Class overview today - December 3, 2018

- **Part I - Basic concepts of thermochronology**
  - Basic concepts of thermochronology
  - Estimating closure temperatures
- **Part II - Low-temperature thermochronology** (online only)
  - Definition of low-temperature thermochronology
  - Three common low-temperature thermochronometers
- **Part III - Quantifying erosion with thermochronology** (online only)
  - Basic concepts of heat transfer as a result of erosion
  - Estimation of exhumation rates from thermochronometers

Introduction to Quantitative Geology
Lecture 6.3
Quantifying erosion with thermochronology

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3.12.18

Goals of this lecture

- Clarify some terminology about rock exhumation and erosion
- Review the basic concepts of heat transfer as a result of erosion
- Discuss the estimation of exhumation rates from thermochronometer data alone

What do thermochronometers record?

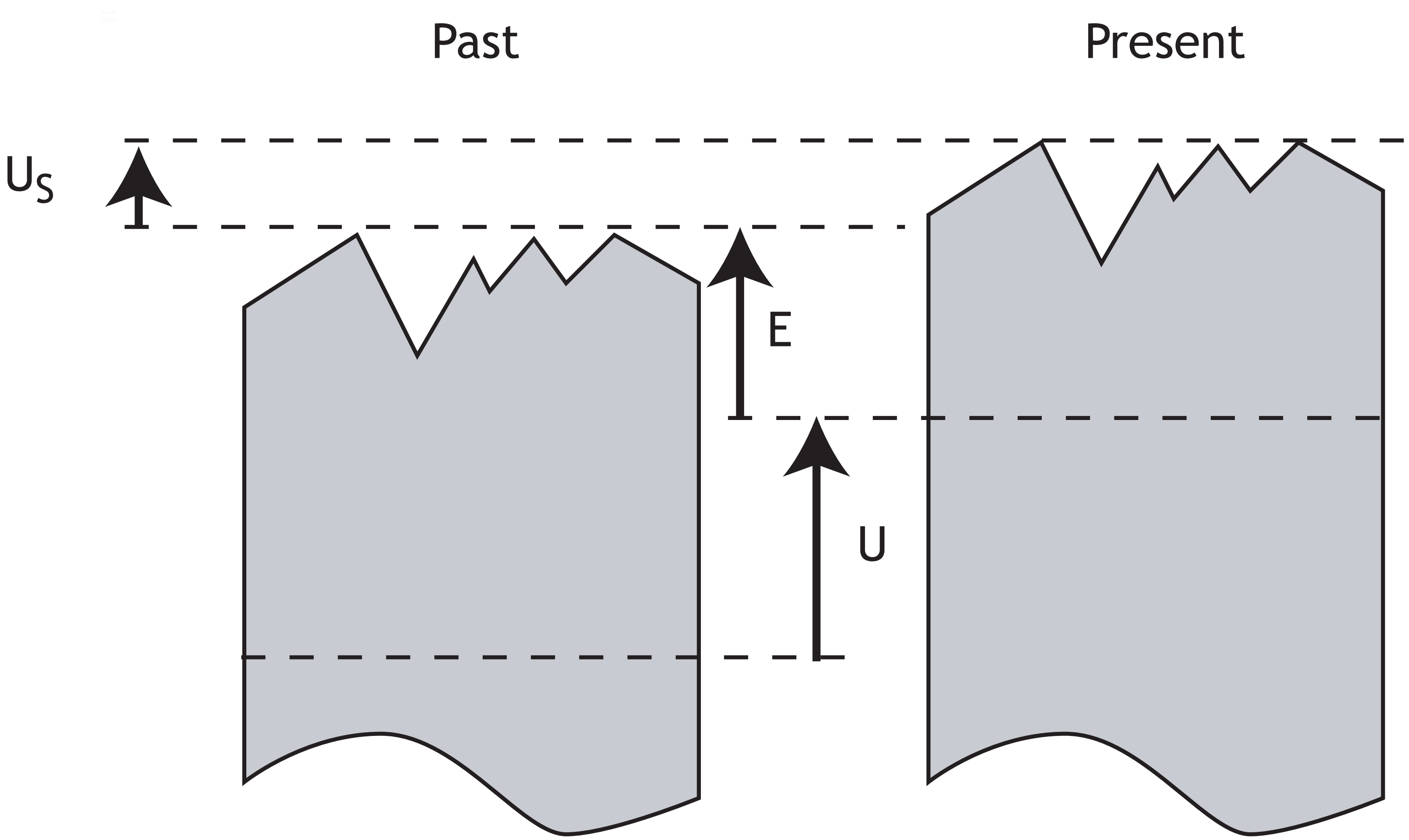
- **Cooling**
  - Time since rocks were at a thermochronometer-specific effective closure temperature T_c
- **Exhumation**
  - Advection of rocks toward the surface of the Earth (exhumation)

Erosion versus exhumation

- Erosion and exhumation are terms that are often misused and confused, so we need to start with some definitions (see Ring et al., 1999 for a detailed discussion)
  - **Exhumation**: The unroofing history of a rock; the vertical distance a rock moves relative to the Earth's surface. Can result from tectonic or surface processes.
  - **Denudation**: The removal of rock by tectonic and/or surface processes at a specific point at or beneath the Earth's surface
  - **Erosion**: The removal of mass at a specific point on the Earth's surface by both mechanical and chemical processes

Exhumation, rock uplift and surface uplift

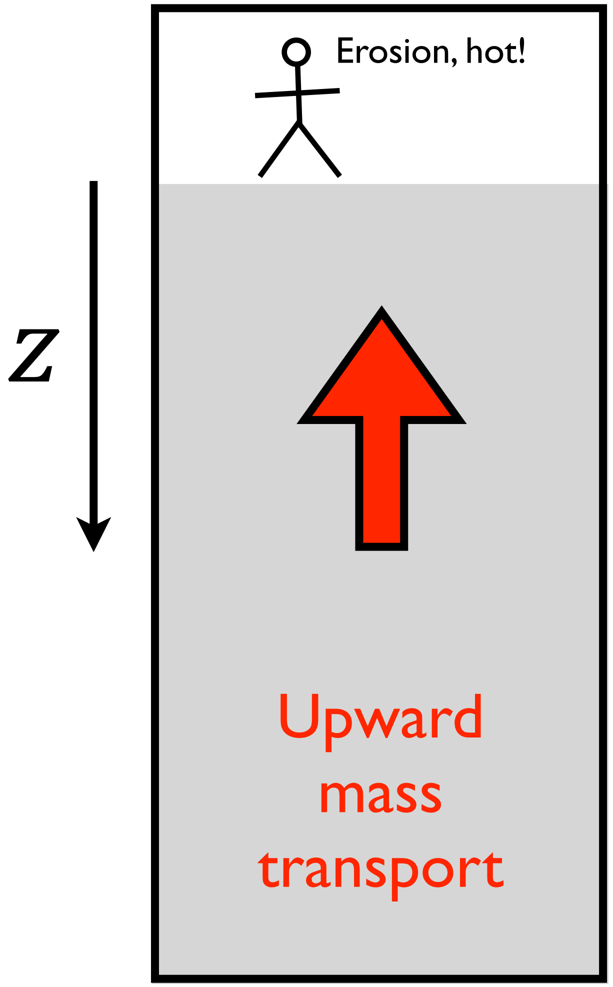
Fig. 5.1; Braun et al., 2006



$$E = U - U_s$$

- Rock exhumation *E* is the result of the combination of rock uplift and surface uplift
  - Rock uplift *U* refers to vertical motion of rock with respect to the center of the Earth
  - Surface uplift U_s is vertical movement of the Earth's surface with respect to the center of the Earth
  - The amount of rock exhumation a sample experiences with reflect both

Exhumation



- **Exhumation** results in upward advection of rock as surface rock is eroded and transported away
- Upward motion brings relatively hot rock up from depth toward the surface, increasing the geothermal gradient
- Exhumation typically becomes important at advection velocities of >0.1 mm/a

1D transient advection-diffusion equation

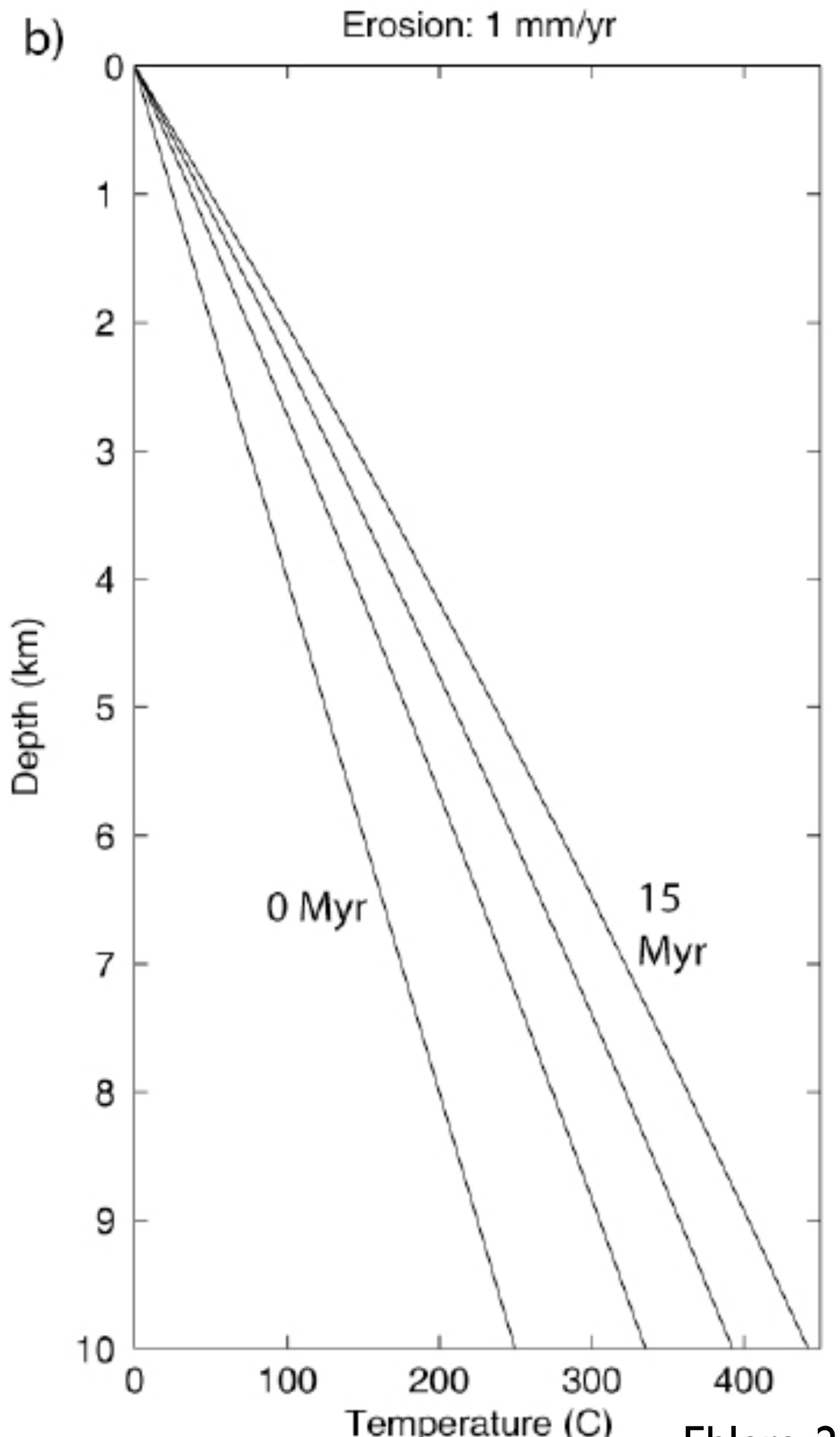
$$T(z,t) = G(z + v_z t) + \frac{G}{2}\left[(z - v_z t)\mathrm{e}^{-v_z z/\kappa}\mathrm{erfc}\left(\frac{z - v_z t}{2\sqrt{\kappa t}}\right) - (z + v_z t)\mathrm{erfc}\left(\frac{z + v_z t}{2\sqrt{\kappa t}}\right)\right]$$

- As we saw in the laboratory exercise last Wednesday, the thermal field in the crust of the Earth will be affected by the rate of vertical advection of rock and the time that the rate of advection is applied (as well as other factors)
    - The equation above is from the laboratory exercise, and the Github page lists the definitions of all variables

Effects of erosion and sedimentation

Erosion increases temperatures in the crust by the largest amount initially, but temperatures will continue to increase with time

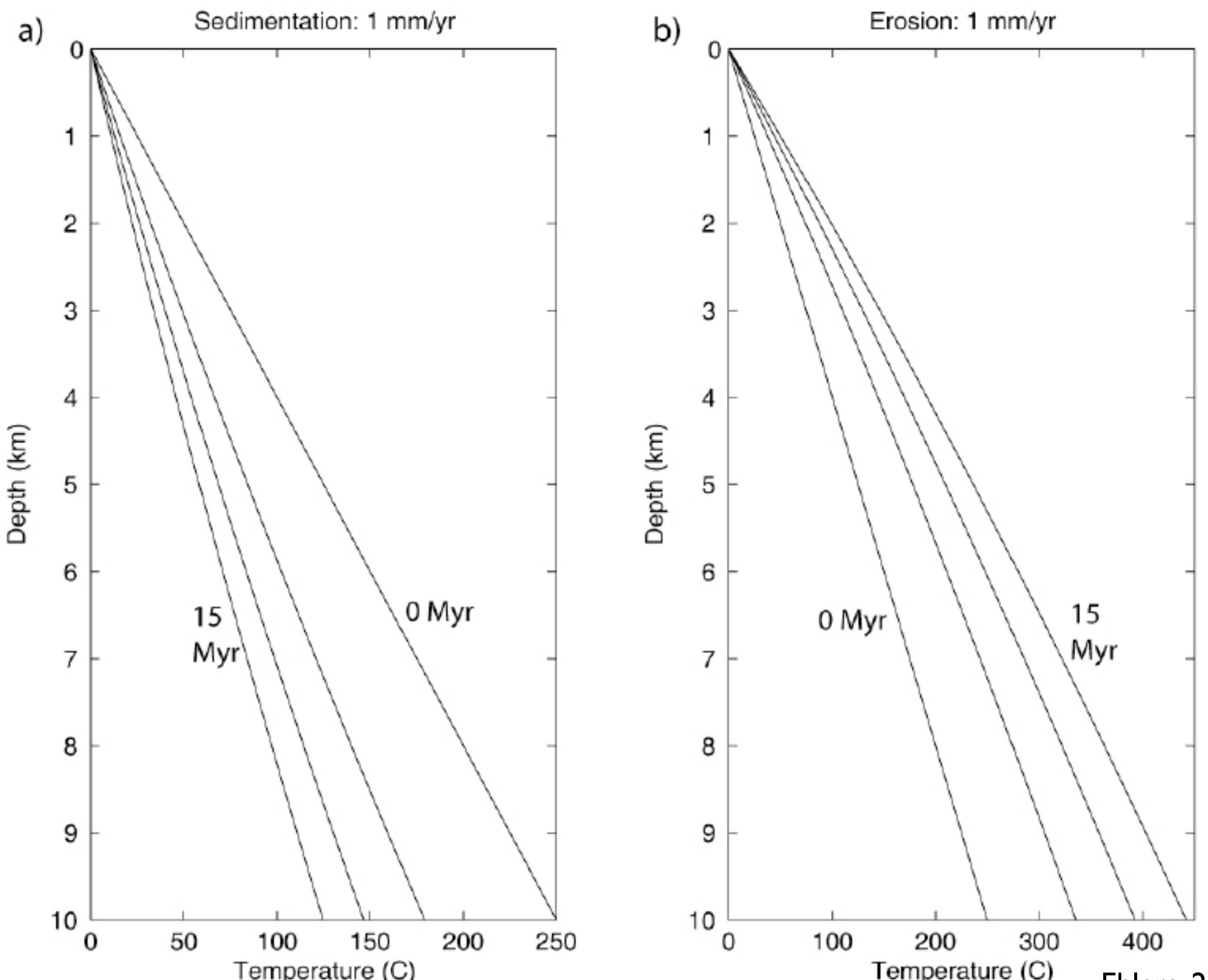
For this specific equation, with a constant basal flux, there is no steady state that will be reached



