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Notes

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ABSTRACT

We study the recent dynamics of the central Nepal Himalaya, focusing on possible reactivation of the footwall of the Main Central thrust, which is marked by an abrupt topographic transition. Different tectonic mechanisms, such as overthrusting of a major crustal ramp, underplating, or out-of-sequence thrusting, have been suggested to explain the morphology and exhumation patterns in this area. We present 25 new apatite fission-track ages collected along a north-south transect in central Nepal, as well as two age-elevation profiles. Ages are consistently younger than 3 Ma old in the Main Central thrust zone and increase continuously to 4–6 Ma old in the south. No jump in apatite fission-track ages is observed across the topographic transition. Apparent exhumation rates from age-elevation relationships vary from 0.46 +0.13/–0.09 km/Ma in the Palung granite south of Kathmandu to 4.4 +4.8/–1.5 km/Ma in the Main Central thrust zone; the latter rate is probably overestimated by a factor of two due to topographic effects. As shown by a new numerical model, these strongly varying exhumation rates can be explained by overthrusting of a crustal ramp, which exerts a primary control on age patterns, and do not require out-of-sequence reactivation of thrusts in the Main Central thrust zone.

INTRODUCTION

The Himalaya is characterized by a south-vergent crustal-scale thrust sequence (Fig. 1). Major thrusts delimit three distinct units: the Siwaliks fold-and-thrust belt between the Main Frontal (MFT) and the Main Boundary (MBT) thrusts; the metasediments of the Lesser Himalaya between the MBT and the Main Central thrust (MCT); and the Greater Himalayan crystalline thrust sheet with overlying Tethyan sediments in the hanging wall of the MCT (Gansser, 1964; Le Fort, 1975). Geophysical and structural studies suggest that the MFT, MBT, and MCT all branch at depth to a single mid-crustal décollement, the Main Himalayan thrust (MHT; e.g., Zhao et al., 1993; Schulte-Pelkum et al., 2005). The MHT is characterized by a ramp-flat geometry with two major ramps: one where the fault emerges with a dip of ~30° at the surface (MFT), and the other at mid-crustal depth, beneath the topographic front of the high range, with a dip of ~15°–30° (Avouac, 2003; Berger et al., 2004). A sharp topographic transition 10–30 km south of the MCT in central Nepal separates a northern high-relief zone at a mean elevation of >3000 m from a southern zone of more moderate relief at a mean elevation of <1500 m (Lavé and Avouac, 2001; Duncan et al., 2003; Wobus et al., 2003).

Two competing models have been proposed recently to describe the present-day kinematics of the central Nepal Himalaya (Fig. 1). These differ in their predictions of which surface-breaking faults accommodate current shortening and what kinematics drive rapid exhumation in the topographic transition zone around the MCT. Avouac (2003) and Bollinger et al. (2004, 2006) argued that recent deformation is concentrated along the MHT and that rapid exhumation in the MCT zone results from underplating along the MHT ramp. In contrast, Wobus et al. (2003) and Hodges et al. (2004) suggested active out-of-sequence thrusting in the topographic transition zone, possibly driven by climatically controlled localized exhumation in this area.

The opposing models predict different exhumation paths for rocks in the Lesser Himalaya and the topographic transition zone that should be recorded by low- and medium-temperature thermochronometers such as apatite fission-track (AFT) and mica Ar-Ar (Fig. 1). In particular, the out-of-sequence model predicts an age jump in the topographic transition zone (Hodges et al., 2004; Wobus et al., 2006), whereas the underplating model predicts a gradual decrease in ages across the Lesser Himalaya from the MBT to the MCT (Bollinger et al., 2004, 2006). However, due to unfavorable lithologies, few thermochronologic data have been collected in the Lesser Himalaya,

