Episodic fluvial incision of rivers and rock uplift in the Himalaya and Transhimalaya

JASON M. DORTCH1*, CRAIG DIETSC1, LEWIS A. OWEN1, MARC W. CAFFEE2 & KELLY RUPPERT3

1Department of Geology, University of Cincinnati, Cincinnati, OH 45221-0013, USA
2Department of Physics/PRIME Laboratory, Purdue University, West Lafayette, IN 47906, USA
3Department of Geological Sciences, California State University, Fullerton, MH 154, Fullerton, CA 92834-6850, USA
*Corresponding author (e-mail: drotchjm@email.uc.edu)

Abstract: Seventeen strath terraces in northern India were dated using 10Be surface exposure methods; ages range from c. 7 to c. 735 ka and provide fluvial incision rates of 0.02 ± 0.003 to 2.6 ± 1.9 mm a⁻¹. On the northern side of the Ladakh Range, incision rates are c. 1 mm a⁻¹; in the northern Zanskar Range they are ≤0.06 ± 0.005 mm a⁻¹. New and published incision rates in southernmost Lahul range from 0.1 ± 0.02 to 13.2 ± 6.2 mm a⁻¹; rates for ages >35 ka are ≤0.4 ± 0.2 mm a⁻¹. Across the Himalaya and Transhimalaya, Holocene fluvial incision rates range from c. 0.02 to c. 26.0 mm a⁻¹, whereas Pleistocene incision rates are ≤5 mm a⁻¹. Many of the Holocene incision rates exceed exhumation rates, whereas Pleistocene incision rates are comparable with exhumation rates. This suggests that long-term fluvial incision is in dynamic steady state with exhumation. The temporal pattern for rates of fluvial incision is probably controlled by episodic incision linked to significant precipitation changes throughout the Quaternary, suggesting that strath terraces with ages >35 ka can be used for assessing long-term rates of rock uplift. In contrast, rates of fluvial incision based on Late Glacial and Holocene strath terraces reflect changes in monsoon intensity and deglaciation events. By determining ages for multiple samples on flights of strath terraces, it is possible to document changes in incision rate, assess whether post-abandonment transient shielding has occurred, and help elucidate tectonic v. climatic controls on their formation.

Supplementary material: Tables (DS1–4) for previously published data and recalculated ages for strath terraces, and figures (DS1 and DS2) showing plots of incision rates against time for the Himalaya and Transhimalaya are available at http://www.geolsoc.org.uk/SUP18454.

Complex feedbacks among tectonics, topography, climate, and sediment fluxes affect how fluvial systems incise bedrock and remove debris, two key surface processes that help control how active mountain landscapes develop through erosion and uplift. Determining the rates and spatial variability of bedrock incision is a key component for understanding how surface and tectonic processes are linked in the evolution of mountain topography and for evaluating whether mountain landscapes are transient or have achieved steady state. Fluvial incision in active mountain landscapes is just one facet of denudation, but river incision rates can control regional denudation rates by setting boundary conditions for hillslope erosion (Burbank et al. 1996; Whipple 2004). In this view, the rate at which channels incise into bedrock sets the rate at which the surrounding landscape evolves, and hence controls the response time to tectonic and/or climatic forcing (Hancock et al. 1998). Moreover, where large rivers are actively incising their bedrock channels in regions of bedrock uplift (e.g. Zeitler et al. 2001; Vannay et al. 2004), equilibrium can be attained wherein incision rates (mainly controlled by stream power) are in balance with bedrock uplift rates. The bedrock channels of these rivers become stable base levels with respect to the geoid (Burbank et al. 1996; Leland et al. 1998). In such cases, uplift of strath terraces along these rivers will record rock uplift, and if there is little or no erosion of the strath terrace bedrock, rock uplift will essentially be equivalent to surface uplift (Bishop 2007).

In other cases, however, fluvial incision can be a response to a variety of episodic geological influences, including changes in climate, glaciation, base level, and seismic and lake dam burst events (Hartshorn et al. 2002; Pratt et al. 2002; Dortch et al. 2011), and over millennial time scales, erosion and bedrock uplift rates are characterized by disequilibrium. The processes of physical erosion into bedrock (incision), including plucking, macro-abrasion, chemical and physical weathering, and cavitation include critical thresholds (Whipple et al. 2000), which suggests that most incision may occur during large floods (Whipple 2004). This, in turn, implies that extreme events such as glacial outburst and landslide-dam break floods may be important factors in controlling fluvial incision rates. Lower thresholds, higher precipitation, and steeper, narrower channels permit a higher percentage of floods to contribute to river incision. Climate change could be a primary control of episodic erosion owing to increased discharge, sediment load, and calibre of the sediment (Burbank & Anderson 2001; Hartshorn et al. 2002; Pratt et al. 2002). For longer-term fluvial incision into bedrock, on time scales of tens of thousands to hundreds of thousands of years, measured rates of incision are aggregates of sustained erosion and low-frequency episodic events (Shroder & Bishop 2000), although Howard et al. (1994) argued that long-term average incision rates are proportional to the shear stress exerted by the dominant discharge.

The development of terrestrial cosmogenic nuclide (TCN)
surface exposure dating allows rates of incision and bedrock uplift to be quantified by dating strath terraces. Many models for the formation of strath terraces have been proposed, including response to periods of balanced (Formento-Trigilio et al. 2003), altered (Pazzaglia & Brandon 2001), and oscillating (Hancock & Anderson 2002) sediment supply; tectonically induced changes in rock uplift (Rockwell et al. 1984; Molnar et al. 1994; Mukul 1999); falling base level (Born & Ritter 1970; Reneau 2000), and falling eustatic sea level (Pazzaglia & Gardner 1993; Merritts et al. 1994). However strath terraces form, they require that a river incise deeper into its channel as it abandons its floodplain to form a bench (Bucher 1932). If the age and height of a strath terrace above present river level are known, a mean rate of fluvial incision can be calculated. Mean rates of fluvial incision calculated by this method have stimulated much debate regarding the role of fluvial incision in landscape development and this has been particularly so for young orogens such as the Himalaya (Leland et al. 1998; Zeitzler et al. 2001; Korup & Montgomery 2008) where mountains are actively uplifting, eroding, and being incised by large river systems.

In addition, long-term (10^6–10^8 years) exhumation rates can be estimated from radiometric mineral cooling ages. In ranges such as the Himalaya with significant topographic relief, the use of the low-temperature (U–Th)/He thermochronometer in apatite (AHe) and zircon (ZHe), and fission-track ages of apatite (AFT) and zircon (ZFT) in vertical transects allow recent exhumation to be quantified. The approximate closure temperatures for these systems can be summarized as AHe, c. 70 °C (Farley 2000; Reiners et al. 2003); AFT, c. 120 °C (Gleadow & Duddy 1981); ZHe, c. 180 °C (Reiners et al. 2003); ZFT, c. 250 °C (Zaun & Wagner 1985). Calculated exhumation rates using age–elevation relationships and a ‘closure temperature-surface’ approach need to take account of how topography affects the geometry of isotherms (Stuwe et al. 1994; Mancktelow & Grasemann 1997; Ehlers & Farley 2003) and the possibility of non-vertical exhumation (Huntington et al. 2007). The age–elevation relationship of low-temperature thermochronometers is also affected by changes in topographic wavelength, exhumation rate, and the geotherm, and the time scale of changes in surface relief that have taken place after cooling through the closure temperature (Mancktelow & Grasemann 1997; Braun 2002; Reiners et al. 2003). Despite these complexities, calculated exhumation rates across the Himalaya range from c. 0.05 to c. 5 mm a^{-1} (e.g. Zeitler 1985; Sorkhabi et al. 1996; Treloar et al. 2000; Kirstein et al. 2006, 2009; Adams et al. 2009) and directly correlate with age: the slowest exhumation rates correlate with the oldest mineral ages. An exception to these rates was presented by Crowley et al. (2009), who calculated an exhumation rate of c. 13 mm a^{-1} for the past million years at the western syntaxis (Wadia 1931) at Nanga Parbat based on U–Pb ages of accessory minerals in migmatites and leucogranites. In landscapes that have achieved steady-state topography when measured over a long-term time scale (e.g. Spotila et al. 2004) where exhumation and rock uplift are equal, long-term incision rates calculated from old strath terraces might be expected to approach exhumation rates calculated from low-temperature thermochronometers.

We present here new 10Be TCN surface exposure ages of strath terraces from the Zanskar and Ladakh Ranges and the adjacent Indus River Valley in the Ladakh region, and the High Crystalline Himalaya in the Lahul region of northern India (Fig. 1). In addition, we summarize and recalculate (to standardize) all previously published 10Be strath terrace ages from these areas, and from Garhwal and Nanda Devi in the High Crystalline Himalaya in northeastern India, from central Nepal and the Everest region, and also from Nanga Parbat in northeastern Pakistan (Fig. 1). We examine the spatial and temporal variation of calculated rates of fluvial incision across this broad region to assess the applicability of using strath terraces dated by TCN methods to better understand how rates of river incision into bedrock can be related to bedrock and surface uplift, and how short-term (millenia) and long-term (10^6–10^8 years) incision rates compare and how they might reflect equilibrium or transient conditions in the landscape. Another aspect of our study is to examine on a regional basis the correlation between the age of strath terraces and their calculated fluvial incision rates, and to determine whether there is a threshold age of strath terraces in the Himalaya when the calculated rate of fluvial incision closely approximates long-term (10^8–10^9 years) rock uplift and exhumation. The semi-arid environment of the Ladakh and Zanskar Ranges allows strath terrace surfaces as old as c. 100 ka to be preserved, permitting calculation of long-term mean incision rates. The large relief and active uplift in the Himalaya aids significantly in reducing the relative importance of elevation and age uncertainty for calculating rates of fluvial incision because the inherent inaccuracies of measuring elevation and calculating ages are small compared with the large elevation and age values of the old and tall strath terrace surfaces that are present (Leland et al. 1998; Seong et al. 2007). Our temporal framework can be divided into ages that record a Holocene millennial time scale, a time scale of the order of tens of thousands of years, and a late Quaternary time scale of the order of a hundred thousand years or more.

**Geological setting and study areas**

The Himalayan–Tibetan orogen was produced by the collision of the Indian and Eurasian continental lithospheric plates at c. 50 Ma (Yin & Harrison 2000; Searle & Richard 2007), producing mountains of impressive size and elevation, and the Tibetan plateau, the world’s largest and highest orogenic plateau. Since the collision, Indian plate lithosphere has continued to move northward, indenting 2000 km into Asia (Dewey et al. 1989; Johnson 2002) with modern global positioning system (GPS) measurements showing northeastward movement of India with respect to Eurasia at a rate of c. 35 mm a^{-1} (Larson et al. 1999). Crustal shortening and thrust and strike-slip faulting across the orogen are still active (Hodges et al. 2004; Vannay et al. 2004; Bojar et al. 2005). Regional geological relations, including details of the timing of movement along the crustal-scale faults that bound the major tectonostratigraphic subdivisions of the orogen, have been described by Hodges (2000), Yin & Harrison (2000) and Streule et al. (2009).

Structural studies and constraints on the timing of movement along the orogen's principal faults led to a model of foreland-propagating thrusting as the Himalayan deformation front has progressed from the Main Central Thrust southward to the Main Boundary Thrust (Gansser 1964; LeFort 1975); with radiometric mineral cooling ages, transfer of movement to the Main Boundary Thrust was constrained to the late Miocene–Pliocene (summarized by Hodges 2000). Thrusting was transferred to the Main Frontal Thrust in Pliocene–Holocene time (Hodges et al. 2004). In addition, a Pliocene to Quaternary phase of exhumation of the High Crystalline Himalaya and early to late Pliocene movement along the Main Central Thrust are supported by the uniform distribution of young AHe and AFT ages across the unit that are spatially related to both thrust and extensional faults (Hurtado et al. 2001; Burbank et al. 2003; Hodges et al. 2004; Vannay et al. 2004; Bojar et al. 2005) as well as 40Ar/39Ar mineral cooling
ages from within the Main Central Thrust itself (McFarlane 1993). Out-of-sequence recent faulting in the central Nepalese Himalaya a few tens of kilometres south of the Main Central Thrust has been deduced from muscovite $^{40}$Ar/$^{39}$Ar cooling ages and calculated cosmogenic erosion rate data (Wobus et al. 2005) along a physiographic transition defined, in part, by increases in mean elevation, relief, and river channel gradients (Wobus et al. 2005, 2008). Wobus et al. (2005) concluded that active faulting could be directly linked to a strong precipitation gradient across this segment of the orogen.

In the areas where we present our new $^{10}$Be TCN ages for strath terraces and report previously published ages, low-temperature thermochronometers have yielded Miocene ages from the Ladakh (Kirstein et al. 2006, 2009) and Zanskar (Sinclair & Jaffey 2001) Ranges, and Plio-Pleistocene ages from Lahul (Adams et al. 2009), Garhwal (Sorkhabi et al. 1996), central Nepal (Burbank et al. 2003), and the Khumbu Himal (Searle et al. 2003, and references therein). At Nanga Parbat, young ages of low-temperature thermochronometers are notable: ZFT ages are 1.3 Ma and younger (Zeitler 1985), and along the Astor River across the core of Nanga Parbat, ZFT ages are as young as 0.33 Ma (Winslow et al. 1996) and AFT ages are as young as 20 ka (Treloar et al. 2000).

