Quaternary channel-focused rapid incision in the Phung Chu-Arun River in Central Himalaya: Implications for a Quaternary capture event

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Abstract

The Phung Chu-Arun River, one of the few major trans-Himalaya rivers, consists of a large drainage area captured in the northern slope of the Himalaya, and provides a key to understand tectonic, surface processes and their interplay in topographic development of the Himalaya. In this study, we carried out thermochronologic and topographic analysis along the Phung Chu-Arun River in Central Himalaya to reveal its incision development. Apatites from a downstream section along its major tributary yield very young fission track and (U-Th)/He ages of 0.8–1.5 Ma. These cooling ages, combined with previously reported data for higher elevations, reveal an abrupt change of the slope in the age-elevation plot suggesting an accelerated channel incision initiated at between \( \frac{C}{2^4} \) 1.5 and 2.5 Ma. The age-elevation relationship yields a high apparent exhumation rate (AER) of \( \frac{C}{2^4} \) 2.6–3.8 mm/a during Quaternary, which is spatially focused along the mainstream of the Kharta-Chentang reaches and the associated nearby tributaries. Topographic analysis suggests that this channel-focused incision acceleration was probably facilitated by a Quaternary capture event in upper drainage of the palaeo Arun River. This capture event greatly enhanced the effective discharge draining southward, causing an accelerated incision wave along the mainstream and tributaries of the palaeo Arun River. Furthermore, thrusting at physiographic transition zone is also required to sustain high channel gradient and the long-term rapid incision. Channel morphology presenting common knick points in major tributaries suggests that the drainage basin in Ama Drime Range area likely remain in pre-steady state adjustment of this capture event.

Keywords:
Phung Chu-Arun River
Central Himalaya
Channel topography
Apatite fission track dating
Apatite (U-Th)/He dating

1. Introduction

It remains a mystery that how Himalaya sustains its high topographic front while remain under a long-term, rapid surface denudation. A range of chronologic data (Herman et al., 2010; Huntington et al., 2006; Streule et al., 2012; Whipp et al., 2007) and erosion data (Burbank et al., 2012; Galy and France-Lanord, 2001; Garzanti et al., 2007) indicate a rapid regional denudation at \( \sim 1-2 \text{ mm/a} \) in the Himalaya (Thiede et al., 2005; Thiede and Ehlers, 2013; Wobus et al., 2003). Indeed, the Himalaya topographic front would have been completely eroded within 3–5 Myr if there was no tectonic force.

One possible explanation for the high topography is that the focused surface denudation has been tectonically compensated by corresponding rapid rock uplift (Beaumont et al., 2001; Koops et al., 2002; Zeitler et al., 2001). In this model, the rock uplift might be dynamically sustained though a positive feedback between surface process and thermally-weakened deep crustal rocks (Beaumont et al., 2001; Willett, 1999). For example, the Pliocene-Quaternary exhumation of the Ama Drime Range was suggested to be enhanced by denudation of the Arun River gorge (Jessup et al., 2008). An alternative model suggests that the high topography has been maintained by a protective effect of surface processes, such as glacial damming developed at high altitudes, which prohibits rivers from headward incision (Korup and Montgomery, 2008; Owen, 2008). In this case, a northward decrease in bedrock denudation is required to maintain the high relief across the Himalayan topographic front.

Across the Himalaya, only a limited number of rivers have successfully dissected through the orogenic divide, capturing significant drainage areas of the northern slope. These trans-Himalaya rivers occur as a key to understanding the nature and development of geomorphic system of the Himalaya, where its erosional topography results from an interplay between tectonic input and
erosional output (Beaumont et al., 2001; Hodges et al., 2004; Zeitler et al., 2001). However, the erosional developments of these trans-Himalaya rivers remain poorly understood. In this study, we performed (U-Th)/He and fission track dating as well as topographic analysis for the Phung Chu-Arun River to investigate its incision development and its topographic implications for the Himalaya.

2. Geology and topography of the Phung Chu area

The Phung Chu-Arun drainage is located in the Central Himalaya, which transects upstream across the Himalaya into Tibet. Its upper drainage (to the north of the main Himalayan divide), which is locally referred to as Phung Chu River, covers a large region in Tibet, and is drained northward by several highest peaks in the Himalayas including the Everest (Fig. 1a and b). Along the western flank of the Ama Drime Range, the Phung Chu River runs southward reaching Nepal, where it is known as Arun River.

