IMPACT OF SURFACE PROCESSES ON THE DYNAMICS OF OROGENIC WEDGES

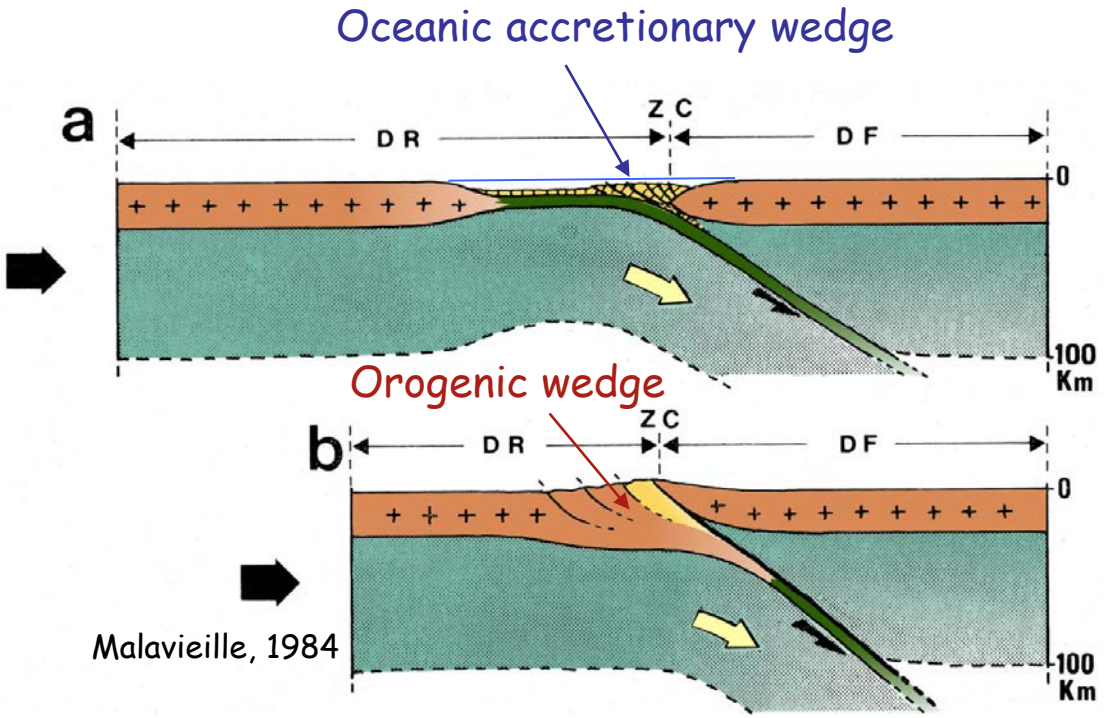
Jacques Malavieille

Géosciences Montpellier

Zhongli 2019

OROGENESIS

Mountain building => Long term process involving large convergence and important crustal deformation

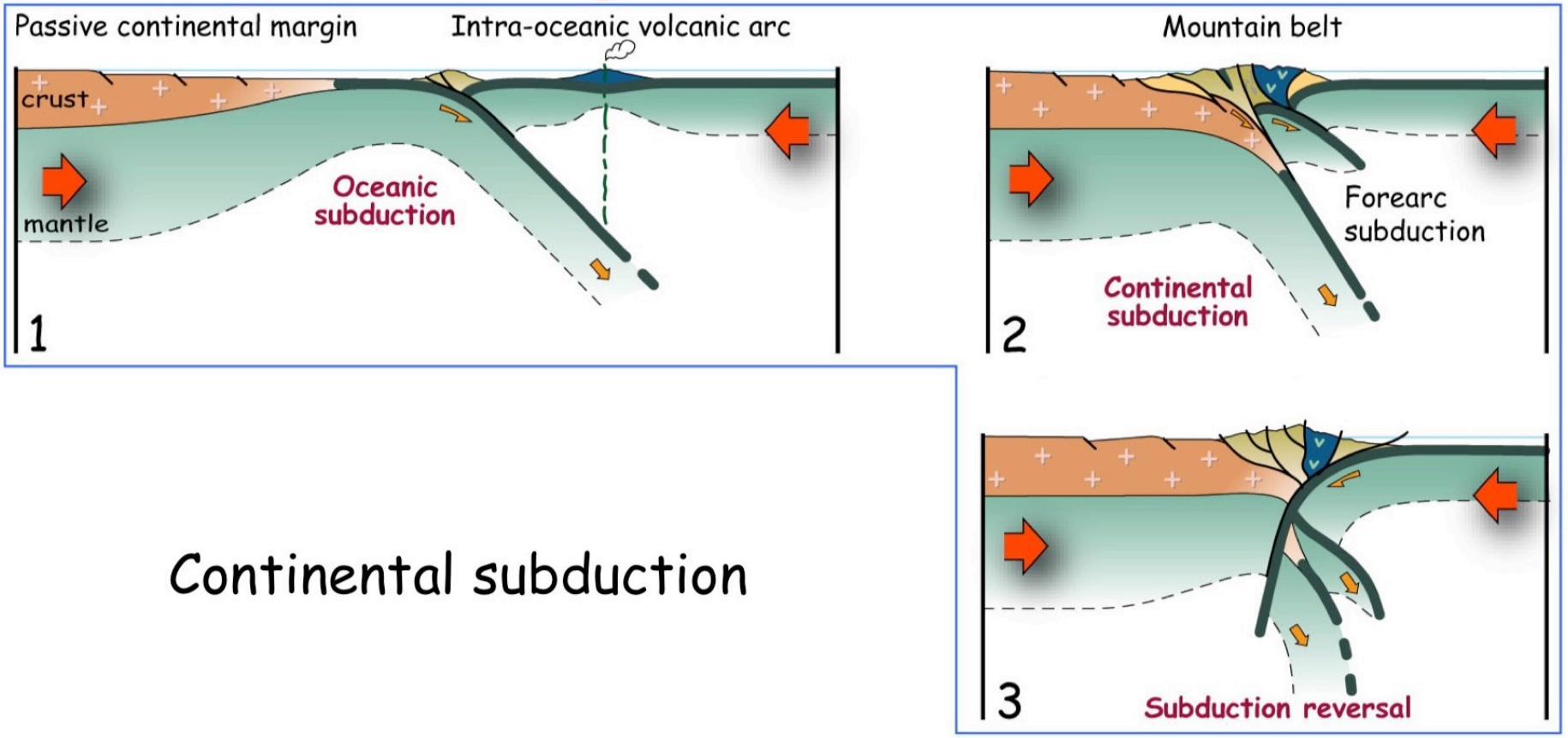


Oceanic subduction
submarine relief

Continental subduction
aerial relief

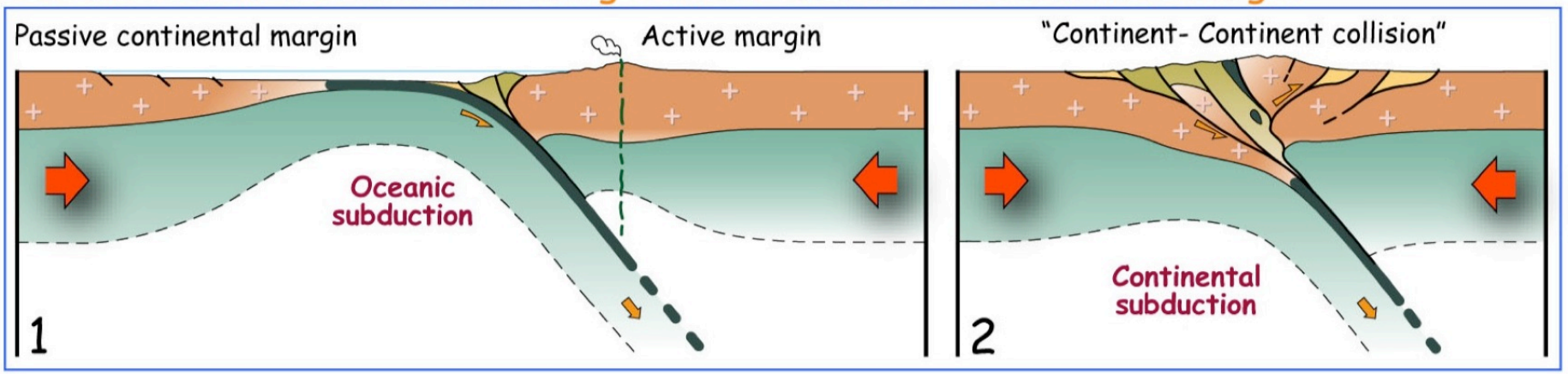
- Subduction of the lithospheric mantle induces thickening of the crust and controls the structural asymmetry of the mountain belt

Subduction of a continental margin under an intra-oceanic volcanic arc



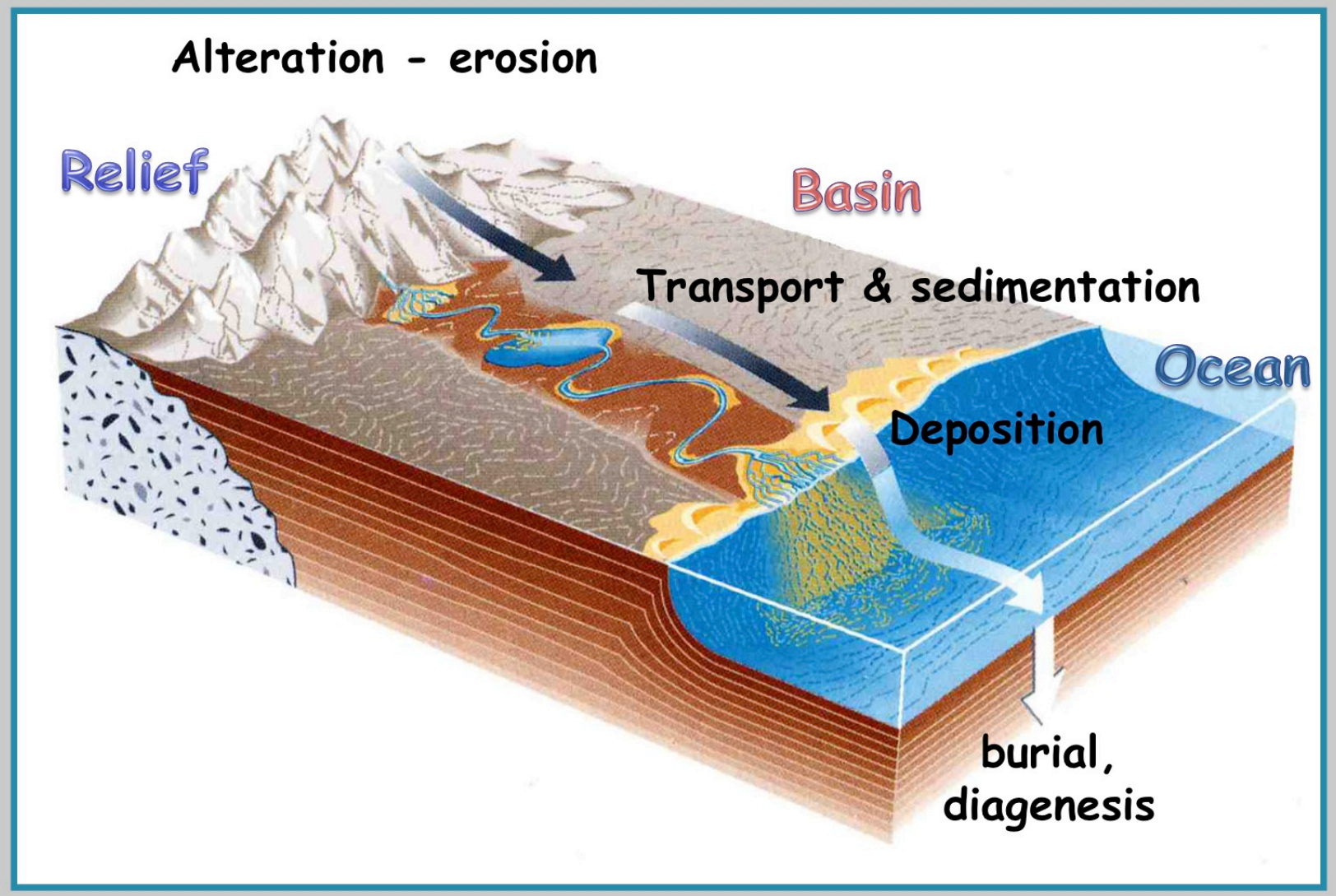
Continental subduction

Subduction of a continental margin under an active continental margin



Malavieille 2006

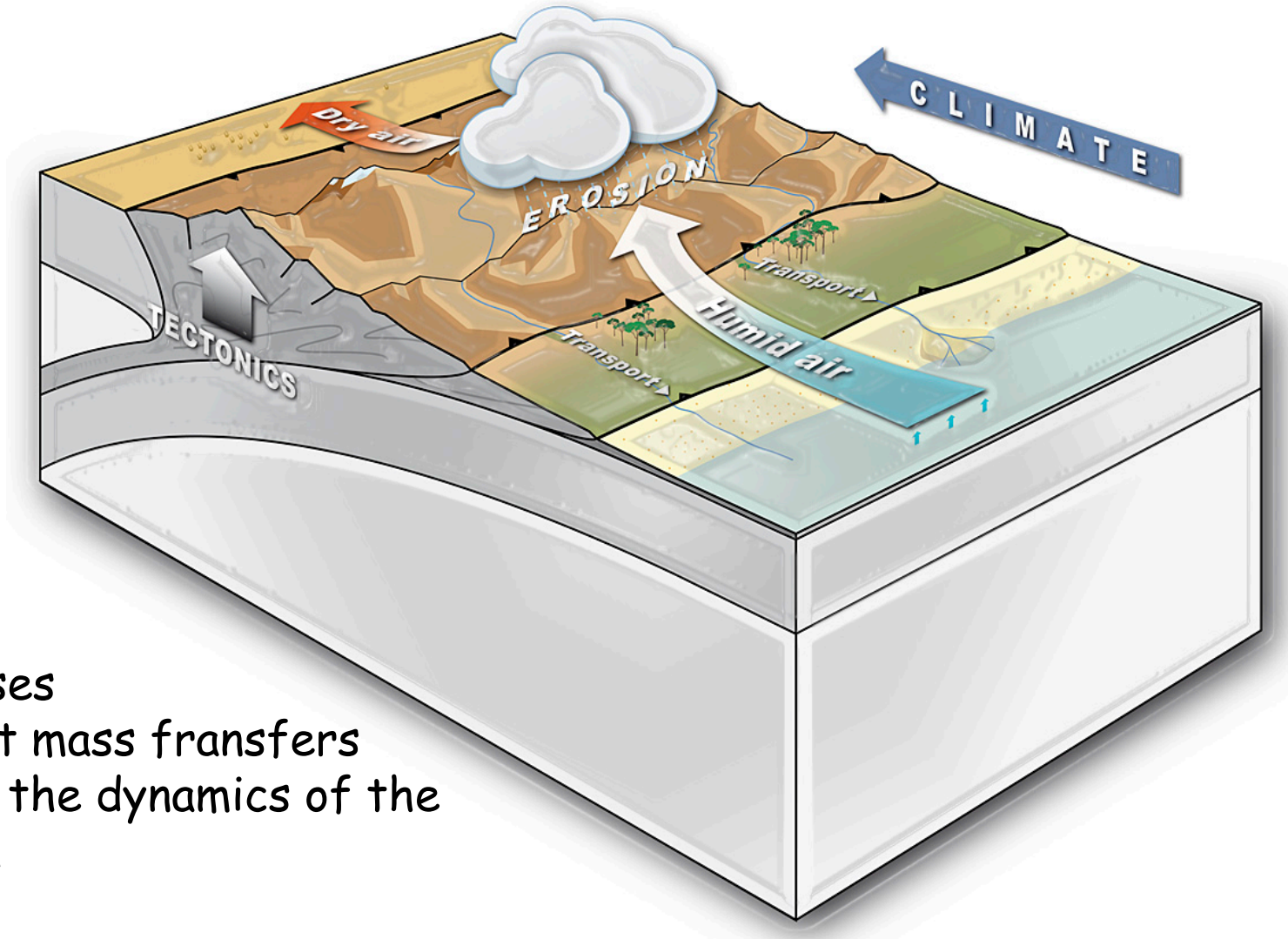
Surface processes



A view from geomorphology...

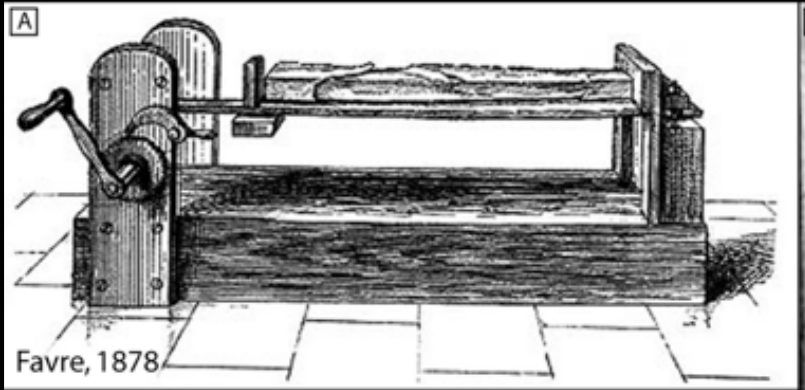
In Understanding Earth, Frank Press & Raymond Siever, W.H. Freeman and Company, ed, New York, 1993

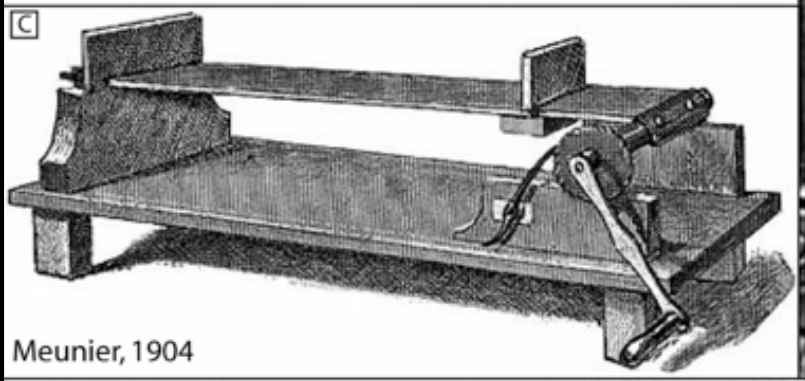
The view of a structural geologist...

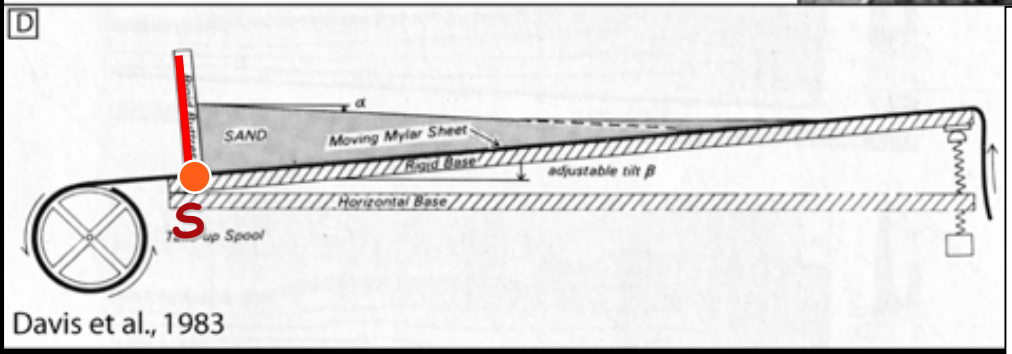


Surface Processes
induce important mass fransfers
that will change the dynamics of the
orogenic system

How to relate surface processes and deep tectonic processes at the scale of a Mountain belt ?







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Experimental modelling of orogenic wedges: A review

Fabien Graveleau [a,c,*], Jacques Malavieille [b,c], Stéphane Dominguez [b,c]

[a] Université Lille 1, CNRS UMR 8217 Géosystèmes F-59655 Villeneuve d'Ascq, France
[b] Université Montpellier II, CNRS UMR 5243 Géosciences Montpellier, F-34095 Montpellier, France
[c] LIA-ADEPT 536 CNRS-NSC, France–Taiwan

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ABSTRACT

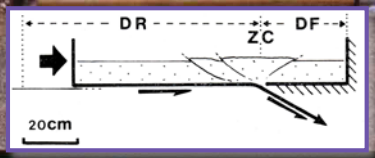
Experimental modelling applied to the study of orogenic wedge dynamics has been a subject of fruitful research for more than 30 years, although the technique dates back as far as the early XIX[th] century. On one hand, several first order parameters controlling the structural evolution of mountain belts have been intensively investigated using the classic tectonic "sandbox" models. The main parameters are the properties of the basal *décollement*, the deforming material, the backstop, and fluxes, kinematics and surface processes. On the other hand, the morphological evolution of a mountain relief subjected to changing tectonic or climatic forcing has been addressed using another kind of approach called "geomorphic" models. Nowadays, the literature is extremely rich, particularly for the sandbox technique, so that it becomes difficult to have an exhaustive view of the effects of the above parameters on mountain evolution. In this article, we propose a detailed review of the main results obtained using both "tectonic" and "geomorphic" approaches. Our goal is to provide an almost complete state-of-the-art in the experimental study of relief dynamics to guide present and future researchers in their understanding of mountain belt evolution.

A view from analog modeling

a story beginning long time ago…

1982

@ Géosciences Montpellier



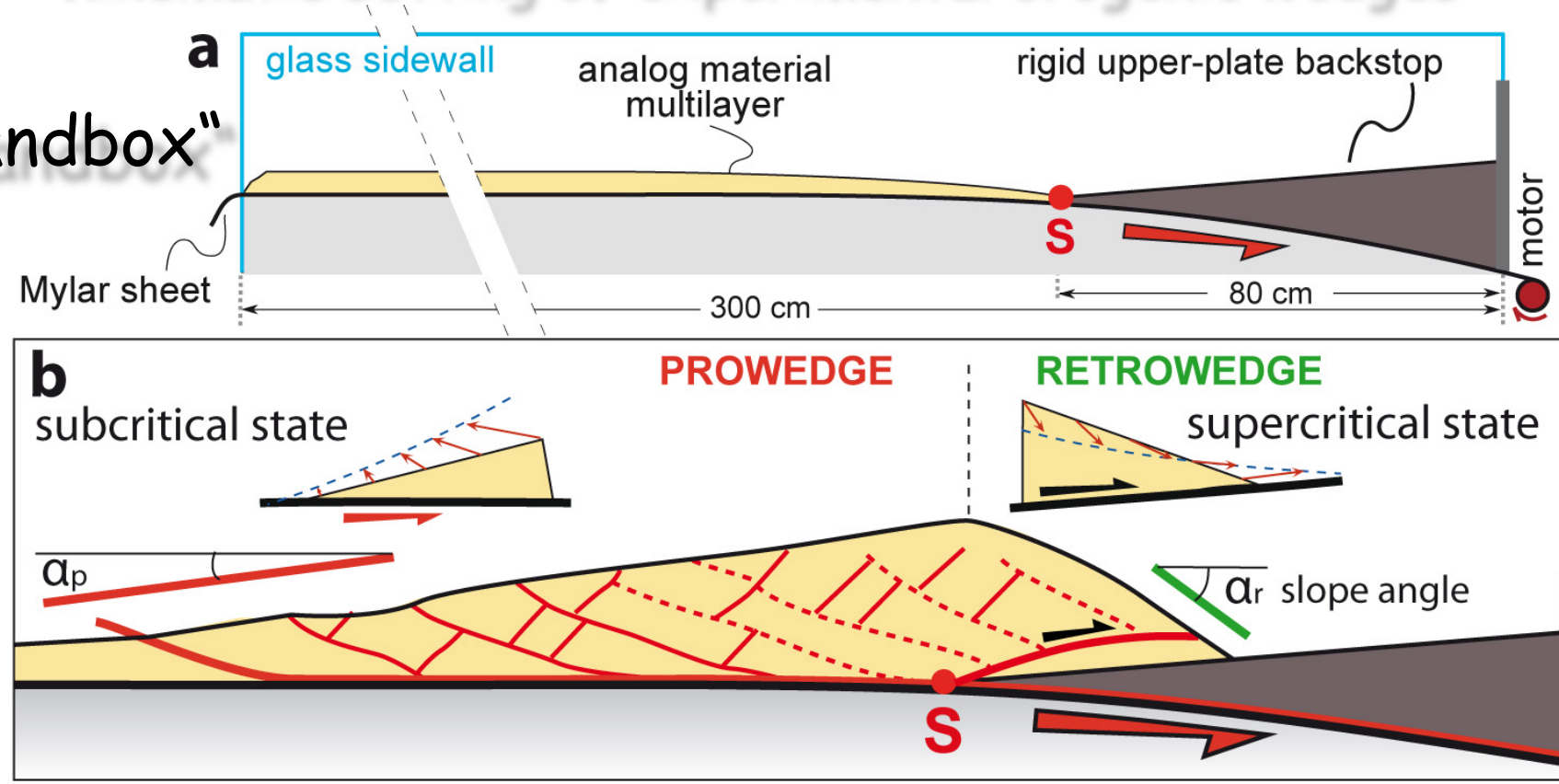
1990

1992

1994

Kinematic setting of experimental orogenic wedges

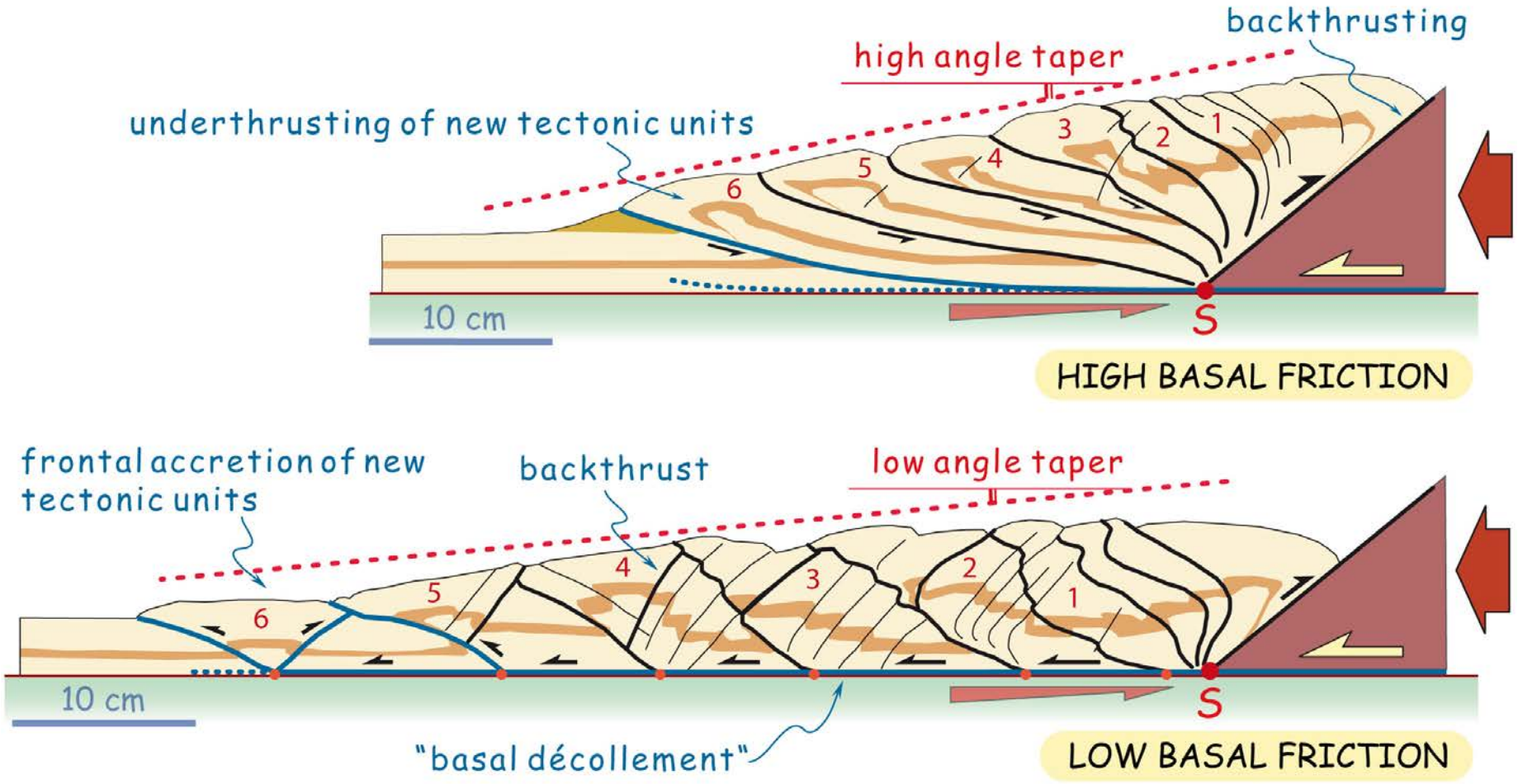
"sandbox"



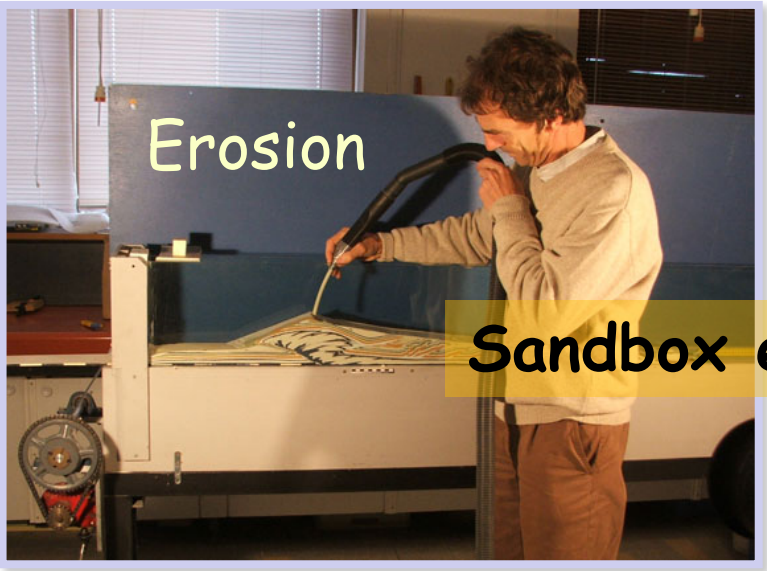
Fixed Backstop

"a subduction setting"