The Ladakh region in northern India encompasses the semi-arid Karakoram, Ladakh, Pangong, and Zanskar Ranges (Fig. 2a), which are considered ranges of the Transhimalaya (Hodges 2000); however, because our data here are from a relatively limited region of the Transhimalaya, we prefer ‘the Ladakh region’ as our geographical reference. All of these ranges contain deeply incised valleys with a relative relief of 1000–3000 m and our new strath terrace ages are from valleys in the Ladakh and Zanskar Ranges, and from the Indus River Valley west and south of Leh (Figs 1 and 2). The Ladakh and Zanskar Ranges in northern India are principally composed of plutonic rocks of a Cretaceous continental arc (Searle 1991) and forearc sedimentary and volcanic rocks, and molasse sedimentary rocks of Late Cretaceous to Neogene age (Steck 2003), respectively. The topography of the Himalaya south of the Zanskar Range rises to >4000 m above sea level (a.s.l.), which restricts summer monsoon precipitation in Ladakh (Bookhagen et al. 2005; Bookhagen & Burbank 2006). The south Asian summer monsoon provides roughly two-thirds of the precipitation in the Ladakh, Pangong, and Zanskar Ranges, whereas it provides only one-third of the precipitation in the Karakoram, which is dominated by the westerlies (Hewitt 1989; Brown et al. 2003; Seong et al. 2007). The Indus, Shyok, and Zanskar Rivers drain the region and are responsible for the transfer of the majority of debris through and out of the mountains.

The High Crystalline Himalaya of Lahul of northern India is formed from the Pir Panjal and Greater Himalaya Ranges, principally composed of Precambrian and Palaeozoic metamorphic rocks intruded by large granitic stocks and sills of Cambrian–Ordovician age (Frank et al. 1973; Miller et al. 2001) and leucogranite of Miocene age (Searle & Fryer 1986; Walker et al. 1986).
al. 1999; Fig. 2b). Peaks in both ranges exceed 6000 m a.s.l. (Webb et al. 2007) and deeply incised valleys have a relative relief of c. 3000 m. Our new strath terrace ages are from the Bhaga and Chandra River Valleys, which run through the High Crystalline Himalaya. Lahul receives the majority of its precipitation from the south Asian summer monsoon, but areas north of the Pir Panjal are in a rain shadow and northernmost Lahul is semi-arid (Bookhagen et al. 2005; Bookhagen & Burbank 2006). The Chandra and Bhagra Rivers drain the mountains and transfer most of the sediment through and out of the region (Owen et al. 1995).

Prell & Kutzbach (1987) showed that monsoon maxima coincide with precession and northern hemisphere insolation maxima. Enhanced monsoon phases in the past probably caused monsoon precipitation to play a more significant role in the Himalaya (Gasse et al. 1996). The lacustrine sediment record and former lake levels and landforms (Fang 1991; Gasse et al. 1991, 1996; Shi et al. 2001), speleothems (Fleitmann et al. 2003), enhanced terrigenous input in marine records (Prins & Postma 2000; Thamban et al. 2002), and increased sedimentation in the Bay of Bengal (Goodbred & Kuehl 2000; Bray & Stokes 2004) show that the south Asian summer monsoon advanced further north, which essentially resulted in intensified monsoon phases in many regions of central Asia including the NW Himalaya, Tibet, south China, Nanga Parbat, the southern portion of the Arabian Peninsula, and the Bay of Bengal during the late Pleistocene (24–29 ka) and Holocene. During these intensified monsoon phases, moisture penetrated more than 75 km beyond the present orographic barrier (mountain ridges at >4500 m a.s.l.) in the Greater Himalaya (Bookhagen et al. 2005). Bookhagen et al. (2005) suggested that enhanced monsoon precipitation can increase sediment flux and flood frequency.

Lacustrine sediments from Tibet and China provide a particularly important record of monsoons as the lakes lie inland of the high Himalaya, suggesting that monsoon precipitation reaching these lakes would also affect the entire Himalayan orogen. Using terraces, sediment cores, and pollen from seven lakes (including Pangong Tso), Shi et al. (2001) showed that lake levels in Tibet were typically higher between c. 34 and 44 ka (all radiocarbon ages we present from previous studies were calibrated using CalPal 2009, the on-line radiocarbon calibrator at http://www.calpal-online.de/). Also, using δ18O variation from two ice cores, the Guliya core in western Tibet (Yao et al. 1996; Thompson et al. 1997) and the Dunde core in northeastern Tibet (Thompson et al. 1989, 1990), Shi et al. (2001) showed that there was c. 40–100% more monsoon precipitation in this time interval (34 to 44 ka) than today. Shi et al. (2001) attributed the higher lake levels and increased precipitation to an exceedingly strong summer monsoon climate over the Tibetan plateau. Fang (1991)
| Sample | Strath | Surface condition | Lithology          | Latitude (°N) | Longitude (°E) | Elevation (m a.s.l.) | Thickness (cm) | Shielding correction | Uncorrected $^{10}$Be atoms g$^{-1}$ SO$_2$ (10$^6$) | Corrected $^{10}$Be atoms g$^{-1}$ SO$_2$ (10$^6$) | CRONUS Age (ka)* | PRIME Age (ka)$^\dagger$ |
|--------|--------|-------------------|--------------------|---------------|----------------|---------------------|----------------|---------------------|-----------------------------------------------|-----------------------------------------------|----------------|-----------------------------|
| I-66   | Indus  | Dark brown varnish | Metasedimentary    | 34.120        | 77.432        | 3240                | 5.0            | 0.98                | 0.969 ± 0.018                                    | 0.878 ± 0.017                                    | 25.4 ± 2.3 | 24.7 ± 1.7                   |
| I-62   | Indus  | Dark brown varnish | Metasedimentary    | 34.121        | 77.419        | 3235                | 5.0            | 0.98                | 1.29 ± 0.025                                    | 1.17 ± 0.023                                    | 34.0 ± 3.1 | 32.8 ± 2.3                   |
| I-63   | Indus  | Dark brown varnish | Metasedimentary    | 34.121        | 77.419        | 3235                | 5.0            | 0.97                | 2.44 ± 0.044                                    | 2.21 ± 0.040                                    | 65.5 ± 5.9 | 63.2 ± 4.4                   |
| I-64   | Indus  | Dark brown varnish | Metasedimentary    | 34.124        | 77.420        | 3120                | 5.0            | 0.95                | 0.413 ± 0.054                                    | 0.374 ± 0.049                                    | 12.0 ± 1.9 | 11.6 ± 1.7                   |
| I-67   | Indus  | Dark brown varnish, boulder | Metasedimentary | 34.007        | 77.689        | 3150                | 5.0            | 0.98                | 2.49 ± 0.037                                    | 2.26 ± 0.034                                    | 70.0 ± 6.2 | 67.6 ± 4.7                   |
| I-71   | Indus  | Dark brown varnish | Sandstone          | 34.263        | 77.067        | 3010                | 5.0            | 0.96                | 0.339 ± 0.012                                    | 0.307 ± 0.011                                    | 10.3 ± 1.0 | 10.0 ± 0.8                    |
| I-72   | Indus  | Dark brown varnish | Metasedimentary    | 34.251        | 77.105        | 3025                | 5.0            | 0.98                | 3.34 ± 0.079                                    | 3.03 ± 0.072                                    | 100.6 ± 9.3 | 97.9 ± 7.1                   |
| I-73   | Indus  | Dark brown varnish | Sandstone          | 34.166        | 77.335        | 3097                | 5.0            | 0.96                | 0.289 ± 0.008                                    | 0.262 ± 0.007                                    | 8.4 ± 0.8  | 8.1 ± 0.6                    |
| I-76   | Indus  | Dark brown varnish | Metasedimentary    | 34.170        | 77.332        | 3065                | 5.0            | 0.99                | 0.486 ± 0.010                                    | 0.440 ± 0.009                                    | 14.0 ± 1.2 | 13.5 ± 0.9                   |
| I-77   | Indus  | Dark brown varnish | Metasedimentary    | 34.169        | 77.332        | 3055                | 5.0            | 0.98                | 0.327 ± 0.010                                    | 0.296 ± 0.009                                    | 9.5 ± 0.9  | 9.2 ± 0.7                    |
| I-78   | Indus  | Dark brown varnish | Metasedimentary    | 34.169        | 77.332        | 3050                | 5.0            | 0.98                | 0.372 ± 0.014                                    | 0.337 ± 0.012                                    | 10.8 ± 1.0 | 10.5 ± 0.8                   |
| zk37   | Stok   | Dark brown varnish | Sandstone          | 34.003        | 77.512        | 3923                | 5.0            | 0.92                | 19.4 ± 0.481                                    | 17.6 ± 0.436                                    | 408.7 ± 40.6 | 396.1 ± 31.2                 |
| zk48   | Sacha  | Dark brown varnish | Sandstone          | 33.787        | 77.805        | 3479                | 5.0            | 0.91                | 25.7 ± 0.725                                    | 23.3 ± 0.657                                    | 752.8 ± 82.1 | 736.9 ± 64.7                 |
| zk49   | Sacha  | Dark brown varnish | Sandstone          | 33.811        | 77.805        | 3495                | 5.0            | 0.92                | 22.1 ± 0.492                                    | 20.1 ± 0.446                                    | 615.8 ± 63.8 | 604.8 ± 49.8                 |
| zk50   | Sacha  | Some debris cover | Sandstone          | 33.736        | 77.741        | 3490                | 5.0            | 0.94                | 16.5 ± 0.409                                    | 15.0 ± 0.371                                    | 433.9 ± 43.3 | 424.8 ± 33.7                 |
| zk78   | Bhgra  | Weathered         | Metasedimentary    | 32.676        | 77.214        | 3471                | 5.0            | 0.92                | 2.03 ± 0.149                                    | 1.84 ± 0.135                                    | 51.2 ± 5.9  | 50.2 ± 5.0                    |
| zk79   | Chandra | Weathered         | Quartzite          | 32.545        | 77.972        | 2900                | 5.0            | 0.92                | 0.208 ± 0.124                                    | 0.189 ± 0.112                                    | 7.3 ± 4.4   | 7.1 ± 4.3                     |
| zk80   | Chandra | Polished          | Quartzite          | 32.526        | 76.974        | 2908                | 5.0            | 0.94                | 1.69 ± 0.210                                    | 1.53 ± 0.190                                    | 57.5 ± 8.8  | 57.4 ± 8.2                    |
| zk81   | Chandra | Potholes          | Quartzite          | 32.526        | 76.970        | 2911                | 5.0            | 0.93                | 4.61 ± 0.561                                    | 4.18 ± 0.509                                    | 162.1 ± 25.1 | 162.2 ± 23.5                 |
| zk82   | Kokhsar | Polished, potholes | Granite            | 32.417        | 77.231        | 3133                | 5.0            | 0.92                | 0.654 ± 0.321                                    | 0.593 ± 0.291                                    | 19.9 ± 10.0 | 19.7 ± 9.8                   |
| zk83   | Kokhsar | Weathered         | Granite            | 32.417        | 77.230        | 3135                | 5.0            | 0.91                | 1.56 ± 0.126                                    | 1.41 ± 0.114                                    | 48.2 ± 5.8  | 47.8 ± 5.1                    |
| LDK-240 | Ladakh | Patchy brown varnish, polished, scapolided | Diorite         | 34.024        | 77.195        | 4037                | 3.0            | 0.81                | N/A                                             | 3.18 ± 0.047                                    | 49.2 ± 4.5  | 47.2 ± 3.4                    |
| LDK-241 | Ladakh | Medium brown patchy varnish, weathered, potholes | Diorite         | 34.517        | 77.416        | 3783                | 1.5            | 1.00                | N/A                                             | 3.18 ± 0.047                                    | 59.0 ± 5.3  | 63.0 ± 4.4                    |
| LDK-239 | Ladakh | Fresh, polished, potholes | Diorite         | 34.517        | 77.416        | 3765                | 2.0            | 0.83                | N/A                                             | 3.15 ± 0.023                                    | 30.3 ± 2.7  | 31.8 ± 2.2                    |
| LDK-240 | Ladakh | Patchy brown varnish, polished, potholes | Diorite         | 34.517        | 77.416        | 3741                | 5.0            | 0.56                | N/A                                             | 0.171 ± 0.005                                   | 5.8 ± 0.5   | 4.8 ± 0.4                     |
summarized core records from 19 lakes throughout China and showed three general periods of increased lake levels in the intervals c. 4–11 ka, c. 24–27 ka and c. 33–43 ka, and suggested that lake hydrology was primarily controlled by rainfall, evaporation, and potentially, glacial meltwater. In Ladakh, sediment cores taken from Pangong Tso (Bangong Co) and Sumxi-Longmu Co indicate three significant periods of increased precipitation during the Holocene: Pangong Tso at 2.1–3.4 ka, 7.2–8.4 ka, and 9.6–11.0 ka; and Sumxi-Longmu Co at 2.6–4.0 ka, 7.1–8.4 ka, and 9.5–11.3 ka (Gasse et al. 1991, 1996).

