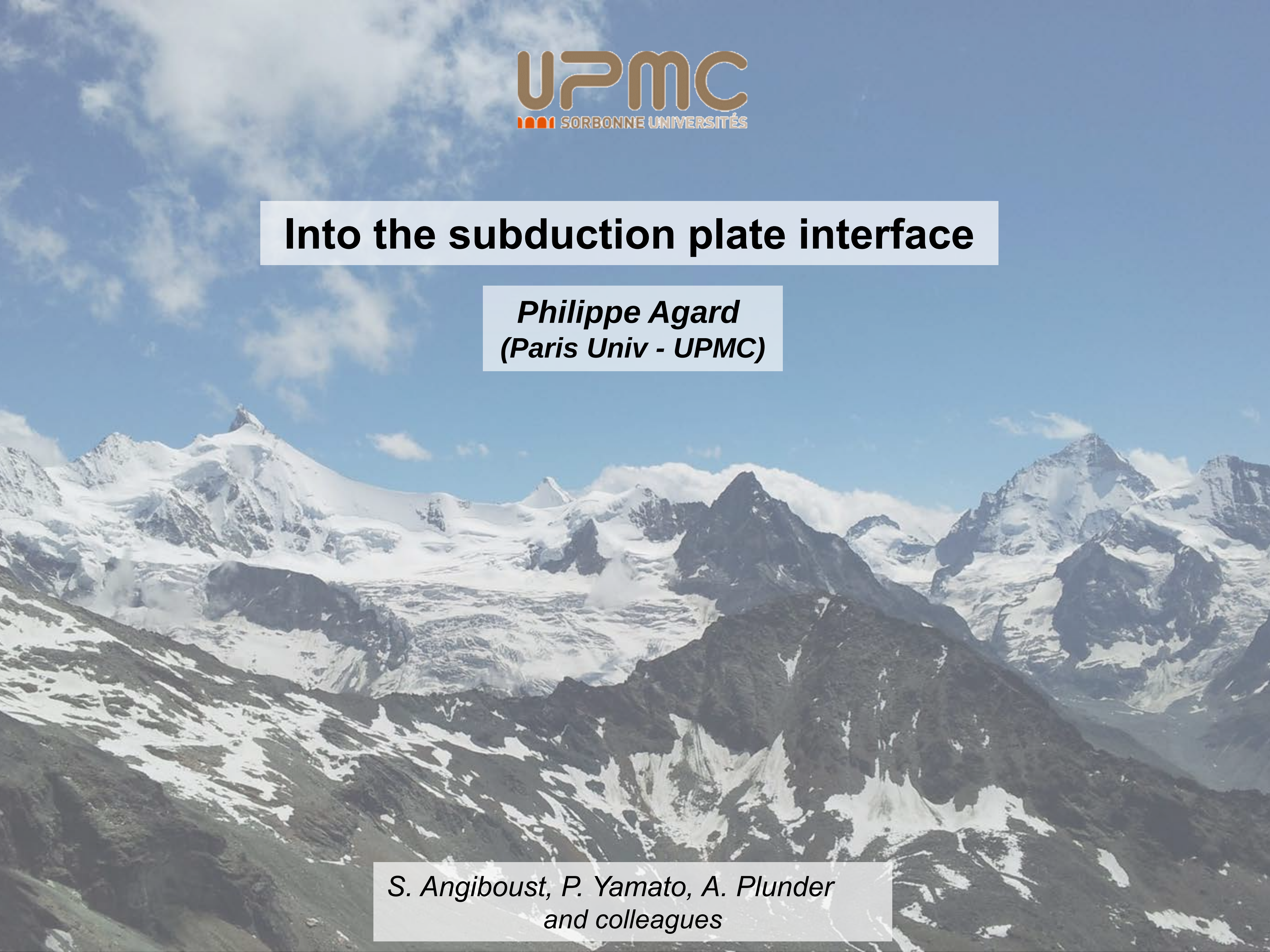


Into the subduction plate interface

Philippe Agard
(Paris Univ - UPMC)

S. Angiboust, P. Yamato, A. Plunder
and colleagues

SCOPE

0. Introduction /geochemical-physical evidence, complex fluid/deformation processes

1. Exhumation of **HP rocks: a proxy** for subduction interface behaviour

2. **What does the subduction interface look like** at ~ 80km depth?
   (structure, blocks, deformation…)

3. **ZIP: a european ITN network** / subduction plate interface (Start. Oct. 2103)

w/r ExTerra

- **What is the nature of the "subduction channel" - the interface between the downgoing subducting slab and the overlying mantle wedge (4.2)?**

- **What happens at the 80 km depth coupling boundary (4.2)?**

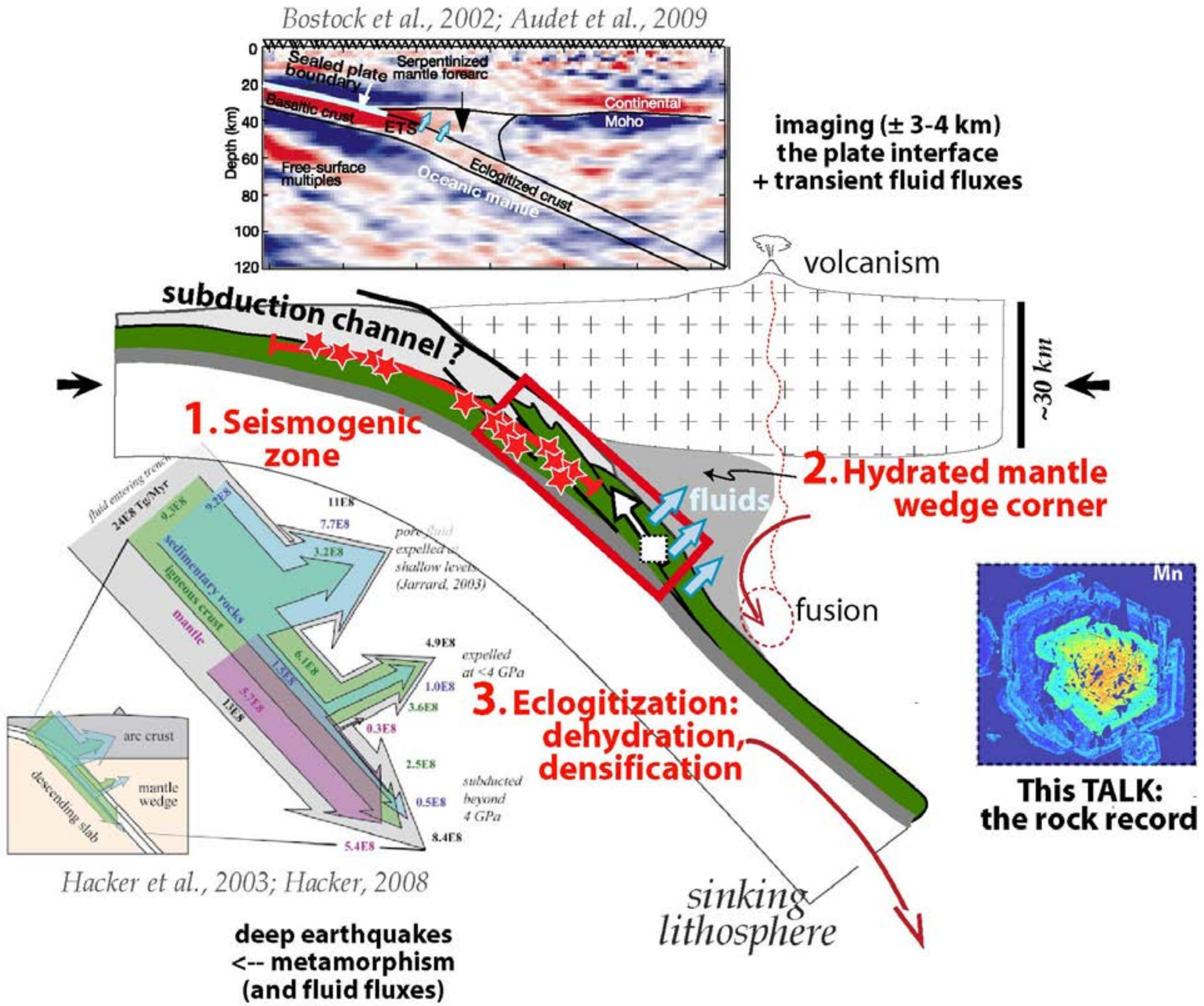
- *What is the detailed thermal evolution of the slab (4.2, 4.4)?*

- *What are the pathways, fluxes and timescales of fluid release in the slab (4.4)?*

- What is the composition of slab-derived fluids (4.4)?

- Can metamorphic reactions "keep up" with changing conditions in the slab? What are the reaction and diffusion rates at relevant conditions (4.4)?

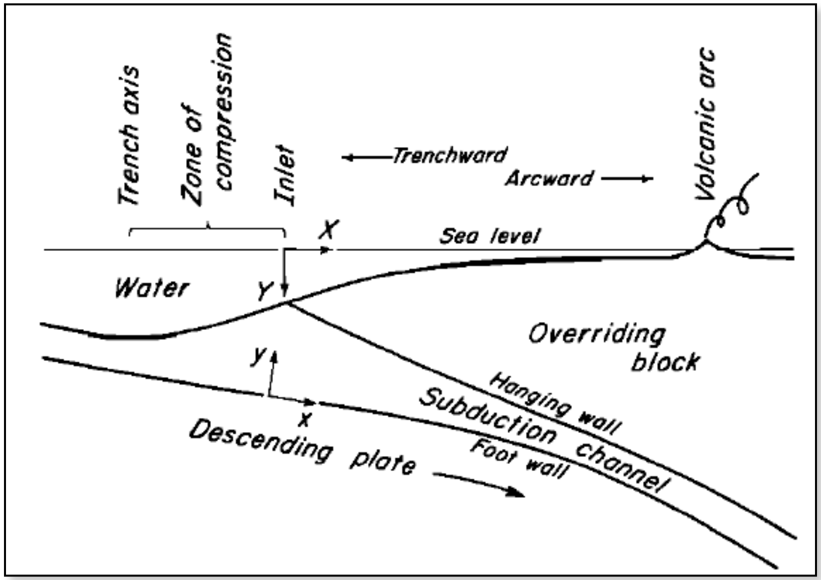
Today's picture:



A number of key processes outlined…

but mysterious feedbacks and interdisciplinarity to be improved

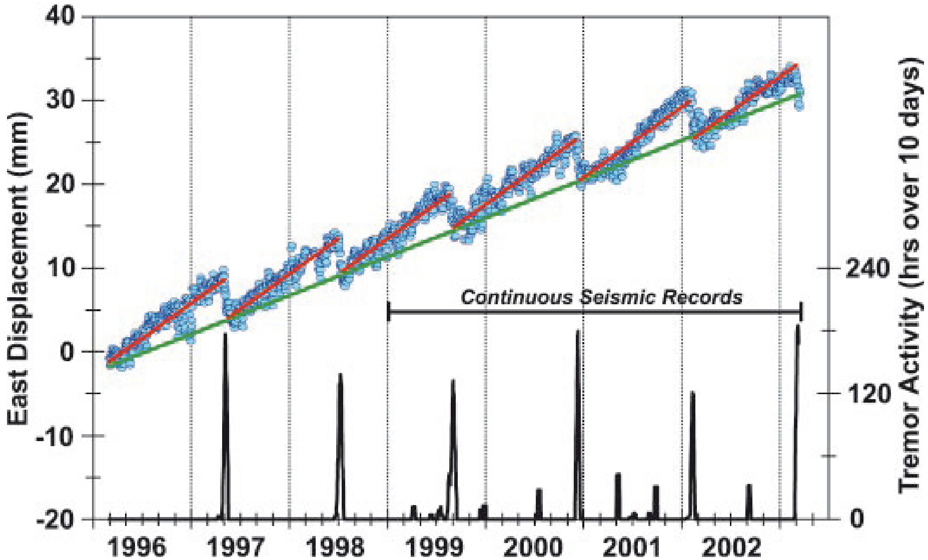
Time to move on, from the 'subduction channel'… to the plate interface



From the inspiring subduction channel…

Shreeve & Cloos, JGR 1986 (England & Holland, 1979)

Cloos 1982, 1985,1993,…



… to processes such as Episodic Tremor and Slip (ETS)

Rogers & Dragert, 2003

From Wadati-Benioff, Uyeda-Kanamori

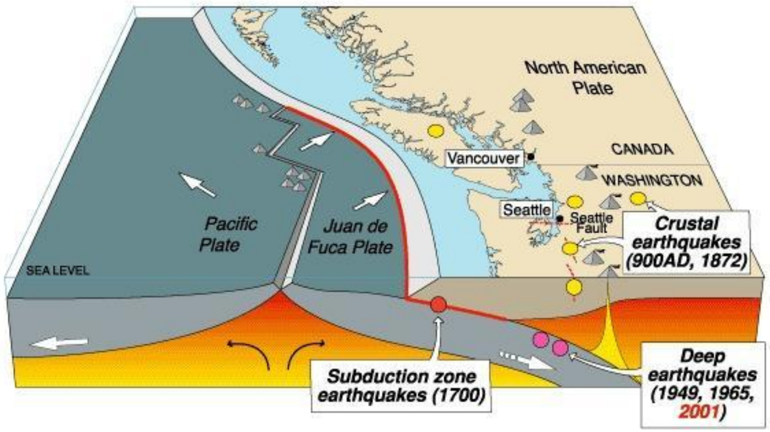
to corner flow, seamount subduction,…

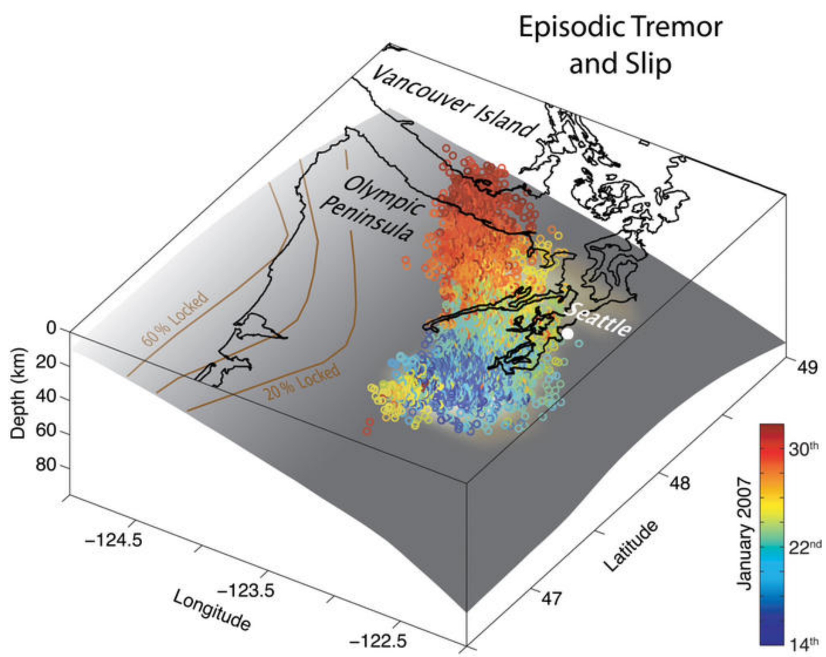
… to slip, metamorphic dehydration, mass/fluid transfer, weakening…

