Géosciences Montpellier

Slab-mantle interaction and dynamics of subduction

Serge Lallemand

with : A. Heuret, A. Quilichini, D. Arcay, C. Faccenna, F. Funiciello, T. Becker, C. Conrad, E. Di Giuseppe …

Slab-mantle interaction and dynamics of subduction

- Common pictures of slab & mantle interactions in subduction zones
- Importance of the choice of the reference frame
- Actualistic and global approach
- Experimental tests and some physical explanations of present behavior of SZs
- Mantle dynamics driven by subduction processes : a few examples

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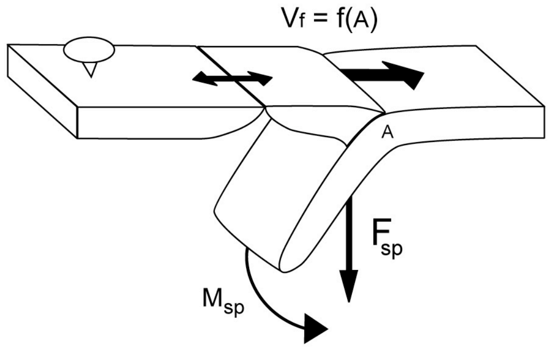
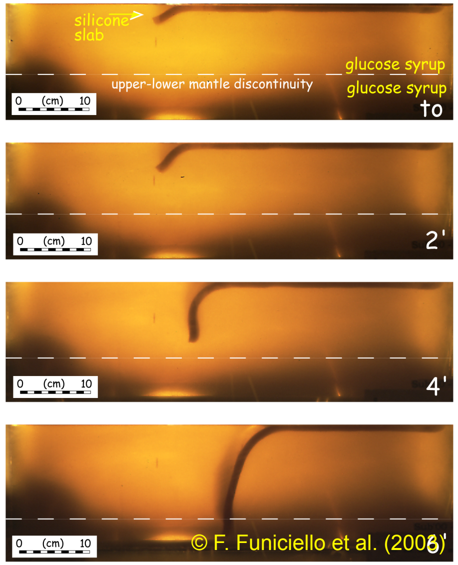
Common pictures of slab & mantle interactions in subduction zones

- Slab rollback

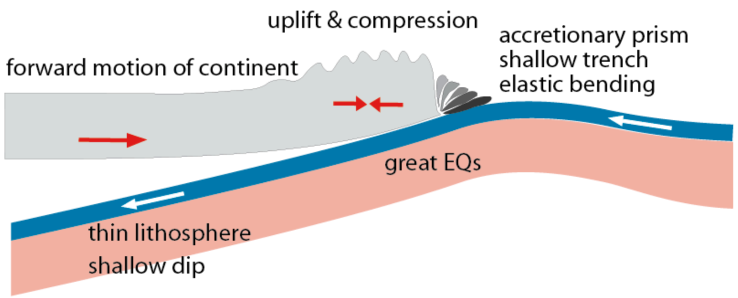


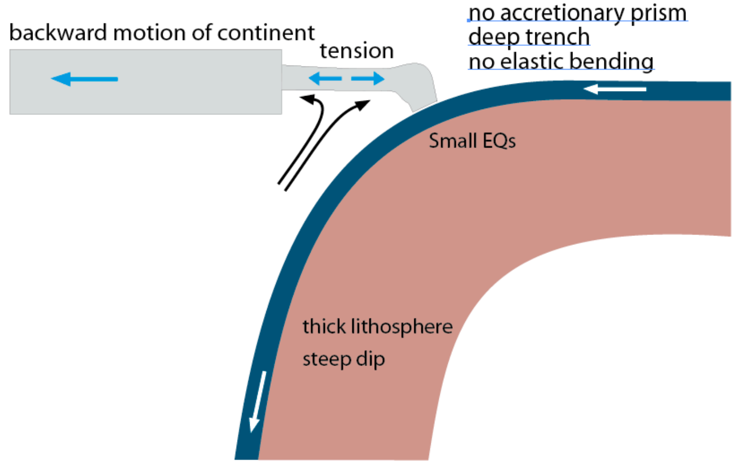


MacKenzy (1977)
Dewey (1980)
Garfunkel et al. (1986)
...
Hamilton (2003)
Goes et al. (2008)

- Slab dip & slab pull

"Forced" subduction of a young and light lithosphere | **"Spontaneous" subduction of an old and heavy lithosphere**





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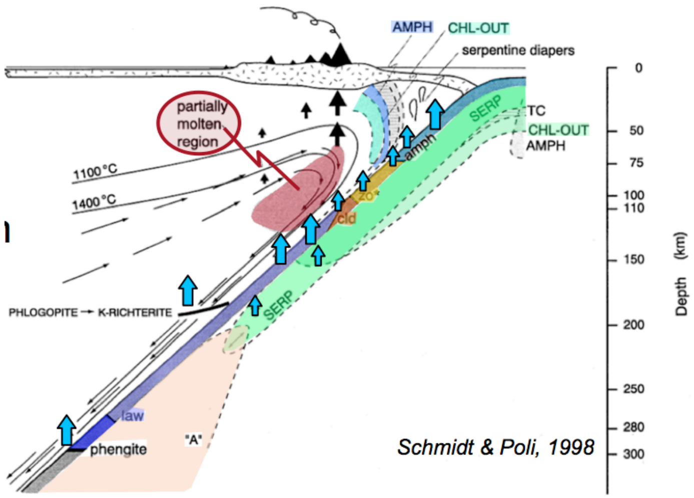
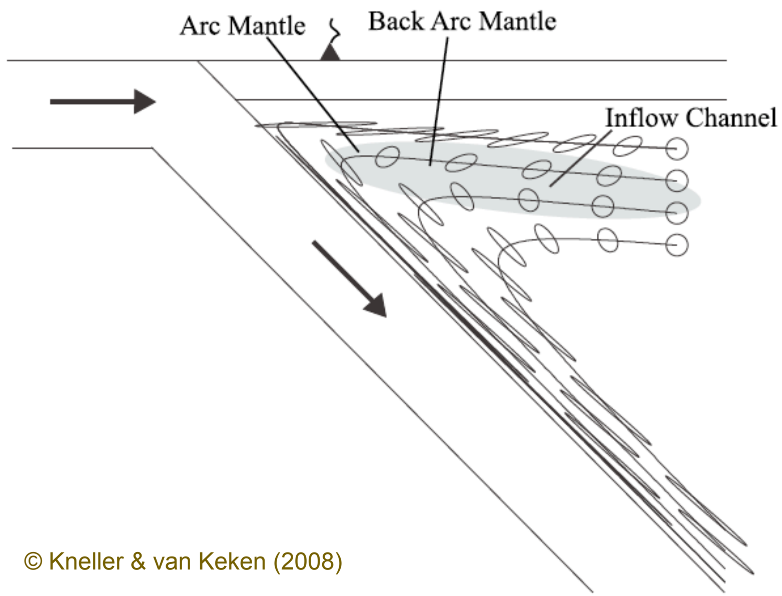
Common pictures of slab & mantle interactions in subduction zones

- Corner flow





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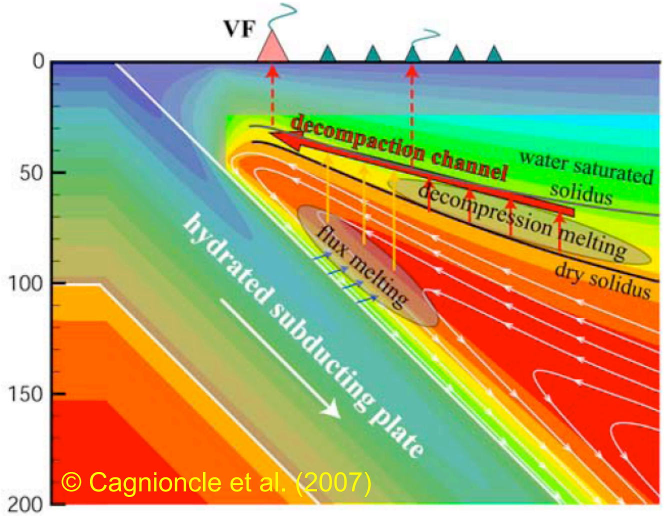
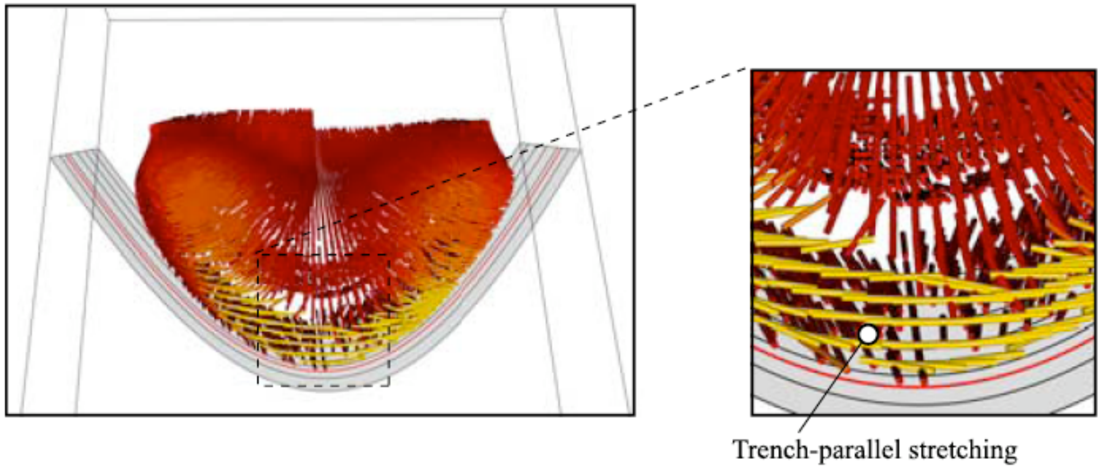
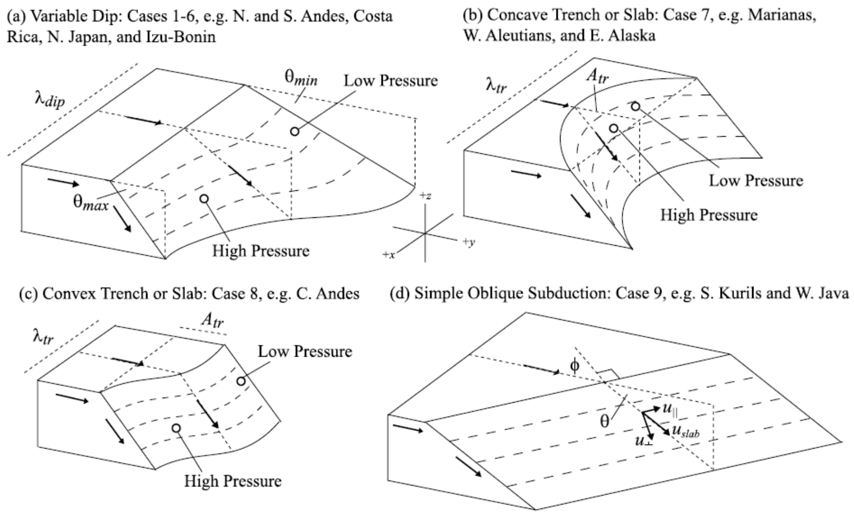
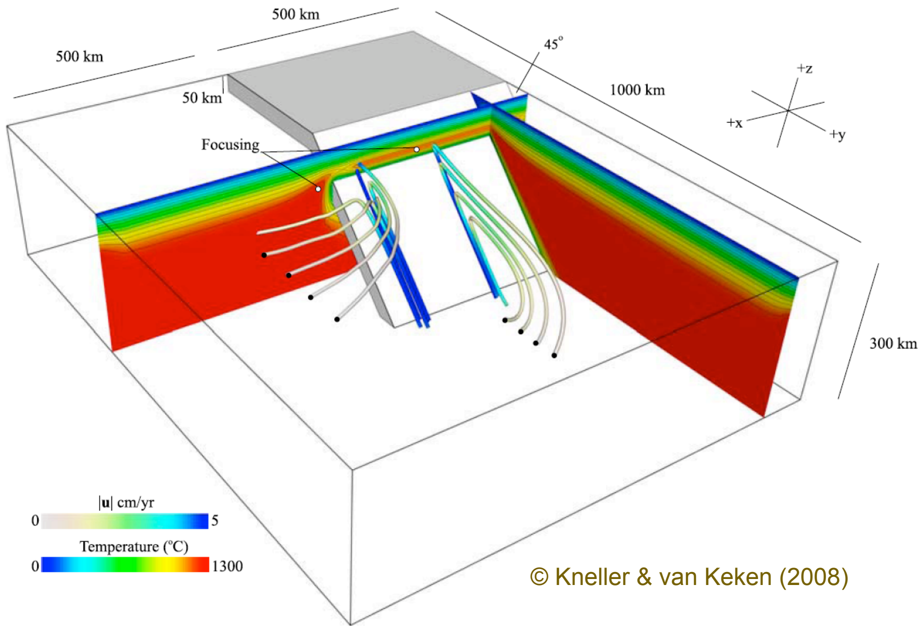