Ehlers, 2005

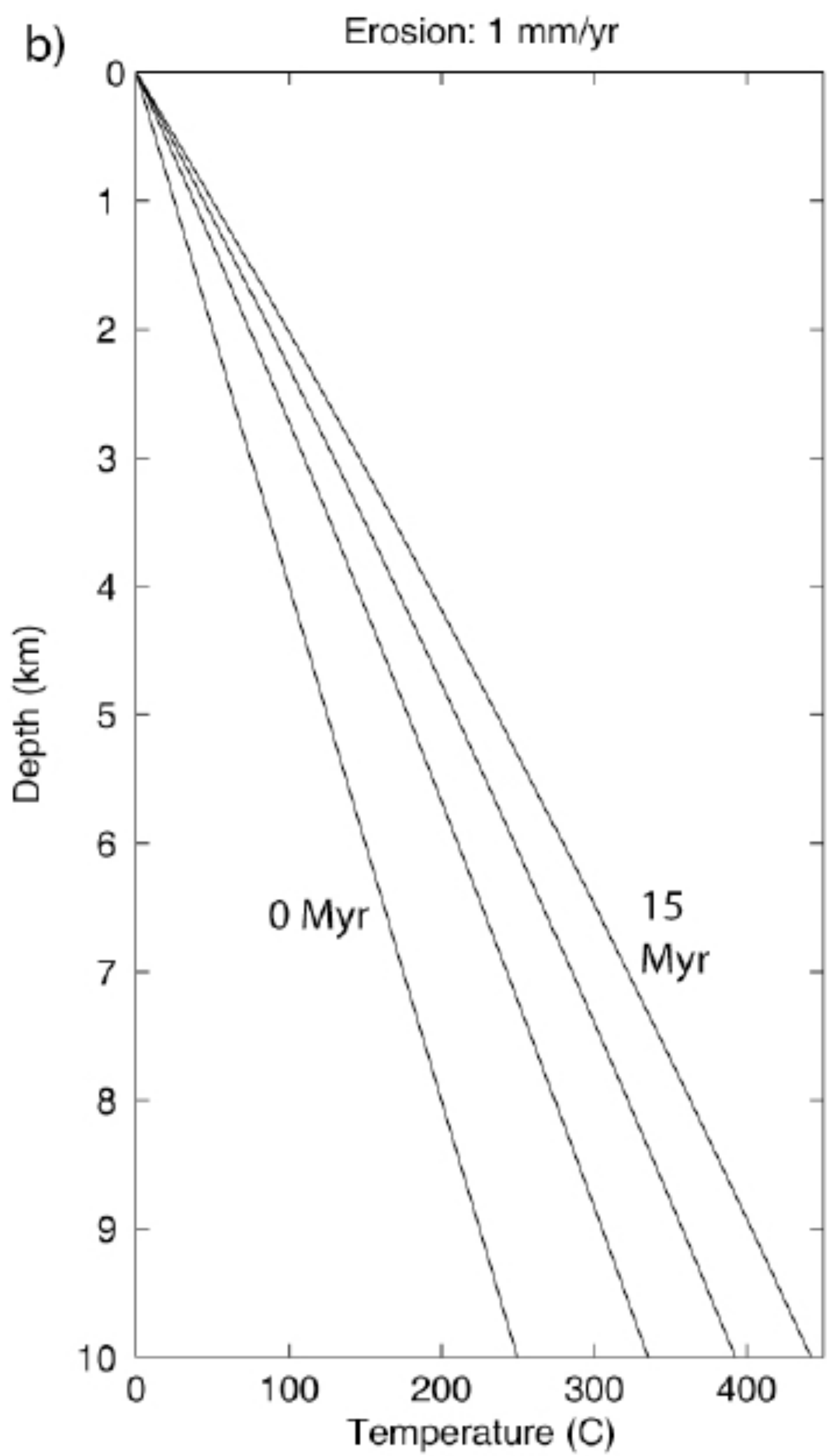
Effects of erosion and sedimentation

Erosion and sedimentation work similarly, but in the opposite sense



Ehlers, 2005

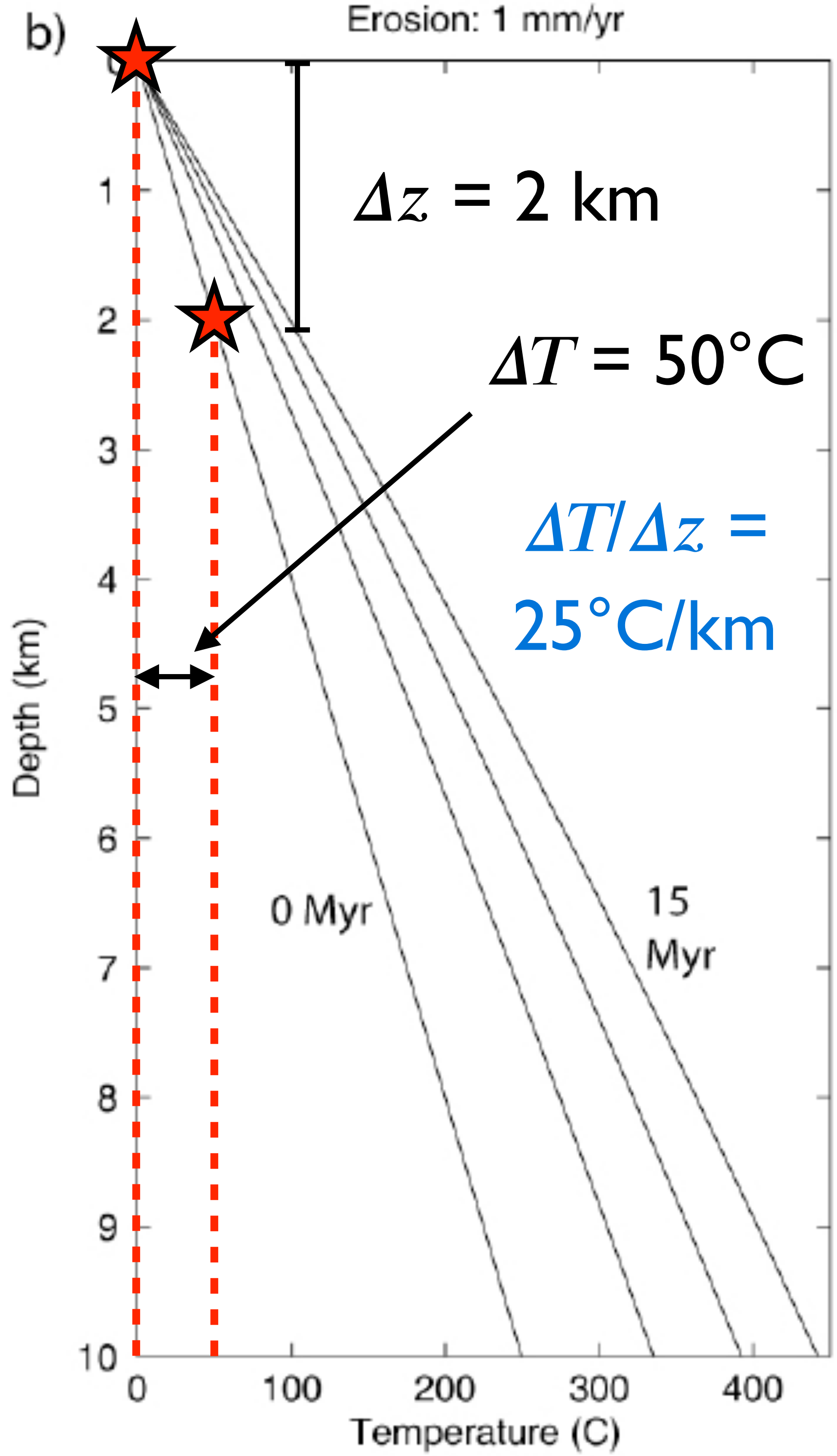
Thermal gradient changes



Ehlers, 2005

- The temperature change measured in the shallow crust, or temperature gradient, is often used to study thermal processes in the crust
- The geothermal gradient is simply the difference in temperature at two different depths in the Earth, with typical values of 15-30°C/km
    - Multiplying the geothermal gradient by the rock thermal conductivity yields the surface heat flow

Thermal gradient changes



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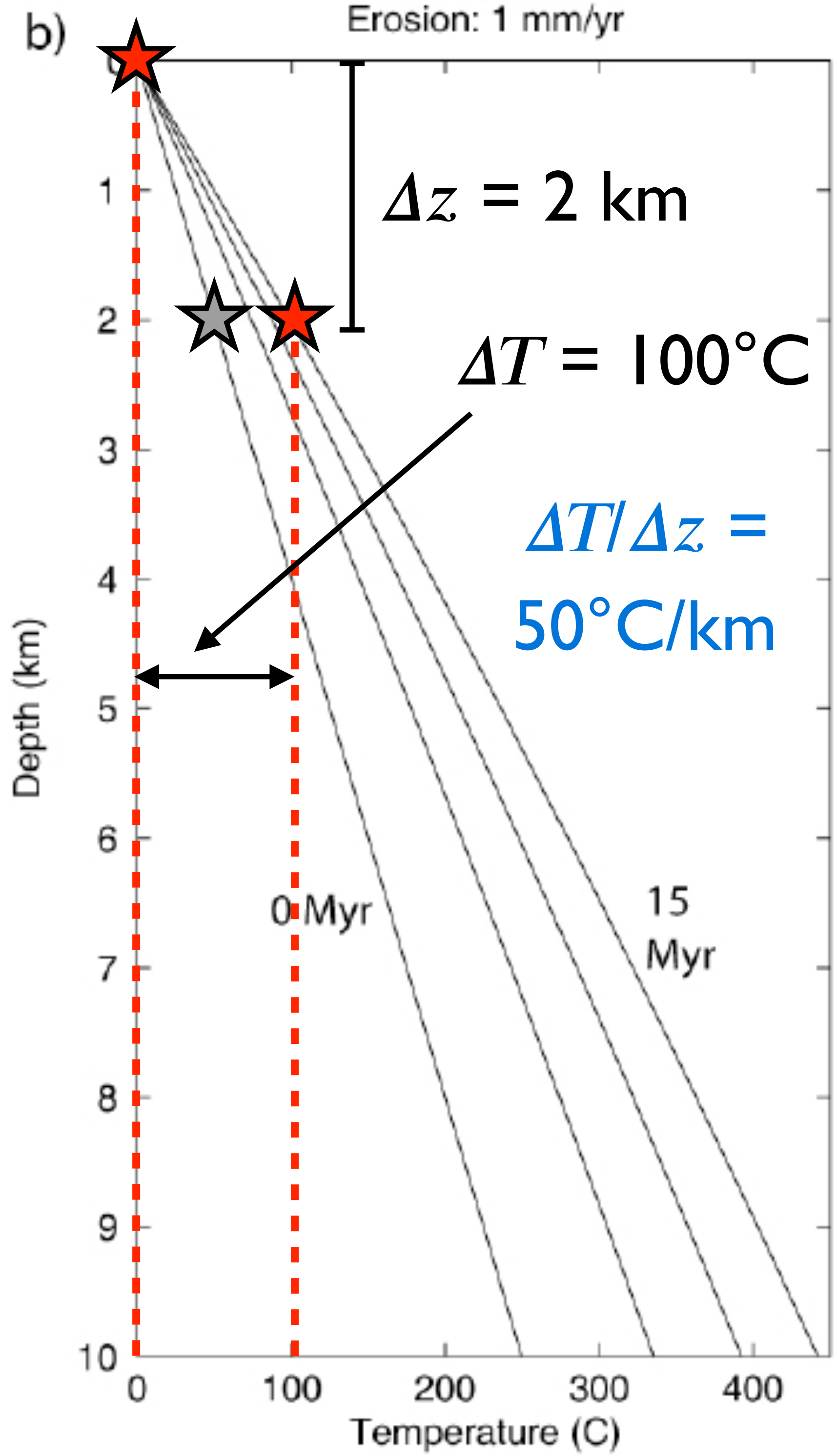
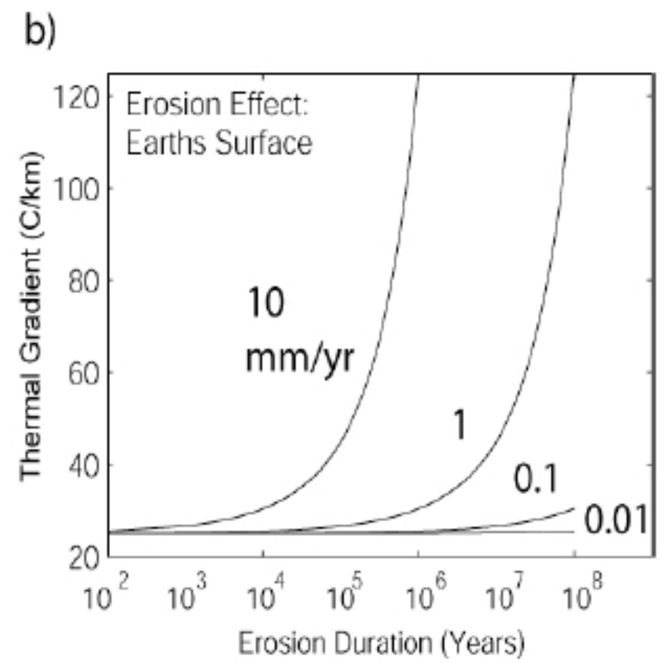
Thermal gradient changes



