Denudation history of the Eastern Nepalese Himalaya constrained by thermochronological methods

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Abstract

The thermochronological method was applied to metamorphic rocks distributed in eastern Nepal to elucidate the denudation process of the upper-crust of the continental collision zone. New results of systematic fission-track (FT) age dating and FT length measurements of zircon and apatite were utilized in the thermochronological inverse analysis to reconstruct the time-temperature (t-T) paths in the temperature range of 60–350°C. Eight t-T paths obtained along the across-strike section in eastern Nepal showed that the cooling process of the metamorphic rocks are characterized by 1) gradual cooling (<30°C/Myr) followed by rapid cooling (˜150°C/Myr) and subsequent gradual cooling (gradual-rapid-gradual cooling: GRG cooling), 2) northward-younging of the timing of the rapid cooling since ca. 9 Ma. The observed FT ages and t-T paths were then compared with the FT ages and t-T paths obtained by forward calculations using 3-D thermokinematic models to test the following four tectono-thermal models which have been proposed in the Central and Eastern Himalayas: 1) The denudation of the upper-crust is associated with the movement of the plate boundary fault (Main Himalayan Thrust: MHT) showing flat geometry (the Flat MHT model) and 2) flat-ramp-flat geometry (the Flat-Ramp-Flat MHT model), 3) the denudation of the upper-crust is mainly controlled by the focused uplift associated with the growth of the Lesser Himalayan Duplex (the Duplex 01-03 model) or 4) slip of the splay fault of the MHT (the Splay Fault model). As a result, only the Flat-Ramp-Flat MHT model reconstructed similar t-T paths and age distribution patterns obtained from eastern Nepal. This suggests that the observed FT ages and t-T paths reflect a denudation process driven by the movement of the MHT showing a flat-ramp-flat geometry. The GRG cooling and the northward-younging of the timing of rapid cooling indicate that the flat-ramp-flat geometry of the MHT was established by ca. 9 Ma and has been stable thereafter. The result of the thermokinematic inverse analysis also indicates that the denudation rate and its spatial distribution have been stable since ca. 9 Ma.

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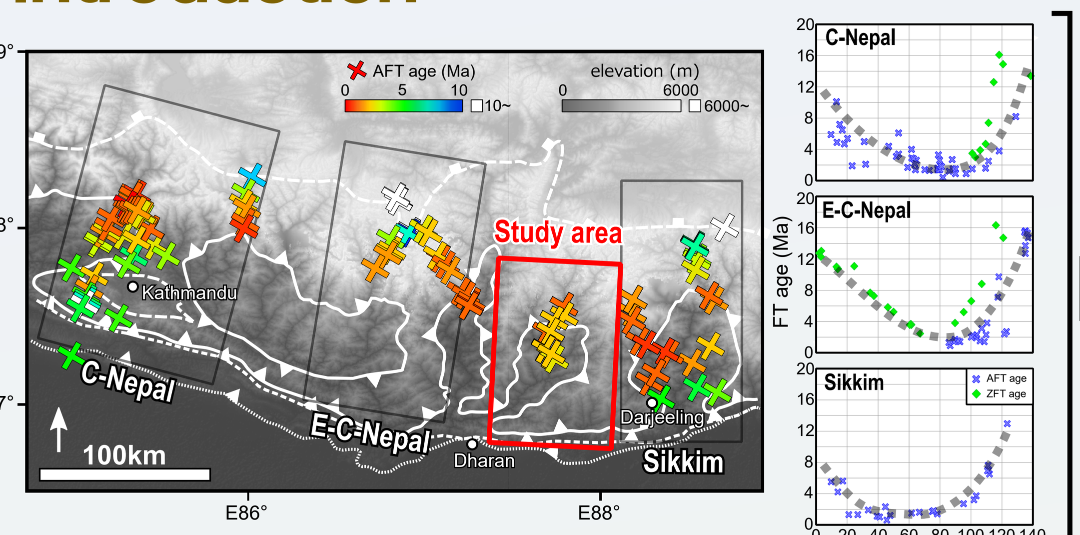
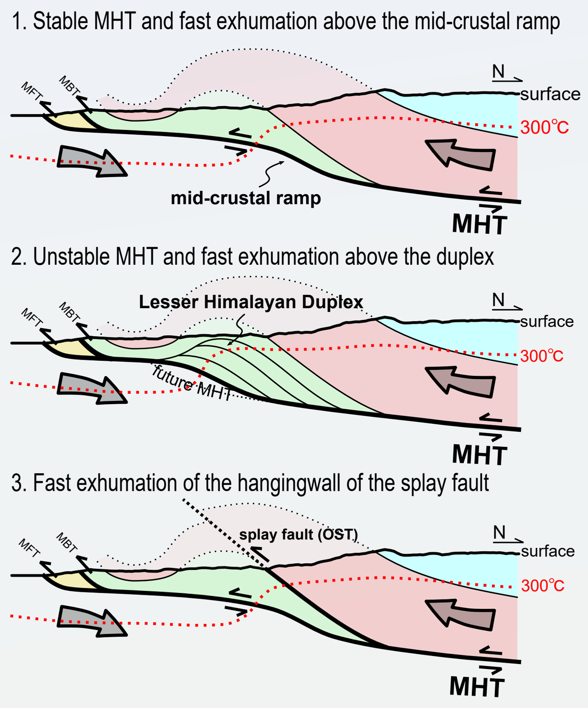
Introduction



