

Introduction

Supporting information for this paper includes text, figures, tables, and videos that give information on the methods and supporting data for ZHe and AFT analyses and the methods and supporting data for the flexural-kinematic, thermal, and landscape evolution models.

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S1. Zircon (U-Th)/He analytical methods

Zircon (U-Th)/He analyses followed the general procedures outlined in Reiners (2005) and Reiners et al. (2004). Individual zircon grains were selected from separates on the basis of size, morphology, and lack of inclusions. Grains lacking obvious fractures and with a minimum radius of 60 μm , with minimal to no inclusions, were selected. However, due to a lack of unbroken zircon grains with radii above 60 μm in certain samples, smaller unbroken grains with radii as close to 60 μm as possible were selected. The dimensions of individual grains were measured from digital photomicrographs, using the approach outlined in Hourigan et al. (2005) for α -ejection corrections. Single grains were then packed into 1 mm Nb foil envelopes. Multiple foil packets were then placed in individual holes in a 30-hole planchette inside a ~ 7 cm laser cell pumped to $<10^{-9}$ torr. Individual packets were heated for 15 minutes by a focused beam of a 1-2 W laser, to extract ^4He . The packets were then re-heated for 15 minutes, often multiple times, until ^4He yields were less than 1% of total. Standards of Fish Canyon Tuff (FCT) zircon (28.48 ± 0.06 Ma (2σ), Schmitz & Bowring, 2001) were analyzed between every 5 unknowns.

Gas released from heated samples was spiked with 0.1-0.2 pmol ^3He and condensed onto activated charcoal at the cold head of a cryogenic trap at 16 K. Helium was then released from the cold head at 37 K into a small volume (~ 50 cc) with an activated Zr-Ti alloy getter and the source of a Balzers quadrupole mass spectrometer (QMS) with a Channeltron electron multiplier. Peak-centered masses at approximately m/z of 1, 3, 4, and 5.2 were measured. Mass 5.2 establishes background, and mass 1 is used to correct mass 3 for HD and H^3+ . Corrected ratios of masses 4 to 3

were regressed through ten measurement cycles over ~15 s to derive an intercept value, which has an uncertainty of 0.05-0.5% over a $^4\text{He}/^3\text{He}$ range of ~103 and compared with the mean corrected ratio to check for significant anomalous changes in the ratio during analysis. Helium contents of unknown samples were calculated by first subtracting the average mass-1 corrected $^4\text{He}/^3\text{He}$ measured on multiple procedural blanks analyzed by the same method, from the mass-1-corrected $^4\text{He}/^3\text{He}$ measured on the unknown. This was then ratioed to the mass-1 corrected $^4\text{He}/^3\text{He}$ measured on a shot of an online reference ^4He standard analyzed with the same procedure. The resulting ratio of measured $^4\text{He}/^3\text{He}$ values was then multiplied by the moles of ^4He delivered in the reference shot.

After He extraction and measurement, foil packets were retrieved, transferred to Teflon vials, and spiked with 0.5-1.0 ng of ^{233}U and ^{229}Th . High-pressure digestion vessels were used for dissolution of the zircon and Nb foil packet. Natural-to-spike isotope ratios of U and Th were then measured on a high-resolution (single-collector) Element2 ICP-MS with all-PFA Teflon sample introduction equipment and sample preparation/analytical equipment. Blanks for zircon analyses were 2.6 ± 0.5 pg U and 5.5 ± 1.0 pg Th. Precision on measured U-Th ratios is typically better than 0.5% for zircon analyses. Propagated analytical uncertainties for typical zircon samples led to an estimated analytical uncertainty on (U-Th)/He ages of approximately 1-3% (1σ). In some cases, reproducibility of multiple aliquots approaches analytical uncertainty. However, in general, reproducibility of repeat analyses of (U-Th)/He ages is significantly worse than analytical precision. Thus (U-Th)/He ages typically show a much greater scatter and higher MSWD than expected based on analytical precision alone, and multiple replicate analyses of (U-Th)/He ages on several aliquots is necessary for confidence in a particular sample age.

S2. Apatite fission track analyses

Minerals were separated by C. Battistella. Standard magnetic and heavy liquid mineral separation processes were used. All analyses were done by A. Blythe. Apatite grains were mounted in epoxy. Sample surfaces were ground and polished. Apatite mounts were etched in 5.5M HNO_3 at 18°C for 21 s. An "external detector" (e.g. Naeser, 1979), consisting of low-U (<5 ppb) Brazil Ruby muscovite, was used for each sample. Samples were irradiated in the Oregon State Triga nuclear reactor. Following irradiation, the muscovites were etched in 48% HF at 18°C for 30 min. Tracks were counted using a 100X dry lens and 1250X total magnification in crystals with well-etched, clearly visible tracks and sharp polishing scratches. A Kintek stage and software written by Dumitru (1993) were used for analyses. Parentheses show number of tracks counted. Standard and induced track densities were determined on external detectors (geometry factor = 0.5), and fossil track densities were determined on internal mineral surfaces. Ages were calculated using $\text{zeta } 359 \pm 10$ (AB) for dosimeter CN-5 (e.g. Hurford & Green, 1983). All ages are central ages, with the conventional method (Green, 1981) used to determine errors on sample ages. The chi-square test estimated the probability that individual grain ages for each sample belong to a single population with Poissonian distribution (Galbraith, 1981). The data were reduced with the program Binomfit (Brandon, 2002).

S3. Flexural-kinematic modelling methods

The restored, balanced cross-section and a 0.5 km x 0.5 km mesh grid were deformed in ~10 km increments using the modelling program Move (Midland Valley/Petex). Models initiate with an elevated topography (~5 km elevation) above the restored position of Greater Himalayan (GH) rocks to account for Paleocene to Eocene shortening and the resulting elevated topography in the Tethyan fold-thrust belt prior to initiation of motion on the MCT (Aikman et al., 2008; DeCelles et al., 2014; Murphy & Yin, 2003; Ratschbacher et al., 1994). The elevated Tethyan topography is inferred to have a similar topographic profile as the modern Himalayan fold-thrust belt and thus increases from sea level at a ~2° angle over 160 km to a maximum of 5 km immediately south of the restored GH-LH boundary.