Ehlers, 2005

- In this example, the geothermal gradient doubles over the first 15 Ma of the calculation

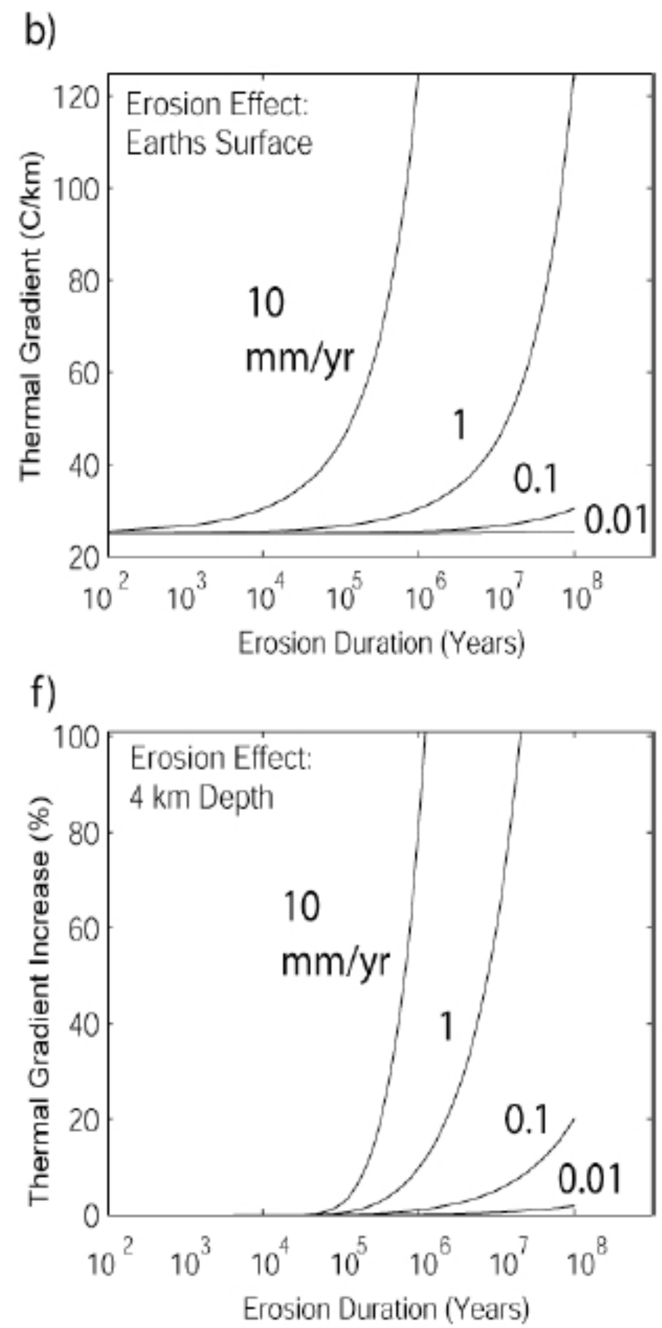
Thermal gradient changes



- Depending on the rate of advection, the timing of changes in the geothermal gradient near the Earth's surface will vary
    - Faster advection velocities result in more rapid changes in geothermal gradient
- Here we can easily see that erosion rates of ≥0.1 mm/a are needed to change temperatures over time scales of millions of years

Ehlers, 2005

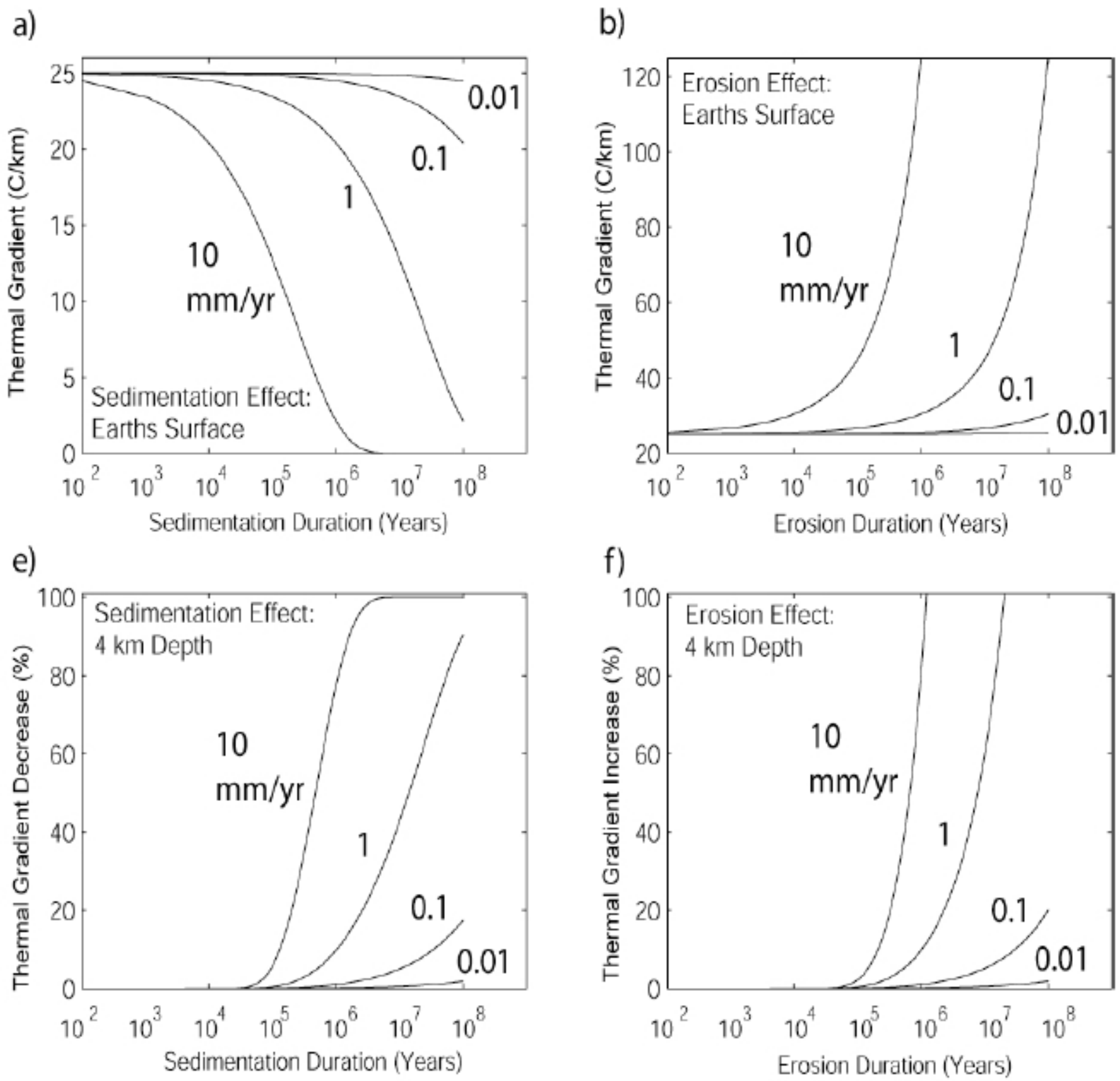
Thermal gradient changes



Ehlers, 2005

- Thermochronometers are sensitive to temperatures deeper in the earth, and the timing of changes in the geothermal gradient will thus lag behind the changes in near the surface

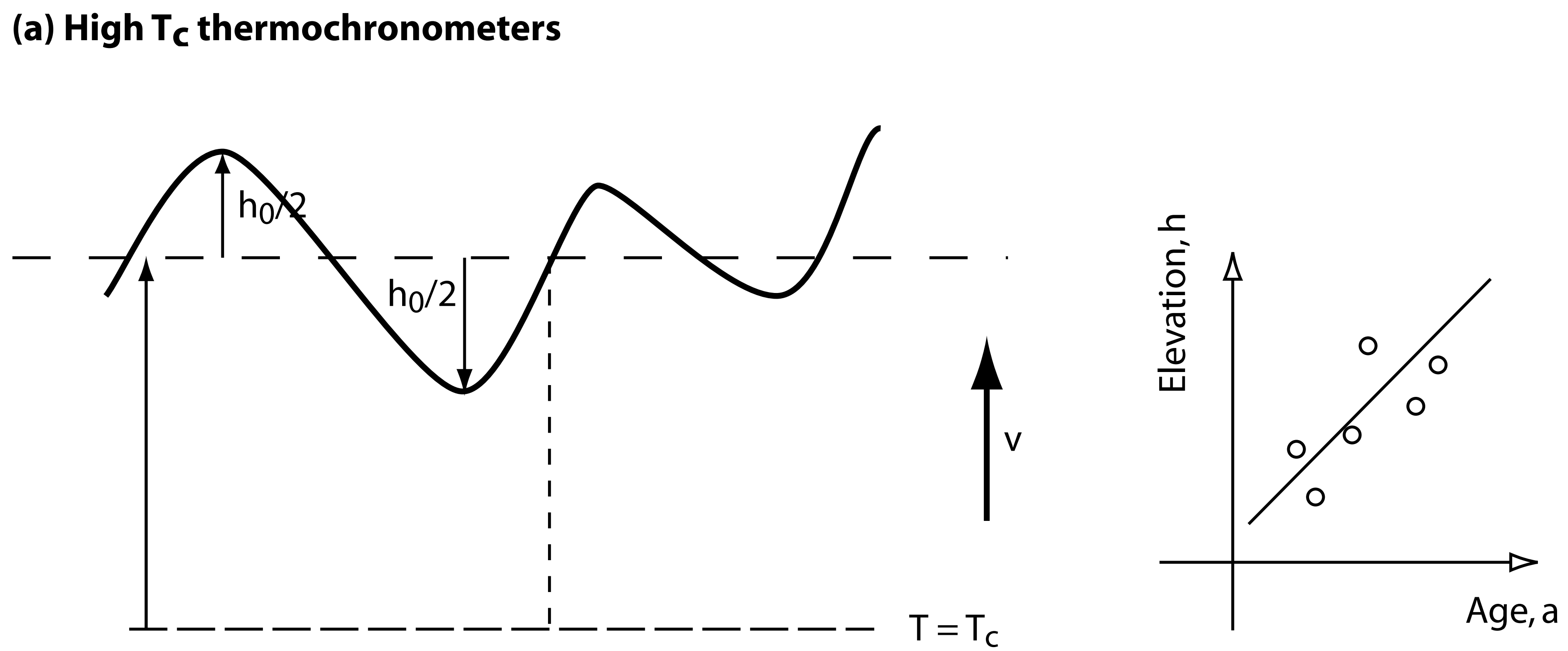
Thermal gradient changes



- As before, the same thing can be said for sedimentation, but in the opposite sense

Ehlers, 2005

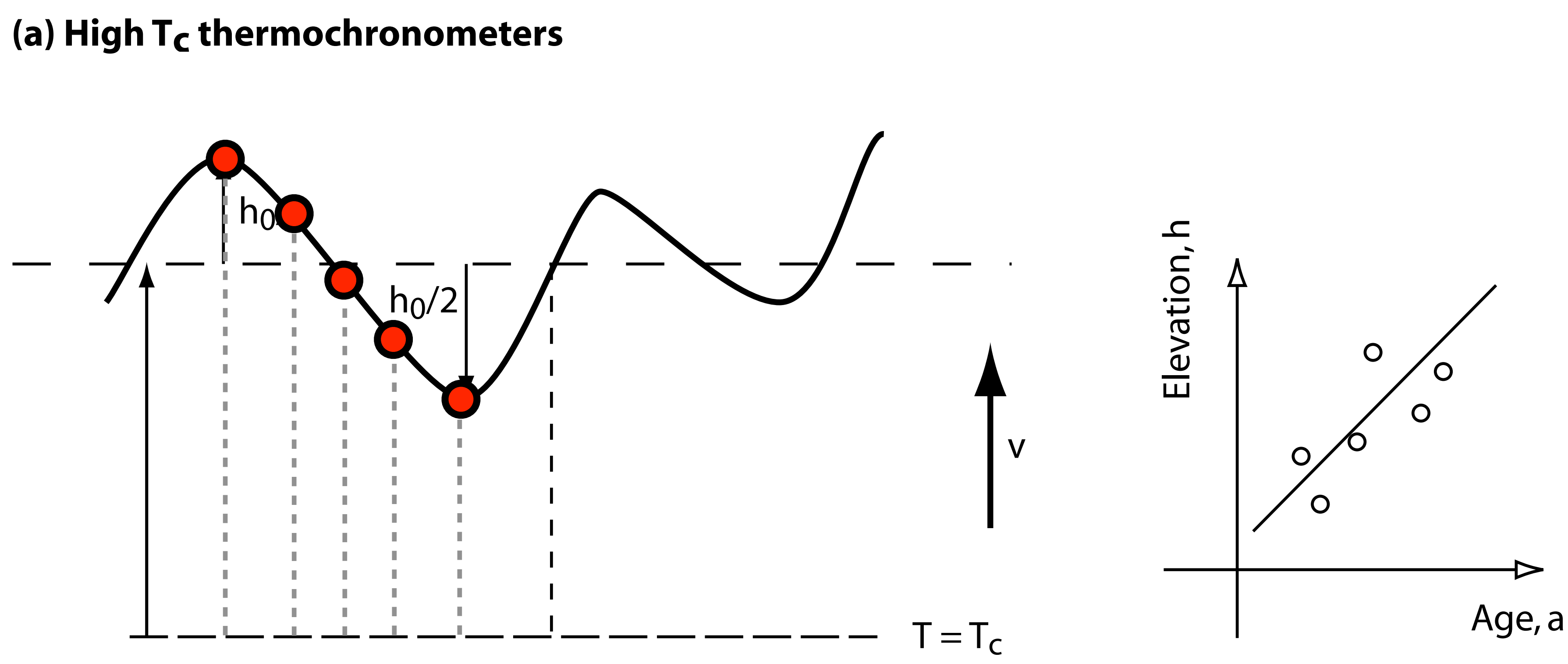
Estimating exhumation rates: The age-elevation approach



