Great Earthquakes:
Observations and modeling

Link between the Great Faults of Asia, continental plate tectonics and continental subduction

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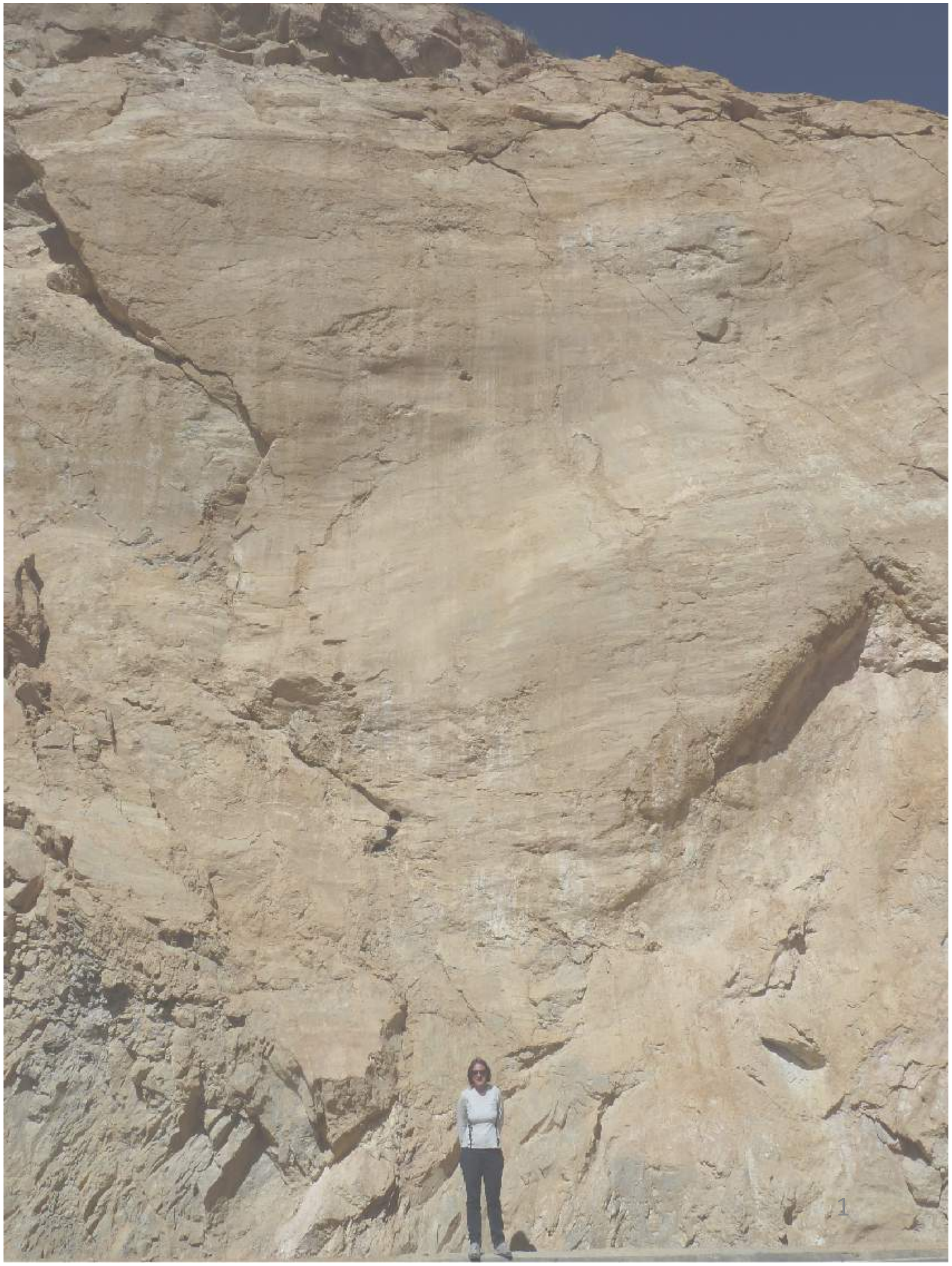
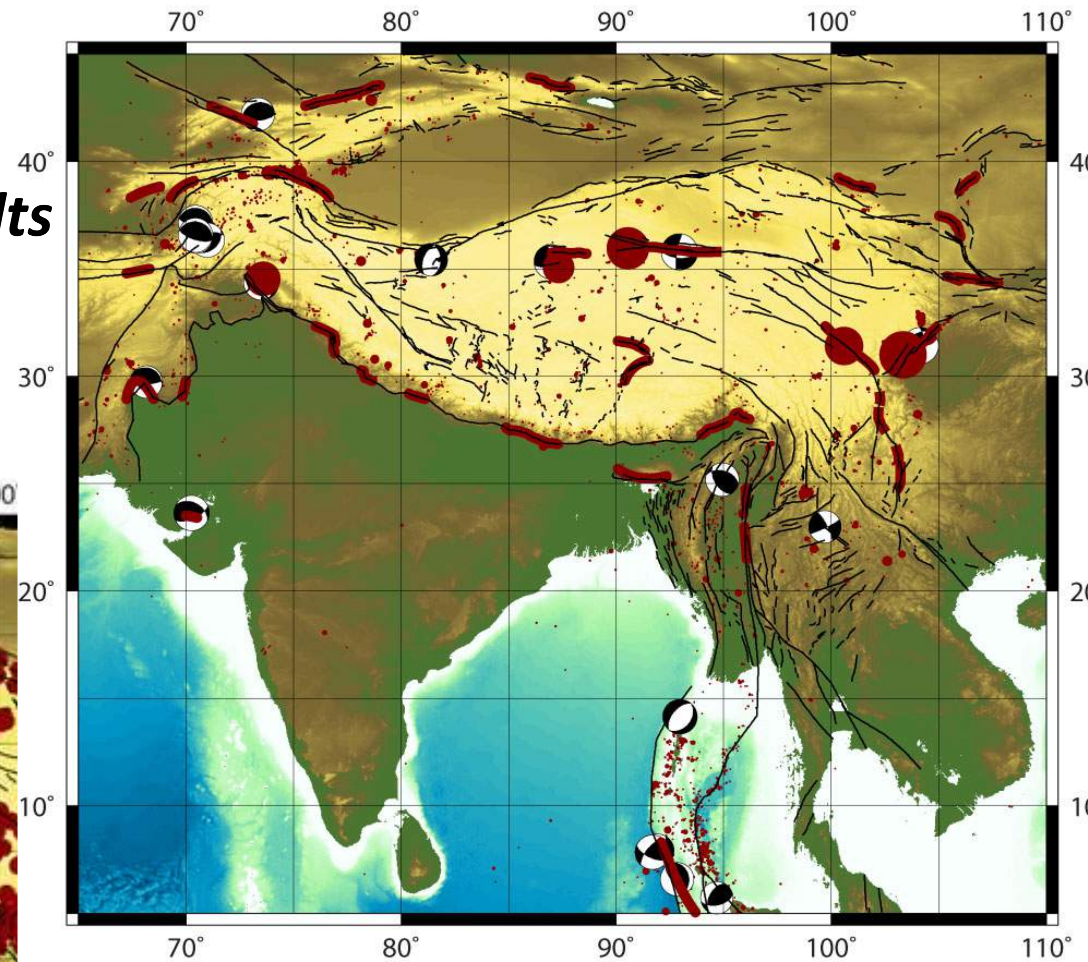
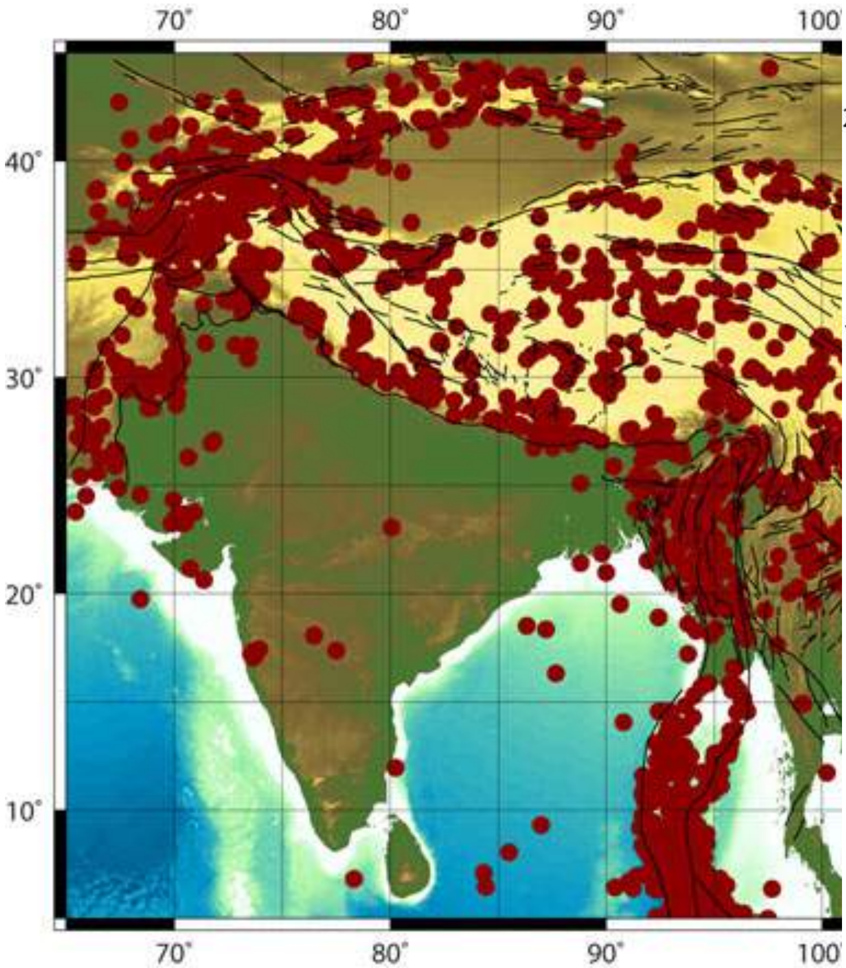
cnrs INSU Observer & comprendre

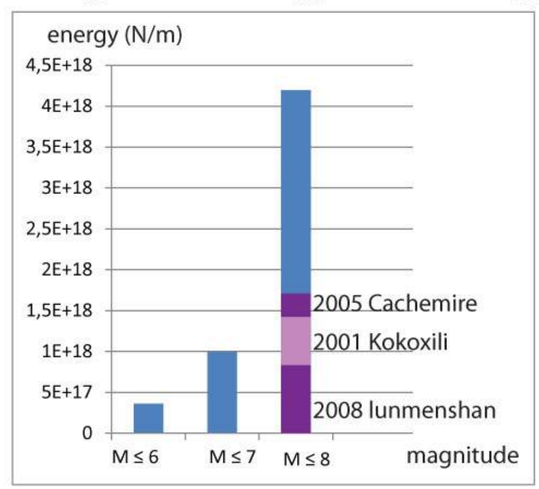


Great Earthquakes, Great Faults

cutting Asia in blocks ?
linked to continental subduction ?





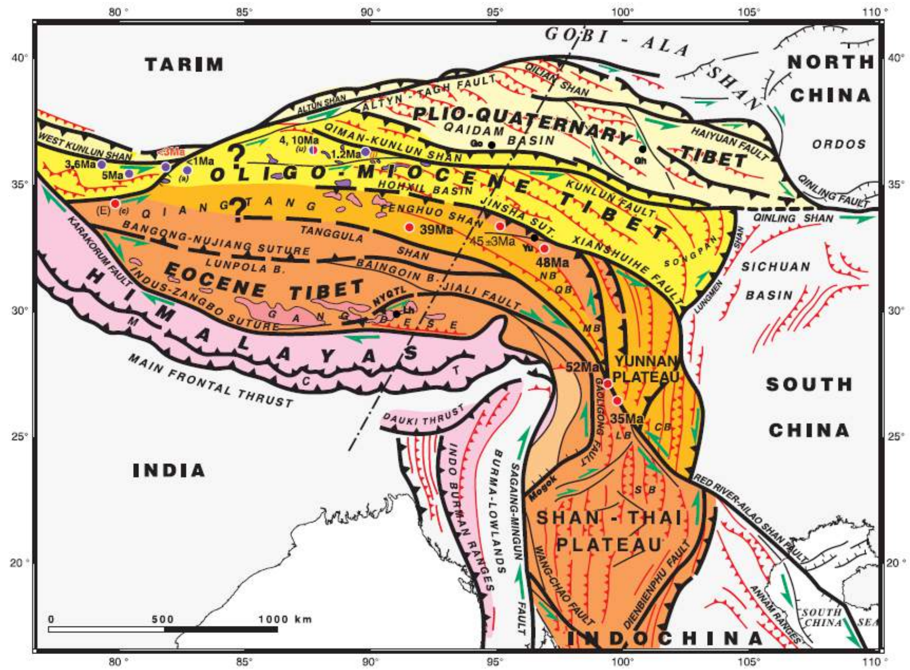


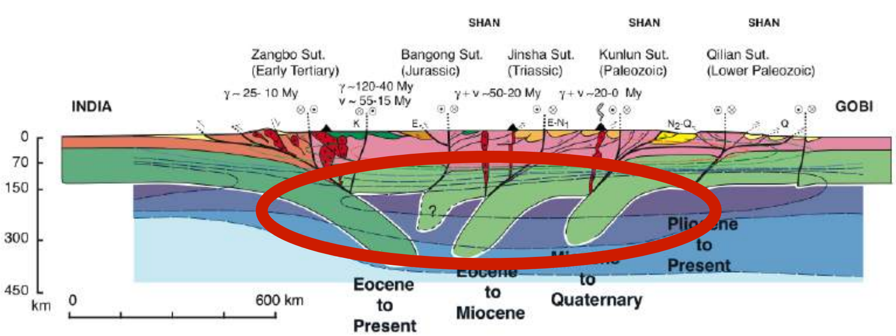
~ 80% energy released By M>7

continental plate-tectonics model

block geometry deduced from fault geometry

Inferring Indian and Asian slabs

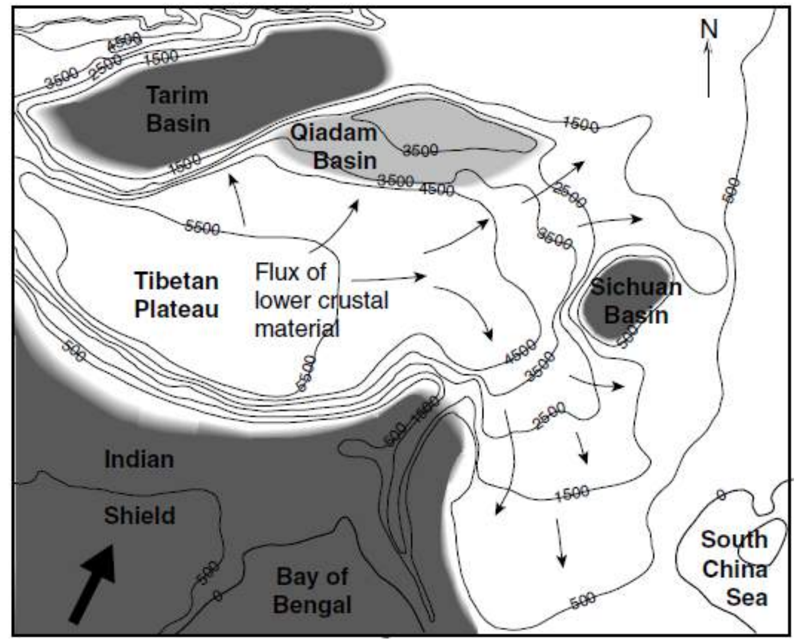


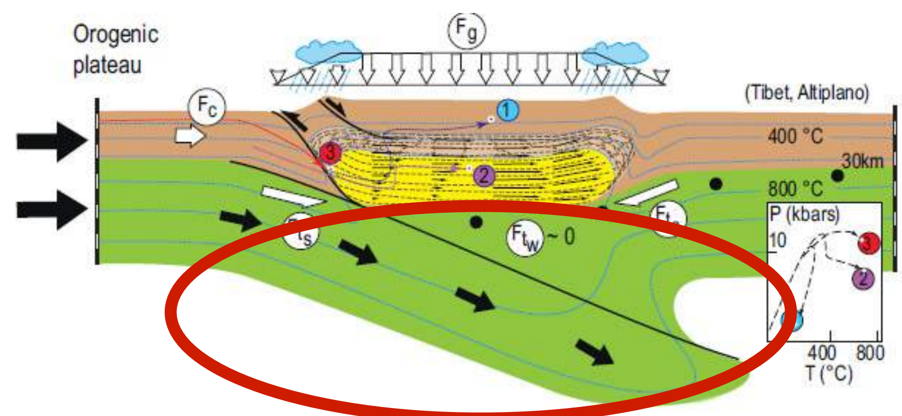


Soft Tibet model

Focus on rheology of the lower crust

Inferring a wide indian slab





Meyer et al., 1998
Tapponnier et al., 2001

Clark& Royden, 2000
Vanderhaeghe et al., 2012

Link between the Great Faults of Asia, continental plate tectonics and continental subduction

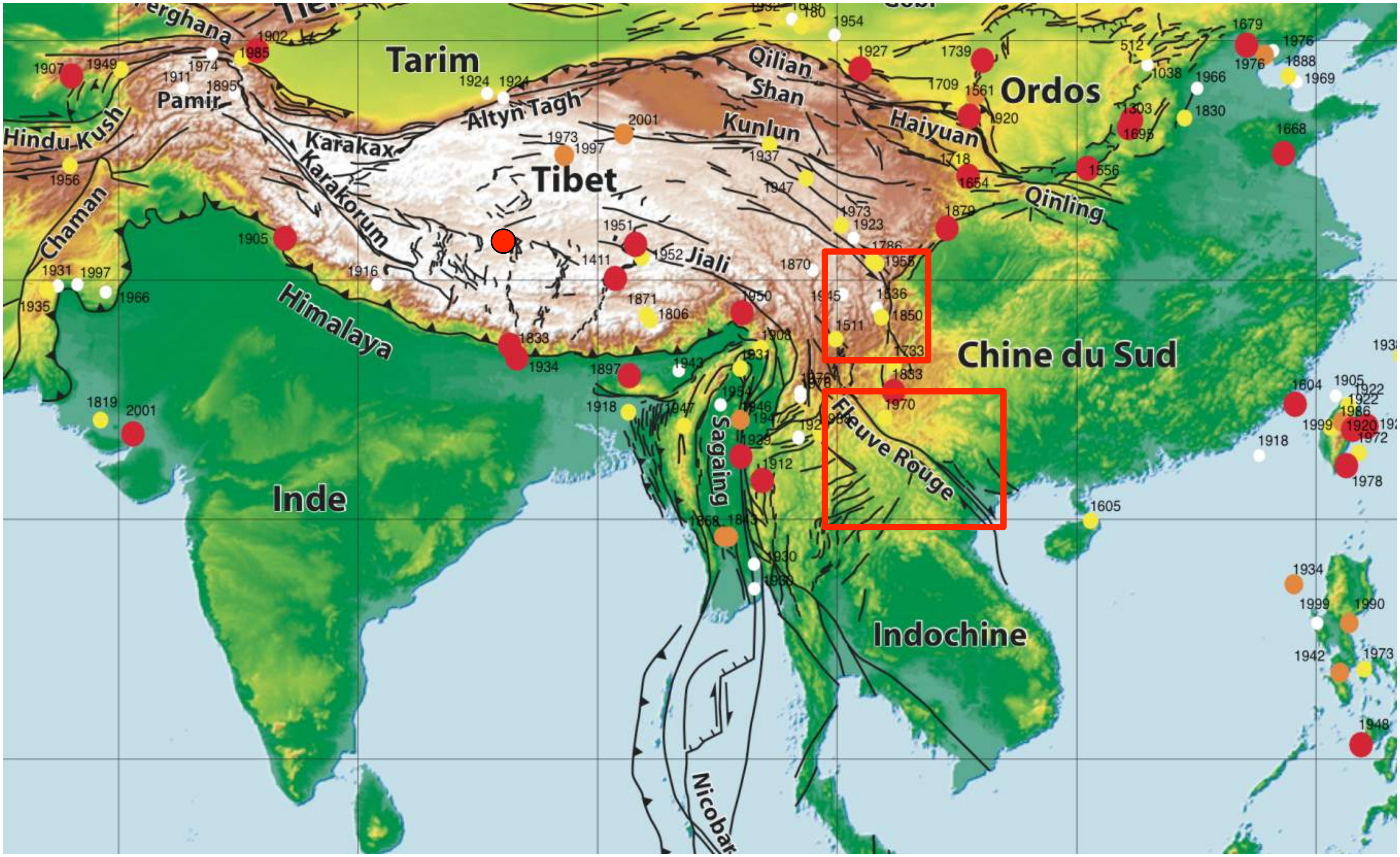
- **Upper crust**
  - ✓ fault rate and offset
  - ✓ 2D tectonics reconstruction

