but the underlying forcing mechanisms are not entirely clear. One key challenge is to understanding the coupling mechanism of how uplift and climate interact in controlling terrace generation. Lack of well-dated fluvial terrace sequences allowing direct comparison with available uplift and climate data prevents resolving this issue. Here we reported a most densely distributed fluvial terrace sequence from the NE Tibetan Plateau. The results reveal two periods of frequent incisions at 90–80 and 55–45 ka, synchronous with indications from other rivers originating from the inner plateau. These two intervals do not align with climatic anomalies, thus indicating accelerated rock uplift. This work demonstrates that the coupling between rapid uplift and erodible substrate increases the sensitivity of fluvial response to suborbital climatic fluctuations to create more terraces in the Yellow River and likely other large rivers.

INTRODUCTION

Rivers are effective agent carving Earth's surface and determining how internal (rock uplift) and external (controls by base-level or/and climate-driven at the drainage basin) forcing worked together to set Earth's geomorphological features,^{1–3} which is one main task of geosciences.^{4,5} As the most direct fluvial archive, terrace occurrence marking the alternation between lateral planation (making a strath), sedimentary aggradation and vertical incision is generally linked with rock uplift, climate change⁶ and base-level variation. Many studies thus have been focusing on disentangling the roles played by them in terrace creation and preservation.^{7–11} By analyzing terrace generation, it is even possible to estimate fluvial response to internal and external forcing, and providing a new insight to the coupling mechanisms of rock uplift, base-level oscillations and climate change in driving landform evolution.^{8,10–16}

During recent decades, climate-driven changes in precipitation, temperature, vegetation, and the resultant variation in sediment flux have been extensively investigated as important factors in the generation of fluvial terraces.^{2,12,14} In particular, efforts have been made to correlate the fluvial deposition–incision alternations with glacial–interglacial cycles dictated by Milankovitch cyclicity, either at the obliquity 41 ka or eccentricity 100 ka scale.^{9,13} However, numerous terrace archives fail to match the frequencies of Milankovitch cyclicity^{15,16} and suborbital climatic fluctuations.¹⁷ As more archives of river terraces have been uncovered and described worldwide, greater complexity in their formation processes and subsequent preservation has emerged.² One of the reasons for this issue is that we remain unclear under what conditions river systems have a high sensitivity to respond to climate variabilities in suborbital scale, leading to terrace generation.¹⁷ Recent numerical simulation implied that variations in the rate of rock uplift may have recorded dissimilar fluvial responses to climate change.

Although rock uplift is undoubtedly an important factor,¹ quantitative and even qualitative evaluation of its effect on terrace occurrence remains a challenging issue to overcome.¹⁸ There has been general agreement that river

terrace staircases have not been formed during basin subsidence, which is marked instead by continuous aggradation.^{19,20} In contrast, rapid rock uplift in tectonically active mountain areas can lead to river responding to the forcing effects of climatic phases of shorter duration.¹¹ The precise mechanism by which that rapid rock uplift is translated into a predictable fluvial response to climate change has remained undetermined, however.

The northeastern Tibetan Plateau (NETP) is a setting, characterized by tectonic activity that has led to rapid rock uplift,²¹ in which the sensitivity of fluvial response to glacial–interglacial climate cyclicity, marked by terrace genesis under different rates of rock uplift, has been widely investigated.^{15,22} Whether a river can respond to short-timescale climatic fluctuations to create multiple terraces at high rates of rock uplift is however still uncertain. To clarify this issue, a successive sequence of up to 14 fluvial terraces generated by the Yellow River within the Gonghe Basin, NETP, has been studied and correlated with regional climatic archives. Chronological studies of this sequence have addressed the basin-fill top (BFT), ascribed widely disparate Early or Late Pleistocene ages,^{22–25} whereas the ages of the lower terraces so far remain undetermined. This study presents a new complete geochronology of this terrace sequence, which is different from published results,²⁴ obtained by using a combination of optically stimulated luminescence (OSL) and cosmogenic radio nuclide (CRN) dating. This detailed chronological sequence is employed to calculate fluvial incision rates and make correlations with independently dated high-resolution climatic records from studies of stalagmites, pollen, and loess–palaeosols,^{26–28} to interpret the pattern of terraces generated by the Yellow River in response to suborbital climatic fluctuations at the high rates of rock uplift recorded in the NETP.

GEOLOGICAL SETTINGS

The India-Eurasia collision has forced the progressive outward growth of the Tibetan Plateau²⁹ accompanied by the propagation of faults and deformation structures into its interior and the surrounding area,³⁰ creating the geomorphic pattern characterized by the alternation between basins and ranges. In the NETP, geomorphic evolution is generally linked with the Haiyuan, East Kunlun, and West Qinling Fault Systems (Figure 1C), which consist of numerous secondary faults, mainly presenting a left-lateral strike-slip pattern.^{31,32} Their slip rates are transformed into tectonic deformation along their paths, leading to a decreasing tendency toward the SE.³² In Mid-Pleistocene, the Gonghe Basin (Figure 1A), like many other basins around the world was reversed (inverted) and therefore began to be uplifted within the NETP.^{33–35} Before that, the initial filling of this basin has been dated back to the late Miocene, then accumulating a set of fluviolacustrine succession with thickness of more than 600 m until the late Mid-Pleistocene.^{22–25,36–38} The Quaternary sediments in this basin are consisted of mud, silt, sand, and gravels, which is defined as the Gonghe Formation, characterized by contemporaneous difference facies deposits (Figures 2, 3C & 4D). In general, it is unconsolidated deposition, which is in keeping with its Quaternary age.³⁷ Physically, this unconsolidated silty-muddy substrate possesses extremely high erodibility and low critical shear stress. Consequently, the substrate is