2.1. Orogenic parallel structures

The Phung Chu drainage covers two major tectono-stratigraphic units of the Himalaya: the Tethyan Himalaya Sequence (THS) in the north and the Greater Himalayan Sequence (GHS) in the south. These two tectono-stratigraphic units are divided by a north dipping extensional fault, the South Tibetan Detachment System (STDS), which was activated in Middle Miocene (Burchfiel et al., 1992; Leloup et al., 2010; Wang et al., 2006).

The THS is composed of Phanerozoic unmetamorphosed sedimentary sequences developed in passive continental margin of the Indian Plate. In contrast, the GHS to its south, is composed of high-grade metamorphic rocks evolved from Precambrian Indian basement (Pan et al., 2012; Yin, 2006). In its upper part, the GHS was commonly intruded by a number of Miocene leucogranites (Harris, 2007; Searle and Godin, 2003; Searle et al., 1997), which have been interpreted as intra-crustal melting due to either crust thickening or decompression by extensional movement of the STDS (Searle et al., 1997).

The STDS, placing the unmetamorphosed THS over GHS of high-grade Precambrian gneissic rocks, can be well traced over the entire orogenic belt. In the Phung Chu and Everest regions, the STDS is characterized by a ductile shear zone over several kilometers in thickness (Carosi et al., 1998). Syntectonic leucogranite veins are widely deformed indicating normal faulting (Leloup et al., 2010; Murphy and Harrison, 1999). Interestingly, the STDS yielded clustered cooling ages of ~16–12 Ma from AFT (Apatite Fission Track; Searle et al., 1997), ZFT (Zircon Fission Track; Streule et al., 2012; A. Wang et al., 2010) and 40Ar/39Ar systems (Leloup et al., 2010; Macfarlane, 1993; Wang et al., 2006; Zhang and Guo, 2007). These thermochronologic data highly suggest fast cooling of the footwall of the STDS by tectonic denudation.

The STDS activity was likely to have ceased in Middle-Late Miocene after its transition from ductile to brittle deformation. This is supported by a number of undeformed leucogranite veins with zircon U/Pb ages of ~17–15 Ma intruding the shear zone (Hodges et al., 1998; Leloup et al., 2010). In the Phung Chu area, the STDS has been clearly deformed and offset by the N-S fault system (Fig. 1c), indicating an orogenic structural transition from the NS to the EW extension (Kali et al., 2010; Leloup et al., 2010). P-T-D-t (Pressure-Temperature-Deformation-time) data in the STDS footwall suggest that the system became inactive since ~13.5–12 Ma, and this timing is considered as the upper limit for the initiation of the EW extension (Kali et al., 2010; Leloup et al., 2010).

The Main Central Thrust (MCT), defining the bottom of GHS in regional, occurs as a key boundary fault (mainly ductile) accommodating hundreds of kilometers shortening between the Indian Plate and Tibetan Plateau during Neogene (Robinson et al., 2003; Schelling, 1992). The specific location of the MCT across the Arun River remains unresolved although a good number of studies have been carried out in this area (Searle et al., 2008). The MCT was initially identified by a kyanite isograd in the upper reaches of the Arun River, located ~5–10 km to the south of Chentang (Bordet, 1961). Similar location was accepted in subsequent studies (Goscombe et al., 2006; Schelling, 1992; Upreti, 1999). Goscombe et al. (2006) later termed it as ‘High Himal Thrust’ (HHT), which divided the GHS into the upper and lower plates. However, based on strain data, Searle et al. (2008) suggested a much lower structural level for the MCT, which is located at Tumlingtar village, ~50 km to the south of the HHT. In this study, we preserve the location of HHT as MCT. It is interesting that in many locations investigated, the MCT (root zone) is located at the foothill of Higher Himalaya, coinciding with a physiographic transition zone across the Himalayan topographic front, which may bear an implication of out-of-sequence tectonics (Hodges et al., 2004; Wobus et al., 2005, 2003; Yin, 2006).

The timing of ductile deformation of MCT, from a regional perspective, occurred from the Early to Middle Miocene (Arita et al., 1997; Hodges, 2000; Johnson et al., 2001; Yin, 2006). In some
localities, a Late Miocene-Pliocene activation was proposed based on chronologic data (Catlos et al., 2004; Harrison et al., 1997). In addition, brittle deformation has also been commonly identified within MCT zone (Searle et al., 2008; Searle and Godin, 2003).

