Uplift and exhumation along the Eastern Nepal Himalayas:
Can erosion increase long-term uplift rates?

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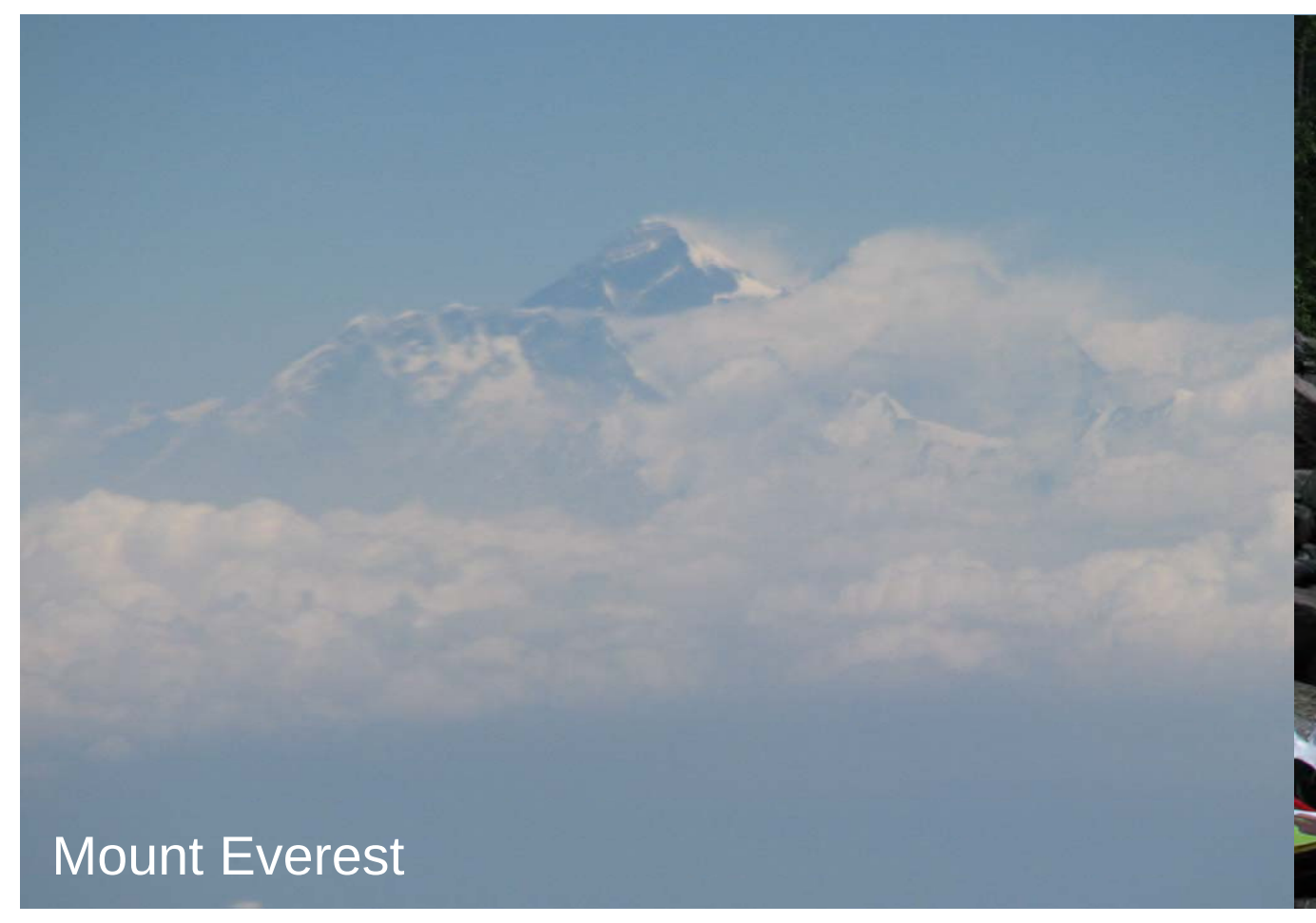
1. Introduction

The Arun river is one of the largest rivers across the Himalaya front draining large areas within the Tibetan Plateau across Eastern Nepal. Its deep valley is flanked by the prominent > 8 km peaks of Mt. Everest and Mt. Makalu. Although its evolution can provide key insights concerning growth of river anticlines, tectonic aneurysm, and the feasibility of mid-crustal channel flow associated with focused erosion (see Box 2), thermochronologic constraints along its course are scarce and limited to the Ama Drime Massif in Tibet (see map).
Utilizing (U-Th)/He low-temperature thermochronology of apatite and zircon, Ar/Ar thermochronology, geomorphologic analysis, and thermo-kinematic modeling coupled with a surface processes model we hope to answer the following key questions:

- What is the mechanism of uplift across the Himalaya mountain front in eastern Nepal? (out-of-sequence thrusting *vs.* underplating and overthrusting across a ramp).
- Does the deep gorge of the Arun river promotes localized higher-than-normal long-term uplift rates? By which mechanism?
- Is the Arun anticline an old, non-active structure or a young, active structure?
- What controls the overthrusting rate across the Himalaya?
- Are climate and tectonics coupled beyond isostasy?