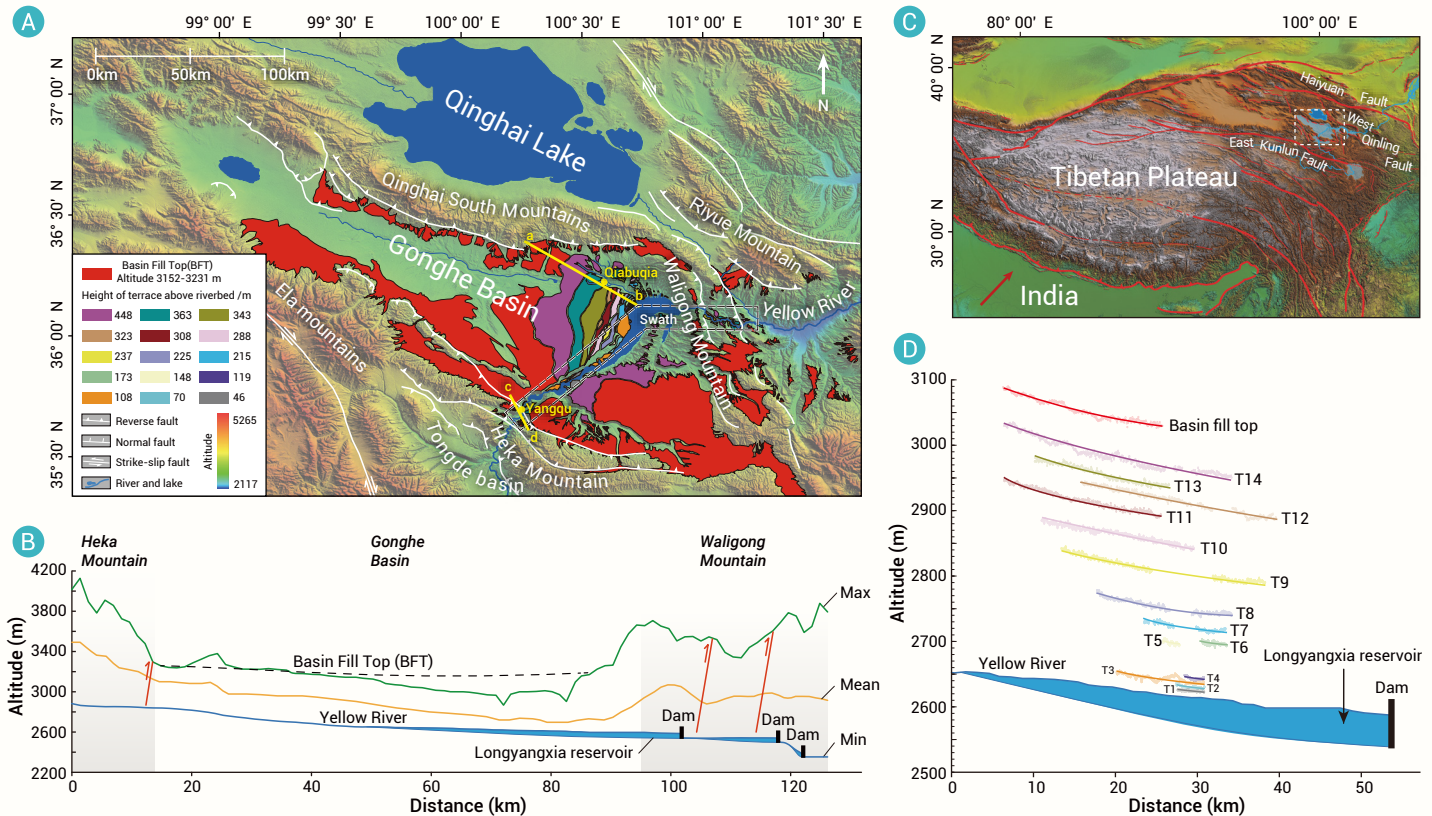


Figure 1. Topographic map, terrace distribution and ancient longitudinal profiles of the riverbed within the Gonghe Basin (A) The Yellow River cuts through the Heka Mountains to flow across the Gonghe Basin and then NE through the Waligong Mountains. OSL (Optical Stimulated Luminescence) and CRN samples were obtained along the two cross-sections of a-b and c-d, which are presented in detail in Figures 3E & 4C, respectively. (B) Maximum, mean, and minimum topography observed along a 15-km-wide swath window (oriented perpendicular to swath transect). See the dashed outline in Figure 1A for its location. (C) The map displays India-Eurasia collision and genetic fault systems in the inner and surrounding Tibetan Plateau, in which the extent of the Figure 1A is marked by dashed rectangle. (D) Ancient longitudinal profiles of the riverbed in the Gonghe Basin. Their altitudes have been extracted from a 30-m resolution DEM, imprinted by the spatial extents of every terrace tread in the Gonghe Basin.

prone to undergo rapid geomorphic adjustment under hydrodynamic forces, a key precondition for the sensitivity of terrace formation to climatic forcing. In the inner basin, the Gonghe Formation comprises lacustrine facies consisting of interbedded mud, silt, and clay, typically with parallel and horizontal lamination (Figures 3C-D). Their color changes from red to green toward the bottom, which perhaps results from a reductive deep-water lake environment. From the center towards the basin margin, there is a gradual lateral change from lacustrine fill to subaqueous fan-delta facies, accompanied by a remarkable increase in grain size. For example, at Yangqu, on the southern boundary of the basin (Figure 1A), the Gonghe Formation is mainly represented by clast-supported fluvial gravels, characterized by cross-stratified and imbricated beds, in which sand lenses are typically interbedded with the gravels (Figures 4A & D). There, quartzose pebbles were exposed well to and burial under the basin fill top (BFT) surface (Figure 3A), therefore favoring samples collection for CRN (Cosmogenic Radio Nuclide) exposure and burial dating.

Fault activity in the mountains surrounding the Gonghe Basin has continued, with an average tectonic uplift rate of 0.1 m/kyr.³⁷ The Yellow River has cut through the Heka and Waligong Mountains as well as across the Gonghe Basin (Figures 1A-B). Its excavation from the BFT into the Gonghe Formation created a sequence of densely occurring strath terraces (Figures 1A, 3D-E & 4D). The gravel layers accumulated on each terrace tread are all well sorted and imbricated, in contrast to the underlying Gonghe Formation strath. Furthermore, their grain size is coarser than the Gonghe Formation, thus providing a well-marked boundary between the underlying basin-fill and terrace deposits (Figures 3B-D & 4D).

Based on detailed fieldwork, the spatial distribution of the Yellow River terraces below the BFT across the Gonghe Basin has been determined (Figure 1A). A total of 14 Yellow River terraces has been identified, a figure that excludes the lowest three terraces, which are submerged beneath the Longyangxia reservoir.³³ Their altitudes have been extracted from a 30-m resolution DEM to reconstruct the longitudinal profiles of the ancient

riverbeds marked by distinct levels of the Yellow River terraces (Figure 1D). Moreover, two cross-sections have also been established here to present the geomorphic sequence and underlying sediments (Figure 1A). The cross-section a-b traversing Qiabuqia in the inner basin, while the cross-section c-d traversing Yangqu at the north front of the Heka Mountain bounding the basin at southwest. Along the two cross-sections (Figures 3E & 4C), the elevation of each terrace tread and the thickness of gravel, overlying overbank sediments, and loess cover were measured using high-precision differential GPS equipment (Trimble GEO 7X) with an uncertainty of <5 cm. It can be observed from the two cross-sections that all the terraces are strath terraces, cutting into the Gonghe Formation. The main characteristics of all 14 terraces and the basin-fill top (BFT) presented by the two cross-sections are summarized in Tables 1-2.

