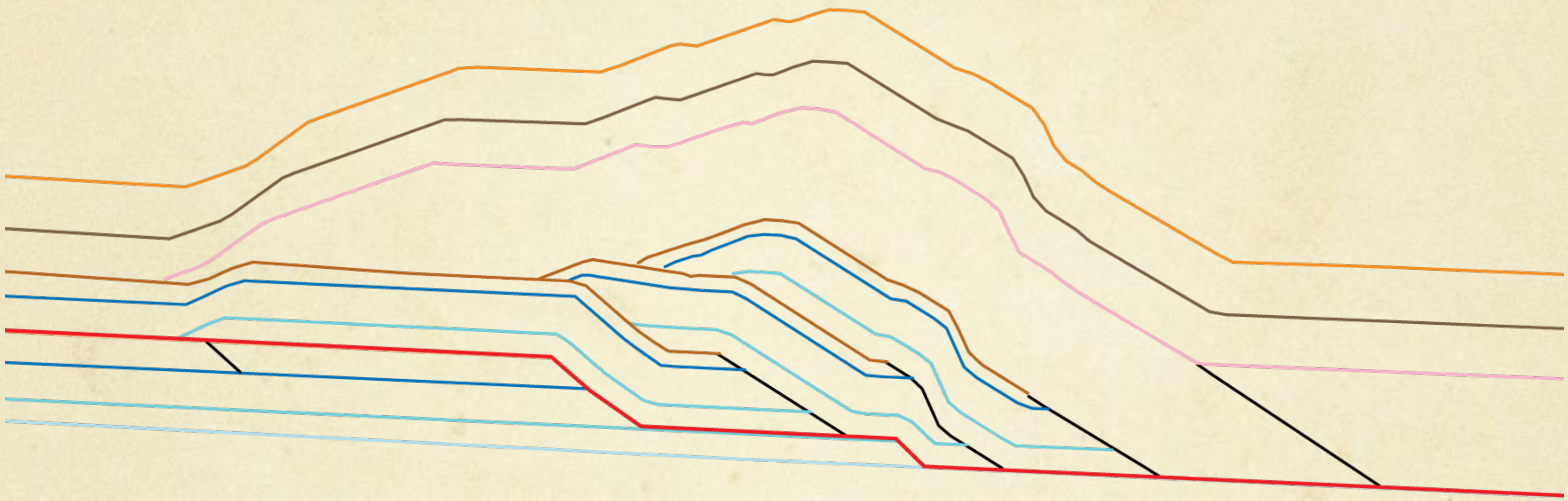
QUANTIFYING DEFORMATION IN THE BHUTAN HIMALAYA: INSIGHTS FROM A THERMAL-KINEMATIC MODEL OF THE TRASHIGANG CROSS SECTION



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2014 GSA Annual Meeting

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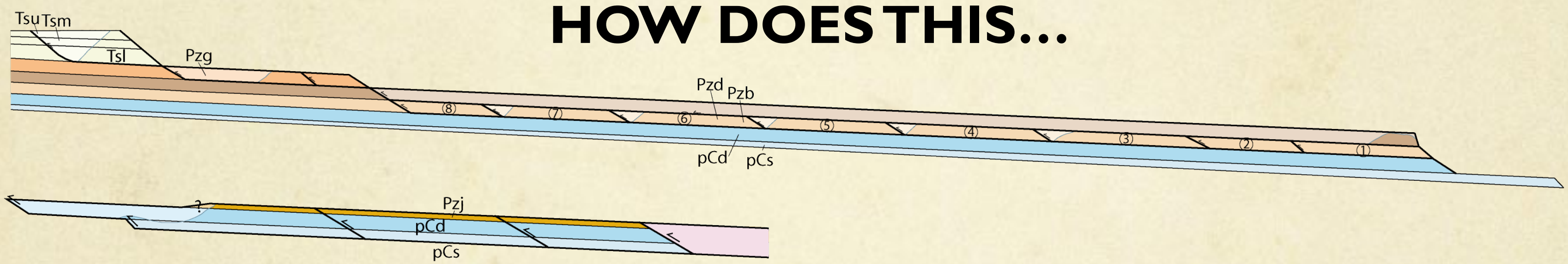
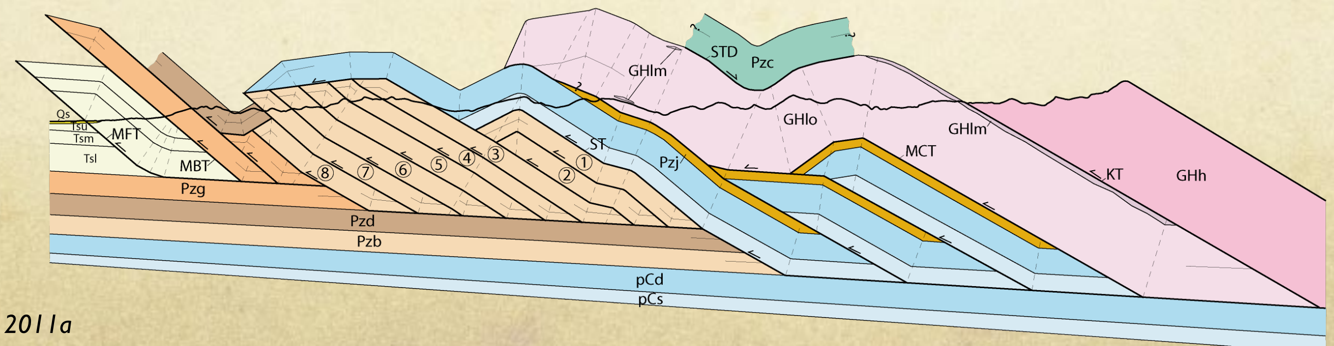
INTRODUCTION

- We want to understand how fold-thrust belts and their associated features form over space and time.
- Can we quantify fold-thrust belt evolution between restored and deformed cross sections?

HOW DOES THIS…



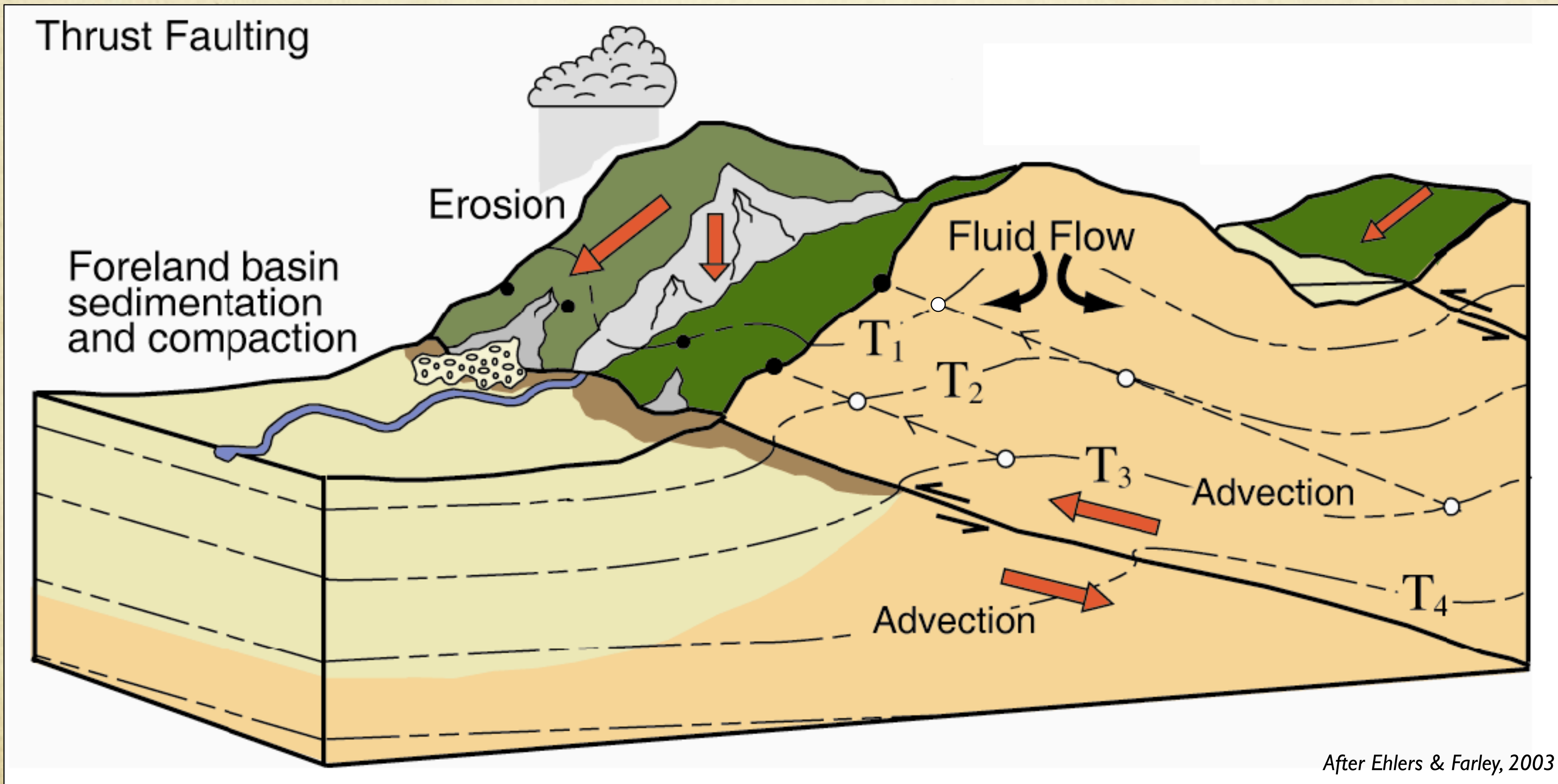
TURN INTO THIS?



