Low-temperature thermochronology

Lesson 1.2 - Applications of thermochronology

David Whipp

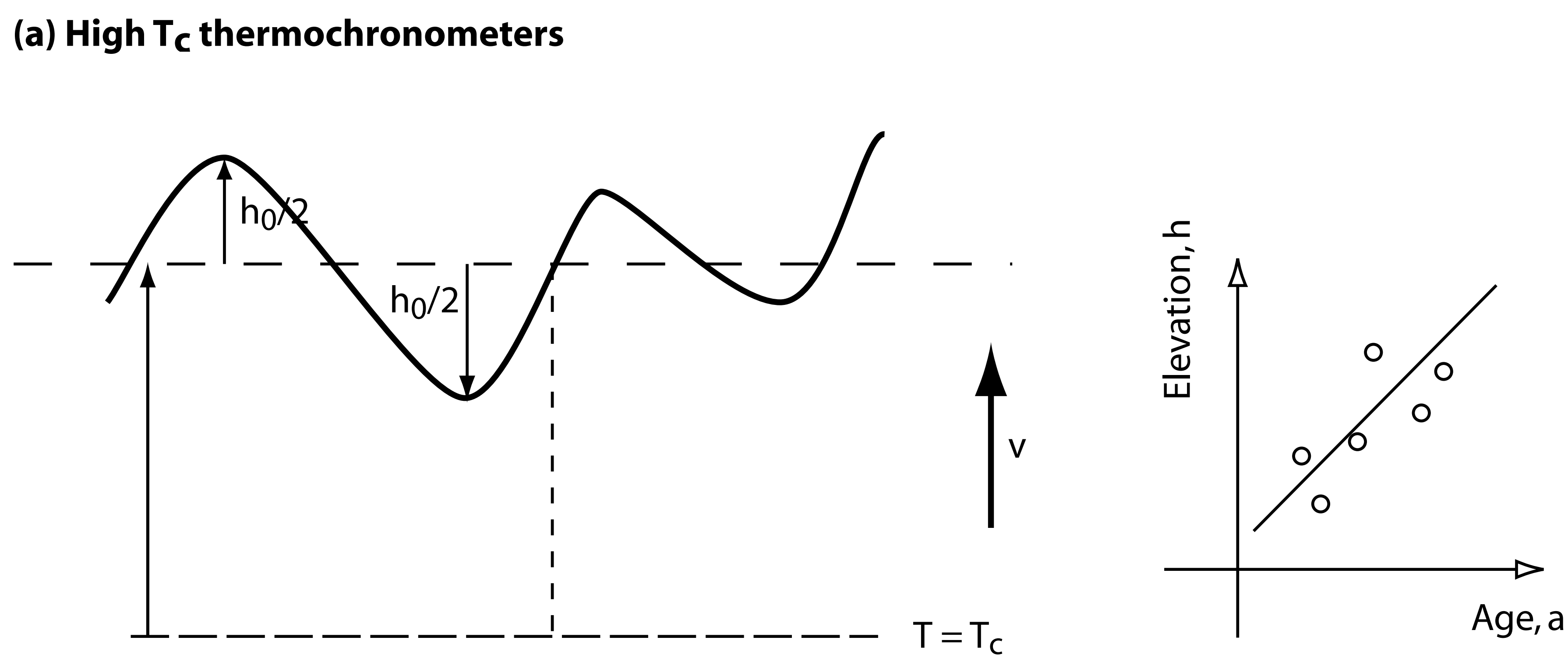
Goals for this lecture

- Discuss methods for converting thermochronometer ages into long-term rates of **rock exhumation**
- Take a look at **thermochronometer data interpretation** by way of a geological excursion to the Nepalese Himalaya

Estimating exhumation rates

- A major focus with low-temperature thermochronometer data is <u>linking ages with rates of rock exhumation</u> as we saw in the previous lecture
    - With the concept of an effective closure temperature, we can relate a thermochronological age to a temperature
    - In order to convert the age to an exhumation rate, however, we must then determine the depth to that paleo-temperature or take advantage of other "tricks"

The age-elevation approach



Braun, 2002a

- As we've seen previously, for high-temperature thermochronometers, the effective closure temperature isotherm will not be "bent" by the surface topography
    - This geometry can be very useful because with it we can estimate long-term average rates of rock exhumation

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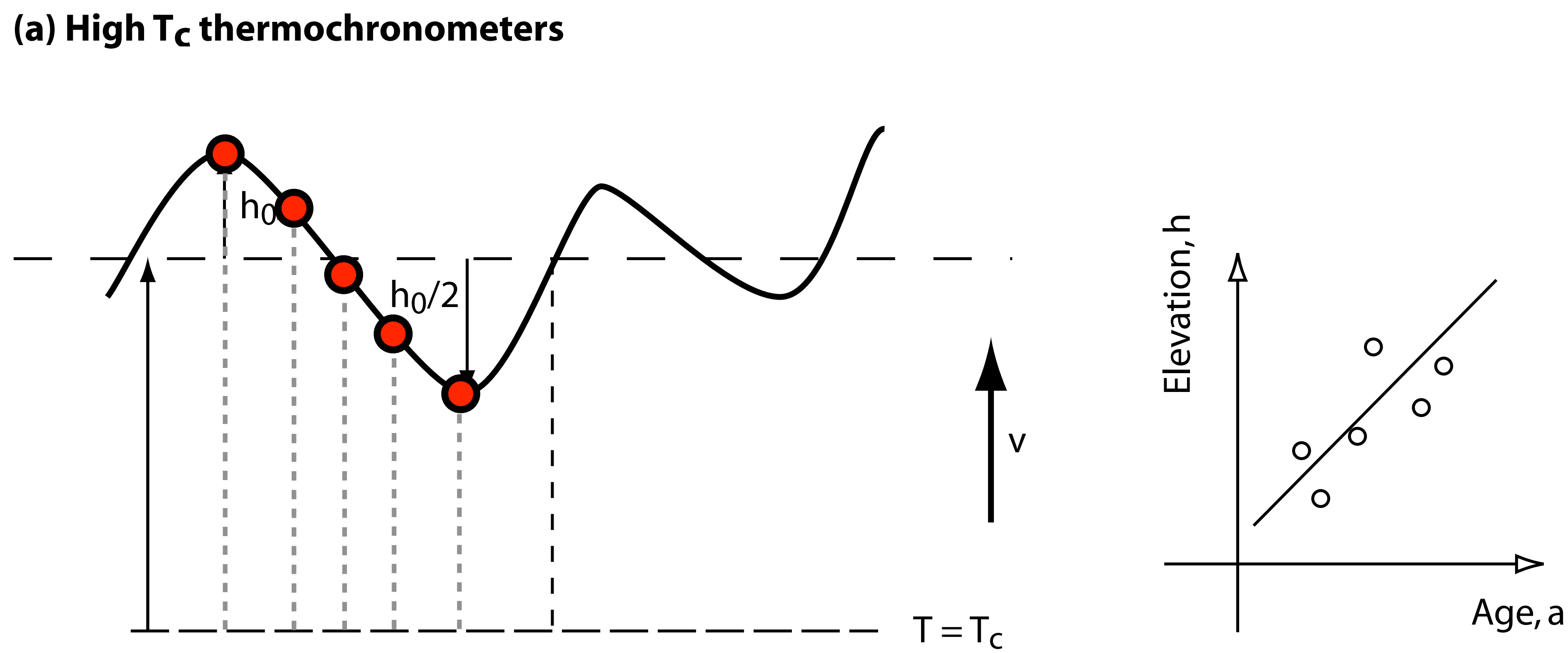

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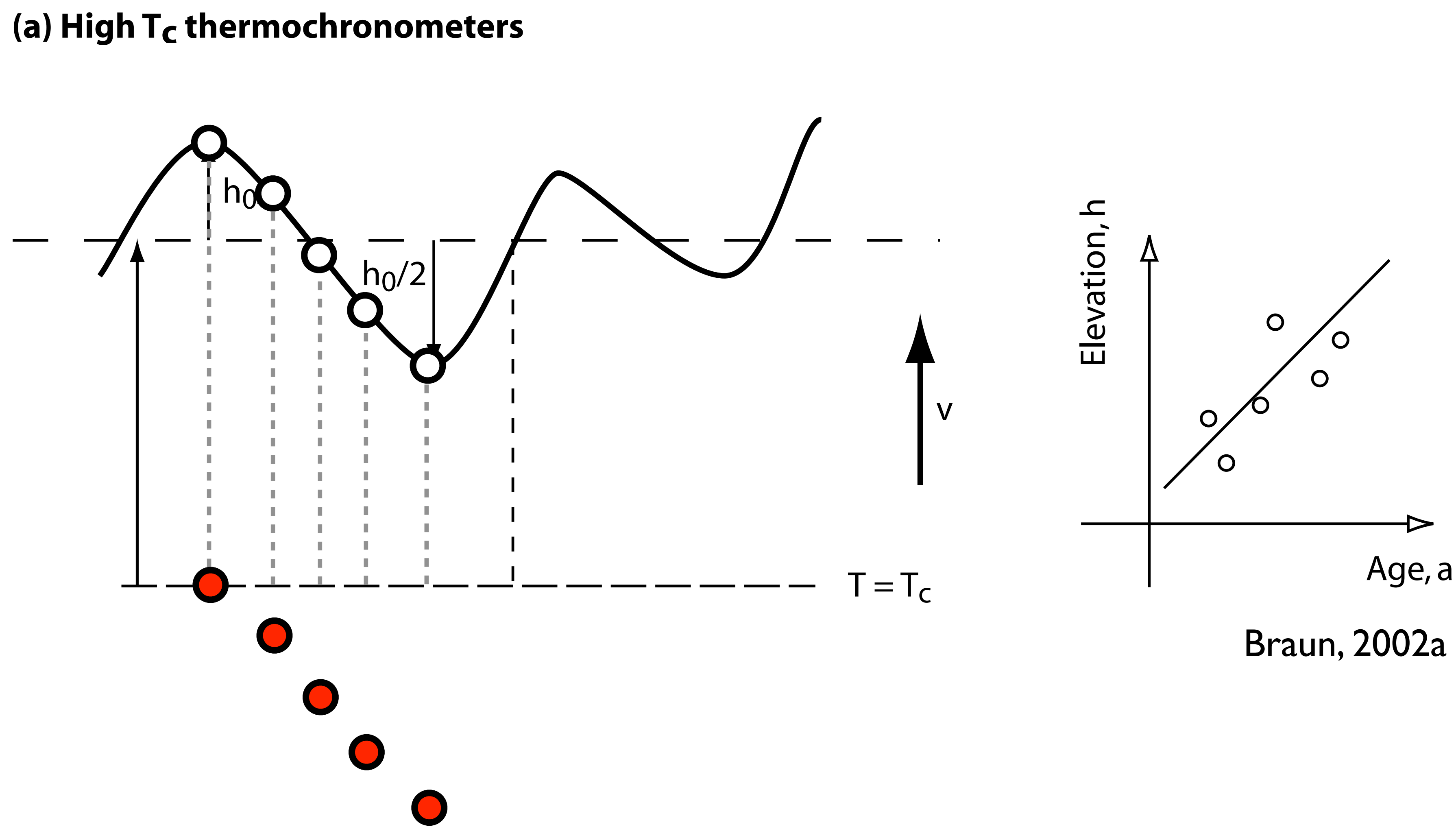

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- If we consider the exhumation of these samples from the time the first cools, we can see why…