MATERIALS AND METHODS

Sampling

Because the formation age of BFT might have been beyond the range of the OSL (Optical Stimulated Luminescence) dating,²³ we employed CRN (Cosmogenic Radio Nuclide) dating for its chronological determination, whereas OSL dating was used for the terraces below. A total of 13 OSL samples were collected from the uppermost lenses in the gravel layers of the terraces T13 ~ T1 along the cross-section a-b traversing Qiabuqia in the inner Gonghe Basin (Figures 3B-E) (36.2144° N, 100.5878° E ~ 36.1597° N, 100.7202° E). They are numbered in sequence from the low to the high terraces as LYX-T1 ~ LYX-T13. In addition, one separate OSL sample of LYX-T14 was taken from the uppermost lens of the gravel layer accumulated on the terrace T14 of the cross-section c-d traversing Yangqu (Figure 4B).

A total of 5 CRN samples, including 2 burial samples (M26 and M28) and 3 exposure samples (LE-18, LE-01 and LE-14) have been taken from the cross-section c-d (Figure 4) (35.7011° N, 100.2980° E). Two CRN burial samples of M26 and M28 were collected respectively from the 20-m and 26-m depths

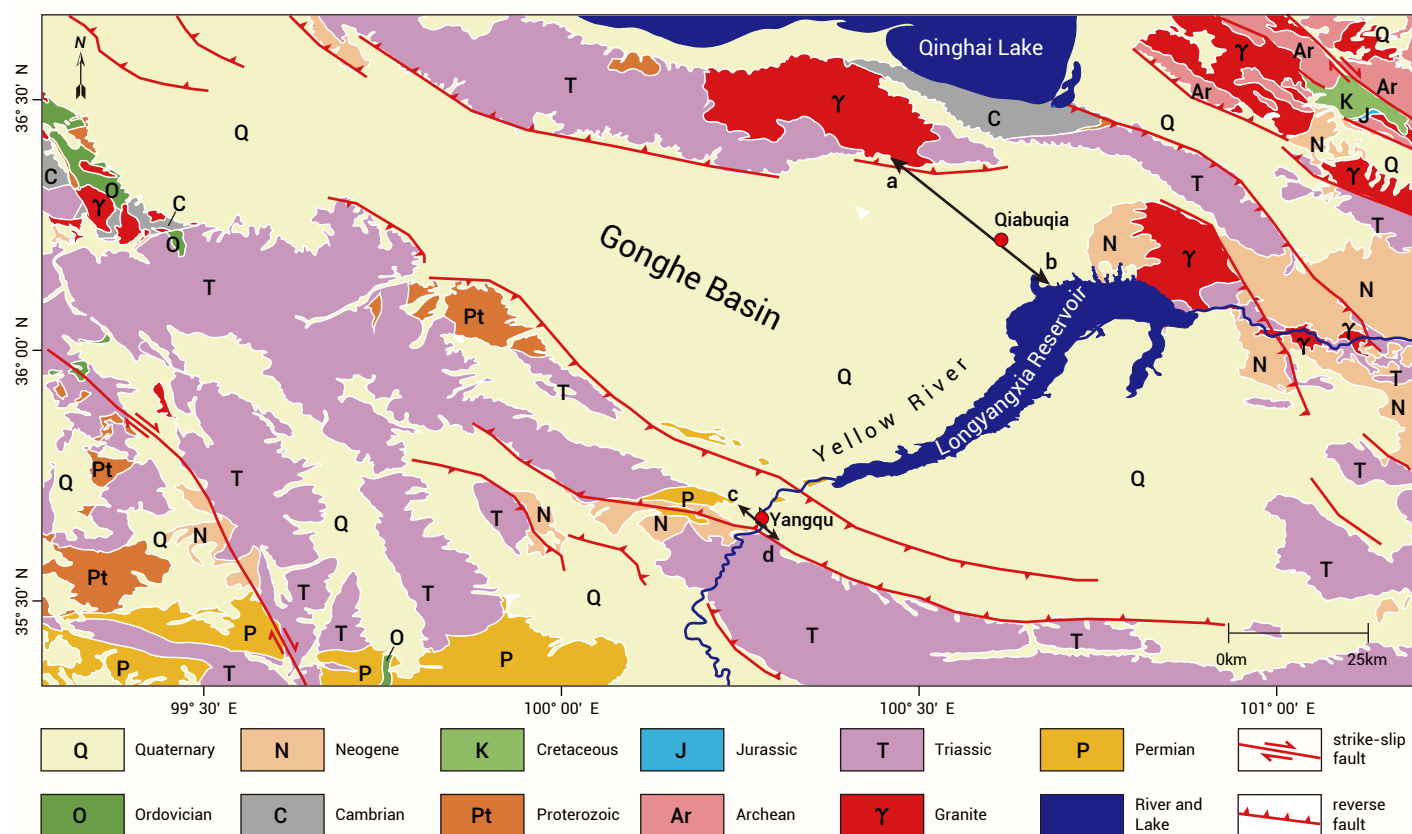


Figure 2. Lithological distribution map of the Gonghe Basin This basin is dominated by the Quaternary fluviolacustrine sediments, which have been down cut deeply by the Yellow River, resulting in occurrence of numerous strath terraces. Samples for CRN and OSL dating were taken from the two cross-sections of a-b and c-d.

below BFT, while one CRN exposure sample of LE-18 was taken from the surface of BFT (Figure 4A), in order to tightly determine the formation age of BFT. To ensure consistency with the dating result of LYX-T14, one CRN exposure sample of LE-01 was collected at the interface between the gravel layer and the 3-m overlying loess on terrace T14 (Figure 4B). Aside from above samples, one CRN sample of LE-14 of amalgamated pure quartz pebbles was taken from the current riverbed of the Yellow River at Yangqu (35.5007° N, 100.1525° E) to correct the possibility of inheritance (Figure 4C).

All 14 OSL samples were taken at a depth more than 50 cm below each terrace tread and inward 30 cm to avoid any possible exposure to sunlight. They were collected by hammering steel tubes into sand lenses closest to the top of each gravel layer (Figure 3B), regardless of whether the surface was covered by loess, to ensure that the OSL age most closely representing the initial time of river incision after the end of each terrace deposition (when the terrace treads were abandoned).

All pure quartz pebbles collected for CRN (burial and exposure) dating are less than 5 cm in diameter to prevent differences in the concentration of nuclide production. For an individual CRN (burial and exposure) sample, the pure quartz pebbles were amalgamated to achieve a total weight in excess of 500 g to ensure that enough quartz remained after pre-treatment.

OSL dating

All experimental steps for the OSL dating were performed in a darkroom room under red light. The samples were treated with 10% HCl and 30% H₂O₂ to remove carbonate and organic matter, and the remaining samples were wet sieved to separate 90–125 μm grain-size components. Samples of this size were treated with 40% HF for approximately 1 hour to remove feldspar minerals. Infrared stimulated luminescence (IRSL) detection was performed above-purified feed quartz. If there was an obvious IRSL signal, H₂SIF₆ was further infiltrated to remove feldspar as completely as possible and avoid over estimation of De.