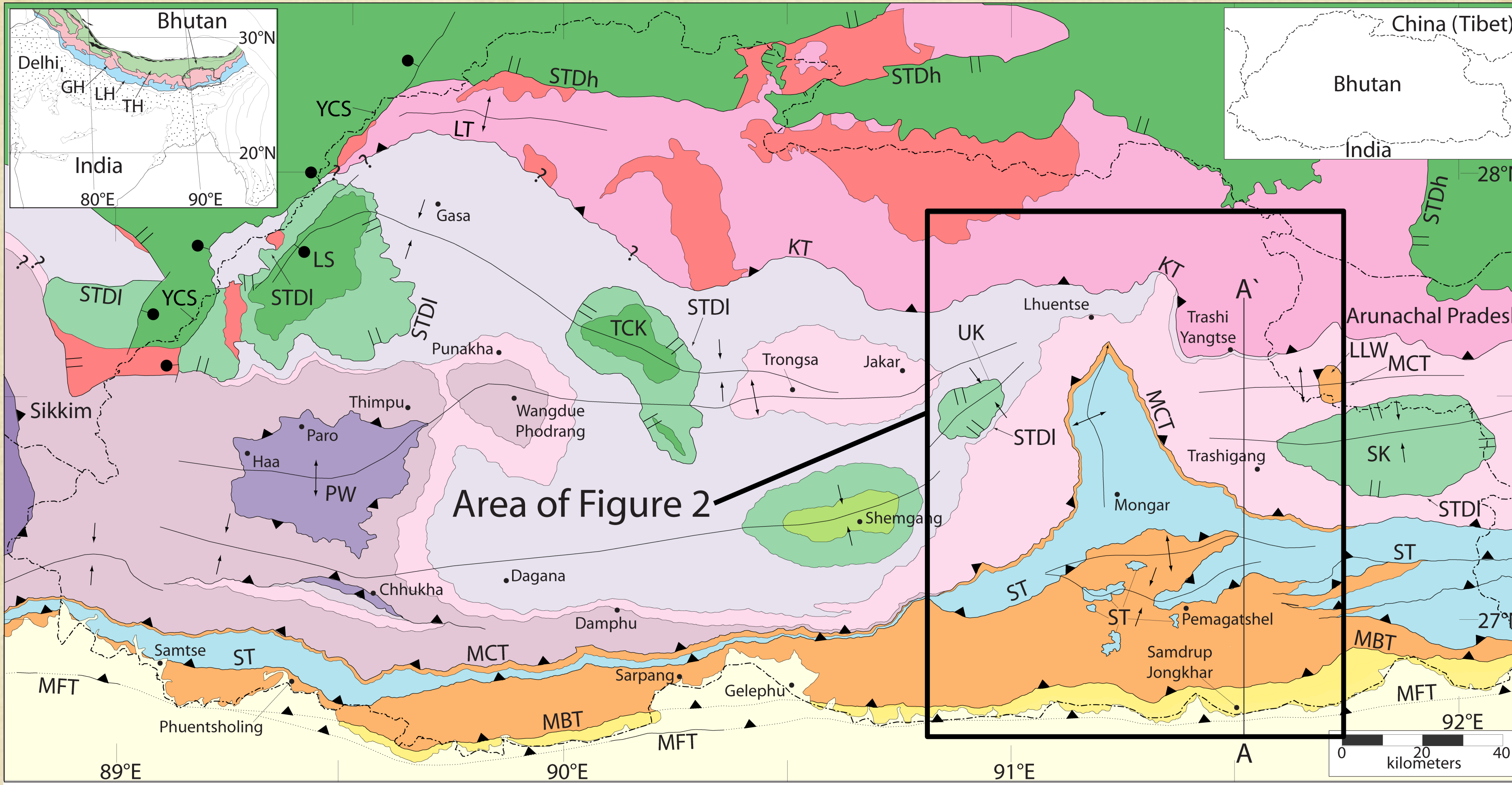
After Long et al., 2011a

THERMOCHRONOMETERS + FAULT MOTION

STRUCTURAL UPLIFT → EROSION → COOLING



GEOLOGIC BACKGROUND



Tethyan (Tibetan) Himalaya:
- Paleozoic and Mesozoic, undiff.
- Maneting Formation
- Chekha Formation

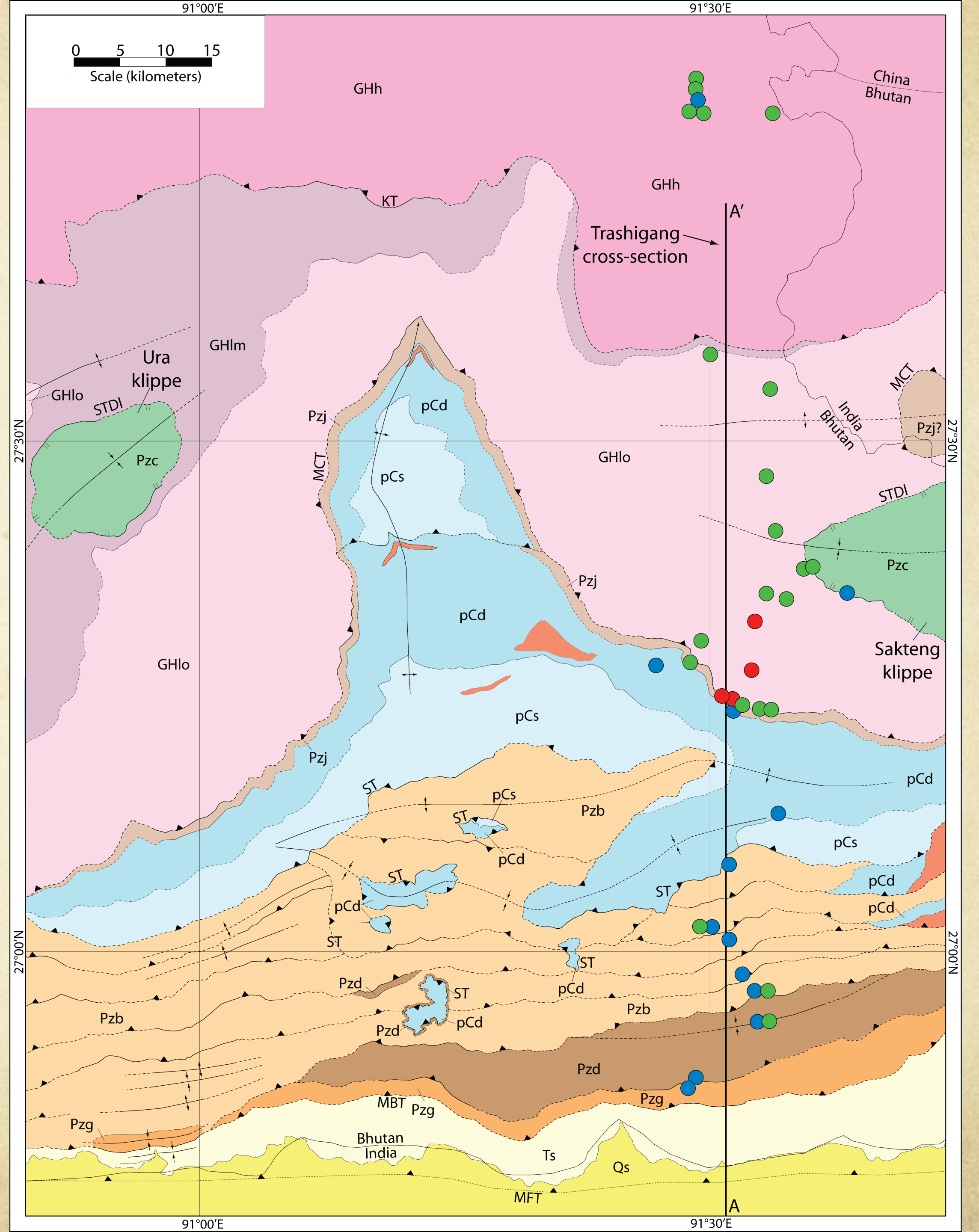
Greater Himalaya:
- Higher structural level, leucogranite
- Higher structural level, undifferentiated
- Lower structural level, upper metased. unit
- Lower structural level, orthogneiss unit
- Lower structural level, lower metased. unit

Paro Fm., Lesser and Subhimalaya:
- Paro Formation
- Lower Lesser Himalayan units
- Upper Lesser Himalayan units
- Subhimalaya (Siwalik Group)
- Quaternary sediment

After Long et al., 2011b

Thermochronologic Data

- Apatite Fission Track (AFT)
- Zircon (U-Th)/He (ZHe)
- White Mica $^{39}Ar/^{40}Ar$ (MAr)



After Long et al., 2012

RECIPE FOR DETERMINING AGES OF FAULT MOTION

1. Create a flexural model that accounts for progressive deformation, exhumation, isostatic and topographic history in small increments

2. Assign ages to fault motion and input flexural model in a thermal-kinematic model to calculate thermal history and cooling ages along the cross section

3. Compare calculated cooling ages to published thermochronologic data to establish timing and rates of deformation

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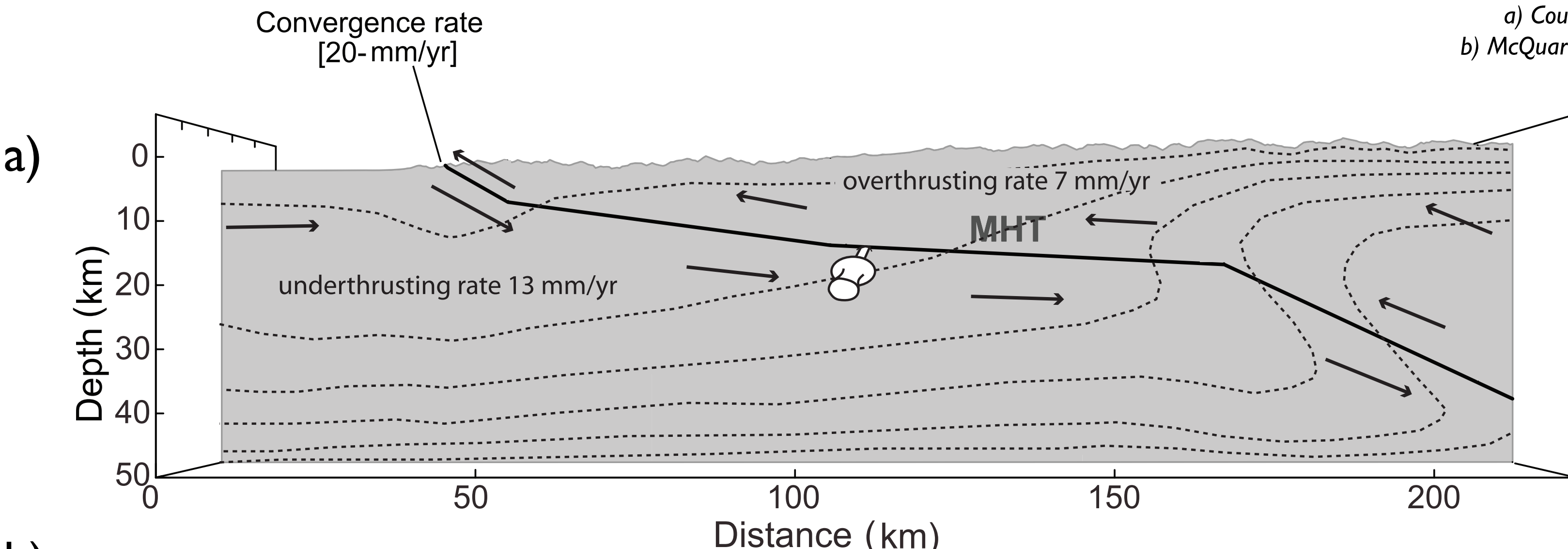
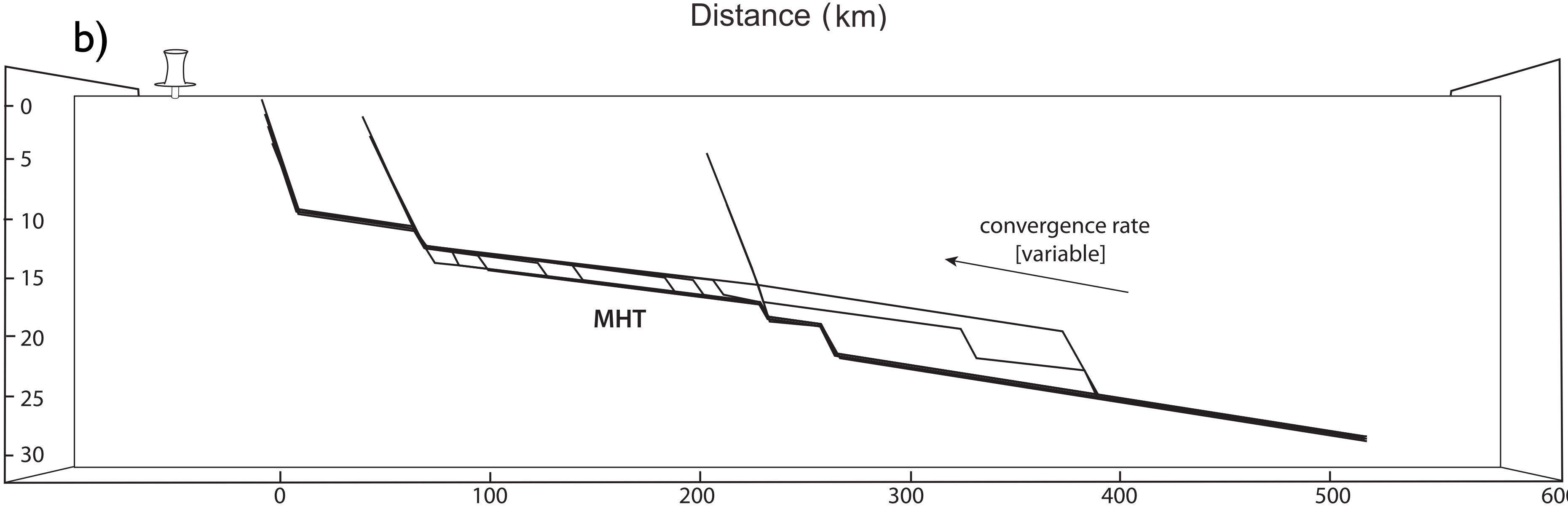
NOT A NEW APPROACH BUT A NEW FRAME OF REFERENCE

a) Coutand et al., 2014
b) McQuarrie et al., in prep.





