Recent Advances in Fold-Thrust Belts

Delores M. Robinson and Nadine McQuarrie

Univ. of Alabama and Univ. of Pittsburgh

dmr@ua.edu

College of Arts & Sciences
Department of Geological Sciences

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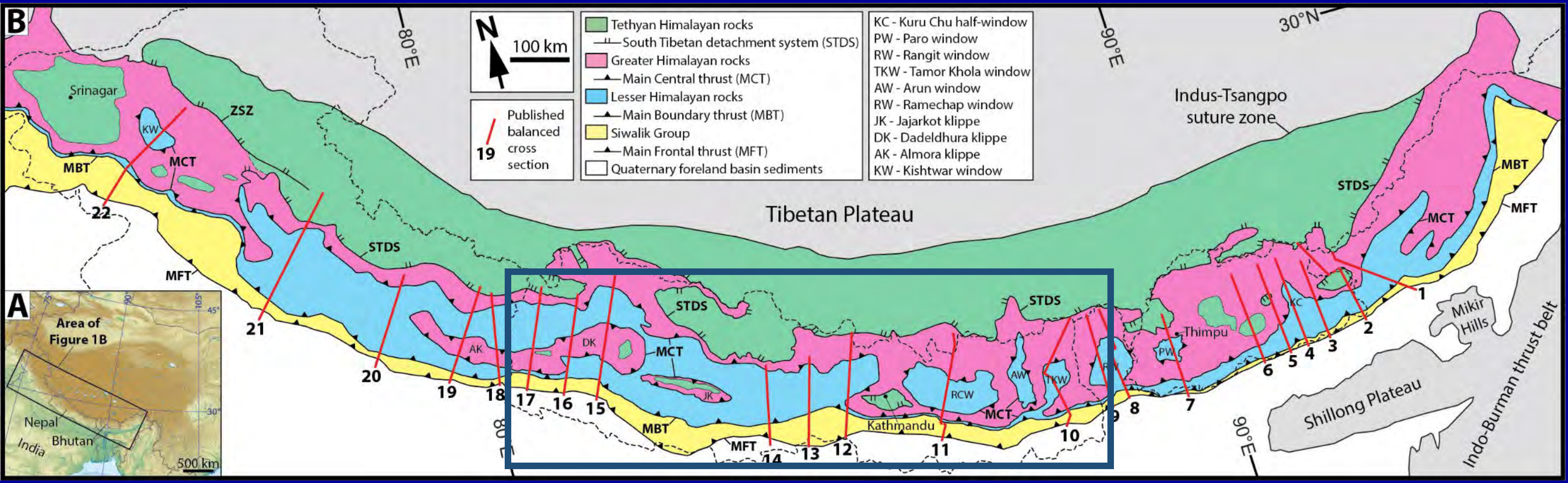
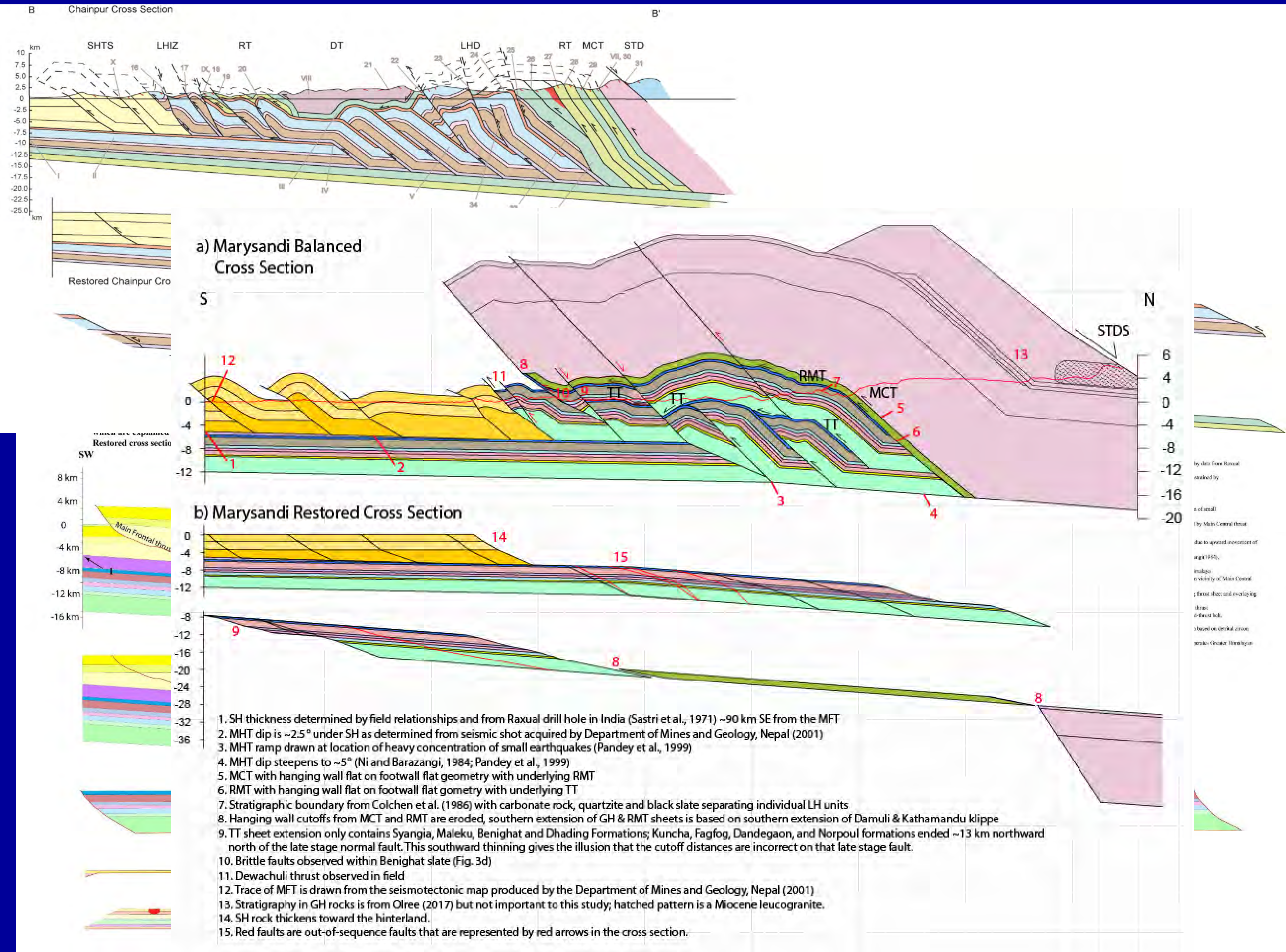
Studying Fold-Thrust Belts (FTB):

- Large Scale Tectonics
- First-order Geology – Stratigraphy & Structure
- Reconstructions of FTBs
- Provenance Studies & Sedimentary Basins – including magnetostratigraphy, isotopes, geo- and thermochronology
- Thermochronology, Geochronology & Structural Geology

Motivation: Give examples of FTB advances beyond balanced cross sections



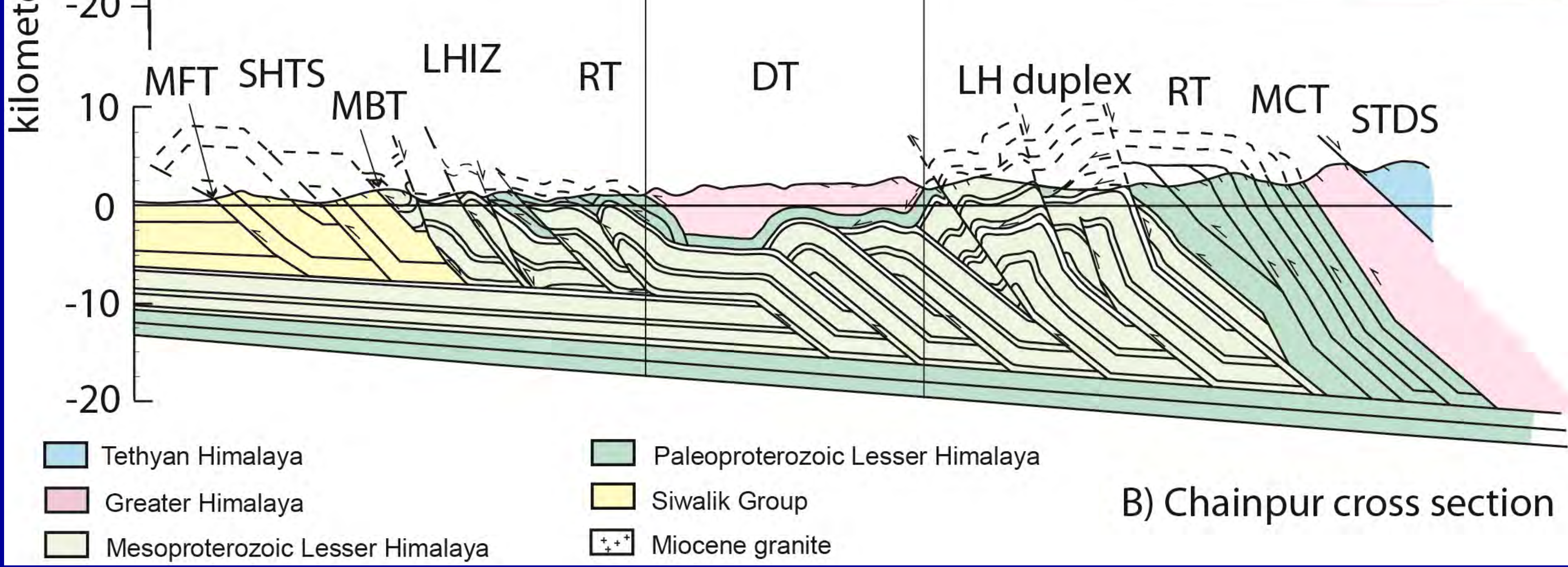
Long and Robinson, 2021



B
Chainpur Cross Section
B'
SHTS
LHIZ
RT
DT
LHD
RT
MCT
STD
Restored Chainpur Cro
a) Marysandi Balanced Cross Section
S
N
STDS
RMT
MCT
TT
b) Marysandi Restored Cross Section
Restored cross sectio
SW
Main Frontal thrust
1. SH thickness determined by field relationships and from Raxual drill hole in India (Sastri et al., 1971) ~90 km SE from the MFT
2. MHT dip is ~2.5° under SH as determined from seismic shot acquired by Department of Mines and Geology, Nepal (2001)
3. MHT ramp drawn at location of heavy concentration of small earthquakes (Pandey et al., 1999)
4. MHT dip steepens to ~5° (Ni and Barazangi, 1984; Pandey et al., 1999)
5. MCT with hanging wall flat on footwall flat geometry with underlying RMT
6. RMT with hanging wall flat on footwall flat gometry with underlying TT
7. Stratigraphic boundary from Colchen et al. (1986) with carbonate rock, quartzite and black slate separating individual LH units
8. Hanging wall cutoffs from MCT and RMT are eroded, southern extension of GH & RMT sheets is based on southern extension of Damuli & Kathamandu klippe
9. TT sheet extension only contains Syangia, Maleku, Benighat and Dhading Formations; Kuncha, Fagfog, Dandegaon, and Norpoul formations ended ~13 km northward north of the late stage normal fault. This southward thinning gives the illusion that the cutoff distances are incorrect on that late stage fault.
10. Brittle faults observed within Benighat slate (Fig. 3d)
11. Dewachuli thrust observed in field
12. Trace of MFT is drawn from the seismotectonic map produced by the Department of Mines and Geology, Nepal (2001)
13. Stratigraphy in GH rocks is from Olree (2017) but not important to this study; hatched pattern is a Miocene leucogranite.
14. SH rock thickens toward the hinterland.
15. Red faults are out-of-sequence faults that are represented by red arrows in the cross section.