The treated samples were tested by RisøTL/OSL-DA-2 automatic lumines-

cence apparatus. The irradiation source was (⁹⁰Sr/⁹⁰Y) β source. The equivalent dose (De) of the samples was measured by the method of single-aliquot regenerative-dose (SAR) protocol and standardized growth curve (SGC). The annual dose of the sample is related to its U, Th and K content, its water content and cosmic rays. The U, Th and K contents of the samples were measured by the neutron activation method. The contribution of cosmic rays to the annual dose was calculated based on the altitude, geographical location, and sampling depth of samples.³⁹ The annual dose can be calculated from the formula and parameters provided by Aitken.⁴⁰ The above experimental pretreatment and testing were completed in the Key Laboratory of Comprehensive and Highly Efficient Utilization of Salt Lake Resources, Qinghai Institute of Salt Lakes, Chinese Academy of Sciences. The obtained data are tabulated in Table S1. All the obtained OSL signals of shine-down curves start with a major decrease in the first second of stimulation, while the growth curves can be well fitted using the exponential plus linear function (Figure S1), indicating that the OSL signals are dominated by the fast component and do not saturate up to 320 Gy.⁴¹

CRN dating

All the CRN samples were manually crushed and sieved to obtain the fractions within the grain-size range 250–500 μm, the remainder being reserved. The selected samples were immersed in H₂O₂ and HCl/HNO₃ to remove organic matter and carbonates, respectively, and then washed with pure water and dried in turn. After weighing and removing magnetic minerals with a magnetic separator, they were added to a mixed acid solution of HF/HNO₃ with a concentration of 3%–5%, and then heated at 60°C for 24 h. The remaining particles were then washed to neutral with pure water for heavy-liquid separation. Pure quartz was obtained by repeated etching with a low concentration (1–2%) of HF/HNO₃ until the Al content of the sample (checked repeatedly by ICP-MS) reached a lower value than 200 g. Finally, sample targets were prepared with reference to Corbett et al.⁴² The above pretreatments were all carried out in the TCN Preparation Laboratory, State Key

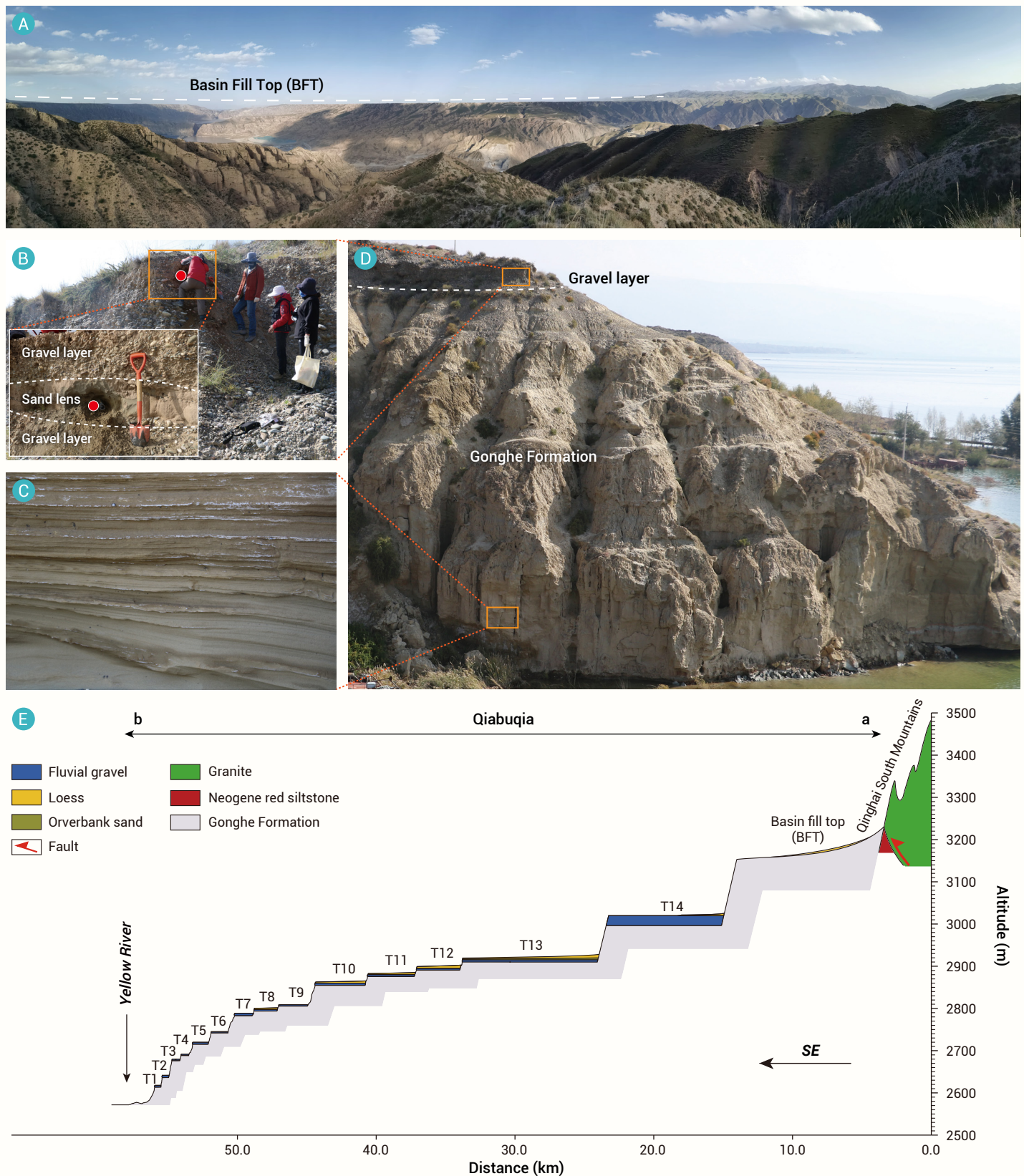


Figure 3. Schematic cross-section a-b traversing Qiabuqian within the inner Gonghe Basin (A) View of the BFT surface, looking north. (B) OSL sampling the Yellow River terraces in a sand lens closest to the top of the gravel layer. (C) Gonghe Formation accumulated within the subsidence center, with typical parallel lamination. (D) Sedimentary disconformity between the terrace T4 (above) and the Gonghe Formation (below), looking north. (E) The cross-section a-b presenting the complete geomorphic sequence of the Gonghe Basin. Its location is marked in Figure 1A. A total of 14 strath terraces was formed by the Yellow River downcutting from BFT into the Gonghe Formation.

Laboratory of Cryospheric Science, Northwest Institute of Eco-Environment and Resources, CAS in Lanzhou.

The sample targets were tested in the Chinese Academy of Science Insti-

tutional Center for Shared Technologies and Facilities of Institute of Earth Environment. The final chronological calculations refer to Balco et al.⁴³ with the parameters tabulated in Tables S2-S3.

