Reconstructing the incision of the Lancang River (Upper Mekong) in southeast Tibet near Yunlong using fluvial terraces and transient river profiles

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ABSTRACT Reconstructing the incision history of the Mekong River is important for understanding the relative role of tectonics, surface processes, and climate on various time and space scales in shaping the rugged landscape in southeast Tibet. To decipher the spatio-temporal pattern of river incision, we combined fluvial terrace investigation with transient tributary profile analysis for the Lancang (Upper Mekong) River, which is characterized by a prominent knickzone ~800 km wide between Weixi and Nangqian (27.3-32.2°N). In the Yunlong reach (25-27.5°N) below the knickzone, we conducted field investigation, uncrewed aerial vehicle (UAV) photogrammetric survey, and K-feldspar post IR-IRSL (pIR-IRSL) dating of fluvial terraces underlain by bedrock strath 60-380 m above the Lancang River. This revealed pulsed incision that has occurred since the Middle Pleistocene (>470 ka), which decelerated over time from <0.75 mm/yr to <0.24 mm/yr. We rectified the incision rate in the Deqin (28.3-29°N) and Mangkang reaches (30°N) at the knickzone by determining the K-feldspar pIR-IRSL ages for the terrace deposits. This yields a temporal increase trend since the Middle Pleistocene (>380 ka) in the Deqin reach, from <0.63 mm/yr to <1.1 mm/yr, which is higher than that in the Mangkang reach of <0.29 mm/yr (>160 ka). Therefore, terrace-derived incision rates seem to be of the same order of magnitude as erosion rates measured by detrital ^{10}Be concentration and low-temperature thermochronological data, and erosion rates derived by the three approaches all yield the maximum value at the prominent knickzone. Transient tributary profile analysis and projection in the Yunlong reach revealed three phases of rapid incision: ~100-450 m, ~650-850 m, and 1350-1550 m, and the former two are demonstrated by fluvial terraces perched along the Lancang River. Published low-temperature thermochronological data along the Lancang valley also recorded rapid exhumation since the Pliocene-Quaternary, which is contemporary with similar magnitudes of ~1150-1350 m of incision in the Yunlong reach and ~600-900 m of incision in the Deqin reach. Regional extensional deformation in southeast Tibet, such as the Lancang River fault intersecting the trunk river, should have played an important role in regulating pulsed incision of the Lancang River in aid of climate change. This may have contributed to the development of the prominent knickzone by selective superposition in addition to local tectonic-induced rock uplift.

What is the spatial and temporal pattern of river incision along the Lancang River?

Basic observations

@ The Mekong River flows roughly parallel to the gently sloping plateau margin in southeast Tibet;

@ The Lancang River roughly runs parallel to the closely spaced Nu-Salween and Jinsha-Yangtze rivers for >300 km, and has carve >3000 m-deep valleys locally perched with various levels of fluvial terraces.

Existing problems

@ Wide valleys along the Lancang River in the Yunlong reach tend to store thick terrace deposits, and this may result in the poor match between the amount and timing of incision and large uncertainty for terrace-derived incision rate ;

@ The erosion rates estimated at scattered spots by various approaches vary widely with space and time along the Lancang River, and a comparison of them is not straightforward because of the large difference in time scales and spatial variability;

What we can do

@ carry out UAV photography, field investigation, and K-feldspar post IR-IRSL (pIR-IRSL) dating on fluvial terraces preserved in the Yunlong reach to acquire a more reliable incision rate;

@ analyze transitent river profiles to offer a regional framework for interpreting erosion rates by multiple approaches and reconstruct the incision history of the Lancnag River over the longe time.