Each 10 km increment of deformation parallel to the fault raises the topographic surface above the previous surface in locations of active uplift above ramps, creating an isostatic load. The magnitude of the load and how it is distributed across the crust is determined by the area between the previous undeformed topography and the deformed topographic surface, the modelled density, and stiffness (effective elastic thickness, EET) of the lithosphere (McQuarrie & Ehlers, 2015). A new post-deformation topographic surface is estimated by assuming topography increases from the deformation front at an ~1.75-2° slope everywhere that has undergone surface uplift. In regions where no surface uplift has occurred, the new topographic profile follows the previous subsided topographic profile (Gilmore et al., 2018; McQuarrie & Ehlers, 2015). Rocks uplifted above the new estimated topography are then eroded away, providing sediment to the foreland basin, and the crust isostatically rebounds in response to the erosional exhumation. Although central Himalaya paleotopography is unknown, we assume the topographic evolution through time can be replicated with the same first-order topographic slope (~1.75-2°) as the modern central Himalaya and that the associated erosion is instantaneous. While the responsive topographic estimate described in this section does not account for topographic relief between interfluvies, it reproduces the primary topographic signature of evolving structures (i.e., valley and ridge topography) (Fig. 7), which is the most significant topographic effect for isostatic and thermal calculations (e.g. McQuarrie & Ehlers, 2017).

Each instance of deformation, loading, erosion, and unloading causes the décollement angle to steepen and crust to subside, creating space in the foreland basin and allowing for accumulation of sediments. The depth of the basin is controlled by the amount and location of subsidence (Braza & McQuarrie, 2022). Flexural modelling is performed by systematically varying EET, density, and topographic evolution until the model reproduces the surface geology, décollement angle, and thickness of the foreland basin. The stratigraphically lowest ~1 km of the basin in the flexural-kinematic model are the early foreland deposits comprising the Dumri Fm. The MHT follows the flat along the top of the Dumri Fm. during shortening on splays of the MFT. As the increments of deformation and deposition in each kinematic model are not tied to an age until coupled with a velocity model, we distribute the basin above the MHT to the Siwalik Group based on the cumulative thickness of the preserved foreland basin. For transect A-A', we specify stratigraphic depths determined by Gautam & Fujiwara (2000) and Sigdel & Sakai (2016), with the middle-upper Siwalik contact at ~1.5 km depth and lower-middle Siwalik contact at ~4.24 km depth (Fig. 2). Any strata remaining in the basin above the MHT are assigned to the lower Siwalik unit.

S4. Thermal modelling and predicting bedrock and basin age distributions

The displacement fields generated by each ~10 km deformation step were converted to velocity fields by assigning an age to each increment of deformation and then used as input into a modified version of Pecube (Braun, 2003; Ehlers, 2023; McQuarrie & Ehlers, 2015; Whipp et al., 2009). Pecube-D solves the advection-diffusion thermal equations for the input velocity fields to determine the subsurface thermal field and resulting time-temperature history for particles that reach the surface. Pecube-D calculates a suite of thermochronometer ages for points at the surface for each deformation step based on the modelled cooling rate and prescribed mineral kinetics (Braun, 2003; Braun et al., 2006; Ehlers et al., 2005). Kinetics of the AFT system use the annealing model of Ketcham et al. (2007). Parameters for the ZHe system are summarized in Reiners et al. (2004). Calculations for the MAr system use thermally activated diffusion (Dodson, 1973) using parameters from Hames & Bowring (1994) and Hodges et al. (2014).

The subsurface thermal field calculated by Pecube-D is dependent on crustal properties assigned to the rocks. A constant temperature of 1300°C is assigned to the base of the model at 110 km depth. Surface temperature is set to an initial value of 24°C at the lowest model elevation (0 m above sea level) in front of the growing orogen. An atmospheric lapse rate of 6°C/km is assigned to account for changes in surface temperature conditions with increasing elevation (Jain et al., 2008). To simulate an exponential decrease in radiogenic heat production with depth, we specify a radiogenic heat production value for the surface and define an *e*-folding depth over which the surface heat production value exponentially decreases (McQuarrie & Ehlers, 2015, 2017). The surface heat production value (A_0) decreases by $1/exp$ across the specified *e*-folding depth, until decaying to a background value at the base of the model. While this approach is limited in that the radiogenic heat production value is not advected with the ongoing deformation, it reproduces viable surface heat flow measurements, temperatures at the base of the model, and honors observations of non-monotonic heat production decline with increasing crustal depths (Brady et al., 2006; Chapman, 1986; Ghoshal et al., 2020; Ketcham, 1996; Braza et al., 2023). A constant *e*-folding depth of 20 km was applied to all models, while the surface heat production was varied between 2–4 $\mu\text{W}/\text{m}^3$ (e.g., England et al., 1992; Herman et al., 2010; Ray et al., 2007; Whipp et al., 2007) in 0.2–0.5 $\mu\text{W}/\text{m}^3$ increments. We emphasize that while the model thermal parameters are reasonable values for the Himalayas, we are not uniquely solving for these values as multiple combinations of parameters can predict similar distributions of cooling ages (e.g., Ghoshal et al., 2020; McQuarrie & Ehlers, 2015).

The thermal parameters applied to the thermokinematic models are constrained using 29 published temperature measurements, with 22 peak temperatures determined from pseudosection modeling, 4 peak temperatures estimated from garnet-biotite exchange reactions, and 7 deformation temperatures estimated from quartz c-axis opening angles (Fig. S1) (Braden et al., 2020; Montomoli et al., 2013; Soucy La Roche et al., 2016, 2018; Yakymchuk & Godin, 2012). The temperature inferred from the quartz c-axis opening angle of JD-06B (~52 km south of the MCT) is interpreted as a maximum temperature, due to a component of flattening strain maximizing the opening angle (Soucy La Roche et al., 2018). The remaining quartz c-axis temperatures are interpreted as minimum estimates of the peak deformation conditions (Braden et al., 2020).

S5. Landscape evolution modelling

The CASCADE model domain spans a width of 60 km along the y-axis and a length of 250 km along the x-axis parallel to the direction of advection, with an initial average node spacing of ~0.5 km. The initial topography for the first landscape model is the Move topography at the model start time (15 Ma), a 1.75° slope that increases in elevation from 175-250 km in model space. The model is then given 200 kyr to simulate fluvial incision and hillslope processes in the absence of fault displacement or uplift. This initial model was run for 15 Ma of model time, and then subsequent models used the CASCADE generated topography at 10.3 Ma from the initial model as the starting point for all other simulations. The landscape created during the first 6.2 Ma of model time (15 to 8.8 Ma) is one where topography at the northern border is simply advected to the south due to motion on the upper LH roof thrust.

The displacement trajectories from Move are assigned to each surface node in the CASCADE triangulated irregular network (TIN). TIN nodes then physically move according to their prescribed vector. Dynamic remeshing based on individual node distances and mesh surface areas are performed every 2500 model years to avoid potential node overlapping (Eizenhöfer et al., 2019). Boundary nodes along the two lateral boundaries of the model (at $y = 0$ and 60 km) move vertically and horizontally, whereas nodes along hinterland boundary maintain the elevation at that boundary (uplift or incision) of the preceding increment. As we are not simulating the exhumation or the elevation of the Tibetan Plateau along the hinterland boundary, the model topography dramatically decreases to ~3 km of elevation to the north of the active ramp, rather than the more moderate decline from 5.5 km to 5 km elevation in the measured topography. The foreland boundary nodes are fixed at zero elevation. All boundary nodes are open to sediment flux.