- **Lithosphere**
  - ✓ slabs in global tomography
  - ✓ 3D lithospheric reconstruction

- **Dynamics of processes**
  - ✓ Numerical models of upper plate deformation due to slab breakoff
  - ✓ Analogue models of upper plate collisional subduction

Deformation of the upper crust

Determination fault rate and offset in SouthEast Tibet



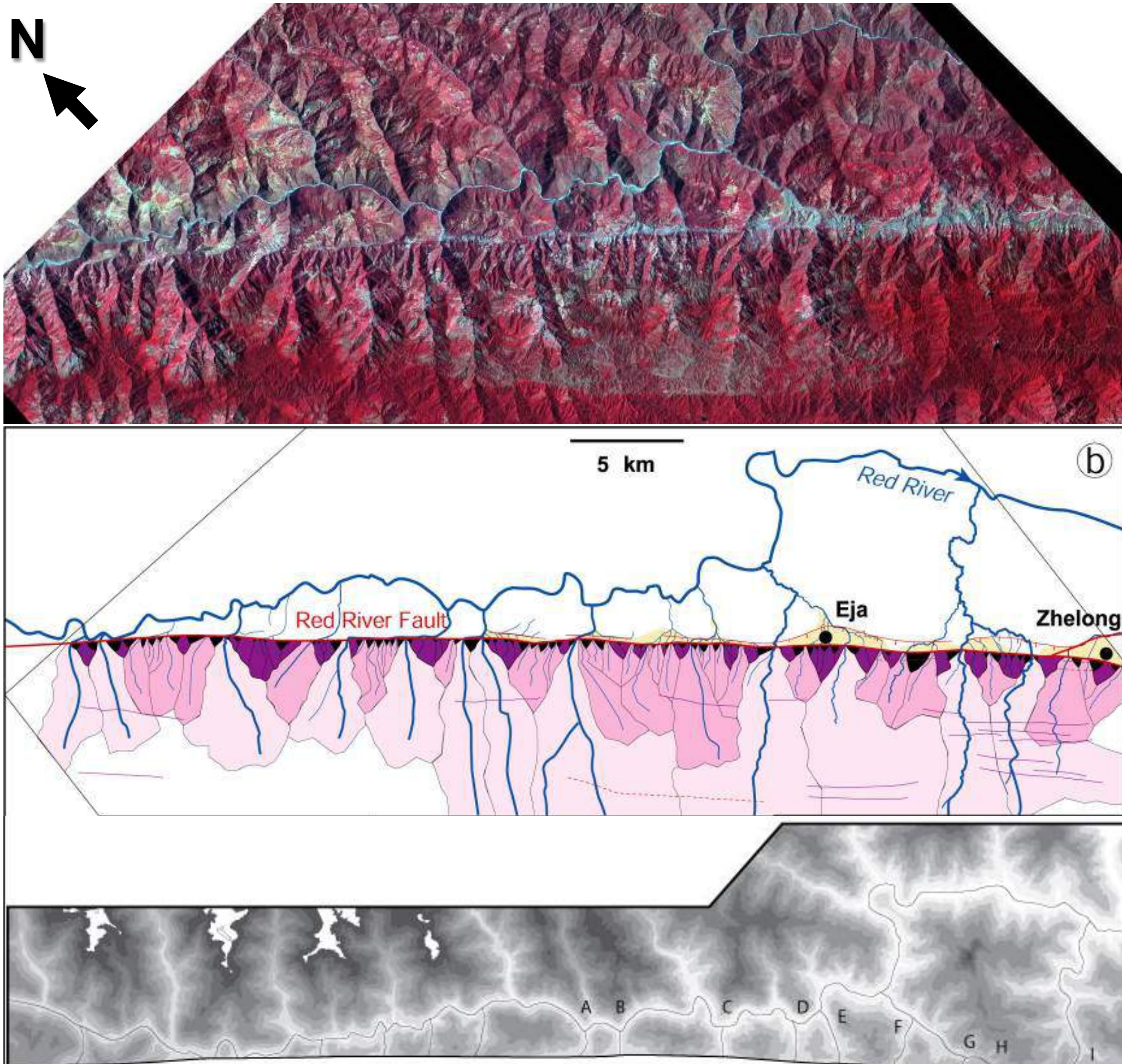
XianShuiHe Fault

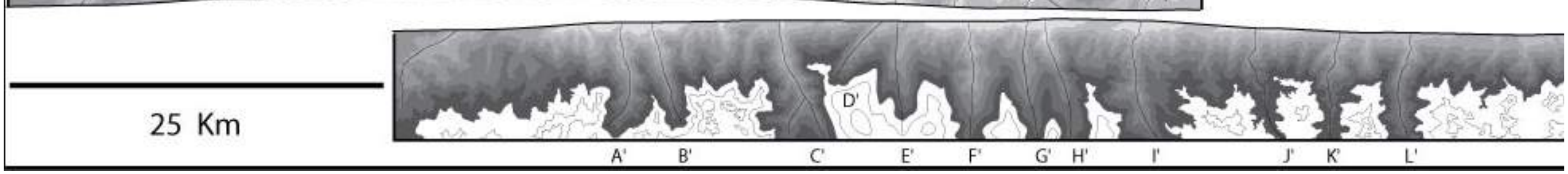
Using thermochronology

Red River Fault

Using morphotectonics

Replumaz et al., 2001

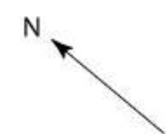




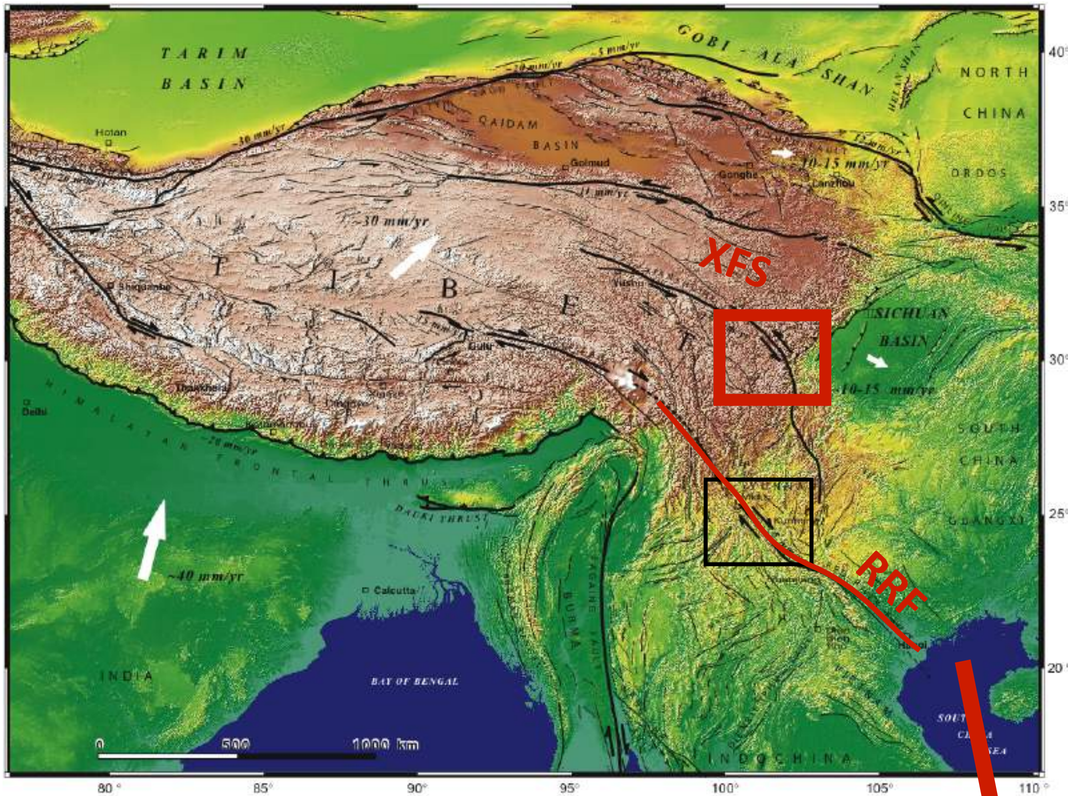
Red River fault

dextral offset of the drainage network:

25 km



Rate and offset of RRF using geomorphology



Total dextral offset 25 km

/

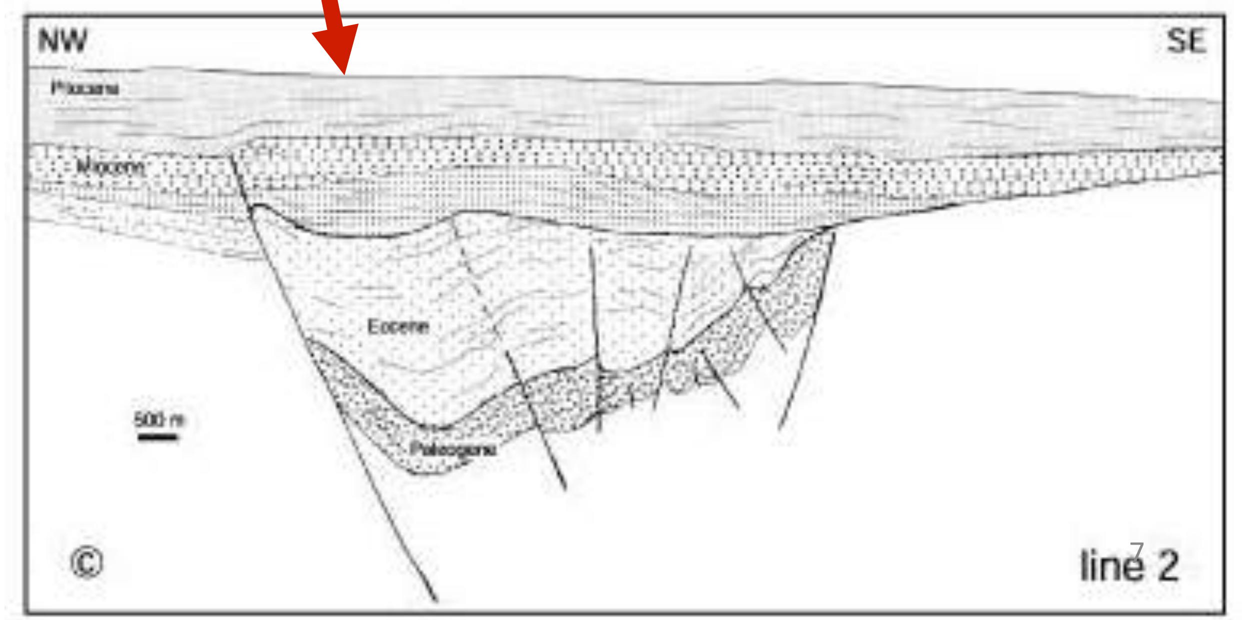
Activation of RRF 5Ma

=>

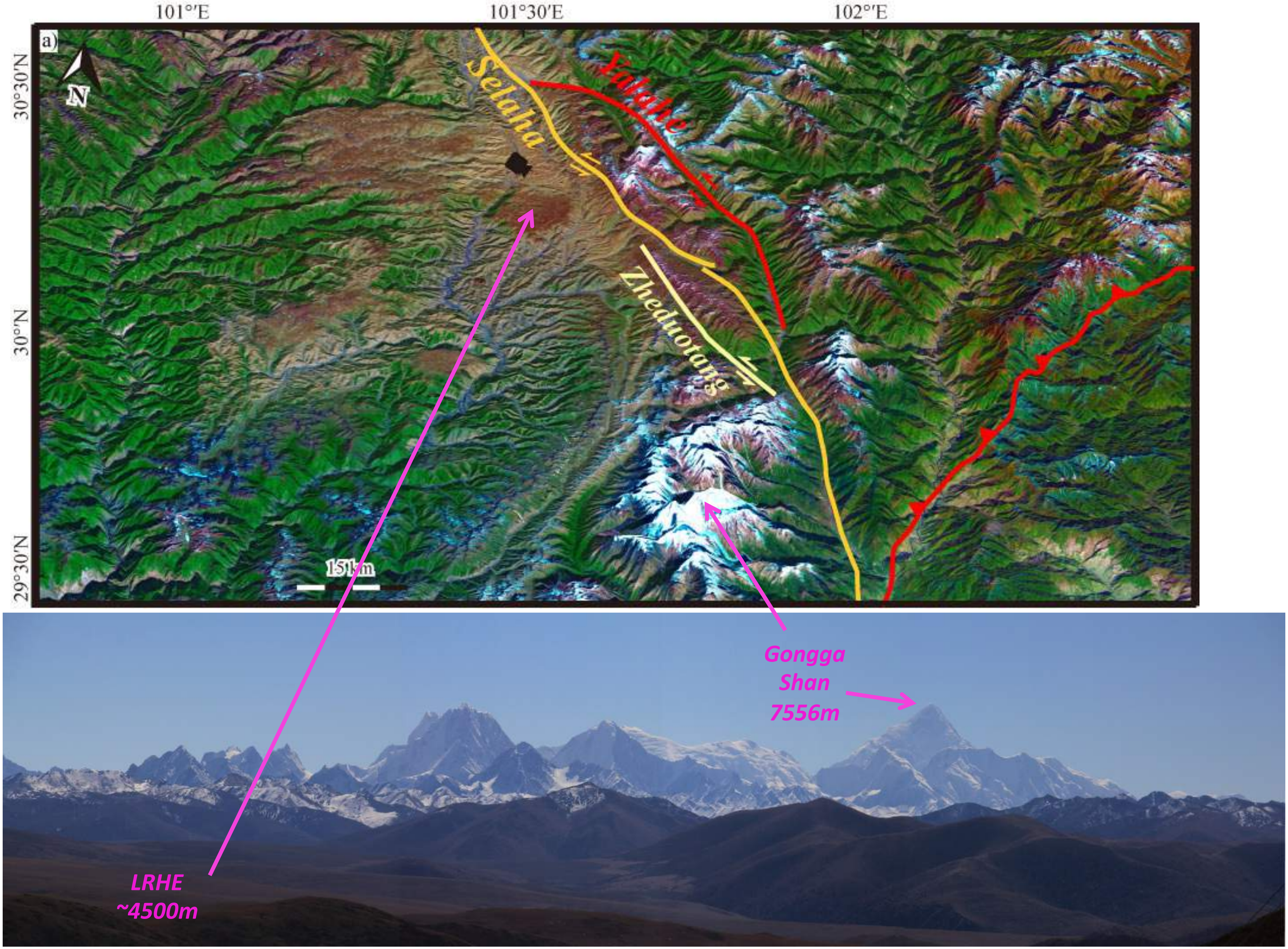
mean Pliocene rate

5 mm/yr

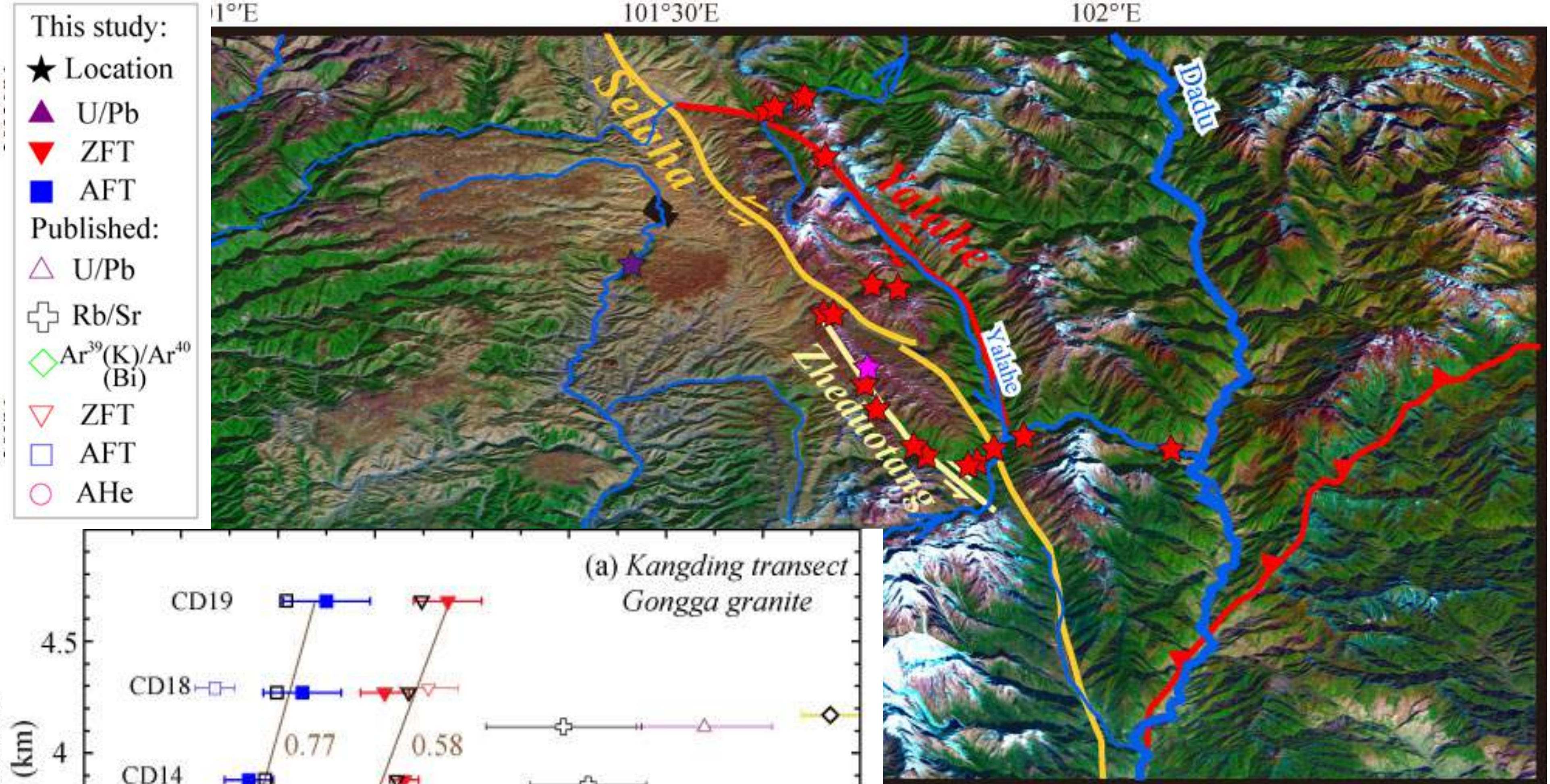
Tectonic inversion at the SouthEast extremity of the fault in the Tonkin Gulf using seismic lines dated at 5 Ma