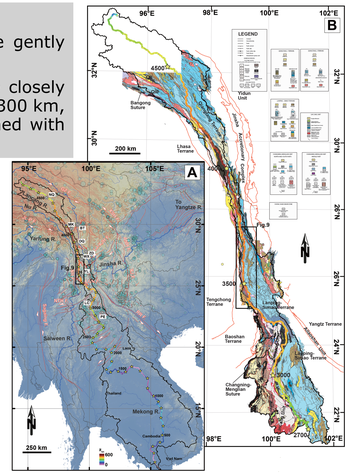

Figure 1. *(A) Topographic map of southeast Tibet based on 90-m-resolution STRM data, showing the distribution of major rivers and drainage basins. The Mekong drainage basin is marked by a black bold line, and the trunk river is marked by a color gradient of varying river steepness by the integral method (Perron and Royden, 2013; Mudd et al., 2014; Schwanghart and Scherler, 2014). Yellow-filled stars with numbers show the distance (km) away from the confluence of the Mekong trunk river with the South China Sea. In addition, active faults and historical earthquakes in China are also shown by red lines with arrows to indicate the direction of the horizontal motion of the main strike-slip faults, based on the work by Tapponnier et al. (2001), Deng et al. (2003), and Taylor and Yin (2009) and our interpretation. GZ F.-Ganzi fault; XSH F.-Xianshuihe fault; ANH F.-Anninghe fault; XJ F.-Xiaojiang fault; RR F.-Red River fault; LJ-XJH F.-Lijiang-Xiaojinhe fault; JSR F.-Jinsha River fault; LCR F.-Lancang River fault; NTH F.-Nantinghe fault; NR F.-Nu River fault; and JL-P F.-Jiali-Parlung fault. Historical earthquakes from 780 B.C. to 2008 are cited from the China Earthquake Networks Center (http://www.ceic.ac.cn/history). Geographic names were NQ-Nangqian; MK-Mangkang; BT-Batang; DQ-Deqin; ZD-Zhongdian; WX-Weixi; YL-Yunling; LC-Lincang; and PE-Pu'er. (B) Simplified geological map of the Lancang drainage basin between kms 700-4500 in southeast Tibet adapted from Burchfiel and Chen (2012). The river steepness and flow distance of the Lancang trunk river are also shown in Fig. 1A. Black rectangles show the Yunlong reach in Fig. 9.*

Fluvial terraces-Yunlong reach

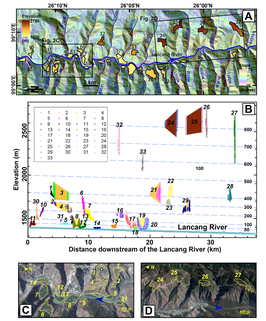

Figure 2. *(A) Topographic map of the Lancang River near Songdeng in the Yunlong reach with the surface gradient map underlain by the hill-shaded DEM based on 30-m STRM data; fluvial terraces identified based on surface gradient are marked with black polygons filled by a yellow-brown gradient according to the elevation difference; black rectangles show the location of fluvial terraces with Google Earth imagery. (B) Absolute elevation of fluvial terraces at Songdeng identified in Fig. 2A with flow distance of the Lancang River. (C) Google Earth imagery for fluvial terraces at Songdeng. (D) Google Earth imagery for fluvial terraces downstream of Songdeng with tread surfaces >600 m above the Lancang River.*

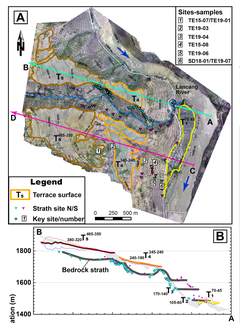

Figure 3. *(A) UAV-derived imagery underlain with the hill-shaded DEM together with 20-m-interval contour lines; three levels of fluvial terraces are marked with polygons, and the contact between the bedrock strath and the overlying terrace deposits is marked by triangles filled with canyon color for the northern part and purple color for the southern part; profiles A-B and C-D across the northern and southern parts are marked by cyan and purple lines accordingly. (B) A-B cross section plot for fluvial terraces in the northern part of Songdeng, including tread surfaces and bedrock strath surfaces. (C) C-D cross section plot of fluvial terraces in the southern part of Songdeng, including tread surfaces and bedrock strath surfaces. The locations for dating samples are marked by green-filled stars.*

@ Fluvial terraces are underlain by bedrock strath at 105-60 m, 170-140 m, 240-190 m, 380-320 m, and >600 m;

@ Terrace sediments overlying bedrock strath at 60-380 m high are characterized by large-river deposits, tribuary alluvial fan deposits, or a combination of both;

@ Terrace sediments have been deposited since the Middle Pleistocene from >470 ka to ~310 ka by the K-feldspar pIR-IRSL method (200℃& 290℃);

@ The river incision rate since the Middle Pleistocene decreases with time in the Yunlong reach, from <0.75 mm/yr since >470 ka, to ~0.54-0.65 mm/yr since >400-330 ka, and to <0.24 mm/yr since >330 ka.

@ Fluvial terraces underlain by bedrock strath reveal at least four phases of enhanced river incision along the Lancang River, including 105-60 m, 240-190 m, 380-320 m, and >600 m, and the former phases of enhanced incision should have been prior to the Middle Pleisotcne.