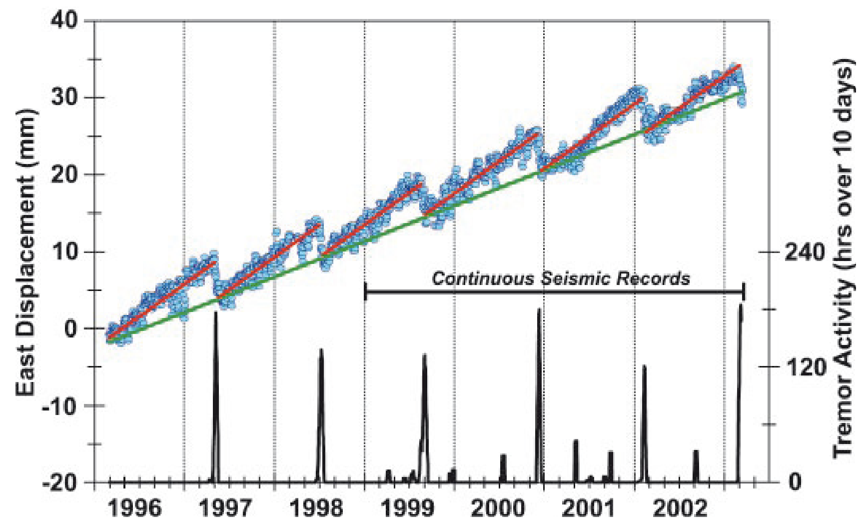
(the subduction channel is too 'loose' now…)

New phenomena! ETS etc …

Cascadia earthquake sources

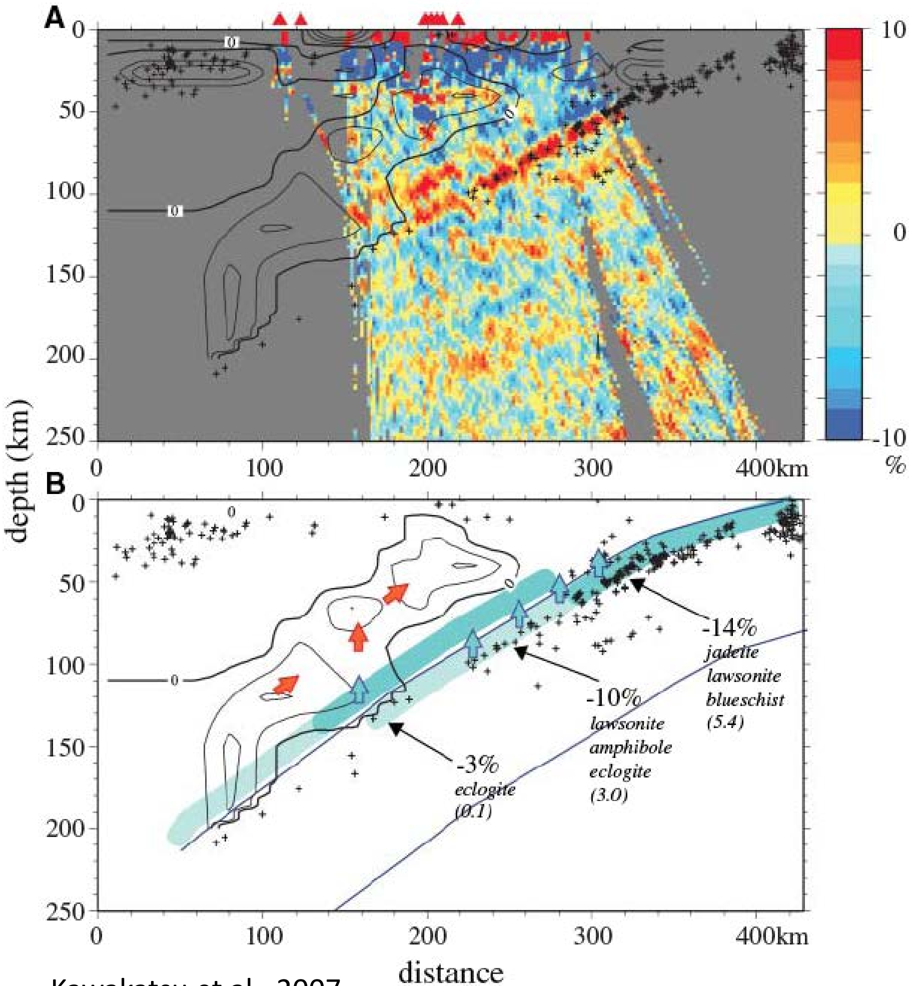




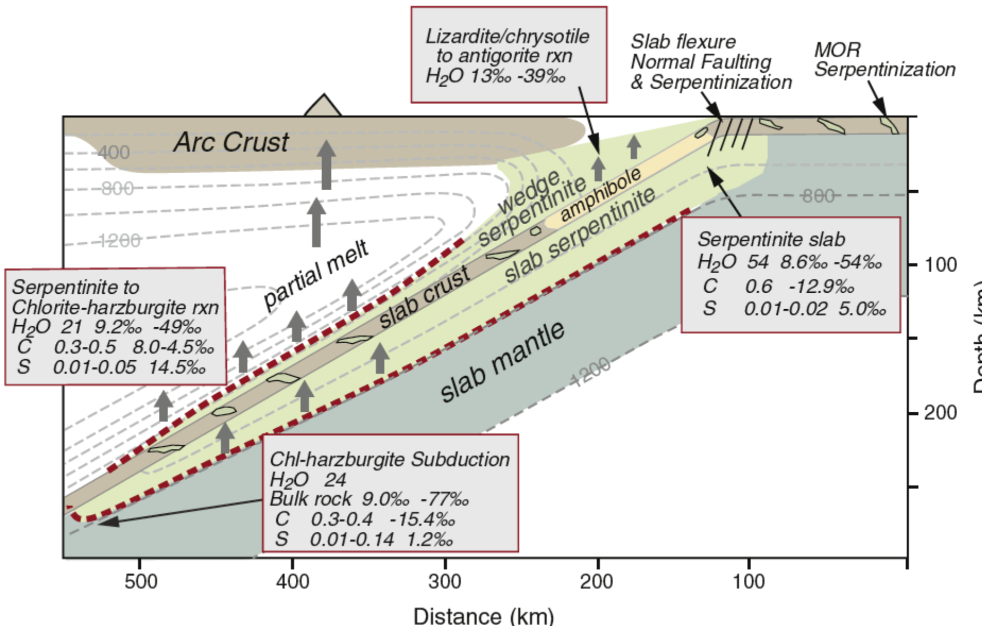


Fluid percolation at 30-40 km?

Improved resolution!



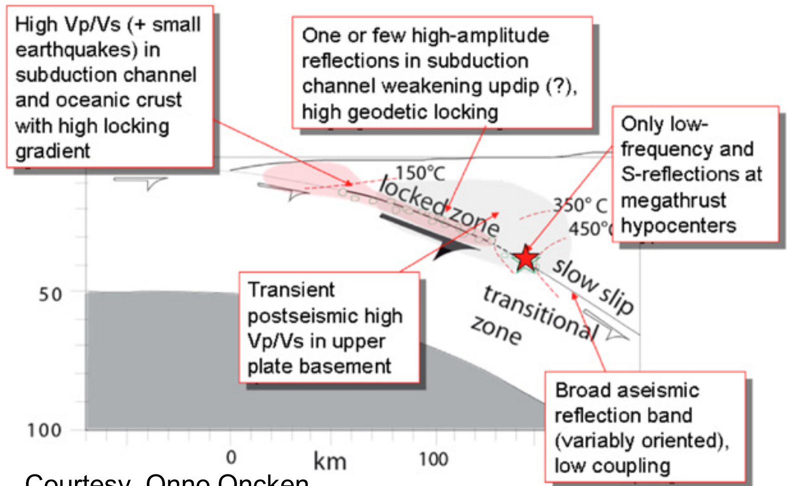
Kawakatsu et al., 2007



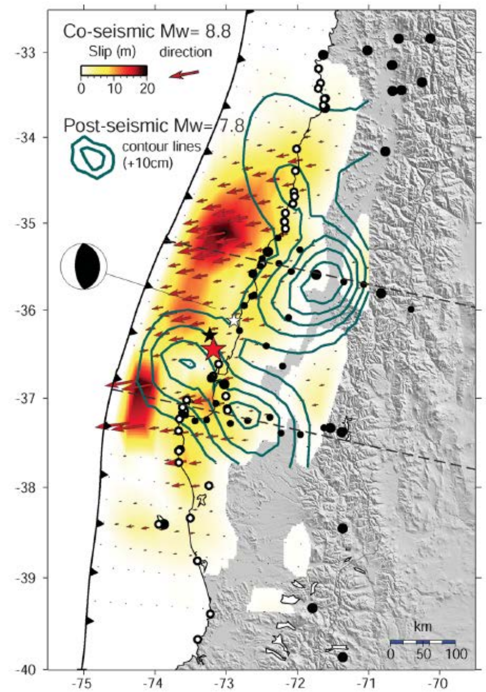
Alt et al., 2012

Vp/Vs ratios, Q attenuation, geochem. tracers, modelling…

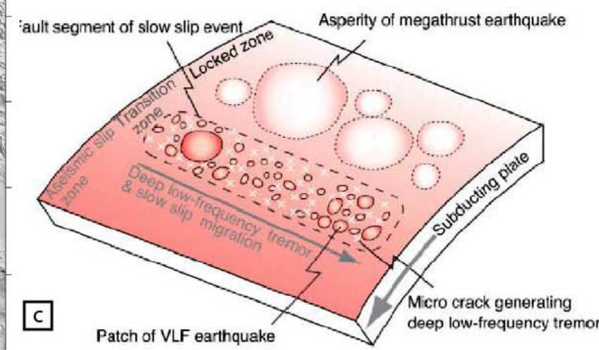
Mechanical coupling!



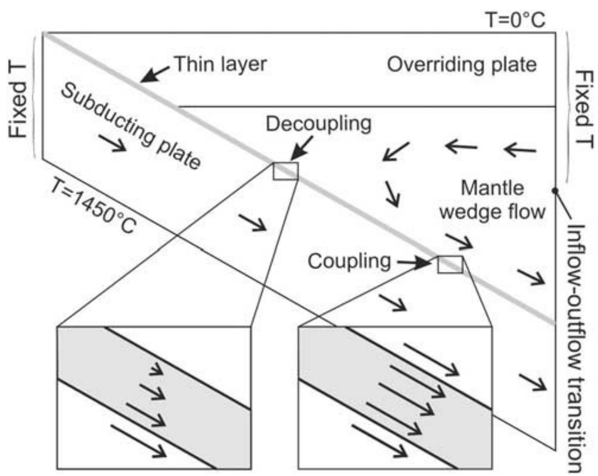
Courtesy Onno Oncken



Vigny et al., 2011



Ito et al., 2007



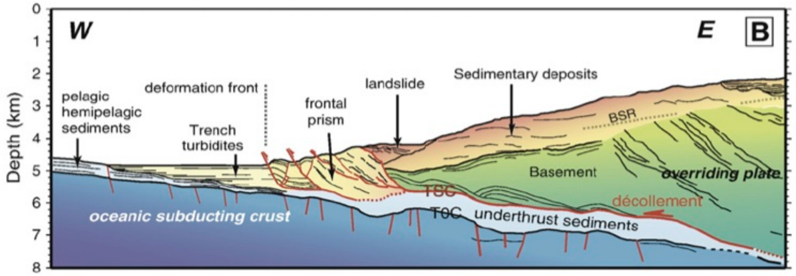
Wada et al., 2008

Many large devastating EQ (over the past decade) yet:

- **Nature of the subduction interface = ?**
- **Long-term v. short-term processes = ?**

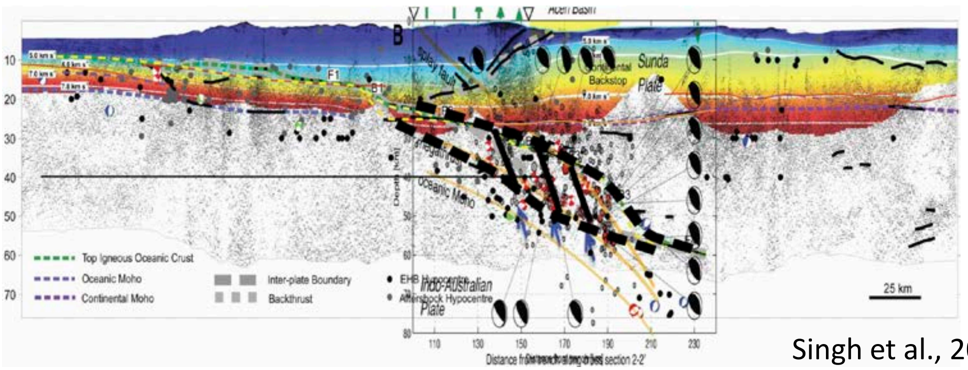
Into the plate interface?

Peru : 10 first km

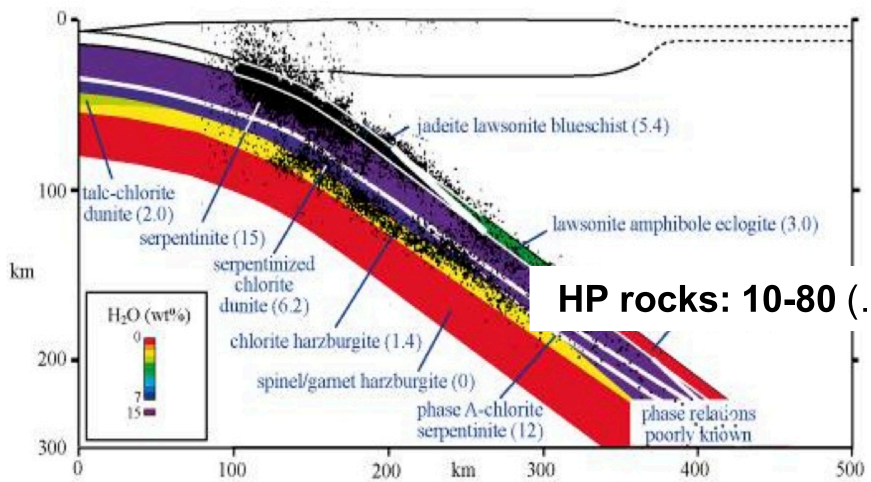


Calahorano et al., 2008

Sumatra : 30 first km?