2.2. Ama Drime Horst

In structure, the Ama Drime Range corresponds to an active NS horst (Figs. 1c and 2) accommodating the EW extension in Himalaya (Jessup et al., 2008; Kali et al., 2010). Its western bounding fault, the Kharta Fault (KF), developed a fault valley extending ~60 km from Moguo at the northern tip of the Ama Drime Range to its southern at Kharta (Fig. 1c). Surface ruptures, which extend along the foot of many giant triangular facets with heights of ~1.6–2 km (Fig. 2c and d), widely offset Quaternary moraines and alluvial fans developed at foothill. In southern segment of the Kharta valley, the KF ruptured a second strand, showing an en echelon pattern of dextral step (Fig. 1c). This western strand extends SW into the Higher Himalaya and phases out at high altitudes, showing a southward attenuation in fault throw.
The eastern range-flanking active fault, Dinggye Fault (DF), extends straight in SSW and ruptures foothill Quaternary glacial deposits (Figs. 1c and 2b). The surface rupture of DF dies out southward in Higher Himalaya at similar latitude as the KF. Along both flanks of the Ama Drime Range, ductile shear zones were developed, in which S-C fabrics, grain tails and lineations are common, and suggest consistent ductile deformation of dip-slip normal sense without apparent oblique slip components (Jessup et al., 2008; Kali et al., 2010; Langille et al., 2010). These ductile shear zones are crosscut by high-angle brittle deformation associated with the KF and DF. The ductile and brittle deformations are considered as a coherent extensional structure developing the horst structure at different crustal level (Jessup et al., 2008; Kali et al., 2010; Kapp et al., 2008).

The NS normal faulting in the Ama Drime area was initiated prior to \( 11 \text{ Ma} \), following the ductile deformation and rapid cooling between \( 17 \) and \( 12 \text{ Ma} \) in the STDS (Leloup et al., 2010, 2009; Murphy and Harrison, 1999; Wang et al., 2010, 2006). There are little direct constraints on the magnitude of displacement of these normal faults. Assuming the STDS as a pre-deformational marker, horizontal offsets by the KF and the DF are \( 15 \text{ km} \) and \( 35 \text{ km} \), respectively (Kali et al., 2010; Leloup et al., 2010), which indicates an apparent less partition in extension along the KF.

### 2.3. Ama Drime Range topography

The horst structure of the NS-trending Ama Drime Range is characterized by a couple of normal faults, which appear conjugate. The topography, in contrast, presents an asymmetrical pattern (Figs. 1c and 3), which implies an apparent contrast in surface erosion between the eastern flank and the western flank. In its western flank, EW glacial and fluvial valleys are relatively longer and wider, and are almost evenly spaced. In contrast, most valleys in the eastern flank are short and narrow displaying an apparent weaker surface erosion (Fig. 1c). As a result, the western flank of the Ama Drime Range is much wider (\(~22 \text{ km}\) km) than the eastern (<5 km).

The differential erosion is also manifested in the swath topographic profile across the Ama Drime Range, which show apparent contrasts in relief and minimum topography between the range flanks (Fig. 3). It is interesting that the maximum topographic line (Fig. 3), represented by EW ridges, presents an overall flat trend across the majority of the range, implying an EW symmetrical topographic pattern. This topographic flat trend is consistent with the main divide of the Ama Drime Range striking NS. These topographic highs share similar elevations of \( 6 \pm 0.5 \text{ km} \). The overall consistent elevations of these topographic highs and the symmetrical pattern are compatible with a low-relief topography of the palaeo Ama Drime Range (possibly analogous to the topography in hinterland of Tibetan Plateau), which was dissected and destructed by a young channel incision event, and transformed into the current high relief topography.

### 3. Methods

#### 3.1. Apatite Fission Track (AFT)

Apatite fission track dating was performed at the State Key Laboratory of Geological Processes and Mineral Resources in China University of Geosciences. Samples were prepared following the standard external detector method (Hurford and Green, 1983). Apatite grains were mounted in epoxy and polished to make scratch-free surfaces, and the mount was etched in \( 5 \text{ N HNO}_3 \) at room temperature for 21 s. Thermal neutron irradiation was car-
ried out at the China Institute of Atomic Energy with a nominal neutron fluence of $8 \times 10^{15}$ cm$^{-2}$, which was monitored by CN5 standard glasses mounted at ends of each sample column. A zeta value of $331.11 \pm 11.52$ was obtained using the Durango apatite standard from multi-irradiated sample columns. Fission tracks were counted under a Zeiss Axioplan 2 microscope at a magnification of 1000.