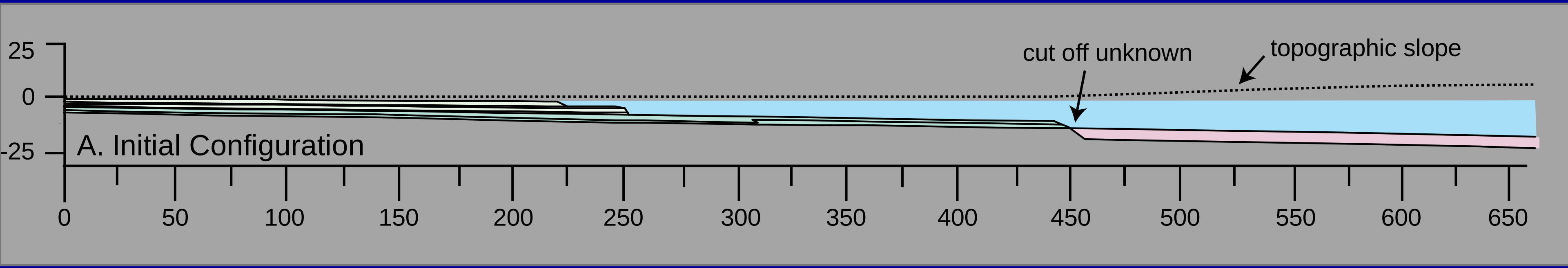
Advances

1. Link deformation, erosion & depositional history
2. Dating individual faults using U-Pb in calcite
3. Validate balanced cross sections using thermochronology
4. Use thermochronology to determine location of large ramps at depth