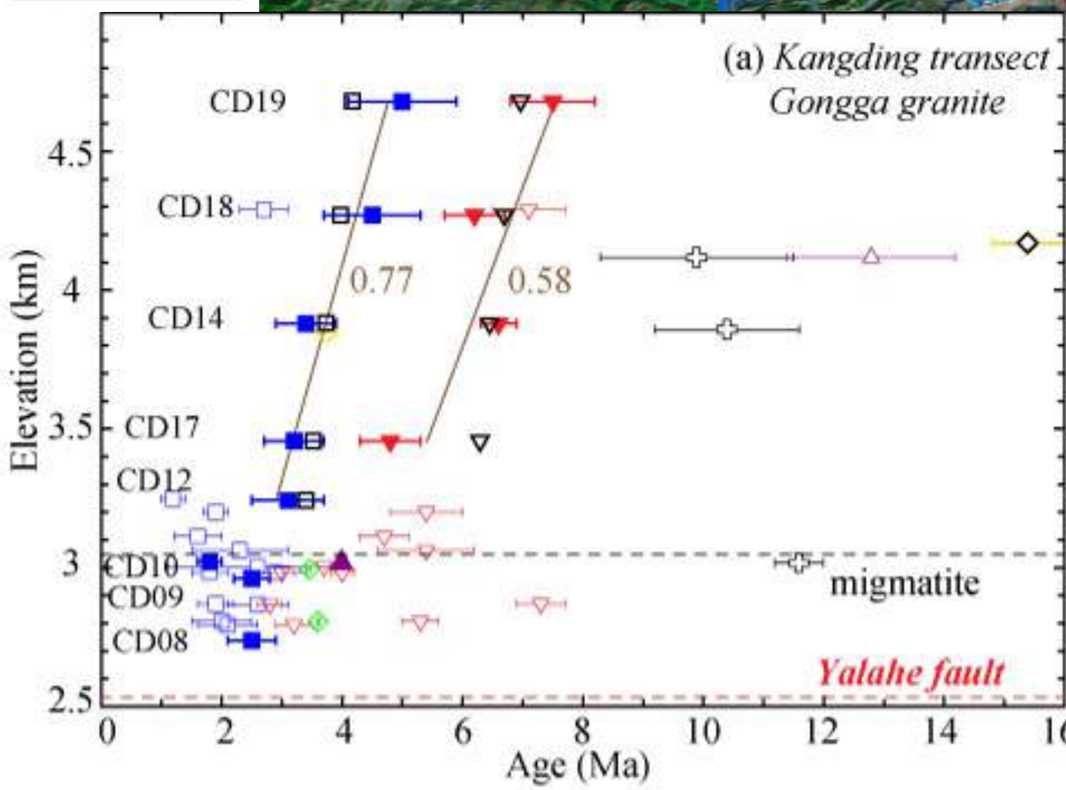


Replumaz et al., 2001



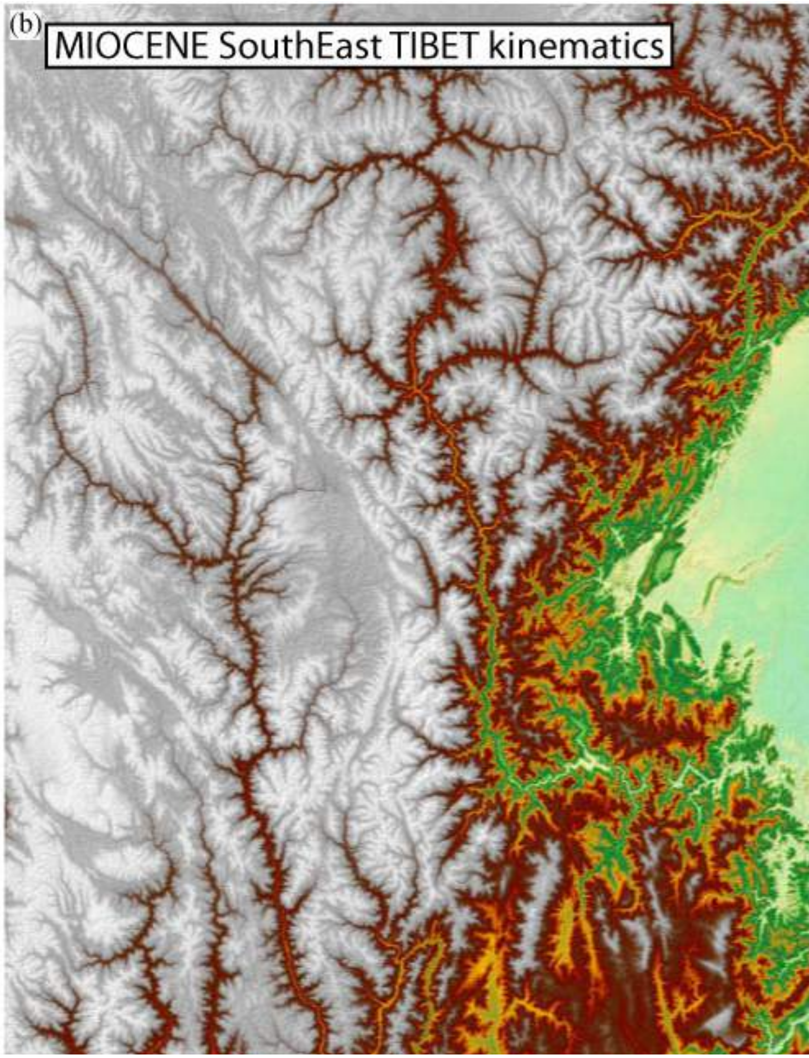
101°'E
101°30'E
102°'E
30°30'N
30°N
29°30'N
a)
N
Selaha
Yalahe
Zheduotang
15 km
Gongga
Shan
7556m
LRHE
~4500m

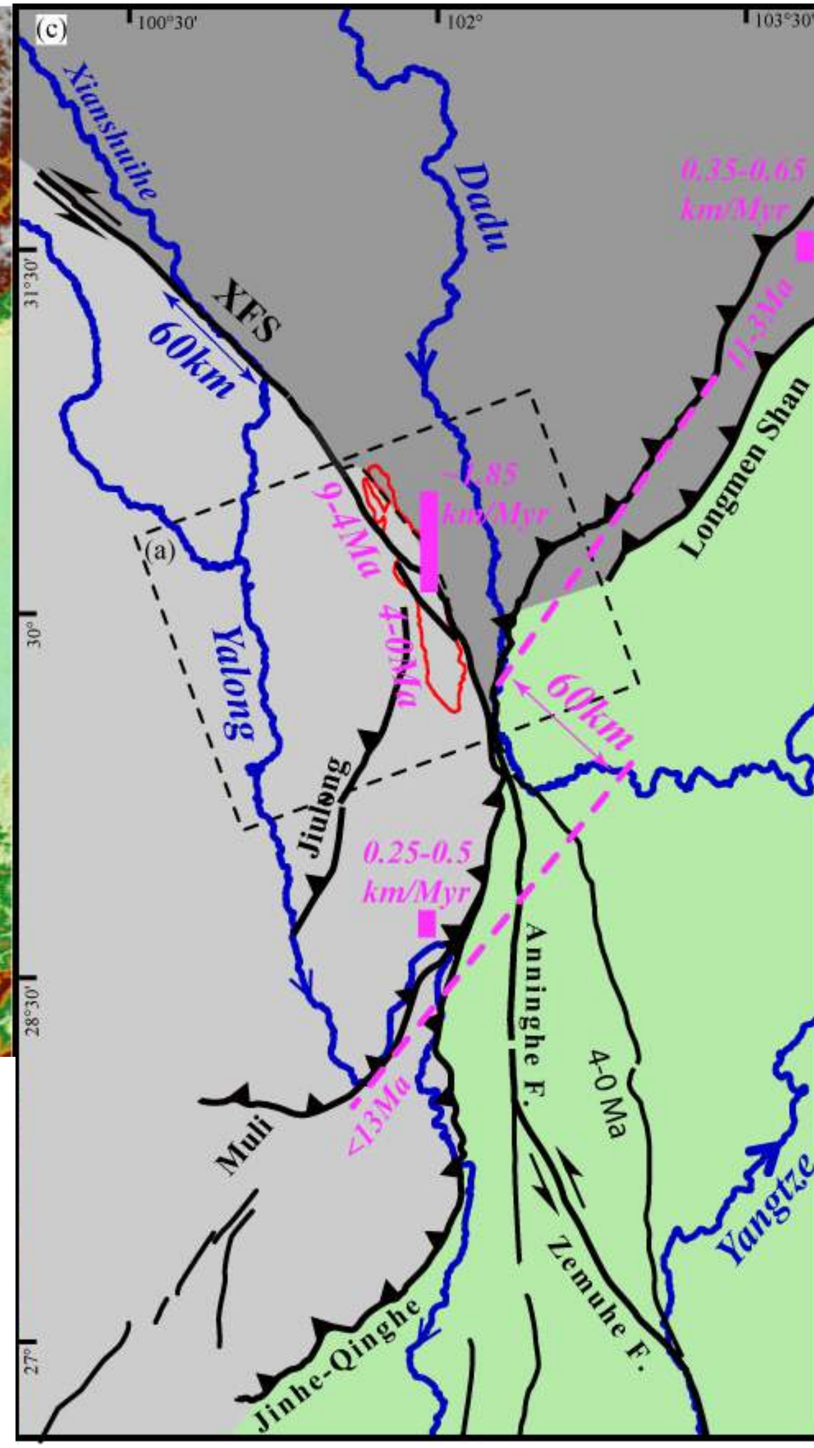




rapid exhumation started at ~9 Ma at a rate of ~1.85 km/Myr

Zhang et al., 2017



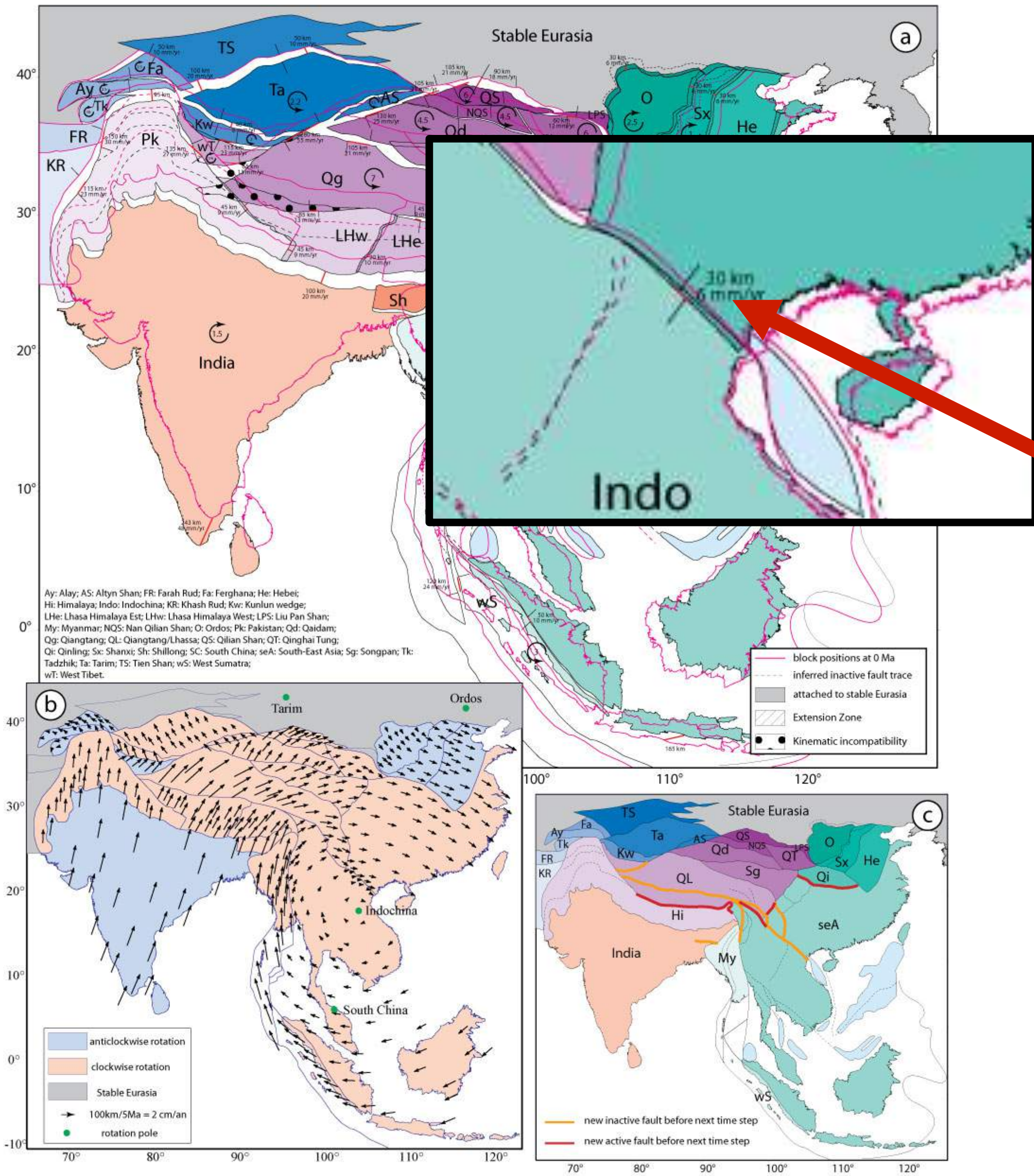


XFS active since ~9 Ma
+ total offset of ~62 km

⇒ average slip rate of the XFS is ~7 mm/yr

Zhang et al., 2017

⇒ ***Tectonics Reconstruction***



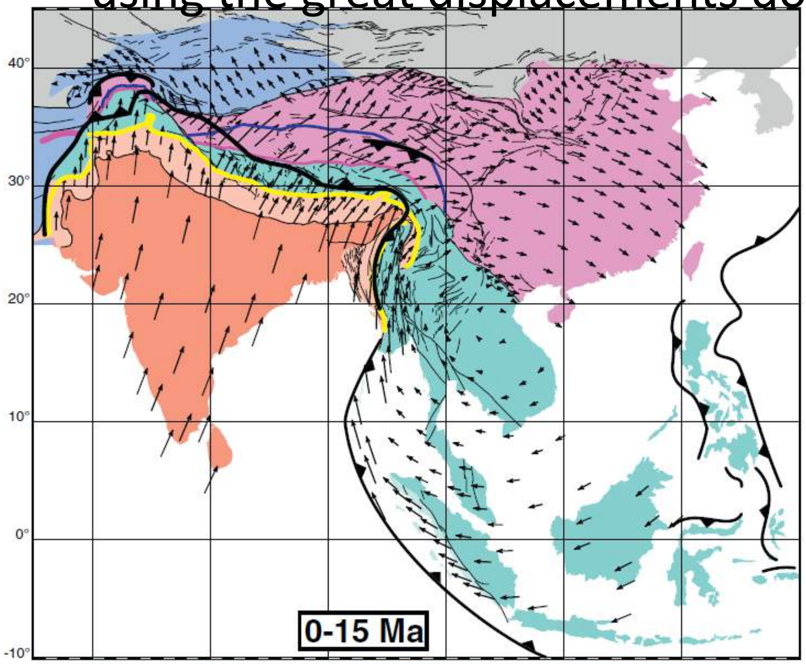
1/ rigid motion of blocks constrain by fault rate and offset

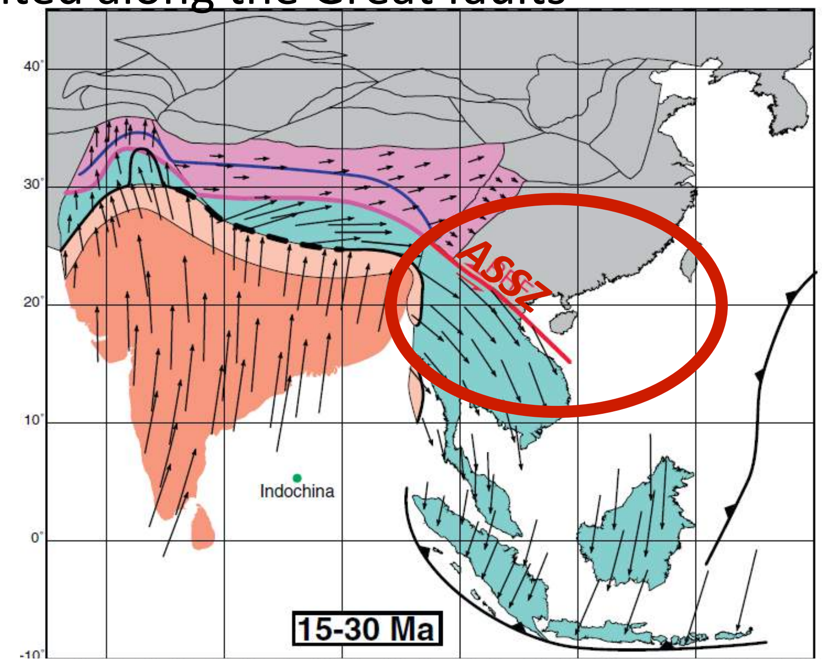
Red River Fault
25km
5Ma

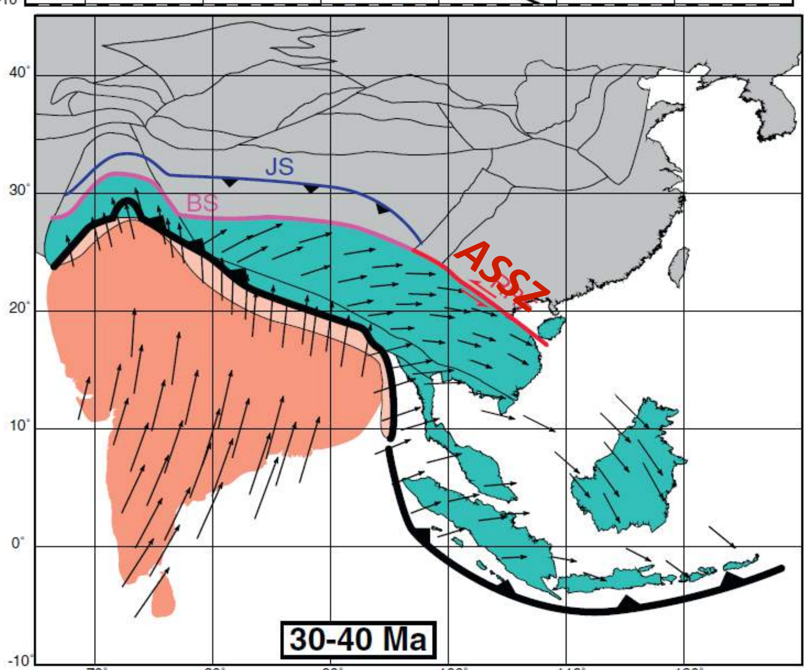
2/ restauration of block continuity and change the fault network

tectonics reconstruction: upper crust evolution

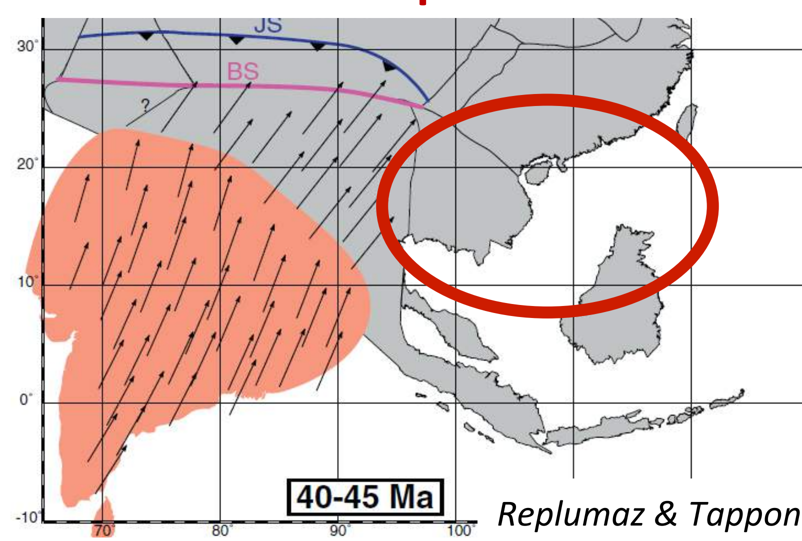
using the great displacements documented along the Great faults







how to accomodate these great displacement at the lithospheric scale ?