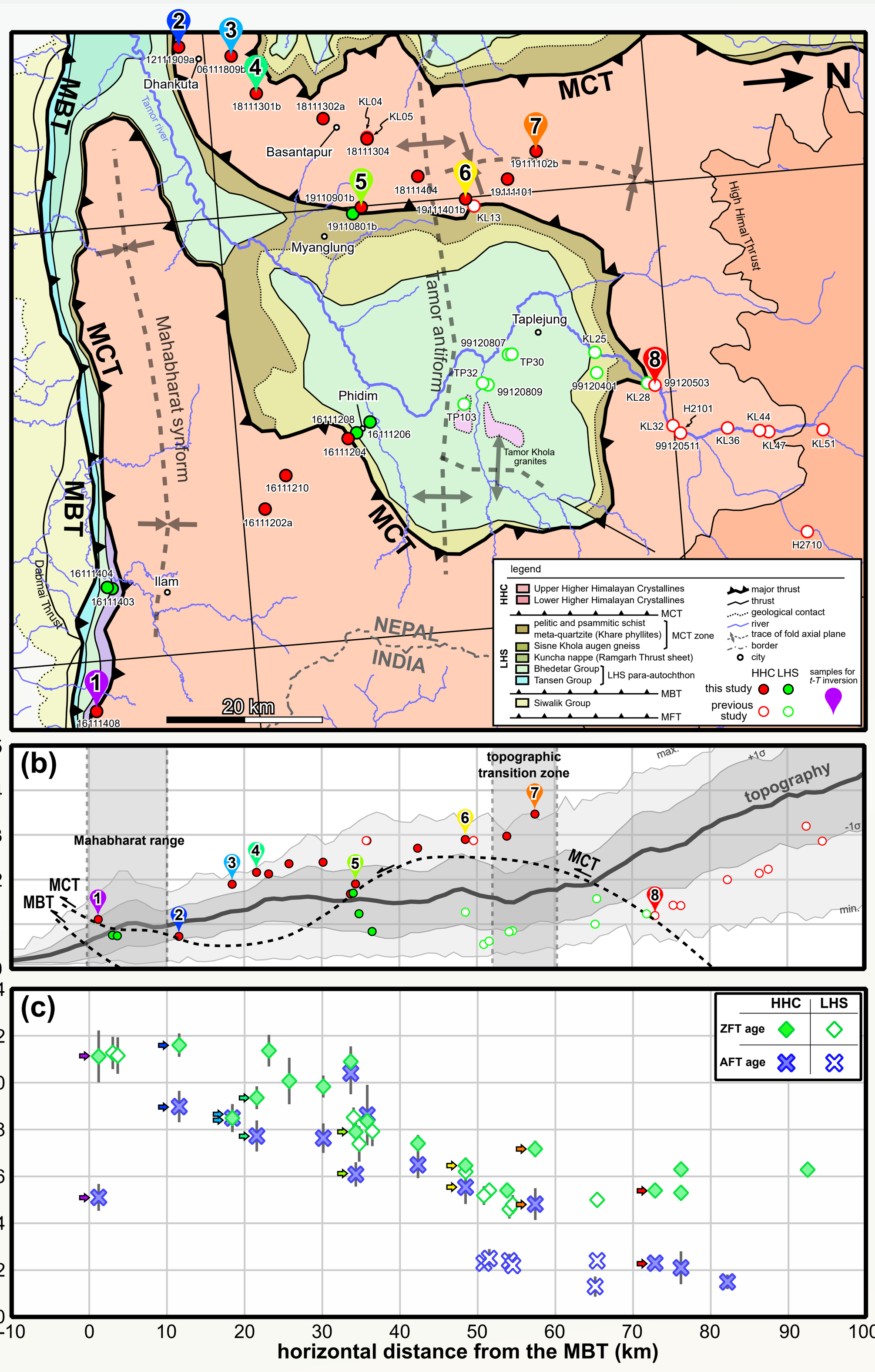
The DEM image of the Central and Eastern Himalayas, with the published AFT ages (central Nepal - Herman et al., 2010; Robert et al., 2009; Wang et al., 2010: eastern-central Nepal - Carrapa et al., 2016; Nakajima et al., 2020b; Sakai et al., 2005; Streule et al., 2012: eastern Nepal - Larson et al. 2017; Sakai et al. 2013a: Sikkim - Landry et al., 2016).