Quaternary glaciation in the Himalaya and Tibet is highly complex, varying both spatially and temporally; this has been summarized by Owen et al. (2008). For our study areas, Owen et al. (2008) showed that in Ladakh, Zanskar, Nanga Parbat, the central Karakoram, and Khumbu, glaciers began to retreat from their maximum extent during the last glacial at about 30–45 ka. However, there are no ages for glacial landforms or sediments in Lahul and Nanda Devi older than marine isotope stage (MIS) 3. Deglaciation in Garhwal is not as well defined, but probably occurred later than in the other areas, probably during MIS 2 (Owen et al. 2008, and references therein). There is evidence in Ladakh, Zanskar, Nanga Parbat, the central Karakoram, Khumbu, Garhwal, Lahul, and Nanda Devi for multiple glacial advances throughout the Holocene (Owen 2009, and references therein). Most of the glacial geological studies that date moraines used TCN methods. TCN ages from glacial landforms and sediments are often interpreted as deglaciation, as this is the time when surface boulders are deposited on moraines and the moraines begin to stabilize (Briner et al. 2005). Because times of deglaciation are those when discharges and sediment flux are high, Pan et al. (2003) argued that glacial to interglacial transitions control short-term strath terrace incision against a tectonic background forcing.

Methods

Field methods

Strath terraces were identified and mapped in the field using a handheld Garmin GPS. Strath terrace locations were plotted on 3 arc-second (c. 90 m) Shuttle Radar Topography Mission (SRTM) digital elevation models (DEMs; CGIAR-CSI 2007). The vertical distance between the sampled strath surfaces and the contemporary rivers was determined with a range finder, tape measure, or rope in combination with an inclinometer.

The strath terraces that we dated in this study are incised into quartz-rich bedrock (granite, granodiorite, diorite, phyllite, quartzite and sandstone). About 350 g of rock was collected from near-horizontal bedrock strath surfaces; sampling depth was 1–5 cm. Where possible, samples were collected from sites that showed little evidence of post-fluvial erosion, typically where the bedrock was fluvially polished and had scallops or potholes, and areas where there was well-developed rock varnish. Topographic shielding was determined by measuring the inclination from the sampled surface to the surrounding horizon. The condition of the sampled surface, sample rock type, topographic shielding, and position of all samples were recorded (Table 1).

$^{10}$Be terrestrial cosmogenic nuclide surface exposure dating

The laboratory methods used for the isolation of quartz, chemistry protocols, and targeting of $^{10}$Be TCN samples have been described by Kohl & Nishiizumi (1992) and Dortch et al. (2009, and references therein). Samples were processed in geochronology laboratories at the University of Cincinnati, and were measured by accelerator mass spectrometry (AMS) on the Purdue Rare Isotope Measurement (PRIME) Laboratory AMS system, which was calibrated using Nishizumi standard Be-0153 with a $^{10}$Be/$^{9}$Be ratio of $3620 \times 10^{-15}$ (PRIME Laboratory 2009).

Seventeen new $^{10}$Be ages of strath terraces were determined, and all previously published strath terrace bedrock, terrace boulder, and fan boulder ages that we assess and compare were recalculated using the PRIME Laboratory Rock Age Calculator (Ma et al. 2007; PRIME Laboratory 2009) to make consistent comparisons among and within regions. Terrace and fan boulder ages are compared with the timing of monsoon phases and are discussed below. All samples measured before 17 December 2007 (PRIME Laboratory) or 29 May 2007 (Lawrence Livermore National Laboratory’s Center for Accelerator Mass Spectrometry) required conversion to the revised isotopic ratio of ICN standard material (Nishiizumi et al. 2007; Balco 2009). All $^{10}$Be/$^{9}$Be ratios were converted to the new $^{10}$Be/$^{9}$Be ratios developed by Nishiizumi et al. (2007) for the ICN standard material. We used a production rate of 4.5 $^{10}$Be atoms g$^{-1}$ of quartz a$^{-1}$ and a half-life of 1.36 Ma for age calculation (PRIME Laboratory 2009; Balco 2009). The PRIME Laboratory Rock Age Calculator employs the scaling factors of Stone (2000), a sea-level low-latitude production rate of 4.5 ± 0.3 $^{10}$Be atoms g$^{-1}$ of quartz a$^{-1}$, a $^{10}$Be half-life of 1.36 Ma, and accounts for spallogenic and fast/slow muogenic $^{10}$Be production (Nishiizumi et al. 2007; http://www.physics.purdue.edu/primelab/News/News0907.php). PRIME Laboratory (2009) presented details of converting $^{10}$Be ratios to the revised ICN standard by Nishiizumi et al. (2007). Ages were also calculated using the CRONUS calculator to allow comparison between calculators and other studies (Table 1). The strath terrace ages reported by Mukul et al. (2007) were not recalculated because they were determined by optically stimulated luminescence dating.

No corrections for geomagnetic field variations were made; the means by which this is done are still being debated (Balco et al. 2008). Owen et al. (2008) recently discussed geomagnetic variations and their effects on $^{10}$Be ages, specifically for the Himalaya. Geomagnetic corrections using a variety of scaling models can change the $^{10}$Be ages reported here by as much as 14%.

All $^{10}$Be ages reported here are model exposure ages, assuming no weathering senso stricto (often referred to as erosion in many previous studies). Weathering can be estimated qualitatively based on surface conditions of a sampled area. A polished, hard, varnished rock surface has experienced little weathering, whereas a surface that has patches of varnish and is exfoliating has undergone some degree of weathering. Alternatively, we can estimate a maximum weathering rate if we assume that the oldest sample is in $^{10}$Be production—weathering equilibrium, that is, the accumulation of $^{10}$Be and weathering are in steady state (Small et al. 2007). This results in a maximum weathering rate of 0.78 m Ma$^{-1}$ based on sample zk48 (736.9 ± 64.7 ka) located in the semi-arid Zanskar Range using the method of Lal (1991). Using an equation developed by Lal (1991) that describes how $^{10}$Be concentration (that is, age) is affected by erosion rate, if all the strath terraces weather at 0.78 m Ma$^{-1}$, then a calculated age of 10 ka would underestimate the true age by a maximum of 1.0%, an age of 100 ka by 6.7%, and an age of 400 ka by 51.9%. This calculated maximum weathering rate might not apply to other areas of the orogen, including the more heavily monsoon-influenced High Crystalline Himalaya and the syntaxes at the
eastern and western ends of the orogen. When comparing fluvial incision rates independent of varying weathering regimes across the orogen, we do not correct for weathering, but recognize that weathering results in younger ages and higher apparent fluvial incision rates. All of the strath terrace surfaces sampled in this study retain fluvial polish, scalloped surfaces, and potholes. Preservation of these bedforms suggests that little degradation and negligible erosion has occurred (Burbank & Anderson 2001).

Calculation of fluvial incision rates

When calculating fluvial incision rates, we do not assume that the river spent a significant amount of time at a particular surface or elevation; that is, we do not assume that horizontal strath surfaces represent periods of fluvial equilibrium. If a river was in equilibrium, a strath surface would either be abandoned (if it was above flood level) or would be actively eroding (if it was within flood level). Floods would occur often enough (owing to annual monsoons, enhanced monsoons, deglaciation, and/or dam bursts) to erode bedrock within a river’s flood level (Hancock et al. 1998). In either case, there would be no inheritance of TCNs. We assume that the TCN age reflects abandonment of the strath surface by the river at that elevation. Therefore, the division of the difference in elevation between the sampled surface and next (lower) sampled surface or the contemporary river by the TCN age provides a mean incision rate. From the literature, we found multiple ages obtained from six flights of strath terraces (that is, multiple near-horizontal surfaces along a vertical transect) where three or more samples were collected each from a different strath surface to determine changes in the mean incision rate. We also found pairs of samples collected from the same strath surface at nearly the same elevation from 22 single strath terraces or flights of terraces; these were dated to check if the age of a strath surface is reliable. When multiple ages were obtained from a sampled surface and/or the data are scattered, we used the average and standard deviation of the ages and elevations to determine the rate of fluvial incision. When reported, elevation uncertainties from previous studies were used. Elevation uncertainties are assumed to be 1 m for the distance between samples on different strath terraces or between strath terraces and the contemporary river level where a measuring tape, range finder, or rope was used in this study and previous studies. Handheld GPS units commonly give elevation uncertainties of 5 m or higher when next to steep bedrock strath surfaces. For previous studies that did not report sample elevation uncertainty or for those that stated a handheld GPS unit was used but did not provide an uncertainty, we assumed an uncertainty of 5 m for the sample elevation and 5 m uncertainty for the elevation of the contemporary river. In our calculations of fluvial incision rates, elevation and age uncertainties are propagated quadratically. All fluvial incision rate uncertainties are reported to $1\sigma$.

Description of newly dated strath terraces

Ladakh

Strath terraces in the Ladakh region are located in tributary valleys along the northern slopes of the Zanskar Range, along the Indus River, and along the northern slopes of the Ladakh Range (Fig. 2a). We have not yet found strath terraces on the southern slopes of the Ladakh Range or along the Shyok River, which separates the Ladakh Range from the Karakoram Range to the north.

Samples that we dated in tributary valleys along the northern slopes of the Zanskar Range were collected from strath terraces from the Stok (zk37) and Sacha (zk48–zk50) Valleys, which are tributaries to the Indus River (Fig. 2a). The Stok and Sacha Valley strath terraces are composed of sandstone and are 9.6 m and 20–36 m above the contemporary river, respectively. The surfaces of the strath terraces in the Stok Valley have a thick rock varnish into which petroglyphs have been carved. Sample zk50 collected in the Sacha Valley has a discontinuous cover of debris. This debris may have shielded the rock so the age for strath terrace sample zk50 is a minimum age and accordingly, the calculated fluvial incision rate for it is a maximum.

We also dated six strath terraces along the Indus River between the confluence of the Sacha River and the village of Tharika (Figs 2a and 3). Sample I-67 is not a bedrock strath terrace sample; rather it was collected from a fluvially polished boulder $>3$ m in length (Fig. 3f). Sample I-67 will provide an exposure age for the boulder that reflects river abandonment from the boulder’s current position, which is essentially equivalent to a bedrock strath terrace. The strath terraces along the Indus are composed of sandstone or phyllite, they are fluvially polished and have potholes, dark brown varnish, and some exfoliation. Samples I-62, I-63, I-64, and I-66 were collected from a succession of strath terraces from the highest strath surface (115 m) to the lowest (11.4 m; Fig. 3c and d). Samples I-76, I-77, and I-78 were collected from a succession of strath terraces that rise to c. 25 m above the contemporary river. All other samples (I-71, I-72, and I-73) were collected from single strath terraces that range in height from c. 9 to 40 m above the contemporary river (Fig. 3g).

A succession of strath terraces was also sampled in the Hundar Valley located along the northern slope of the Ladakh Range c. 15 km north of the range’s divide (Fig. 2a). This flight of strath terraces is c. 500 m long, discontinuous, and varies in height from c. 10 m (upstream) to c. 50 m (downstream; Fig. 3a and b) above the contemporary river. These strath terraces are polished, contain many benches at each locality, and vary from having exfoliated surfaces with medium brown desert varnish on the upper parts to being fresh, unvarnished diorite incised by the contemporary river on the lower parts. The Hundar Valley strath terraces contain numerous potholes and scalloped surfaces at all elevations. Three samples were collected from one flight of these strath terraces to determine if there have been significant variations in incision rate; two samples (LDK-240 and LDK-241) from the upper accessible part of the strath terraces, and one sample (LDK-239) by rappelling to c. 4 m above the river (Fig. 3a and b). A thin discontinuous layer of debris was present on this low strath terrace surface but our samples were collected from the highest parts of this surface to avoid potential problems with shielding by the thin debris cover.

Lahul

Fluvial systems in Lahul are controlled by meltwater dynamics (Owen et al. 1995), but the paucity of active gauging stations makes quantifying this dynamic difficult, and penetration of monsoon airflow into Lahul creates low-frequency, high-magnitude storm flows (Adams et al. 2009). Six strath terraces were sampled in Lahul (Fig. 2b) for dating. One strath terrace (zk78) is located in the Bhaga River Valley near the bridge to the village of Darcha, which is semi-arid, but was probably monsoon-influenced during the past (Owen et al. 2001). Along the Chandra River, two strath terraces are located near the village of Khoksar (zk82 and zk83) and three (zk79 to zk81) are located
near its confluence with the Bhaga River, an area that is influenced by the south Asian summer monsoon. A sample was collected from each strath terrace, which range in height from 7.4 m (zk82) to 15.8 m (zk81) above the contemporary river level. These strath terraces along the Bhaga and Chandra Rivers are cut into granite and quartzite bedrock and each is polished and has numerous potholes; samples zk79 and zk83 are slightly weathered. Although weathering is minor, the $^{10}$Be ages should be considered minimum ages that will yield maximum fluvial incision rates.

### Ages and rates of fluvial incision of newly dated strath terraces

**Ladakh**

In the Zanskar Range, single strath terrace ages range from 396.1 ± 31.2 ka (zk37) to 736.9 ± 64.7 ka (zk48; Fig. 4; Table 1). The mean rates of fluvial incision based on strath terraces from the Stok Valley (zk37) and the Sacha Valley (zk48, zk49, and zk50) vary between 0.02 ± 0.003 and 0.06 ± 0.005 mm a$^{-1}$ (Table 2). Mean rates of fluvial incision from the two valleys located c. 60 km apart are similar, ≈0.06 mm a$^{-1}$, which suggests that these rates are indicative of the order of magnitude of fluvial incision in the northernmost Zanskar Range.