QUESTIONS FOR MODELING CROSS SECTIONS AND COOLING AGES

1. How do constant versus variable deformation rates affect model output?
2. Does changing out-of-sequence thrust timing affect output?
3. Does topographic resolution matter?
4. Which velocity, kinematic scenario, and topography combination best matches published cooling data?

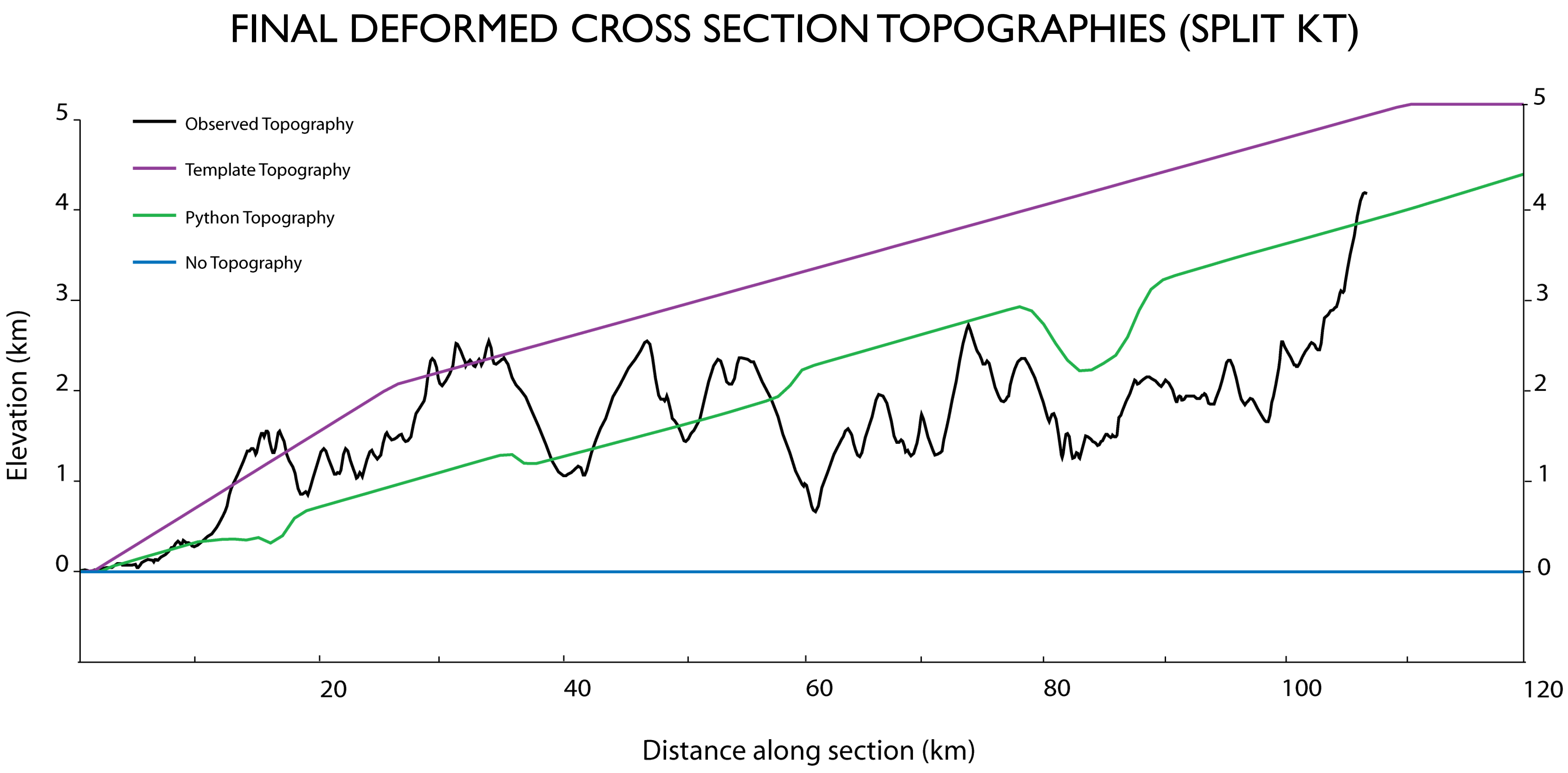
FLEXURAL MODEL OF CROSS SECTION

MOVE by Midland Valley Exploration

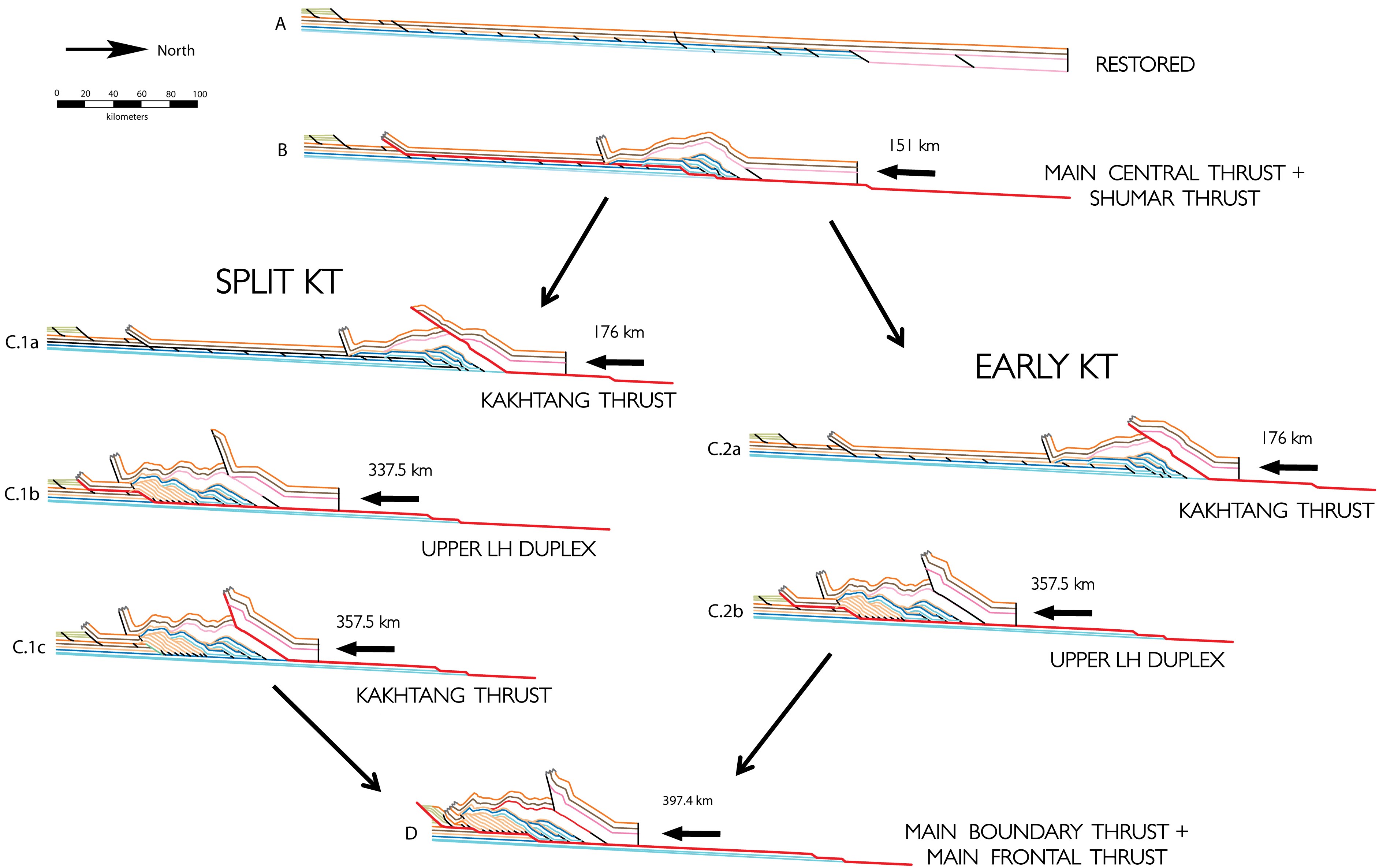
- Use ~10 km increments of shortening to sequentially deform cross section
- Account for evolving topography, structural loading, erosional offloading at each deformation step
- Attain best fit to known parameters of Trashigang Cross Section:
    1. Mapped surface geology
    2. Foreland basin thickness
    3. Dip of the Main Himalayan Thrust (MHT)

FLEXURAL MODEL

ESTIMATING TOPOGRAPHY



KINEMATIC SCENARIOS

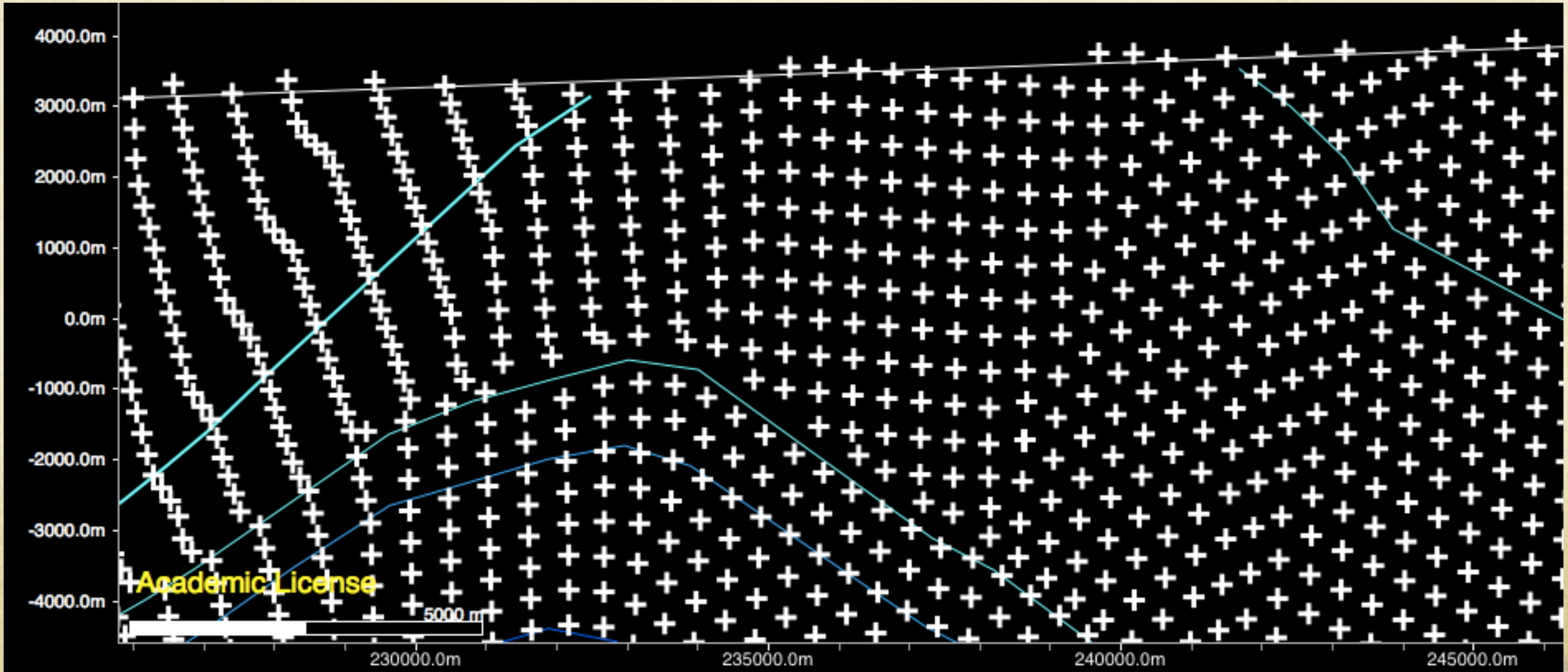


THERMAL-KINEMATIC MODEL - PECUBE

Turning a spatial model into a displacement field

- Emplace a 0.5 x 0.5 km resolution grid of points in the flexural model's subsurface

