From tectonically to erosionally controlled development of the Himalayan orogen

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ABSTRACT

Whether variations in the spatial distribution of erosion influence the location, style, and magnitude of deformation within the Himalayan orogen is a matter of debate. We report new $^{40}Ar/^{39}Ar$ white mica and apatite fission-track (AFT) ages that measure the vertical component of exhumation rates along an ~120-km-wide NE-SW transect spanning the greater Sutlej region of northwest India. The $^{40}Ar/^{39}Ar$ data indicate that first the High Himalayan Crystalline units cooled below their closing temperature during the early to middle Miocene. Subsequently, Lesser Himalayan Crystalline nappes cooled rapidly, indicating southward propagation of the orogen during late Miocene to Pliocene time. The AFT data, in contrast, imply synchronous exhumation of a NE-SW–oriented ~80 × 40 km region spanning both crystalline nappes during the Pliocene–Quaternary. The locus of pronounced exhumation defined by the AFT data correlates with a region of high precipitation, discharge, and sediment flux rates during the Holocene. This correlation suggests that although tectonic processes exerted the dominant control on the denudation pattern before and until the middle Miocene; erosion may have been the most important factor since the Pliocene.

Keywords: Himalaya, exhumation, erosion, uplift, geochronology.

INTRODUCTION

The evolution of mountain belts can be strongly influenced by a dynamic coupling between climate-driven erosion and tectonics (e.g., Koons, 1990; Brandon et al., 1998; Reiners et al., 2003; Thiede et al., 2004). This is in good agreement with the results of numerical and analog modeling that imply that the topographic evolution of orogens is largely controlled by the relative importance of accretionary influx and erosional removal, and that changes in topography may, in turn, affect the architectural evolution of fault systems (e.g., Dahlen and Suppe, 1988; Willett, 1999; DeCelles and DeCelles, 2001; Hilley and Strecker, 2004; Whipple and Meade, 2004; Hoth et al., 2005). These models also indicate that localized erosion can cause a self-organized compensation by internal deformation within an orogen (e.g., Dahlen and Suppe, 1988; Whipple and Meade, 2004; Hoth et al., 2005). Although these models make specific predictions of how these processes interact, there are few field studies with sufficient temporal resolution and spatial coverage to test them. The active Himalayan orogen formed through thickening and shortening and has been affected by high monsoonal precipitation and erosional removal over million year time scales (Fig. 1A). Although some studies imply a positive feedback of erosion on tectonically controlled uplift near the southern front of the High Himalaya, others indicate that erosion is primarily related to uniform tectonic uplift (e.g., Burbank et al., 2003).

Here we combine new $^{40}Ar/^{39}Ar$ white mica and apatite fission-track (AFT) ages with published thermochronology data sets (Jain et al., 2000; Thiede et al., 2004; Vannay et al., 2004) to provide a detailed reconstruction of the exhumation history along a NE-SW–oriented transect across the Himalayan core in northwest India (Fig. 1). This study characterizes the evolution of the Himalayan orogen from the Miocene to the present, and it indicates a change from tectonically to erosionally controlled exhumation since the Miocene.

GEOLOGIC SETTING OF THE NORTHWESTERN HIMALAYA

Sustained Eurasian-Indian convergence since the continental collision ca. 50 Ma has caused persistent lateral and vertical growth of the Himalaya (e.g., Hodges, 2000, and references therein), which has been accommodated by progressive motion along a series of major crustal fault systems: the Southern Tibetan detachment, the Main Central thrust, the Main Boundary thrust, and the Main Frontal thrust. These orogen-parallel fault systems bound the main Himalayan tectonostratigraphic domains, which are underthrust by the Indian plate along the basal Main Himalayan thrust.

Along the Sutlej Valley in the northwest Himalaya (Fig. 1A), two crystalline nappes are characterized by different Miocene cooling and exhumation histories (Vannay and Grasemann, 1998; Vannay et al., 2004). In the north, the High Himalayan Crystalline unit, a ~10-km-thick, northeast-dipping sequence of highly deformed amphibolite to migmatitic gneisses, is bounded by the Main Central thrust at the base and by the South Tibetan detachment at the top; these faults were contemporaneously active during the early and middle Miocene (Hubbard and Harrison, 1989; Burchfiel et al., 1992). During motion along the Main Central thrust, the sedimentary rocks associated with the Lesser Himalaya were underthrust beneath the High Himalayan Crystalline nappes.