Some authors account for natural complexities such as the effect of the 3D geometry







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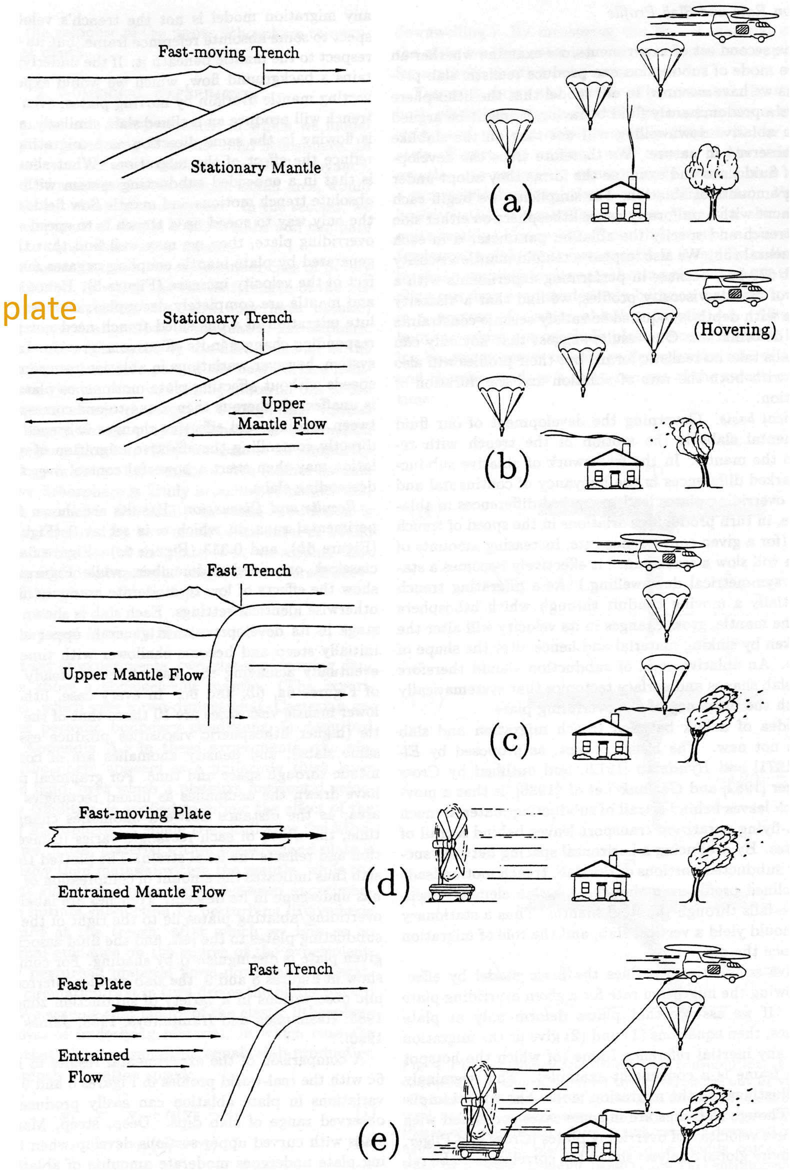
Importance of the choice of the reference frame

Fixed upper plate

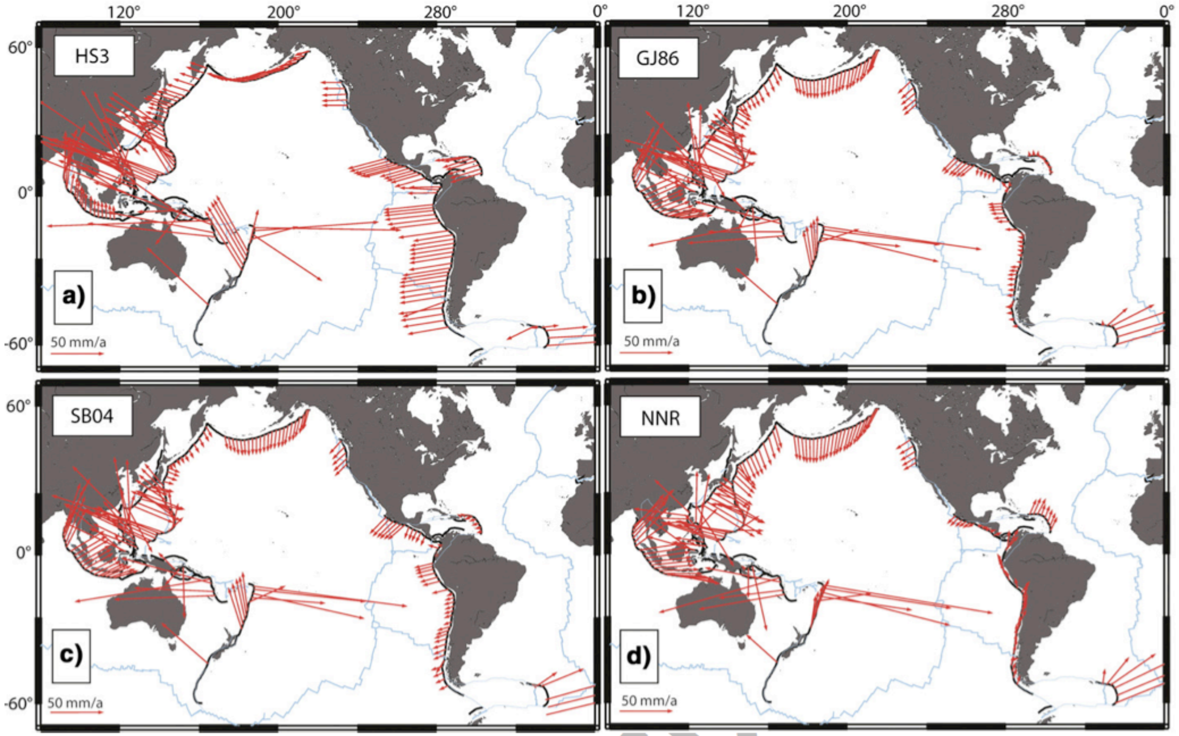


Helicopter = trench

Aligned « parachutes » = slab

Wind (see smoke & tree) = mantle flow

Importance of the choice of the reference frame



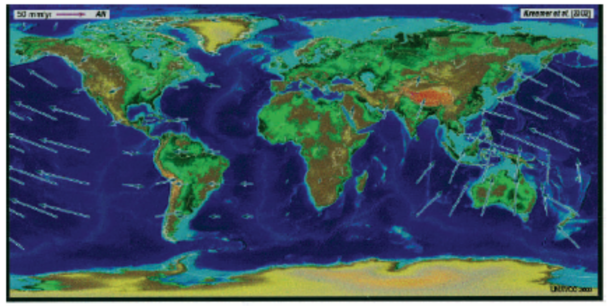
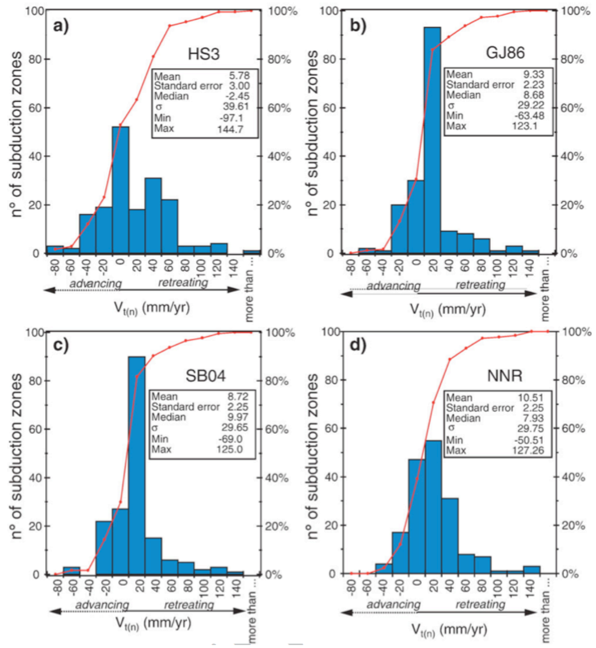


Figure 8. Relative-motio
Antarctica-fixed framew
subduction, due to top-
plates, that ridges are pa
that drive, and that lowe
participate in plate moti
framework when allowa
arc spreading and plate-
Data from geodesy-dom
Kreemer et al. (2003). In
Estey, University NAVST
http://jules.unavco.ucar.

© Hamilton (2003)

© Funiciello et al. (2008)



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Characteristics of trench motions in three reference frames

Reference frame	NNR-NUVEL1A Gripp and Gordon (2002)	SB04 Steinberger et al. (2004)	HS3-NUVEL1A Gripp and Gordon (2002)
Selected hot spots	No hot spots	Indo-Atlantic hot spots	Pacific hot spots
Age of hot spots	-	80 Ma - present	5.8 Ma - present
Mean/max net rotation	0 by definition	1.4/1.8 cm/yr	3.8/4.9 cm/yr
Mean trench motion	1.1 ± 3.0 cm/yr (rollback)	0.9 ± 3.0 cm/yr (rollback)	0.6 ± 4.0 cm/yr (rollback)
Maximum rate of trench rollback	12.7 cm/yr	12.5 cm/yr	14.5 cm/yr
Maximum rate of trench advance	5.1 cm/yr	6.9 cm/yr	9.7 cm/yr
Rollback/Advance transects ratio	1.56	2.33	0.89

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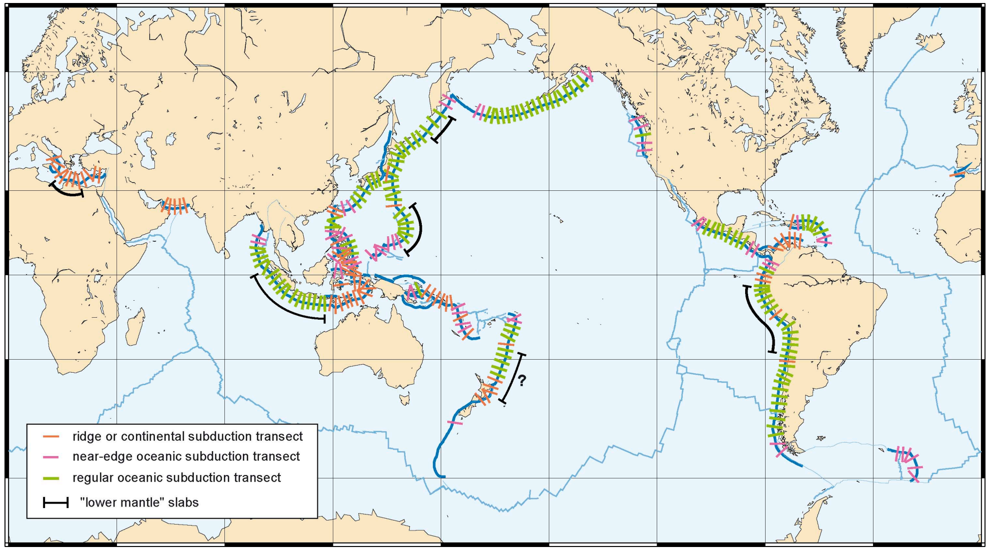
Actualistic and global approach