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

Estimating exhumation rates: The age-elevation approach



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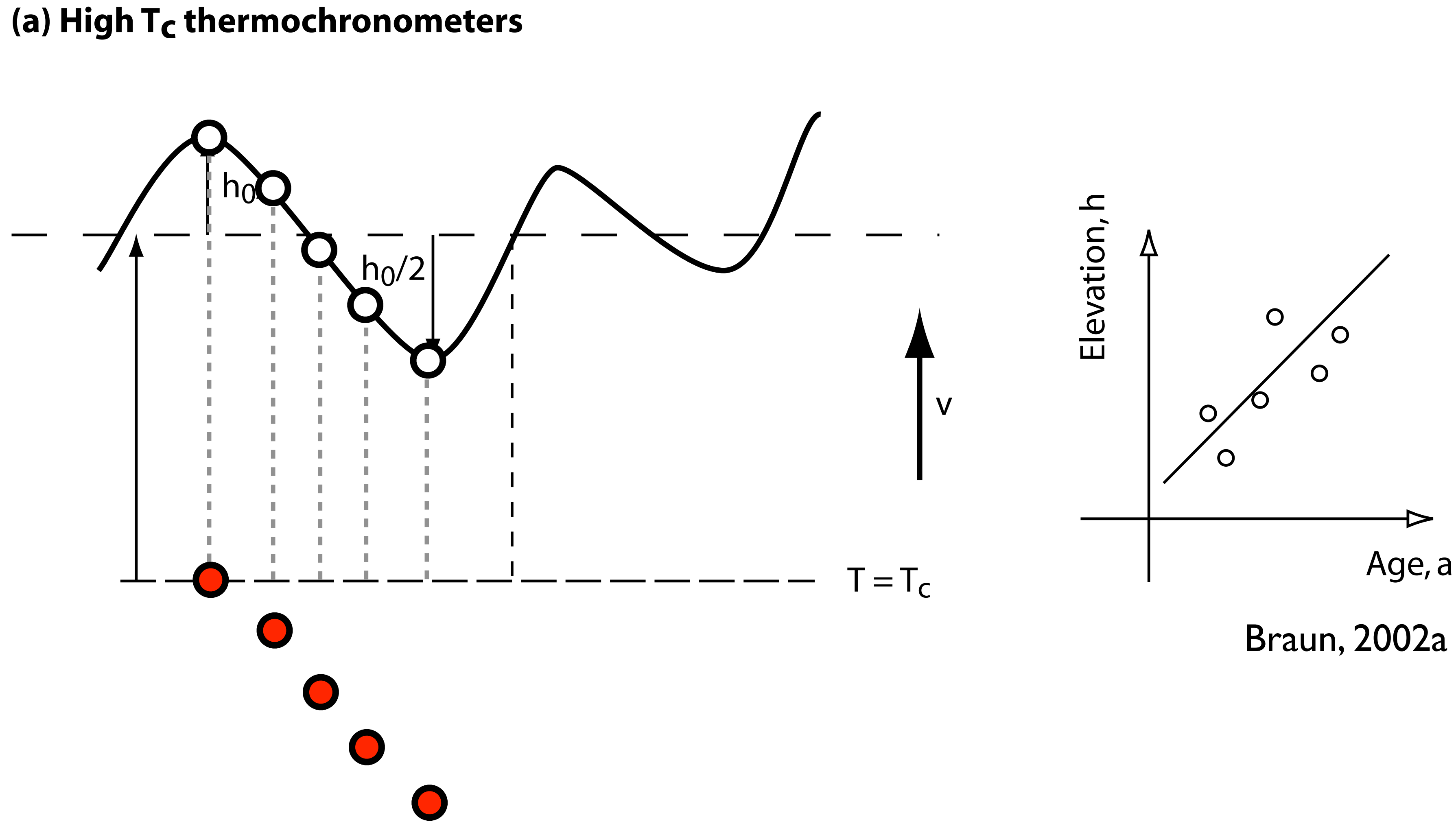
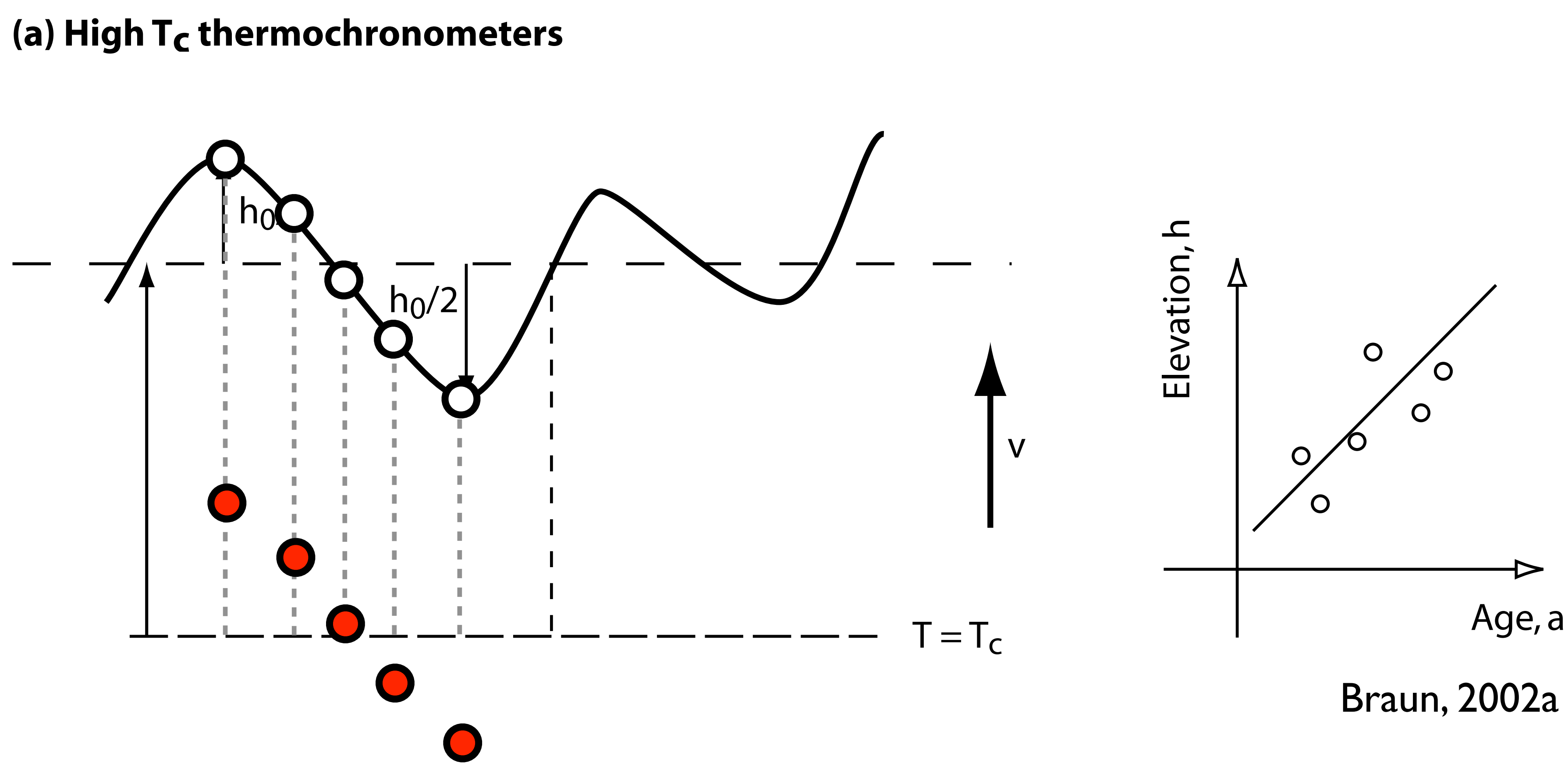


- If we consider the exhumation of these samples from the time the first cools, we can see why…

Estimating exhumation rates: The age-elevation approach



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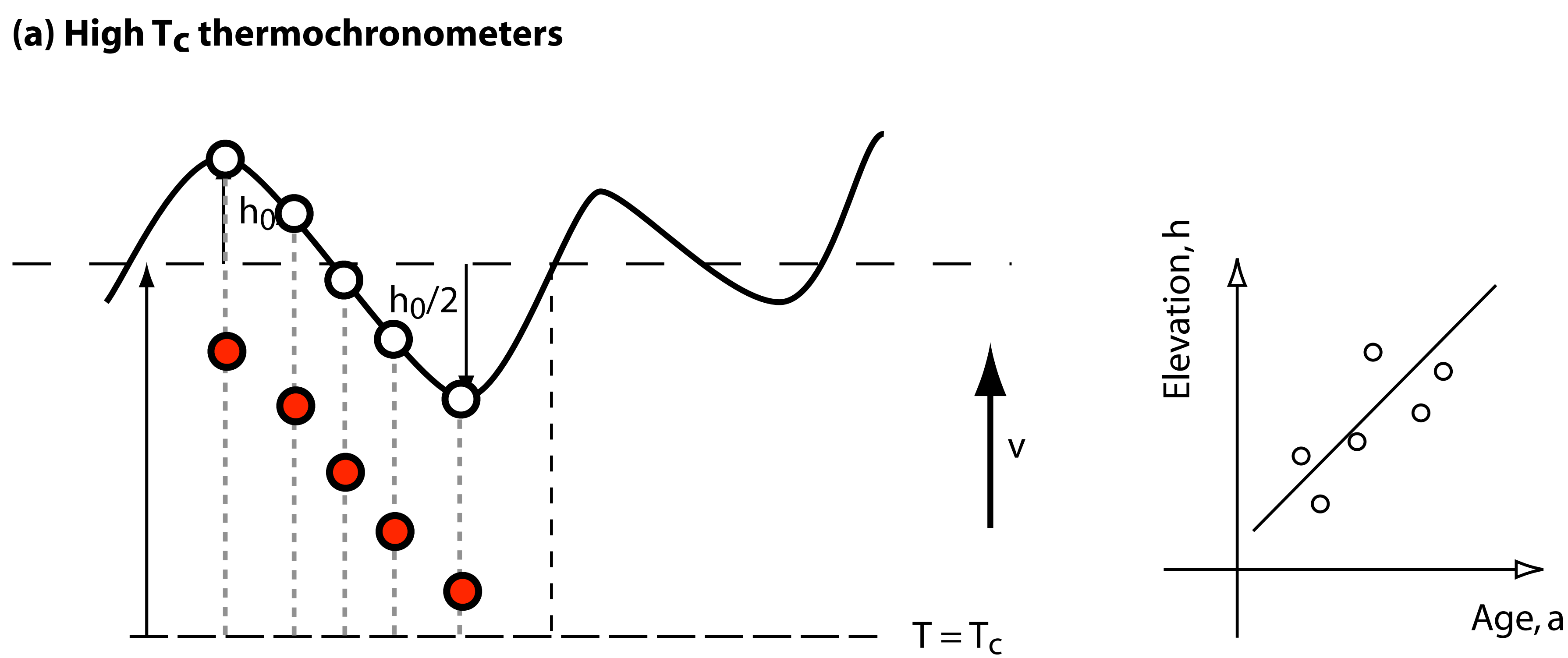