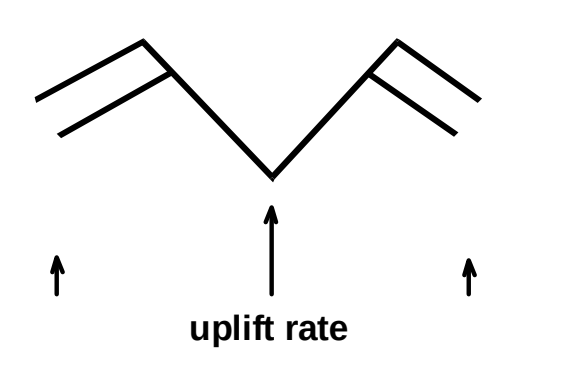
We collected ~80 samples for (U-Th)/He thermochronology and ~20 samples for Ar/Ar thermochronology along transects parallel and perpendicular to the convergence, spanning an elevation range of 300-5750 m. The results below are work in progress. Most of the samples were not yet analyzed.


Mount Everest

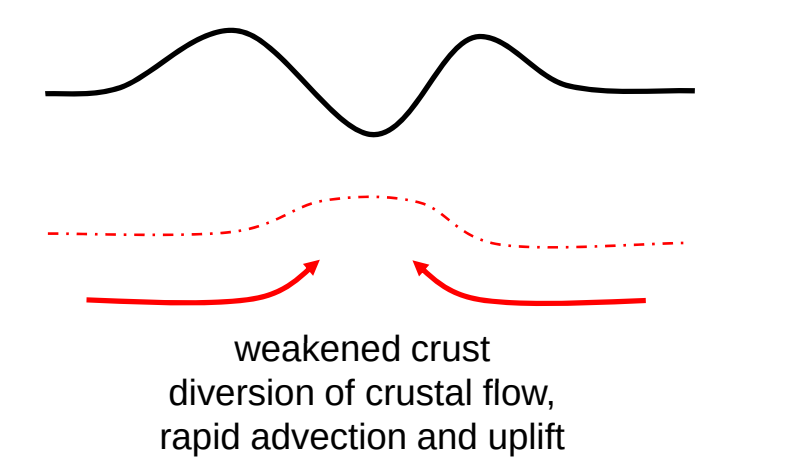

Arun river

2. Theoretical modes of coupling between erosion and uplift rates and their predictions for the Arun river setting:

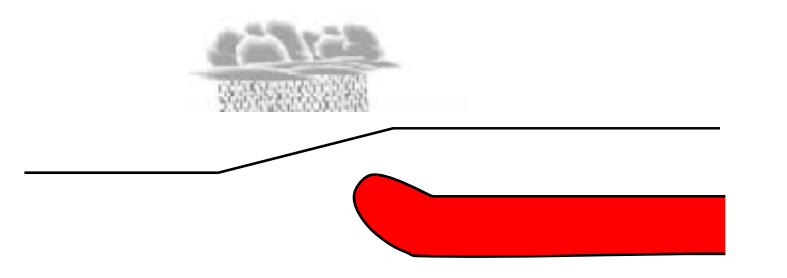
River anticlines
Incision of a deep valley may lead to anticline growth due to flexural isostasy (e.g., Montgomery & Stolar, 2006). The axes of the anticline is expected to follow the axis of the valley and the anticline wave length will vary with the elastic thickness.
If such an anticline is currently active along the Arun river uplift and exhumation rates near the valley axis should be higher than along the interfluves.
Without a positive feedback mechanism which increases the local uplift rates beyond the isostatic response the activity of a river anticline will decay with time. However, it is also possible that a river anticline will eventually trigger tectonic aneurysm.