### 3.2. Apatite (U-Th)/He (AHe)

Apatite (U-Th)/He dating was performed at University of Florida. All apatite grains were examined under a binocular stereomicroscope at a magnification of 160 to avoid samples with significant inclusions. Alpha ejection ($F_T$) factor for each grain was calculated based on measured linear dimensions (Farley et al., 1996). Single or multiple apatite grains were wrapped in Pt tubes, and heated using a diode laser under high vacuum. The extracted gas was purified and spiked with $^3$He, followed by isotopic measurements using a quadrupole mass spectrometer. All the samples were re-extracted at least once to ensure complete degassing. The degassed sample packets were spiked and dissolved in 5% nitric acid at 120 °C overnight. The sample solutions’ U-Th-Sm isotopic compositions were measured using an Element2 ICP-MS.

### 3.3. Channel morphology processing

For topographic analysis, we used the data from ASTER Global Digital Elevation Model (2nd version released in 2011). These data have an average precision of 2.4 arc-sec in horizontal and 15 m in vertical, with substantial quality improvements compared to the previous version (Tachikawa et al., 2011). Processing of channel longitudinal profiles was carried out using the software package of Arc Hydro on the platform of ArcGIS.
4. Results

4.1. Thermochronology

4.1.1. Apatite Fission Track (AFT)

Six samples collected on valley bottom along the Chentang tributary yielded AFT ages between 1.1 and 13.6 Ma (Figs. 1c and 4; Table 1). These ages generally increase upstream/northward, which represent a positive correlation with elevation. The sample P44, which is located in the hanging wall of DF, yielded an exceptionally older age than others. This may be due to a lower erosion rate in hanging wall than in footwall of normal fault. Therefore, the sample P44 is excluded from the exhumation-rate calculation for the Ama Drime Range. It is worthy to note that all samples to its south are essentially unaffected by the normal faulting of DF, (1) Surface rupture along the upper reaches of the Chentang tributary initiated in the middle Miocene. Thus samples to the south of P42 yielded AFT ages between 1.1 and 13.6 Ma which indicate no evidence of active faulting. (2) These young cooling ages are much younger than the timing of KF and DF which terminated to the north of sample P42. (3) Field investigation along the upper reaches of the Chentang tributary identified no evidence of active faulting. (3) These young cooling ages are much younger than the timing of KF and DF which initiated in the middle Miocene. Thus samples to the south of P44 most likely preserve a complete and original exhumation history of Ama Drime Range rather than NS faulting of the KF and the DF.

4.1.2. Apatite (U-Th)/He (AHe)

The AHe ages (Table 2) range from 0.8 to 13.2 Ma, and show a similar positive correlation with elevation (Fig. 4). Samples P40 and P42 yielded dispersed ages ranging from 2.8 to 26.0 Ma and 4.9 to 11.2 Ma, respectively. This may be due to unidentified high-U-Th inclusions, U-Th zonation, or He implantation from outside of the grains. Considering that these ages are older than their AFT ages, and are apparently in odd with existing AHe ages at higher elevations in the Ama Drime range (Jessup et al., 2008; Kali et al., 2010), we precluded these ages from apparent exhumation rate (AER) calculation. AHe ages of P34, P35 and P37 are internally consistent within their uncertainties, and cope well with their AFT ages, suggesting that they can provide more reliable constraints for documenting exhumational processes.

Sample P44 in the hanging wall of DF yields an average age of 13.2 ± 0.7 Ma, which is slightly younger than its AFT age of 13.6 ± 0.9 Ma. These ages are consistent with a number of Middle Miocene cooling ages obtained at equivalent structural locations at the top of GHS and below STDS in Central Himalaya (Macfarlane, 1993; Searle et al., 1997; Wang et al., 2010, 2006), which indicate syntectonic denudation by the STDS (Wang et al., 2010, 2006).