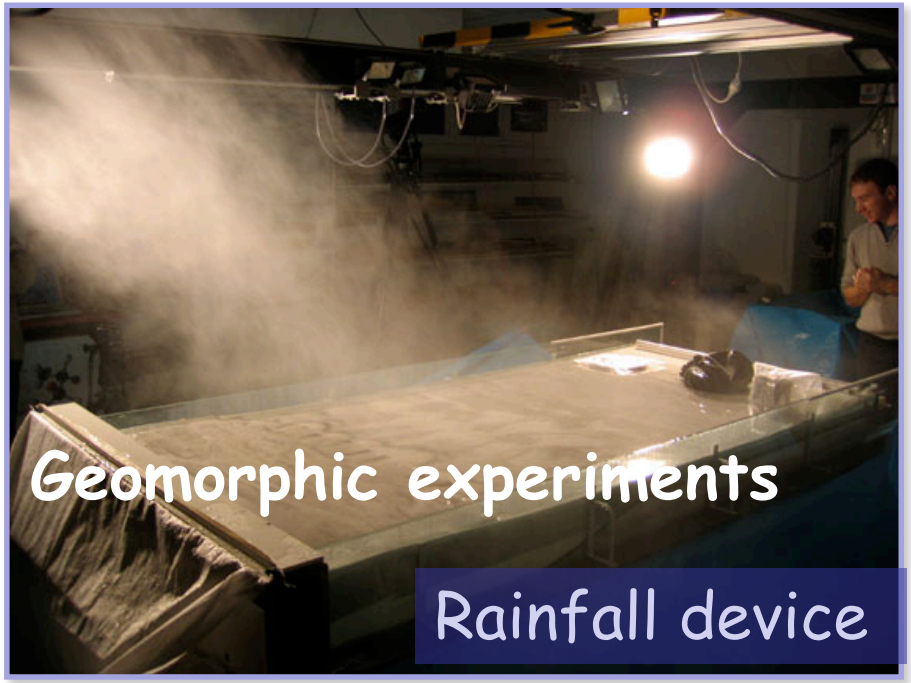
no erosion


backthrusting
high angle taper
underthrusting of new tectonic units
1
2
3
4
5
6
10 cm
S
HIGH BASAL FRICTION
frontal accretion of new tectonic units
backthrust
low angle taper
1
2
3
4
5
6
10 cm
S
"basal décollement"
LOW BASAL FRICTION

Experiments involving erosion and sedimentation…



Sandbox experiments



Accounts for large deformations

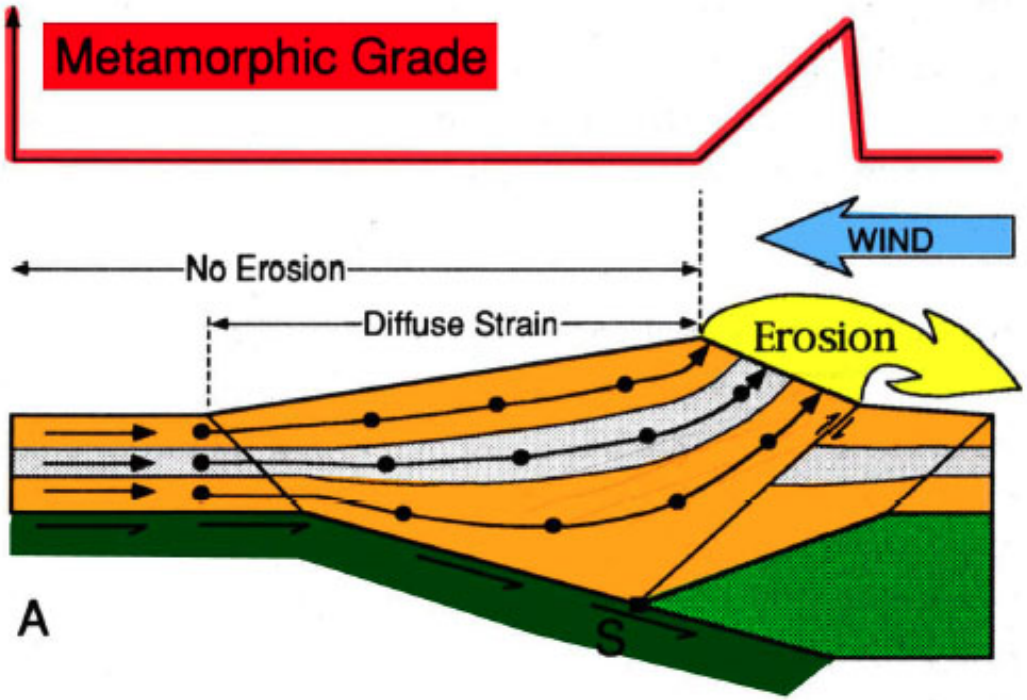
Integration of very long time scales 1 -> 10 Ma

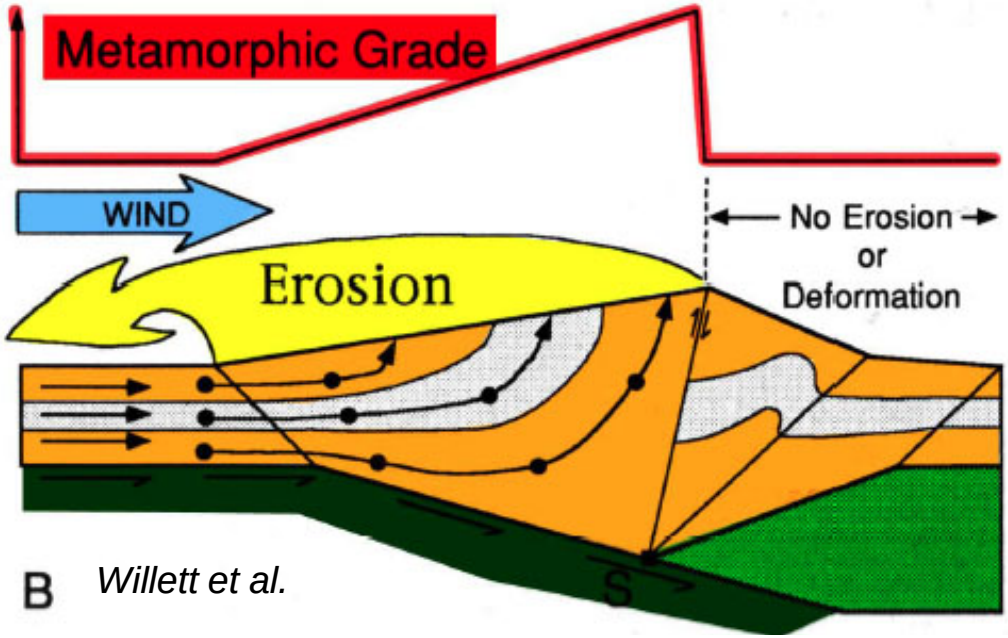
Look at the green particle

no erosion

erosion

OK, erosion allows exhumation, but it's not so simple…



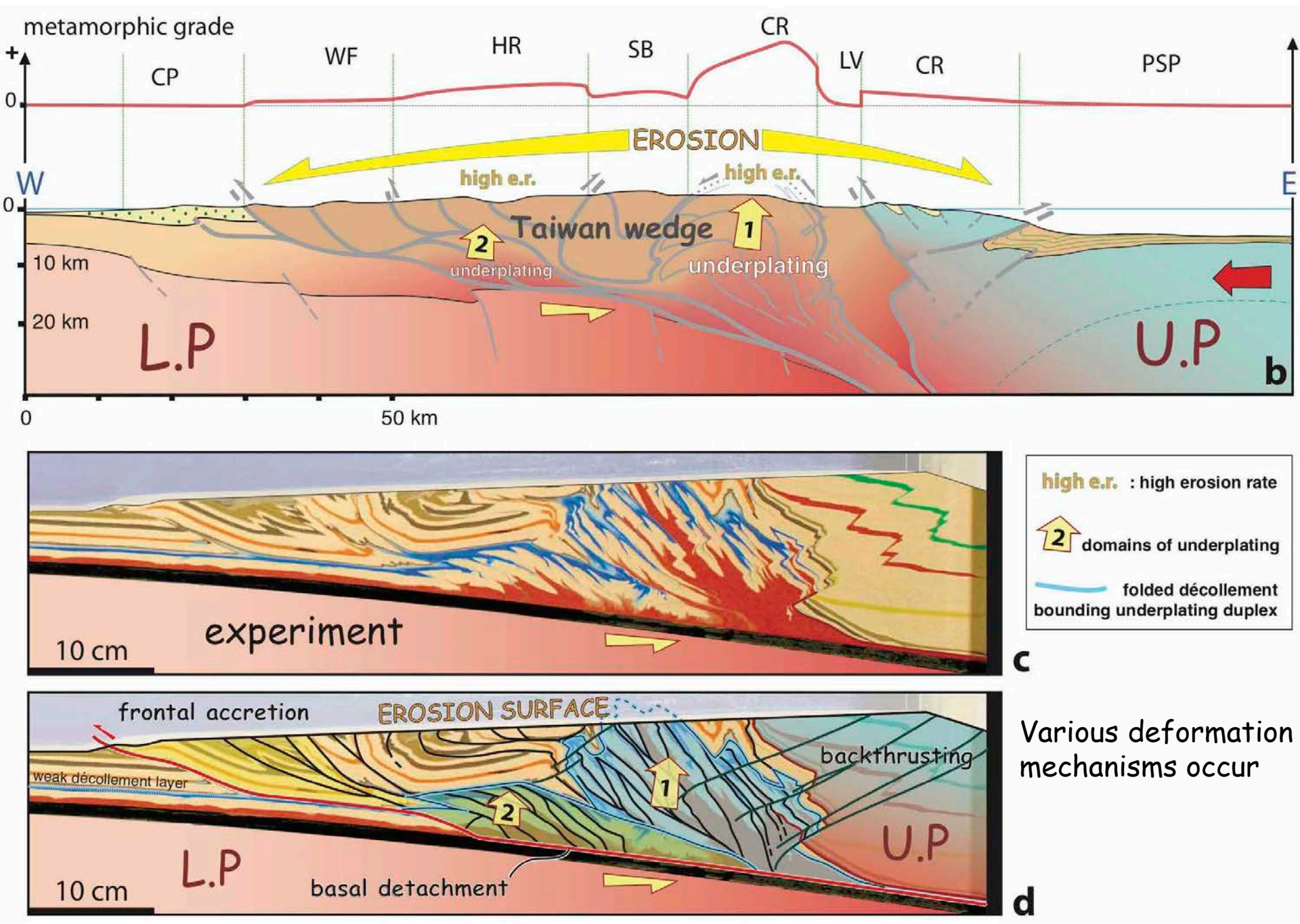


Willett et al.

end members

Theoretical effects of climate & erosion on orogenic wedge

A mountain belt is not so simple…

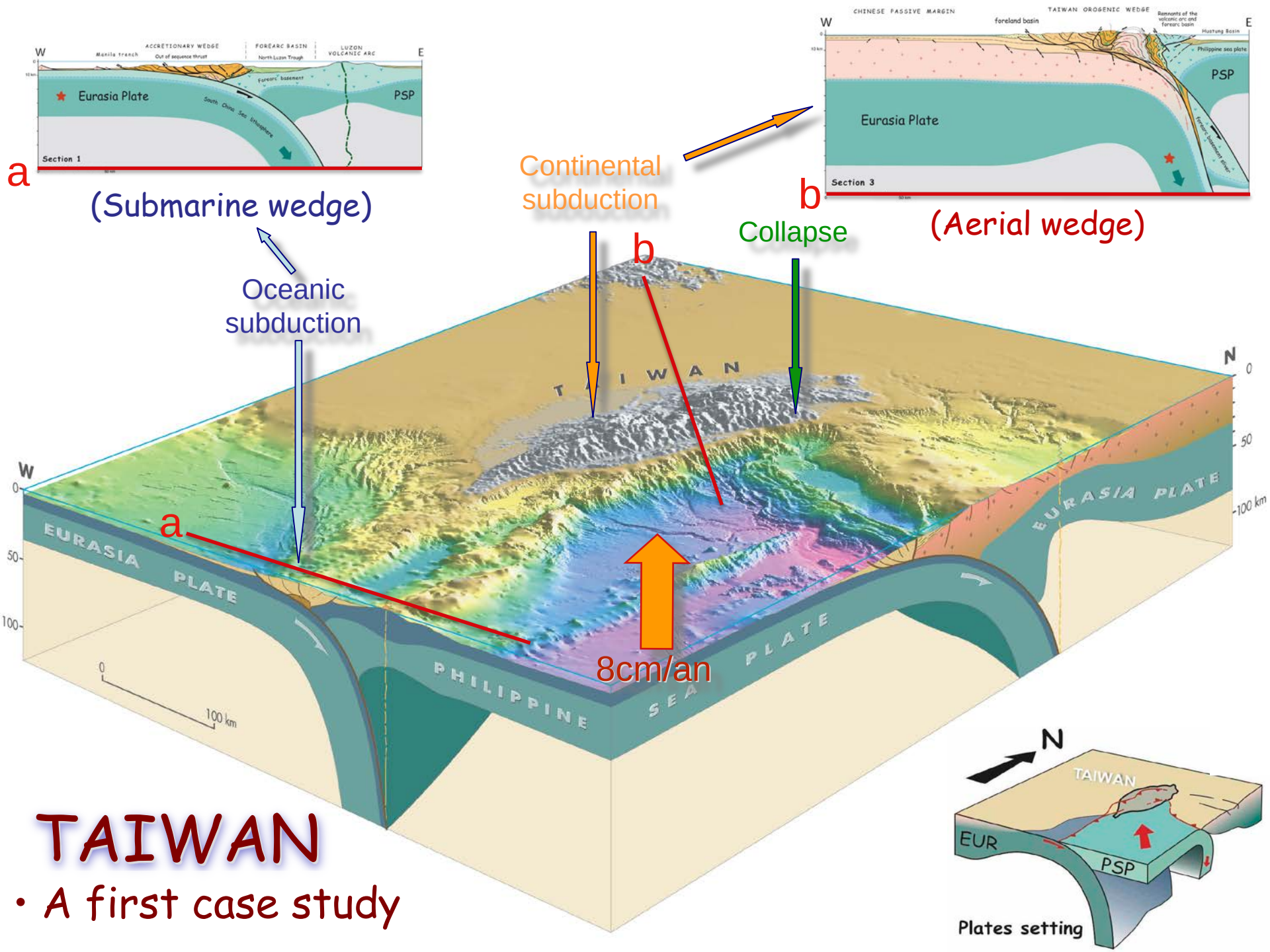


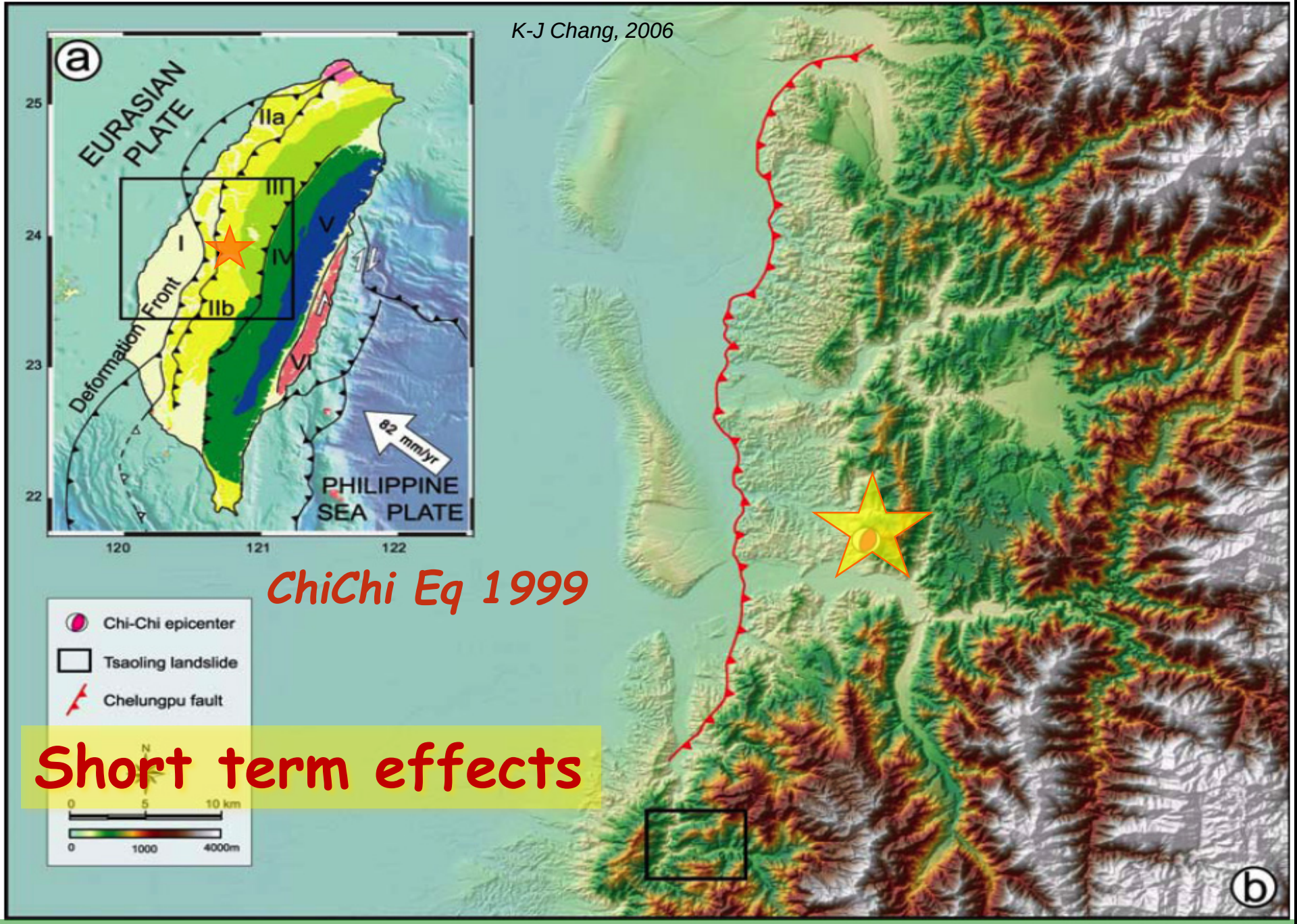
Various deformation mechanisms occur

Impact of surface processes on wedge dynamics ?

from short term to long term effects...

Taiwan 99 Peaks

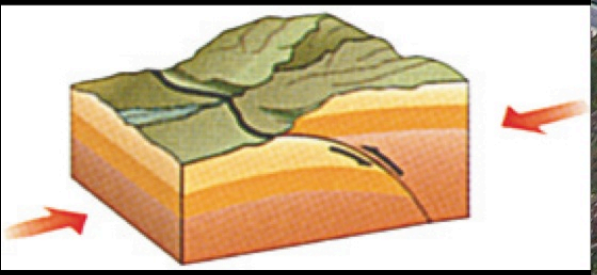

a
W
ACCRETIONARY WEDGE
Manila trench
Out of sequence thrust
FOREARC BASIN
North Luzon Trough
LUZON VOLCANIC ARC
E
Eurasia Plate
South China Sea lithosphere
PSP
Section 1
(Submarine wedge)
Continental subduction
b
CHINESE PASSIVE MARGIN
TAIWAN OROGENIC WEDGE
foreland basin
Remnants of the volcanic arc and forearc basin
Hsutung Basin
Philippine sea plate
Eurasia Plate
PSP
Section 3
(Aerial wedge)
Collapse
Oceanic subduction
T A I W A N
N
W
0
50
100
a
EURASIA PLATE
PHILIPPINE SEA PLATE
8cm/an
0
100 km
TAIWAN
• A first case study
N
TAIWAN
EUR
PSP
Plates setting



Short term effects

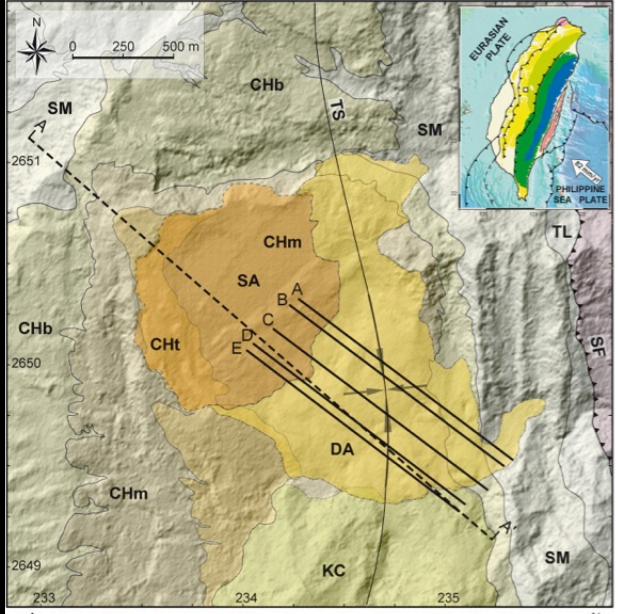
Erosion mechanisms are largely impacted by tectonics…

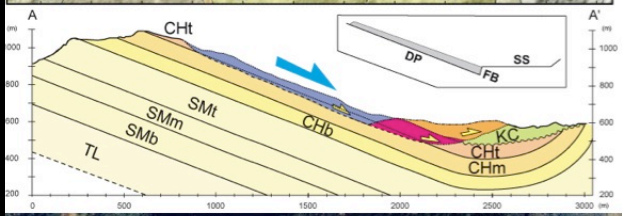
ChiChi Eq, 1999,
Mw 7.6

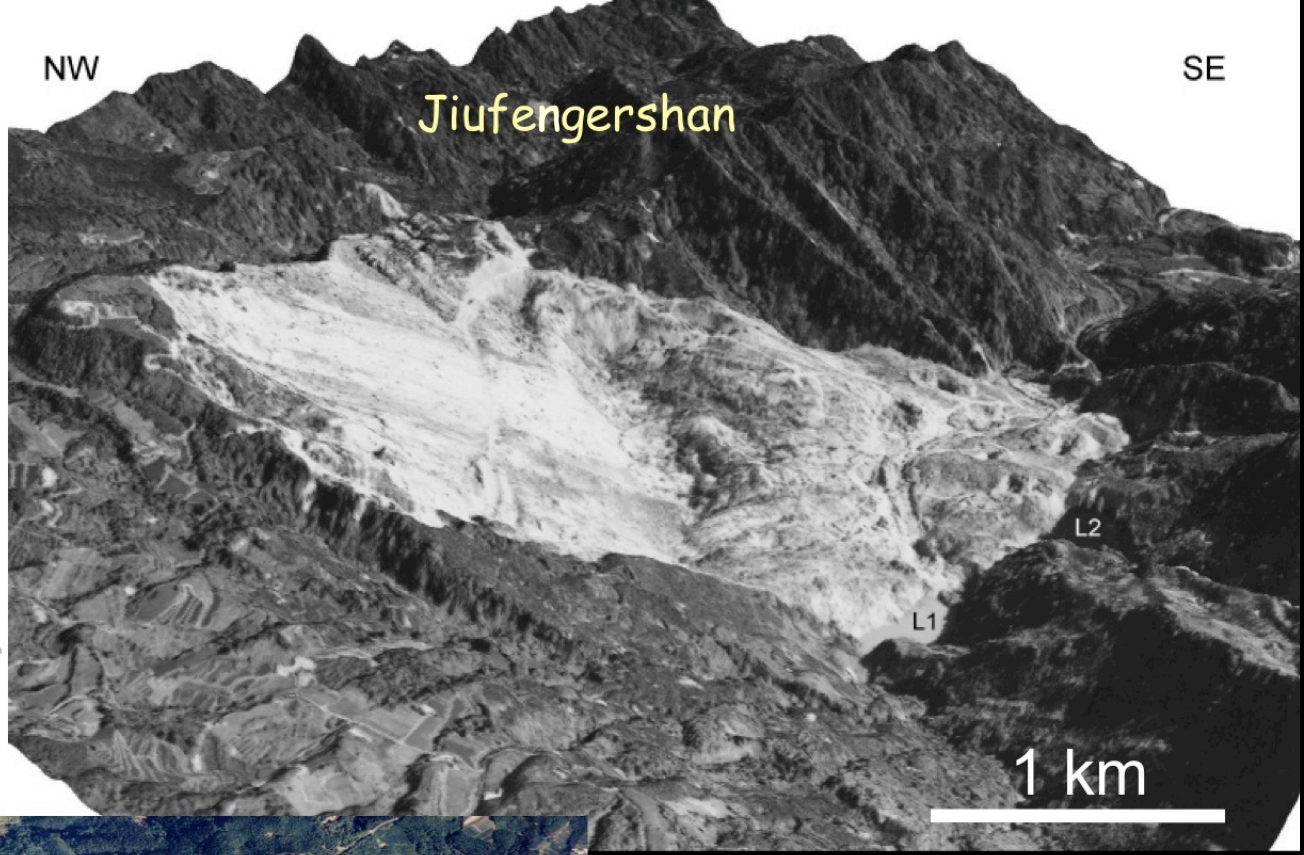


A reverse fault

Impact of large earthquakes on morphology and material transfer…







KJ Chang et al. 2005

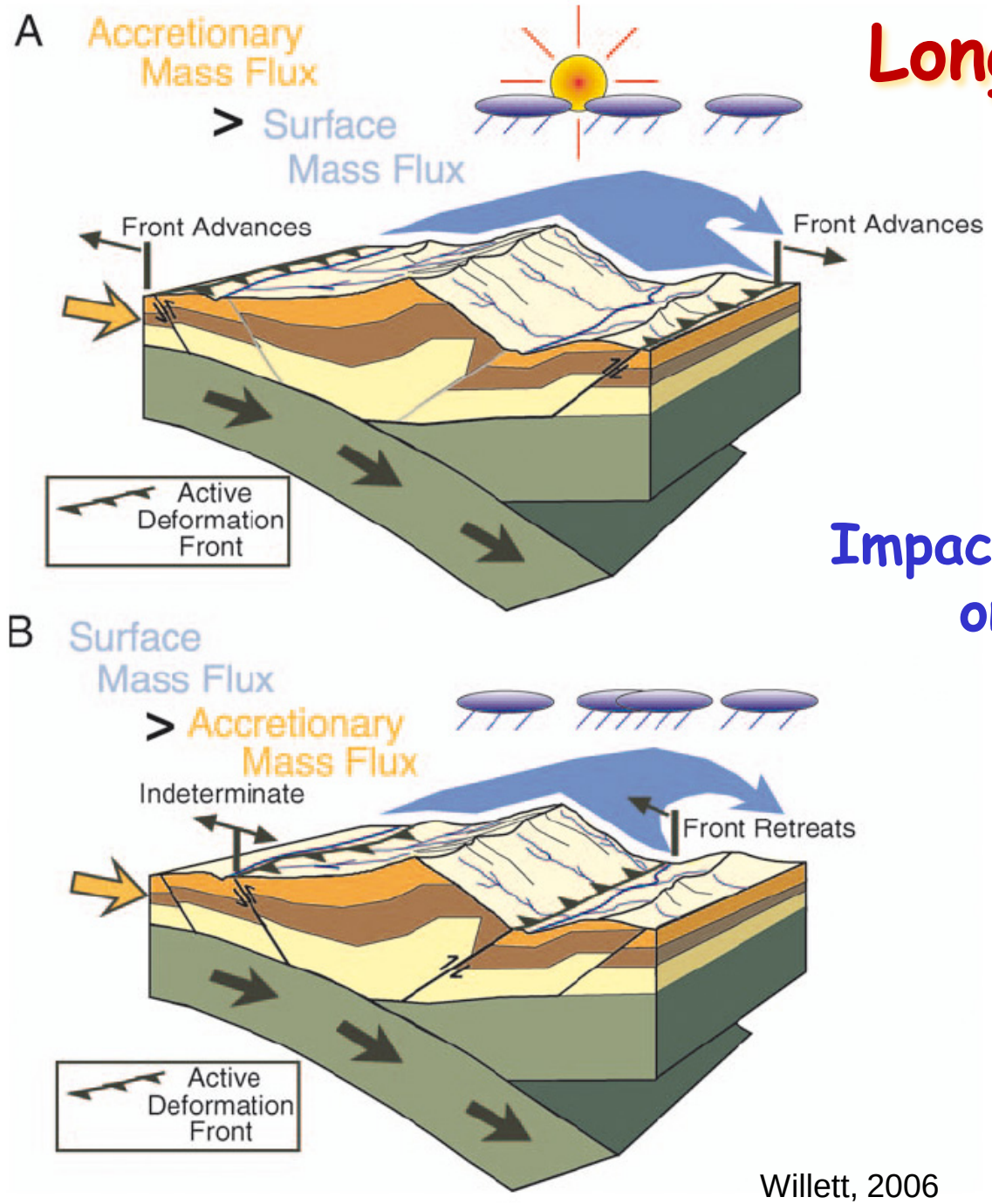
Gigantic landslides triggered by earthquaques…