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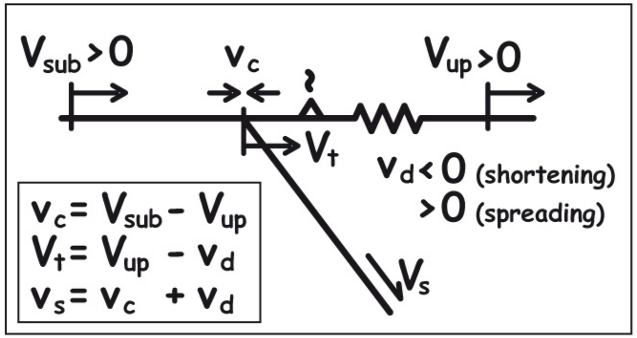

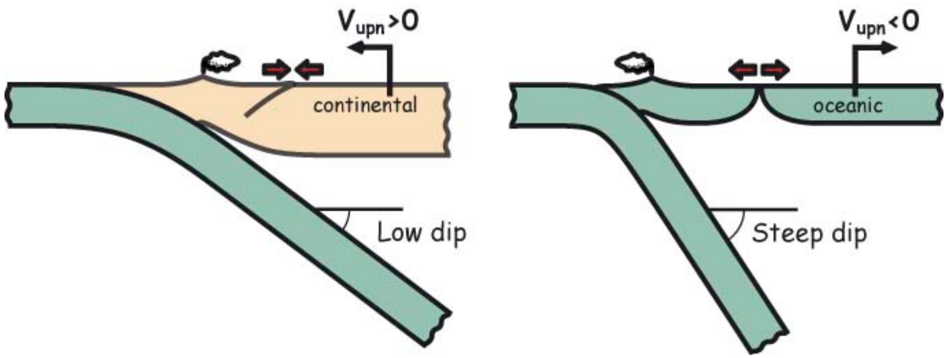

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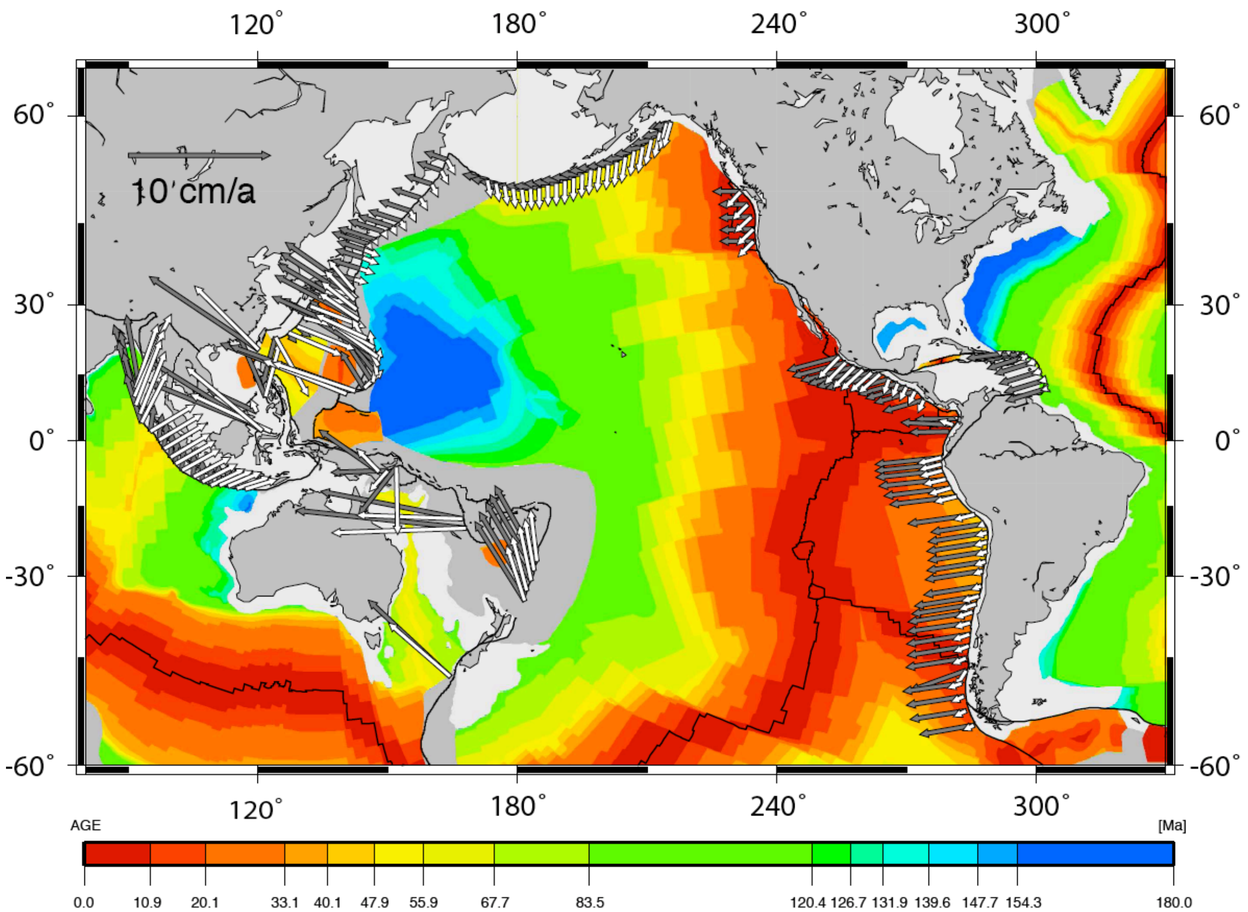
Actualistic and global approach



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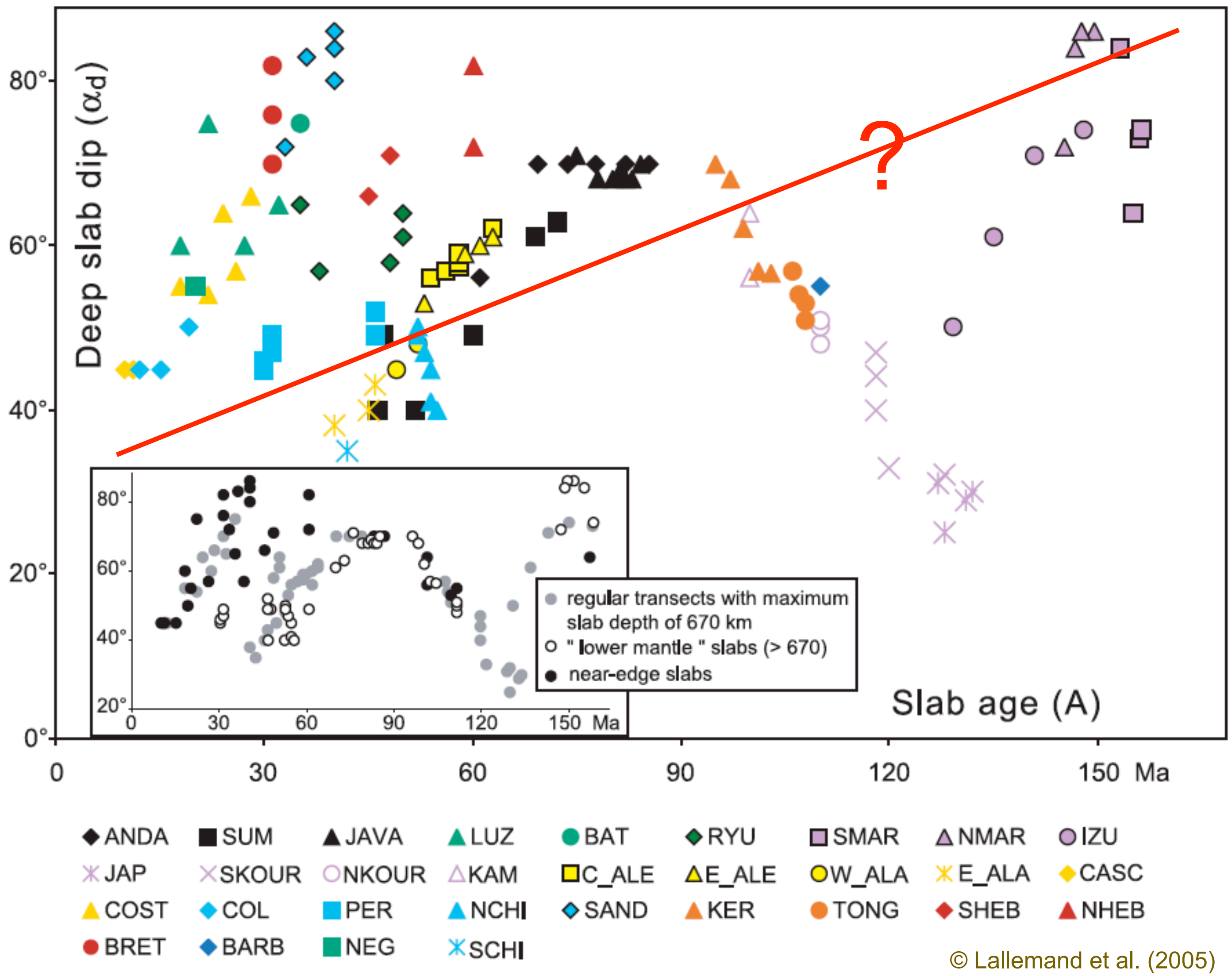
- *Trench rollback is not systematic !*
- *Retreating trenches are associated with young slabs !*
- *No relation between back-arc spreading and trench rollback !*

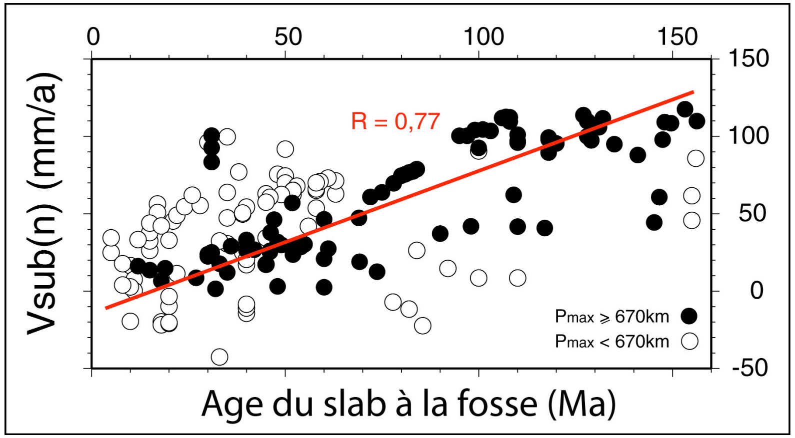


In a more general way, there is no relation between slab age and slab dip

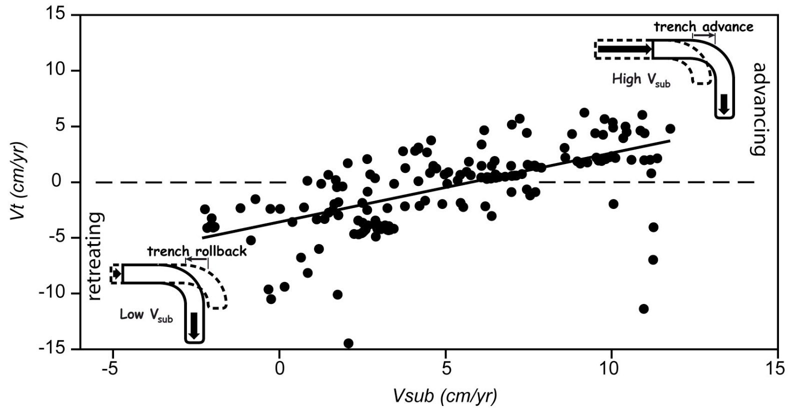
Actualistic and global approach

- *The velocity of the subducting plate correlates with its age at trench*

  → *Slab pull = driving force*



- *The velocity of the trench correlates with the velocity of the subducting plate*