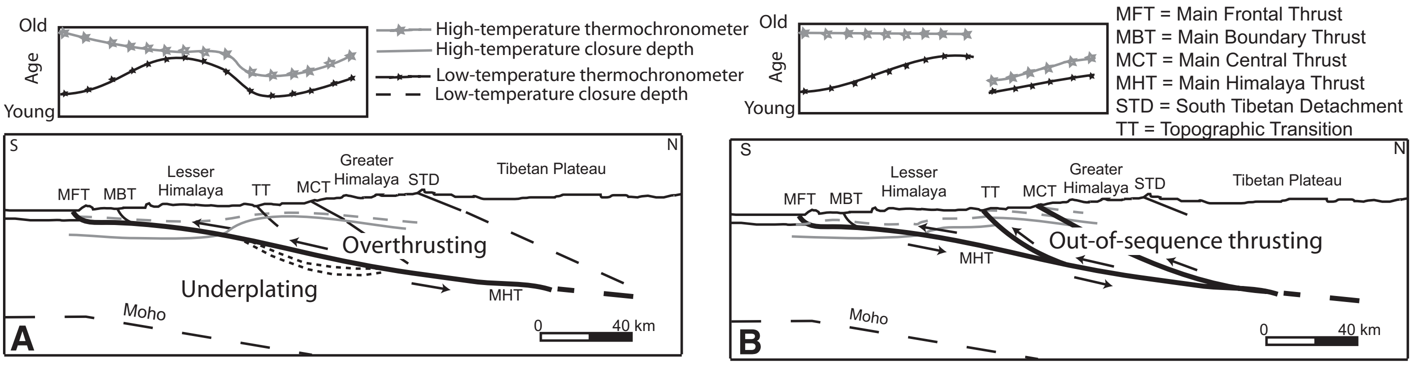

Figure 1. Two schematic tectonic scenarios for central Himalaya (modified from Hodges et al., 2004) and their predicted thermochronological age trends. A: In model of Avouac (2003), shortening is concentrated on Main Himalayan thrust (MHT), which includes crustal ramp below topographic transition between Lesser and Greater Himalaya. Expected thermochronologic age trends should young continuously toward the MCT. B: In model of Hodges et al. (2004), out-of-sequence faulting occurs in topographic transition (TT) zone. Thermochronologic age trends should present a jump at the TT.

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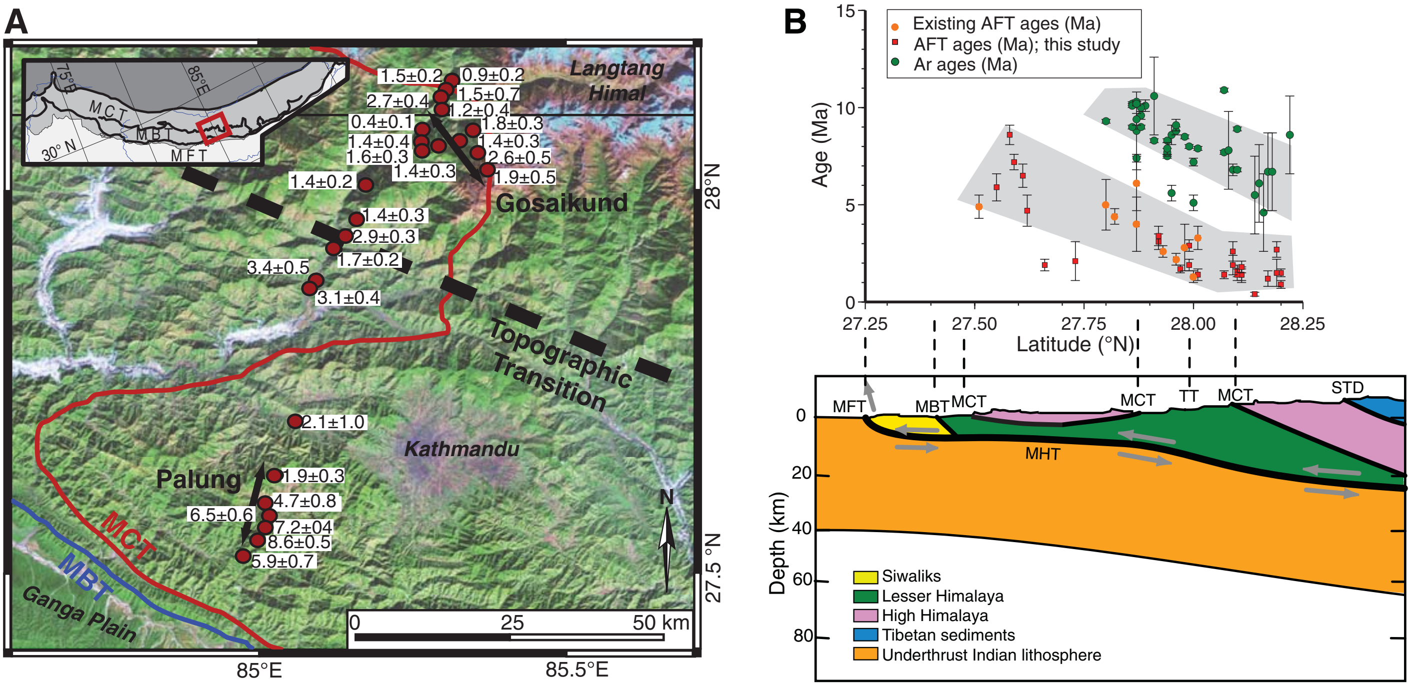

