Dynamic modelling of subducting slab interaction with transition zone

Huw DAVIES
(Cardiff University)
Fanny Garel, Rhodri Davies, Saskia Goes
Cian Wilson, Stephan Kramer, Rebekah Lawton

Collège de France, Paris ***December 2016***

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

Mantle Geo Deinameg Dynamics y Fantell

Imperial College London

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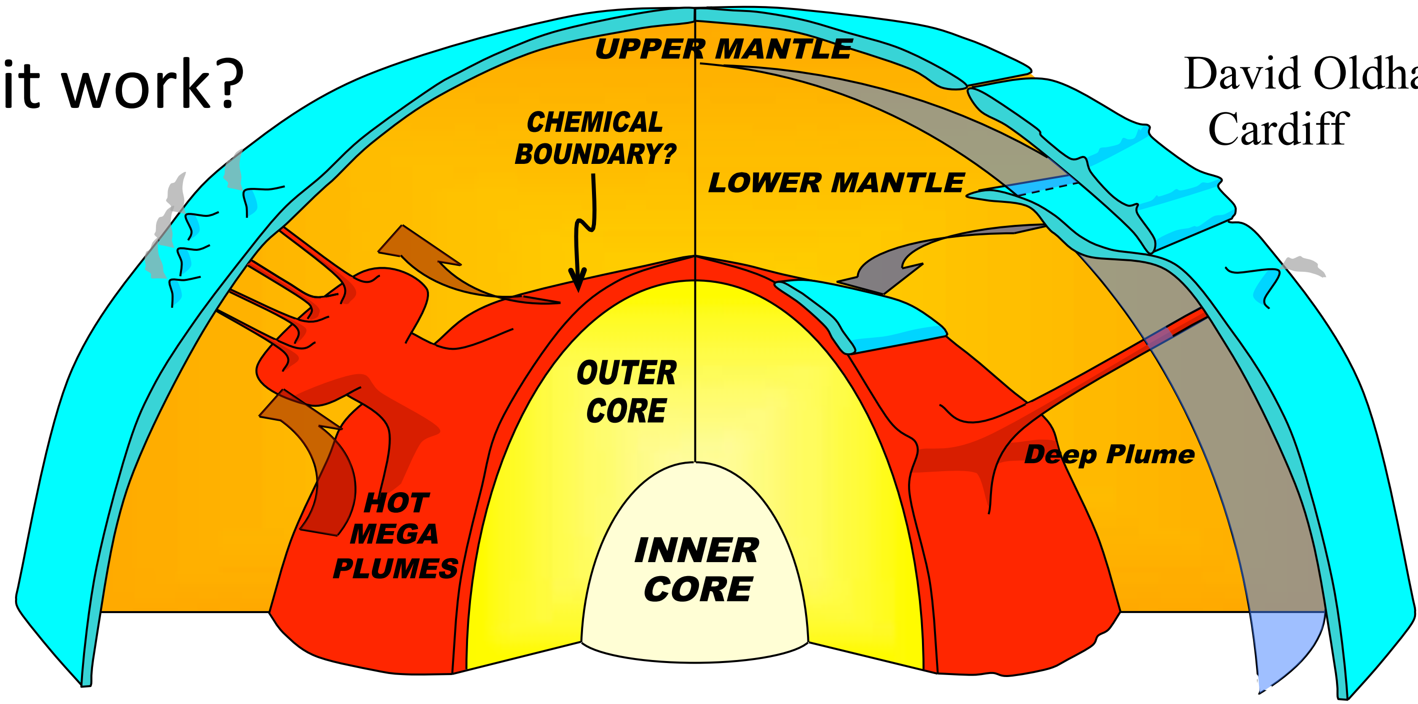
Garel, Goes, Davies, Davies, Kramer, Wilson; "Interaction of subducted slabs with the mantle transition-zone: A regime diagram from 2-D thermo-mechanical models with a mobile trench and an overriding plate", *Geochem. Geophys. Geosys.*, **15**, 1739-1765, 2014. Open Access

Mantle Convection Engine – 'Valve'

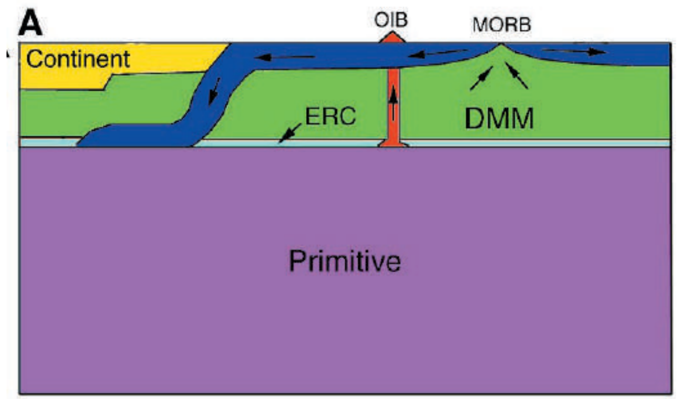
How much material transfers between upper and lower mantle?
How much material gets through the 'valve'?
Is it fully open, or only partly open? What controls how 'open'?

How does it work?



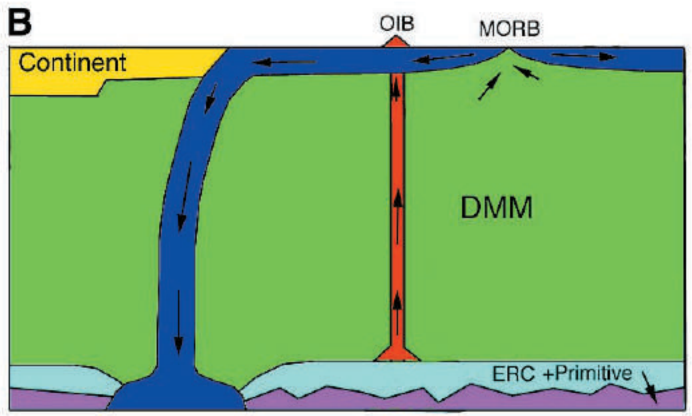
David Oldham, Cardiff

‘Valve’



Valve closed – Layered mantle

No transport between upper
and lower mantle; isolated reservoir

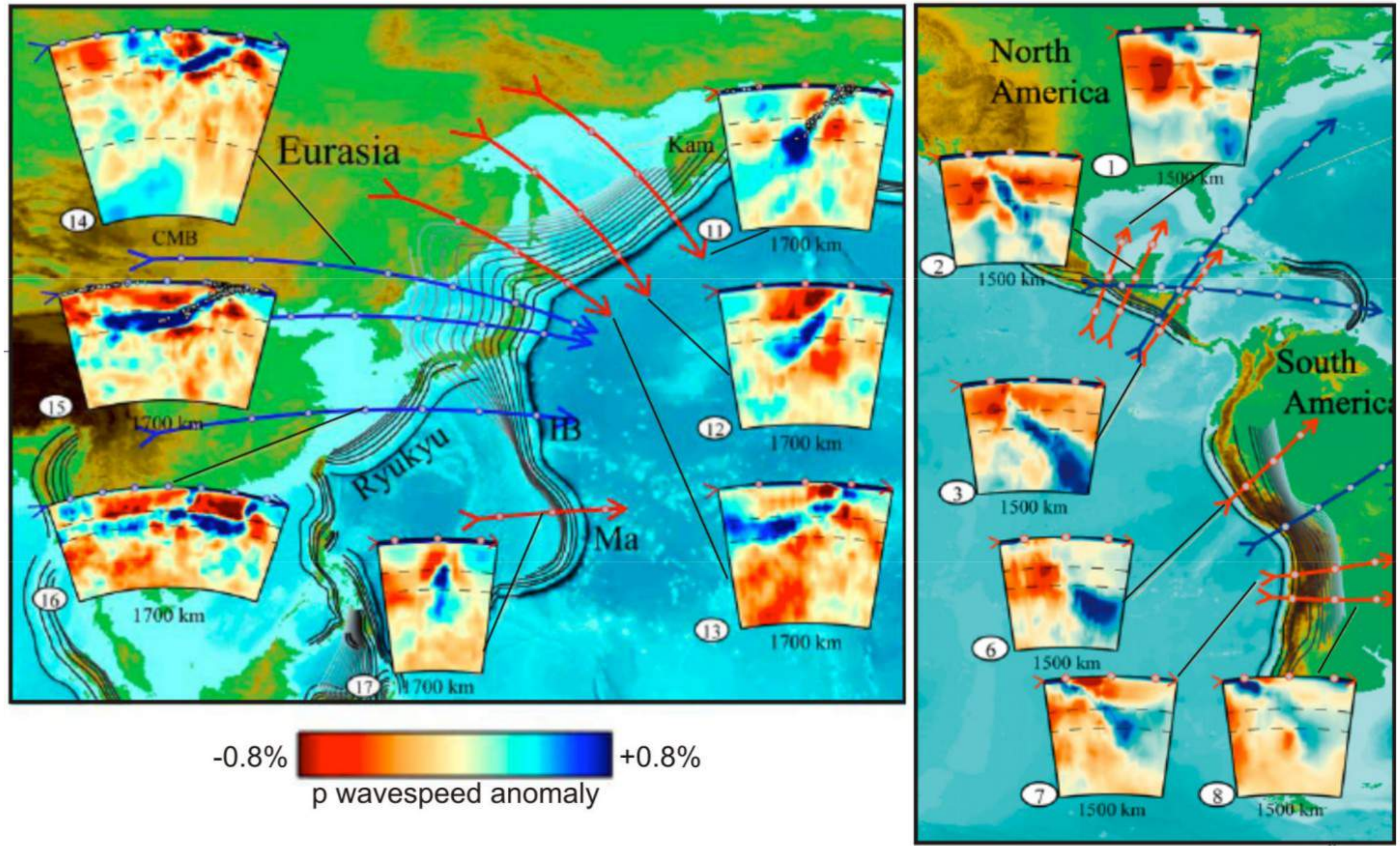


Valve open – whole mantle convection

No hindrance in transport between upper
and lower mantle

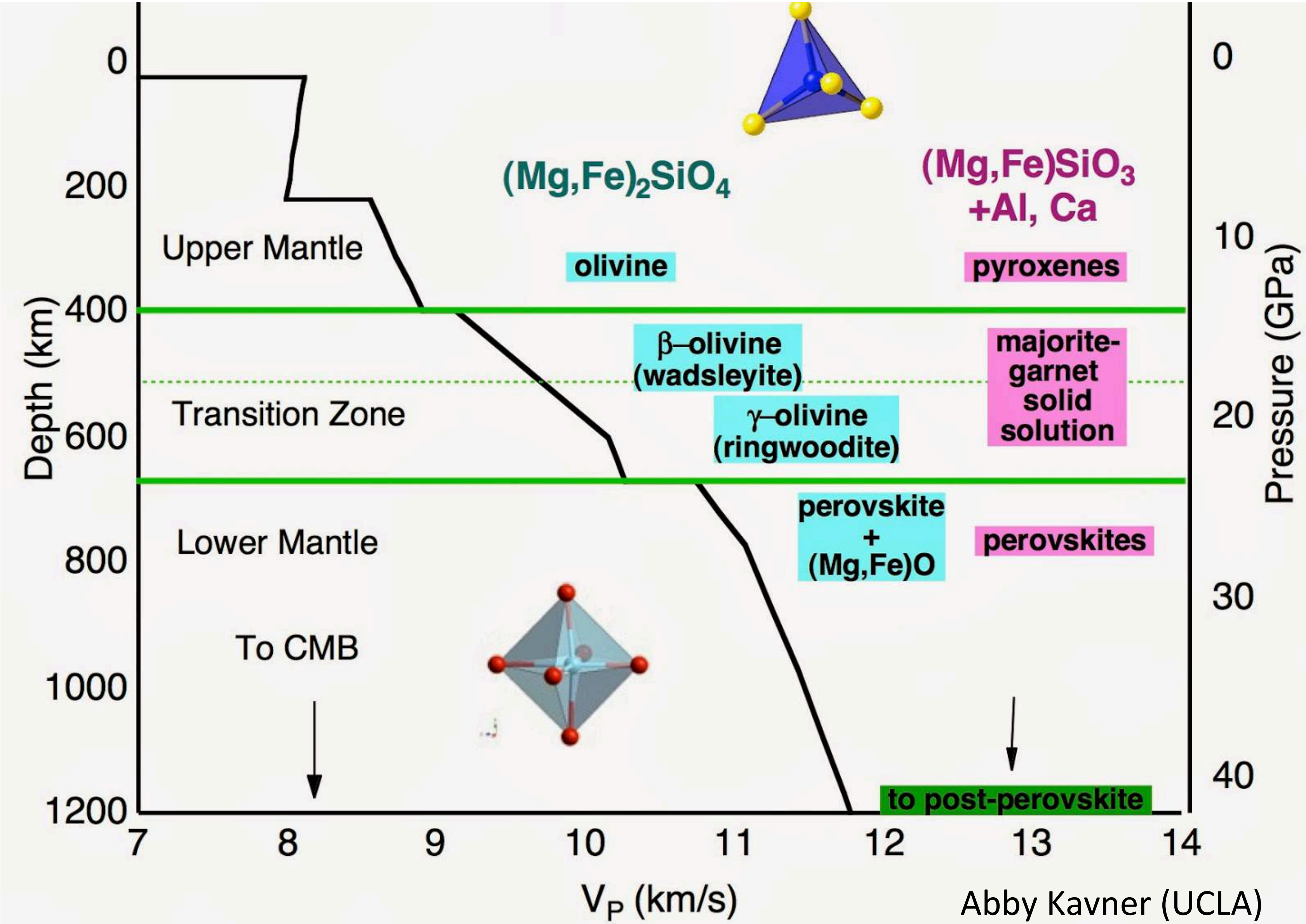
Tackley, 2000

Seismic imaging of slabs in the Earth's mantle



(Li et al., G3, 2008)

‘Valve’

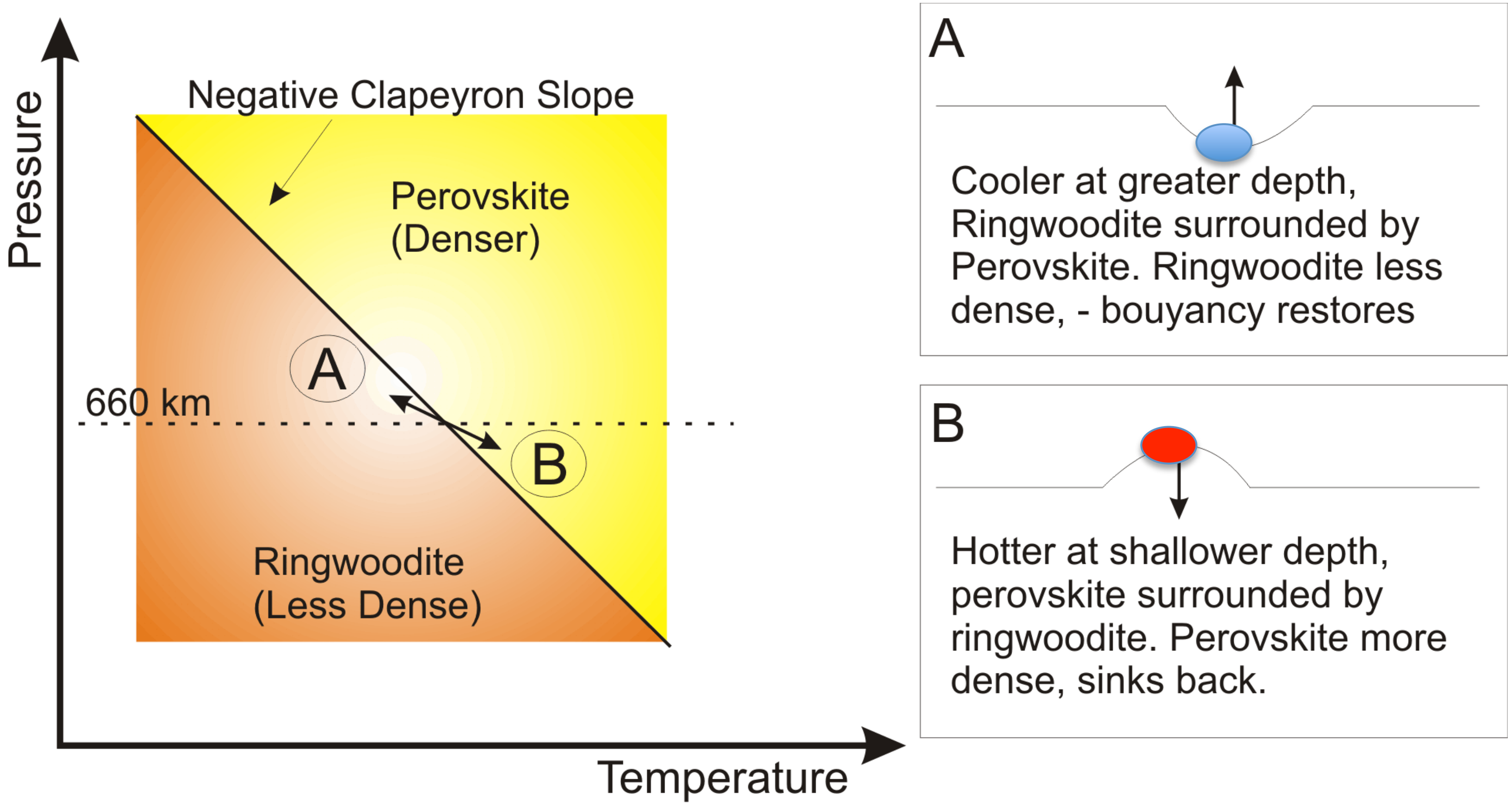


Abby Kavner (UCLA)

Mechanism of Layering

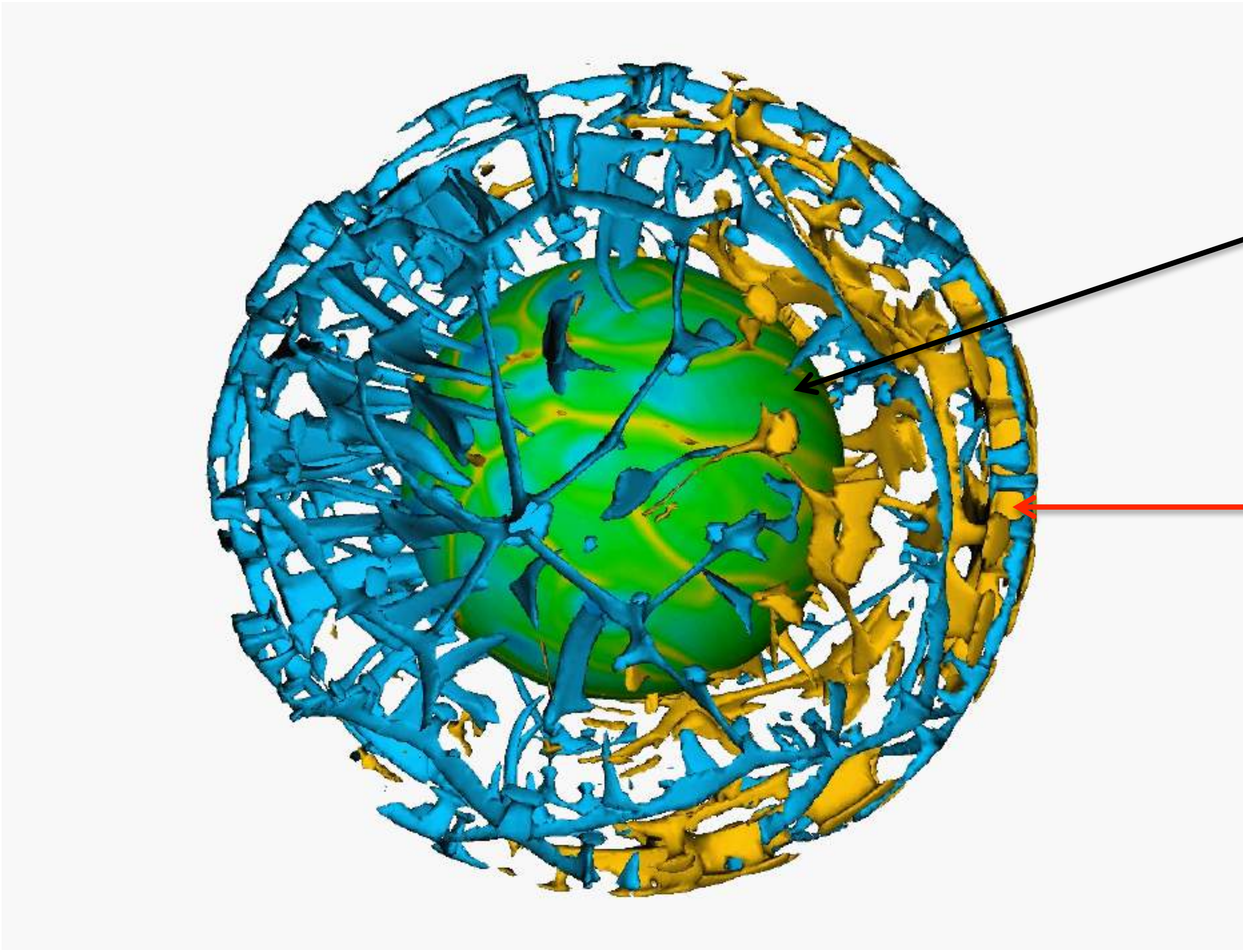
Sketch Phase Diagram

Clapeyron slope = dP/dT of phase change

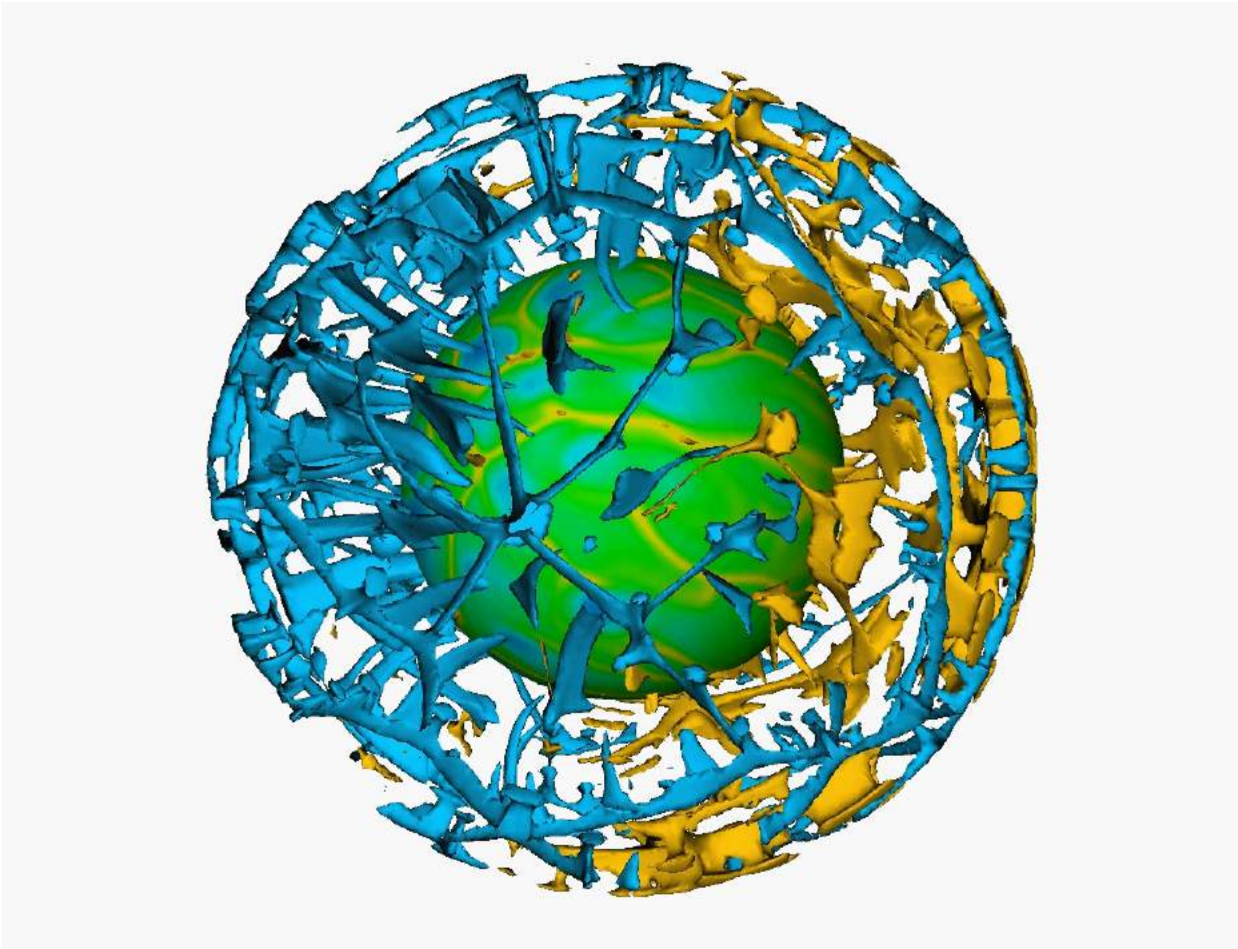


Earth Cl660: -1.5 to -3 MPa/K

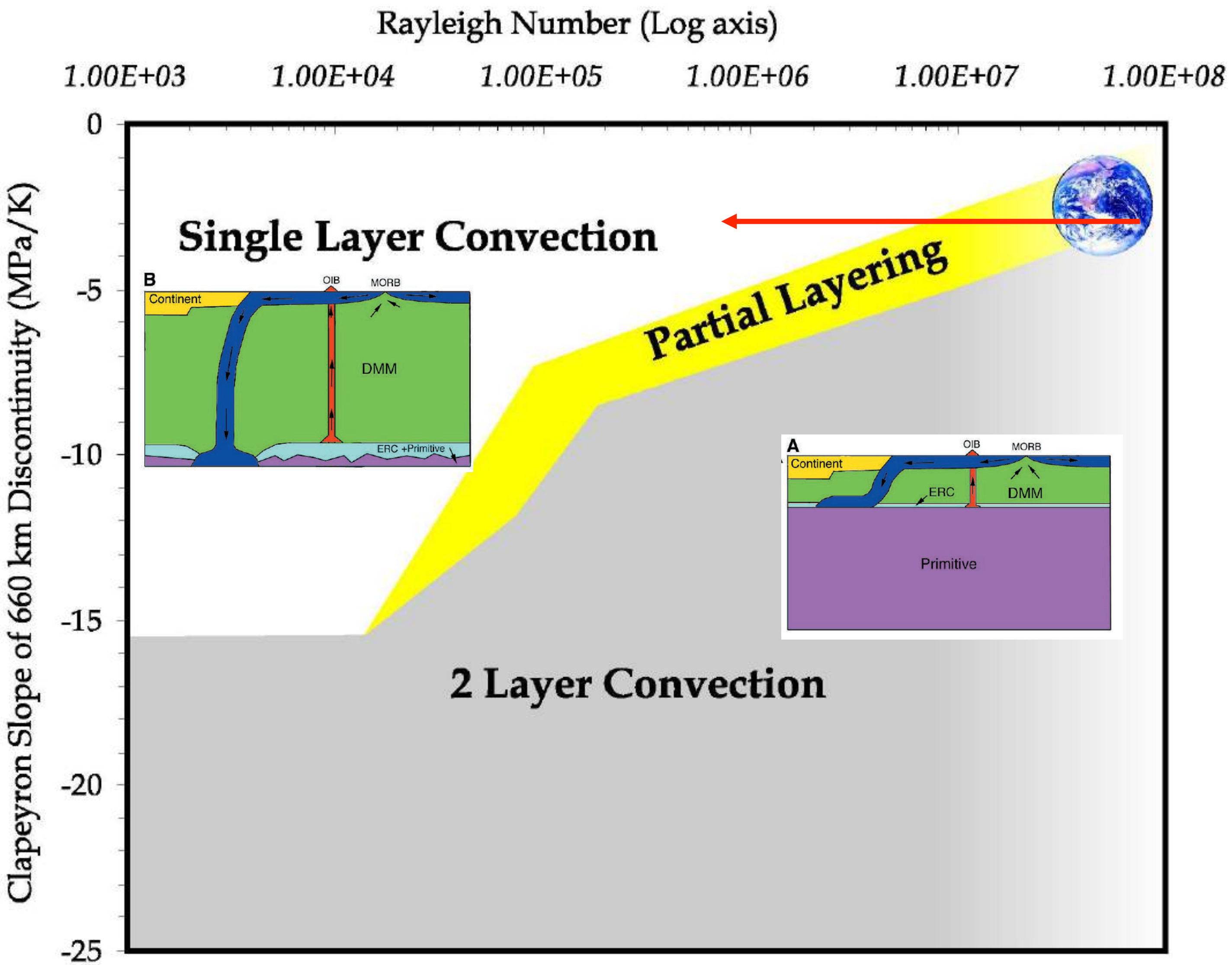
Layering and breakdown



Layering and breakdown



Result: Parameter space mapping



43 cases modelled

Wolstencroft, Davies, SE, 2011

Subduction

- Models just presented show
  - Closed valve – in principle possible
  - Significant – time-dependence
  - Evolving over Earth evolution
- BUT mantle downwellings – actually subduction
- Need models to cope with complexity of subduction
  - only then can we hope to understand over Earth history

Numerical Model

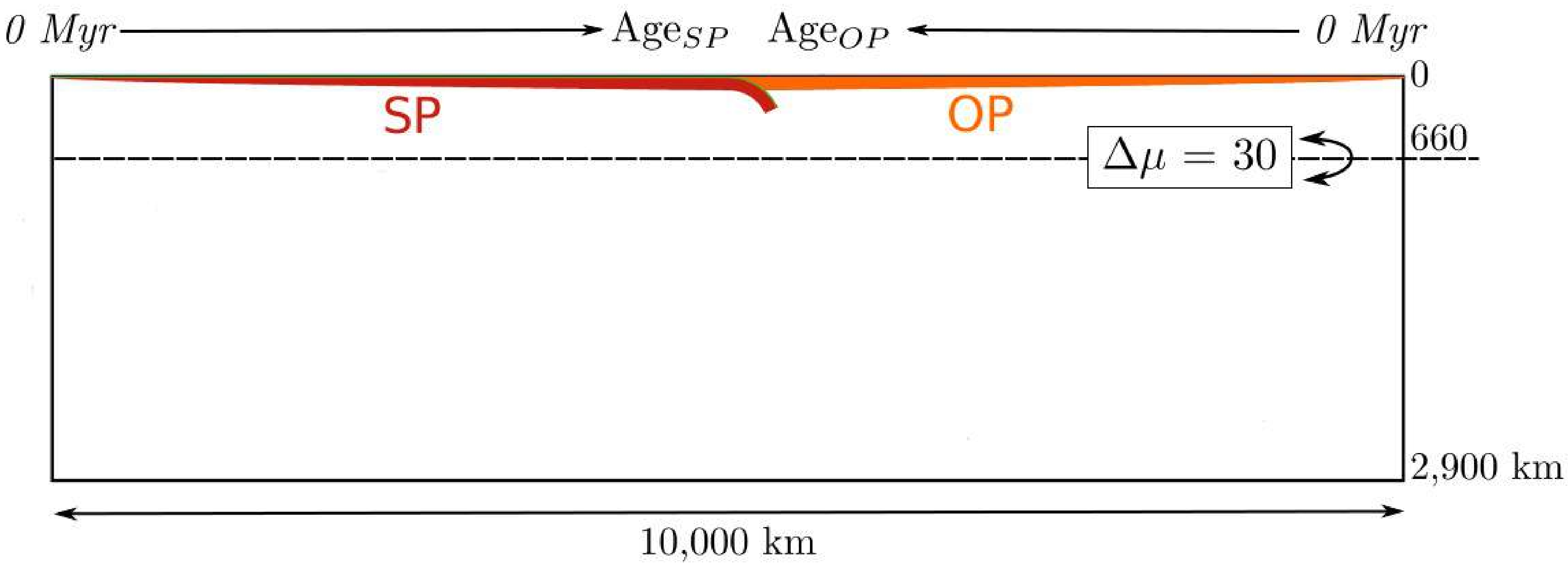
Solve equations for conservation of

- Mass
- Momentum i.e. F=ma, F=0
- Energy

In Boussinesq Approximation (BA)
(no dissipation, incompressible)

And Extended Boussinesq Approximation (EBA)
(viscous dissipation, adiabat, latent heat of phase change)

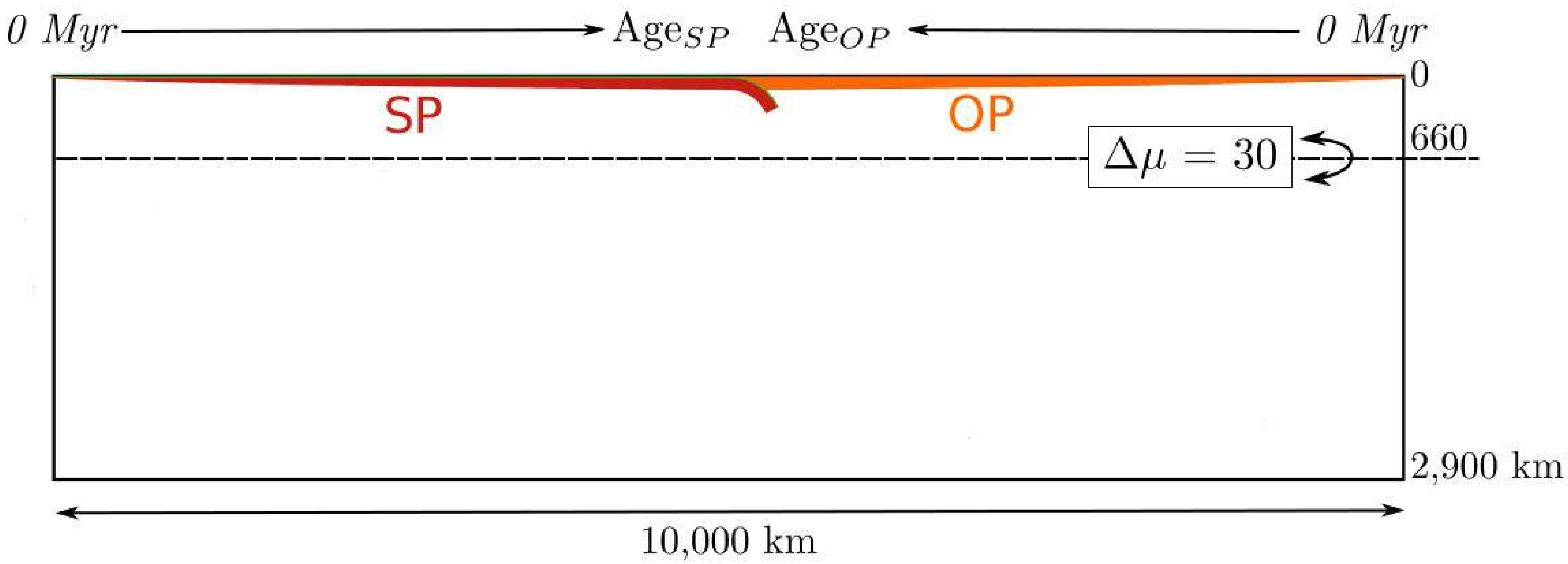
1. Thermo-mechanical model of subduction



SP = Subducting plate

OP = Overriding plate

1. Thermo-mechanical model of subduction



SP = Subducting plate

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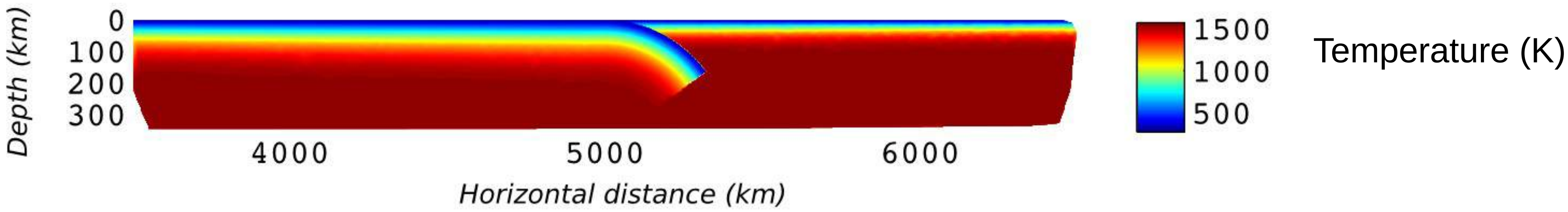
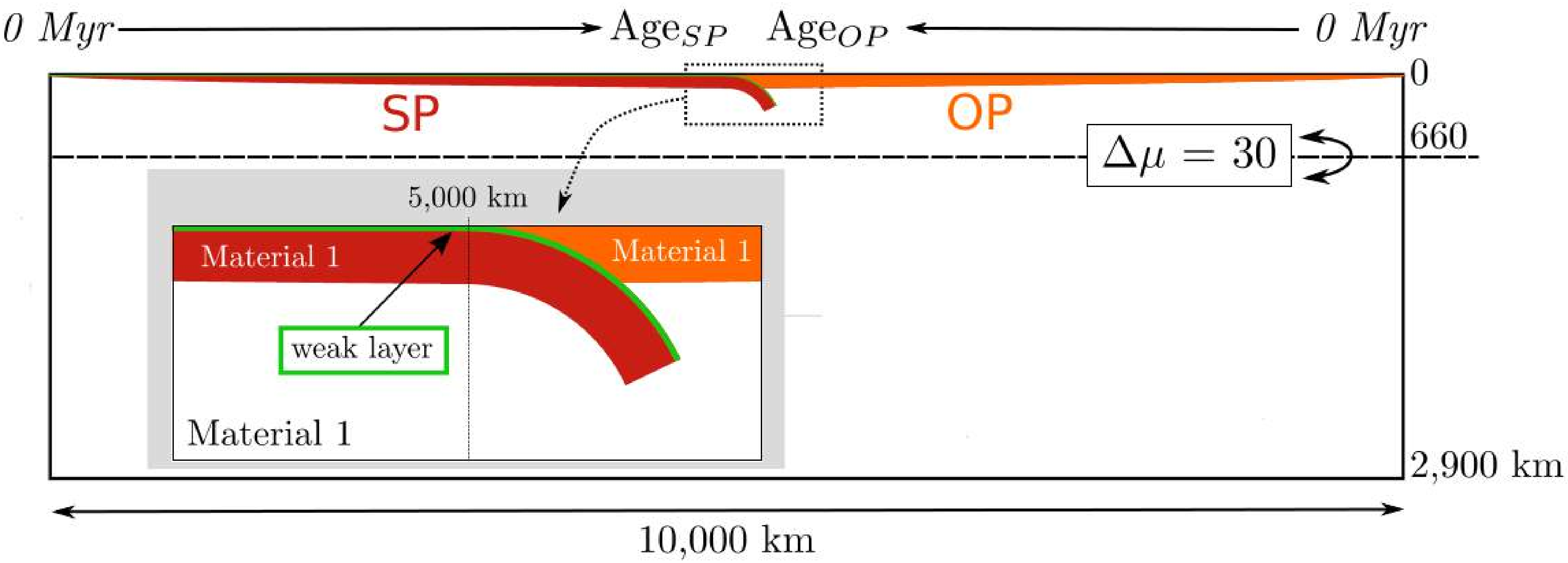
Initial thermal structure (half-space cooling model)



1. Thermo-mechanical model of subduction

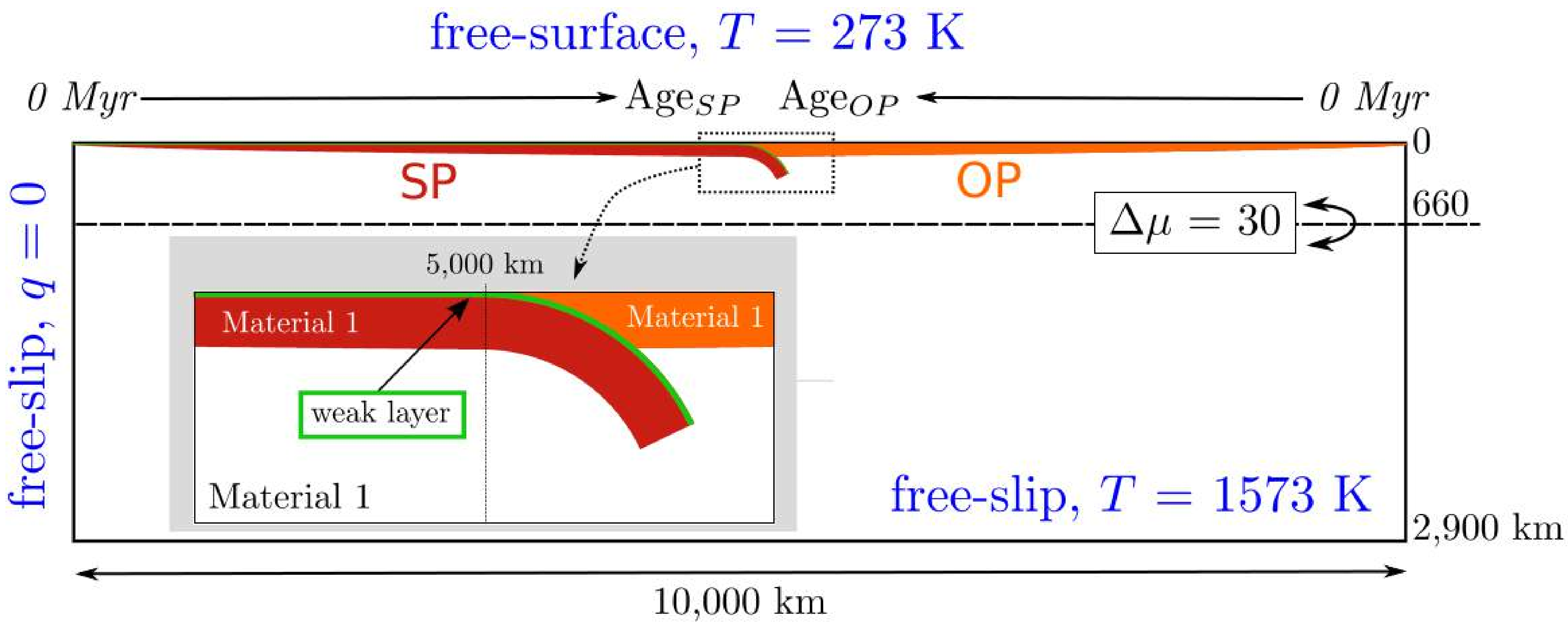


SP = Subducting plate

OP = Overriding plate

- 5-km thickness decoupling weak layer (sediments, oceanic crust)

1. Thermo-mechanical model of subduction



SP = Subducting plate

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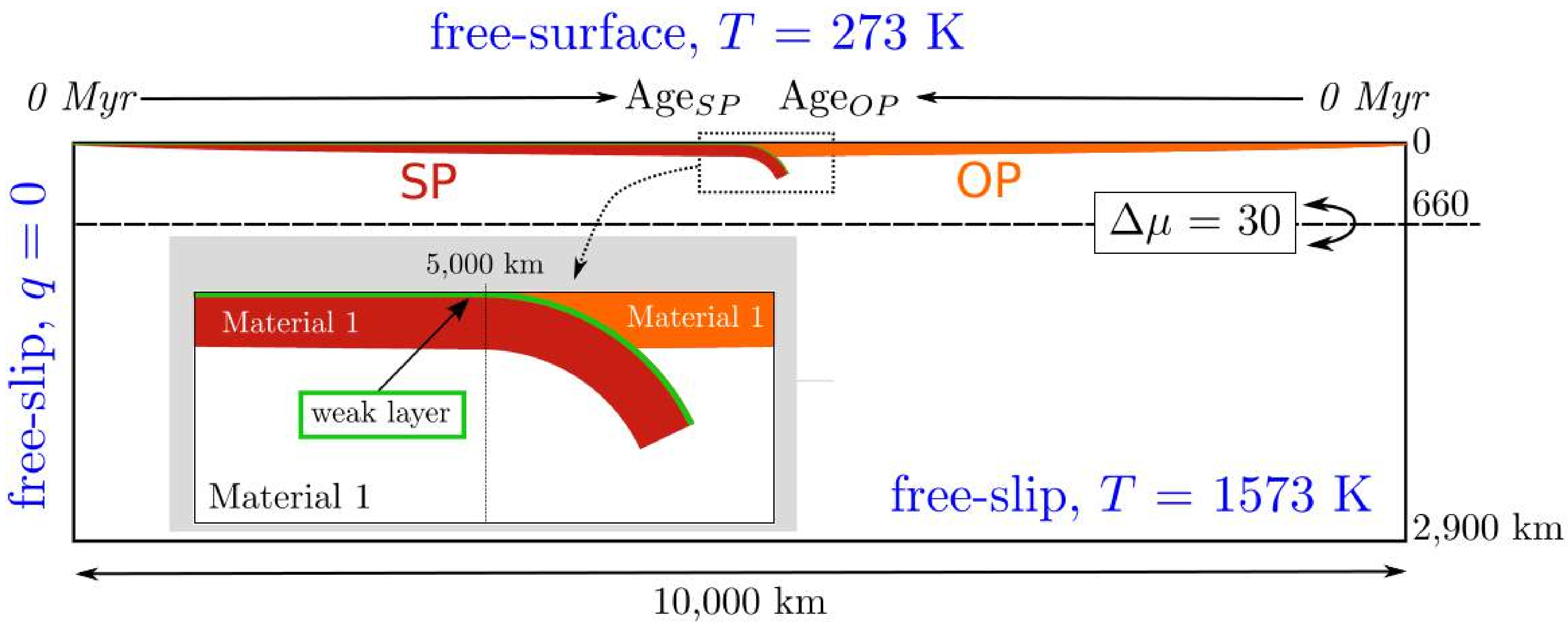
- 5-km thickness decoupling weak layer (sediments, oceanic crust)
- renewal of cold material by thermal diffusion at the surface
- incompressible simulation