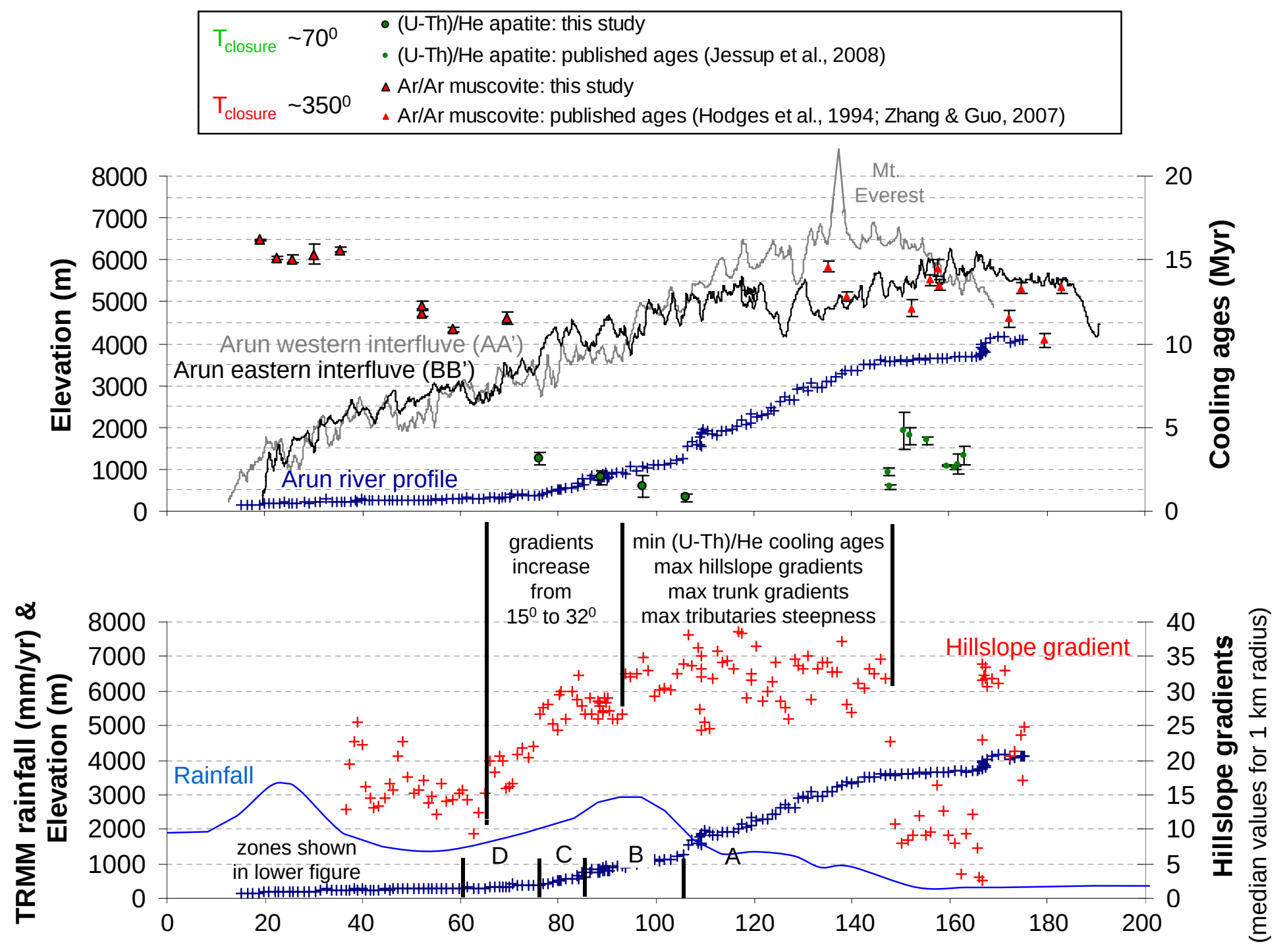
Tectonic aneurysm
Incision of a large river, forming a deep valley, can weaken the crust both thermally and mechanically. This weakening can eventually divert the tectonic flux and increase the local uplift rates relative to the surroundings.
Such a mechanism was proposed in order to explain the extreme long-term exhumation rates along the Indus and Tsangpo rivers at the Himalaya western and eastern syntaxes, respectively (Zeitler et al., 2001).
If such a mechanism is active along the Arun river the long-term uplift and exhumation along its valley should be high relative to small valleys such as the Dudh river 50 km to the west.