Sediment transport mainly duringTyphons…

Erosion by rivers


"river pebbles"
Geologist

Long term effects



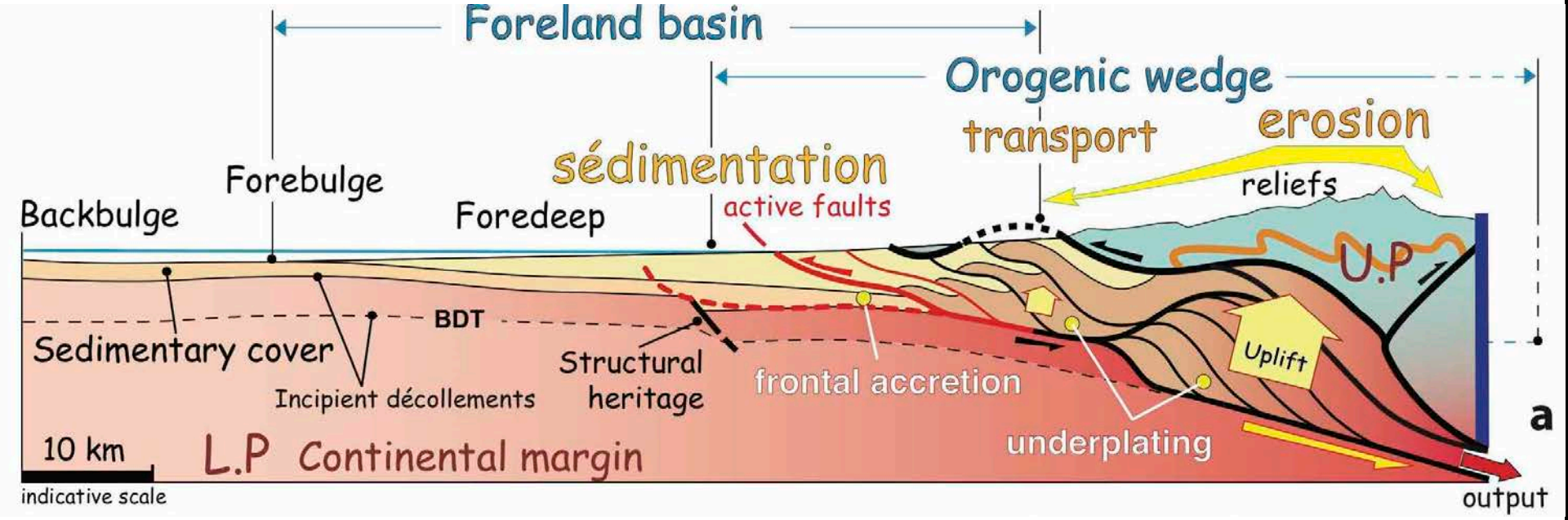
DRY

Impact of climate changes on mass transfer in orogens

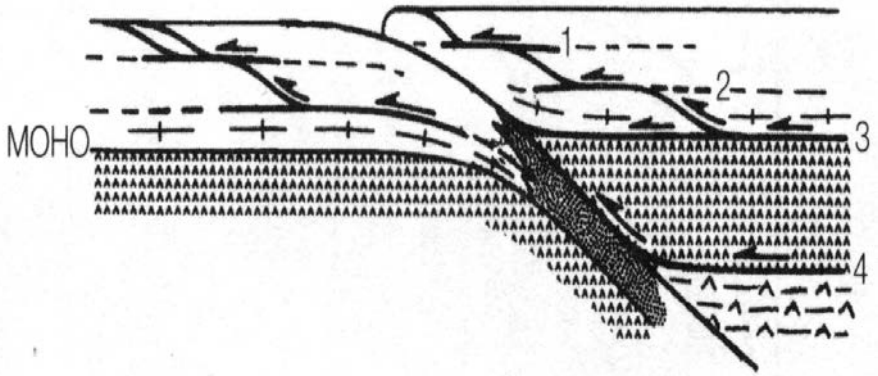
WET

Willett, 2006

Long term effects of erosion and impact of rheological layering of the continental crust

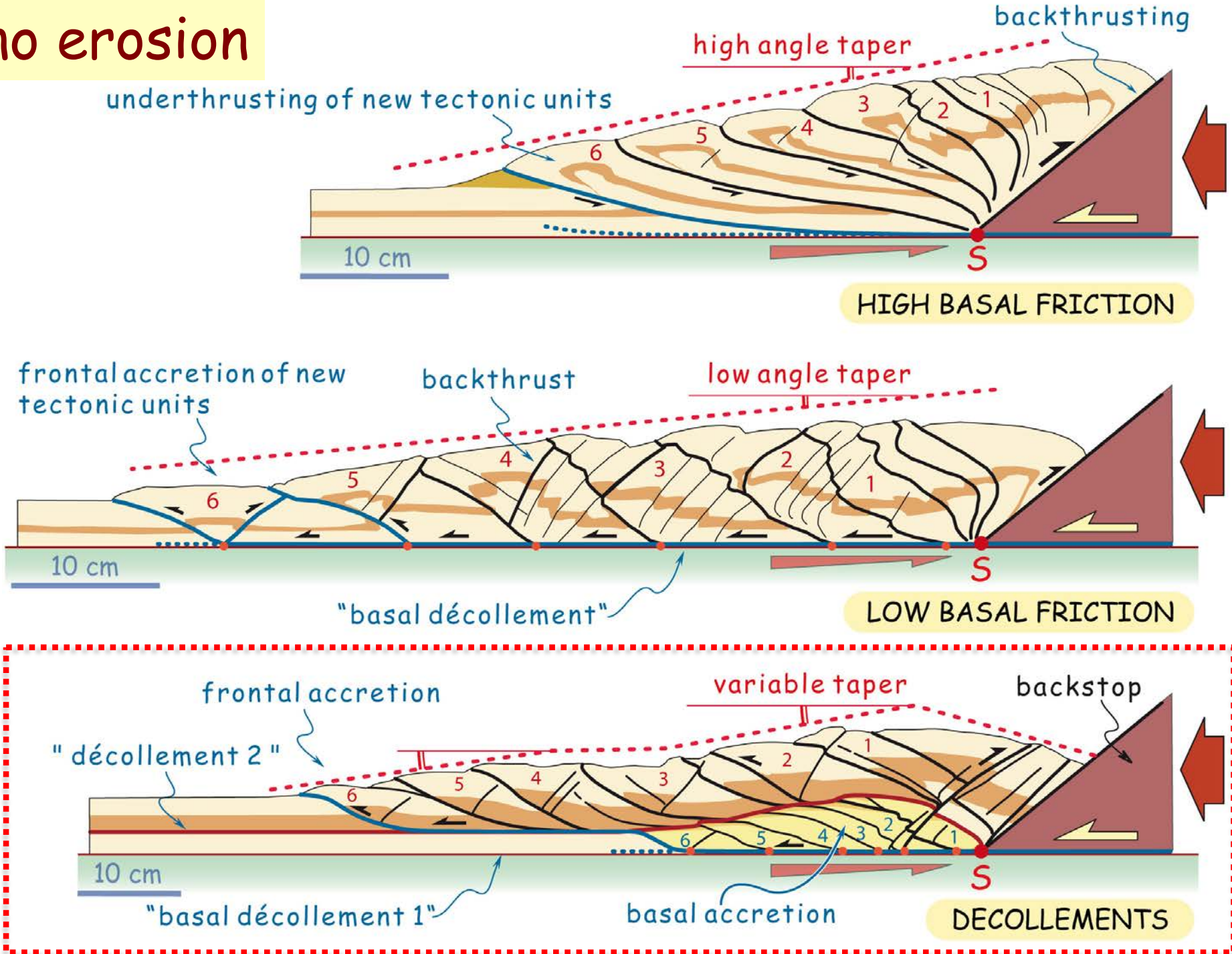


Thrust wedges and décollements...



Influence on deformation mechanisms

no erosion

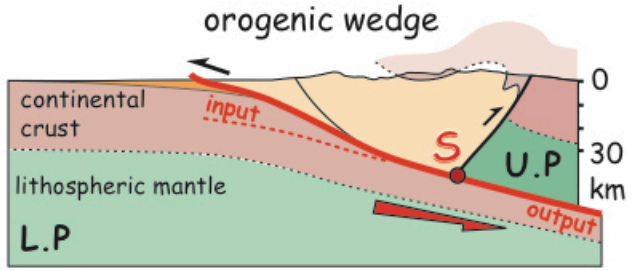

backthrusting
high angle taper
underthrusting of new tectonic units
1
2
3
4
5
6
10 cm
S
HIGH BASAL FRICTION
frontal accretion of new tectonic units
backthrust
low angle taper
1
2
3
4
5
6
10 cm
S
"basal décollement"
LOW BASAL FRICTION
frontal accretion
variable taper
backstop
" décollement 2 "
1
2
3
4
5
6
10 cm
"basal décollement 1"
basal accretion
S
DECOLLEMENTS

A sandbox example of deformation partitioning

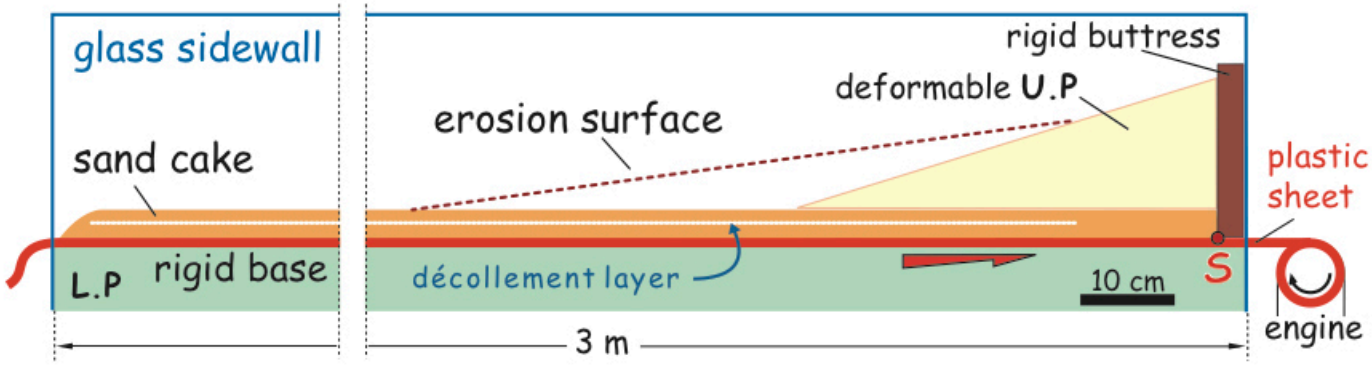
U.P = Upper Plate

L.P = Lower Plate

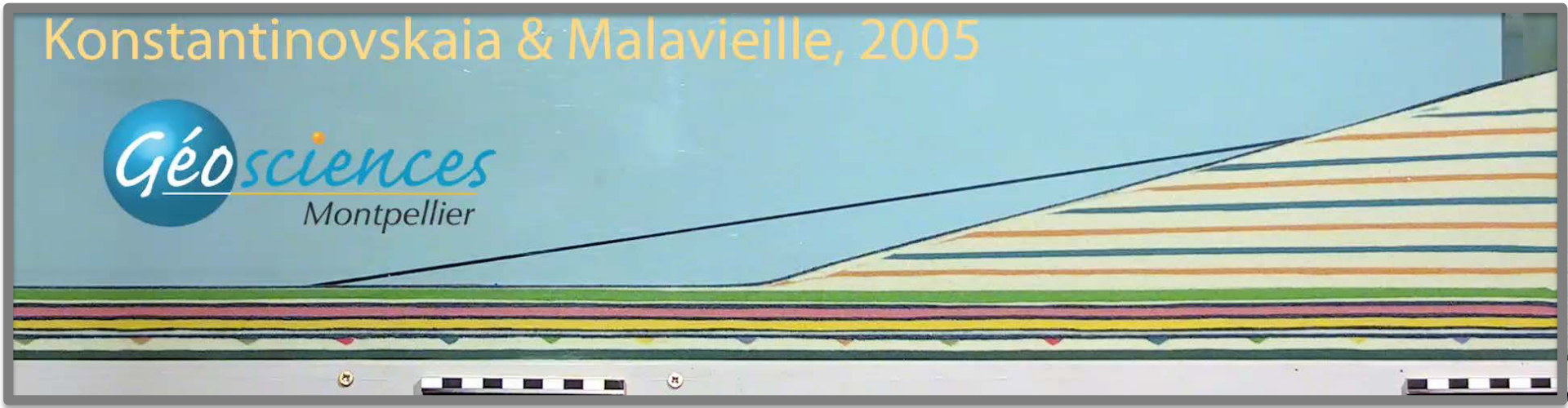
S velocity discontinuity

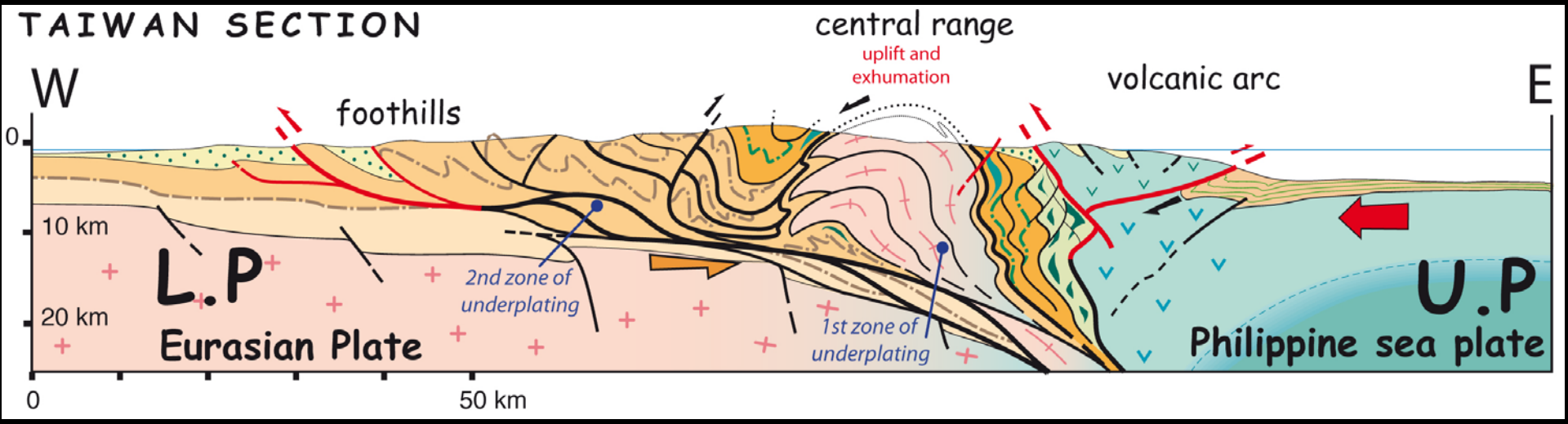


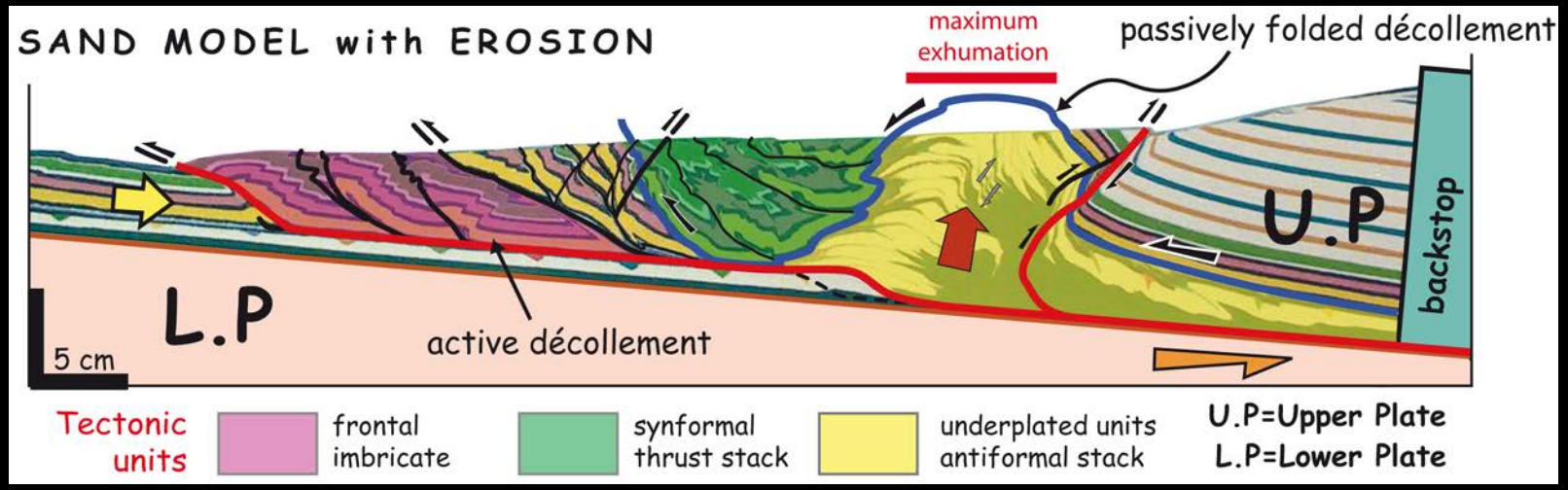
Flux steady state
(Input=Output)



Erosion + Décollement ⇒ high deformation partitioning

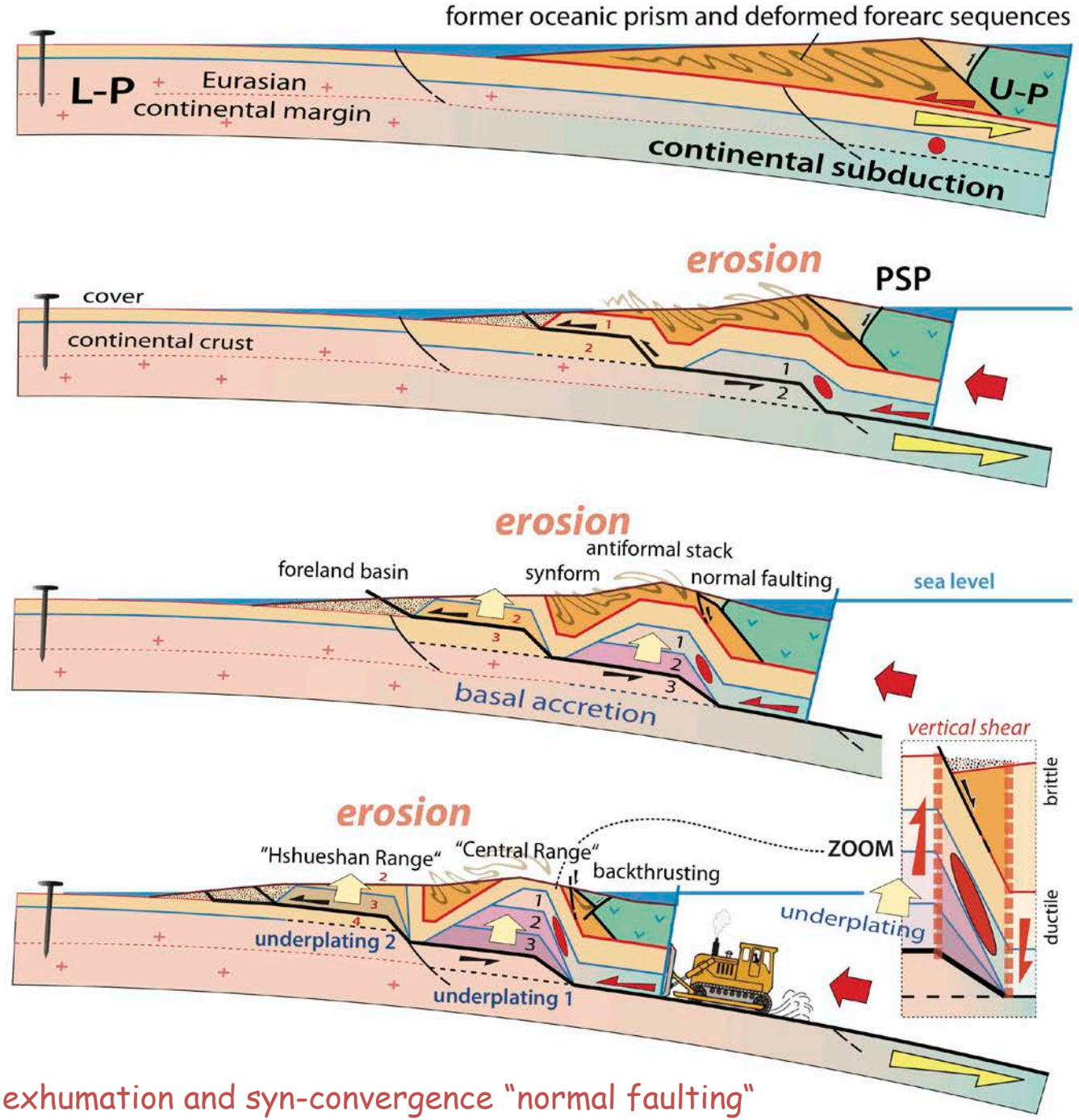






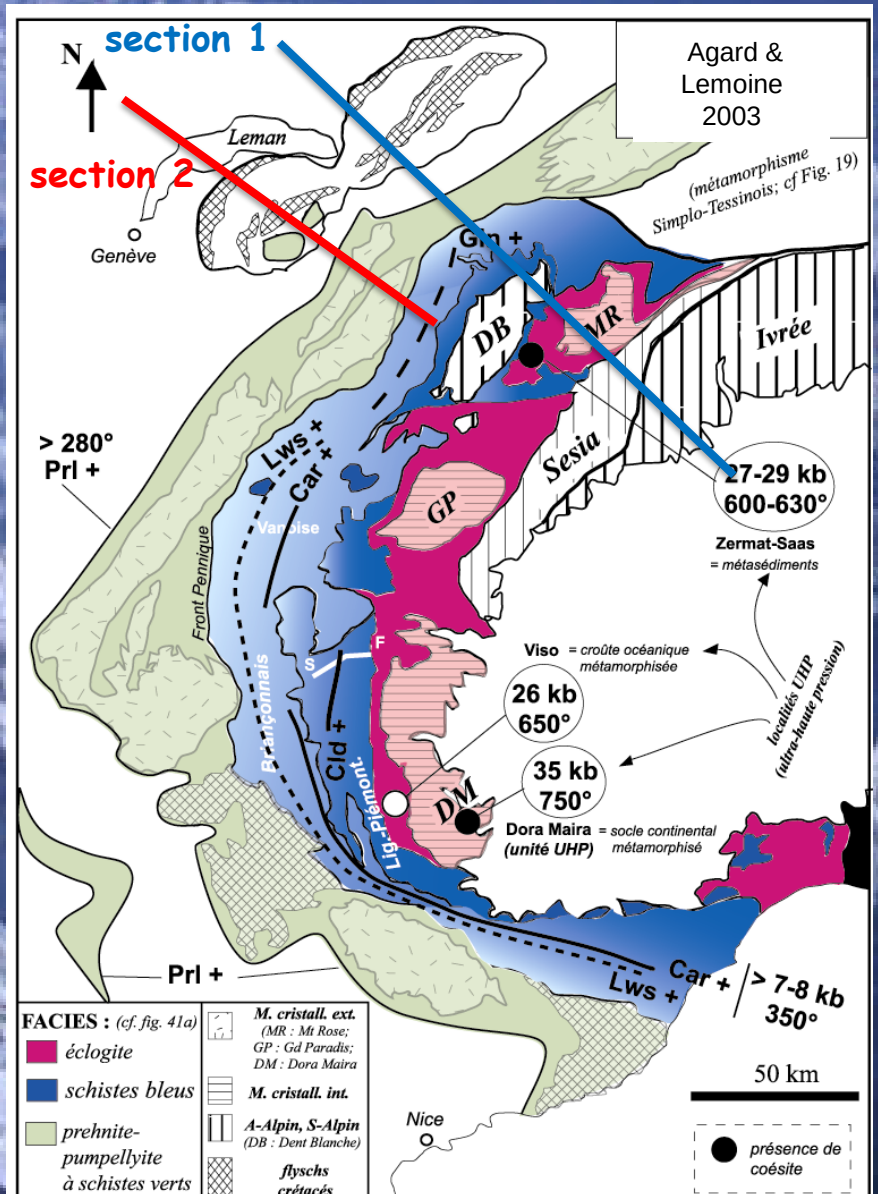
accretion mechanisms

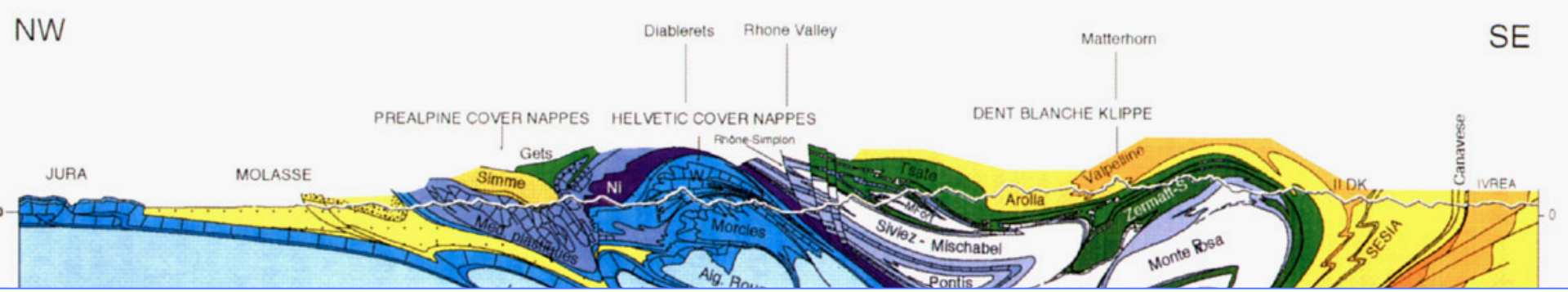
A simplified 2D kinematic model for deformation partitioning



Basal accretion, exhumation and syn-convergence "normal faulting"

The Western Alps





Escher et al. 1994

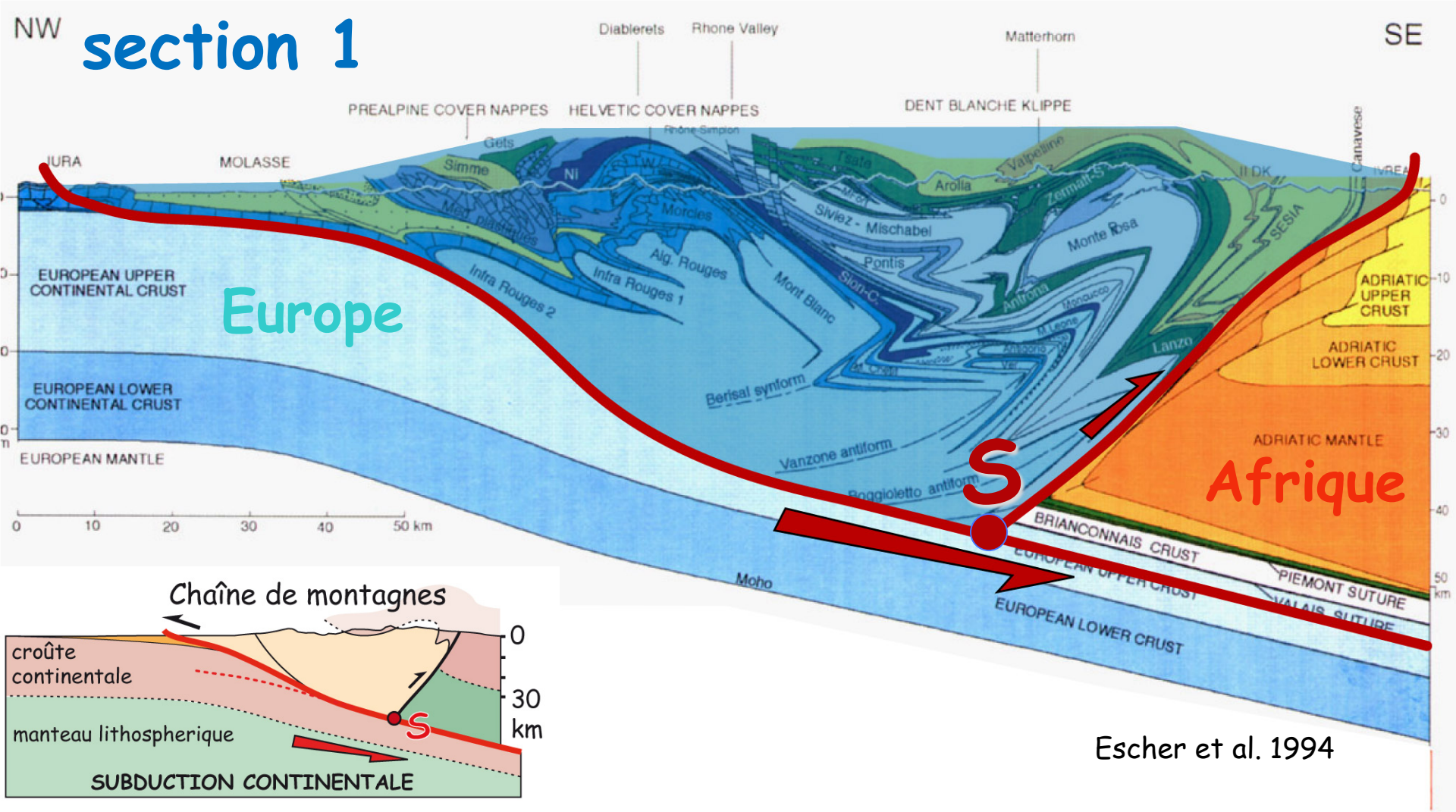
section 1

The Alpine orogenic wedge

observation :

a complex geology !