Figure 2. A: Location of samples collected in central Nepal. Apatite fission-track (AFT) ages (±1σ error) are indicated. B: AFT (squares—this study; circles—data from P. Copeland reported by Bollinger et al., 2006) and mica Ar/Ar (Arita et al., 1997; Rai, 1998; Bollinger et al., 2004) age transects, plotted as function of latitude. Relationship to major structures of central Himalaya is indicated by crustal-scale cross section (modified from Bollinger et al., 2004; acronyms as in Fig. 1).

precluding a clear discrimination between the two models. Here we present new AFT data from a transect across central Nepal and combine these with a forward numerical model in order to assess the different models.

THERMOCHRONOLOGICAL DATA

Samples were collected along a north-south transect from the Langtang Himal to the Ganga plain in central Nepal (Fig. 2). In this area, the MCT forms a large klippe of Greater Himalayan rocks, the Kathmandu klippe (Upreti, 1999). The central part of the klippe is intruded by the Ordovician Palung granite, which was one of our sampling targets. In the half-window exposing Lesser Himalaya to the northwest of the Kathmandu klippe, we sampled quartzites and sandstones of the Lower Nawakot Group as well as Ulleri gneiss (Upreti, 1999). Two age-elevation profiles were collected; one within the topographic transition zone from the Trisuli River valley up to Gosaikund mountain, with sample elevations spanning 1780–4500 m, and another in the Palung granite between 770 and 2500 m elevation.

Details on sample processing and AFT data are provided in the GSA Data Repository[1]. An AFT-age transect shows a continuous trend (Fig. 2), with ages younging nearly linearly from the MBT to the MCT (with the exception of two young AFT ages in the Palung granite). The northernmost samples from the MCT zone are consistently very young (younger than 3 Ma old), similar to data collected farther west (Blythe et al., 2007). This trend crosses the topographic transition and MCT zone without a significant jump in ages. Mica Ar-Ar data from the same region (Arita et al., 1997; Rai, 1998; Bollinger et al., 2004), although less spatially extensive than the AFT data reported here, show the same pattern (Fig. 2).