Mean rates of fluvial incision along the Indus River Valley range from 0.01 ± 0.01 mm a$^{-1}$ since 97.9 ± 7.1 ka (I-72) to 2.6 ± 1.9 mm a$^{-1}$ since 8.1 ± 0.6 ka (I-73; Tables 1 and 2). Our calculated rates of incision along the Indus River cluster into two distinct groups: (1) strath terraces with ages >60 ka have slow mean rates of fluvial incision, ≈0.4 ± 0.04 mm a$^{-1}$; (2) strath terraces with ages <15 ka have relatively fast mean rates of fluvial incision, ≈1.1 ± 0.4 mm a$^{-1}$.

One strath terrace along the Indus River (samples I-62, -63, -64, and -66) has $^{10}$Be ages between 25 and 63 ka at heights of 115 ± 4.2 to 110 ± 3.0 m above the contemporary river. These samples do not have an age–height correlation and two of them from the same surface give widely different ages (Table 1); this age scatter may be due to inheritance as spallation occurs to a depth of several metres, although the production of $^{10}$Be drops off at 1/e for the folding length of 60 cm (Gosse & Phillips 2001) and it is also possible that $^{10}$Be could have accumulated in a rock before a river cuts down to it. Inheritance in I-63 is not the cause of its older age (63 ka) because it has essentially the same elevation as samples with younger ages (I-62 and I-66) and all of them have been exposed to cosmic rays. The age scatter may be due to transient shielding; the strath terrace surface was clear of debris when sampled. Leland et al. (1998) showed that when two samples at similar elevations are collected from a strath terrace, the flatter parts of the terrace surface will yield a
younger age than a sample from a steeper or higher part of the terrace such as a knob. They attributed younger ages to transient debris cover and/or erosion after abandonment. The presence of well-preserved fluvially polished/scalloped bedrock on our sampled strath surface suggests that erosion is minor. Therefore, we suggest the younger ages of I-62 and I-66 are probably due to shielding by transient debris cover, which is difficult to account for in the field. We are unconvinced that the scatter of these data will result in a correct age and so an incision rate was not determined for this strath terrace (Table 1). We address the issue of sampling strath terraces and propose a method to limit the influence of transient debris below.

Bracketed rates of fluvial incision determined from strath terraces in the Hundar Valley on the northern side of the Ladakh Range vary with age: strath terrace surfaces with ages between 63 and 31 ka yielded a mean incision rate of 0.6 ± 0.1 mm a⁻¹ whereas surfaces with ages <31 ka gave an incision rate of 0.9 ± 0.1 mm a⁻¹ (Fig. 3a and b; Tables 1 and 2). Although these calculated rates of fluvial incision are modest, they are generally within 1σ uncertainty of the Indus River incision rates and are a magnitude of order greater than those for the Zanskar Range. In addition, the positive age–elevation relationship given by these three samples indicates that this flight of strath terraces has not been significantly affected by inheritance or shielding, and hence the calculated changes in incision rate based on their age–height data are meaningful.

Lahul

Four strath terraces along the Chandra River (samples zk80–zk83) range in age from 162.2 ± 23.5 ka (zk81) to 19.7 ± 9.8 ka (zk82; Tables 1 and 2). The calculated rates of fluvial incision range from 0.1 ± 0.02 mm a⁻¹ for the oldest sample (zk81) to 0.4 ± 0.2 mm a⁻¹ for the youngest sample (zk82). These new strath terrace incision rates do not overlap with those recalculated from Adams et al.’s (2009) data, which range between 1.4 ± 1.1 and 13.2 ± 6.2 mm a⁻¹ for samples collected between 10 and 15 km upstream along the Chandra. Our sample zk79 gave an age of 7.1 ± 4.3 ka and an incision rate of 2.2 ± 1.3 mm a⁻¹. Sample zk79 is problematic owing to debris cover on the strath.
terrace surface and the incision rate for zk79 is an order of magnitude higher than those for our other Chandra River samples. Sample zk78 along the Bhaga River has an age and rate of fluvial incision of \(50.2 \pm 5.0\) ka and \(0.2 \pm 0.03\) mm a\(^{-1}\), respectively (Tables 1 and 2).

### Spatial and temporal patterns of fluvial incision

Orogen-wide variations in fluvial incision are probably controlled by topography, lithology, tectonic rock uplift, and climate (Leland et al. 1998; Bookhagen et al. 2005; Bookhagen & Burbank 2006). Bookhagen et al. (2005) and Bookhagen & Burbank (2006) suggested that fluvial systems in the Himalaya are most strongly affected by monsoon precipitation, which is most dominantly controlled by location with respect to the Himalayan front (Barros et al. 2000; Burbank et al. 2003), with local variations in the exact location of high precipitation (Hodges et al. 2004). It follows that rates of fluvial incision based on strath terrace ages should group spatially and temporally. Hence regional differences in rates of fluvial incision throughout the Himalaya might be broadly grouped into two tectonic–climatic regions for which we have ages of strath terraces: the semi-arid Ladakh region (including the Zanskar, Ladakh, and Pangong Ranges) that receives an annual rainfall of 250–500 mm a\(^{-1}\) and the monsoon-influenced Lahul region (including the High Crystalline Himalaya) that receives an annual rainfall of 250–1000 mm a\(^{-1}\) (Fig. 4, based on Tropical Rainfall Measuring Mission (TRMM) data from Bookhagen & Burbank 2006). We consider a third region with previously dated strath terraces, the western syntaxis at Nanga Parbat, where high elevation and great relief help concentrate monsoon precipitation and runoff. Based on these same TRMM data, Nanga Parbat appears to receive annual rainfall of 250–750 mm a\(^{-1}\), but the peak itself is a feature beyond the spatial resolution of the TRMM data. Owen & England (1998) compiled annual precipitation data for several locations in northern Pakistan and India, including Astor and Bunji, immediately south and north of Nanda Parbat, respectively; annual precipitation was \(c. 400\) mm on Astor and \(c. 160\) mm on Bunji. Our new data on the ages of strath terraces and incision rates together with previous results are discussed below for each of these regions. In addition, exhumation rates of the Zanskar, Ladakh, and Pangong Ranges based on low-temperature thermochronometers can be compared with our rates of long-term fluvial incision as a guide to how the rates compare and how fluvial incision contributes to denudation in the Ladakh region of northern India.

#### Semi-arid Ladakh region

Strath terraces from the Stok and Sacha Valleys of the Zanskar Range are all older than 400 ka and yield very low mean incision rates, as low as \(0.02 \pm 0.003\) mm a\(^{-1}\) with the time-averaged rate since \(c. 740\) ka being \(<0.06 \pm 0.005\) mm a\(^{-1}\) (Fig. 5a). It has not been possible, however, to define a temporal pattern of incision here because of the limited number of ages. Exhumation rates for the Zanskar Range based on AFT ages of \(c. 14\) Ma have been estimated at \(0.1–0.4\) mm a\(^{-1}\) by Sinclair & Jaffey (2001) and interpreted to show that the Zanskar Range is over-thrusting the Ladakh Range (Clift & Vannucci 2003; Kirstein et al. 2009). The lack of any young strath terraces and the very low time-averaged incision rate indicates that there has been very limited fluvial incision of the Zanskar Range over the last 700 ka. In the Indus River Valley, mean rates of fluvial incision based on strath terraces with ages \(>45\) ka range between \(0.4 \pm 0.04\) and \(0.1 \pm 0.01\) mm a\(^{-1}\), rates equivalent to estimated exhumation of the Zanskar Range noted above (Fig. 5a). Jamison et al. (2004) proposed that the high sediment discharge from Zanskar Range tributaries and the aggradation of alluvial fans into the

### Table 2. Strath terrace height, age, and incision rate

| Sample | Strath | Location | Region | TRMM precipitation (mm a\(^{-1}\)) | Incision height (m)* | Incision error (m) | PRIME Lab age (ka)† | Incision rate (mm a\(^{-1}\)) |
|--------|--------|----------|--------|----------------------------------|----------------------|-------------------|---------------------|--------------------------|
| zk37   | Stok   | Zanskar Range | Ladakh | 0.25–0.5                         | 9.6                  | 1.0               | 396.1 ± 31.2         | 0.02 ± 0.003             |
| zk48   | Sacha  | Zanskar Range | Ladakh | 0.25–0.5                         | 20.3                 | 1.0               | 736.9 ± 64.7         | 0.03 ± 0.003             |
| zk49   | Sacha  | Zanskar Range | Ladakh | 0.25–0.5                         | 35.9                 | 1.0               | 604.8 ± 49.8         | 0.06 ± 0.005             |
| zk50   | Sacha  | Zanskar Range | Ladakh | 0.25–0.5                         | 23.5                 | 1.0               | 424.8 ± 33.7         | 0.06 ± 0.005             |
| zk78   | Bhaga  | Bhaga      | Lahul  | 0.5–1.0                          | 8.2                  | 1.0               | 50.2 ± 5.0           | 0.2 ± 0.03               |
| zk79   | Chandra | Chandra   | Lahul  | 0.25–0.5                         | 15.6                 | 1.0               | 7.1 ± 4.3            | 2.2 ± 1.3                |
| zk80   | Chandra | Chandra   | Lahul  | 1.0–1.5                          | 12.7                 | 1.0               | 57.4 ± 8.2           | 0.2 ± 0.04               |
| zk81   | Chandra | Chandra   | Lahul  | 0.5–1.0                          | 15.7                 | 1.0               | 162.2 ± 23.5         | 0.1 ± 0.02               |
| zk82   | Chandra | Chandra   | Lahul  | 0.5–1.0                          | 7.4                  | 1.0               | 19.7 ± 9.8           | 0.4 ± 0.2                |
| zk83   | Chandra | Chandra   | Lahul  | 0.5–1.0                          | 15.8                 | 1.0               | 47.8 ± 5.1           | 0.3 ± 0.04               |
| I-66   | Indus  | Indus Valley | Ladakh | 0.25–0.5                         | 5.0                  | 2.4               | 24.7 ± 1.7           | 2.6 ± 1.9                |
| I-62   | Indus  | Indus Valley | Ladakh | 0.25–0.5                         | 98.6                 | 3.0               | 32.8 ± 2.3           | 2.6 ± 1.9                |
| I-63   | Indus  | Indus Valley | Ladakh | 0.25–0.5                         | 98.6                 | 3.0               | 63.2 ± 4.4           | 2.6 ± 1.9                |
| I-64   | Indus  | Indus Valley | Ladakh | 0.25–0.5                         | 11.4                 | 0.1               | 11.6 ± 1.7           | 2.6 ± 1.9                |
| I-67   | Indus  | Indus Valley | Ladakh | 0.25–0.5                         | 7.1                  | 0.1               | 67.6 ± 4.7           | 0.1 ± 0.01               |
| I-71   | Indus  | Indus Valley | Ladakh | 0.25–0.5                         | 18.6                 | 5.4               | 10.0 ± 8.8           | 1.9 ± 0.6                |
| I-72   | Indus  | Indus Valley | Ladakh | 0.25–0.5                         | 40.0                 | 3.0               | 97.9 ± 7.1           | 0.4 ± 0.04               |
| I-73   | Indus  | Indus Valley | Ladakh | 0.25–0.5                         | 8.7                  | 3.0               | 8.1 ± 0.6            | 1.1 ± 0.4                |
| I-76   | Indus  | Indus Valley | Ladakh | 0.25–0.5                         | 8.5                  | 0.1               | 13.5 ± 0.9           | 2.3 ± 0.8                |
| I-77   | Indus  | Indus Valley | Ladakh | 0.25–0.5                         | 3.7                  | 3.0               | 9.2 ± 0.7            | 1.5 ± 0.3                |
| I-78   | Indus  | Indus Valley | Ladakh | 0.25–0.5                         | 12.6                 | 3.0               | 10.5 ± 0.8           | 1.5 ± 0.3                |
| LDK-241| Ladakh | Ladakh Range | Ladakh | 0.25–0.5                         | 18.0                 | 1.4               | 63.0 ± 4.4           | 0.6 ± 0.1                |
| LDK-240| Ladakh | Ladakh Range | Ladakh | 0.25–0.5                         | 23.9                 | 0.1               | 31.8 ± 2.2           | 0.9 ± 0.1                |
| LDK-239| Ladakh | Ladakh Range | Ladakh | 0.25–0.5                         | 4.0                  | 0.1               | 4.8 ± 0.4            | 0.8 ± 0.1                |

* Incision height is the distance between \(^{10}\)Be sample locations or contemporary river.
† PRIME Laboratory ages were calculated using the scaling scheme of Stone (2000).
Indus River Valley during northwestwards thrusting of the range raised base level by depositing alluvium and forced the Indus north, leading to the formation of strath terraces on its northern bank. The strath terrace from where samples I-62, I-63, I-64, and I-66 were collected has an mean age of 40.2 ± 20.3 ka and an average rate of fluvial incision of 2.6 ± 1.9 mm a⁻¹; shielding of this strath terrace along the Indus by transitory debris is indicated by the large uncertainty associated with its age. (Shielding of three dated strath terraces out of a total of 15 is also supported by discordant age–height relations in flights of strath terraces dated by Adams et al. (2009) along the Chandra River in Lahul.) In this case in the Ladakh region, linkage among exhumation of the Zanskar Range, transfer of sediment to the Indus River Valley, and long-term incision of the Indus River is supported by our calculated mean incision rates using all of the data along the Indus River Valley (Table 1) and presents an example of the scale for which first-order Himalayan landscape features can attain equilibrium. However, mean incision rates calculated for strath terraces we dated along the Indus with ages <15 ka are 1.1 ± 0.4 mm a⁻¹, suggesting downcutting.