Replumaz & Tapponnier, 2003

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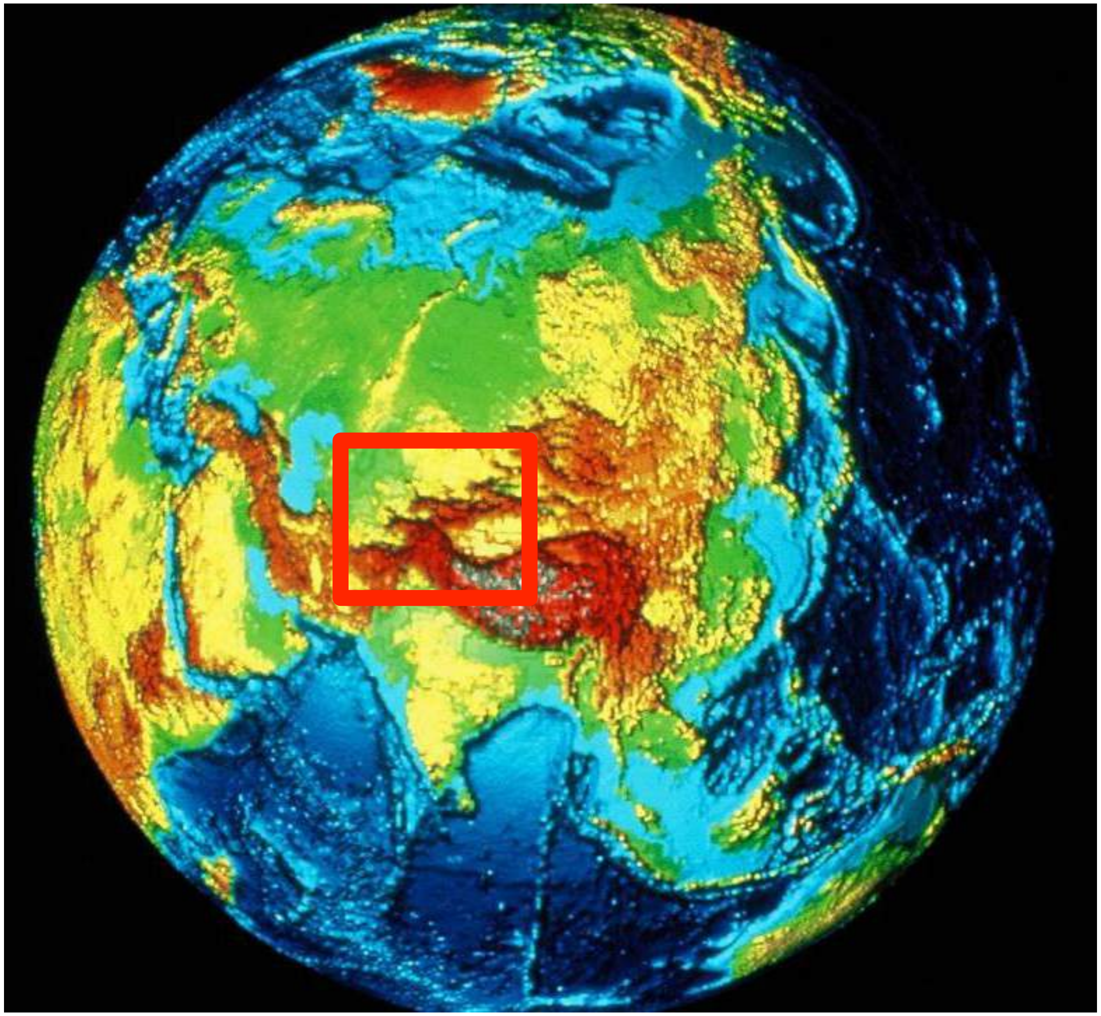
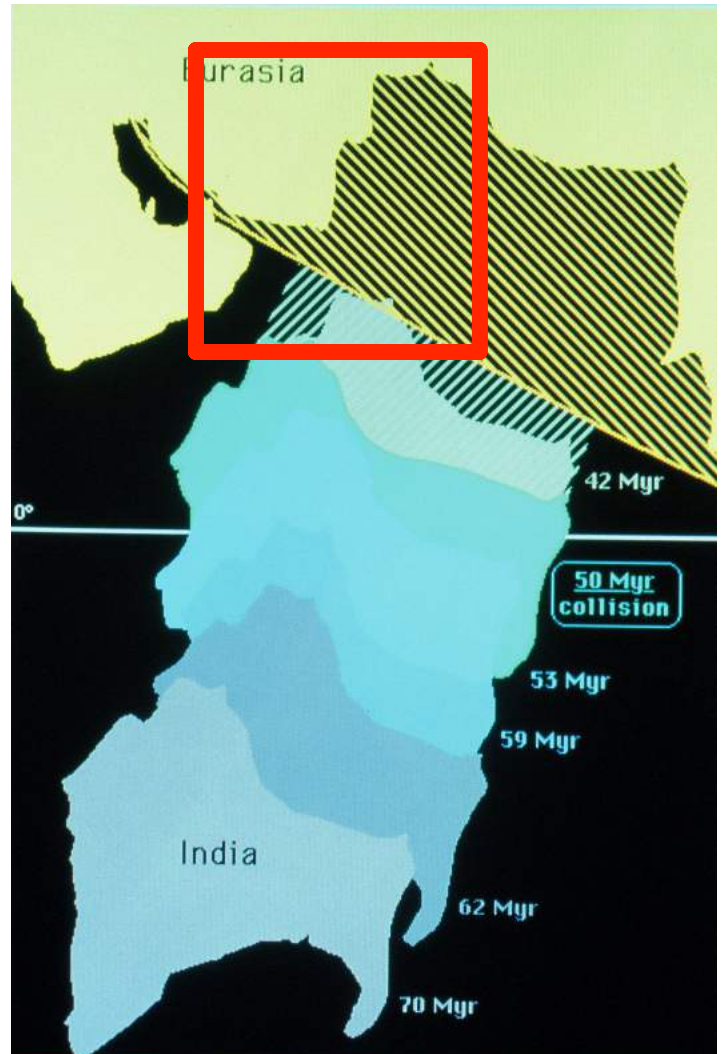




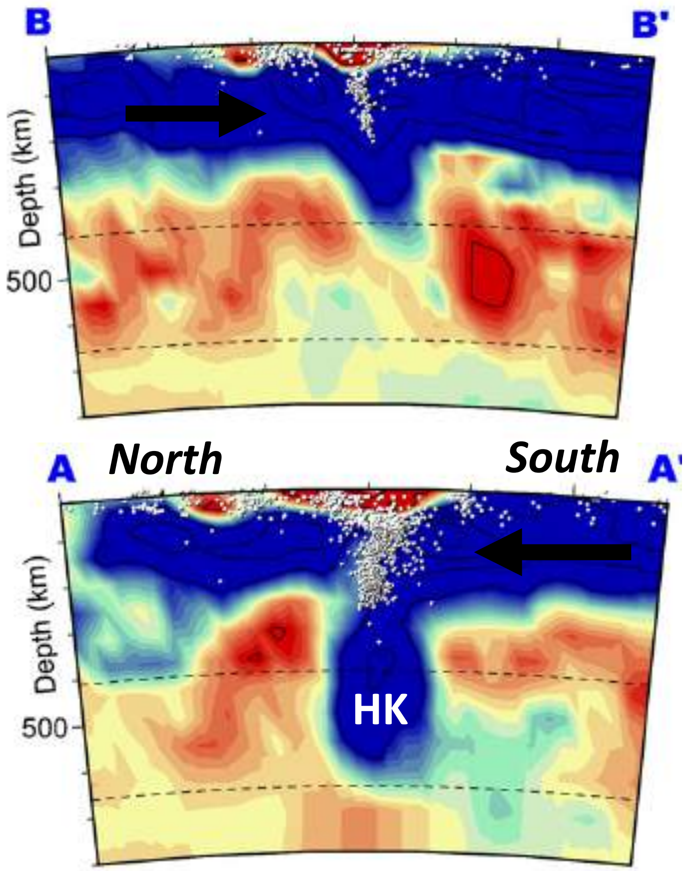
Coupling tectonics of Asia and geodynamics :

formation of Tibetan plateau

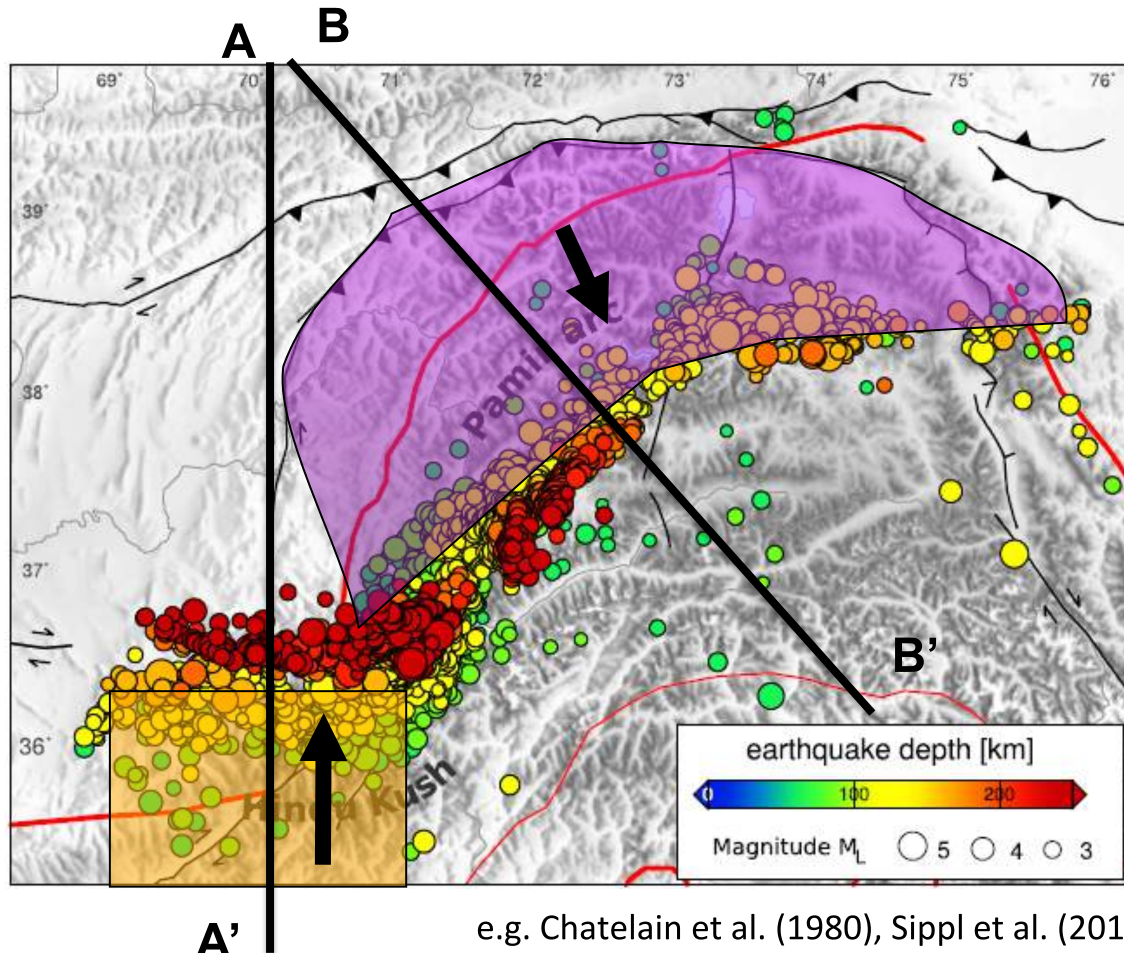
e.g. Patriat &Achache, 1984

deepest intracontinental seismicity in the world,
⇒ 2 on-going continental subductions
with opposite vergence

Asian slab
Dipping southward



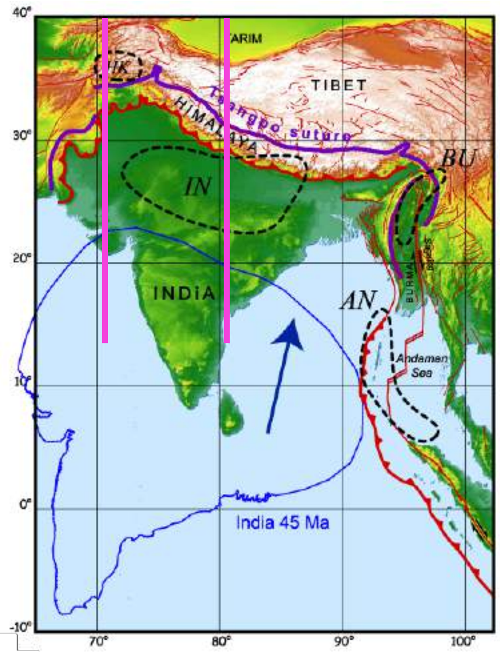
Indian slab
Dipping northward

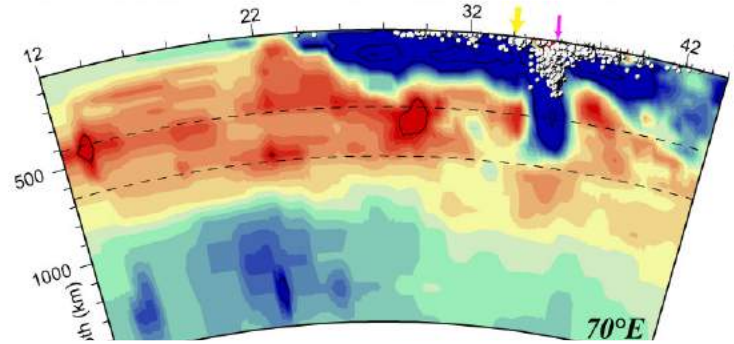


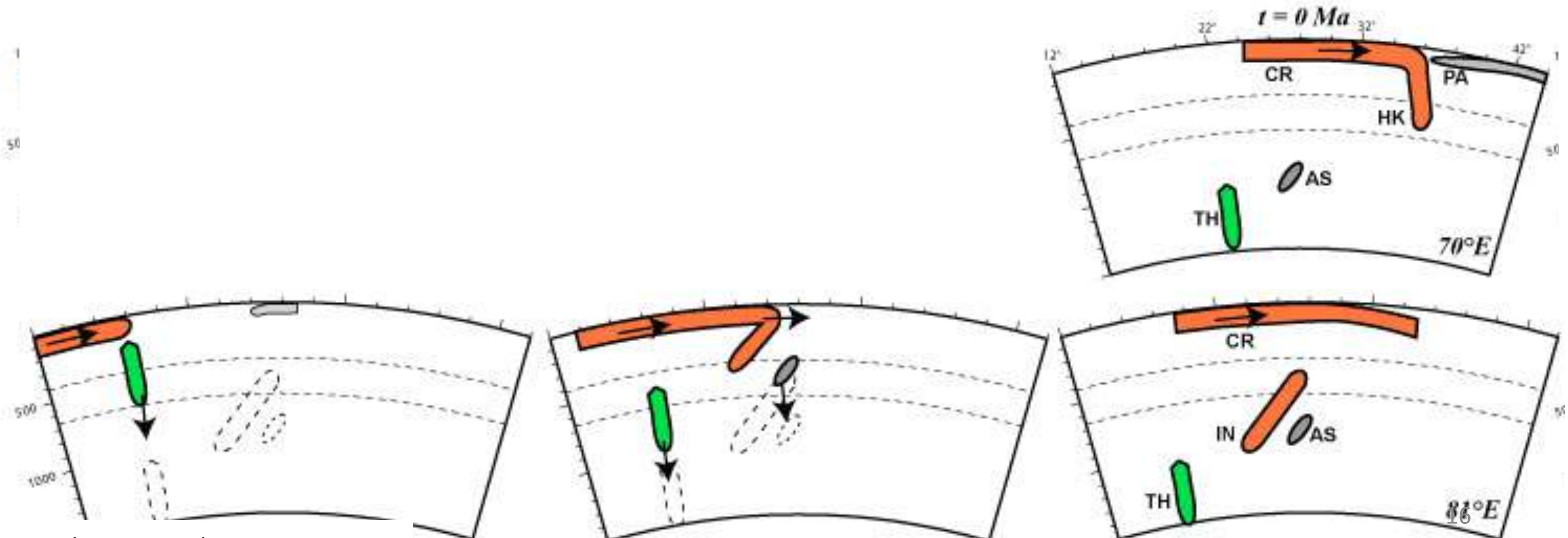
e.g. Chatelain et al. (1980), Sippl et al. (2015)
Kufner et al. (2016)

P wave global tomographic model (Villasenor et al., 2003)
Negredo et al., 2007

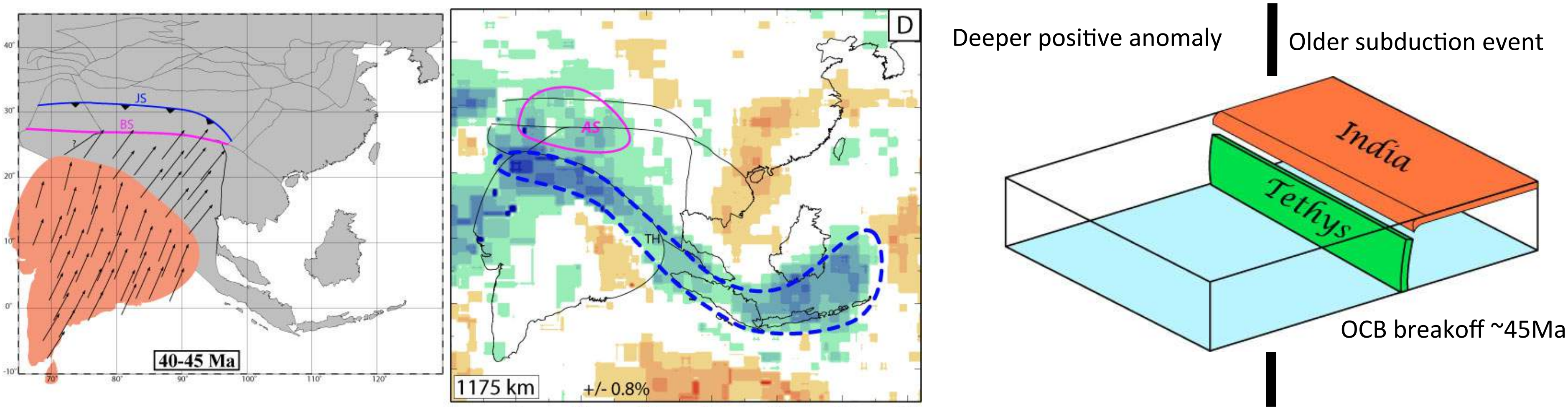
Several slabs
⇒ successive subduction events







Replumaz et al., 2010, 2014

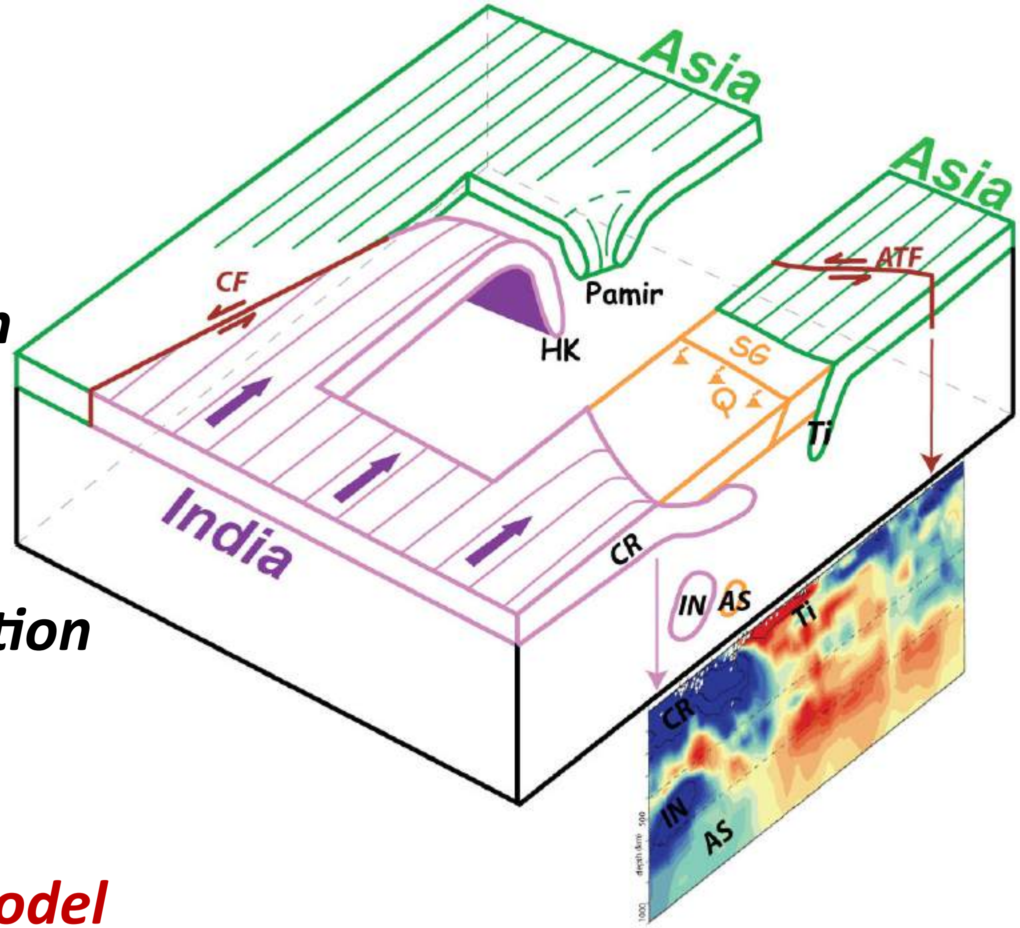

JS
BS
40-45 Ma
D
AS
TH
1175 km
+/- 0.8%
Deeper positive anomaly
Older subduction event
India
Tethys
OCB breakoff ~45Ma