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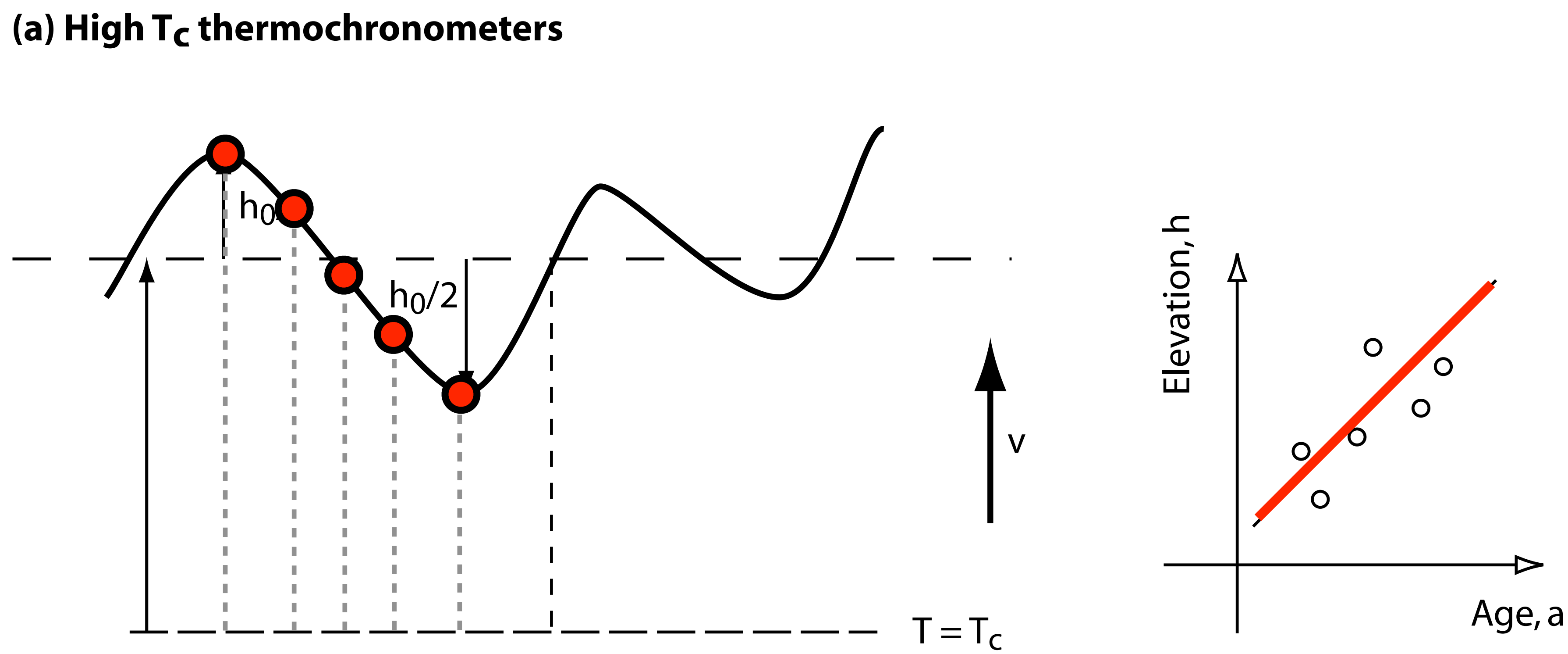
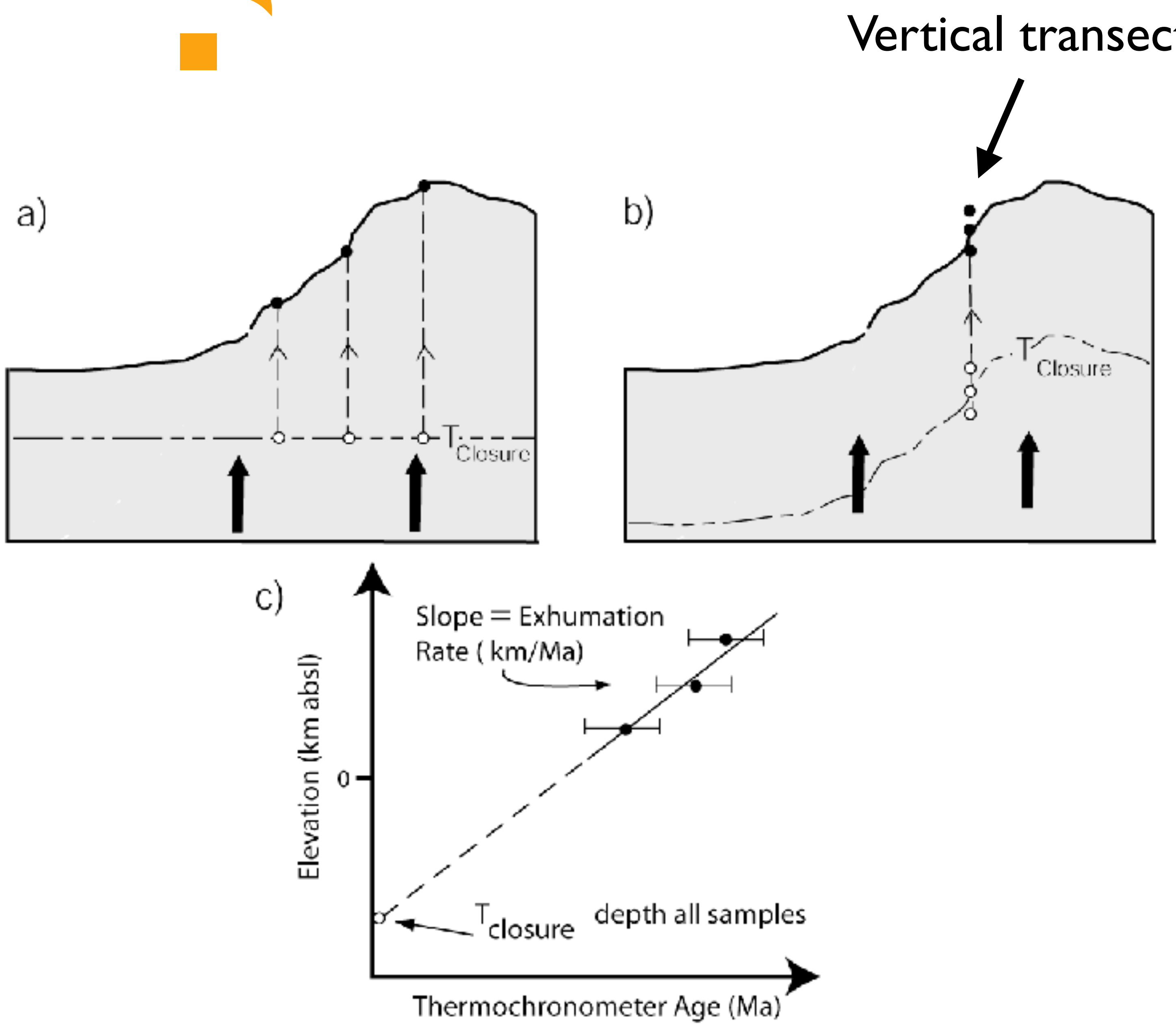
Estimating exhumation rates: The age-elevation approach



Braun, 2002a

- What you'll notice is that the difference in ages 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 (!)

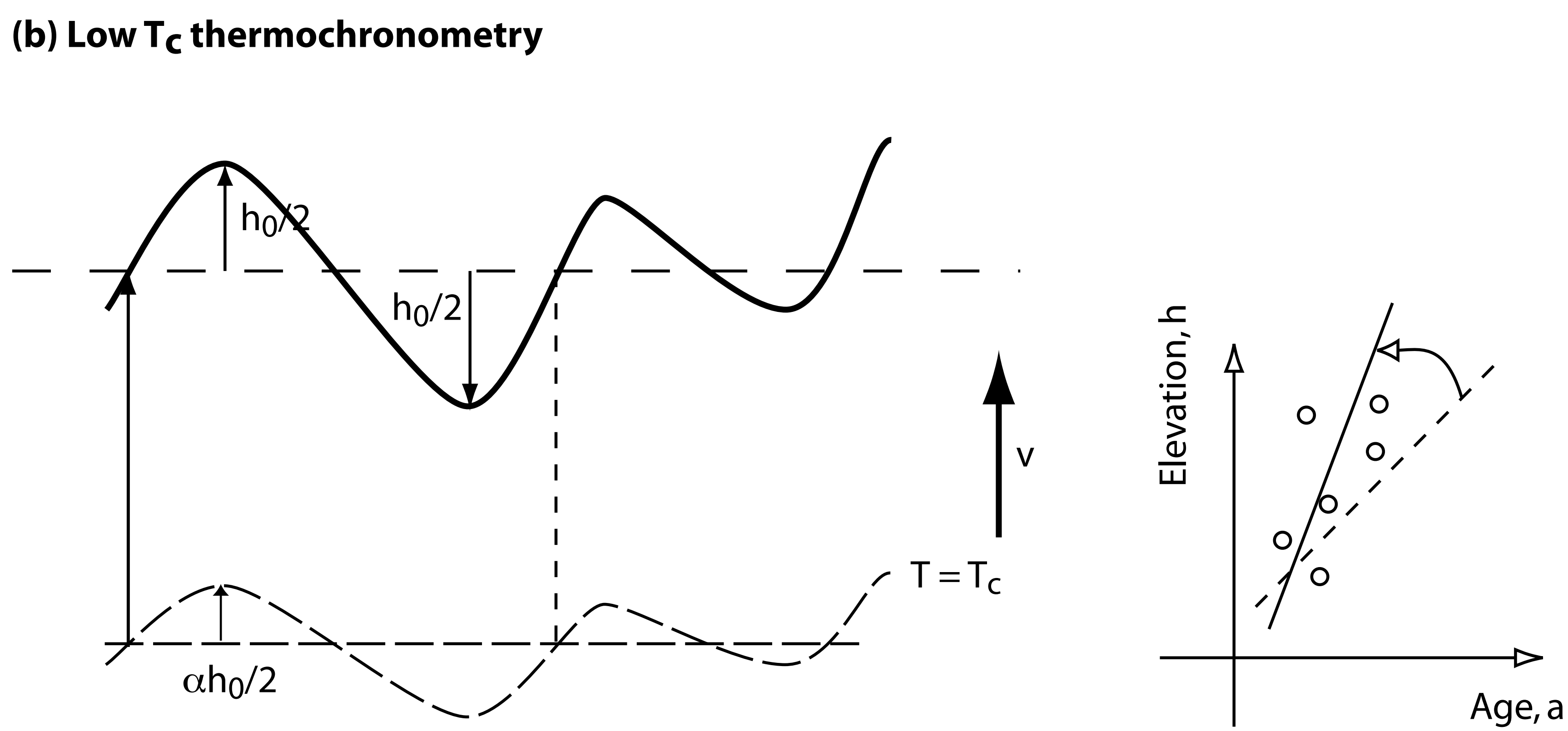
Scenarios where this technique works…



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)