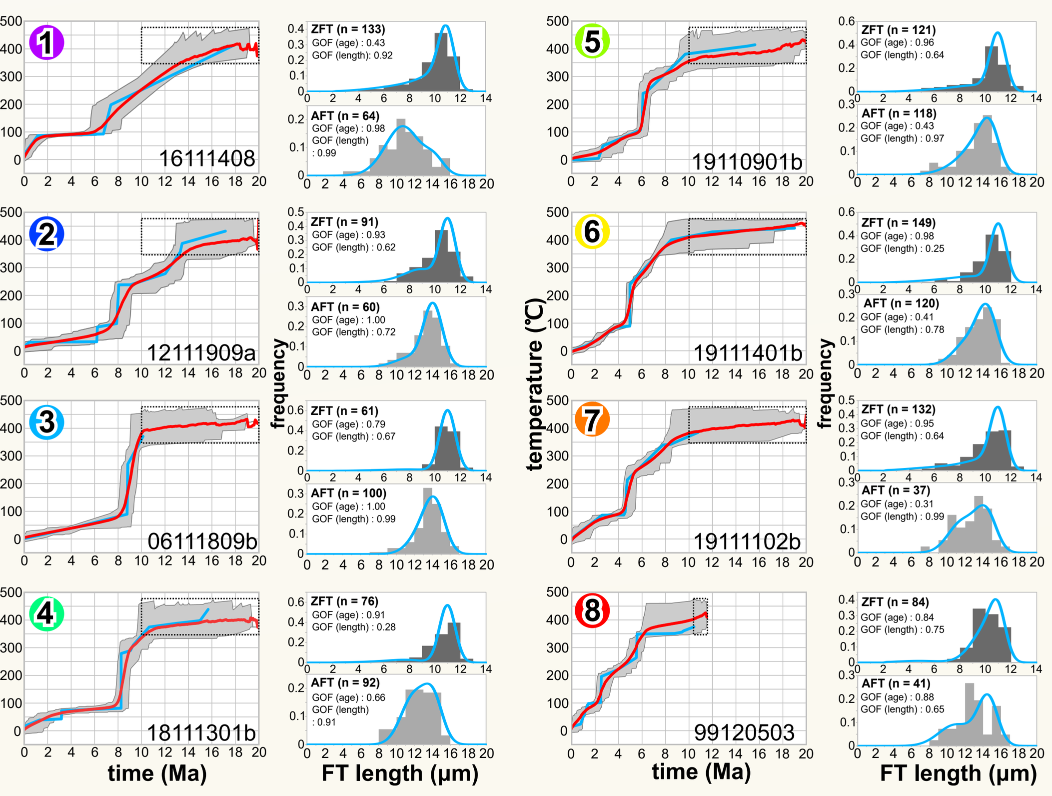
The Himalayas are the modern example of orogen associated with a continental collision and have been the subject of many studies as a natural laboratory to understand the continental collision processes. A number of thermochronological studies have been carried out to understand the denudation process and suggested that ongoing crustal denudation are accompanied by deformations accommodated in the plate boundary fault (**Main Himalayan Thrust: MHT**). Thermochronological studies have focused on the distribution of the cooling age along an elevation profile (e.g., Blythe et al., 2007) or an across-strike section (e.g., Robert et al., 2009) to understand the interaction between the tectonics and cooling process. However, in spite of a substantial amount of thermochronological age data-set, different tectono-thermal models have been proposed to account for the same data-set, and there is little consensus on a tectonic process that primarily drove the denudation. This situation shows the limitation of the studies based solely on the thermochronological ages and their distribution patterns. Evaluation of the tectonic models by another approach with high-temporal resolution is required.

Here, we applied **the ZFT-AFT joint-inversion method** to improve the temporal resolution of the thermal history reproduced. We also performed **the forward and inverse modelings of the FT ages and thermal history** using a thermokinematic model in order to discuss the interaction between the tectonics and cooling processes.

Fission-Track data and time-temperature paths



The geotectonic map, topographic transect (modified after Sakai et al., 2013a, Schelling and Arita, 1991, and the unpublished report by Department of Minerals and Geology, Government of Nepal), and the across-strike distribution of the ZFT and AFT ages (this study; Larson et al., 2017; Sakai et al.,2013a) in eastern Nepal. Sample localities of these dated samples are projected perpendicularly onto the N5°E line. Arrows denote the FT ages used for thermochronological inverse analysis.