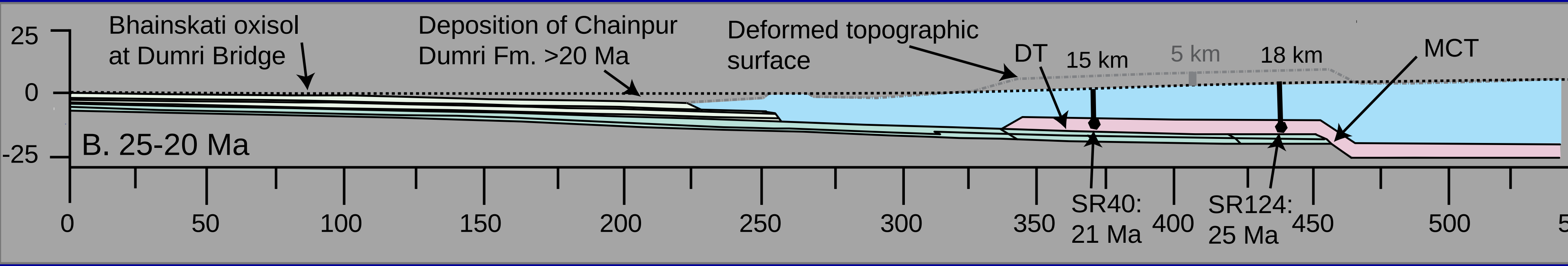


- Advance 1: Link deformation, erosion & depositional histories

Starting Conditions



25-20 Ma

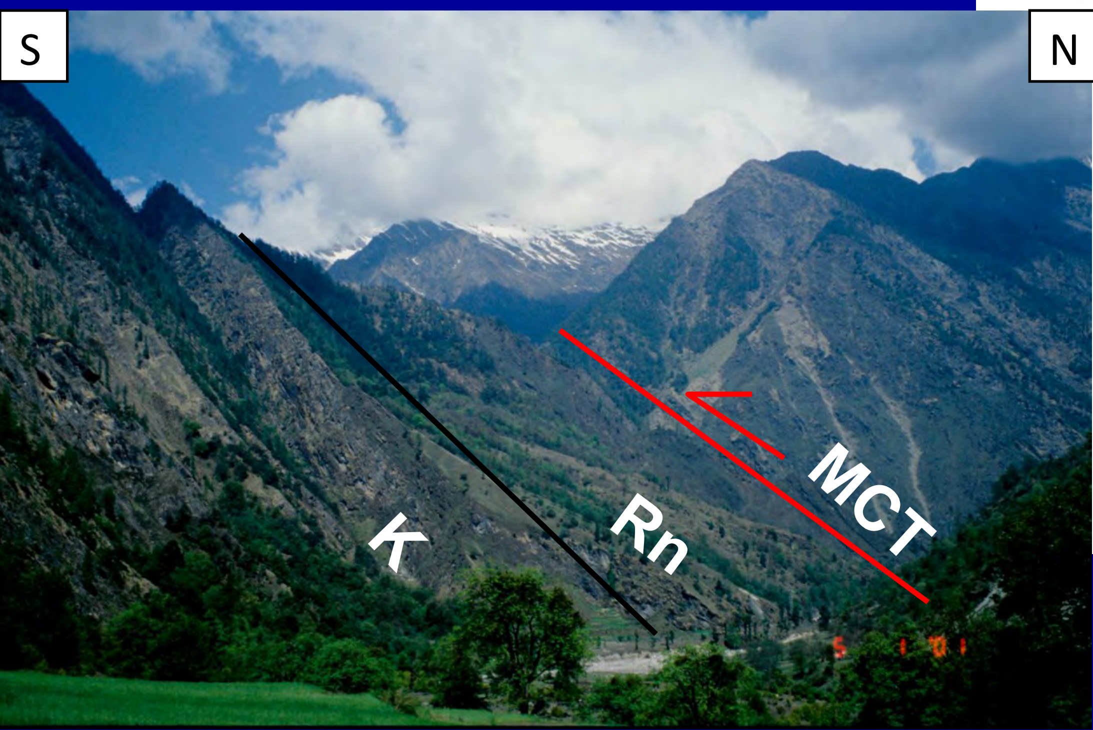


Grey vertical lines – amt of vertical exhumation

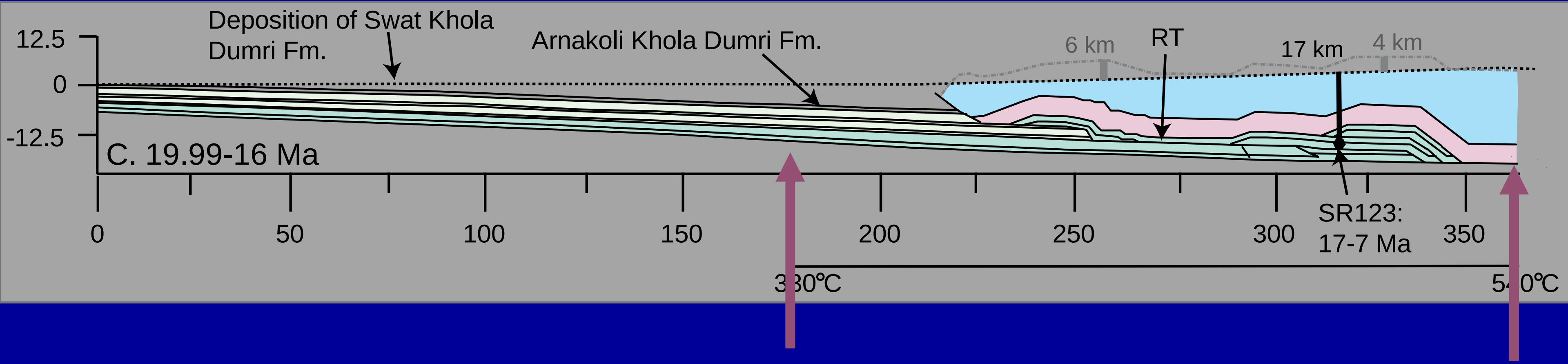

S
N


S
N
MCT
Rn
K


N
S


S
N
K
Rn
MCT

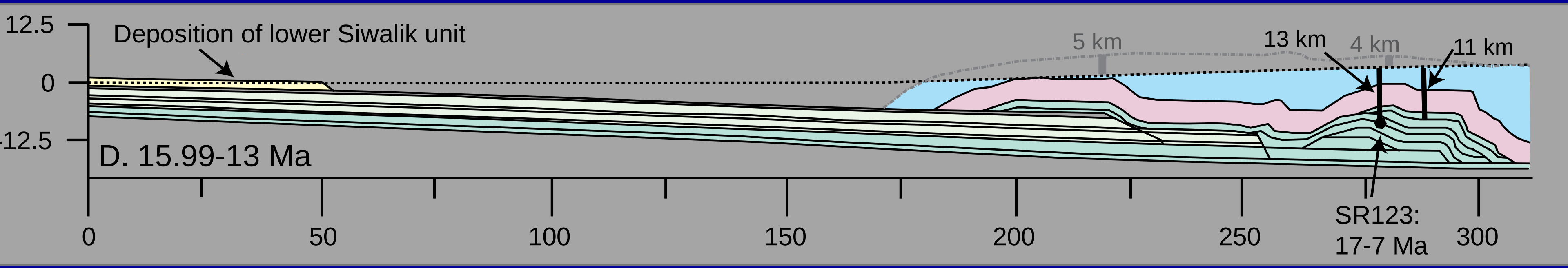
19.99-16 Ma

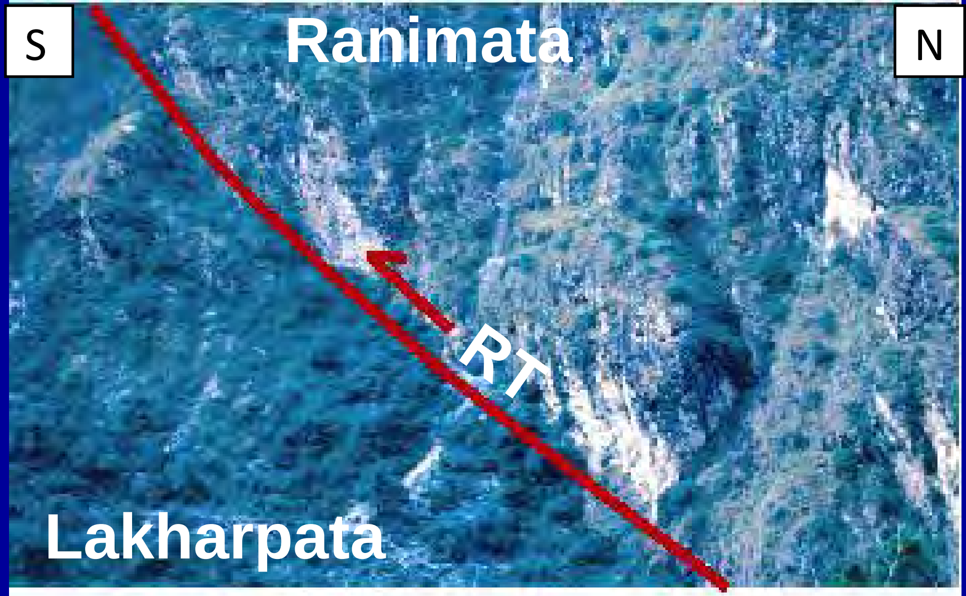


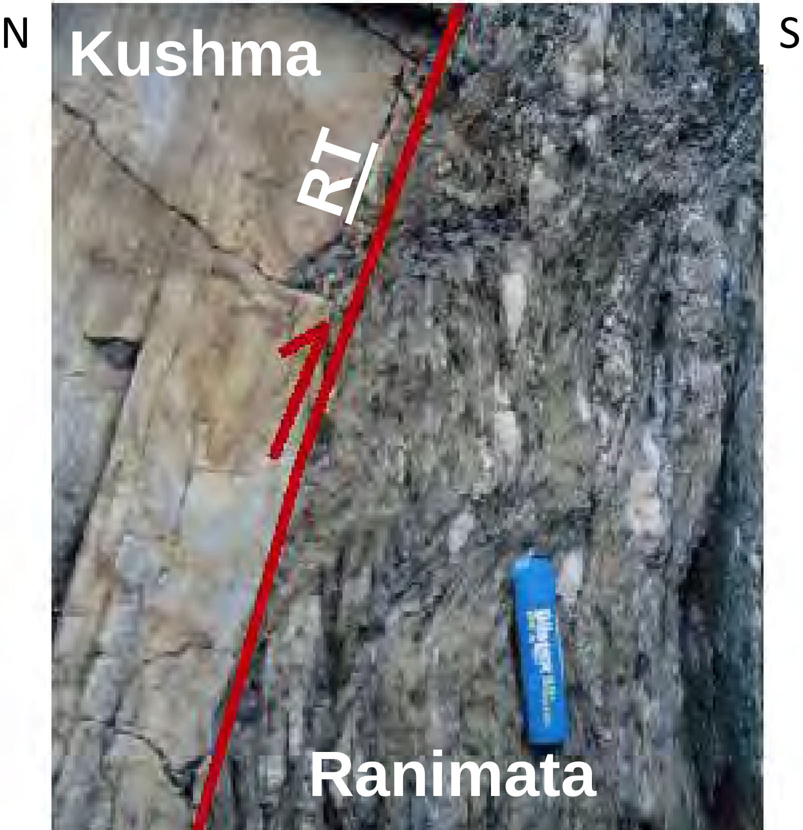
330℃

540℃

15.99-13 Ma

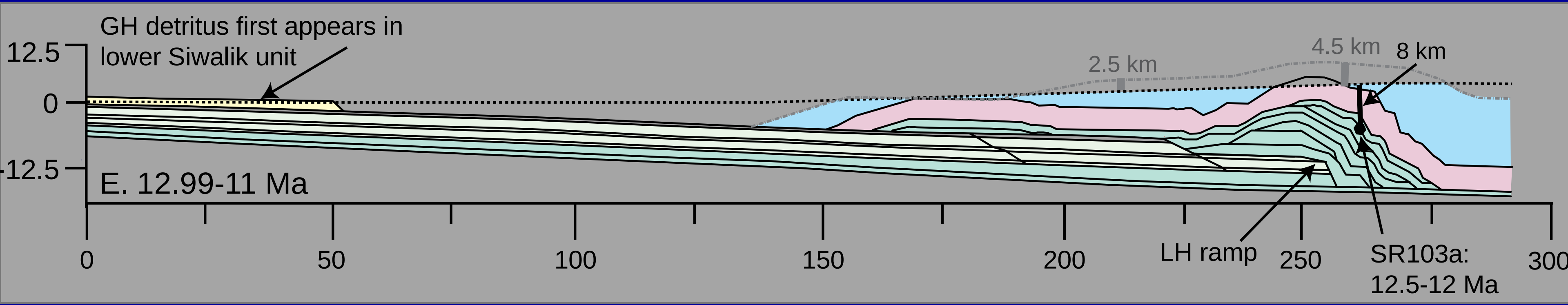




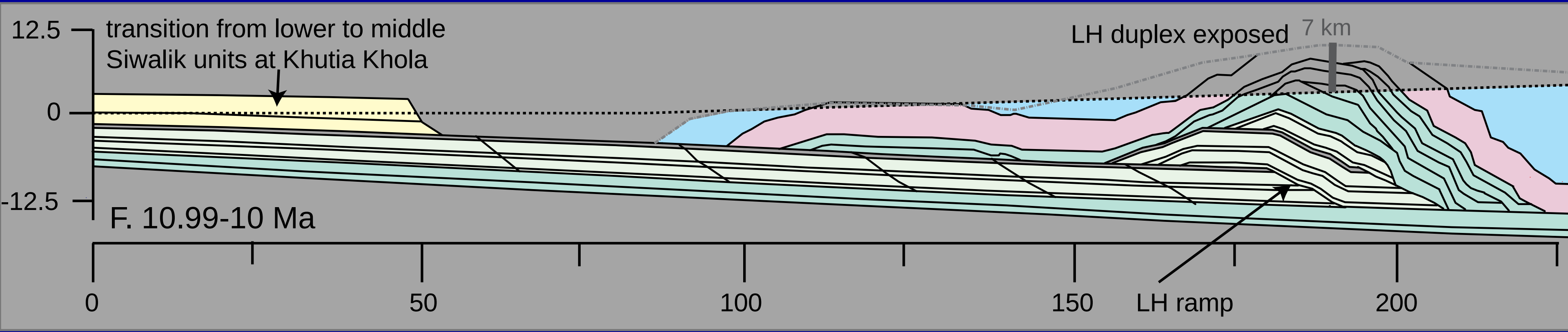


Dumri Fm.
Upper part – red shale

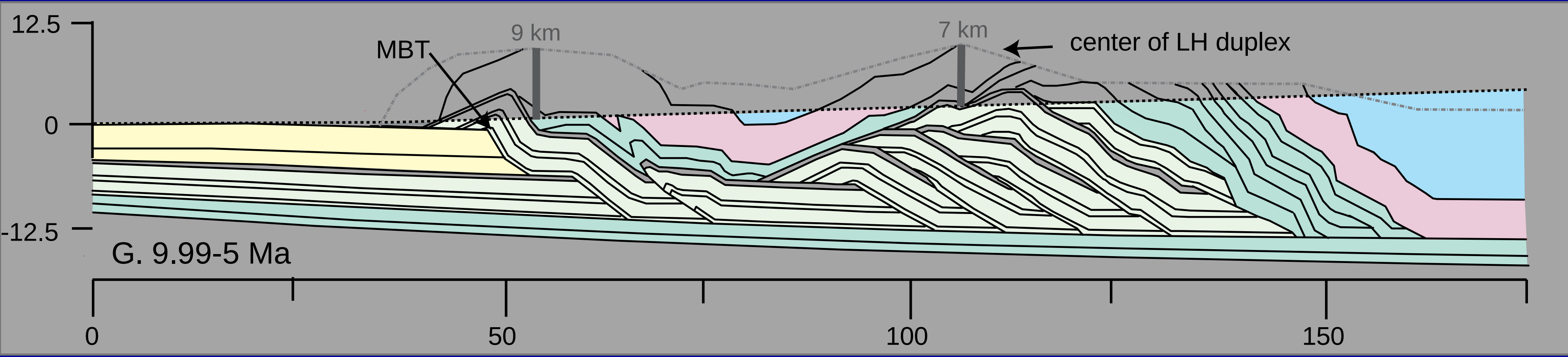
12.99-11 Ma



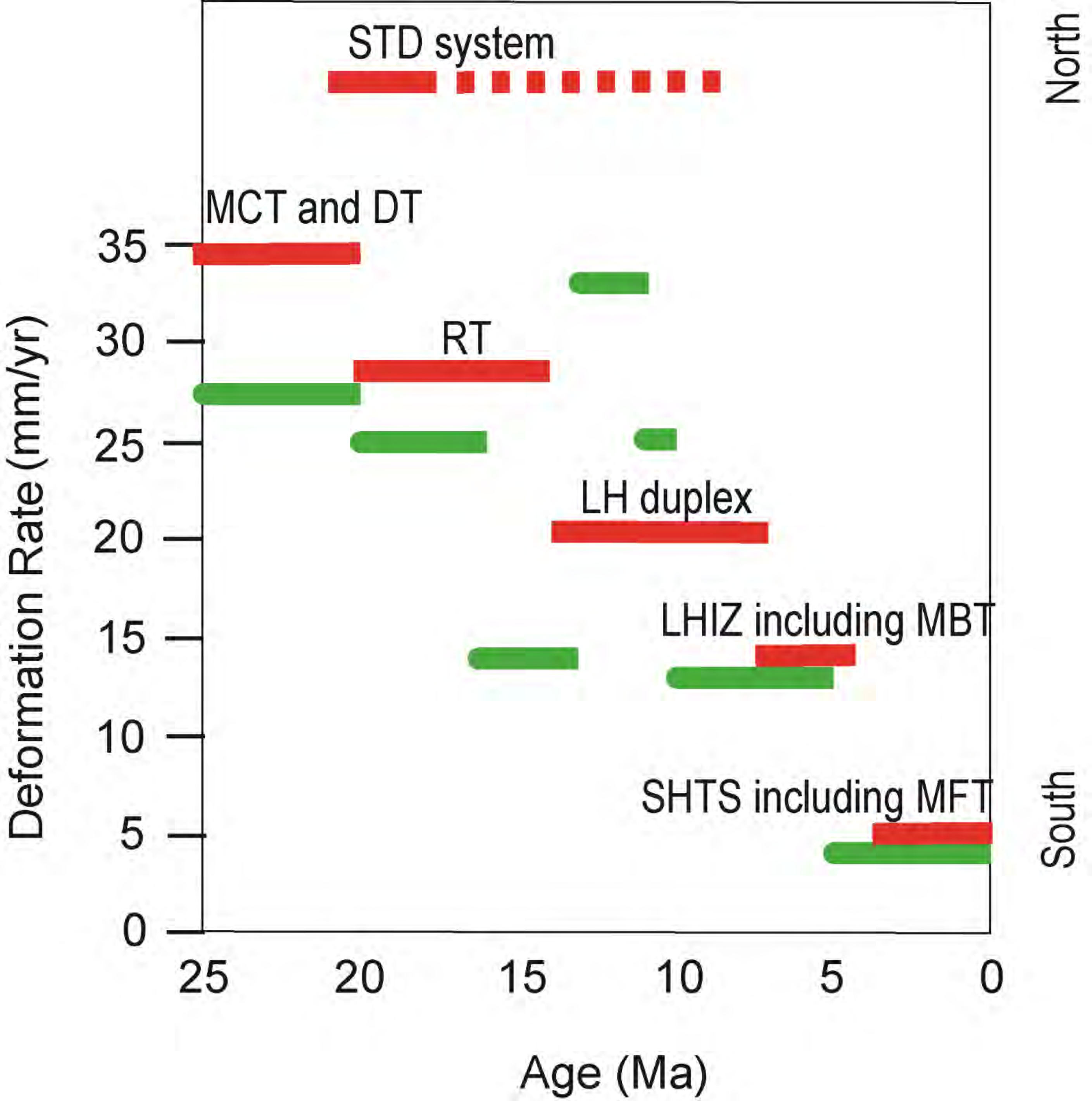
10.99-10 Ma



9.99-5 Ma



N E

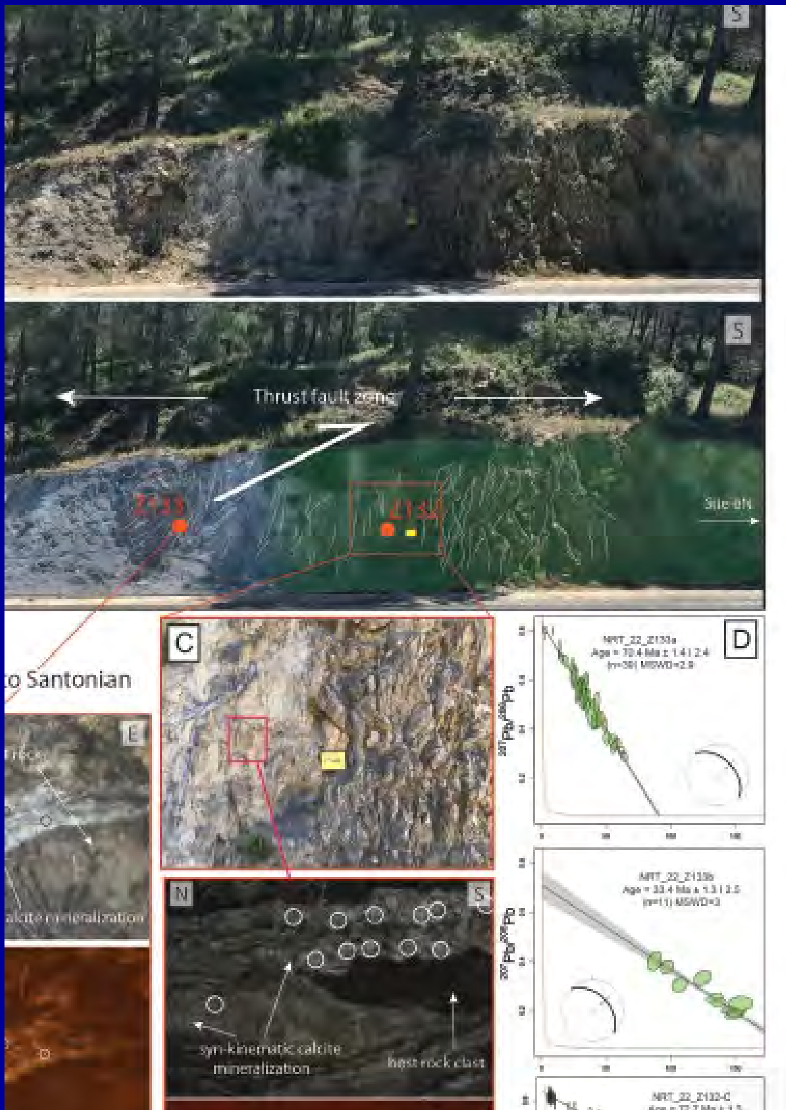


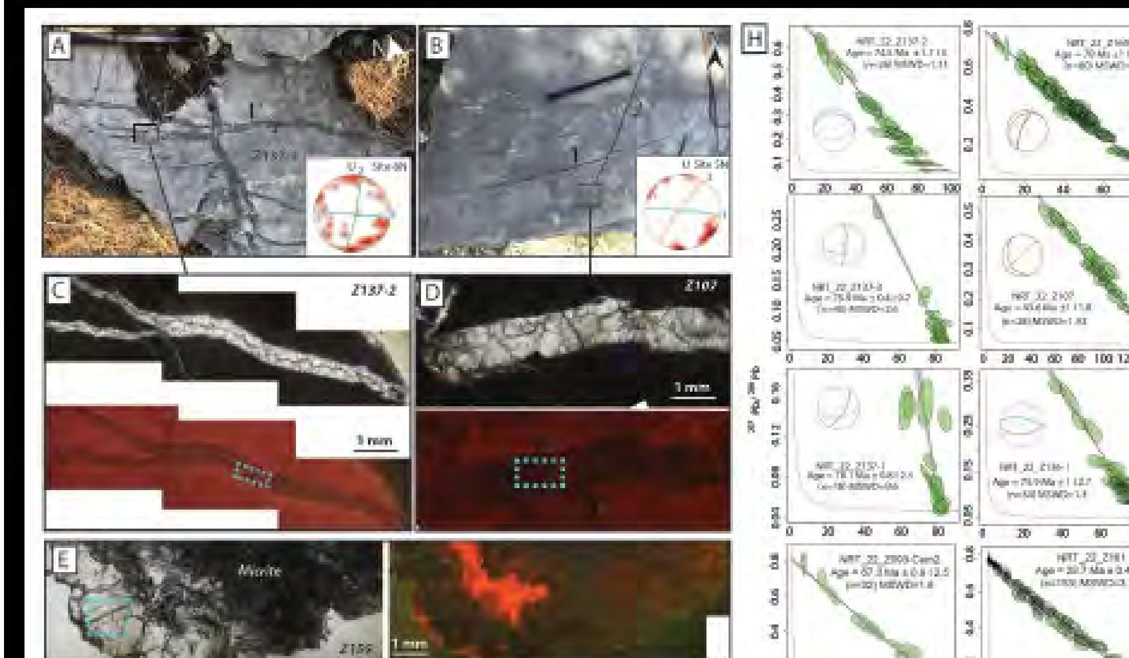
STD system
MCT and DT
RT
LH duplex
LHIZ including MBT
SHTS including MFT
North
South
Deformation Rate (mm/yr)
35
30
25
20
15
10
5
0
25
20
15
10
5
0
Age (Ma)