2D tectonics reconstruction

+

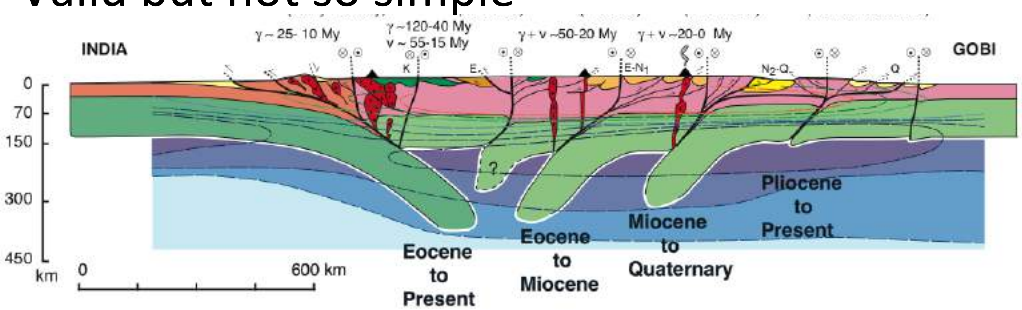
global tomography

⇒ 3D lithospheric reconstruction



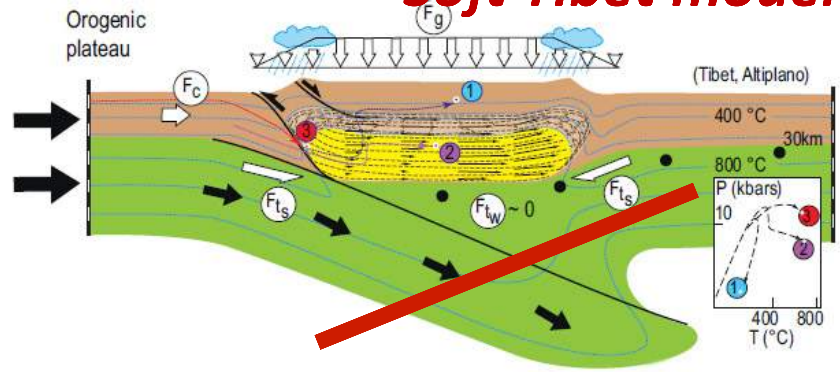
Continental plate-tectonics model

Valid but not so simple



Tapponnier et al., 2001

Soft Tibet model



Vanderhaeghe et al., 2012

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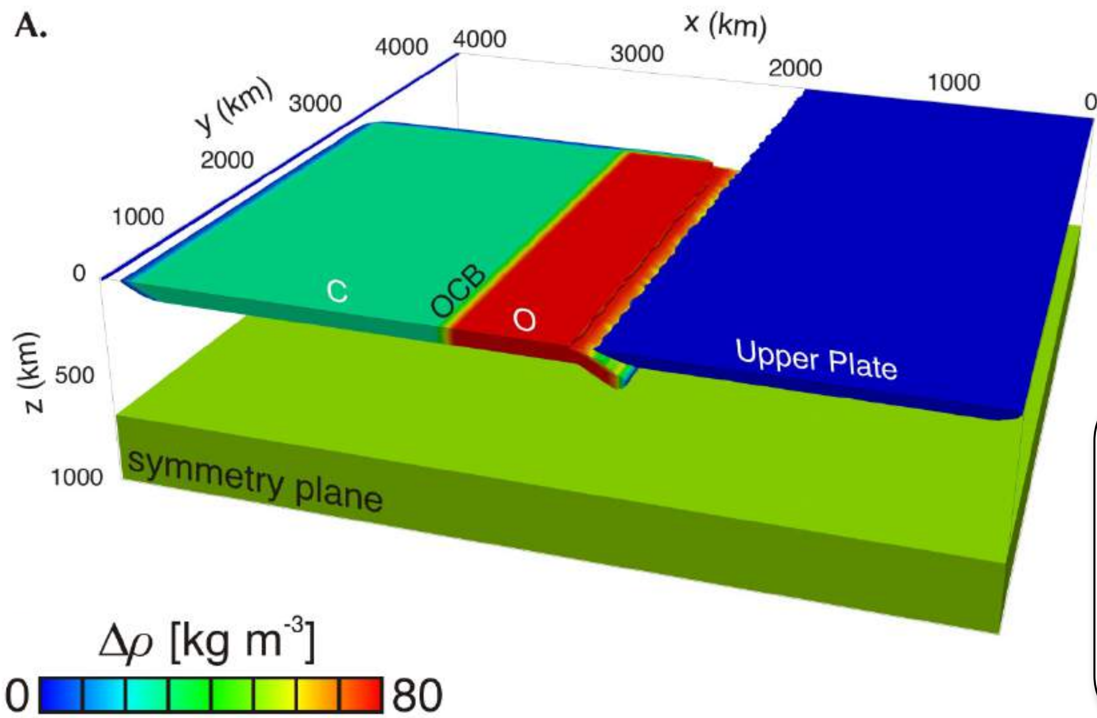
  - ✓ **Analogue models of upper plate collisional subduction**

Numerical models of upper plate deformation due to subduction of continental plate attached to oceanic plate

Particle-in-cell finite element method, Underworld (Moresi et al., 2003; Stegman et al., 2006)



Density contrast

3 plates
viscoplastic rheology

$$\nabla \cdot \mathbf{u} = 0$$
$$\nabla \cdot \tau - \nabla p = \rho \mathbf{g}$$
$$\begin{cases} \tau = 2\eta\dot{\epsilon} & \tau_{II} < \tau_Y \\ \tau = C_0 + \mu p & \tau_{II} \geq \tau_Y \end{cases}$$

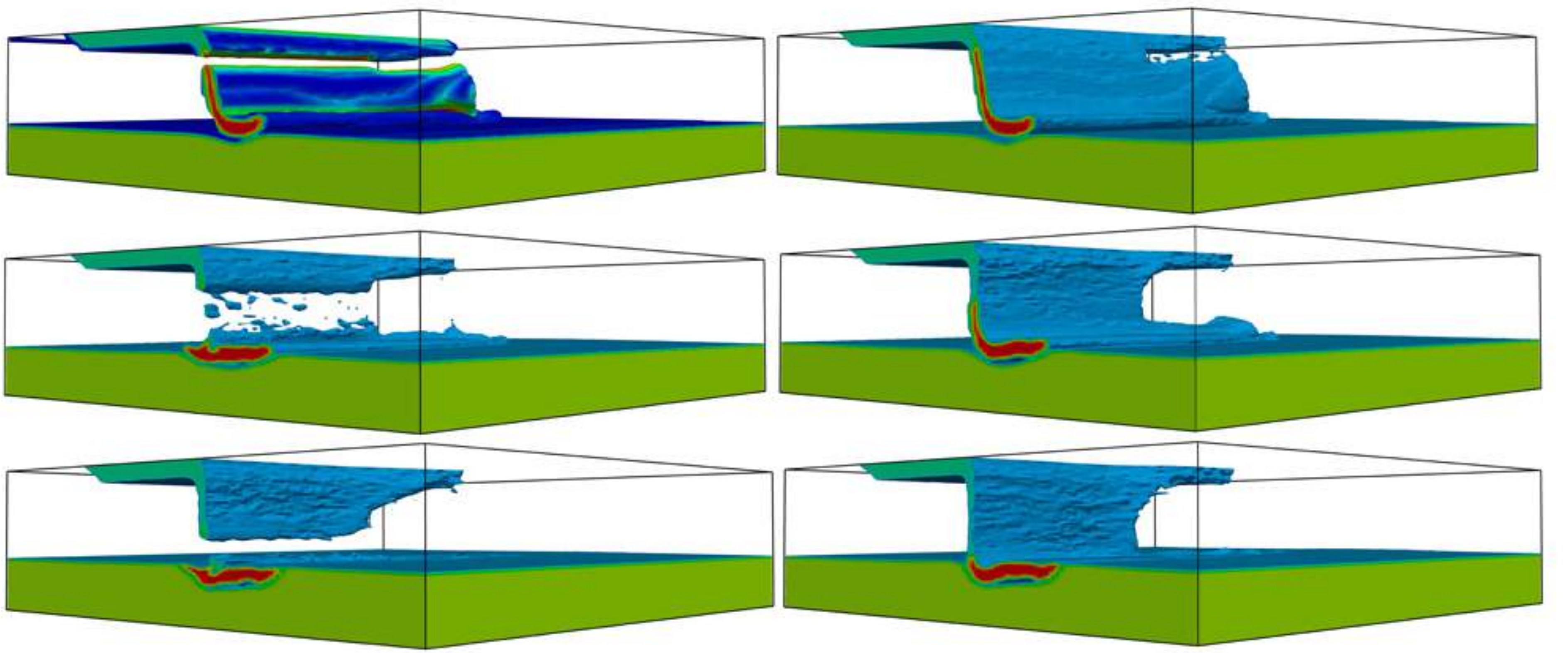
Under incompressibility approximations
force balance governed by :
conservation of mass,
and momentum equations.

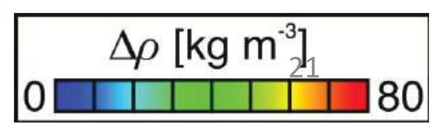
Capitanio and Replumaz, 2013

Subduction of continental lithosphere after OCB breakoff ?

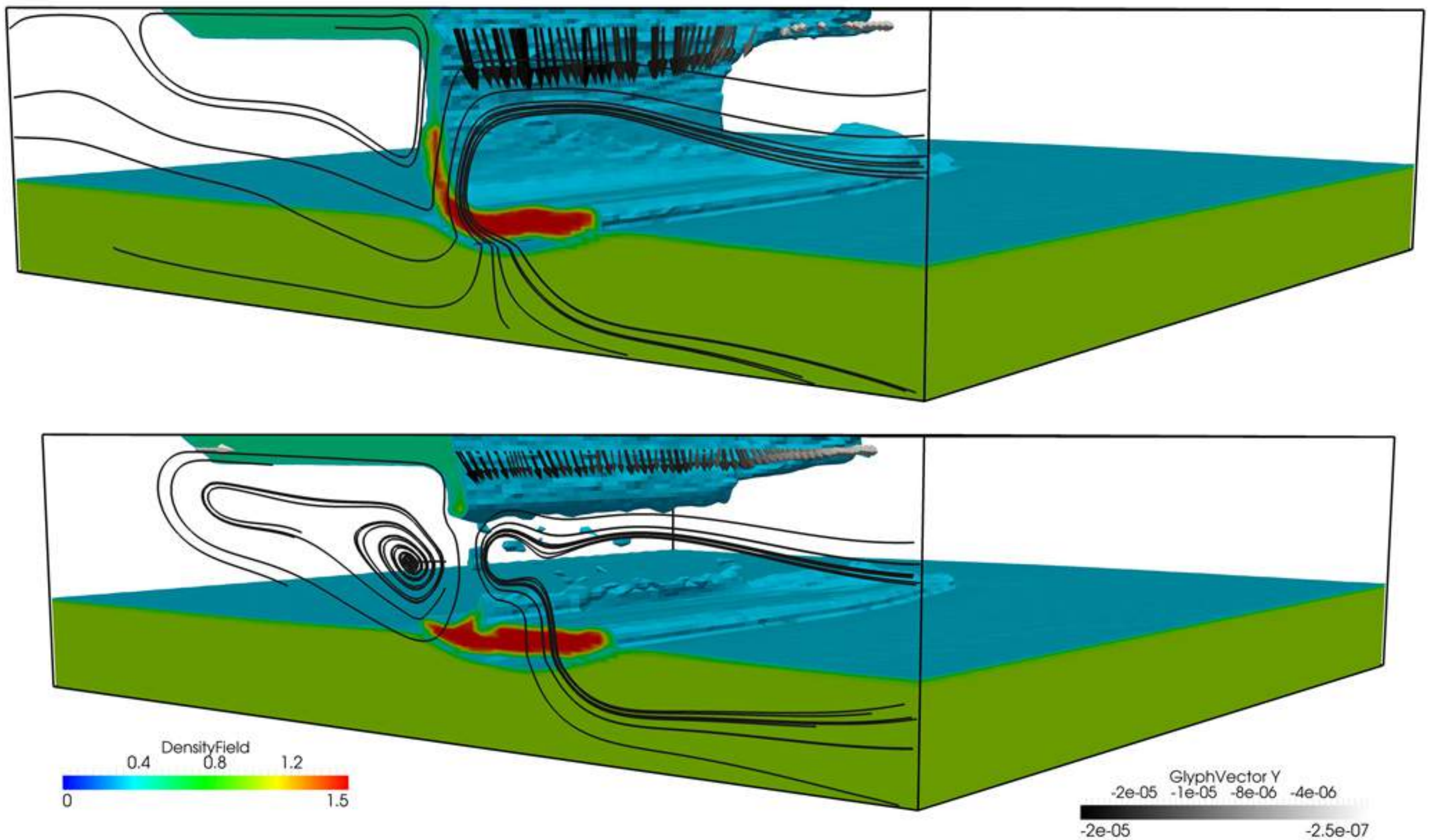
Breakoff imposed at the Ocean-Continent Boundary
by reducing locally the plate's plastic limit

COMPLETE PARTIAL





Capitanio & Replumaz, 2013

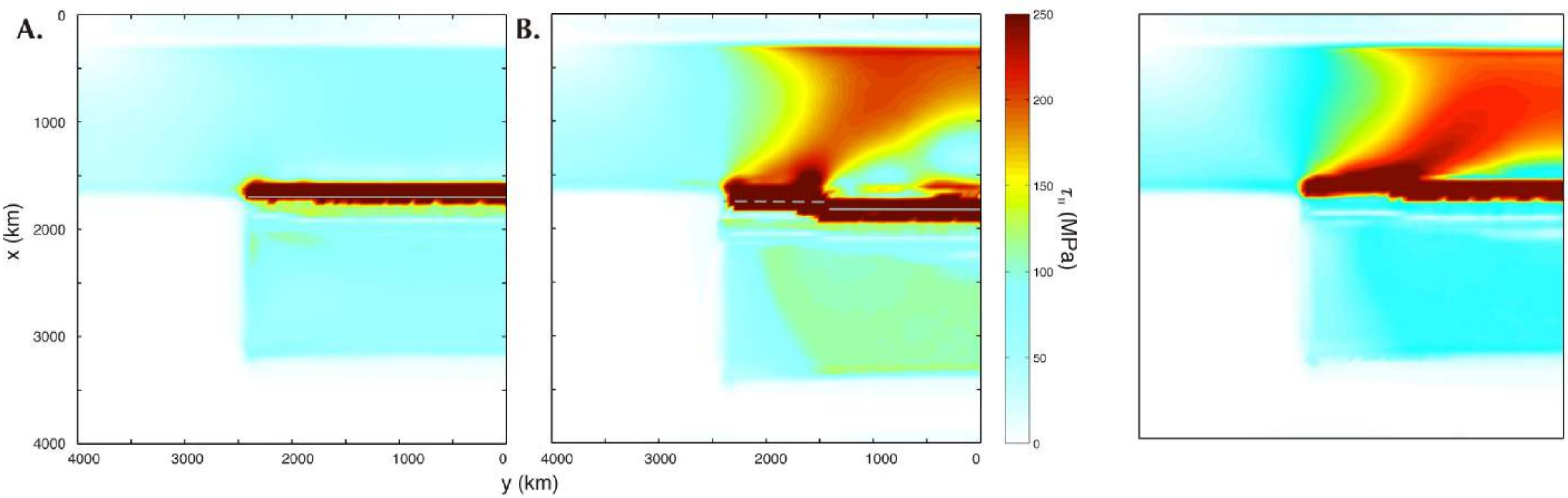


The complete breakoff preserves the poloidal mantle flow in the center of the slab
⇒ dragging the continental plate in the mantle

Except at the slab edge, where indentation of the upper plate occurs

Stress in the upper plate due to slab breakoff
(top view)

No breakoff | partial breakoff | complete breakoff



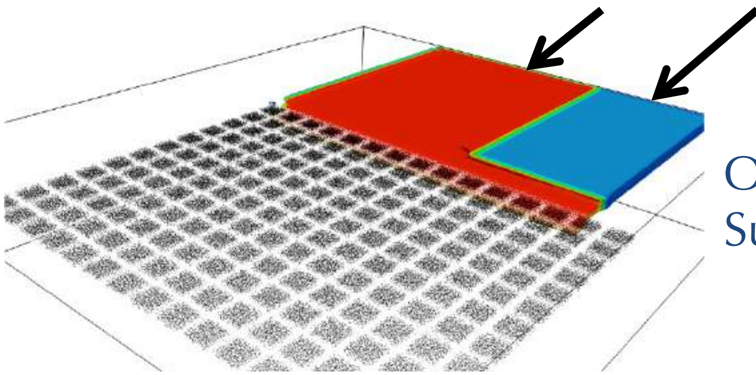
shearing at the margin

stress in the upper plate localised along a stress belt

at an angle with the trench of 45˚±5˚

result of **stress coupling gradients at the trench**

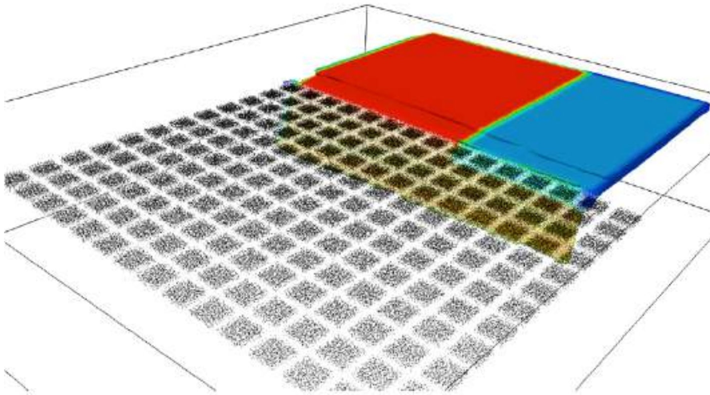
Capitanio & Replumaz, 2013



Far field forces > ridge push

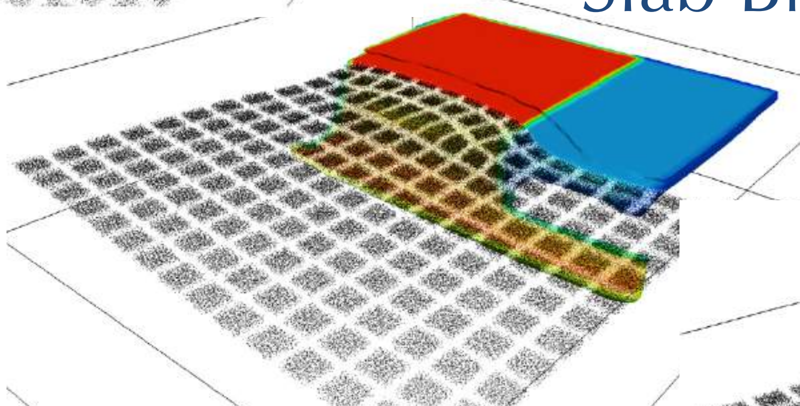
Oceanic Subduction

stress coupling gradient at the trench
⇒ spontaneous slab breakoff ?