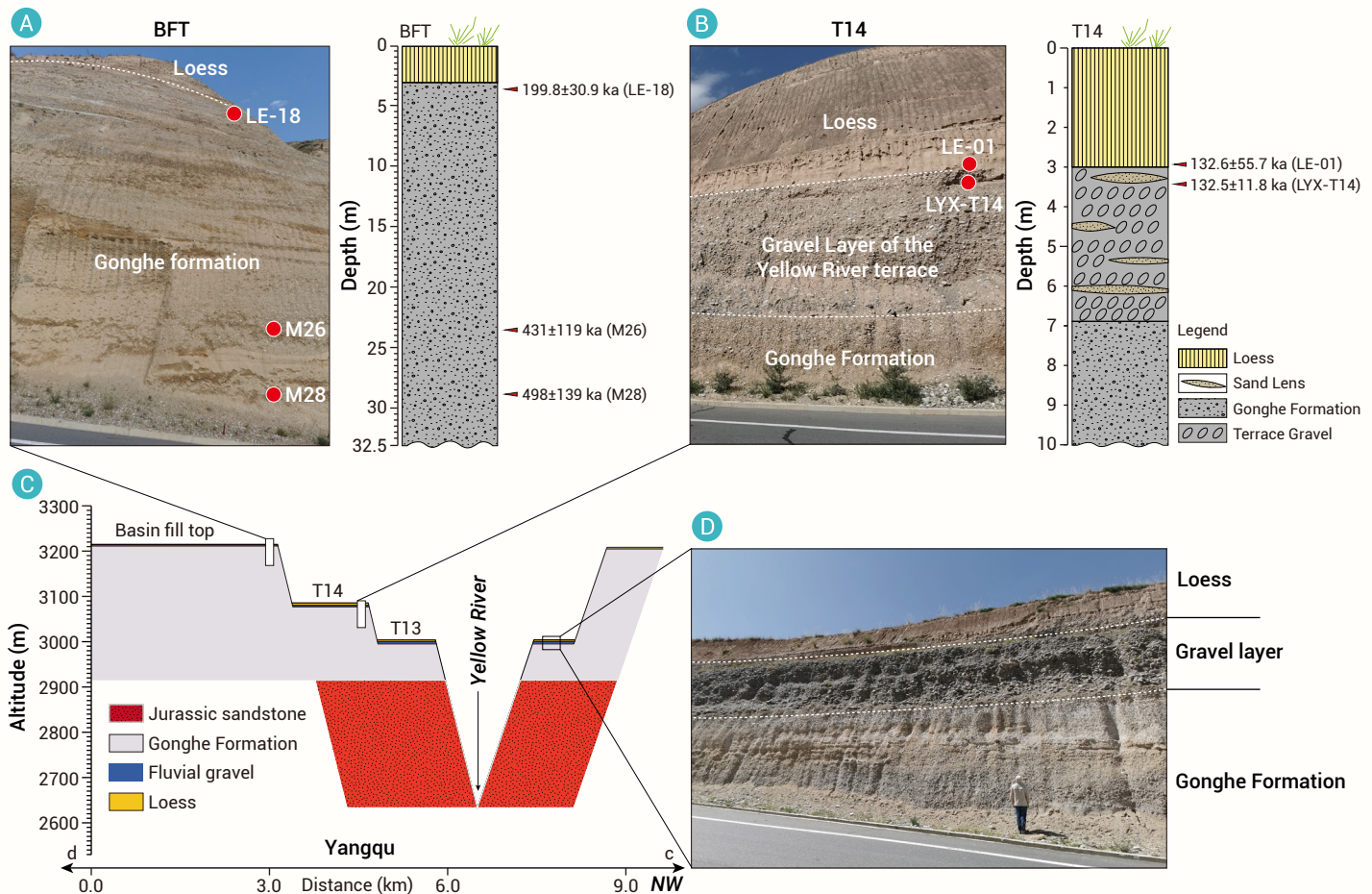


Figure 4. Schematic cross-section c-d traversing Yangqu at the north front of the Heka Mountain (A) An outcrop below BFT, from which two CRN burial samples of M26 and M28 were obtained respectively from the 20-m and 26-m depths, while one CRN exposure sample of LE-18 was taken from the surface of BFT. Their dating results are also marked at the sampling positions. (B) An outcrop of the highest terrace 14, marked by dating results. One OSL sample of LYX-T14 was taken from the uppermost lens of the gravel layer accumulated on this terrace. The adjacent CRN exposure sample of LE-01 was collected at the interface between the gravel layer and the 3-m overlying loess. (C) The cross-section c-d exposed at the north front of the Heka Mountain. Its location is marked in Figure 1A. The Yellow River deeply downcutting from BFT through the Gonghe Formation into underlying Jurassic sandstone. Only two terraces of T14 and T13 were formed below BFT here. (D) The remarkable boundary between the gravel layer of the Yellow River terrace and the underlying Gonghe Formation, which can be observed intuitively at the edges of the basin. The sedimentary facies of Gonghe Formation changes from fluviallacustrine facies in the inner to subaqueous fan delta facies at the edges of the basin.

RESULTS

The results of OSL and CRN dating are provided in Tables 1-2. The OSL samples of LYX-T1~T14 were obtained from the uppermost sand lenses in the gravel layers on individual Yellow River terraces within the Gonghe Basin (Figures 3B & D-E), providing an approximation of the sediment age towards the top of each terrace, approximating to the timing of the beginning of fluvial downcutting.

The BFT marking the onset of Yellow River excavation into the Gonghe basin-fill (Gonghe Formation) was previously broadly determined to have formed between 2.47 Ma and 200 ka.^{23,24,44} Despite these advances, the underlying Gonghe Formation has been constrained tightly by biostratigraphy to be accumulated in the Quaternary period.³⁴ Moreover, the combined approach of magnetostratigraphy and cosmogenic nuclide burial dating has also confined the upper part of the Gonghe Formation well to be accumulated posterior to 700 ka.^{22,25} Its top age (i.e., the formation age of BFT) of 2.47 Ma,²⁴ assigned by the electron spin resonance (ESR) dating, almost reaches up to the lower boundary of Quaternary, therefore, seems to be excluded. It is evident that the precise age of the BFT formation remains undetermined. To solve this issue, we employ here a multi-dating of the burial and exposure cosmogenic nuclide. Two CRN burial samples of M26 and M28 obtained respectively from the 20-m and 26-m depths below BFT (Figure 4A), representing their individual burial times, have been determined at 431±119 and 489±139 ka, respectively (Table 2). The two results versus their depths define a sedimentary rate of 103.45 m/Myr, which is in good correspondence with that (104 m/Myr) of the neighboring Tongde Basin.²² Extrapolation of this