1. Thermo-mechanical model of subduction

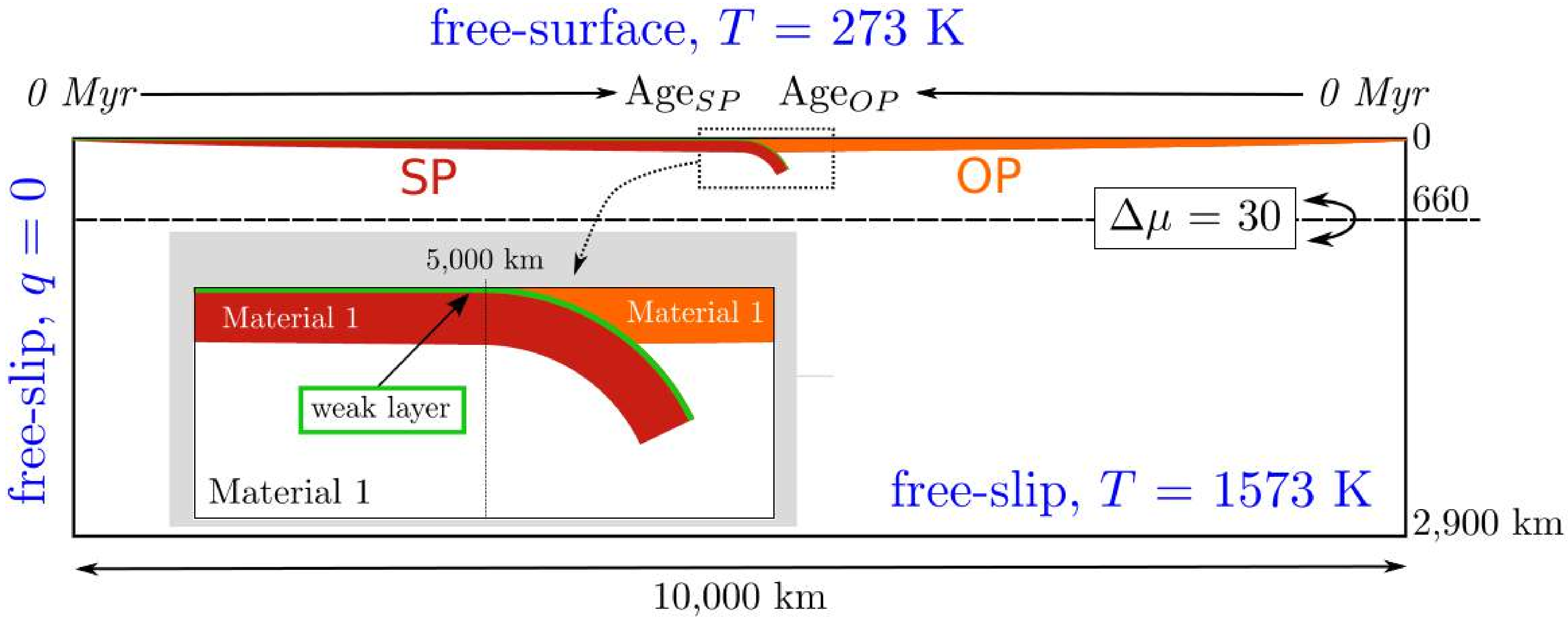


SP = Subducting plate

OP = Overriding plate

- 5-km thickness decoupling weak layer (sediments, oceanic crust)
- renewal of cold material by thermal diffusion at the surface
- incompressible simulation
- “free” trench motion in response to subduction dynamics

1. Thermo-mechanical model of subduction



SP = Subducting plate

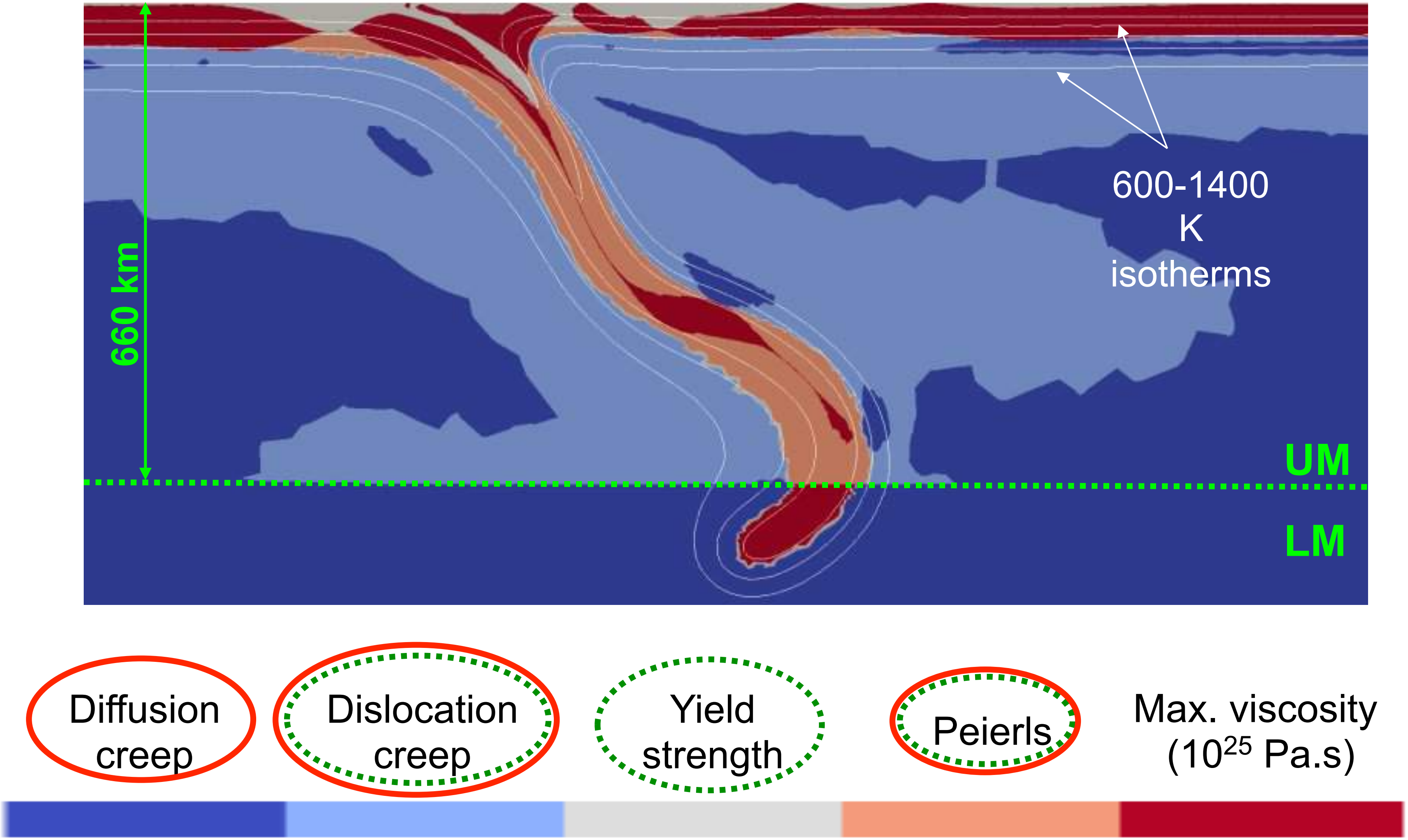
OP = Overriding plate

Phase changes implemented using the method of Christensen and Yuen (1983) – gives them a width

Extended Boussinesq Approximation - reference adiabat similar to Bossman & van Keken (2013) - include viscous dissipation, adiabatic heating, latent heat of phase changes

Composite rheology:

temperature and strain-rate dependent viscosity



Fluidity

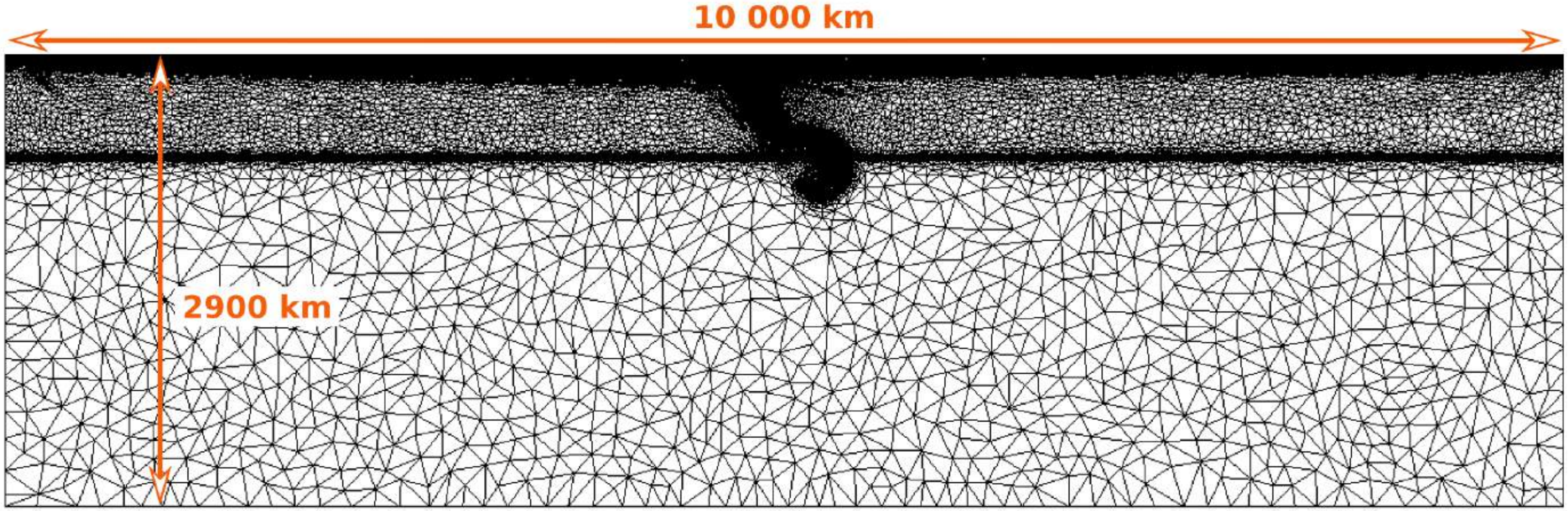
- Finite-element, parallel-running code
- Developed by the AMCG group (Imperial College London)
- Automatic adaptive meshing depending on spatial variations of temperature, velocity, viscosity...

  → adapted for multi-scale systems

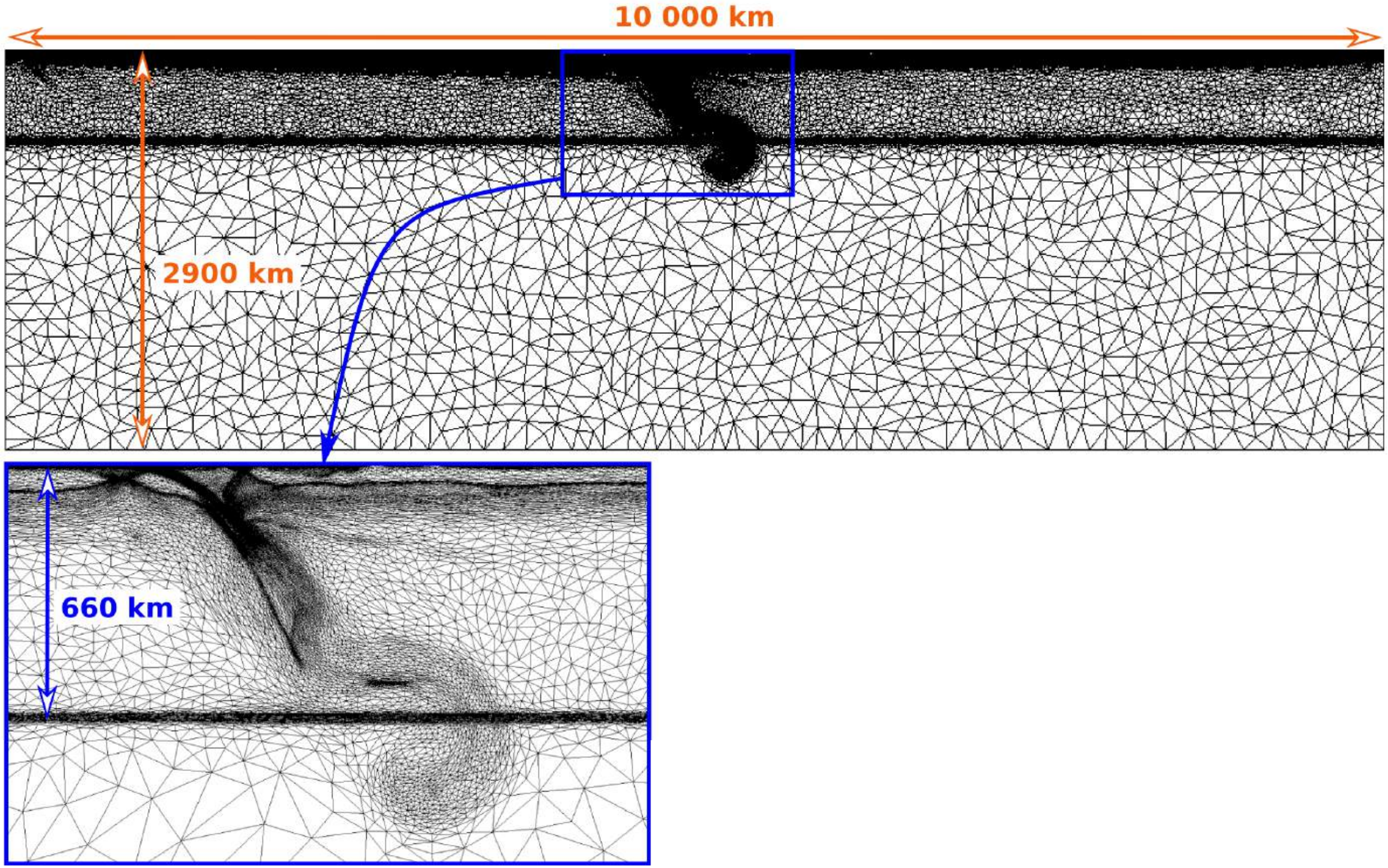
  → element sizes between 400 m and 200 km
- Free surface
- Sharp variations in viscosity, dynamic load balancing
- Extensively benchmarked (analytical + numerical)

  → *Davies et al. G3, 2011*
  → *Kramer et al., PEPI, 2012*

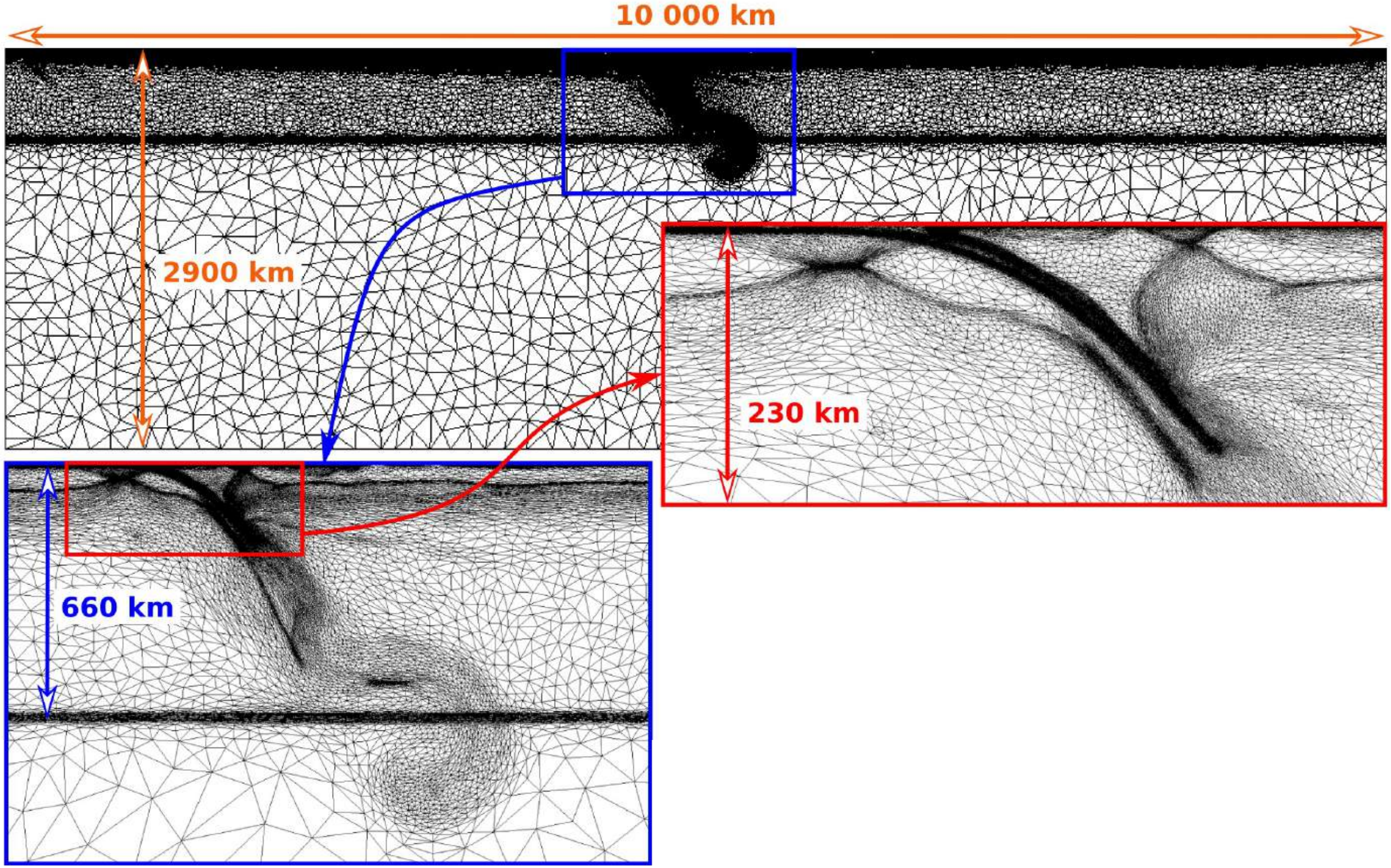
Auto-adaptive meshing



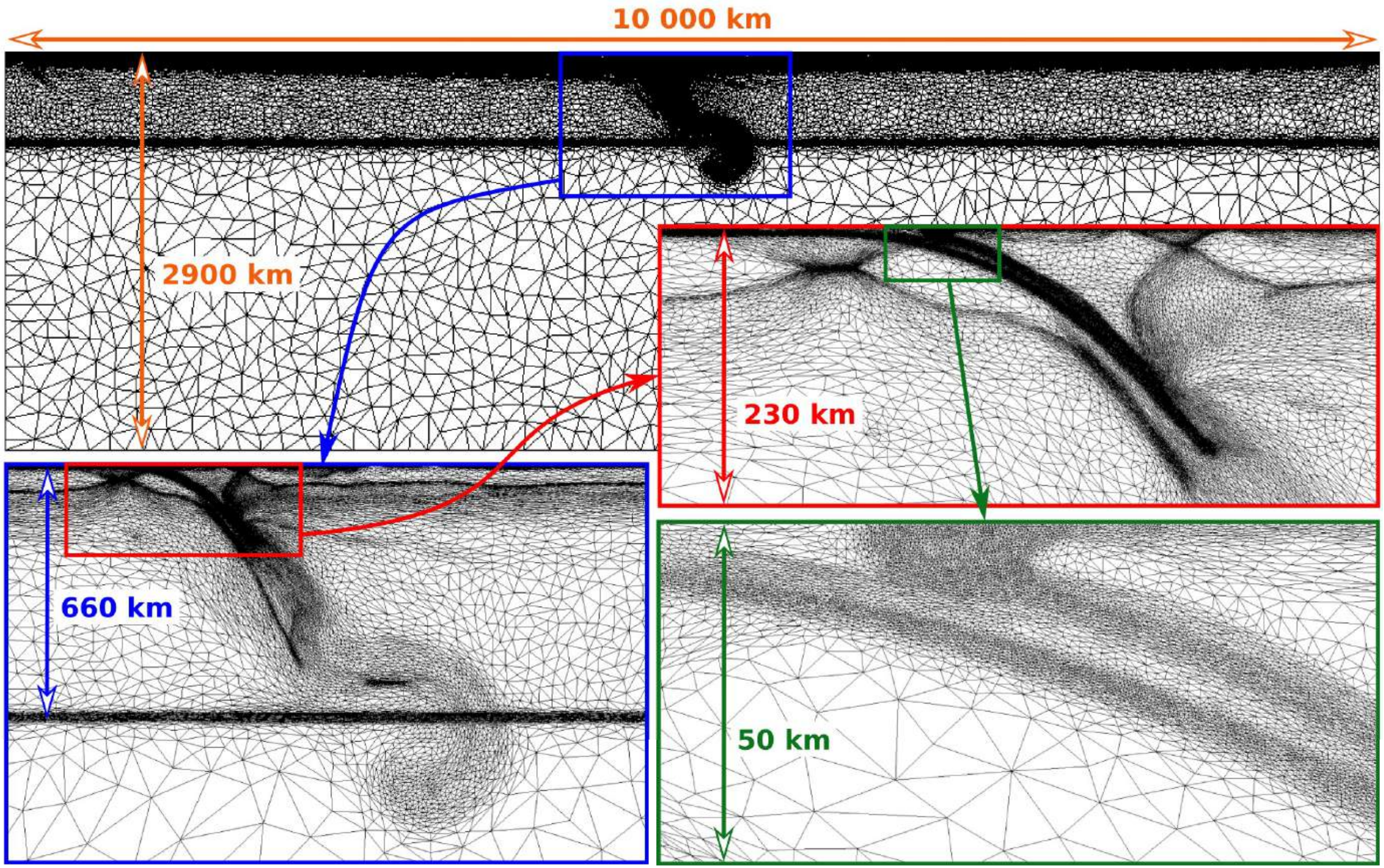
Auto-adaptive meshing



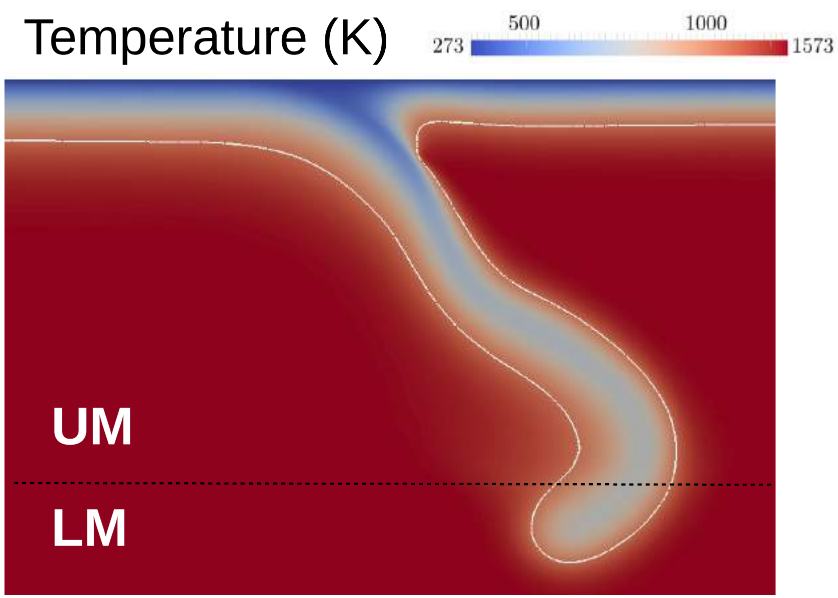
Auto-adaptive meshing

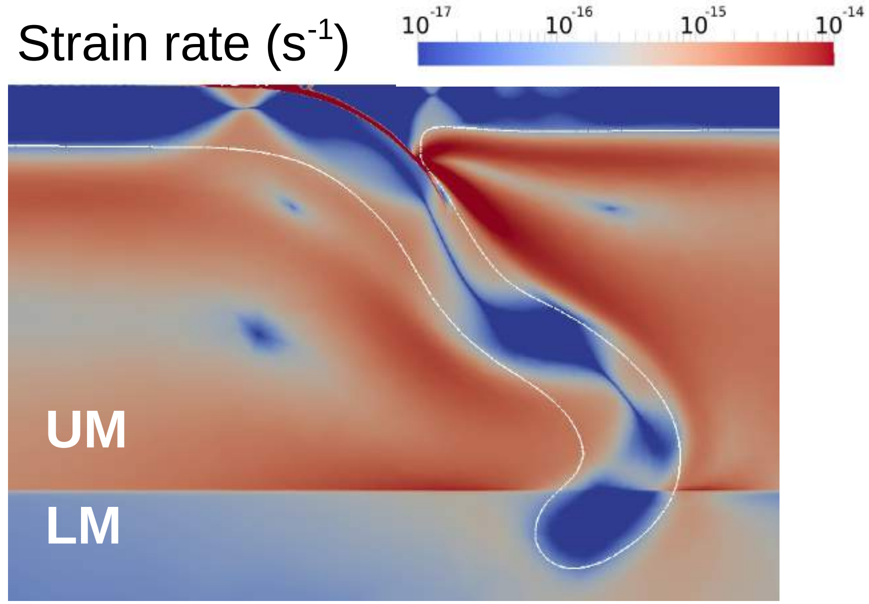


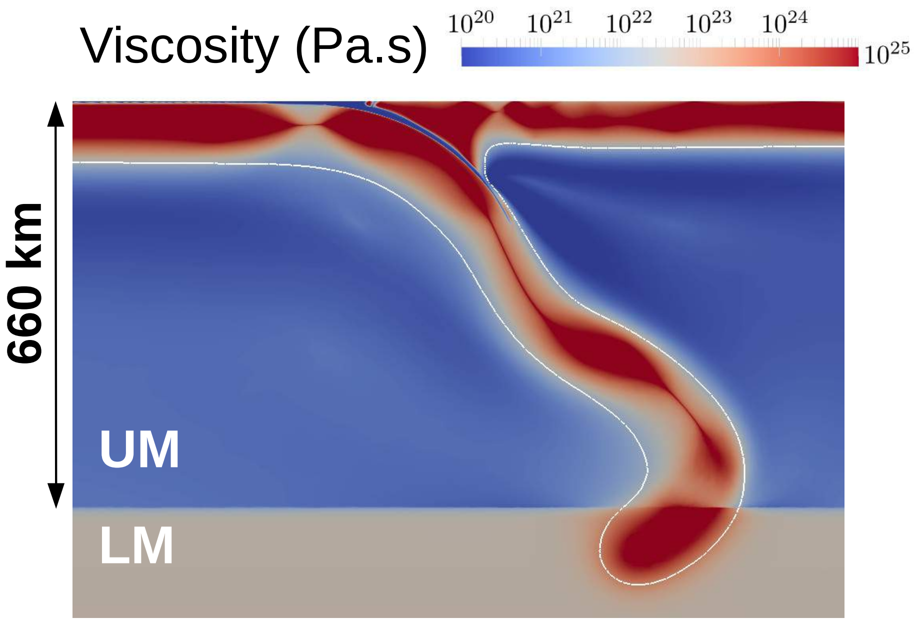
Auto-adaptive meshing



Subduction dynamics: an example

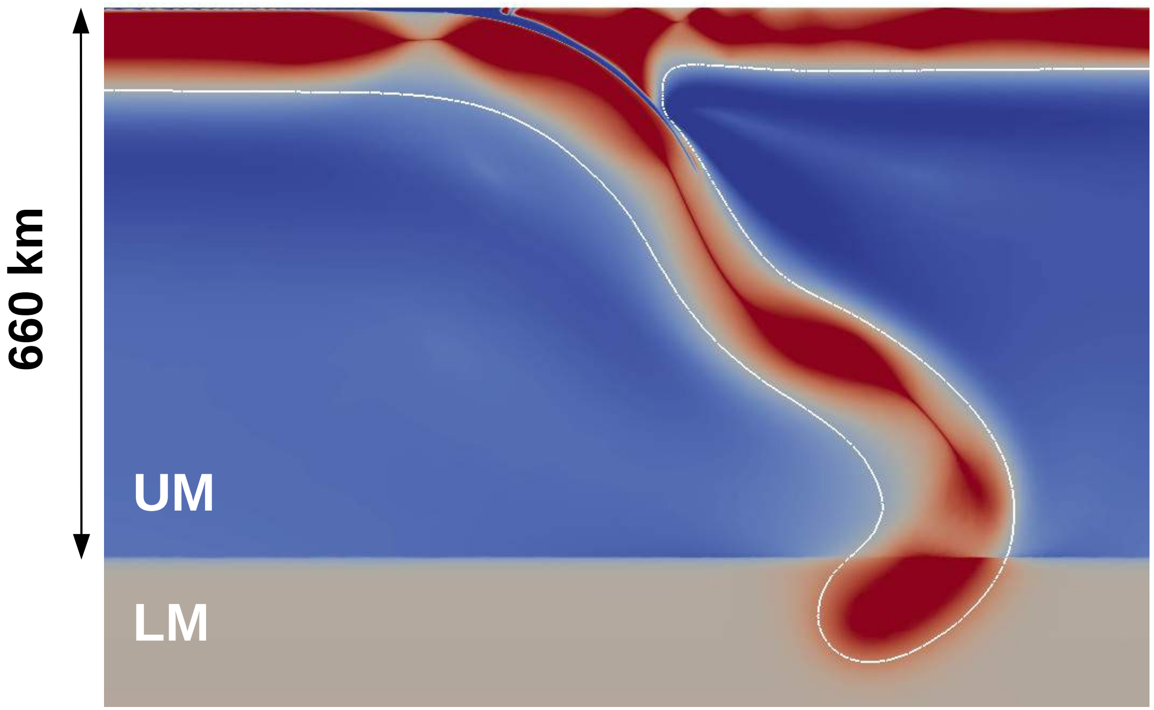




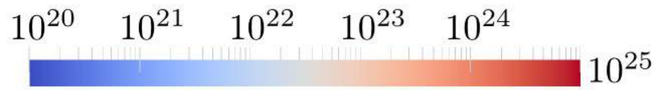


- Thermal vs. mechanical slab
- Regions of strain-rate weakening in mantle and in slab
- Strong slab core (max. viscosity) vs. highly deformed weak regions

Subduction dynamics: an example



Viscosity (Pa.s)

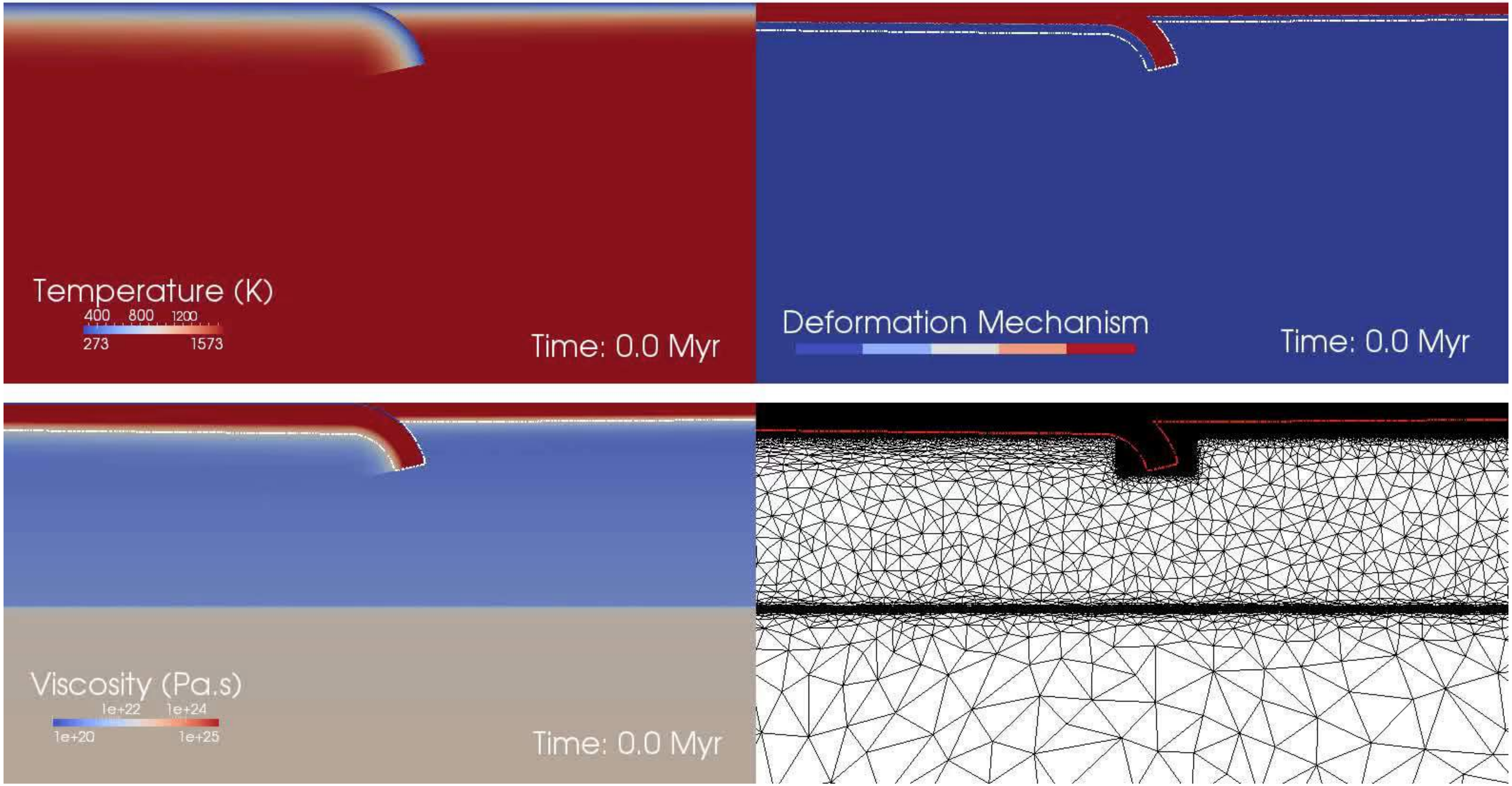


Boussinesq Approximation – No phase change

- Initial subducting plate age = 100 Myr
- Initial overriding plate age = 40 Myr
- Movie duration = 48 Myr

Movie animation !

Zoomed in!

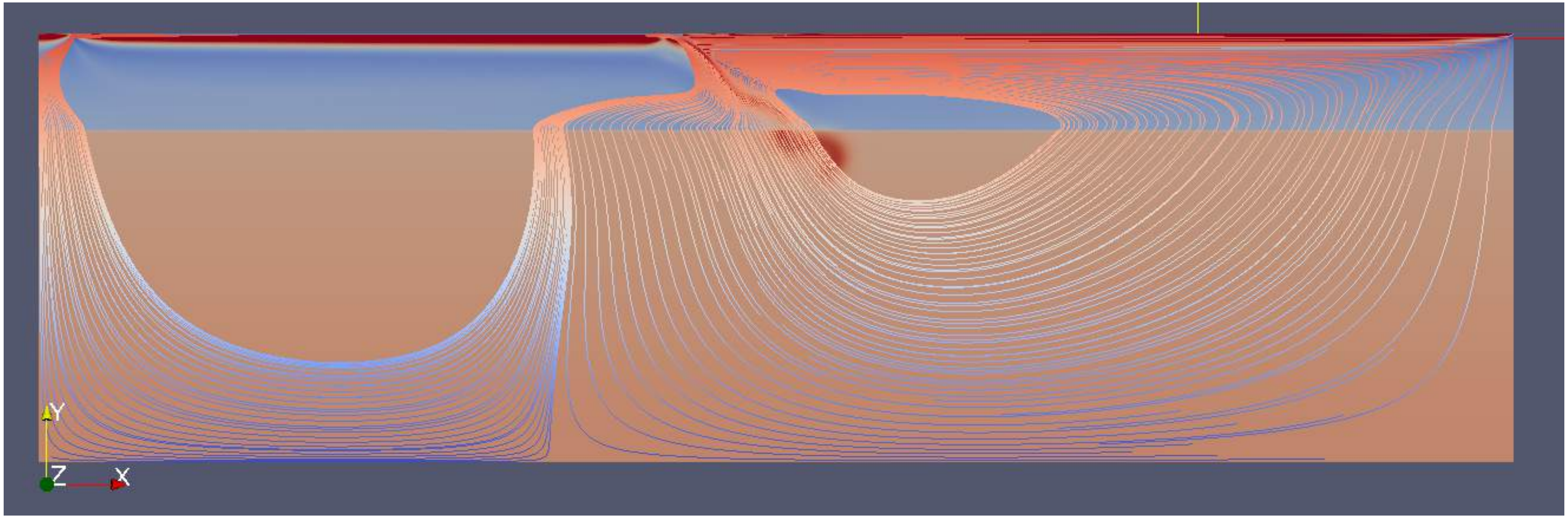


Temperature (K)
400 800 1200
273 1573
Time: 0.0 Myr
Deformation Mechanism
Time: 0.0 Myr
Viscosity (Pa.s)
1e+22 1e+24
1e+20 1e+25
Time: 0.0 Myr

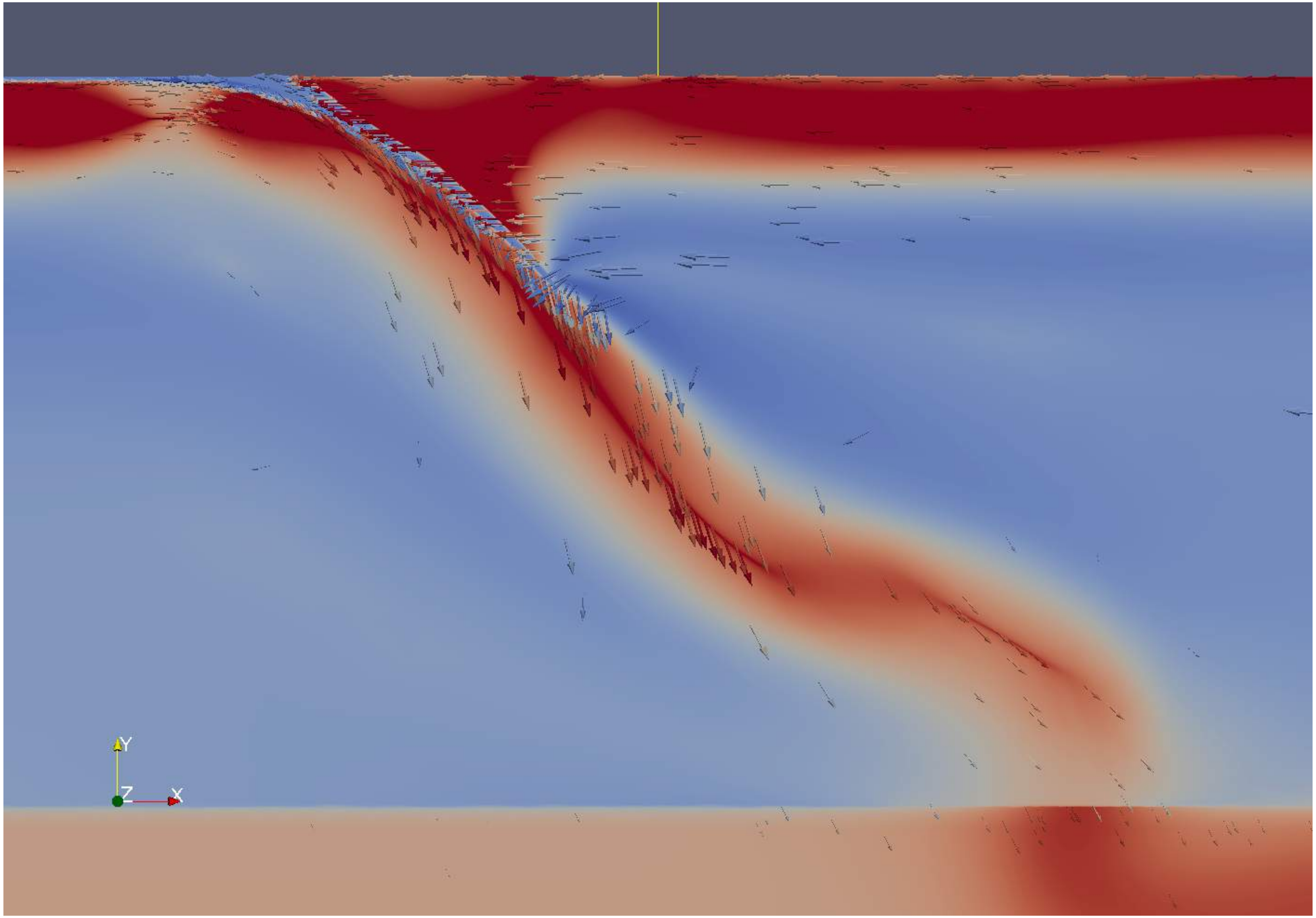
Velocity Streamlines

Snapshot

Note how roll-back is accommodated. There is flow in missing gaps – just streamlines not seeded. Note flow senses viscosity changes.

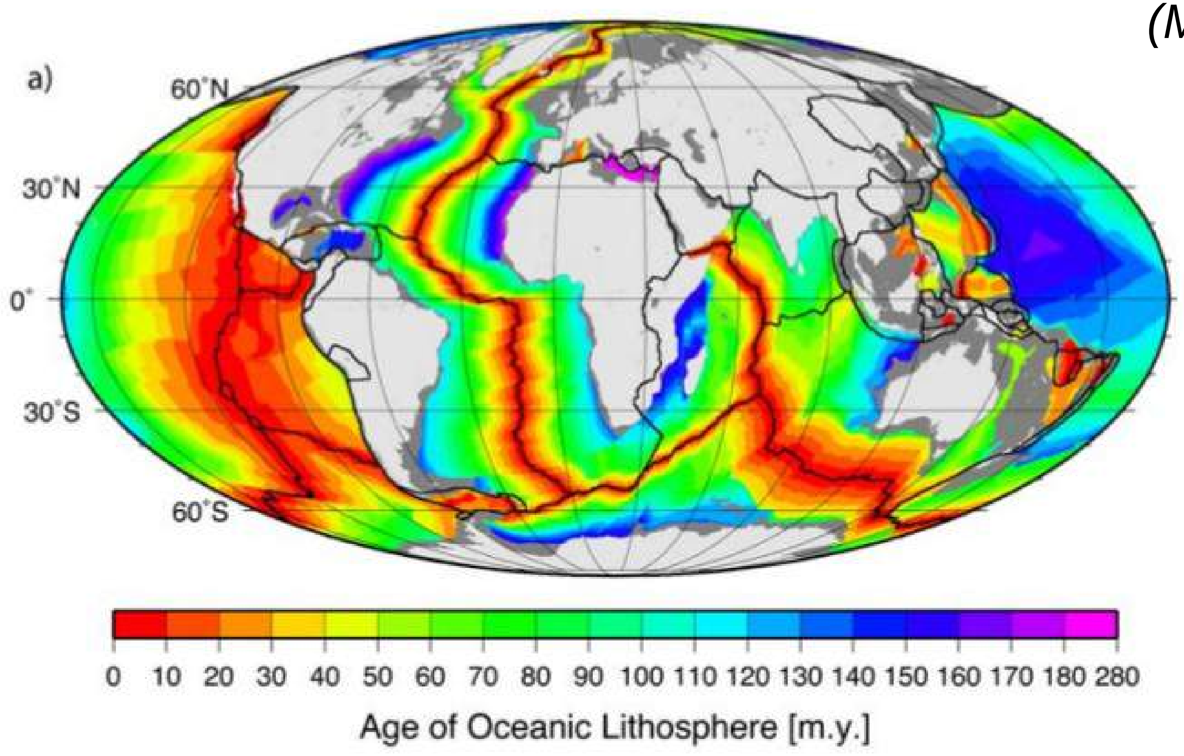


Velocity arrows – overlying viscosity field – zoomed in on slab



2. Slab deformation in the Earth's mantle

(Müller et al., 2008)



What is the effect of the initial subducting AND overriding plate ages on slab morphology and trench dynamics?