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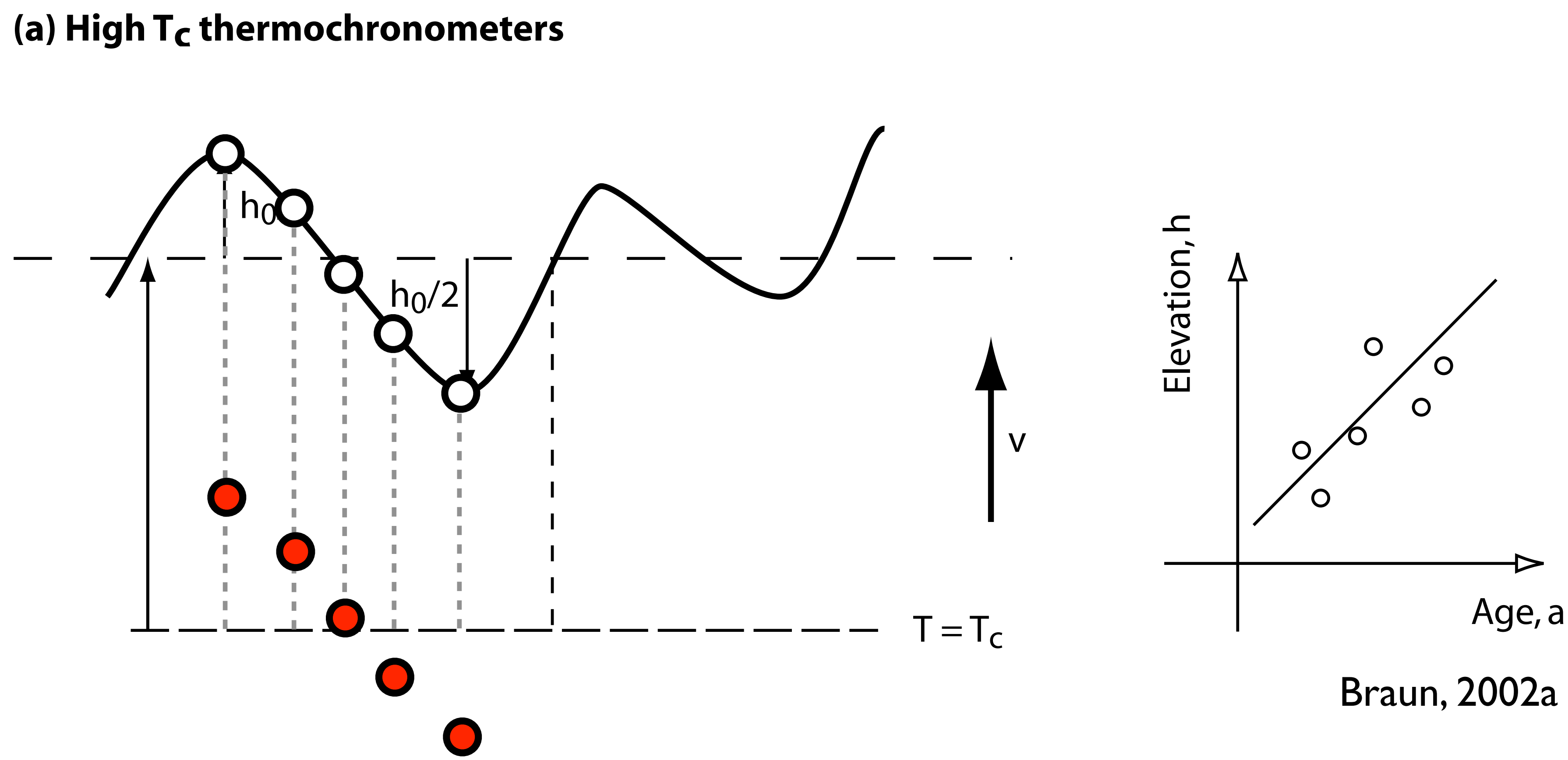

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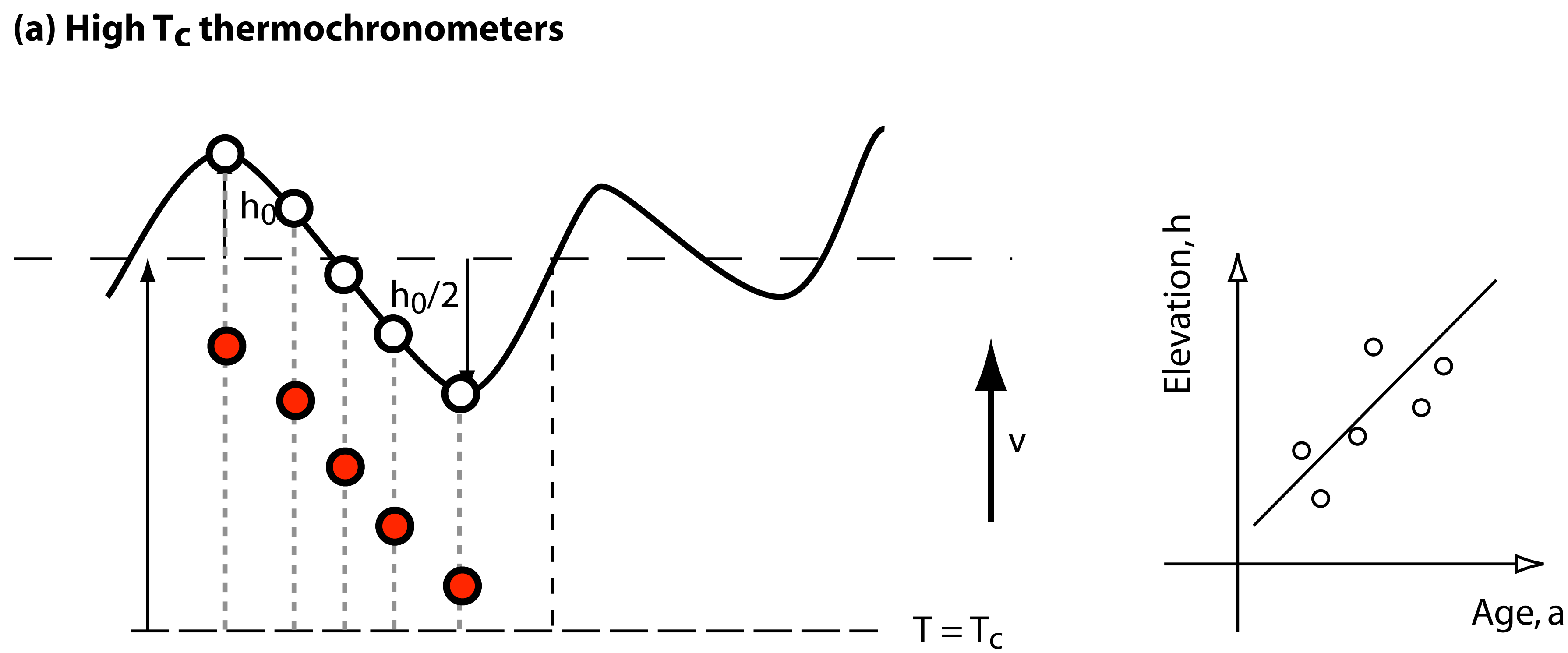

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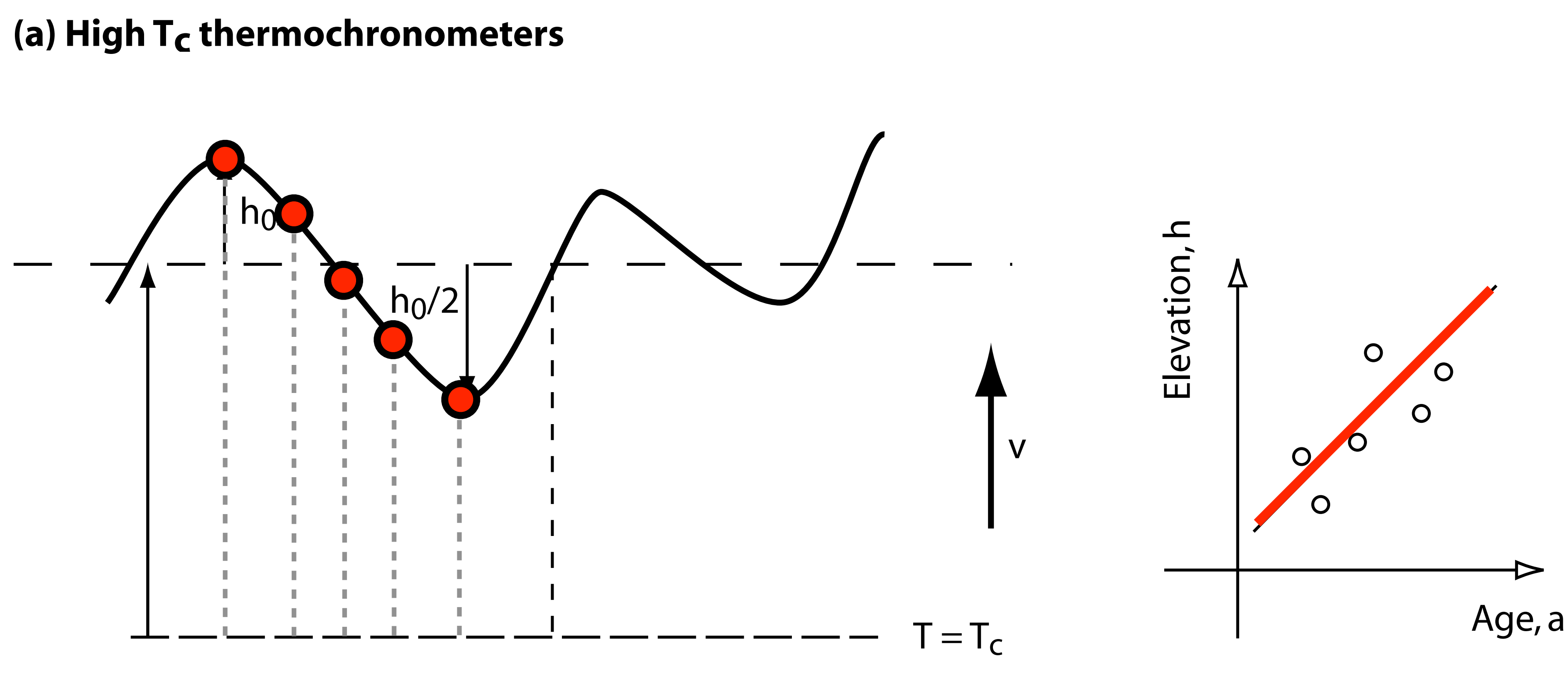

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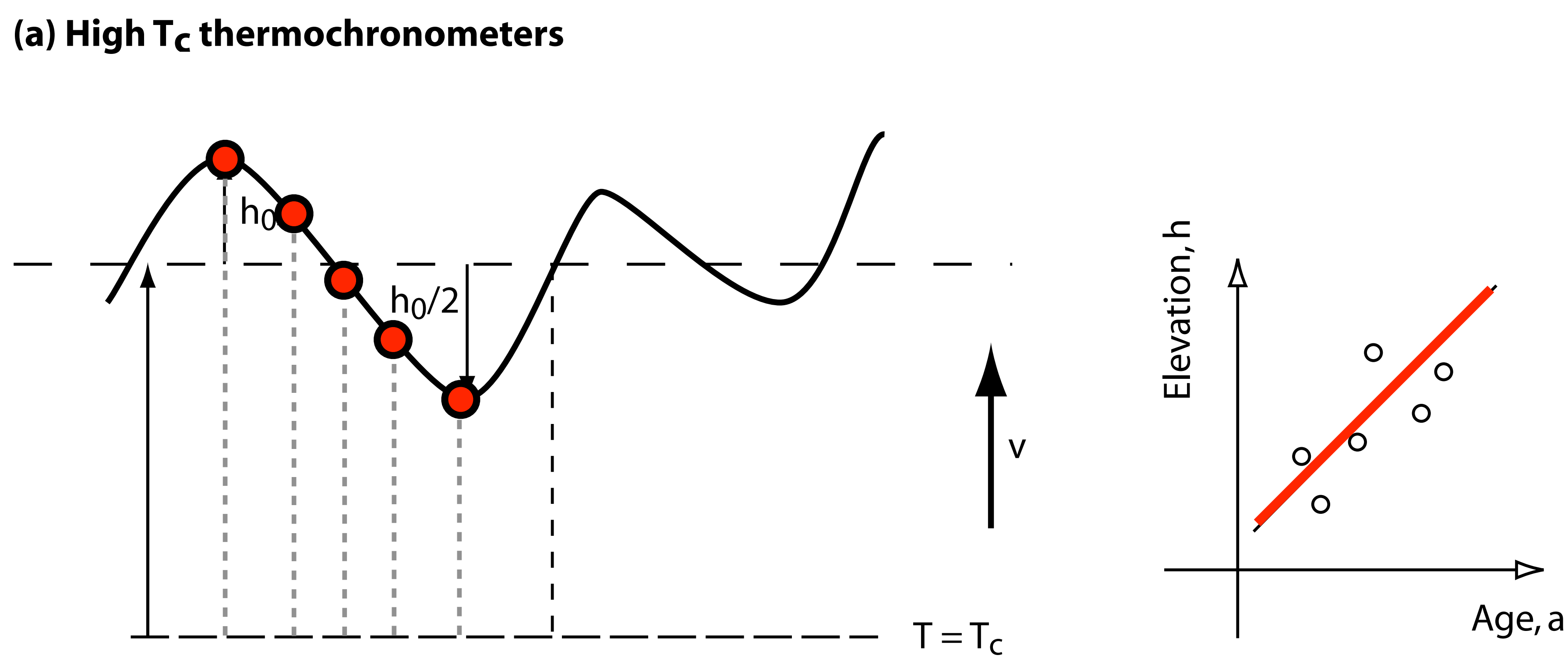
- What you'll notice is that the difference in age for the samples only results from the time since they passed through the effective closure temperature isotherm
- In other words, the slope of the relationship between sample age and elevation is the long-term exhumation rate (!)