The two age-elevation profiles are shown in Figure 3. In the Palung granite, ages vary from 2.1 ± 1.0 Ma at 770 m to 6.5 ± 0.6 Ma at 2360 m elevation. Weighted linear regression on these data suggests an exhumation rate of 0.46 +0.13/–0.09 km/Ma. In contrast, ages from the Gosaikund profile vary between 1.2 ± 0.4 and 2.6 ± 0.5 Ma old, suggesting an exhumation rate an order of magnitude higher, 4.4 +4.8/–1.5 km/Ma. However, at such high rates of exhumation, topographic disturbance of the closure isotherm may lead to seriously overestimating exhumation rates from age-elevation relationships (e.g., Mancktelow and Grasemann, 1997). This overestimate can be quantified as (Braun, 2002):

$$\frac{dh}{da} = \frac{\dot{e}}{(1-\alpha)}, \qquad (1)$$

where dh/da is the apparent age-elevation relationship, $\dot{e}$ is the real exhumation rate, and α is the vertical deflection of the closure temperature isotherm relative to the amplitude of the surface topography, varying from 0 (no deflection of the isotherm) to 1 (the isotherm follows the surface topography).

We have estimated α for the AFT closure isotherm of 120 ± 10 °C using the method of Mancktelow and Grasemann (1997) for topographic wavelengths (~30 km) and amplitudes (~3 km) that characterize the Gosaikund sampling area. We find that α ≈ 0.5, so that we should expect to overestimate exhumation rates by ~100%; real exhumation rates for the Gosaikund profile are thus probably ~2.0–2.5 km/Ma.

We use a simple geometric model (Fig. 3) to test whether these large differences in exhumation rate are compatible with overthrusting on a crustal ramp, by estimating the ramp and flat angles required to explain them. Previous thermokinematic models (Bollinger et al., 2006; Brewer and Burbank, 2006; Wobus et al., 2006; Whipp et al., 2007) have shown that, in order to explain the AFT and mica Ar-Ar ages observed in the MCT zone, the ~21 km/Ma convergence rate accommodated by the central Himalaya (Lavé and Avouac, 2000; Mugnier et al., 2004) should be partitioned into 5–6 km/Ma of overthrusting over the MHT and ~15 km/Ma of underthrusting of the Indian plate. The rate of overthrusting (V) can be linked to the exhumation rate through the detachment angle (φ): tan φ = $\dot{e}$ /V (Fig. 3). Applying this approach to the exhumation rate inferred for

[1]GSA Data Repository item 2009176, Apatite fission-track data from the central Nepal Himalaya, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