section 1



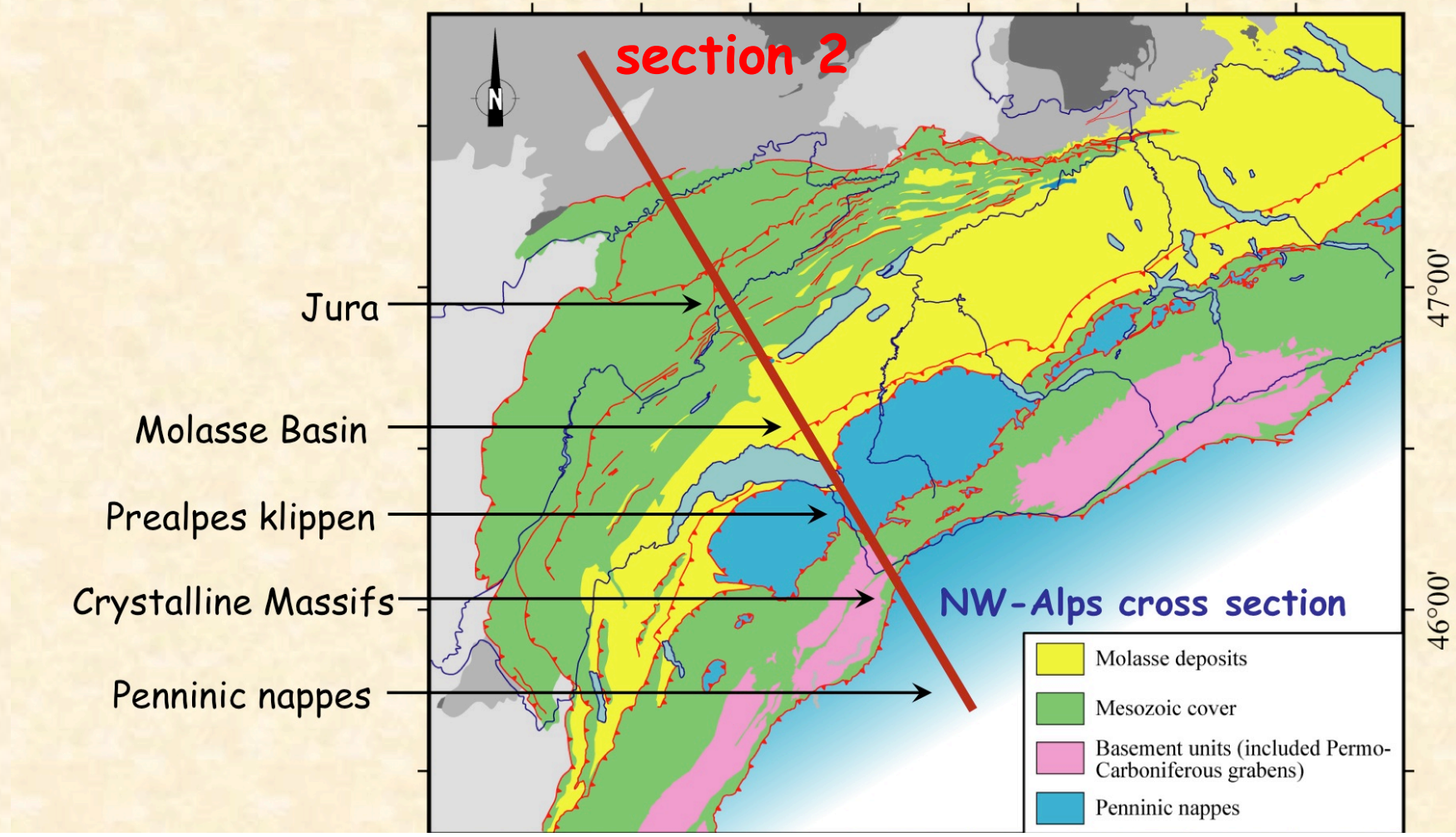
Escher et al. 1994

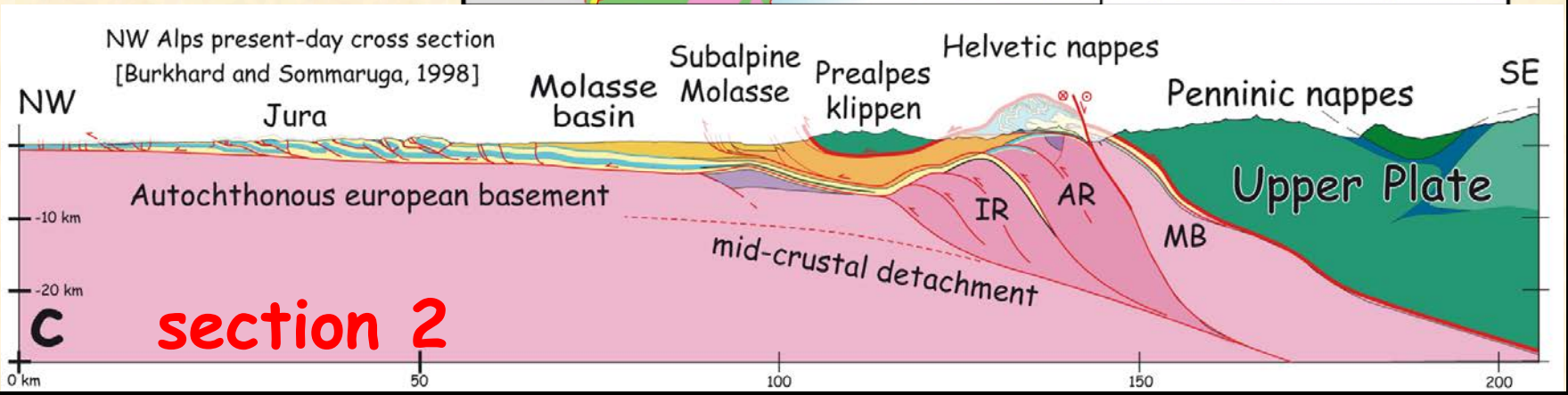
Boundary conditions :

a simple kinematics at lithosphere scale…

but how is produced this complex geological structure ?

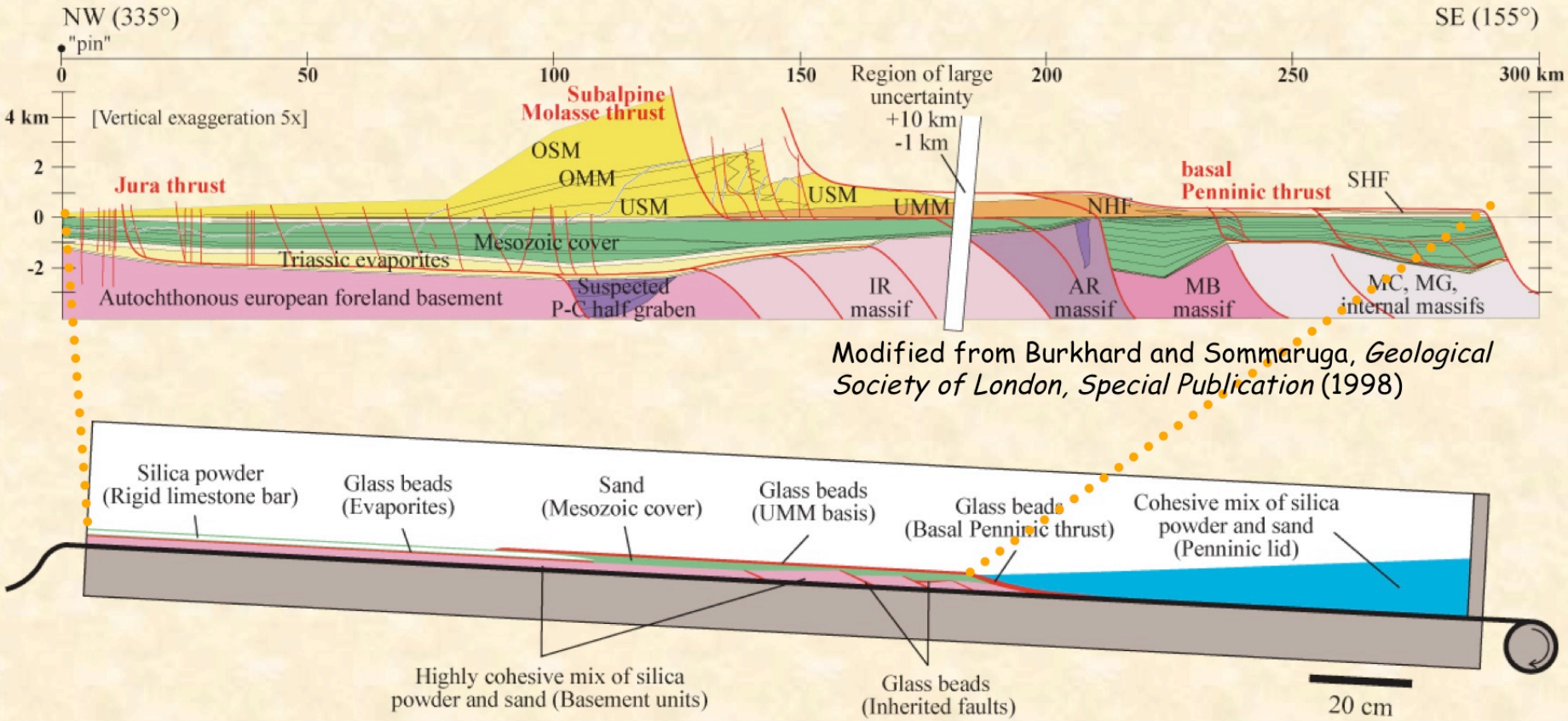
Impact of erosion, sedimentation and structural heritage on the tectonic evolution of the Alpine foreland ?





Modeling the subduction of the European continental margin…

Restored cross section

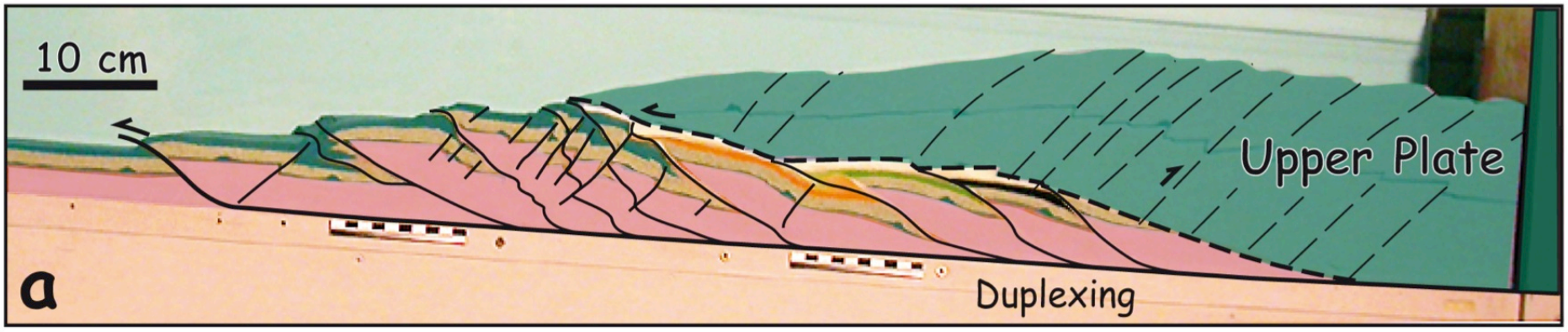


Modified from Burkhard and Sommaruga, *Geological Society of London, Special Publication* (1998)

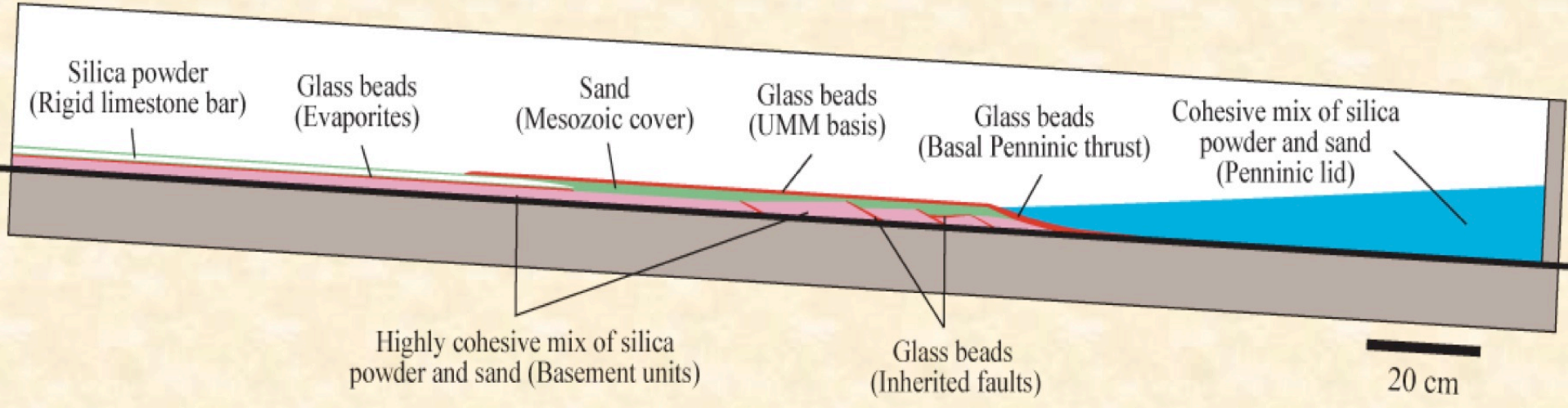
Experimental set up and Boundary conditions

A model playing with

erosion, sedimentation, & structural heritage….



No erosion

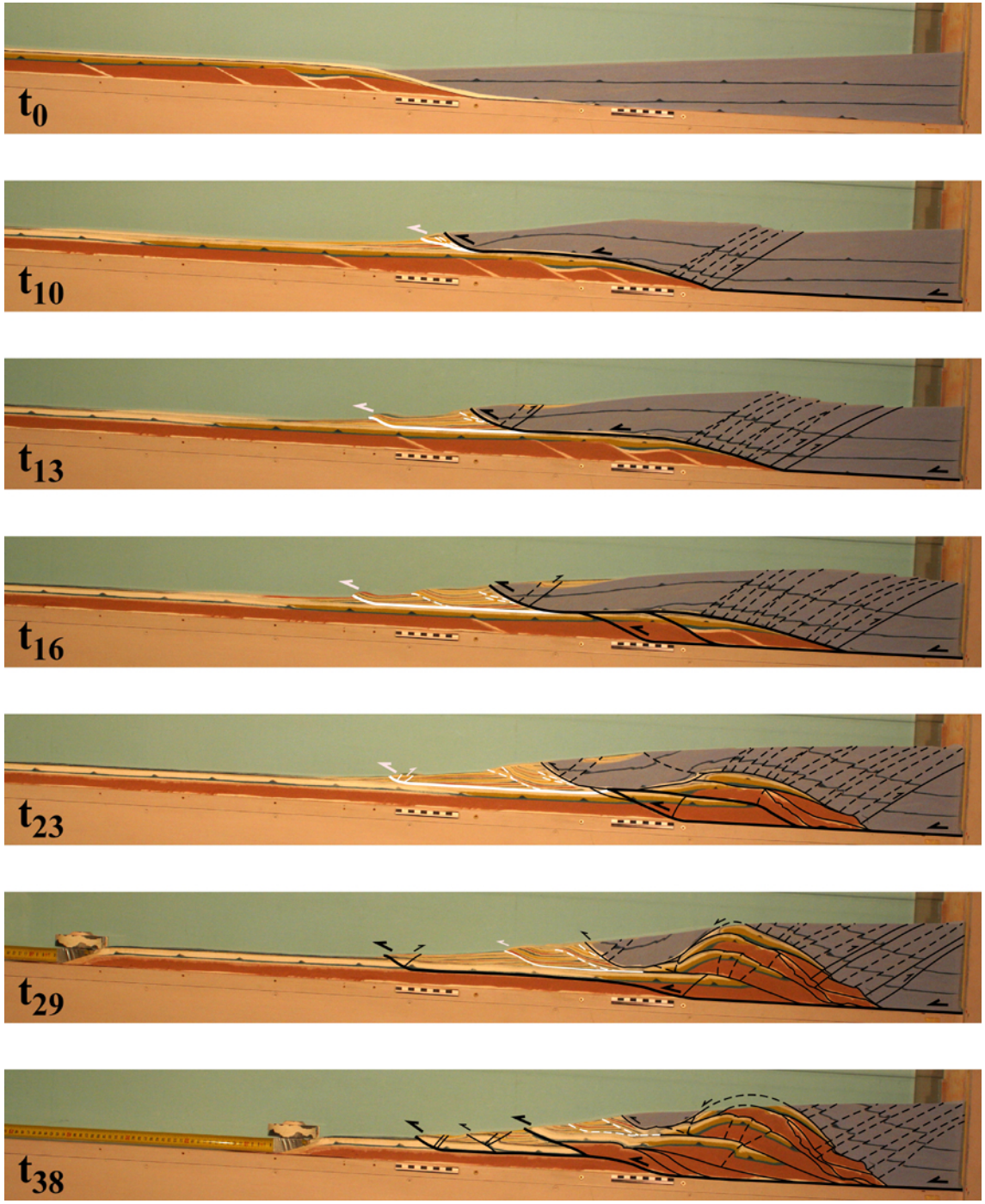


initial setting

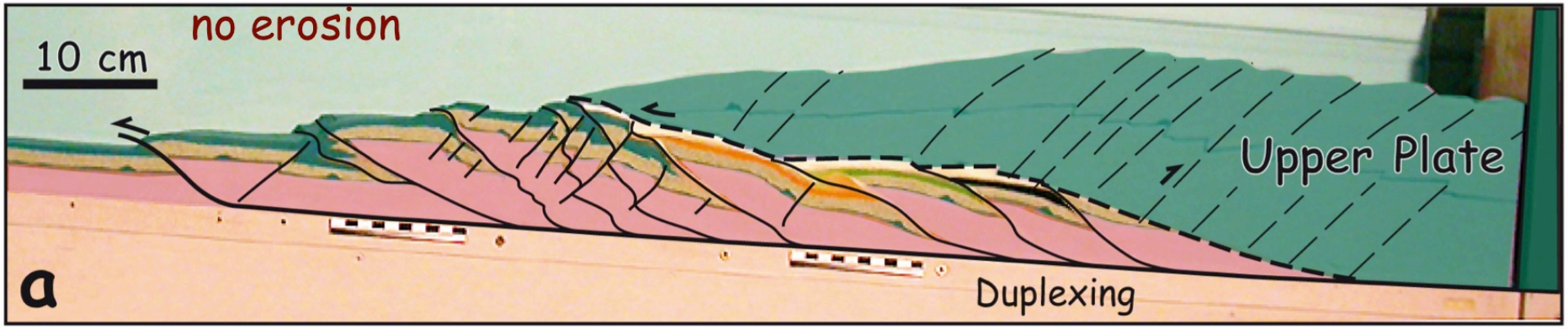
initial state

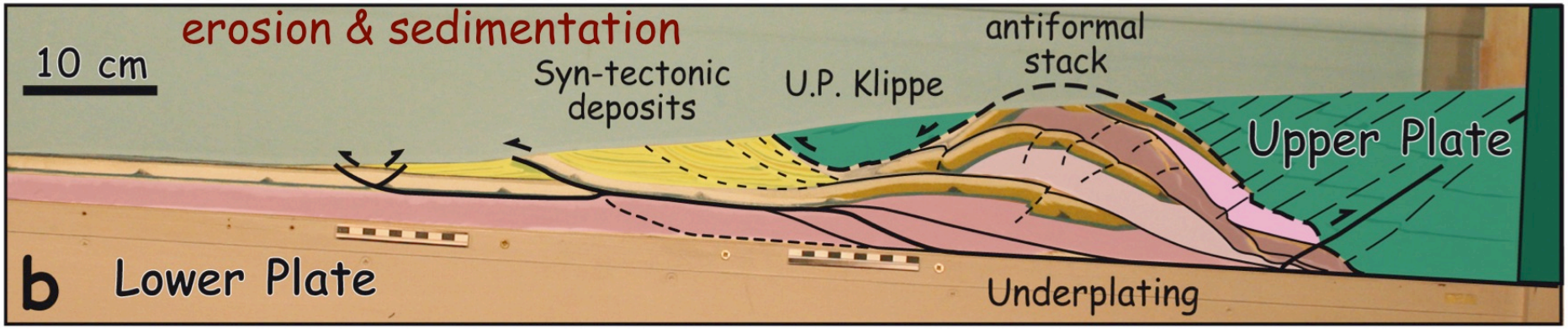
evolution

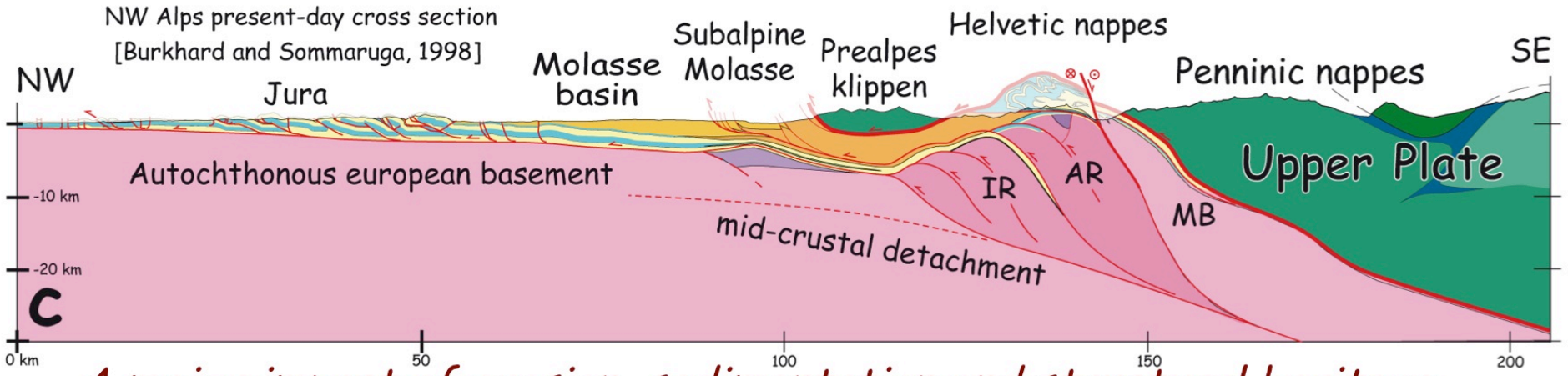
erosion & sedimentation



Bonnet et al., 2006



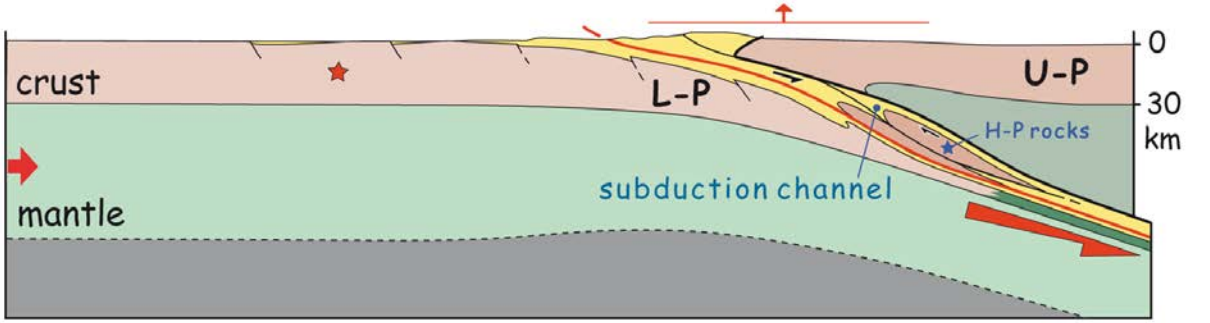


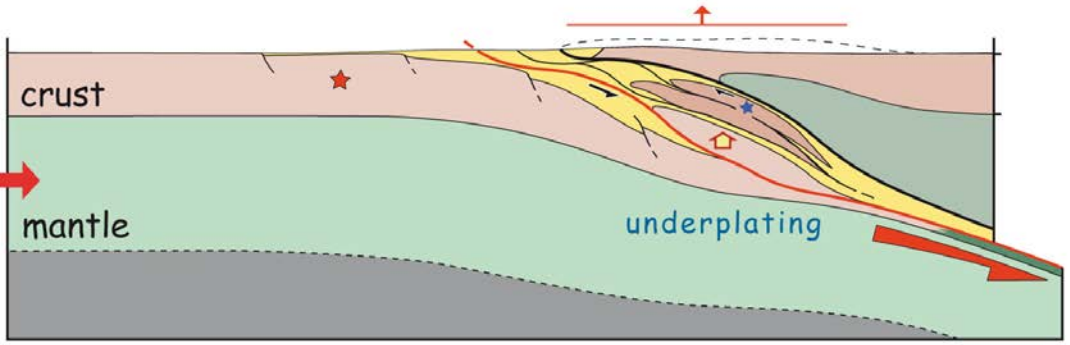


A major impact of erosion, sedimentation and structural heritage

Bonnet, Malavieille & Mosar, 2007

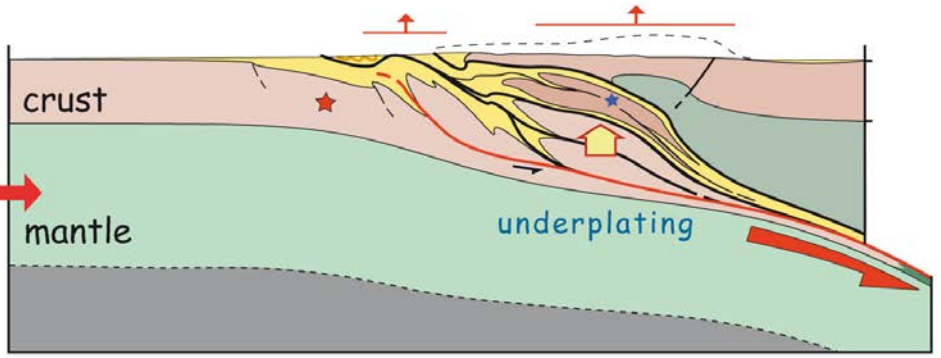
At lithospheric scale, the role of the upper-plate is major

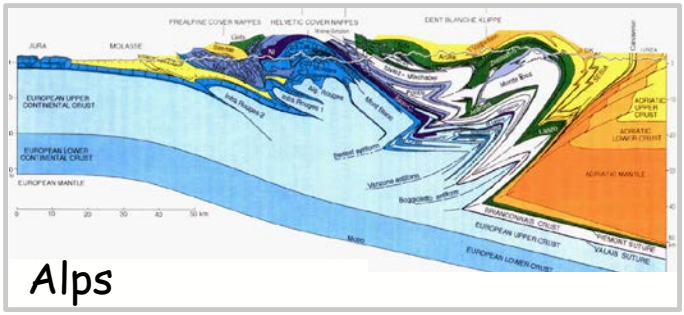




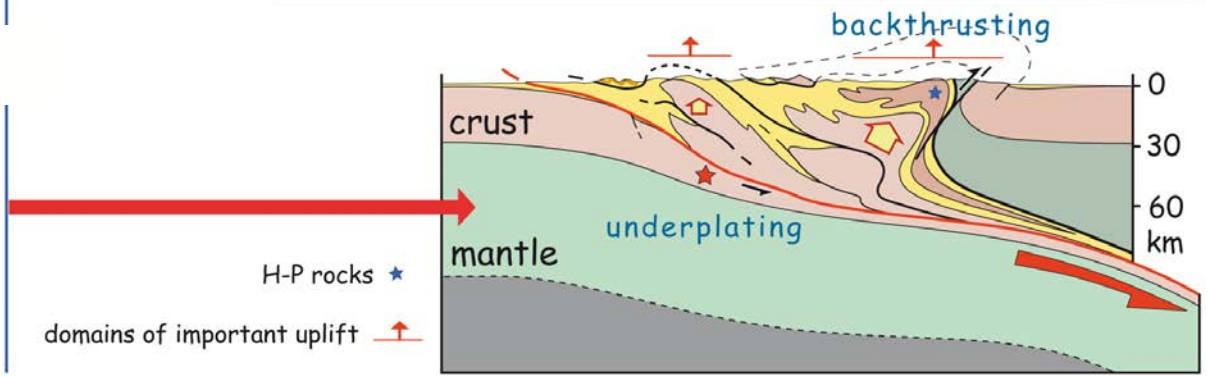
Impact of upper-plate erosion on wedge evolution