Shortening rate varied through time – pulsed deformation

Robinson and McQuarrie, Lithosphere (2012)

Advance 2: U-Pb in Calcite – dating individual faults



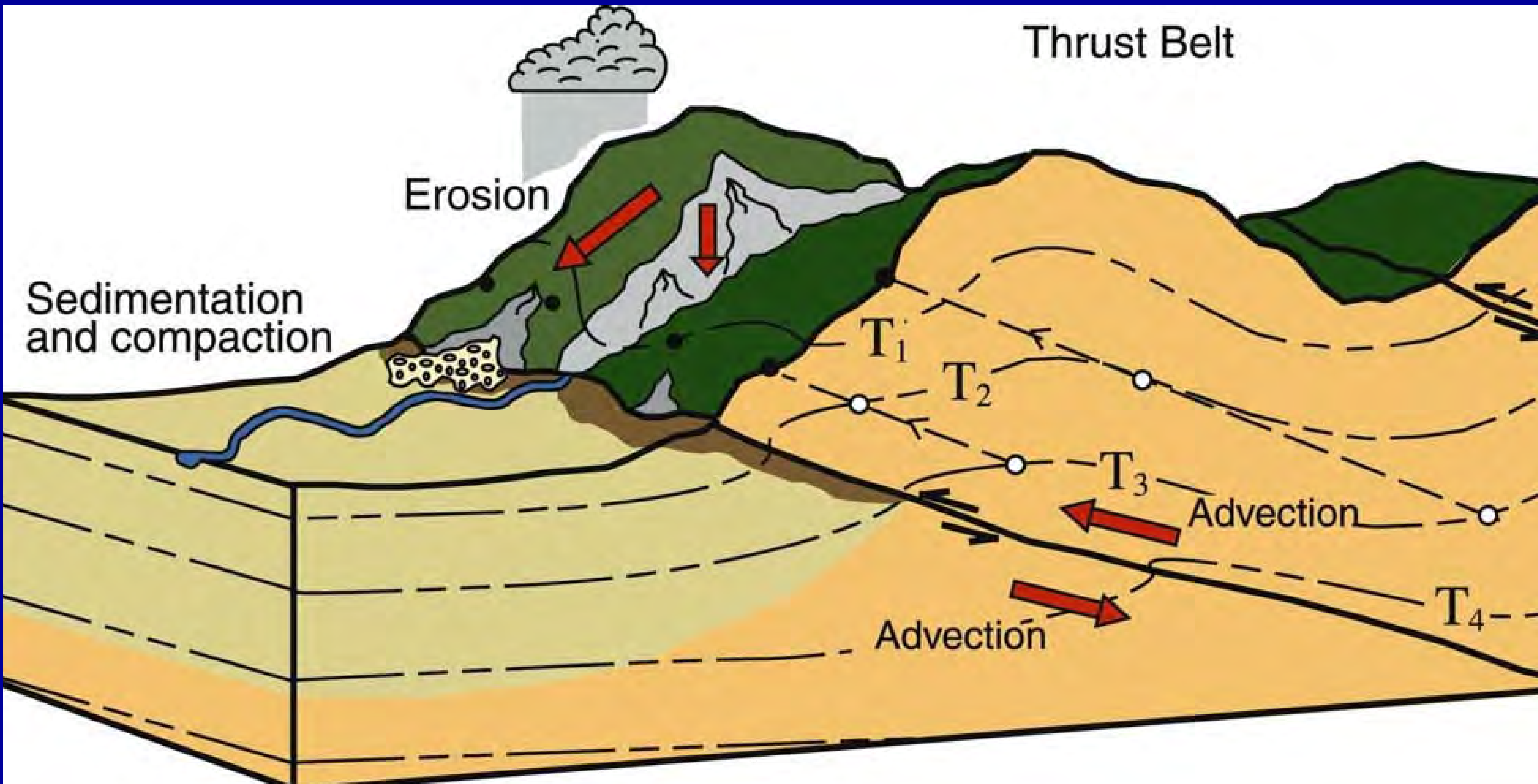


Possibilities?

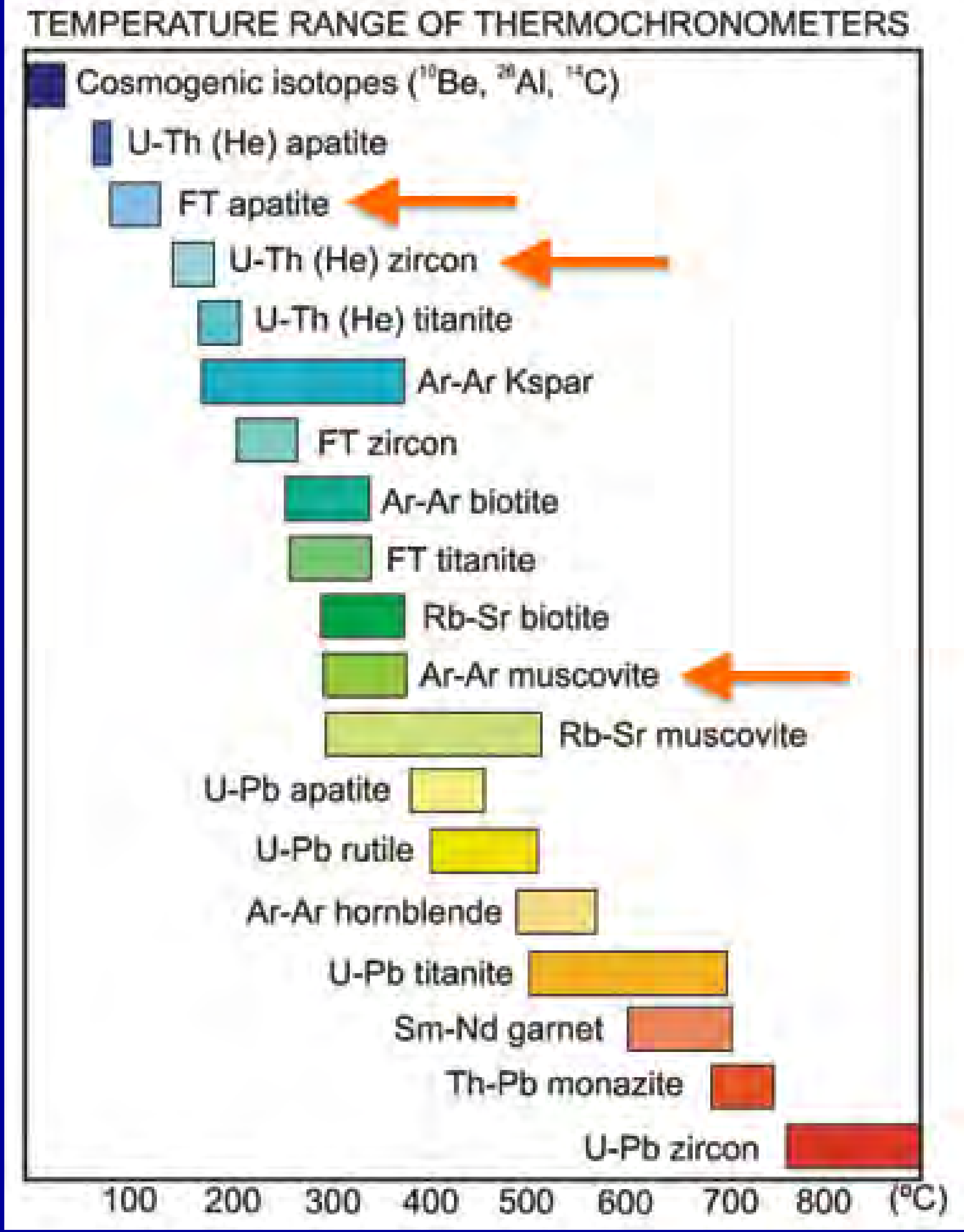
Zeboudj et al. (2025)

How do you know if a balanced cross section is correct?

Advance 3: validate balanced cross sections using thermochronology



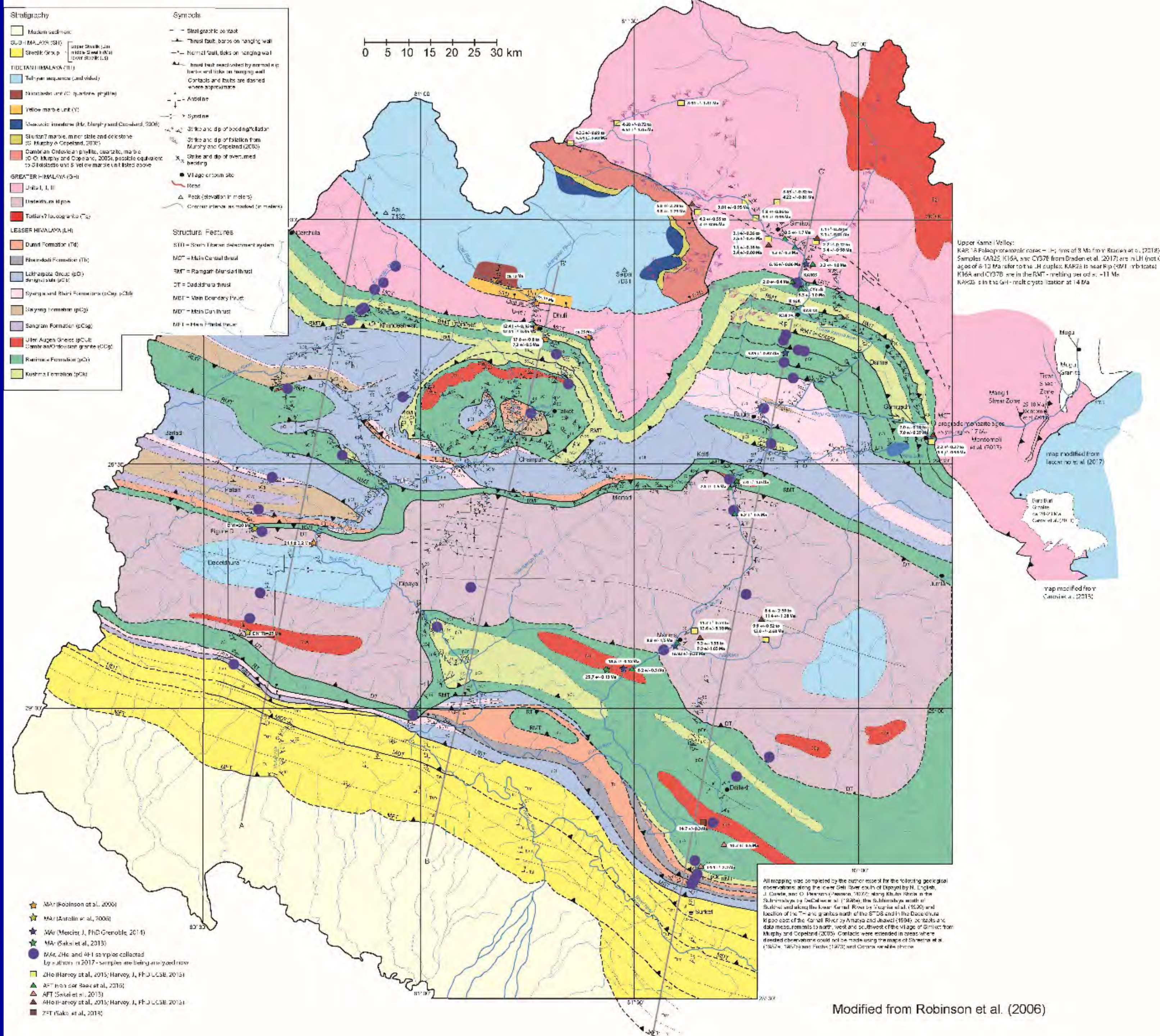
Ehlers & Farley, 2003



Modified from Pangea.stanford.edu

A lot of low temperature thermochronologic ages are needed to determine how ages change across a ftb

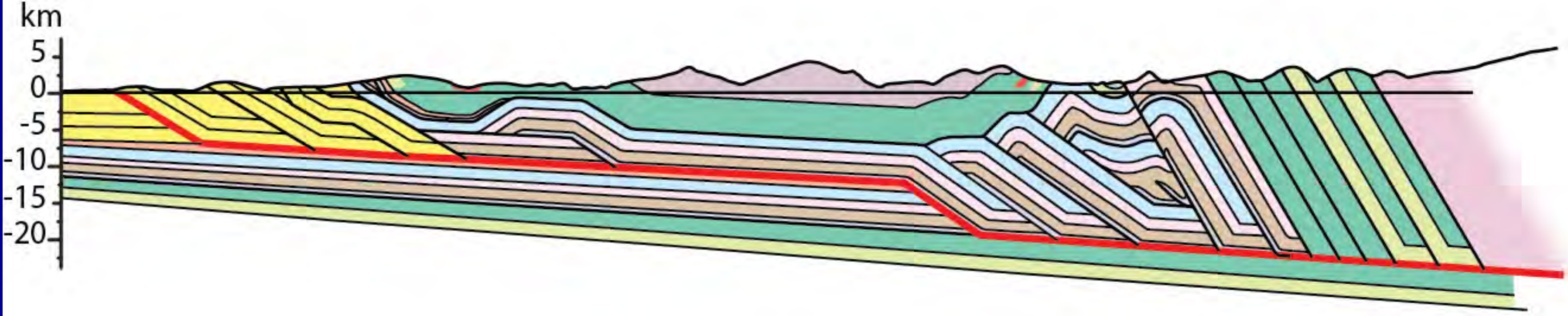
Field work!