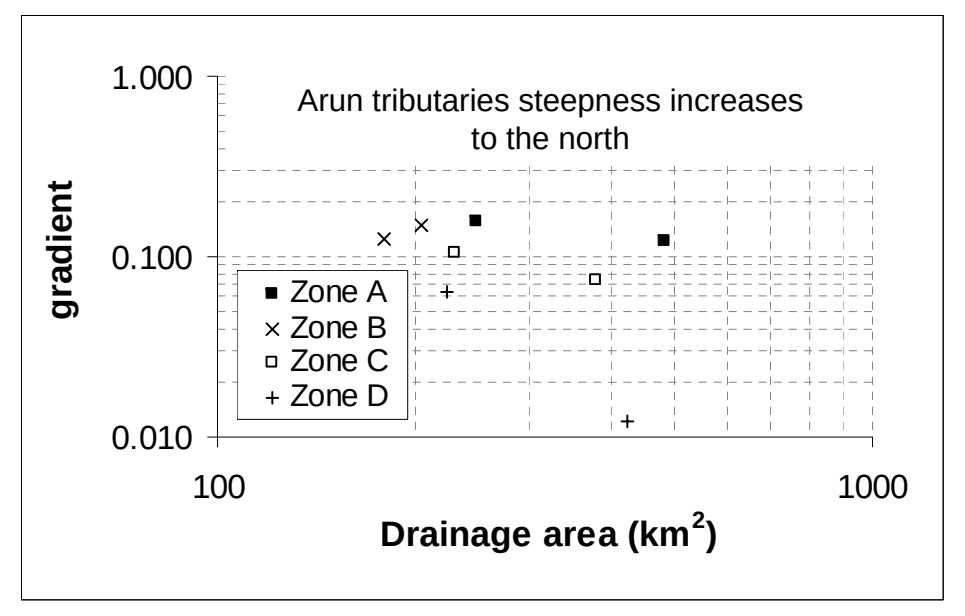


Channel flow coupled with surface erosion
Topographically-induced pressure gradients can promote channel-like flow of mid-crustal material towards a zone of high topographic gradients. Rapid erosion within this zone can thermally weaken the upper crust and increase both flow velocity within the channel and uplift rates within the exhumation window (e.g.,Beaumont et al., 2001; 2004).
According to this model a wide enough zone of intense rainfall (i.e., higher erodibility) over an area of steep topographic gradients should delineate a zone with higher uplift and exhumation rates.



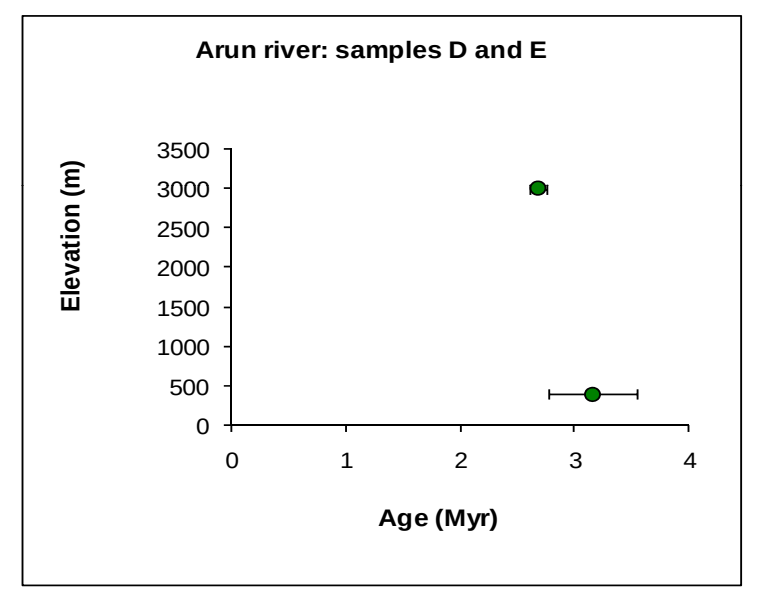
3. Cooling ages and geomorphic indices along the Arun river