Underplating + erosion will favor major backthrusting -> doubly vergent wedge



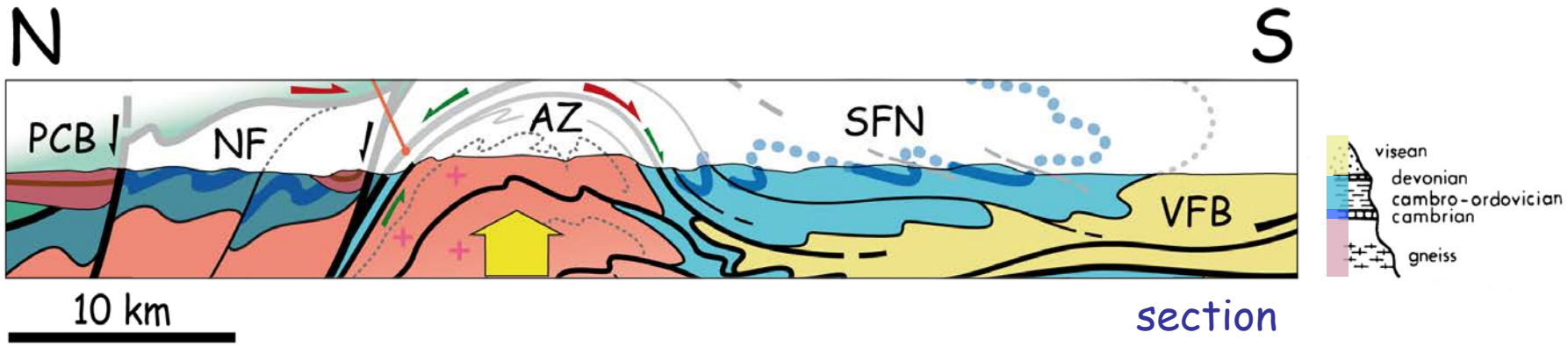


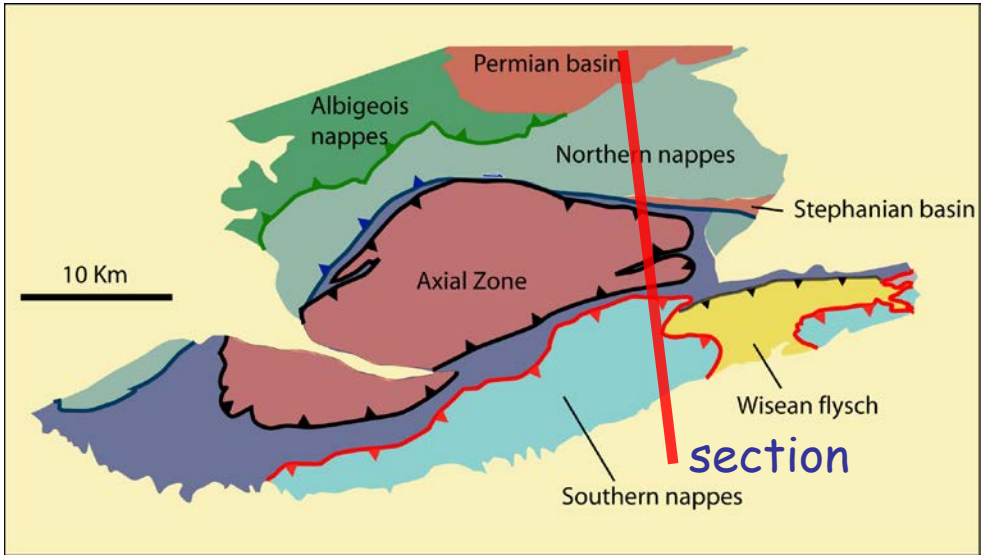
Alps

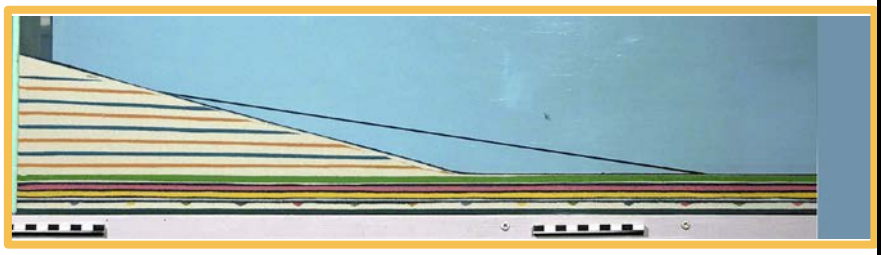


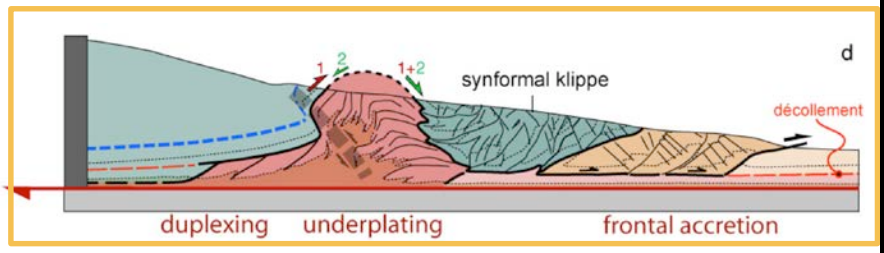
- Syntectonic surface processes (last case study)

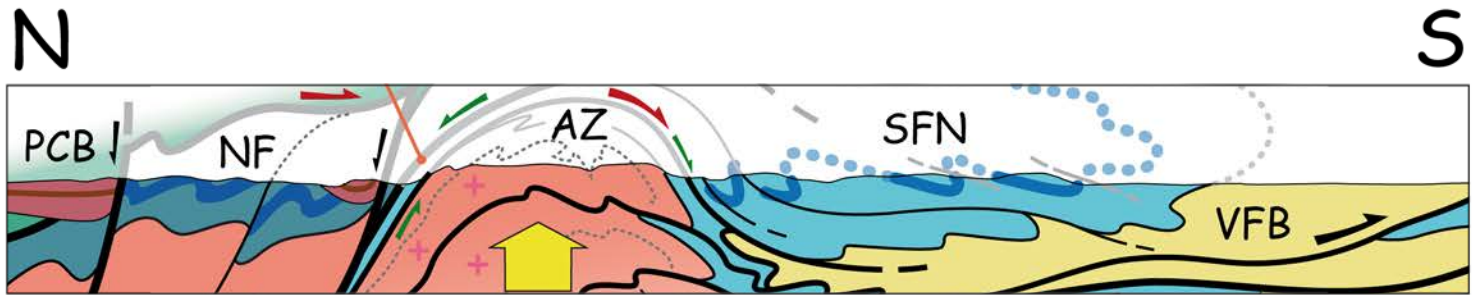
The Hercynian "Montagne Noire"



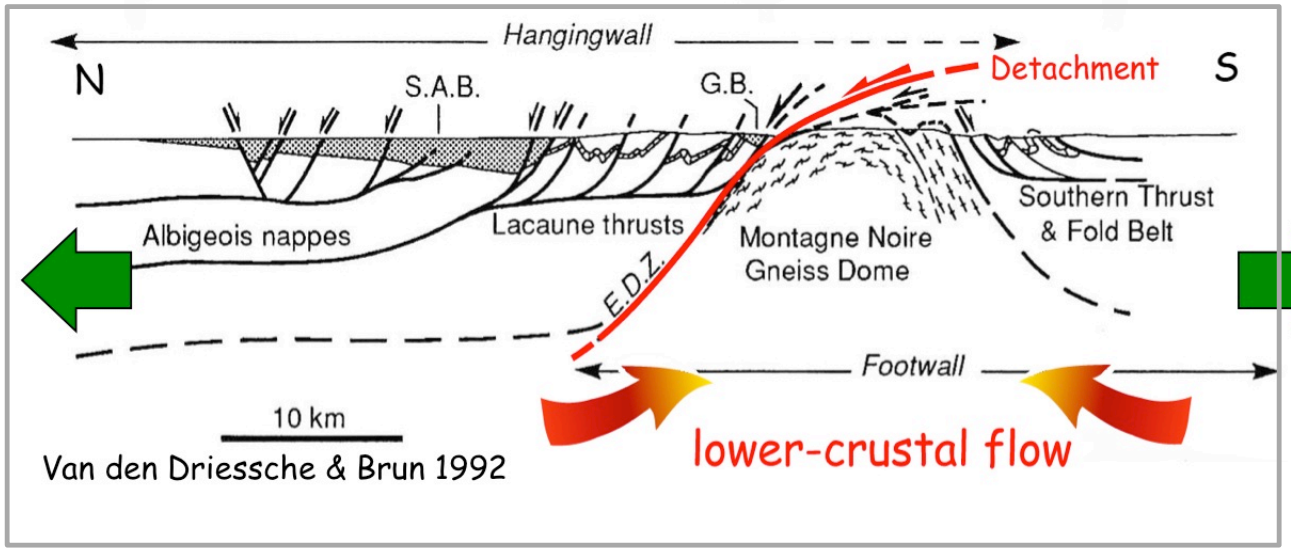








A model inspired by experiments involving erosion…



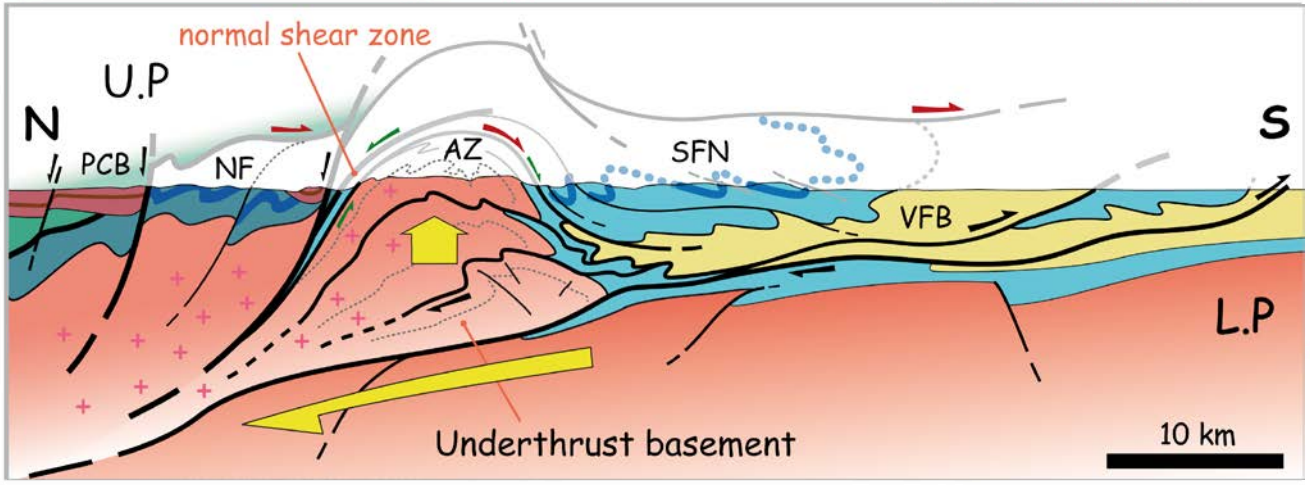
Van den Driessche & Brun 1992

Buoyancy forces dominant

MCC 90% extensional

Erosion negligible

or ?



Malavieille 2007

Tectonic forces dominant

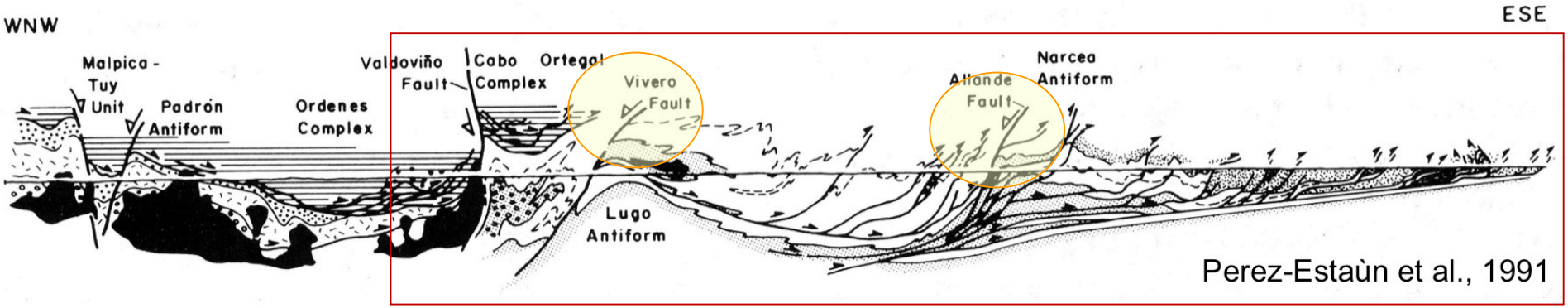
MCC 90% compressional

Major role of Erosion

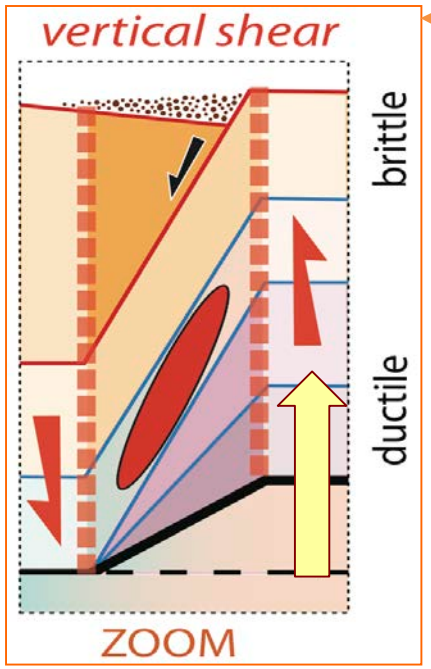
Juxtaposition of tectonic units showing contrasted tectono-metamorphic history & paradoxical normal faults…

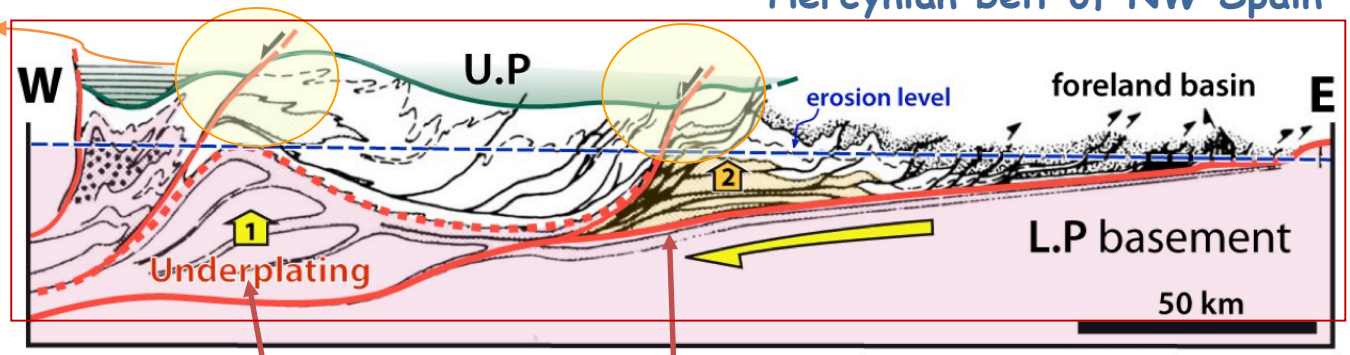
Causes & consequences of deformation partitioning in mountain belts ?

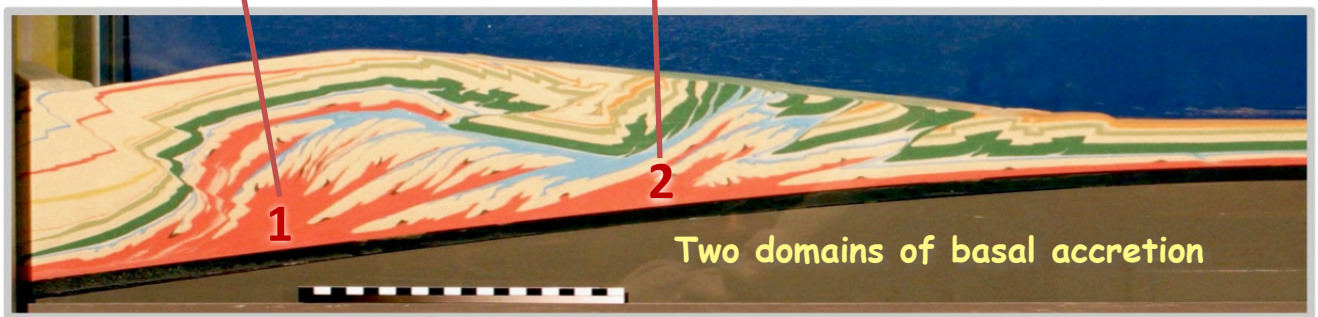
Decoupling levels induce **deformation partitioning**, allowing duplex formation and basal accretion **(underplating)**.
Underplating localizes zones of fast uplift with **high angle surface slopes** favoring **high erosion rates**.
Self maintained zones of exhumation enhance the development of **antiformal nappe stacks** involving **syn-convergence normal shear deformation ("normal faults")**…



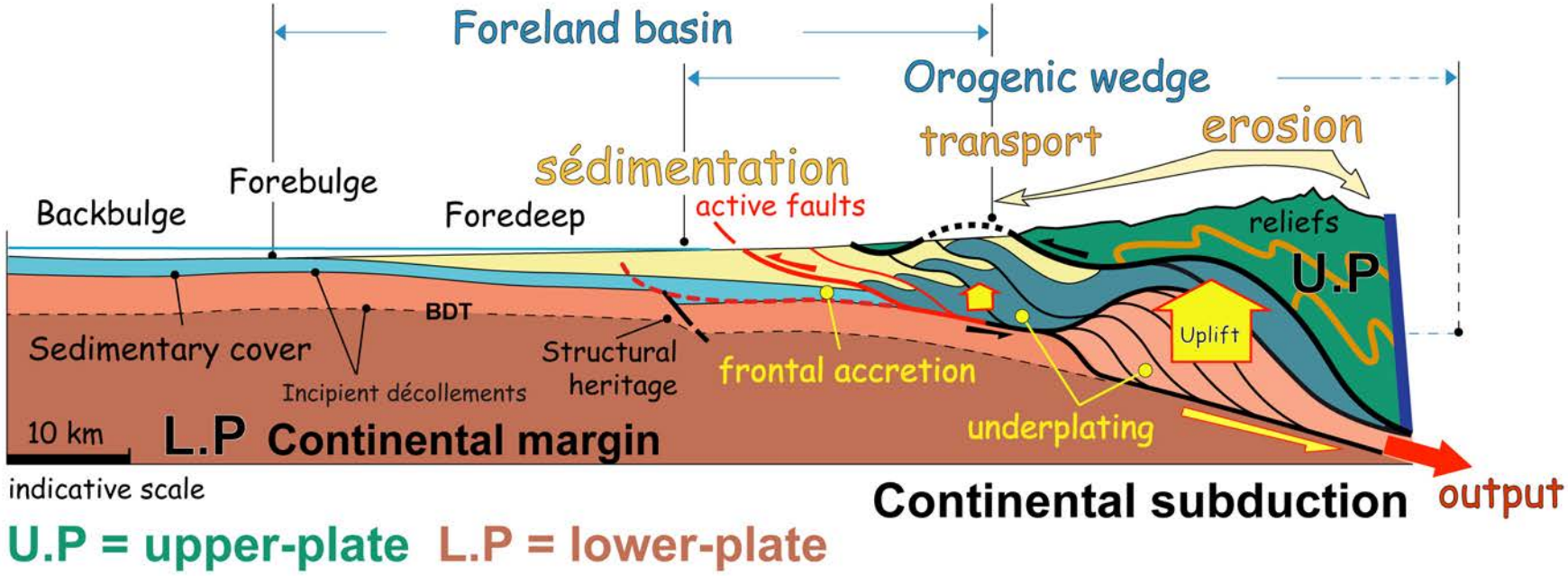
Hercynian belt of NW Spain







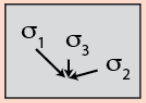
Coupling tectonics & surface processes



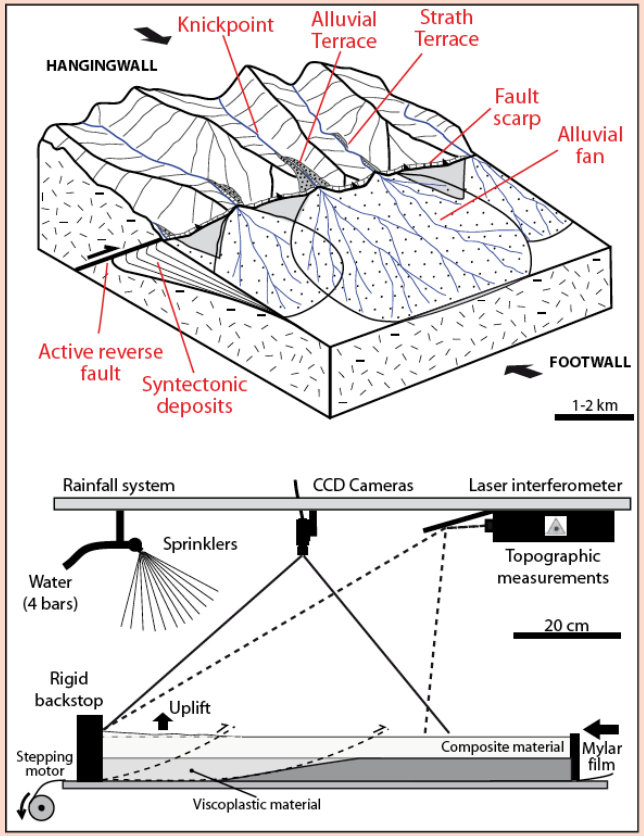
- Complex balance between tectonics and surface processes at different time scales
- Mechanical evolution is affected by material transfer
- Deformation partitioning & structural heritage play a major role
- Deformation controls the evolution of morphology

Deformation and climate dependant surface processes control the evolution of morphology and landscapes

Thrust fault setting

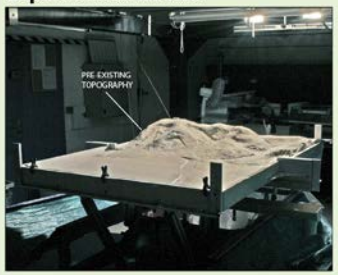


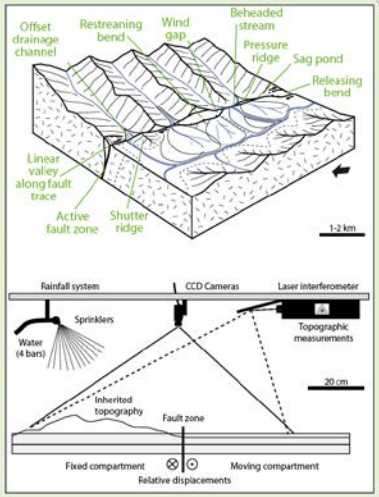
Experimental device



Strike-slip fault setting

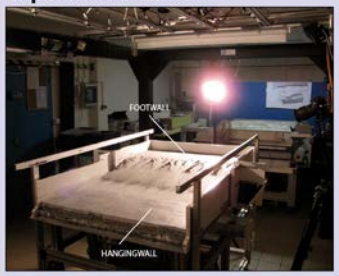
Experimental device

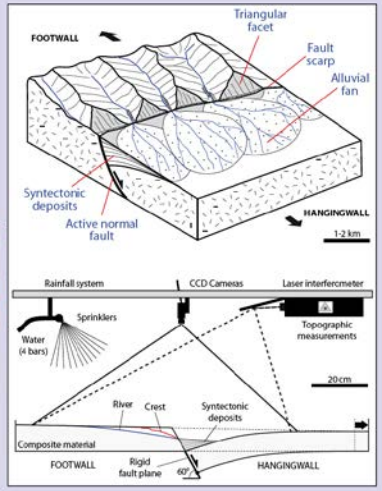




Normal fault setting

Experimental device

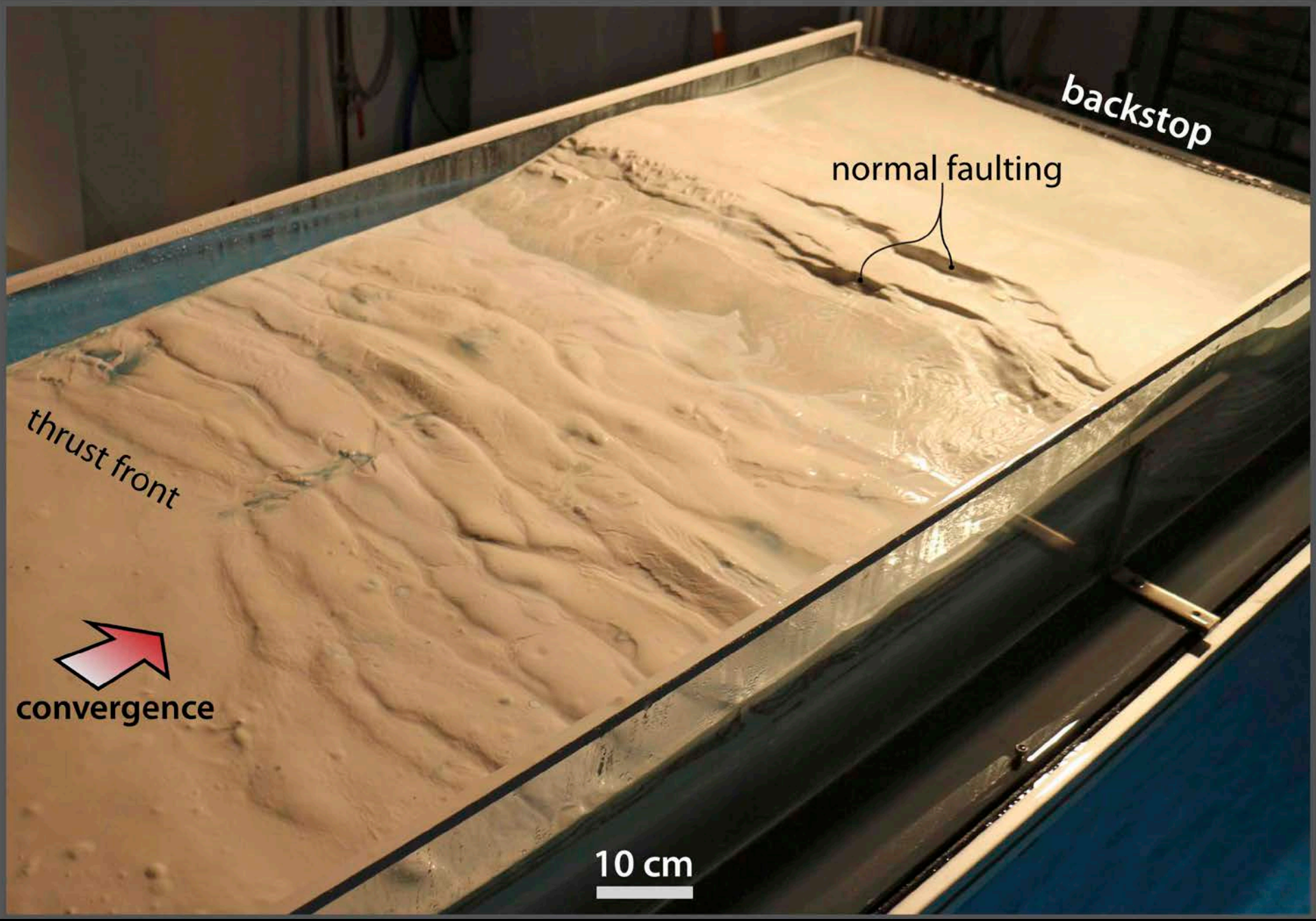




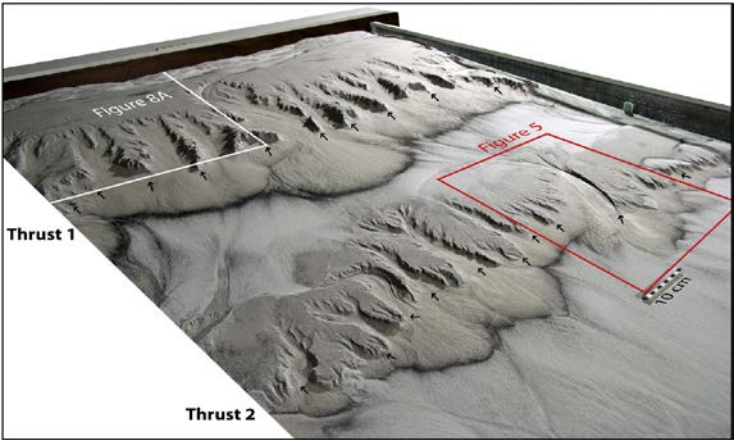

foreland experiment

top view

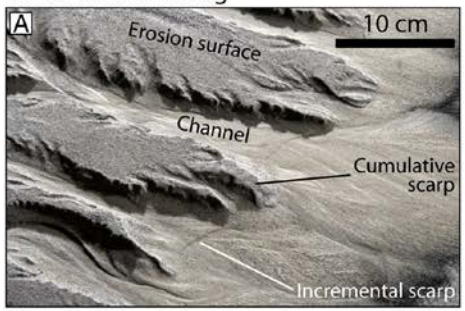
Graveleau 2008
(Phd)