Along the northern slope of the Ladakh Range, the mean rate of fluvial incision increases slightly from 0.6 ± 0.1 to 0.9 ± 0.1 mm a⁻¹ at c. 31 ka (as recorded by samples LDK-240 and LDK-241). This small increase in incision rate recorded when the strath terrace was abandoned may be due to increased stream power from deglaciation upstream, although increase in the quantity and calibre of bed sediment could offset increased fluvial discharge by producing a transient alluvial cover on the channel (Howard et al. 1994). The ages of deglaciation are poorly defined on the northern side of the Ladakh Range, although Owen et al. (2006) and Dortch et al. (2010) have shown that major glacial advances in the Ladakh Region occurred at c. 40 ka, 80 ka, and 160 ka. There is a 9 ka difference in age between the youngest moraines and the increased fluvial incision rate recorded by samples LDK-240 and LDK-241, but the lack of resolution in the incision rate data prevents us from concluding with any certainty that the increase in incision rate was directly due to deglaciation.

In the Pangong Range, located between the Ladakh and Karakoram Ranges (Fig. 2a), Dortch et al. (2011) sampled two flights of strath terraces along the Tangtse River. The ages of the oldest surfaces are 47.2 ± 3.4 ka (Pang-14) and 121.6 ± 8.8 ka.

**Fig. 5.** Plots of strath terrace age v. incision rate (crosses) separated by climatic–tectonic region (the oldest Lahul strath terrace (zk81, 162.1 ± 25.1 ka) is not shown for clarity). The horizontal grey bar in each plot represents the range of estimated exhumation rates for each region; in (e), the very high exhumation rate of Crowley et al. (2009) is also shown. Rates of fluvial incision based on strath terraces that plot above the grey bars are probably climatically controlled, rates that plot inside the grey bars accord with exhumation, and rates that plot below the grey bars indicate that exhumation is accommodated through denudational processes other than fluvial incision (i.e. with little to no base-level change). Light grey dashed lines (red in online version) marks the Holocene–Pleistocene transition (11.5 ka). Power-law trends (curved grey lines; green lines in online version) show how incision varies with time. The dark grey dashed line (purple in online version) in (a), (b), and (e) represents the 35 ka limit that is discussed in the text. Exhumation rates are taken from Foster et al. (1994), Winslow et al. (1994), Sorkhabi et al. (1996), Dunlap et al. (1998), Sinclair & Jaffey (2001), Kirstein et al. (2006), Blythe et al. (2007), Adams et al. (2009) and Crowley et al. (2009).
The mean rates of fluvial incision based on one set of strath terraces range from 0.6 ± 0.3 mm a⁻¹ for strath terraces with ages >23 ka to 1.1 ± 0.3 mm a⁻¹ for strath terraces with ages <23 ka. Mean rates from the second set of strath terraces range from 0.3 ± 0.1 mm a⁻¹ for strath terraces older than >11 ka to 1.5 ± 0.5 mm a⁻¹ for younger strath terraces (Dortch et al. 2011). Taking two sets of fluvial terraces from the Pangong Range together, strath terraces with ages >47 ka have lower mean rates of fluvial incision, <0.6 ± 0.3 mm a⁻¹, relative to younger strath terraces, whose mean rates of incision are >1.1 ± 0.3 mm a⁻¹.

In the Ladakh and Pangong Ranges in the semi-arid Ladakh region, strath terrace age and incision rate data can be compared with exhumation rates based on mineral cooling ages (Dunlap et al. 1998; Sinclair & Jaffey 2001; Kirstein et al. 2006, 2009). On the basis of AFT and AHe ages, Sinclair & Jaffey (2001) and Kirstein et al. (2006) suggested that the Ladakh Range has been exhumed at a rate of 0.06 ± 0.16 mm a⁻¹ since c. 28 Ma and c. 0.05 ± 0.05 mm a⁻¹ since c. 20 Ma. In the Pangong Range, Dunlap et al. (1998) suggested that significant exhumation has not occurred since 7 Ma based on ⁴⁰Ar/³⁹Ar ages. Mean rates of fluvial incision based on strath terraces with ages >45 ka in the Ladakh and Pangong Ranges are low, 0.6 ± 0.1 mm a⁻¹ and 0.3 ± 0.1 to 0.6 ± 0.1 mm a⁻¹, respectively, but still higher than the estimated exhumation rates since the Miocene (Fig. 5a). For strath terraces with ages <45 ka in the Ladakh Range, mean incision rates are significantly higher, 1.1 ± 0.3 to 1.5 ± 0.5 mm a⁻¹; for strath terraces with ages <45 ka in the Pangong Range, mean incision rates are also higher, 0.9 ± 0.1 mm a⁻¹. The exhumation history of the Ladakh Range may be further linked to the strath terraces found there. From north to south across the range, AFT, AHe, and ZFT ages all become younger and Kirstein et al. (2009) used Monte Carlo models of this age distribution to propose that the Ladakh Range has tilted, with 5–6 km of relief within the high end of this range because, for example, in Lahul, only one TRMM data site received the low 250 mm a⁻¹ value. In Lahul, we find that older strath terraces yield lower incision rates whereas younger strath terraces yield much higher incision rates, and typically these higher incision rates exceed rates of exhumation based on low-temperature thermochronometers. Sample zk78 along the Bhaga River has an age of 50.2 ± 5.0 ka and incision rate of 0.2 ± 0.03 mm a⁻¹. Our dated strath terraces along the Chandra River (zk80-83) are all older than 15 ka and yield incision rates <0.4 mm a⁻¹ showing that fluvial incision over a time scale >15 ka is very slow (Table 2). The five strath terraces examined by Adams et al. (2009) along the Chandra River and one of its tributary valleys are young, with ages <6 ka, and yield calculated rates of fluvial incision between 13.2 ± 6.2 and 1.4 ± 1.1 mm a⁻¹.

Along the Chandra River in Lahul, fluvial incision rates based on strath terraces older than 15 ka are significantly lower than the Plio-Pleistocene exhumation rate of 1–2 mm a⁻¹ based on the AHe ages determined by Adams et al. (2009) from vertical profiles taken along slopes bordering the Chandra; Adams et al.’s (2009) ages range between 2.5 ± 0.3 and 1.4 ± 0.7 Ma. Fluvial incision rates in Lahul calculated from terraces younger than 15 ka range between 1.1 and 13.2 mm a⁻¹ but are typically significantly higher than the calculated long-term exhumation rate (Fig. 5b): of the 15 incision rates calculated by Adams et al. (2009) from strath terraces younger than 6 ka, nine range between 3.9 ± 1.9 and 13.2 ± 6.3, and of these six are >5 mm a⁻¹.

We can gain further insight into the temporal variation of fluvial incision along the Chandra River by noting that with respect to exhumation rates on a time scale of 10⁶ years that record time-averaged rates of both tectonic and geomorphological processes, until the past 15 ka, longer-term exhumation has actually been faster that fluvial incision. However, during the past 15 ka, high rates of incision calculated from young strath terraces along the Chandra River indicate that there are short-term adjustments to a lowering of local base level or to climatic factors, including deglaciation (Owen et al. (2001) recognized five late Quaternary glacial stages in Lahul, with the dated stages in the age range 10–15.5 ka). The very young, high, but variable rates of fluvial incision, together with the relatively slow rate of Plio-Pleistocene exhumation, indicate a landscape in disequilibrium in this portion of Lahul (Adams et al. 2009), at least during the Holocene. Moreover, the fact that incision rates along the Chandra from strath terraces with ages >15 ka are much lower than the long-term exhumation rate indicates that apart from episodic increases, fluvial incision has not been the dominant mechanism of erosion in Lahul during the Pleistocene, in accord with Owen et al.’s (1995) conclusion that the dominant mechanism has been hillslope mass movement. In this case, the Plio-Pleistocene Chandra River has responded to dynamic interplay between glaciation and hillslope mass movement by transporting sediment rather than incising bedrock, perhaps influenced by a high sediment flux and sediment calibre that increased the resistance of the river bed to erosion.

In other regions of the monsoon-influenced Himalaya, Holocene or Late Pleistocene strath terraces yield fluvial incision rates that exceed the rate of long-term exhumation. The Imja Khola, Marsyandi, and Tista Rivers are located in the central monsoon-influenced Himalaya (Figs 4 and 5c), which currently receives annual rainfall of 1000–2000 mm a⁻¹ (based on TRMM data of Bookhagen & Burbank 2006). Eight strath terraces from Pratt et al. (2002), Barnard et al. (2006), and Mukul et al. (2007) in this region are all younger than 15 ka and range in age from 6.0 ± 0.8 ka to 10.8 ± 0.8 ka. Mean rates of fluvial incision based on these strath terraces range from 19.4 ± 1.9 mm a⁻¹ to 2.5 ± 0.9 mm a⁻¹. Exhumation rates in the central monsoon-influenced Himalaya of eastern India based on AFT ages are 2.2–4.6 mm a⁻¹ (Blythe et al. 2007) and six of the 10 published strath terrace incision rates are higher (Fig. 5c).

The monsoon-influenced Garhwal region (Fig. 4) of India includes the Bogdiar, Gori and Lilam Rivers, and currently receives annual rainfall of 1000–1500 mm a⁻¹ (based on TRMM data of Bookhagen & Burbank 2006). Recalculated ⁴⁰⁸Be ages for seven strath terraces dated by Barnard et al. (2001, 2004a,b, 2006) in Garhwal range from 4.2 ± 0.8 ka to 18.1 ± 0.6 ka. Rates of fluvial incision based on these strath terraces range from
3.0 ± 0.1 mm a⁻¹ to 13.2 ± 2.5 mm a⁻¹. Sorkhabi et al. (1996) calculated exhumation in the Garhwal region to be c. 1.7–2.5 mm a⁻¹ based on AFT ages. Like the majority of strath terraces in Lahul with ages <15 ka, all of the strath terraces dated by Barnard et al. (2004a) have incision rates that exceed the long-term exhumation rate (Fig. 5d). In other words, strath terraces younger than 20 ka in both Lahul and Garhwal record fluvial incision that outpaces bedrock exhumation. Barnard et al. (2004a) argued that the high incision rates along the Gori River were the product of exceptionally high fluvial discharge and sediment loads during the mid-Holocene, which were probably the result of deglaciation.

### Himalayan syntaxes

The high peaks (>8 km a.s.l.) associated with the syntaxes at the eastern and western ends of the Himalaya, with up to 7 km of relief, help concentrate monsoon precipitation and runoff. There are no reported strath terrace incision rates from the eastern syntaxes so the only the western syntax is discussed in this section. The western syntaxis currently receives annual rainfall of 250–1000 mm a⁻¹ (based on TRMM data of Bookhagen & Burbank 2006). Based on strath terrace ages determined by Leland et al. (1998) near Nanga Parbat along the Indus River, mean rates of fluvial incision based on strath terraces with exposure ages >35 ka range from 2.2 ± 0.1 to 4.1 ± 0.2 mm a⁻¹, whereas the mean rates of incision based on strath terraces with ages <35 ka range from 6.8 ± 0.8 to 18.9 ± 10.1 mm a⁻¹. Similarly, mean rates of fluvial incision based on strath terraces with exposure ages <35 ka near K2 north of the western syntax range from 2.2 ± 0.2 to 26.8 ± 5.1 mm a⁻¹ (Seong et al. 2007). There are no strath terraces older than 35 ka at K2. Mean rates of fluvial incision based on strath terraces with exposure ages >35 ka near Nanga Parbat are in general agreement with the exhumation rates of 3–6 mm a⁻¹ estimated by Foster et al. (1994) and Winslow et al. (1994) based on AFT and ⁴⁰Ar/³⁹Ar ages, respectively (Fig. 6e). However, Crowley et al. (2009) calculated an exhumation rate of 13 ± 1.6 mm a⁻¹ for the past million years based on thermobarometry of melting reactions and U–Pb dating of accessory minerals in the melt phase of migmatites and in leucogranites. Near Nanga Parbat and K2, 10 of 13 rates of fluvial incision based on strath terraces younger than 35 ka exceed the lower range of exhumation rates, and of these 10, six are comparable with or exceed the very high exhumation rate calculated by Crowley et al. (2009; Fig. 5e). Compared with Crowley et al.’s (2009) exhumation rate, strath terraces along the Indus near Nanga Parbat with ages >35 ka yield mean incision rates that are much less than the rate of bedrock exhumation, meaning that bedrock exhumation outpaced the rate at which the Indus incised its channel. This relationship between exhumation and incision rates is similar to that in Lahul recorded by strath terraces with ages >15 ka.

### Discussion

#### Age variation of rates of fluvial incision based on strath terraces

The data discussed in the previous section show that mean rates of fluvial incision based on strath terrace surfaces with ¹⁰Be ages >45 ka in Ladakh and >10 ka in the central Himalaya are similar to exhumation rates determined by low-temperature thermochronometers (Fig. 5). Mean incision rates calculated from strath terraces with ages >15 ka in Lahul are significantly lower than calculated exhumation, as are those for strath terraces with ages >35 ka in the western syntax compared with Crowley et al.’s (2009) very high calculated rate of exhumation for Nanga Parbat. If exhumation rates other than Crowley et al.’s (2009) are considered, mean rates of incision calculated from strath terraces older than 35 ka in the western syntax are also similar to calculated exhumation rates.