Erosion is a function of both river incision and hillslope failure. The slope of the bedrock channel is defined by:

$$dh/dt = v_u(x) - v_h(x)dh/dt - KA(x)^m S(x)^n$$

where $v_u(x)$ = rock uplift rate, $v_h(x)$ = horizontal translation/ lateral advection rate, $m = 0.5$, and $n = 1$. Bulk erodibility (K) is a function of fluvial erosion constant (K_f) [unitless], precipitation (P) [m/yr], erosion-deposition length scale (l_f), and a coefficient controlling channel width as a function of discharge (c)

$$K = (K_f P^{1/2}) / (l_f c)$$

(Miller et al., 2007, Willet et al., 2001, Eizenhöfer et al., 2019). For all models (l_f) was 1000 m in bedrock channels and 100 m in fluvial channels. We tested K_f values ranging from $3.50 - 5.40 \times 10^{-4}$. The value in the best-fit model is 4.00×10^{-4} . Hillslope diffusivity was defined by the hillslope diffusion coefficient with a value of $2.0 \times 10^{-6} \text{ km}^2/\text{yr}$. The threshold hillslope angle for landsliding was 30°.

Precipitation was applied using both constant precipitation values of 1.75 m/yr as well as imposed orographic precipitation fields modified from the range of modern precipitation measurements for the Simikot region (Fig. S2) (Andermann et al., 2011). To accommodate topography that is changing in space and time, precipitation profiles have been stretched or compressed to maintain observed orographic relationships with topography. Deviations from the modern precipitation field are imposed from 2.4 Ma to modern to focus precipitation on the region of high topography to better facilitate erosion there (Fig. S2). Over this window of time, the growth of glaciers at high elevations would facilitate erosion in the high Himalaya (Herman et al., 2013) and glacial erosion is not included in the landscape model. Modelled topography also best replicates measured with an increase in precipitation at the southern mountain front

~90-110 km south of the MCT (Fig. S2). Our goal was to assess the ability of the flexural-kinematic models to replicate locations of active uplift versus fully replicating topography. For simplicity, the models are limited in that they do not include variations in rock strength, significant lateral variations in fault kinematics and geometry apparent to the east and west of the transect, or glacial effects. The largest model limitation is the lack of the Karnali river, which has headwaters that extend ~75 km to the east and west of the model edge thus incorporating a much larger drainage basin than modelled here. The best-fit model is shown in Figs. 5, 8, S5, and Video S2.

S6. Assessing cross-section geometry, kinematics, and rates

The new geometry in Model C is based on the updated geologic mapping and the fit/misfit to the measured cooling ages in Models A and B. The results for Models A and B indicate that the modern active ramp cannot be placed south of the young measured AFT and AHe ages in the north, especially not beneath the ~5-10 Ma AHe age measured in the Dadeldhura klippe (Fig. 4). We tested multiple ramp locations in the northern region of the cross-section, to the south and to the north of the MCT, to constrain the specific location of the active ramp presented in Model C. The final geometry, kinematics, and shortening rates presented for Model C are the result of more than 30 flexural-kinematic models and more than 60 thermal models. The location and angle of the ramp, magnitude of displacement, and the timing of the young out-of-sequence fault beneath the Dadeldhura klippe in Model C is further constrained by 20 landscape evolution models that tested the sensitivity of fault kinematics and geometry on topography. This thermokinematic-landscape evolution modeling is an iterative process, where the results of the Move, Pecube, and Cascade models each inform the changes that will be made in the next iteration.

The size of decollement ramps in Model C is constrained by the stratigraphic thicknesses, as determined from the map distances and unit orientations (Fig. 1), and the location is constrained by either the requirement to reproduce a specific exhumation signal at a particular location or from the restored length of the beds in the cross-section. The location of the GH ramp in the undeformed section for the geometry in Model C is based on the restored length of the upper LH units in the LH duplex and the lower LH units in the RMT duplex. The size of the GH ramp is set to cover the extent of the GH units in the hanging wall of the MCT in Fig. 1. The initial geometry of the GH section simulates burial beneath the Tethyan fold-thrust belt (e.g., Aikman et al., 2008; Murphy & Yin, 2003; Ratschbacher et al., 1994), with the GH rocks initiating at their peak depth and temperature conditions (Soucy La Roche et al., 2016; 2018) (Video S1). However, faults repeating the GH rocks have been proposed for nearby cross-sections, such as the Oligocene Tojiem shear zone observed ~75 km to the east of the Simikot section (Carosi et al., 2010). This top-to-the-south displacement is proposed to have occurred prior to initiation of MCT motion (Soucy La Roche et al., 2018), which is when our models begin. Cooling and decompression proposed for GH rocks that extends from the start of our model (25 Ma) to as young as 16 Ma was evaluated by assessing if additional cooling or thinning (e.g. Soucy La Roche et al., 2018) was needed to reproduce cooling constraints. That we are able to replicate MAr ages through the Dadeldhura klippe without ductile deformation, argues that the thinning recorded in these rocks predates ~20 Ma. Incorporating faults that repeat the GH implies a smaller ramp, as a thinner initial package of GH rocks would define the height of the ramp. This pre-MCT faulting would influence the depth of the GH rocks and the temperature conditions at the beginning of MCT motion.

The required displacements are constrained by the cross-section geometry and begins with the minimum amount of shortening required to reproduce the surface geology, and in the case of Model C, still maintain a more northern ramp location. The total displacement on the fault is broken down into ~10 km steps and each step is isostatically accommodated and eroded in Move (McQuarrie & Ehlers, 2015, 2017). The shortening rate is determined by the amount of displacement and the increment of time this displacement occurs over. The timing of each increment of shortening is determined by the cooling ages and which modelled cooling ages are sensitive to a given fault motion and age (McQuarrie & Ehlers, 2015, 2017). The modelled velocities are adjusted to better reproduce the measured ages and/or the measured basin depositional ages (Braza & McQuarrie, 2022a,b; McQuarrie & Ehlers, 2015, 2017). For example, sediments at ~4 km depth in the modelled basin accumulate in Step 52 of Model C, during LHD-1 motion in the LH duplex (Video S1). The depositional age of strata measured at an equivalent depth in the basin is ~6.8-12.7 Ma, so the timing of Step 52 must fall within that window. Multiple different combinations of shortening rates are tested to identify the best fit to the cooling ages and basin depositional ages, and to assess the sensitivity of the cooling ages to the rates. The number of velocity combinations tested depends on how poorly the measured ages are reproduced and whether any geologically viable changes in shortening rate are sufficiently improving the model fit. In general, thermokinematic models of the Nepal Himalaya show a stronger sensitivity to the age of fault motion, rather than the shortening rate (Braza et al., 2023). The geometry (ramp location) and/or kinematic sequence (in- or out-of-sequence order of faulting) is modified and input into a flexural-kinematic model and then thermal model and finally a landscape evolution model. This iterative process is completed until a viable exhumation pathway is identified.