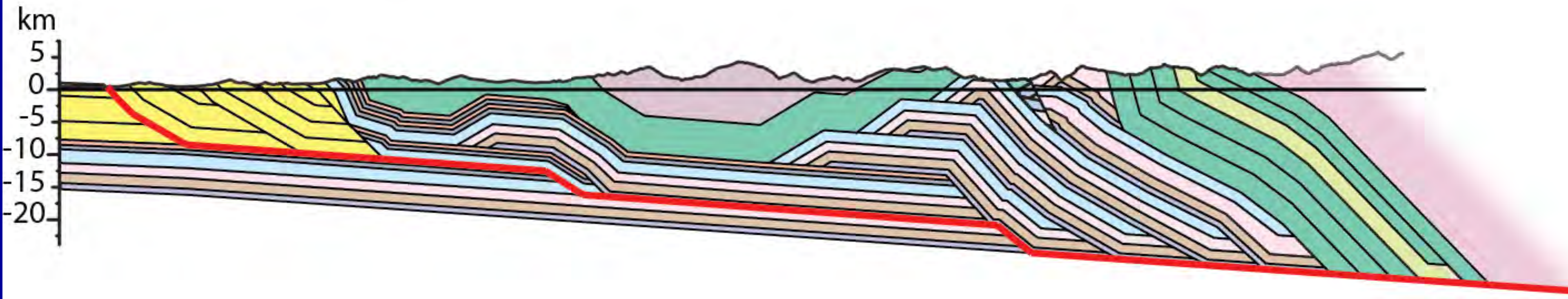
Stratigraphy
Modern sediment
SUB-HIMALAYA (SH)
Siwalik Group
TIBETAN HIMALAYA (TH)
Yellow marble unit (Y)
GREATER HIMALAYA (GH)
Tertiary? leucogranite (Tg)
LESSER HIMALAYA (LH)
Dumri Formation (Td)
Sangram Formation (pCsg)
Kushma Formation (pCk)
Symbols
Stratigraphic contact
Thrust fault, barbs on hanging wall
Normal fault, ticks on hanging wall
Contacts and faults are dashed where approximate
Anticline
Syncline
Strike and dip of overturned bedding
Village or town site
Road
Peak (elevation in meters)
Structural Features
MCT = Main Central thrust
RMT = Ramgarh-Munsiari thrust
DT = Dadeldhura thrust
MBT = Main Boundary thrust
0 5 10 15 20 25 30 km
Modified from Robinson et al. (2006)

Balanced Cross Sections

(A) Simikot Cross Section and Restoration from Robinson et al. (2006)

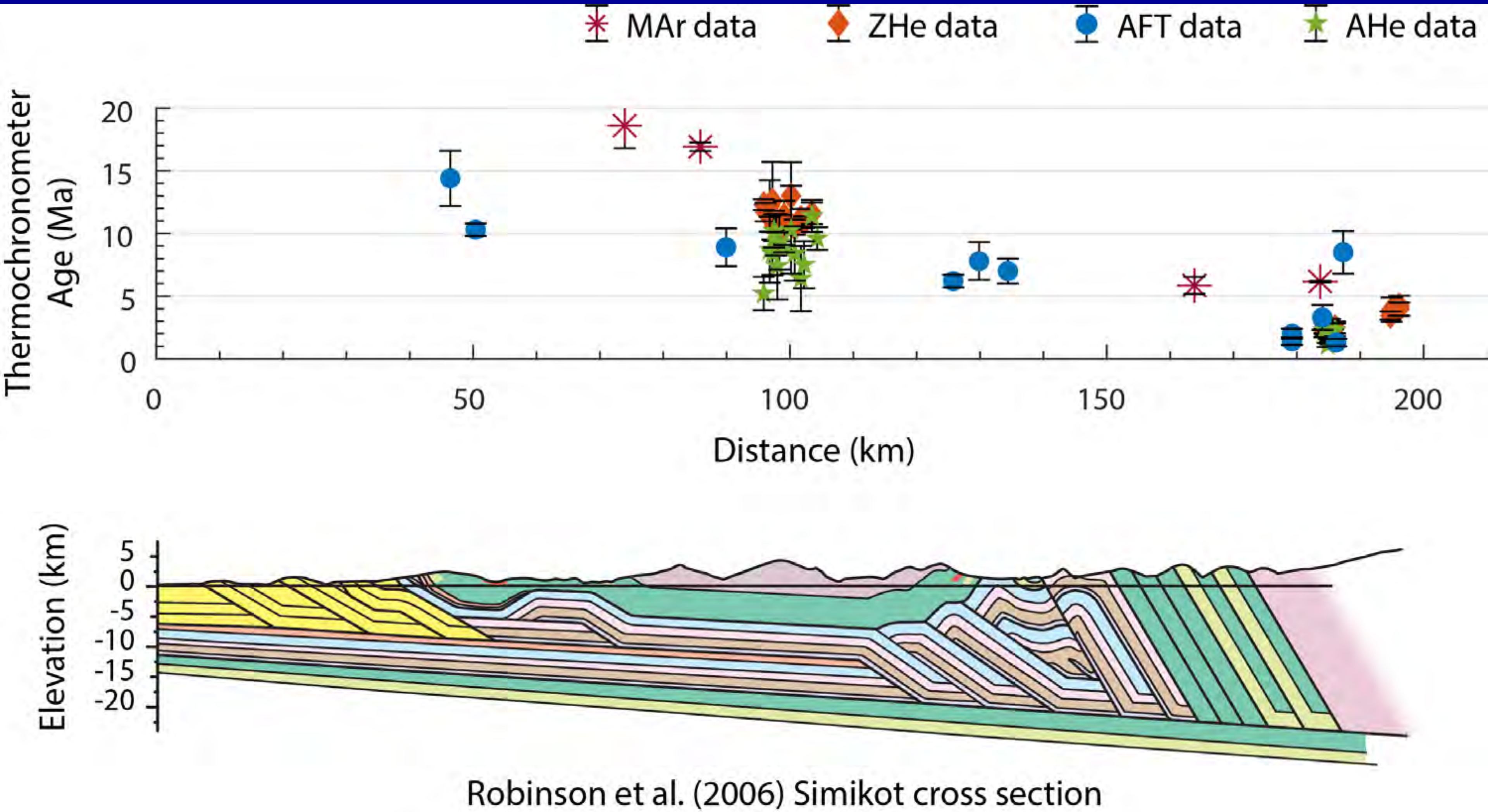


(B) Simikot Cross Section and Restoration from Olsen et al. (2019)

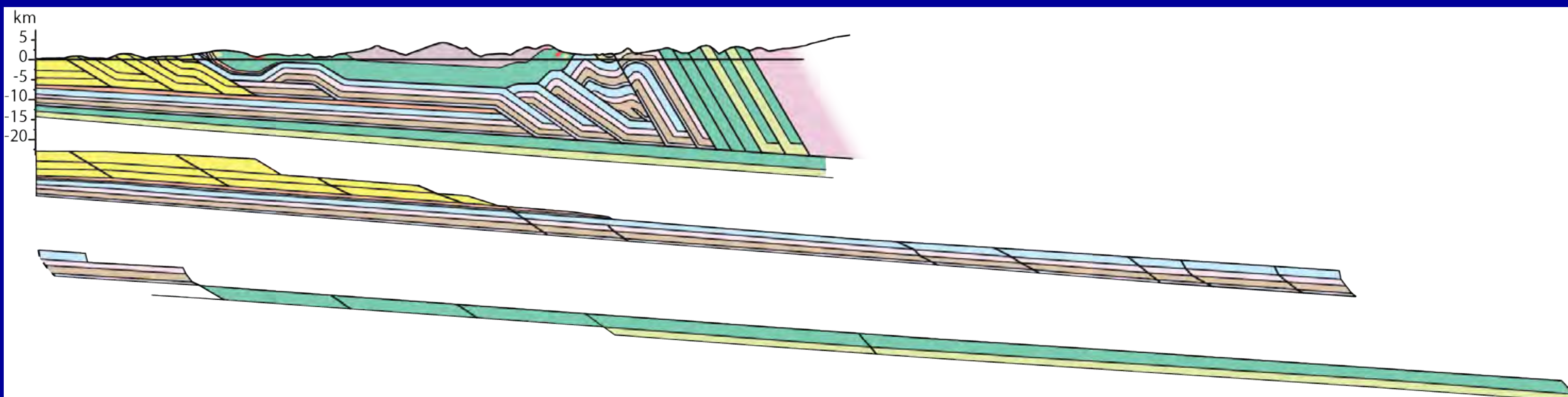


- Methods from McQuarrie & Ehlers (2015):
  - Use balanced cross sections to provide a testable geometry and kinematic scenarios
  - Thermal modeling to predict cooling ages
  - Compare predicted cooling ages to observed cooling ages
  - Adjust models to better fit predicted to observed cooling ages

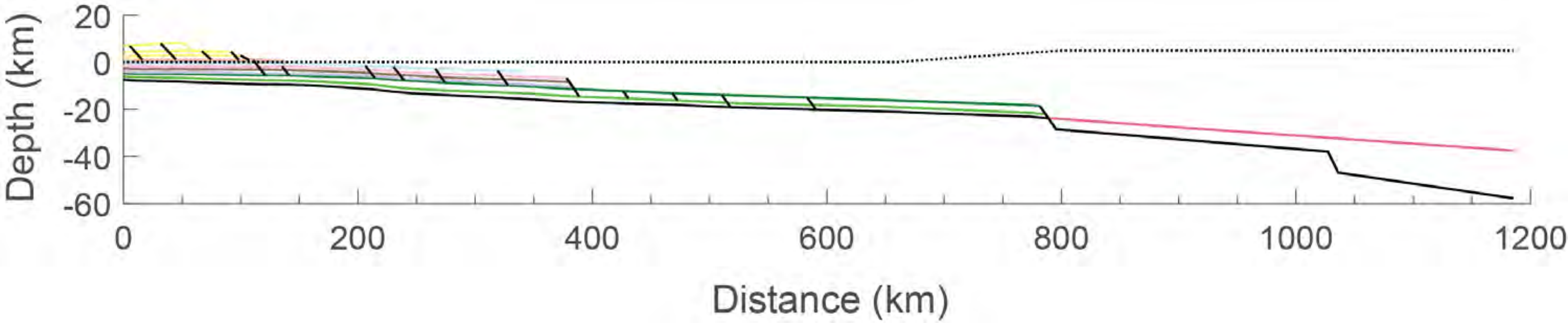
Plot lab derived data



McCallister et al. (2014), Sakai et al. (2013), van der Beek et al. (2016), and unpublished data from Harvey (2015) and Mercier (2014).

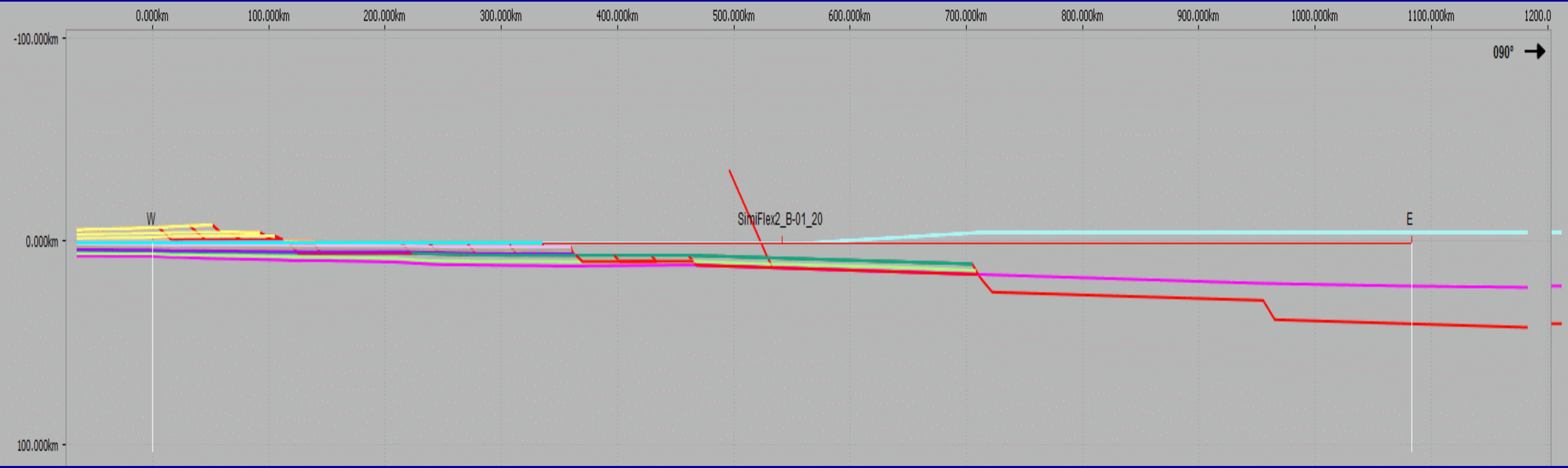


km
5
0
-5
-10
-15
-20



Depth (km)
20
0
-20
-40
-60
0
200
400
600
800
1000
1200
Distance (km)