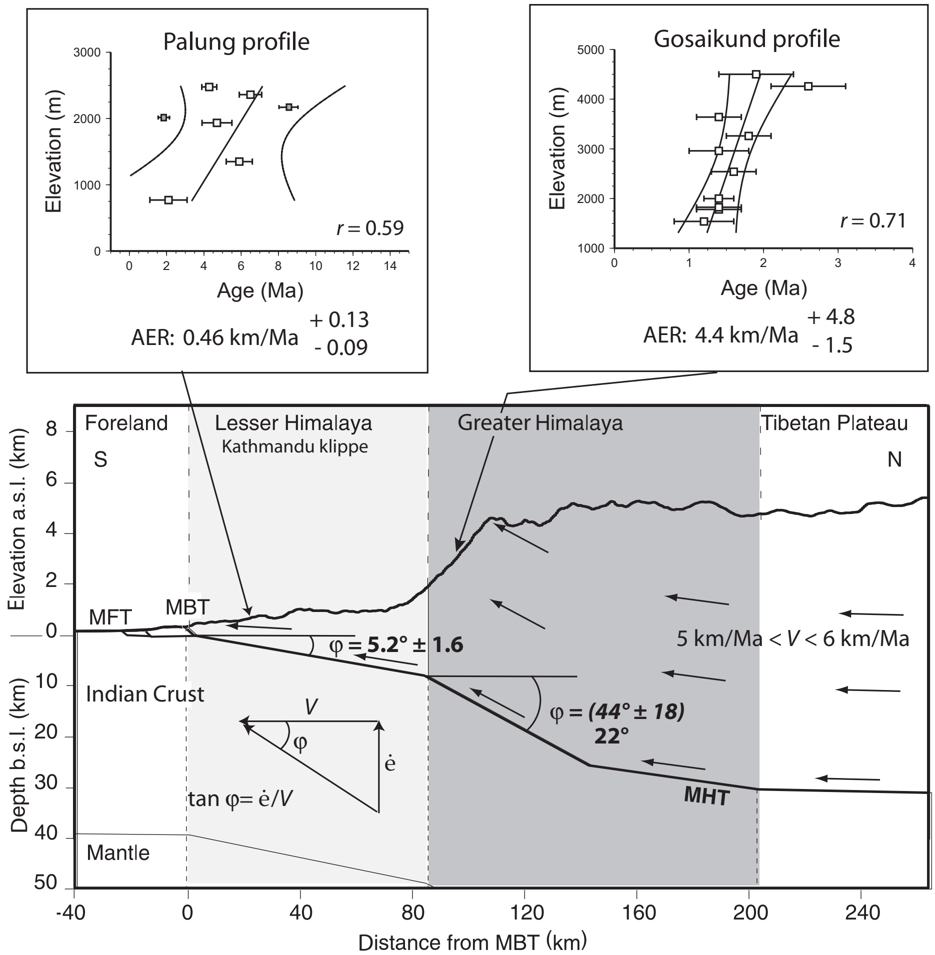

Figure 3. Palung and Gosaikund age-elevation profiles. Straight line is weighted linear regression; envelopes show 95% confidence limits on age-elevation relationship (gray data points in Palung profile were excluded from regression); *r*—Pearson correlation coefficient; AER—apparent exhumation rate. Lower plot shows kinematic context and determination of detachment dip φ: *V* is overthrusting velocity and *ė* is exhumation rate (b.s.l.—below sea level; a.—above; acronyms as in Fig. 1). Value for ramp dip in parentheses takes apparent exhumation rate from Gosaikund profile without correcting for topographic effects.

the Palung granite suggests a detachment dip below the Lesser Himalaya and Kathmandu klippe of 5.2° ± 1.6°, in good agreement with earlier estimates from elastic dislocation modeling of the present-day displacement field (Larson et al., 1999; Berger et al., 2004). The exhumation rate of 4.4 +4.8/–1.5 km/Ma from the Gosaikund profile would imply a ramp angle of 44° ± 18°, only just overlapping with the highest estimates from geophysical and geodetic data (Avouac, 2003; Berger et al., 2004). However, when taking topographic perturbation into account, the exhumation rate recorded by the Gosaikund profile is compatible with a ramp angle of ~22°, within the range (15°–30°) of ramp angles favored by geophysical and geodetic data. We thus conclude that the spatial pattern of thermochronologic ages and inferred exhumation rates do not require out-of-sequence thrusting in the MCT zone, but can be explained by a model of overthrusting on a crustal ramp.

NUMERICAL MODEL

The topographic perturbation taken into account in the above analysis assumes vertical exhumation, whereas the geometric model we use implies highly oblique particle trajectories, which may strongly affect inferred exhumation rates from age-elevation profiles (e.g., Huntington et al., 2007). Although the effect should be limited in the Palung profile because of relatively low exhumation rates and limited relief, and in the Gosaikund profile because it was sampled orthogonal to the tectonic transport direction (Huntington et al., 2007), we employ a numerical model to study the relationship between structure, kinematics, and exhumation rate more quantitatively.

We use a modified version of Pecube (Braun, 2003), a finite-element code that predicts the thermal structure in a crustal block affected by vertical and/or horizontal advection. New features in the code include the incorporation of fault-controlled kinematics, using the approach of Braun et al. (1994). We predict AFT ages by combining predicted cooling paths of rocks currently at the surface and a forward annealing model (Stephenson et al., 2006), assuming steady-state topography for the models presented here. Thermal parameters are chosen to fix a stable geothermal gradient of 32 °C km^{-1} (cf. Table DR2 in the Data Repository). The input geometry for the numerical model is based on the crustal-scale cross section of Avouac (2003; Fig. 3). The model is run for 10 Ma; the MBT is active from 10 to 3 Ma ago and the MFT from 3 Ma ago to the present. The overthrusting and underthrusting velocities on the MHT are 6 and 15 km/Ma, respectively (Fig. 4).