Effect of subducting plate age

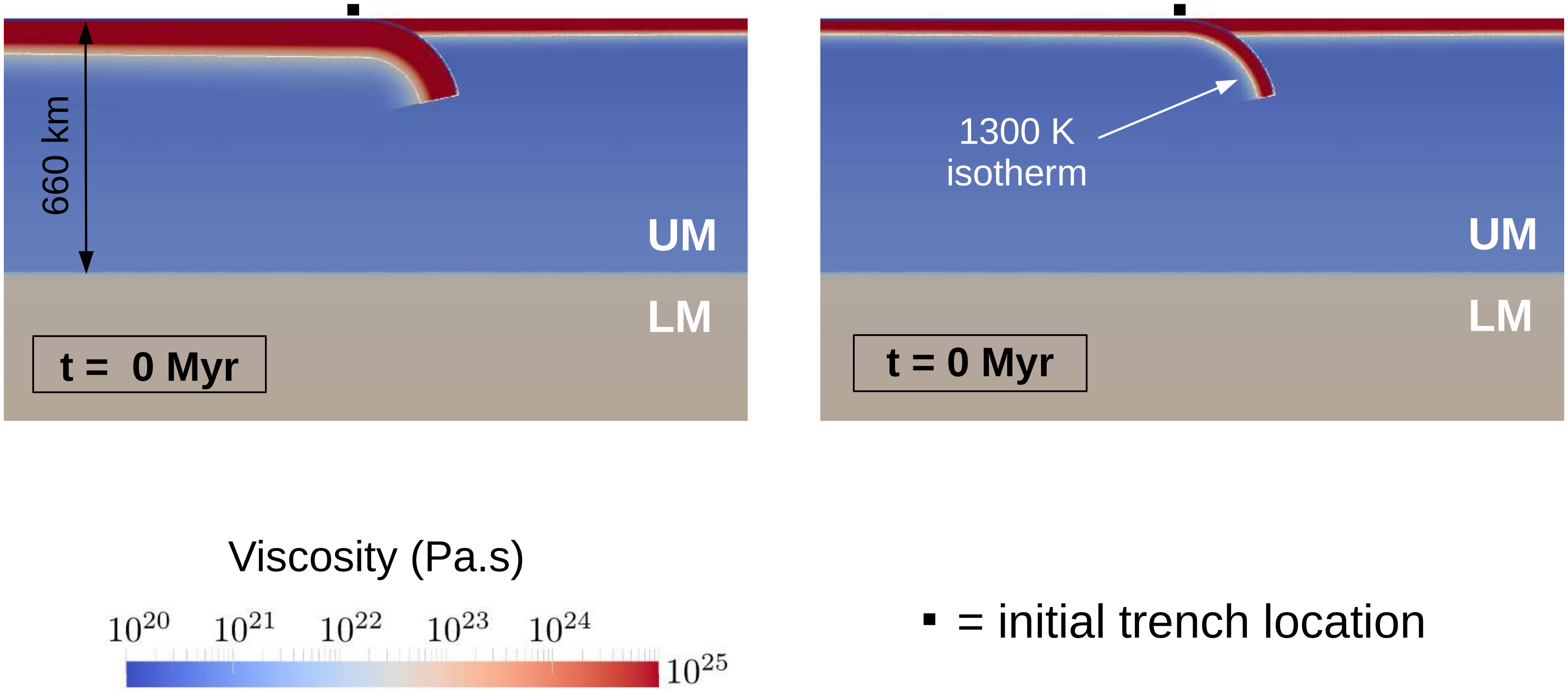
Old, thick SP

SP initial age = 100 Myr

Young, thin SP

SP initial age = 20 Myr

OP initial age = 20 Myr



▪ = initial trench location

Effect of subducting plate age

Old, thick SP

SP initial age = 100 Myr

Young, thin SP

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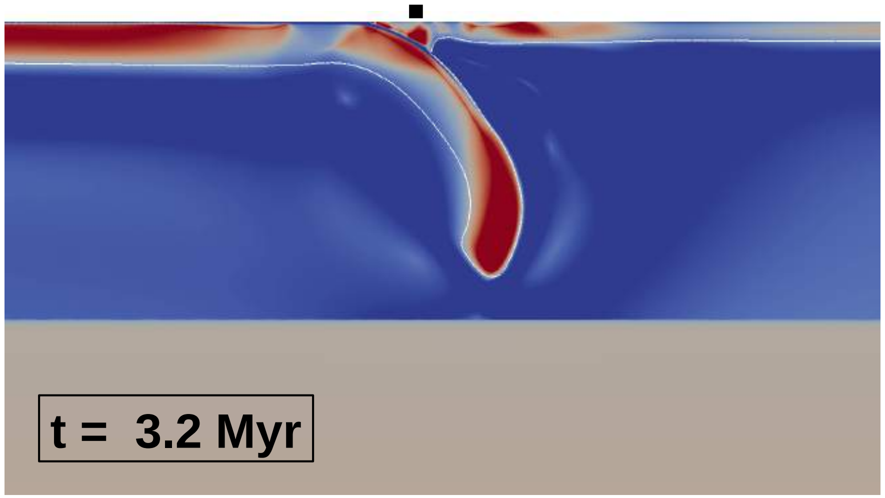
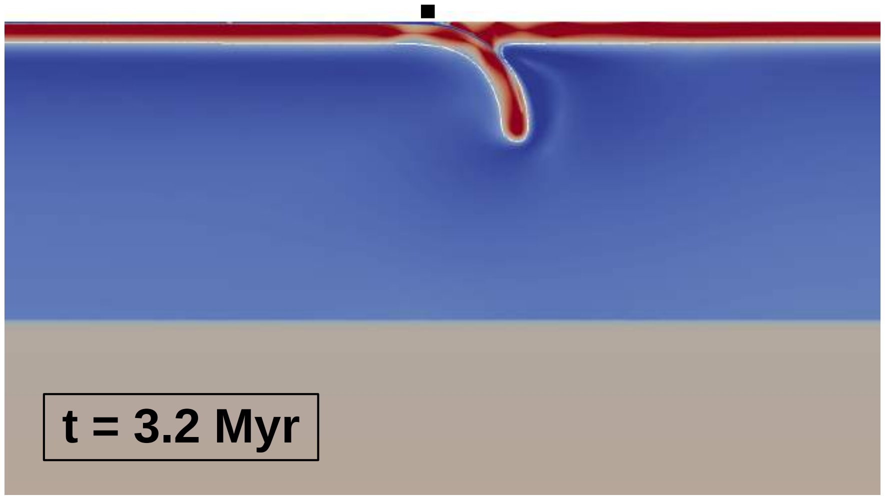




Faster sinking of the old,
more negatively buoyant plate

→ large mantle weakening

→ faster sinking

Mild mantle lubrication

→ slow sinking

Effect of subducting plate age

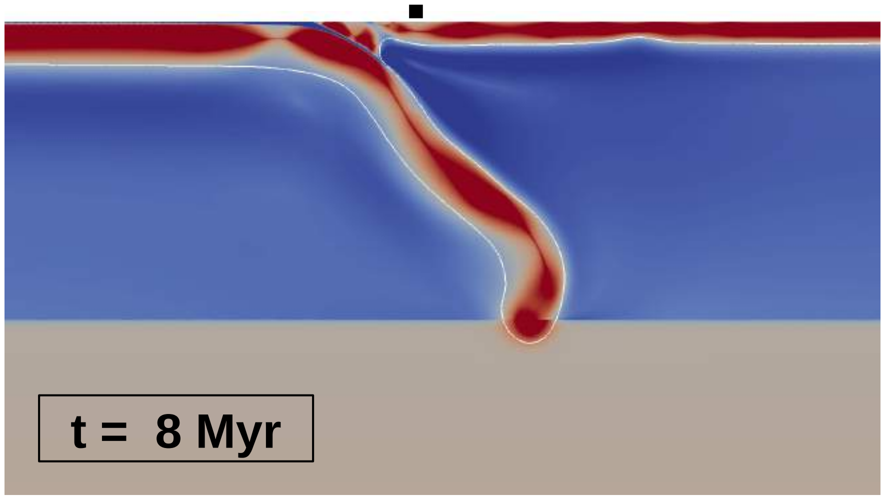
Old, thick SP

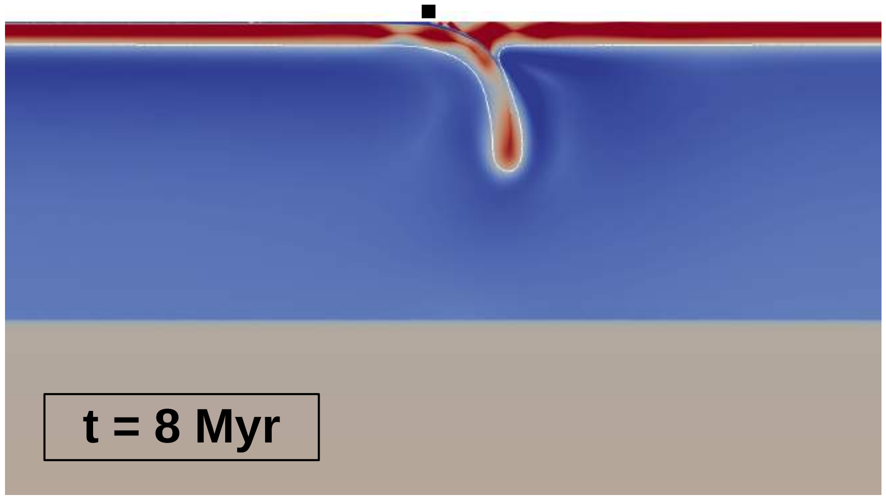
SP initial age = 100 Myr

Young, thin SP

SP initial age = 20 Myr

OP initial age = 20 Myr





Slab rollback

Slow sinking

→ important loss of negative buoyancy due to thermal diffusion

→ slower sinking

Effect of subducting plate age

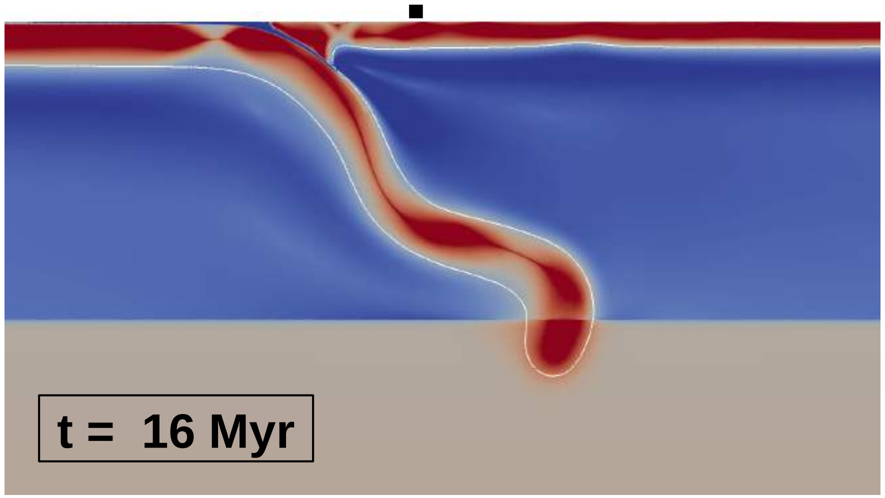
Old, thick SP

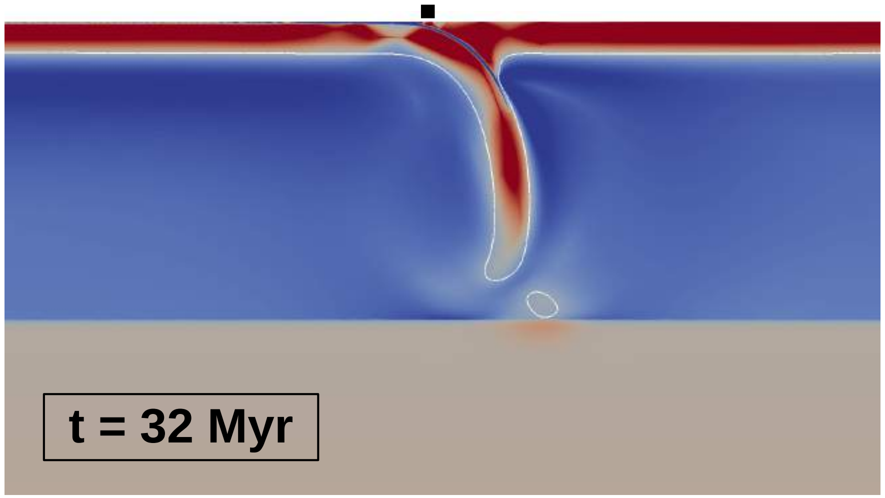
SP initial age = 100 Myr

Young, thin SP

SP initial age = 20 Myr

OP initial age = 20 Myr





- Tip anchored in the lower mantle
- Trench retreat lowers slab dip

Warm / weak slab tip

Effect of subducting plate age

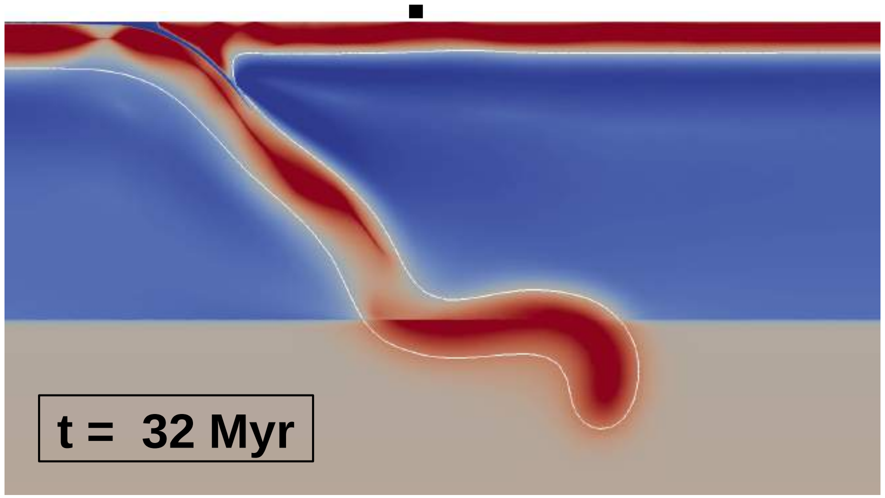
Old, thick SP

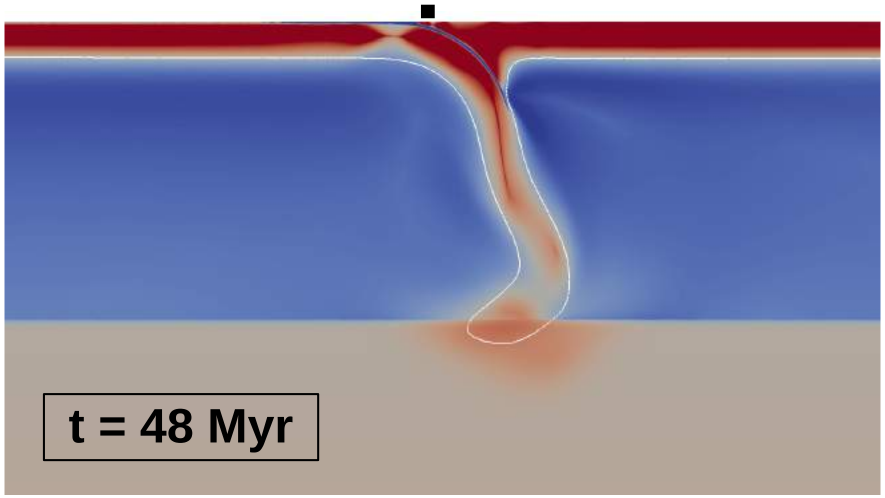
SP initial age = 100 Myr

Young, thin SP

SP initial age = 20 Myr

OP initial age = 20 Myr





Flattening above 660 km

Vertical impact on the viscosity jump
+ weak slap tip

→ piling and folding

Effect of subducting plate age

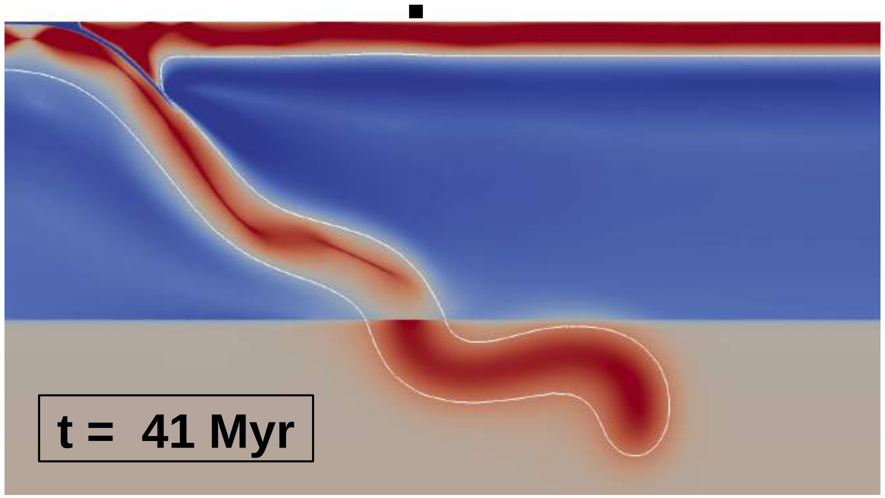
Old, thick SP

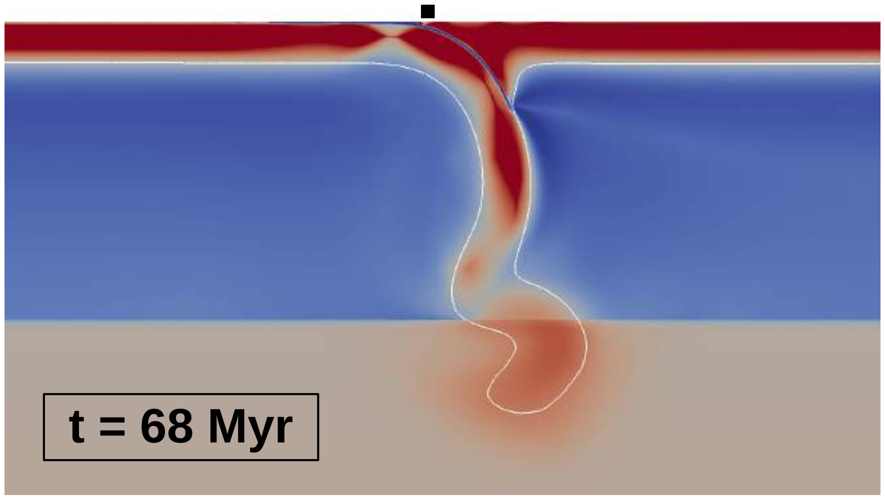
SP initial age = 100 Myr

Young, thin SP

SP initial age = 20 Myr

OP initial age = 20 Myr





Inclined slab / Strong retreat

- Initially old, buoyant subducting plate
- Rapid sinking, mantle weakening
- Large trench retreat

Vertical folding

Young subducting plate
→ slow sinking, slab weakening

- no trench retreat and folding upon jump encounter

Effect of overriding plate age

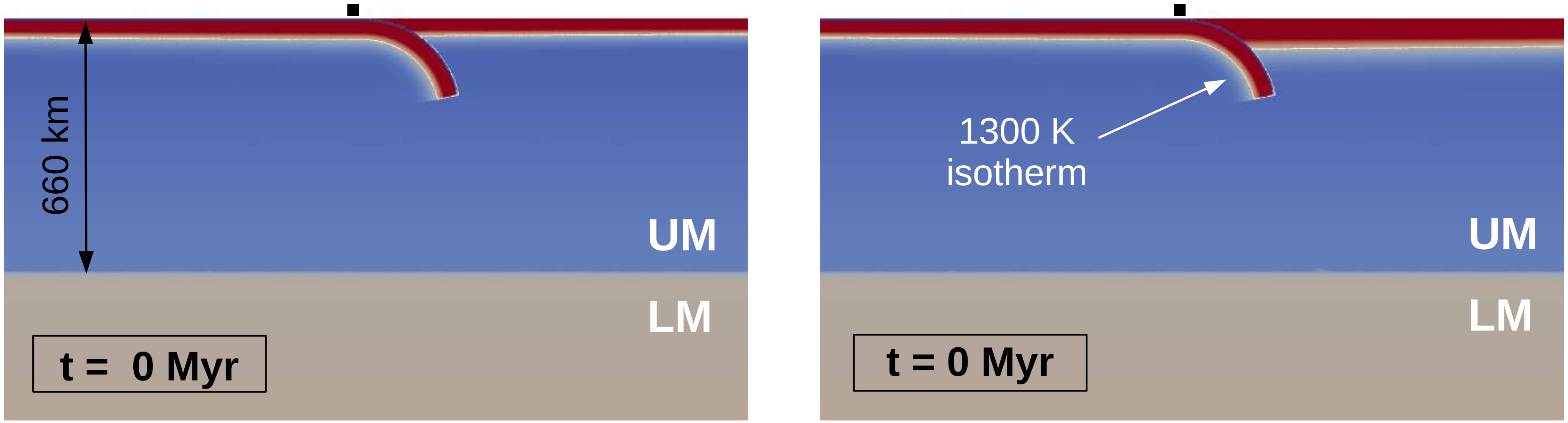
Young, thin OP

OP initial age = 20 Myr

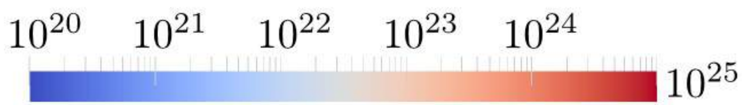
Old, thick OP

OP initial age = 65 Myr

SP initial age = 30 Myr



Viscosity (Pa.s)



▪ = initial trench location

Effect of overriding plate age

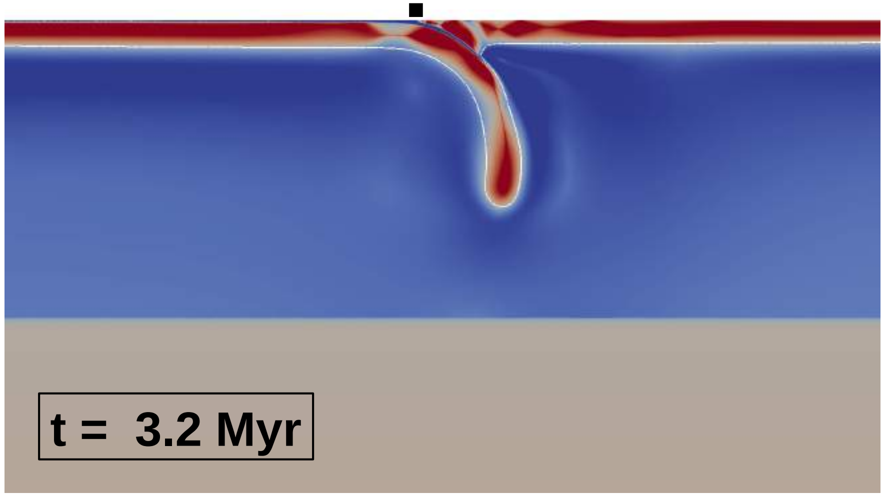
Young, thin OP

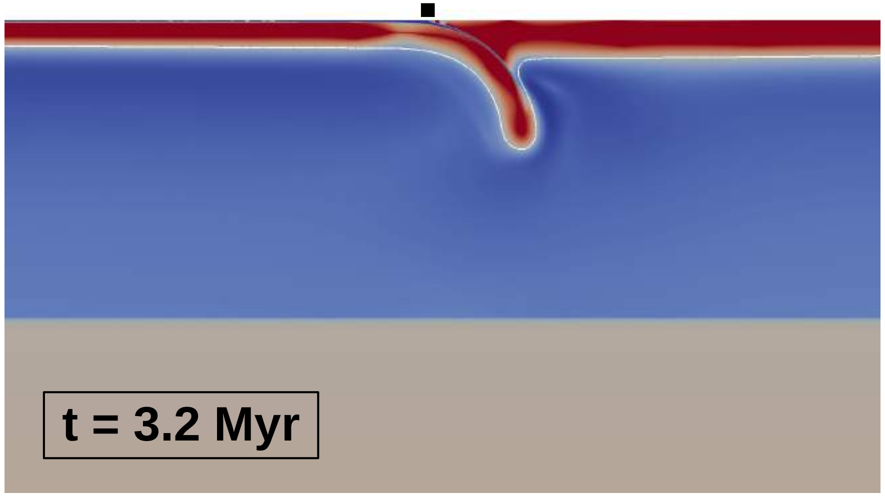
OP initial age = 20 Myr

Old, thick OP

OP initial age = 65 Myr

SP initial age = 30 Myr





A thicker overriding plate slows down slab sinking.

Effect of overriding plate age

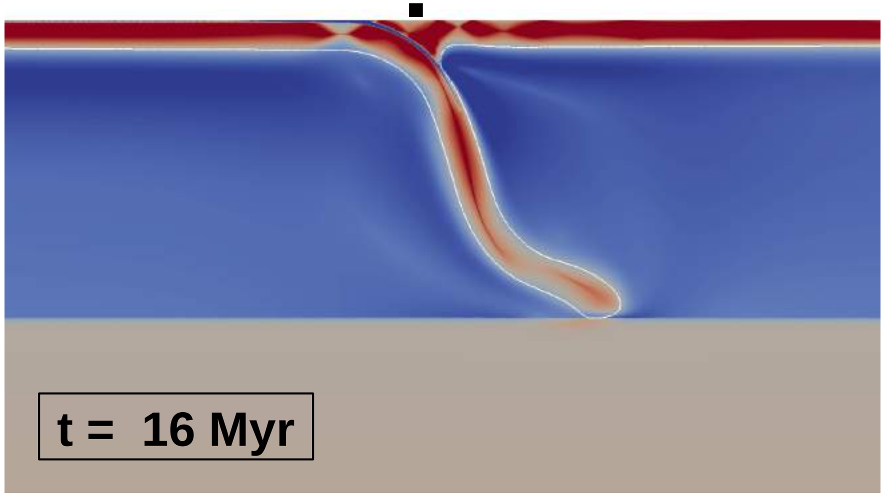
Young, thin OP

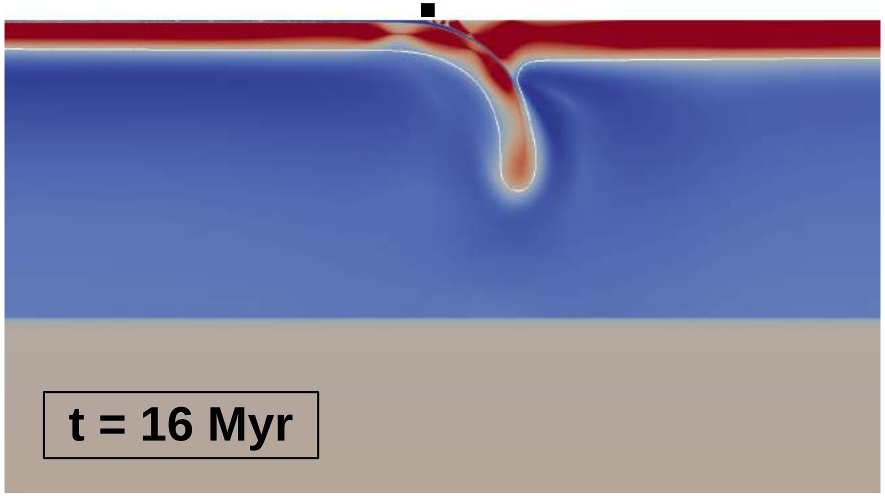
OP initial age = 20 Myr

Old, thick OP

OP initial age = 65 Myr

SP initial age = 30 Myr





Young (thin) slab is deflected
above the viscosity jump.

Effect of overriding plate age

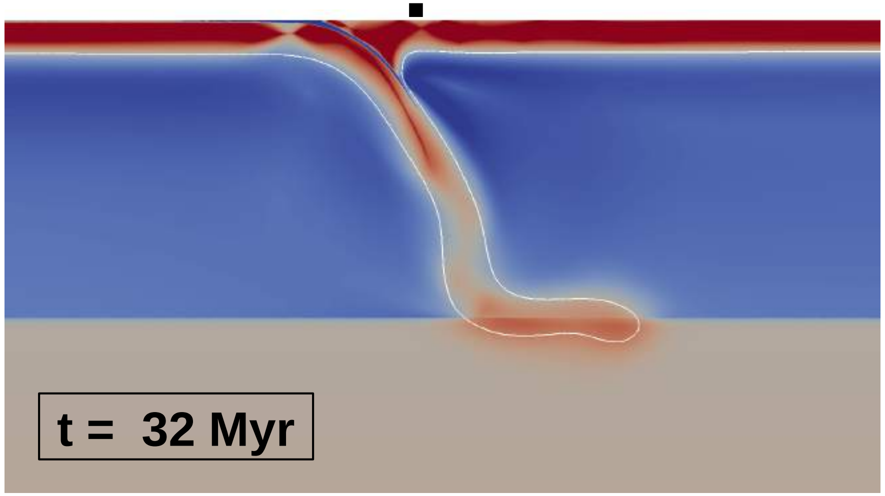
Young, thin OP

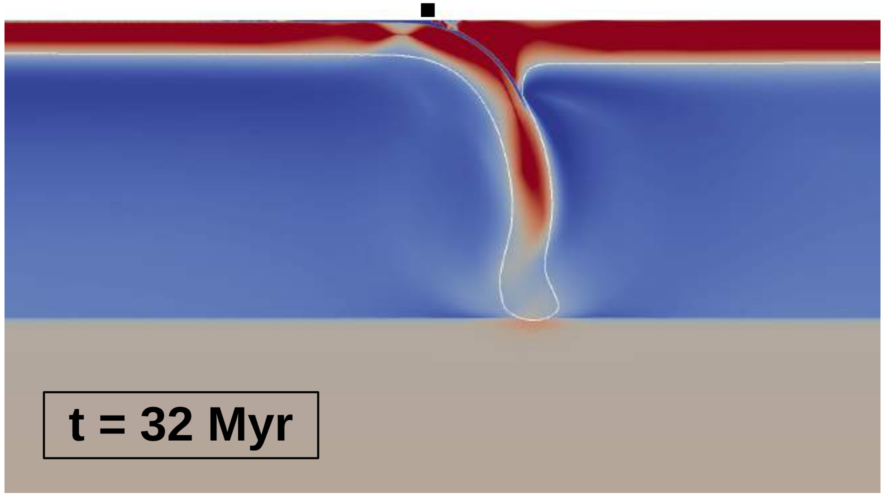
OP initial age = 20 Myr

Old, thick OP

OP initial age = 65 Myr

SP initial age = 30 Myr





Slab is able to rollback.

Warm, weak slab tip gets much deformed by the viscosity jump.

Effect of overriding plate age

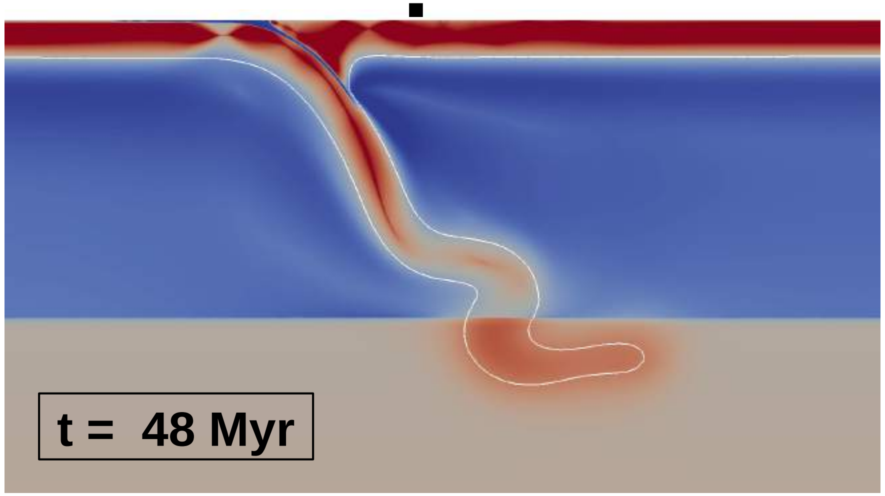
Young, thin OP

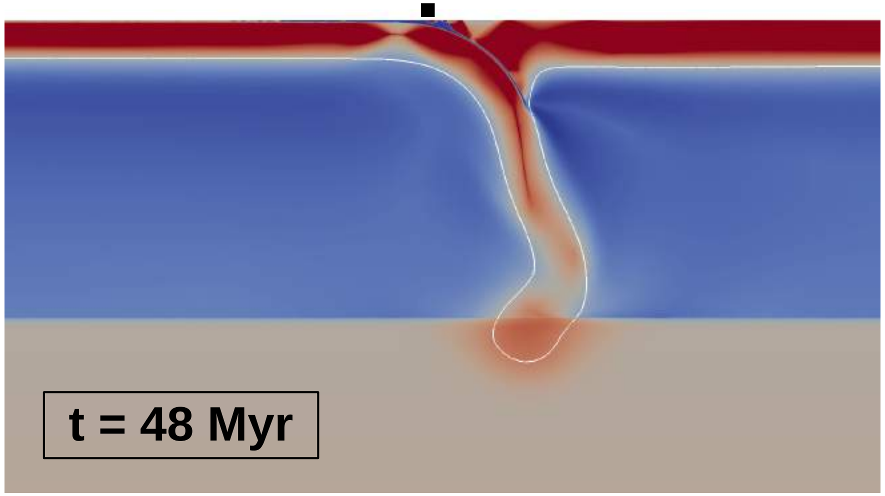
OP initial age = 20 Myr

Old, thick OP

OP initial age = 65 Myr

SP initial age = 30 Myr





Effect of overriding plate age

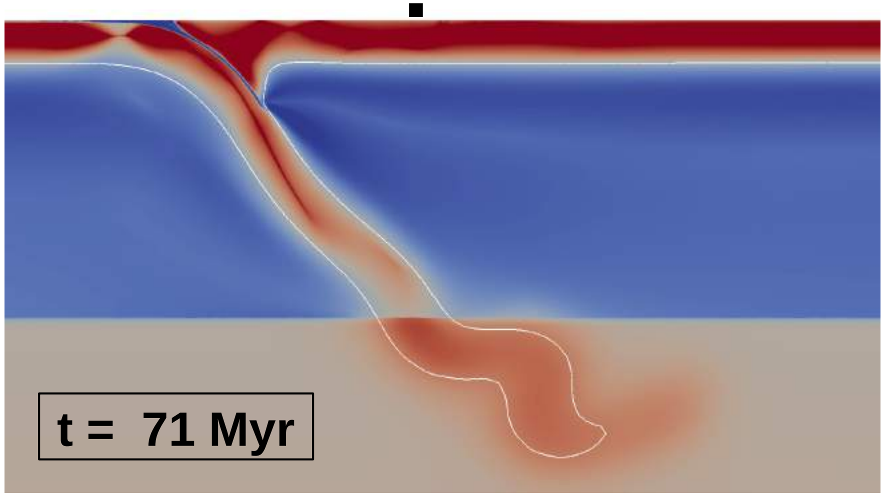
Young, thin OP

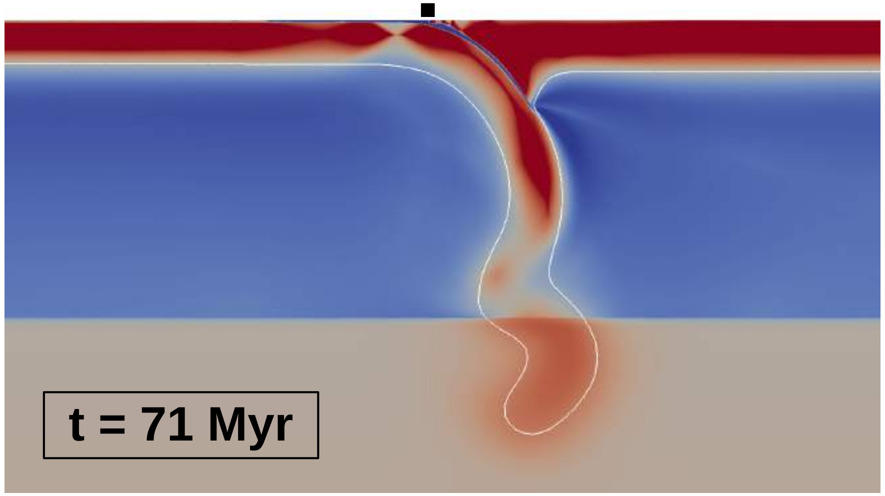
OP initial age = 20 Myr

Old, thick OP

OP initial age = 65 Myr

SP initial age = 30 Myr





Horizontally deflected slab

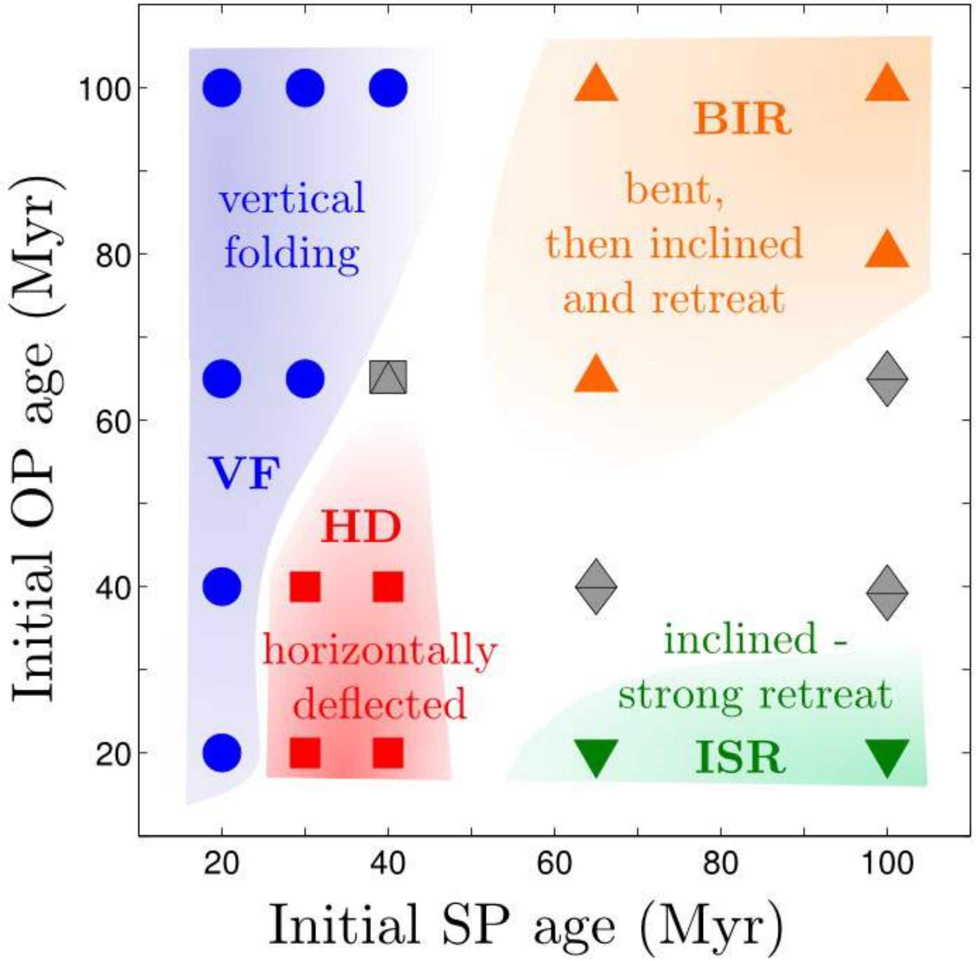
- Young SP and OP
- Thin slab deflected above 660 km
- trench retreat

Vertical folding

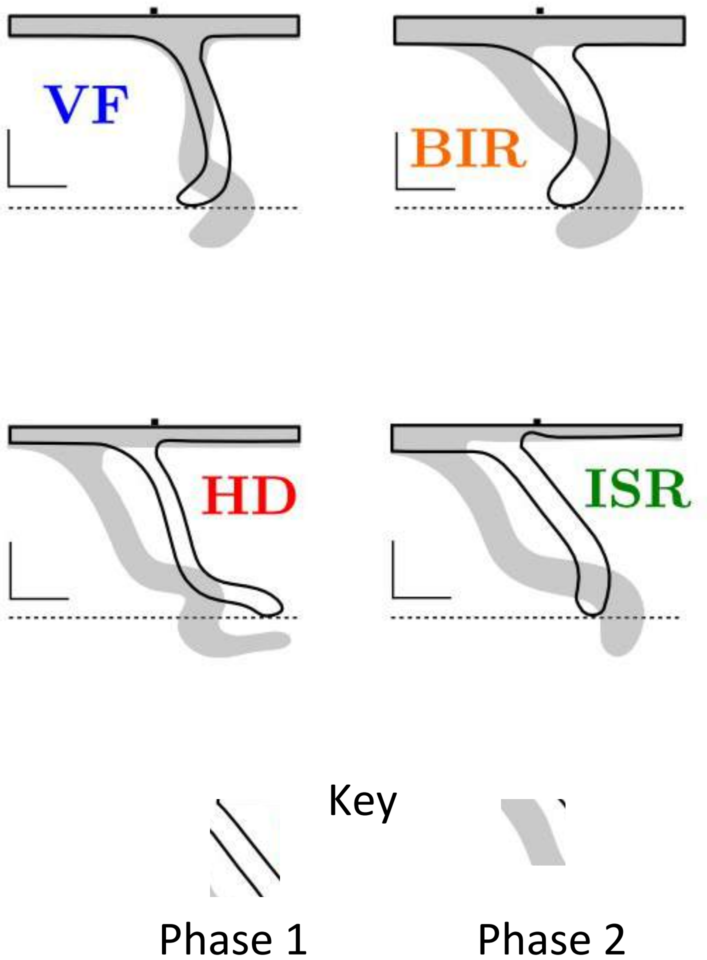
- Initially young SP, older OP
- OP inhibits of trench retreat

Slab morphology: a regime diagram

Resistance to trench motion



Buoyancy
Strength / Resistance to deformation

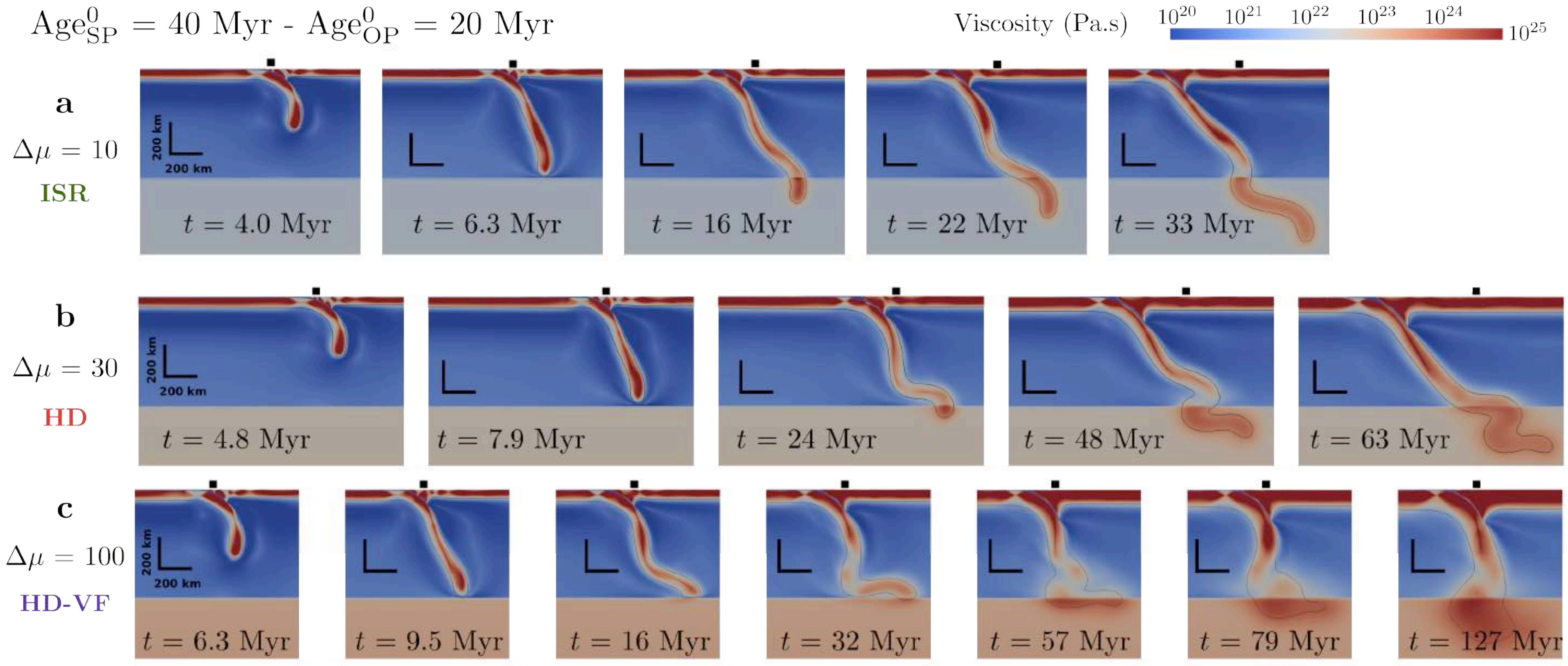


Upper mantle to lower mantle
Viscosity jump

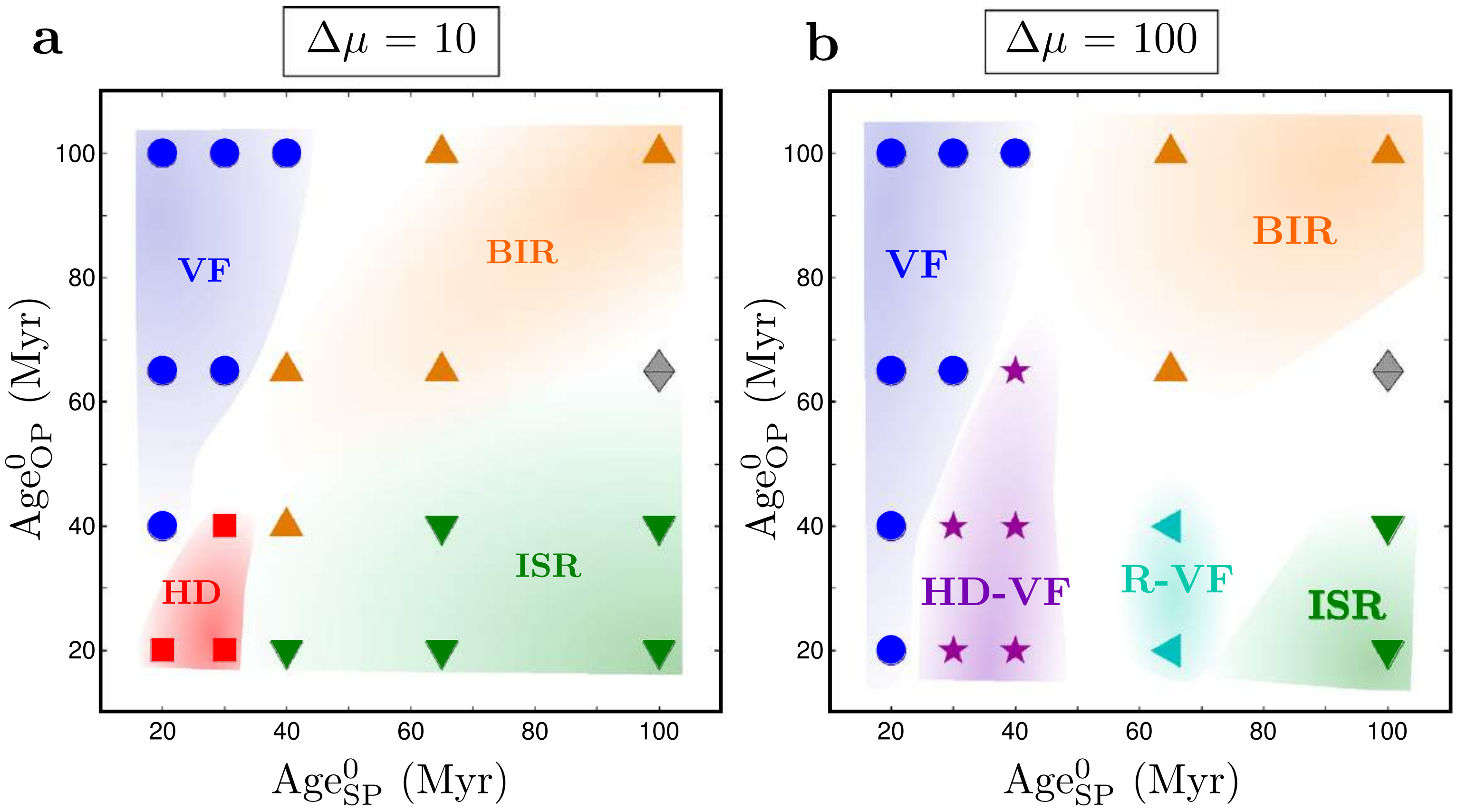
Investigated increases in viscosity from upper to lower mantle of x10, x30 and x100.