sedimentary rate to the top of the Gonghe Formation yields an age of ca. 238 ka for BFT. Considering the persistent deposition of loess overlying fluvial gravels in the Gonghe Basin since approximately 15 ka, and coupled with its local provenance from fluvial sediments,⁴⁵ the presence of similar thin loess covers on T14 and BFT (Tables 1-2 & Figures 3-4) appears to provide support for our hypothesis that the two geomorphic surfaces may have undergone comparable erosional exposures, as well as subsequent aeolian sediment coverage. The shielding history of the 15-ka loess covers is so short that their influence on the CRN exposure dating results of the underlying geomorphic surfaces can be ignored.⁴⁶ In contrast, without incorporating the erosion rate to correct the dating result of the CRN exposure sample of LE-01, collected from the tread of terrace T14, a chronological result of 46.8 ka can be calculated, which significantly deviates from the dating result of the OSL sample of LYX-T14 derived from the same terrace T14. Concurrent application of CRN exposure and OSL dating techniques was therefore conducted here on the gravel layer of terrace T14 to calculate the extent of erosional exposure experienced by this surface (Figure 4B). We preset the dating result of the CRN exposure sample LE-01 as the age of the OSL sample LYX-T14. The erosion rate of the terrace tread can be calculated, by subtracting the inherited nuclide ¹⁰Be concentration, represented by the sample LE-14, from the nuclide ¹⁰Be concentration of the sample LE-01. An erosion rate of 0.00119–0.0008 cm/a was thus obtained for the tread of terrace T14 and above BFT surface. Although this result is slightly higher than the erosion rate that was corrected according to the basal age of the loess overlying BFT,²³ it seems to be more consistent with the rapid wind erosion

Table 1. Characteristics and dating results of the Yellow River terraces along the cross-section a-b.

Geomorphic surface names	Sample ID from each geomorphic surface	Height of tread above original river level (2572 m)	The thickness of the gravel layer (m)	The thickness of overbank (m)	The thickness of loess deposits on the terrace (m)	Age (ka)(1 σ)
Modern River Level		0	0	0	0	N.A.
T1	LYX-T1	46	3	0	0	47.7 $\pm$ 4.6
T2	LYX-T2	70	4	0	0	50.3 $\pm$ 4.3
T3	LYX-T3	108	3	0	0	51.2 $\pm$ 4.2
T4	LYX-T4	119	2	0	0	53.6 $\pm$ 4.3
T5	LYX-T5	148	4	0	0	54.0 $\pm$ 6.2
T6	LYX-T6	173	3	0	0	60.3 $\pm$ 5.3
T7	LYX-T7	215	5	0	0	71.5 $\pm$ 5.5
T8	LYX-T8	225	3	0	2	77.1 $\pm$ 6.8
T9	LYX-T9	237	3	0	0	80.4 $\pm$ 10.9
T10	LYX-T10	288	5	0	5	82.7 $\pm$ 11.7
T11	LYX-T11	308	4	0	3	83.9 $\pm$ 8.9
T12	LYX-T12	323	4	0	5	86.4 $\pm$ 8.5
T13	LYX-T13	343-363	3	2	3	88.4 $\pm$ 9.8
T14		448	22	0	3	
BFT		580-659	0	0	2.5	

Table 2. Characteristics and dating results of the Yellow River terraces T14, T13 and above BFT along the cross-section c-d.

Geomorphic surface names	Sample ID from each geomorphic surface and underlying sediments	Height of tread above original river level (2638 m) *	The thickness of the gravel layer (m)	The thickness of overbank (m)	The thickness of loess deposits on the terrace (m)	Age (ka)(1 σ)
Modern River Level	LE-14	0	0	0	0	N.A.
T13		362	5	0	3	
T14	LYX-T14	448	3	0	5	132.5 $\pm$ 11.8
	LE-01					132.6 $\pm$ 55.7
	M26					431 $\pm$ 119
BFT	M28	574	0	0	3	498 $\pm$ 139
	LE-18					199.8 $\pm$ 30.9

experienced by this surface.⁴⁵ Without using this erosion rate to correct the dating result of the CRN exposure sample LE-18, taken from the BFT, a young age of 88.4 ka can be obtained. Nevertheless, we still take into account the fact that a larger erosion rate will increase the error in the exposure age calculation of the cosmogenic nuclide ¹⁰Be.⁴³ An exposure age of ca. 200 ka, based on this erosion rate and combined with a cosmogenic exposure sample LE-18, can be tentatively assigned to the BFT, with the minimum possible error. Clearly, it is generally consistent with the formation age of BFT, extrapolated from the deposition rate defined by the two cosmogenic nuclide burial ages. The excellent matching of above results thus well points to the reliability of our multi-dating results. Ultimately, BFT and the uppermost Yellow River Terrace T14 were determined here to occur at 238~200 ka and 132.5 ka (Table 2), respectively. Other Yellow River terraces below T14 have been confined directly by the OSL ages of the uppermost sand lenses in their overlying gravel layers (Table 1).

DISCUSSION

Rock uplift assessed by fluvial incision rates

Along the cross-section a-b, the height of each terrace tread above the river level (reservoir level) versus its age defines the time-averaged incision

rate of the Yellow River within the inner Gonghe Basin since 238~200 ka. Five phases of terrace formation have been dated, by linear regression analysis, to 238~200–90, 90–80, 80–55, 55–45, and 45–0 ka (Figure 5A). The Gonghe Basin is too far from the Yellow River estuary to be significantly affected by eustatic variations,⁴⁷ and the onset of terrace formation is later than the Mid-Pleistocene Climatic Revolution.⁴⁸ Moreover, no drainage reorganization events occurred in the Yellow River catchment during this time interval, so rapid incision resulting from transient waves of headward erosion can be excluded. Differences in the underlying lithology can also be excluded as a cause for different incision rates, since the Yellow River has been incising into a basin fill consisting of unconsolidated fluvio-lacustrine sediments without alternating hard and soft strata (Figures 2, 3C-D & 4D). Variation in the fluvial incision rate may therefore be ascribed to rock uplift and climate change. A series of climatic archives reveals that wet and dry, warm and cold stages have alternated repeatedly in the NETP (Figures 5B-D), since the late Mid-Pleistocene.^{26,28} However, there appears to be no clear match between such alternate climatic stages and Yellow River incision rates in the Gonghe Basin (Figure 5). Despite this mismatch, we still cannot completely rule out the possibility that the climate mode characterized by high-frequency Dansgaard-Oeschger cycles at MIS 3 can inherently drive a rapid fluvial incision. Archives