To the south, in the footwall of the Main Central thrust, Lesser Himalayan Crystalline rocks, which constitute a portion of the Lesser Himalaya (Valdiya, 1980), are exposed within the Larji-Kulu-Rampur window (Vannay and Grasemann, 1998). The Munsiari thrust at the base and the Main Central thrust at the top bound the Lesser Himalayan Crystalline unit. The rocks of the Lesser Himalayan Crystalline sequence are amphibolite facies augengneisses and paragneisses. Timing of southward propagation of the Himalayan deformation front is not well constrained, but the Lesser Himalaya probably began thrusting onto the Sub-Himalaya along the Main Boundary thrust system during late Miocene (Huyghe et al., 2001, and references therein).

THERMOCHRONOLOGIC DATA

The primary objective of our study is to determine the regional extent and timing of rapid exhumation of rocks from the High and Lesser Himalayan Crystalline nappes. In addition to a compilation of relevant data from the region, we present five new $^{40}Ar/^{39}Ar$ ages and

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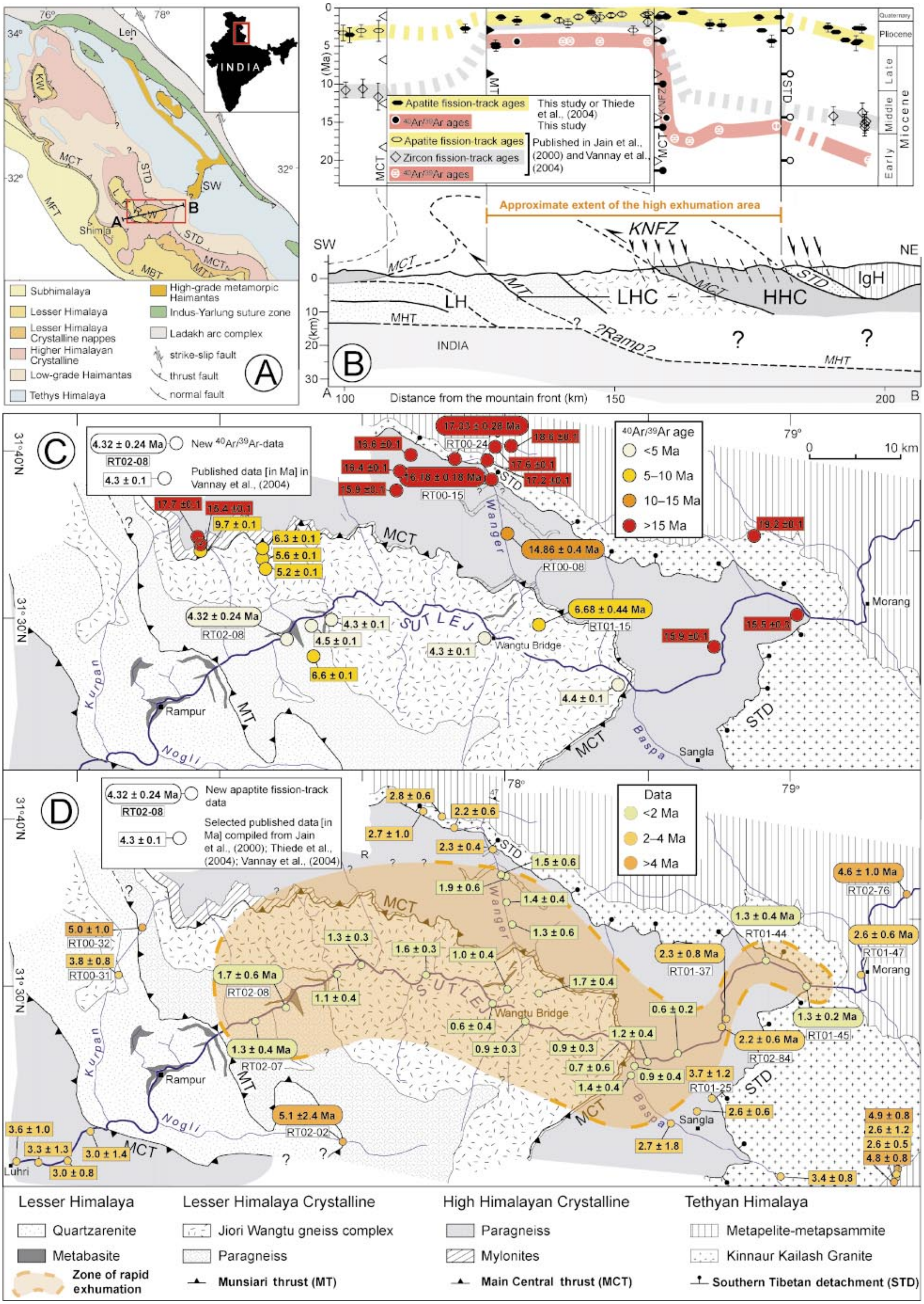