The age-elevation approach



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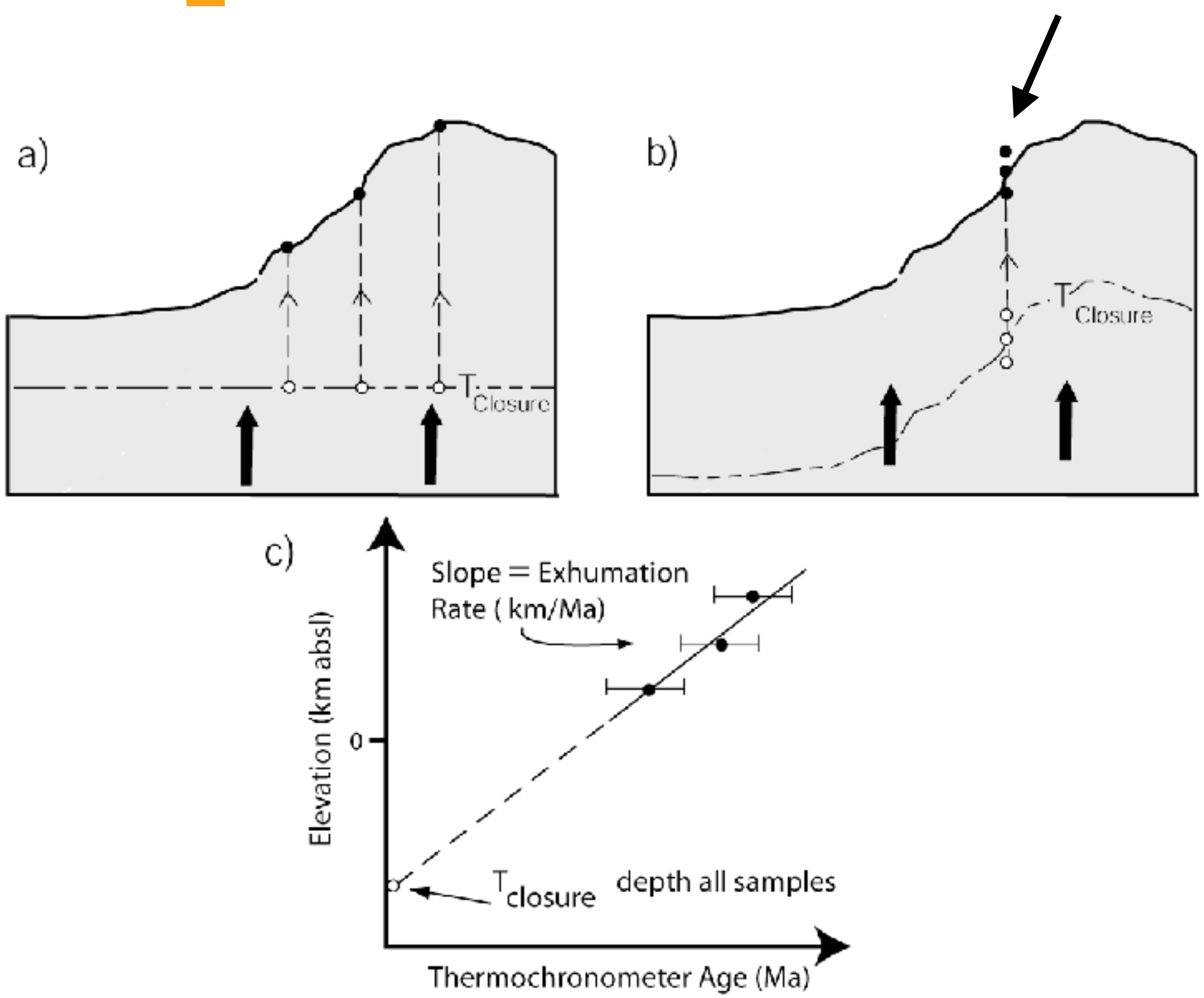
Scenarios where this technique works…

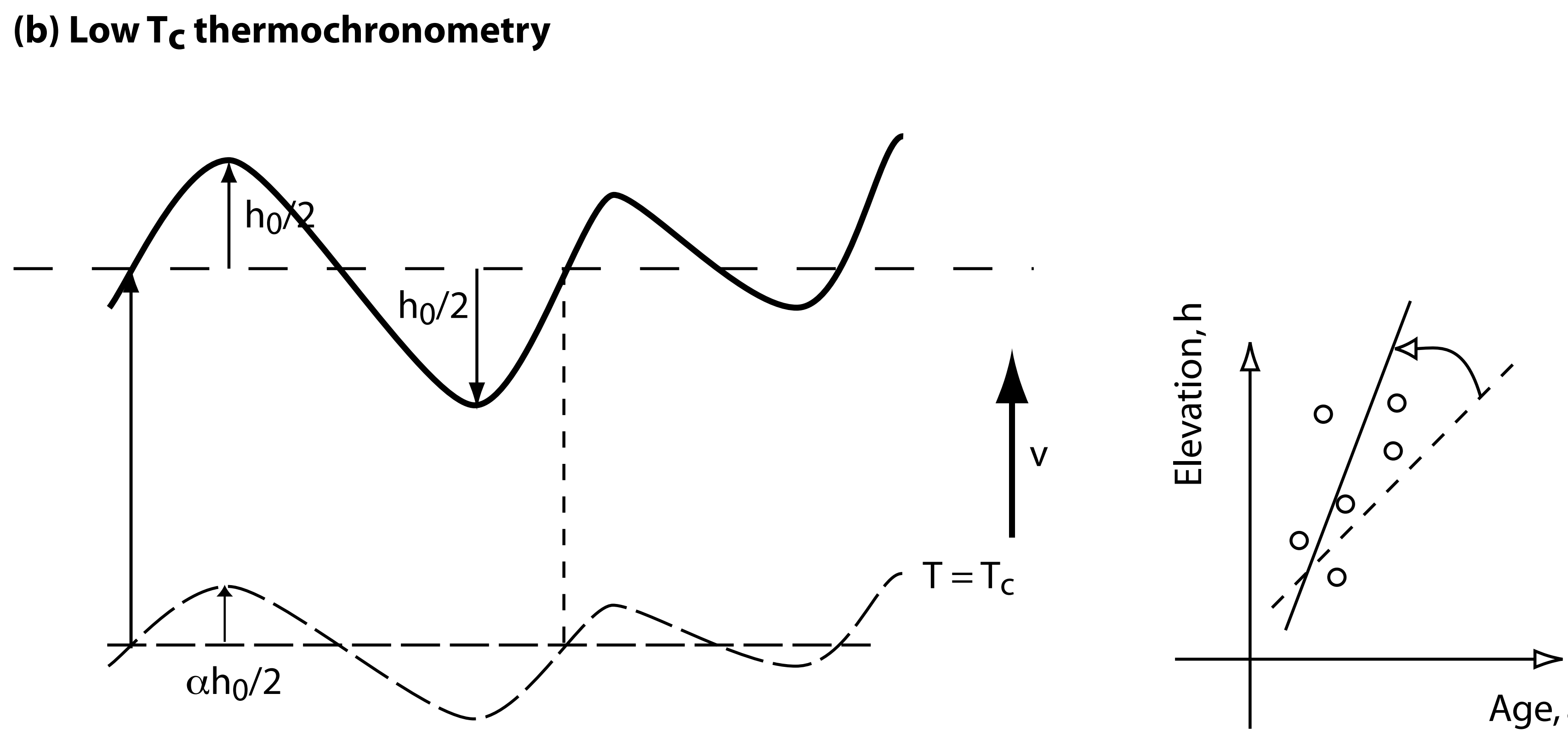
Vertical transect



Ehlers, 2005

- There are two situations in which this technique "works":
  - When the closure temperature isotherm is flat
  - When samples are collected along transects parallel to the exhumation pathway (typically this is vertical sampling)

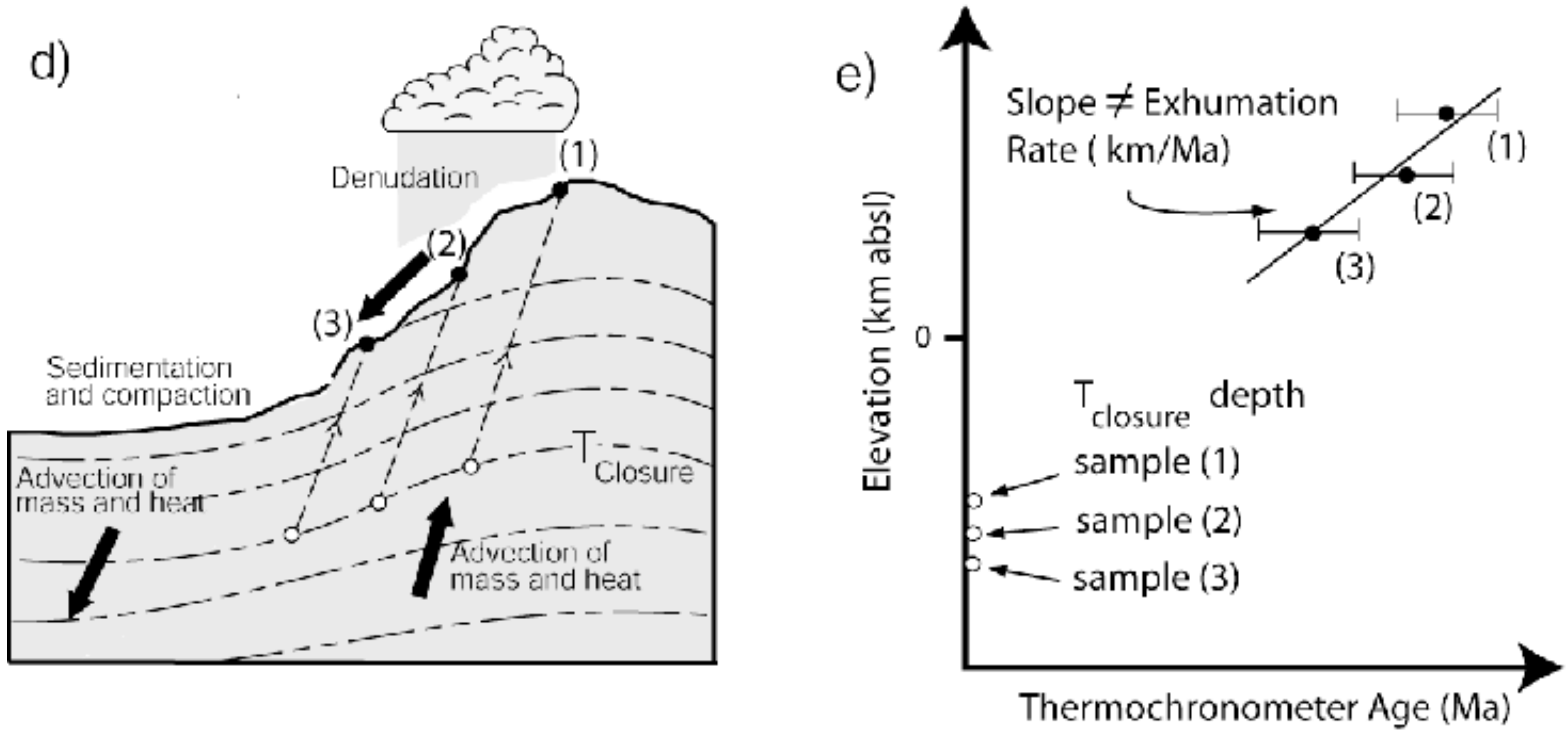
The trouble with low-T thermochronology



Braun, 2002a

- As we've seen, however, low-temperature thermochronometers are sensitive to the surface topography and their effective closure temperature isotherms will be "bent" because they are close to the Earth's surface

The trouble with low-T thermochronology



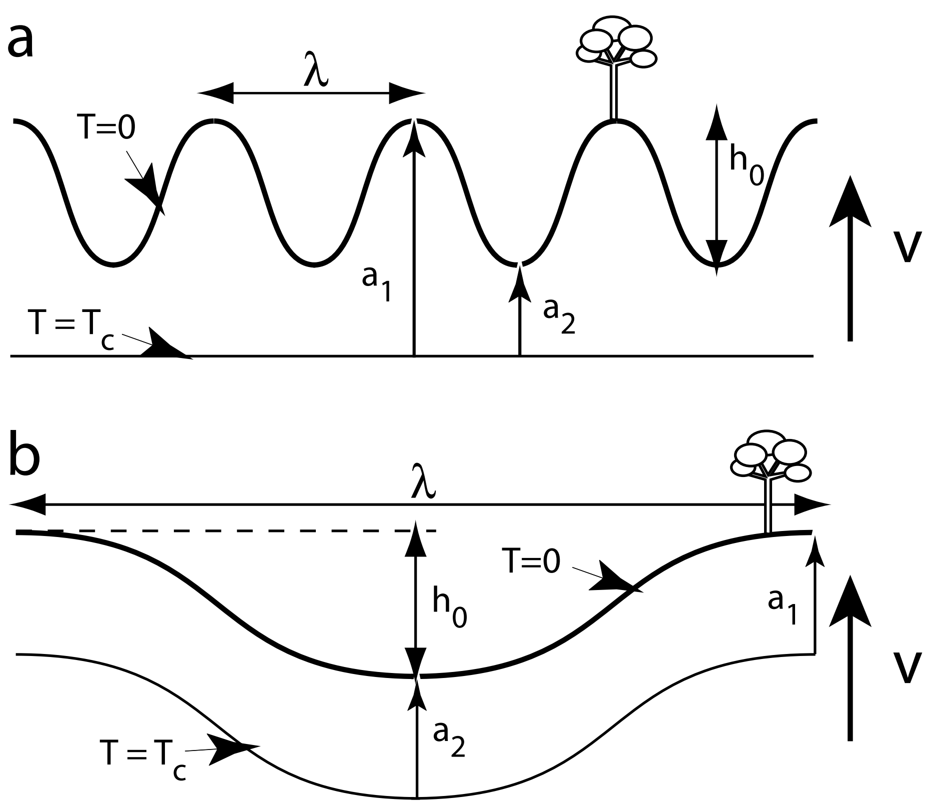
Ehlers, 2005

- In this case, the relationship between sample age and elevation will not recover the long-term average exhumation rate, providing an overestimate