Table 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Elev (m)</th>
<th>N</th>
<th>(p_i/N_i)</th>
<th>(p_i/N_i)</th>
<th>(p_i/N_i)</th>
<th>U (ppm)</th>
<th>(P(\chi^2)) (%)</th>
<th>Age (Ma) ± 1(\sigma)</th>
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</thead>
<tbody>
<tr>
<td>P44</td>
<td>28.0553</td>
<td>87.6919</td>
<td>4654</td>
<td>14</td>
<td>3.43E5/397</td>
<td>4.77E6/5518</td>
<td>1.139E6/3776</td>
<td>50.9 ± 1.9</td>
<td>2.9</td>
<td>13.6 ± 0.9</td>
</tr>
<tr>
<td>P42</td>
<td>27.9399</td>
<td>87.6408</td>
<td>4354</td>
<td>15</td>
<td>8.89E4/113</td>
<td>4.68E6/5952</td>
<td>1.123E6/3751</td>
<td>50.7 ± 1.8</td>
<td>7.06</td>
<td>3.5 ± 0.4</td>
</tr>
<tr>
<td>P40</td>
<td>27.9032</td>
<td>87.5816</td>
<td>4165</td>
<td>15</td>
<td>2.18E4/24</td>
<td>1.59E6/1750</td>
<td>1.115E6/3738</td>
<td>17.3 ± 0.9</td>
<td>65.5</td>
<td>2.5 ± 0.6</td>
</tr>
<tr>
<td>P37</td>
<td>27.9120</td>
<td>87.5275</td>
<td>3771</td>
<td>17</td>
<td>4.76E4/89</td>
<td>5.82E6/1087</td>
<td>1.099E6/3713</td>
<td>64.5 ± 2.0</td>
<td>73.1</td>
<td>1.5 ± 0.2</td>
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<tr>
<td>P35</td>
<td>27.8757</td>
<td>87.4582</td>
<td>2933</td>
<td>21</td>
<td>6.96E4/102</td>
<td>1.04E6/1619</td>
<td>1.034E6/3688</td>
<td>45.4 ± 1.4</td>
<td>98.4</td>
<td>1.2 ± 0.2</td>
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<tr>
<td>P34</td>
<td>27.8522</td>
<td>87.4473</td>
<td>2533</td>
<td>21</td>
<td>2.06E4/71</td>
<td>4.04E6/11048</td>
<td>1.083E6/3688</td>
<td>45.4 ± 1.4</td>
<td>98.4</td>
<td>1.2 ± 0.2</td>
</tr>
</tbody>
</table>

* N is number of grains analyzed. \(p_i\) is spontaneous track density (cm\(^{-2}\)); \(N_i\) is number of spontaneous tracks; \(p_i\) is induced track density (cm\(^{-2}\)); N is number of induced tracks; \(p_i/N_i\) is track density on fluence monitor (cm\(^{-2}\)); \(N_i\) is tracks counted on fluence monitor. U ± 2\(\sigma\) is the average uranium concentration (ppm). \(P(\chi^2)\) is Chi-squared probability. Ages (Ma) are determined using the Zeta method and calculated using the computer program and equations by Brandon (1992). All listed ages are pooled ages with 1\(\sigma\) error. See context for other lab parameters and processes.

Table 2

<table>
<thead>
<tr>
<th>Sample</th>
<th>(N^a)</th>
<th>(F_{v^b})</th>
<th>(^4He) (fmol)</th>
<th>Th (ppm)</th>
<th>Sm (ppm)</th>
<th>Age (Ma)</th>
<th>1(\sigma^c) (Ma)</th>
<th>Mean</th>
<th>SD(^d)</th>
</tr>
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<tbody>
<tr>
<td>P44</td>
<td>1</td>
<td>0.84</td>
<td>61.48</td>
<td>46.0</td>
<td>1.6</td>
<td>207.2</td>
<td>12.4</td>
<td>0.3</td>
<td>11.2</td>
</tr>
<tr>
<td>P42</td>
<td>1</td>
<td>0.87</td>
<td>121.77</td>
<td>57.6</td>
<td>1.8</td>
<td>265.7</td>
<td>13.8</td>
<td>0.3</td>
<td>4.9</td>
</tr>
<tr>
<td>P40</td>
<td>1</td>
<td>0.87</td>
<td>187.70</td>
<td>77.0</td>
<td>4.3</td>
<td>297.2</td>
<td>13.2</td>
<td>0.3</td>
<td>2.8</td>
</tr>
<tr>
<td>P37</td>
<td>1</td>
<td>0.90</td>
<td>165.87</td>
<td>46.0</td>
<td>3.5</td>
<td>237.4</td>
<td>9.7</td>
<td>0.3</td>
<td>1.1</td>
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<tr>
<td>P35</td>
<td>1</td>
<td>0.92</td>
<td>590.81</td>
<td>73.2</td>
<td>9.9</td>
<td>258.3</td>
<td>11.2</td>
<td>0.3</td>
<td>4.9</td>
</tr>
<tr>
<td>P34</td>
<td>1</td>
<td>0.86</td>
<td>17.20</td>
<td>41.6</td>
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<td>243.5</td>
<td>4.9</td>
<td>0.1</td>
<td>2.8</td>
</tr>
</tbody>
</table>

* A number of apatite grains analyzed in a single packet.

b Alpha recoil correction factor calculated from linear dimensions of each grain.

c Analytical errors added 4\% relative error by alpha correction factor.

d Standard deviation.