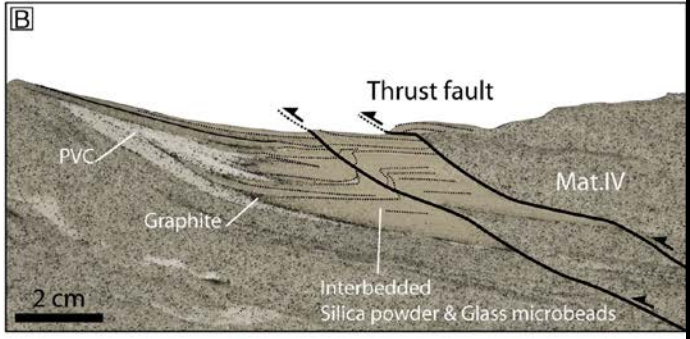


Hamon et al., 2018

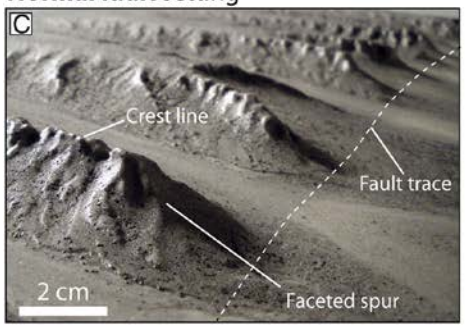


Thrust fault setting

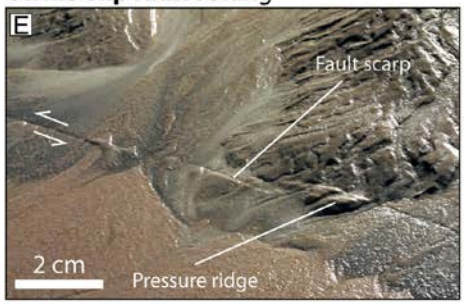


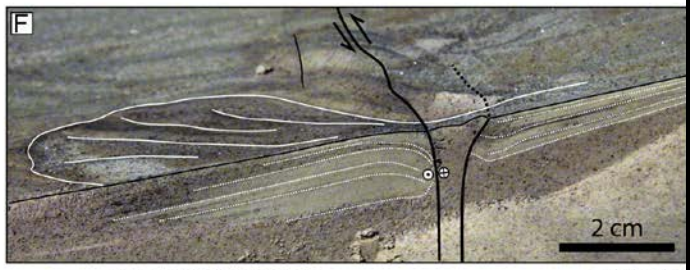


Normal fault setting

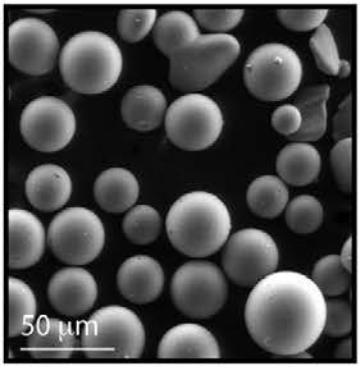


Strike-slip fault setting

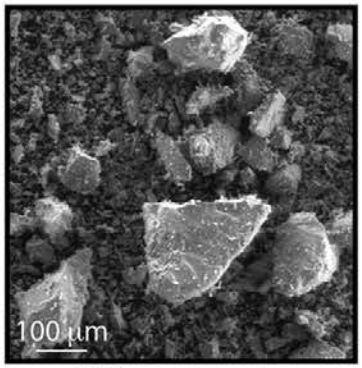




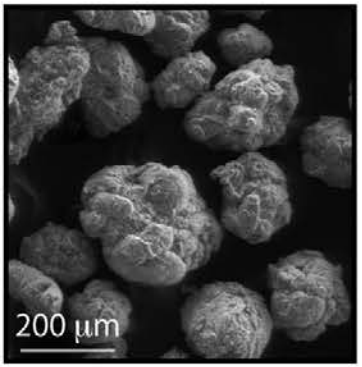
specific new materials



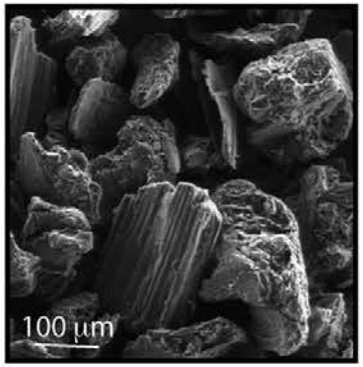
Glass microbeads



Silica powder

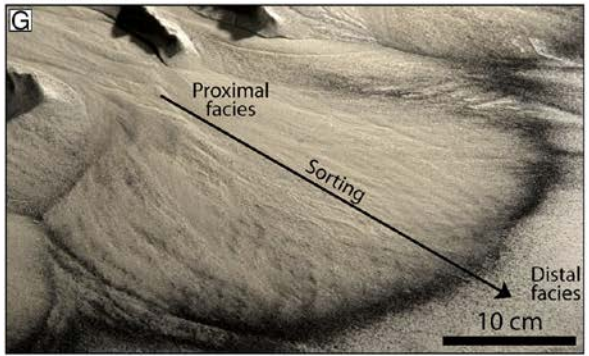


Plastic powder

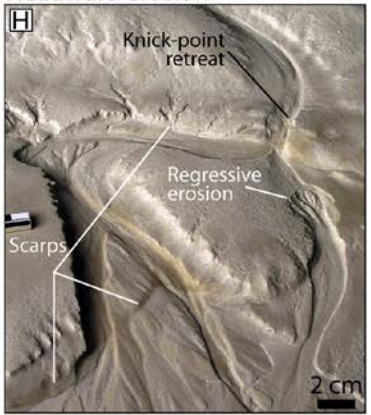


Graphite powder

Alluvial fan



Headward erosion

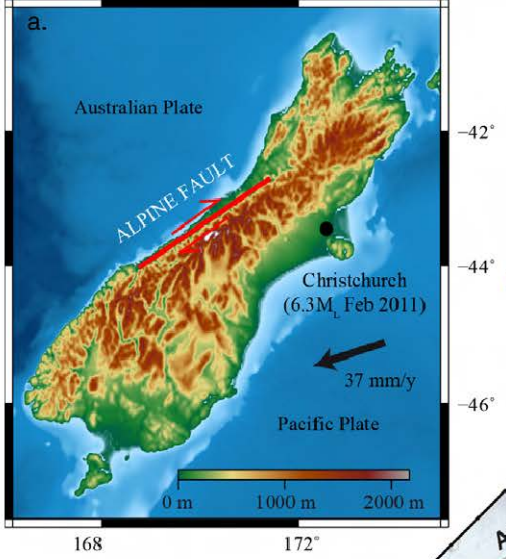


Terraces

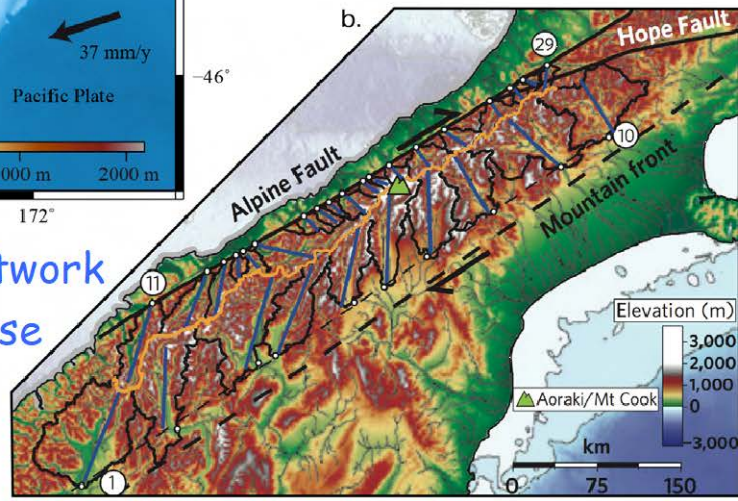
Oblique convergence (long term)

How to infer deformation partitioning from the analysis of morphology ?

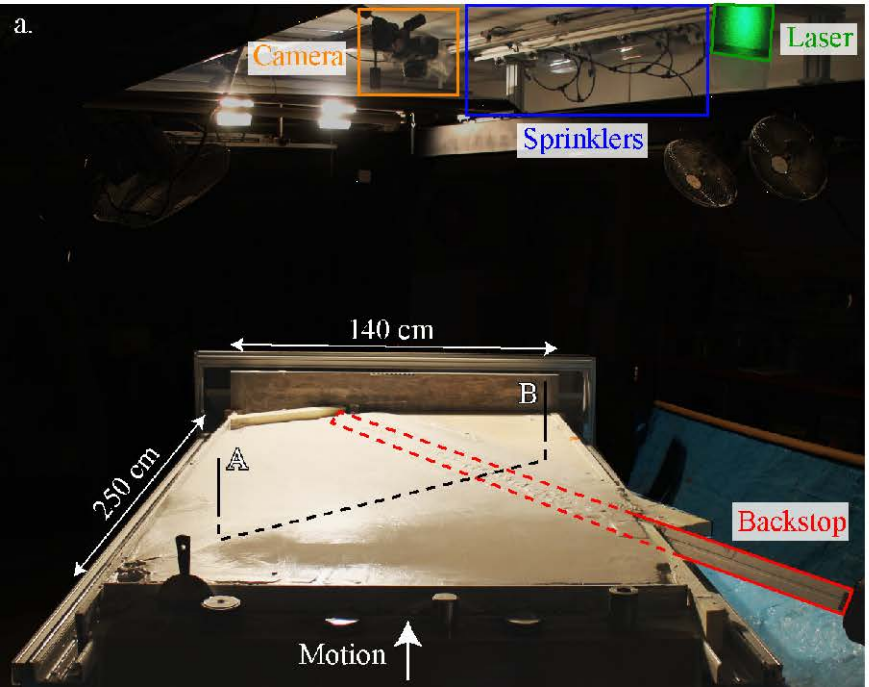
Some research tracks

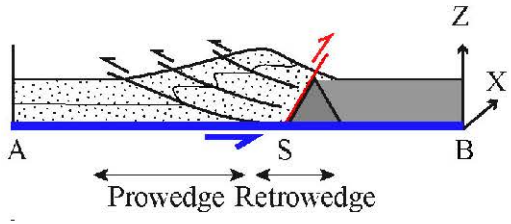


Castelltort et al., 2012



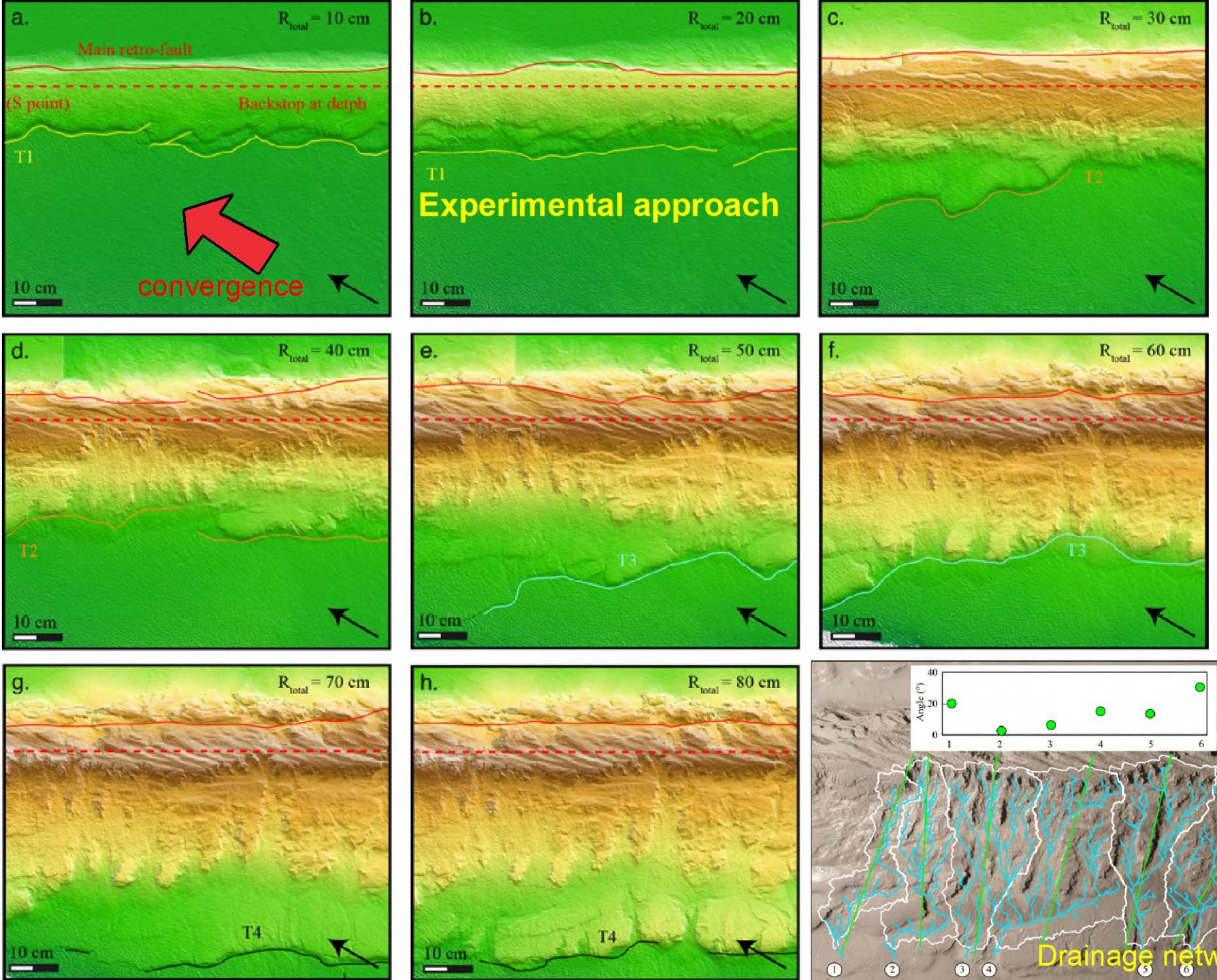
Deformation of drainage network in oblique collision : New-Zealand case



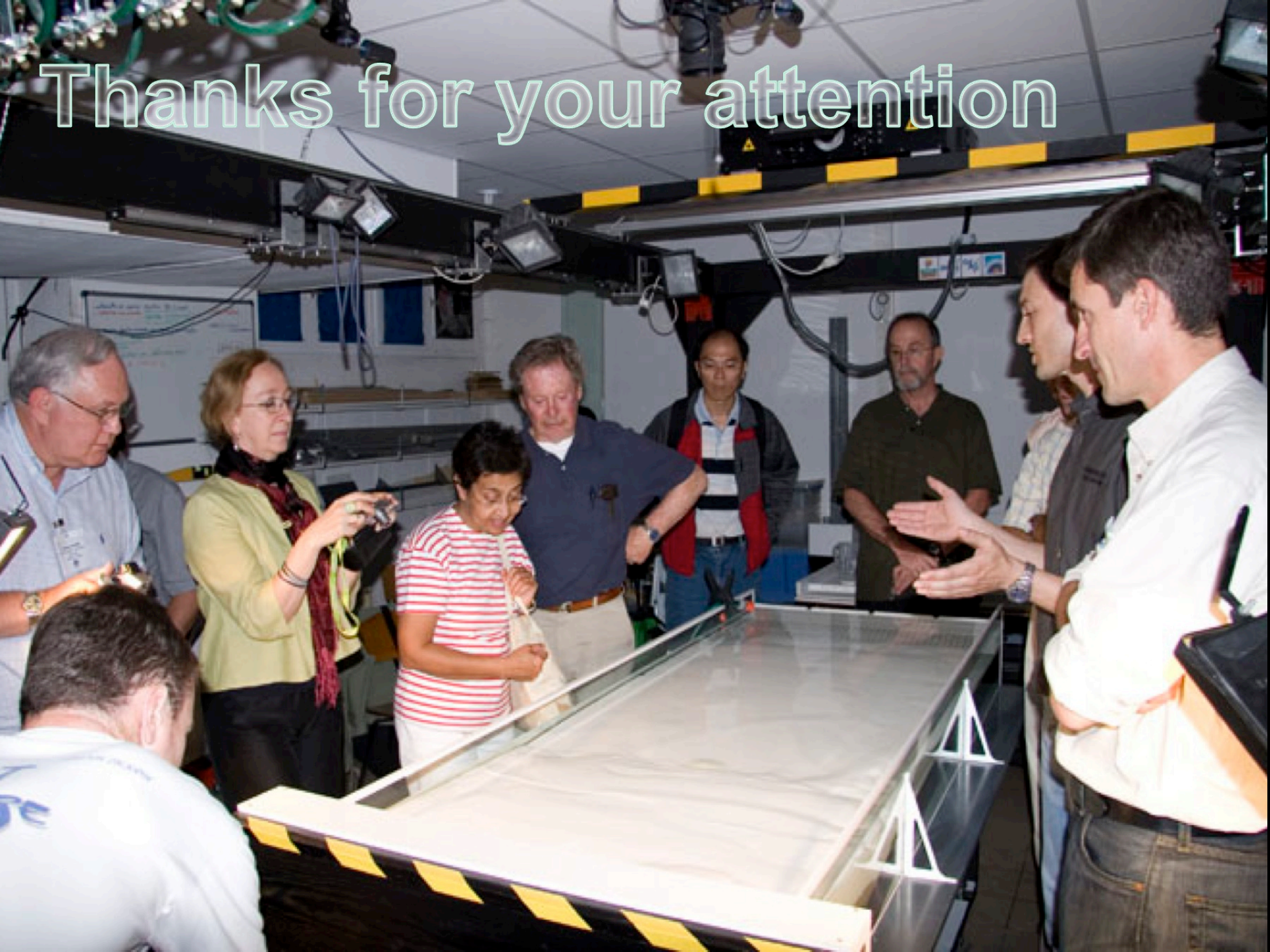


Geomorphic experiments with erosion, sediment transport and deposition

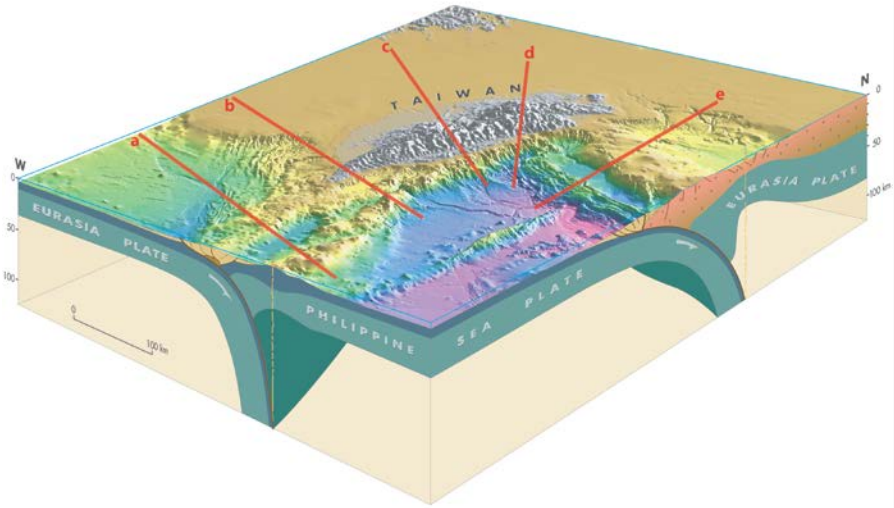
Guerit et al., 2016



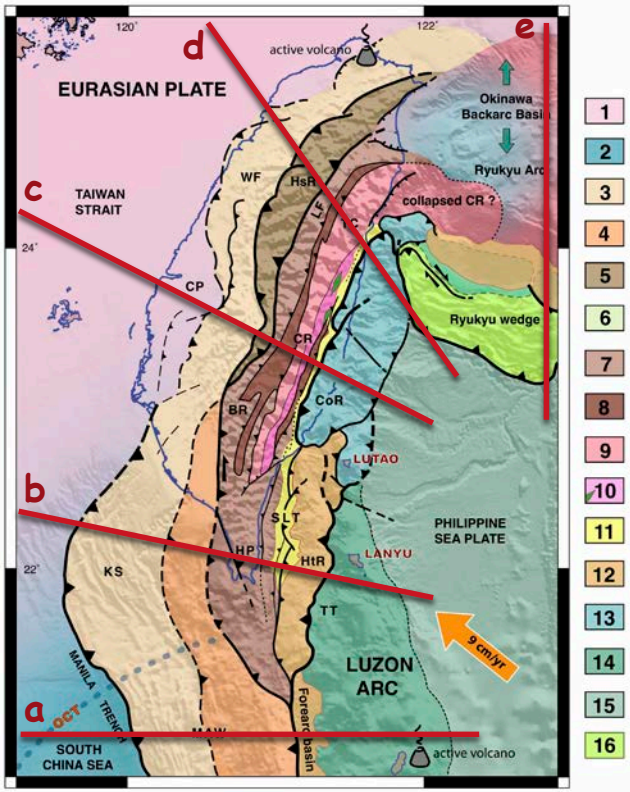
Guerit et al., 2016

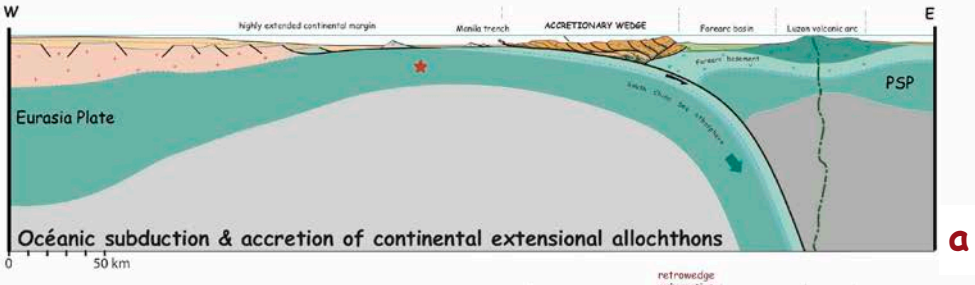

Thanks for your attention

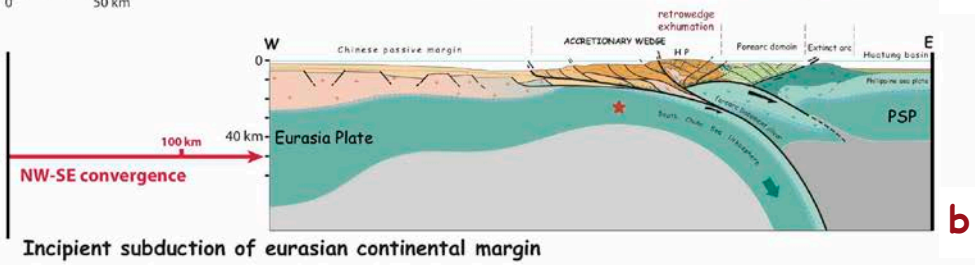
Available for teaching (on Youtube)…

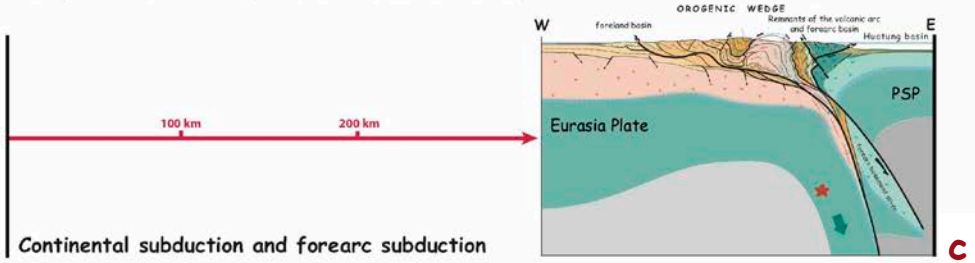


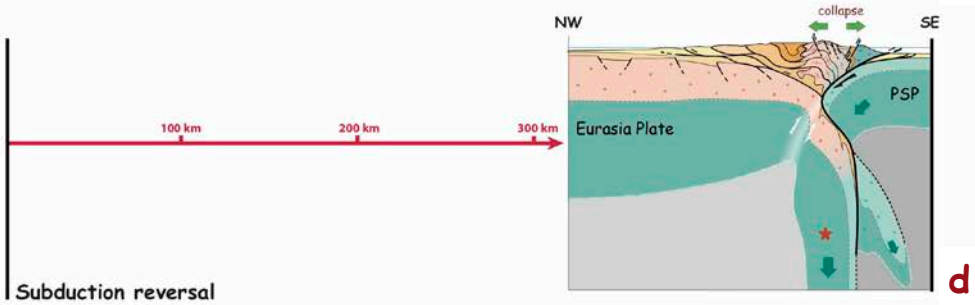
Impact on orogenic processes...



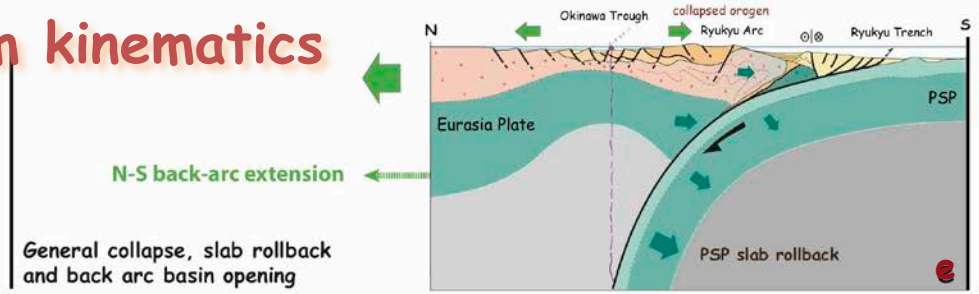




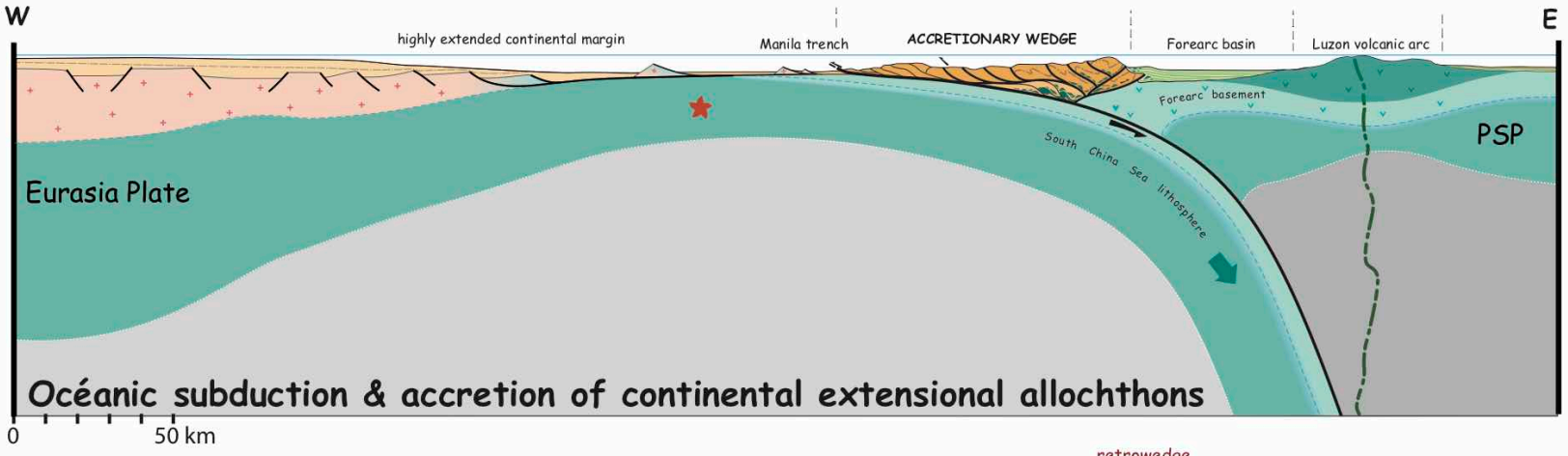




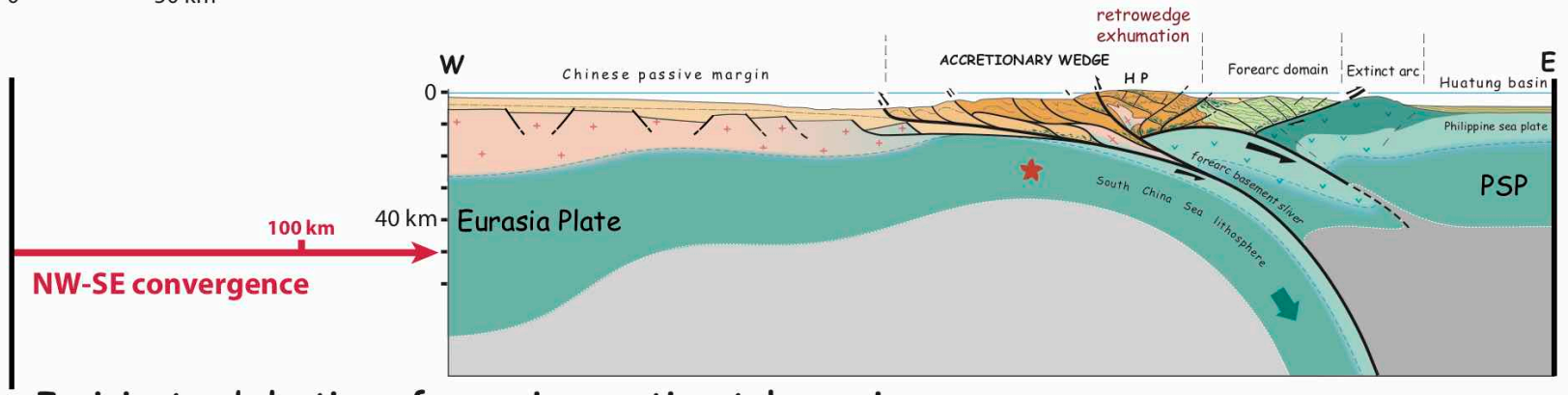
long term kinematics



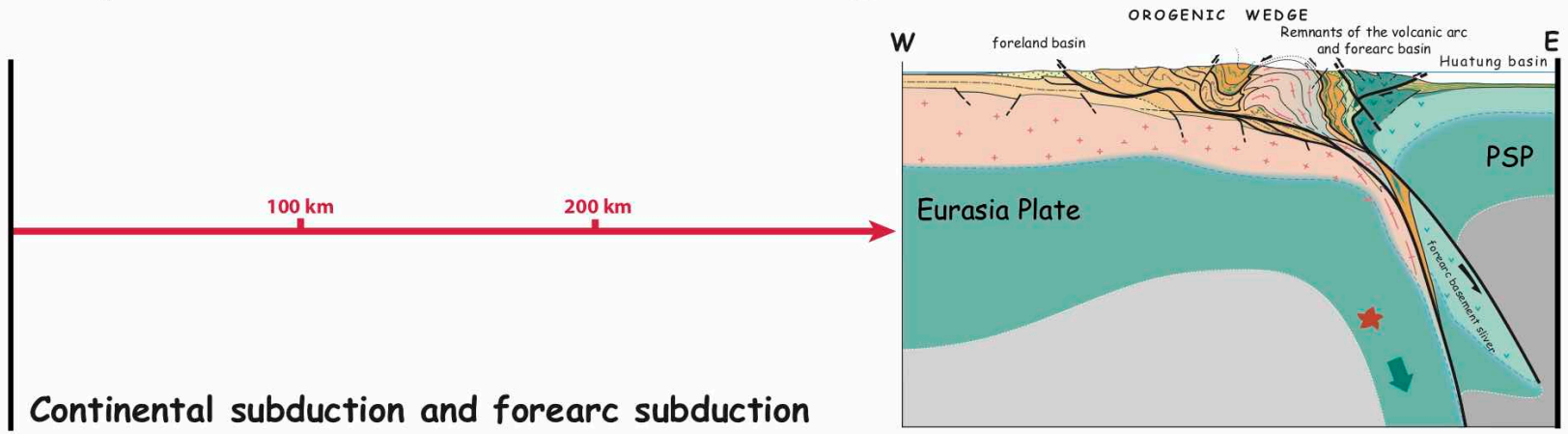
Malavieille et al., 2019


W
E
highly extended continental margin
Manila trench
ACCRETIONARY WEDGE
Forearc basin
Luzon volcanic arc
Forearc basement
PSP
South China Sea lithosphere
Eurasia Plate
Océanic subduction & accretion of continental extensional allochthons
0
50 km