All previous examples have been for a viscosity jump of x30.

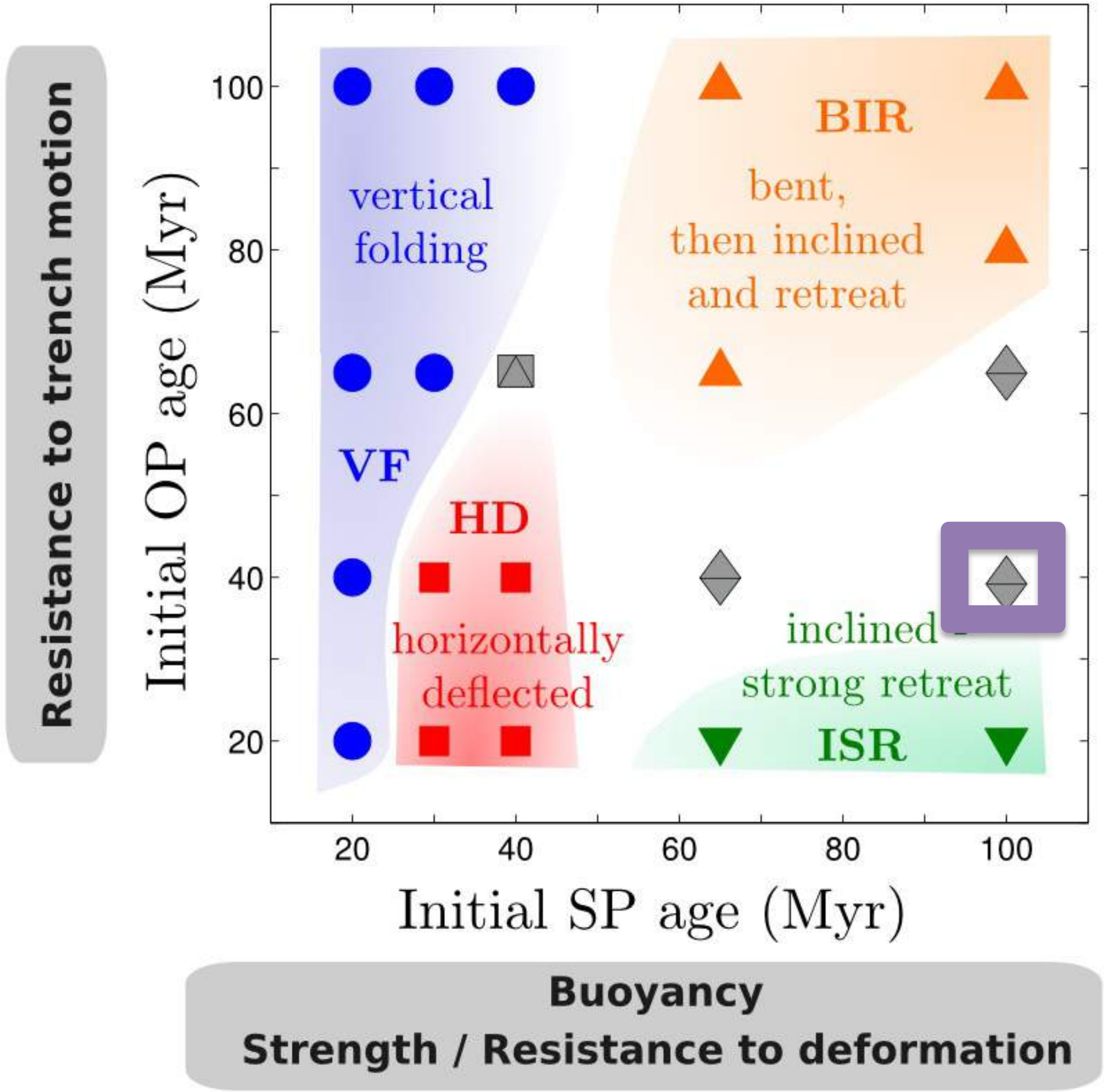
Effect of different upper to lower mantle viscosity jump

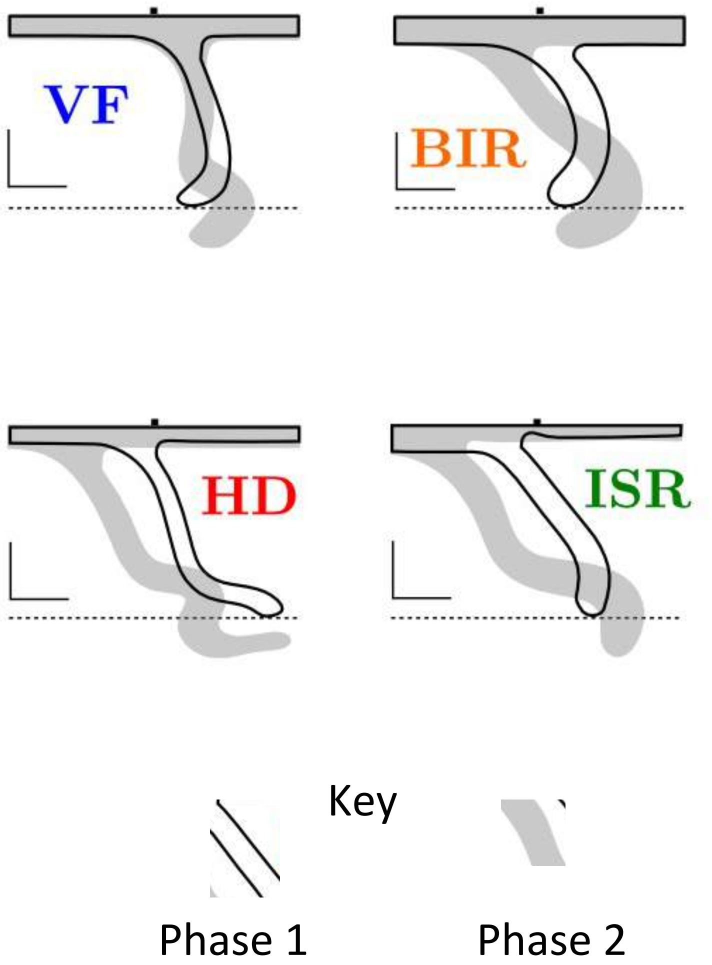


Regime Diagrams
Different viscosity contrast

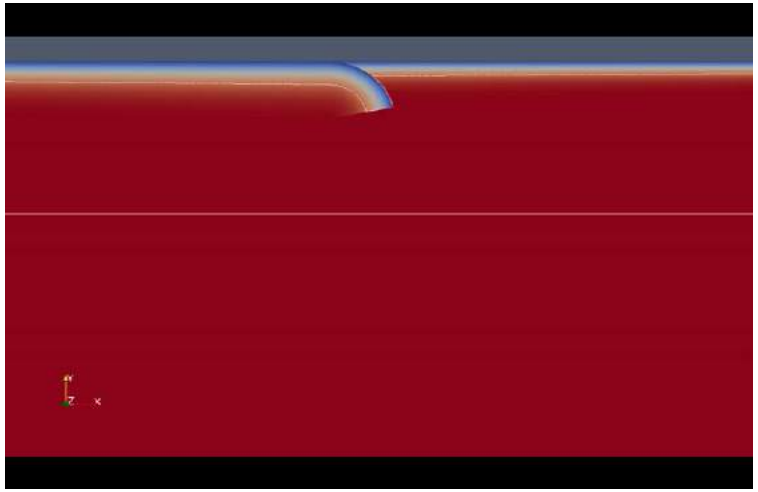


Slab morphology: a regime diagram

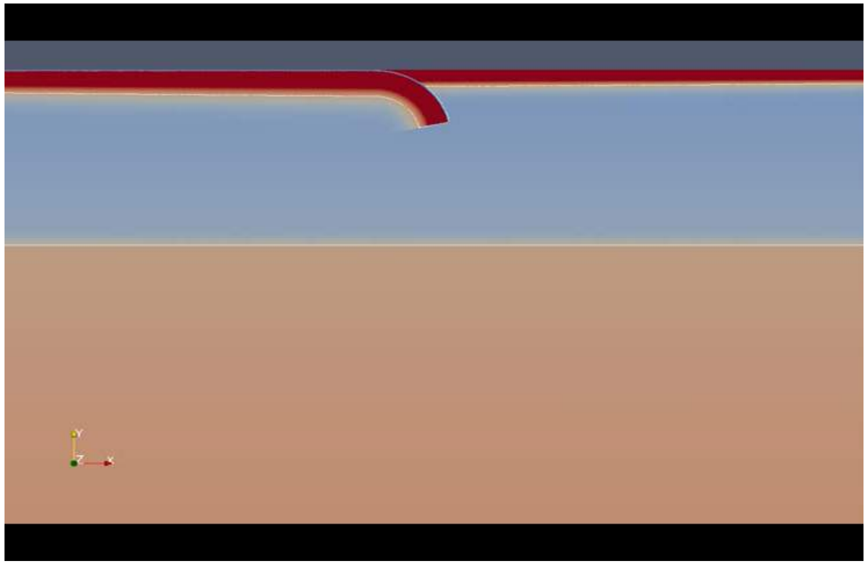




Boussinesq Approx. with Phase Change
Limited effect in this class of model



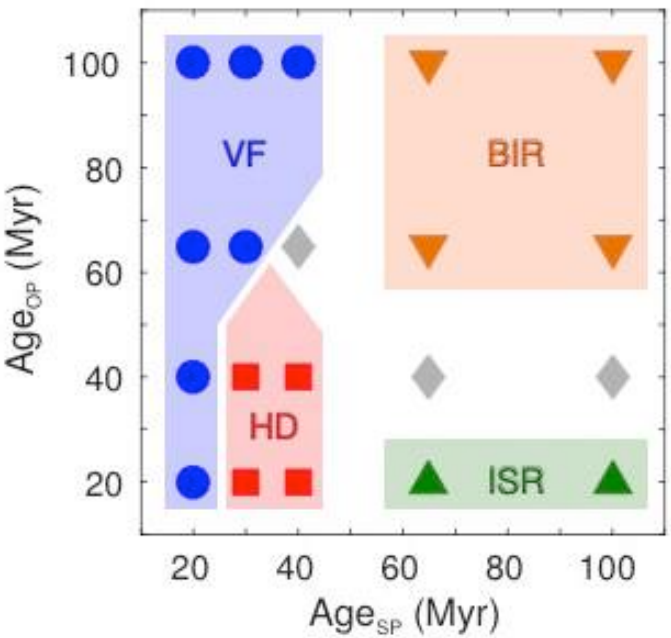
SP 100Myr, OP 40 Myr – but with 660km phase change – Clapeyron Slope = - 2.5 MPa/K, delta rho = 6%
Boussinesq Approximation =>
Incompressible, no latent heat



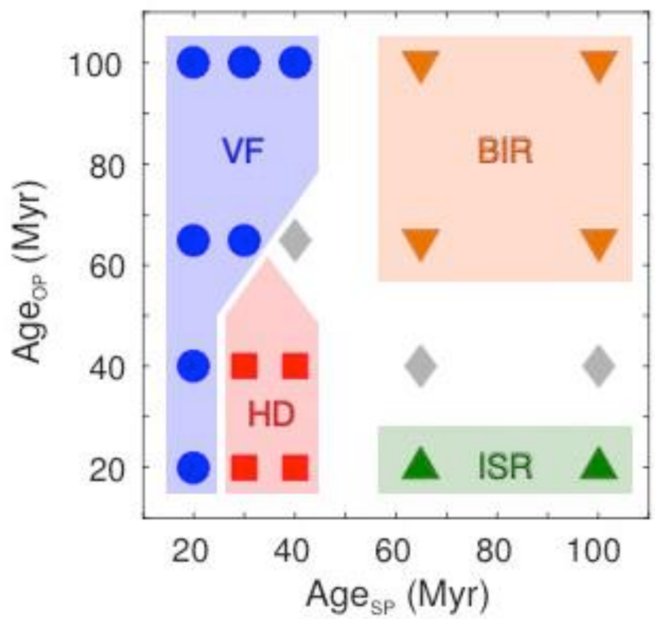
Frame gap of video is different!
Looks to not penetrate as easily – but does penetrate – and Mode is ISR, Inclined Strong Retreat

Regime Diagrams of Subduction Behaviour for Boussinesq Approximation with Phase Changes

Clapeyron Slope = -2.5 MPa / K



Clapeyron Slope = -4 MPa / K

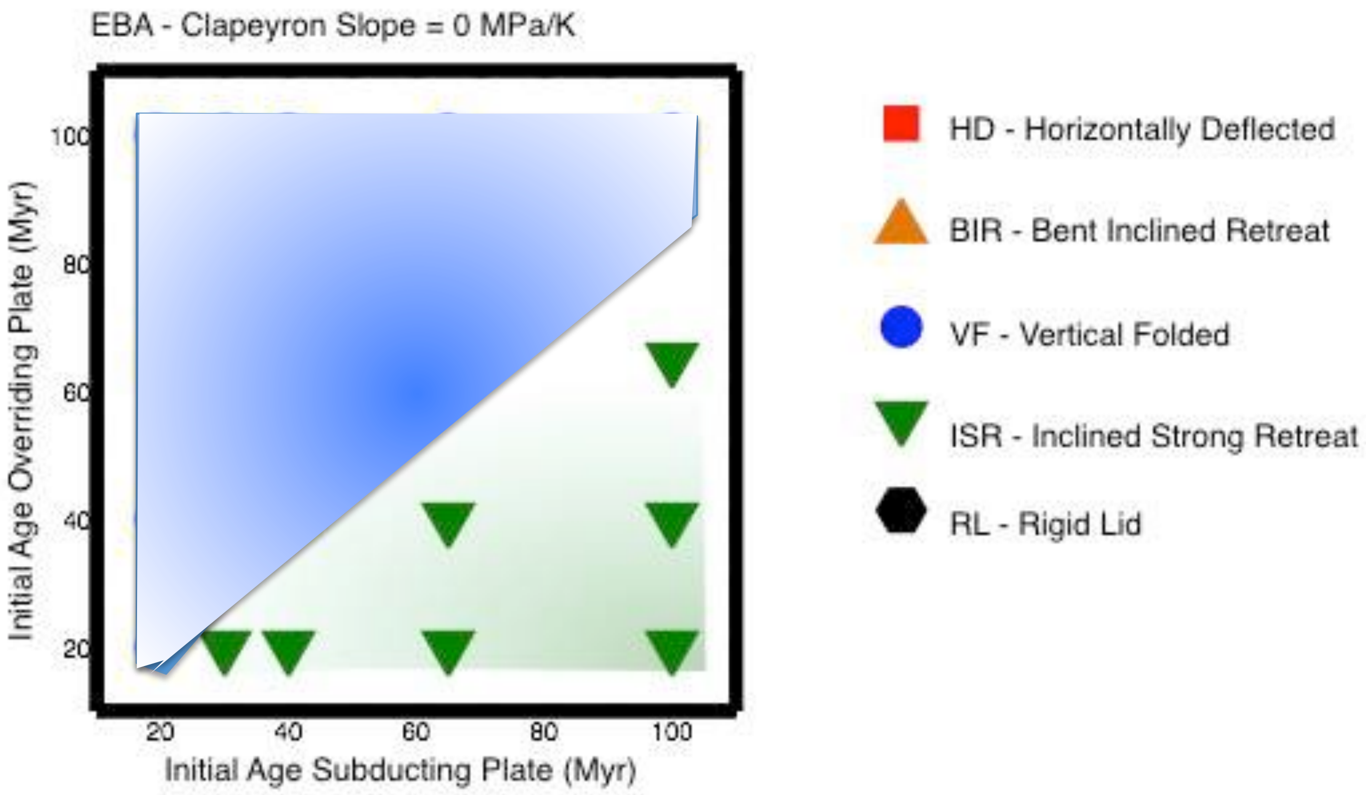


Extended Boussinesq Approximation with no Phase Change

SP 65Myr, OP 40 Myr – EBA – Viscous dissipation, adiabat

Extended Boussinesq Approximation with no Phase Change

Regime Diagram

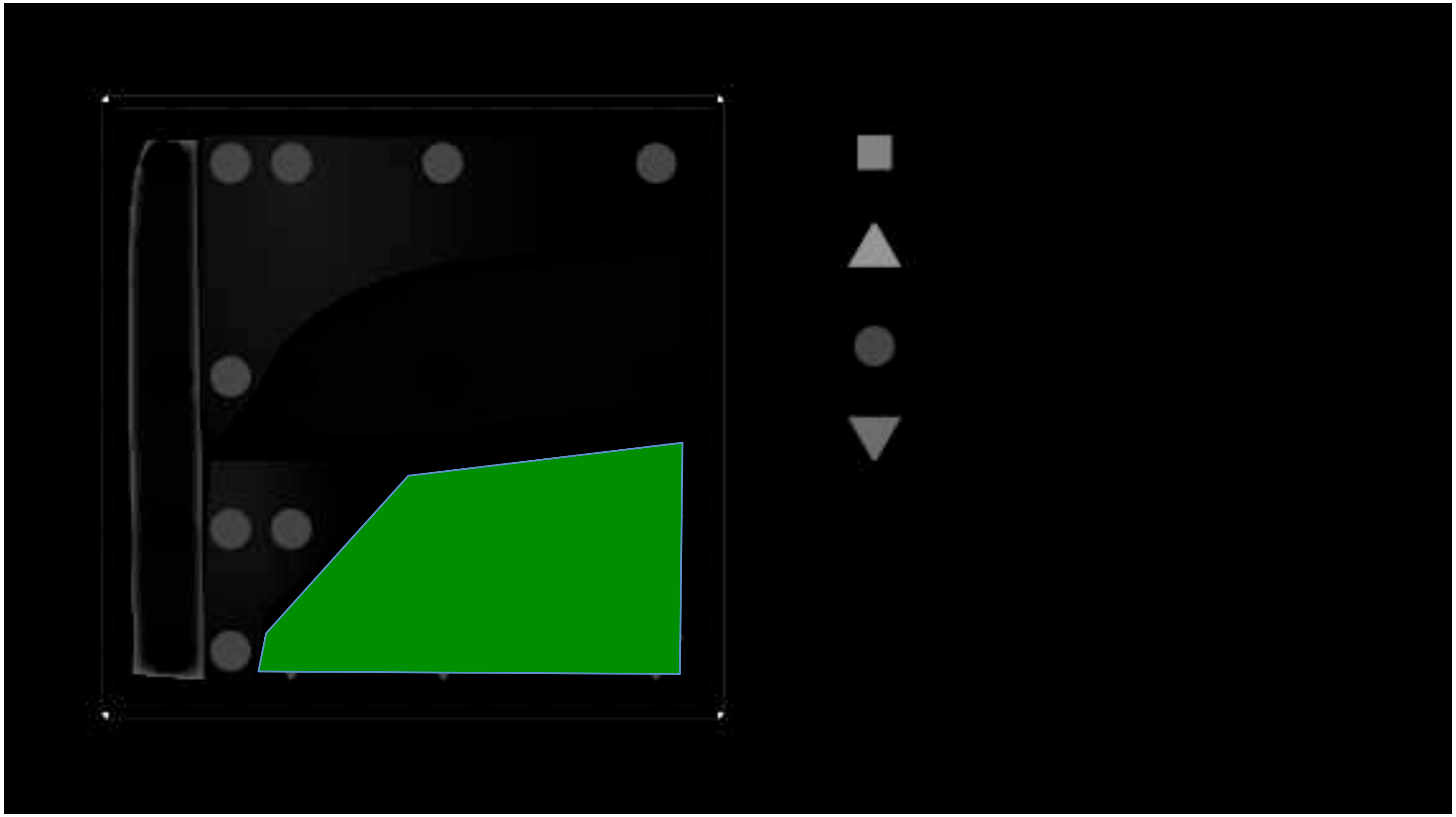


Extended Boussinesq Approximation with Phase Change – Clapeyron Slope -2MPa / K

SP 65Myr, OP 40 Myr – EBA – Viscous dissipation, adiabat, latent heat phase change

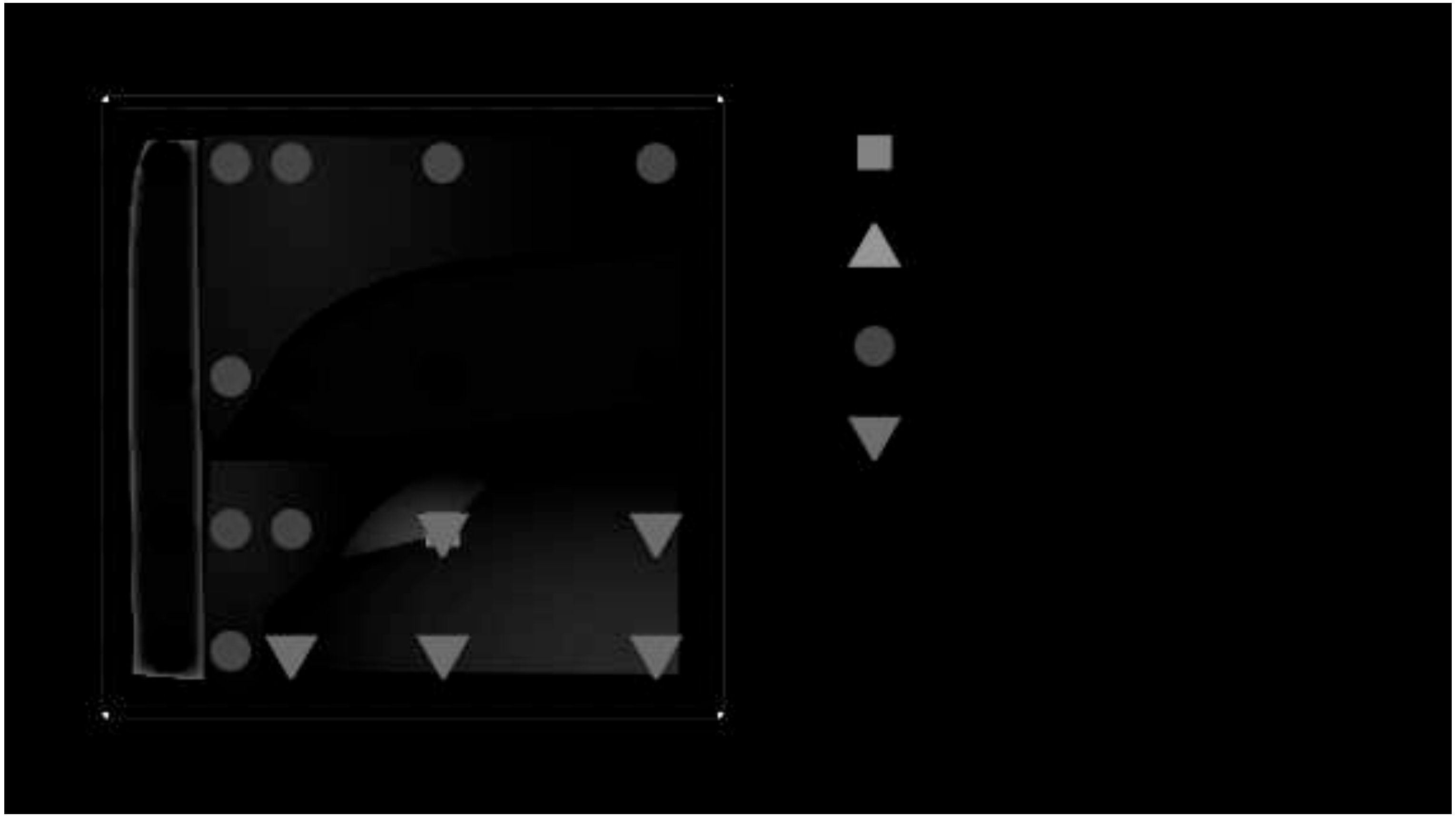
Extended Boussinesq Approximation with Phase Change – Clapeyron Slope -2MPa / K

Regime Diagram



Extended Boussinesq Approximation with Phase Change – Clapeyron Slope -2MPa / K

Regime Diagram

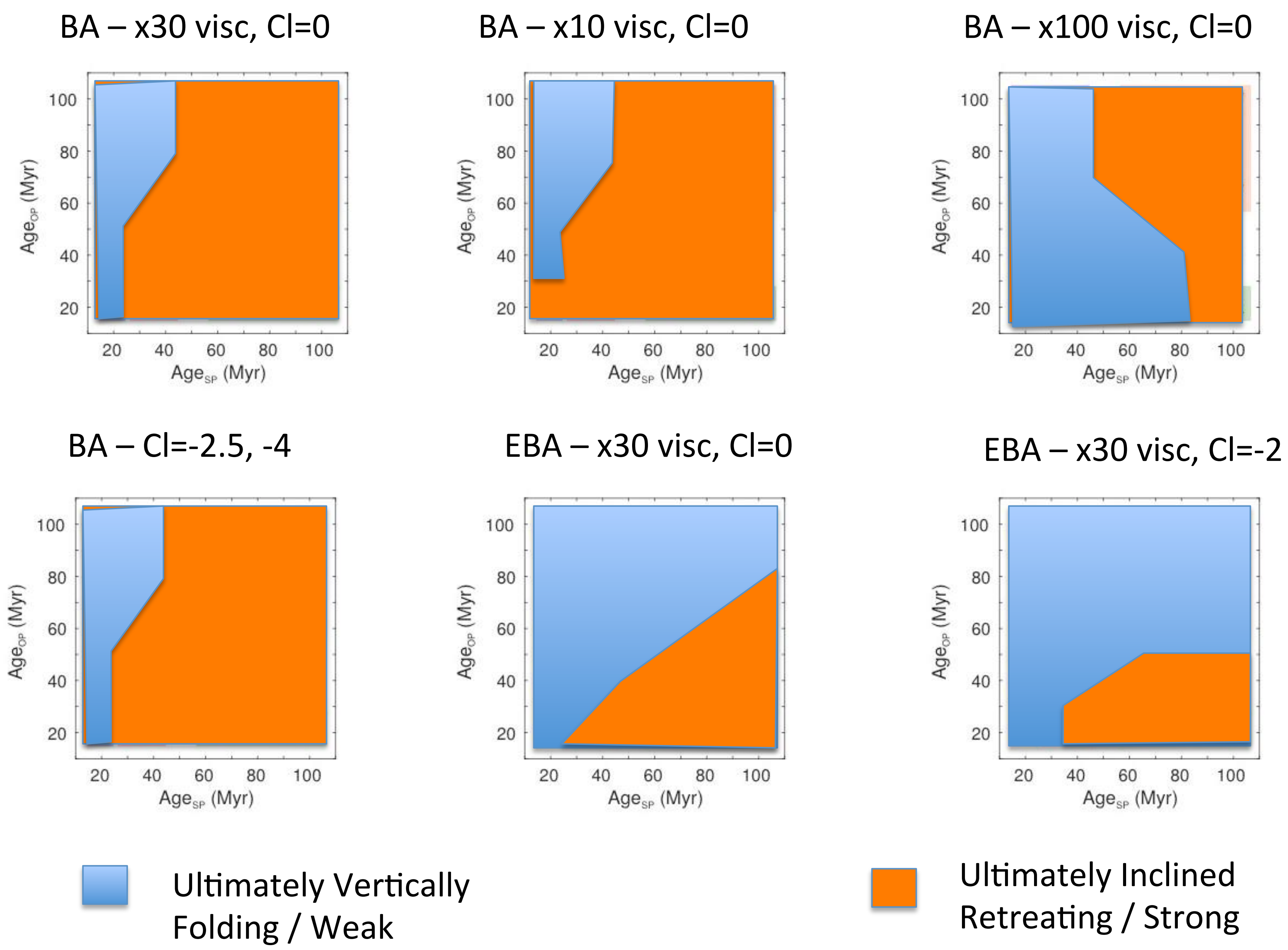


Summary of all investigations

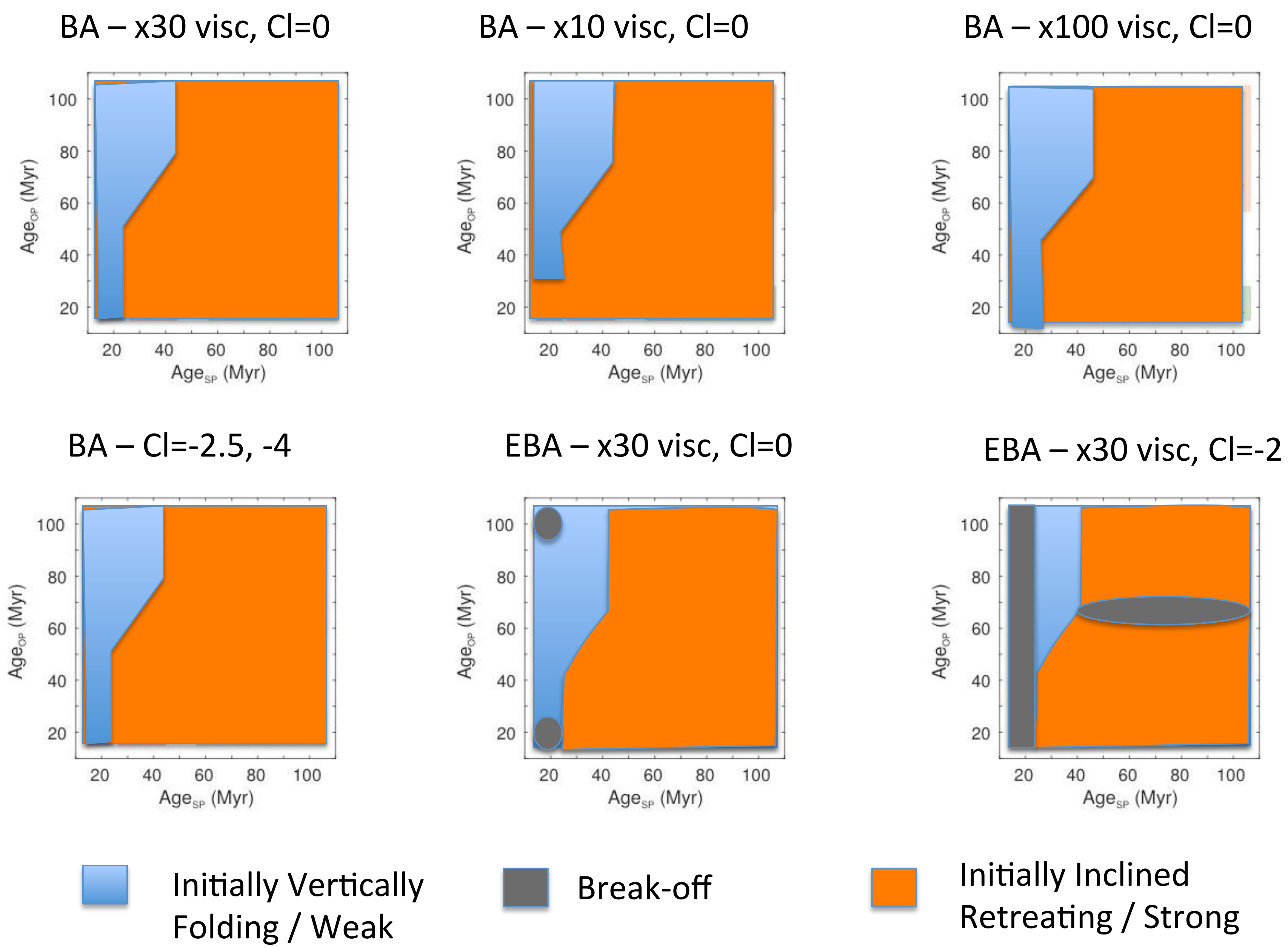
1. BA – NP - x 30 visc jump – Base case
2. BA - NP – x 10 visc jump – pass through more easily
3. BA - NP – x 100 visc jump – pass through more slowly
4. BA – MP - x 30 visc jump – virtually no change from Base
5. BA – SP - x 30 visc jump – virtually no change from Base
6. EBA – NP – x30 visc jump – weaker slabs – more vertically folded cases
7. EBA – MP - x 30 visc jump – weaker still – vertical folding dominates – but also Break-off and rigid lid

- BA – Boussinesq Approximation, EBA – Extended BA; NP – no phase change, MP – moderate phase change, SP – Strong phase change

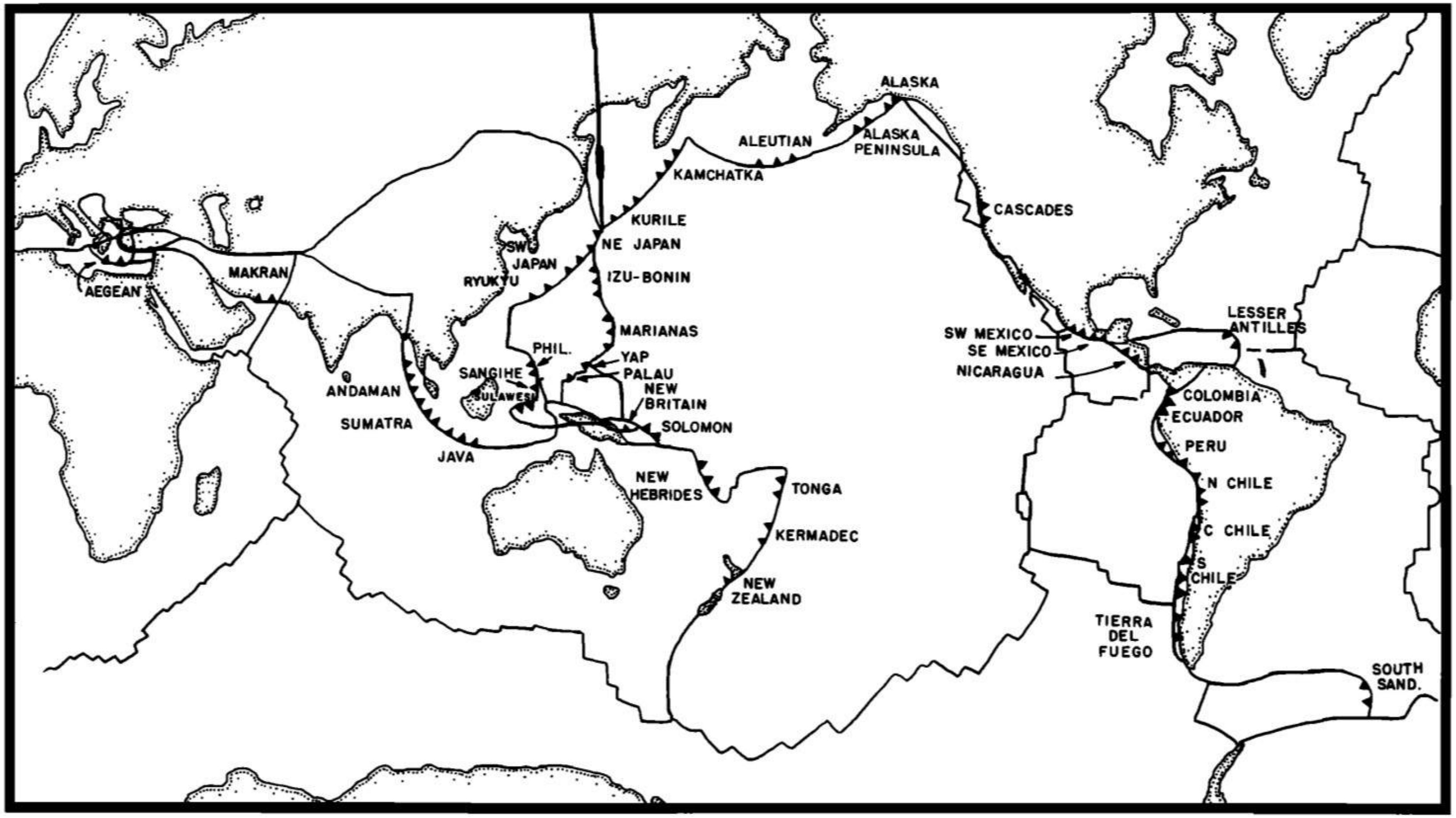
Summary 7 cases – BA – Boussinesq Approximation; EBA – Extended BA; Cl – Clapyeron Slope



Summary 7 cases – BA – Boussinesq Approximation; EBA – Extended BA; Cl – Clapyeron Slope



Comparison with data: a complex issue



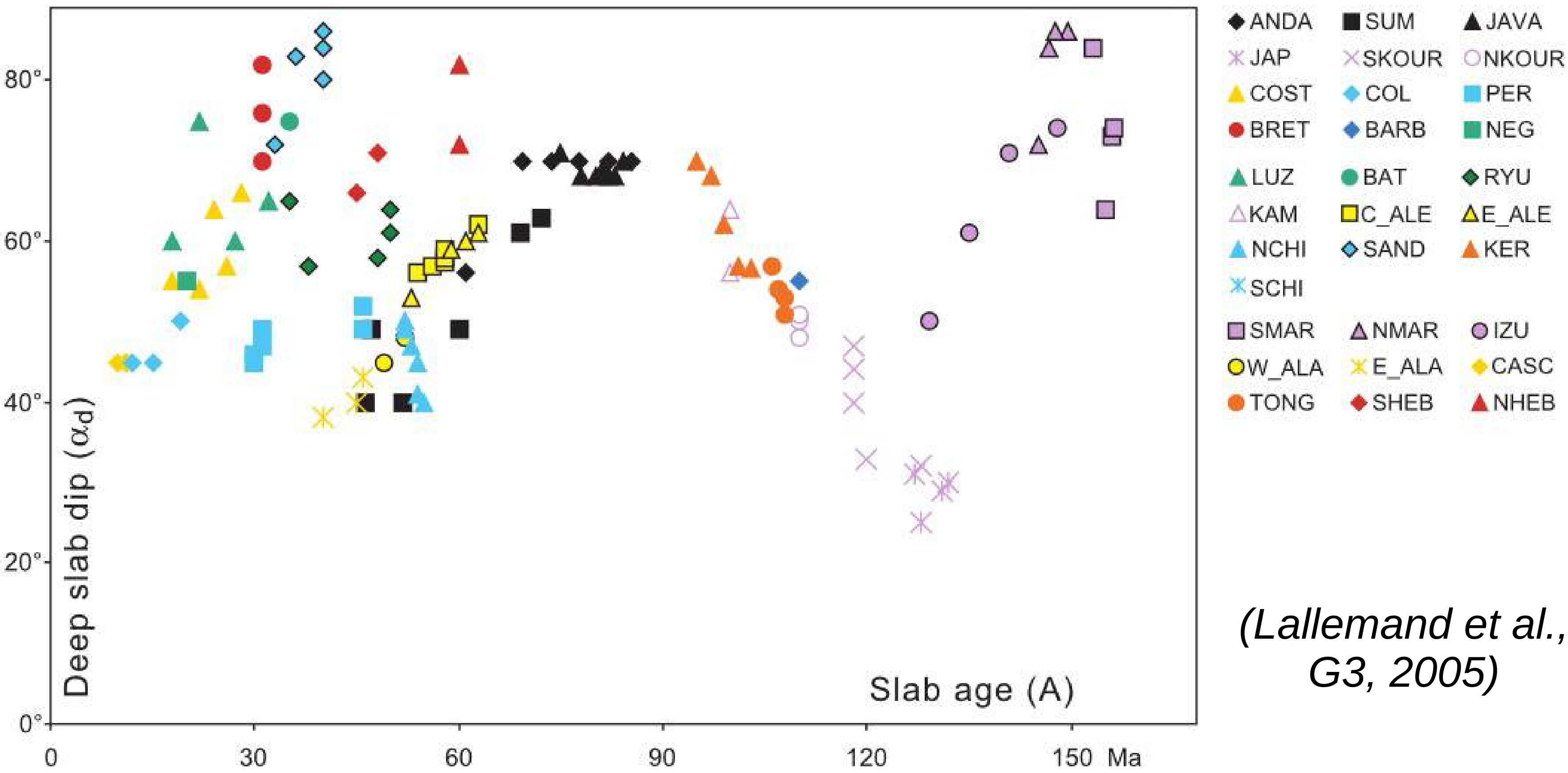
(Jarrard, 1986)

→ when did subduction initiate?