In contrast, rates of fluvial incision based on Holocene strath terrace surfaces in all four regions are greater than exhumation rates (Fig. 5). In general, a ¹⁰Be age of c. 35 ka separates strath terrace surfaces that record mean rates of fluvial incision similar...
to rates of exhumation from those that record rates greater than exhumation (Foster et al. 1994; Winslow et al. 1994; Sorkhabi et al. 1996; Dunlap et al. 1998; Sinclair & Jaffey 2001; Kirstein et al. 2006; Blythe et al. 2007; Adams et al. 2009). For our age and incision data in Ladakh, the central Himalaya, and the western syntaxis, mean rates of fluvial incision recorded by strath terraces with 10Be ages > 35 ka (n = 11) approximate geological rates (\(>10^5\) years) of exhumation. As rock uplift occurs, channel bottoms and strath terraces are also being uplifted as rivers incise; strath terrace surfaces are typically scoured and polished and record very little, if any, erosion. The concordance of our calculated mean incision rates for these old strath terraces and the long-term exhumation rates indicates a landscape approaching dynamic equilibrium where exhumation is matched by river incision (Hack 1975; Brandon et al. 1998; Willet & Brandon 2002). The age and incision rate data for strath terraces younger than 35 ka compared with long-term exhumation rates show that equilibrium is no longer in effect. The consistency of AFT ages of c. 0.5 ± 0.2 Ma across the monsoon-influenced Greater Himalaya led Burbank et al. (2003) to conclude there is a tectonic control of uniform erosion there and it appears that strath terraces a few tens of thousands of years old record time-averaged incision rates that reflect this rate of tectonic control. A notable exception is strath terraces in a setting, such as Lahul, where glaciation and hillslope processes control erosion, not fluvial incision, and so old strath terraces record very low time-averaged incision rates.

Figure 6 shows all strath terrace ages for the Himalaya and Transhimalaya plotted against the mean rate of fluvial incision but no clear linear \((r^2 = 0.58)\) or exponential \((r^2 = 0.46)\) relationship emerges (strath terrace profiles PK95-31-1A and PK93-36 from the western syntaxis have >50% uncertainty in their ages and are not accurate enough to be considered in detail). However, the data in Figs 4 and 6b show a distinct change in the calculated mean rates of fluvial incision at 11.5 ka. Mean rates of fluvial incision determined from Holocene strath terraces \((ages < 11.5 \text{ ka}; n = 39)\) range from <1 mm a\(^{-1}\) to >26 mm a\(^{-1}\); 23 of these rates exceed 5 mm a\(^{-1}\). In contrast, mean rates of fluvial incision determined on Pleistocene strath terraces \((ages > 11.5 \text{ ka}; n = 26)\) do not exceed 5 mm a\(^{-1}\) and many are <1 mm a\(^{-1}\) (Fig. 6b). The large number of sampled Quaternary strath terraces shows that the absence of mean incision rates >5 mm a\(^{-1}\) is not the result of a sampling problem. In addition, transient, post-abandonment shielding of strath terraces is not a significant problem affecting the incision rates calculated from the ages of strath terraces we have determined and compiled from the literature. We can ascribe post-abandonment shielding to only one set of three strath terraces along the Indus River (samples I-62, -63, -64) where we have multiple samples from a flight of strath terraces, and to three strath terrace samples dated by Adams et al. (2009; KL2, KL3, and PPT3), out of a total of 15, along the Chandra River that have discordant age-elevation relationships. If many strath terraces were affected by shielding, older strath terraces as well as younger strath terraces would be affected. The effect of transient shielding for 10 ka would be reduced on strath terraces with ages >100 ka as the shielding time would only be 10% of the age and for younger strath terraces, the effect on age would be progressively greater. However, older strath terraces, those the in age range 35–60 ka, do not yield fast rates (indeed, many of them give very, very slow rates).

Bedrock lithology, occurrence of high-magnitude, low-frequency outburst floods, and reach-scale controls on incision rates vary along rivers, between rivers, and across the Himalaya. Yet our new and compiled data from regions with different tectonic and lithological characteristics (Fig. 4) across the Himalaya show no obvious difference in Holocene and Pleistocene mean rates of fluvial incision between regions. However, all regions do show a significant difference between higher Holocene and lower Pleistocene mean rates of fluvial incision. The increase in fluvial incision across the orogen during the Holocene might reflect increased rock uplift across the orogen since 11.5 ka and/or climate change. The rate of rock uplift may vary on short time scales (<10 ka) as thrust or extensional faults become active (or reactivate). Burbank & Godard (2010) proposed that fault slip rates can be changed by changes in the magnitude and geographical distribution of erosion during glacial-interglacial cycles and model results show that fault slip rates can double (or halve) at geomorphological time scales. However, there are very few data to suggest that there would be synchronous movement on the major regional faults that bound the lithotectonic zones of the orogen leading to similar rates and magnitudes of rock uplift. Without a record of Holocene faulting (e.g. Kumar et al. 2006), assessing episodic rock uplift is difficult and thermochronological data yield Holocene ages only where exhumation rates are exceptionally high or where near-surface geotherms are exceptionally high, as at the western syntaxis (Winslow et al. 1994; Crowley et al. 2009). Given that typically 2–3 km of material needs to be removed to expose even the lowest temperature AHe chronometer (e.g. Spotila et al. 2004), exhumation rates are a long-term average. We argue that tectonic processes alone cannot explain the difference between rates of fluvial incision determined from Holocene v. Pleistocene strath surfaces because the same temporal pattern of increased Holocene incision is recorded spatially in disparate lithotectonic zones across the entire orogen. Hartshorn et al. (2002) and Pratt et al. (2002) argued that fluvial incision is controlled by increased discharge events on 10 ka time scales and our data support this view.

As climate has changed significantly throughout the Quaternary, the timing and extent of glaciation between adjacent regions within the Himalayan–Tibetan orogen vary considerably and have been discussed in detail by Owen et al. (2008) and Owen (2009). In general, glaciers throughout monsoon-influenced Tibet and the Himalaya and Transhimalaya appear to have responded in a similar fashion to changes in monsoon-driven and Northern Hemisphere cooling cycles (Owen et al. 2008). The response was multiple glacial advances of varying extent throughout the last glacial cycle. In most regions, glacial advances during the early part of the last glacial (mainly in MIS 3) were more extensive than during the global Last Glacial Maximum (Owen et al. 2008). In the Transhimalaya and western and central Tibet, glaciation during the penultimate or older glacial cycles was much more extensive (Owen et al. 2008, and references therein). Throughout most regions, glaciers advanced during the early Holocene possibly because of increased precipitation and cloudiness during a time of enhanced monsoon (Owen et al. 2008; Owen 2009). Multiple glacial advances, albeit small (c. 1–2 km from the present glacial margins), occurred during the late Holocene (Owen 2009).

In the interval between 11.5 and 35 ka there is a general lack of enhanced monsoons and major deglaciation events (Owen et al. 2008). If stream power is reduced during this interval, river channel longvalley profiles will move towards hydrological disequilibrium if rock uplift continues at a steady rate. In regions without rock uplift during this interval (Lahul could be an example), low mean fluvial incision rates could reflect reduced stream power, or channel profiles may reach a new equilibrium under these drier, reduced stream power conditions. We refer to
drier periods as times of disequilibrium because wetter periods will provide the dominant discharge, delivering higher stream power, and will control incision rates in regions with rock uplift. In our view, the higher incision rates determined from Holocene strath terraces probably reflect increased incision associated with the transition from glacial to interglacial times and enhanced monsoons, as rivers, in disequilibrium, start incising their channels at rates faster than rock uplift owing to increased stream power and accumulated perturbations in channel profiles during the drier times. In addition, we might expect a higher paraglacial sediment flux with Holocene deglaciation, contributing tools for fluvial incision, but also potentially pottering channel beds, depending on the sediment calibre. The presence in monsoon-influenced Garhwal of nearly vertical surfaces of strath terraces, scoured and fluvially polished, and some nearly 70 m tall, is consistent with our view that Holocene rivers have incised their channels to regain equilibrium profiles.

In addition, the intensity of the south Asian summer monsoon has fluctuated on 1000 year time scales throughout the Quaternary, which strongly influences sediment flux, discharge, and incision of Himalayan fluvial systems (Prell & Kutzbach 1987; Fang 1991; Gasse et al. 1996; Shi et al. 2001; Bookhagen et al. 2005; Bookhagen & Burbank 2006). Dortch et al. (2009) showed that increased precipitation from intensified monsoon phases played a significant role in the triggering of large landslides in Ladakh and Lahul. If enhanced monsoons dramatically affect geomorphological systems, then increased precipitation from intensified monsoons would result in the formation of depositional terraces and alluvial fans (Fig. 7). 10Be ages of depositional terraces and alluvial fans from Barnard et al. (2004a,b, 2006) show a general correlation with the monsoon phases of Gasse et al. (1991, 1996; Fig. 7). The large uncertainties associated with dating alluvial fans and depositional terraces are due to the considerable spread of ages on single surfaces because of toppling, weathering, burial, and exhumation of boulders. The linkage between increased sediment fluxes and monsoon phases suggests that increased runoff, too, probably occurs during distinct time intervals and affects surficial processes, including increasing fluvial discharge (as well as sediment load). Enhanced monsoon cyclicity can have a major impact on Holocene strath terraces, as they do not span a full insolation cycle (Prell & Kutzbach 1987, 1992; Sirocko et al. 1993), which is a primary driver of the south Asian summer monsoon and fluvial discharge. Detailed relationships, however, between monsoon intensity and fluvial incision and sediment production, including response time between sediment flux and incision rate, are not yet fully understood (Bookhagen et al. 2005).

If rivers were in disequilibrium, Holocene deglaciation and increased precipitation across the Tibetan Plateau, supplying more water to major rivers during insolation maxima, would provide the increased stream power, sediment flux, and the calibre of sediment required to achieve the fast incision rates in areas across the orogen inferred to have both rapid rock uplift (Nanga Parbat and K2) and slow rock uplift (Ladakh, Lahul, Garhwal, and central Himalaya). The Garhwal Himalaya, for example, has an average Holocene fluvial incision rate of 7.6 mm a⁻¹ whereas the central Himalaya has an average incision rate of 10.0 mm a⁻¹, but pre-Holocene incision rates do not exceed 3.8 mm a⁻¹ and 4.1 mm a⁻¹, respectively. The Garhwal and central Himalaya, currently receiving 1000–2000 mm a⁻¹ precipitation, show that even monsoon-influenced areas do not receive enough precipitation to down-cut steadily throughout glacial and monsoon cycles (Figs 4 and 5d).

The higher mean incision rates from across the orogen during Fig. 7. Summary of the timing relationships between aggradational terrace and fan surface ages and the intense monsoon phases of Gasse et al. (1991, 1996). In the lower part of the figure, terrace and fan surface ages are plotted as black crosses with a time axis across the bottom, with the timing of intense monsoon phases shown as vertical grey bars labelled P-1, P-2, and P-3. The weighted mean of the ages of Groups 1, 2, and 3 are indicated by the three crosses (red in online version). In the middle part of the figure, a histogram of fan and terrace ages in 1 ka bins corresponds to core proxies showing increased precipitation. Shown in the upper part of the figure are Prell & Kutzbach’s (1987) simulated monsoon pressure index (ΔM percentage, dashed line; blue in online version) for the Indian Ocean, simulated changes in precipitation (P percentage, continuous black line) in southern Asia, and variations in Northern Hemisphere solar radiation (AS percentage, dotted line; red in online version). The lack of dated terrace and fan surfaces in the time interval (>15 ka) of Prell & Kutzbach’s modelled low monsoon should be noted. The Khumbu fan from Barnard et al. (2006) with an average age and standard error of 73.0 ± 65.9 ka is not shown for clarity.
the Holocene are probably controlled by climate perturbations, which cause Himalayan rivers over short time spans (10 ka) to rapidly incise as they move toward equilibrium. These rates of fluvial incision are typically significantly higher than inferred rates of exhumation. Because Holocene incision is not averaged over long time spans, as would be the case for incision rates based on late Pleistocene strath terraces, rock uplift rates based on Holocene strath terraces together with the assumption of landscape equilibrium overestimate rates of rock uplift. Leland et al. (1998) suggested that rates of fluvial incision based on ‘older’ strath terraces reflect long-term rock uplift but they did not delineate the time limit over which rates of fluvial incision approximate rates of rock uplift. We suggest that to obtain a tectonic signal recorded by rock uplift from Himalayan rivers, strath terraces need to be older than 35 ka, which is the minimum time needed to average the rate of incision over at least one glacial–deglacial cycle and one insolation–monsoon cycle. In effect, strath terraces with ages <35 ka are revealing climatic cyclicity, whereas older strath terraces (ages >35 ka) average out deglaciation events and monsoon phase cyclicity and approach long-term rock uplift rates.