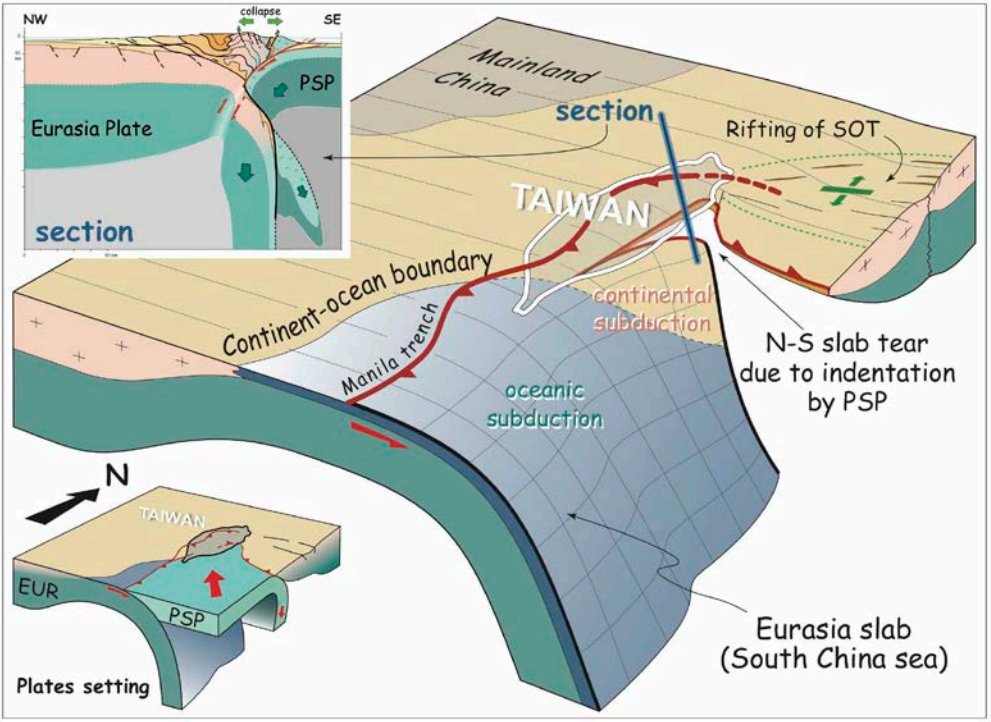
a

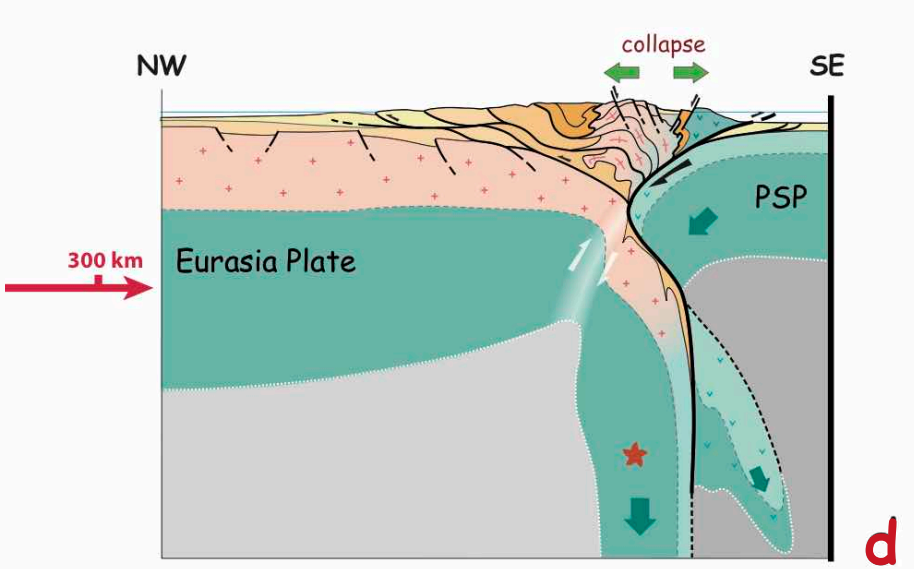

retrowedge exhumation
W
E
Chinese passive margin
ACCRETIONARY WEDGE
HP
Forearc domain
Extinct arc
Huatung basin
Philippine sea plate
0
40 km
100 km
NW-SE convergence
Eurasia Plate
South China Sea lithosphere
forearc basement sliver
PSP
Incipient subduction of eurasian continental margin

b


OROGENIC WEDGE
W
E
foreland basin
Remnants of the volcanic arc and forearc basin
Huatung basin
PSP
100 km
200 km
Eurasia Plate
forearc basement sliver
Continental subduction and forearc subduction

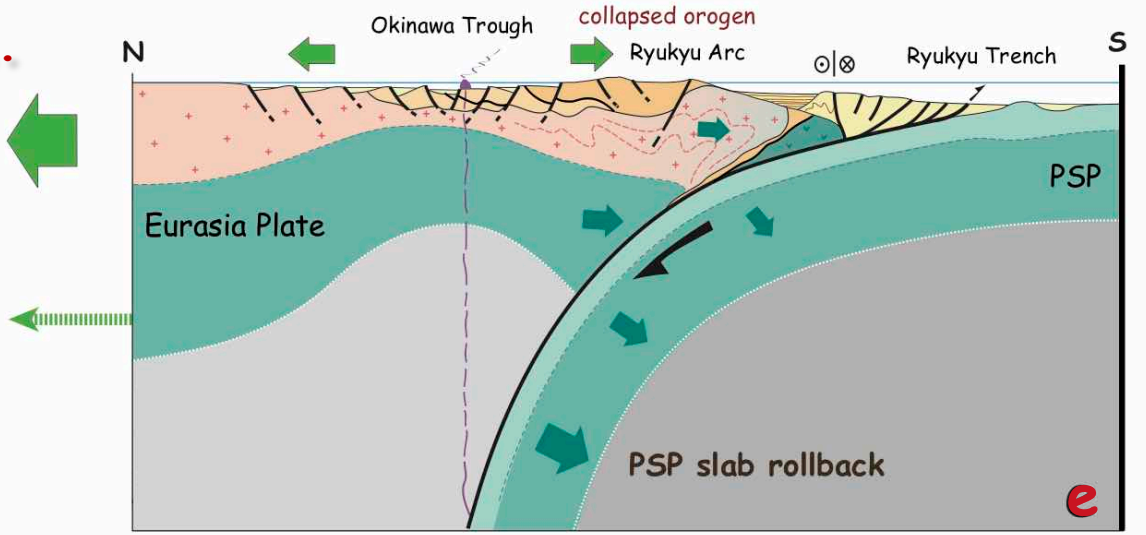
c





Subduction reversal

A complex 3D evolution...



N-S back-arc extension

General collapse, slab rollback and back arc basin opening

final stages characterize different styles of forelands

Sedimentation

\+

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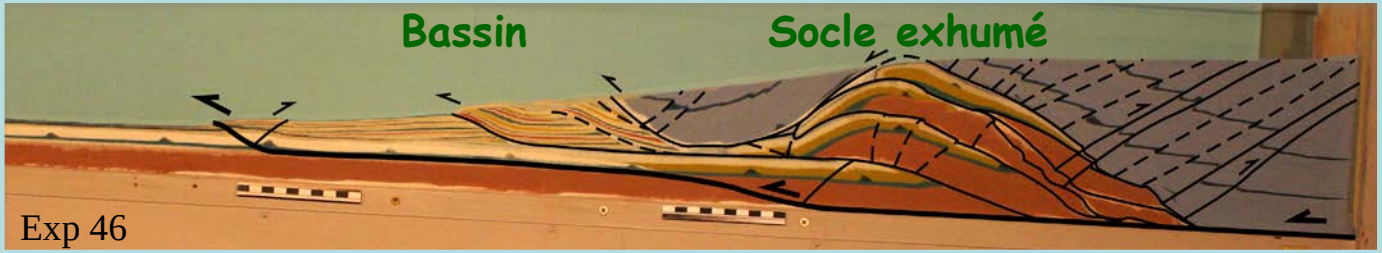
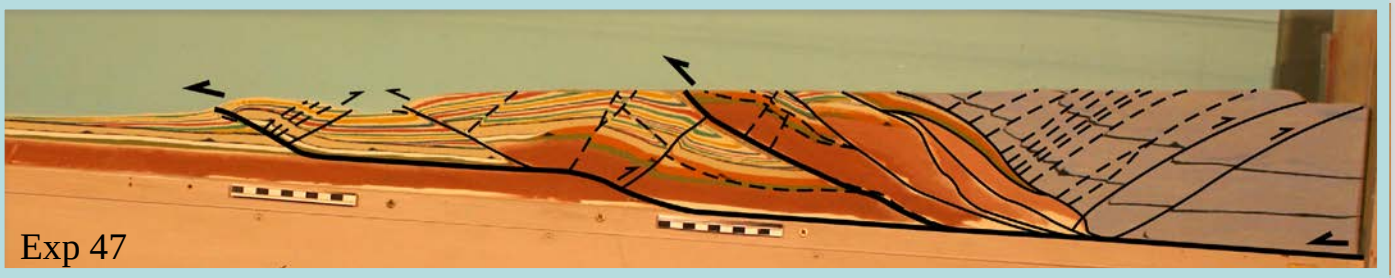
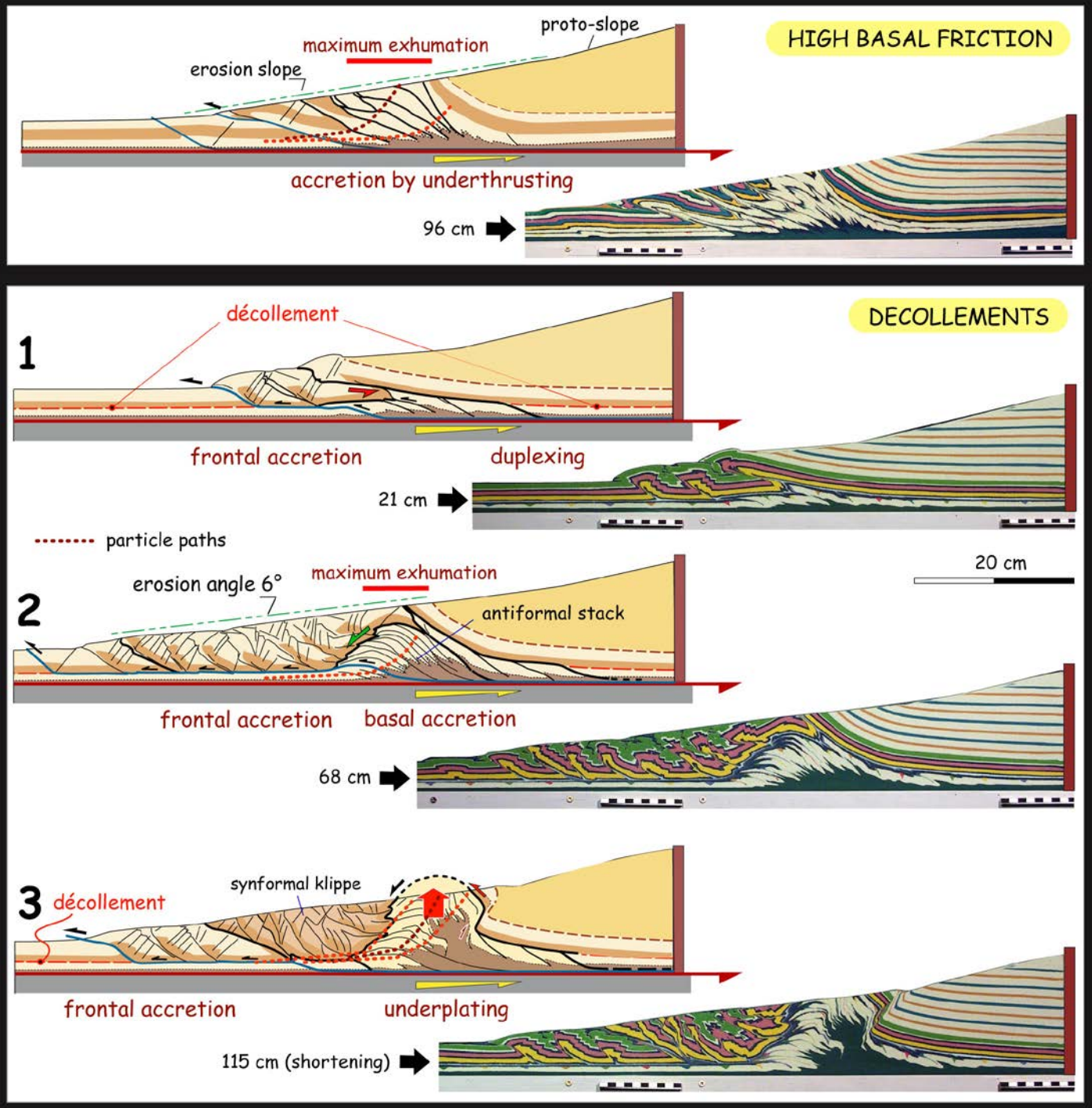
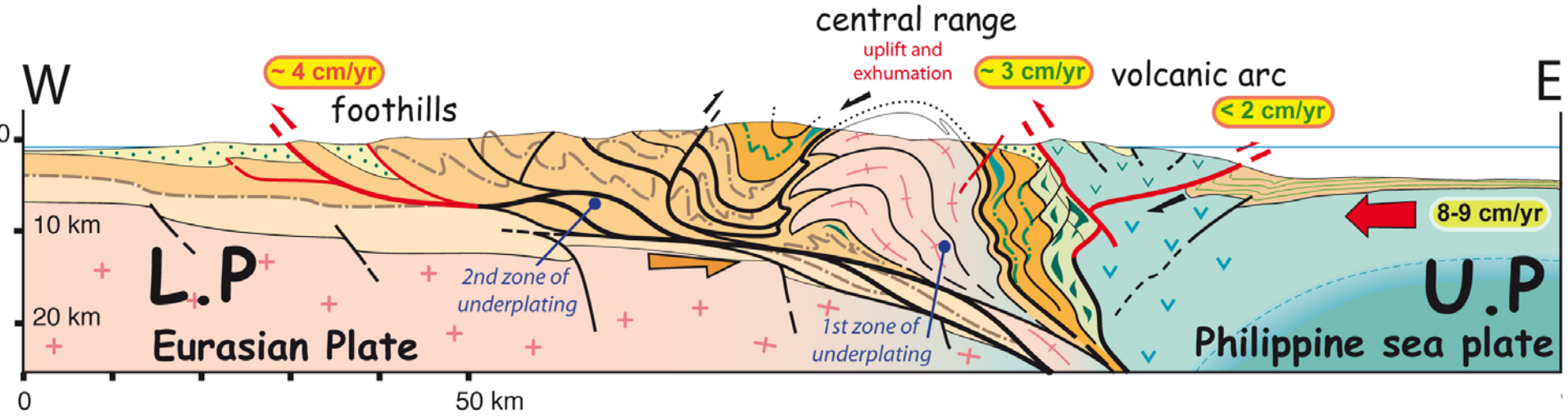
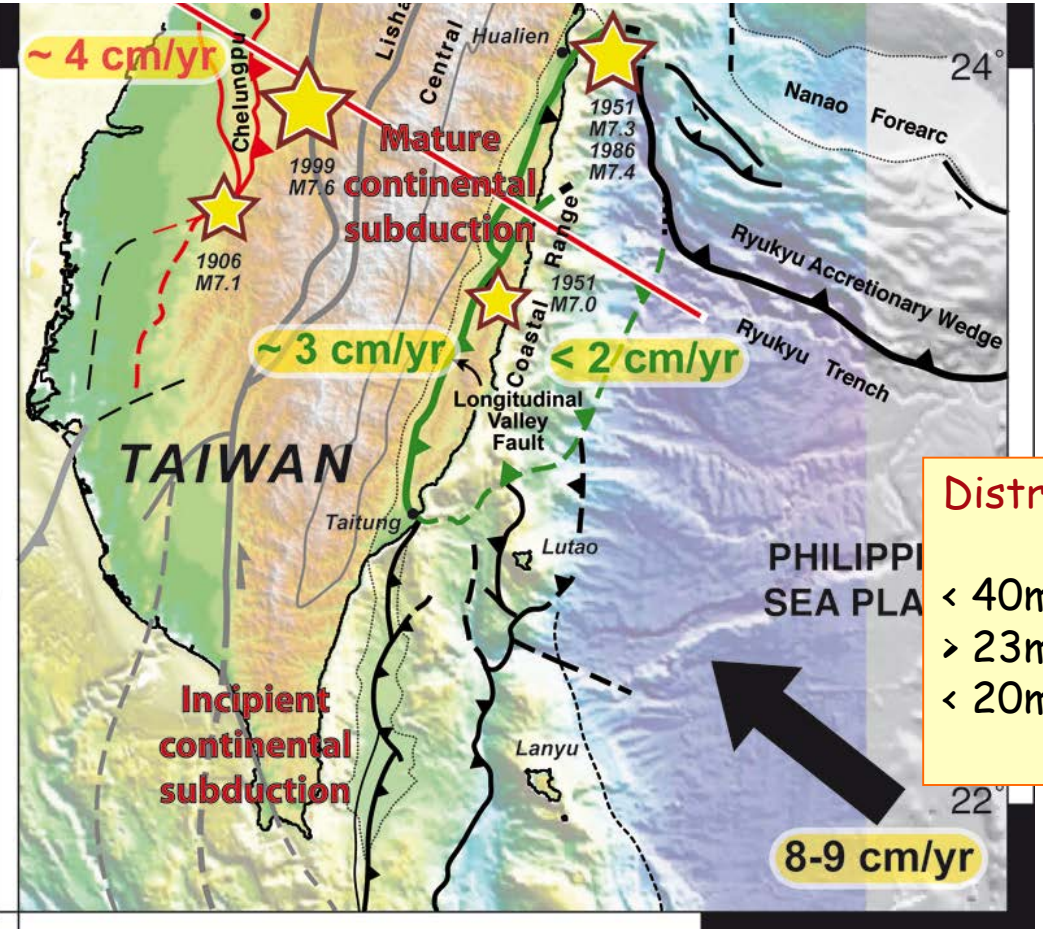





HIGH BASAL FRICTION
proto-slope
maximum exhumation
erosion slope
accretion by underthrusting
96 cm
DECOLLEMENTS
1
décollement
frontal accretion
duplexing
21 cm
particle paths
20 cm
2
erosion angle 6°
maximum exhumation
antiformal stack
frontal accretion
basal accretion
68 cm
3
décollement
synformal klippe
frontal accretion
underplating
115 cm (shortening)
Underplating + erosion
Fast and localized exhumation





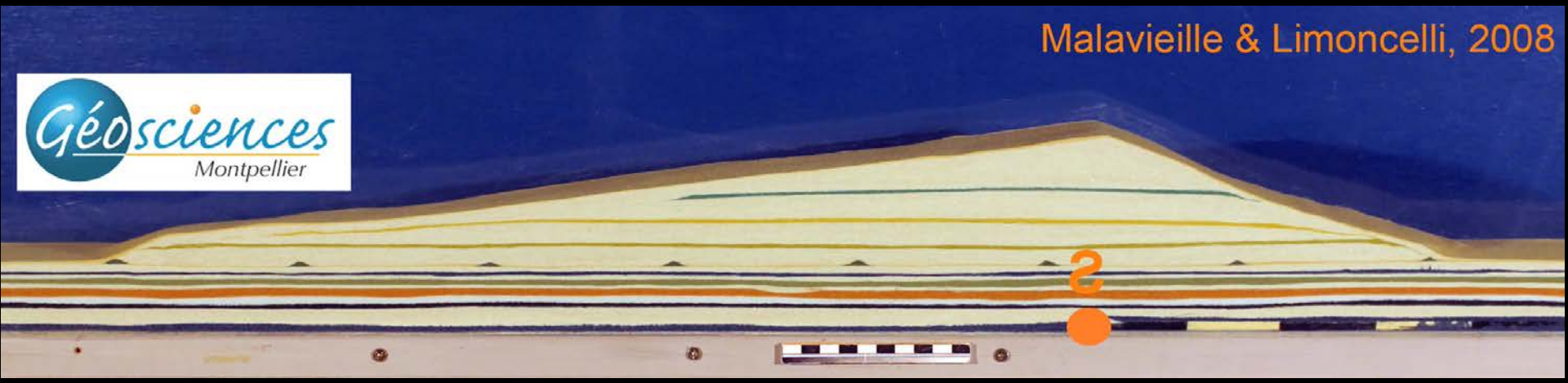
Average shortening rates estimated on major faults

Distribution in the wedge:

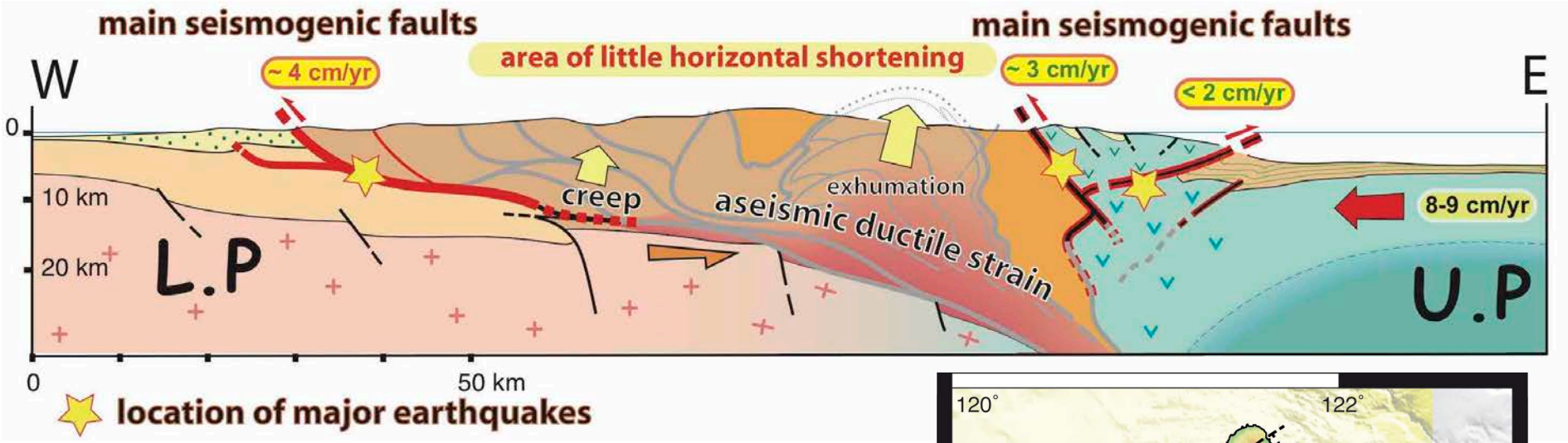
< 40mm/yr (Foothills, Simoes et al., 2006)
> 23mm/yr (Longitudinal Valley, Shyu, et al., 2007)
< 20mm/yr (Offshore, Malavieille et al., 2002)

Another consequence…

A doubly vergent wedge with a strong erosion & a décollement



A surprising behavior…

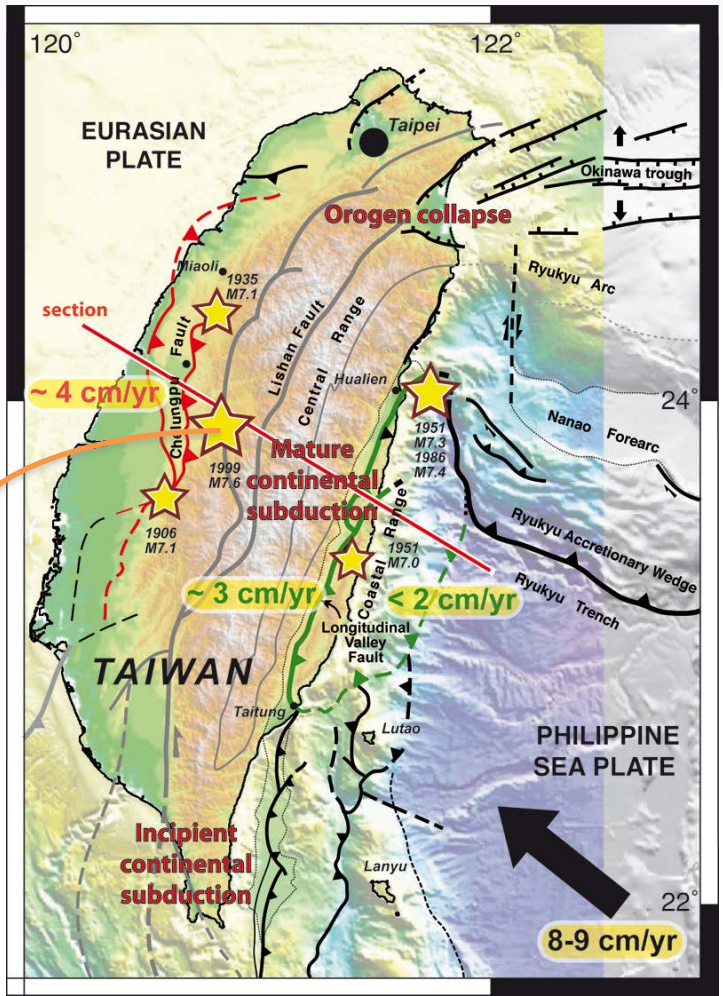


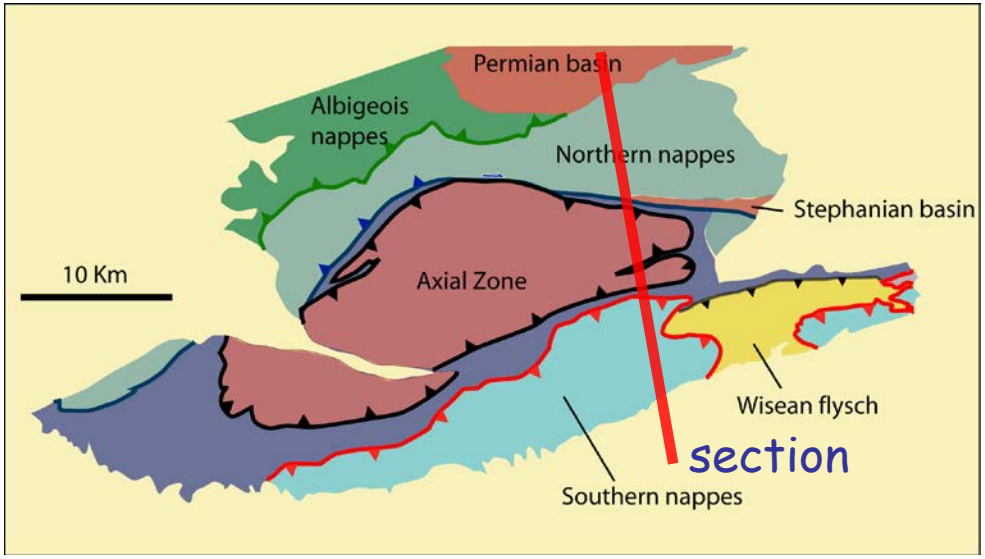
Strain partitioning
(ductile vs brittle)
and seismic behavior

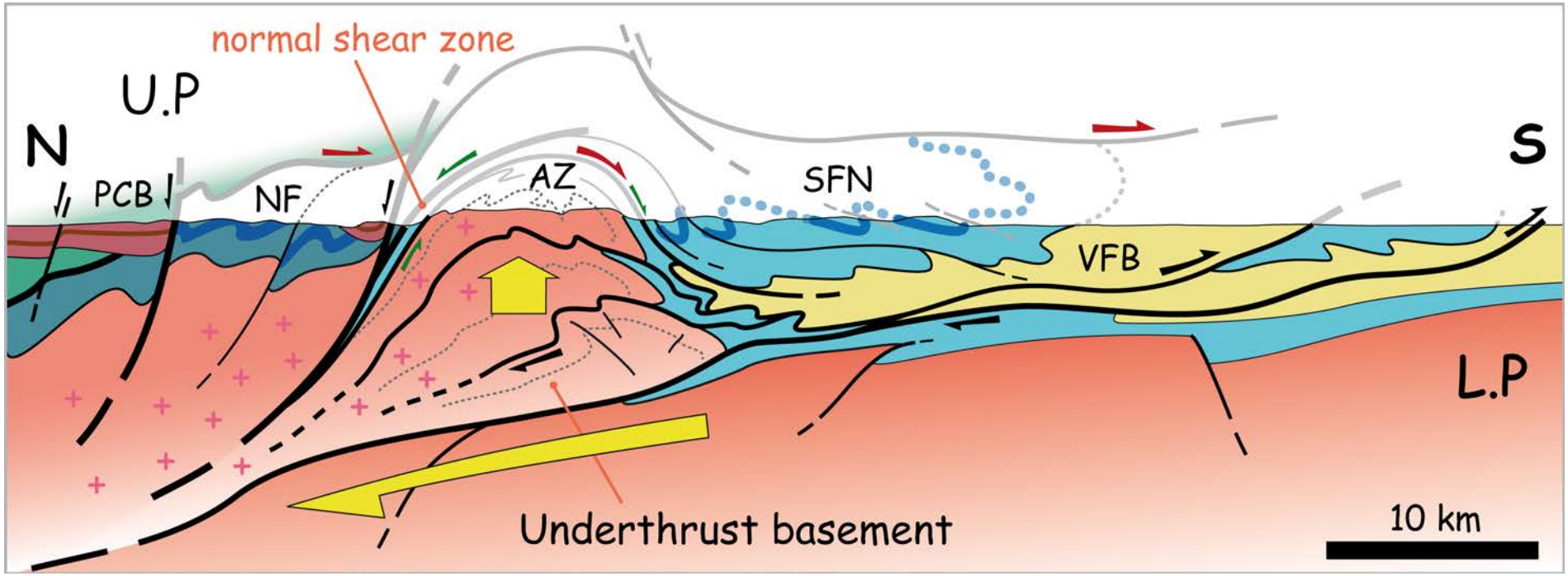
(location of faults prone to generate big quakes)

Big earthquakes

Impact of deformation partitioning on the location of big earthquakes

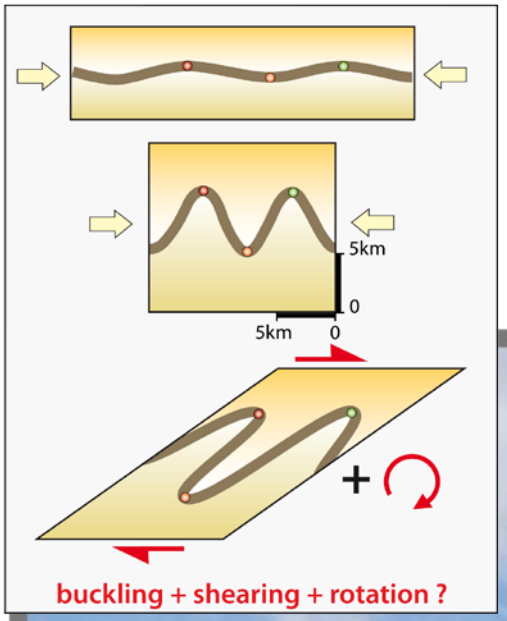


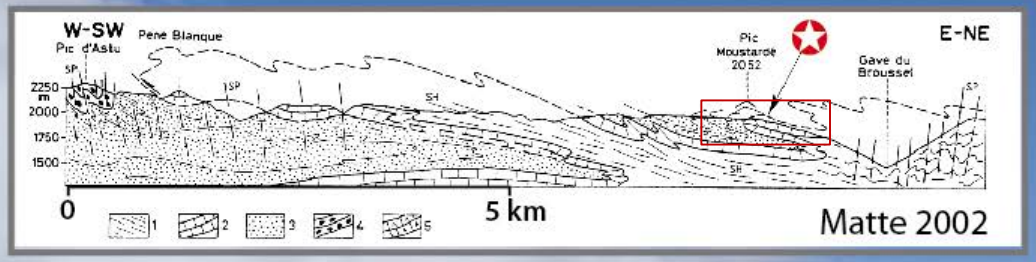

Permian basin
Albigeois nappes
Northern nappes
Stephanian basin
10 Km
Axial Zone
Wisean flysch
section
Southern nappes


normal shear zone
U.P
N
S
PCB
NF
AZ
SFN
VFB
L.P
Underthrust basement
10 km

• Complex rheologies

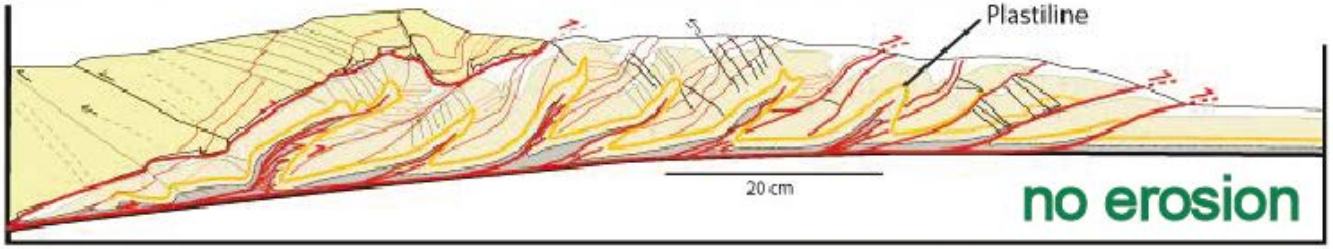
Folding processes ?