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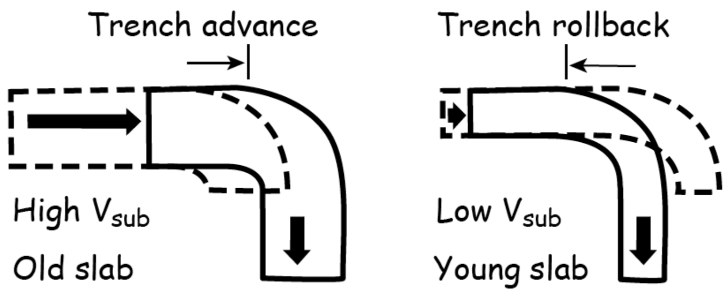
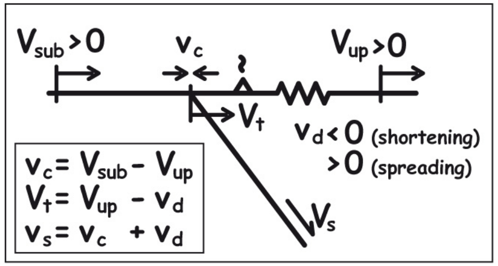
- → *By combination of both observations, we obtain :*

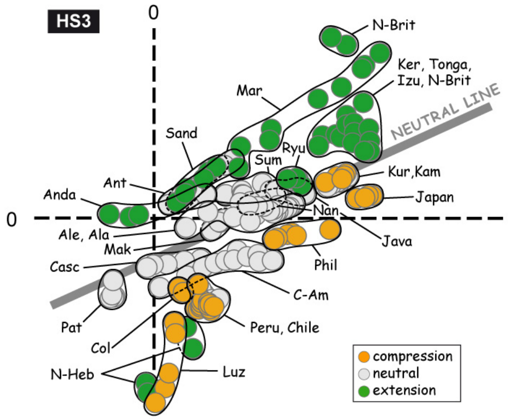
  The subduction velocity $v_s = V_{sub} - V_{up} + v_d$ is kept to 5 ± 5 cm/an

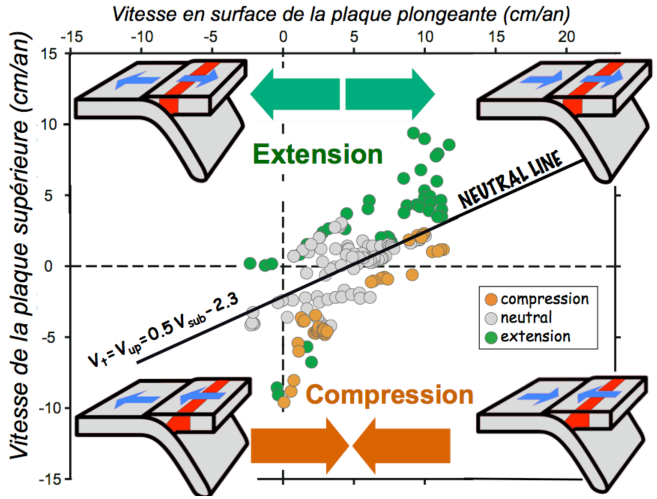


Actualistic and global approach

- *Extension, compression and « neutrality » are observed in the upper plate for given combinations of plates velocities*







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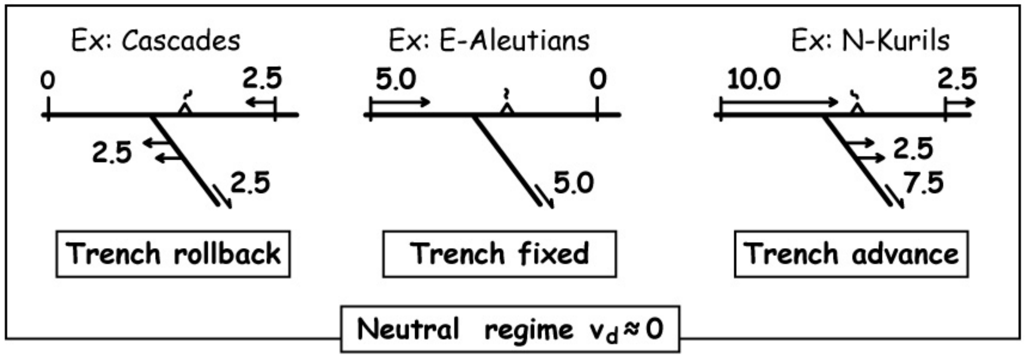
- *By using the arc as a strain sensor, we define a « neutral line » along with a kinematic equilibrium between converging plates is satisfied*

- *Thus empirically, we can link the « spontaneous » migration of trenches to the velocity of the subducting plate*



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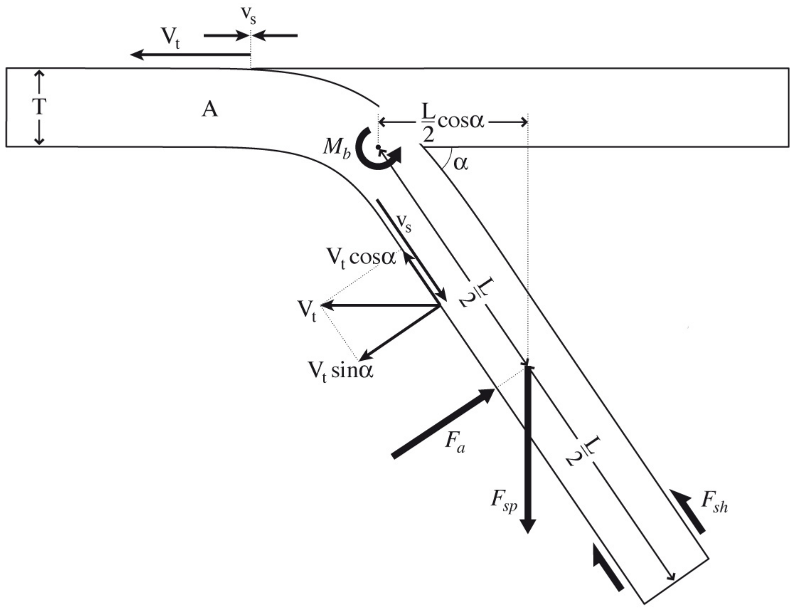
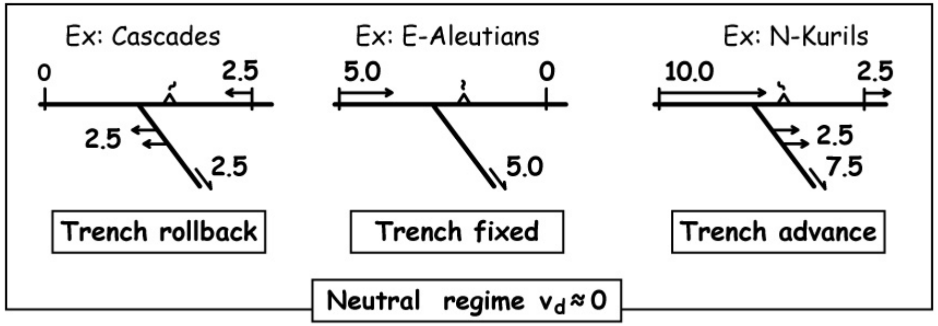
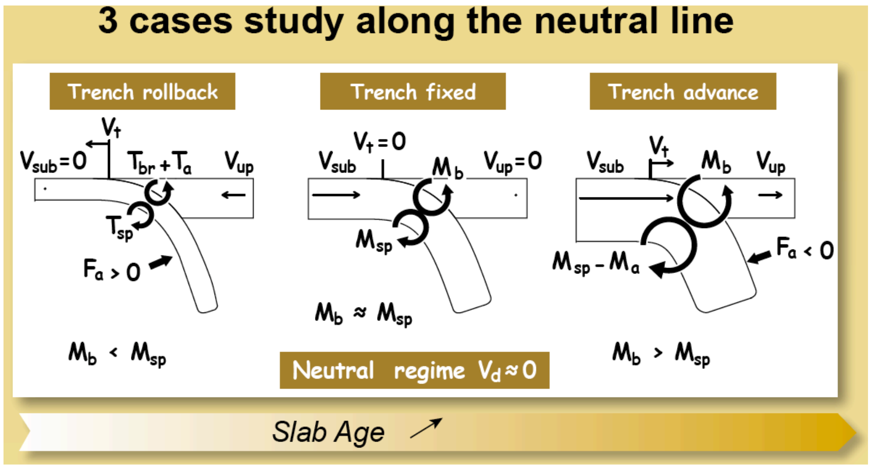
Some physical explanations of present behavior of SZs and experimental tests

- *Torques balance between bending and unbending forces show that old and stiff slabs prevent rollback and favor trench advance because bending resistance scales with $A^{3/2}$ whereas the slab pull scales with A*







- $$M_{sp} = M_b + M_a$$

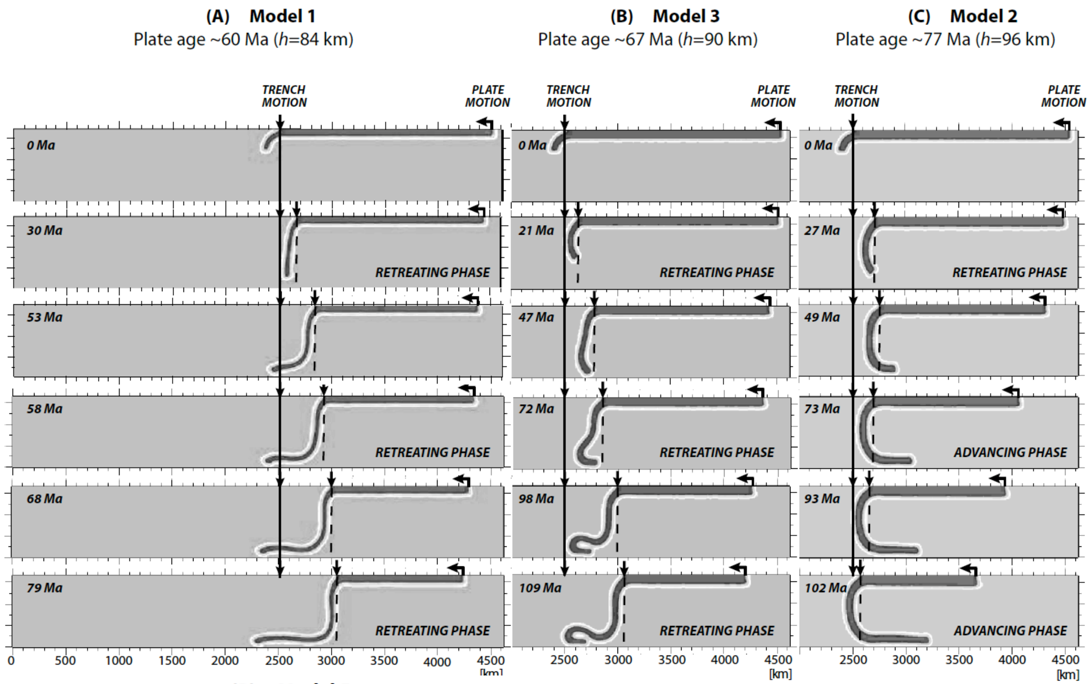
$$M_{sp} = F_{sp}\frac{L}{2}\cos\alpha \qquad F_{sp} = 0.25\Delta\rho g T_{th} L \qquad T_{th} = 2.32\sqrt{\kappa A}$$