We use the peak temperatures (Fig. S1) to gain insight into the conditions the rocks experienced while at temperatures hotter than the MAr closure and to ensure the cooling path begins at an appropriate temperature. The exhumation history of the GH rocks is constrained by the amount of shortening required to connect the lower LH and GH rocks in the Dadeldhura klippe with the respective units in the north (Fig. 1), the requirement for a flat-on-flat relationship between the GH and lower LH rocks that is formed by emplacement of GH rocks atop the lower LH rocks by MCT motion (e.g. Robinson et al., 2006), that the MCT was active by ~25-30 Ma (e.g. Soucy La Roche et al., 2018), the MAr ages in the Dadeldhura klippe are ~18 Ma in the southern limb and young to ~14 Ma in the northern limb, and the MAr ages in the north are ~6 Ma (Fig 3). As our models highlight that the MAr ages in the Dadeldhura klippe were set during RMT motion when GH and lower LH rocks were translated over the northern edge of the upper LH rocks, the full shortening on the MCT must occur between ~25-30 Ma and ~18 Ma, prior to initial uplift of the southern limb of the Dadeldhura klippe over the northern edge of the upper LH rocks. In addition, ~16 Ma detrital Mica ages are present in the basal Siwalik section that is dated to ~16 Ma (Fig. 2) (Szulc et al., 2006) providing another constraint on the magnitude and rate of shortening that must occur before this time. Exhumation of the northern GH rocks by the young out-of-sequence motion is constrained by the ~6 Ma MAr ages that indicate a significant pulse of cooling at this time. These constraints do not preclude additional periods of significant in- or out-of-sequence motion during MCT motion (prior to 18 Ma) or from ~18-6 Ma on faults that are not present in the current section because they are north of our section, or were in strata to the south of preserved GH and lower LH rocks that have been erosionally removed (Fig. 6; Video S1).

Model C also tests a young, low-displacement out-of-sequence fault beneath the Dadeldhura klippe to produce the raised topography and elevated ksn values observed in the klippe (Fig. 3, S3). Initial attempts to reproduce the modern topography in the landscape evolution models without the new out-of-sequence fault resulted in low elevation, relief, and slope regions in the Dadeldhura klippe, where the elevated values are observed. We tested fault locations within ~80-60 km south of the MCT, with varying ramp angles and amounts of shortening to evaluate the influence of the location and angle of the proposed fault on the AHe ages measured in the Dadeldhura klippe in the thermal model and on the location, magnitude, and slope of the elevated topography in the klippe in the landscape evolution model. Model tests demonstrate that the region of elevated topography is <20 km wide with a ramp angle of 35° and increases in width with decreasing ramp angle, to ~30 km wide with the best fit ramp angle of 25°. Tests also demonstrate that displacement magnitudes of >4 km influence the AHe ages predicted in the Dadeldhura klippe. In Model C, we incorporate 3.75 km of displacement on a fault splay that cuts through the upper LH units at ~80-60 km south of the MCT (Fig. 5, Video S1). The location of the new fault is consistent with the region of recent duplexing proposed by Harvey & Burbank (2024), though it occurs at a shallower structural level, in part due to the overall shallower decollement depth in Model C (as constrained by the measured basin depth) compared to the geometry proposed by Harvey & Burbank. The position and geometry of the new out-of-sequence fault allows slip to be fed to the RMT splays in the southern limb of the Dadeldhura klippe, consistent with the distribution of observed microseismicity in the region (e.g. Laporte et al., 2021). While the young faulting under the Dadeldhura klippe could indicate an imminent reorganization of where the active ramp is, the out-of-sequence motion is co-eval with motion over the active ramp at ~13 km north of the MCT and out-of-sequence faulting at 0 km north of the MCT (Video S1). This suggests that the faulting is better explained as local adjustments to the taper conditions that allow the fold-thrust to continue to propagate towards the foreland.

The geometry and kinematic sequence for Model C are more complex than a geometry that focuses on minimizing shortening or a strictly in-sequence progression of faulting. However, the complexities we introduce are required components of the burial and exhumation history to be able to reproduce the surface geology, measured cooling ages, basin thickness and accumulation data, and modern topographic relief, slope, and elevation with an integrated thermokinematic-landscape evolution model.

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Supplementary tables

Table S1. Model A parameters for the Robinson et al. (2006) geometry

Structural Zone	Kinematic Model Details			Variable Velocity Model	
	Model Step	Fault	Fault Displ. (km)	Time Window (Ma)	Velocity (mm/yr)
MCT	A	MCT	252	28.0-24.0	63
RMT	B	RMT-1	186	24.0-19.7	43.2
	C	RMT-2	66.9	19.7-18.2	45.2
	D	RMT-3	36.7	18.2-17.4	45.2
	E	RMT-4	36.4	17.4-16.6	45.2
	F	RMT-5	36.4	16.6-15.8	45.2
LHD	G	LHD-1	48.5	15.8-14.7	45.2
	H	LHD-2	31.7	14.7-14.0	45.2
	I	LHD-3	19.7	14.0-13.6	45.2
	J	LHD-4	14.2	13.6-13.3	45.2
MBT	K	LHD-5	12.1	13.3-13.0	45.2
MFT	L	SH-1	21.7	13.0-9.8	6.8
	M	SH-2	15.8	9.8-7.5	6.8
	N	SH-3	17.6	7.5-4.9	6.8
	O	SH-4	13.9	4.9-2.6	6.8
OOS	P	OOS-1	2.9	2.6-2.4	6.8
	Q	OOS-2	11.0	2.4-0.8	6.8
	R	OOS-3	5.5	0.8-0.0	6.8
Total	A-R		828.9	28-0	6.8-63