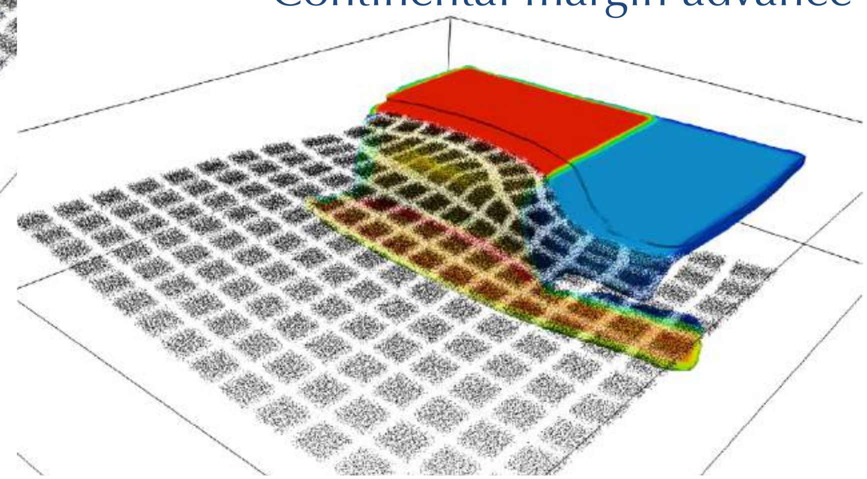


Continent Subduction

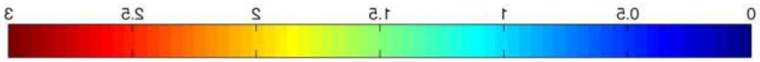
Slab Break-Off at OCB



Oceanic Trench Retreat
Continental margin advance

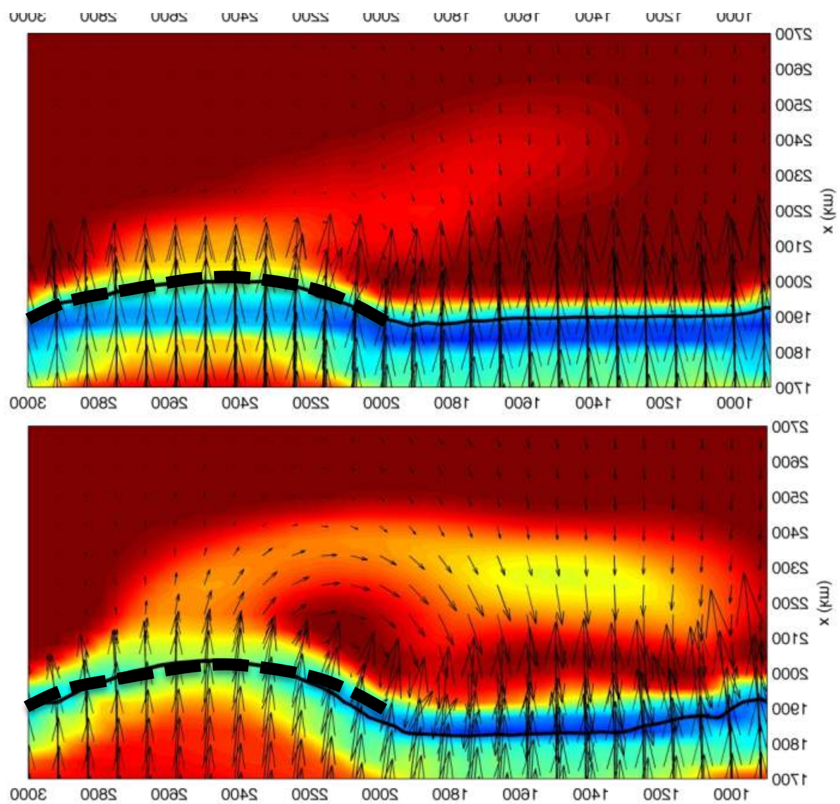


Capitanio, Replumaz and Riel, 2015



Time

But no rupture in the upper plate, and no asian continental subduction



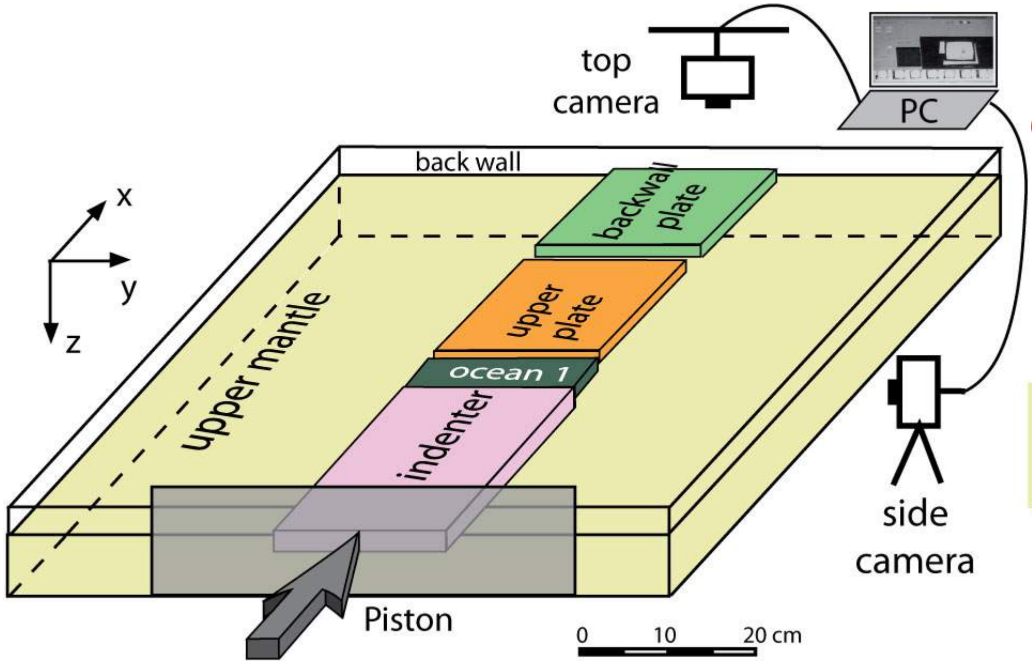
OCB
Slab Breakoff
& Indentation

Indentation
& Extrusion

Far field forces > ridge push

Capitanio, Replumaz and Riel, 2015

subduction of Asian continental lithosphere ?



Far field forces = piston

Lithosphere: silicone putty

visco-elastic materials, quasi-Newtonian at experimental strain rates

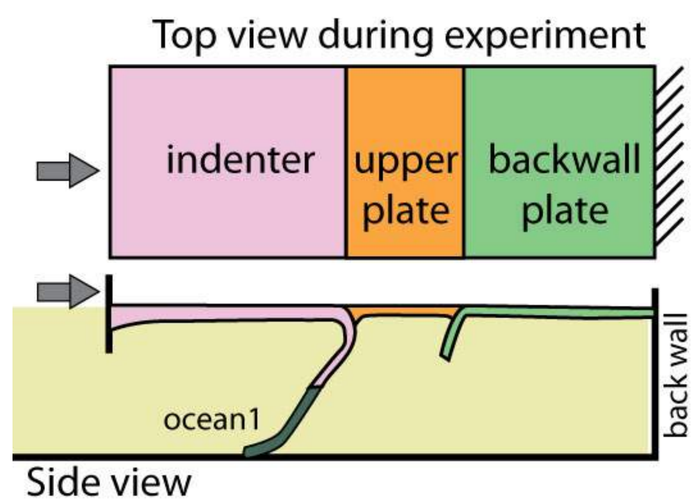
Indenter η= 4.9 x 104 Pa*s D = 1411 kg/m3

mantle: glucose syrup

Newtonian fluid

*Density D = 1428 kg/m3 viscosity η=22 Pa*s*

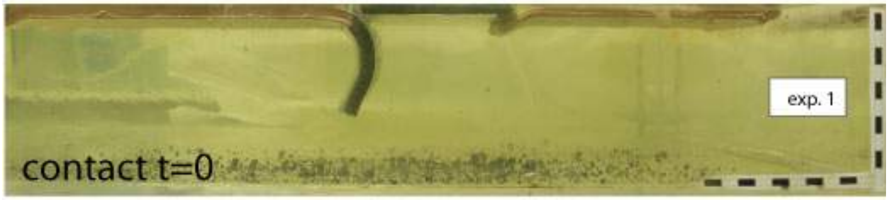
- scale factor for length of about 1.7 10-7 (upper mantle 11cm in model, 660 km in nature)
- scale for time (1 minute = 0.55 Myr)
- Scale for velocity (piston 0.54 cm/min = 5.7 cm/yr)



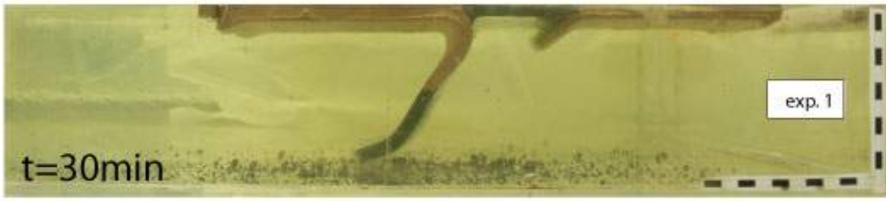
$$t_{model}/t_{nature} = (\Delta\rho\ h\ /\ \eta_l)_{nature}\ /\ (\Delta\rho\ h\ /\eta_l)_{model}$$

$$U_{model}/U_{nature} = t_{nature}\ /\ t_{model} \times L_{model}\ /L_{nature}$$

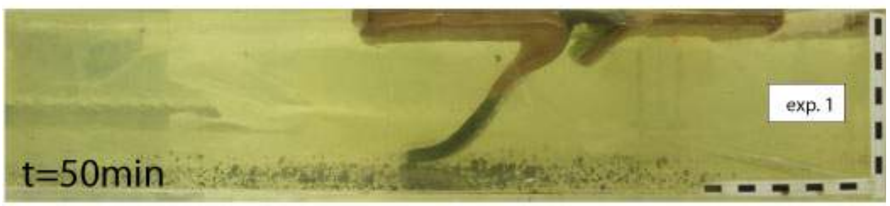
Replumaz, Funiciello,
Reitano, Faccenna, Balon
Geology, 2016



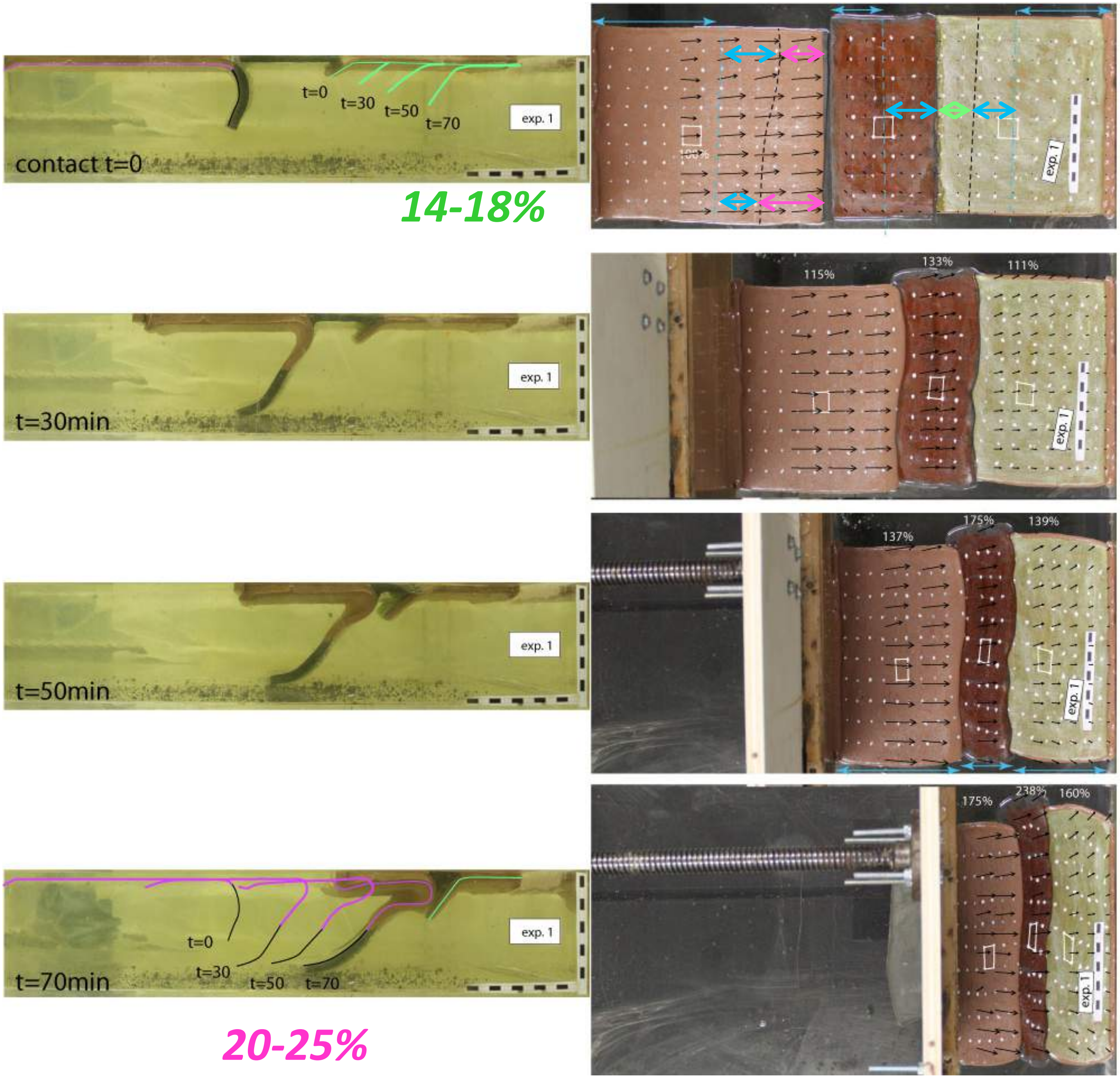
indenter subducts
pushed by the piston
and pulled by the dense oceanic slab



Indenter continental slab
reaches 2/3 of the box
overturns



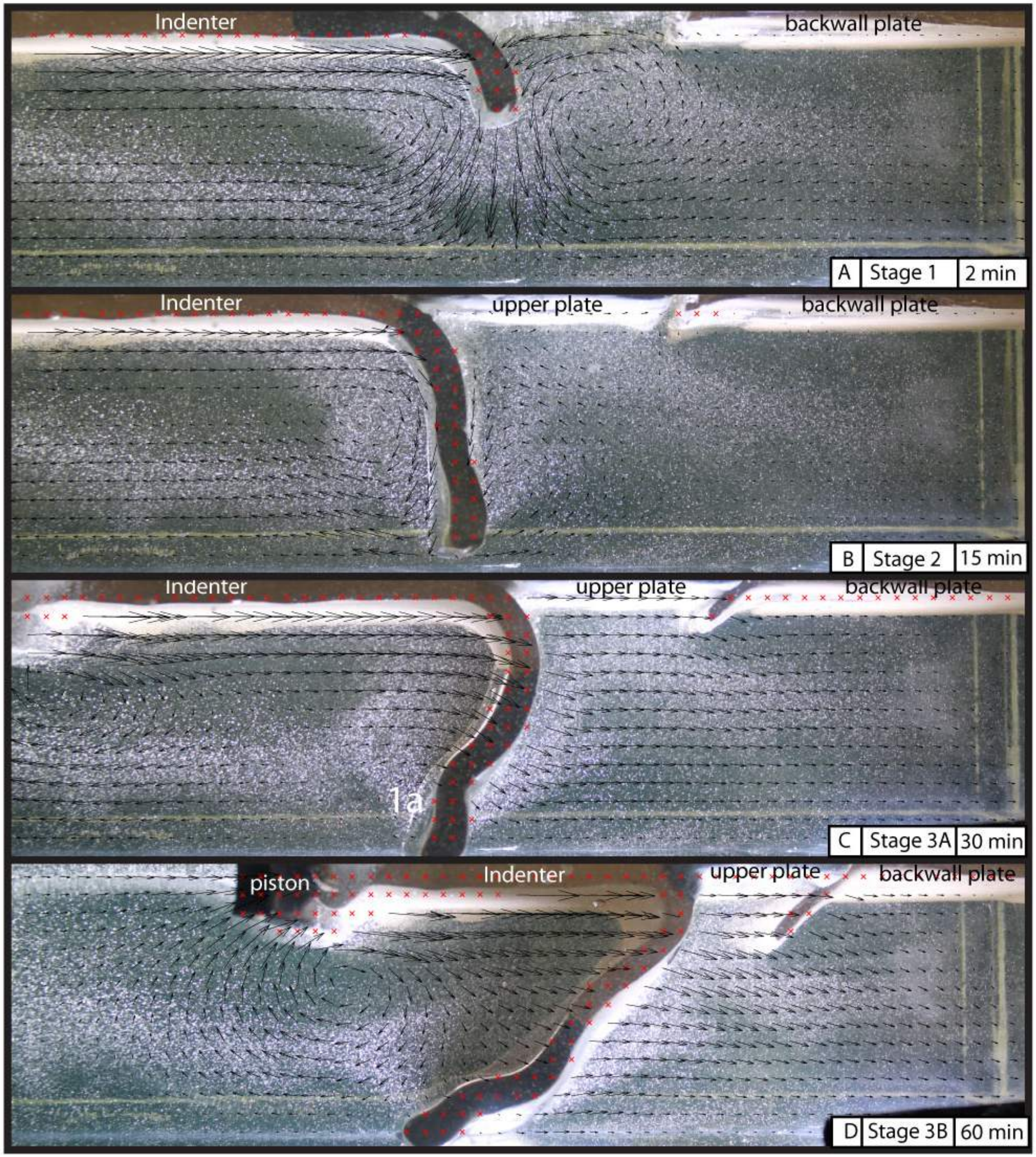
backwall continental slab
Not attached to any dense slab
steep but not vertical
reaches 1/3 of the box



Convergence (100%)

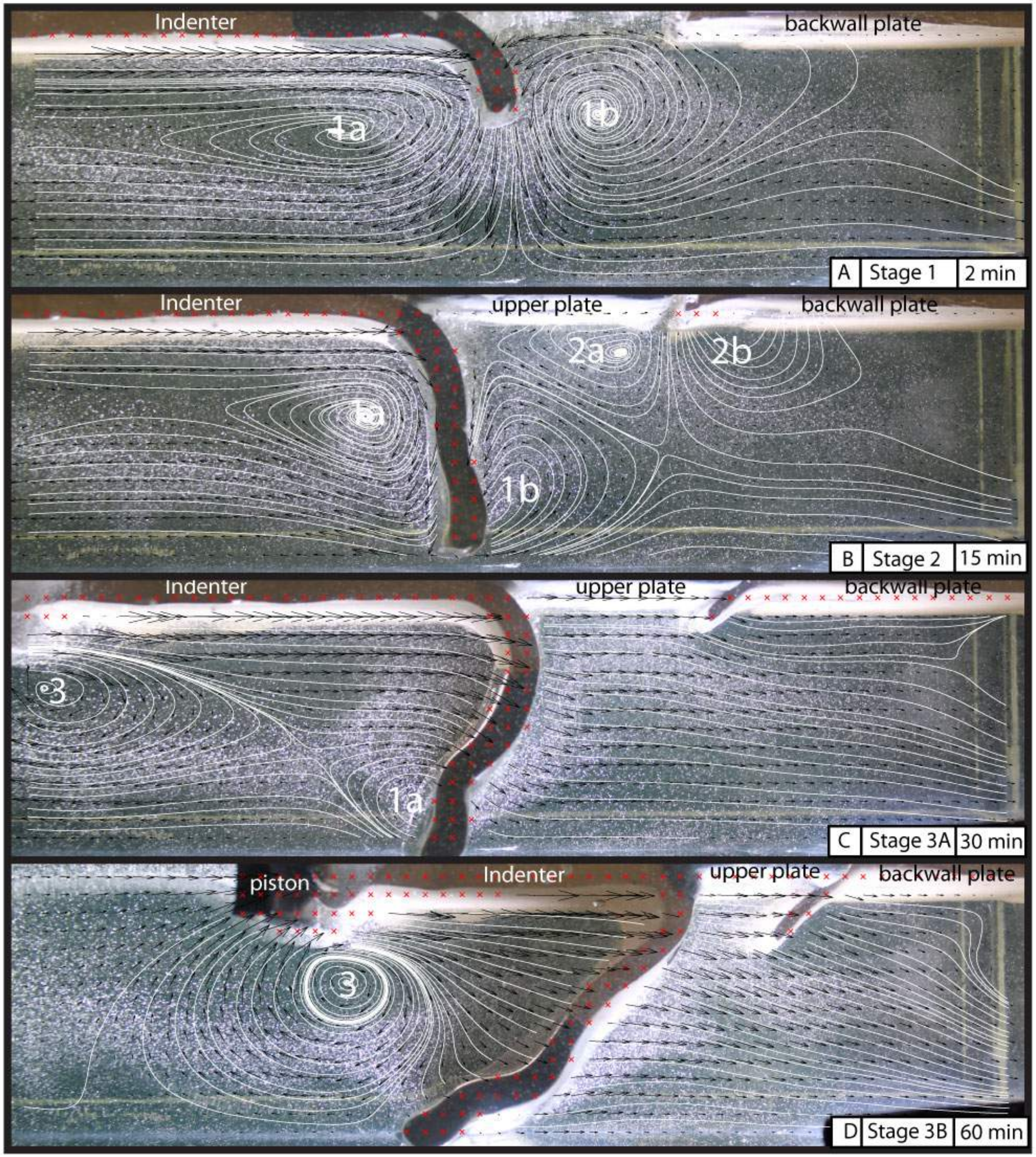
absorbed by:

- **Subduction ~ 40%**
  - Indenter (20-25%)
  - **backwall plate (14-18%)**
- **Thickening** ~ 60%
  - Indenter (17-24%)
  - Backwall plate (16-18%)
  - Upper plate (23%)



counter-intuitive subduction not driven by positive slab pull

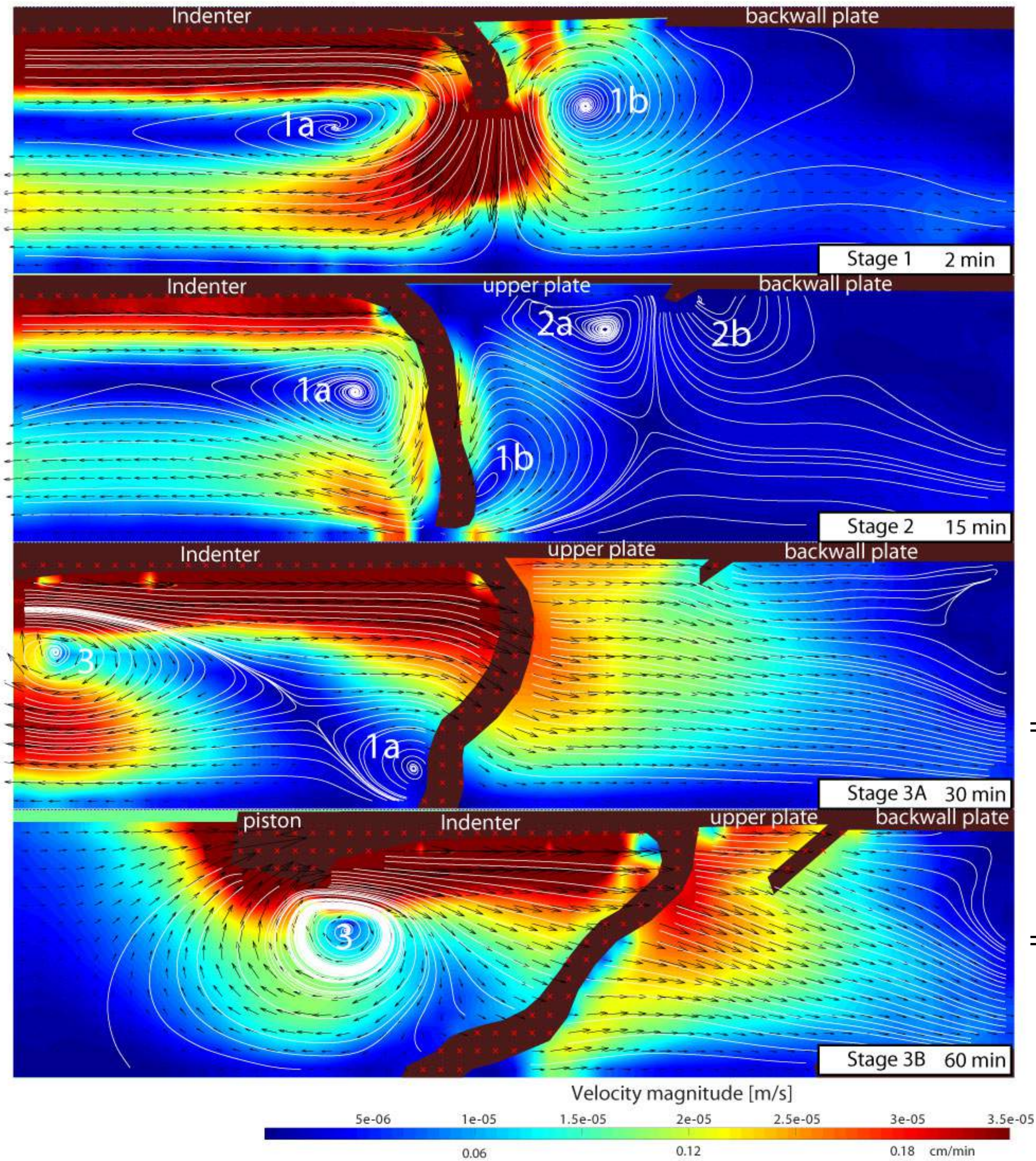
mantle kinematics and dynamics ?