Topographic sensitivity

- As we have seen, the magnitude of topographic bending of effective closure temperature isotherms generally decreases for higher temperature thermochronometers
- In addition, the average wavelength of the topography is important, with short wavelength topography producing less bending of subsurface isotherms
- Furthermore, the advection velocity for rock exhumation is also significant, with a larger amount of bending at higher rates of exhumation

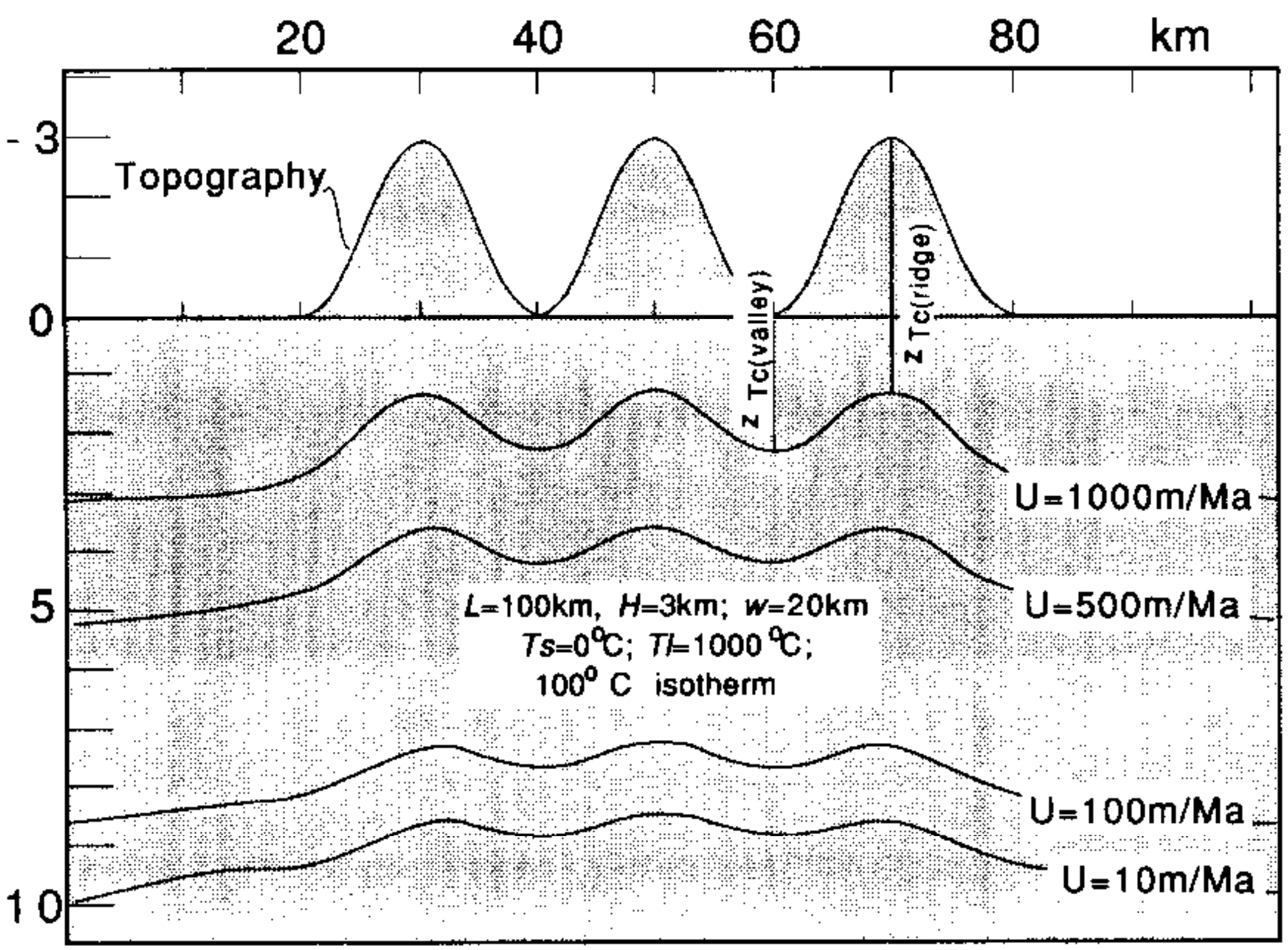
Topographic sensitivity



Braun, 2002b

- Short wavelength topography can have high relief, but tends not to bend subsurface isotherms at depth
- For very long wavelengths, the subsurface isotherms may even exactly mimic the surface topography
- The magnitude of this effect can be estimated mathematically, of course :)

Topographic sensitivity



Stüwe et al., 1994

- The rate of rock exhumation is another important consideration
  - As we can see, higher rates of exhumation push closure temperature isotherms closer to the surface, resulting in increased bending
  - For slow exhumation, or high-temperature systems, the bending effect is minimal

Alternatives: Constant geothermal gradient

- An alternative method for determining exhumation rates from thermochronometer ages is to assume a constant geothermal gradient, use that to estimate the depth to the closure temperature, and calculate an exhumation rate using the age

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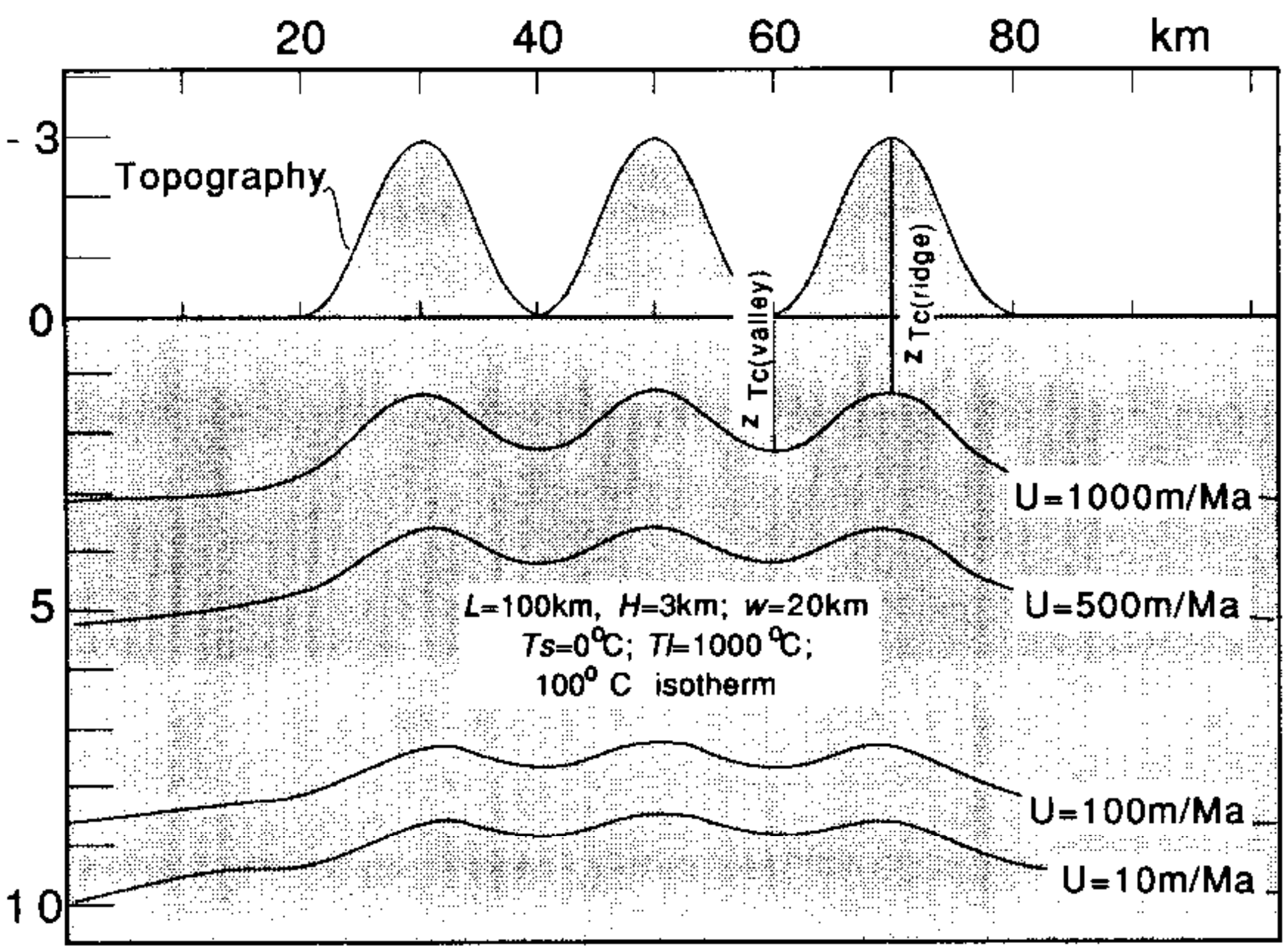
- Assume we have an apatite (U-Th)/He thermochronometer age of 4.2 Ma, and that the effective closure temperature is 75°C

- **What is the average rate of exhumation assuming a constant geothermal gradient?**

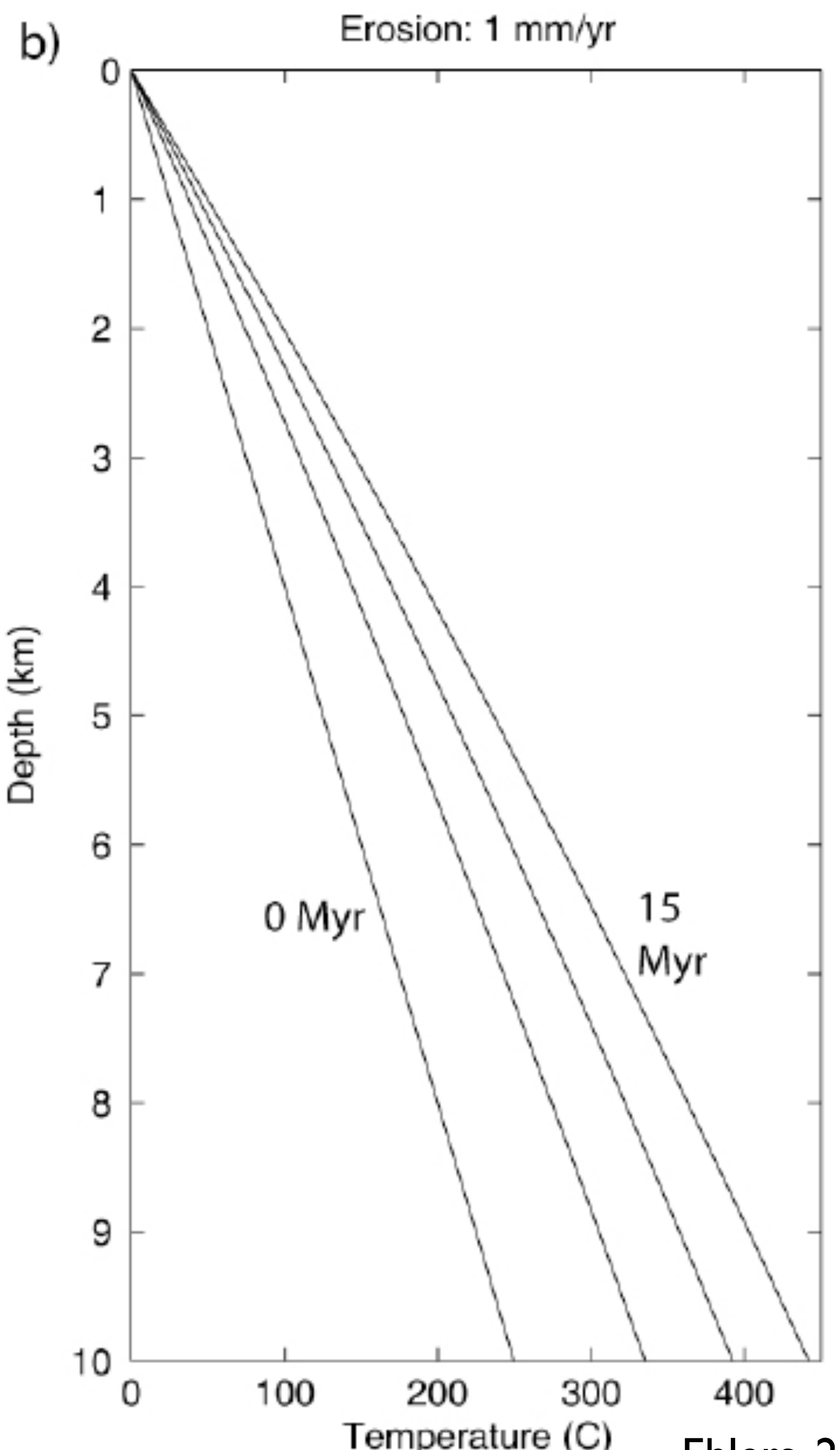
Alternatives: Constant geothermal gradient