- High-resolution tracking of rock particles as they move from subsurface to surface

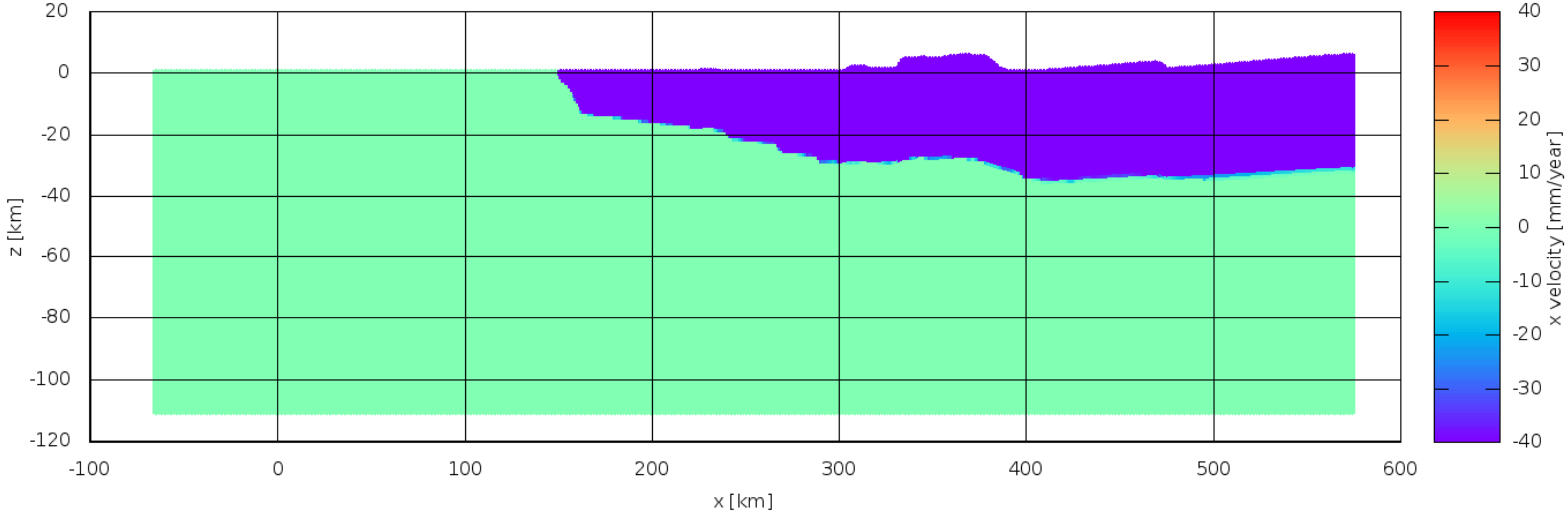


THERMAL-KINEMATIC MODEL - PECUBE

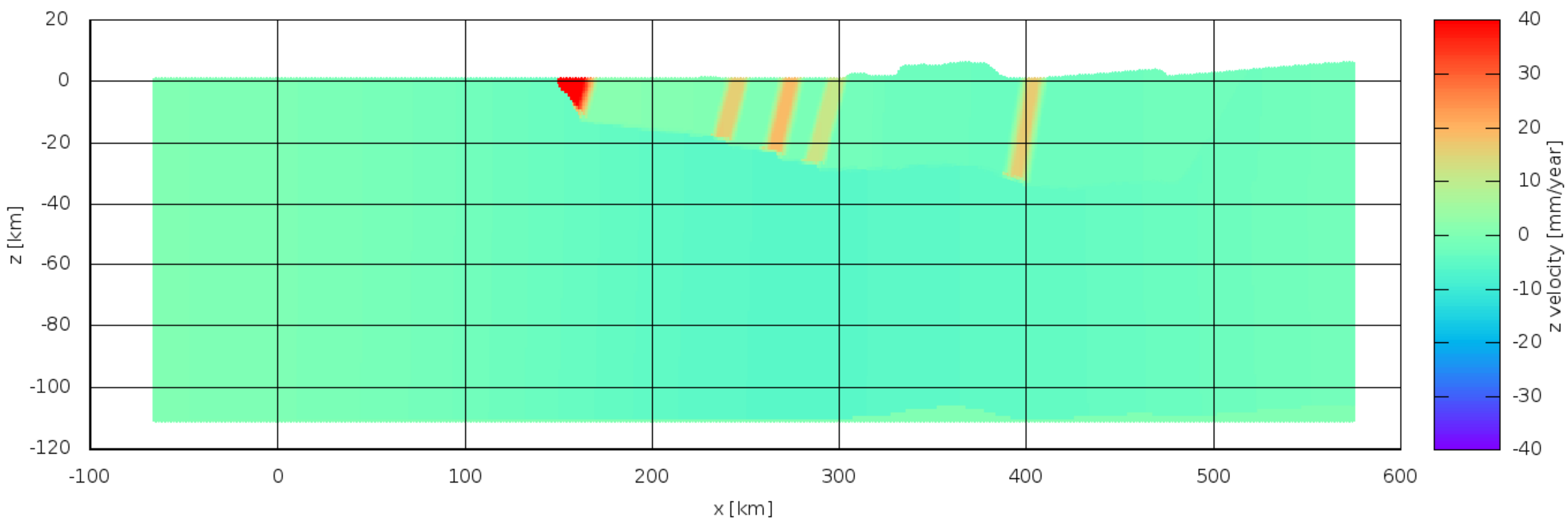
Turning a spatial model into a displacement field

- Emplace a 0.5 x 0.5 km resolution grid of points in the flexural model's subsurface
- High-resolution tracking of rock particles as they move from subsurface to surface
- **Assign ages of fault motion to create velocity field for each ~10-km deformation step**

simply put: $v = \Delta x / \Delta t$



horizontal (above) and vertical (below) velocities inside the model

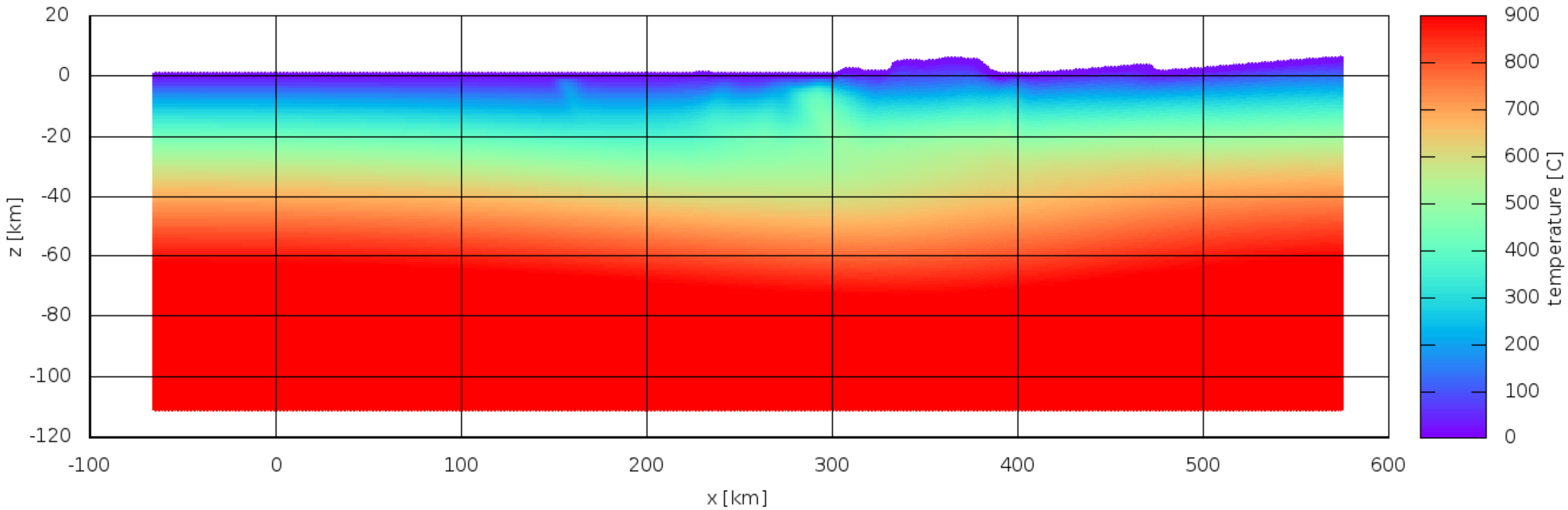


FAULT MOTION + EROSION + THERMAL CONDITIONS

↓

THERMAL MODEL

temperature inside the model



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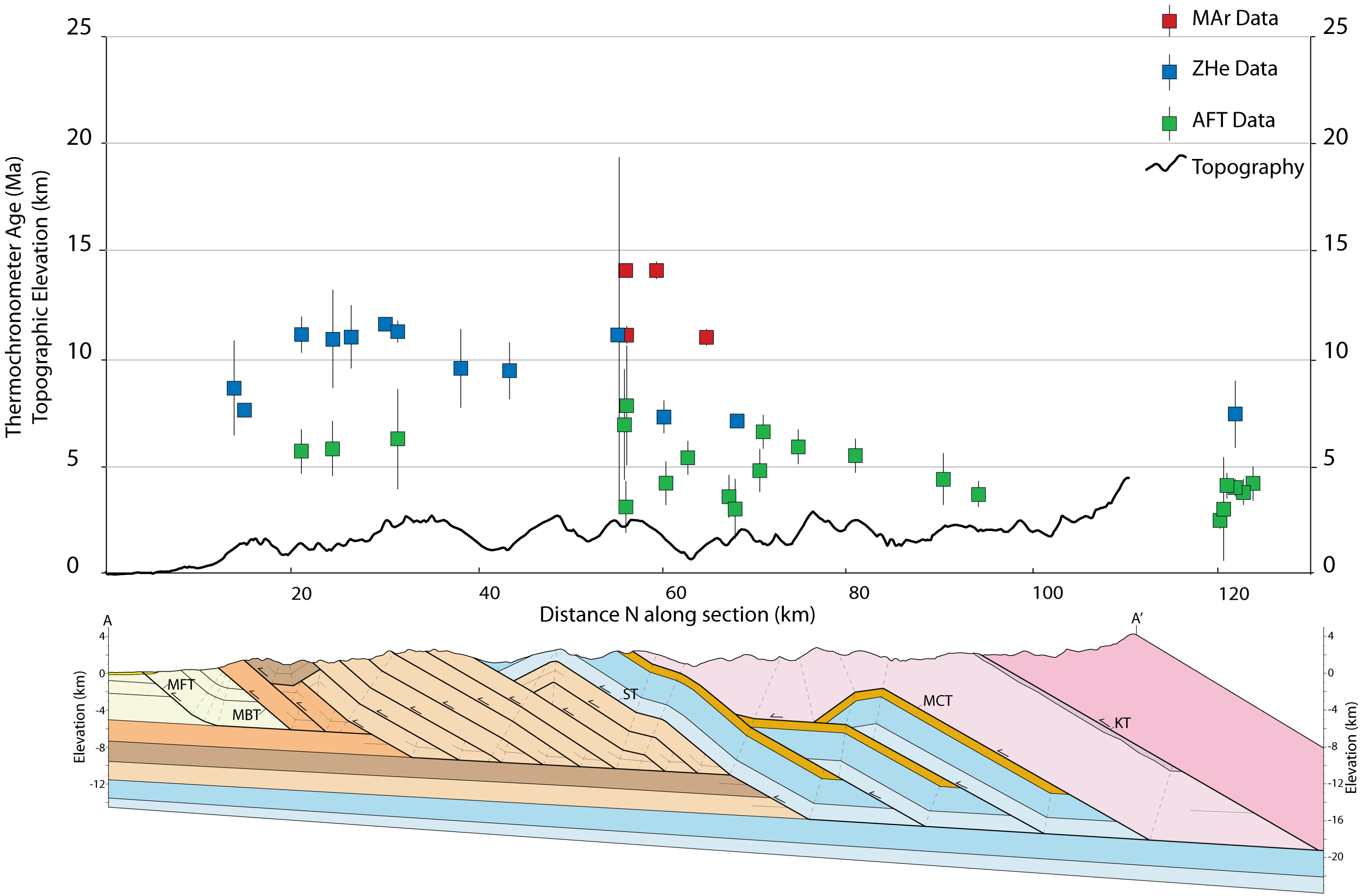
THERMOCHRONOMETER AGES