→ is trench motion governed by slab descent or by external forcings?

→ lateral variations in the subduction geometry? (3D effects)

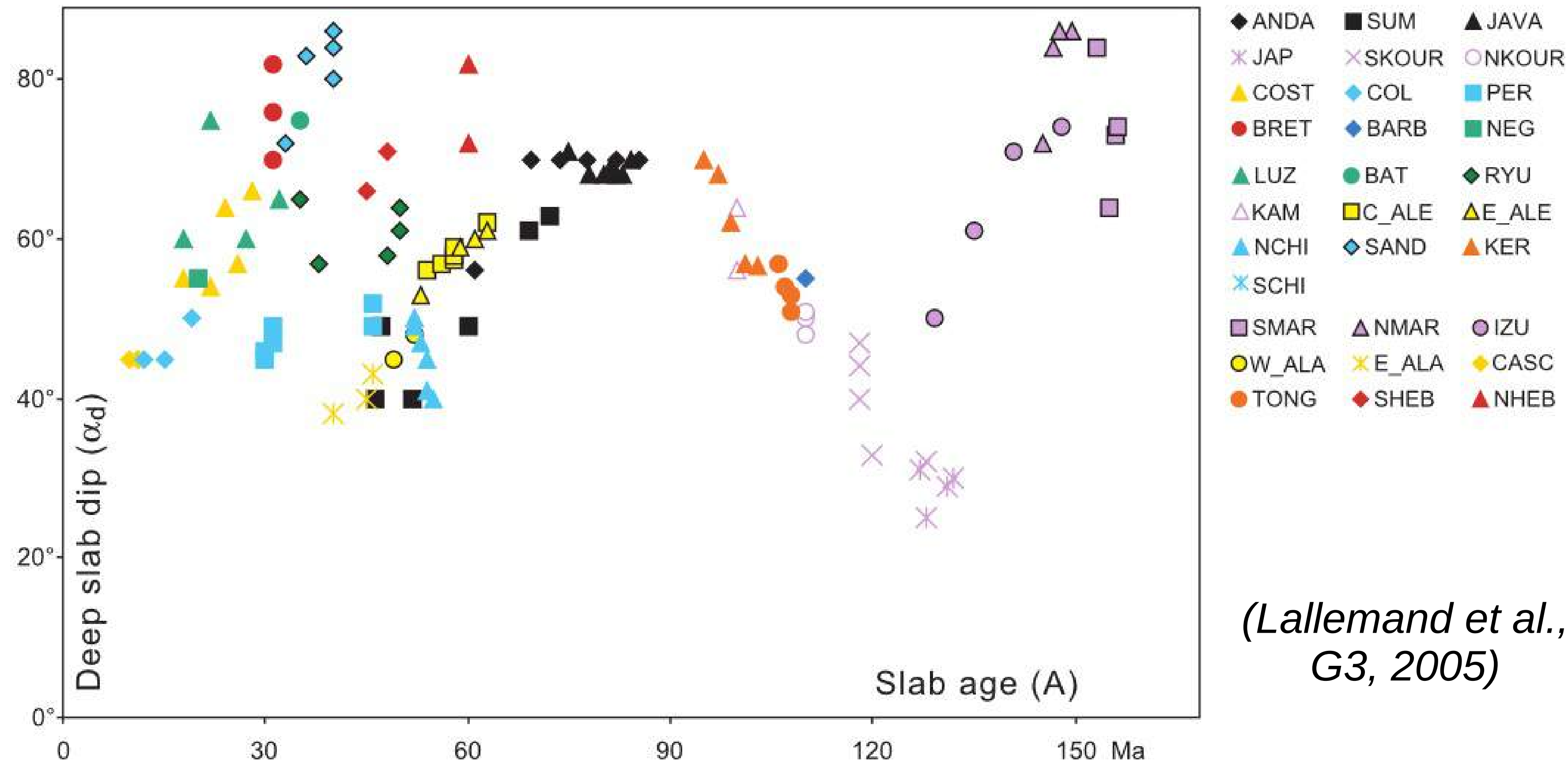
Slab morphology vs. SP age at trench



(Lallemand et al., G3, 2005)

No correlation between present-day age at the trench and slab geometry

Slab morphology vs. SP age at trench

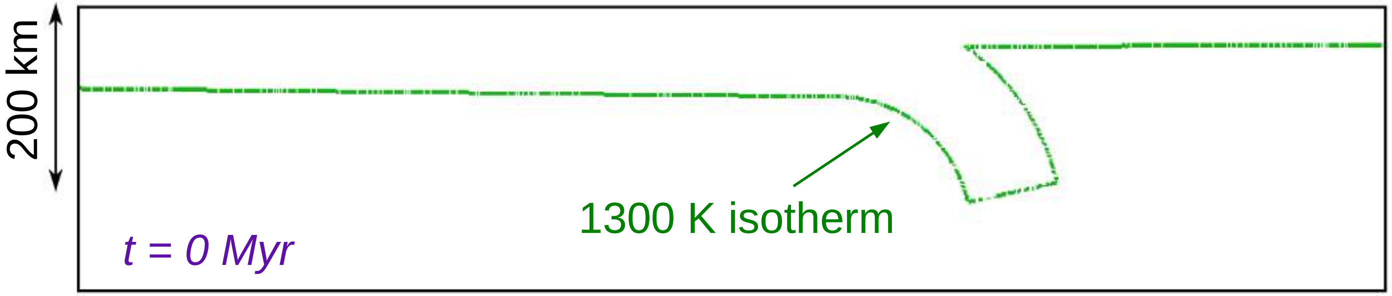


(Lallemand et al., G3, 2005)

No correlation between present-day age at the trench and slab geometry

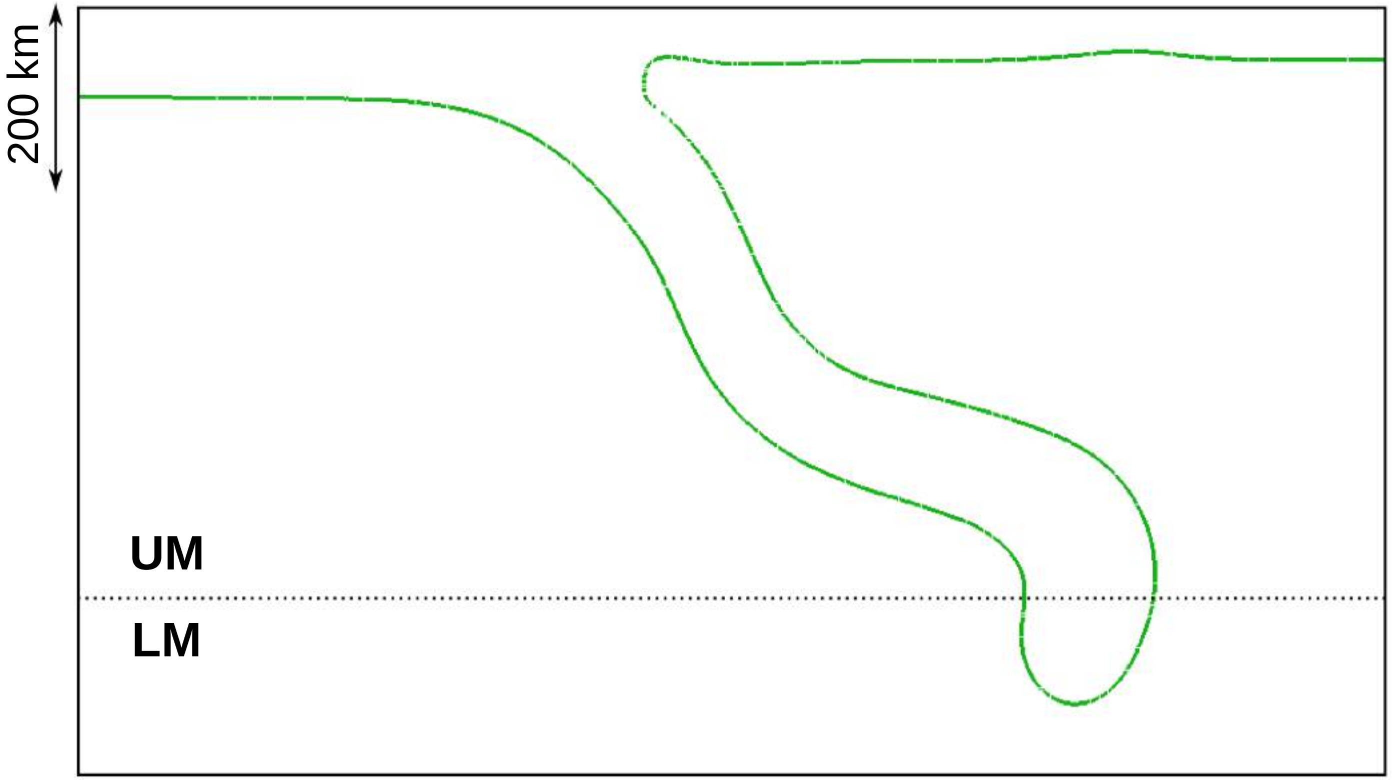
could be explained by evolution of plate ages during subduction

Slab morphology vs. SP age at trench



Initial SP age / OP age

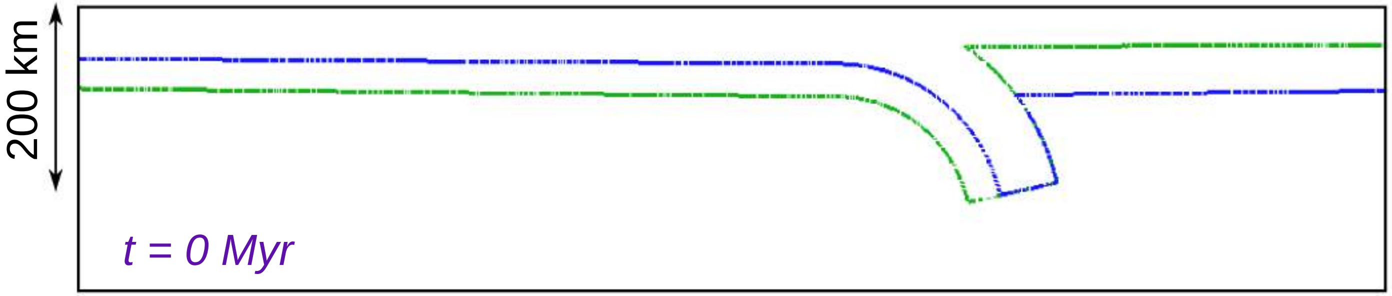
100 Myr / 20 Myr



SP age at trench
~ 100 Myr

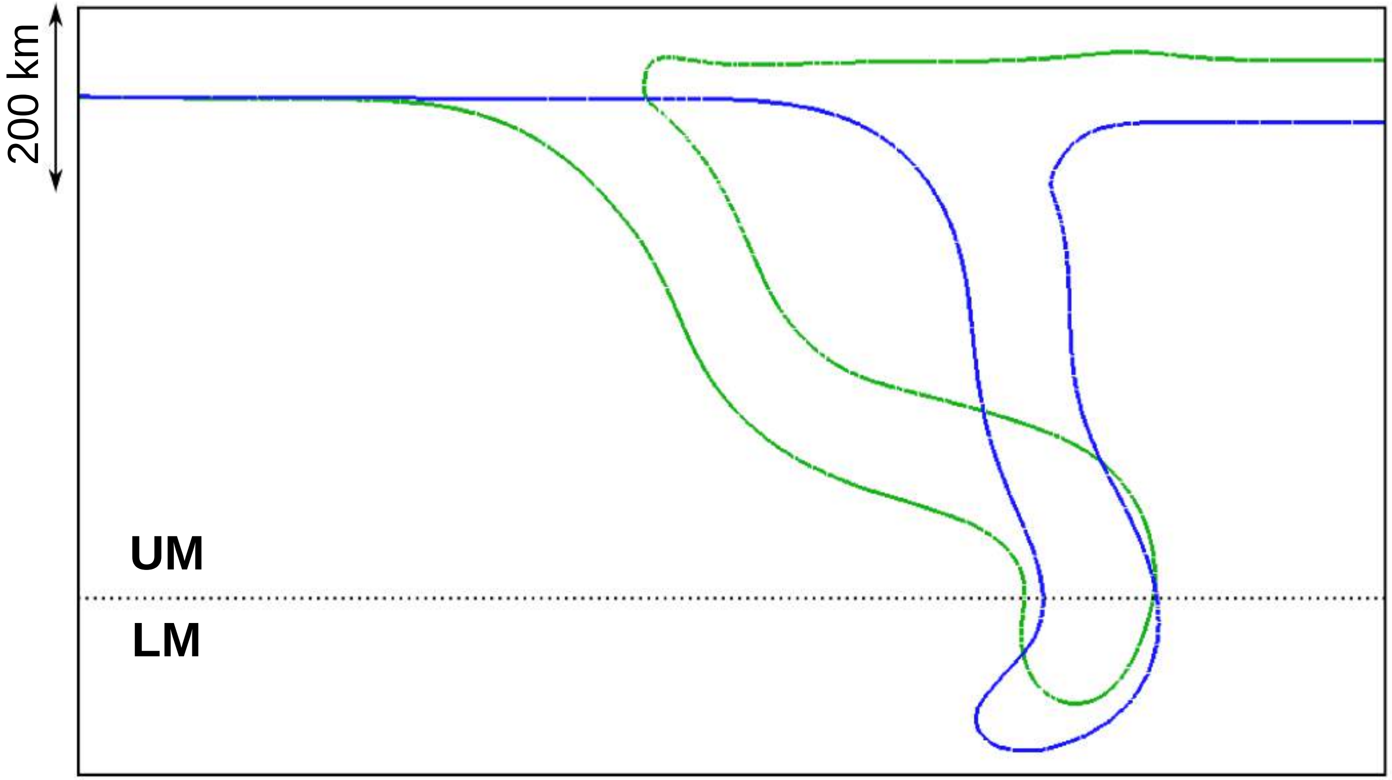
t = 16 Myr

Slab morphology vs. SP age at trench



Initial SP age / OP age

100 Myr / 20 Myr
40 Myr / 100 Myr



SP age at trench
~ 100 Myr

t = 16 Myr
t = 65 Myr

Limitations

- 2D only
- Limited phase change parameterisation
- Fixed grain-size
- No crust (Chemical buoyancy)
- Already initiated
- No detailed investigation varying rheology parameters, (water in wedge?)

- Pluses – Dynamic whole thermo-mechanical mantle model, composite rheology, large viscosity variations

Conclusions

System Feedbacks - with temp., strain-rate dependent viscosities:

- coupling of plate strength and buoyancy
- coupling between dynamics and strength (for plate and mantle)

(deformation➛ rheology➛flow ➛deformation)

Subtle balance – sometimes small changes (BA -> EBA) can have big effects; other times big changes, e.g. phase changes in BA have virtually no effect

Trench motion and rheology keys to understand slab deformation in mantle (➛also upper plate) – trench rollback can be significant

Conclusions

Regime diagram -> wide range of slab morphology

= function(initial plate ages)

[SP ➛ driving sinking force, slab strength]

[OP ➛ resistance to trench retreat]

Recover virtually all observed deep subduction morphologies

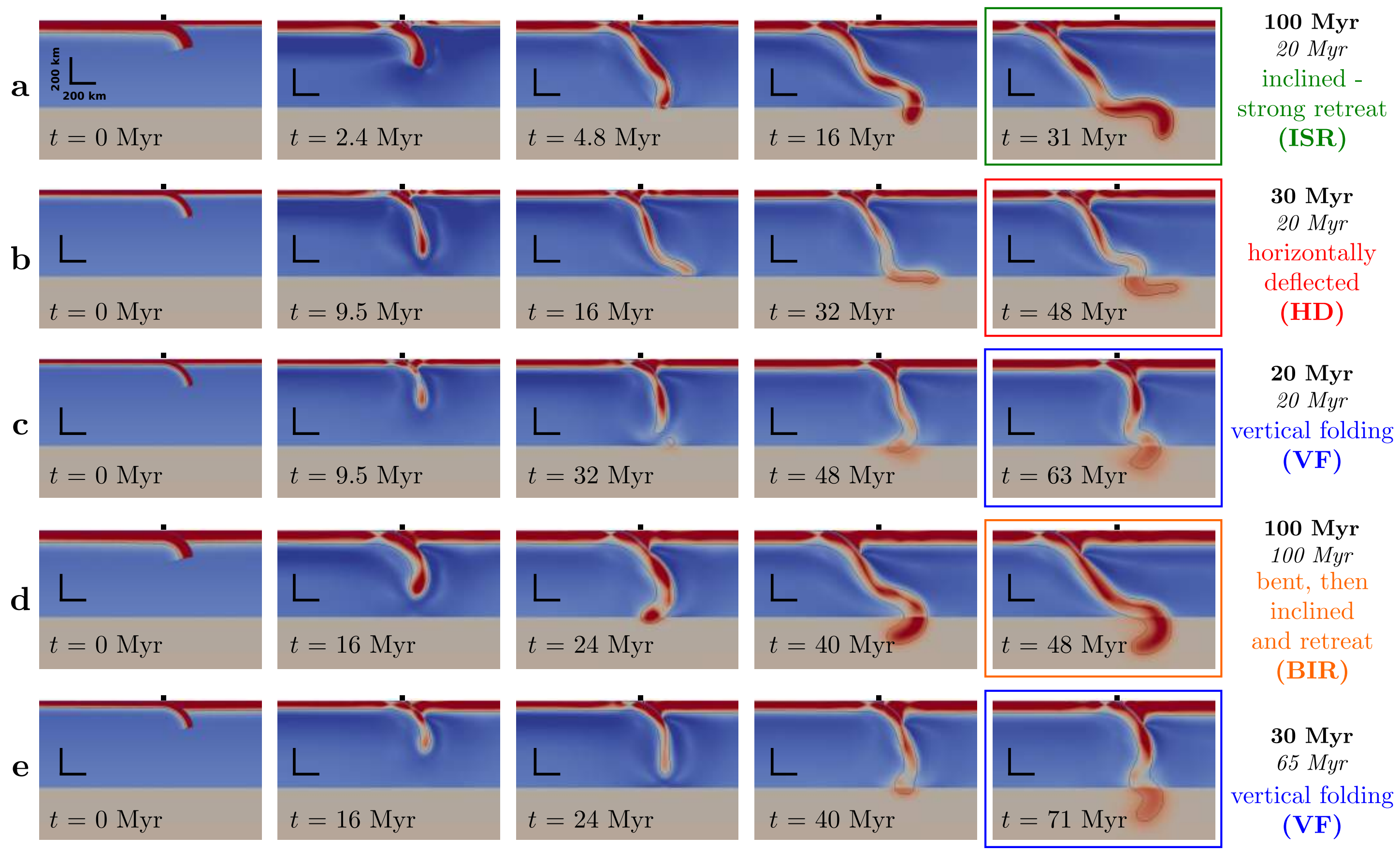
Different morphologies can exhibit the same plate age at trench

➛ importance of evolution

'Valve' is complicated

- ➛ Subducting slab buoyancy/strength is most important
- ➛ 'valve' is **open** for all cases shown
- ➛ **ALL** modelled slabs descend through "660", even if they lie out flat on the boundary for a time, descent rate varies

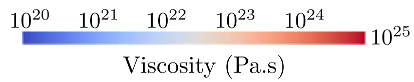
Boussinesq Approximation, x30 upper to lower mantle viscosity jump, no “660” phase change



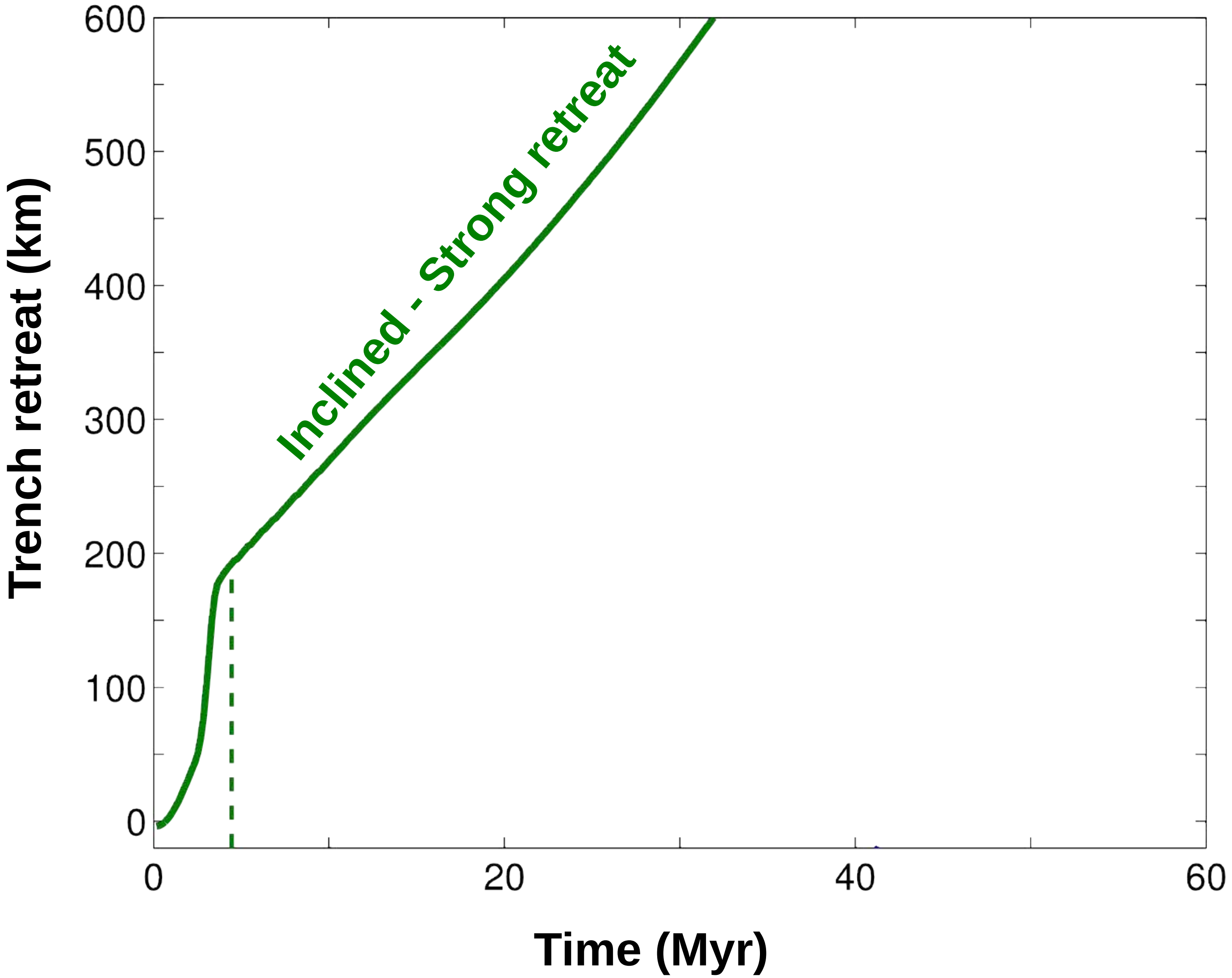
	a	b	c	d	e
$\mathbf{Age^0_{SP}}$ (Myr)	100	30	20	100	30
Age^0_{OP} (Myr)	20			100	65

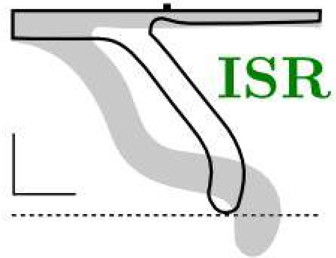
Influence of $\mathbf{Age^0_{SP}}$: a, b, c

Influence of Age^0_{OP}: a/d and b/e

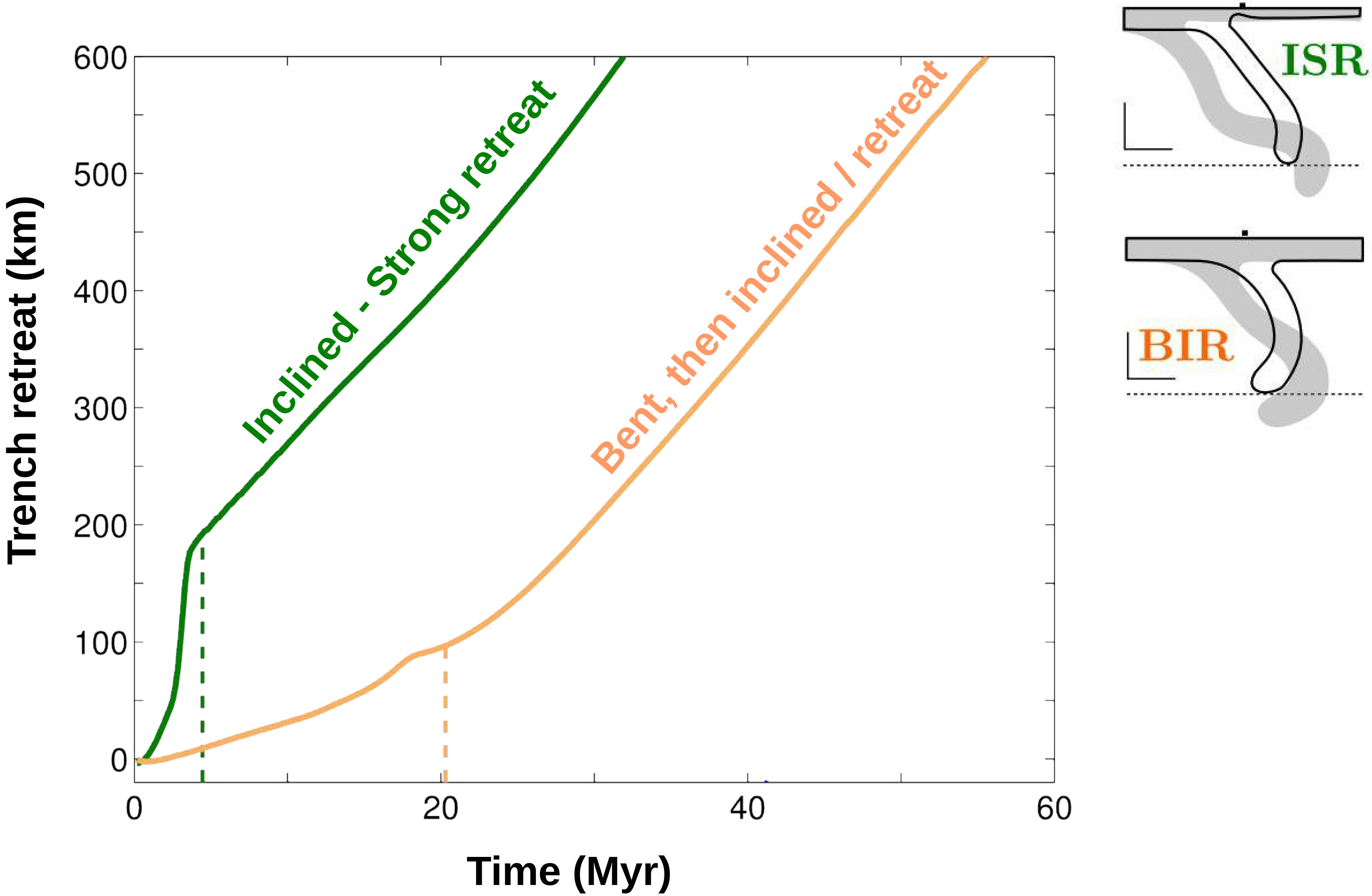


Slab morphology: associated trench motion

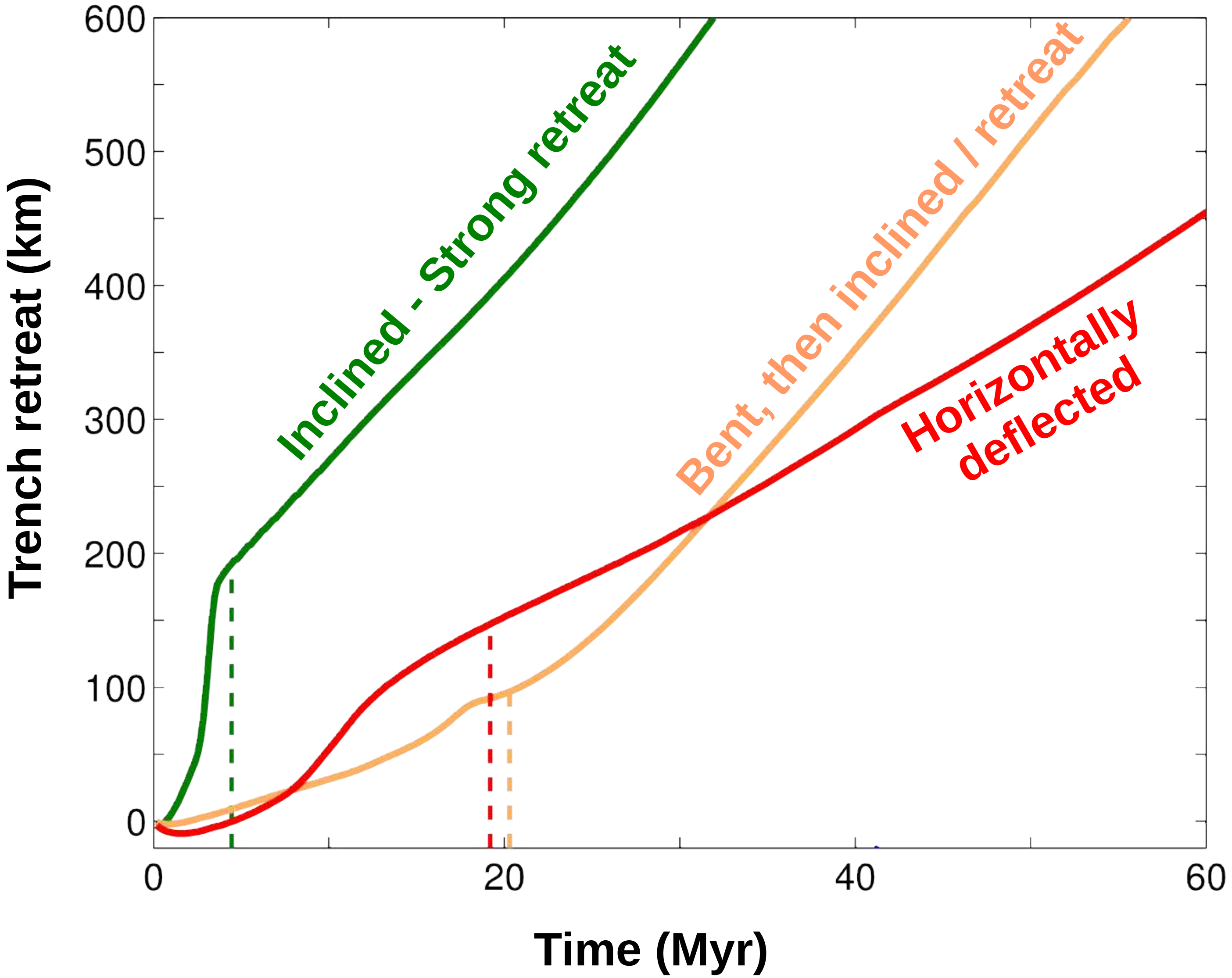


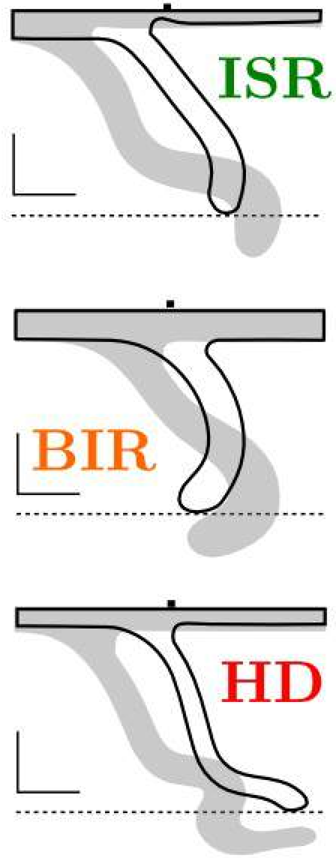


Slab morphology: associated trench motion

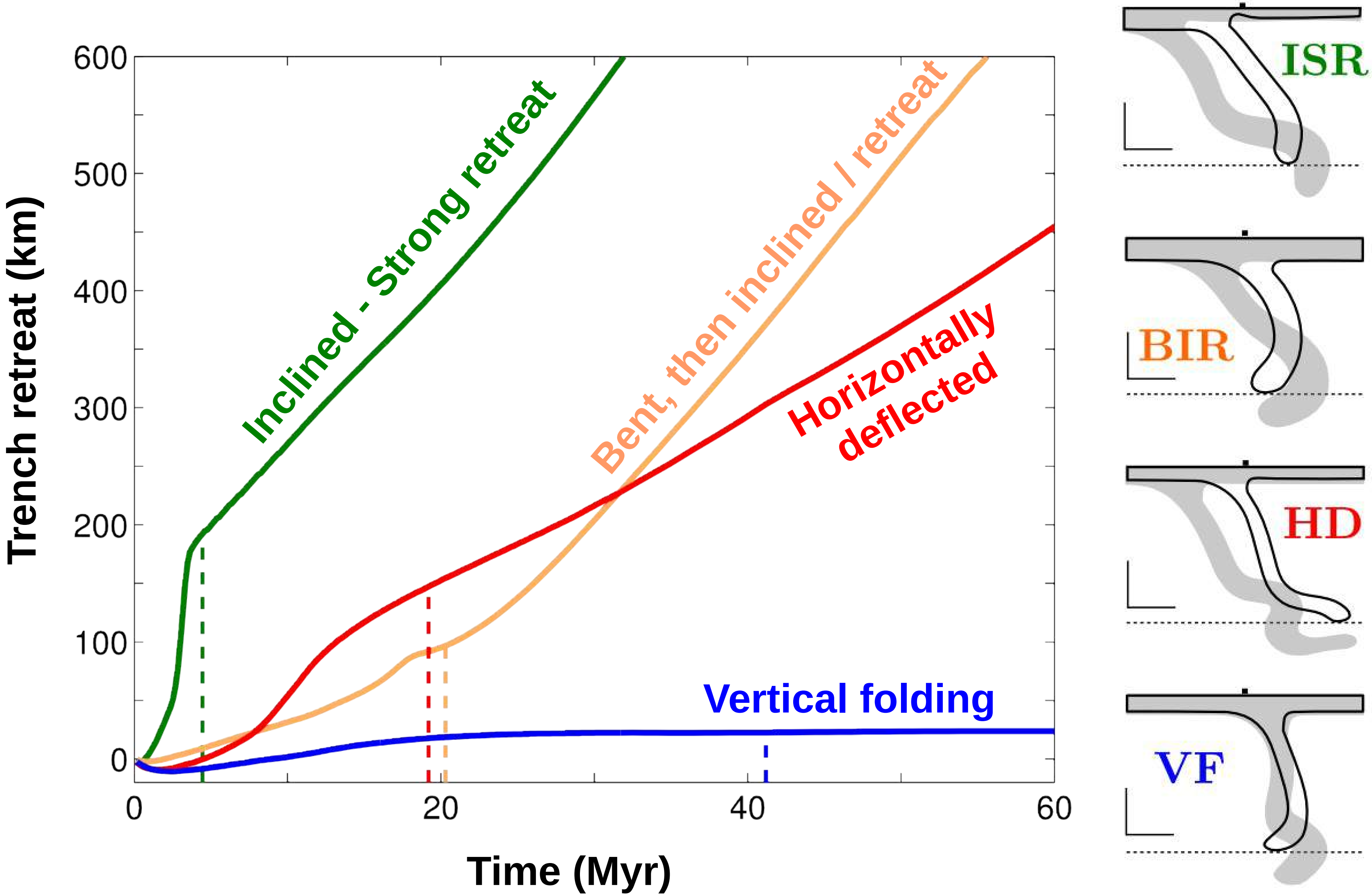


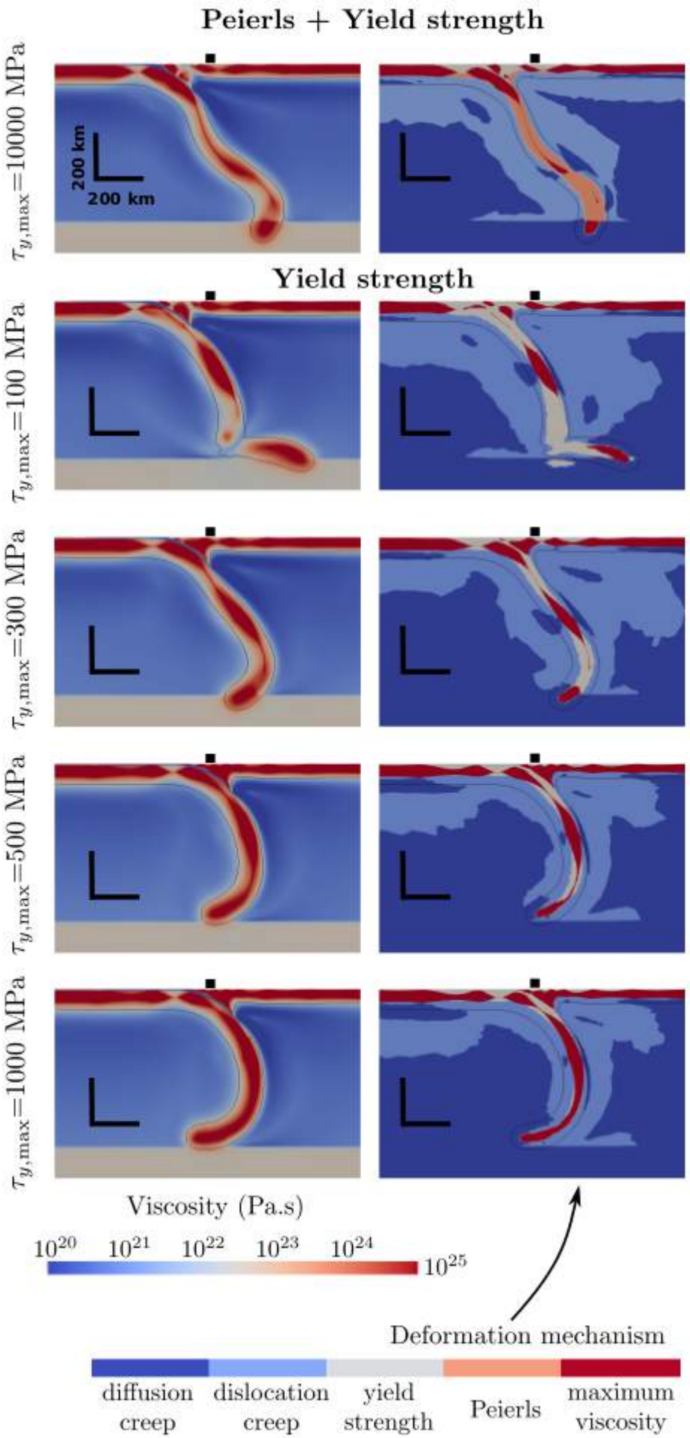
Slab morphology: associated trench motion





Slab morphology: associated trench motion




Peierls + Yield strength
$\tau_{y,\max}$=10000 MPa
200 km
200 km
Yield strength
$\tau_{y,\max}$=100 MPa
$\tau_{y,\max}$=300 MPa
$\tau_{y,\max}$=500 MPa
$\tau_{y,\max}$=1000 MPa
Viscosity (Pa.s)
10^{20} 10^{21} 10^{22} 10^{23} 10^{24} 10^{25}
Deformation mechanism
diffusion creep
dislocation creep
yield strength
Peierls
maximum viscosity

Composite Rheology

$$\mu = \left(\frac{1}{\mu_{diff}} + \frac{1}{\mu_{disl}} + \frac{1}{\mu_{p}} + \frac{1}{\mu_{yielding}} \right)^{-1}$$

Composite rheology

Diffusion creep

$$\mu_{diff} = A \exp\left(\frac{E + PV}{RT}\right)$$

Viscosity — μ_{diff}

pre-factor — A

Activation energy — E

Lithostatic pressure — P

Activation volume — V

potential temperature + adiabatic gradient — T

Upper mantle

$$E = 300 \text{ kJ/mol}$$
$$V = 4 \text{ cm}^3\text{/mol}$$

Lower mantle

$$E = 200 \text{ kJ/mol}$$
$$V = 1.5 \text{ cm}^3\text{/mol}$$

Composite rheology

Dislocation creep

$$\mu_{disl} = A \exp\left(\frac{E + PV}{nRT}\right) \dot{\varepsilon}^{\frac{1-n}{n}}$$

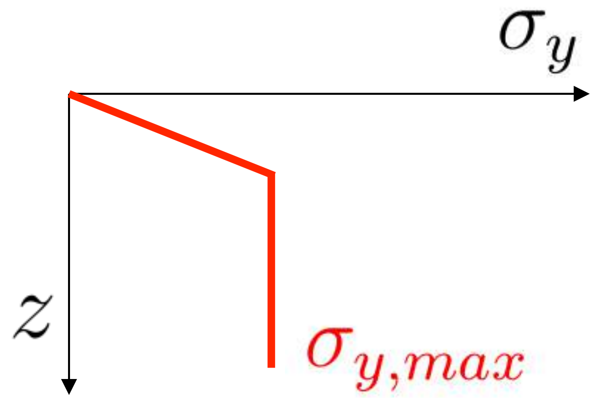
Strain rate

Upper mantle

$E = 540$ kJ/mol
$V = 12$ cm^3/mol
$n = 3.5$

Composite rheology

Stress-limited deformation mechanism



→ <u>Yield-strength</u> ("Byerlee-like")

surface yield strength

Yield strength

$$\mu_y = \frac{\tau_y}{2\dot{\varepsilon}} = \frac{\tau_0 + f_c P}{2\dot{\varepsilon}}$$

Strain rate

friction coefficient

$$\tau_0 = 2 \text{ MPa}$$
$$f_c = 0.2$$

Composite rheology

Stress-limited deformation mechanism

→ Yield-strength (“Byerlee-like”)

→ Peierls mechanism

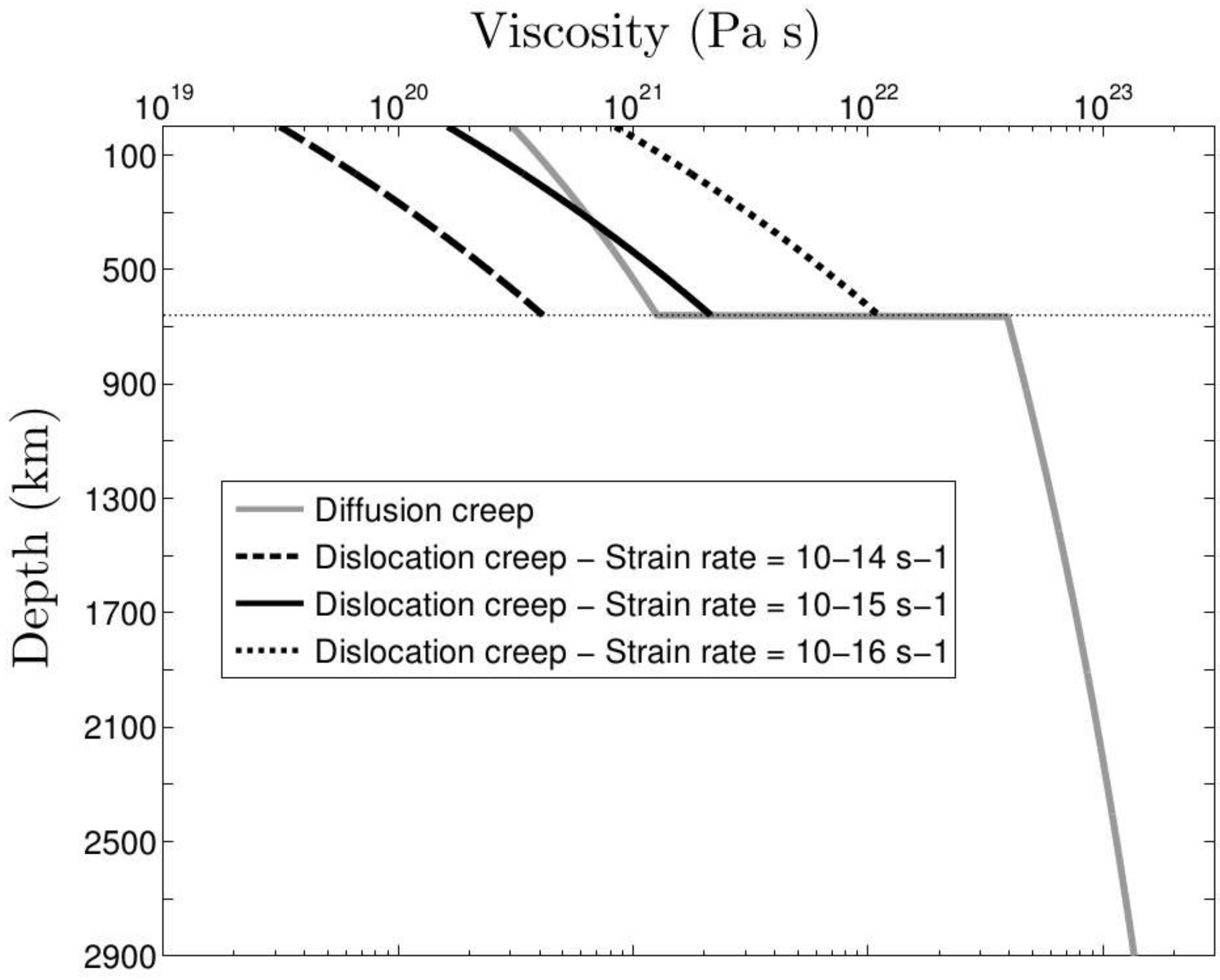
$$\mu_P = A \exp\left(\frac{E+PV}{nRT}\right)\dot{\varepsilon}^{\frac{1-n}{n}}$$