Tectonics horizontal forces

⇒ wide cell with mostly horizontal component of motion

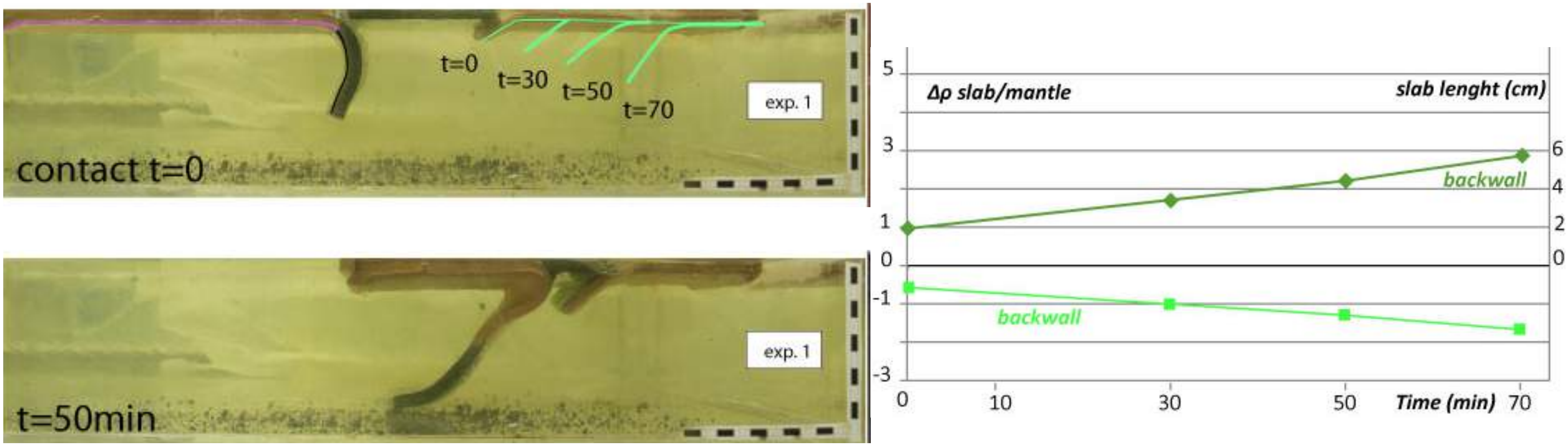
⇒ Advecting passively the back wall slab



Tectonics horizontal forces

⇒ Strong horizontal component of motion

⇒ Mantle push



- rigid continental lithosphere subducts in a collision context
- the slab pull is not the driving force
- **tectonic forces, mostly horizontal, generated by the motion of the piston are the driving forces**
- The term “subduction” is not describing adequately this process

⇒ ***collisional subduction***

Replumaz, et al., Geology, 2016

Link between the Great Faults of Asia, continental plate tectonics and continental subduction

Coupling 2D tectonics reconstruction, using fault rate and offset, and position of slabs in global tomography

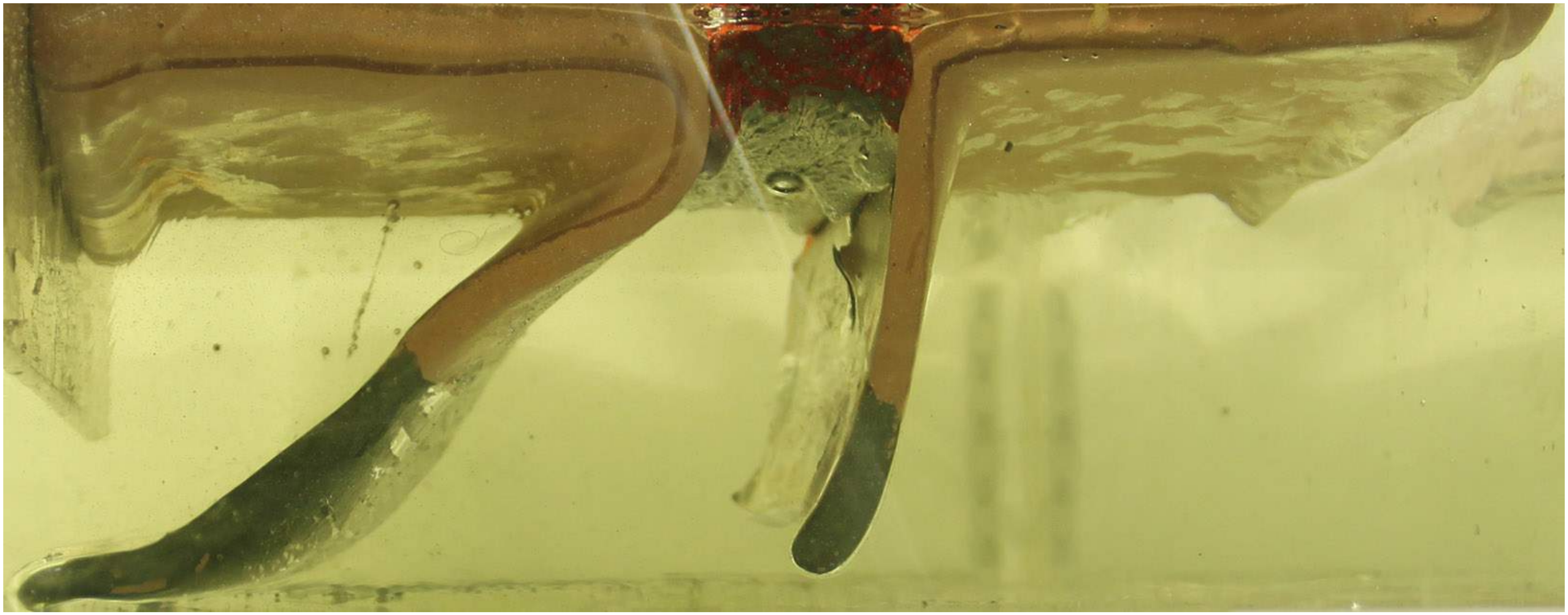
⇒ 3D tectonics reconstruction, showing importance of continental subduction of both Indian and Asian lithospheres during the collision

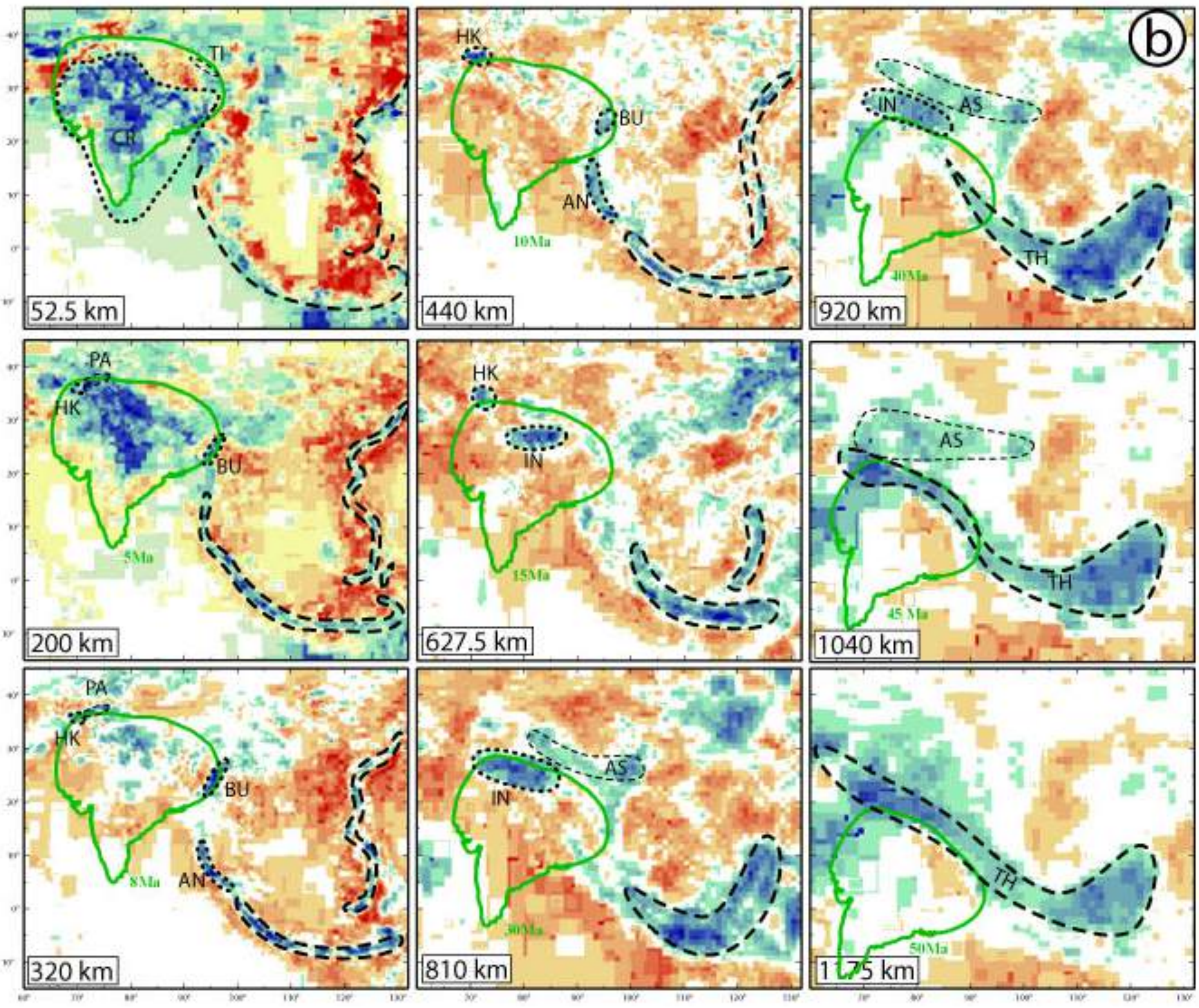
mantle kinematics and dynamics associated with such counter-intuitive subduction not driven by positive slab pull ?

⇒ Tectonics horizontal forces

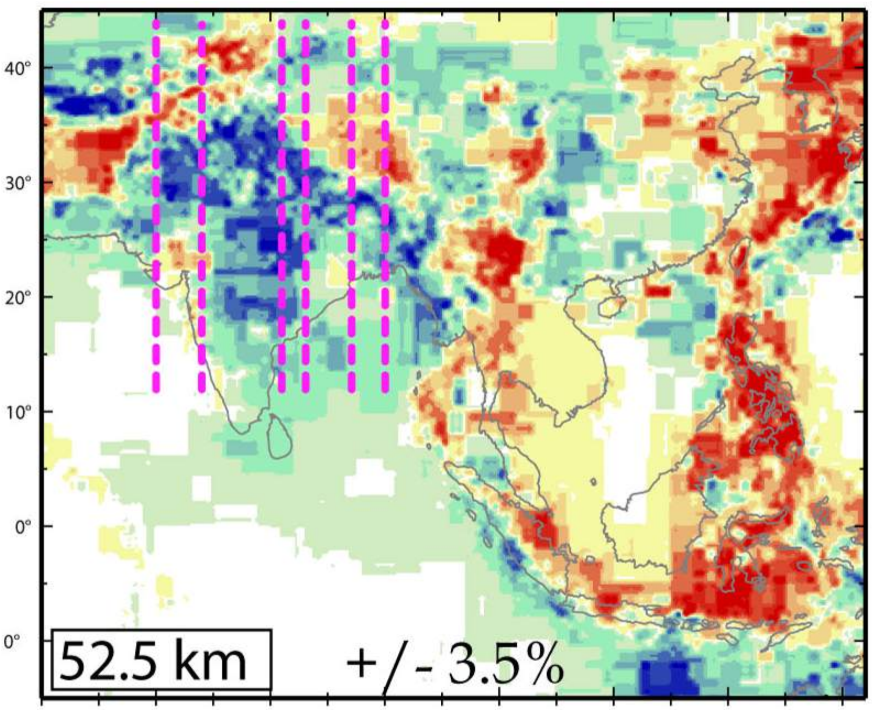
⇒ continental plate tectonics dynamically sustainable

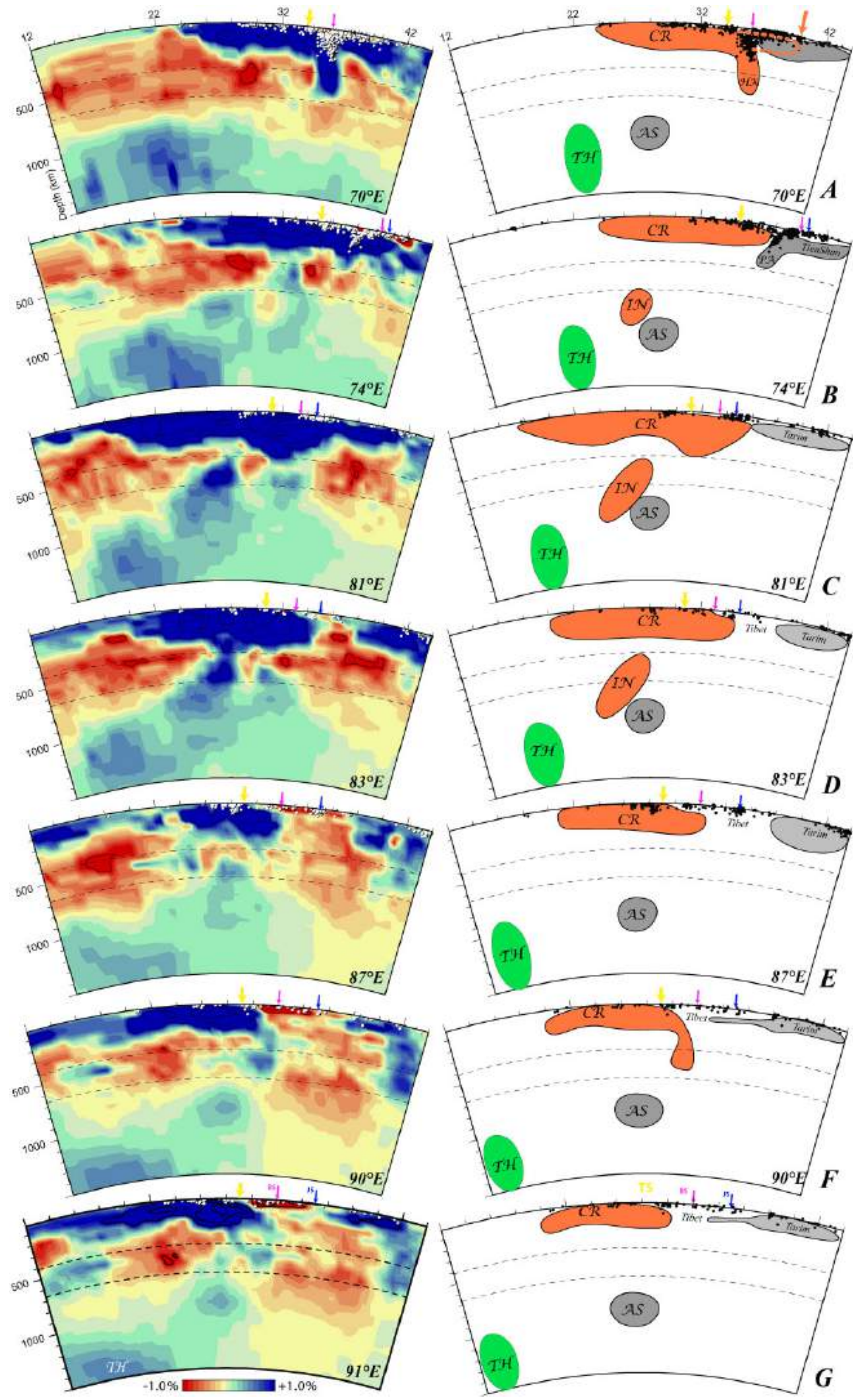
Questions ?