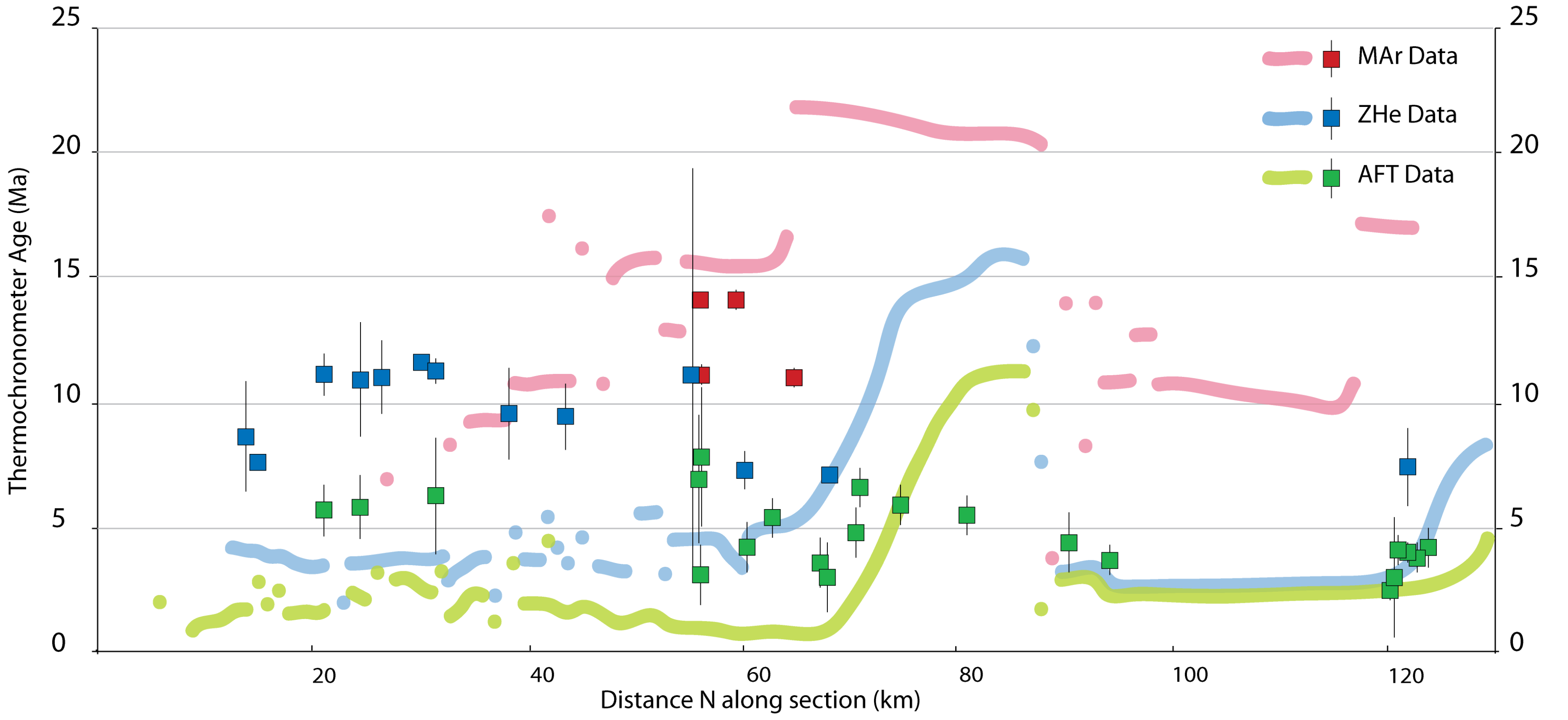
THERMOCHRONOLOGIC DATA



CONSTANT VELOCITY (23-0 Ma = 17.3 mm/yr)

SPLIT KT – PYTHON TOPOGRAPHY

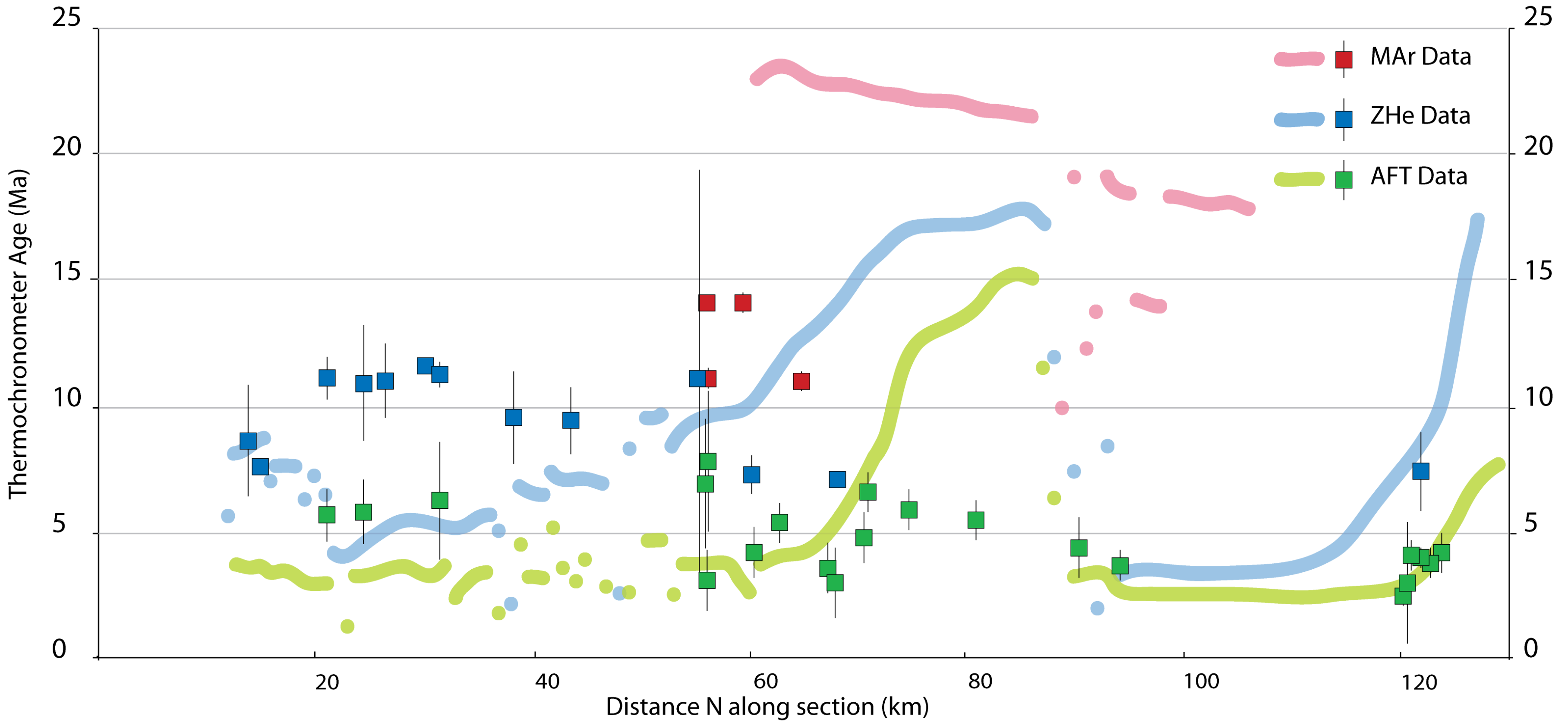
Heat production (Ao) = 2.5 μ W/m^3



CONSTANT VELOCITY (23-0 Ma = 17.3 mm/yr)