Each 10 km fault displacement is followed by loading, eroding, and unloading



Successful model matches:

Surface geology

Dip & depth of decollement

Depth of foreland basin

Achieved by varying:

EET & Flexural rigidity

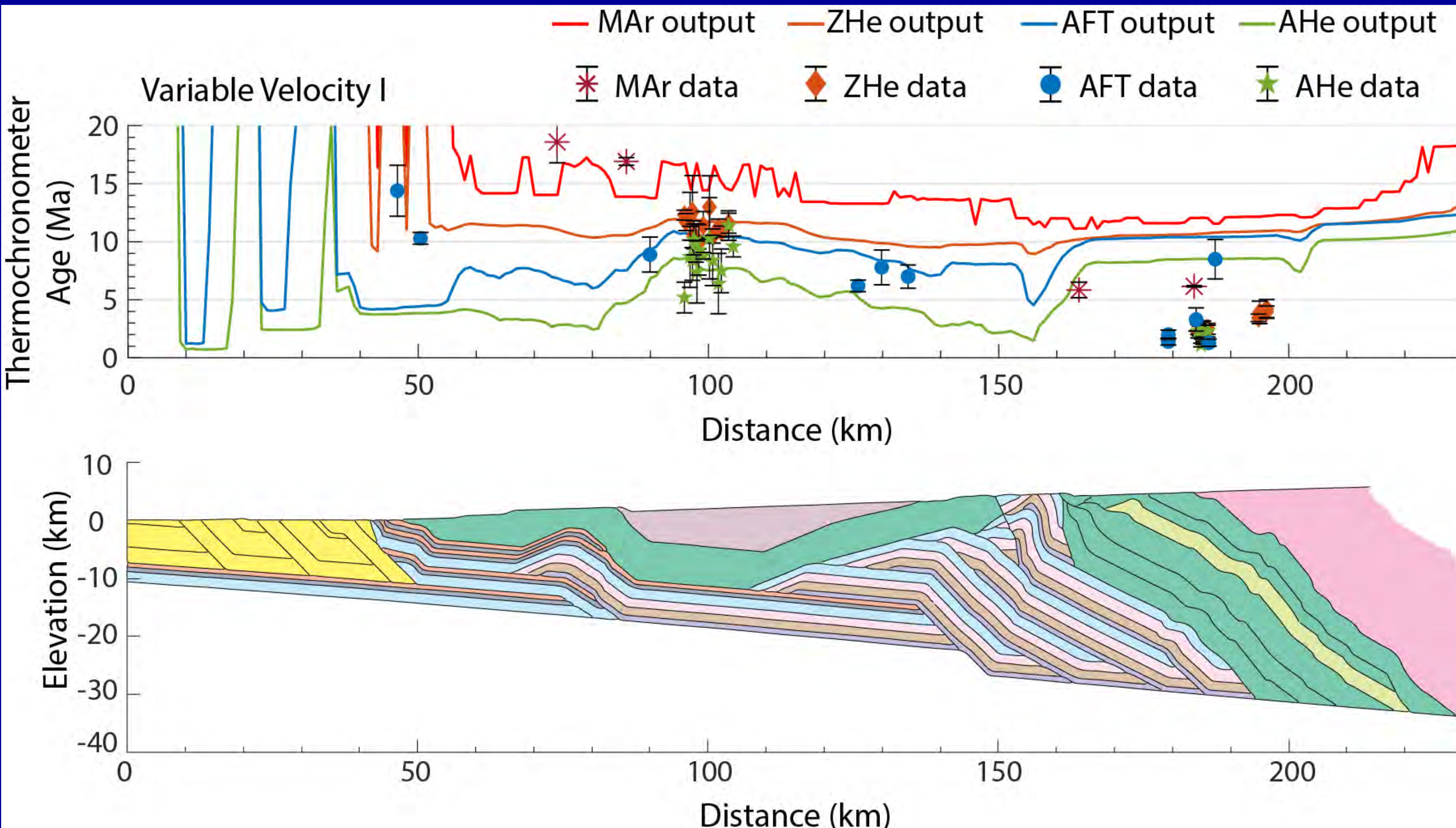
Bulk density

Topographic angle

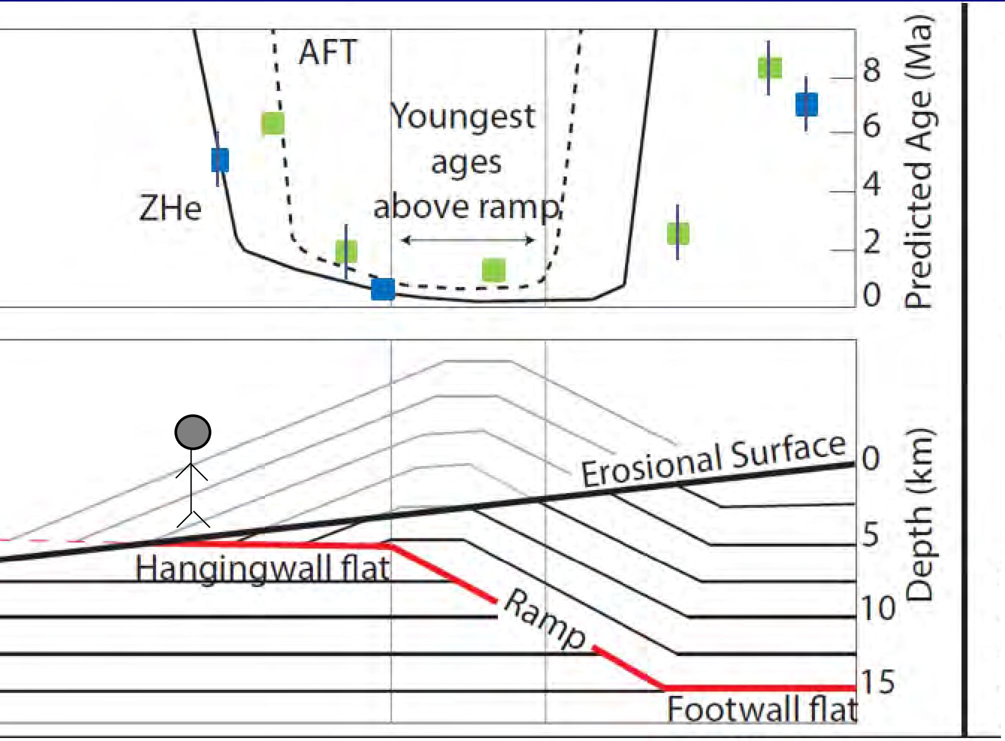
New Proposed Cross Section Geometry

- Ramp between ~180 – 185 km

Battistella (2019)

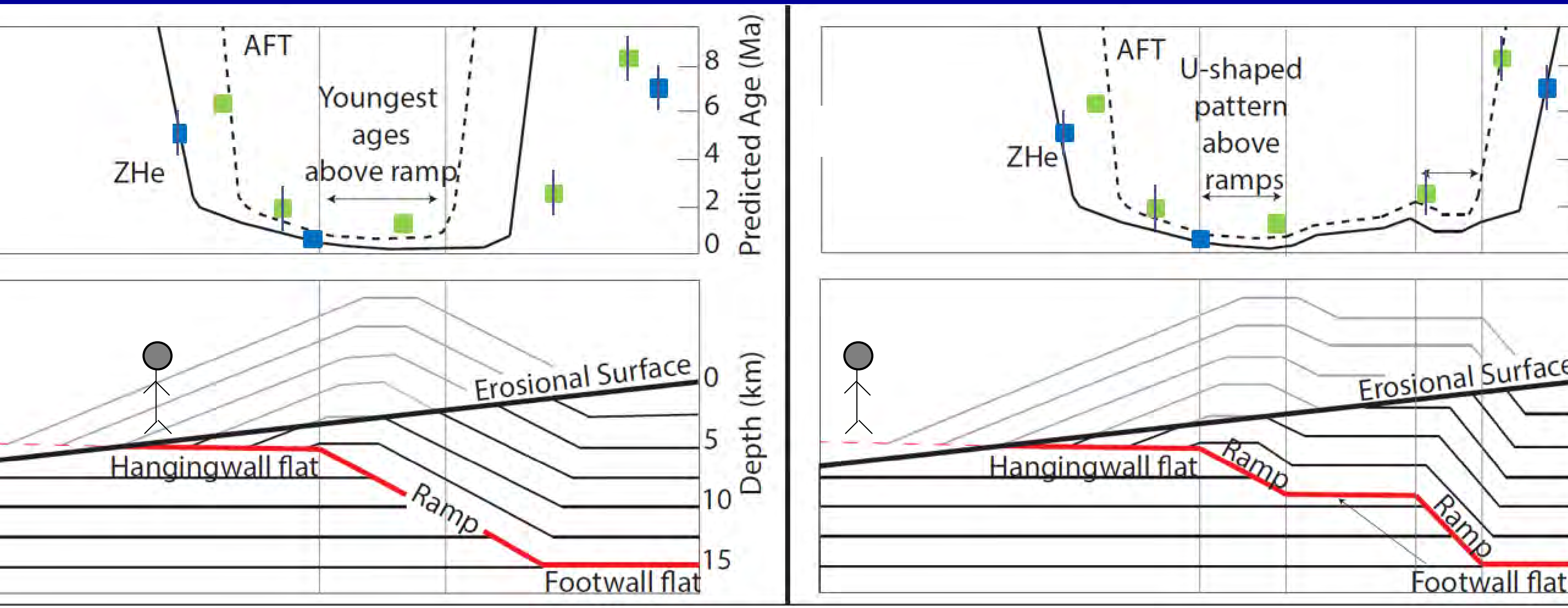


Advance 4: Use thermochronology to determine location of large ramps at depth Large ramps create U's