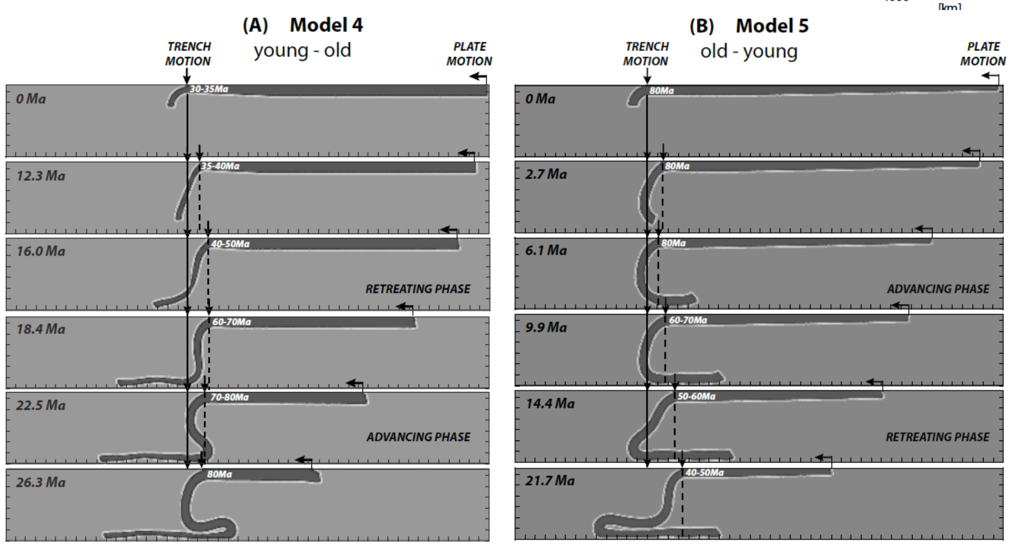
$$M_b = \frac{D}{R_b} \qquad D = \frac{E(T_e)^3}{12(1-\nu^2)} \qquad T_e = 4.2\cdot 10^3\sqrt{A}$$

$$M_a = F_a\frac{L}{2} \qquad F_a = 6.6\eta_m V_t \sin\alpha$$

Some physical explanations of present behavior of SZs and experimental tests

- *Plate's stiffness effect on trench migration tested using Citcom FEM in 3D (visco-plastic, purely compositional model, subduction driven by potential energy)*

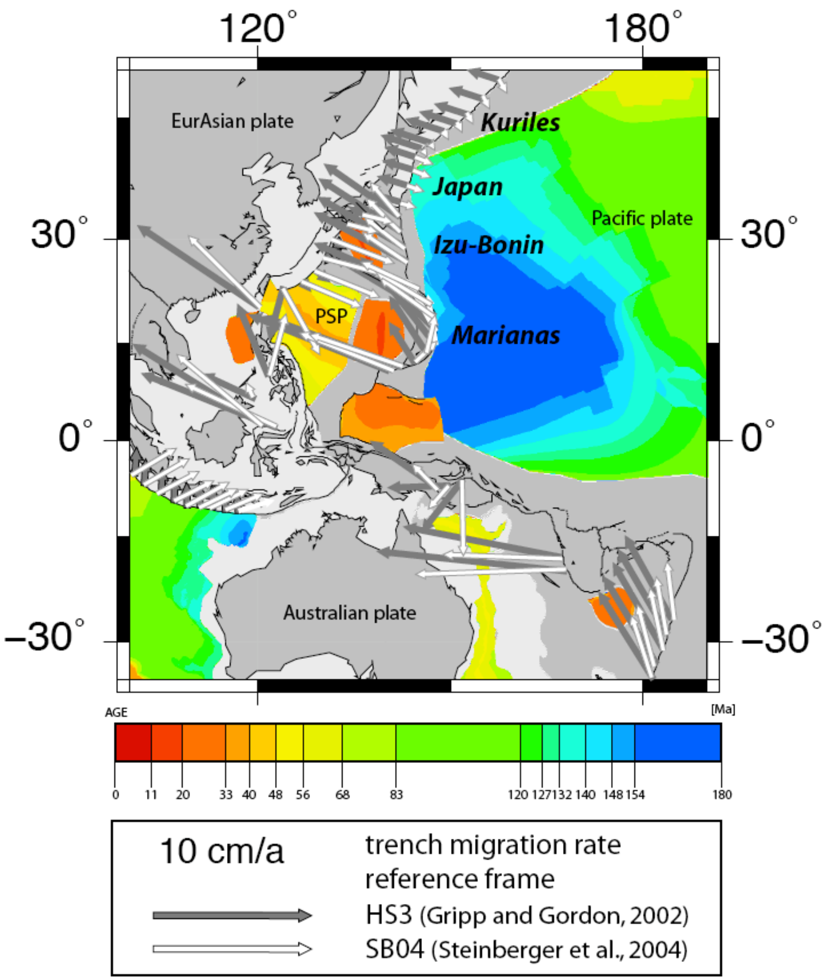


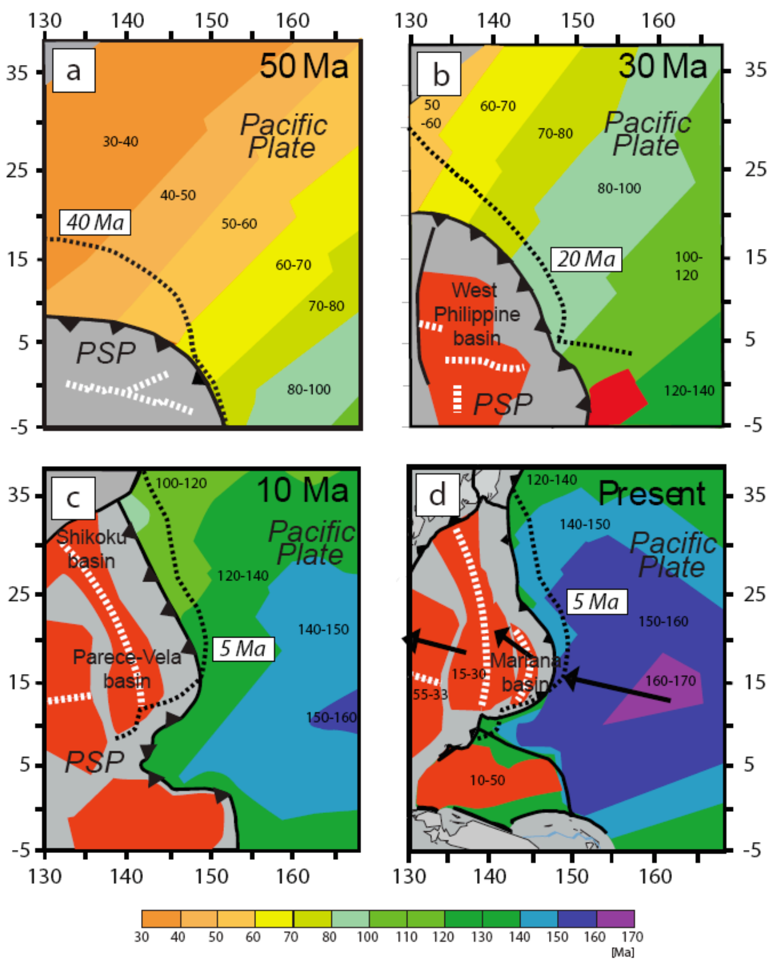


Plate's stiffness plays a key role in controlling subduction velocity and the partitioning between trench and plate motion

Some physical explanations of present behavior of SZs and experimental tests

- *The « recent » change of motion of the Izu-Bonin trench*





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Some physical explanations of present behavior of SZs and experimental tests

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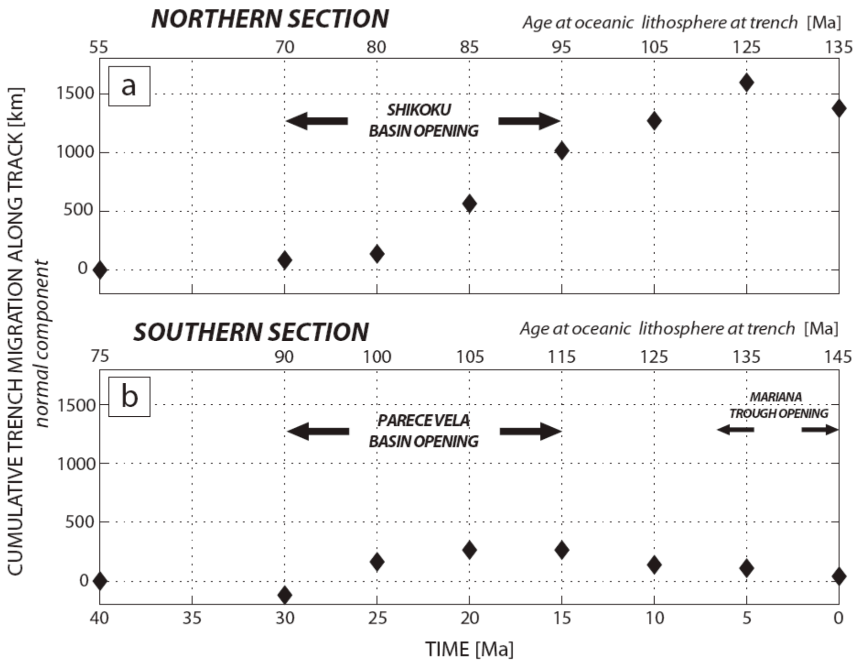