For samples P40 and P42, which are poor in age replication, minimum age packet is given as reference. See context for details.
4.2. Channel morphology

4.2.1. Mainstream

The longitudinal profile of the Phung Chu-Arun River mainstream shows multiple channel segments with contrasting channel gradient anomalies (Fig. 5). The upstream-most high-gradient anomaly is located at the Yo Ri gorge, which connects upstream the Moguo valley and downstream the Kharta valley. Both the Moguo and the Kharta segments are characterized by flat braided channels with lower channel gradient. An unusual aspect of the Yo Ri gorge, as has long been noticed, is its planar course, which is locally trapped in erosional-resistant footwall of the KF forming a sharp bedrock relief over ~1.5 km (Armijo et al., 1986; Kali et al., 2010; Wager, 1937). Note that the relief of the topographic barrier between the Moguo and the Kharta valley is only <400 m (Fig. 2d), which is much less than that in the Yo Ri gorge. Apparently, this peculiar gorge course is inconsistent with a formation of upstream progression by headward incision, but may imply a capture event (Armijo et al., 1986).

The second high-gradient anomaly coincides with the Kharta-Chentang gorge, which covers a longitudinal length of ~50 km (Figs. 1c and 5). Both its upstream (the Kharta fault valley) and downstream reaches are characterized by lower channel gradient. It is interesting that the lower break in channel gradient, marking a major physiographic transition in the Arun River, coincides with the location of the MCT (Figs. 1c and 5). This coincidence simply implies an active tectonic significance if it is no accident.

4.2.2. Tributaries

As is consistent with previous observations (Robl et al., 2008), tributaries developed along the Phung Chu River show an interesting style in channel longitudinal profile. Most of these tributaries show a convex pattern, which means that channel gradients increase downstream overall (Fig. 6). This is contrasted with graded channel longitudinal profiles, which in order to maintain a constant erosion rate along longitudinal profile, channel gradients attenuate downstream due to the effect of downstream accumulation in discharge (Brookfield, 1998; Burbank and Anderson, 2011). Note that in first order, most of these tributaries consist of linear segmented reaches. These reaches have almost constant channel gradients, instead of a gradual change in gradient, which indicate apparent existence of knick points. Segments downstream knick points show high average gradients of 6.5–8.1%, which are significantly higher than those upstream of 1.4–5.0%.

![Fig. 5. Longitudinal profile of the Phung Chu-Arun River. Histogram indicates local channel gradient, of which high-anomaly zones are indicated by shaded rectangle. Percentage numbers indicate average channel gradients of specified zones. Note that the Kharta-Chentang anomaly zone is characterized by an approximate constant channel gradient, indicated by short dashed line. Dashed circle marks an apparent deficiency in DEM data. Top-right inset illustrates the response of channel longitudinal profile to channel uplift, in which gradient anomaly forms in uplifting wall (modified from Brookfield, 1998). Note that the downstream boundary of the channel gradient anomaly zone predicts the location of fault.](image1)

![Fig. 6. Longitudinal profiles of major tributaries of the Phung Chu River. Circles mark interpreted knick points. Percentage numbers indicate average channel gradients for specified segments of tributary, which are indicated by dashed lines. See Fig. 1c for locations of labelled tributaries.](image2)
5. Discussion

5.1. Early-Quaternary strengthened exhumation

In age-elevation diagram our newly obtained and the previously reported AHe data show two linear segments, which presents an abrupt slope change at between 2.5 and 1.5 Ma (Fig. 4). The strengthened AER since ~1.5 Ma also occurs in the AFT data sets, which shows an identical trend with a contemporaneous slope change. Three low elevation/southernmost samples from the Chentang tributary yield AERs (Apparent Exhumation Rates) of 3.8 mm/ a and 2.5 mm/a for AHe and AFT, respectively. In contrast, the AFT and the AHe data from higher elevation samples (>~3.7 km) define AERs of 0.29 mm/a and 0.63 mm/a, respectively, which are significantly lower.

The strengthened exhumation in Quaternary is apparent, if we employ the recently implemented analytical methods (Willett and Brandon, 2013) to convert cooling ages to time-averaged erosion rates. Samples P34, P35, P37 at downstream of the Chentang tributary yield high erosion rates of 4.0–2.3 mm/a and 4.2–1.8 mm/a for AFT and AHe, respectively; while upstream samples P40 and P42 yield much lower average erosion rates of 1.2–0.75 mm/a, assuming a geothermal gradient of 35 °C/km and an average local elevation of 3500 m.