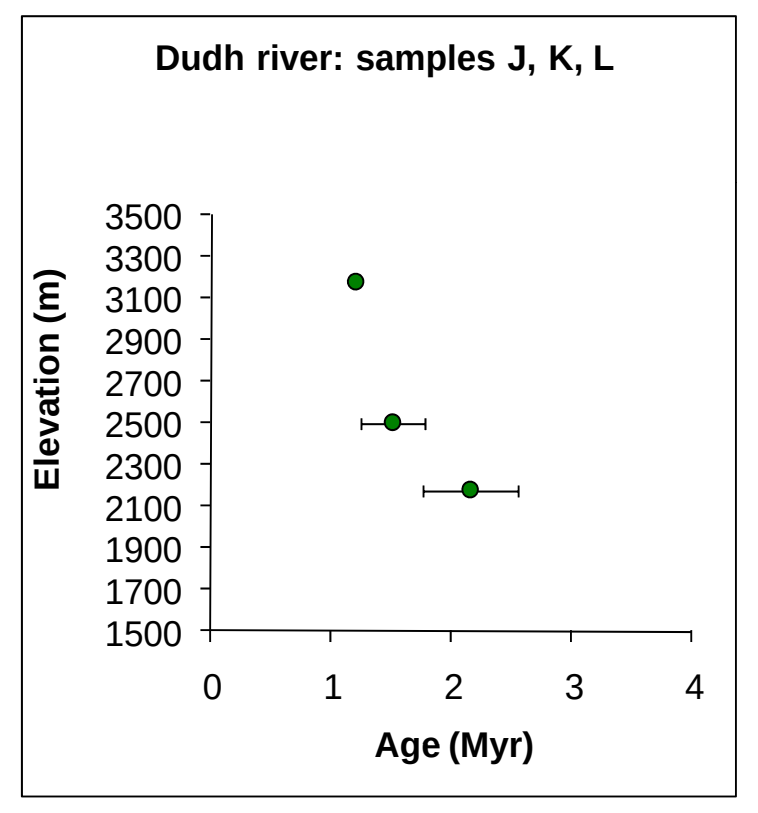


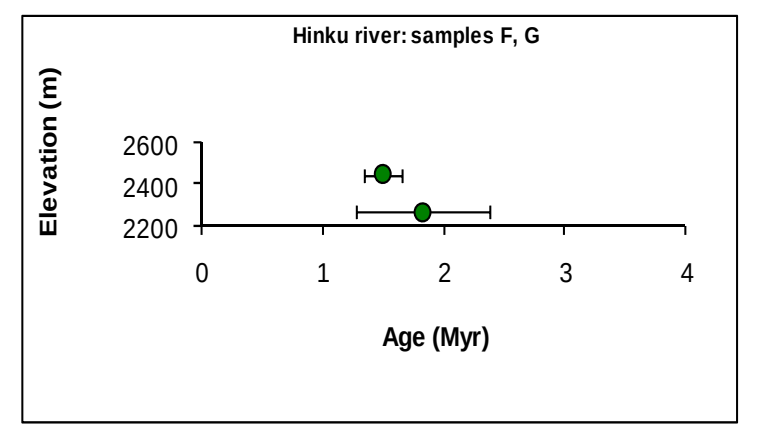


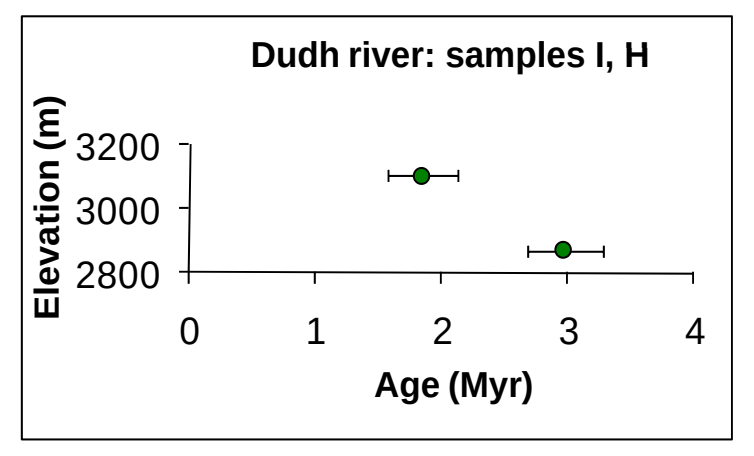
- (U-Th)/He apatite ages decrease gradually northwards from 3.2±0.4 Myr to 0.8±0.2 Myr along a 40 km transect. Active thrusting within this zone is unlikely.
- Ages at the northern edge of this zone are as young, or younger than ages ~ 50 km farther to the north along the Ama Drime massif. Spatial correlation between apatite cooling ages and geomorphic indices (median hillslope gradients, tributaries steepness, trunk knickpoints & shear stress) suggest that the zone of most rapid exhumation is ~ 50 km long. This zone only marginally overlaps the area of intense monsoon precipitation.
- Ar/Ar muscovite cooling ages decrease from 15-16 Myrs near the Main Boundary Thrust (MBT) to 11 Myr, 50 km to the north. A possible cause for this pattern is discussed in Box 6.

4. Age-elevation gradients & decreasing relief


Arun river: samples D and E


Dudh river: samples J, K, L


Hinku river: samples F, G


Dudh river: samples I, H

Preliminary results suggest that (U-Th)/He apatite ages along transects perpendicular to the convergence decrease with elevation. This abnormal pattern may result from a decrease in relief over time.
Where the local relief (R) decreases with time the age elevation gradient can be expressed as (Braun, 2002):

$$V_e\beta(\beta-\alpha)$$

V_e : vertical exhumation rate
α : the ratio between the relief of the isotherm and the topographic relief across the sampling transect.
β : the ratio between the current relief and relief at $t = t_{closure}$.