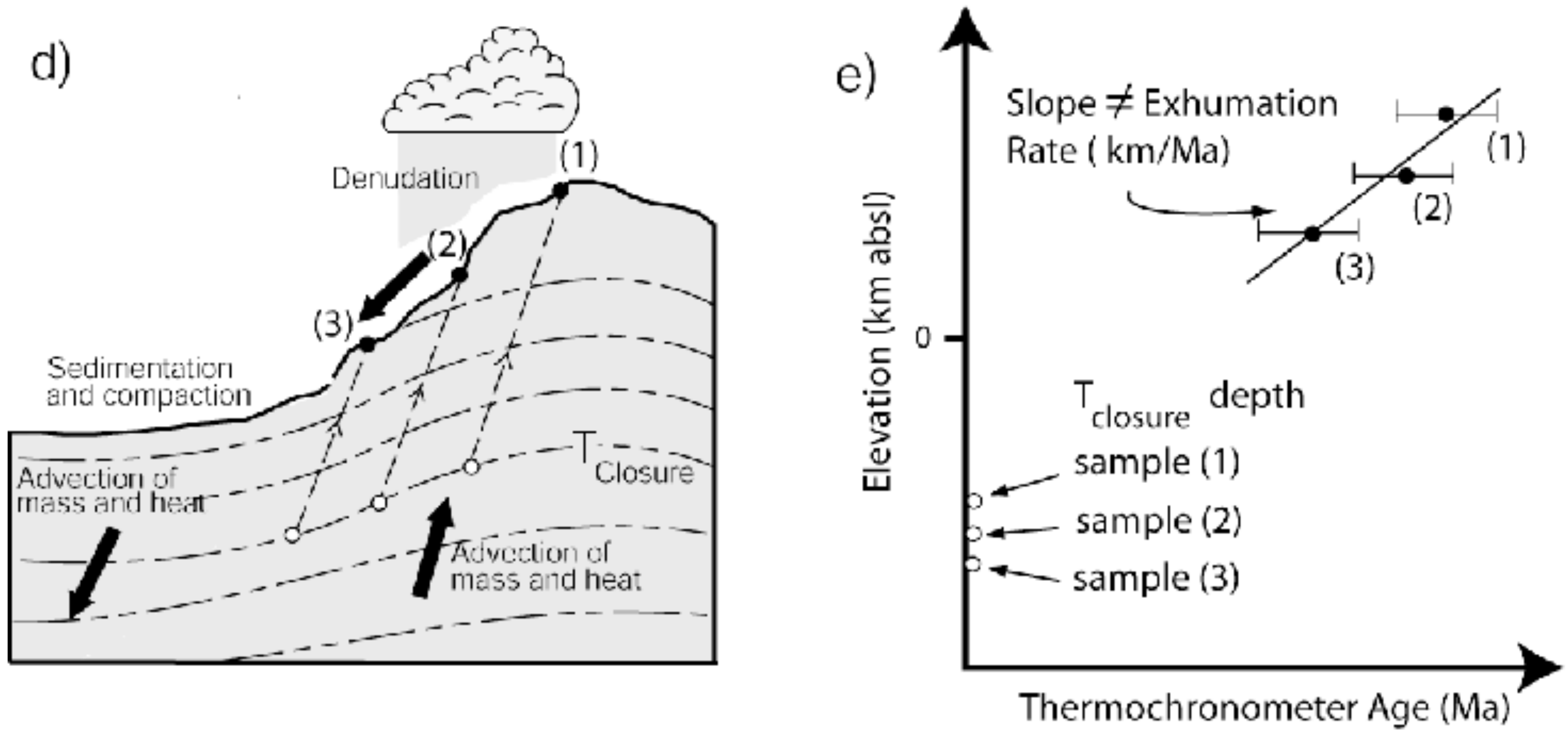
The trouble with low-T thermochronology



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



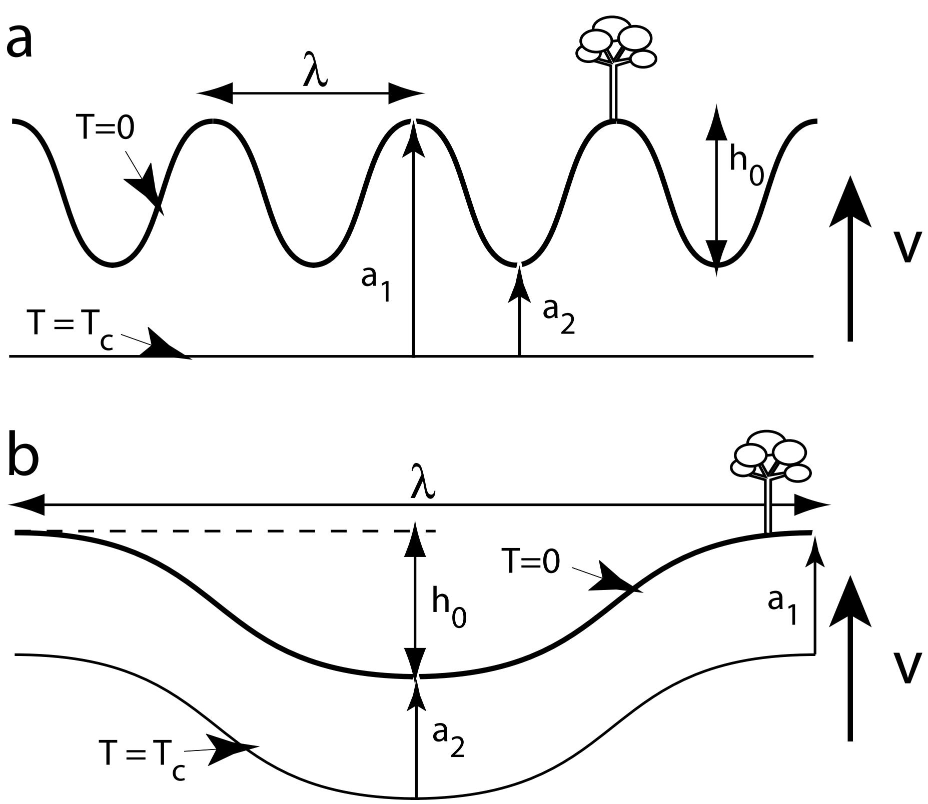
Ehlers, 2005

- 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

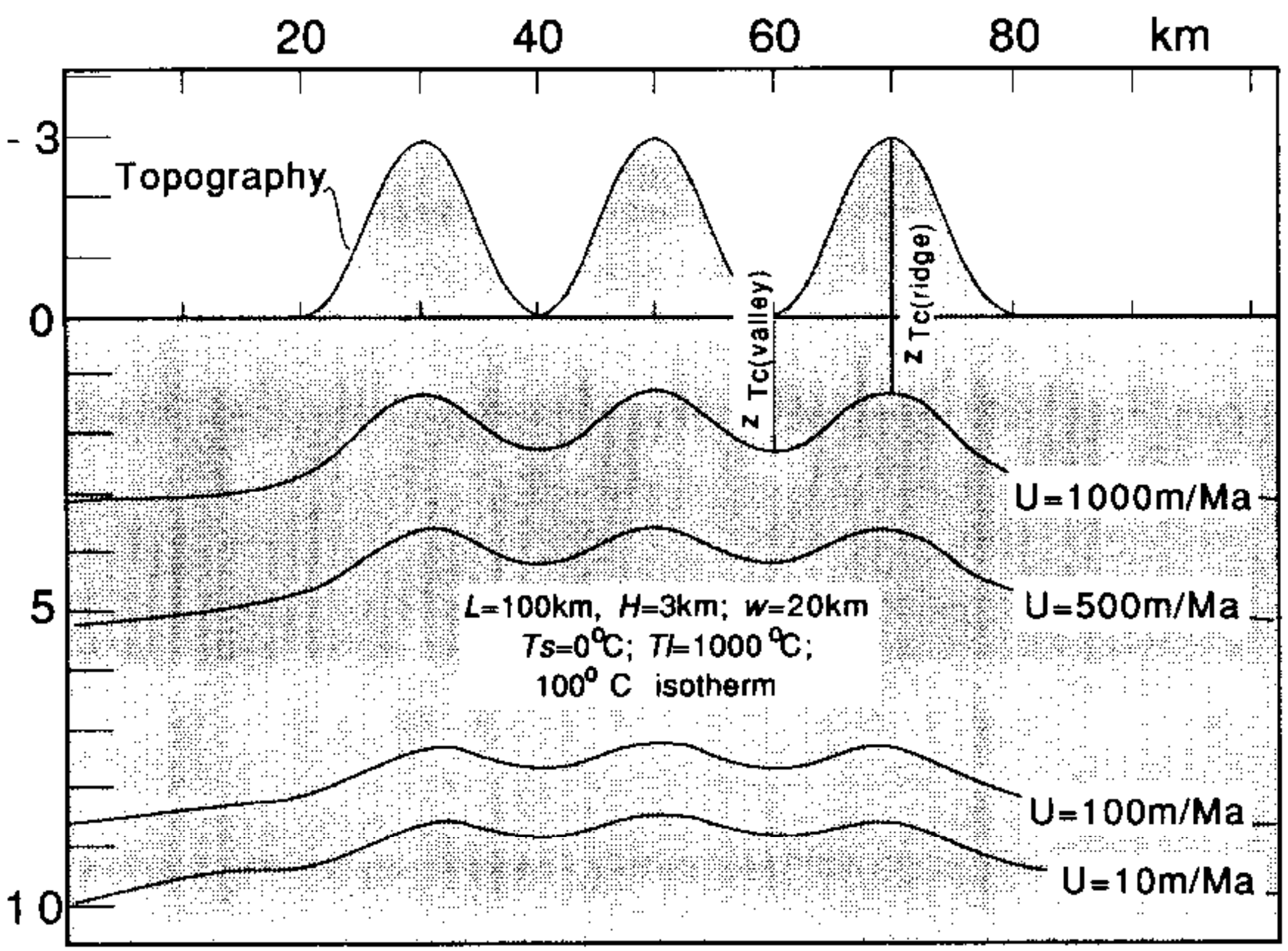
Topographic sensitivity



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

Summary

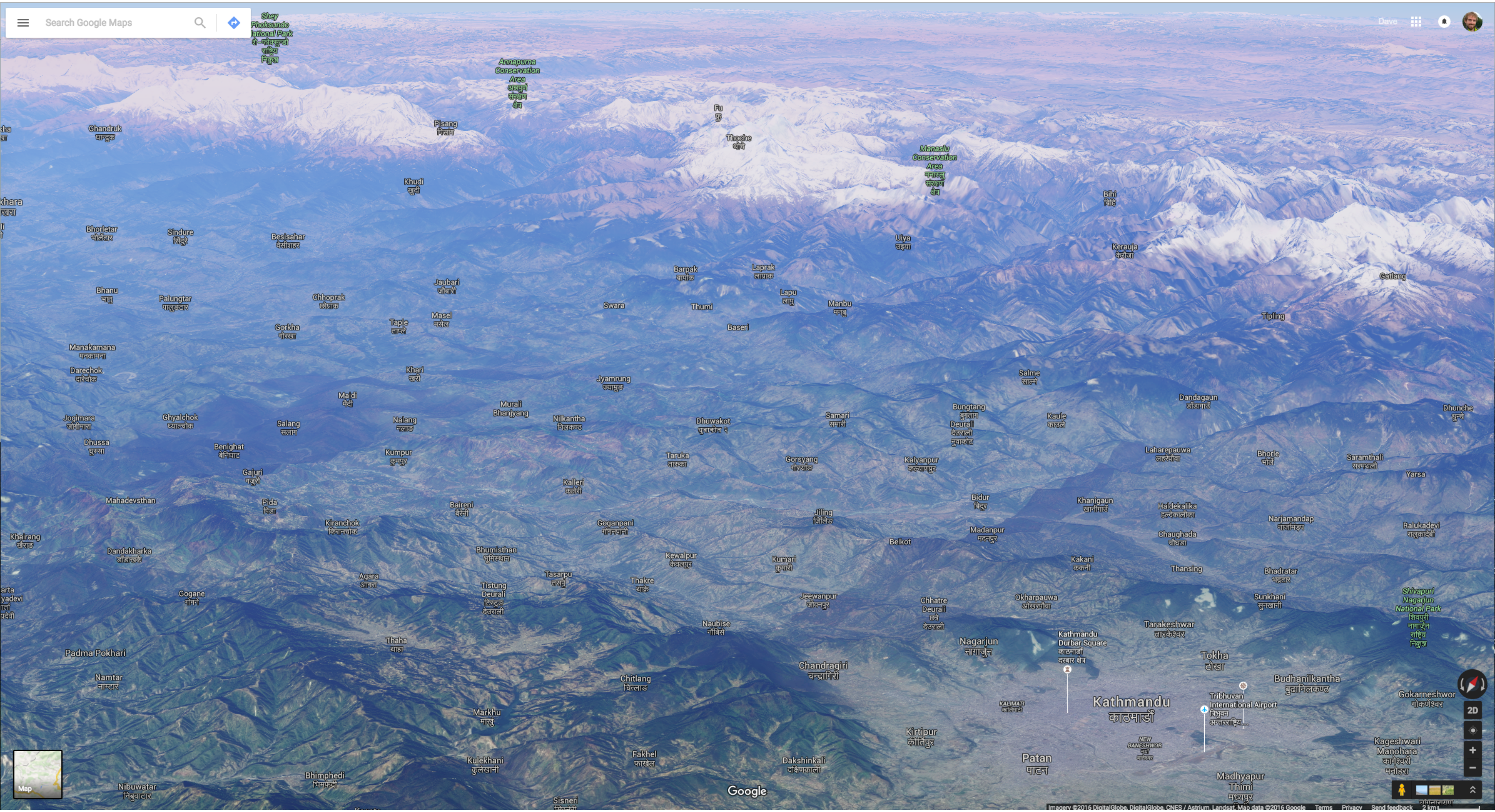
- In cases where the effective closure isotherm was likely flat during exhumation, the slope of the relationship between sample age and elevation will yield the long-term average exhumation rate
  - This is likely for samples collected in a vertical profile, regions of very slow rock exhumation, regions with short-wavelength topography, and for high-temperature thermochronometers

- Generally speaking, the conditions above generally don't occur where most people utilize low-temperature thermochronology, suggesting numerical tools are needed to interpret the thermochronometer data