Jessup et al. (2008) reported an overall AER of ~1 mm/a for the period between 1.4 and 3.0 Ma based on datasets with AHe ages of ~2.3–4.2 Ma (elevation = 4418–5580 m) from EW valleys in the Ama Drime, and one young AHe age of 1.44 Ma (elevation = 3435 m) from the entrance to the Kharta-Chentang gorge (Figs. 1c and 4). Worthy to note that the authors realized that these data might reflect a possible slower exhumation prior to 2–3 Ma acknowledging that data was limited. By synthesizing subsequent AHe ages (3.3–3.8 Ma) obtained from the eastern limb of Ama Drime Range at similar elevations (5217–5419 m; Kali et al., 2010), our reinterpretation of these data as a whole yields a lower average AER of ~0.63 mm/a between 2.3 and 4.2 Ma (0.78 mm/a between 1.5 and 4.2 Ma when taking into account the sole lowest/southernmost young AHe data).

The pre-Quaternary lower exhumation rate is also supported by an AFT age of 8.2 Ma (elevation = 5040 m; Liu et al., 2005) and an AHe age of 3.3 Ma (3959 m; Jessup et al., 2008) obtained from a leucogranite outcropped at the northern tip of the Ama Drime Range. These data yield an overall AER of ~0.45 mm/a between 8.2 and 3.3 Ma, assuming a temperature gap of 40 °C between effective closure temperatures of the AFT and AHe, and a geothermal gradient of 35 °C/km.

Acknowledging that AERs over non-vertical transects may possibly deviate from true exhumation rates (Braun et al., 2012; Valla et al., 2010), we suggest that the Ama Drime Range area experienced a slower exhumation (AER < ~0.8 mm/a) prior to 2.5–1.5 Ma, followed by an abrupt strengthened exhumation (AER ~ 2.6–3.8 mm/a) at between 2.5 and 1.5 Ma.

5.2. Associated erosional topography

In this section, we argue that the Quaternary strengthened exhumation has been driven by fluvial process at surface, of which rapid channel incision dominated the development of gorge landforms along reaches from Chentang, Kharta to Yo Ri gorge. This channel-incision associated erosional landforms also involve many EW valleys dissecting the western flank of the Ama Drime range due to base level lowering at the mainstream.

As noted, the very young cooling ages along the Chentang tributary coincide in space with the high channel gradient zone downstream the knick point (Figs. 1c and 6). According to the stream power law (Burbank and Anderson, 2011; Howard et al., 1994; Whipple and Tucker, 1999), bedrock channel incision rate is a power law function of channel gradient, which means that the channel gradient anomaly corresponds to high channel incision. The spatial coincidence between the young cooling ages and the high channel incision rate, as predicted by the stream power law (Burbank and Anderson, 2011; Howard et al., 1994; Whipple and Tucker, 1999), allows us to hold that it is the focused channel incision dominated the cooling of channel bedrocks and formation of gradient anomaly.

Robl et al. (2008) proposed that the downstream increase in channel gradient of tributaries is driven by the erosional-driven rock uplift, which strengthens downstream toward the mainstream, i.e., the “river anticline effect” (Montgomery and Stolar, 2006; Robl et al., 2008). We notice that most tributary longitudinal profiles in the study area contain knick points, and both its upstream and downstream are characterized by linear segments with almost constant gradients (Fig. 6). These features are inconsistent with a continuous downstream increase in channel gradient predicted by the “river anticline effect” (Montgomery and Stolar, 2006; Robl et al., 2008). Therefore, we interpret the convex longitudinal profile as a result of strengthened channel incision at surface rather than the “river anticline effect” a tectonic feedback to fluvial erosion.

The Kharta channel segment is bounded by the Yo Ri and Kharta-Chentang gorges (Figs. 1c and 5), both of which are of rapid incision due to high channel gradient. Therefore, we suggest that the fluvial erosion in the Kharta valley is passive, and may have been dominated by its local base level lowering at the Kharta-Chentang gorge. This implies that the Kharta valley probably shared a similar incision rate to those at the bounding gorges. Rapid erosion in the Kharta valley is consistent with the young AHe cooling age of 1.44 Ma (Jessup et al., 2008) obtained from the southern tip of the Kharta valley (the entrance to the Kharta-Chentang gorge; Fig. 1c). It is worthy to note that the topographic outcropping of many giant triangular facets with height of 1.6–2 km, is unlikely a sole result of tectonics by normal faulting, but might be greatly facilitated by rapid fluvial erosion in the Kharta valley. This is because the time-averaged slip rate across the KP is only 0.12–0.36 mm/a, assuming that the vertical offset of STDS is 1.3–4 km since ~11 Ma when the NS horst initiated (Kali et al., 2010; Leloup et al., 2010, 2009). This tectonic rate is much lower than the exhumation rates suggested by AFT and AHe cooling ages at the Ama Drime Range, which requires extra surface erosional contribution to the exhumation of footwall. The suggested erosion episode in the Kharta valley further likely promoted the development of many EW sub-valleys sculpting the western flank of the Ama Drime Range, which progressively migrated the Ama Drime Range divide eastward forming asymmetric range flanks.