A
INDIA
Leh
KW
MCT
STD
SW
MFT
Shimla
MBT
Subhimalaya
Lesser Himalaya
Lesser Himalaya Crystalline nappes
Higher Himalayan Crystalline
Low-grade Haimantas
Tethys Himalaya
High-grade metamorphic Haimantas
Indus-Yarlung suture zone
Ladakh arc complex
strike-slip fault
thrust fault
normal fault
B
(Ma)
Apatite fission-track ages
40Ar/39Ar ages
This study or Thiede et al., (2004)
This study
Apatite fission-track ages
Zircon fission-track ages
40Ar/39Ar ages
Published in Jain et al., (2000) and Vannay et al., (2004)
Quaternary
Pliocene
Late
Middle
Early
Miocene
Approximate extent of the high exhumation area
KNFZ
SW
NE
MCT
MT
LH
LHC
HHC
IgH
MHT
INDIA
?Ramp?
(km)
Distance from the mountain front (km)
C
New 40Ar/39Ar-data
Published data [in Ma] in Vannay et al., (2004)
40Ar/39Ar age
<5 Ma
5–10 Ma
10–15 Ma
>15 Ma
10 km
SUTLEJ
Wangtu Bridge
Wanger
Rampur
Kurpan
Nogli
Baspa
Sangla
Morang
D
New apaptite fission-track data
Selected published data [in Ma] compiled from Jain et al., (2000); Thiede et al., (2004); Vannay et al., (2004)
Data
<2 Ma
2–4 Ma
>4 Ma
Luhri
Lesser Himalaya
Quartzarenite
Metabasite
Zone of rapid exhumation
Lesser Himalaya Crystalline
Jiori Wangtu gneiss complex
Paragneiss
Munsiari thrust (MT)
High Himalayan Crystalline
Paragneiss
Mylonites
Main Central thrust (MCT)
Tethyan Himalaya
Metapelite-metapsammite
Kinnaur Kailash Granite
Southern Tibetan detachment (STD)

nine new AFT ages, which improve the spatial sample coverage and clarify critical structural relationships. Analytical and sample preparation details, $^{40}Ar/^{39}Ar$ analysis release spectra, inverse isotope correlation diagrams, and AFT data results are documented in the Data Repository.[1]

We obtained $^{40}Ar/^{39}Ar$–white mica cooling ages of 4.3 ± 0.2 and 6.7 ± 0.4 Ma for samples of the Lesser Himalayan Crystalline units and 14.9 ± 0.4 and 17.3 ± 0.3 Ma for the High Himalayan Crystalline units and the Tethyan Himalaya (Fig. 1C; consistent with other published data; Vannay et al., 2004). All AFT samples pass the chi-square test, and therefore pooled ages are reported with 2σ errors (Table DR1; see footnote 1). Only samples with high U content yielded a sufficient number of Dpar measurements (Table DR1; see footnote 1), indicating a fairly homogenous kinetic characteristic close to those of Durango apatite (Donelick et al., 1999), implying a closure temperature of 140 ± 10 °C, assuming a high cooling rate (~100 °C/m.y.) (Ketcham et al., 1999).