Singh et al., 2008



HP rocks: 10-80 (…400) **first km**

Hacker et al., 2003

FOCUS POINTS:

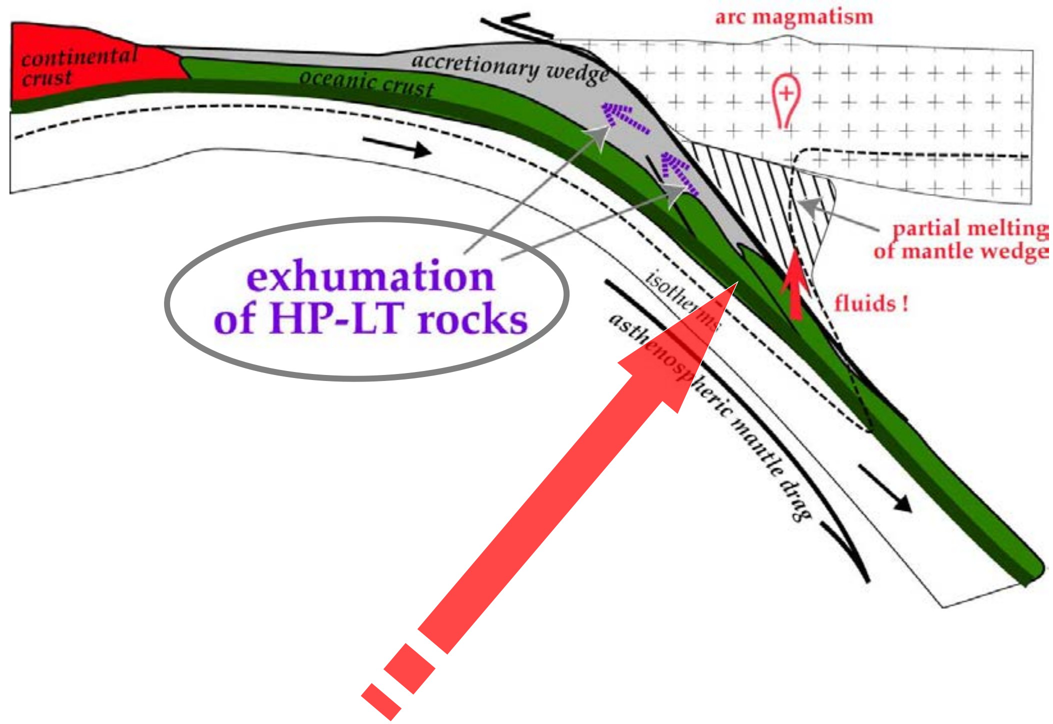
1 — Where do rocks return from? How much underplating, slicing, return flow?...

2 — What is the plate interface looking like? (+ 3: ZIP)

What goes in?…

2 **Continental crust**
down to… 350-400 km !?

1 **Sediments**
paleoaccretionary complexes

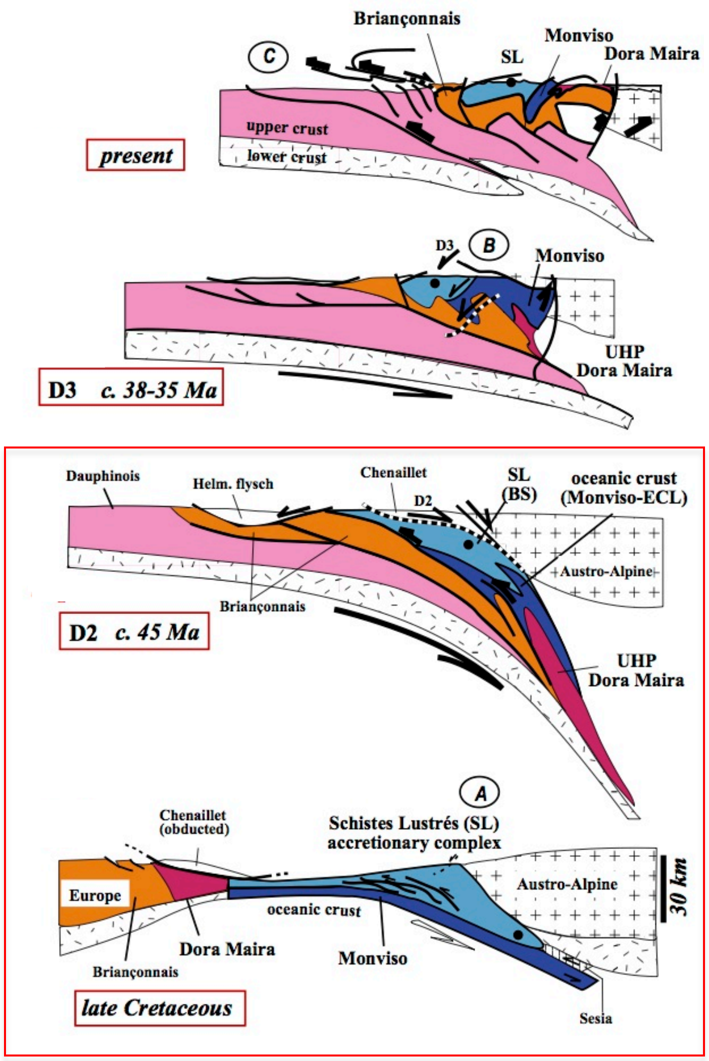


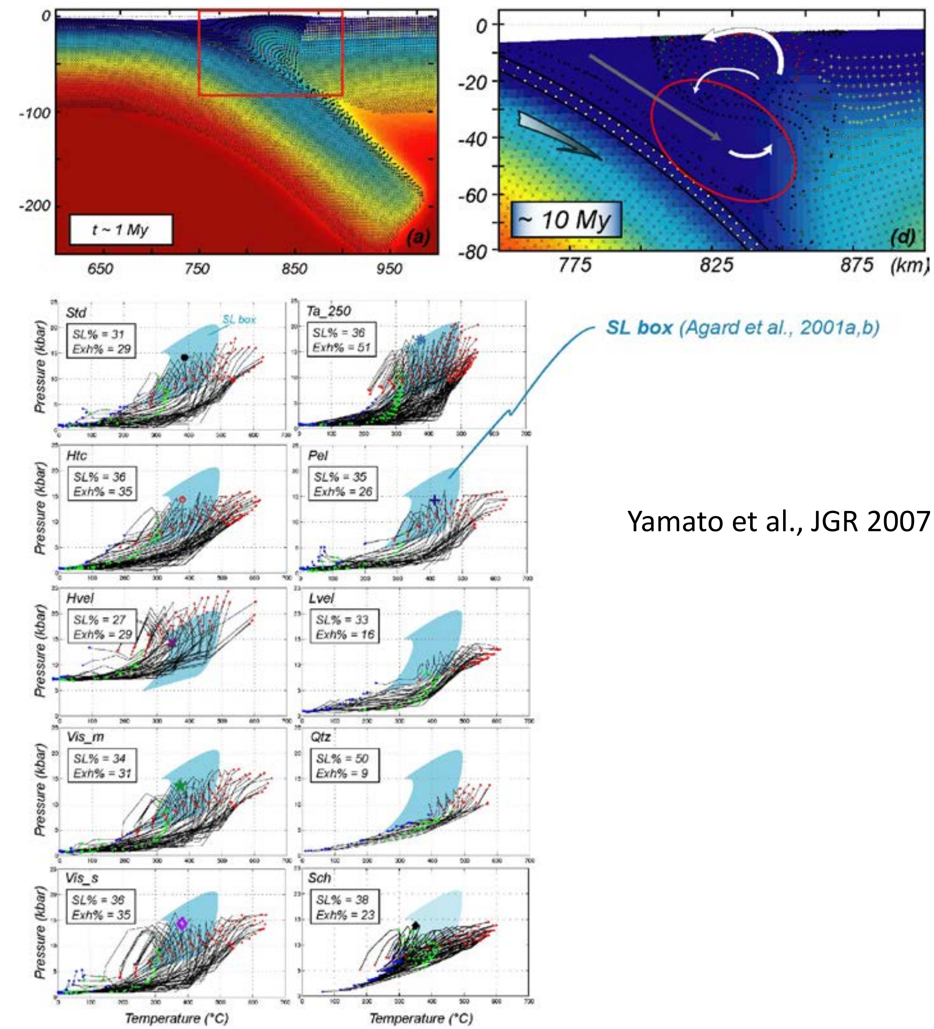
3
Fate of oceanic lithosphere?

doomed to disappear… yet pieces exhumed!

=> PROXY / SUBD. MECHANICS!

Sediments (1): accretionary wedges [15-50 km]



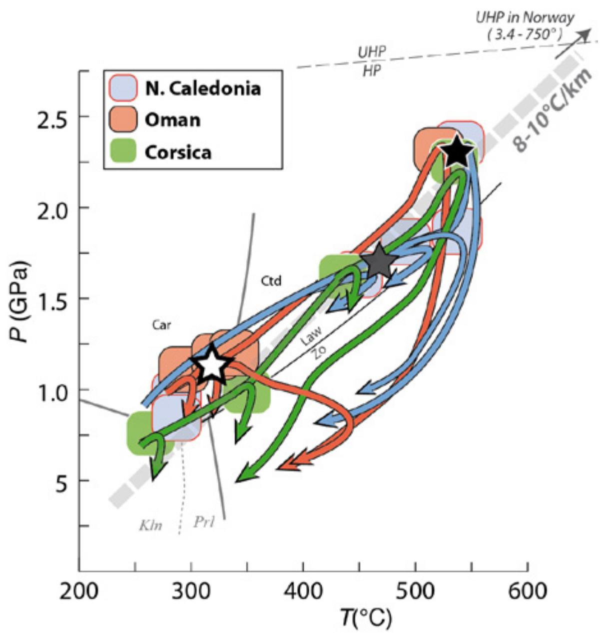


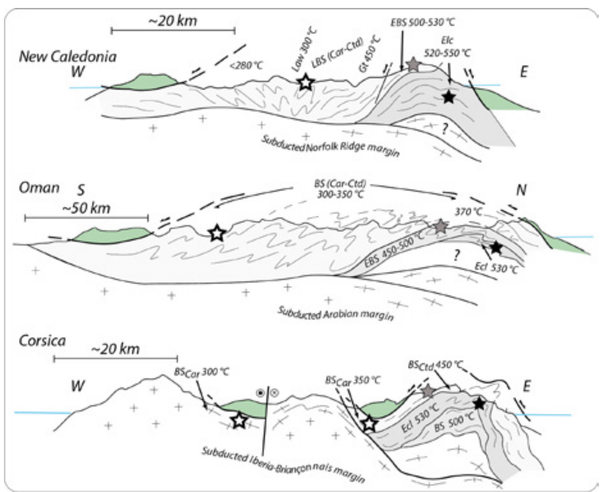
Yamato et al., JGR 2007

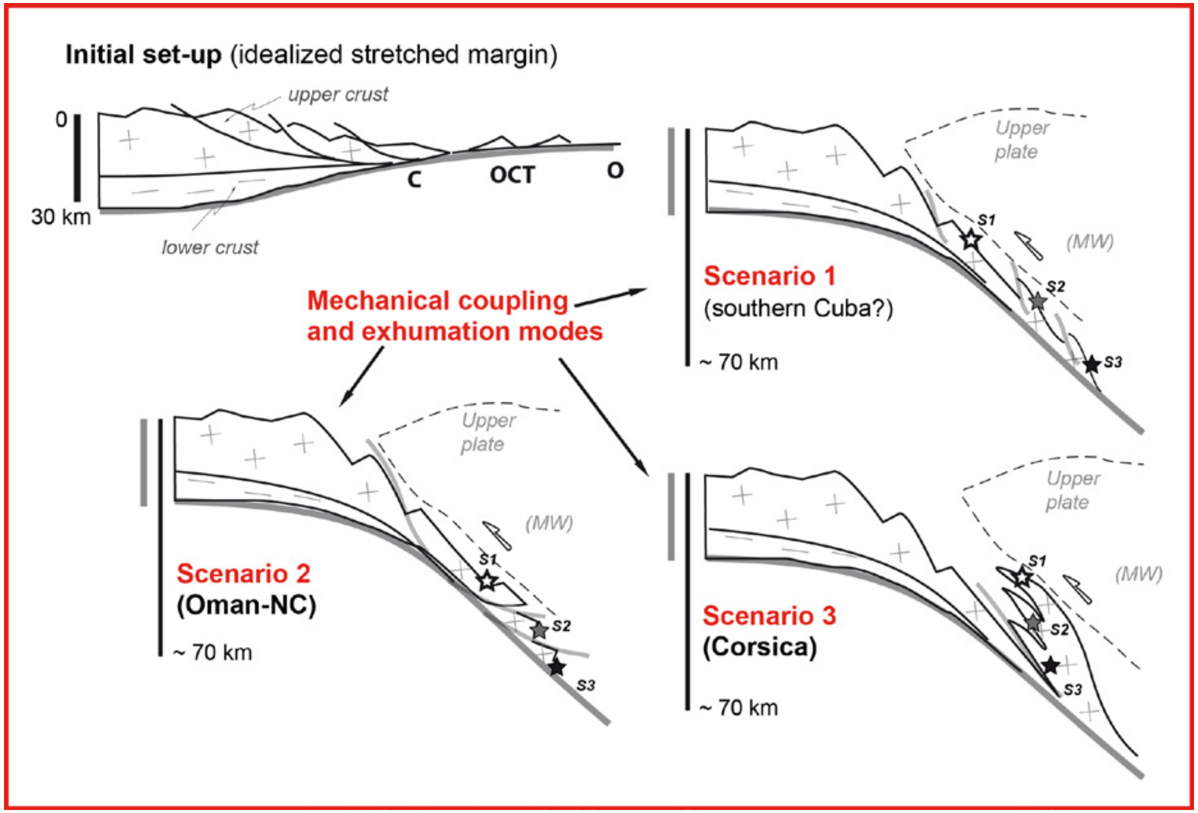
Agard et al., JMG 2002, ESR 2009
Plunder et al., JMG 2012 Bebout, Agard et al., 2013