Stüwe et al., 1994

- Assuming a constant geothermal gradients turns out to be a bad idea for low-temperature thermochronology
- There are two main issues:
  - Geothermal gradients are often steepest near the surface and lower with depth
  - Shallow crustal isotherms will be affected by topography

Alternatives: Thermal modelling



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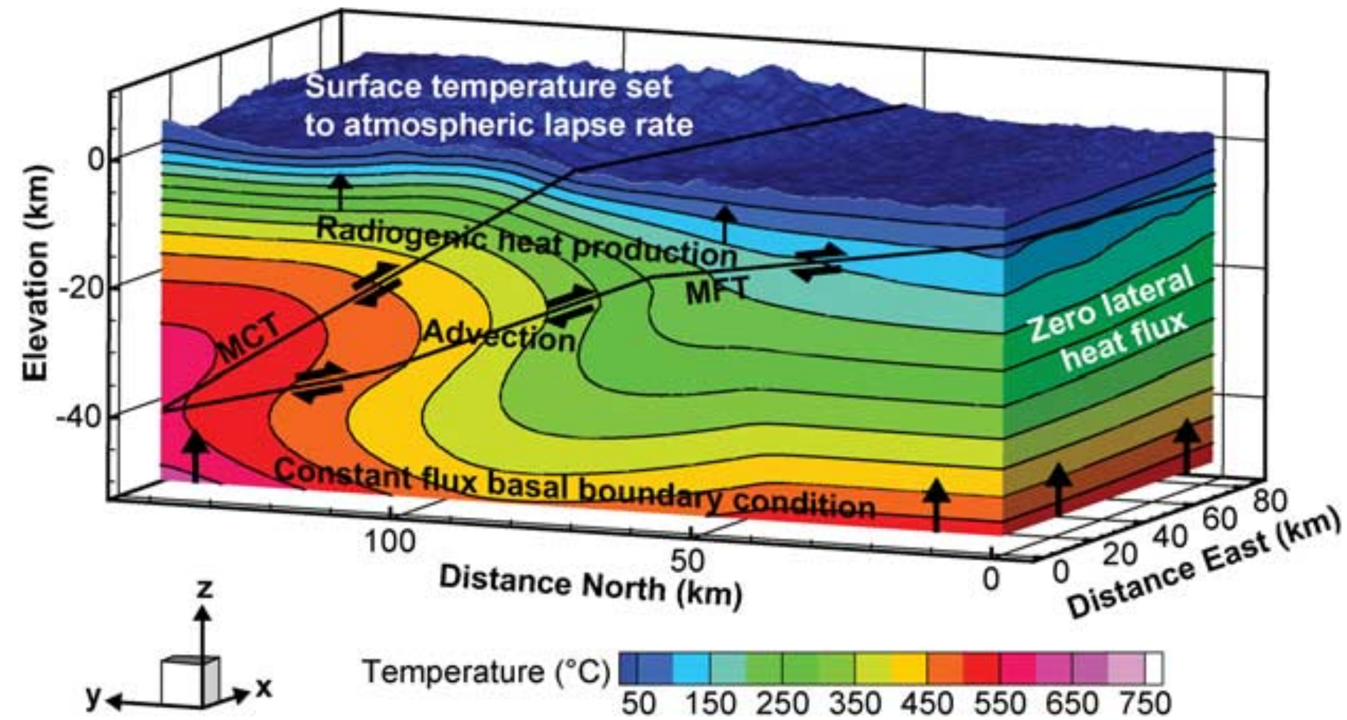
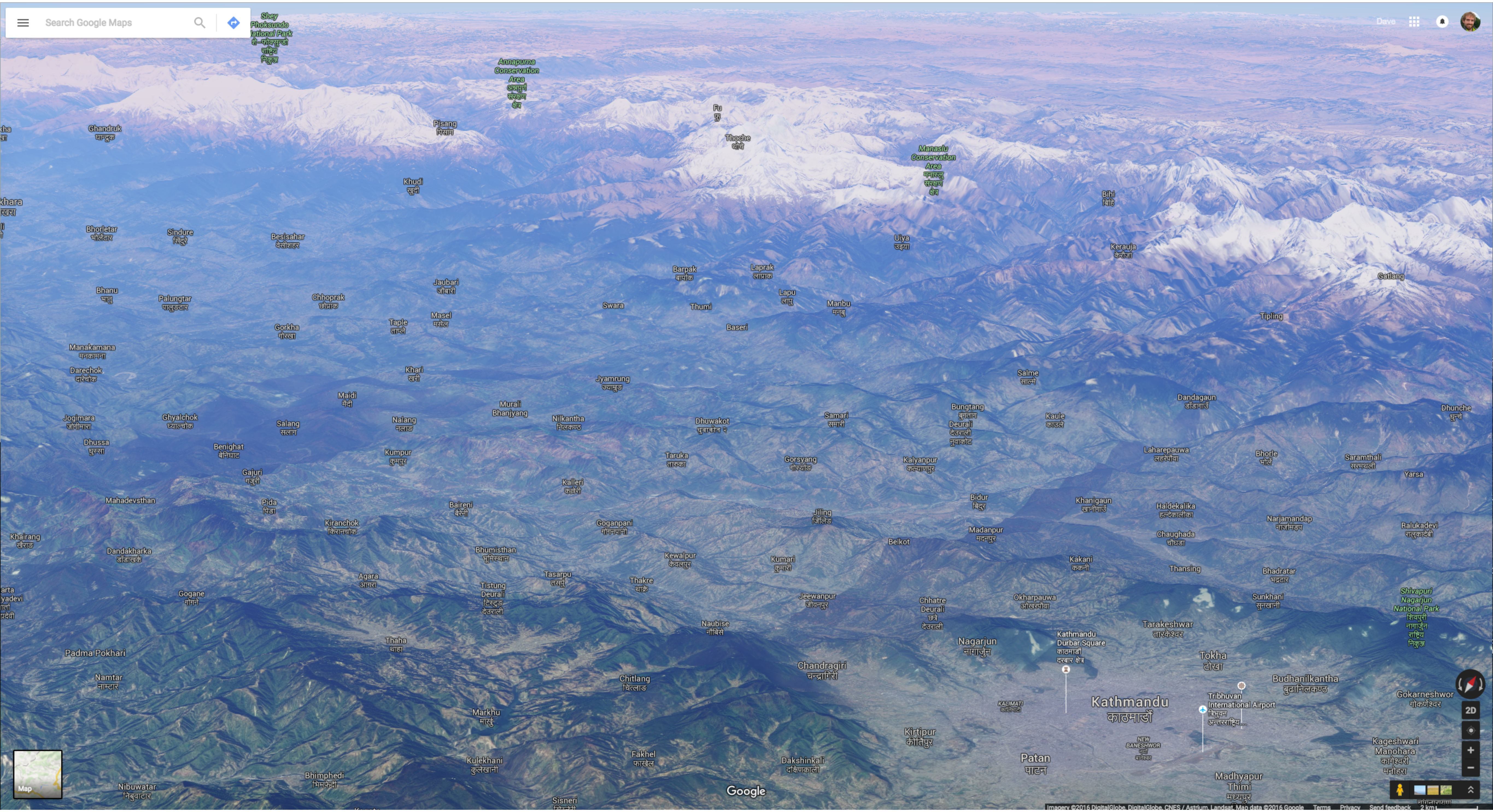


- We can account for some of the effects of changes in thermal structure with depth using **thermal models** for thermochronology
  - The complexity of the model will depend on the geological setting where samples were collected

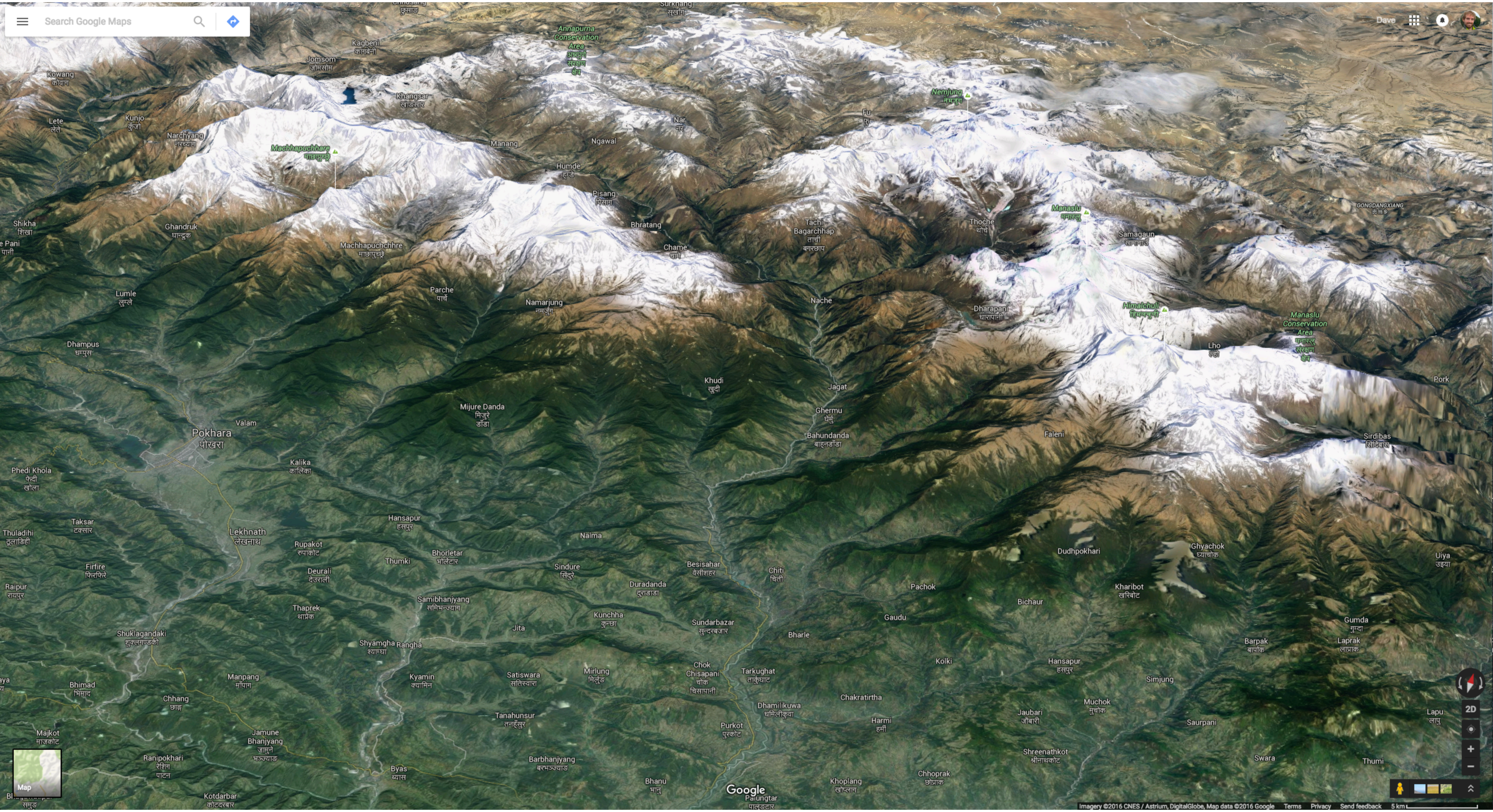
Exhumation of the central Nepal Himalaya

- We’ll now look briefly at a “case study” of how thermochronometer data and numerical models can be used to quantify rates of tectonic and erosional processes
- For the example, we’ll be in the Marsyandi River valley in central Nepal