Precipitation- and rock uplift-driven fluvial incision model

As a starting point toward understanding the relationships among rock uplift, stream power, and fluvial incision for the last 60 ka, we developed a simple numerical model in which rock uplift is countered by variable incision. The focus of this model is to investigate if variable strath incision rates can form tall strata terraces with fast Holocene incision and slower >35 ka incision in two regions with distinct tectonic histories. A period of 60 ka was chosen to investigate longer-term incision than the 35 ka suggested in the previous section. We focused the model on two areas: Nanga Parbat and the Indus River, and Lahul and the Chandra River (Fig. 8). Despite the fact that we have argued that incision along the Chandra River has not been the dominant mechanism of Pleistocene erosion in Lahul, both of these areas have similar high average Holocene fluvial incision rates (9.1 mm a⁻¹ and 7.1 mm a⁻¹, respectively) based on strath terraces, but significantly different tectonic settings and exhumation rates. At Nanga Parbat, recalculated bedrock incision rates from Leland et al. (1998) range between 6.8 and 12.4 mm a⁻¹ along the gorge of the Indus River during the Holocene, and Winslow et al. (1994) estimated that Pleistocene exhumation rates have been as high as 3–6 mm a⁻¹. The more recent exhumation rate at Nanga Parbat of 13 ± 1.6 mm a⁻¹ presented...
by Crowley et al. (2009) is based on converting pressure estimates for dated melting events into crustal depths. In Lahul, recalculated bedrock incision rates from Adams et al. (2009) and this study range between 1.4 and 13.2 mm a⁻¹ during the Holocene whereas time-averaged exhumation since the Pliocene has been 1–2 mm a⁻¹ (Adams et al. 2009). We suggest that the high rates of Holocene incision in both regions can be accounted for by large climate fluctuations; in particular, deglaciation and enhanced monsoon phases.

The model is idealized and focuses on whether 10 ka variations in incision can account for the observed fast Holocene and slow >35 ka mean incision rates. The model takes a simplified climate signal for changes that affect stream power (deglaciation and monsoon variability) over the past 60 ka. To monitor climate, we use sediment core proxies from Pangong Tso and Sumxi-Longmu Co because they reflect real precipitation reaching the ground and a longer, although non-continuous, record from lake and ice cores in Tibet and China (c. 45 ka calibrated ¹⁴C years) compared to the TRMM data (Gasse et al. 1991, 1996; Shi et al. 2001; Bookhagen & Burbank 2006). Gasse et al. (1991, 1996) used δ¹³C and δ¹⁸O data, pollen, a hydrogen index, and diatom and plankton speciation to monitor wet v. dry conditions and Shi et al. (2001) used δ¹⁸O and δD data from ice and lake cores, and sediment and pollen from lake cores from locations across Tibet, including western Tibet, to argue for a very strong summer south Asian monsoon event during the interval c. 30–40 ka. Pangong Tso and Sumxi-Longmu Co are both located well inland of the syntaxis and Lahul (Fig. 4), as are Shi et al.’s (2001) sampled localities in western Tibet; hence, if enhanced monsoon precipitation penetrated the Himalayan front and reached these lakes and western Tibet, then it must have reached the syntaxis and Lahul. Moreover, glaciation occurred in both regions during the Holocene and between 35 and 40 ka on Nanga Parbat (Owen 2009). Based on the proxy data, there are two generally wet times, the Holocene and 35–45 ka. The intervals between these wet periods, 11.5–35 and 45–60 ka, are drier times with reduced stream power (Fig. 8). Pangong Tso and Sumxi-Longmu Co cores show three enhanced monsoon cycles during the Holocene and there is an additional MIS-2 glacial phase on Nanga Parbat. For simplicity, however, the model uses the Holocene as a general wet period and the MIS-2 Nanga Parbat glacial phase has been omitted because the duration of increased discharge owing to deglaciation is unknown. Shorter-term variations on the river and reach scale are not accounted for as these variables will average out over several thousand years, cannot account for the temporal pattern of incision throughout the Himalaya, and scale with stream power. We assume that rock uplift is relatively constant during the past 60 ka and that perturbations in the channel profile are solely controlled by climate. We do not have a record of changes in sediment flux or calibre of sediment owing to deglaciation or enhanced monsoons, but these processes scale exponentially with stream power.

For the model, we use the average Holocene incision rate for each region to define river downcutting during times of increased stream power and the oldest (closest to long-term) fluvial incision rate to define background fluvial incision during intervals of reduced stream power (Fig. 8). The oldest strath terrace provides a maximum estimate of incision for reduced stream power (that is, incision during dry periods) because this incision rate averages periods of both high and low stream power. Our model is not affected by using this maximum incision rate for dry periods because there is still a large difference between dry and wet period incision rates. With less than maximum incision rates for intervals of reduced stream power, even taller strath terraces would be formed during the 35–45 ka and Holocene wet periods, which supports our view that tall strath terraces are cut episodically during distinct time periods of increased stream power.

Results from the model show that for slow rock uplift rates, both of the rivers incise back to equilibrium (zero elevation), whereas fast rock uplift rates show an overall increase in the rivers’ elevation (Fig. 8). Irrespective of fast or slow rock uplift rates, the model shows that the channel bottoms can actually increase in elevation during drier times when stream power is reduced (11.5–35 and 45–60 ka) and then are rapidly incised during the wetter 35–45 ka and Holocene intervals. This supports the view of Gage (1970), who suggested that cumulative stream gradient adjustments are the sum of incremental positive and negative changes.

The model shows that a river could occupy a strath terrace for (1) a long time interval when the channel bottom is in disequilibrium during a dry period, (2) a short time interval when the channel bottom is in disequilibrium during a wet period and incision is greater than rock uplift, and (3) a moderate time interval when the channel bottom is in equilibrium during a wet period because rock uplift is equal to incision. The majority of vertical incision occurs during wet–dry transitions and through-out intervals of increased stream power, but depends on the durations of the wet period and the previous reduced stream power interval. If the previous reduced stream power interval is short, then accumulated changes in channel elevation owing to rock uplift would be small, which leads to short strath terraces during the following interval of increased stream power. Fast vertical incision during an interval of increased stream power is much more likely to be preserved as a strath terrace owing to its height above the river flood level. These are also the strath terraces most likely to be sampled for exposure age dating as they make up most of the strath terrace surface.

In addition, the model suggests that during the Holocene along the Indus River, strath terraces between c. 50 m and 180 m can be cut depending on whether slow (3 mm a⁻¹) or fast (6 mm a⁻¹) rock uplift rates are used, respectively (Fig. 8). Similarly, along the Chandra River, strath terraces between c. 35 m and 65 m can be cut using slow (1 mm a⁻¹) or fast (2 mm a⁻¹) rock uplift rates, respectively. The lower strath terrace height formed during slow rock uplift is caused by the channel bottom reaching equilibrium (Fig. 8). If the rivers stayed in equilibrium (zero elevation), then strath terraces would probably not be produced or be preserved as the very tall strath terraces (up to 400 m) observed today. The modelled channel bottoms suggest that during intervals of reduced stream power, rivers move into disequilibrium (elevation changes accumulate gradually) until an interval of increased stream power, when the rivers incise rapidly trying to reach equilibrium. The model accounts for the fast Holocene incision rates. Moreover, in the context of exposure age dating only one elevation on a strath older than 35 ka, the model accounts for the pre-Holocene 5 mm a⁻¹ incision rate limit across the Himalaya. The punctuated equilibrium of response of geomorphological systems has been well established (see Gage 1970) and probably applies to bedrock incision in the Himalaya as well.

Lastly, the model does not include lateral incision and valley widening. Hartshorn et al. (2002) suggested that high discharge events widen channels more than they vertically incise. Whipple (2004) suggested that bedrock strength, bedload flux, drainage area, rock uplift rate, and incision rate can all affect the strath terrace width, and that increased incision is intuitively appealing
for controlling the width of incision that occurs in some settings but not in others. Unfortunately, the paucity of valley width data from strath terrace locations in the Himalaya precludes further elucidation of how strath surfaces are preserved and how fluvial systems incise their channels. Recording valley width data on appropriate paired strath terraces is essential to understanding the nature of fluvial incision and should be undertaken in future studies.

**Sampling strategy and uncertainty**

The ages of c. 75% of the pre-Holocene strath terraces, including single strath surfaces and flights of strath terraces, are based on surfaces dated with only one $^{10}$Be age. For flights of strath terraces with multiple ages, four show a marked increase in the rate of fluvial incision between 10.5 and 22.7 ka, one shows a decrease in the rate of fluvial incision at 15 ka, and one was averaged owing to a poorly defined age-elevation relationship. The five flights of strath terraces that show changes in the rate of fluvial incision illustrate that by collecting multiple samples at different elevations above the river level it is possible to refine the timing and accuracy of fluvial incision rates, and to document changes in incision rate. Dating multiple samples from a single flight of terraces, especially those with exposure ages >35 ka, can help elucidate tectonic versus climatic controls on their formation and potentially allow rates of rock uplift to be estimated.

There is no way to determine if transient debris cover was ever present on strath terraces and if this problem affects all of the cosmogenically dated strath surfaces in the Himalaya. Leland et al. (1998) suggested that steeper strath surfaces yield more reliable ages than flatter surfaces because flatter surfaces are more likely to be affected by transient shielding. Because mean incision rate is based on river abandonment of the sampled surface and the vertical distance to the next sampled strath surface or the contemporary river, we suggest that samples collected from steep or even vertical surfaces of a strath terrace should be used to calculate mean incision rates. (The correction for exposure geometry for a sampled vertical surface taking up 180° of the topographic horizon would be large, of the order of 50%, for half of the skyline, but a cosmogenic age and its uncertainty could still be calculated.)

Uncertainty in determining the elevation of both the sampling location and the contemporary river level needs to be propagated with the exposure age uncertainty for determining a mean incision rate. It is clear that strath terrace incision rates contain large uncertainties and the age resolution of $^{10}$Be dating constitutes a large part of this uncertainty. However, significant uncertainty in many cases can be avoided by more accurate field measurement. Although handheld GPS units are common and easy to use, they typically yield 3–10 m of elevation uncertainty when next to a tall flight of nearly vertical strath terraces. More accurate elevations can be determined, even in areas that are not easily accessible, with the use of a measuring tape range finder or rope and an inclinometer.

To better understand exposure age sampling of strath terraces, we have numerically modelled an idealized history for a flight of strath terraces where constant rock uplift is countered by incision that varies with stream power (Fig. 9). We assume that there is no erosion of the strath terraces once they are abandoned; therefore, the rock uplift rate is equal to the uplift rate of the surfaces of the strath terraces. The channel bottom and uplifting terraces diverge from 60 ka to the present and the distance between the two represents the cumulative incision at any time.
When stream power is reduced, the incision rate is 0.1 mm a$^{-1}$ (the rate calculated from the oldest strath terrace along the Chandra River (zk81), 162.1 ± 25.1 ka) and when stream power is increased the incision rate is 8 mm a$^{-1}$ (the average of the Holocene-age rates of the Indus River near Nanga Parbat and the Chandra). A ‘model zero’ elevation marks the conditions under which the river is in equilibrium. Five strath terraces were created and the formation ages of these five terraces were used as ‘exposure ages’ for the calculation of bracketed incision rates. The mean incision rate calculation is based on the sample elevation and age, and the contemporary river (zero elevation and zero age). The mean incision rate begins to converge on the rock uplift rate when exposure ages are 35 ka. Variations in the mean incision rate are not as large as the exposure ages become older. Moreover, bracketing incision rates between ‘model exposure ages’ shows that climatic cyclicity could be resolved by collecting multiple samples from a single flight of strath terraces.

Based on the dataset of our new strath terrace ages and incision rates, and those previously published, the strath terrace exposure age model (Fig. 9), suggestions of Leland et al. (1998), and the fact that the published data we have analysed do not allow us to resolve episodic incision for strath terraces with ages between 35 and 735 ka, we propose an ideal sampling strategy for a flight of strath terraces. Our strategy allows episodic incision to be identified and defined, and correlation between fast incision and climate to be better evaluated. Sampling should be carried out on strath terrace surfaces with well-preserved fluvial erosional features and no debris cover, and specific samples should be taken from steep, if not vertical, surfaces of a strath terrace. It is important that the vertical distance between sampled strath terraces is greater than observed flood heights to ensure that exposure ages reflect river abandonment. On strath terraces that are older than 35 ka, further sampling and dating should be carried out to verify a positive age–elevation relationship (which has been commonly assumed but not proven) and with a density of sampling to potentially reveal episodic, higher rates of incision. Flights of strath terraces with age reversals probably have a complex shielding history and so are unfit for determining episodic incision. In the data we analysed, there are several rivers in the Himalaya with tall flights of strath terraces with ages >35 ka and only one exposure age that are good candidates for further sampling. Additional sampling should be located between two samples where incision rates are very slow to determine variation in those rates. Incision rates from strath terraces with ages >35 ka can be used to define rock uplift on geomorphological time scales of $10^3$–$10^5$ years.

**Conclusions**

Seventeen strath terraces in semi-arid Ladakh and monsoon-influenced Lahul were newly dated using $^{10}$Be TCN surface exposure methods. These include the oldest bedrock strath terraces dated in the Himalaya: two at >100 ka and four at >400 ka. Rates of fluvial incision based on strath terraces in the Ladakh vary from 0.06 ± 0.005 to 2.6 ± 1.9 mm a$^{-1}$. These rates of fluvial incision show that rivers on the northern side of the Ladakh Range and the Pangong Range are actively incising at c. 1 mm a$^{-1}$ whereas parts of the Zanskar Range are tectonically inactive with negligible fluvial incision (0.06 ± 0.005 mm a$^{-1}$). Rates of Holocene fluvial incision reported here and by Adams et al. (2009) for Lahul based on strath terrace ages vary from 1.4 ± 1.1 to 13.2 ± 6.2 mm a$^{-1}$. However, long-term (>35 ka) fluvial incision rates for Lahul are slow (<0.3 ± 0.04 mm a$^{-1}$).