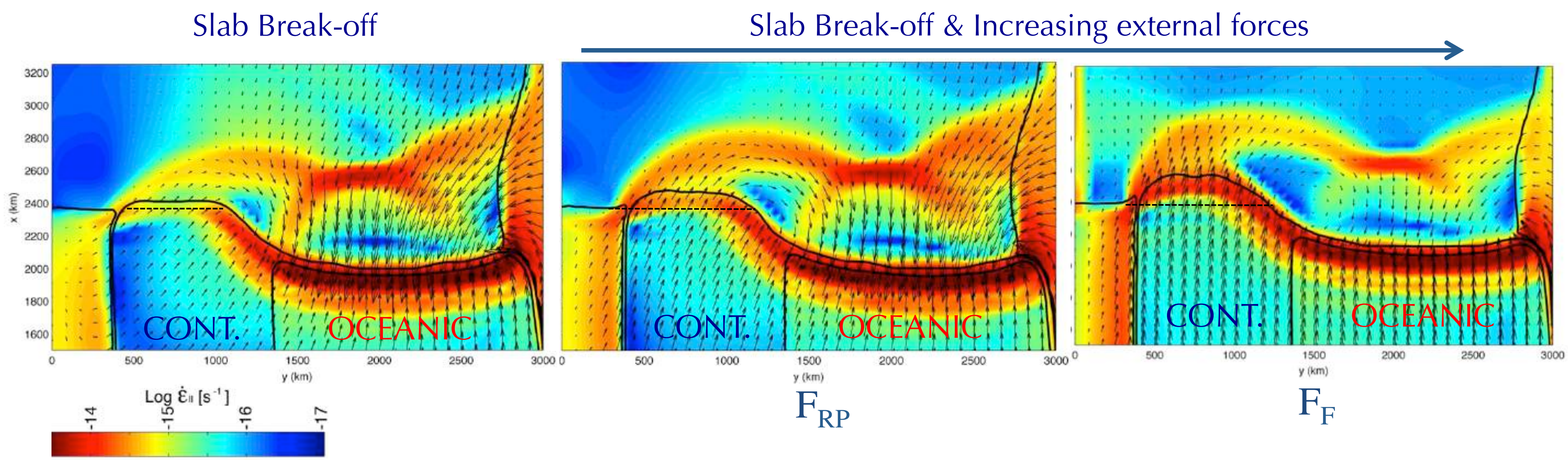


b
52.5 km
TI
CR
440 km
HK
BU
AN
10Ma
920 km
IN
AS
TH
40Ma
200 km
PA
HK
BU
5Ma
627.5 km
HK
IN
15Ma
1040 km
AS
TH
45 Ma
320 km
PA
HK
BU
AN
8Ma
810 km
IN
AS
30Ma
1175 km
TH
50Ma


52.5 km
+/- 3.5%


70°E
A
74°E
B
81°E
C
83°E
D
87°E
E
90°E
F
91°E
G
CR
AS
TH
IN
Tibet
Tarim
-1.0%
+1.0%

Upper Plate Extrusion & Indentation Tectonics



2) Far-field Forces → Trench Advance

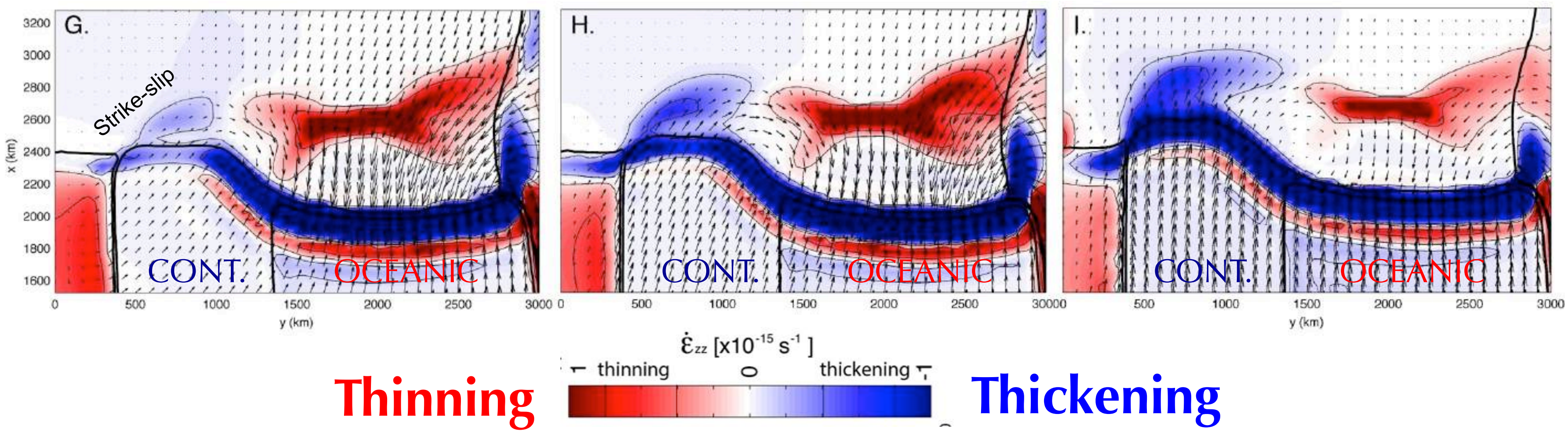
Continental Subduction Margin advance a.k.a. **Indentation**

and

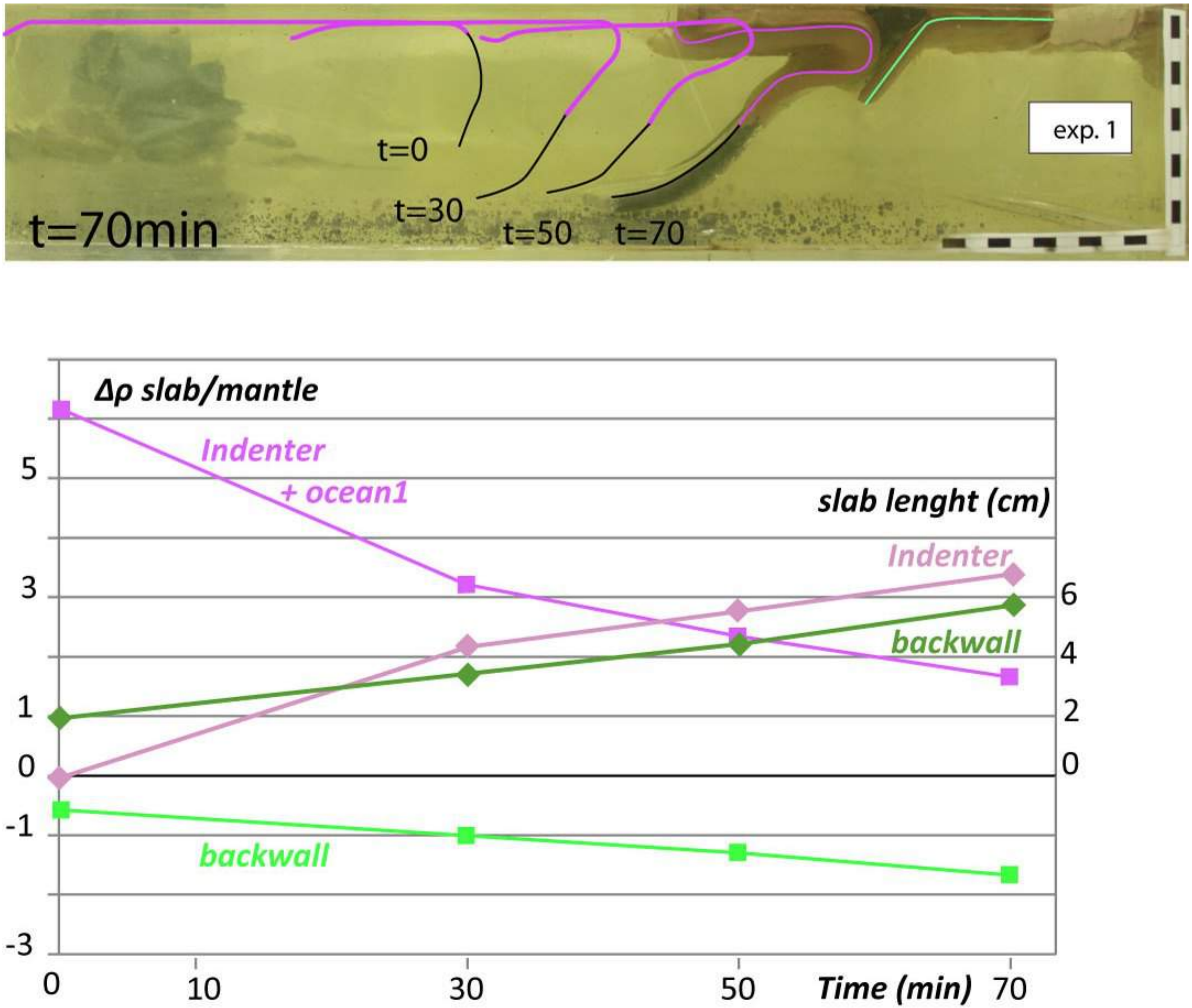
Hampered Oceanic Trench Retreat (when large F_F)

Slab Break-off

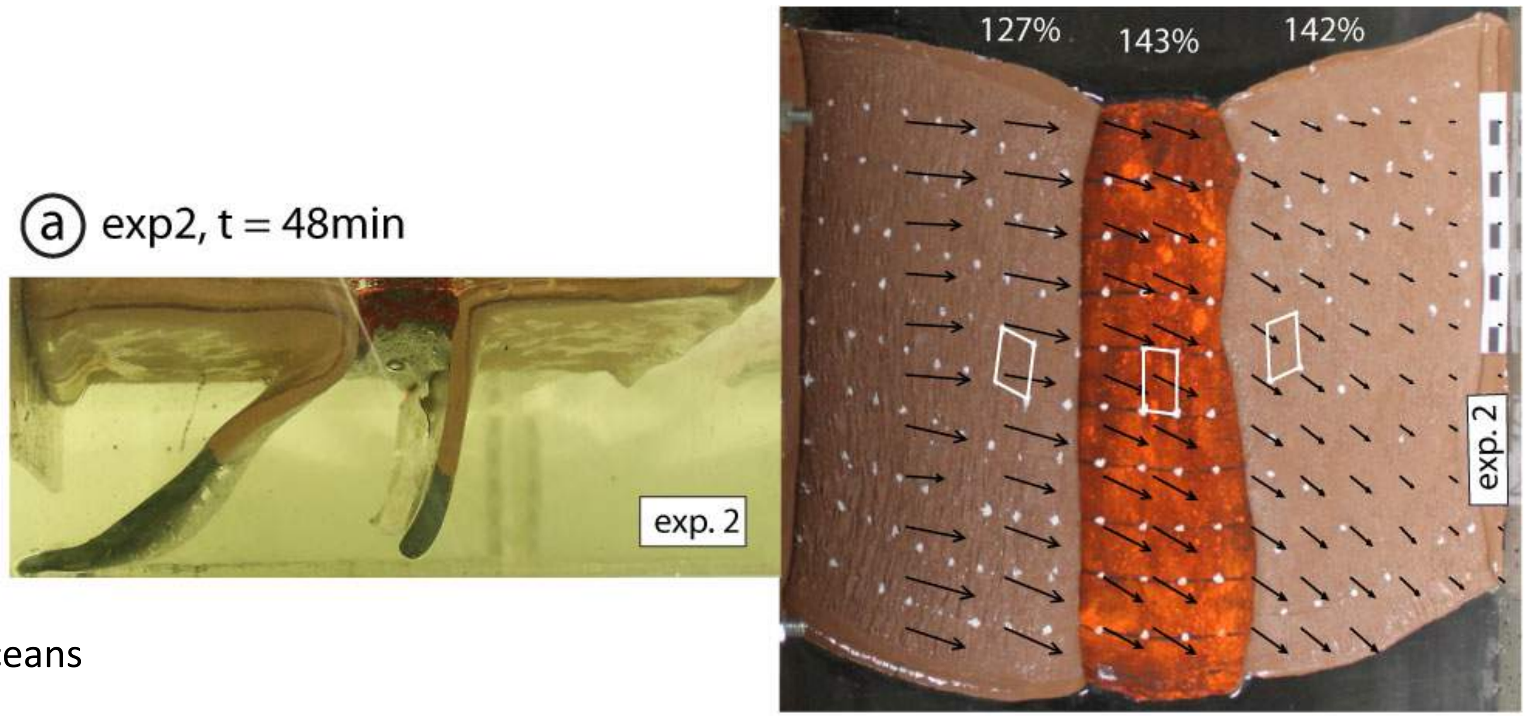
Slab Break-off & Increasing external forces



Far-field Forces necessary for sufficient Trench Advance
Generating Indentation and **thickening**
Of the upper plate similar to Tibet

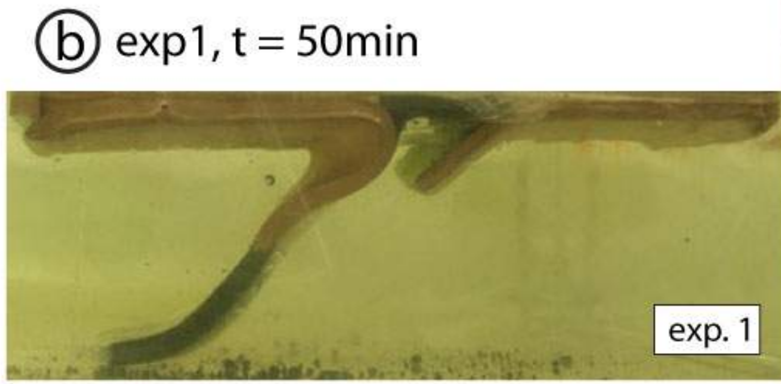


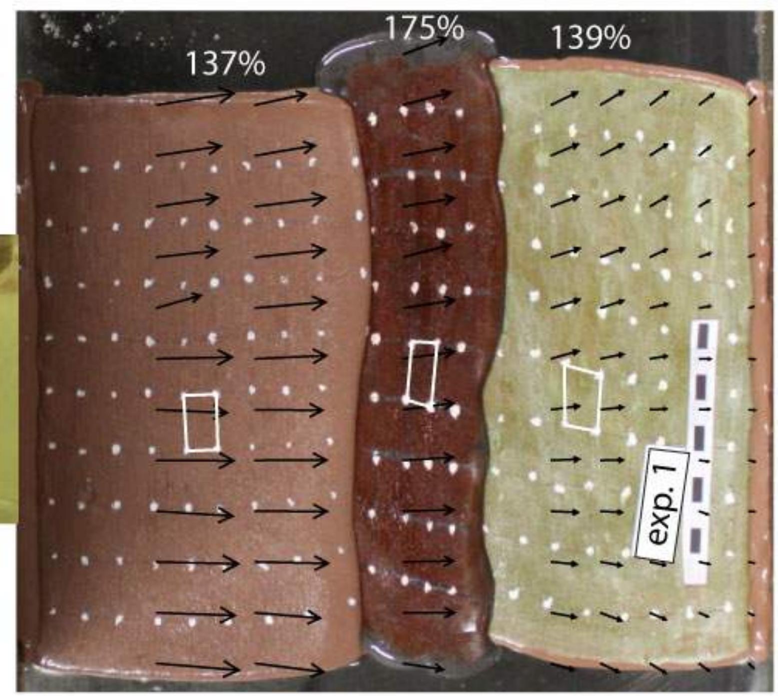
t=70min
t=0
t=30
t=50
t=70
exp. 1
Δρ slab/mantle
Indenter
+ ocean1
slab lenght (cm)
Indenter
backwall
backwall
5
3
1
0
-1
-3
6
4
2
0
0
10
30
50
Time (min)
70



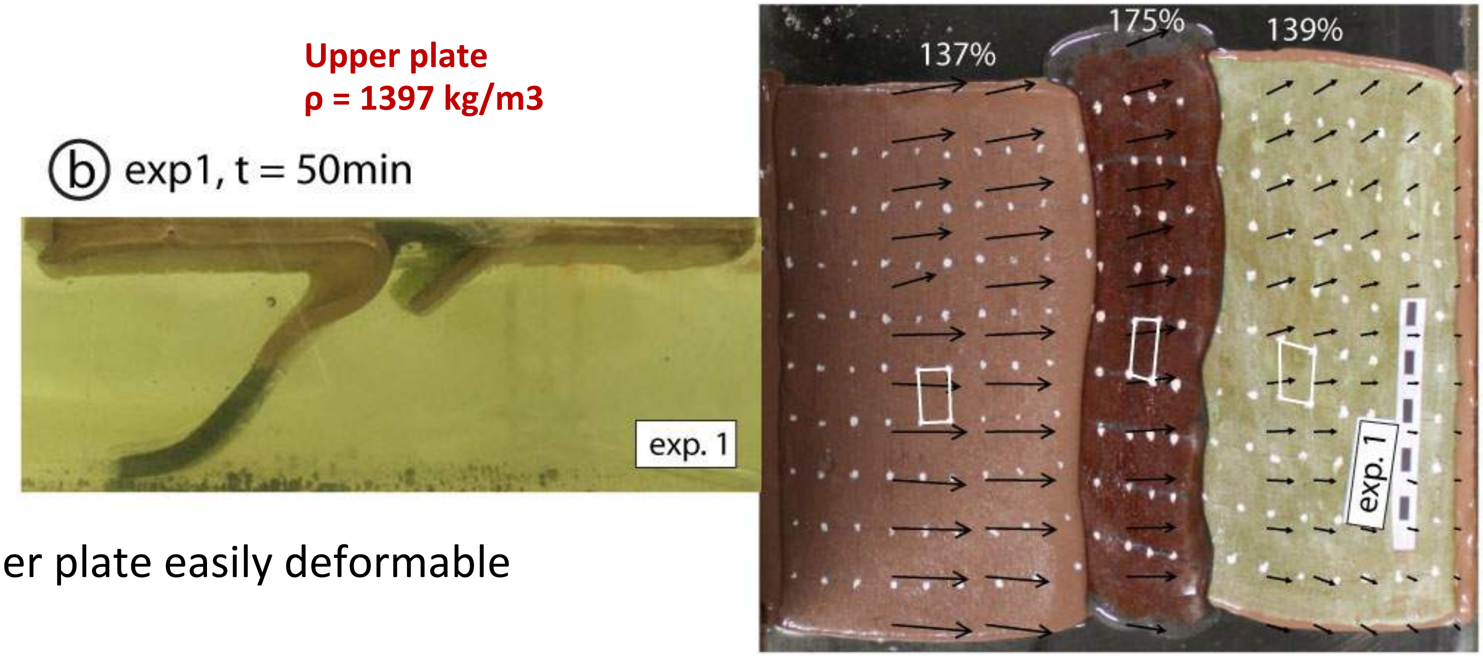
Experiment 2: 2 oceans

backwall slab :
twice the length observed in the experiment 1.



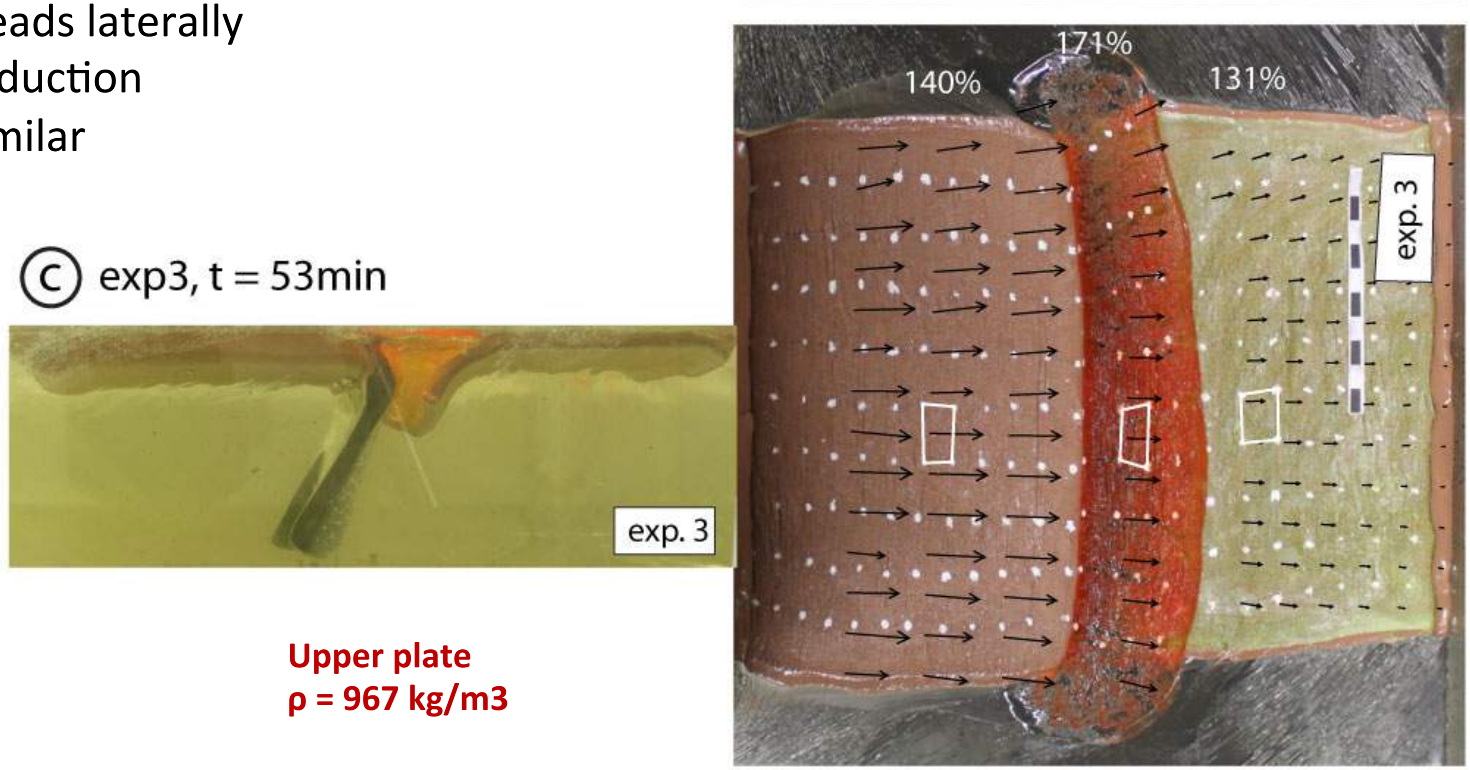


Upper plate
ρ = 1397 kg/m3



Experiment 3: upper plate easily deformable

⇒ upper plate spreads laterally
⇒ no indenter subduction
⇒ backwall slab similar



Upper plate
ρ = 967 kg/m3