Upper mantle

$E = 540 \text{ kJ/mol}$
$V = 10 \text{ cm}^3\text{/mol}$
$n = 20$

Max. viscosity	$\mu_{\max}$	Pa s	10^{25}
Min. viscosity	$\mu_{\min}$	Pa s	10^{18}
Diffusion creep			
Activation energy	E	kJ mol^{-1}	300 (UM)
			200 (LM)
Activation volume	V	$\text{cm}^3\ \text{mol}^{-1}$	4 (UM)
			1.5 (LM)
Prefactor[a]	A	$\text{Pa}^{-1}\ \text{s}^{-1}$	$3.0\ 10^{-11}$ (UM)
			$6.0\ 10^{-17}$ (LM - $\Delta\mu = 30$)
			$2.0\ 10^{-17}$ (LM - $\Delta\mu = 10$)
			$2.0\ 10^{-16}$ (LM - $\Delta\mu = 100$)
	n	-	1
Dislocation creep (UM)[b]			
Activation energy	E	kJ mol^{-1}	540
Activation volume	V	$\text{cm}^3\ \text{mol}^{-1}$	12
Prefactor	A	$\text{Pa}^{-n}\ \text{s}^{-1}$	$5.0\ 10^{-16}$
	n	-	3.5
Peierls mechanism creep (UM)[b]			
Activation energy	E	kJ mol^{-1}	540
Activation volume	V	$\text{cm}^3\ \text{mol}^{-1}$	10
Prefactor	A	$\text{Pa}^{-n}\ \text{s}^{-1}$	10^{-150}
	n	-	20
Yield strength law			
Surface yield strength	τ_0	MPa	2
Friction coefficient	f_c	-	0.2[c]
	$f_{c,\text{weak}}$	-	0.02 (weak layer)
Maximum yield strength	$\tau_{y,\max}$	MPa	10 000[d]

Composite rheology



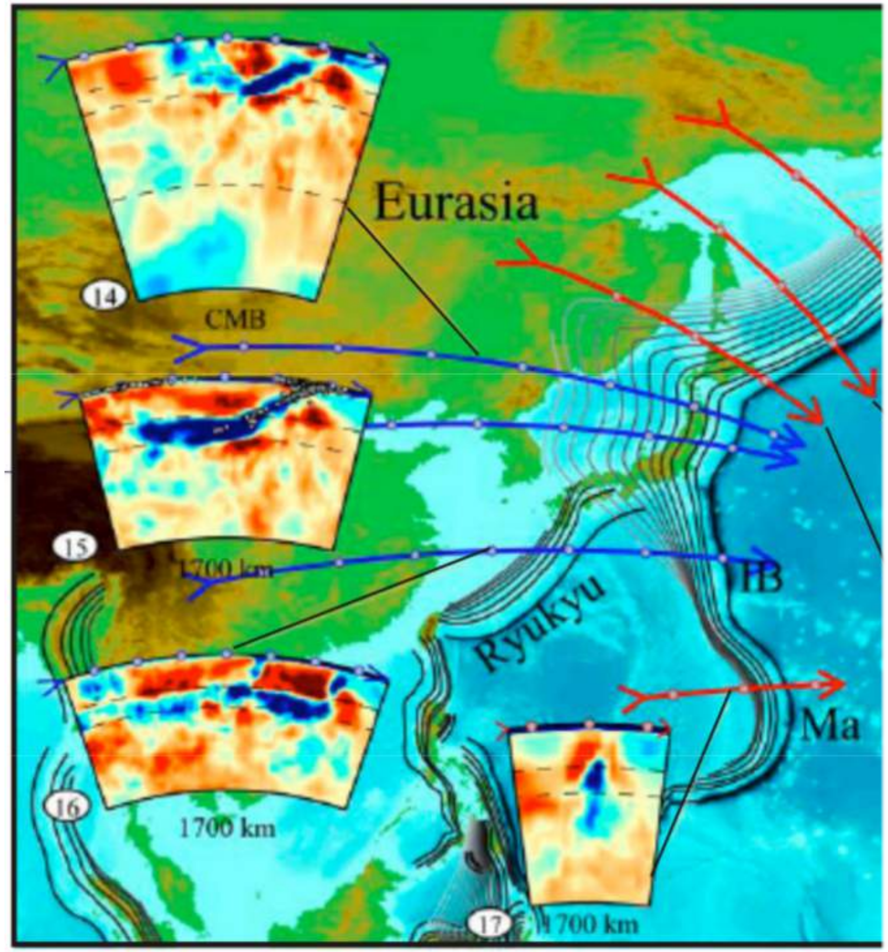
Viscosity profiles for the hot mantle

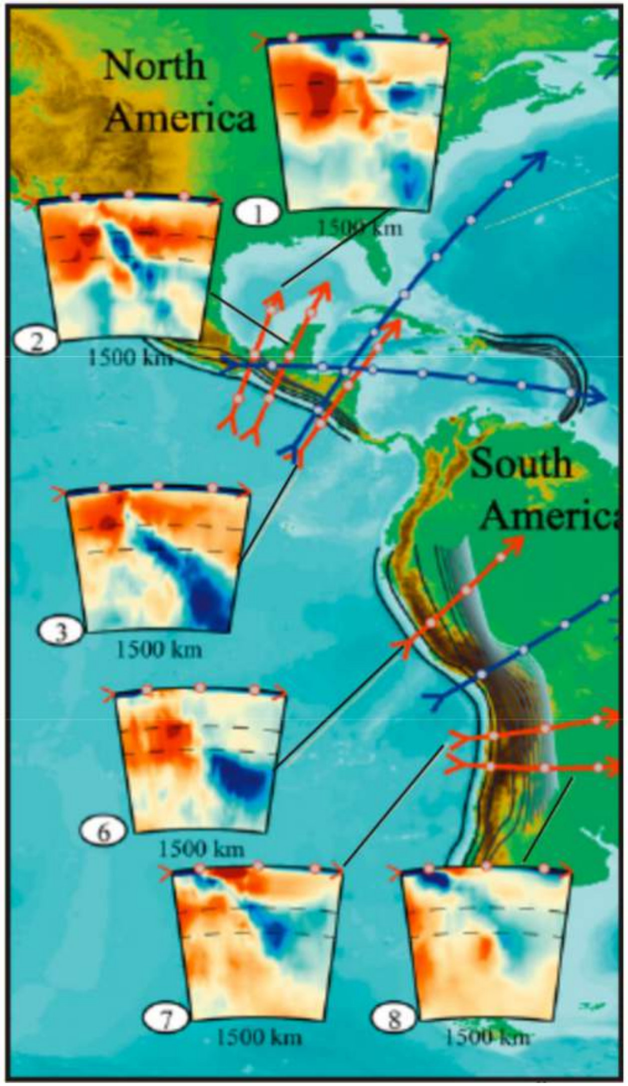
(diffusion creep profile in agreement with constraints from geoid and post-glacial rebound)

(e.g. *Mitrovica and Forte, 2004*)

Relevance for Earth subduction zones

(*Li et al., G3, 2008*)



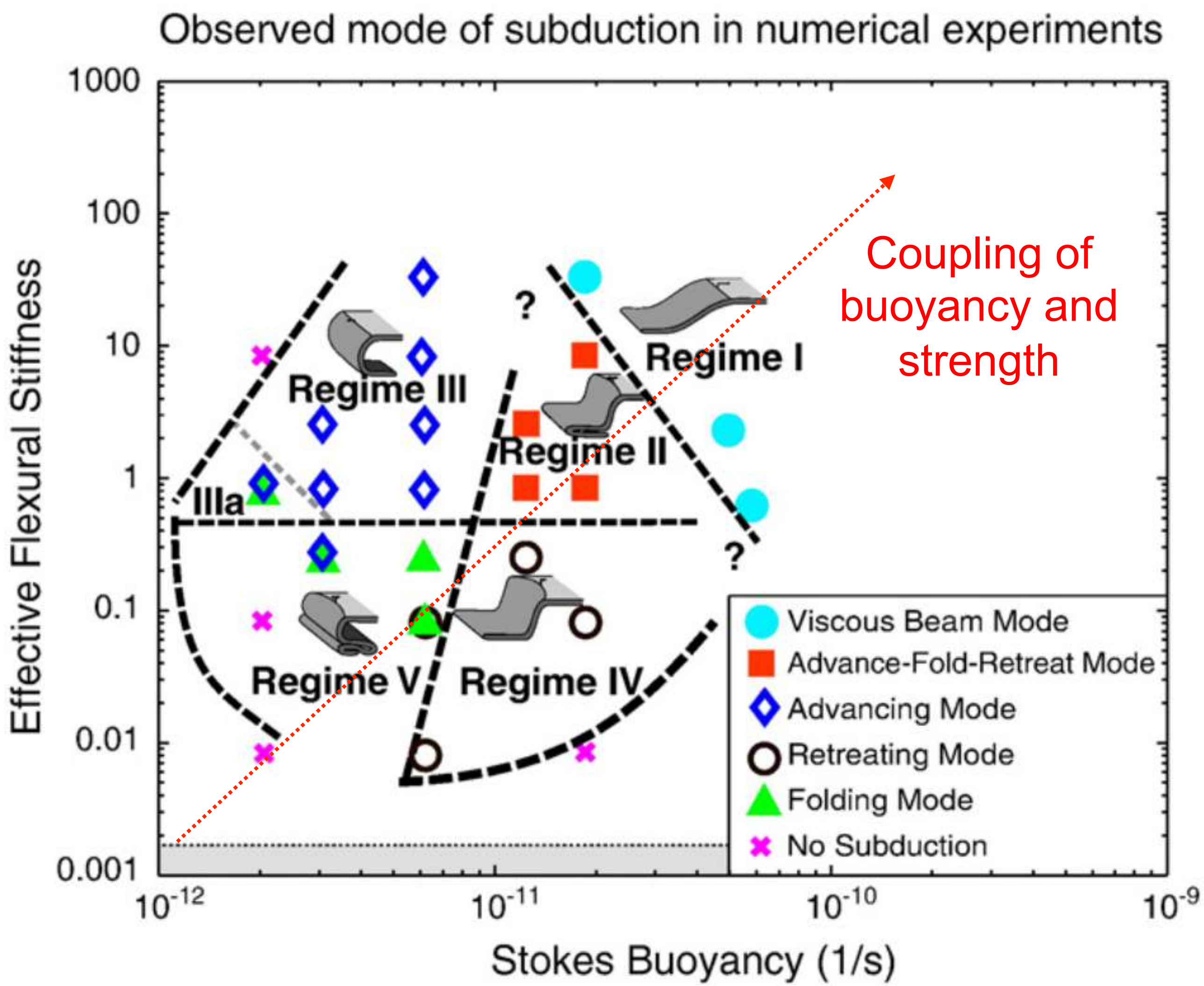


Horizontal-deflected morphologies
↔ young slabs?

Present-day age **OLD**

Inclined / old slabs?
YOUNG

Comparison with previous regime diagram

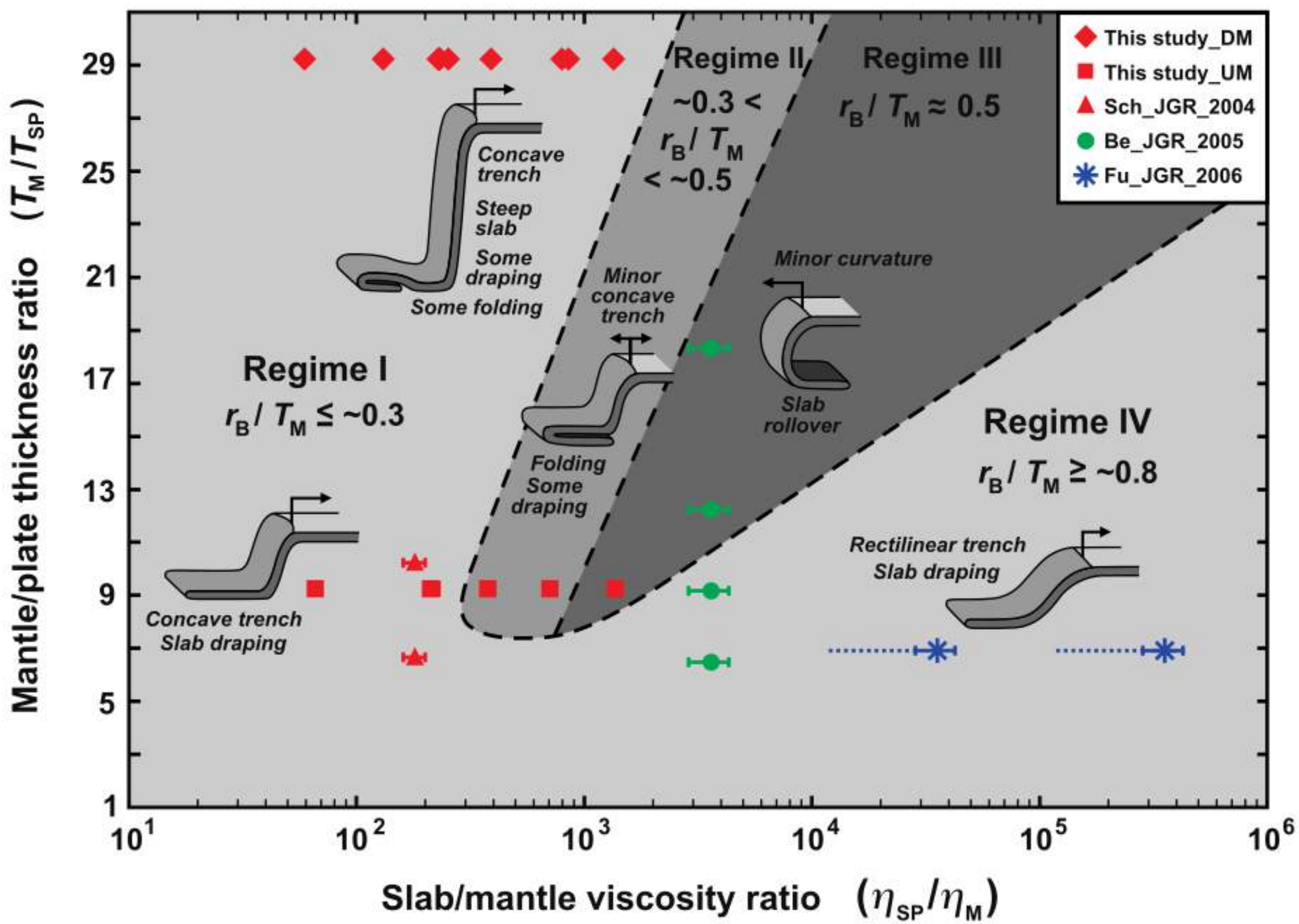


Regime V
↔ Style A

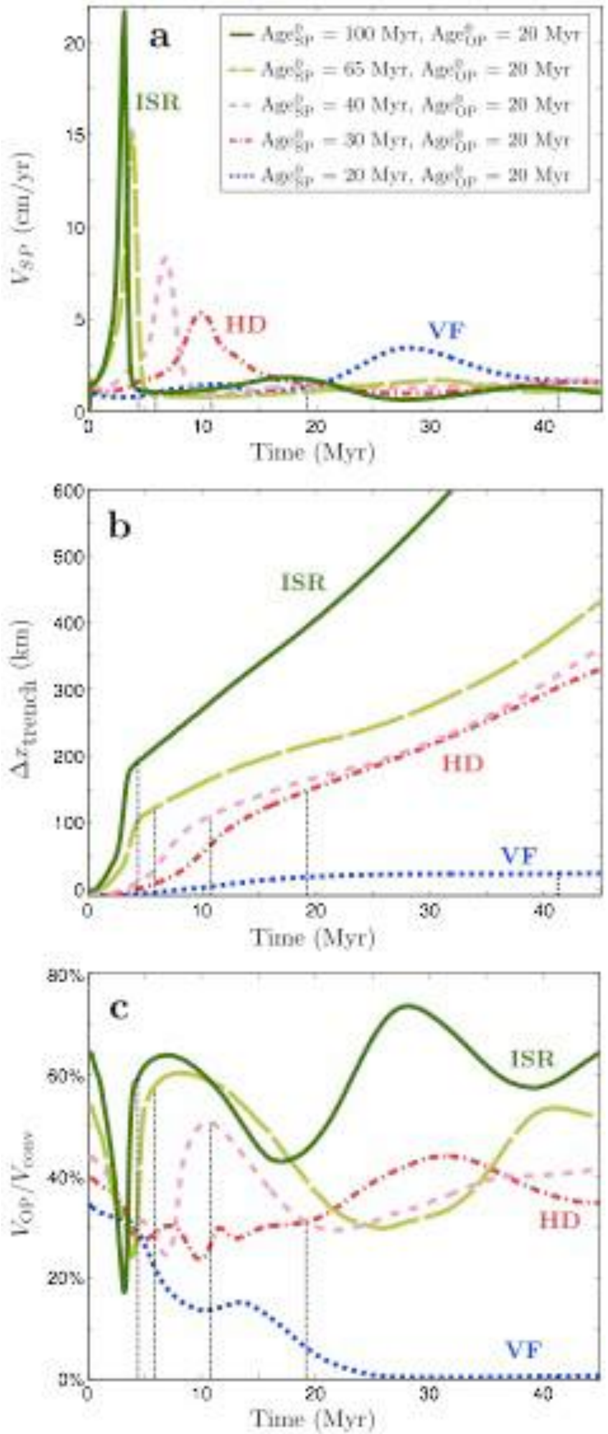
Regime I
↔ Style C

(Stegman et al., 2010)

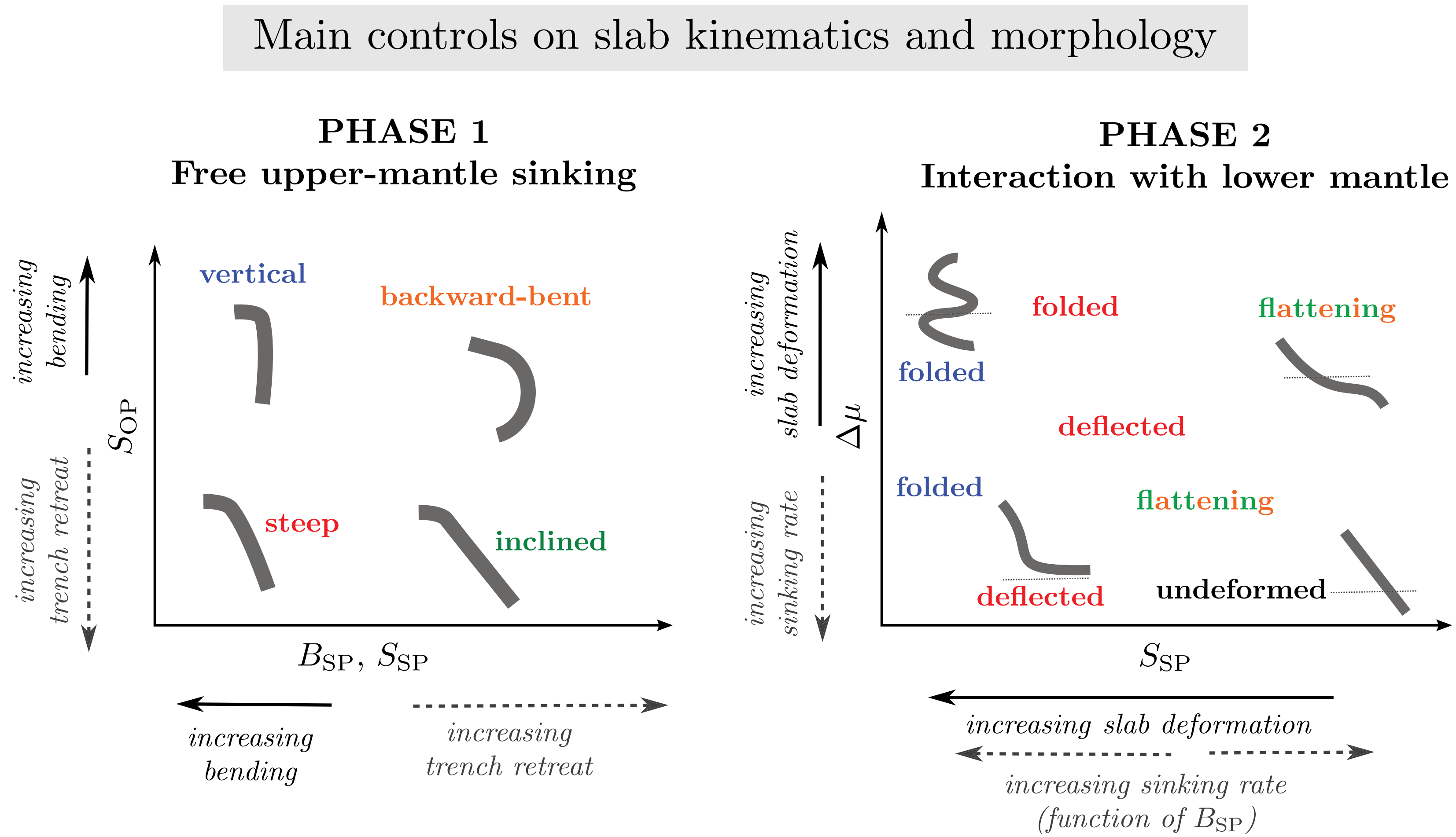
Comparison with previous regime diagram



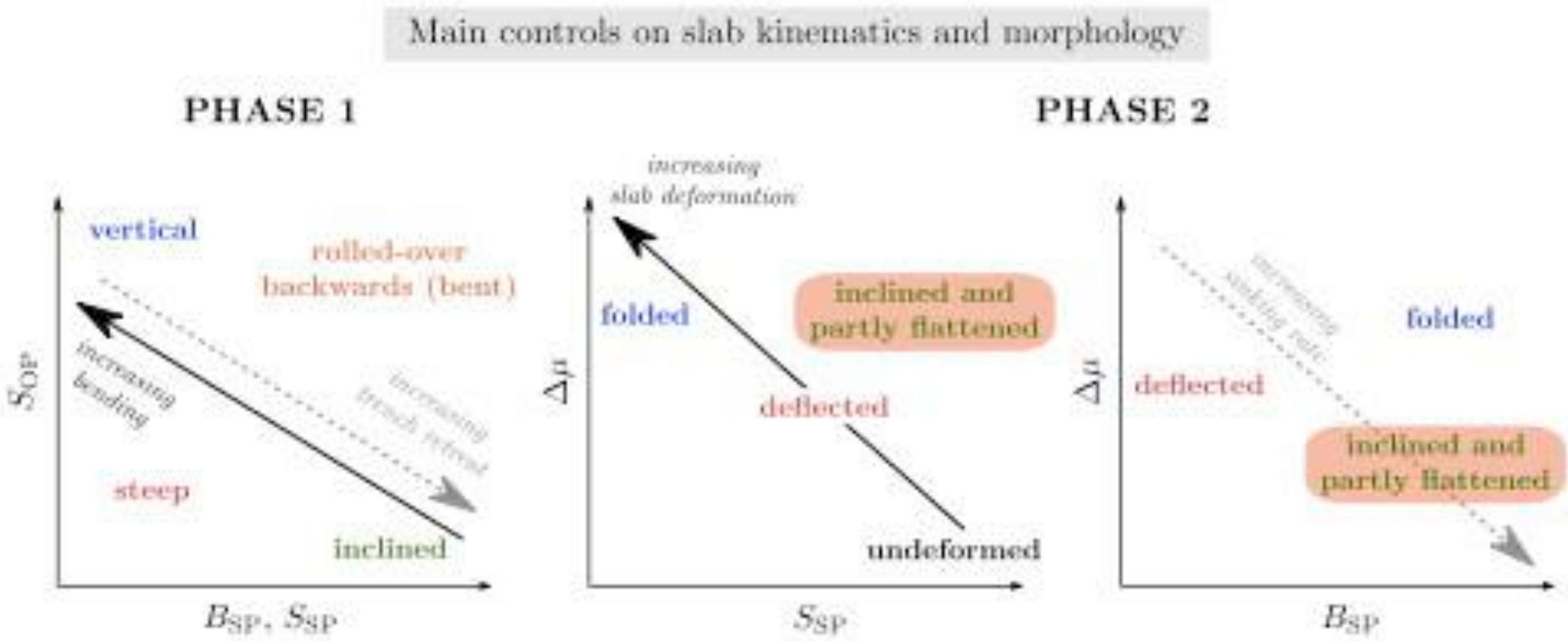
Schellart, G3, 2008



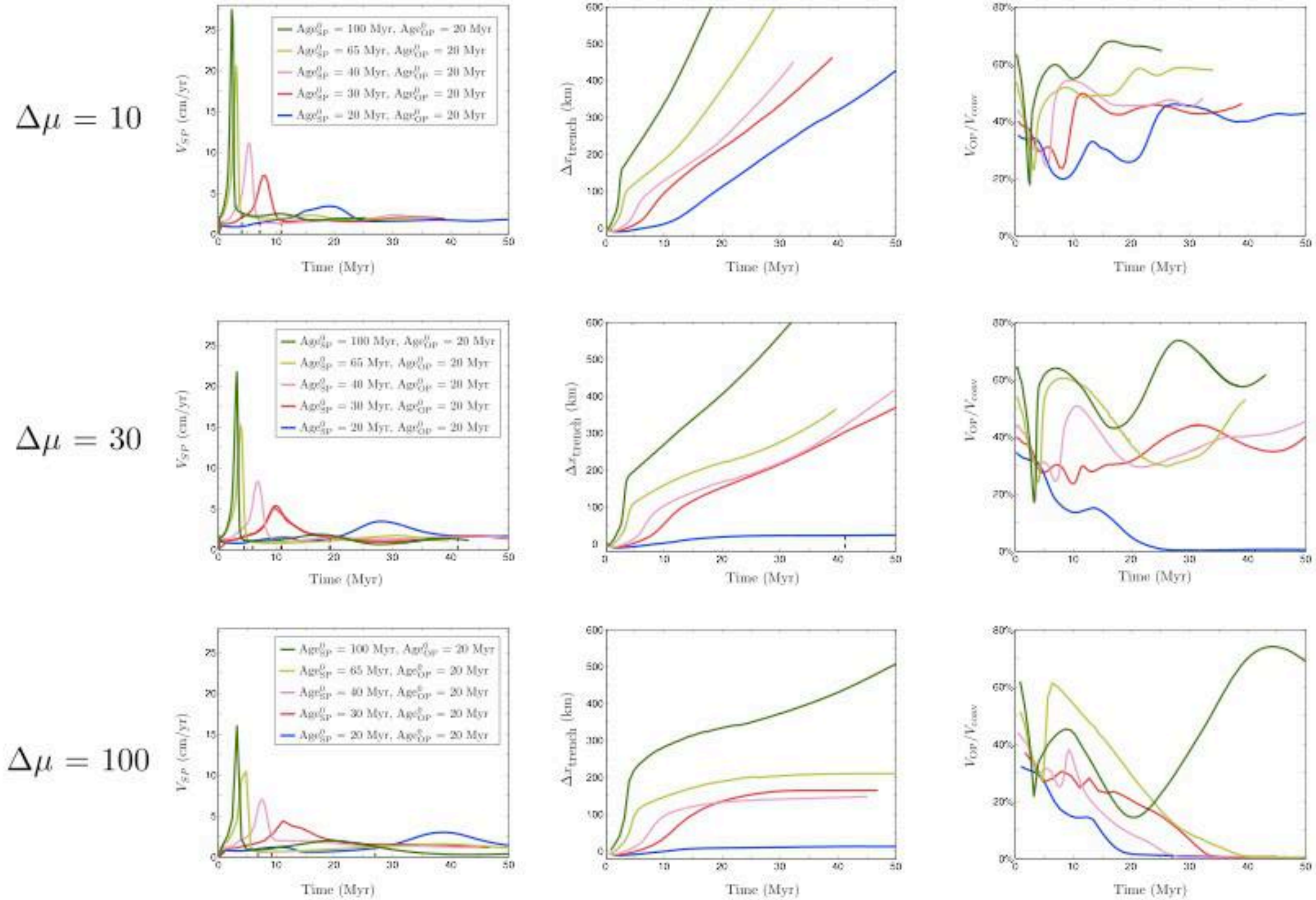
a
$\mathrm{Age}^0_{\mathrm{SP}}$ = 100 Myr, $\mathrm{Age}^0_{\mathrm{OP}}$ = 20 Myr
$\mathrm{Age}^0_{\mathrm{SP}}$ = 65 Myr, $\mathrm{Age}^0_{\mathrm{OP}}$ = 20 Myr
$\mathrm{Age}^0_{\mathrm{SP}}$ = 40 Myr, $\mathrm{Age}^0_{\mathrm{OP}}$ = 20 Myr
$\mathrm{Age}^0_{\mathrm{SP}}$ = 30 Myr, $\mathrm{Age}^0_{\mathrm{OP}}$ = 20 Myr
$\mathrm{Age}^0_{\mathrm{SP}}$ = 20 Myr, $\mathrm{Age}^0_{\mathrm{OP}}$ = 20 Myr
ISR
HD
VF
V_{SP} (cm/yr)
Time (Myr)
b
ISR
HD
VF
$\Delta x_{\mathrm{trench}}$ (km)
Time (Myr)
c
ISR
HD
VF
$V_{\mathrm{OP}}/V_{\mathrm{conv}}$
Time (Myr)



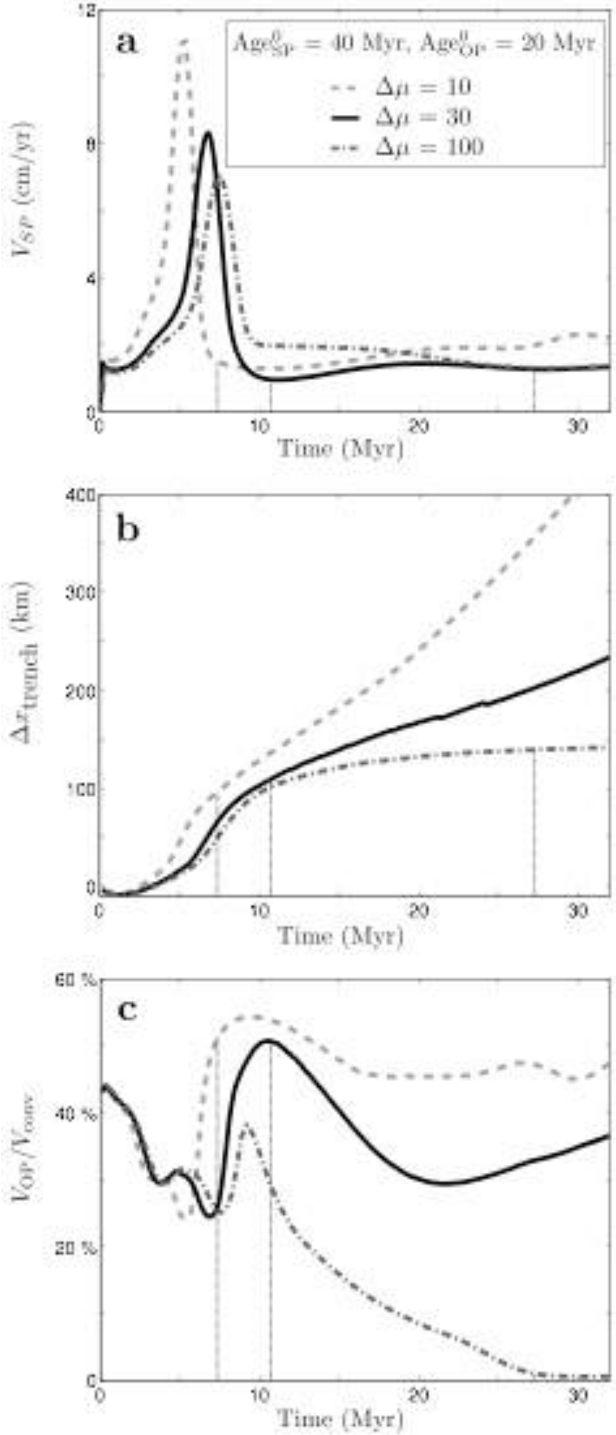
Main controls on slab kinematics and morphology
PHASE 1
Free upper-mantle sinking
increasing bending
increasing trench retreat
S_{OP}
vertical
backward-bent
steep
inclined
B_{SP}, S_{SP}
increasing bending
increasing trench retreat
PHASE 2
Interaction with lower mantle
increasing slab deformation
increasing sinking rate
$\Delta\mu$
folded
folded
flattening
deflected
folded
flattening
deflected
undeformed
S_{SP}
increasing slab deformation
increasing sinking rate
(function of B_{SP})



Main controls on slab kinematics and morphology
PHASE 1
PHASE 2
vertical
rolled-over
backwards (bent)
increasing
bending
increasing
trench retreat
steep
inclined
S_{OP}
B_{SP}, S_{SP}
increasing
slab deformation
folded
inclined and
partly flattened
deflected
undeformed
$\Delta\mu$
S_{SP}
increasing
sinking rate
folded
deflected
inclined and
partly flattened
$\Delta\mu$
B_{SP}



$\Delta\mu = 10$
$\Delta\mu = 30$
$\Delta\mu = 100$
$\mathrm{Age}^0_{\mathrm{SP}}$ = 100 Myr, $\mathrm{Age}^0_{\mathrm{OP}}$ = 20 Myr
$\mathrm{Age}^0_{\mathrm{SP}}$ = 65 Myr, $\mathrm{Age}^0_{\mathrm{OP}}$ = 20 Myr
$\mathrm{Age}^0_{\mathrm{SP}}$ = 40 Myr, $\mathrm{Age}^0_{\mathrm{OP}}$ = 20 Myr
$\mathrm{Age}^0_{\mathrm{SP}}$ = 30 Myr, $\mathrm{Age}^0_{\mathrm{OP}}$ = 20 Myr
$\mathrm{Age}^0_{\mathrm{SP}}$ = 20 Myr, $\mathrm{Age}^0_{\mathrm{OP}}$ = 20 Myr
V_{SP} (cm/yr)
$\Delta x_{\mathrm{trench}}$ (km)
$V_{\mathrm{OP}}/V_{\mathrm{conv}}$
Time (Myr)



a
b
c
$\mathrm{Age}^0_{\mathrm{SP}}$ = 40 Myr, $\mathrm{Age}^0_{\mathrm{OP}}$ = 20 Myr
$\Delta\mu$ = 10
$\Delta\mu$ = 30
$\Delta\mu$ = 100
V_{SP} (cm/yr)
$\Delta x_{\mathrm{trench}}$ (km)
$V_{\mathrm{OP}}/V_{\mathrm{conv}}$
Time (Myr)
0
4
8
12
100
200
300
400
20 %
40 %
60 %
10
20
30

Appendix B. Viscosity jump between upper and lower mantle

Fig. B.11 presents the evolution of the ratio V_{OP}/V_{conv} for simulations with different viscosity jumps.

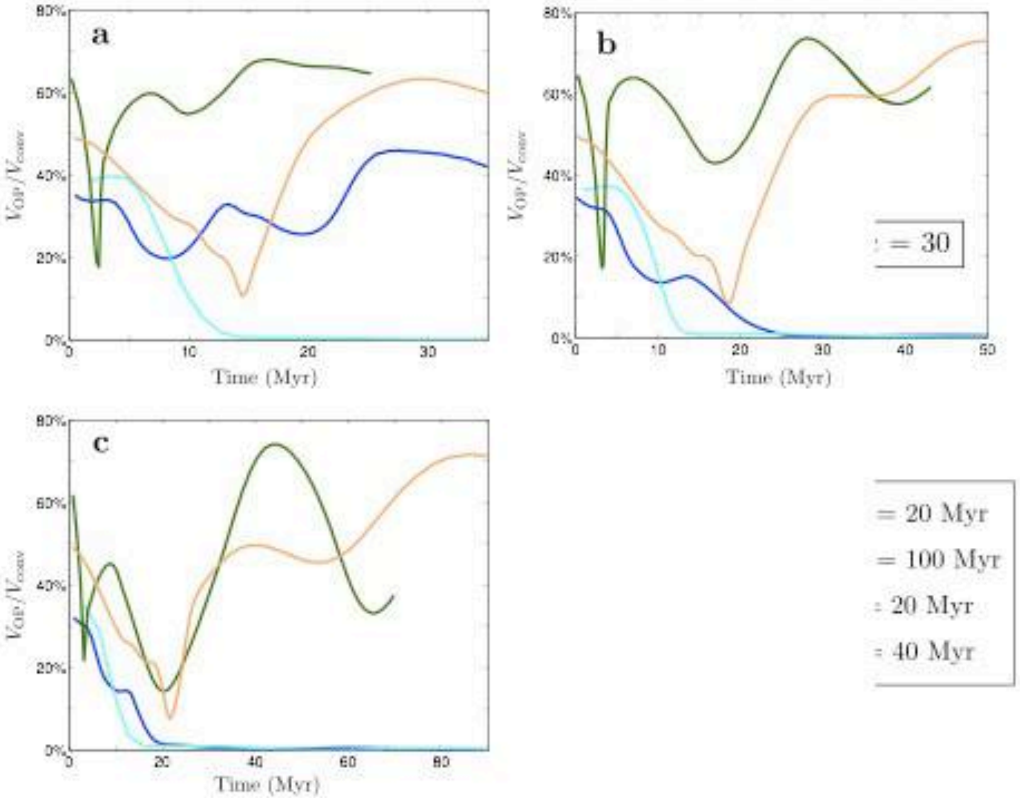
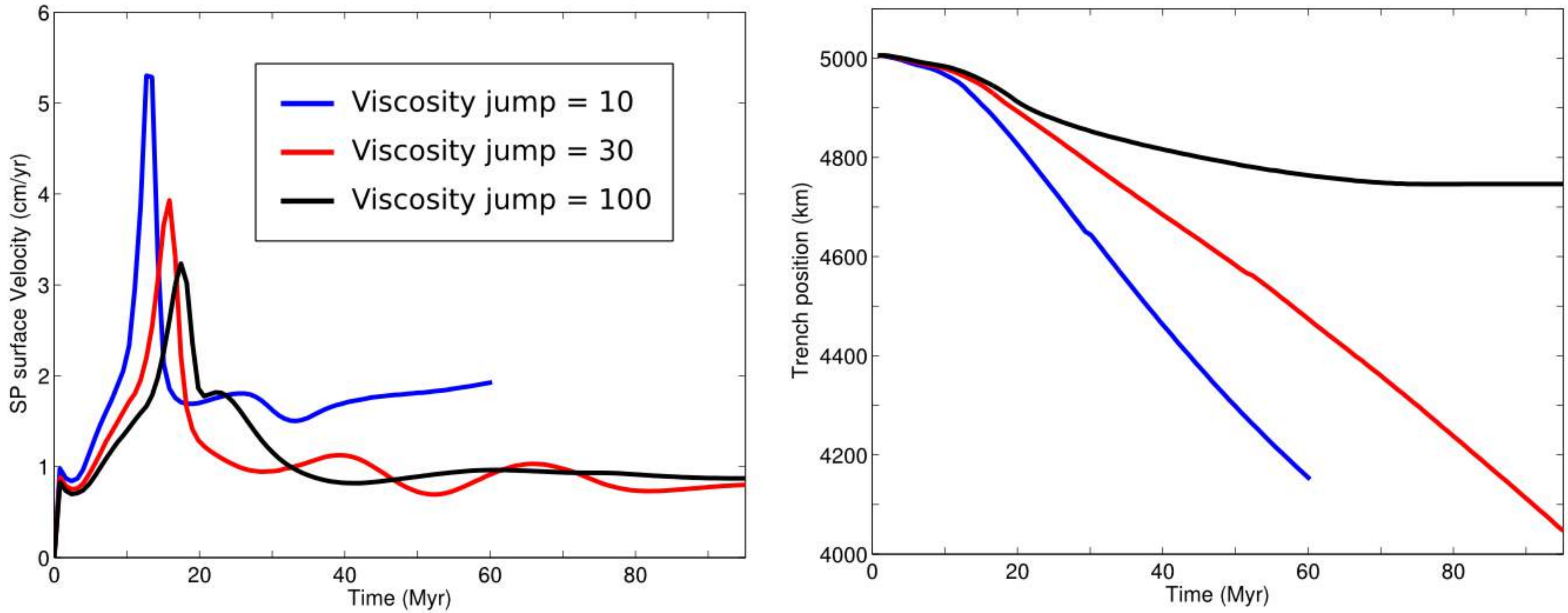
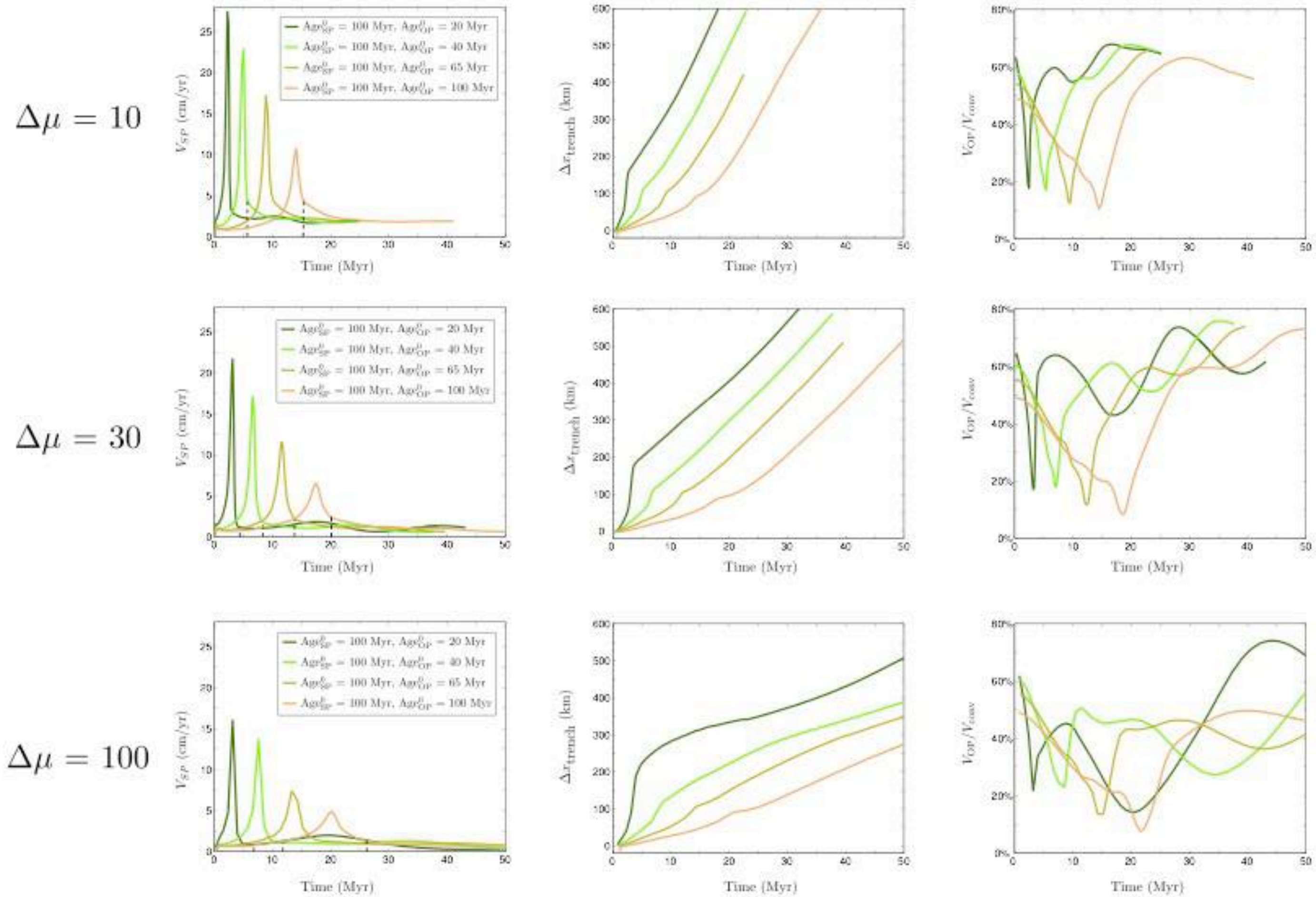


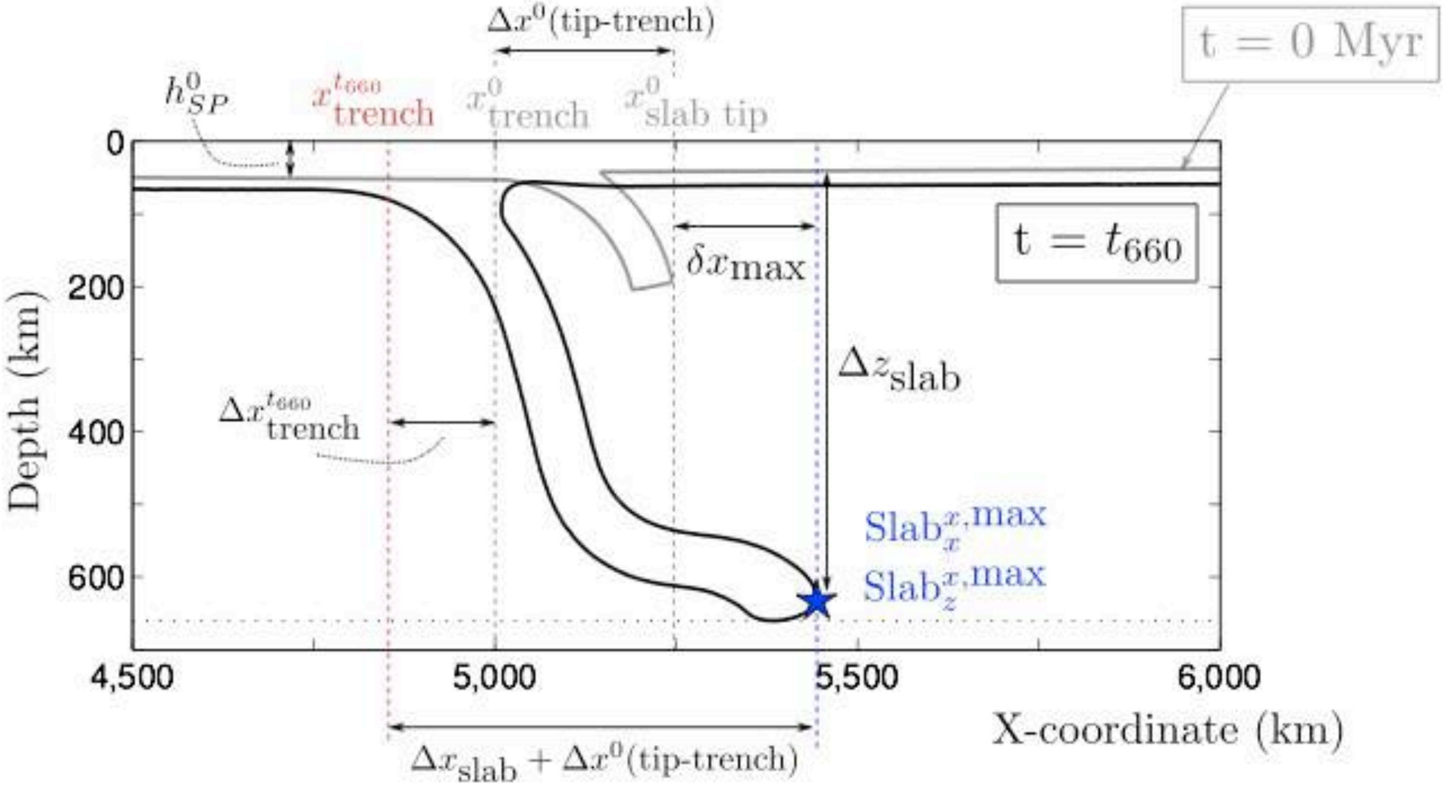
Figure B.11: Influence of the viscosity jump $\Delta\mu$ between upper and lower mantle on subduction dynamics, shown as the ratio V_{OP}/V_{conv}, for $\Delta\mu$=10 (a), 30 (b) or 100 (c). Note that the horizontal time scale differs between the subplots.