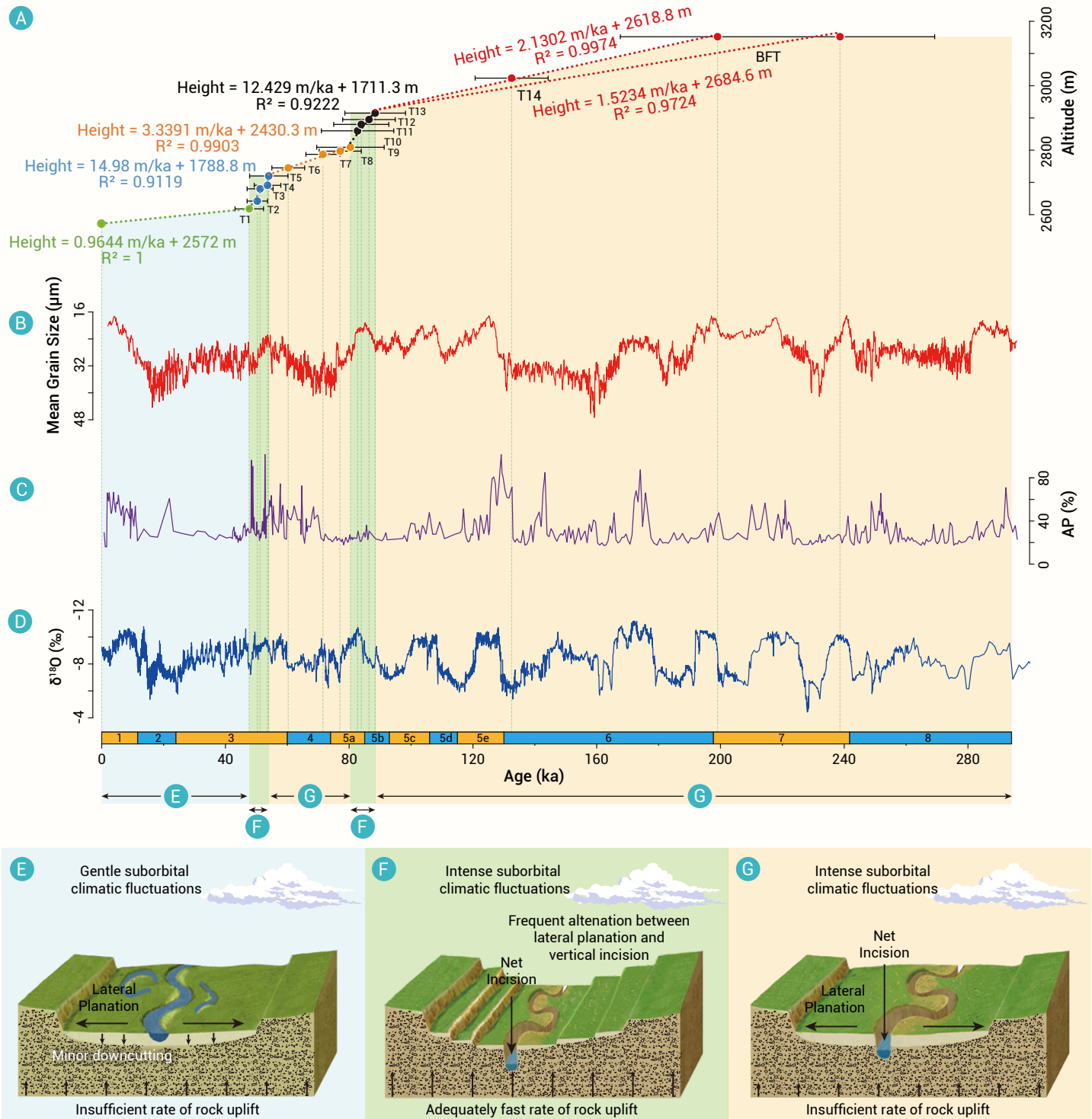


Figure 5. Calculated fluvial incision rates correlated with regional climatic archives, and Mechanistic pattern of the geomorphic processes of fluvial response to coupling of rock uplift and suborbital climatic fluctuation with a background of loose substrate (A) Calculated fluvial incision rate (color indicates correspondence between stages and formulae). Green shaded rectangles represent two periods of extremely fast rock uplift. (B) East Asian Winter Monsoon (EAWM) intensity based on mean grain size of loess in the Gulang section (red).²⁸ (C) Arboreal pollen percentages AP% from the Zoige Basin drill core (violet).²⁷ (D) East Asian Monsoon (EAM) record based on speleothem oxygen-isotopes ($\delta^{18}\text{O}$) (blue).²⁶ (E) A pattern that fails to develop terrace. Forced by an insufficient rate of rock uplift, river systems will absorb suborbital climatic fluctuations through a combination of lateral adjustments and/or minor vertical incision without a distinct phase of major downcutting, thus preventing the formation and preservation of a clear terrace. (F) A pattern to form terrace successively. River systems stimulated by adequately fast rate of rock uplift can be perpetually at or near the state of erosional threshold, leading to remarkable alternations between incision and lateral planation to form terraces in correspondence to almost any suborbital climatic perturbation. (G) A pattern to form terrace occasionally. Triggered by an insufficient rate of rock uplift, river systems will initiate net incisions to form some terraces only when more intense suborbital climatic fluctuations occur occasionally.

of other mega rivers in the world being able to form multiple terraces during this period to mark rapid incision, however, have hardly been observed, especially in the slowly uplifting regions where fluvial terraces are extremely rare,⁴⁹ implying that climatic changes were in general probably not the cause for differences in the rate of incision.

After an initial period of subsidence, the Gonghe Basin has been regarded as a block that has uplifted since the late Mid-Pleistocene,³³ a result of accelerated uplift and expansion of the Tibetan Plateau.²¹ The reverse faults accompanying the uplift of the surrounding mountains were also active in the late Mid-Pleistocene.⁵⁰ In general, no simple relationship can be defined

between fluvial incision and rock uplift phases. In tectonically active regions, however, it has been assumed that terrace staircases can be considered as archives of regional rock uplift over at least one glacial–interglacial cycle. The idea that long-term fluvial incision can be used to quantify rates of rock uplift at least approximately was subsequently widely accepted on the condition that the river gradient remained relatively constant.⁵¹ Fluvial terraces are the ancient riverbeds, the longitudinal profiles of the Yellow River, marked by distinct terrace levels, therefore, can be extracted from the 30-m-resolution DEM (Figure 1D), based on their spatial distribution in the Gonghe Basin (Figure 1A). They are characterized by the style of nearly parallel with each other, implying that the Yellow River as a mega river system, with immense self-regulating capacity,⁵² tends to maintain a longitudinal profile of riverbed with relatively stable gradient. In this way, the variation in incision rate of the Yellow River within this basin can seem to be transformed approximately into rock uplift rate.

In the NETP, mountains growth since the late Mid-Pleistocene, which is generally linked with crust shortening,³⁶ was sufficient to trigger an averaged incision rate of 1 m/kyr.^{22,44} In contrast, the averaged fluvial incision rate observed in the Gonghe Basin has exceeded this value, reaching up to 3.35 m k/yr since 238–200 ka (Figure 5A). This remarkable increase in fluvial incision rate here can probably be attributed to faster rock uplift caused by local tectonic uplift superimposed on the isostatic compensation over the NETP.^{38,53} Rapid local tectonic uplift indeed has been observed in adjacent basins on the north side of the West Qinling Mountains at the same times,⁵³ but the existing evidence and data here cannot yet clearly attributed it to specific fault activities, leaving an unresolved issue that requires further exploration. The sharp increase in incision rates up to 12.5–15 m/kyr in the two episodes 90–80 and 55–45 ka thus indicates two phases of accelerated fluvial incision rate in the Gonghe Basin.