Results of thermochronological inverse analysis showing t-T paths. The solid sky-blue lines represent the best-fit path, and the solid red line indicates the weighted mean path. The gray fields represent the "good" path ($p > 0.5$) envelopes. The dotted rectangles represent initial condition. The histograms of the ZFT and AFT lengths are shown in each row.

Geology of the study area

The Himalayas are generally divided into four geotectonic units: the Tibetan Tethys sediments (TTS), the Higher Himalayan Crystallines (HHC), the Lesser Himalayan sediments (LHS), and the sub-Himalayas. These geotectonic units are separated by four north-dipping large-scale shear zones: from the north to the south, they are the South Tibetan Detachment (STD), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT), and the Main Frontal Thrust (MFT).

The **HHC** composed of high-grade metamorphic rocks and the **LHS** composed of low- to medium-grade metasediments are distributed in the Lesser Himalaya in eastern Nepal. The HHC overthrusts above the LHS to form a large nappe. Rock samples were collected from the HHC nappe and the LHS along the N-S section.

Fission-Track ages

A total of 17 ZFT and 10 AFT ages were newly obtained from the HHC and LHS in eastern Nepal. ZFT ages from the HHC and the underlying LHS ranged from 5.4 ± 0.3 Ma to 11.4 ± 0.7 Ma and showed the northward-younging distribution from the frontmost part to the root part of the HHC. On the other hand, AFT ages did not exhibit the northward-younging along the across-strike section due to a young apatite FT age (5.1 ± 0.6 Ma) obtained from the frontmost part of the HHC nappe.

The ZFT and AFT age distributions along the across-strike section of this study are in good agreement with published age distribution patterns in other regions (Coutand et al., 2014; Nakajima et al., 2020a,b; Robert et al., 2009).

Time-temperature (t-T) paths

The ZFT-AFT joint-inversion was performed using the computer program HeFTy version 1.9.3 (Ketcham, 2005). The fanning curvilinear models (ZFT: Ketcham, 2019; AFT: Ketcham et al., 2007) were adopted in the FT age and FT length forward calculation.

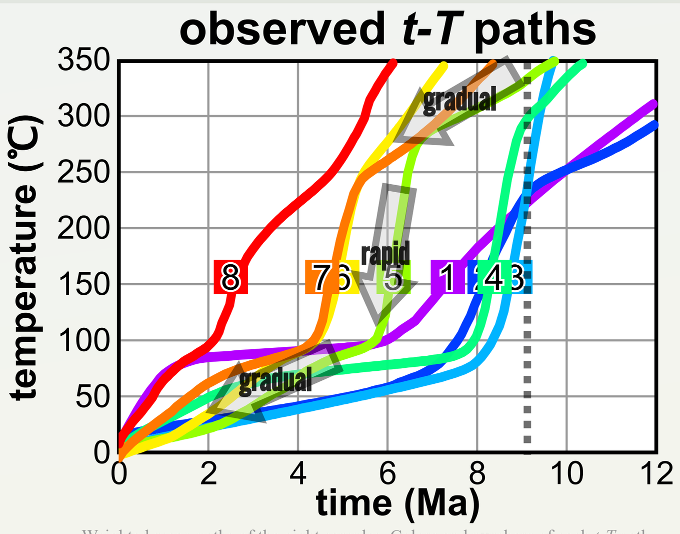
Eight t-T paths newly obtained from the HHC nappe revealed that the cooling process of the HHC nappe was characterized by the following three aspects:

1) gradual cooling (250–350℃) followed by rapid cooling to a temperature below 100℃ and subsequent gradual cooling (gradual-rapid-gradual cooling: GRG cooling)
2) northward-younging of the timing of the rapid cooling (since ca. 9 Ma)
3) gradual cooling followed by Quaternary rapid cooling in the frontmost part

Thermokinematic modeling

In order to interpret the FT ages and t-T paths observed in eastern Nepal () in the context of the denudation process, a 3-D thermokinematic modeling was performed. Forward calculations of t-T paths were carried out using the modified version of the finite element code of PECUBE version 4. 2. 0 (Braun, 2003; Braun et al., 2012).

Following three thermokinematic models were designed to test the published three tectono-thermal models proposed in the Central and Eastern Himalayas. The result of the forward modeling revealed that a relatively simple tectono-thermal process could explain the t-T paths observed in eastern Nepal.