5.3. Driving force of Quaternary incision

Factors that could enhance channel incision rate include climate (e.g., heavy precipitation, glaciation: Burbank et al., 2003; Huntington et al., 2006), channel uplift or base-level lowering by tectonics (Brookfield, 1998; Lang and Huntington, 2014), and drainage reorganization by capture (Clark, 2004; Snyder et al., 2003). Climate factors such as heavy precipitation and glaciation are often of large spatial scale in regional, of which associated incision strengthening is likely to occur over the entire drainage. However, the rapid incision observed occurs exclusively along the mainstream, and appears to be radiating peripherally upstream along tributaries (Fig. 1c). This is inconsistent with the climate change of a drainage-scaled precipitation enhancement, which appears to steepen channel gradients at the whole drainage scale rather than locally at certain reaches. Furthermore, glaciation appears to
drive rapid erosion at high altitudes where glacial and periglacial landforms prevail. The spatial coupling between the young cooling ages and the high channel gradient suggests a fluvial dynamic for channel incision instead of glaciation related erosion in high altitudes. Therefore, we conclude that climate change is not the dominating force for the observed incision rate change, although it is a most common factor enhancing surface erosion in Quaternary.

We propose that the Quaternary rapid incision was most likely driven in potential by tectonic movements, and was facilitated by a Quaternary capture event. According to the channel gradient response to faulting (Fig. 5 inset), the high channel gradient zone of the Kharta-Chentang gorge (Figs. 1c and 5) can be simply explained by an active thrust fault lying around the MCT, where channel gradient leaps greatly upstream. By southward thrusting along this out-of-sequence fault, the rapid incision and high channel gradient can be well tectonically maintained over long term. This suggestion is supported by a growing number of thermochronologic and topographic data, as well as field evidence, indicating active thrusting in the Central Himalaya, at the foothill of Higher Himalaya along strike coinciding the physiographic transection, indicating active thrusting in the Central Himalaya, at the foothill

We notice that the abrupt incision rate hike (between ~1.5 and 2.5 Ma) appears occurred long after the onset of the out-of-sequence thrusting in regional, which is dated as late Miocene-Pliocene inferred from thermochronologic data and modeling results (Catlos et al., 2004; Harrison et al., 1997). If the timing of out-of-sequence tectonics is correct, then an addition triggering force is required for the incision rate hike. Recognizing that the peculiar course of the Yo Ri gorge is unlikely formed by a normal headward incision progression, but might reflect a capture event (Armijo et al., 1986), we suggest that the Quaternary incision was greatly facilitated by a capture event, rather than solely driven by tectonics of thrusting at the physiographic transition zone. In this capture event, large drainages previously draining the Tibet headwater were finally incorporated into the Ganges drainage. These young erosional landforms favor that this Quaternary rapid incision most likely reflects a Quaternary capture event at the Yo Ri gorge. Sustained out-of-sequence thrusting at the physiographic transition zone (near the MCT) is required to serve as a long-term potential force maintaining high channel gradient and rapid incision across the Higher Himalaya.

6. Conclusions

The Phung Chu-Arun River, one of the major trans-Himalaya rivers, consists of a large drainage captured from the northern slope of the Himalaya. Apatite fission track and (U-Th)/He data provide cooling and exhumation histories during Pliocene-Quaternary, and suggest an abrupt increase of fluvial incision rate occurred at ~1.5–2.5 Ma with a four-fold increase in apparent exhumation rate.

Topographic analysis suggests that the Quaternary rapid incision is spatially focused along channels in reaches downstream the Yo Ri gorge. Cooling ages, channel morphology and associated erosional landforms favor that this Quaternary rapid incision most likely reflects a Quaternary capture event at the Yo Ri gorge. Sustained out-of-sequence thrusting at the physiographic transition zone (near the MCT) is required to serve as a long-term potential force maintaining high channel gradient and rapid incision across the Higher Himalaya.

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References