=> underplating processes (exhum. vel. ~ 1-2 mm/yr), **fluids**

Continental cover (2): Oman/NewCaledonia/Corsica — no collision! **[15-70 km]**





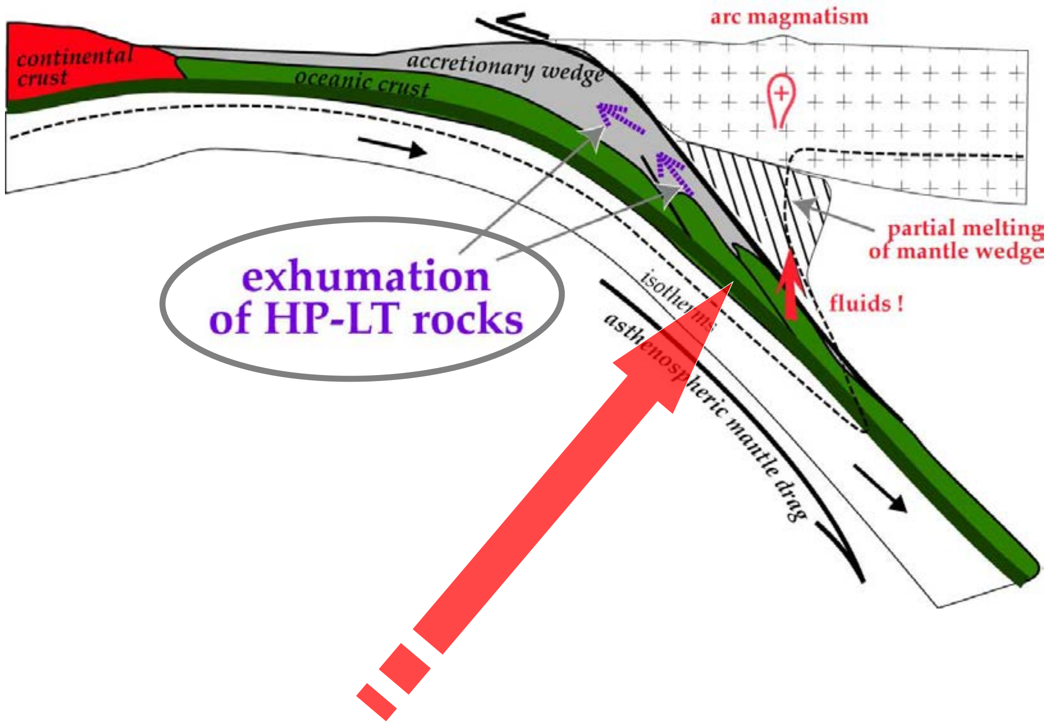


⇒ **buffered thermal regime**

⇒ **modes of mechanical coupling**

Agard & Vitale-Brovarone, Tectonophysics 2013

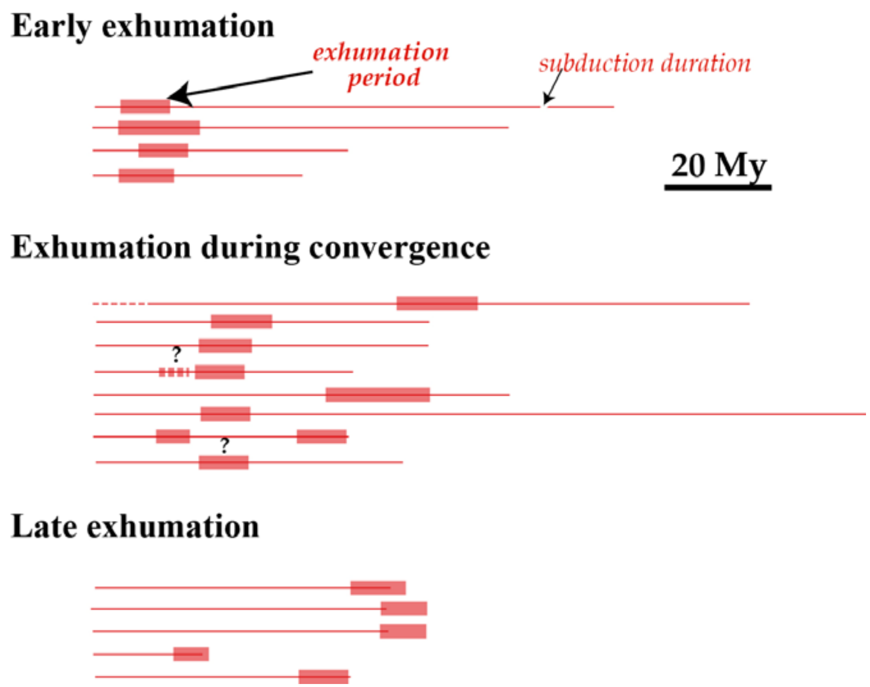
What goes in?…



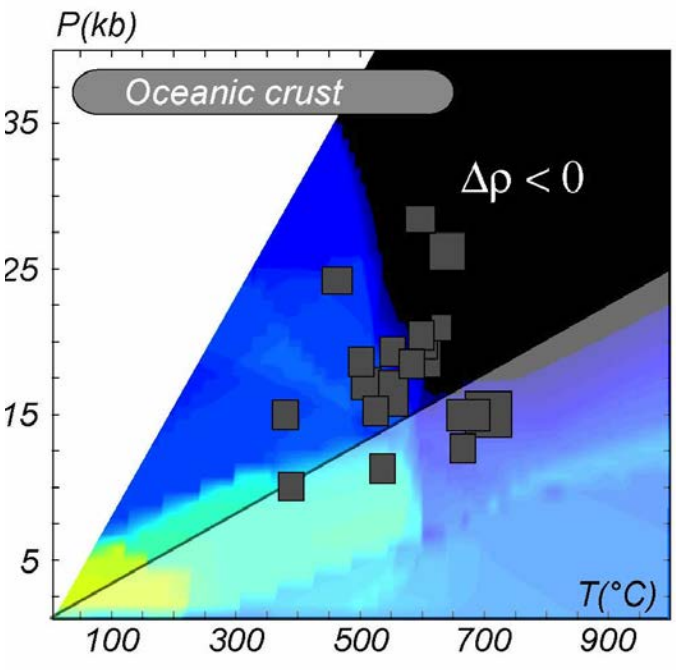
3

Oceanic lithosphere

Exhumation of oceanic lithosphere worldwide (3) [20-80+… km]



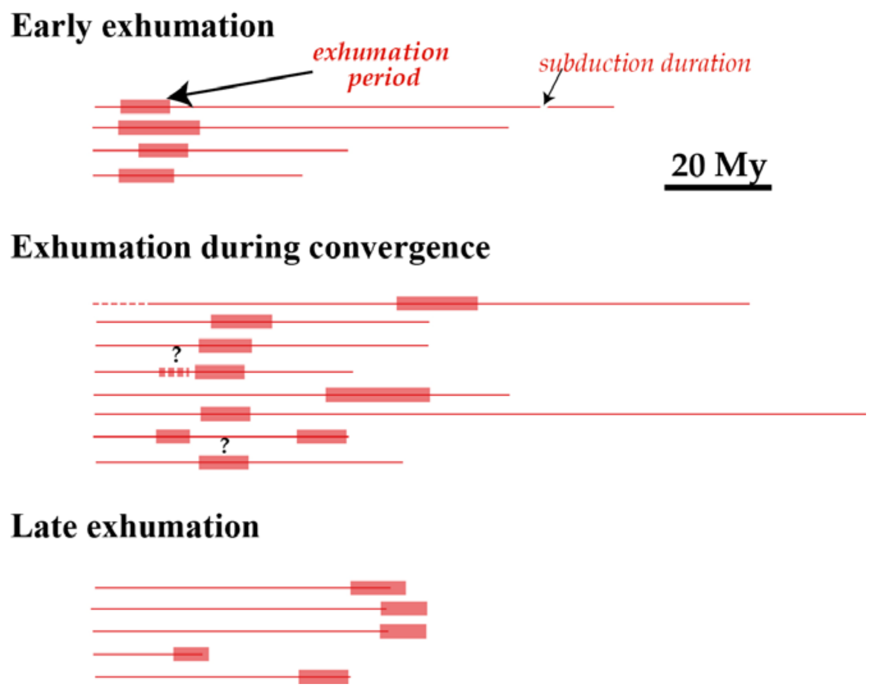
=> exhumation is transient!

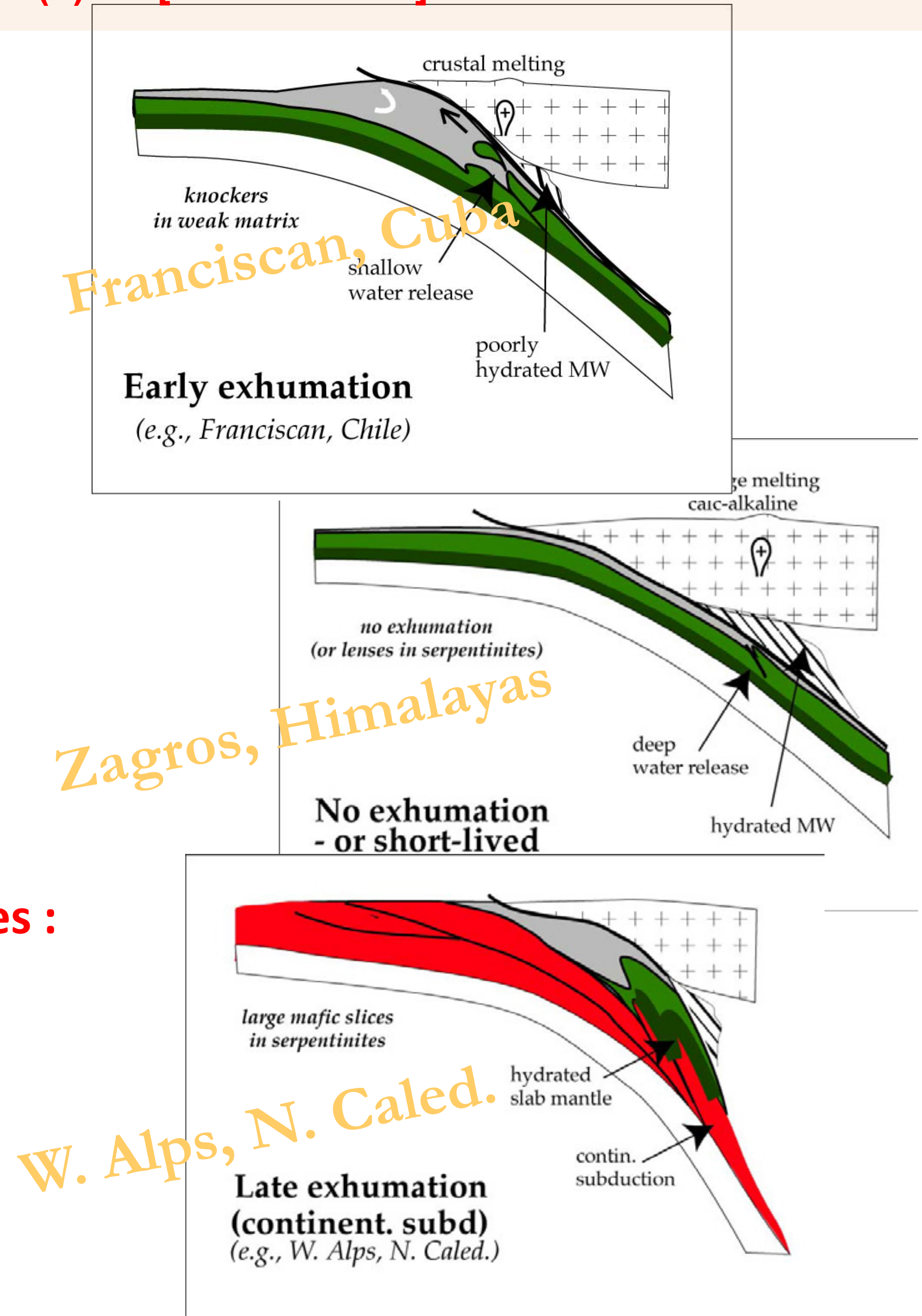


=> max. depths of exhumed eclogites: ~ 80 km

Agard et al., Earth Sci. Reviews 2009

Exhumation of oceanic lithosphere worldwide (3) [20-80+… km]



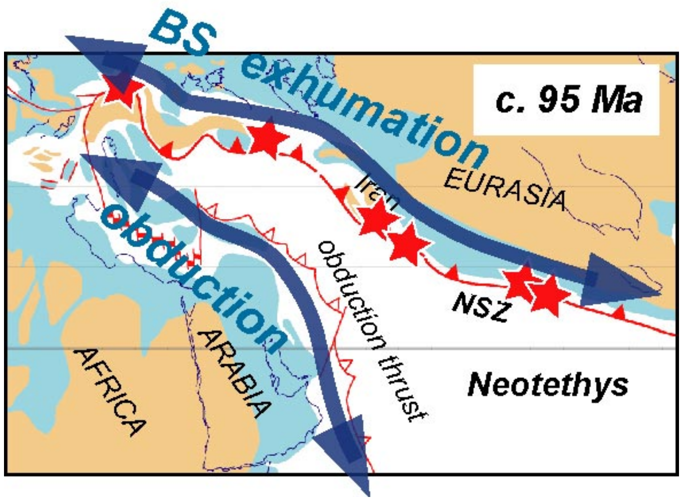


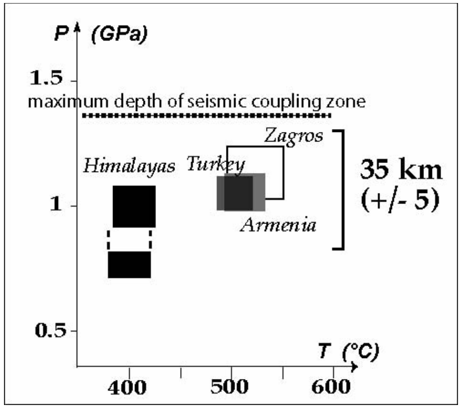
=> 3 end-members modes :

Agard et al., Earth Sci. Reviews 2009

Neotethyan HP rocks = good proxies for mechanical coupling!

Monié & Agard, G-cubed 2009

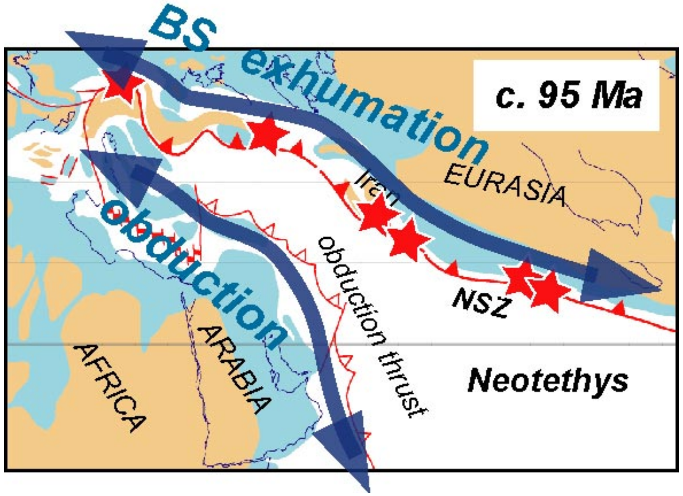


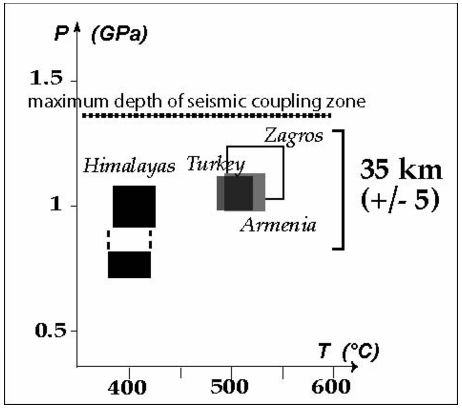


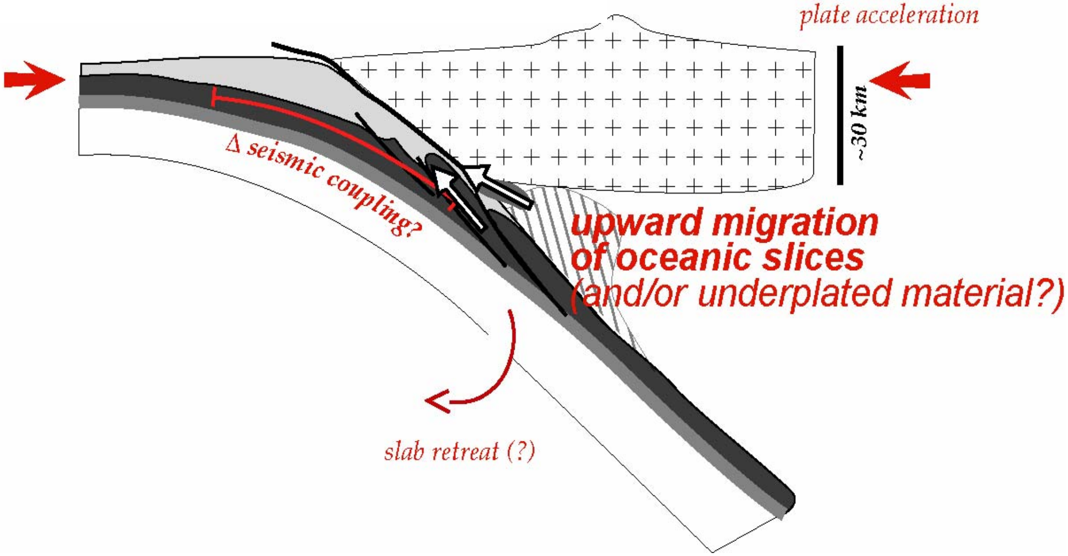
=> regional-scale exhum. pulse from down-dip of the seismogenic zone!