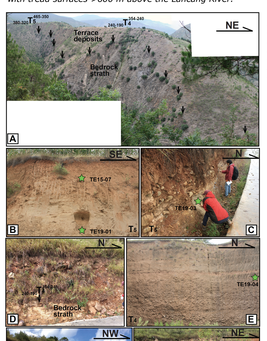

Figure 4. *Field pictures for fluvial terraces at Songdeng with sampling locations marked by green-filled stars and sample names, and the contact between the terrace deposits and the underlying bedrock strath is marked by black arrows with the relative elevations. (A) Tread surfaces of Terraces T_5 and T_4 with the underlying contact between the terrace deposits and bedrock strath marked by black arrows. (B) The fine-grained overbank deposits of the T_5 terrace deposits with two samples, TE15-07 and TE19-01. (C) The alluvial fan boulder conglomerate layers of Terrace T_5 with sand lenses collected as sample TE19-03. (D) The contact between the bedrock strath and the overlying alluvial fan boulder conglomerate layer for Terrace T_4. (E) The trunk river cobble to pebble conglomerate layers and overlying fine-grained deposits of Terrace T_4 and one sample, TE19-04. (F) Terrace deposits with sand layers underlain by the bedrock strath of Terrace T_3 and one sample, TE19-06. (G) Fine-grained sand layers underlain by the bedrock strath of Terrace T_2, and two samples, SD18-01 and TE19-07, collected below the pebble conglomerate layer.*

Fluvial terraces-Mangkang& Deqin reaches

Five levels of fluvial terraces with strath heights at 200-240 m, 140-170 m, 100-120 m, 35-60 m, and 10-20 m.

Mangkang Reach

@ one prominent terrace surface: 130-180 m;
@ three levels of strath surfaces: 220-240 m, 100-140 m, and 35-60 m;
@ ~45 m strath & > 160 ka terrace deposits & <0.29 mm/yr;

Deqin Reach

@ four levels of strath surfaces: 210-250 m, 140-190 m, 90-110 m, and 10-20 m;
@ one prominent bedrock strath at 140-190 m & 10-100 m terrace deposits straddle the Lancang River for 80 km;
@ terrace deposits: > 380-9 ka vs. terrace abandonment: 57-6 ka
@ The incision rate since the Middle Pleistocene increases with time in the Deqin reach, from <0.63 mm/yr at >380 ka, to <0.72 mm/yr at >230 ka, and to <1.1 mm/yr at 16-9 ka.

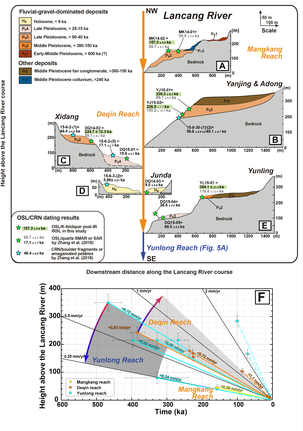

Figure 6. *Simplified cross sections for various levels of fluvial terraces along the Lancang River modified based on Zhang et al. (2018): (A) Mangkang reach and (B-E) Deqin reach. Dating results by the K-feldspar pIR-IRSL method in this study were marked by a green background, as well as optically stimulated luminescence (OSL) and cosmogenic radionuclide (CRN) dating results published by Zhang et al. (2018). (F) Plots of quartz OSL and K-feldspar pIR-IRSL dating results vs. height above the Lancang River for fluvial terraces along three reaches of the Lancang River, together with interpretation of river incision rates.*

River profiles-Mekong River & Tributaries

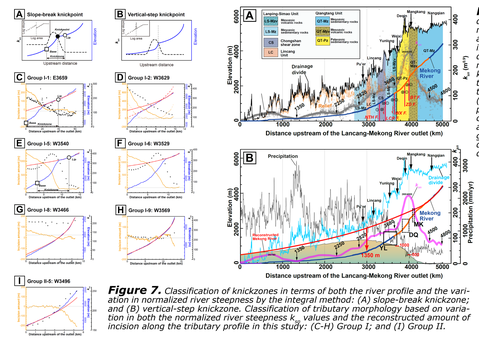

Figure 7. *Classification of knickzones in terms of both the river profile and the variation in normalized river steepness by the integral method: (A) slope-break knickzone; and (B) vertical-step knickzone. Classification of tributary morphology based on variation in both the normalized river steepness k_{sn} values and the reconstructed amount of incision along the tributary profile in this study: (C-H) Group I; and (I) Group II.*

@ The Mekong River displays a stepwise variation of the normalized river steepness index, with the prominent knickzone at kms 3680-4500 between Weixi and Nangqian;
@ the Mangkang (km 4110) and Deqin reaches (kms 3830-4000) at the knickzone, and the Yunlong reach (kms 3400-3700) below it;
@ The maximum incision of ~1350 m occurs at km 3000, and ~500 m incision occurs at km 4000 of the steepest knickzone;
@ Transient tributary profiles in the Yunlong reach record three phases of rapid incision, which involve ~100-450 m, ~650-850 m, and ~1150-1350 m, and a phase of rock uplift (~100-300 m) downstream of km 3590 on the western bank;
@ ~500 m incision offset between the oppositing tributaries may result from either two separate pulses of external perturbation due to differential response time, or later modification by local tectonic uplift of the Lancnag River fault.