Himalaya of central Nepal



The Marsyandi River region



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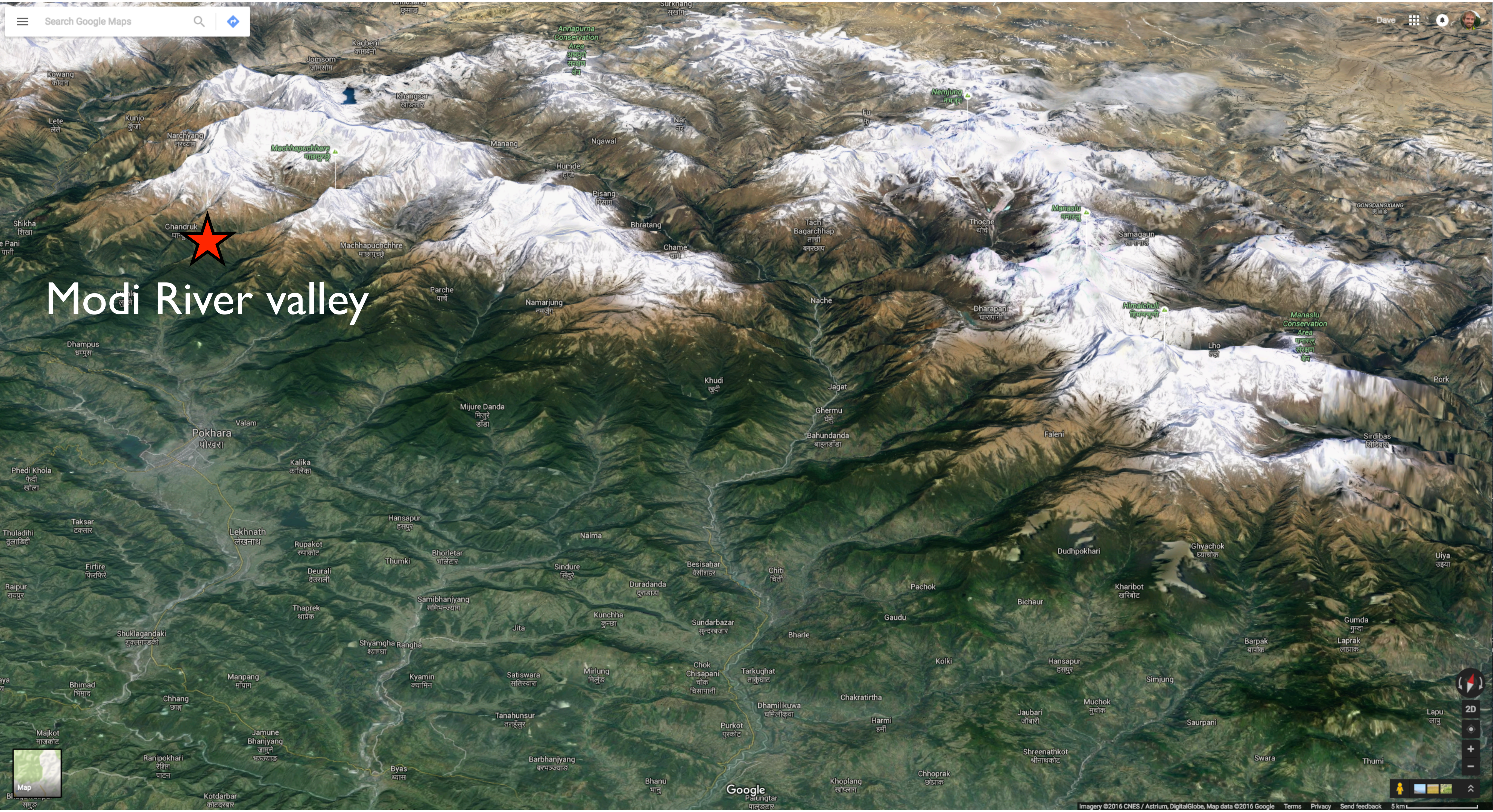