Note: EET = 110 km, $\rho_{\text{rock}} = 2700 \text{ kg/m}^3$

Table S2. Model B parameters for the Olsen et al. (2019) geometry

Structural Zone	Kinematic Model Details			Variable Velocity Model	
	Model Step	Fault	Fault Displ. (km)	Time Window (Ma)	Velocity (mm/yr)
MCT	A	MCT	220.5	25.0-18.0	31.5
RMT	B	RMT-1	205.7	18.0-15.1	70.9
	C	RMT-2	57.0	15.1-14.3	74.3
	D	RMT-3	51.6	14.3-13.6	74.3
	E	RMT-4	48.5	13.6-13.0	74.3
	F	RMT-5	9.2	13.0-12.9	74.3
LHD	G	LHD-1	52.2	12.9-12.2	74.3
	H	LHD-2	39.8	12.2-11.6	74.3
	I	LHD-3	10.0	11.6-11.5	74.3
	J		27.7	11.5-11.1	74.3
	K	LHD-4	37.7	11.1-10.6	74.3
	L	LHD-5	31.8	10.6-10.2	74.3
MBT	M	LHD-6	14.0	10.2-10.0	74.3
MFT	N	SH-1	5.0	10.0-9.3	6.9
	O	SH-2	19.6	9.3-6.5	6.9
	P	SH-3	8.0	6.5-5.3	6.9
OOS	Q	OOS-1	12.1	5.3-3.2	6.9
		OOS-2	2.8		
MFT	R	SH-3	7.7	3.2-2.1	6.9
	S	SH-4	14.2	2.1-0.0	6.9
Total	A-S		874.9	25-0	6.9-70.9

Note: EET = 90 km, $\rho_{\text{rock}} = 2600 \text{ kg/m}^3$, $\rho_{\text{sed}} = 2350 \text{ kg/m}^3$

Table S3. Model C parameters for the revised cross-section geometry

Structural Zone	Kinematic Model Details			Variable Velocity Model		Constant Velocity Model	
	Model Step	Fault	Fault Displacement (km)	Time Window (Ma)	Velocity (mm/yr)	Time Window (Ma)	Velocity (mm/yr)
MCT	1-17	MCT	170	25.2-18.1	24	25.6-18.5	24
RMT	18-32	RMT-1	150.3	18.1-14.9	45-48	18.5-12.3	24
	33-34	RMT-2	19	14.9-14.5	48	12.3-11.5	24
	35-36	RMT-3	12.3	14.5-14.2	45	11.5-11.0	24
	37-39	RMT-4	27.5	14.2-13.6	45	11.0-9.8	24
LHD	40-51	LHD-RMT	115.2	13.6-7.7	16-35	9.8-5.0	24
	52-53	LHD-1	16.3	7.7-6.6	16	5.0-4.3	24
OOS	54-55	RMT-1	16.0	6.6-5.6	15	4.3-3.7	24
	56	RMT-4	7.0	5.6-5.0	15	3.7-3.3	24
		LHD-1	2.0				
LHD	57-59	LHD-2	29.8	5.0-3.0	15	3.3-2.1	24
OOS	60	RMT-4	5.0	3.0-2.6	15	2.1-1.9	24
MFT	61-62	SH-1	19.6	2.6-1.3	15	1.9-1.0	24
MBT	63	LHD	3.4	1.3-1.1	15	1.0-0.9	24
MFT/ OOS	64	SH-2	9.0	1.1-0.6	18	0.9-0.5	24
	65	SH-3	4.7	0.6-0.3	20.5	0.5-0.3	24
		LHD	1.8				
	66	SH-3	3.0	0.3-0.0	20.5	0.3-0.0	24
		LHD	2.0				
		RMT-1	1.0				
Total	1-66		614.9	25.2-0	15-48	25.6-0	24

Note: EET = 75 km, $\rho_{\text{rock}} = 2700 \text{ kg/m}^3$, $\rho_{\text{sed}} = 2000 \text{ kg/m}^3$