Figure 8. *(A) Longitudinal profile for the Mekong River (blue) and its drainage divide (black) and the relief between them (Yellowish brown), normalized river steepness (gray cross-shaped points), and geological units and active tectonics exposed within the Lancang drainage basin, as shown in Fig. 1. Geographic names are marked on the longitudinal profile of the drainage divide, and key flow distances in kilometers are marked on the river steepness to show the boundary points. The Mekong trunk river at the knickzone is marked as a reddish brown line instead of a blue line. (B) Longitudinal profile for the Mekong River (blue, reddish brown for the segment at the knickzone) and its drainage divide (canyon), normalized river steepness (pink), and TRMM-derived (Tropical Rainfall Measuring Mission precipitation) precipitation (green) (adapted from http://www.geog.ucsb.edu/~bodo/TRMM/). The reconstructed Mekong River profile is shown by a red line, and the amount of incision is the wave shape is indicated with a green to brown gradient. Three reaches with fluvial terraces in this study are denoted by black rectangles with solid lines for the Yunlong reach (YL) and dashed lines for the Deqin (DQ) and Mangkang (MK) reaches.*

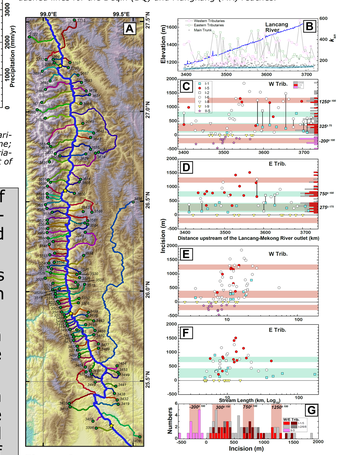

Figure 9. *(A) Topographic map of the Lancang River in the Yunlong reach based on 30-m-resolution STRM data, showing the distribution of tributaries on both banks with names. (B) The variation in the tributary k_{sn} value at the outlet with distance upstream from the Mekong River confluence in the Yunlong reach. (C) The incision amount reconstructed by west-bank tributaries in the Yunlong reach with the histogram on the right to show the distribution. (D) The incision amount reconstructed by east-bank tributaries in the Yunlong reach with the histogram on the right to show the distribution. (E) The stream length vs. incision amount plot for west-bank tributaries in the Yunlong reach. (F) The stream length vs. incision amount plot for east-bank tributaries in the Yunlong reach. (G) Histogram for the incision amount reconstructed by tributaries on both banks in the Yunlong reach.*

Discussion and Summary

@ Terrace-derived incision rates along the Lancang River vary from 0.24-<1.1 mm/yr, and are roughly on the same magnitude as erosion rates estimated from cosmogenic ^{10}Be concentrations in river sediments and low-T thermochronology;

@ River incision along the Lancang River since >330-160 ka of the Middle Pleistocene reaches the maximum rate at the southern part of the prominent knickzone, which is corroborated by erosion rates since by low-temperature thermochronological data (the middle-late Miocene) and detrital ^{10}Be concentration;

@ Geomorphic evidence that includes fluvial terraces and transient tributary profiles reveals at least five pulses of enhanced incision of the Lancang River in the Yunlong reach: 105-60 m, 240-190 m, 380-320 m, 650-850 m, and 1150-1350 m, as well as a phase of 100-300 m rock uplift;

@ Given that the terrace-derived average incision rate of <0.5±0.25 mm/yr since the Middle Pleistocene can be temporally extrapolated to several million years old, the arrival time of an external perturbation was constrained to be prior to the Late Pliocene-Early Pleistocene for the ~600-700 m incision, and the Pliocene-Early Pleistocene for the ~1150-1350 m incision;

@ Regional extensional deformation in aid of climate change may have driven the pulsed enhanced incision of the Lancang River in the Yunlong reach, which may have transmitted upstream to be superposed at the Mekong prominent knickzone.

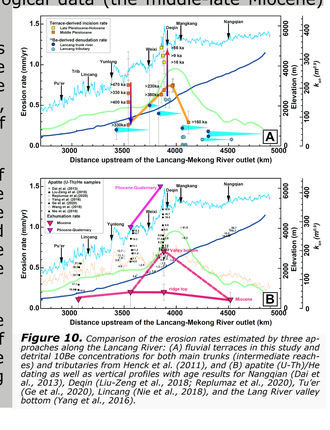

Figure 10. *Comparison of the erosion rates estimated by three approaches along the Lancang River: (A) fluvial terraces in this study and detrital 10Be concentrations for both main trunks (intermediate reaches) and tributaries from Henck et al. (2011), and (B) apatite (U-Th)/He dating as well as vertical profiles with age results for Nanggian (Dai et al., 2013), Deqin (Liu-Zeng et al., 2018; Replumaz et al., 2020), Tu'er (Ge et al., 2020), Lincang (Nie et al., 2018), and the Lang River valley bottom (Yang et al., 2016).*