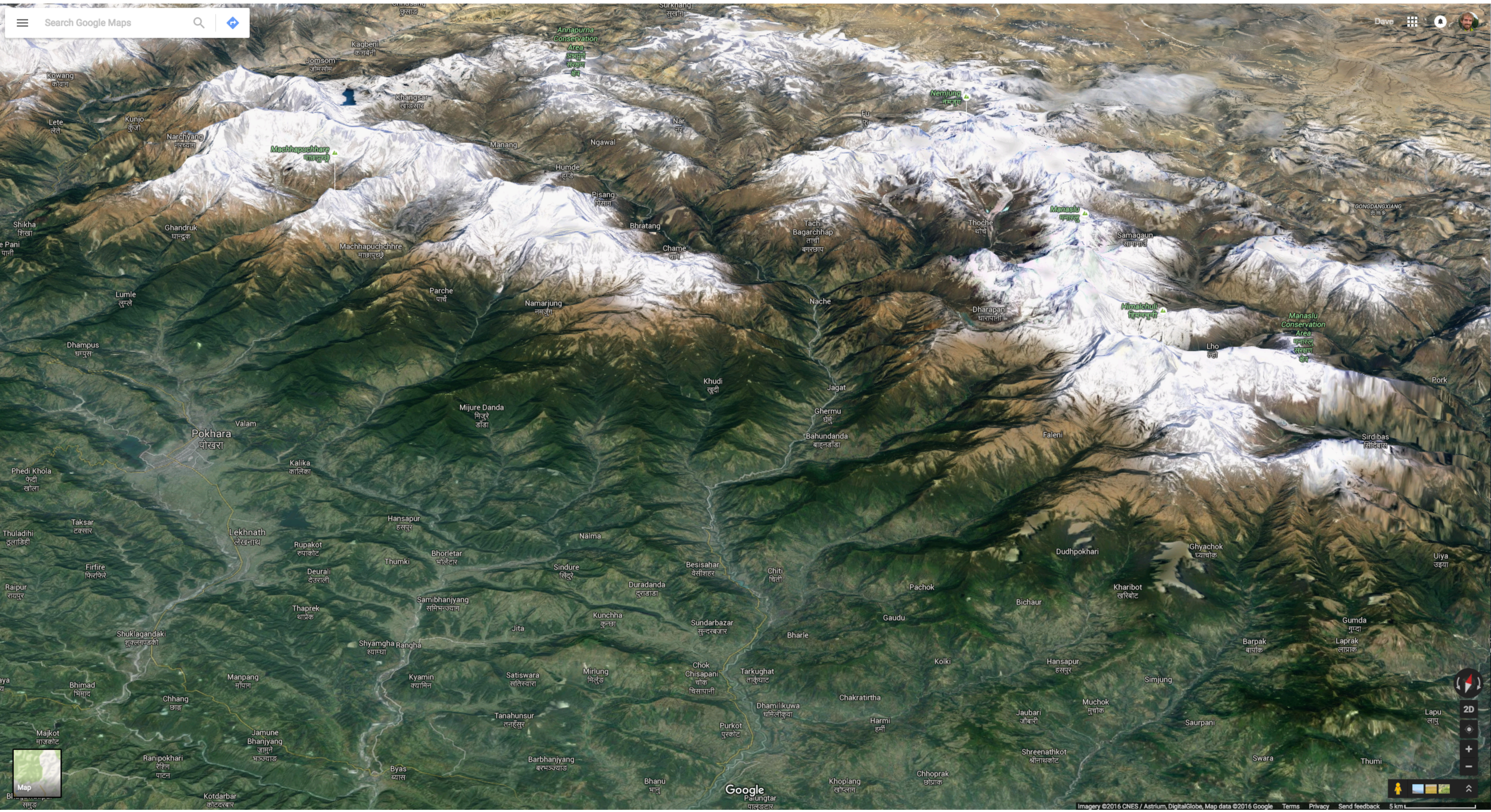
Erosion of the central Nepal Himalaya

- 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

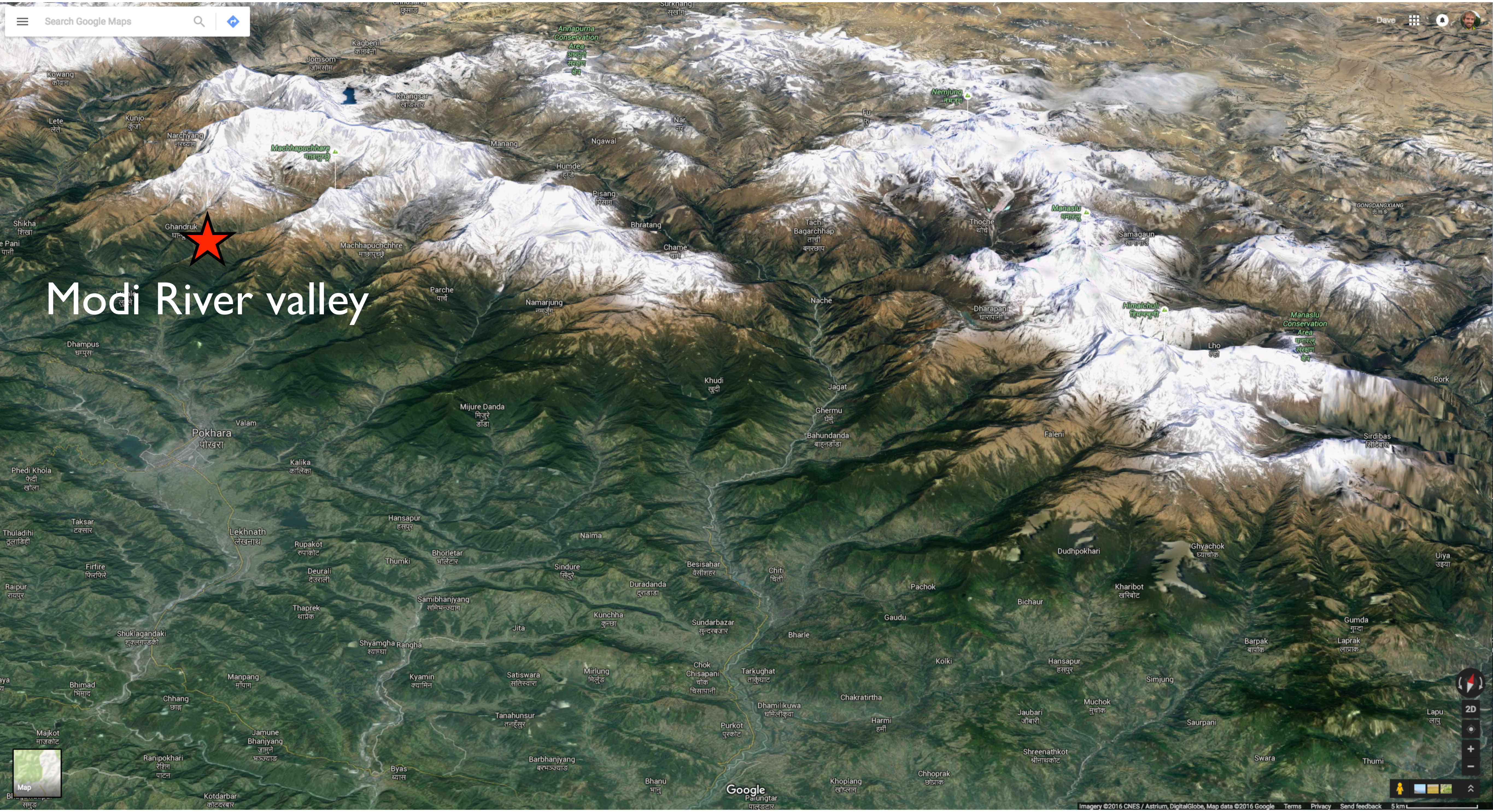
Himalaya of central Nepal



The Marsyandi River region



The Marsyandi River region



Looking north from the Lesser Himalaya


Lesser Himalayan landscape

Rhododendron forest

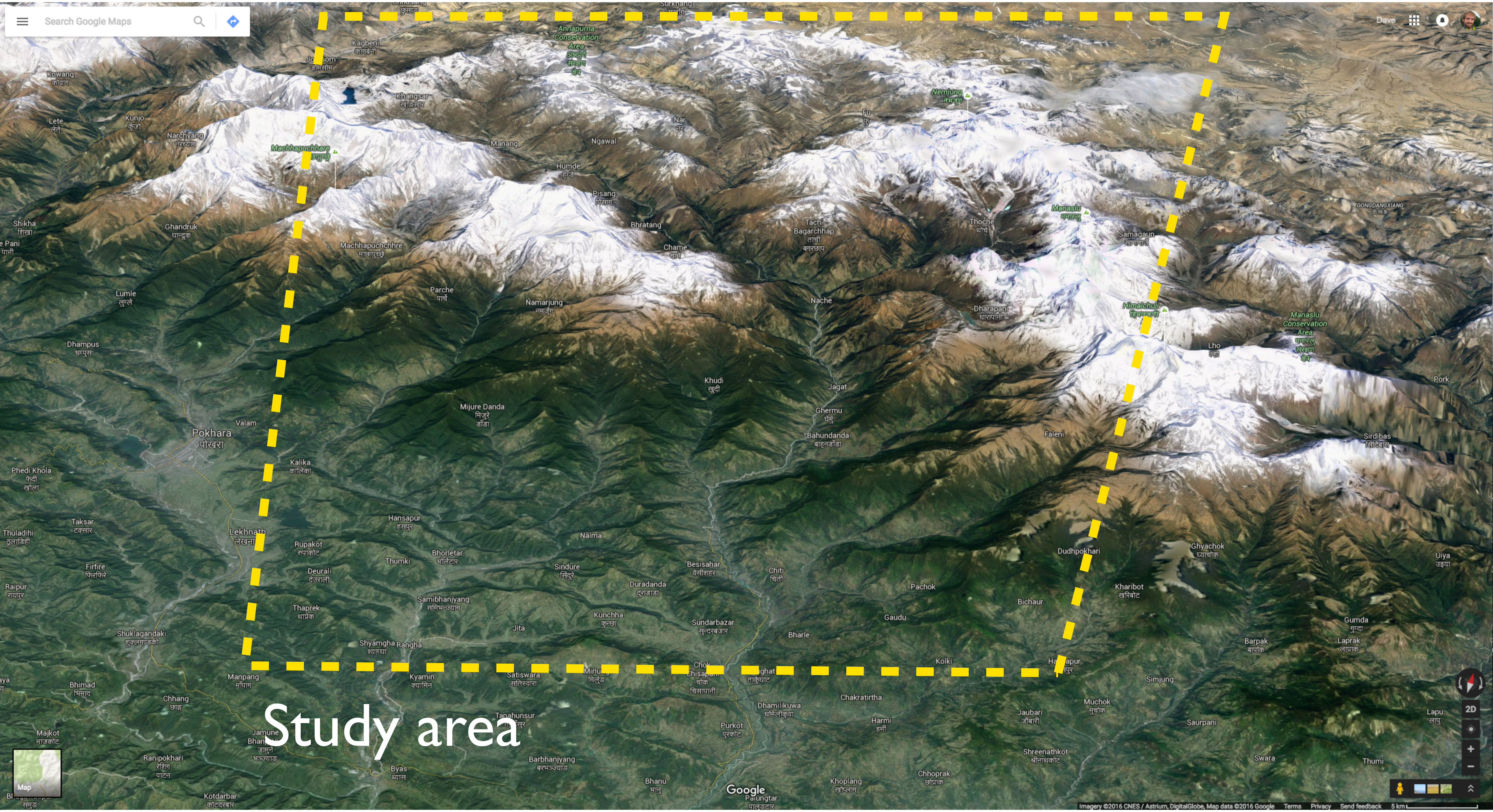
View northeast to the Dhaulagiri range


Getting closer to the high peaks

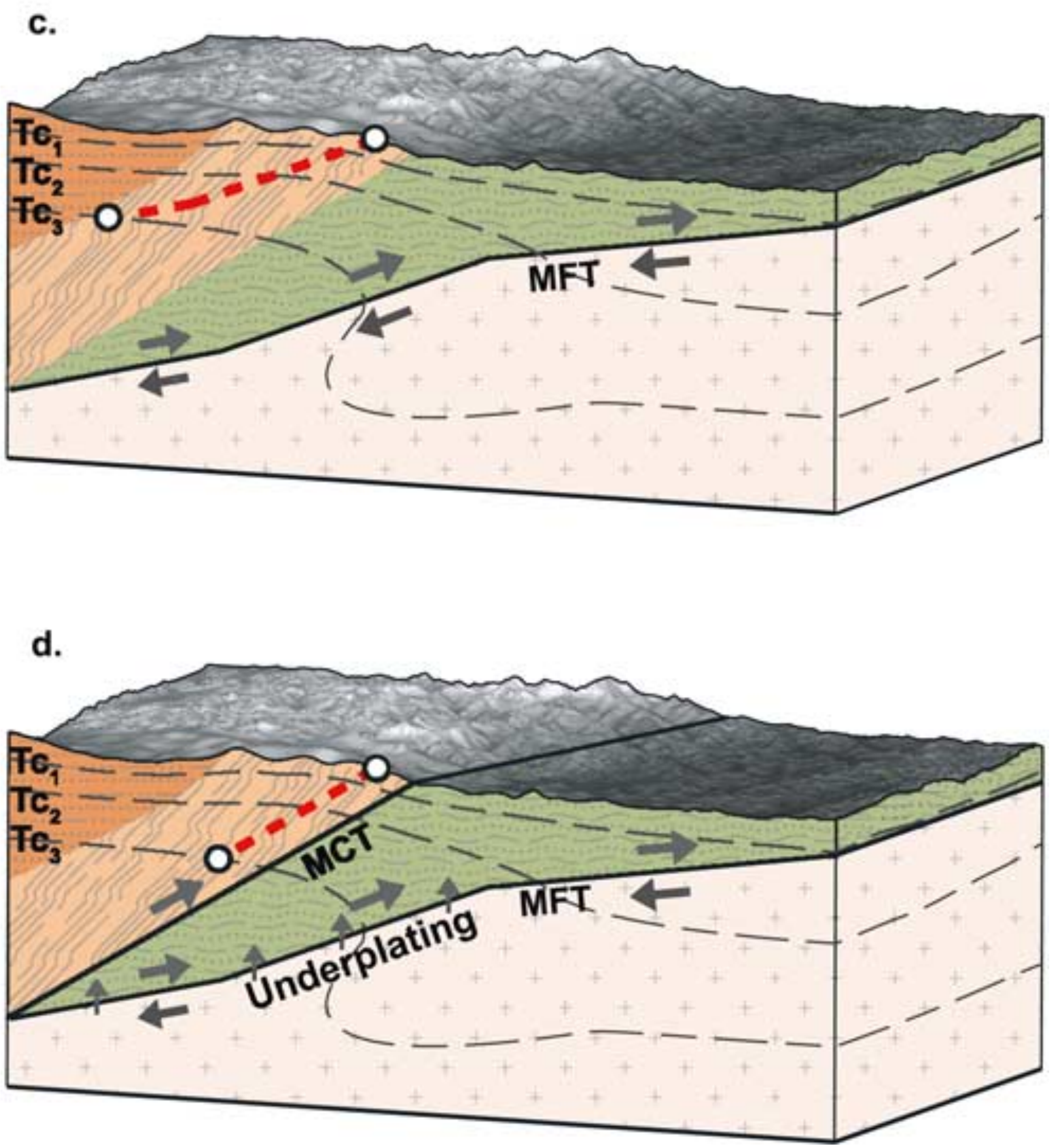

Closer still


Steeper topography entering the High Himalaya

The Marsyandi River region



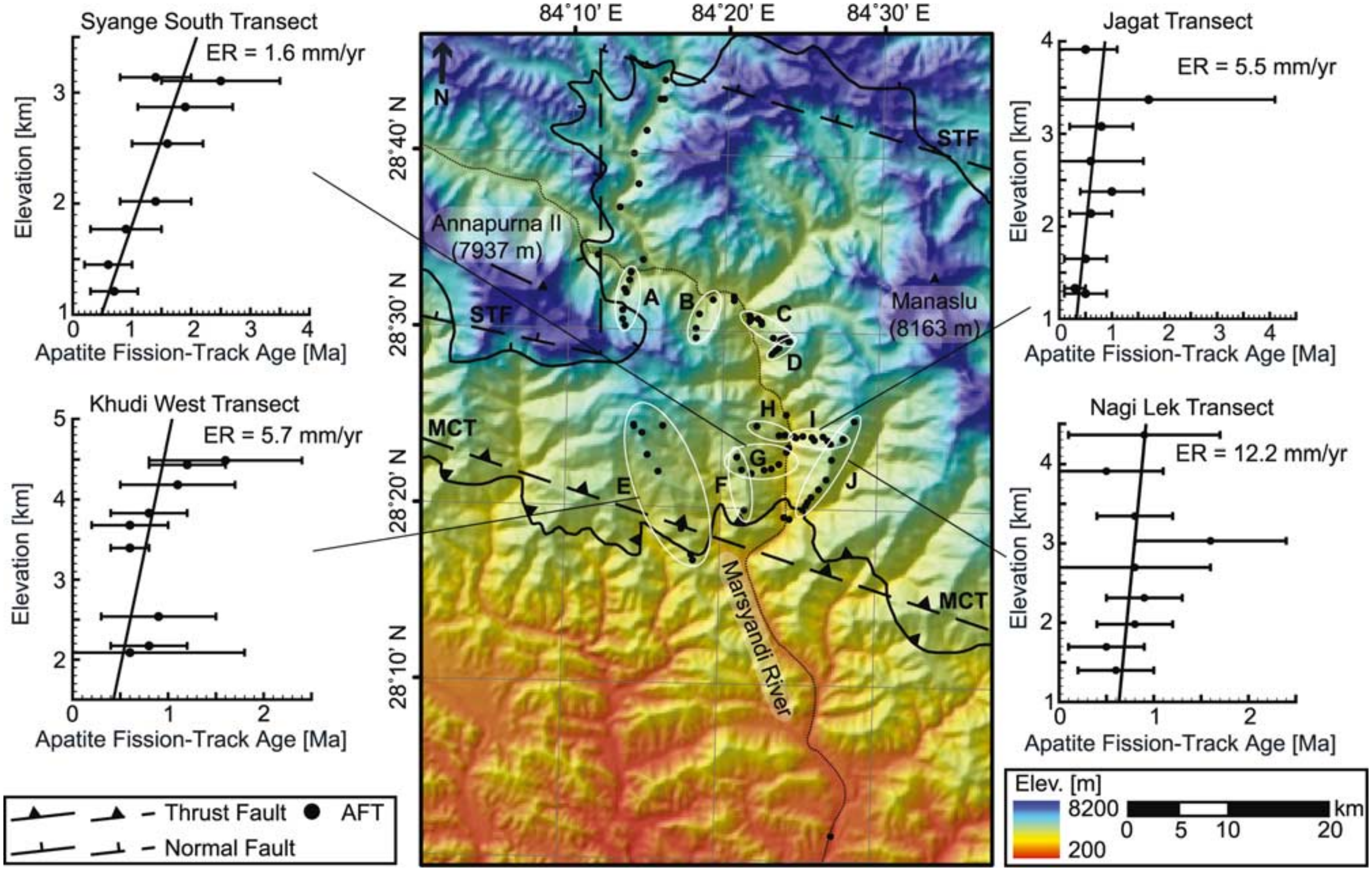
Tectonic hypothesis



Whipp et al., 2007

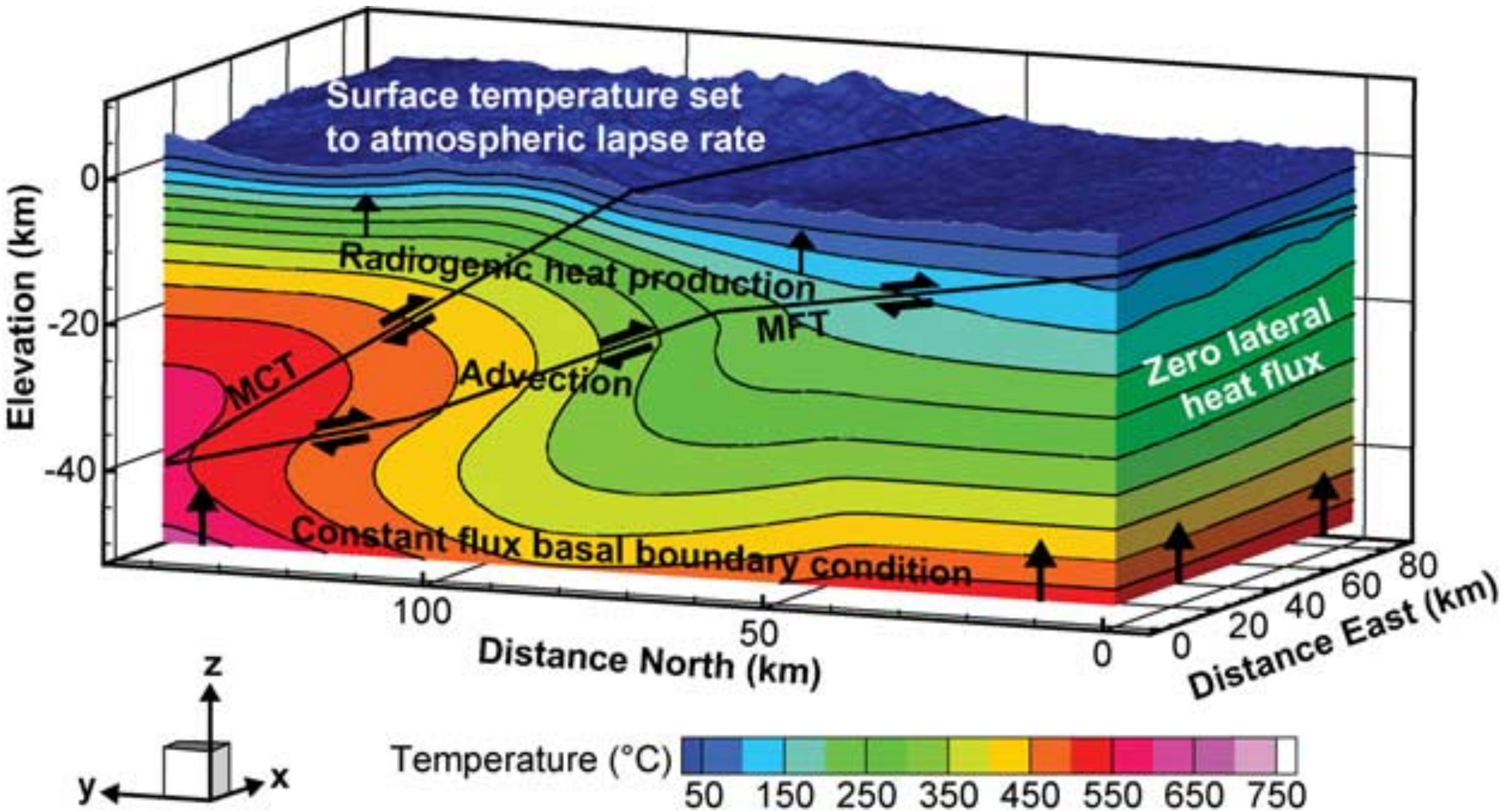
- We were testing the idea that the Main Central Thrust (MCT) has been reactivated since its main period of activity ending in the Middle Miocene
- The underlying idea was that monsoon precipitation may have eroded enough material locally to reactivate this older fault

Apatite fission-track age dataset



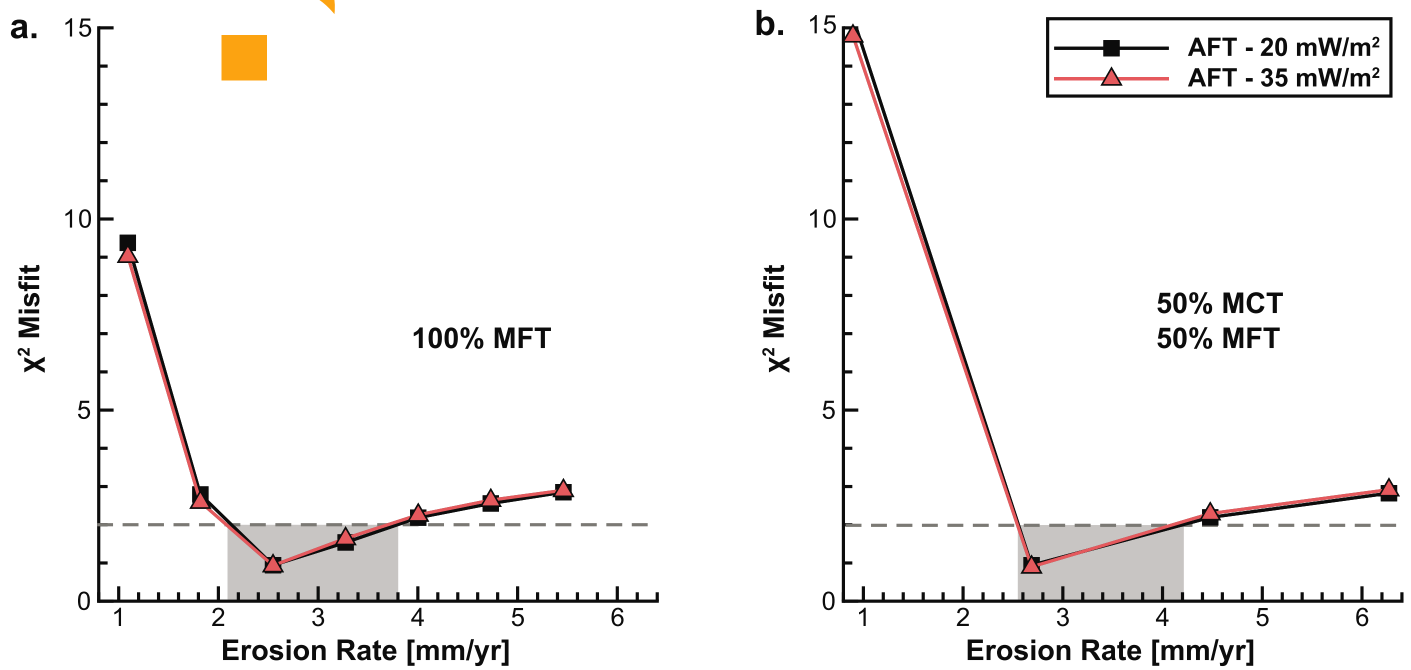
Whipp et al., 2007

3D thermal-kinematic numerical model



Whipp et al., 2007

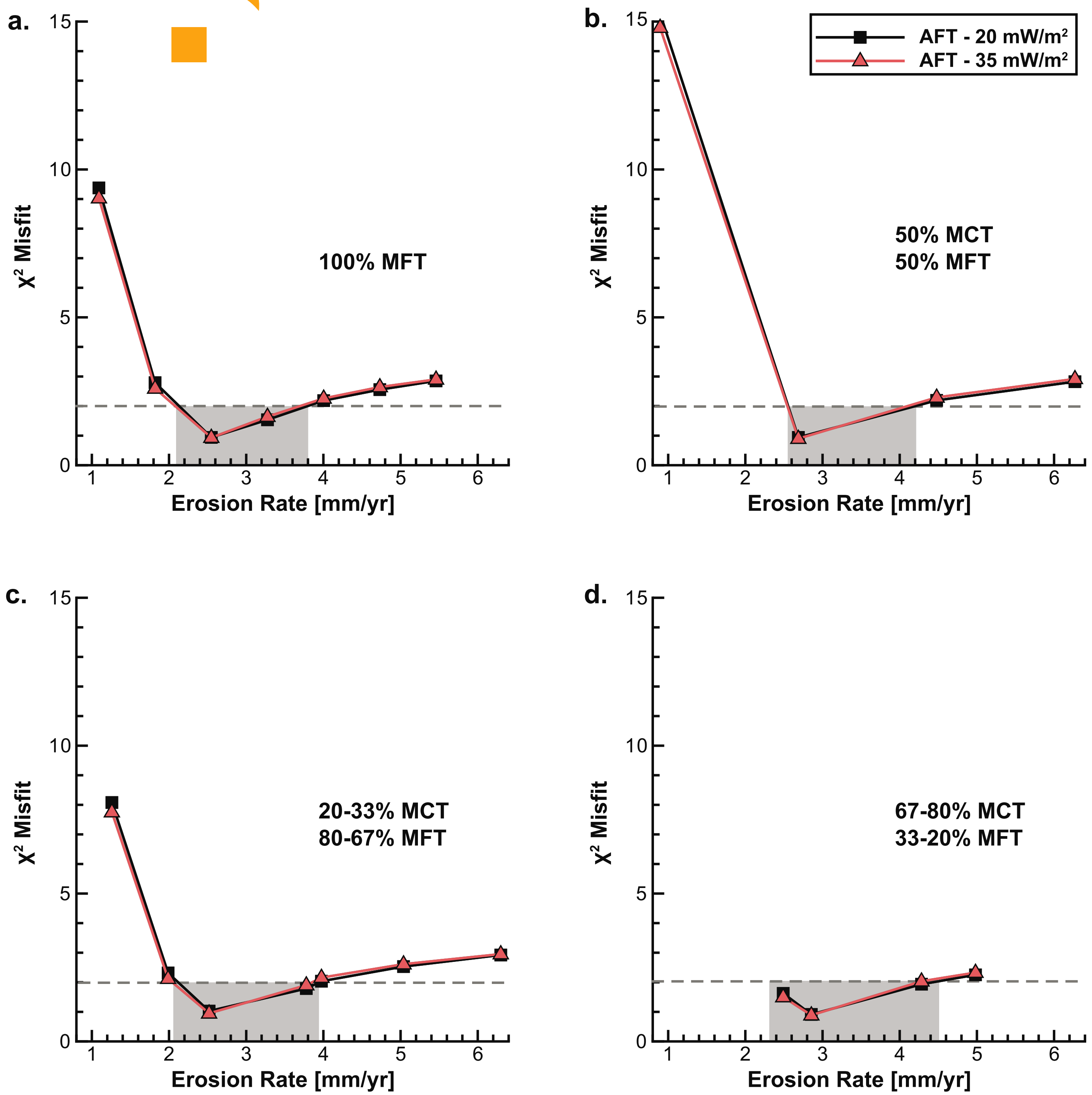
Main findings - Lack of tectonic sensitivity



