Assessing Quaternary reactivation of the Main Central Thrust zone (central Nepal Himalaya): New thermochronologic data and numerical modeling

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To be submitted to Geology

ABSTRACT

We study the recent dynamics of the Himalayan orogen in central Nepal with the goal of quantifying the onset of activity and the deformation history recorded by the different major thrusts. Here, we focus on the possible reactivation of the footwall of the MCT, which is marked by a strong topographic transition. Different tectonic mechanisms, such as out-of-sequence thrusting or underplating over a major crustal ramp, have been suggested to explain the morphology and exhumation patterns in this area. We present 25 new apatite fission-track (AFT) ages collected in central Nepal.
along a north–south transect from the Langtang Himal to the active deformation front, as well as two age-elevation profiles. Ages are consistently < 3 Ma in the MCT zone and increase continuously in age to 4 - 6 Ma in the south. The topographic transition does not correspond to a sharp jump in AFT ages. Apparent exhumation rates from the age-elevation relationships vary from $4.4^{+1.5}_{-1.5}$ km.My$^{-1}$ in the Palung granite south of Kathmandu to $8.4^{+4.8}_{-5.1}$ km.My$^{-1}$ in the MCT zone, although 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 a model of overthrusting over a crustal ramp, which exerts a primary control on age patterns, and do not require out-of-sequence reactivation of thrusts in the MCT zone.

**Keywords:** Himalaya, Nepal, Main Central Thrust, Tectonics, Thermochronology, Numerical modeling.

**INTRODUCTION**

The Himalayan orogen is characterized by a north-dipping, southward-propagating, crustal-scale thrust sequence (Fig. 1). Major thrusts delimit three distinct units that are, from south to north: the Siwaliks foreland 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); the Greater Himalayan crystalline thrust sheet with overlying Tethyan sediments (Gansser, 1964; Le Fort, 1975). Geophysical and structural studies suggest that all major faults in the central Himalaya, including the MFT, MBT and MCT, branch at depth to a single major mid-crustal decollement, the Main Himalayan Thrust (MHT; Hirn and Sapin, 1984; Zhao et al., 1993; Makovsky et al., 1996; Schulte-Pelkum et al.,
The MHT is characterized by a ramp-flat geometry, probably with two major ramps. One is shallow and corresponds to where the fault emerges with a dip angle of around 30° at the surface (MFT). The other is envisaged at mid-crustal depth beneath the sharp topographic front of the high range with a dip angle to the north of about 15-30° (Avouac, 2003; Berger et al., 2004). Ten to thirty kilometres south of the MCT in central Nepal, a sharp topographic transition separates a northern high-relief zone at a mean elevation >3000 m and a southern zone of more moderate relief at a mean elevation <1500 m (Lavé and Avouac, 2001; Duncan et al., 2003; Wobus et al., 2003).

Recently, two competing models have been proposed to describe the present-day kinematics of the Central Nepal Himalaya (Fig. 1). These differ principally 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) argue 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, Hodges et al. (2004) suggest active out-of-sequence thrusting in the MCT zone, possibly driven by climatically-controlled and strongly localized exhumation in this area. A jump in detrital thermochronologic and cosmogenic ages across the topographic transition in central Nepal has been argued to support the latter model (Wobus et al., 2005; 2006).

The opposing models predict different upper-crustal exhumation paths for rocks in the Lesser Himalaya and the topographic transition zone, which should be recorded by low- and medium-temperature thermochronometers such as apatite fission-track (AFT) and mica Ar-Ar data (Fig. 1). In particular, the out-of-sequence model predicts a jump in ages in the MCT zone (Hodges et al., 2004; Wobus et al., 2006), whereas the underplating model would predict 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, little thermochronologic data has been collected until recently in the Lesser Himalaya, precluding a clear discrimination between the two models. Here, we present new apatite fission-track data from a transect across the central Nepal Himalaya 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 a main target for our sampling. In the half-window of Lesser Himalayan sequences to the northwest of the Kathmandu klippe, we targeted quartzites and sandstones of the Lower Nawakot Group as well as the Ulleri gneiss (Upreti, 1999) for sampling. Two age-elevation profiles were collected; one within the topographic transition zone from the Trisuli River valley at Dunche up Gosainkund mountain, with sample elevations spanning 1780-4500 m; another in the Palung granite between 770 and 2500 m elevation.