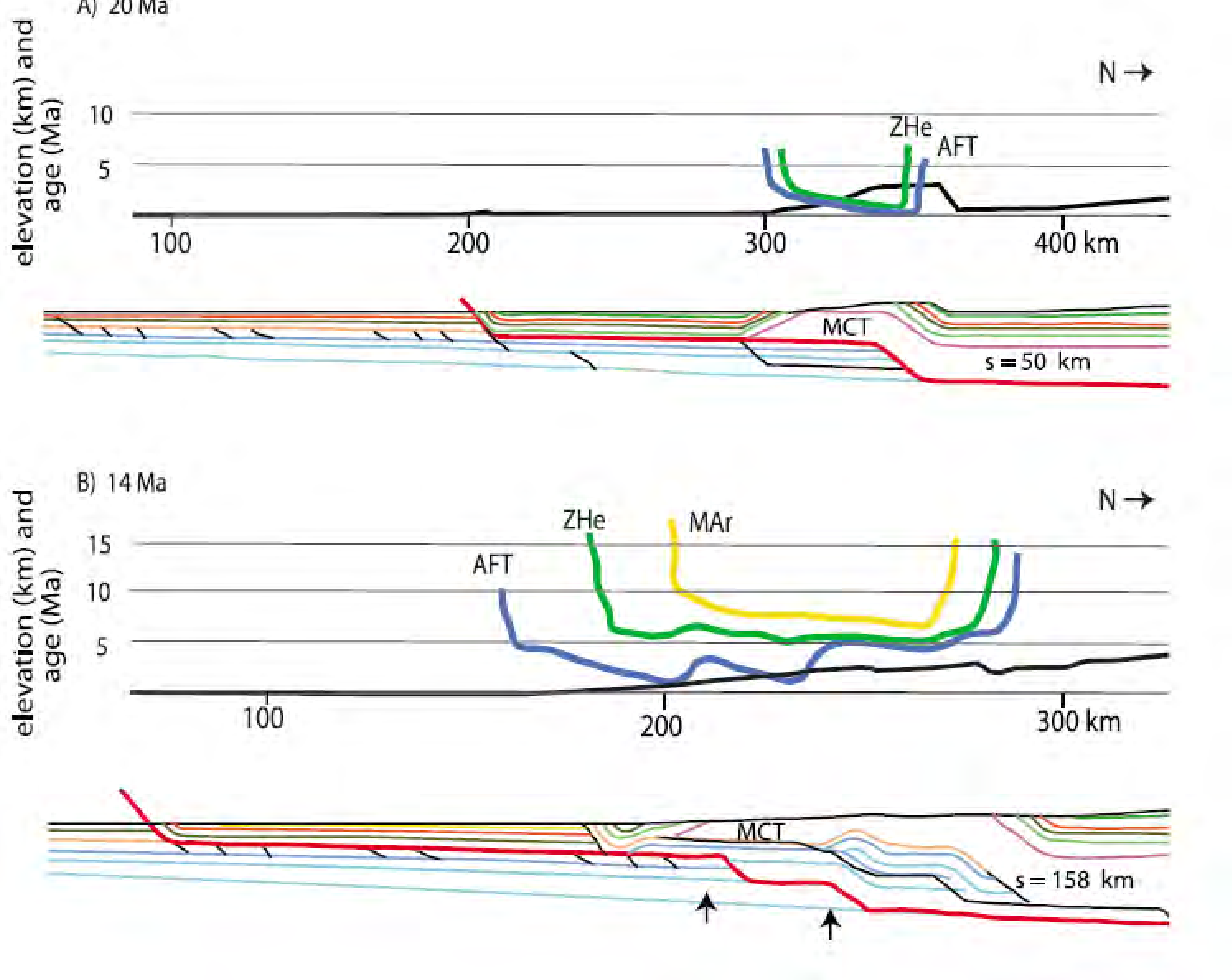


Revised from Lock & Willett, 2008

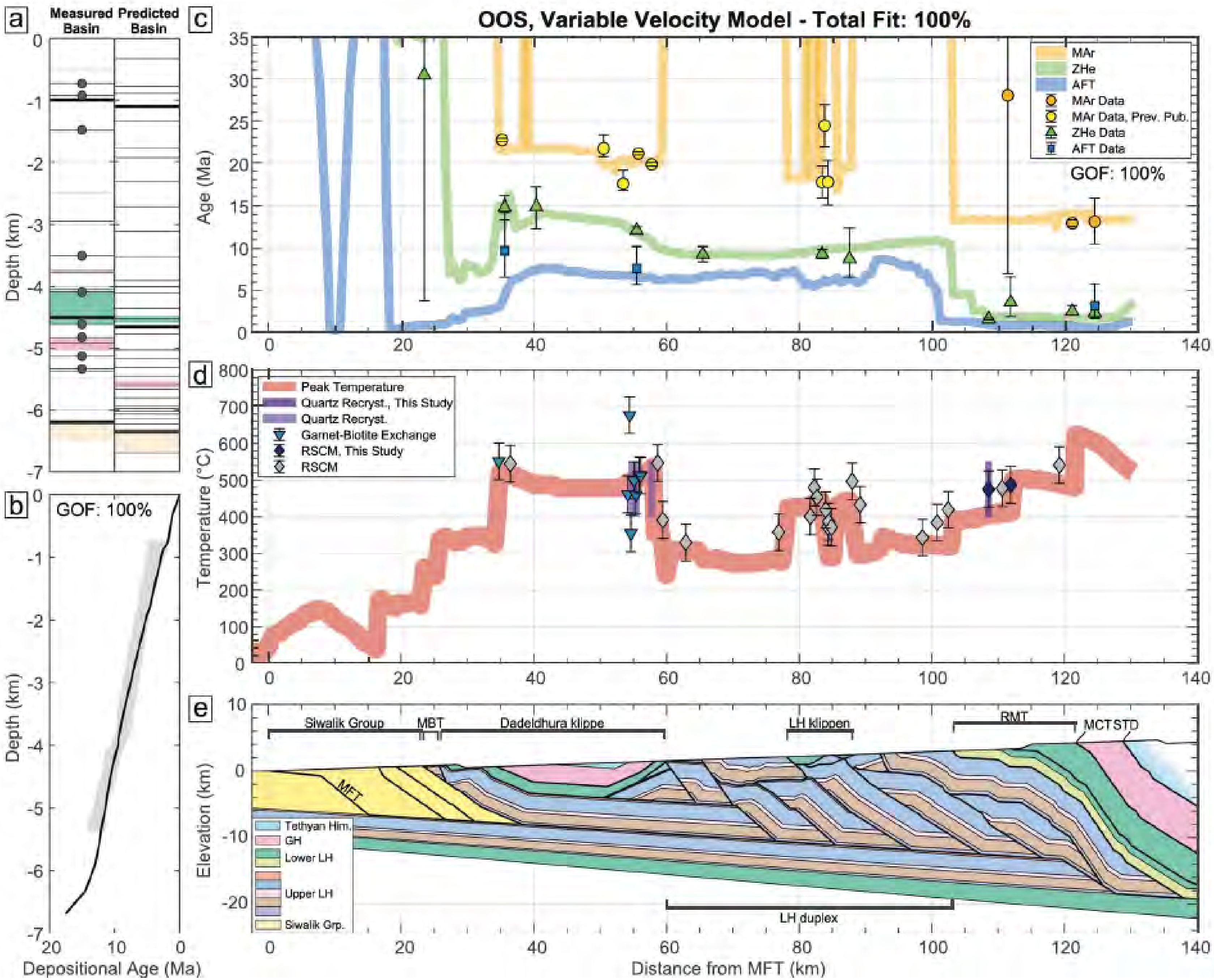
Large ramps create U's in model data (solid and dashed lines)
Laboratory data are points



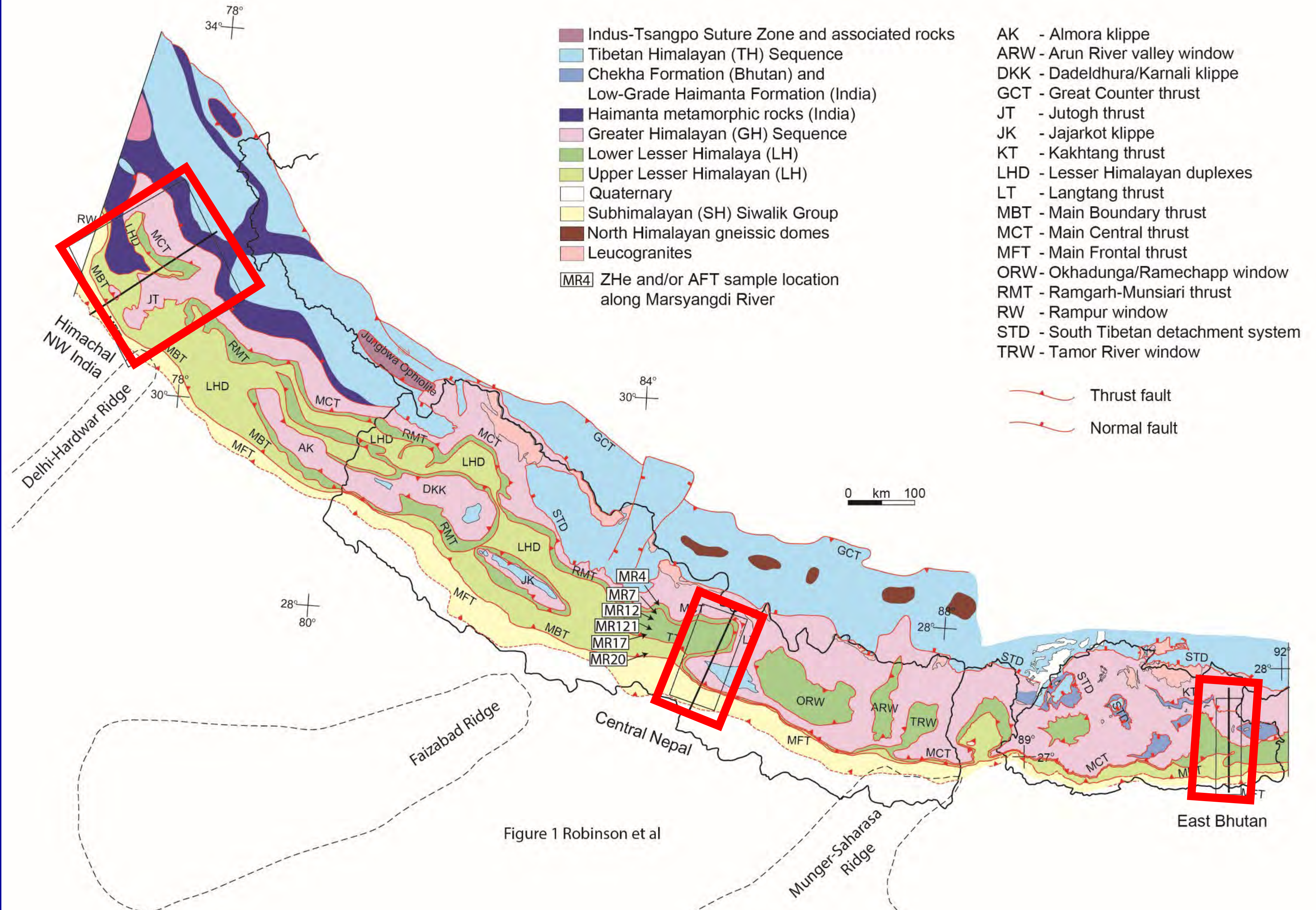
Revised from Lock and Willett, 2008



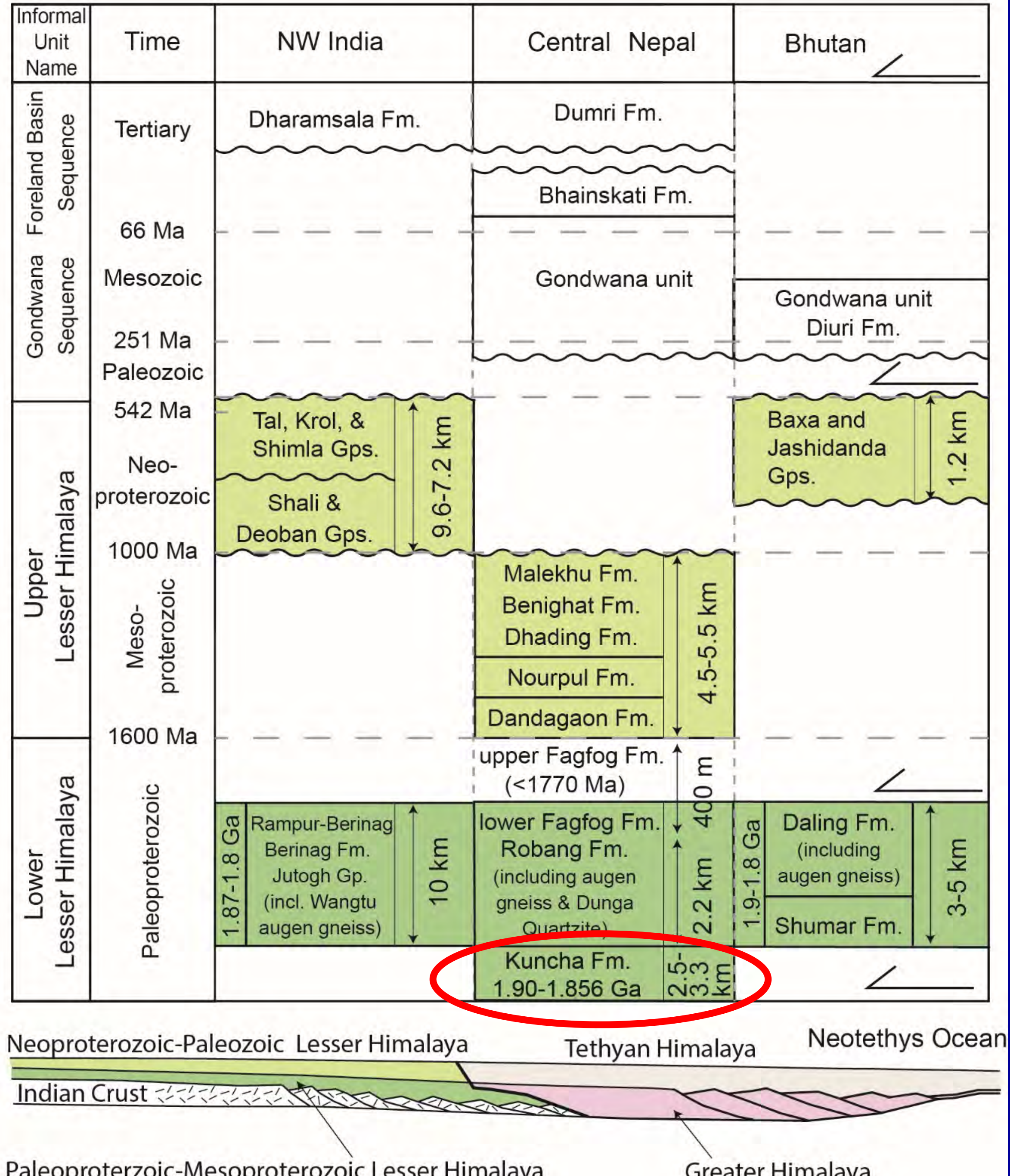
McQuarrie & Ehlers, 2015



Braza et al., 2023



Modified from Robinson & Pearson (2013)