Supplementary figures

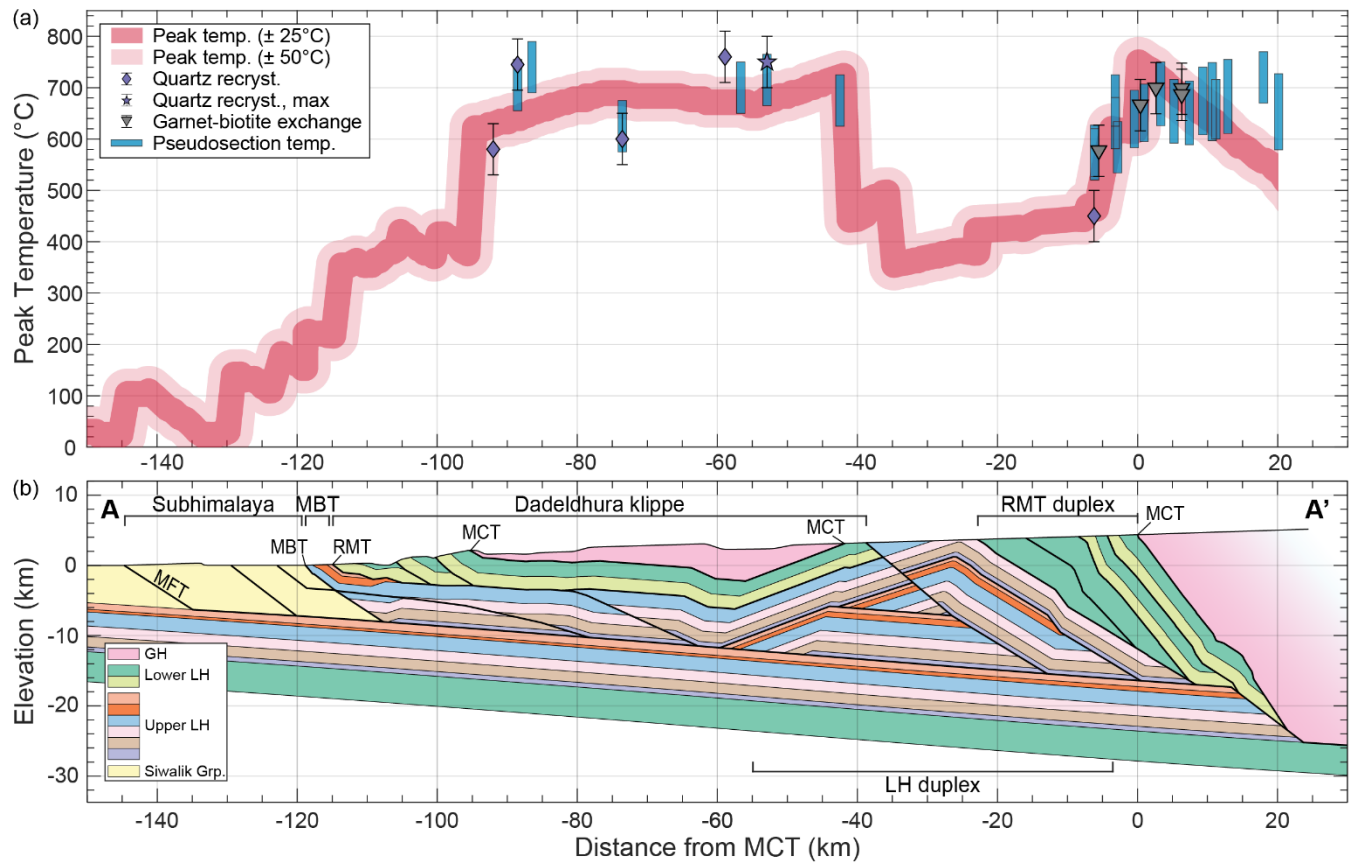


Figure S1: Modelled versus measured peak temperatures for A-A'. (a) The pattern of peak temperatures predicted by Model C with $A_0 = 2.85 \mu\text{W}/\text{m}^3$ is shown by the thick red line. Peak temperature data is from Braden et al. (2020), Montomoli et al. (2013), Soucy La Roche et al. (2016, 2018), and Yakymchuk & Godin (2012). (b) Cross-section geometry for transect A-A'. Lithologies and abbreviation of structures are the same as Figs. 1 and 3.

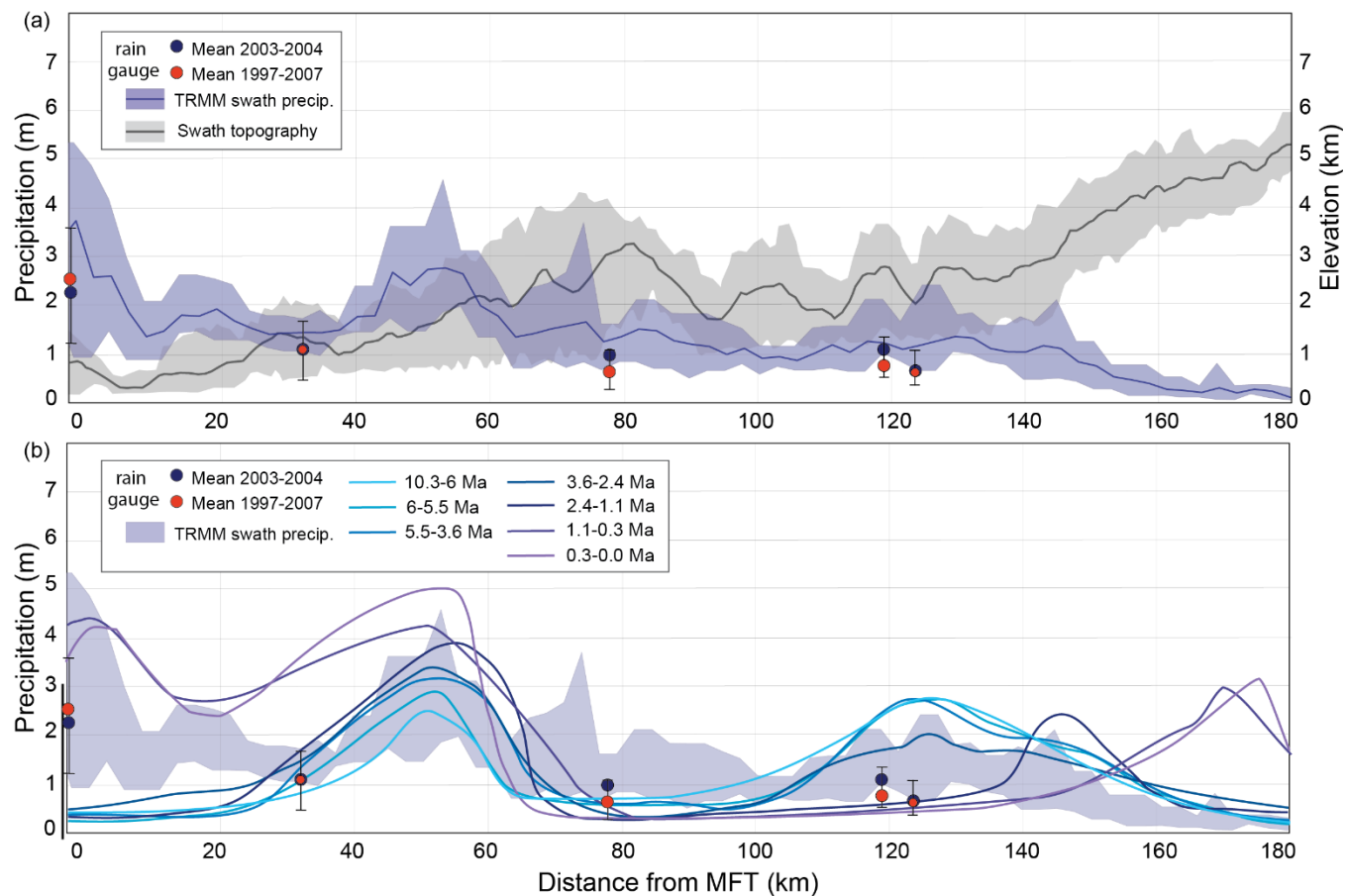


Figure S2: Precipitation data utilized for landscape evolution modeling. (a) Measured swath topography for A-A' and modern precipitation measurements for western Nepal (Andermann et al., 2011). Topography is ~2.5x vertically exaggerated. (b) Modern precipitation measurements (Andermann et al., 2011) and imposed orographic precipitation fields. The timing of the imposed orographic precipitation field is indicated by the line color.