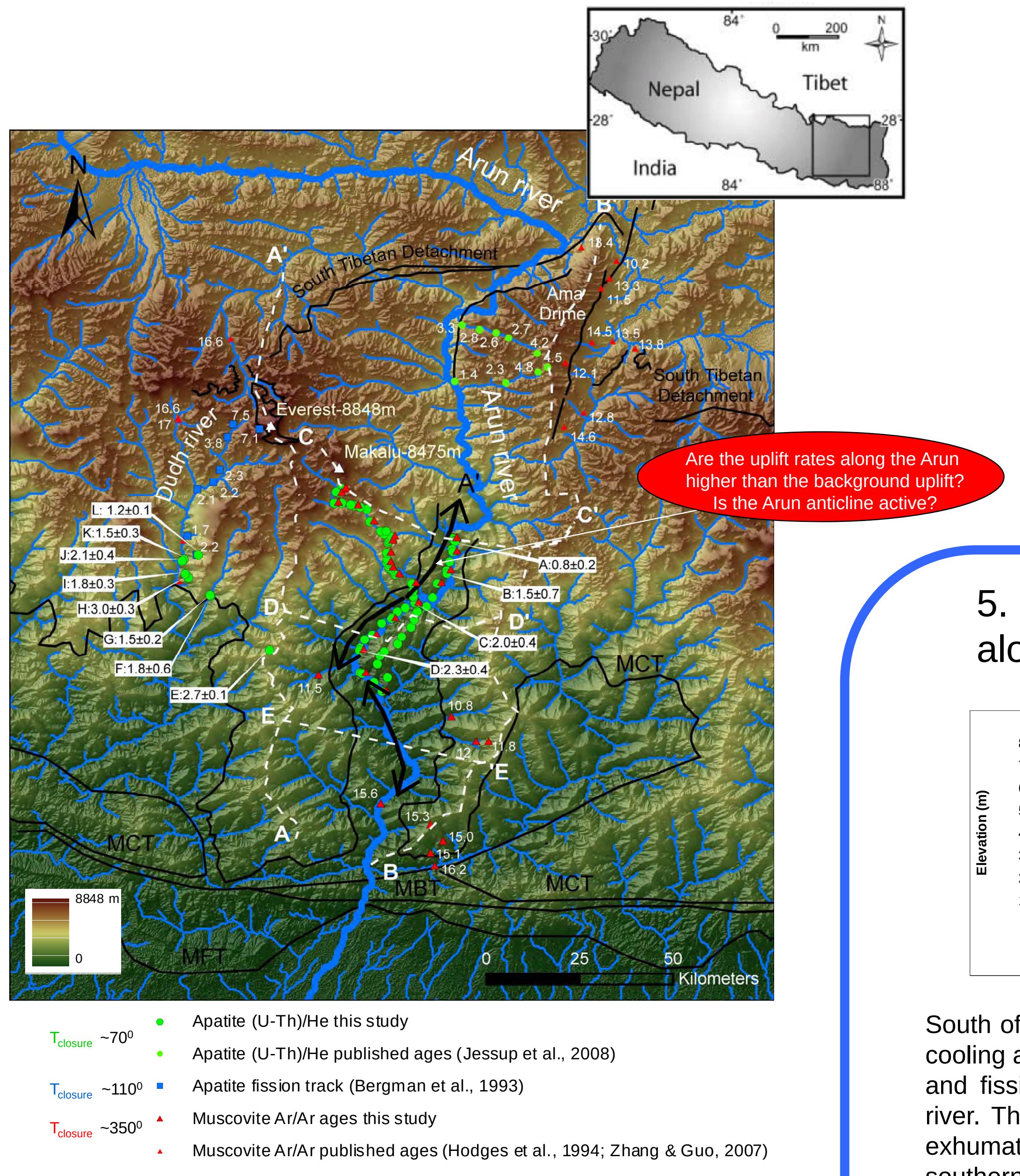
Ages will decrease with elevation where

$$\beta < \alpha$$

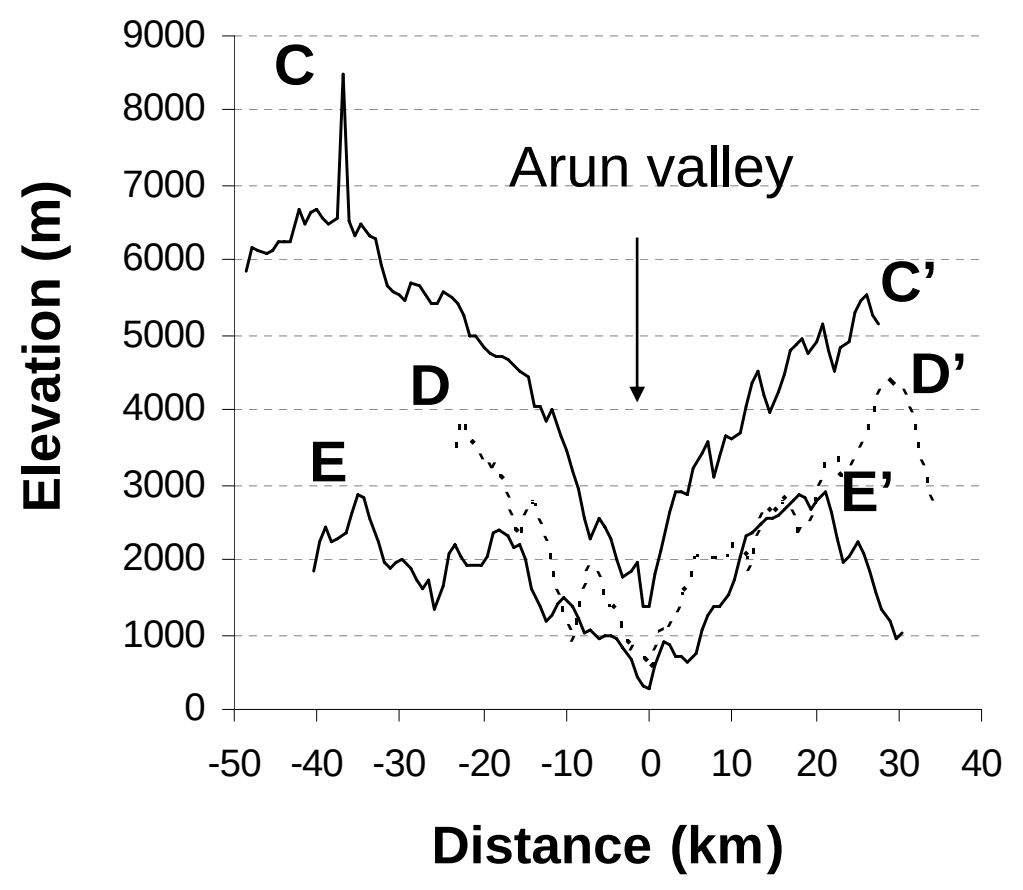
Assuming steady state topography and an overthrusting rate of V_{OT} the spatial, north-to-south decrease in relief across the high Himalaya $(\partial R/\partial x)$ can be used to estimate the temporal change in relief and β using:

$$\beta = \frac{R}{R+\Delta R_{t_{closure}}} \cong \frac{R}{R+V_{OT}t_{closure}\partial R/\partial x}$$