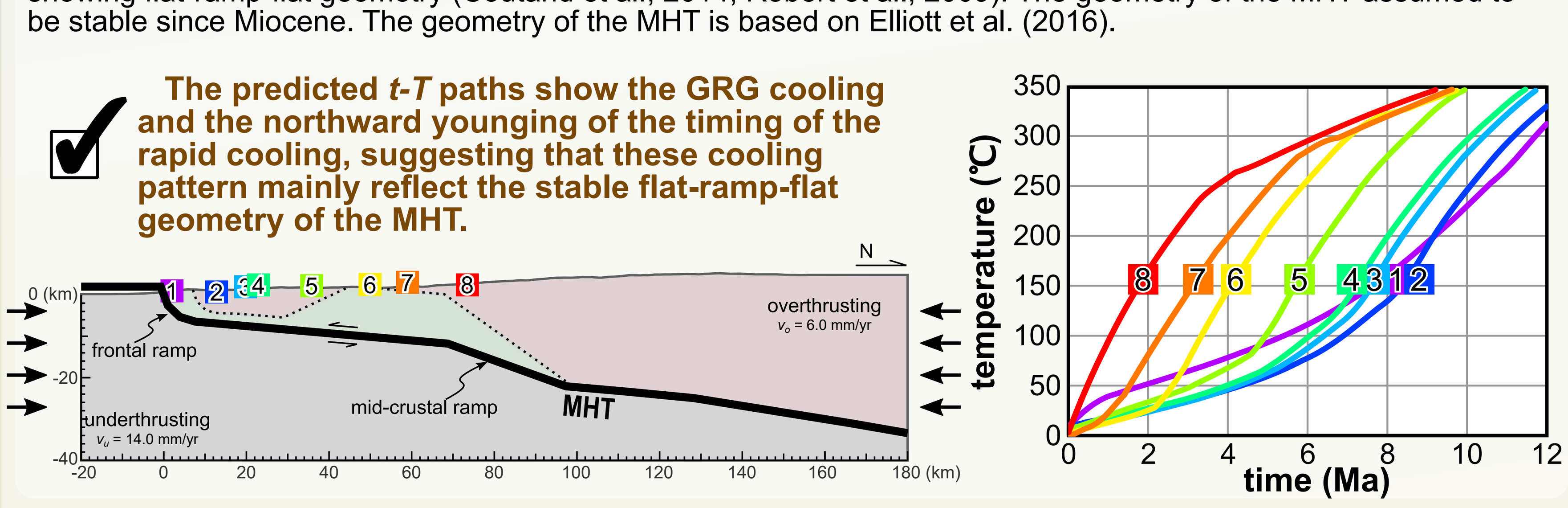


Weighted mean paths of the eight samples. Colors and numbers of each t-T path correspond to those of the location pins 1-8 shown in geological map. The GRG cooling and northward younging started at ca. 9 Ma.

1. Stable MHT and fast exhumation above the mid-crustal ramp

In this model, the HHC and the underlying LHS are denudated, accompanied by the movement of the MHT showing flat-ramp-flat geometry (Coutand et al., 2014; Robert et al., 2009). The geometry of the MHT assumed to be stable since Miocene. The geometry of the MHT is based on Elliott et al. (2016).

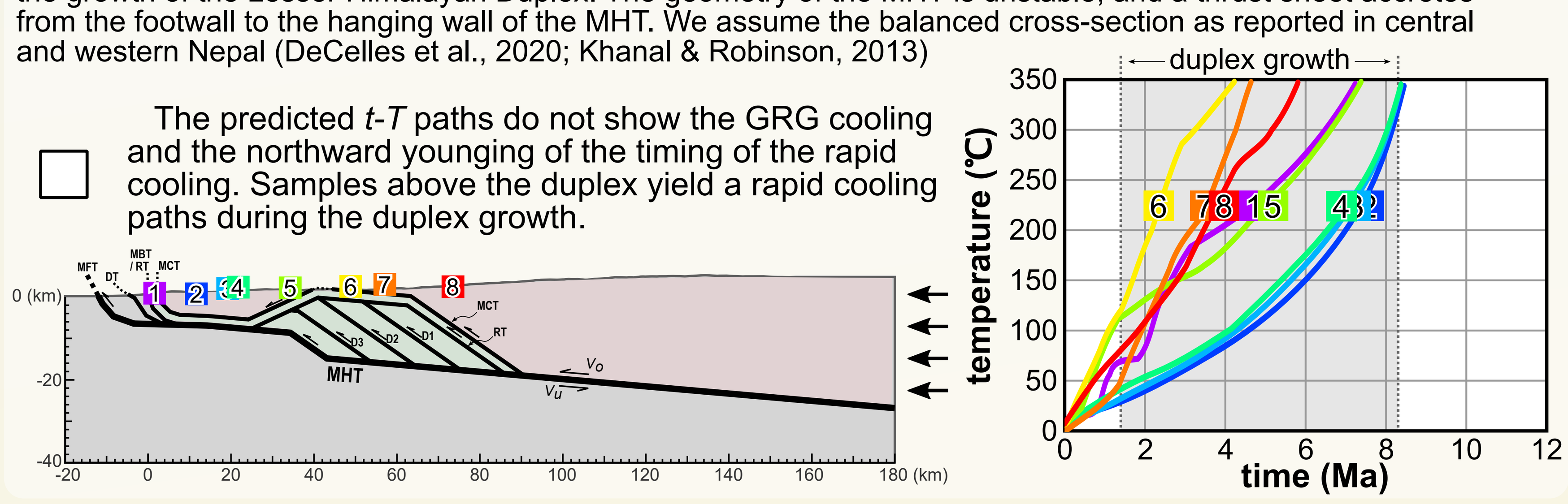
☑ **The predicted t-T paths show the GRG cooling and the northward younging of the timing of the rapid cooling, suggesting that these cooling pattern mainly reflect the stable flat-ramp-flat geometry of the MHT.**