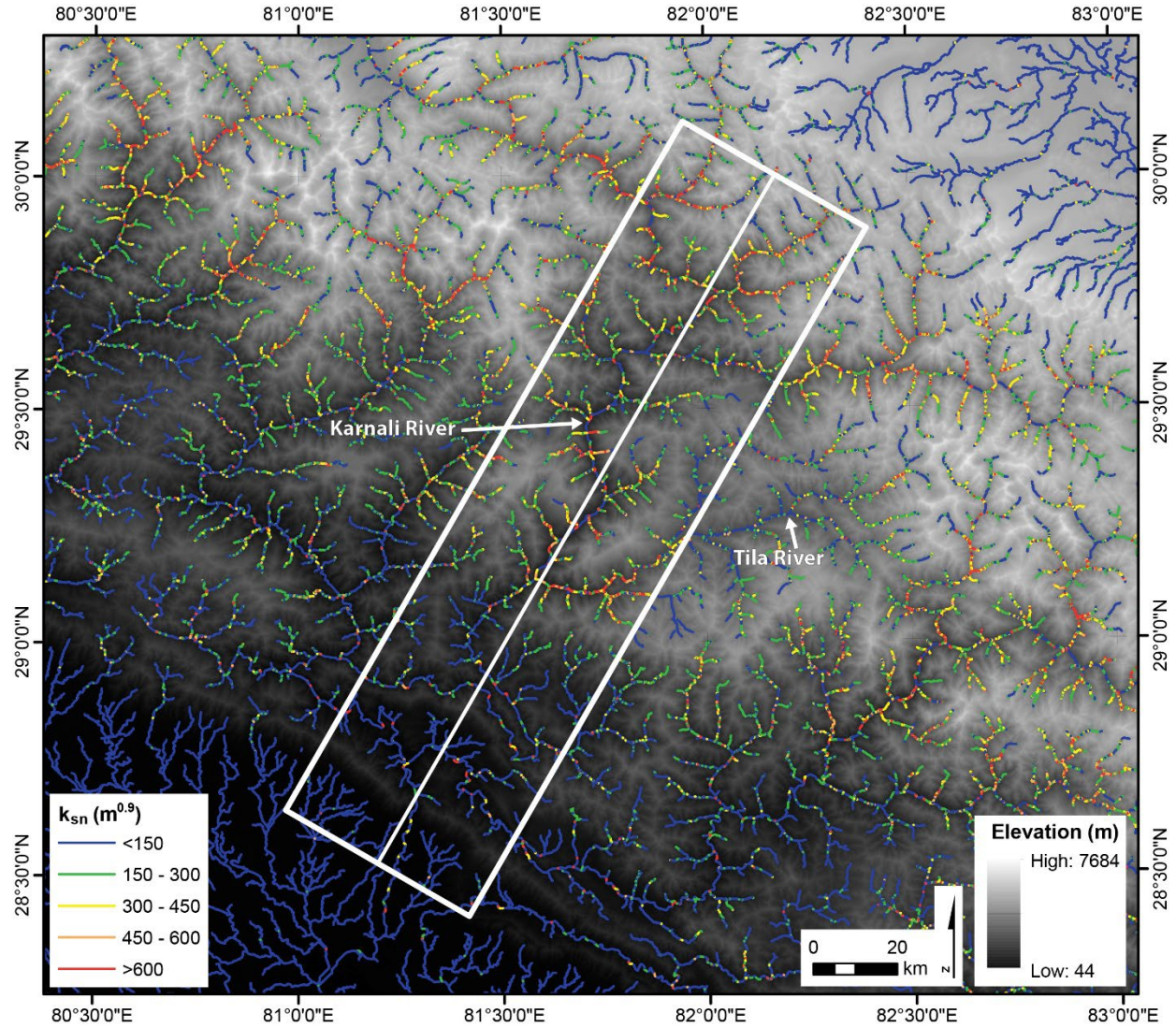


Figure S3: Normalized river steepness index map of western Nepal. K_{sn} map of fluvial channels calculated with TopoToolBox v2 (Schwanghart & Scherler, 2014) above a ~ 30 m ASTER digital elevation model (U.S./Japan ASTER Science Team, 2019). White box depicts the footprint of the swath profile in Fig. 3b. White line indicates transect A-A' at the center line of the swath. $\theta_{ref} = 0.45$.

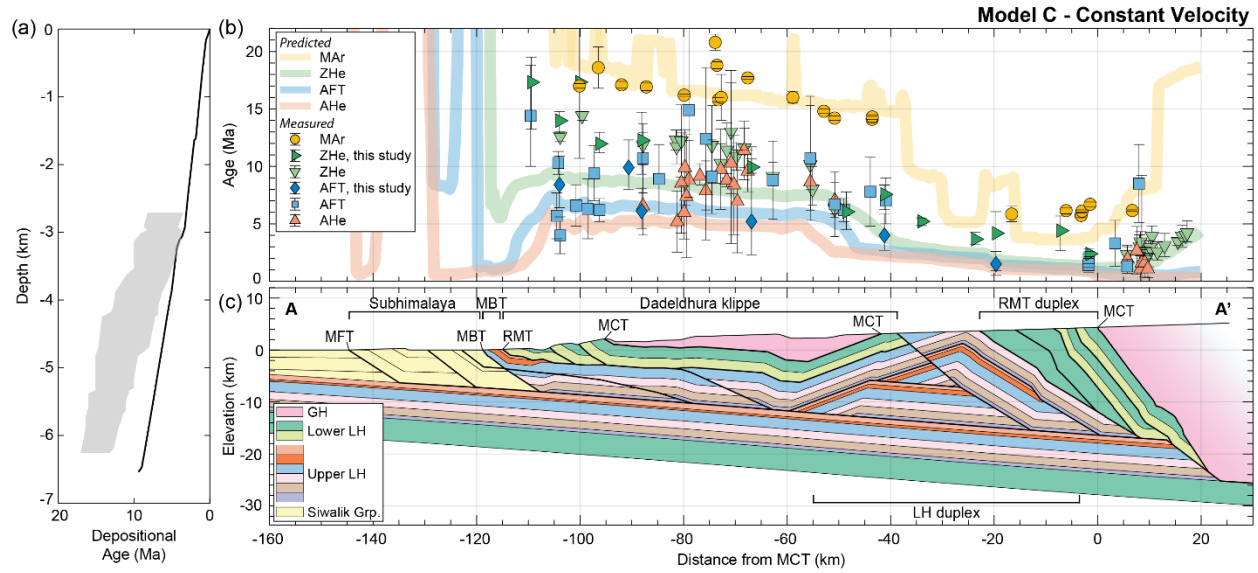


Figure S4: Thermokinematic model results for the Model C cross-section geometry and kinematic sequence with a constant shortening rate of 24 mm/yr (Table S3). (a) Accumulation rate of the modelled and measured basins. Grey shading denotes the range of measured depositional ages and the black line shows the modelled accumulation rate. The predicted basin thickness is the same as Fig. 5a. The pattern of (b) MAr, ZHe, AFT, and AHe cooling ages are shown above their associated (c) structures. Lithologies and abbreviation of structures are the same as Figs. 1 and 3 in the main text. Predicted MAr ages reproduce the MAr ages measured in the Dadeldhura klippe due to the initiation age of RMT motion over the ramp at the restored edge of upper LH rocks (~216 km north of the MFT) at ~18.5 Ma. Predicted cooling ages generally reproduce the younger population of measured AFT ages across the section, the younger AHe ages measured at ~89–67 km south of the MCT in the Dadeldhura klippe, and only three ZHe ages measured at ~60–40 km south of the MCT. The clusters of ZHe and AHe ages at ~5–20 km north of the MCT are also reproduced. Predicted ZHe ages are ~2–4 Myr younger than the measured ages, reflecting the younger start time of the LH duplex faults (~9.8 Ma vs ~13.6 Ma in the best fit variable velocity). Out-of-sequence motion on the RMT faults at ~4.3–3.3 Ma predicts MAr ages in the north above the RMT duplex and MCT that are ~2–3 Myr younger than the measured ages. The depositional ages in the basin are only reproduced for ~3–3.5 km basin depth. The lower LH-derived detritus is initially deposited in the basin ~6 Ma, younger than the ~10 Ma measured depositional age.