Neotethyan HP rocks = good proxies for mechanical coupling!

Monié & Agard, G-cubed 2009





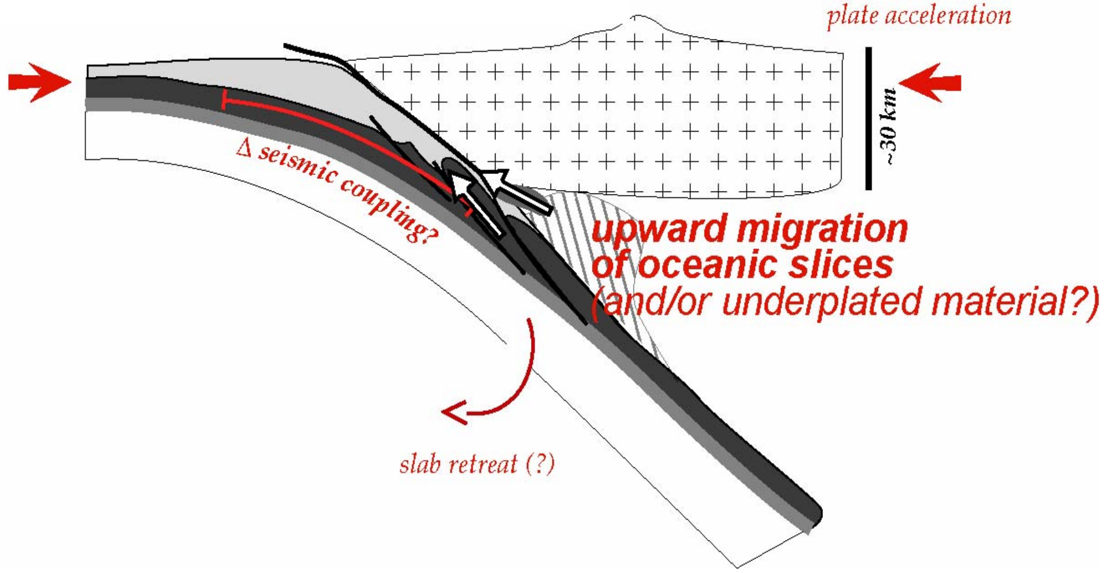


⇒ **Geodyn. (coupling) changes are exhumation triggers!**

⇒ A biased sampling?...

Plate interface: long-term mechanical behavior

1. *Exhumation is* ***the EXCEPTION rather than the rule***
2. *Exhumation is* ***short-lived***
3. *Exhumation is* ***most probably triggered by geodynamic pulses/events/drama***



Q? Underplating sediments: discontinuous process… or is only exhumation discontinuous?

SCOPE

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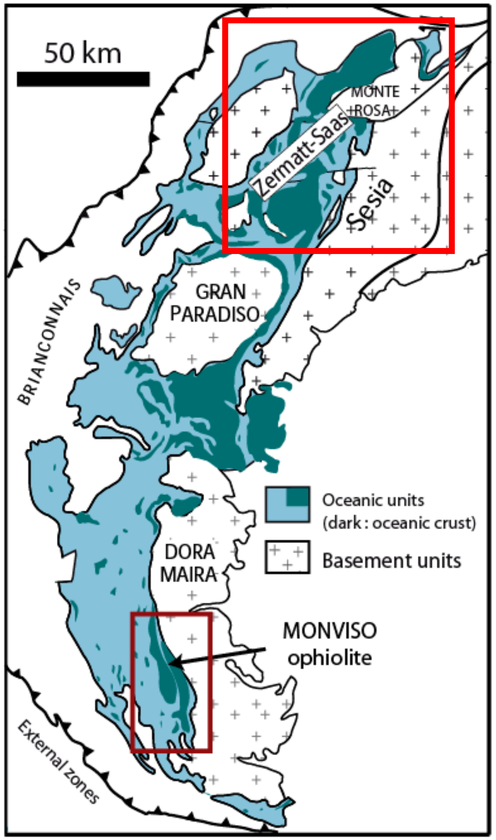
1. Exhumation of HP rocks: a proxy for subduction interface behaviour

2. **What does the subduction interface look like at ~ 80km depth?**

3. ZIP: a european ITN network / subduction plate interface (Start. Oct. 2103)

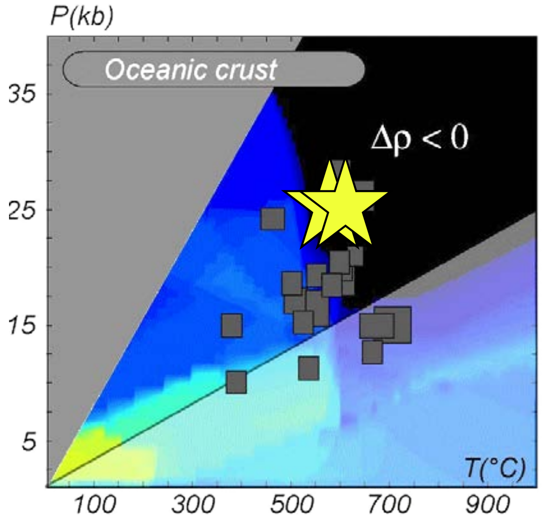
Into the Alpine subducted slab — 60-80 km depths

Structure…



Lawsonite pseudomorphs!

Eclogitized pillows

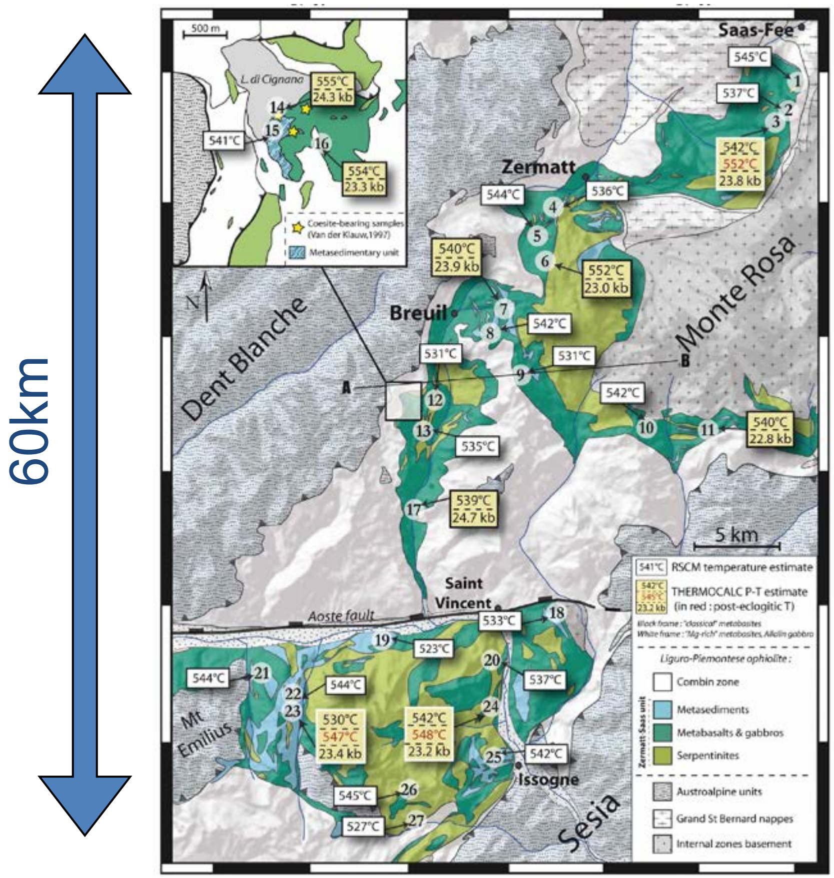


Peak P-T conditions

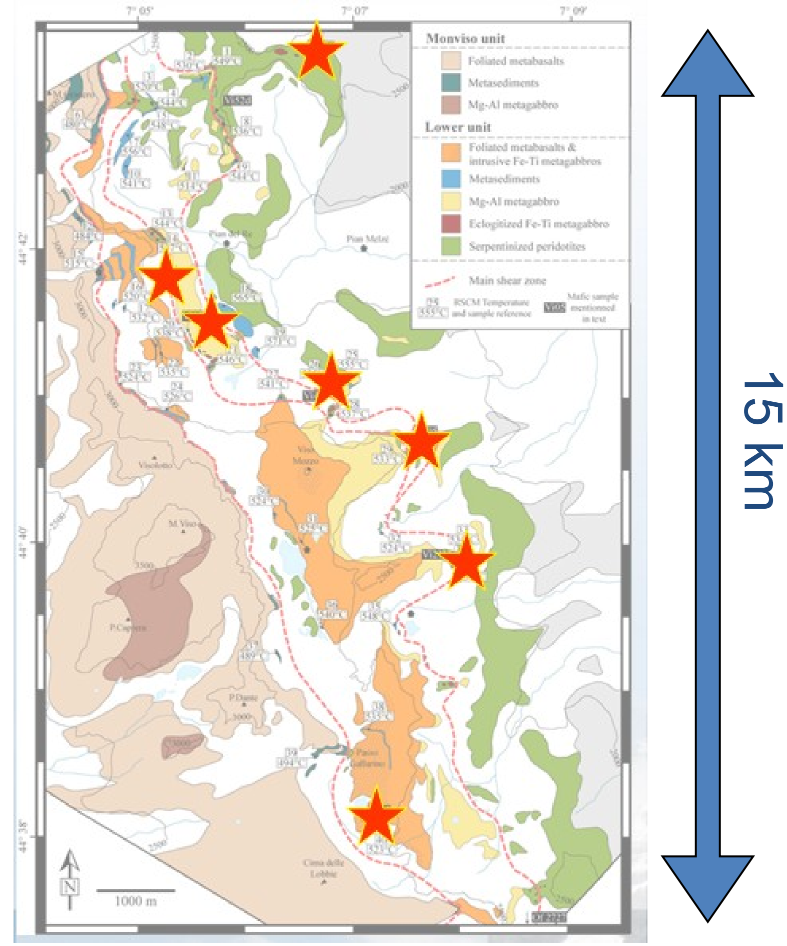
Zermatt-Saas + Monviso: the deepest oceanic pieces on Earth!

Into the Alpine subducted slab — 60-80 km depths

1. *Homogeneity of peak P-T conditions* ***(550° C, 2.5 GPa)***



Zermatt-Saas: Angiboust et al., *Terra Nova, 2009*

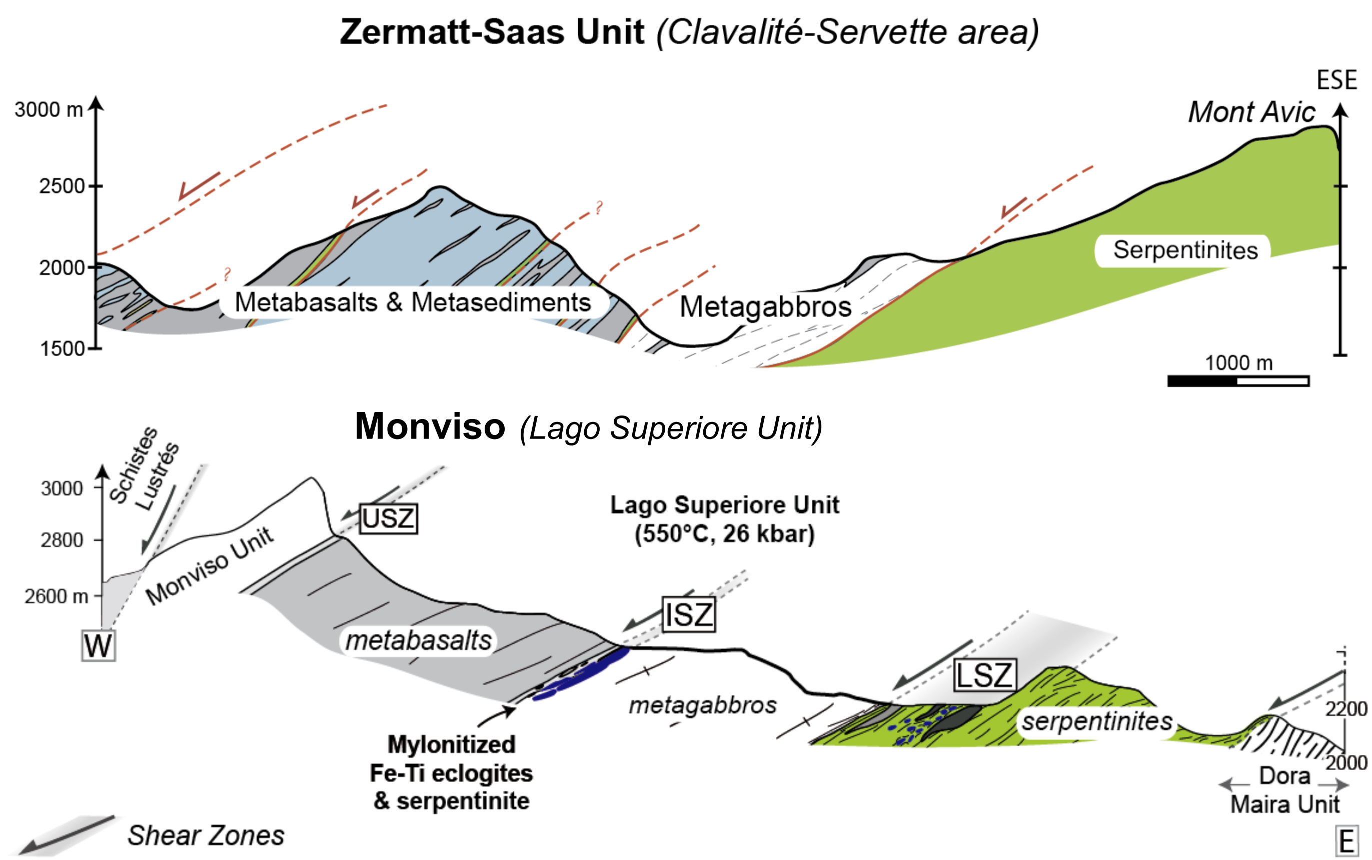


Monviso: Angiboust et al., *JMG, 2012*

→ Large tectonic slices exhumed relatively coherently from *ca*. 80 km depth
(thanks to subduction of buoyant continent beneath)