SPLIT KT – PYTHON TOPOGRAPHY

Heat production (Ao) = 1.0 $\mu W/m^3$



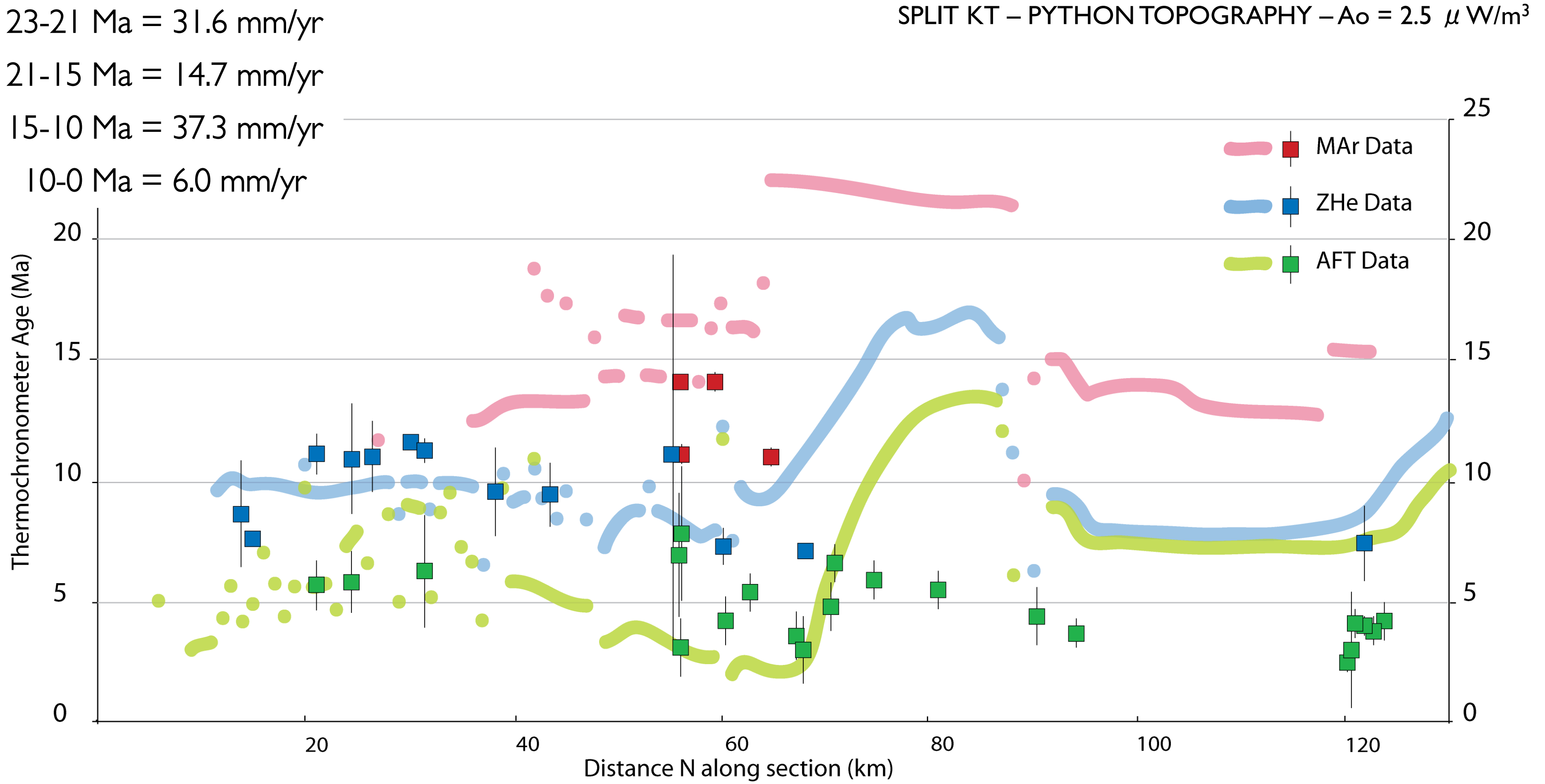
VARIABLE VELOCITY A

23-21 Ma = 31.6 mm/yr

21-15 Ma = 14.7 mm/yr

15-10 Ma = 37.3 mm/yr

10-0 Ma = 6.0 mm/yr



VARIABLE VELOCITY B

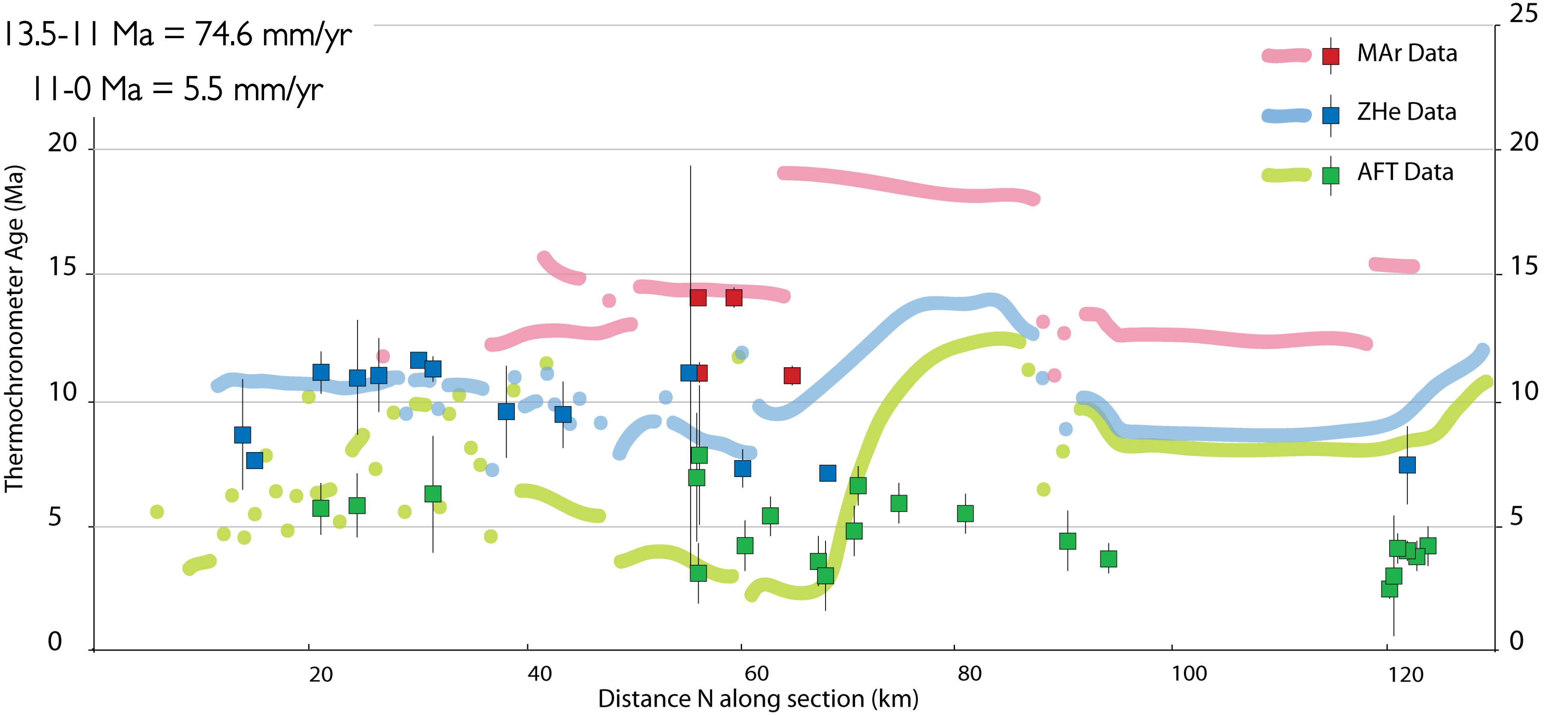
20-17 Ma = 21.1 mm/yr

17-13.5 Ma = 25.1 mm/yr

13.5-11 Ma = 74.6 mm/yr

11-0 Ma = 5.5 mm/yr

SPLIT KT – PYTHON TOPOGRAPHY – Ao = 2.5 μ W/m^3