Rates of Holocene fluvial incision based on strath terraces across the Himalaya and Transhimalaya range from c. 0.02 to c. 26.0 mm a$^{-1}$, but among these data, strath terraces with exposure ages >11.5 ka yield fluvial incision rates ≤5 mm a$^{-1}$. Many of the Holocene rates of fluvial incision across the Himalaya exceed independently determined exhumation rates, whereas strath terraces with ages >11.5 ka are generally comparable with the exhumation rates. Moreover, there are only five strath terraces with ages >35 ka that yield incision rates >1.0 mm a$^{-1}$.

In general, a $^{10}$Be age of c. 35 ka separates strath surfaces that record mean rates of fluvial incision similar to rates of exhumation from those that record rates greater than exhumation; that is, strath terraces with ages >35 ka can provide a realistic proxy for rates of rock uplift at geomorphological time scales. The higher incision rates determined from Holocene strath terraces probably reflect increased incision associated with the transition from glacial to interglacial times and enhanced monsoons as rivers, in disequilibrium, start incising their channels at rates faster than the rock uplift owing to increased stream power and accumulated perturbations in channel profiles during the drier times. Uplift of strath terrace surfaces can be approximated through time averaging incision rates whereas climatic cyclicity can be revealed through bracketing incision rates between samples from a flight of strath terraces. Moreover, multiple samples need to be collected from successions of strath terraces with ages >35 ka to resolve episodic fluvial incision, which is probably controlled by significant (40–100%) precipitation changes owing to intense monsoon phases and increased discharge owing to deglaciation.

J.D. thanks the University of Cincinnati Department of Geology for supporting this study as part of his doctoral research, B. Bookhagen for supplying TRMM data for this project, Sigma Xi, the American Alpine Club, and the University Research Counsel of the University of Cincinnati for funding this study, S. Ma for helping calculate our $^{10}$Be ages and recalculate ages from other studies, and T. Dorje for providing logistical support in the field and gracious hospitality in Leh. We sincerely thank P. Bishop and S. Brocklehurst, and journal editor J. Woodward for thorough, thoughtful, and constructive comments that significantly improved versions of this paper.

**References**

ADAMS, B., DEITSCH, C., OWEN, L.A., CAFFEY, M.W., SPOTILA, J. & HANEBERG, W.C. 2009. Exhumation and incision history of the Ladul Himalaya, northern India, based on ($U$–$Th$)/He thermochronology and terrestrial cosmogenic nuclide methods. *Geomorphology*, 107, 265–299.

BALCO, G. 2009. $^{26}$Al–$^{10}$Be exposure age/erosion rate calculators: update from v. 1 to v. 2. 2. http://hess.ess.washington.edu/math/docs/al_be_v22/AlBe_changes_v22.pdf.

BALCO, G., BRINER, J., FINKEL, R.C., RAYBURN, J., RIDGE, J.C. & SCHAFFER, J.M. 2009. Regional beryllium-10 production rate calibration for late-glacial northeastern North America. *Quaternary Science Reviews*, 4, 93–107.

BARNARD, P.L., OWEN, L.A., SHARMA, M.C. & FINKEL, R.C. 2001. Natural and human-induced landsliding in the Garhwal Himalaya of Northern India. *Geomorphology*, 40, 21–35.

BARNARD, P.L., OWEN, L.A., SHARMA, M.C. & FINKEL, R.C. 2004a. Late Quaternary landscape evolution of a monsoon-influenced high Himalayan valley, Gori Ganga, Nanda Devi, NE Garhwal. *Geomorphology*, 61, 91–110.

BARNARD, P.L., OWEN, L.A. & FINKEL, R.C. 2004b. Style and timing of glacial and paraglacial sedimentation in a monsoon-influenced high Himalayan environment, the upper Bhagirathi Valley, Garhwal Himalaya. *Sedimentary Geology*, 165, 199–221.

BARNARD, P.L., OWEN, L.A. & FINKEL, R.C. 2006. Quaternary fans and terraces in the Khumbu Himal south of Mount Everest: Their characteristics, age and formation. *Journal of the Geological Society, London*, 163, 383–399.

BARROS, A.P., JOSEI, M., PUTKONEN, J. & BURBANK, D.W. 2000. A study of the 1999 monsoon rainfall in a mountainous region in central Nepal using TRMM products and rain gauge observations. *Geophysical Research Letters*, 27, 3683–3686.

**EPIDEMIC FLUVIAL INCISION AND SURFACE UPLIFT** 801
Prell, W.L. & Kutzbach, J.E. 1997. Sensitivity of the Indian summer monsoon to climate forcings in the past 200,000 years. Nature, 387, 611–614.

Prins, M.A. & Postma, G. 2000. Effects of climate, sea level, and tectonics unraveled for last deglaciation: Turbidite records of the Arabian Sea. Geology, 28, 375–378.

Reiners, P.W., Zhou, Z., Ehlers, T.A., Xu, C., Brandon, M., Donelick, R.A. & Nicolas, S. 2003. Post-oregenetic evolution of the Dabie Shan, eastern China, from (U-Th)/He and fission-track thermochronology. American Journal of Science, 303, 489–518.

Reneau, S.L. 2000. Stream incision and terrace development in Frijoles Canyon, Bandelier National Monument, New Mexico, and the influence of lithology and climate. Geomorphology, 32, 171–193.

Rockwell, T.K., Clark, M.N., Johnson, D.L. & Keller, E.A. 1984. Chronology and rates of faulting of Ventura River terraces. California. Geological Society of America Bulletin, 95, 1466–1474.

Searle, M.P. 1991. Geology and Tectonics of the Karakoram Mountains. Wiley, Chichester.

Searle, M.P. & Fryer, B.J. 1986. Garnet and muscovite-bearing leucogranites, gneisses, and migmatites of the Higher Himalaya from Zanskar, Kulu, Lahaul, and Kashmir. Collision Tectonics, 19, 185–201.

Searle, M.P. & Richard, J.P. 2007. Relationships between right-lateral shear along the Karakoram fault and metamorphism, magmatism, exhumation and uplift: Evidence from the K2–Gasherbrum, Pangong Ranges, north Pakistan and Ladakh. Journal of the Geological Society, London, 164, 439–450.

Searle, M.P., Simpson, R.L., Law, R.D., Parrish, R.R. & Waters, D.J. 2003. The structural geometry, metamorphic and magmatic evolution of the Everest massif, High Himalaya of Nepal–south Tibet. Journal of the Geological Society, London, 160, 345–366.

Sirocko, F., Zahn, S., Leventer, R.R., et al. 2007. Quaternary glacial history of the Central Karakoram. Quaternary Science Reviews, 26, 3384–3405.

Shroder, J.F. & Bishop, M.P. 2000. Unroofing of the Nanga Parbat Himalaya. In: Khan, M.A., Treloar, P.J., Searle, M.P. & Jan, M.Q. (eds) Tectonics of the Nanga Parbat Synthesis and the Western Himalaya. Geological Society, London, Special Publications, 170, 163–179.

Sinclair, H.D. & Jaffey, N. 2001. Sedimentology of the Indus group, Ladakh, northern India: Implications for the timing of initiation of the Indus–Baltoro River. Journal of the Geological Society, London, 158, 152–162.

Sirocko, F., Sarnthein, M., Erlenkeuser, H., Lange, H., Arnold, M. & Duplessy, J.C. 1993. Century-scale events in monsoon climate over the last 240,000 years. Nature, 364, 322–324.

Small, E.E., Anderson, R.S., Repka, J.L. & Finkel, R. 2007. Erosion rates of alpine bedrock summit surfaces deduced from (U-Th)/He and (206)Pb–(230)U nuclide production and climate. Earth and Planetary Science Letters, 256, 359–370.

Spitola, J.A., Buscher, J.T., Meigs, A. & Reiners, P.W. 2004. Long-term glacial erosion of active mountain belts: example of the Chuguch/St. Elias Range, Alaska. Geology, 32, 501–504.

Steck, A. 2003. Geology of the NW India Himalaya. Eclogae Geologicae Helveticae, 96, 147–196.

Stone, J.O. 2000. Air pressure and cosmicogenic isotope production. Journal of Geophysical Research, 105, 23753–23759.

Stuwe, K., Brown, R. & White, L. 1994. The influence of eroding topography on steady-state isotherms: Application to fission track analysis. Earth and Planetary Science Letters, 124, 63–74.

Thambynayagam, M., Tao, V.P. & Schneider, R.R. 2002. Reconstruction of late Quaternary monsoon oscillations based on clay mineral proxies using sediment cores from the western margin of India. Marine Geology, 186, 527–539.

Thompson, L.G., Mosley-Thompson, E., et al. 1999. Holocene–Late Pleistocene climatic ice cores from Qinhai–Tibetan Plateau. Science, 246, 478–477.

Thompson, L.G., Mosley-Thompson, E., et al. 1990. Glacial stage ice-core records from the subtropical Dunde ice cap, China. Annals of Glaciology, 14, 288–297.

Thompson, L.G., Yao, T., et al. 1997. Tropical climate instability: the last glacial cycle from a Qinhai–Tibetan ice core. Science, 276, 1821–1825.

Treloar, P.J., Rex, D.C., Guse, P.G., Wheeler, J., Hurford, A.J. & Carter, A. 2000. Geochemical constraints on the evolution of the Nanga Parbat Synthesis, Pakistan Himalaya. In: Khan, M.A., Treloar, P.J., Searle, M.P.
& JAN, M.Q. (eds) Tectonics of the Nanga Parbat Syntax and the Western Himalaya. Geological Society, London, Special Publications, 170, 137–162.
VANNAY, J.-C., GRASSMANN, B., RAHN, M., FRANK, W., CARTER, A., BAUDRAZ, V. & COSCA, M. 2004. Miocene to Holocene exhumation of metamorphic crustal wedges in the NW Himalaya: Evidence for tectonic extrusion coupled to fluvial erosion. Tectonics, 23, TC1014. doi:10.1029/2002TC001429
WADE, D.N. 1931. The syntaxis of the northwest Himalaya: its rocks, tectonics and orogeny. Records of the Geological Survey of India, 65, 189–220.
WALKER, J.D., MARTIN, M.W., BOWRING, S.A., SEARLE, M.P., WATERS, D.J. & HODGES, K.V. 1999. Metamorphism, melting, and extension: Age constraints from the High Himalayan slab of southeast Zanskar and northwest Lahul. Journal of Geology, 107, 473–495.
WEBB, A.G., YIN, A., HARRISON, T.M., CELERIER, J. & BURGESS, W.P. 2007. The leading edge of the Greater Himalaya Crystalline complex revealed in the NW Indian Himalaya: Implications for the evolution of the Himalayan orogen. Geology, 35, 955–958.
WHIPPLE, K.X. 2004. Bedrock rivers and the geomorphology of active orogens. Annual Review of Earth and Planetary Sciences, 32, 151–185.
WHIPPLE, K.X., HANCOCK, G.S. & ANDERSON, R.S. 2000. River incision into bedrock: Mechanics and relative efficacy of plucking, abrasion, and cavitation. Geological Society of America Bulletin, 112, 490–503.
WILLET, S.D. & BRANDON, M.T. 2002. On steady state in mountain belts. Geology, 30, 175–178.
WINSLOW, D.M., ZEITLER, P.K., CHAMBERLAIN, C.P. & HOLLISTER, L.S. 1994. Direct evidence for a steep geotherm under conditions of rapid denudation, Western Himalaya, Pakistan. Geology, 22, 1075–1078.
WINSLOW, D.M., CHAMBERLAIN, C.P., WILLIAMS, I.S. & ZEITLER, P.K. 1996. Geochronologic constraints on syntaxial development in the Nanga Parbat region, Pakistan. Tectonics, 15, 1292–1308.
WOBUS, C., HELMSATH, A., WHIPPLE, K. & HODGES, K. 2005. Active out-of-sequence thrust faulting in the central Nepalese Himalaya. Nature, 434, 1008–1011.
WOBUS, C., PRINGLE, M., WHIPPLE, K. & HODGES, K. 2008. A Late Miocene acceleration of exhumation in the Himalayan crystalline core. Earth and Planetary Science Letters, 269, 1–10.
YAO, T., THOMPSON, L.G., MOSLEY-THOMPSON, E., YANG, Z., ZHANG, X. & LIN, P.-N. 1996. Climatological significance of δ18O in north Tibetan ice cores. Journal of Geophysical Research, 101, 29531–29537.
YIN, A. & HARRISON, T.M. 2000. Geologic evolution of the Himalayan–Tibetan orogen. Annual Review of Earth and Planetary Sciences, 28, 211–280.
ZAUN, P.E. & WAGNER, G.A. 1985. Fission-track stability in zircons under geological conditions. Nuclear Tracks and Radiation Measurements, 10, 303–307.
ZEITLER, P.K. 1985. Cooling history of the NW Himalaya Pakistan. Tectonics, 4, 127–151.
ZEITLER, P.K., MELTZER, A.S., ET AL. 2001. Erosion, Himalayan geodynamics and the geomorphology of metamorphism. Geological Society of America, Today, 113, 1443–1455.

Received 5 November 2009; revised typescript accepted 26 November 2010.
Scientific editing by Jamie Woodward.