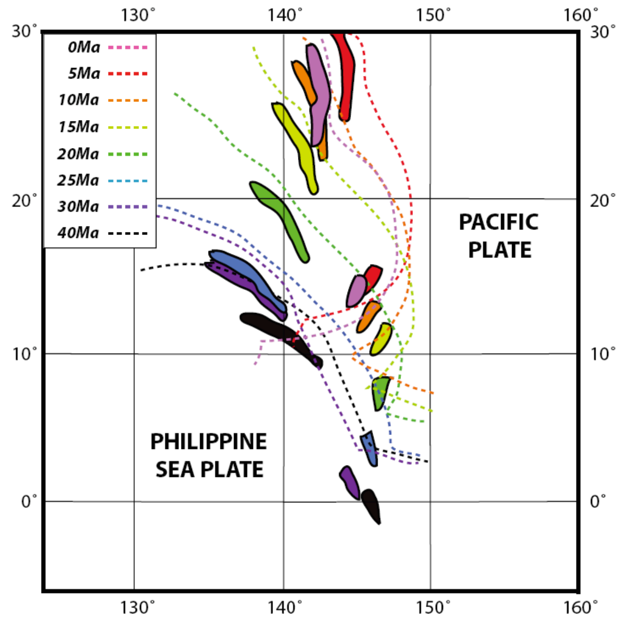

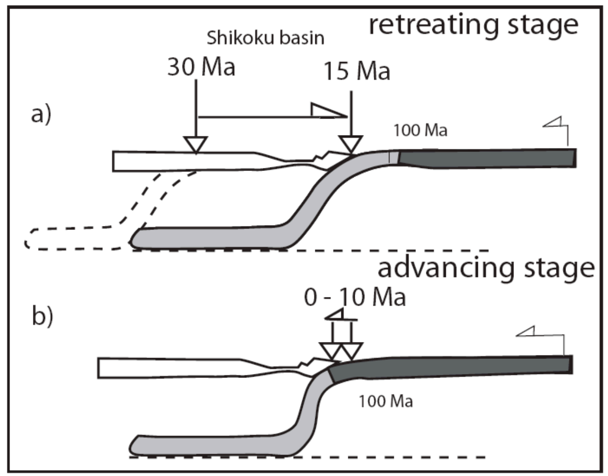

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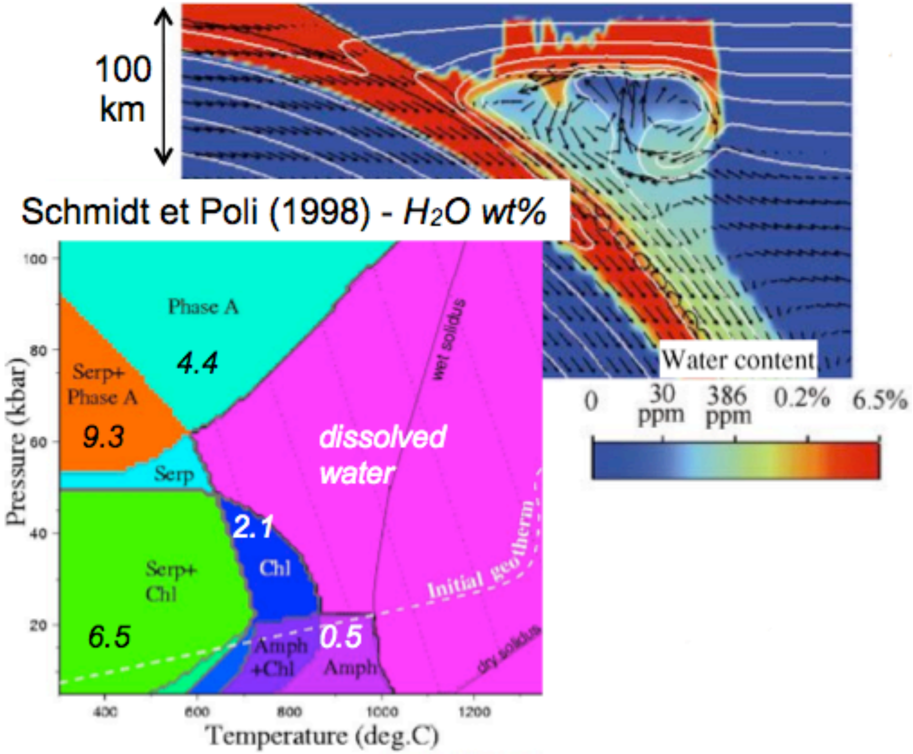
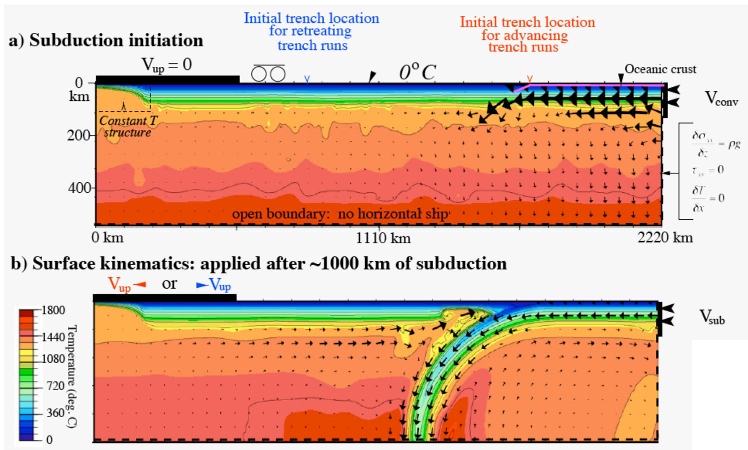
Some physical explanations of present behavior of SZs and experimental tests

- *2D thermo-chemical convection model (Christensen, 1992) with imposed kinematics and an upper plate. Pseudo-brittle and non-Newtonian viscous rheology function of T, P, strain rate and crust/mantle composition. Slab dehydration and consequent mantle hydration reduces its viscosity.*

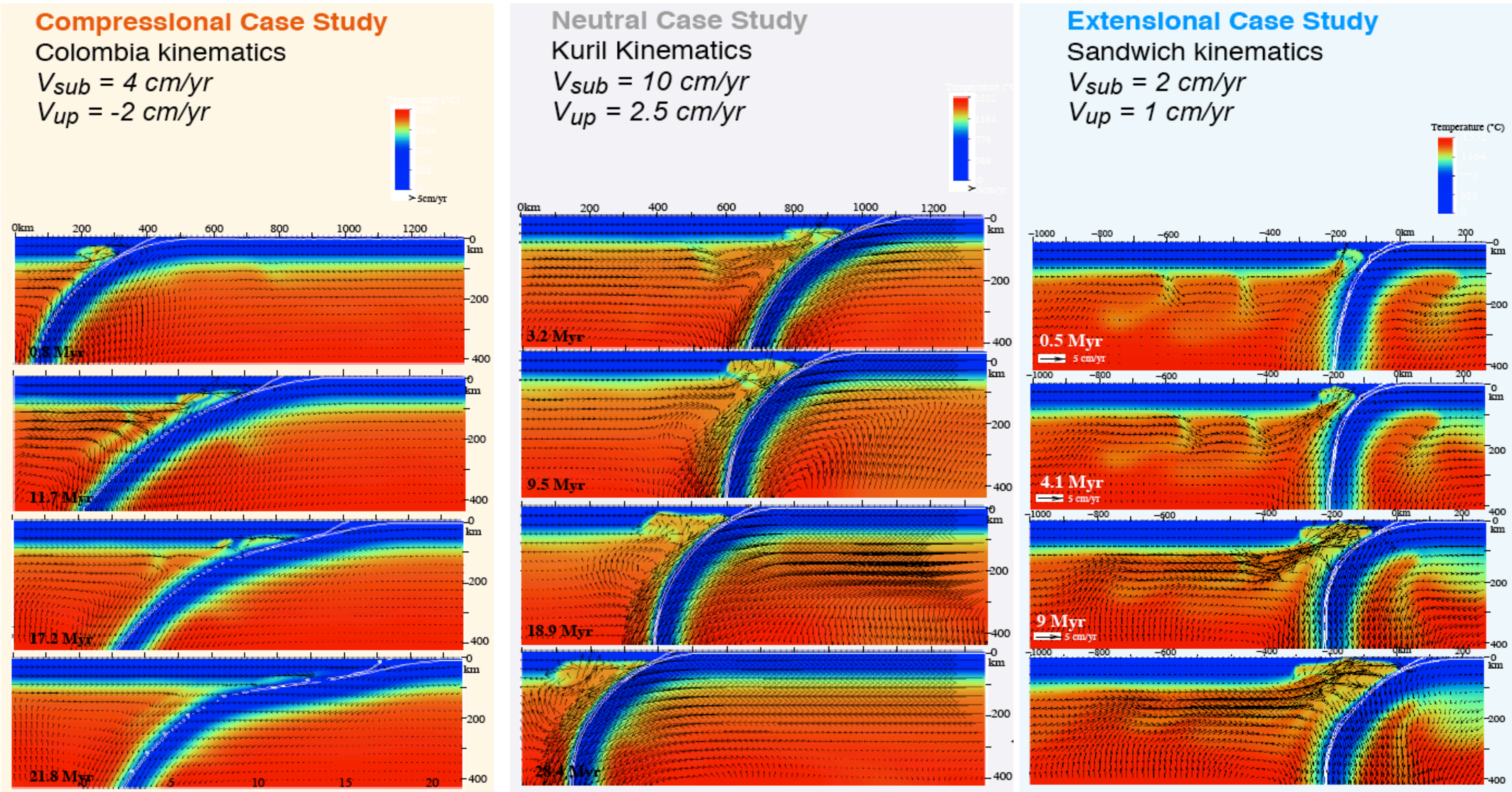


Once the subduction starts, the trench is free to migrate self-consistently.



Some physical explanations of present behavior of SZs and experimental tests

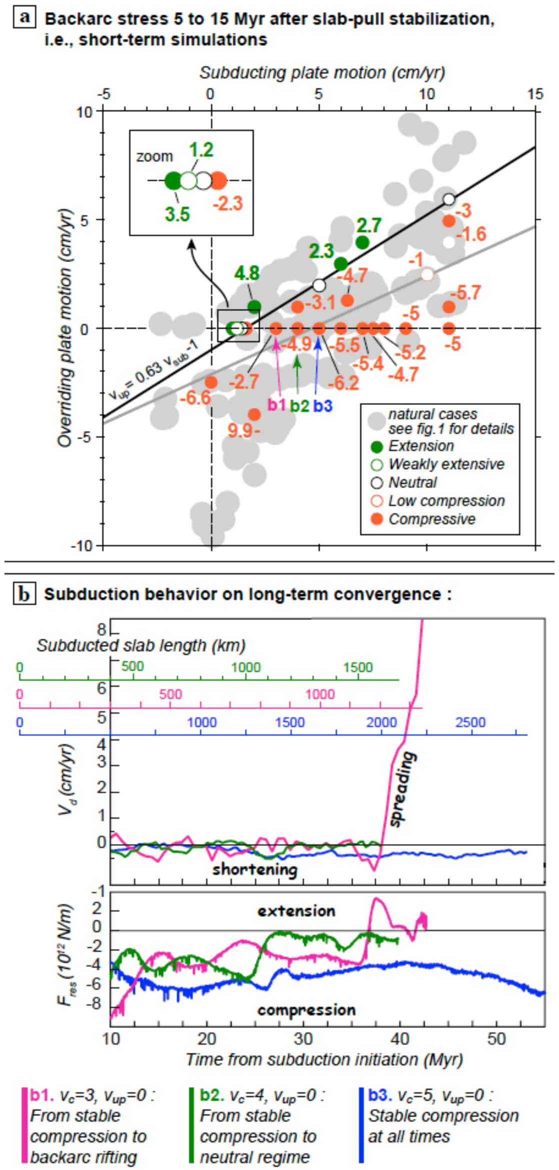
- *Three kinematic combinations that result in trench migration and upper plate strain compatible with natural cases.*

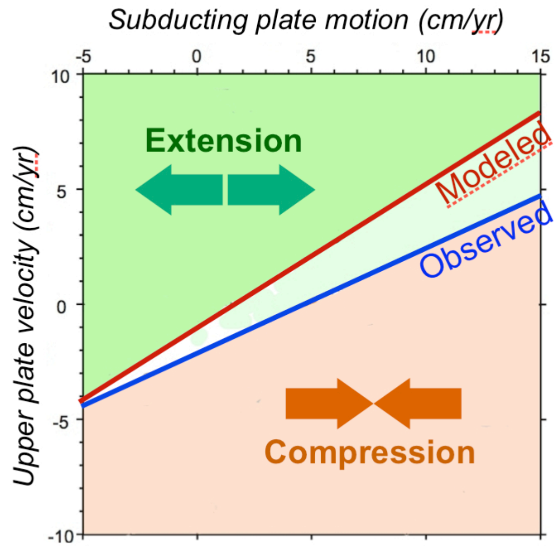


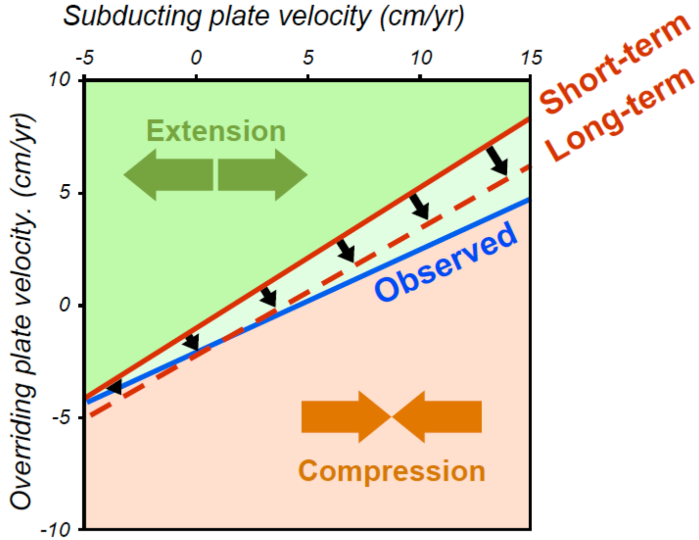
Strain mode evolves with time like in nature because of complex retroactions