Into the Alpine subducted slab — 60-80 km depths

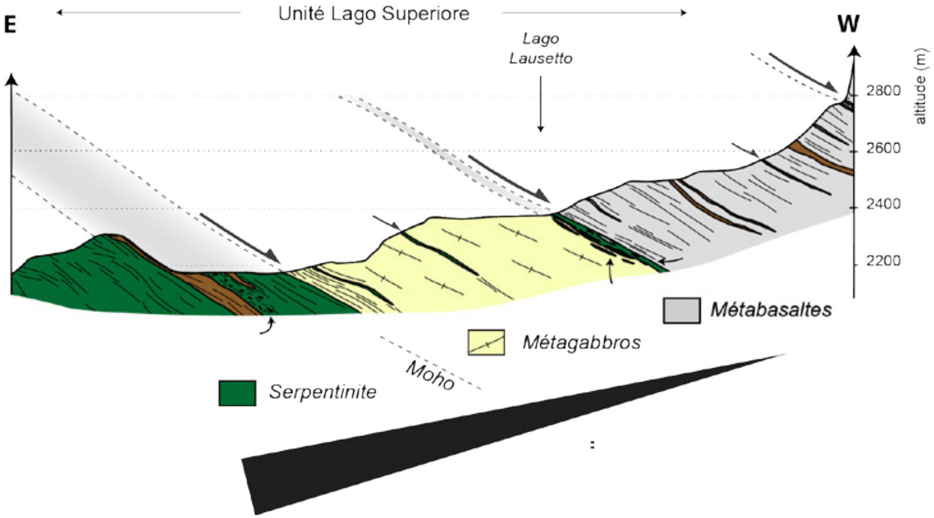
2. *Homogeneity in composition and first-order tectonic architecture*

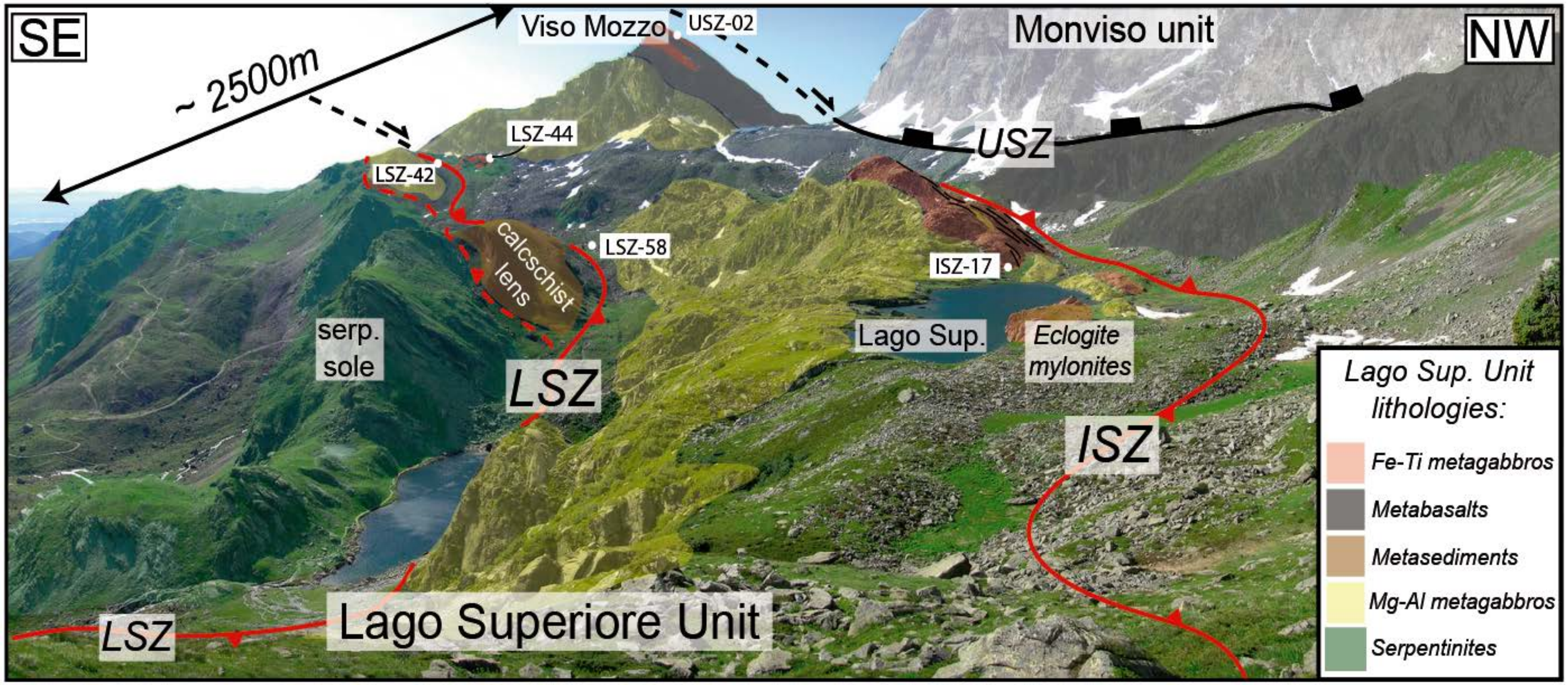


→ Good preservation of the seafloor structure in both ophiolitic massifs

Angiboust & Agard, *Lithos, 2010*

A recent discovery: eclogite breccia (Monviso)





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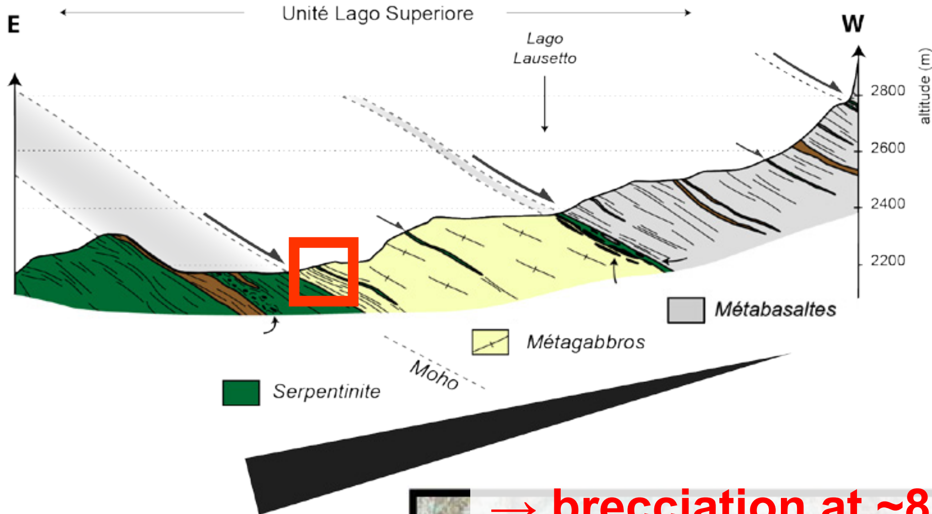
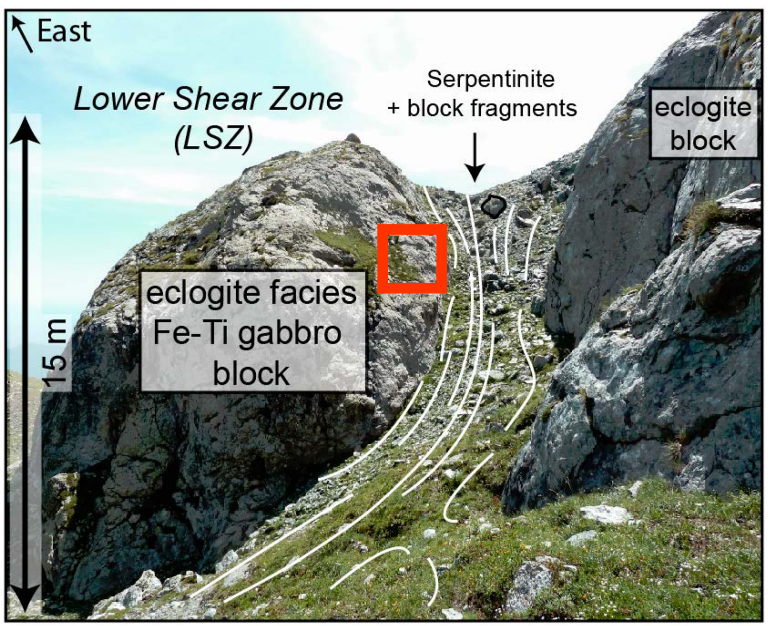
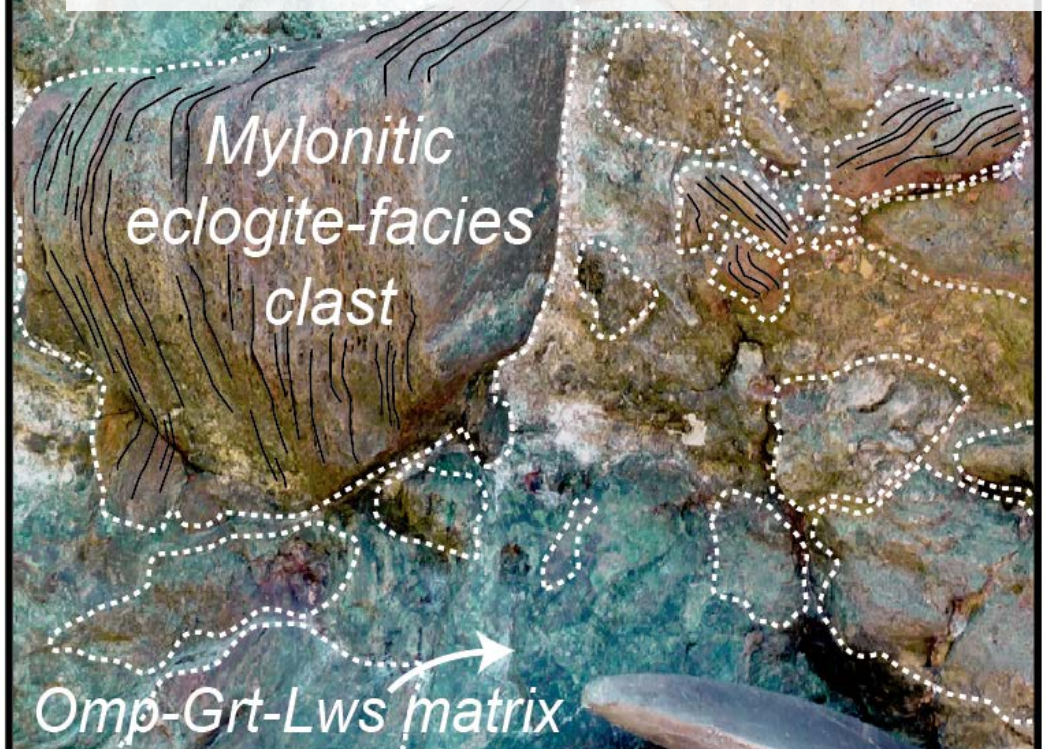




→ brecciation at ~80 km, fluid ingression



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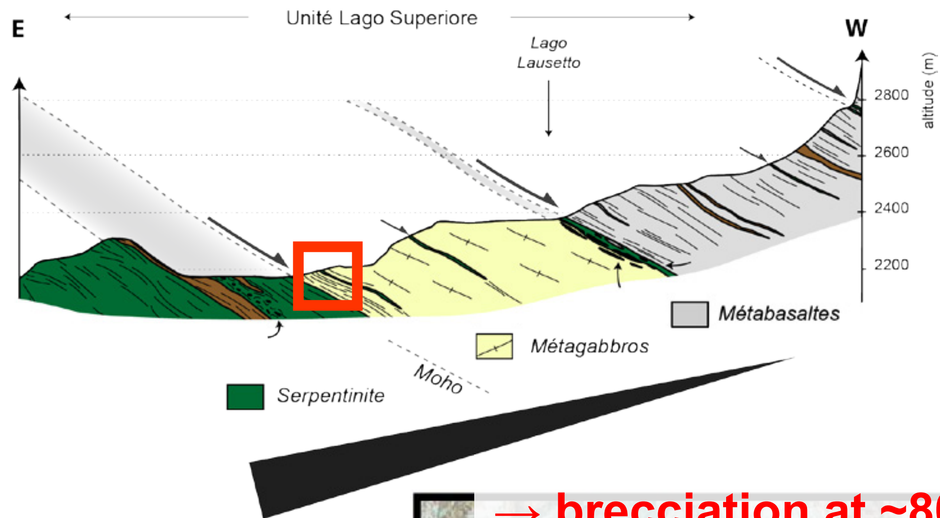