SP = 40 Myr - OP = 40 Myr

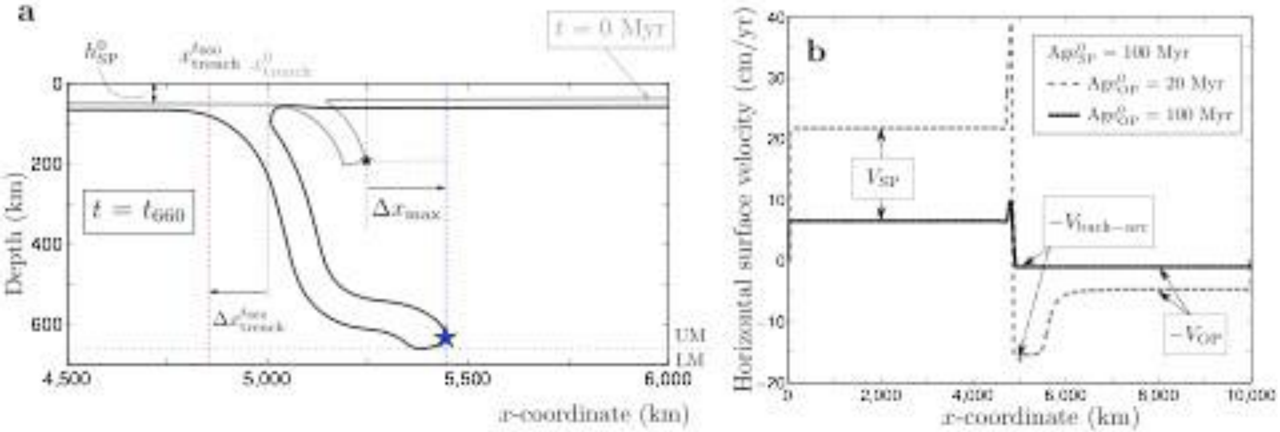




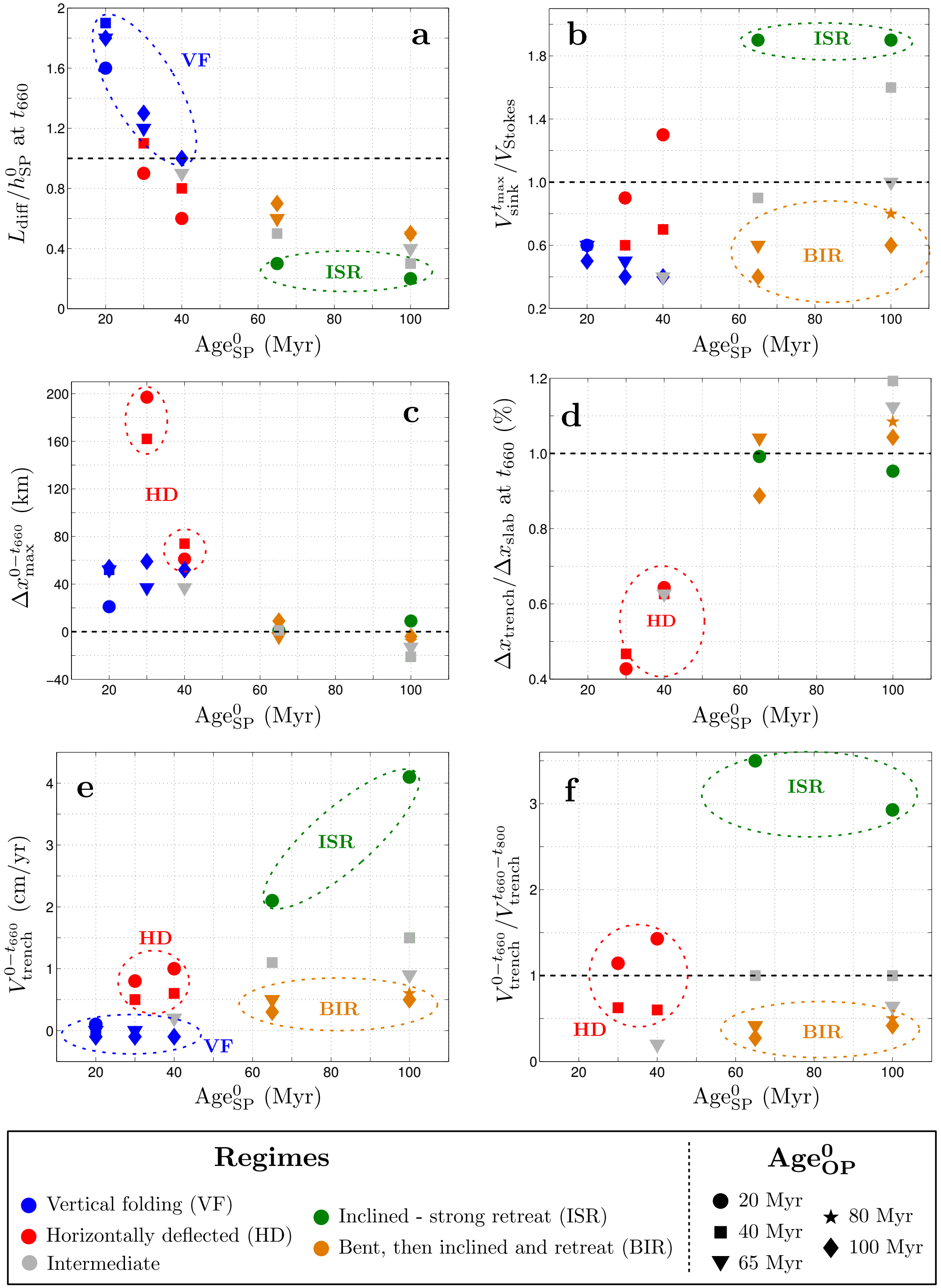
Δμ = 10
Δμ = 30
Δμ = 100
Age⁰SP = 100 Myr, Age⁰OP = 20 Myr
Age⁰SP = 100 Myr, Age⁰OP = 40 Myr
Age⁰SP = 100 Myr, Age⁰OP = 65 Myr
Age⁰SP = 100 Myr, Age⁰OP = 100 Myr
V_SP (cm/yr)
Δx_trench (km)
V_OP/V_conv
Time (Myr)



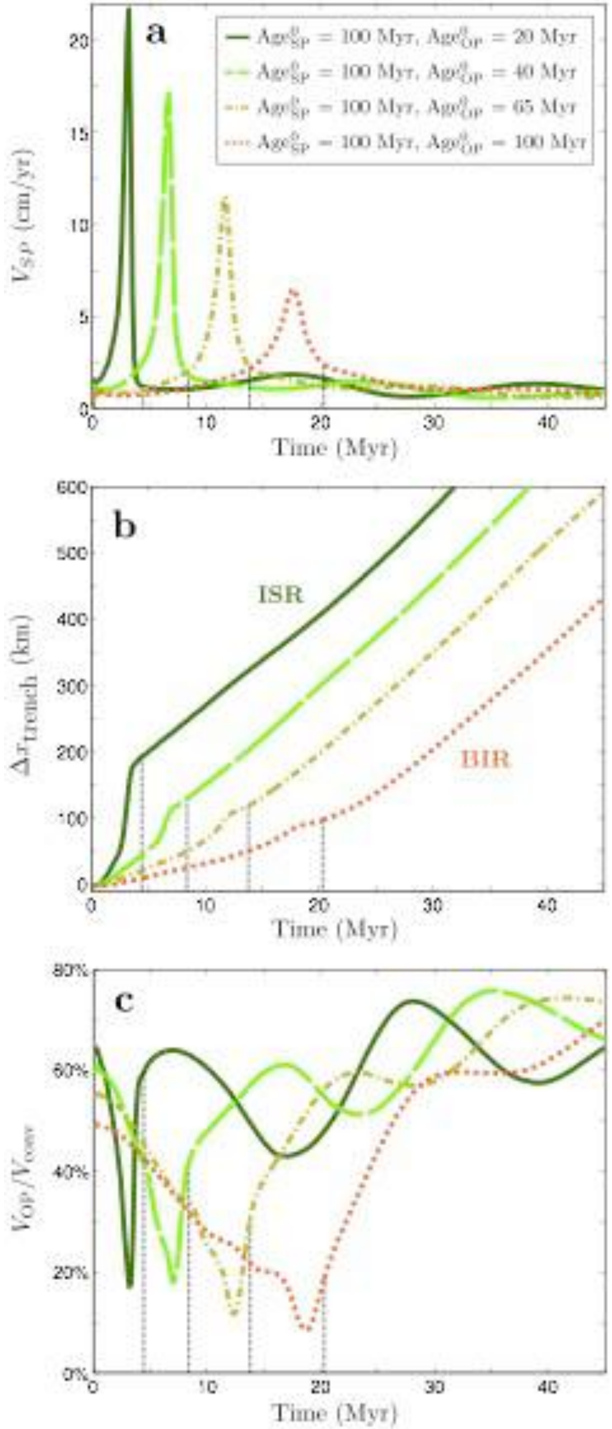
Δx⁰(tip-trench)
t = 0 Myr
h^0_{SP}
$x^{t_{660}}_{\text{trench}}$
x^0_{trench}
$x^0_{\text{slab tip}}$
t = t_{660}
$\delta x_{\max}$
Δz_{slab}
$\Delta x^{t_{660}}_{\text{trench}}$
$\text{Slab}^{x,\max}_x$
$\text{Slab}^{x,\max}_z$
Depth (km)
0
200
400
600
4,500
5,000
5,500
6,000
X-coordinate (km)
$\Delta x_{\text{slab}} + \Delta x^0(\text{tip-trench})$



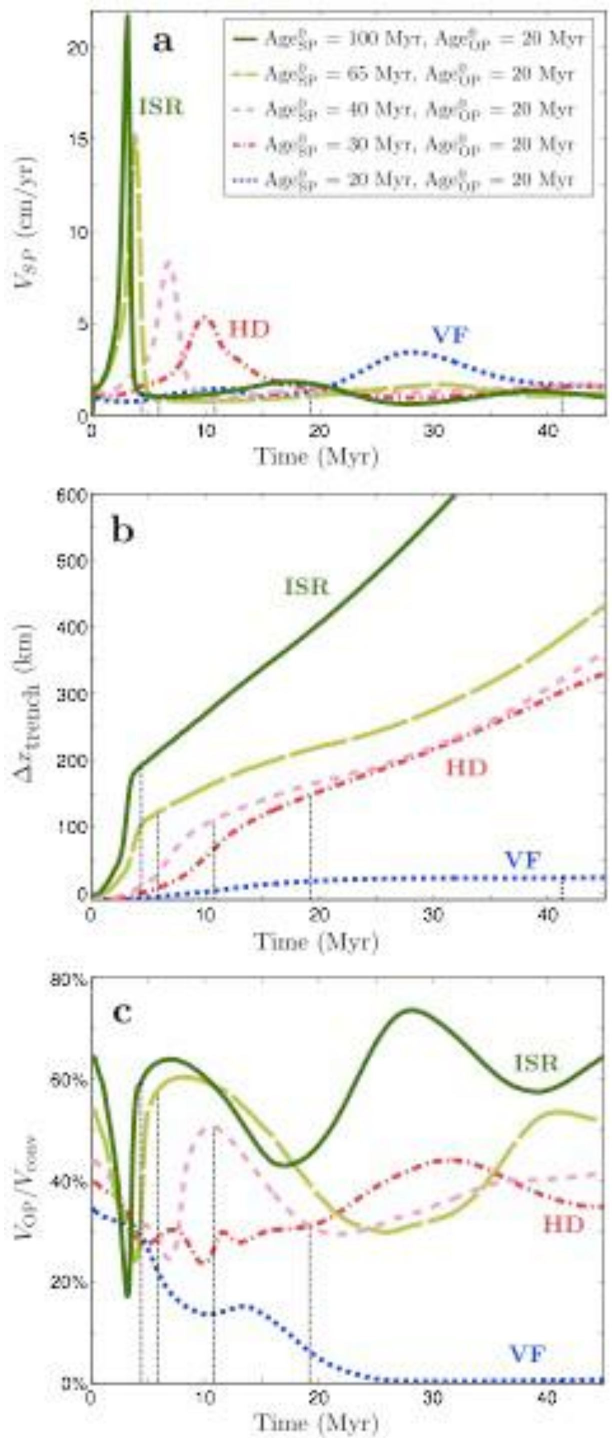
a
t = 0 Myr
t = t660
Δx_max
Depth (km)
x-coordinate (km)
UM
LM
b
Horizontal surface velocity (cm/yr)
x-coordinate (km)
V_SP
−V_back−arc
−V_OP



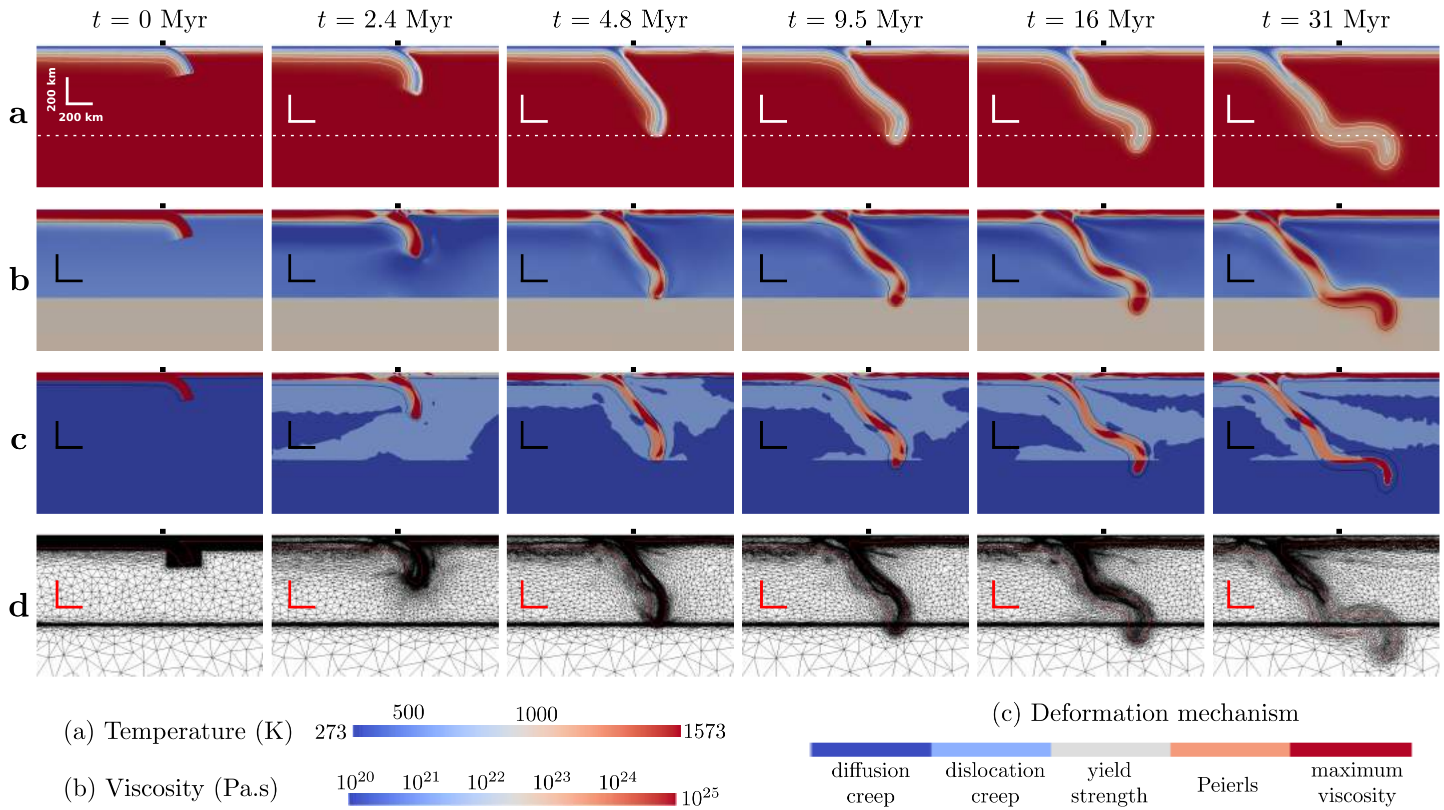
a
b
c
d
e
f
VF
ISR
HD
BIR
$L_{\mathrm{diff}}/h^0_{\mathrm{SP}}$ at t_{660}
$V^{t_{\max}}_{\mathrm{sink}}/V_{\mathrm{Stokes}}$
$\Delta x^{0-t_{660}}_{\max}$ (km)
$\Delta x_{\mathrm{trench}}/\Delta x_{\mathrm{slab}}$ at t_{660} (%)
$V^{0-t_{660}}_{\mathrm{trench}}$ (cm/yr)
$V^{0-t_{660}}_{\mathrm{trench}}/V^{t_{660}-t_{800}}_{\mathrm{trench}}$
$\mathrm{Age}^0_{\mathrm{SP}}$ (Myr)
Regimes
Vertical folding (VF)
Horizontally deflected (HD)
Intermediate
Inclined - strong retreat (ISR)
Bent, then inclined and retreat (BIR)
$\mathrm{Age}^0_{\mathrm{OP}}$
20 Myr
40 Myr
65 Myr
80 Myr
100 Myr

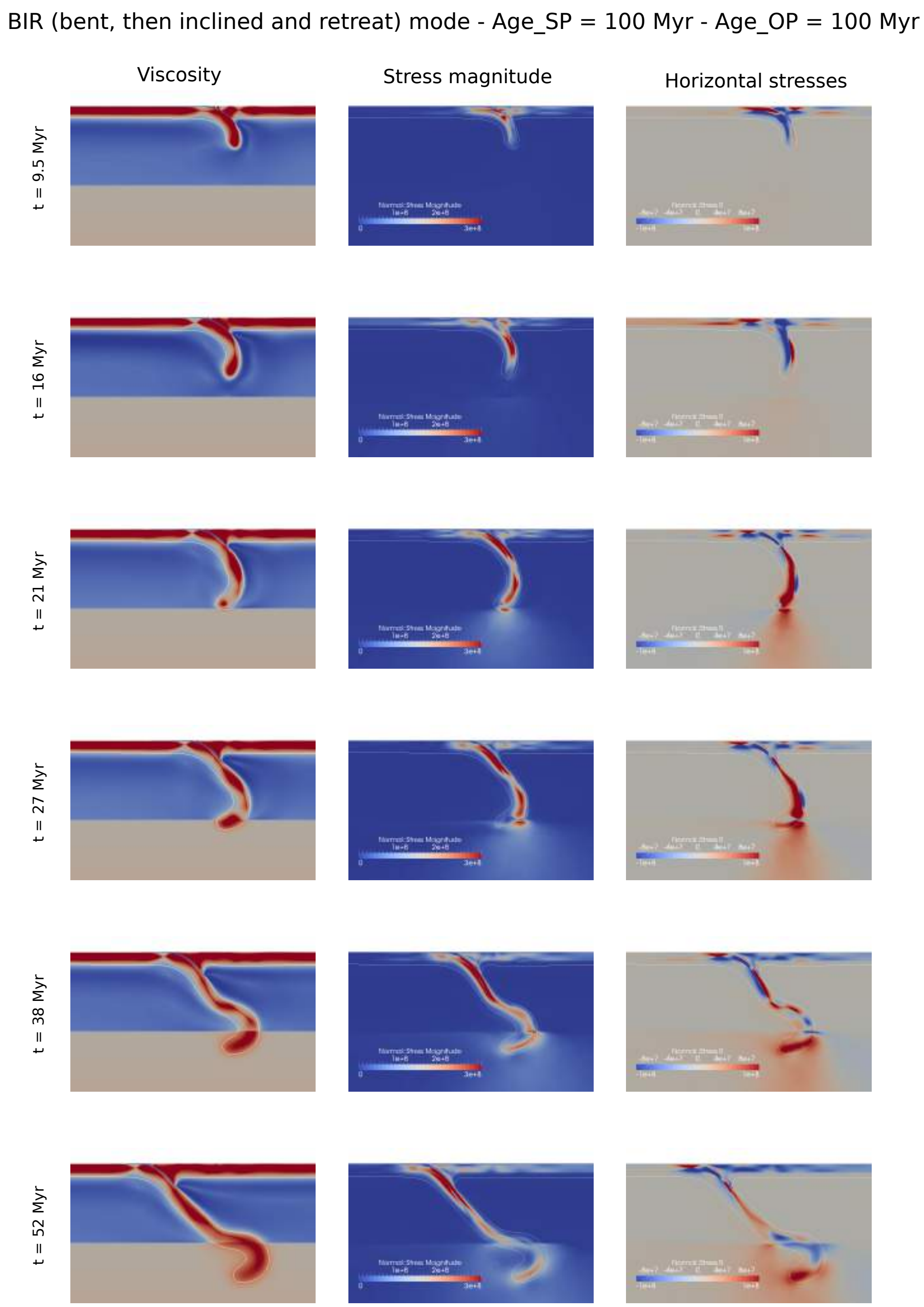


a
$\mathrm{Age}^0_{\mathrm{SP}}$ = 100 Myr, $\mathrm{Age}^0_{\mathrm{OP}}$ = 20 Myr
$\mathrm{Age}^0_{\mathrm{SP}}$ = 100 Myr, $\mathrm{Age}^0_{\mathrm{OP}}$ = 40 Myr
$\mathrm{Age}^0_{\mathrm{SP}}$ = 100 Myr, $\mathrm{Age}^0_{\mathrm{OP}}$ = 65 Myr
$\mathrm{Age}^0_{\mathrm{SP}}$ = 100 Myr, $\mathrm{Age}^0_{\mathrm{OP}}$ = 100 Myr
V_{SP} (cm/yr)
Time (Myr)
b
ISR
BIR
$\Delta x_{\mathrm{trench}}$ (km)
Time (Myr)
c
$V_{\mathrm{OP}}/V_{\mathrm{conv}}$
Time (Myr)



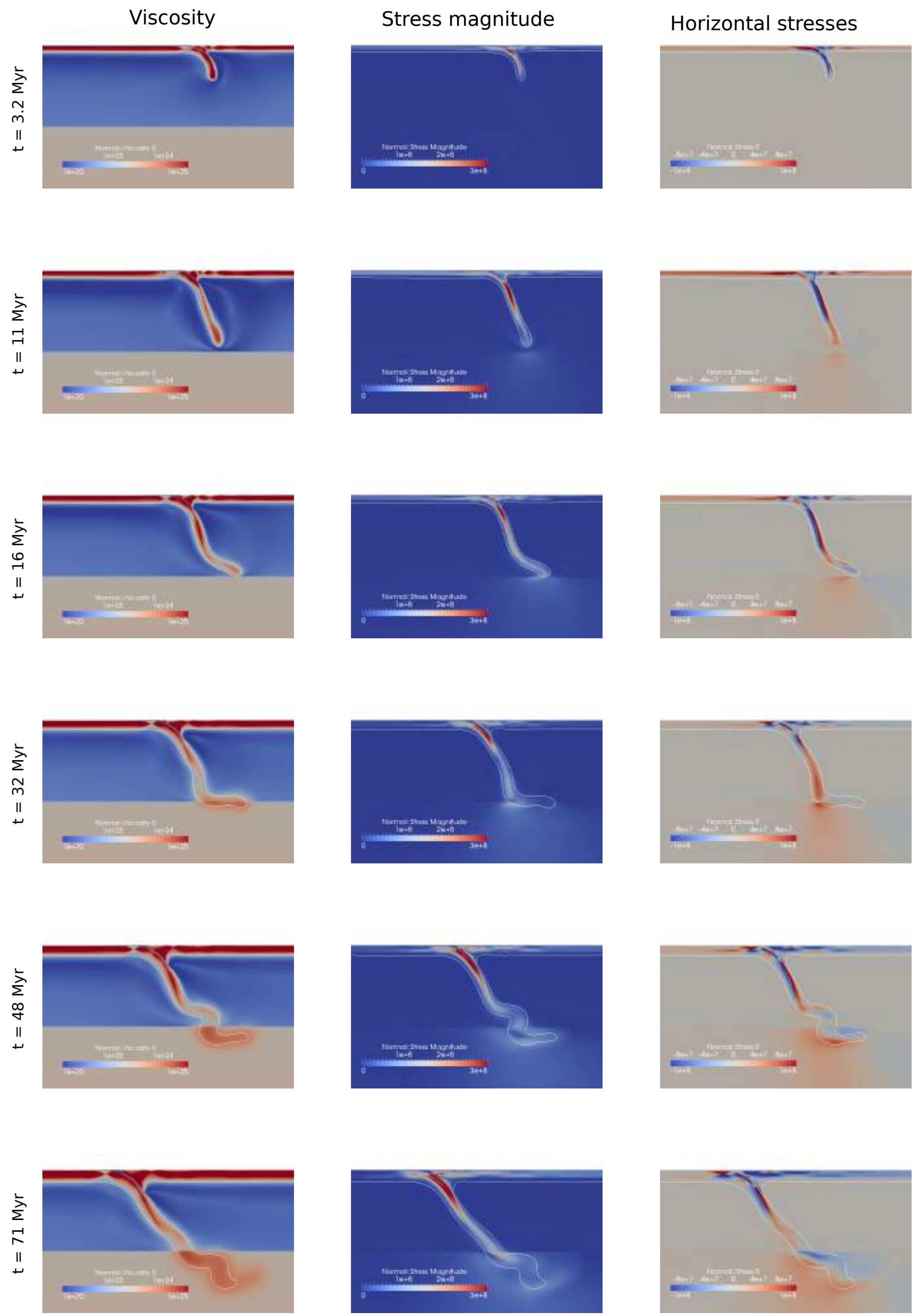
a
Age^0_{SP} = 100 Myr, Age^0_{OP} = 20 Myr
Age^0_{SP} = 65 Myr, Age^0_{OP} = 20 Myr
Age^0_{SP} = 40 Myr, Age^0_{OP} = 20 Myr
Age^0_{SP} = 30 Myr, Age^0_{OP} = 20 Myr
Age^0_{SP} = 20 Myr, Age^0_{OP} = 20 Myr
ISR
HD
VF
V_{SP} (cm/yr)
Time (Myr)
b
ISR
HD
VF
Δx_{trench} (km)
Time (Myr)
c
ISR
HD
VF
V_{OP}/V_{conv}
Time (Myr)


t = 0 Myr
t = 2.4 Myr
t = 4.8 Myr
t = 9.5 Myr
t = 16 Myr
t = 31 Myr
a
b
c
d
200 km
200 km
(a) Temperature (K)
273
500
1000
1573
(b) Viscosity (Pa.s)
10^20
10^21
10^22
10^23
10^24
10^25
(c) Deformation mechanism
diffusion creep
dislocation creep
yield strength
Peierls
maximum viscosity

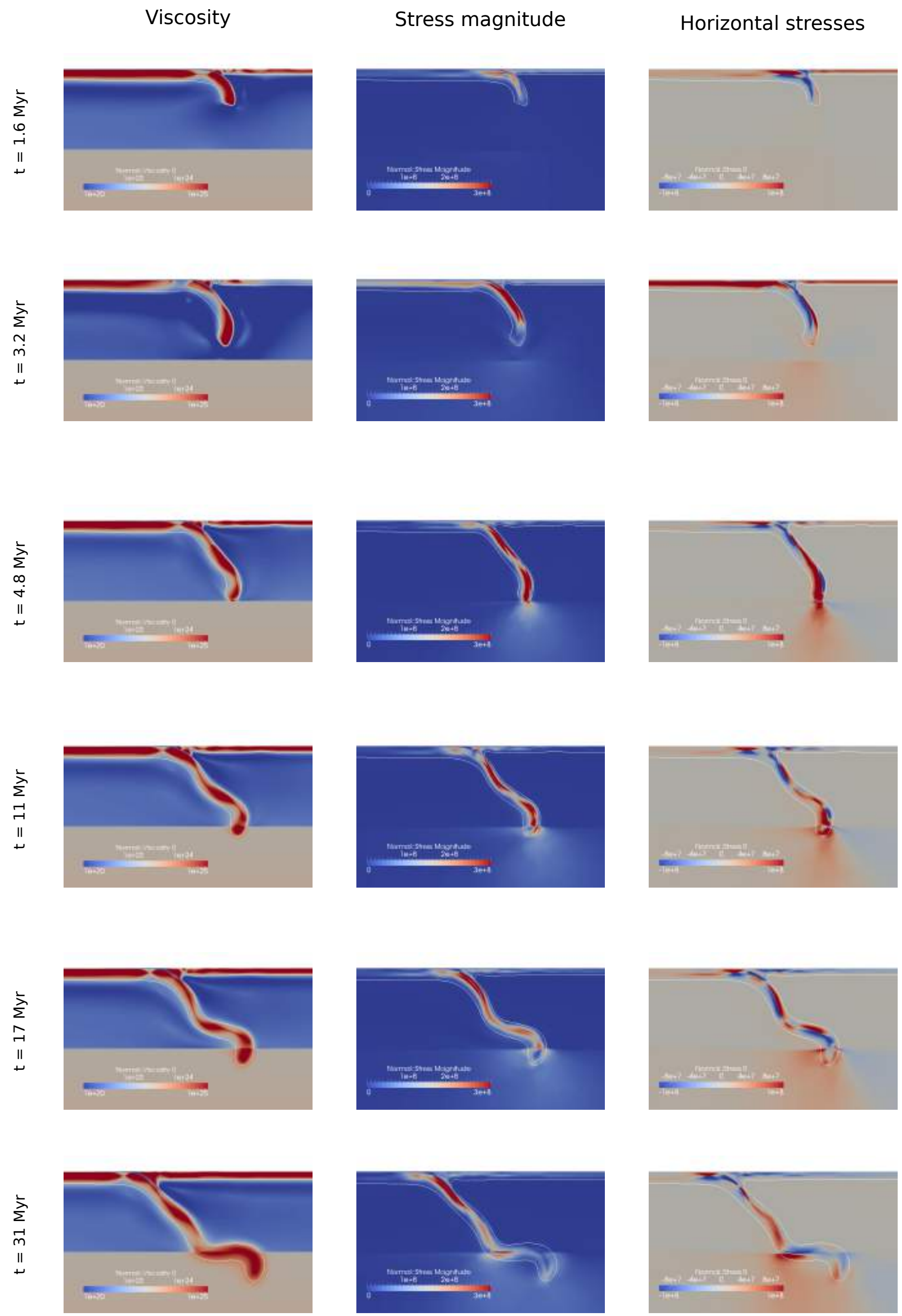


BIR (bent, then inclined and retreat) mode - Age_SP = 100 Myr - Age_OP = 100 Myr
Viscosity
Stress magnitude
Horizontal stresses
t = 9.5 Myr
t = 16 Myr
t = 21 Myr
t = 27 Myr
t = 38 Myr
t = 52 Myr

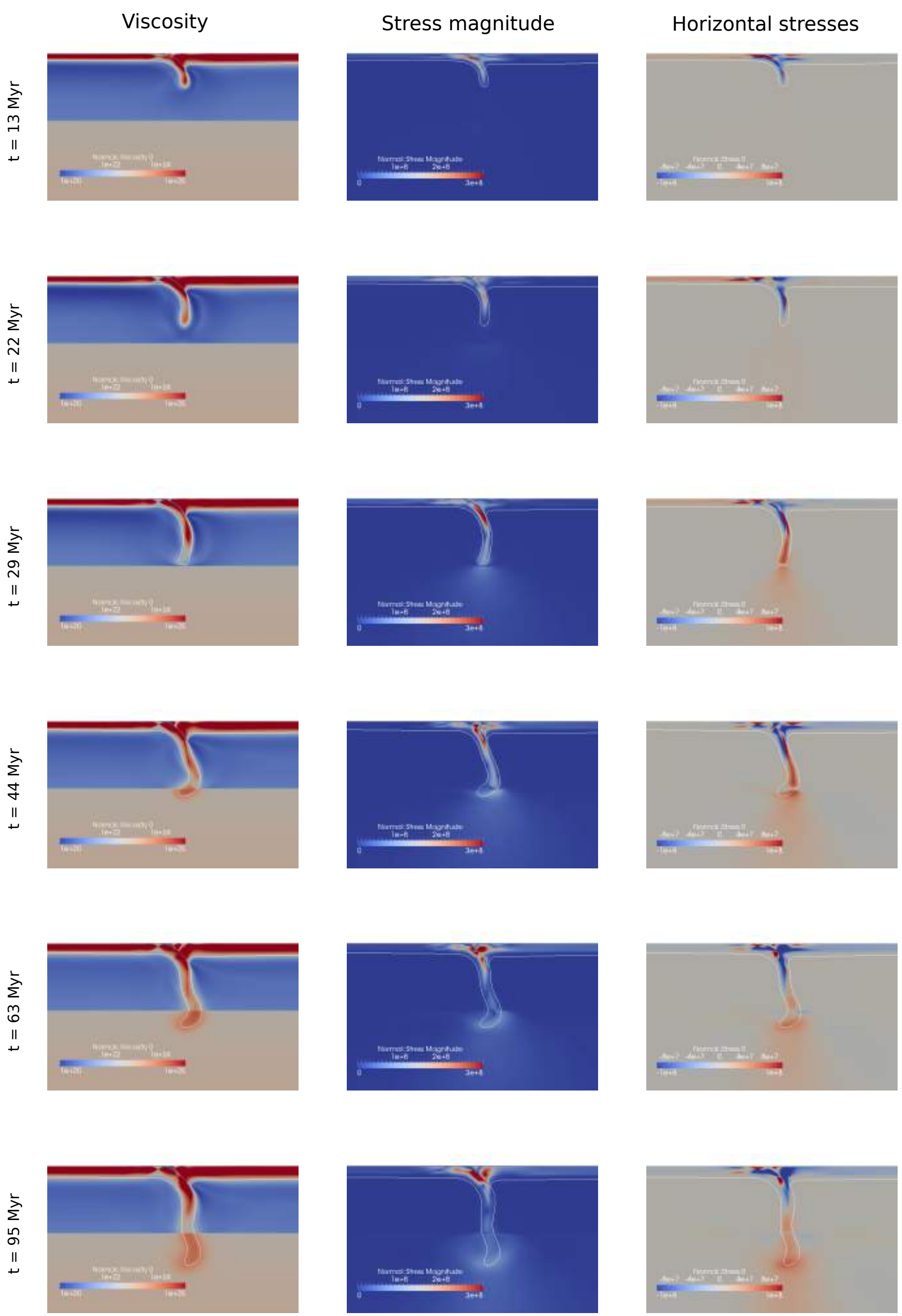
HD (horizontall deflected) mode - Age_SP = 30 Myr - Age_OP = 20 Myr

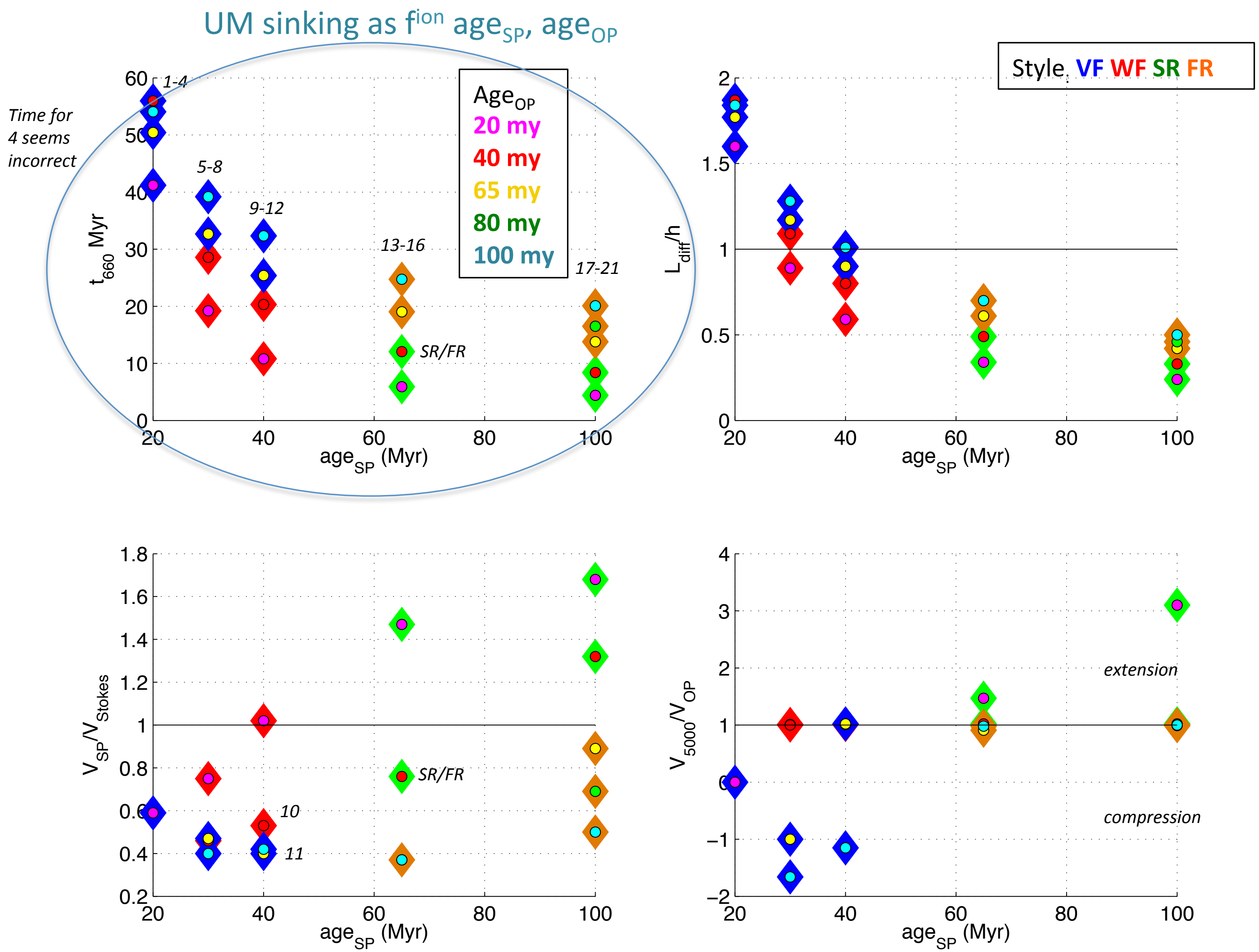


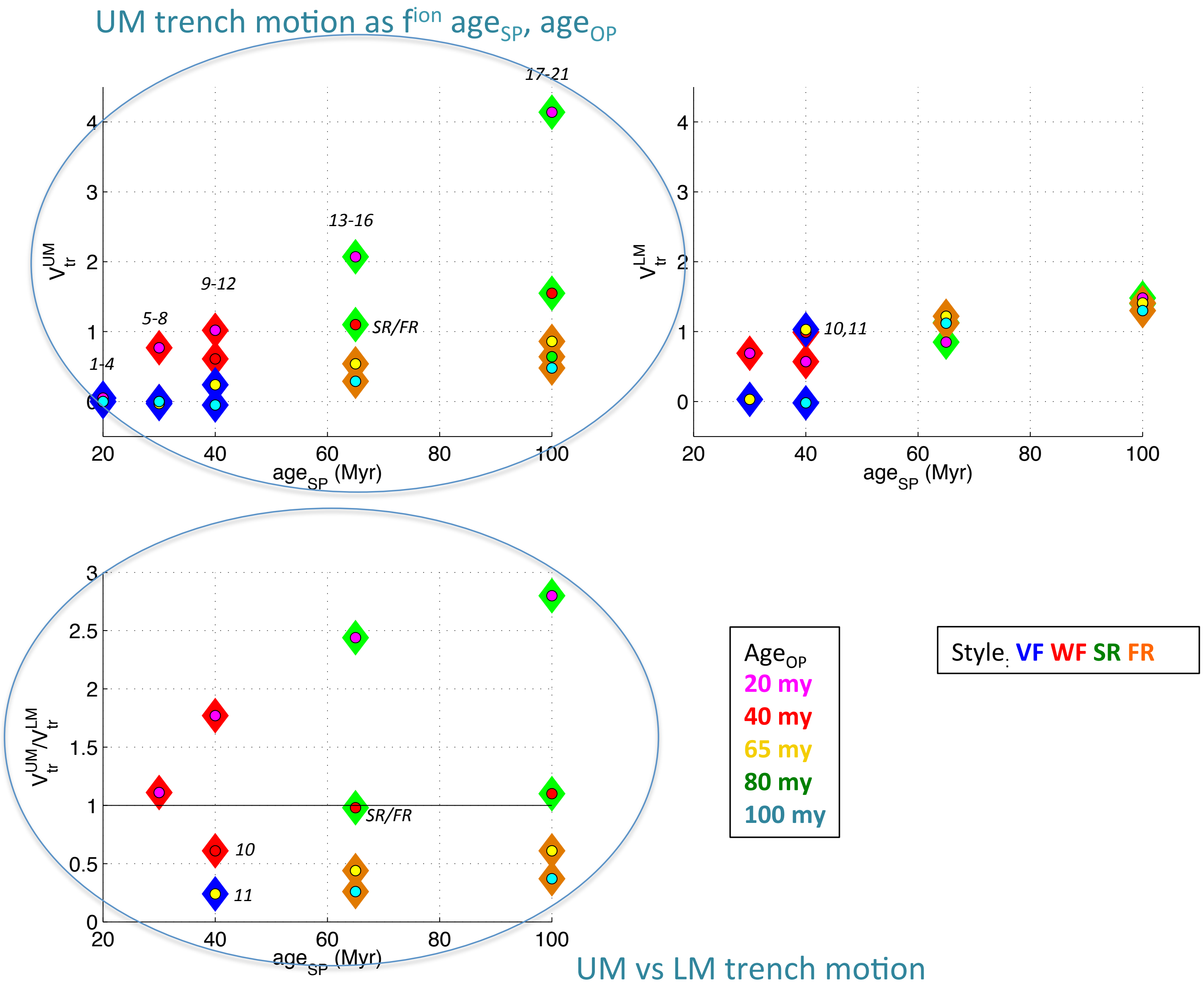
ISR (inclined - strong retreat) mode - Age_SP = 100 Myr - Age_OP = 20 Myr