Looking north from the Lesser Himalaya


Lesser Himalayan landscape

Rhododendron forest

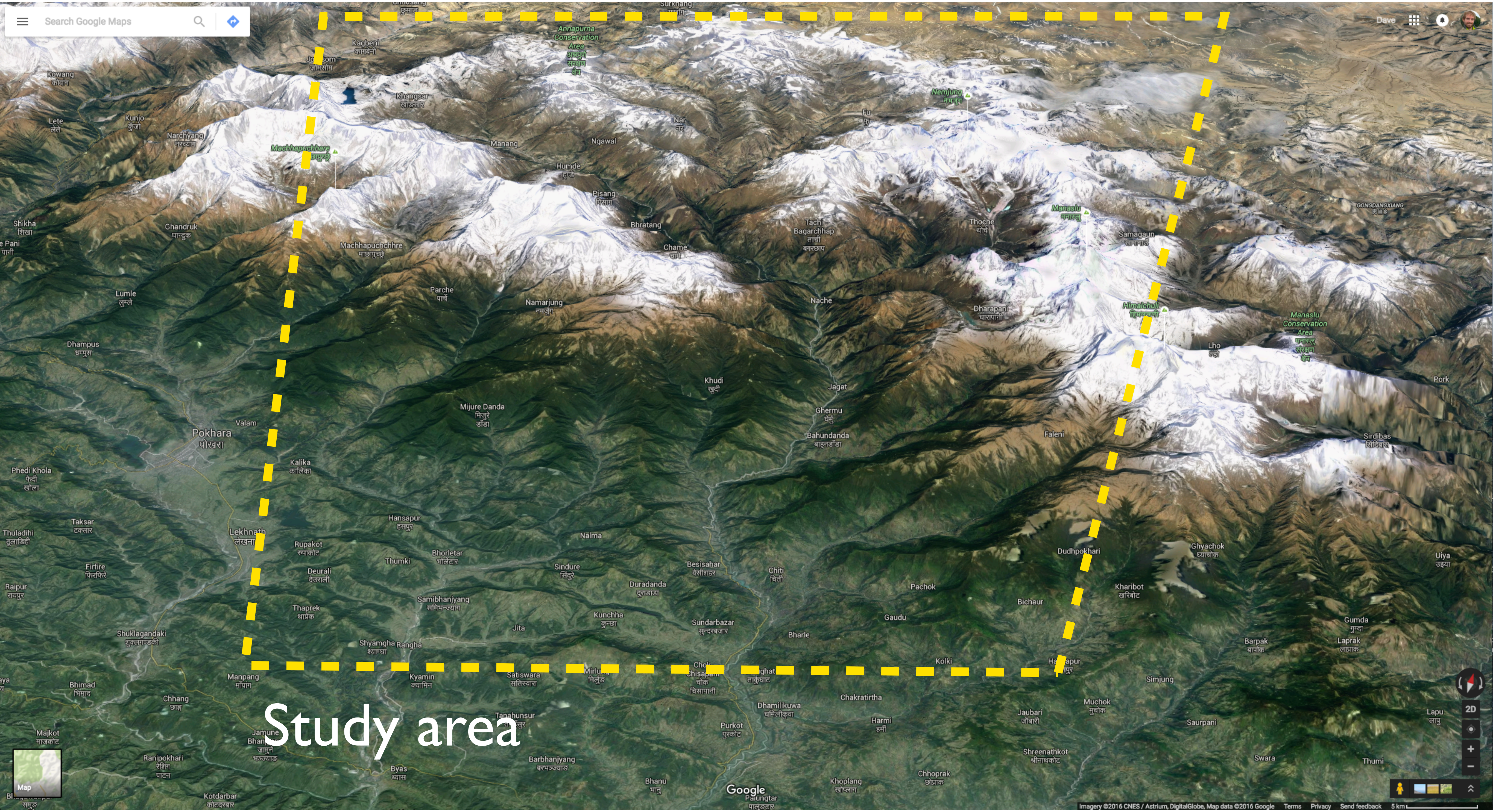
View northeast to the Dhaulagiri range


Getting closer to the high peaks

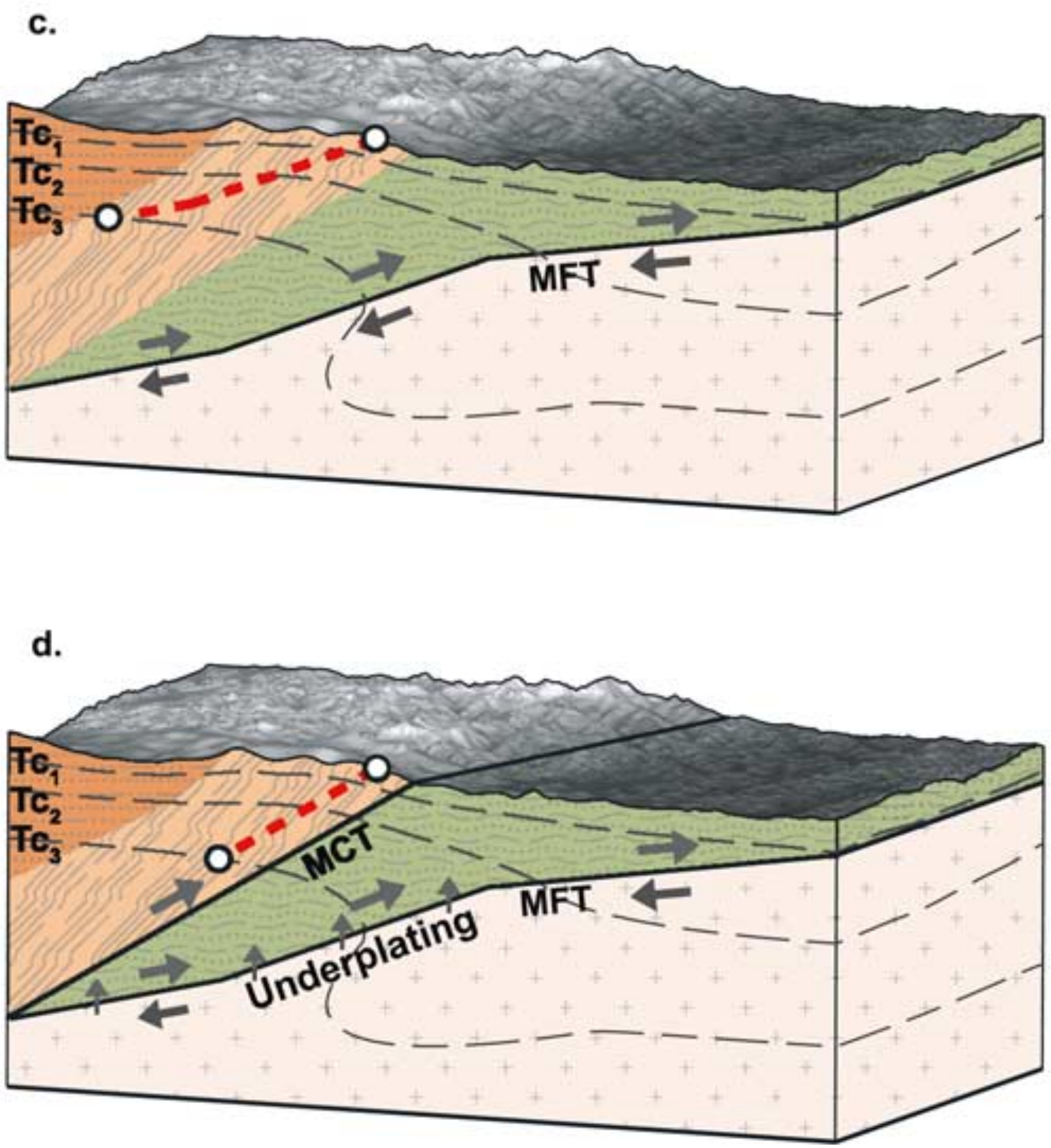

Closer still

Steeper topography entering the High Himalaya

The Marsyandi River region



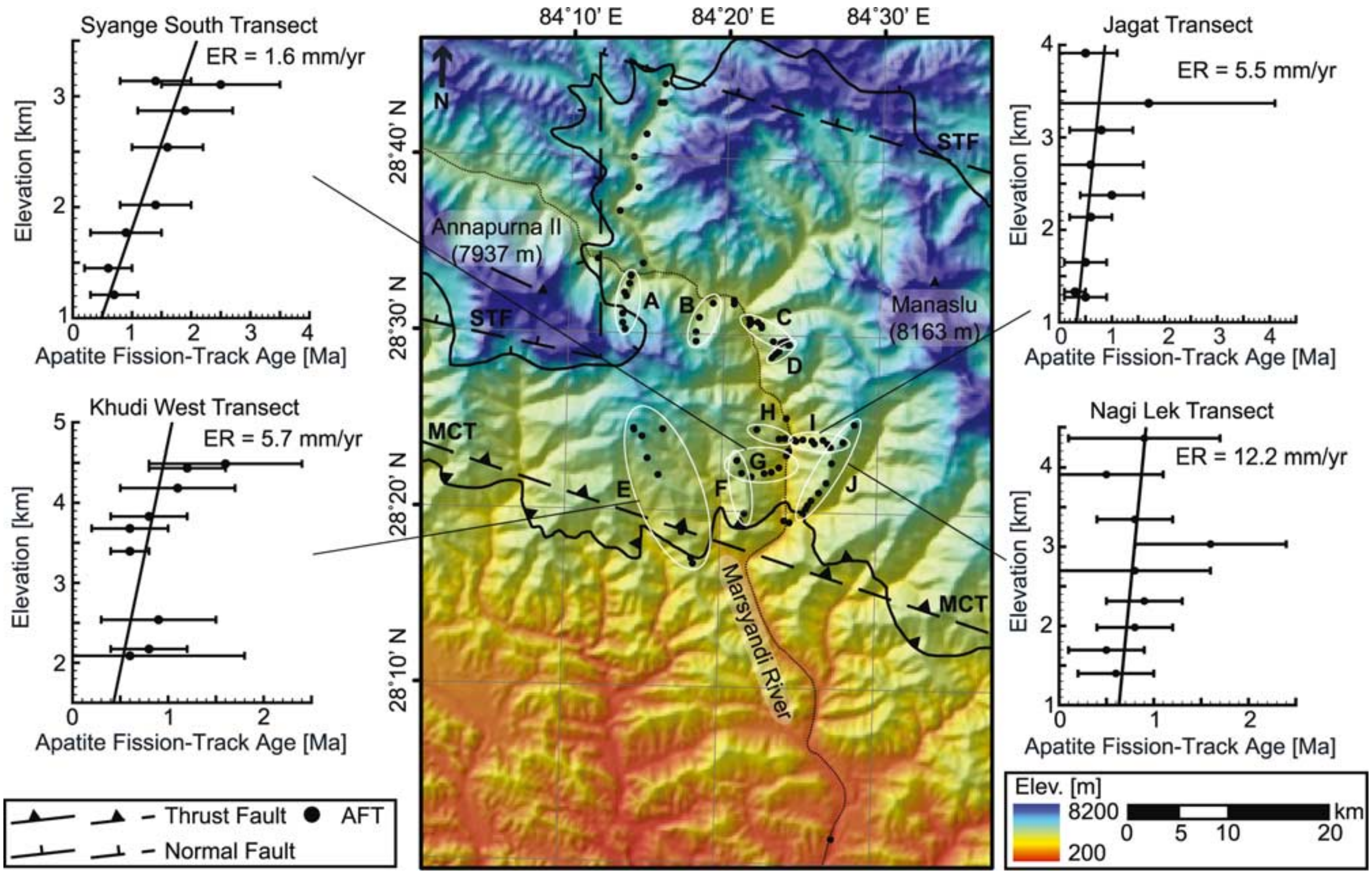
Tectonic hypothesis



Whipp et al., 2007

- We were testing the idea that the Main Central Thrust (MCT) has been reactivated since its main period of activity ending in the Middle Miocene
- The underlying idea was that monsoon precipitation may have eroded enough material locally to reactivate this older fault

Apatite fission-track dataset



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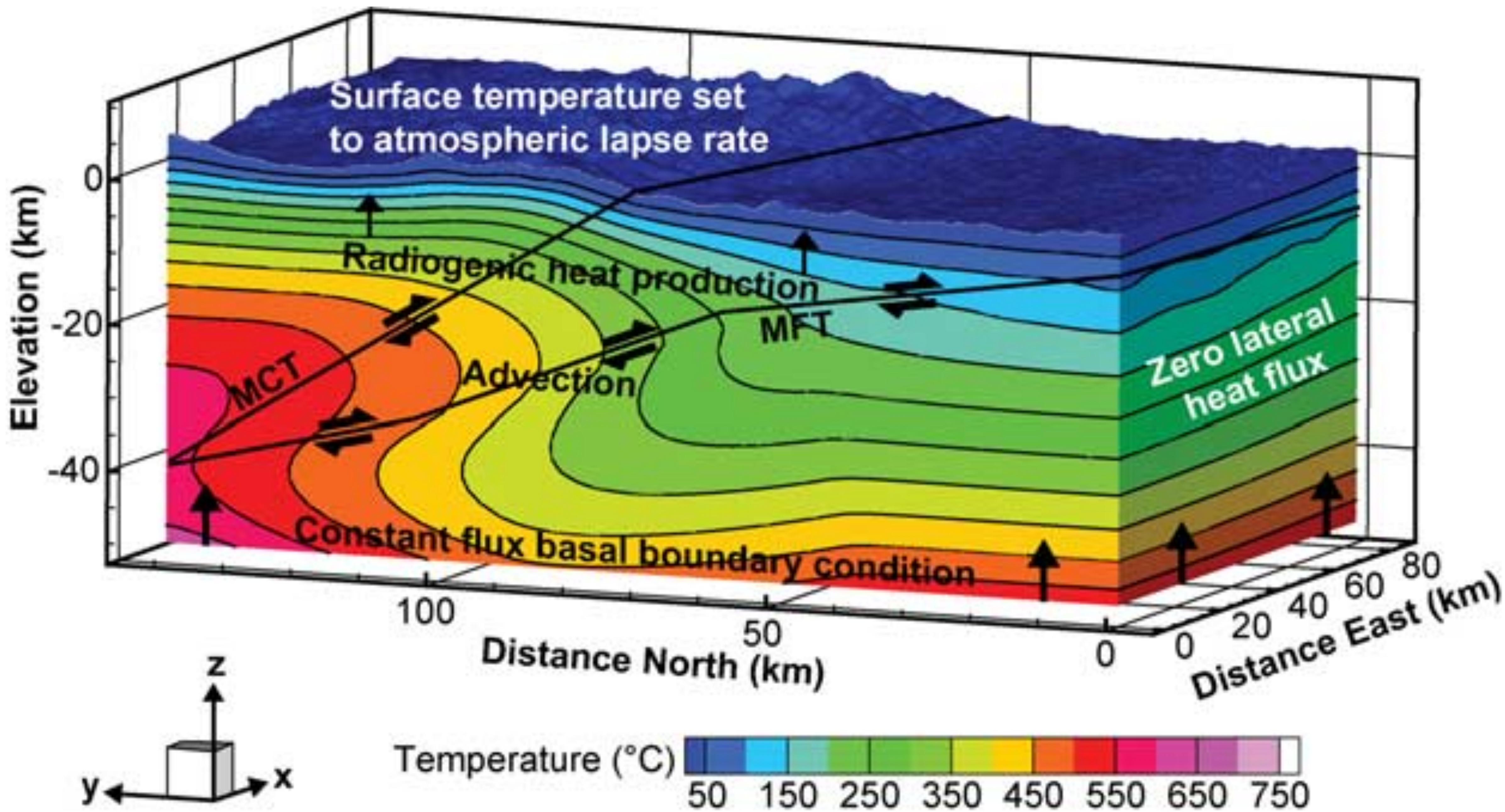
3D thermal-kinematic numerical model



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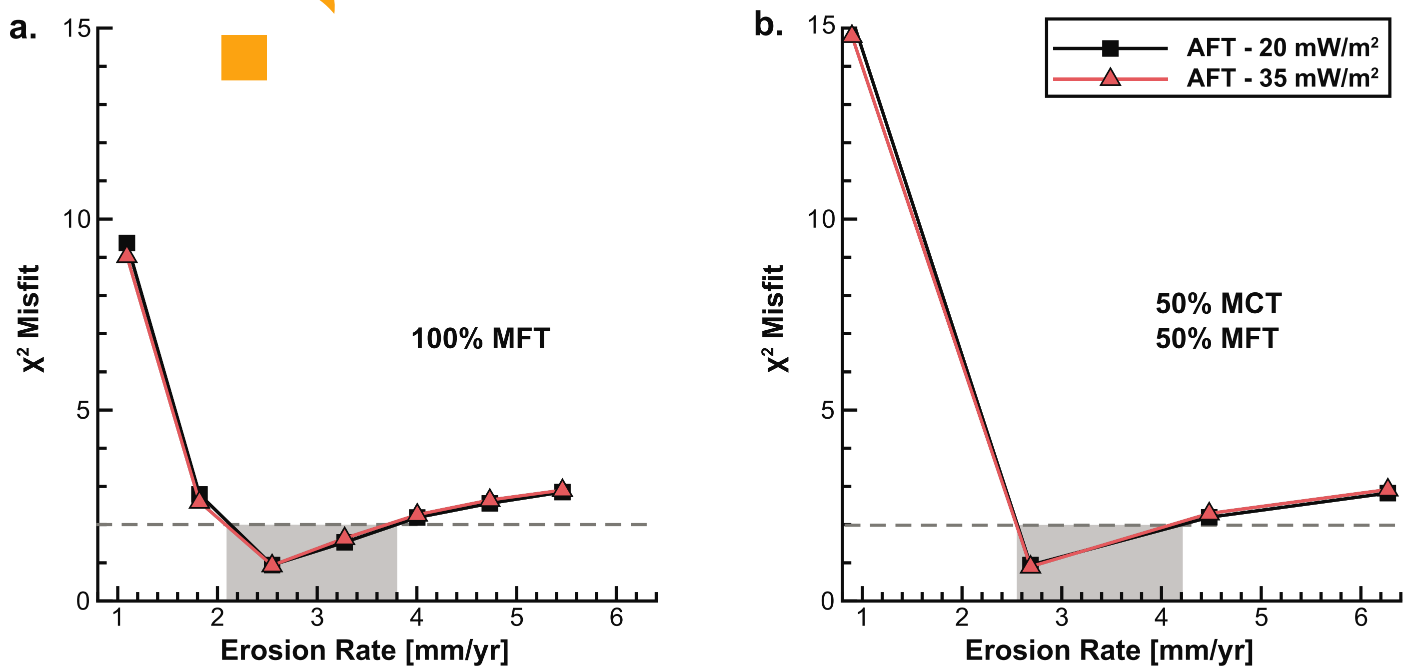
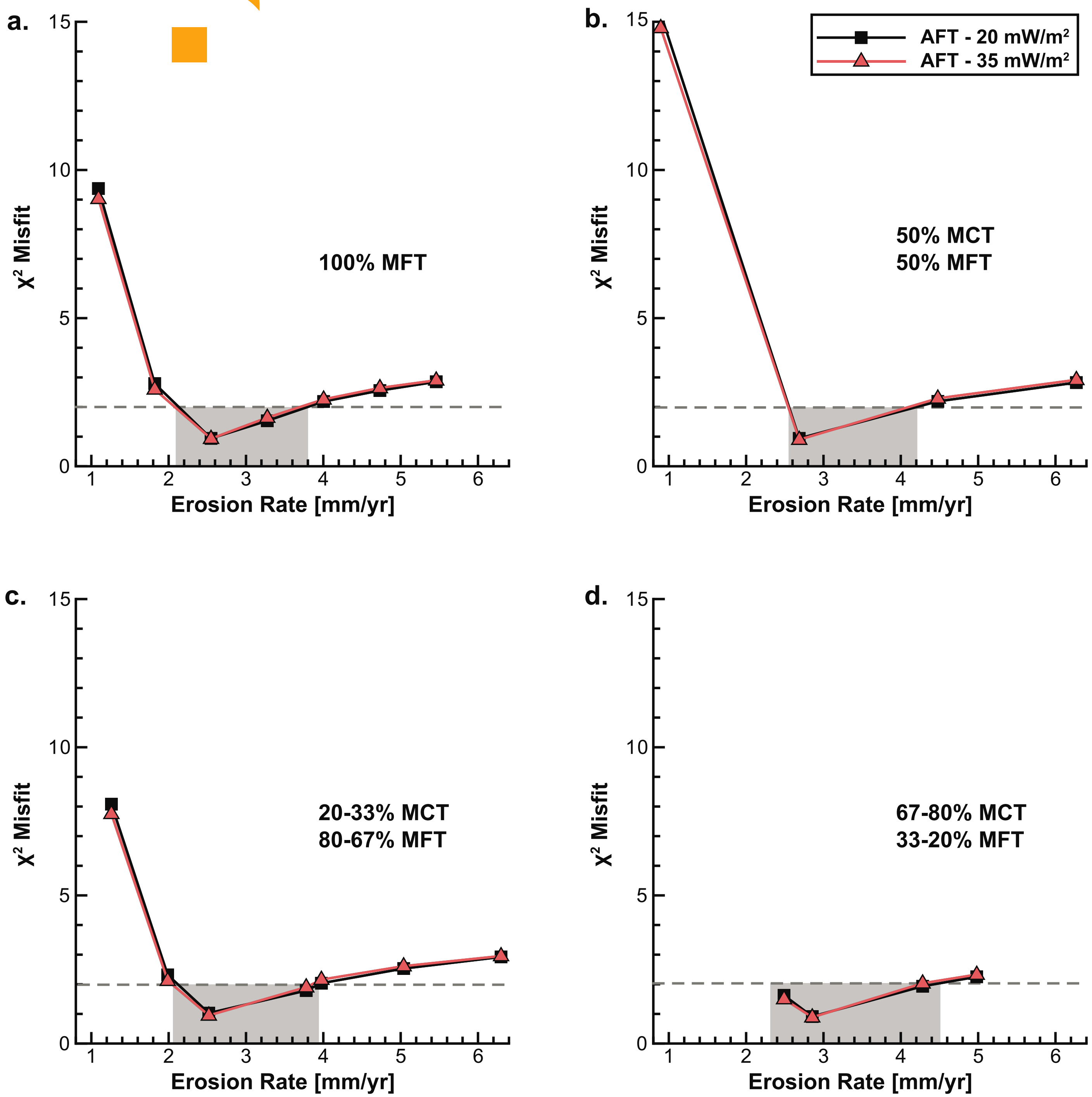
Main findings - Lack of tectonic sensitivity