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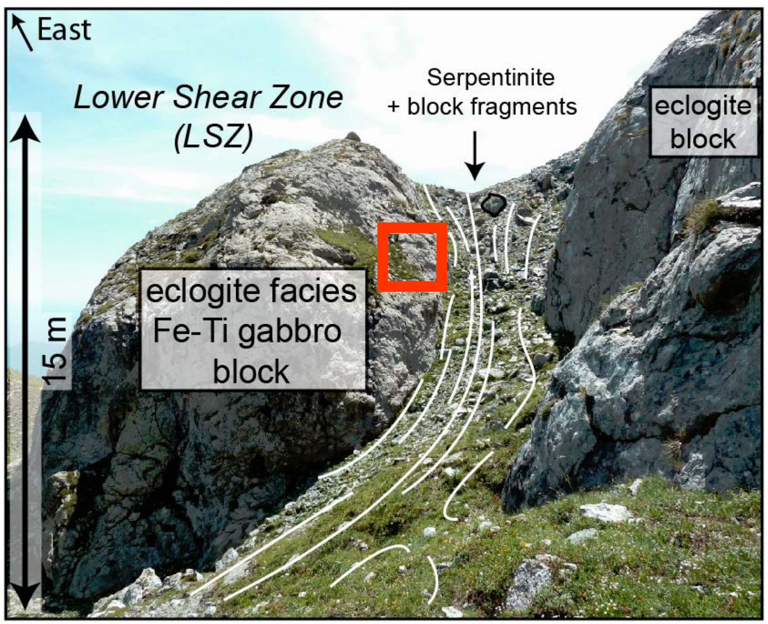
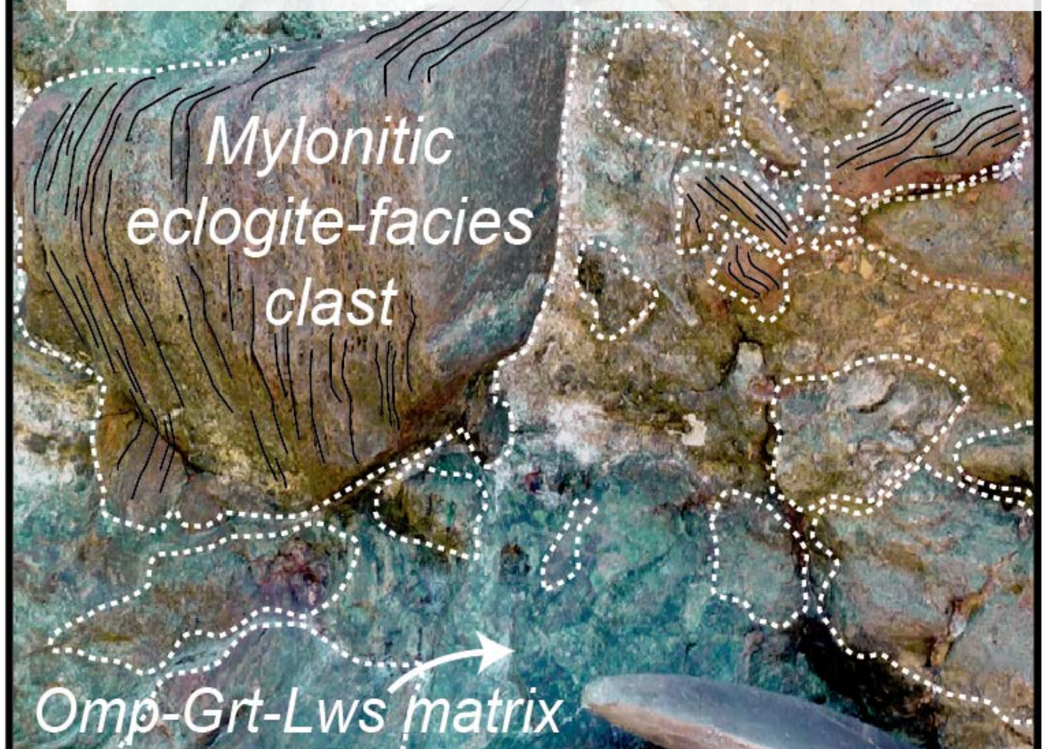
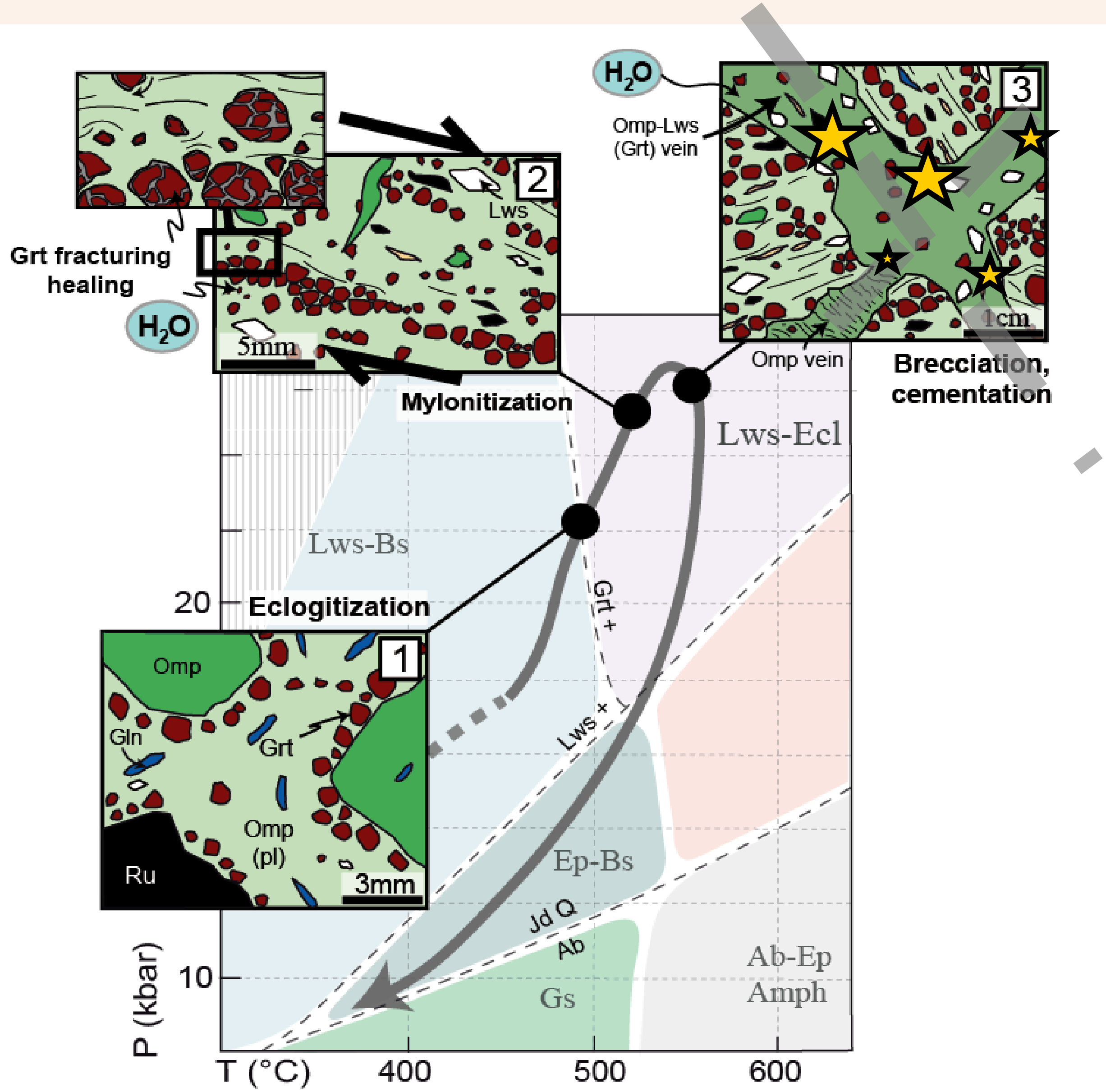




P-T evolution of Eclogite breccias



Angiboust et al., *Lithos, 2011*

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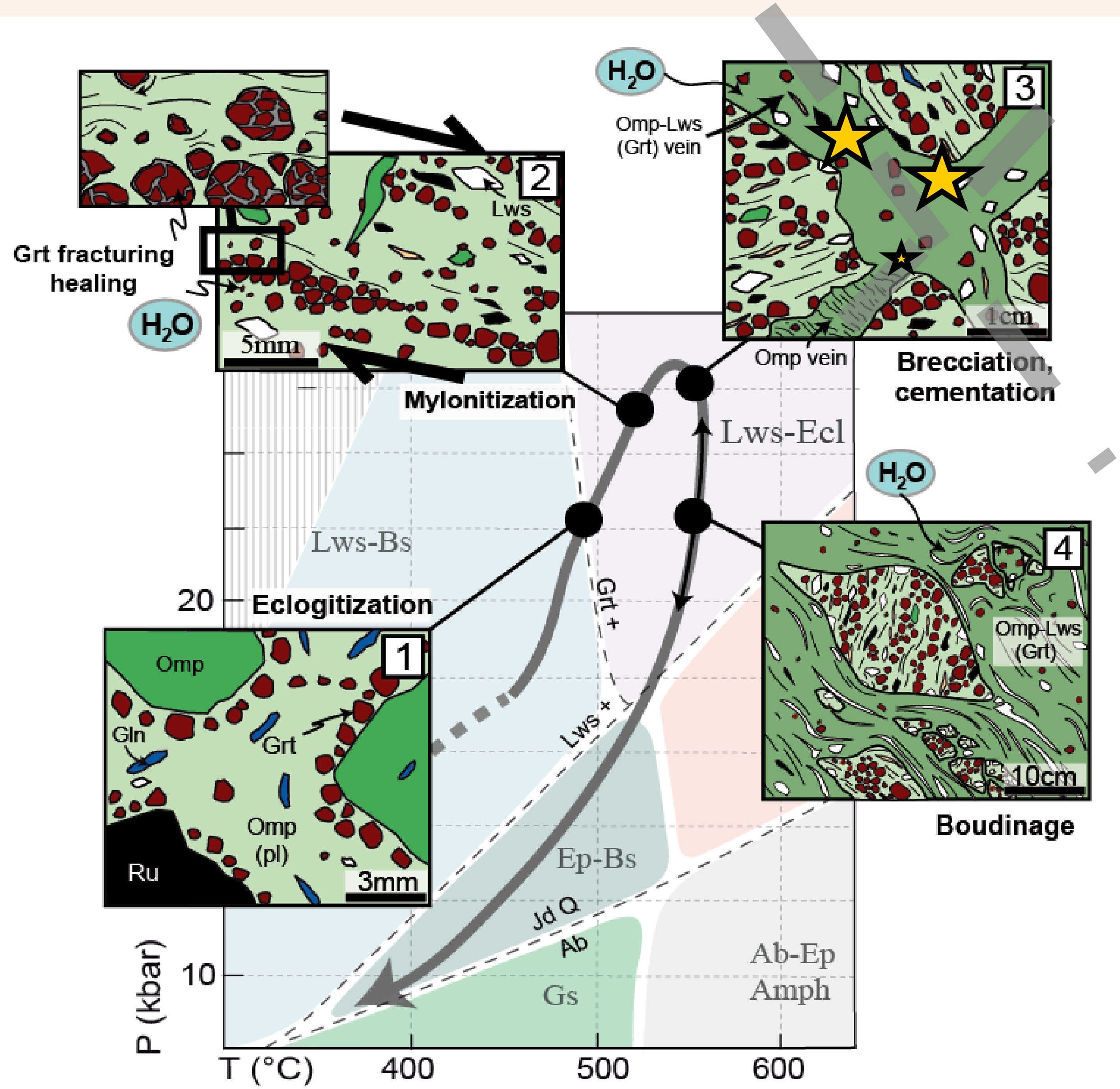
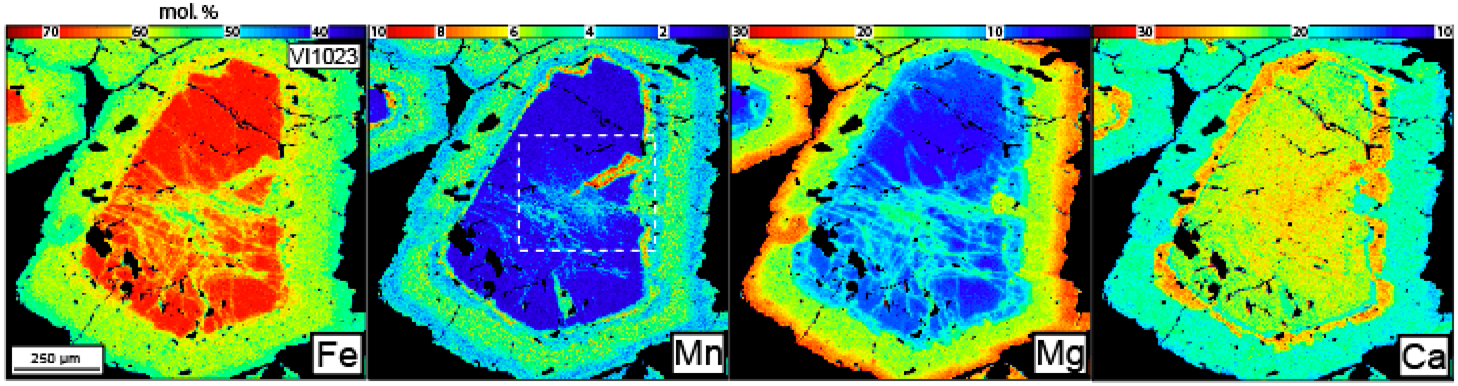
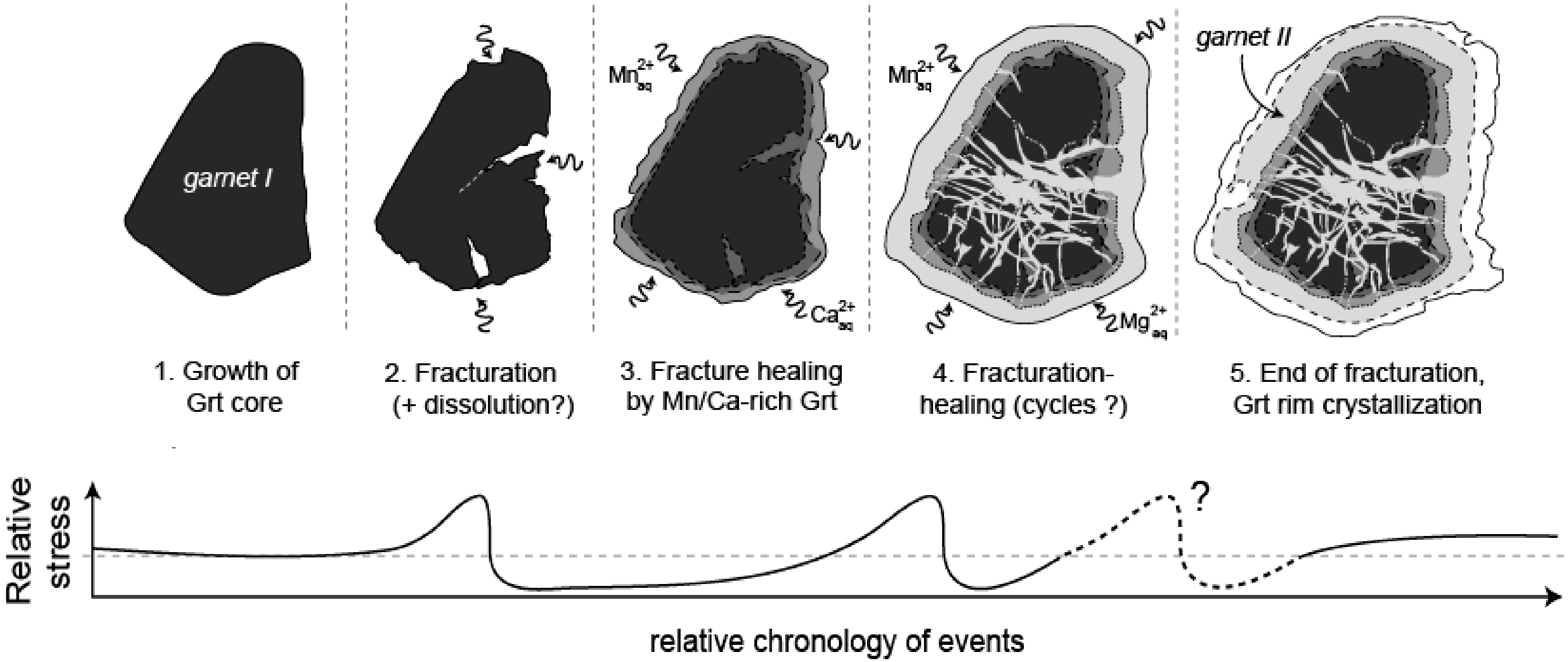