The model predicts a region of very young (younger than 2 Ma old) AFT ages overlying the MHT ramp (Fig. 4), where the vertical component of motion reaches 2.2 km/Ma. Ages increase both to the north and the south of this zone, reaching non-reset zones at both edges of the model. Model exhumation rates above the southern flat are 0.5 km/Ma. The AFT ages predicted by the model compare very favorably with observed ages, reproducing both the spatial pattern in a north-south transect across the central Himalaya and the two age-elevation profiles.

CONCLUSIONS

An AFT-age transect through central Nepal shows a continuous younging trend from the Lesser Himalaya through the topographic transition and the MCT zone, and therefore no evidence for out-of-sequence thrusting in the latter area. Two age-elevation profiles, one from the zone of high relief above the MHT ramp and the other from the Kathmandu klippe above the southern flat of the MHT, show apparent exhumation rates that vary by an order of magnitude. However, when taking topographic perturbation of isotherms into account, these exhumation rates are consistent with overthrusting at a rate of 5–6 km/Ma over an ~22° dipping crustal ramp and an ~5° detachment, respectively, in accord with independent geophysical and geodetic data defining the geometry of the MHT. A numerical thermokinematic model shows that both the spatial pattern of AFT ages and the age-elevation relationships are well fitted by such a scenario. Therefore, the new thermochronologic data, collected with the specific objective to test the various kinematic models proposed for the central Nepal Himalaya, do not require out-of-sequence reactivation of a thrust in the MCT zone.

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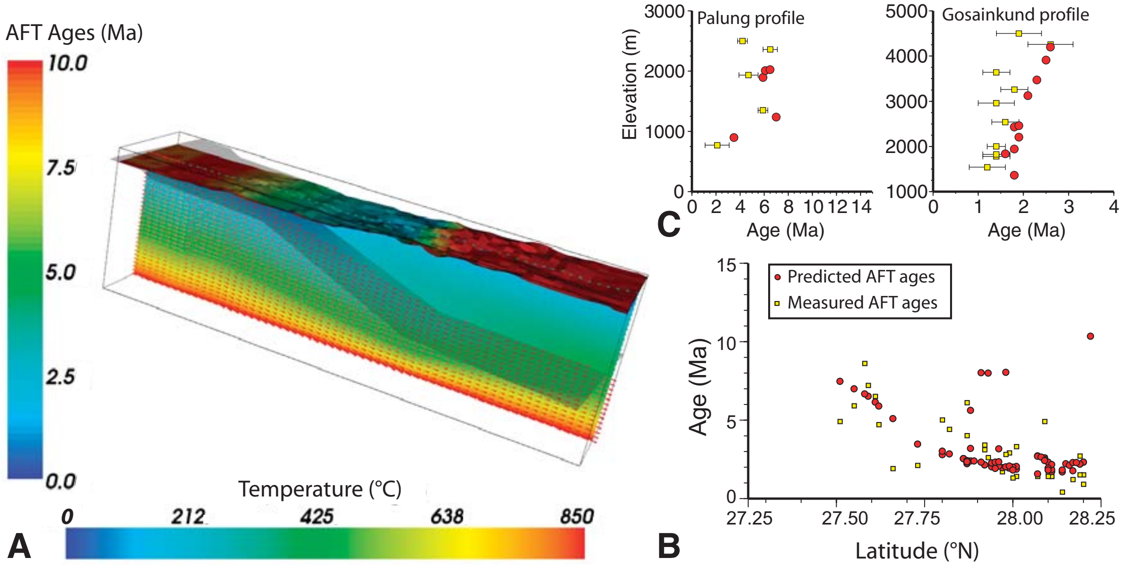

Figure 4. A: Forward-model geometry showing model Main Himalayan thrust, kinematics, predicted thermal structure, and thermochronological age pattern at surface. B: Comparison between measured and predicted apatite fission-track (AFT) ages, plotted as function of latitude. C: Comparison between observed and predicted age-elevation relationships for Palung and Gosaikund profiles.

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