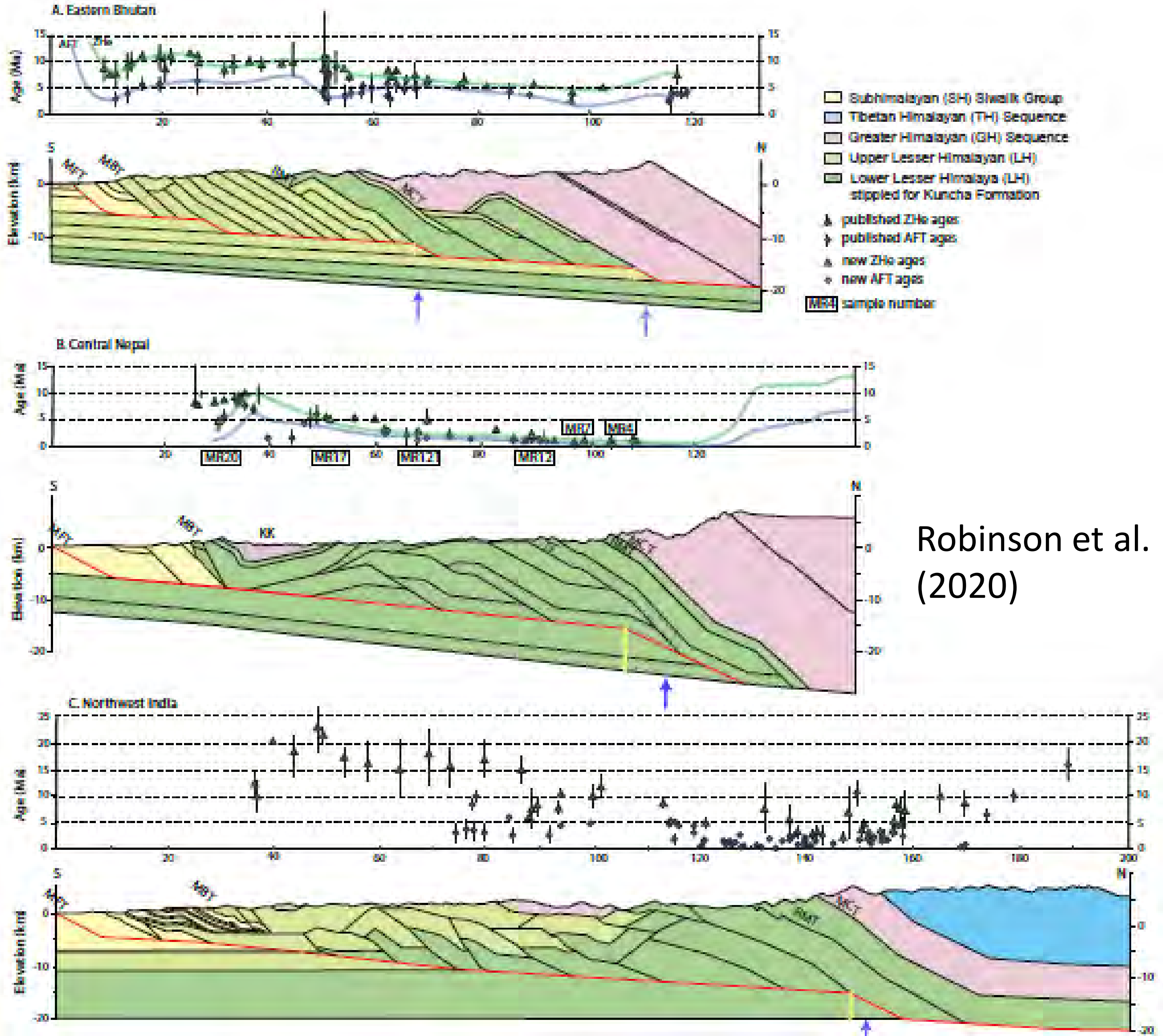


Informal Unit Name
Time
NW India
Central Nepal
Bhutan
Foreland Basin Sequence
Gondwana Sequence
Upper Lesser Himalaya
Lower Lesser Himalaya
Tertiary
66 Ma
Mesozoic
251 Ma
Paleozoic
542 Ma
Neo-proterozoic
1000 Ma
Meso-proterozoic
1600 Ma
Paleoproterozoic
Dharamsala Fm.
Dumri Fm.
Bhainskati Fm.
Gondwana unit
Gondwana unit
Diuri Fm.
Tal, Krol, & Shimla Gps.
Shali & Deoban Gps.
9.6-7.2 km
Baxa and Jashidanda Gps.
1.2 km
Malekhu Fm.
Benighat Fm.
Dhading Fm.
Nourpul Fm.
Dandagaon Fm.
4.5-5.5 km
upper Fagfog Fm.
(<1770 Ma)
400 m
1.87-1.8 Ga
Rampur-Berinag
Berinag Fm.
Jutogh Gp.
(incl. Wangtu augen gneiss)
10 km
lower Fagfog Fm.
Robang Fm.
(including augen gneiss & Dunga Quartzite)
2.2 km
1.9-1.8 Ga
Daling Fm.
(including augen gneiss)
Shumar Fm.
3-5 km
Kuncha Fm.
1.90-1.856 Ga
2.5-3.3 km
Neoproterozoic-Paleozoic Lesser Himalaya
Tethyan Himalaya
Neotethys Ocean
Indian Crust
Paleoproterzoic-Mesoproterozoic Lesser Himalaya
Greater Himalaya

Eastern Bhutan

Central Nepal

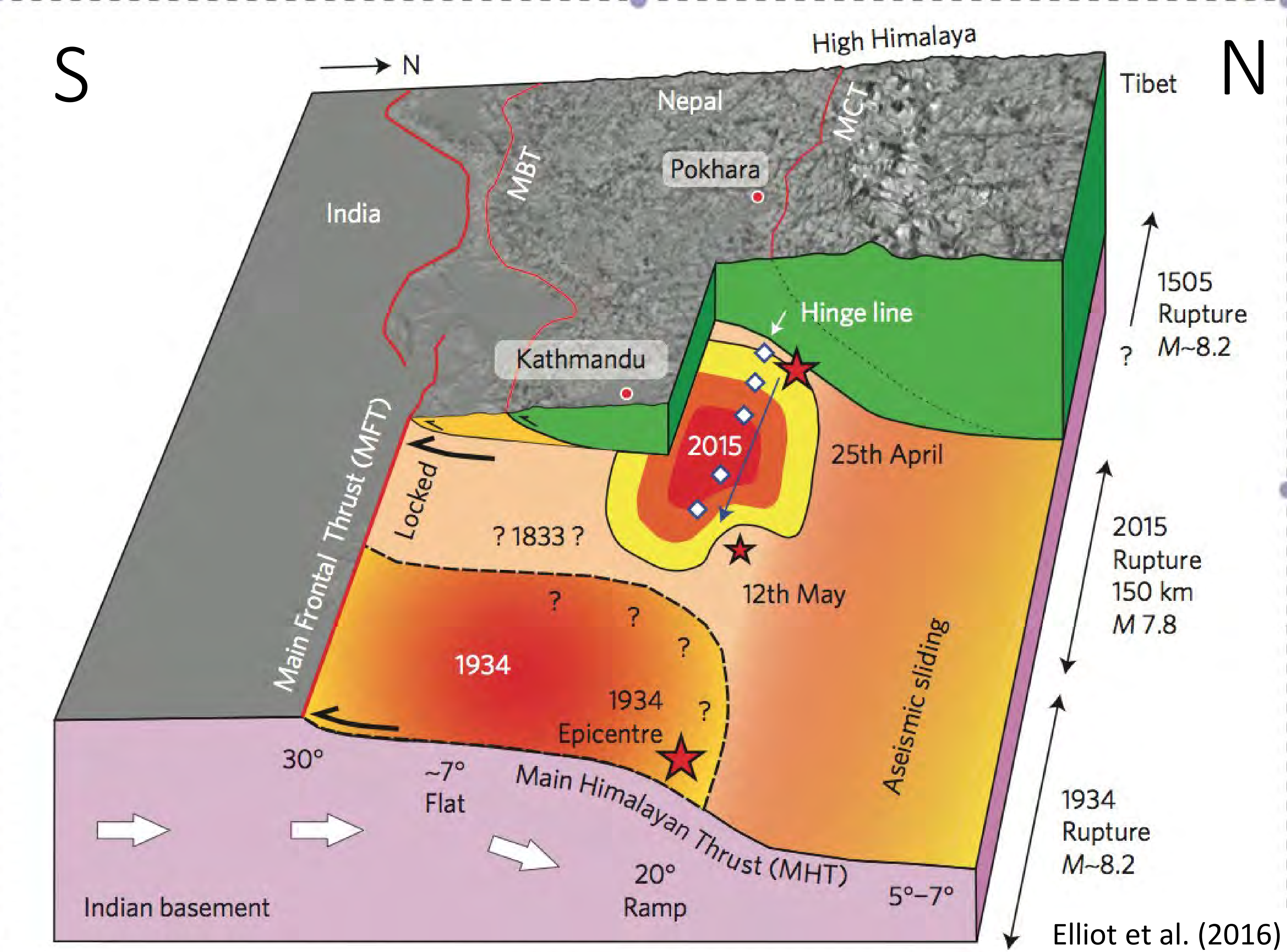
NW India



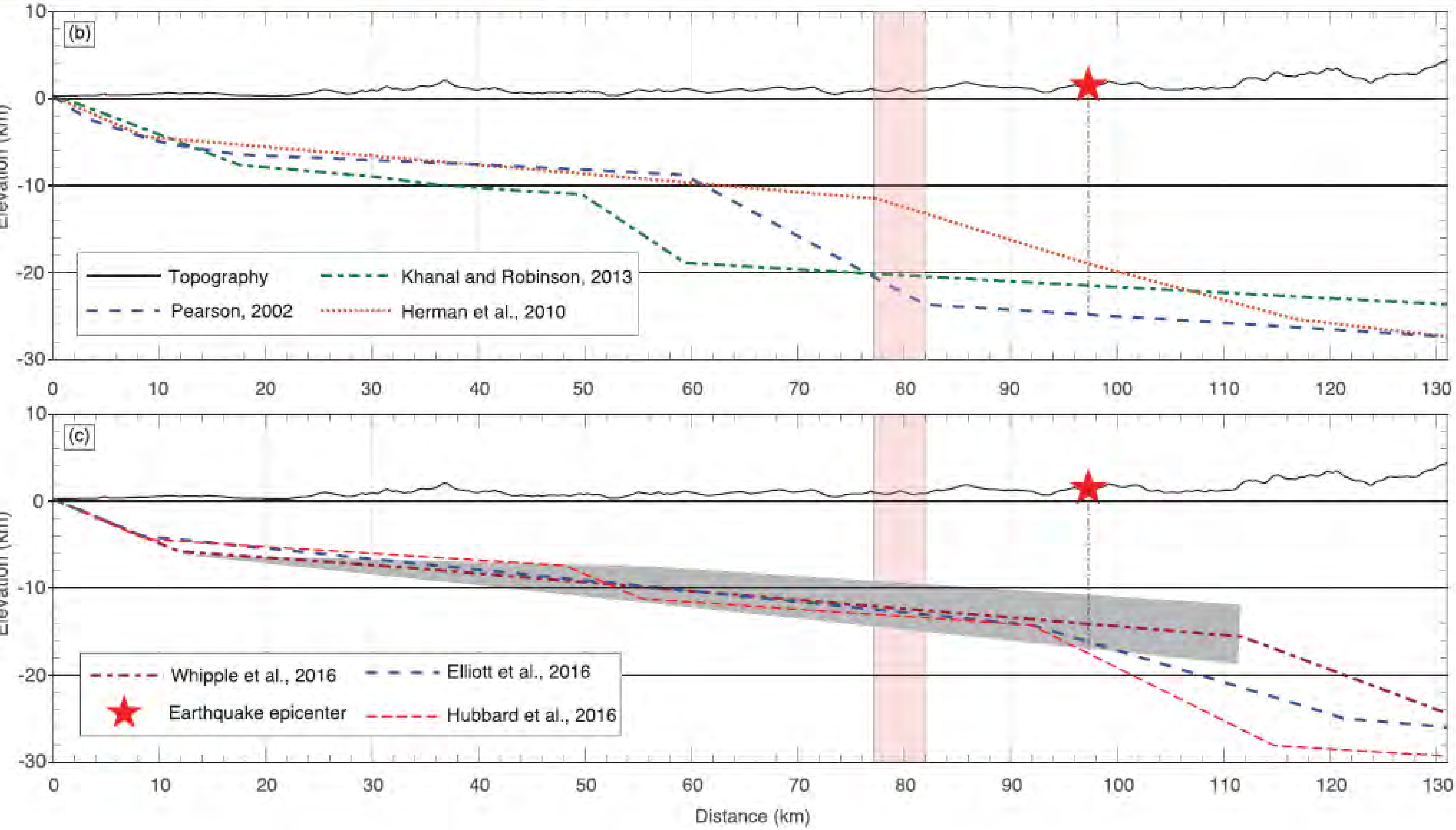
Robinson et al. (2020)

- Large 10 km + ramps cause anomalously young ZHe & AFT ages in central Nepal ftb hinterland
- Thick Paleoproterozoic Kuncha Formation allows ramp to be larger in central Nepal than eastern Bhutan or NW India

Large EQs occur on MHT ramps
Thermochronology can find ramps
Location of ramps can help predict EQs



Elliot et al. (2016)



Ghoshal et al. (2020)

Advances

1. Link deformation, erosion & depositional history
2. Dating individual faults using U-Pb in calcite
3. Validate balanced cross sections using thermochronology
4. Use thermochronology to determine location of large ramps at depth
5. Tying ramps to large EQs


dmr@ua.edu
Thank You & Questions