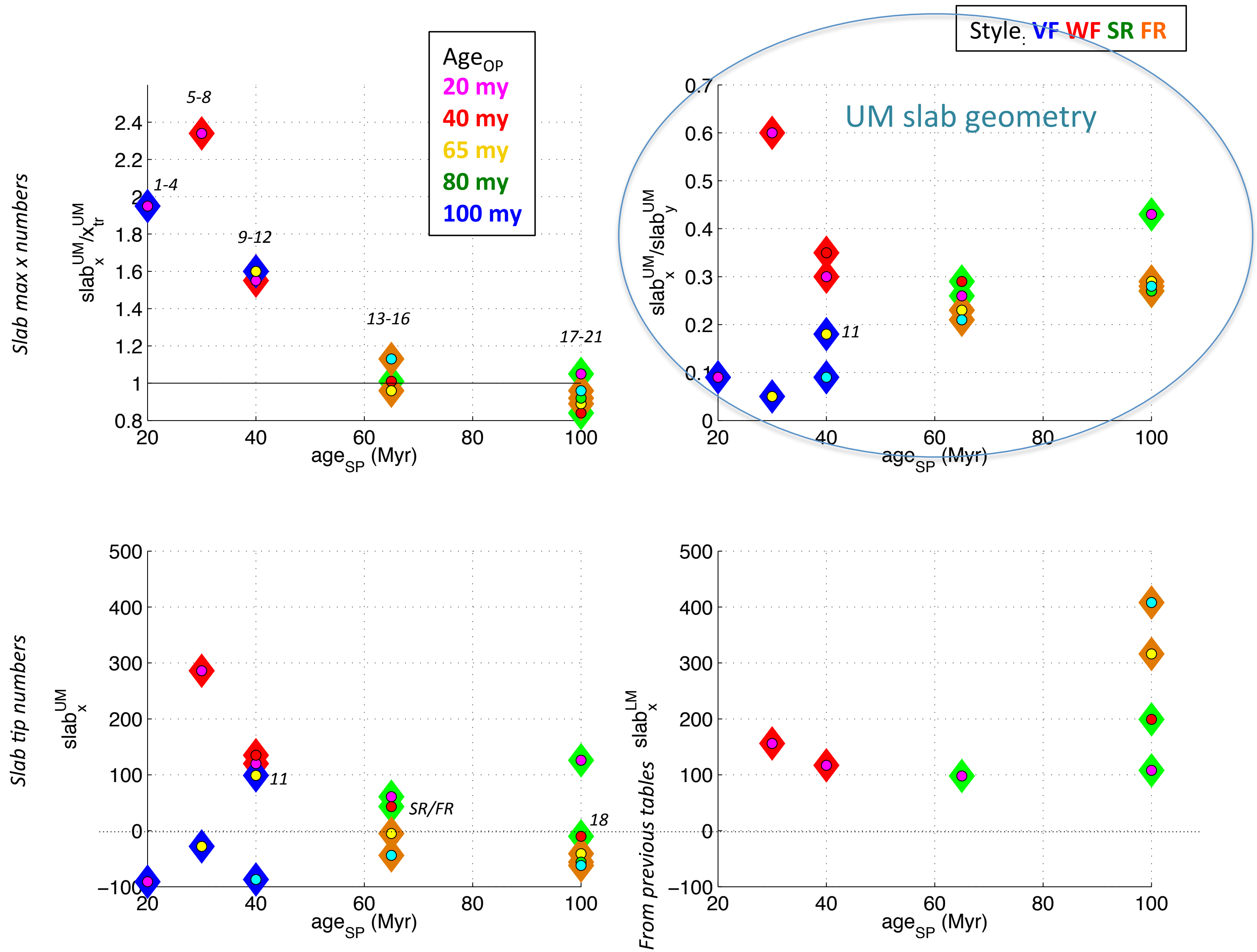
VF (vertical folding) mode - Age_SP = 40 Myr - Age_OP = 100 Myr



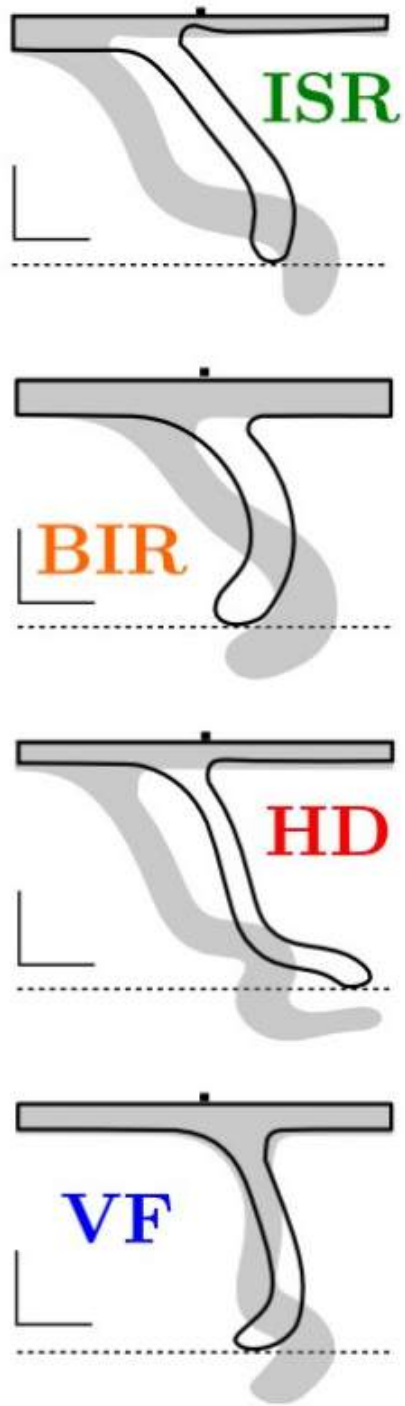

UM sinking as f^ion age_SP, age_OP
Time for 4 seems incorrect
Age_OP
20 my
40 my
65 my
80 my
100 my
Style. VF WF SR FR
1-4
5-8
9-12
13-16
17-21
SR/FR
10
11
extension
compression
t_660 Myr
L_diff/h
V_SP/V_Stokes
V_5000/V_OP
age_SP (Myr)



UM trench motion as f^ion age_SP, age_OP
17-21
13-16
9-12
5-8
1-4
SR/FR
10,11
V_{tr}^{UM}
V_{tr}^{LM}
V_{tr}^{UM}/V_{tr}^{LM}
age_SP (Myr)
10
11
Age_OP
20 my
40 my
65 my
80 my
100 my
Style. VF WF SR FR
UM vs LM trench motion



Style: VF WF SR FR
Age$_{OP}$
20 my
40 my
65 my
80 my
100 my
Slab max x numbers
$slab_x^{UM}/x_{tr}^{UM}$
5-8
1-4
9-12
13-16
17-21
age$_{SP}$ (Myr)
UM slab geometry
$slab_x^{UM}/slab_y^{UM}$
11
Slab tip numbers
$slab_x^{UM}$
11
SR/FR
18
From previous tables
$slab_x^{LM}$


ISR
BIR
HD
VF

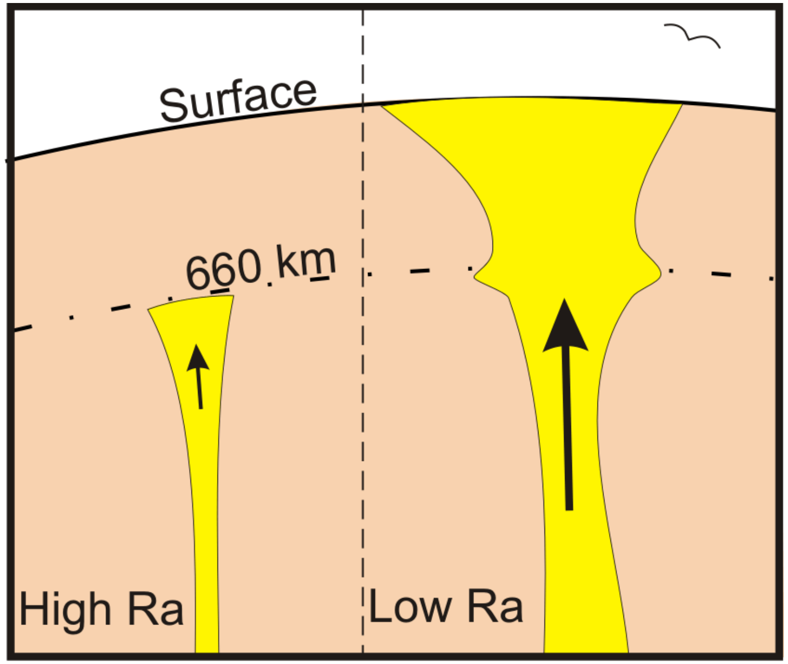
Motivation – Global Phase Change driven layering – closed 'valve'

Wolstencroft, Martin and J. H. Davies; Influence of the Ringwoodite-Perovskite transition on mantle convection in spherical geometry as a function of Clapeyron slope and Rayleigh number; *Solid Earth*, **2**, 315-326, 2011.
Open Access

Global models – but with simple viscous rheology

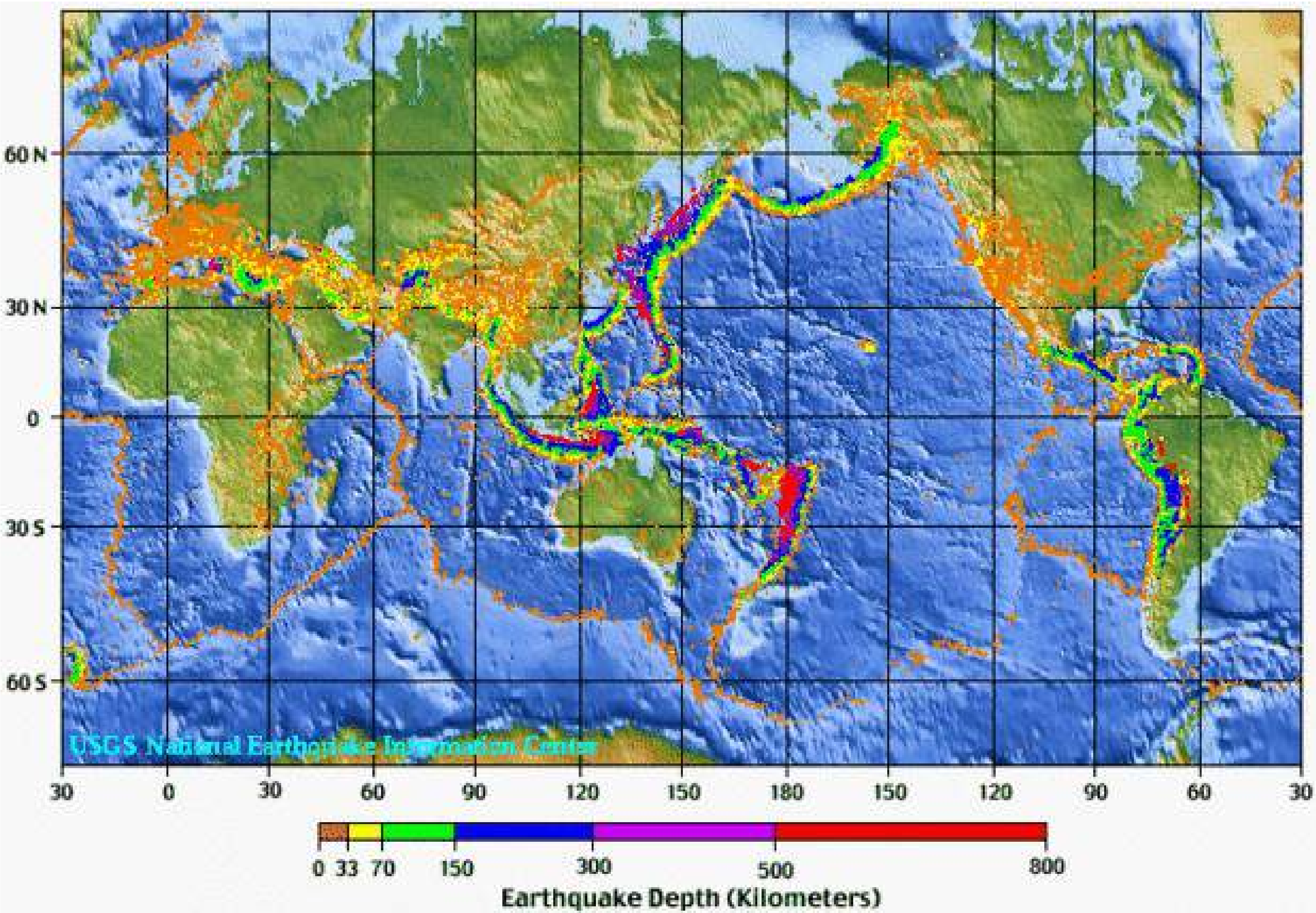
The Effect of Vigour

- Rayleigh number (Ra):
- Higher Ra – thinner plumes, more likely to be layered.
- Early Earth, (higher T) Ra could be an order of magnitude higher than present.



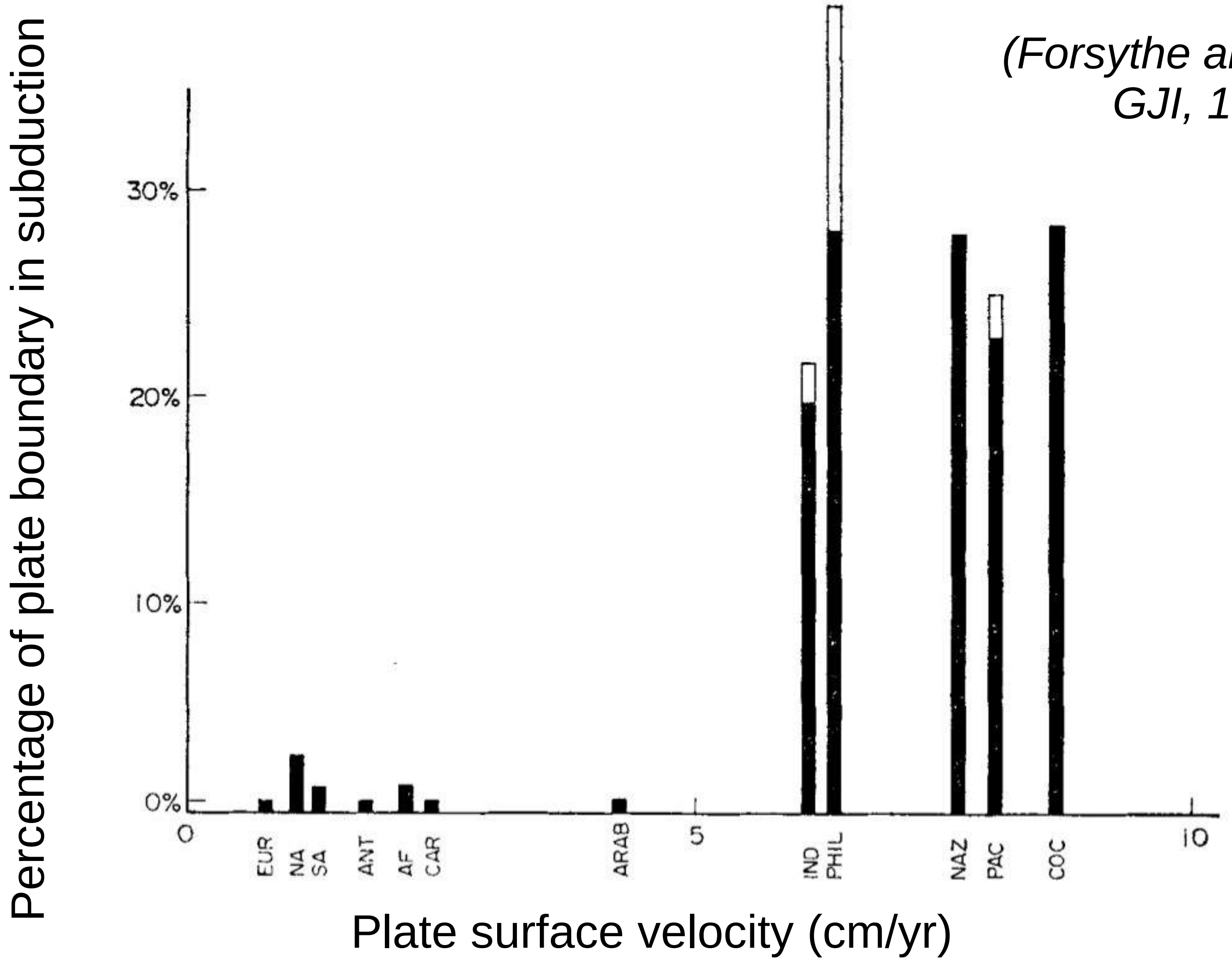
$$Ra = \frac{g\rho\alpha\Delta T D^3}{\kappa\mu}$$

Subduction zones

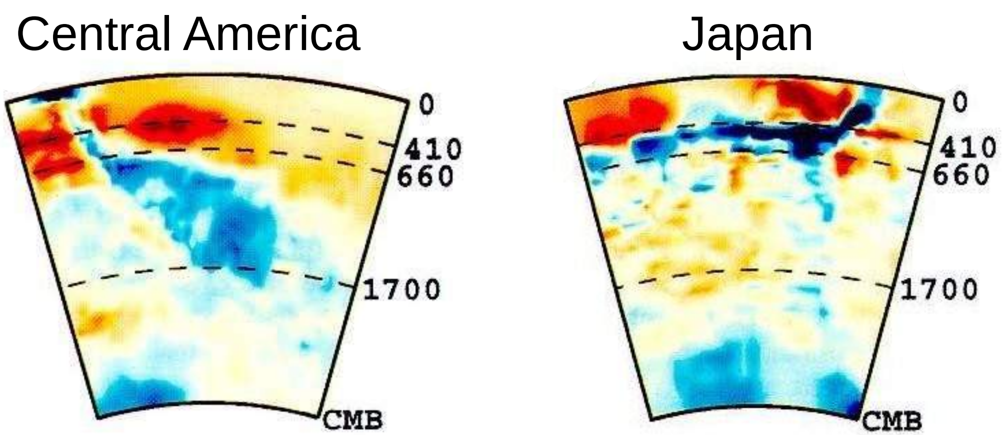


Subduction driving plate tectonics?

(Forsythe and Uyeda, GJI, 1975)



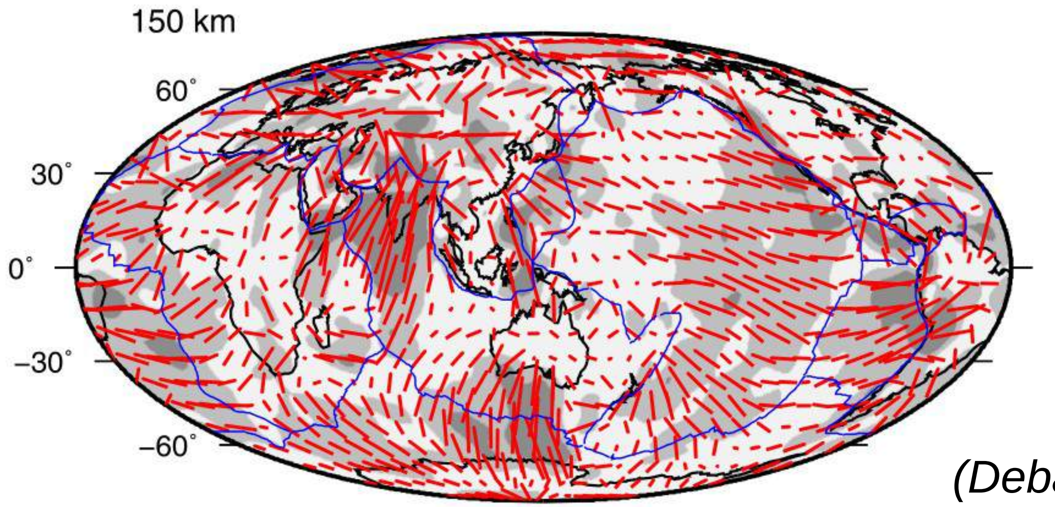
Subduction: a multi-scale system



(Karason and van der Hilst, 2000)

Large scale
(100 – 1000 km)

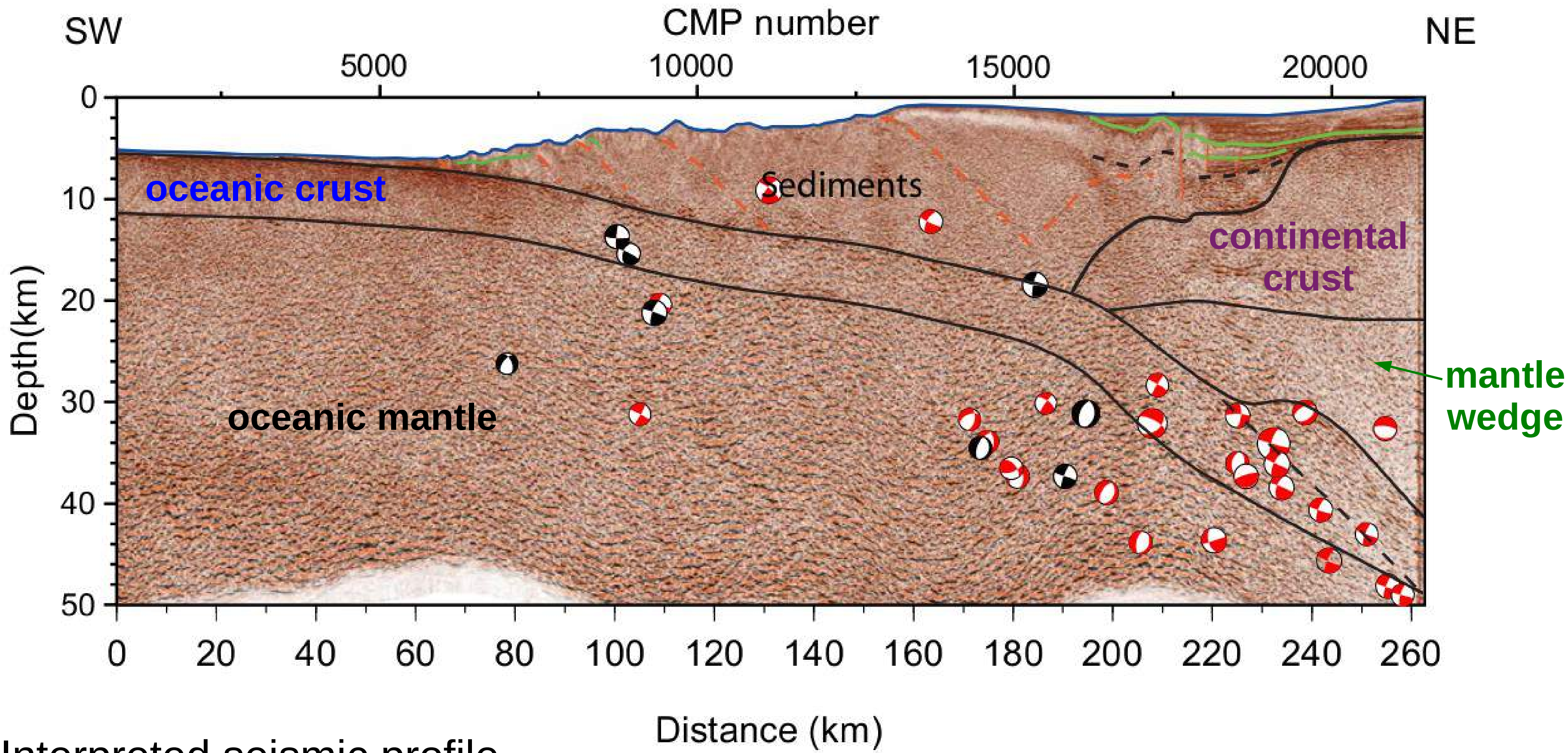
- mantle convection
- plate motions



Directions of SV-wave azimuthal anisotropy at 150 km depth

(Debayle and Ricard, EPSL, 2013)

Subduction: a multi-scale system

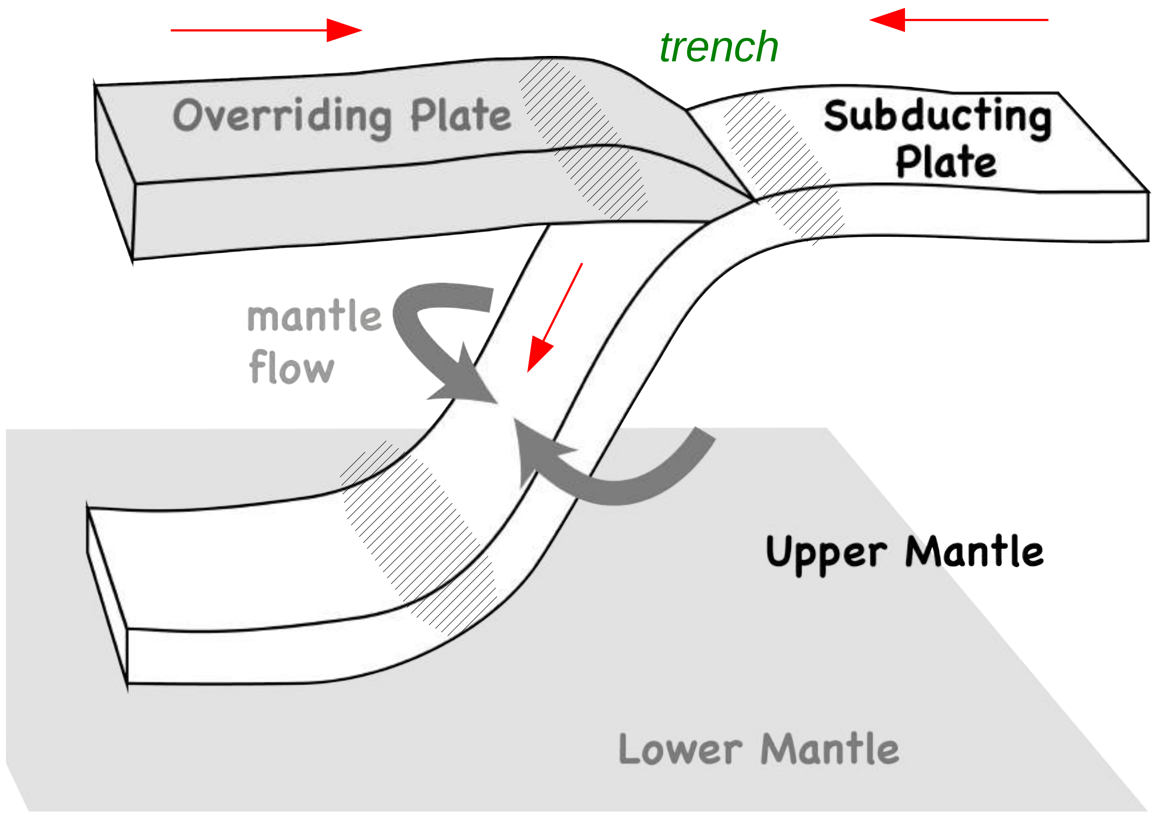


Interpreted seismic profile through the Sumatra subduction zone

(Singh et al, Nature Geosci., 2011)

Small scale (<10 km)

Subduction: a complex dynamic system



- Plate & trench motions
- Mantle flow
- Slab pull
- Viscous resistance
- Deformation of plates
- Decoupling layer
  Friction
- Free surface
- Rheology

+ 3D, interface UM/LM
+ phase transitions, grain size, metastability
+ how subduction initiate...

Future

1 Further analyse models with phase change in Boussinesq Approximation, including investigating stronger phase change

2 Undertake models in Extended Boussinesq Approximation, Incompressible, but depth-dependent alpha; shear heating

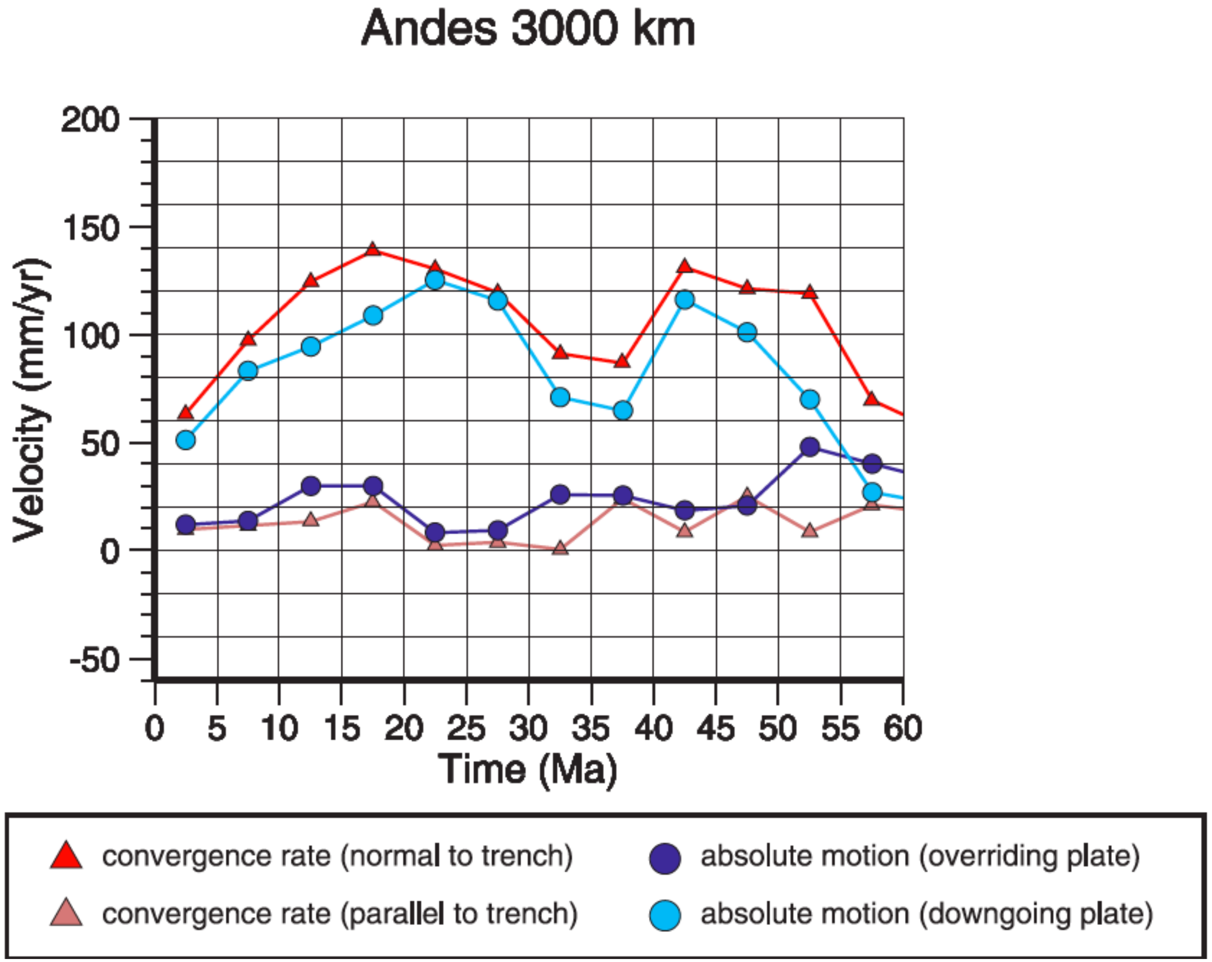
3 Undertake models in Extended Boussinesq Approximation, with Phase change => with latent heat

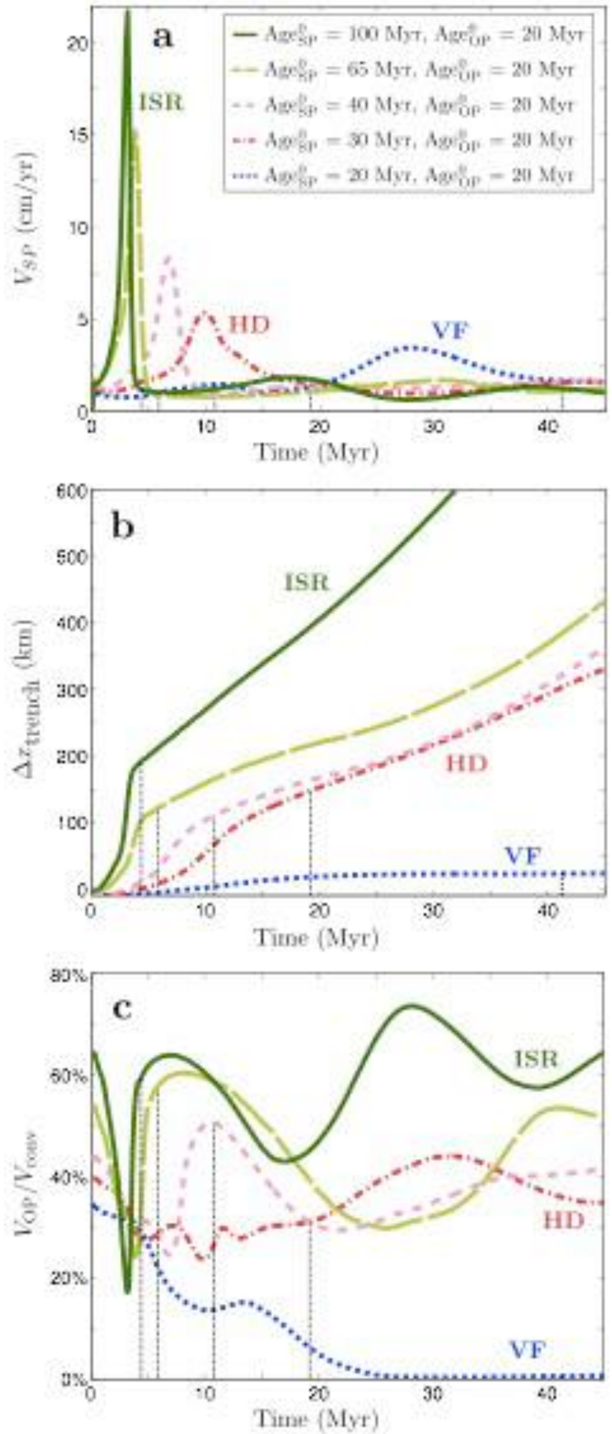
4 Undertake fully compressible models + add thermodynamic models of mineral behaviour – so all phase changes incorporated

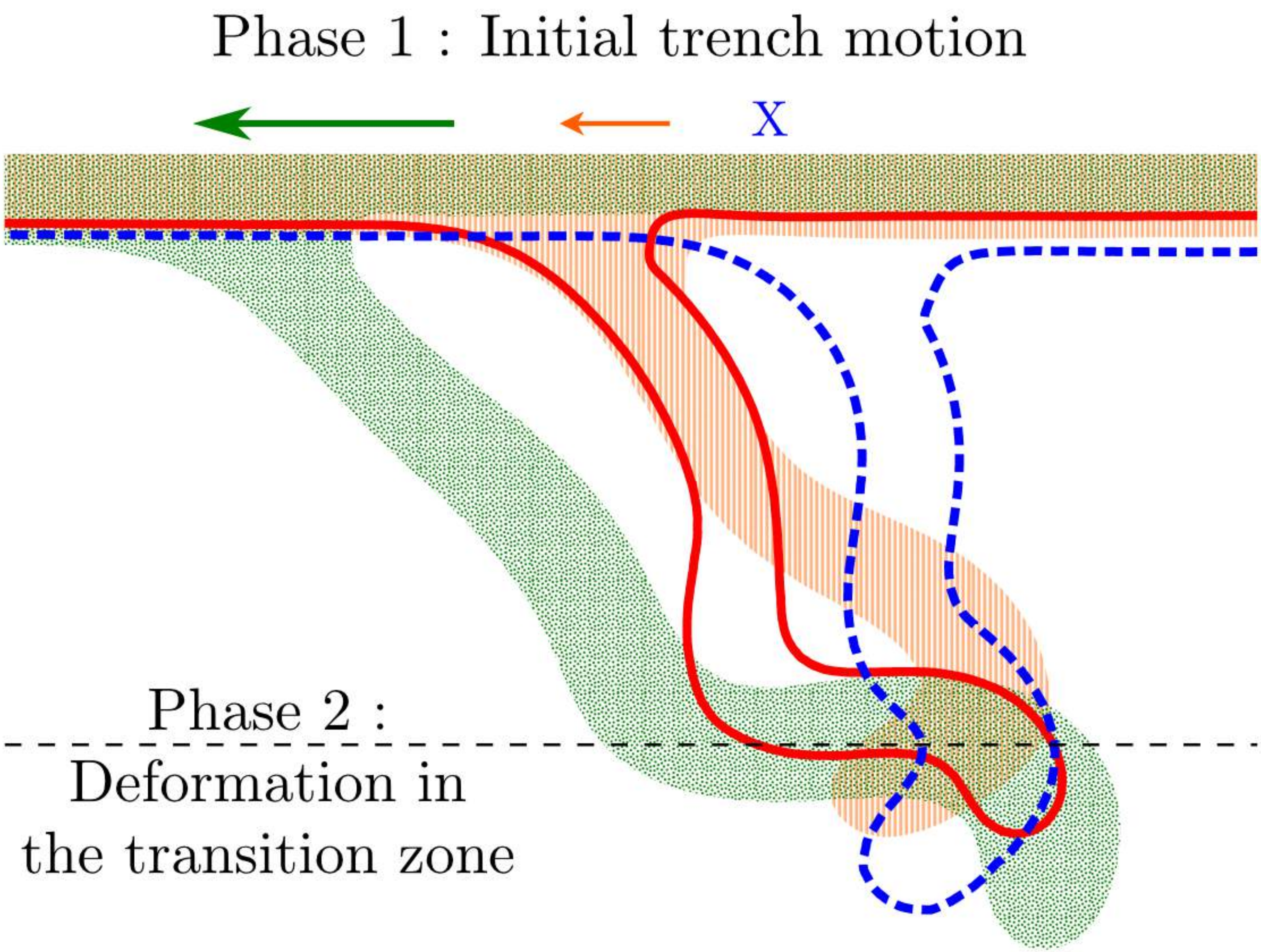
5 Investigate effects of better constrained values of rheology

6 Three dimensional – 3D

Viscosity jump leads to time oscillations – maybe observed in data – Sdrolias + Muller, 2006

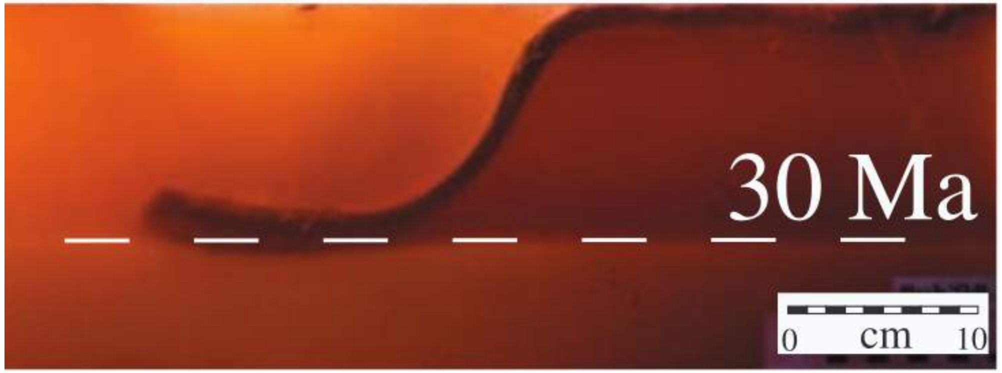





Phase 1 : Initial trench motion
X
Phase 2 :
Deformation in
the transition zone

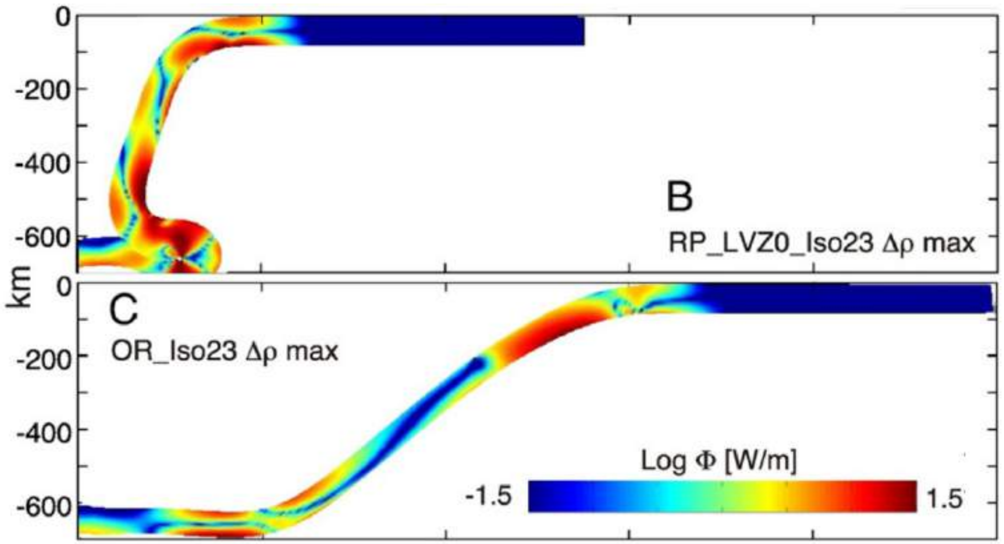
Subduction modelling: free subduction

Prescribed constant viscosity, density and thickness for mantle vs. slab.



Laboratory experiments:
silicone slab in glucose syrups

(Funiciello et al., JGR, 2003)



(Capitanio et al., EPSL, 2007)

Diversity of morphology as a function of the subducting plate buoyancy and viscosity / stiffness...

Schellart et al., Nature, 2007
Stegman et al., Tectonophysics, 2010
Ribe, GJI, 2010...

Subduction modelling: thermal models

…but...

- subduction occurs with an overriding plate !
- subduction is mainly a thermally-driven process !

Thermo-mechanical models allow

- the self-consistency of the coupling between buoyancy and strength through temperature, and between flow and viscosity

- a dynamic plate renewal through surface thermal diffusion

- the evolution of plate ages during the subduction history

Example of thermal models:

Gurnis and Hager, Nature, 1988
Zhong and Gurnis, Nature, 1996
Schmeling et al., EPSL, 1999
van Hunen et al., EPSL, 2000

Cizkova et al., PEPI, 2007
Billen et al., PEPI, 2010
Arcay et al., G3, 2008
Leng and Gurnis, G3, 2011
Nakakuki and Mura, EPSL, 2013