Whipp et al., 2007

- We used a misfit function to calculate how well the ages predicted from the 3D thermal model matched the observed ages
  - In our case, $\chi^2 \leq 2$ corresponded to ages that were within the measurement uncertainty on average, which we considered a good fit
- As you can see, tectonic models with and without fault slip on the MCT fit the data equally

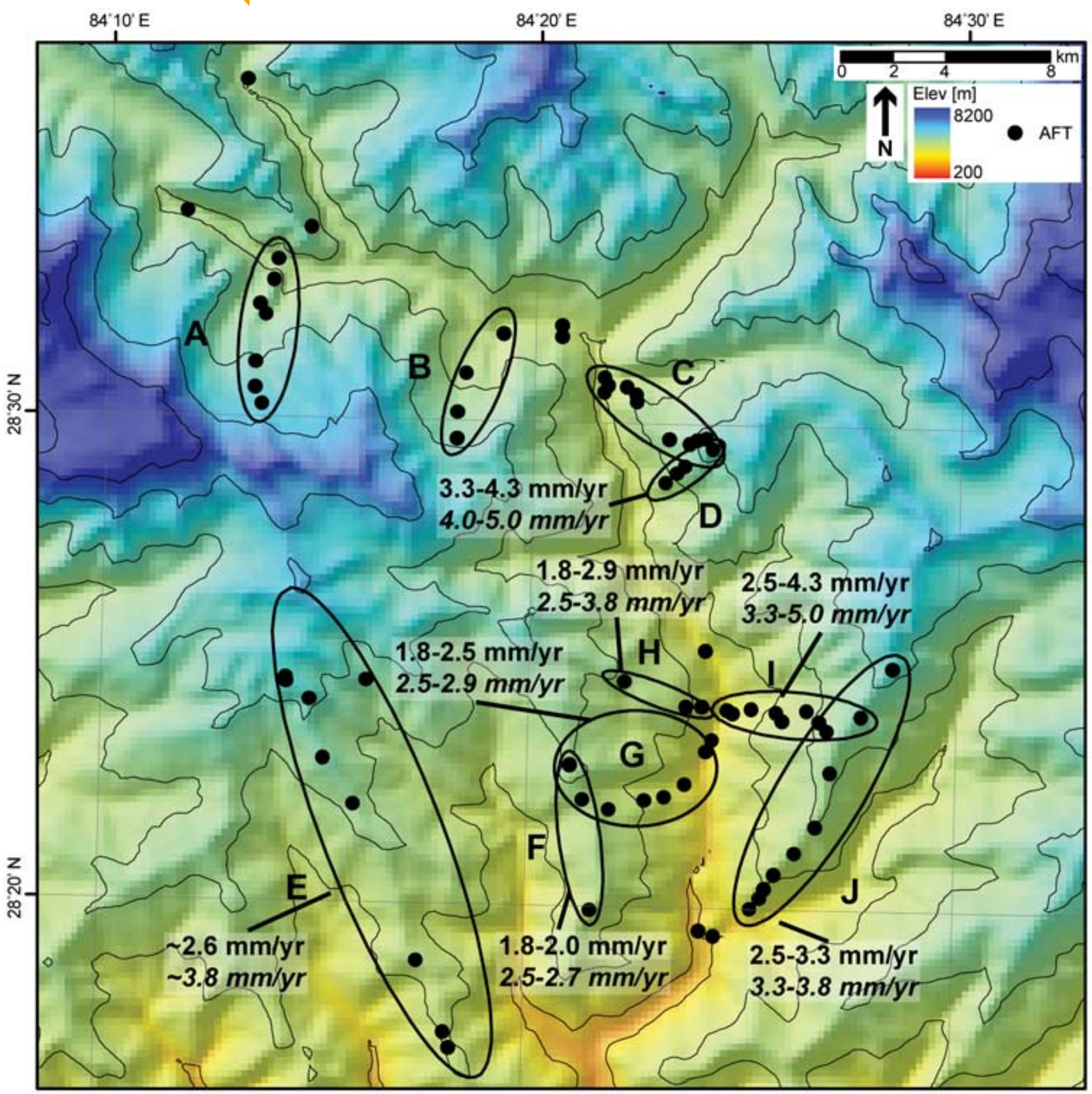
Main findings - Lack of tectonic sensitivity



Whipp et al., 2007

- This was not what we had hoped, but there was some good news
- Using the misfit values we could define the range of long-term erosion rates in the study area over the past 3 Ma

Main findings - Rates of long-term exhumation



Whipp et al., 2007

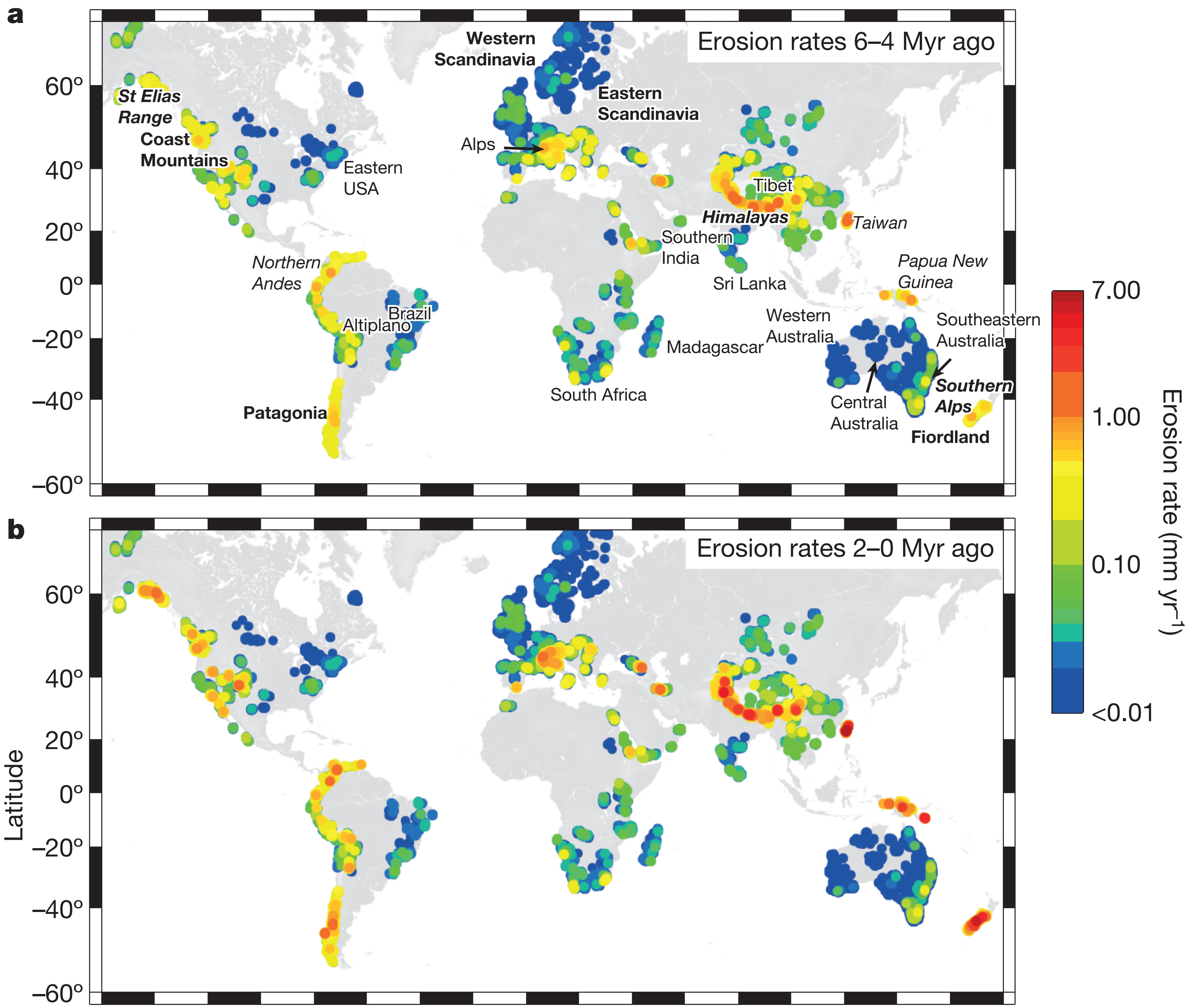
- We were also able to define erosion rates at the transect scale

- Here, we see there is some spatial variability, but most transects experience similar rates of erosion

Study conclusions

- We could not distinguish between tectonic models with and without activity on the Main Central Thrust
- The central Nepal Himalaya have been eroding at ~2-5 mm/a over the past ~3 Ma
- The exhumation rates estimated from the slope of the sample age versus elevation can overestimate the rates from the thermal model by >200%

A global tool

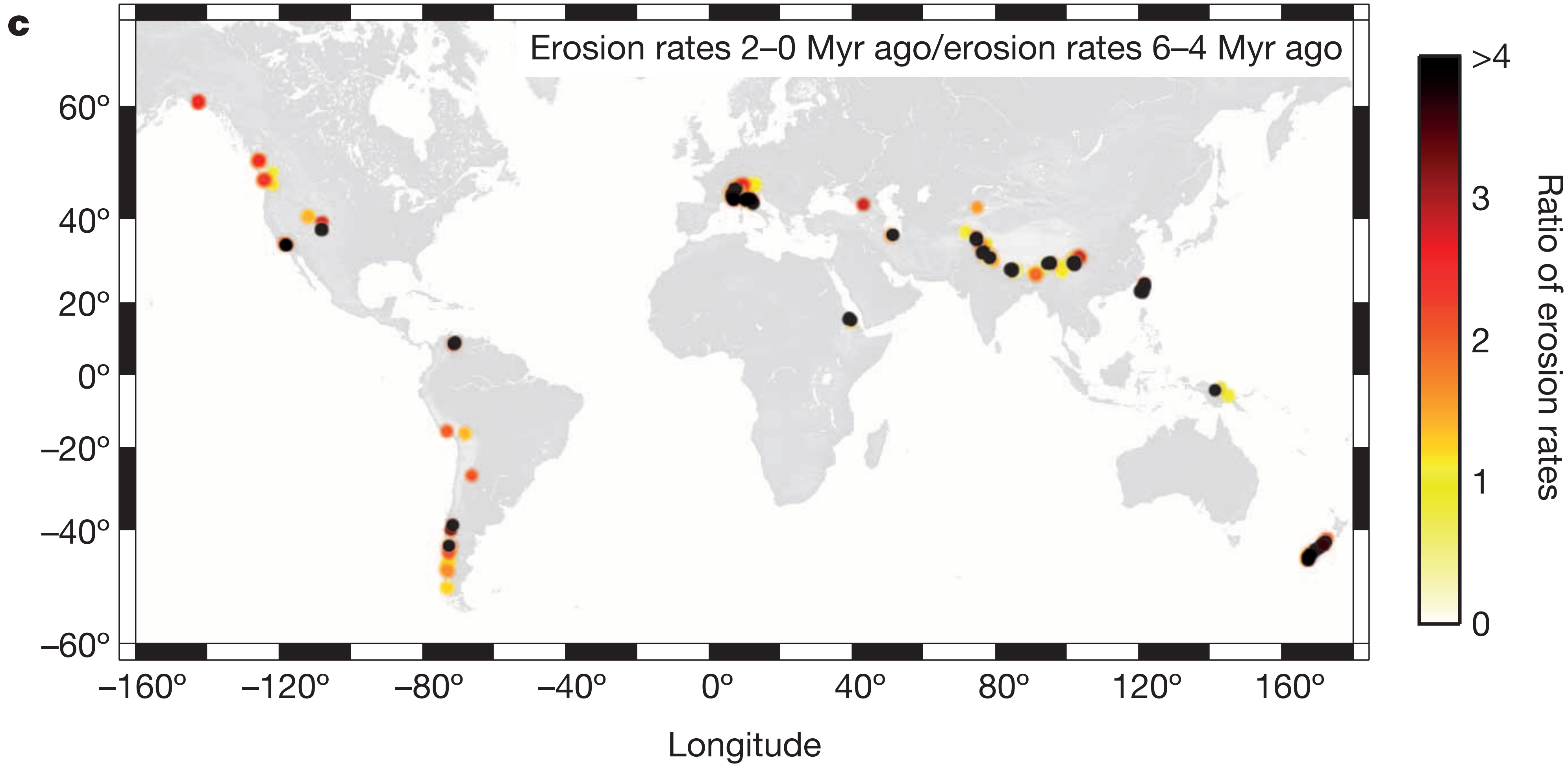


Herman et al., 2013

- A recent compilation highlighted the use of thermochronology not only for application to individual study areas, but also across the globe

A global tool

Herman et al., 2013



- A key finding of this compilation was that global rates of rock exhumation had increased in the past 2-3 Ma, which the authors linked to the onset of glaciation in the northern hemisphere

Summary

- **What are some of the different methods we can use for estimating exhumation rates from thermochronometer data?**

- What are some of their advantages and drawbacks?

- Can thermochronology be used to study geological processes across the globe?

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