2. Unstable MHT and fast exhumation above the duplex

The denudation of the HHC and the underlying LHS are mainly controlled by the focused uplift associated with the growth of the Lesser Himalayan Duplex. The geometry of the MHT is unstable, and a thrust sheet accretes from the footwall to the hanging wall of the MHT. We assume the balanced cross-section as reported in central and western Nepal (DeCelles et al., 2020; Khanal & Robinson, 2013)

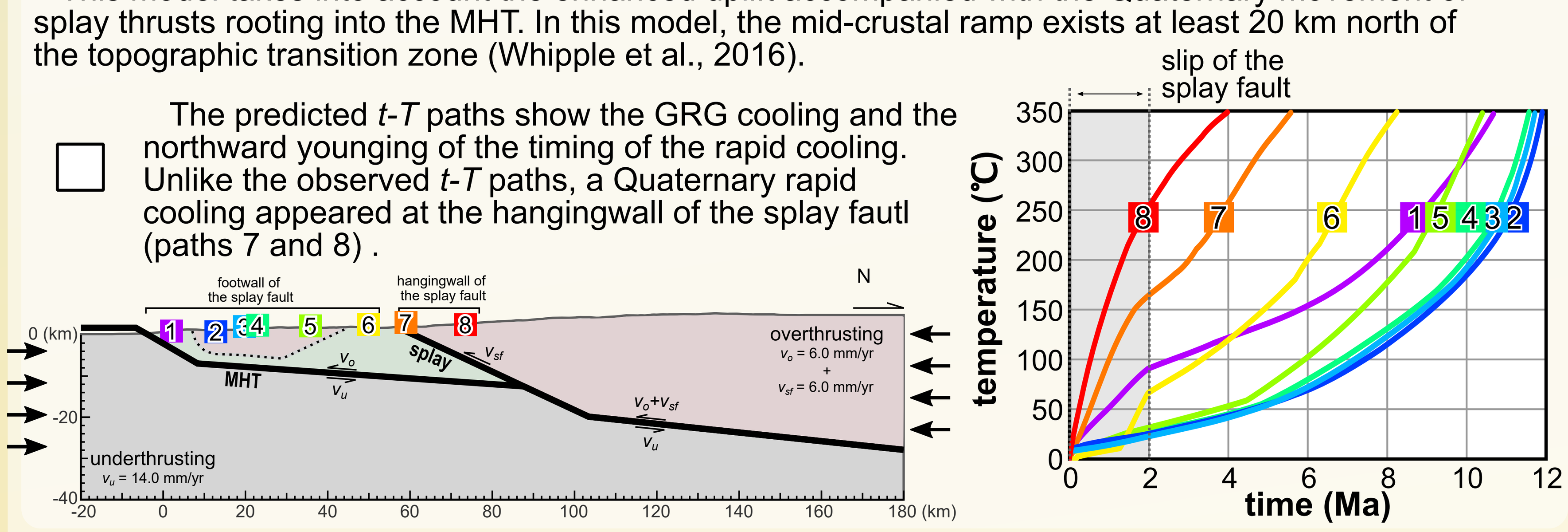
☐ The predicted t-T paths do not show the GRG cooling and the northward younging of the timing of the rapid cooling. Samples above the duplex yield a rapid cooling paths during the duplex growth.