Some physical explanations of present behavior of SZs and experimental tests

- *Short-term vs long-term evolution of the models*
- *Same behavior than in natural cases when using HS3 reference frame*







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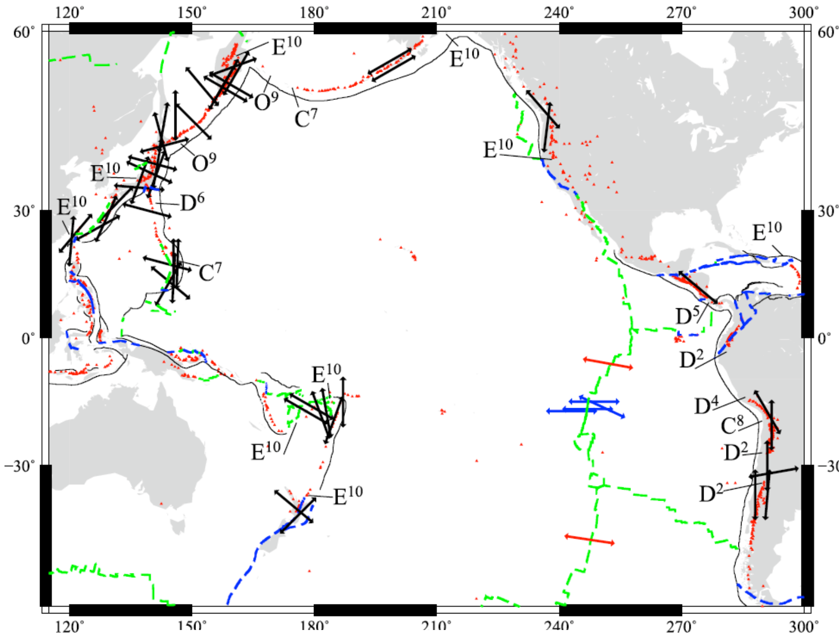
Some physical explanations of present behavior of SZs and experimental tests

- *We have seen that the absolute plates kinematics (and the subducting plate's age) controls the strain in the upper plate.*

- *What about the circulation and strain in the mantle wedge ?*

  It is commonly estimated from seismic anisotropy and is …
  « debated »



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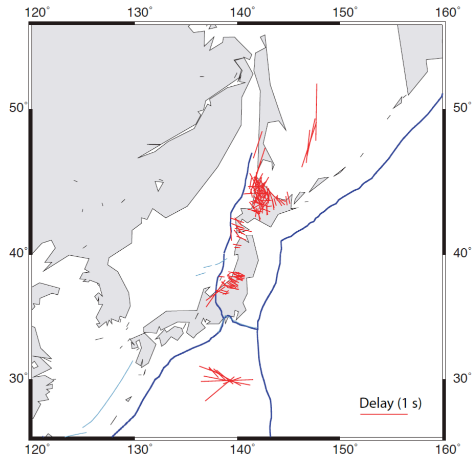

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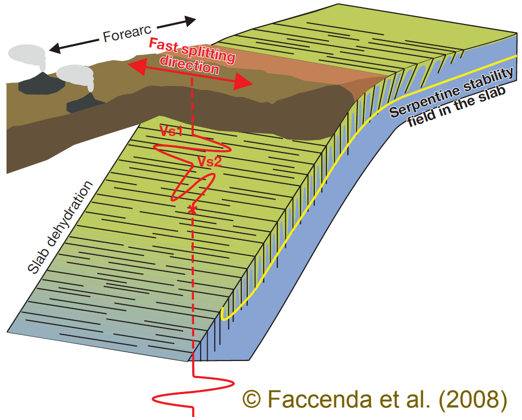

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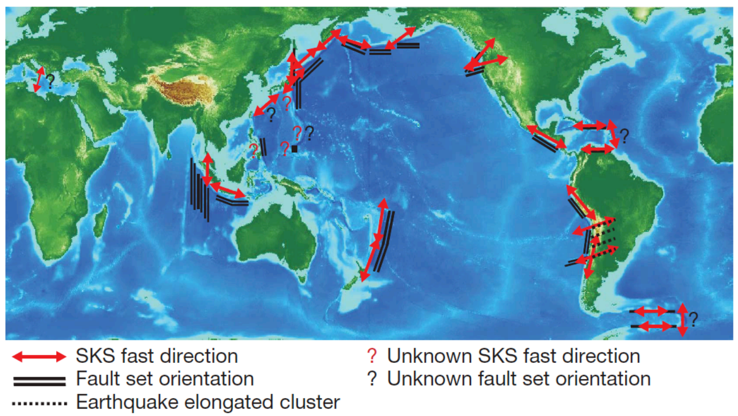
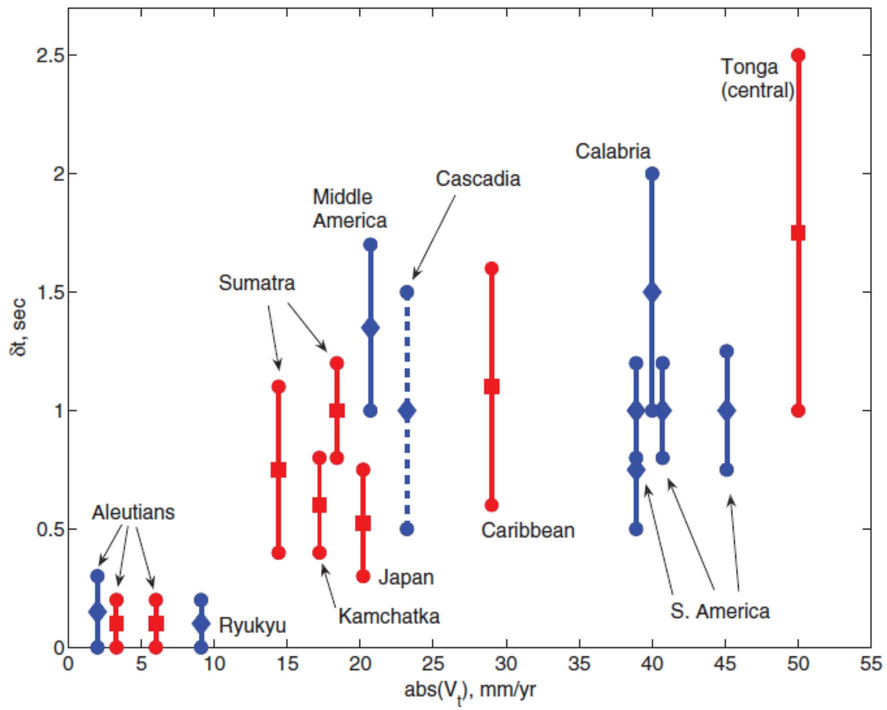
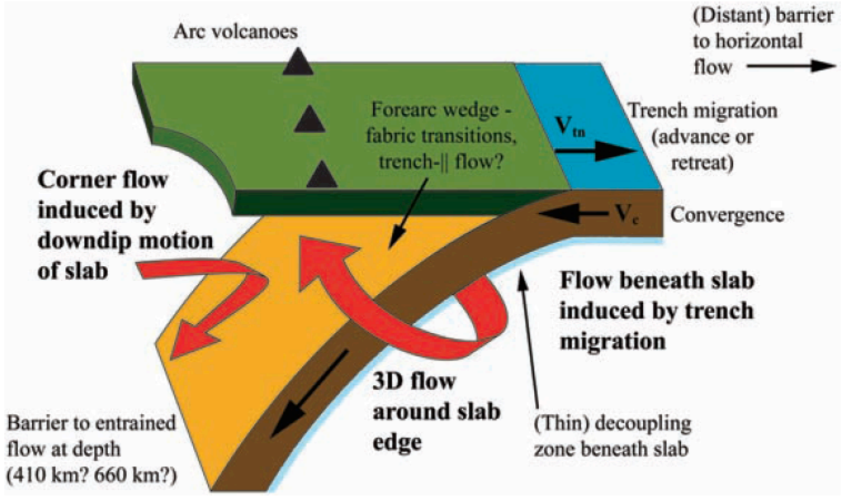


Some physical explanations of present behavior of SZs and experimental tests

- *First attempt to relate the subslab seismic anisotropy with the magnitude of the trench migration velocity*





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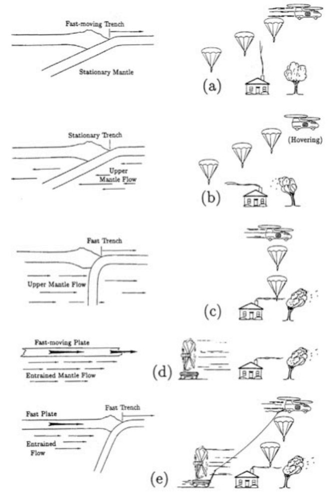
Authors explanation : mantle flow along the strike of the trench induced by the trench motion

Some physical explanations of present behavior of SZs and experimental tests

- *Observation of present-day subduction zones and laboratory experiments clearly indicate that we must account for the dynamics of the system if we want to characterize the interaction between the slab and the surrounding mantle in a subduction zone.*

- *Dynamics of the system includes :*
  - plates and trench kinematics
  - active or passive mantle
  - evolution of the deformation
  with time



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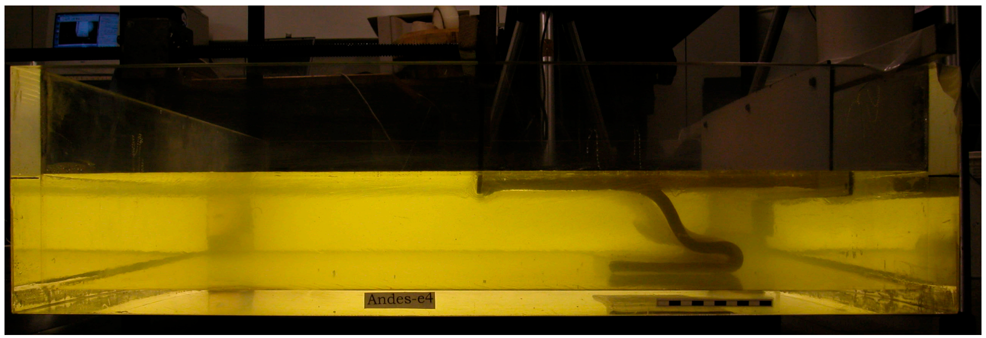

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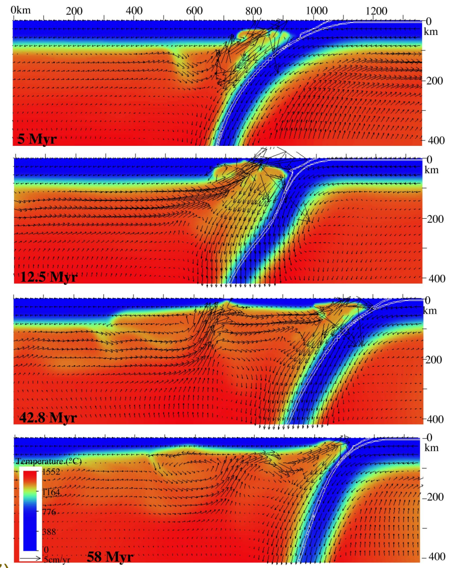