Three AFT samples were collected in the hanging wall of the Munsiari thrust to further constrain the southern extent of the sector of rapid exhumation. Along the bottom of the Sutlej Valley, two samples yield ages of 1.3 ± 0.4 and 1.7 ± 0.6 Ma, and one in the upper part of the Nogli Valley was dated as 5.1 ± 2.4 Ma (Fig. 1D). Six additional samples were collected along the Sutlej River, covering the transition from the High Himalayan Crystalline units into the Tethyan Himalaya; these help to determine the extent of the rapidly exhumed sector to the north. We obtained cooling ages between 1.3 ± 0.2 and 2.3 ± 0.8 Ma for rocks from the High Himalayan Crystalline units, and 2.6 ± 0.6 and 4.6 ± 1.0 Ma for Tethyan-Himalaya rocks (Fig. 1D).

To view our new results and compiled thermochronological data (Jain et al., 2000; Thiede et al., 2004; Vannay et al., 2004) in a regional context, we plotted all the data along a cross section and compared them to the main structures (Fig. 1B). Within a transect from the Munsiari thrust to the South Tibetan detachment along the Sutlej River, AFT cooling ages range between younger than 1 and 2.3 Ma, whereas farther southwest and northeast, they increase to 2.5–5 Ma (Figs. 1B, 1D). In contrast, samples collected along strike of the Munsiari thrust to the north (RT00–32 and RT00–31, 2200 m) and south (RT02–02, 1900 m) yield ages as old as 5 Ma. Therefore, within the resolution of the method, segments of the Munsiari thrust situated farther away from the Sutlej Valley bottom may have been inactive for the last several million years. However, the increase in age is not exclusively related to an age-elevation relationship. Comparable results are obtained in the footwall of the South Tibetan detachment, where 1.3 Ma (RT01-45) samples were collected near the Sutlej Valley bottom, and 3–4 Ma samples come from locations along the South Tibetan detachment to the south (e.g., RT01-25). Building on earlier interpretations (Thiede et al., 2004), this indicates that major tectonic structures, which had accommodated displacement during Miocene ductile deformation in this area, did not control near-surface deformation and exhumation of the high-grade core, but rather have acted as passive markers during Pliocene-Quaternary time.

[1]GSA Data Repository item 2005128, Appendix, Figure DR1, and Table DR1, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA. P.O. Box 9140, Boulder, CO 80301-9140, USA.

FROM DIACHRONOUS TO SYNCHRONOUS COOLING OF THE HIMALAYAN CRYSTALLINE CORE

In the Sutlej region the distributions of $^{40}Ar/^{39}Ar$ cooling ages are strongly correlated with the major tectonic units (High and Lesser Himalayan Crystalline) and indicate diachronous thrusting and cooling during the Miocene (Figs. 1B, 1C; Vannay et al., 2004). The Main Central thrust hanging wall cooled through the argon–white mica closure temperature during early-middle Miocene time, consistent with the exhumation of the High Himalayan Crystalline units controlled by thrusting along the Main Central thrust since ca. 23 Ma (e.g., Hubbard and Harrison, 1989). In the Main Central thrust footwall, $^{40}Ar/^{39}Ar$ ages document late Miocene to early Pliocene cooling, indicating significantly younger exhumation for the Lesser Himalayan Crystalline nappe. Thus, differential rock uplift between the High and Lesser Himalayan Crystalline rocks are possibly accommodated by a zone of pervasive high-angle ductile to brittle-ductile normal shear zone in the vicinity of the Main Central thrust, which has been described as the Karcham normal fault zone (Fig. 1B; Vannay et al., 2004).

This diachronous exhumation may have been caused by vigorous erosion and foreland-directed growth of the Himalaya with a tectonically driven zone of high uplift moving toward the foreland (DeCelles et al., 2001; Vannay et al., 2004) or by underthrusting of a crystalline nappe detached from the Indian plate (Avouac, 2003).