3. Fast exhumation of the hangingwall of the splay fault

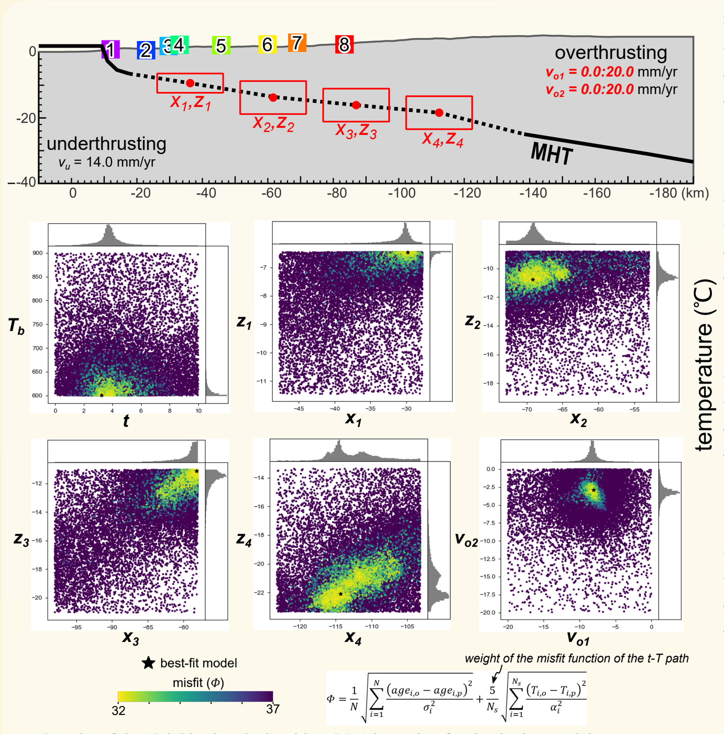
This model takes into account the enhanced uplift accompanied with the Quaternary movement of splay thrusts rooting into the MHT. In this model, the mid-crustal ramp exists at least 20 km north of the topographic transition zone (Whipple et al., 2016).

☐ The predicted t-T paths show the GRG cooling and the northward younging of the timing of the rapid cooling. Unlike the observed t-T paths, a Quaternary rapid cooling appeared at the hangingwall of the splay fautl (paths 7 and 8) .



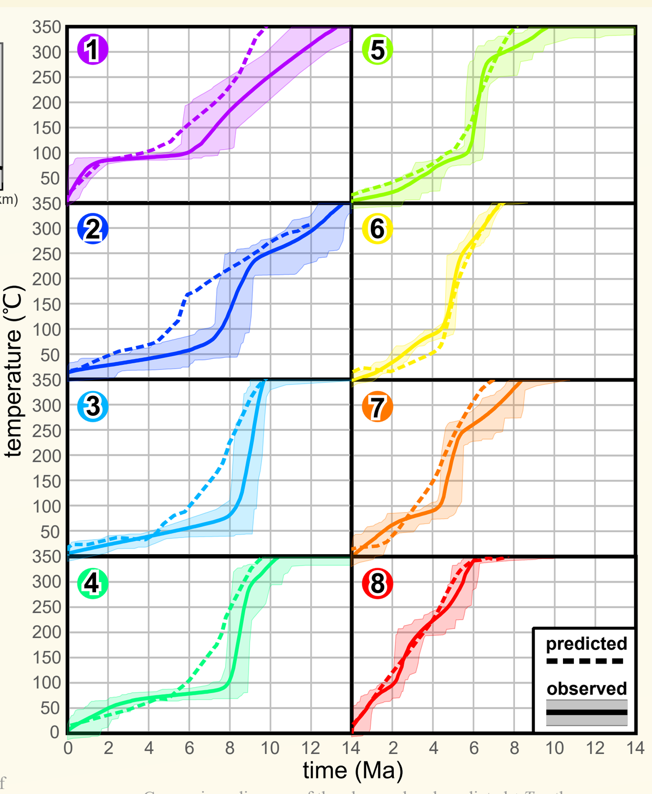
Thermokinematic inverse modeling

Based on the results of the forward modeling, we invert the observed FT ages and t-T paths using a thermokinematic model with a constant MHT geometry. The shape of the MHT (x_{1-4}, z_{1-4}), the transition period of the displacement velocity (t) , the overthrusting velocity ($v_{o1,2}$), and the temperature at the base of the model (T_b) were set as free parameters. Inverse analysis was performed by the NA algorithm, and the mean of the posterior distribution was determined by sampling 51,000 times.