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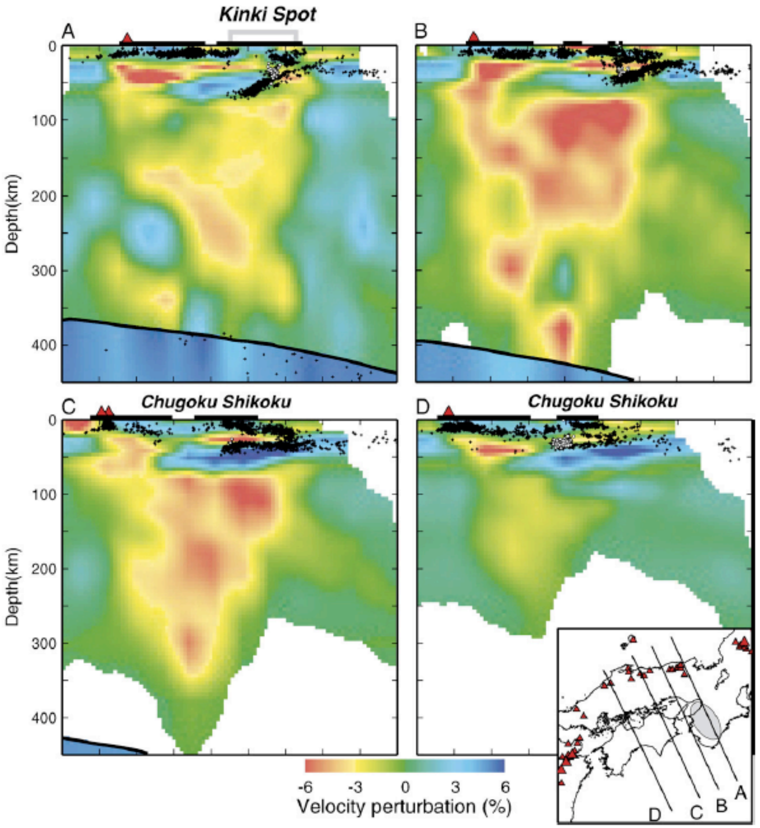
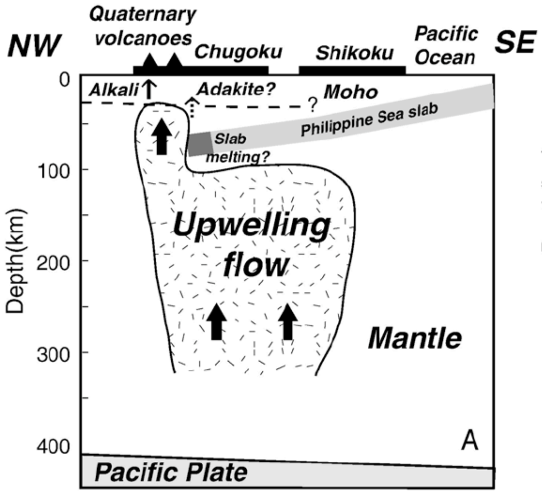
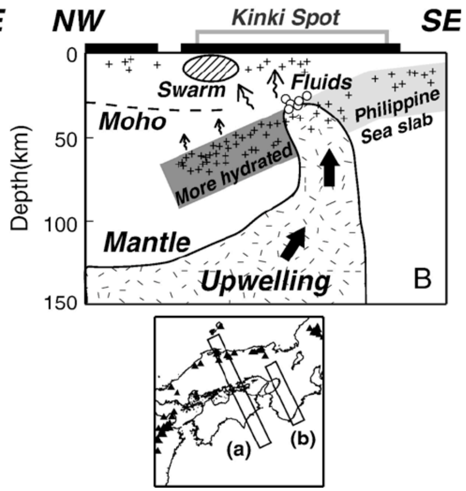
Mantle dynamics driven by subduction processes : a few examples

- *Subduction and mantle upwelling ? : cause and effect ?*







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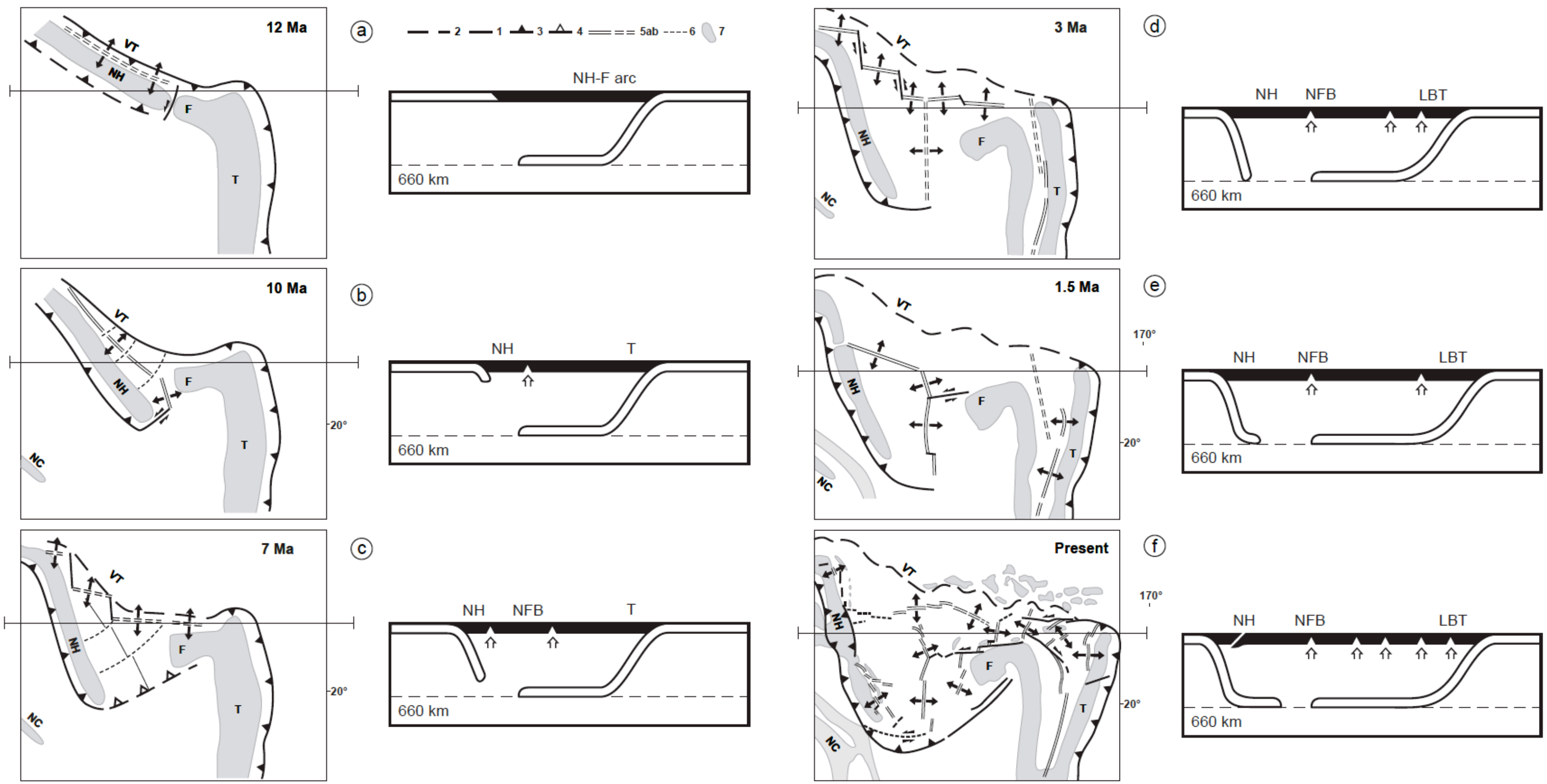
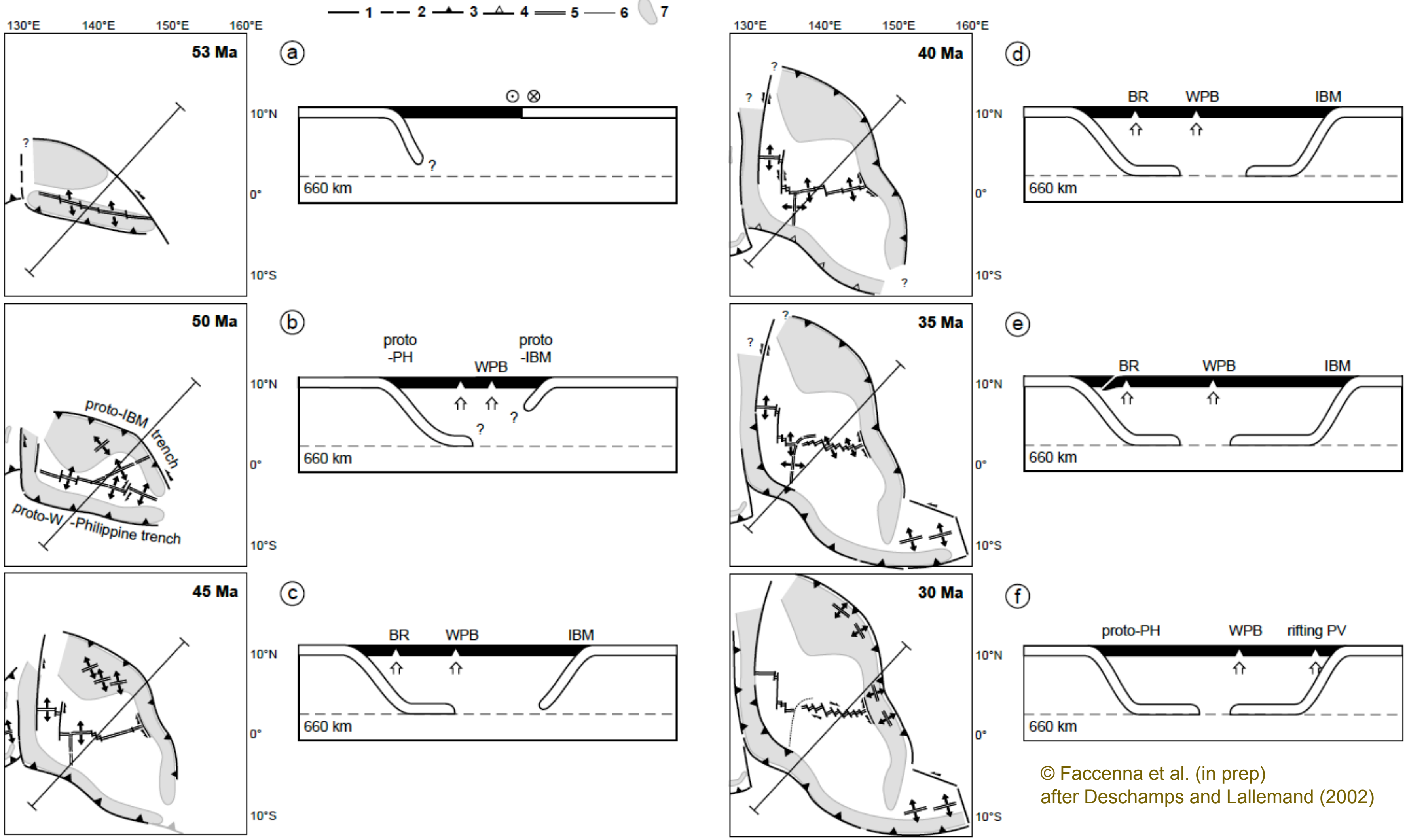
Mantle dynamics driven by subduction processes : a few examples

Evolution of the North Fidji Basin during the last 12 Ma



Mantle dynamics driven by subduction processes : a few examples

- *Evolution of the West Philippine Basin during the Eo-Oligocene time*



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after Deschamps and Lallemand (2002)

Conclusions

- Trench/slab forward/backward motion must be taken into account when describing the circulation of the mantle in a subduction zone
- Trench-parallel mantle flow can only result from a high convergence obliquity, not trench migration
- The interpretation of seismic anisotropy in the mantle wedge or subslab mantle is still speculative