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

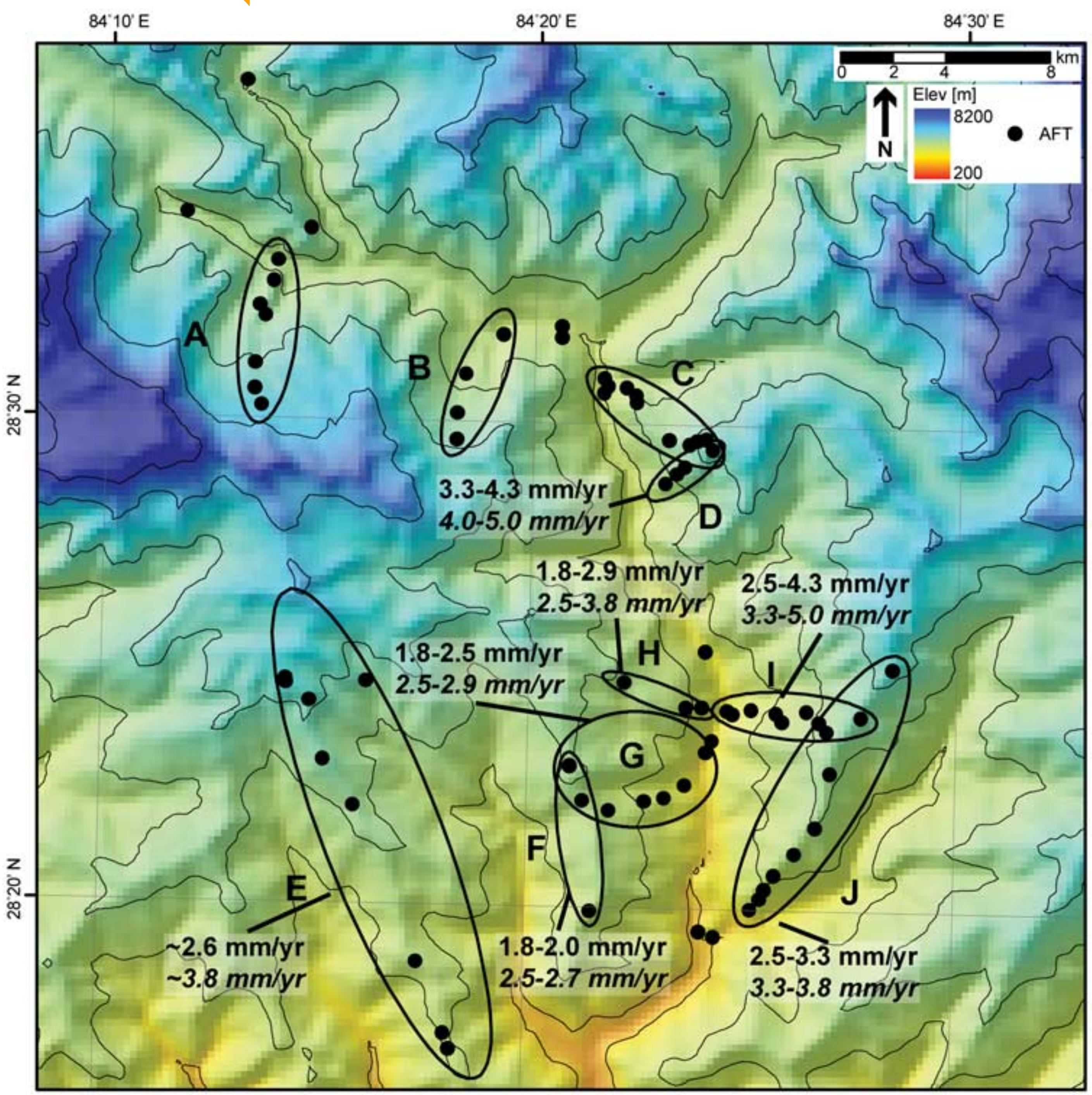
Main findings - Lack of tectonic sensitivity



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 erosion



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

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%

About this lecture

- You may not directly use much of this lecture material in Exercises 6 and 7, but it may be helpful to consider for your final paper
    - For example, you may want to use some of the material about estimating exhumation rates from the slope of sample age versus elevation, and why that might not be useful for the age data you are analysing. In other words, you can use this to make a case for why a numerical model is needed.

Recap

- Thermochronometers record rock exhumation, the vertical motion of rock toward the surface of the Earth
- Rapid exhumation or slower exhumation for long time periods will significantly heat the upper crust. Sedimentation has the opposite effect.
- The slope of thermochronometer ages versus elevation can be used to estimate long-term rates of rock exhumation in select situations. In most cases, a numerical model is needed.

References

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