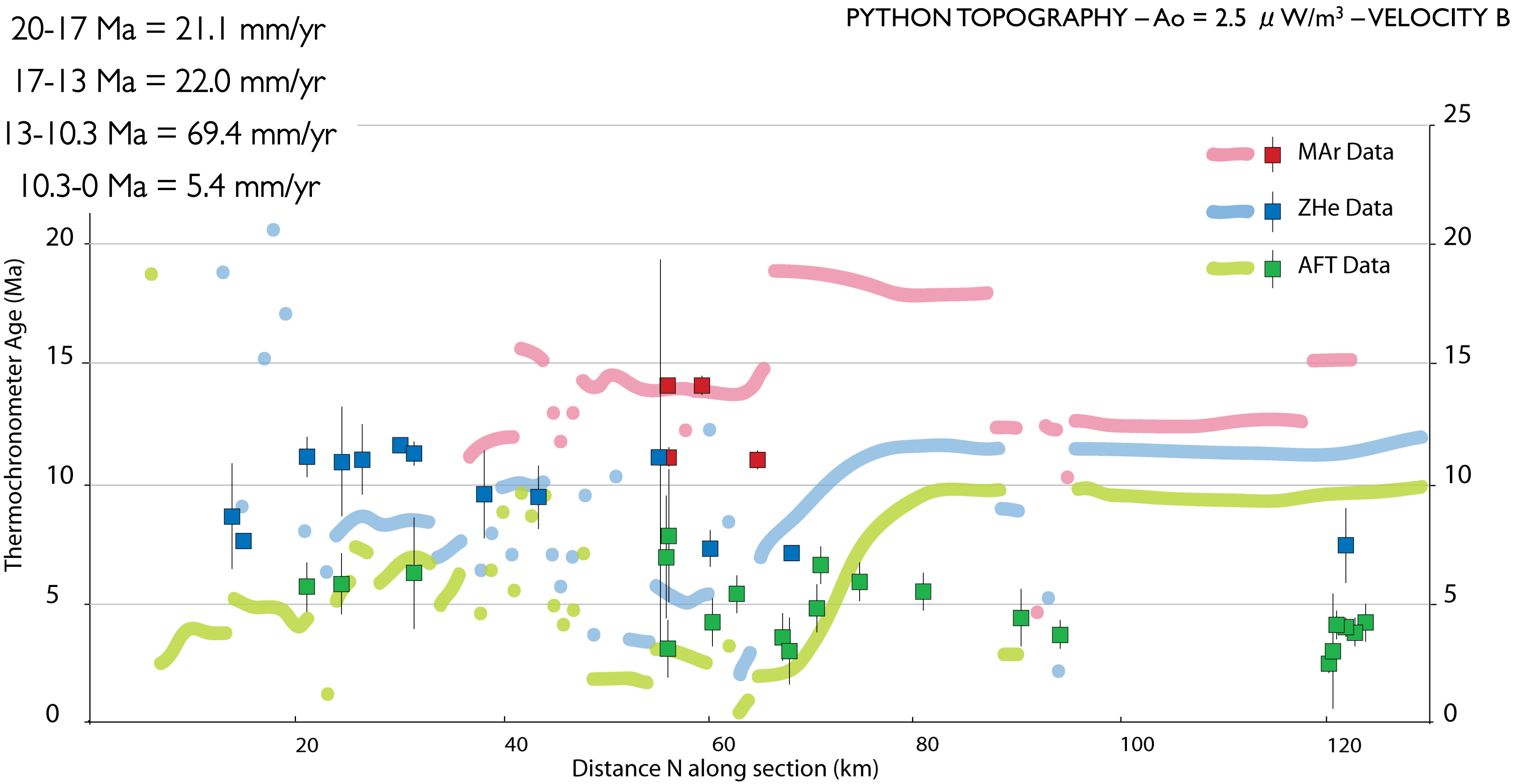
KINEMATIC SENSITIVITY – EARLY KT

20-17 Ma = 21.1 mm/yr

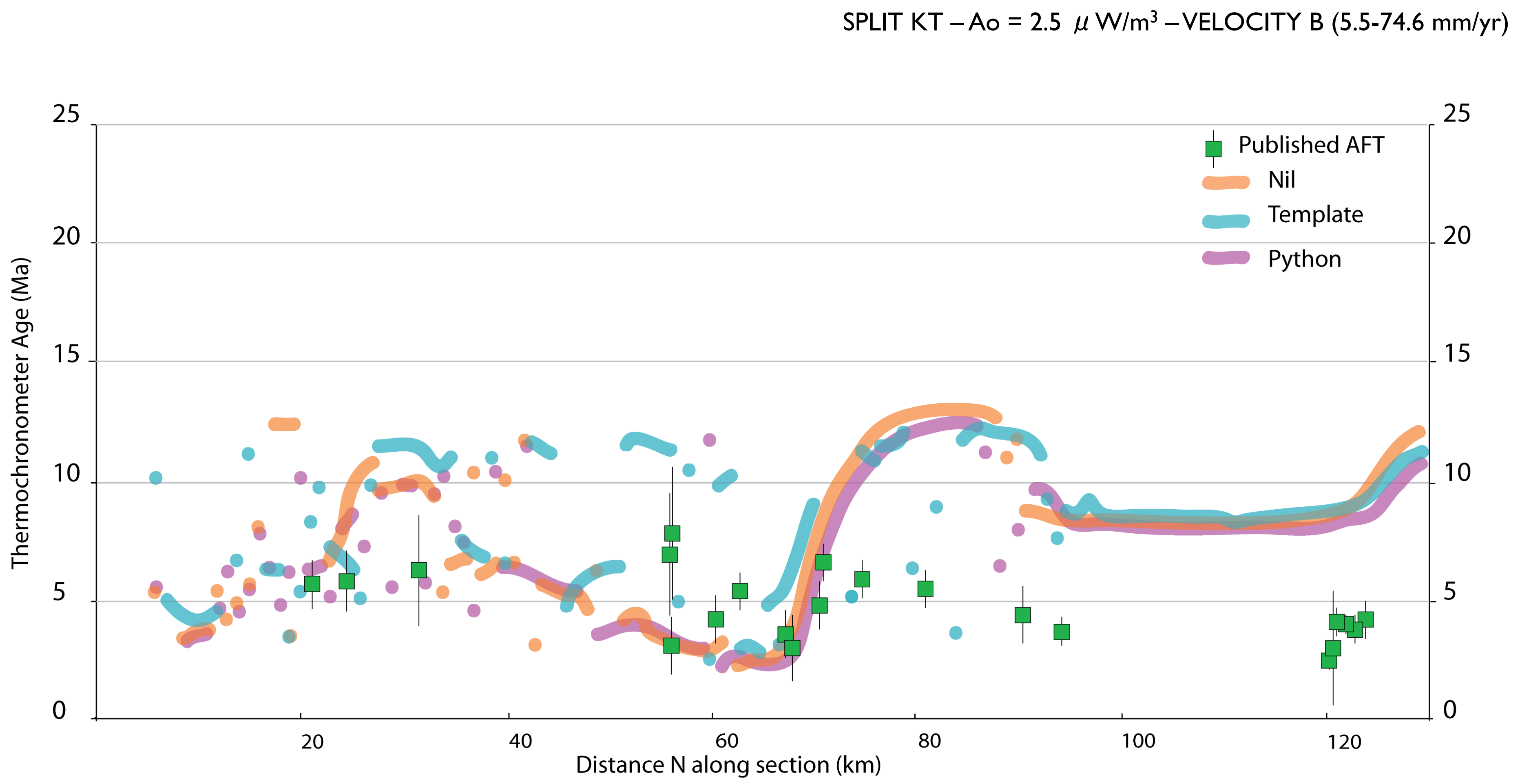
17-13 Ma = 22.0 mm/yr

13-10.3 Ma = 69.4 mm/yr

10.3-0 Ma = 5.4 mm/yr

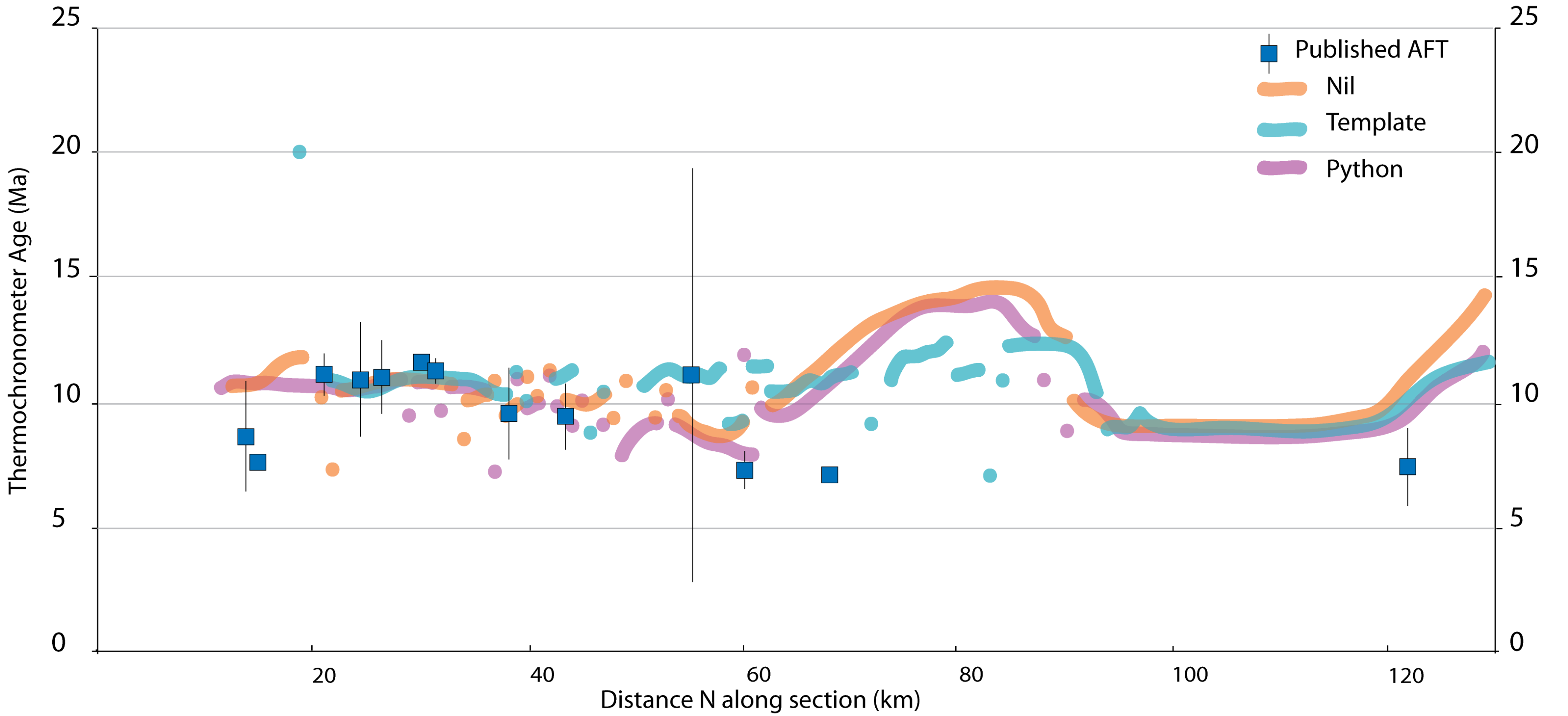


TOPOGRAPHIC SENSITIVITY – APATITE FISSION TRACK



TOPOGRAPHIC SENSITIVITY – ZIRCON (U-Th/He)

SPLIT KT – Ao = 2.5 μ W/m^3 – VELOCITY B (5.5-74.6 mm/yr)