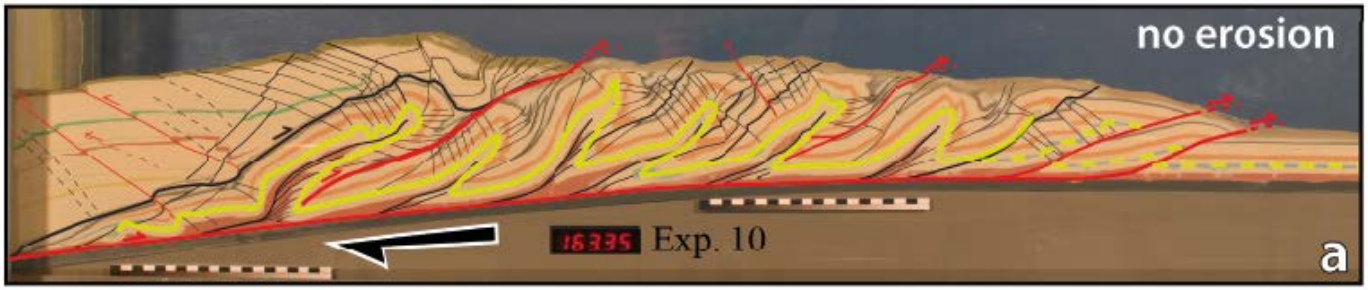


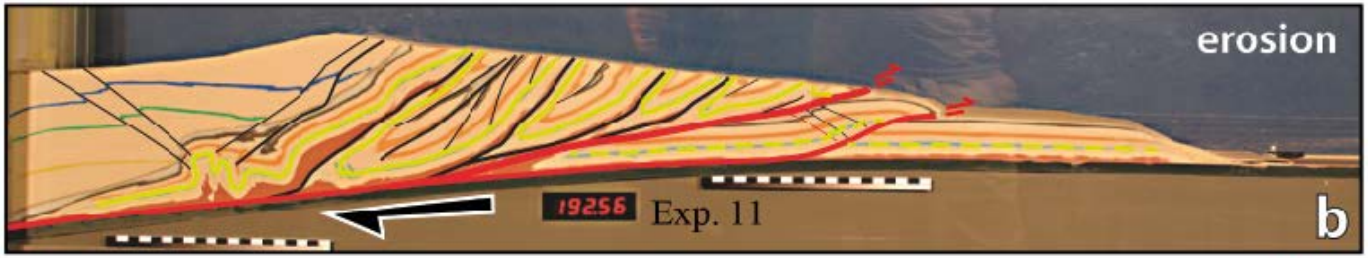
Pic Moustardé (Pyrénées)

brittle/plastic multilayer

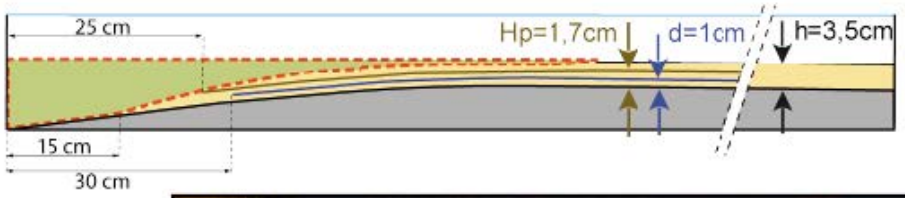


no erosion

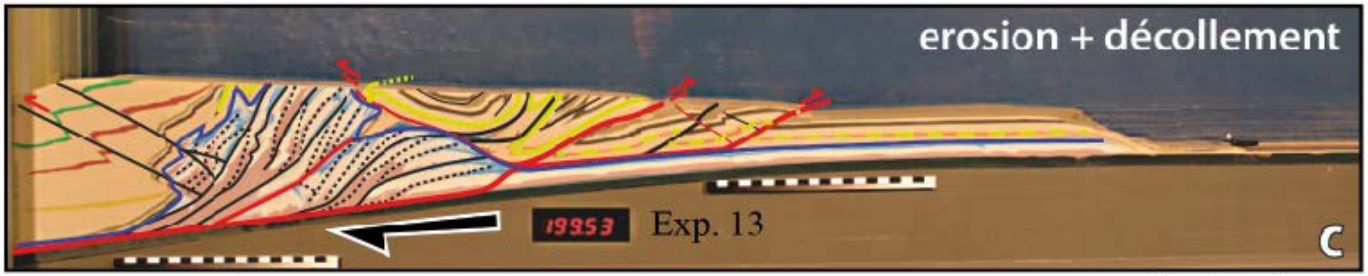




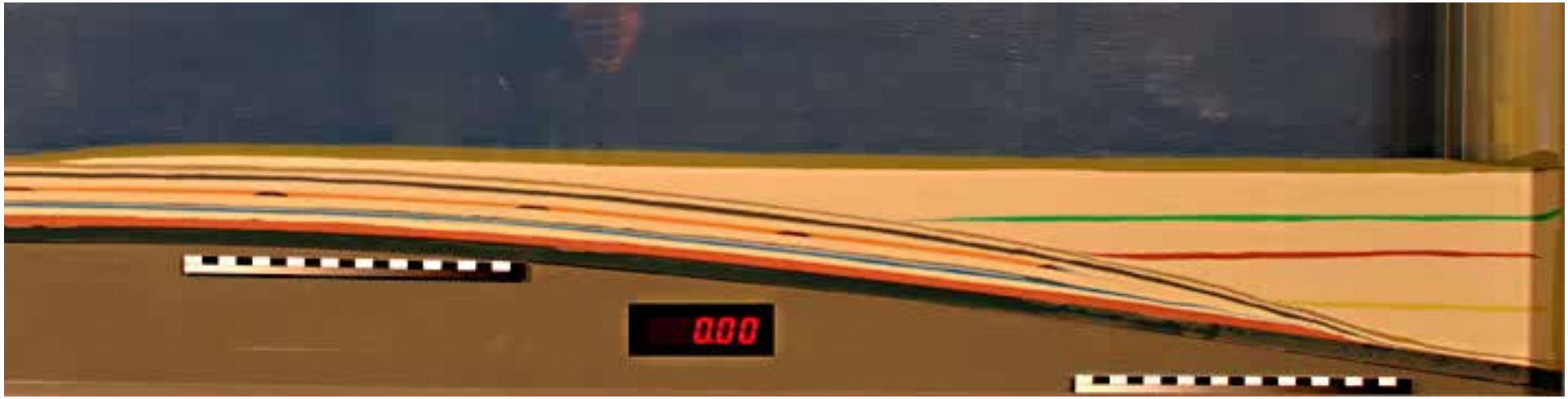
erosion



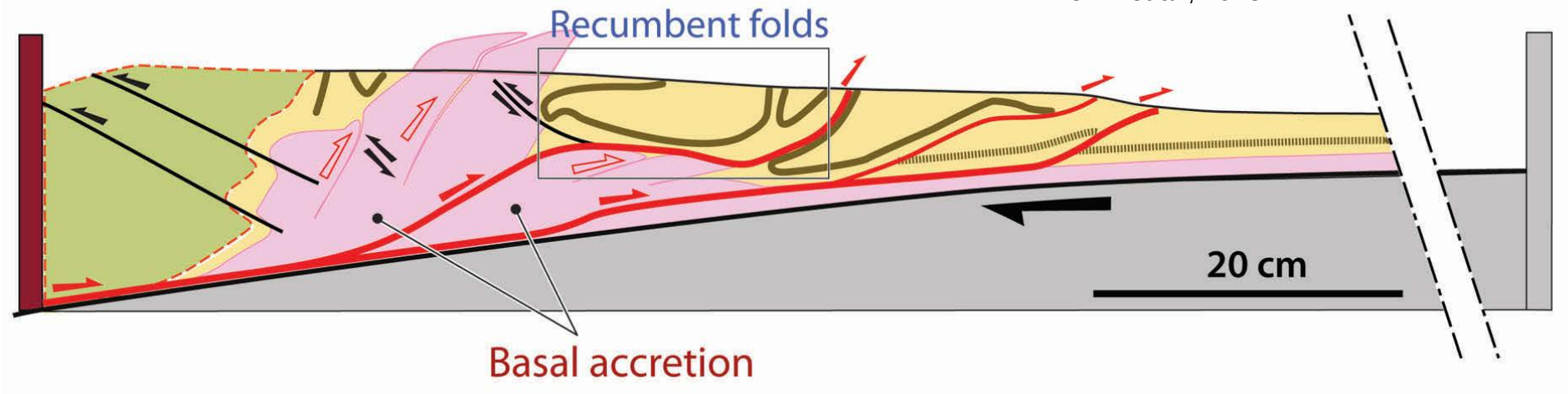
erosion + décollement



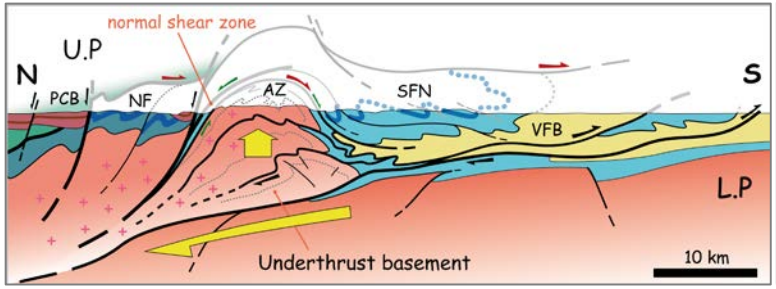
Active faults Inactive faults Décollement layer (microbeads) Plasticine layer



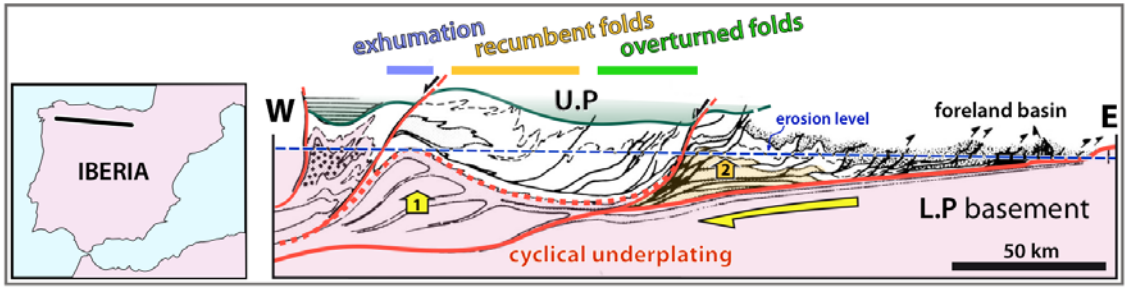
Perrin et al., 2013



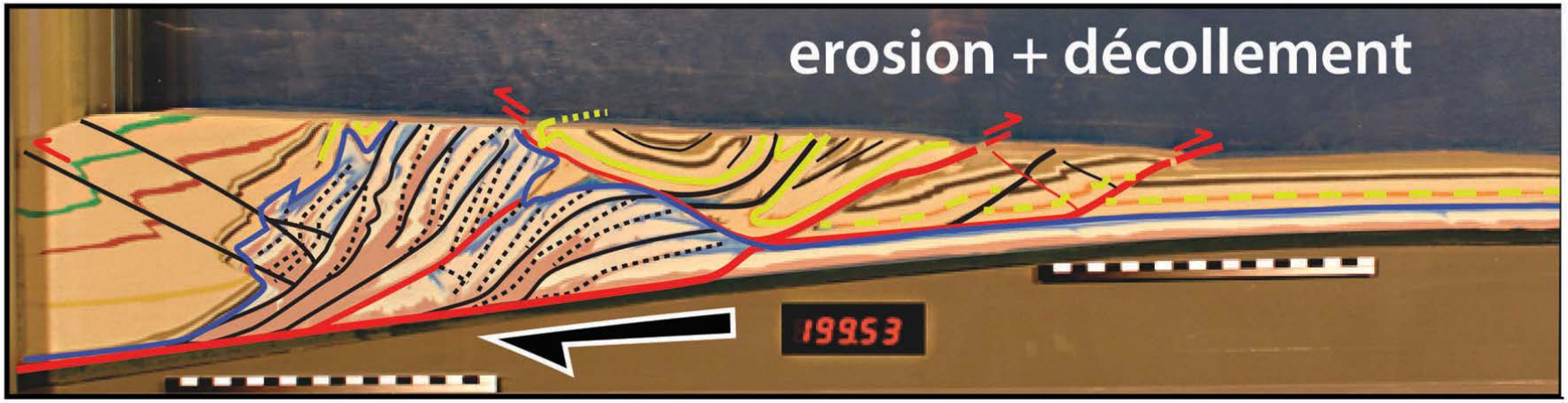
Montagne Noire



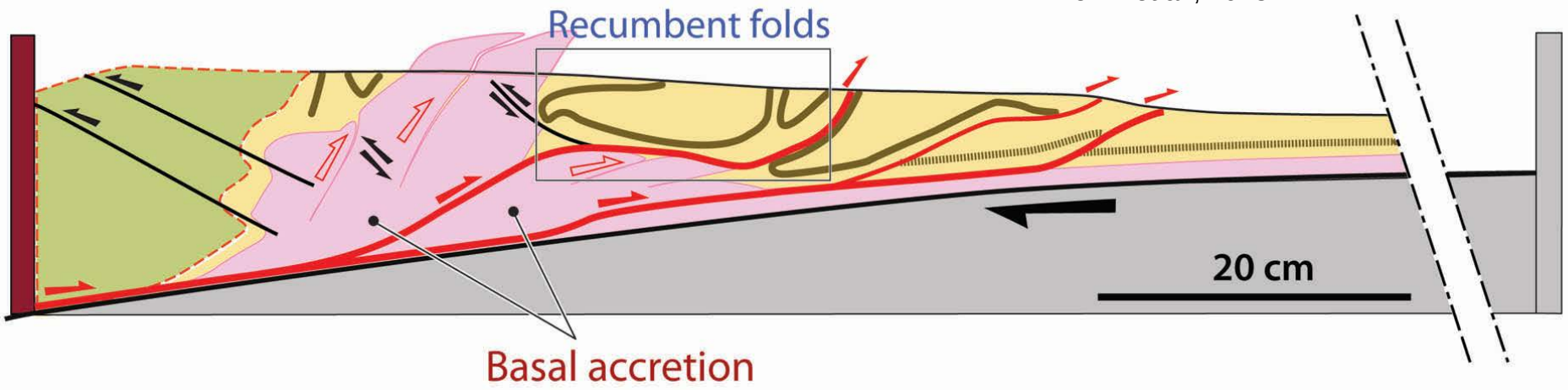
Iberian hercynian belt



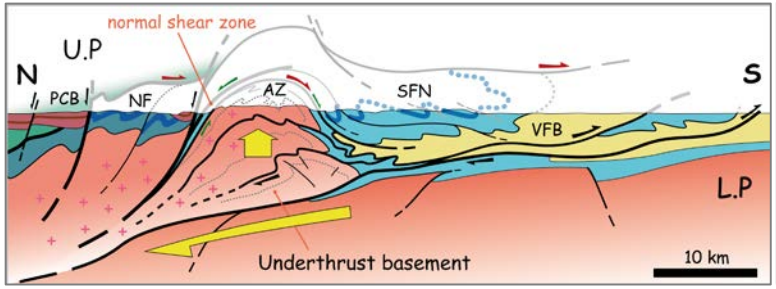
Perez-Estaun et al., 1991, modified



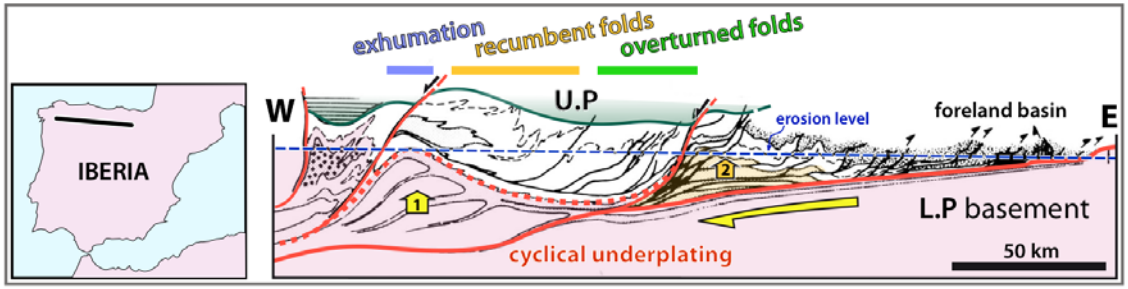
Perrin et al., 2013



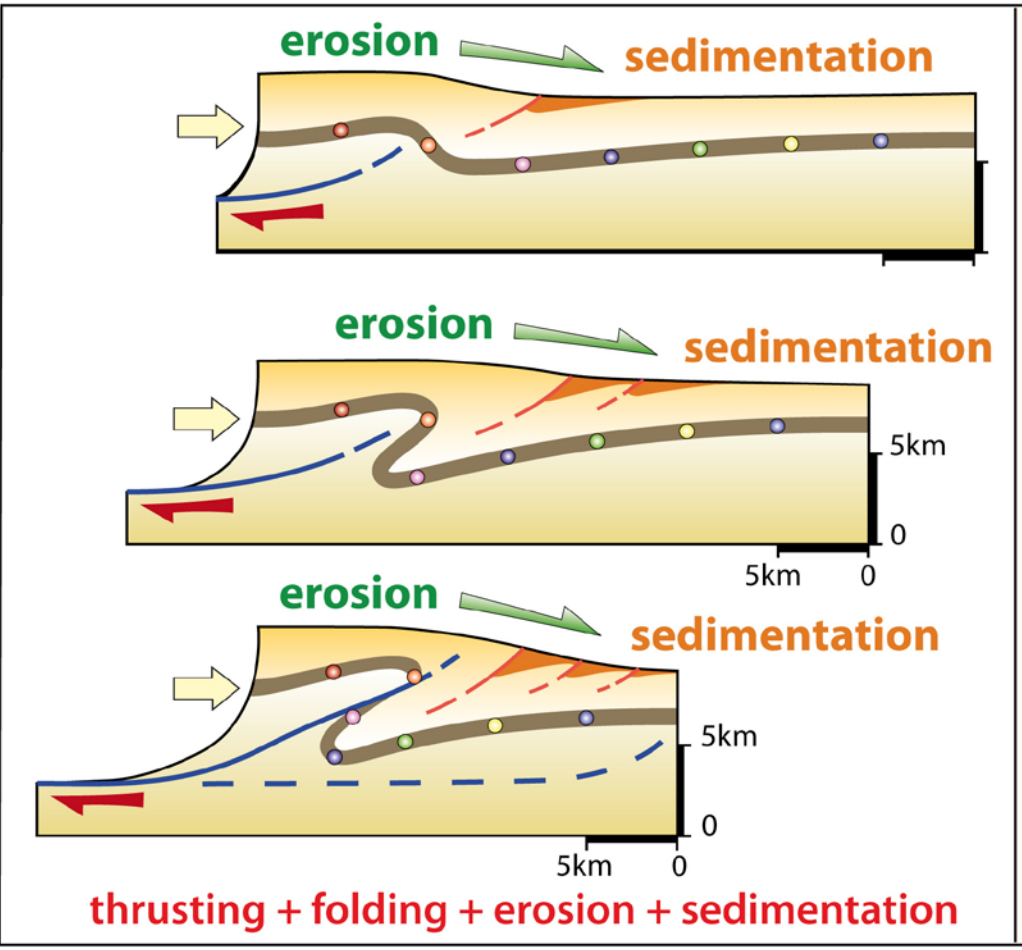
Montagne Noire

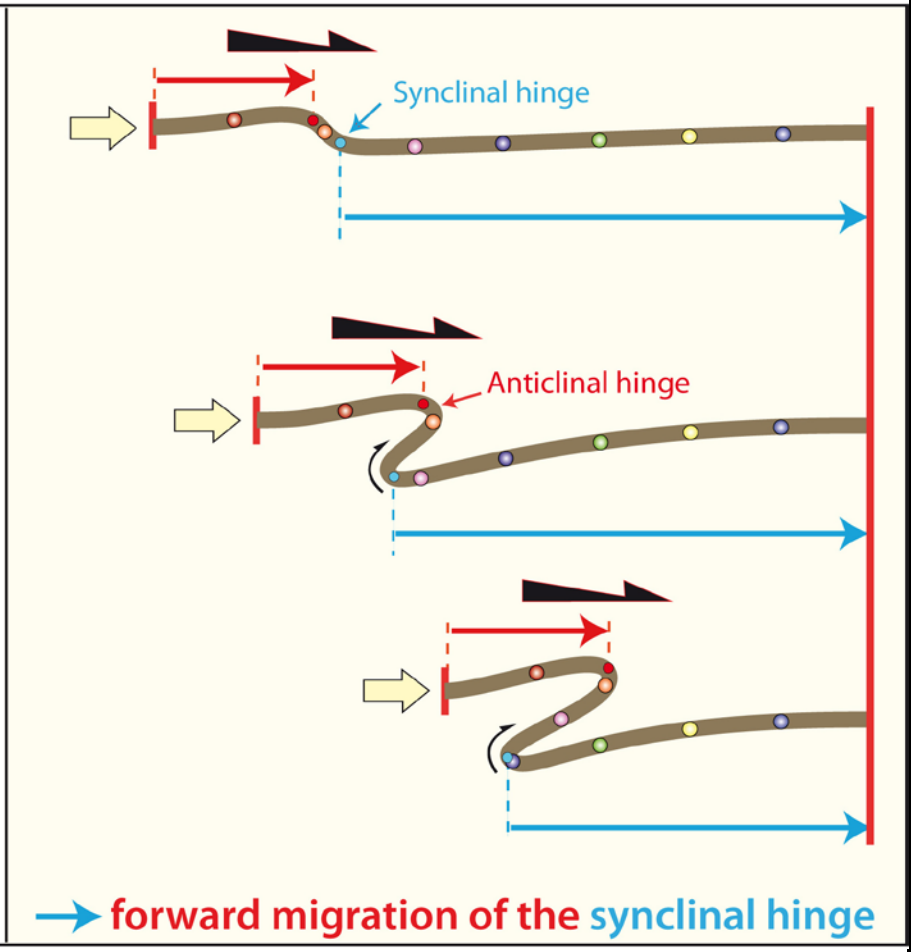


Iberian hercynian belt



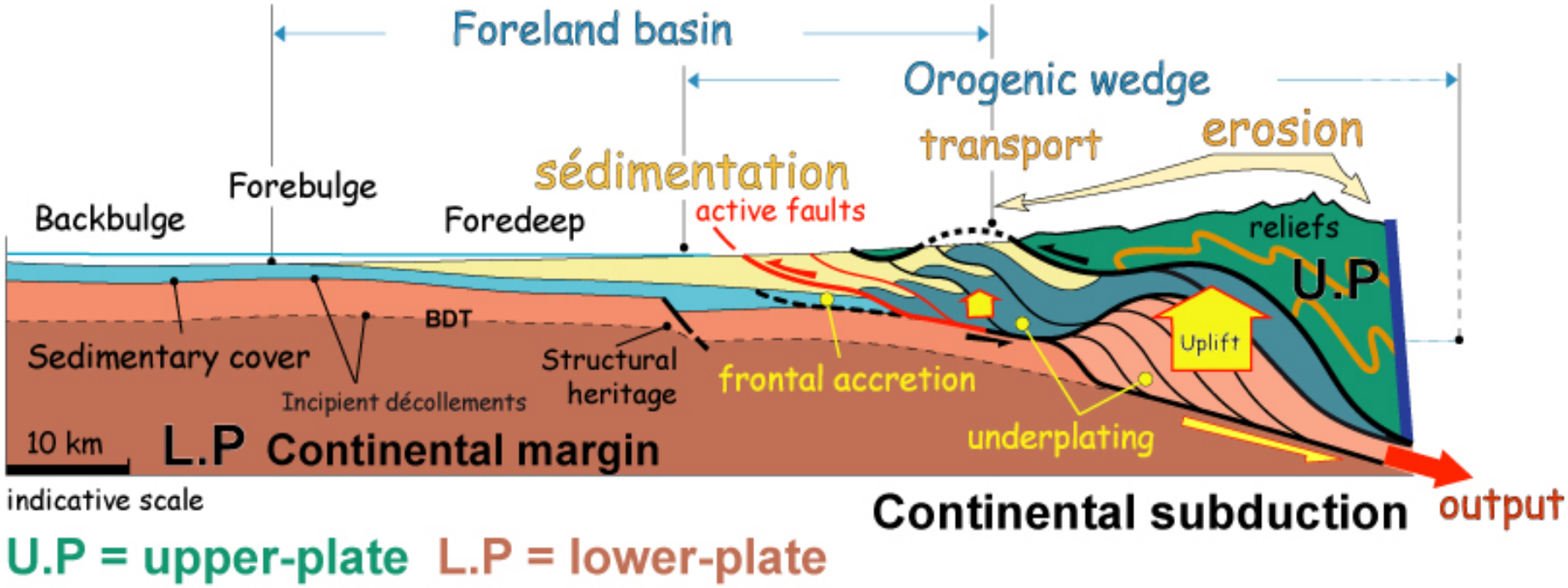
Perez-Estaun et al., 1991, modified





Folding & faulting mechanisms in fold and thrust belts

Wedge dynamics



- Complex balance between tectonics and surface processes.
- Material transfer (sediments coming from erosion),

behavior of the upper-plate, structural and/or mechanical heritage play a major role in the evolution of orogenic wedges.