Details on sample processing and the data reported in this paper are provided in the Data Repository*. 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 at low elevations in the Palung granite south of Kathmandu). The northernmost samples from the MCT zone are consistently very young (<3 Ma) and comparable to data collected from further west (Blythe et al., 2007). This trend crosses the topographic transition and the MCT zone

* A data repository item, Apatite fission-track data from the central Nepal Himalaya, is submitted with this manuscript
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 as the AFT data reported here, show the same pattern (Fig. 2).

The two age-elevation profiles are shown in Fig. 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.My$^{-1}$. In contrast, ages from the Gosainkund profile only vary between 1.2±0.4 and 2.6±0.5 Ma, suggesting an exhumation rate an order of magnitude higher, at $4.4^{+4.8}_{-1.5}$ km.My$^{-1}$. However, at such high rates of exhumation, topographic disturbance of the closure isotherm may lead to seriously overestimating exhumation rates from age-elevation relationships (Stüwe et al., 1994; Manktelow and Grasemann, 1997; Braun, 2002; Ehlers, 2005). This overestimate can be quantified as (Braun, 2002):

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

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

We have estimated $\alpha$ for the AFT closure isotherm of 110±10 °C using both the methods of Stüwe et al.(1994) and Manktelow and Grasemann (1997; cf. Braun et al., 2006 for a review), using topographic wavelengths (~30 km) and amplitudes (~3 km) that characterize the Gosainkund (Langtang Himal) sampling area. In both cases, we find that $\alpha \approx 0.5$, so that we should expect to overestimate exhumation rates by approximately 100%; “real” exhumation rates for the Gosainkund profile are thus probably in the order of 2.0-2.5 km.My$^{-1}$. 

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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. We assume a ramp and flat geometry for the MHT and estimate the angles of the flat and ramp that are required to explain these differences. Previous thermo-kinematic 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.My$^{-1}$ convergence rate accommodated by the central Himalaya (Lavé and Avouac, 2000; Mugnier et al., 2004) should be partitioned into 5-6 km.My$^{-1}$ of Himalayan overthrusting over the MHT and ~15 km.My$^{-1}$ of underthrusting of the Indian plate (see also Robert et al., submitted). The rate of overthrusting ($v$) can be simply linked to the exhumation rate through the detachment angle ($\phi$): $\tan \phi = \dot{e} / v$ (Fig. 3). Applying this approach to the exhumation rate inferred for 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 modelling of the present-day displacement field (Larson et al., 1999; Berger et al., 2004). When taking the exhumation rate of $4.4^{+4.8}_{-3.5}$ km.My$^{-1}$ from the Gosainkund profile at face value, this 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 into account their probable 100% overestimation, the exhumation rate recorded by the Gosainkund profile is compatible with a ramp angle of ~22°, exactly within the range (15-30°) of allowable ramp angles from the 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 Gosainkund profile because it was sampled orthogonal to the tectonic transport direction (Huntington et al., 2007), we use 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 faults and associated kinematics, assuming vertical shear. Thermochronological ages are predicted by combining predicted cooling paths of rocks currently at the surface and a forward model of AFT annealing (Stephenson et al., 2006), assuming steady-state topography for the models presented here. Thermal parameters are described in Table 1. The input geometry for the numerical model is based on the crustal-scale cross-section proposed by Avouac (2003; Fig. 3). The model is run for 10 My in order to predict AFT ages up to this age. The MBT is active from 10 to 3 Ma and the MFT from 3 Ma to the present. The total overthrusting and underthrusting velocity on the MHT are 6 km.My$^{-1}$ and 15 km.My$^{-1}$ respectively (Fig. 4).