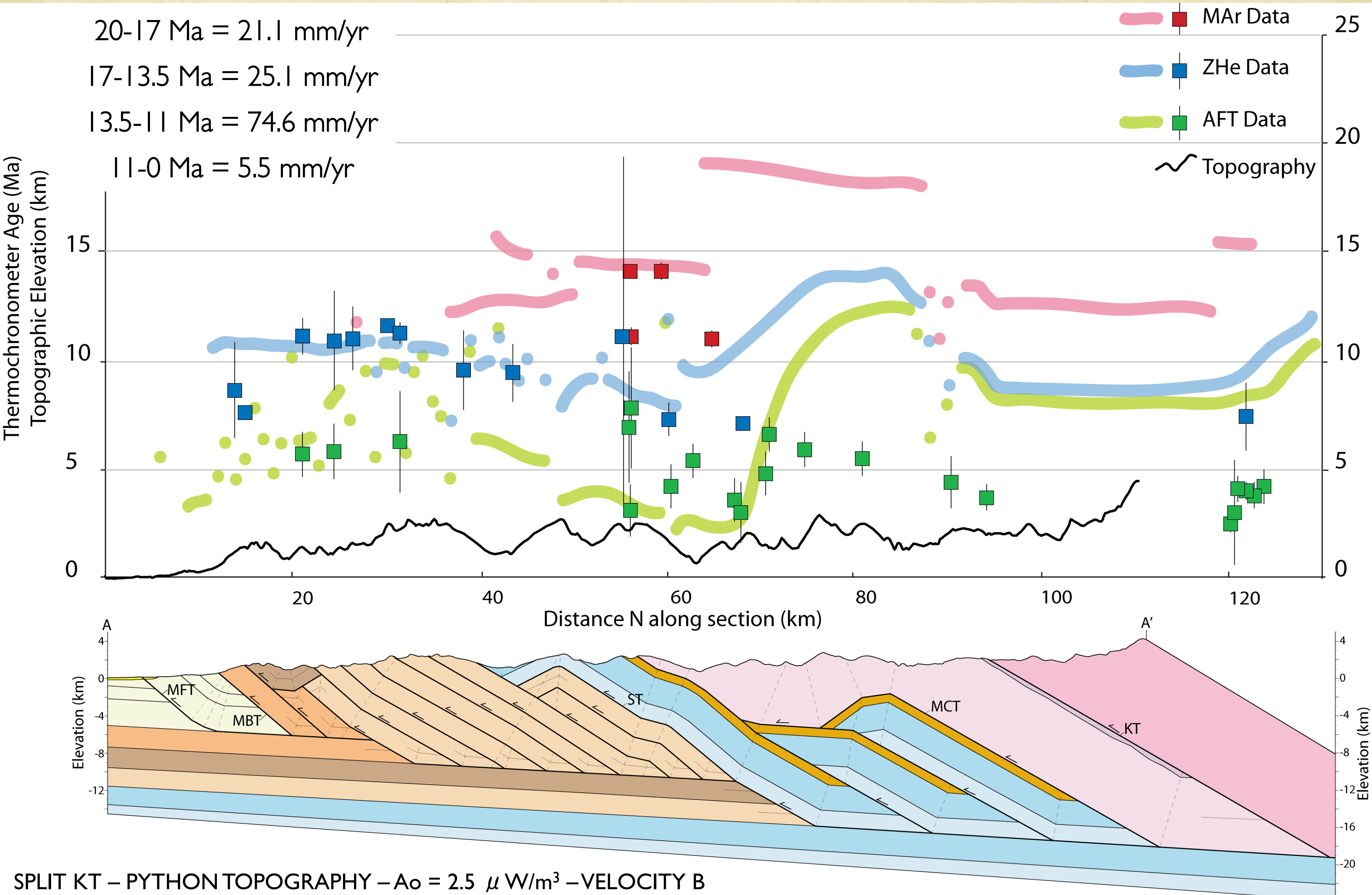
BEST FITTING MODEL

20-17 Ma = 21.1 mm/yr

17-13.5 Ma = 25.1 mm/yr

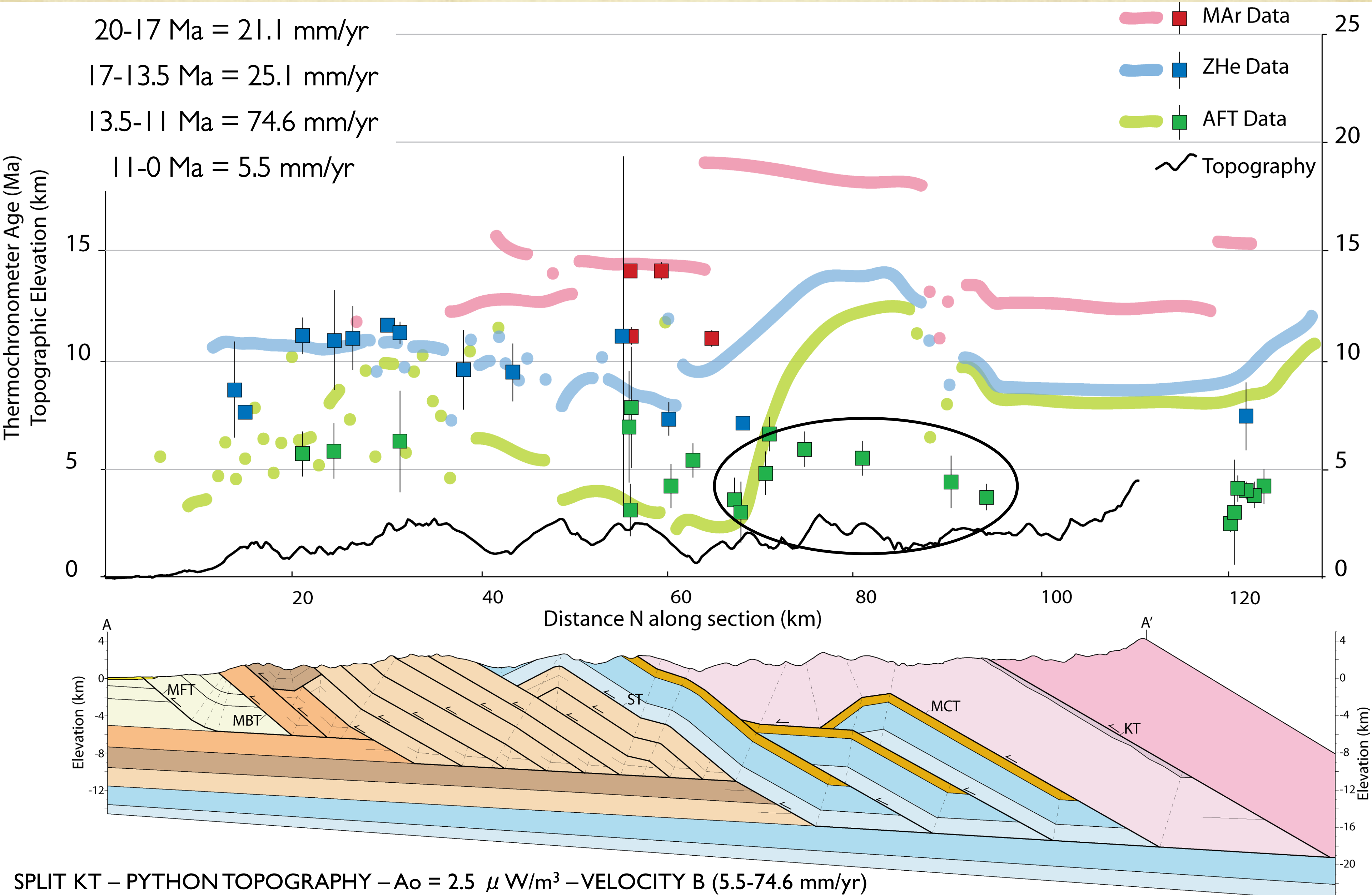
13.5-11 Ma = 74.6 mm/yr

11-0 Ma = 5.5 mm/yr



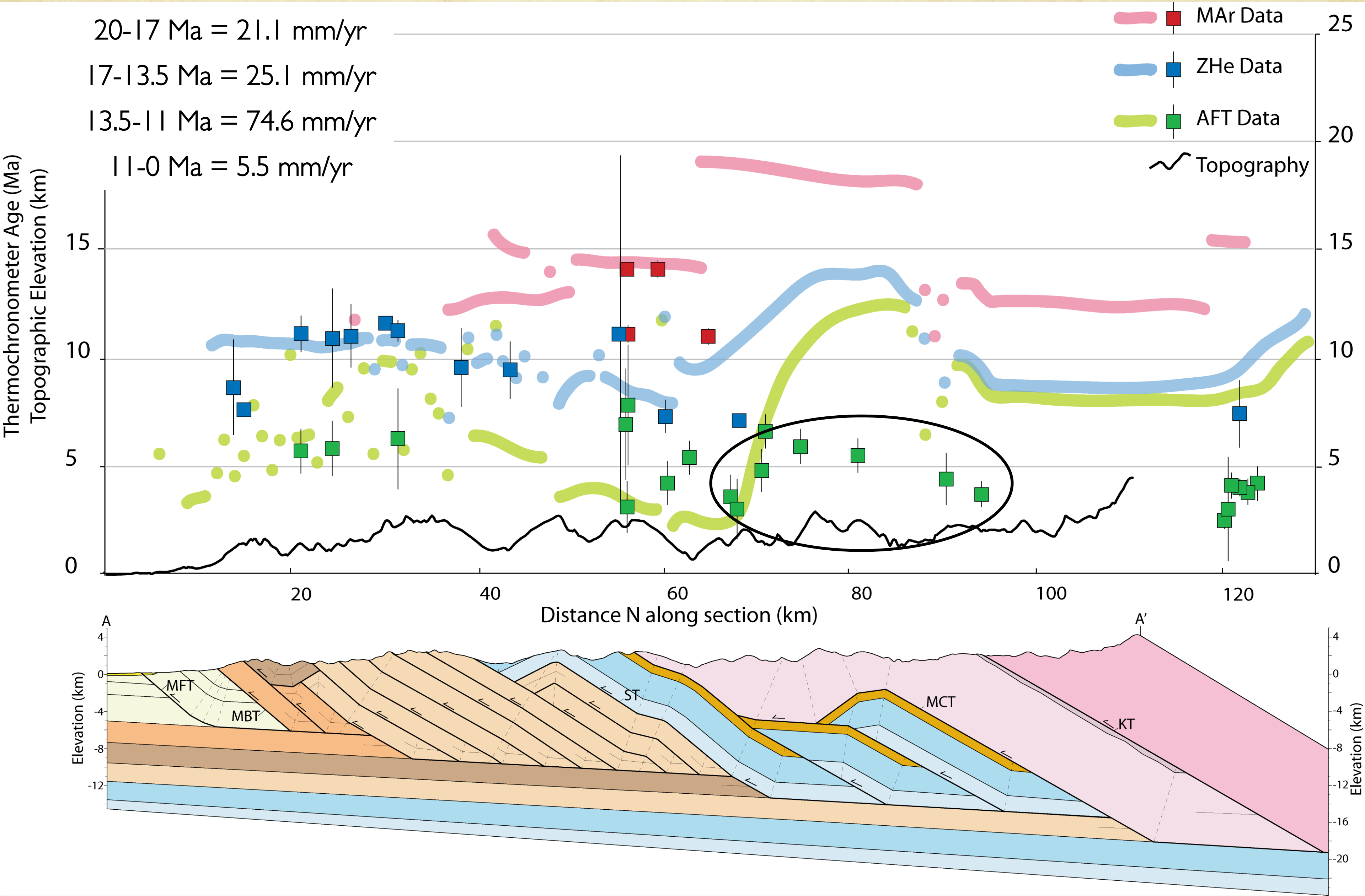
SPLIT KT – PYTHON TOPOGRAPHY – Ao = 2.5 μ W/m^3 – VELOCITY B

BEST FITTING MODEL – CONSIDERING GEOMETRY



SPLIT KT – PYTHON TOPOGRAPHY – Ao = 2.5 μ W/m³ – VELOCITY B (5.5-74.6 mm/yr)

BEST FITTING MODEL – CONSIDERING GEOMETRY



CONCLUSIONS

1. Using this forward model with a pinned footwall and evolving fault geometry, fold-thrust belt evolution can be modeled over longer spans of time than with pinned-fault models.

2. Predicted cooling ages are most sensitive to (1) variable rates of deformation, (2) kinematic timing of fault motion, (3) modeled topography's ability to account for structural uplift and flexural loading, and (4) cross section geometry.

3. Best fits to published AFT, ZHe, and MAr cooling ages along the Trashigang line of section use deformation rates that vary over the time of fold-thrust belt development (5-75 mm/yr).

4. Geometry of the Main Himalayan Thrust may differ from the published Trashigang cross section below the Greater Himalaya.

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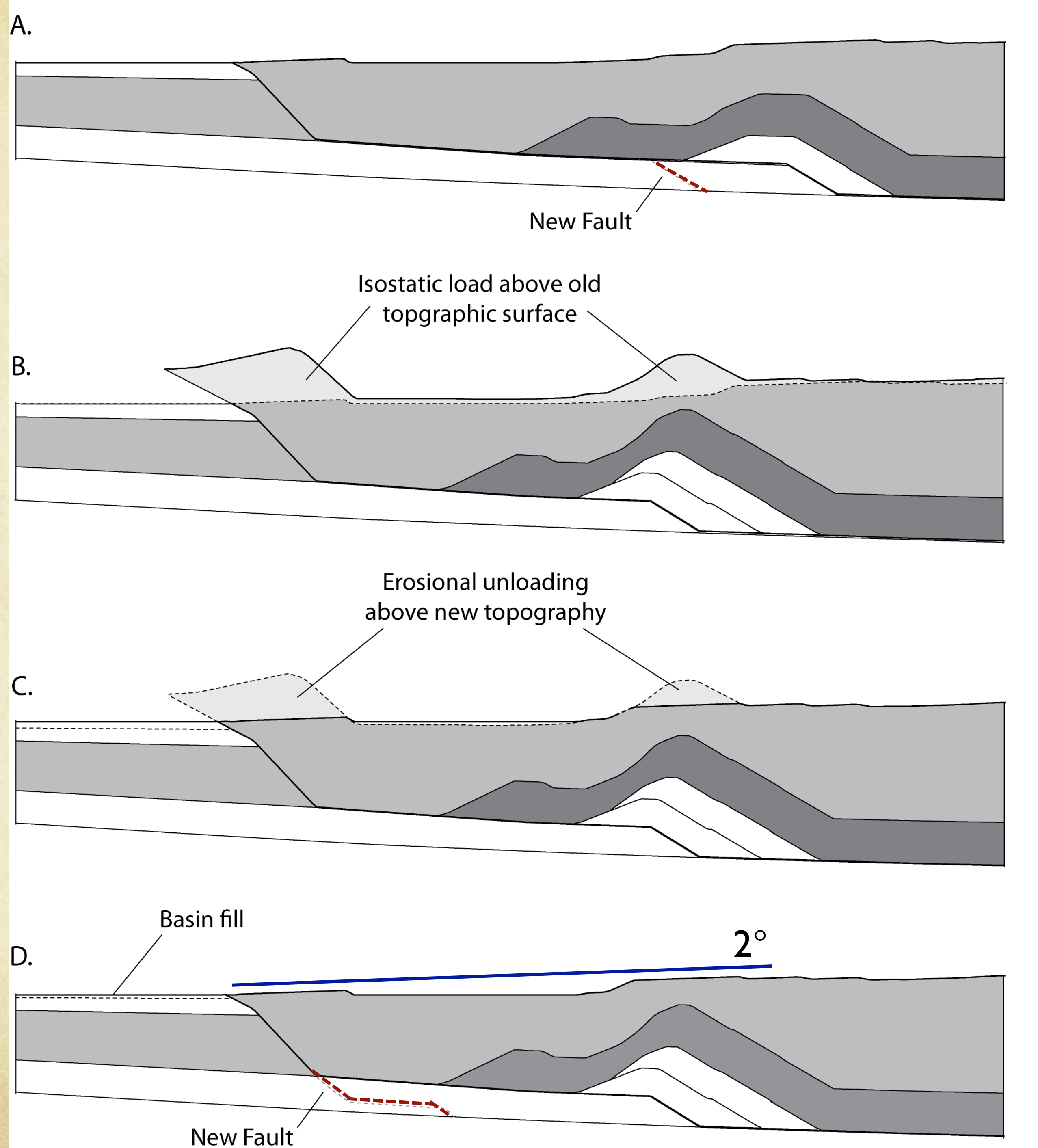
EXTRA SLIDES



A.
New Fault
Isostatic load above old
topgraphic surface
B.
Erosional unloading
above new topography
C.
Basin fill
2°
D.
New Fault

THERMAL-KINEMATIC MODEL

PECUBE

Functions as…

1. *a kinematic model that calculates rock transport (advection) velocities*

2. *a thermal model that calculates a thermal field* using fault motion, erosion above the topographic surface, rocks' thermal properties, and thermal boundary conditions

3. *a set of age prediction algorithms* that calculate thermochronometer ages at the topographic surface for each deformation step

THERMAL-KINEMATIC MODEL

VARYING AGES AND VELOCITIES OF FAULT MOTION

- Constant Velocity

  23-0 Ma =17.28 mm/yr

- Velocity A [Long et al., 2012] – 1D model estimates in study area

  23-21 Ma = 31.6 mm/yr
  21-15 Ma = 14.65 mm/yr
  15-10 Ma = 37.28 - 41.28 mm/yr
  10-0 Ma = 3.99 - 5.99 mm/yr

- Velocity B [McQuarrie & Ehlers, 2013] – 2D model 20-30 km west of Trashigang

  20-17 Ma = 21.07 mm/yr
  17-13.5 or 13 Ma = 21.98 - 25.11 mm/yr
  ~13-11 or 10.25 Ma = 69.42 - 74.56 mm/yr
  ~11-0 Ma = 5.40 - 5.54 mm/yr