Coupling imprint of rock uplift and climatic fluctuation in geomorphic archive

Fluvial terraces are generally formed by the autogenic dynamic evolution (intrinsic behavior) of the river system or by the response to variation in allo-genic (extrinsic) controls, such as climate, rock uplift, and base level.¹² Intrinsic processes may induce trends and events when thresholds are crossed, generally leading to the formation of local terraces, mainly at relatively small spatial and temporal scales.⁵⁴ The Yellow River terraces here are more than 1000 m wide and span a timescale of > 1000 years, which suggests that they are most likely to result from extrinsic controls.⁴⁷

In recent decades, studies have increasingly considered the glacial–interglacial climate cycles as the driving force for fluvial incision and subsequent terrace genesis.²⁹ Based on stratigraphic analysis of overlying loess–paleosol sequences, the abandonment of terrace treads resulting from Yellow River incision was considered likely to have occurred at transitions from glacial to interglacial stages.⁴⁷ In the NETP, however, only 11 glacial–interglacial sub-cycles have occurred during the late Mid-Pleistocene: a stark mismatch with the sequence of 14 Yellow River terraces in the Gonghe Basin (Figure 5). Although some evidences stressed that fluvial incision did not occur only at cold–warm transitions but also at warm–cold transitions,¹² the 14 terraces clearly exceed the number of significant climatic transitions within the late Mid-Pleistocene interglacial–glacial record. This striking mismatch appears to imply that greater (sub-Milankovitch) frequencies of climatic fluctuation have impacted on fluvial incision and terrace formation.¹⁵ Other recent studies of numerous terrace archives from the NETP have also invoked climatic control of river systems at a sub-Milankovitch scale in the context of rapid rock uplift.¹⁶ It is suggested that at high Tibetan altitudes, the late Mid-Pleistocene climatic fluctuations may have induced a series of changes in vegetation, temperature, and fluvial discharge, triggering hydrological events that broke the balance between sediment supply and discharge, thus resulting in the frequent alternation between fluvial incision and stability.¹² Remarkably, few or no terraces have been formed during the periods of 238–200–90 ka, 80–55 ka and posterior to 45 ka in the Gonghe Basin, despite the strong climatic fluctuations that occurred in this period. This implies that with an insufficient rate of rock uplift, the river system primarily absorbed climatic fluctuations through a combination of lateral adjustments and/or minor vertical incision. This ongoing, gradual adjustment

was sufficient to accommodate climatic fluctuations without a distinct phase of major downcutting, thus preventing the formation and preservation of a clear terrace record during these intervals (Figure 5E). It is only when more intense climatic fluctuations occur occasionally that net incisions may be possible (Figure 5G), thus forming a very limited number of terraces.

During the two episodes 90–80 ka and 55–45 ka, the Gonghe Basin experienced even faster rates of rock uplift compared with the period in between, steepening the gradient of the riverbed through it. The Yellow River therefore can probably be stimulated perpetually at or near the state of erosional threshold,⁵⁵ leading to a sensitive response to almost any minor climatic perturbation (affecting discharge or sediment load), which can easily trigger a remarkable switch between incision and lateral planation. We suggest that such rapid rates of rock uplift have forced the Yellow River to incise sufficiently to generate the sharp separation of adjacent terrace levels and favor the preservation of terrace flights (Figure 5F). Previous numerical simulation however has revealed that overly rapid rate of rock uplift can keep the river in a state of intense vertical incision, leaving no time for lateral erosion needed to form a wide terrace tread, consequently hindering terrace formation.⁵⁶ Despite this potential possibility, the current geomorphic archive in the Gonghe Basin cannot constrain it yet, and further geological check is still needed.

It is also observed from the cross-section c-d that two levels of the highest and second-highest terraces (T14 and T13) can be formed by the Yellow River downcutting into the Quaternary loose basin fill (Figures 4C–D). Nevertheless, once further excavating into the underlying harder Jurassic sandstone, no more terraces form. This contrast illustrates the high sensitivity endowed by the loose substrate. Theoretically, substrate resistance dictates the 'relaxation time' of a fluvial system. The resistant sandstone (as seen at Yangqu, Figure 4) acts as a 'low-pass filter', dampening high-frequency sub-orbital climatic signals. In contrast, the unconsolidated basin fill minimizes the geomorphic response time, enabling the river to faithfully record rapid climatic oscillations as a dense sequence of terraces. The spectacular and dense sequence of 14 terraces generated by the Yellow River downcutting into the Gonghe Basin is thus explained as the geomorphic expression of fluvial response to suborbital climatic fluctuations driven by the coupling of fast rock uplift and soft substrate.

CONCLUSIONS

The sequence of 14 Yellow River terraces preserved in the Gonghe Basin has been formed entirely during the late Middle and Late Pleistocene, as evidenced by a combination of cosmogenic radio nuclide and optically stimulated luminescence dating. This spectacular terrace staircase provides a precious archive of the incision rate evolution of the NETP, characterized by intermittent acceleration during the intervals 90–80 and 55–45 ka. Correlation with high-resolution regional climatic records suggests that faster fluvial incision can drive a more sensitive fluvial response to climatic fluctuations to create more terraces. While rapid uplift provides the necessary vertical accommodation space, the unconsolidated basin fill lowers the erosional threshold, allowing the river to record high-frequency signals as a dense terrace sequence. The sequence of Yellow River terraces in the Gonghe Basin is thus understood as the product of suborbital climatic fluctuations, whose geomorphic expression was ultimately enabled by the unique coincidence of exceptionally high rock uplift rates and a physically responsive, soft substrate, providing a new insight to understanding the relative impact of rock uplift, substrate and climatic changes on the suborbital-scale landform evolution in the NETP.

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AUTHOR CONTRIBUTIONS

Z.Hu. and M.L. designed the study and wrote the paper. B.P., D.B., and E.G., did an initial review. Z.D., Q.M., X.L., Y.W., M.Z., R.P., performed the analyses. J.V. and J.N. improved the manuscript. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Samples and raw Chronological data used in this study are publicly available through the Figshare database: https://figshare.com/articles/dataset/The_age_data_for_Rock_uplift_increased_sensitivity_of_fluvial_response_to_suborbital_climatic_fluctuations_/26861941 or in the Table S1–S3. Data are available from the corresponding author upon reasonable request.

SUPPLEMENTAL INFORMATION

It can be found online at <https://doi.org/10.59717/j.xinn-geo.2026.100205>.