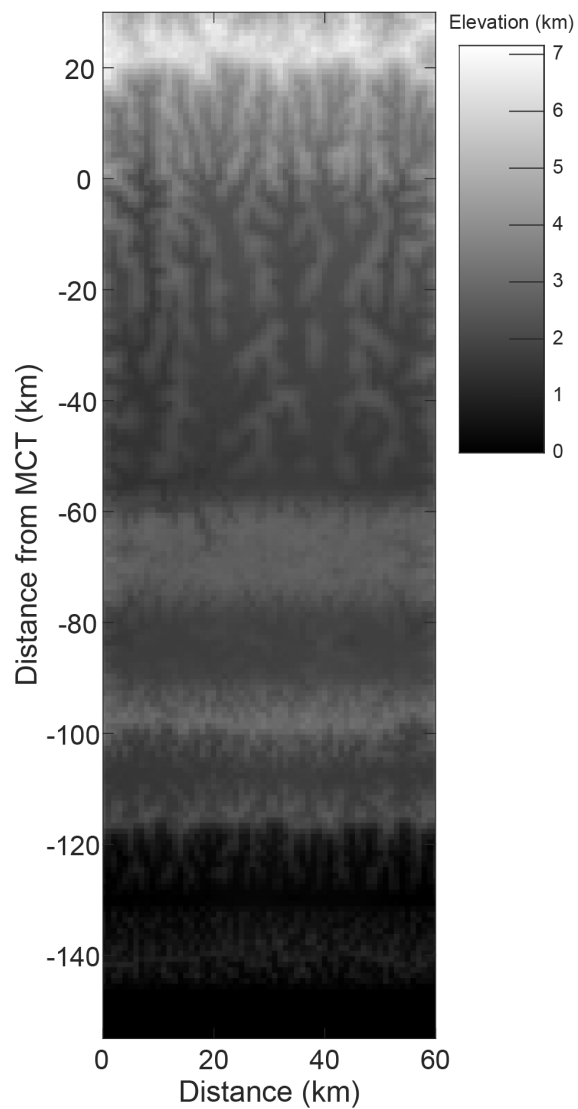


Figure S5: Topographic surface predicted by the landscape evolution model of Model C ($\theta_{\text{ref}} = 0.5$).

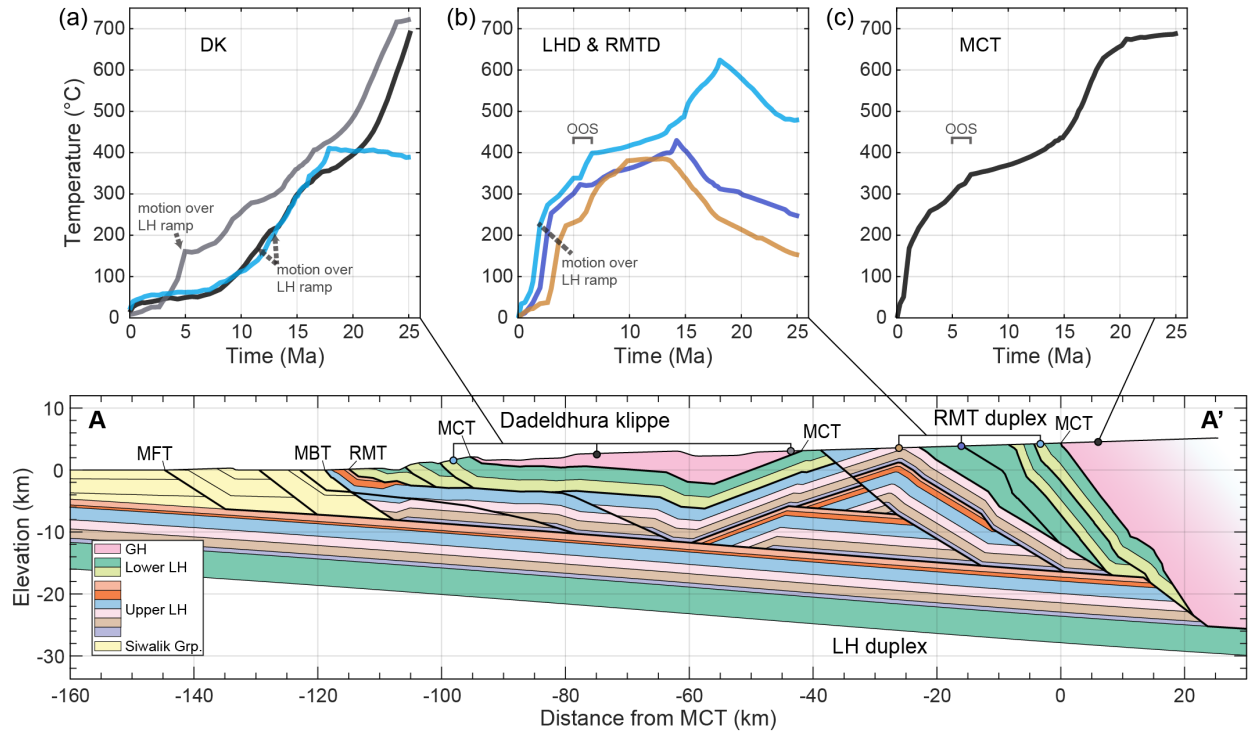


Figure S6: Time-temperature histories predicted by Model C for (a) lower LH and GH rocks in the Dadeldhura klippe (DK), (b) upper LH rocks in the LH duplex (LHD) and lower LH rocks in the RMT duplex (RMTD), and (c) GH rocks in the hanging wall of the MCT in the north.

Supplementary Videos

Video S1: Video of the sequential deformation and resulting predicted cooling ages for Model C with the best fit variable velocity. (a) Predicted MAR, ZHe, AFT, and AHe cooling ages. (b) Thrust displacement and perturbations of the thermal field. The thick black line indicates the active fault. Fault abbreviations are same as depicted in Fig. 3.

Video S2: Video of the landscape evolution model results for Model C. The top left panel shows the development of the modelled topographic surface with each displacement step. The top right panel shows the slope of the modelled topography. The bottom panel shows the modelled swath topography and precipitation field.