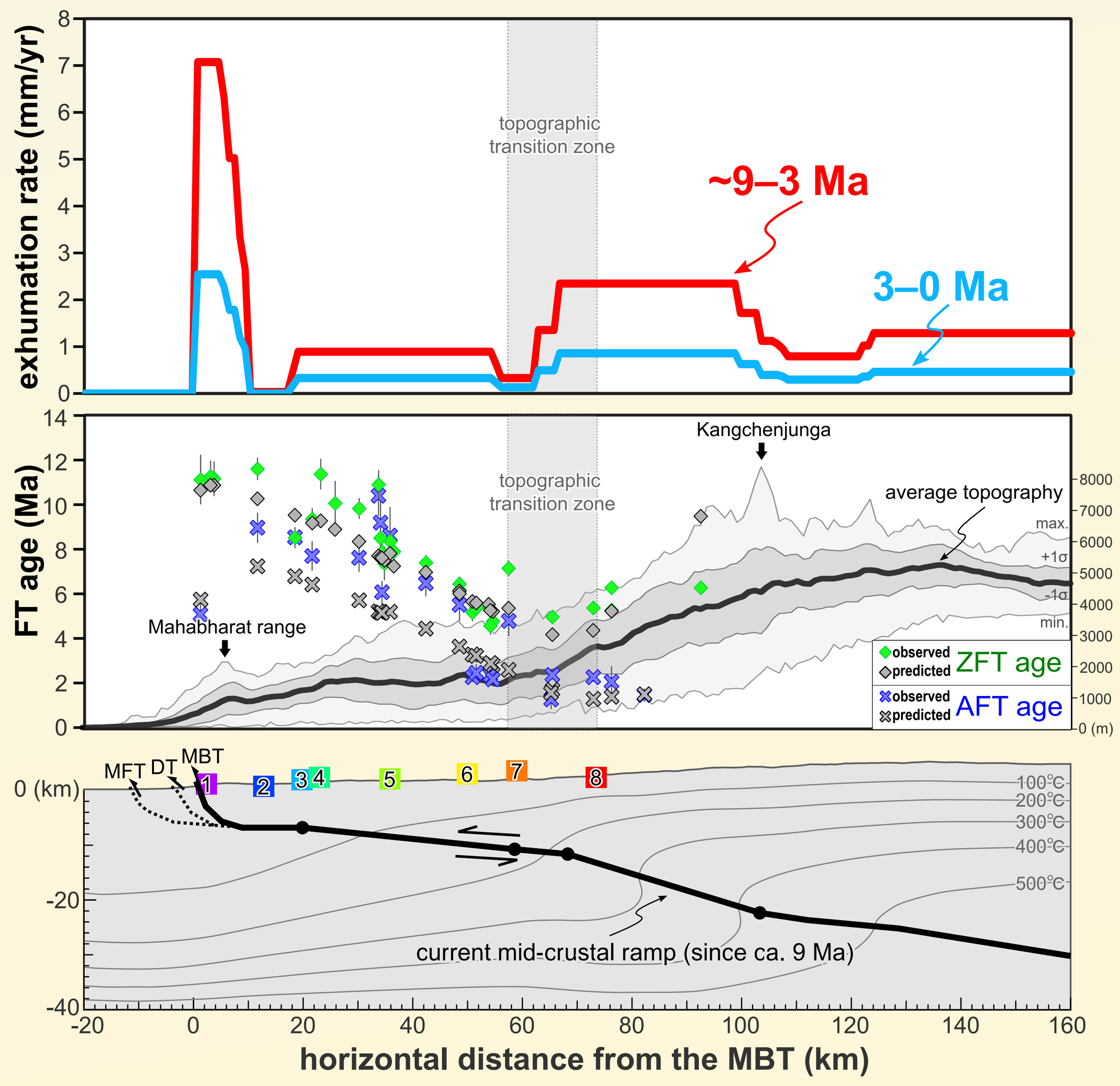


$$\Phi = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\frac{(age_{i,o}-age_{i,p})^2}{\sigma_i^2}} + \frac{5}{N_s}\sqrt{\sum_{i=1}^{N_s}\frac{(T_{i,o}-T_{i,p})^2}{\alpha_i^2}}$$

Results of the Neighborhood Algorithm (NA) inversion for the duplex model as scatter diagrams of the misfit between observed and predicted FT ages and t-T paths. Each dot corresponds to a single forward model,and the color of the dots is proportional to the value of the calculated misfit (Φ). A histogram represents the PDF of eash parameter.



Comparison diagram of the observed and predicted t-T paths.



Modeled exhumation rate distribution, topography, observed and predicted FT ages, and the cross-section of the thermokinematic model constrained by the thermokinematic inverse modeling. The mean topographic profile ± 1σ (represented by a bold blackline and gray fields) and minimum/maximum elevations (represented by gray lines) in eastern Nepal.

Geometry of the MHT and exhumation rate

The inverse analysis suggests that the shape of the MHT shows the flat-ramp-flat geometry. In eastern Nepal, observed GRG cooling and Northward younging has started at ca. 9 Ma, indicating that the geometry of the MHT has been stable since that time.

The N-S distribution of the exhumation rate based on the inverse analysis shows two peaks at the Mahabharat range in the frontmost pasrt of the Lesser Himalaya and the high-mountain range. This is consistent with the result of the levering study (Jackson and Bitham, 1994) and the topographic study (Lavé and Avouac, 2001). The inverse analysis also suggests that the exhumation rate decreased at ca. 3 Ma.

Conclusions

1) The observed FT ages and t-T paths reflect a denudation process driven by the movement of the MHT showing a flat-ramp-flat geometry.
2) The flat-ramp-flat geometry of the MHT was established by ca. 9 Ma and has been stable thereafter.
3) The denudation rate decreased at ca. 3 Ma.