The model predicts a region of very young (<2 Ma) AFT ages overlying the MHT ramp (Fig. 4), where the vertical component of motion reaches 2.2 km.My$^{-1}$. Ages increase both to the north and the south of this zone, until reaching non-reset zones at both edges of the model.
Model exhumation rates above the southern flat are 0.5 km. My\(^{-1}\). The AFT ages predicted by the model compare very favorably with observed ages, both when comparing the spatial pattern in a north-south transect across the central Himalaya, and when comparing 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 direct evidence for out-of-sequence thrusting in the latter area. Two age-elevation profiles, one from the topographic transition 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 constant rate of 5-6 km. My\(^{-1}\) over a ~20° dipping crustal ramp and a ~5° detachment respectively, in accord with independent geophysical and geodetic data constraining the geometry of the MHT. A numerical thermo-kinematic 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 dataset that we sampled throughout the Lesser Himalaya 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. This does not, however, mean that they are incompatible with it. In a separate contribution, we will use a formal inversion approach together with our numerical model in order to address this question further.
ACKNOWLEDGEMENTS

We thank Rodolphe Cattin, Frédéric Hermann and Jean-Philippe Avouac for helpful discussions and ideas. This study was supported by the Institut National des Sciences de l’Univers through the Reliefs de la Terre programme. We thank Ananta Gajurel of Tribuvhan University, Kathmandu, for assistance during field work.

REFERENCES CITED


**TABLE AND FIGURE CAPTIONS**

**Table 1.** Thermal parameters assumed for the numerical model. These values lead to a 32 °C.km$^{-1}$ stable geothermal gradient.

**Figure 1.** Two schematic scenarios suggested for the central Himalaya (modified from Hodges et al., 2004) with the expected thermochronological age trends. A: In the model of Avouac (2003), shortening is concentrated on the Main Himalayan Thrust (MHT), which includes a crustal ramp below the High Himalaya. Expected high- and low-temperature thermochronologic age trends should show continuous younging toward the MCT zone and the topographic transition. B: In the model of Hodges and co-workers (e.g., Hodges et al., 2004), out-of-sequence faulting occurs in the MCT zone. Both high- and low-temperature thermochronologic age trends should present a jump at the topographic transition / the MCT zone.

**Figure 2.** A: Location of samples collected along a north-south transect along the Trisuli River and across the Mahabarat Range, from the Langtang Himal to the Ganga plain in Central Nepal. Apatite fission-track (AFT) ages 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 a function of latitude. The
relationship to the major structures of the central Himalaya is indicated by the crustal-scale cross-section (modified from Bollinger et al., 2004).

**Figure 3.** Palung and Gosainkund age-elevation profiles placed in their kinematic context. Straight line is weighted linear regression using the method of Williamson (1968); envelopes show 95% confidence limits on age-elevation relationship. AER: apparent exhumation rate. Lower plot shows inferred kinematics and how we determine detachment slope from these data; \( v \) is the overthrusting velocity, \( \phi \) the detachment angle (\( \eta \) for the frontal flat; \( \theta \) for the ramp) and \( \varepsilon \) the erosion rate. Value for ramp dip in parentheses takes the apparent exhumation rate from the Gosainkund profile without correcting for topographic effects.

**Figure 4.** (A) Forward-model geometry showing the modeled MHT, model kinematics and predicted thermal structure and thermochronological age pattern at the surface. B: Comparison between measured and predicted AFT ages, plotted as a function of latitude. C: comparison between observed and predicted age-elevation relationships for the Palung and the Gosainkund profiles.
<table>
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<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Basal temperature</td>
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<td>Thermal diffusivity</td>
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<td>Temperature at z = 0</td>
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<tr>
<td>Atmospheric lapse rate</td>
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Fig. 4. *Robert et al.* Geology.