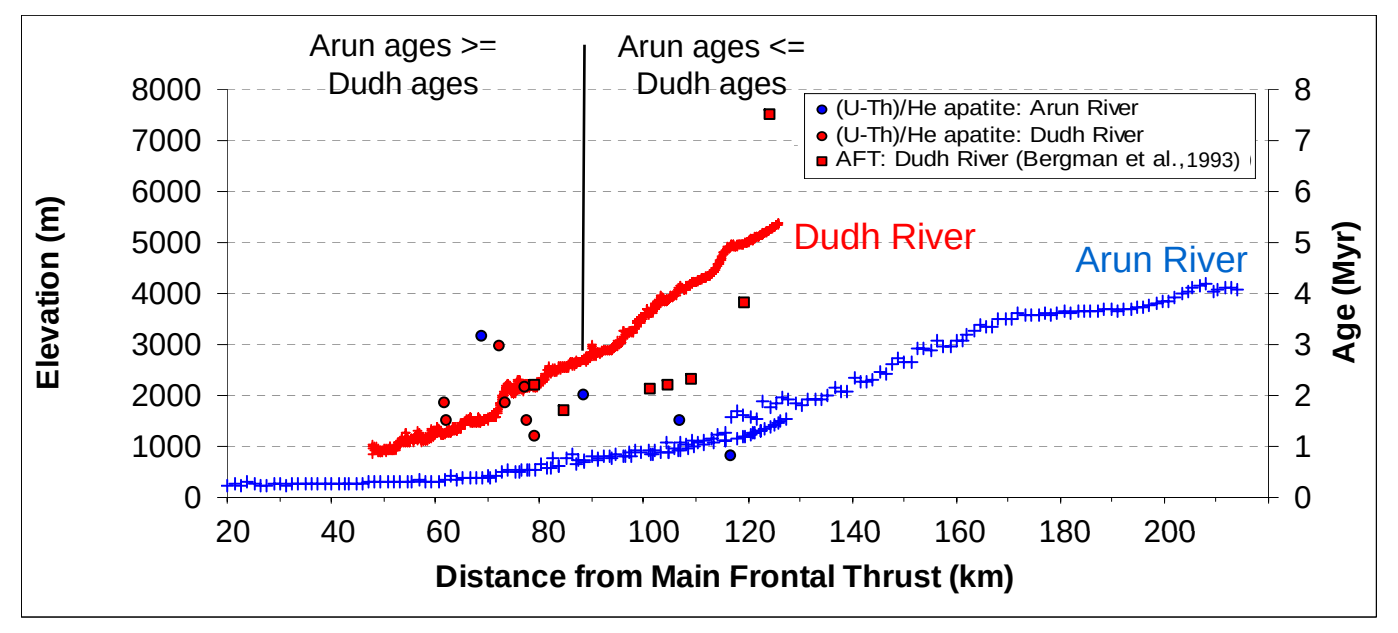
For an estimated overthrusting rate of 5-10 mm/yr (see Box 6) β is as low as 0.5-0.75 and could be lower than α .



Are the uplift rates along the Arun higher than the background uplift? Is the Arun anticline active?