In contrast, Pliocene–Quaternary AFT cooling ages reveal a marked change in the pattern of exhumation across the Himalayan high-grade core. Certain sectors along the Southern Himalayan front yield significantly younger AFT ages (0.5–2 Ma), indicating high exhumation rates (Thiede et al., 2004, and references therein). In the Munsiari hanging wall, exhumation rates have remained nearly constant since the late Miocene (Vannay et al., 2004). Modifying earlier interpretations, exhumation accelerated dramatically in the Main Central thrust hanging wall in the Pliocene–Quaternary to match the exhumation rates in the Munsiari hanging wall. Thus, the new AFT ages indicate focused exhumation and erosion in a NE-SW–oriented region of ~80 × 40 km along the Sutlej corridor, extending from the Munsiari thrust to the South Tibetan fault system (Fig. 1D, dashed line). Consequently, our data also record a cessation of normal-sense slip along the Karcham normal fault zone at the same time. However, topographic effects have a negligible effect on the extent of this zone of rapid exhumation, because the exhumation rates exceed 1 mm/yr (Mancktelow and Grasemann, 1997).

Notably, within this sector AFT ages are particularly young where the longitudinal profile of the Sutlej River has a steep gradient and is deeply incised across the southern front of the High Himalaya. This region of pronounced exhumation correlates with the local maximum of focused monsoonal precipitation, river discharge, and sediment flux, indicating intense erosion (Thiede et al., 2004; Vannay et al., 2004; Bookhagen et al., 2005a, 2005b), rather than being uniform along strike and parallel to major structures of the orogen.

GEODYNAMIC IMPLICATIONS AND CONCLUSIONS

The migration of a tectonically driven zone of high uplift from Higher to Lesser Himalayan Crystalline rocks indicates foreland-directed mid-Miocene growth of the Himalayan orogen (e.g., DeCelles et al., 2001; Vannay et al., 2004). Limited paleoelevation estimates indicate that the High Himalaya and southern Tibet had reached ele-

Figure 1. A: Generalized geologic map of northwest Himalaya, India, after DiPietro and Pogue (2004). Red box shows location of C and D; black line denotes cross section in B. B: Simplified geologic cross section and distribution of cooling ages along Sutlej Valley modified after Vannay et al. (2004). Dashed line defines approximate extent of zone of rapid exhumation. AFT—apatite fission track; HHC—High Himalayan Crystalline; KNFZ—Karcham normal fault zone; LH—Lesser Himalaya; LHC—Lesser Himalayan Crystalline; lgH-low-grade Haimantas; LKRW—Larji-Kulu-Rampur window; MBT—Main Boundary thrust system; MCT—Main Central thrust system; MHT—Main Himalayan thrust; MT—Munsiari thrust; STD—South Tibetan detachment.

vations similar to present by 10–12 Ma (Garzione et al., 2000; Rowley et al., 2001). The Himalayan orogen had established an orographic barrier by at least late Miocene time, and this coincides with the onset of monsoonal circulation (e.g., Dettman et al., 2003). Although the southern Himalayan front is affected by heterogeneous erosion at the million year time scale, the topography forms a nearly perfect arc (e.g., Bendick and Bilham, 2001). Focused erosion is thus compensated by self-organized thrust activation resulting in heterogeneous distribution of rock uplift and exhumation. Rapid rock uplift in turn may keep the longitudinal river profiles steep, forcing the rivers to further incise (Whipple and Mead, 2004). For example, the removal of the 10–15-km-thick High Himalayan Crystalline nappe, which today is replaced by Lesser Himalayan Crystalline rocks forming the Larji-Kulu-Rampur window, indicates pronounced removal of crystalline rocks along the Sutlej River network (Figs. 1C, 1D). This assessment is consistent with the spatial distribution of ^{40}Ar/^{39}Ar and AFT cooling ages. The distribution of AFT cooling ages thus may reflect the regional degree of effectiveness of erosion. Alternatively, orogen growth toward the foreland may leave in its wake a zone of more passive uplift in which surface processes dominate.

The development, however, toward synchronous exhumation of both crystalline nappe systems may suggest that when a critical mass removal threshold is exceeded (Koons et al., 2002), the orographic barrier may play a fundamental role in intercepting moisture and focusing discharge, erosion, and sediment transport along an orogenic front. To compensate the erosional loss, the orogen is forced to internally reorganize, and therefore erosion may control the distribution of exhumation and rock uplift. For the past 10 m.y., the Himalayan deformation front has migrated only 20–50 km southward. Therefore internal rock uplift and focused exhumation concentrated orogenic deformation in this internal sector, rather than propagating the deformation front southward.

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