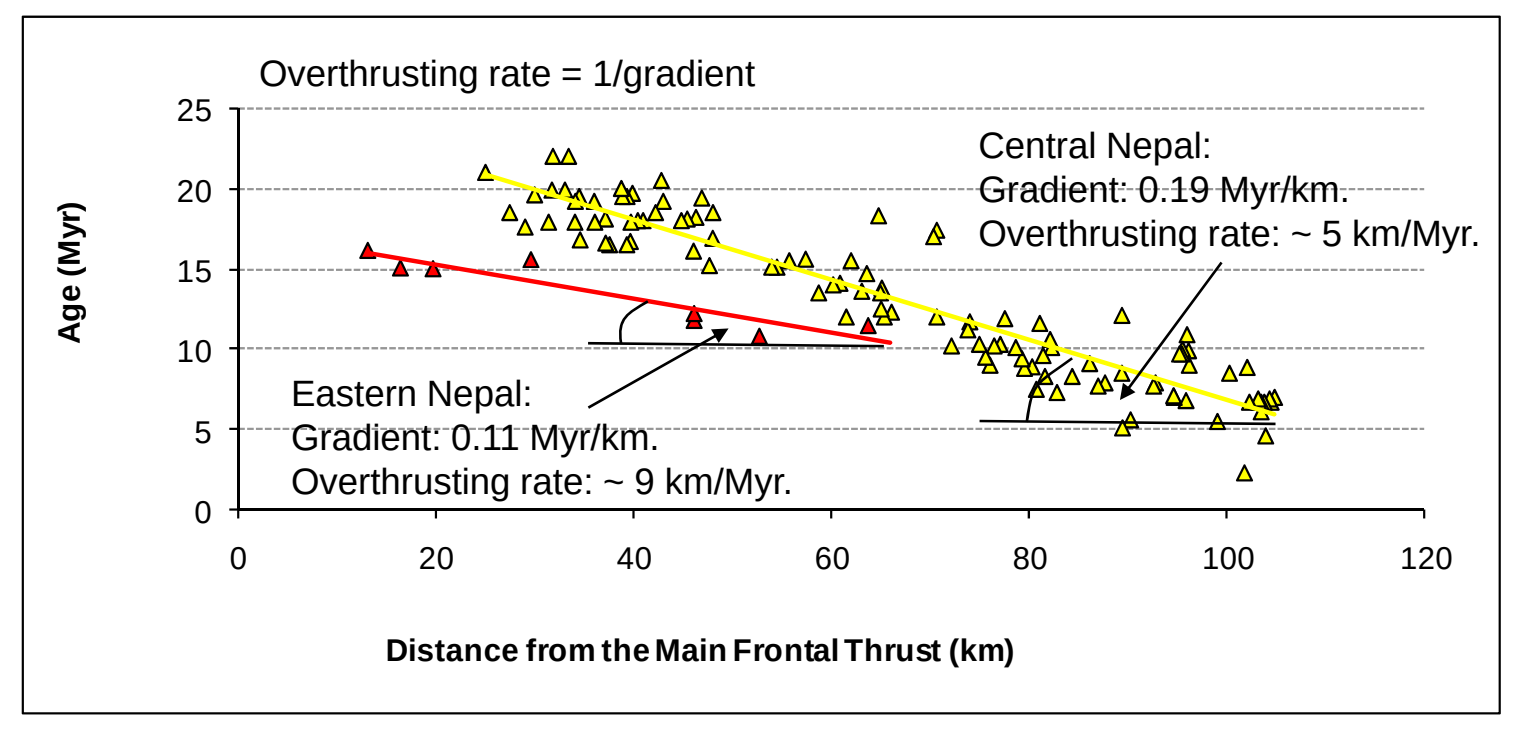


5. Enhanced uplift and exhumation along the Arun river?



South of ~90 km from the Main frontal thrust (U-Th)/He apatite cooling ages along the Arun valley are similar to both (U-Th)/He and fission track apatite ages along the much smaller Dudh river. This suggest that within this stretch long-term uplift and exhumation along the Arun valley are not amplified and the southern part of the Arun anticline is not significantly active.
Farther to the north ages along the Arun valley are younger than ages along the Dudh valley. This could suggest more rapid exhumation along the Arun valley but more data is needed in order to be conclusive.

6. Eastern Nepal *vs.* central Nepal



In eastern Nepal the gradient in muscovite Ar/Ar cooling ages as a function of the distance from the MFT is lower by a factor of ~2 relative to the gradient in central Nepal.
Bollinger et al., 2004 demonstrated that gradients in cooling ages observed across central Nepal could be interpreted as ~$1/V_{OT}$ were V_{OT} is the overthrusting rate.
Applying similar reasoning to the data of eastern Nepal suggests a west-to-east increase in the overthrusting rate from ~ 5 mm/yr to ~ 9 mm/yr across a distance of 200 km.

7. Future work

We expect to obtain several tens of additional apatite and zircon (U-Th)/He ages as well as 20 additional muscovite Ar/Ar ages. Our samples will span an elevation range of 300 m to 5750 m. Modeling utilizing a coupled thermo-kinematic (Pecube) and surface processes model (Cascade) will commence thereafter.

8. Preliminary conclusions

- A gradual, rather than abrupt, increase in cooling ages along the bottom of the Arun Valley, does not support out-of-sequence thrusting at the front of the range.
- (U-Th)/He apatite cooling ages along the Arun River and the Dudh Kosi suggest that the southern part of the Arun anticline is not significantly active. Future thermochronologic data will enable to constrain the activity along the northern part of this structure.
- (U-Th)/He Cooling ages along the Arun River are decoupled from precipitation.
- The gradient in Ar/Ar muscovite cooling ages as a function of the distance from the Main Frontal Thrust in eastern Nepal is lower by a factor of two relative to central Nepal. This may suggests a west-to-east increase in the overthrusting rate from ~ 5 mm/yr to ~ 9 mm/yr across a 200 km stretch.
- Observed age-elevation gradients are apparently consistent with a temporal decrease in local relief due to significant overthrusting rates.