→ brecciation at ~80 km, fluid ingression, brittle/ductile switches

Multiple garnet fracturing events

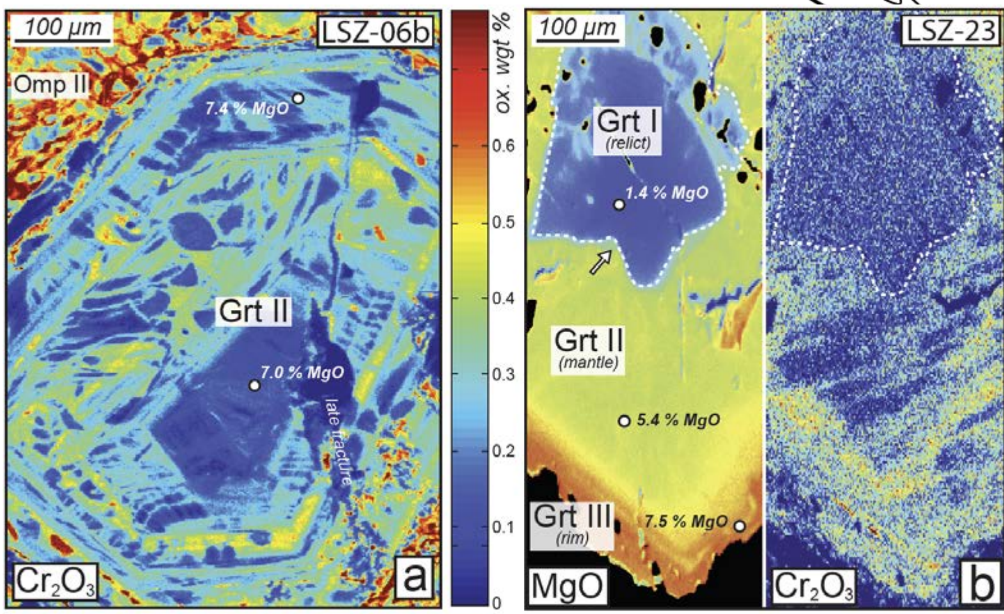


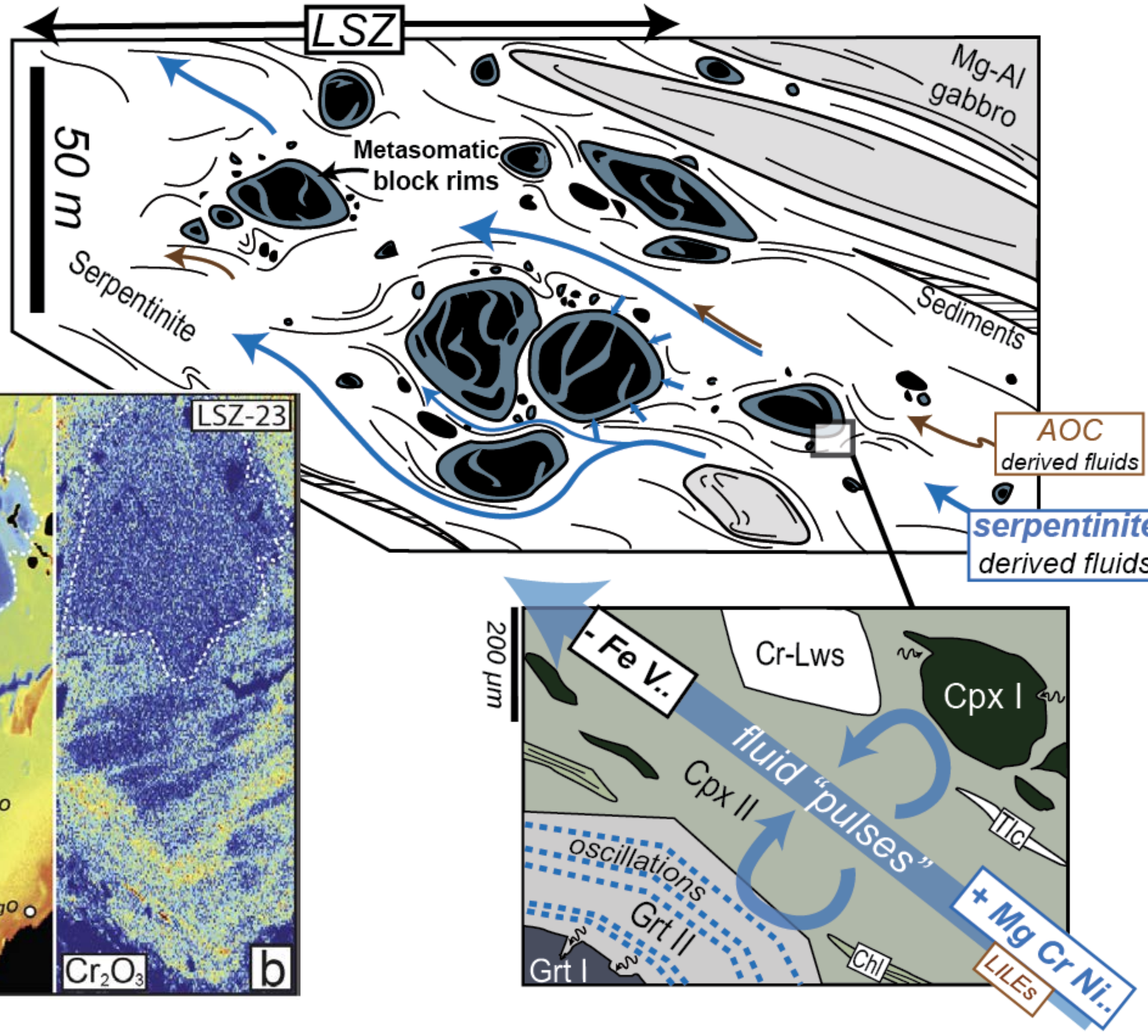


Angiboust et al., *Lithos, 2011*

Evidence for fluid/rock interaction along the LSZ

Angiboust et al., in prep.

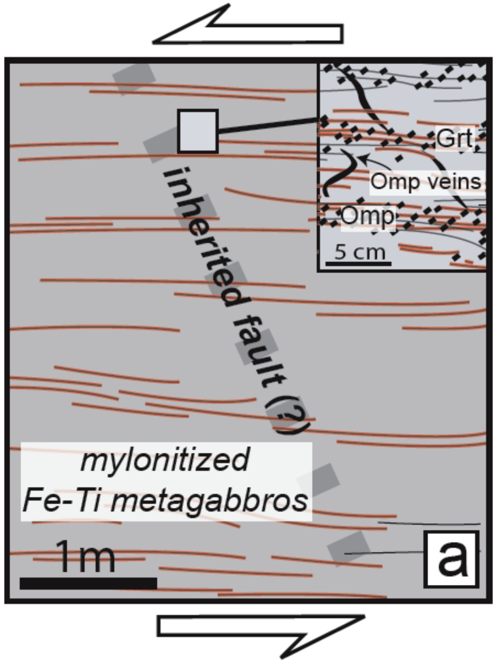




A deformation-enhanced fluid pathway → Evidence for **transient fluid pulses**

→ Fluids derived from **serpentinites**

How do eclogite breccias form?



Angiboust et al., *Geology, 2012*

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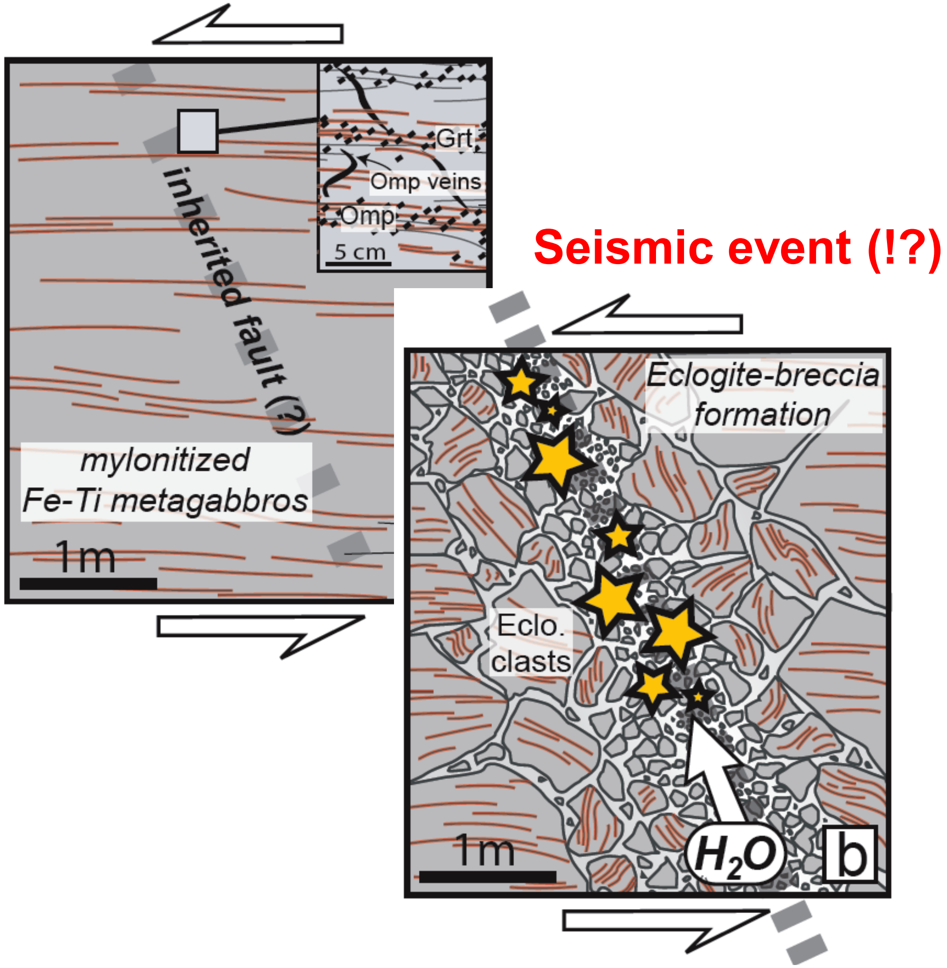

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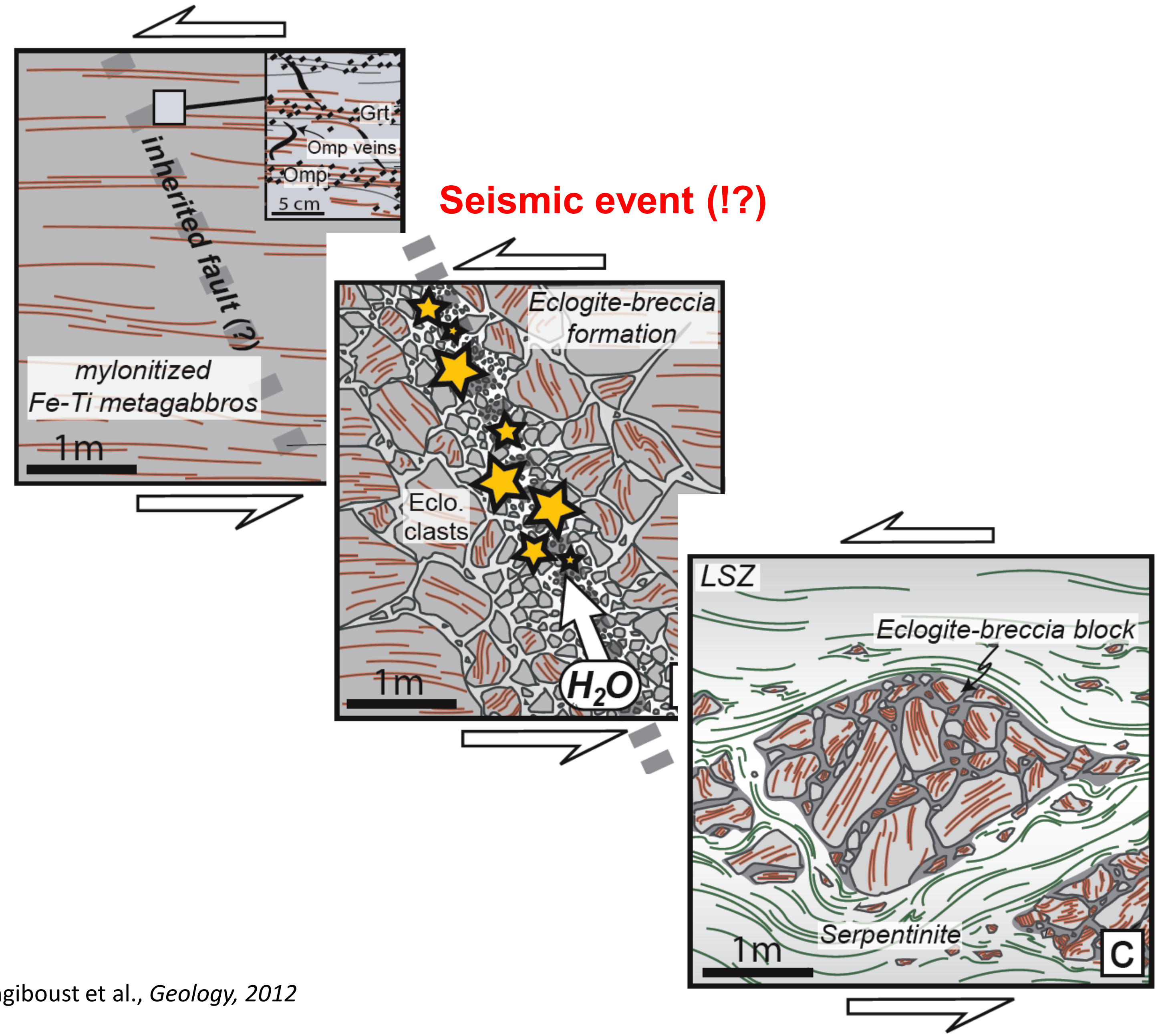
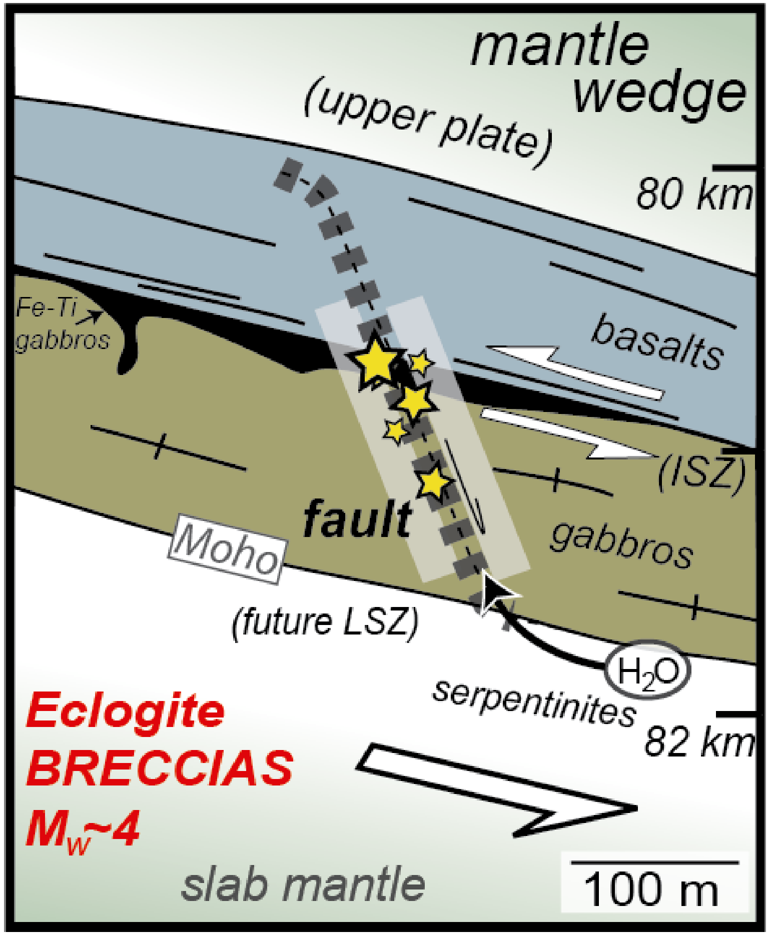


Angiboust et al., *Geology, 2012*

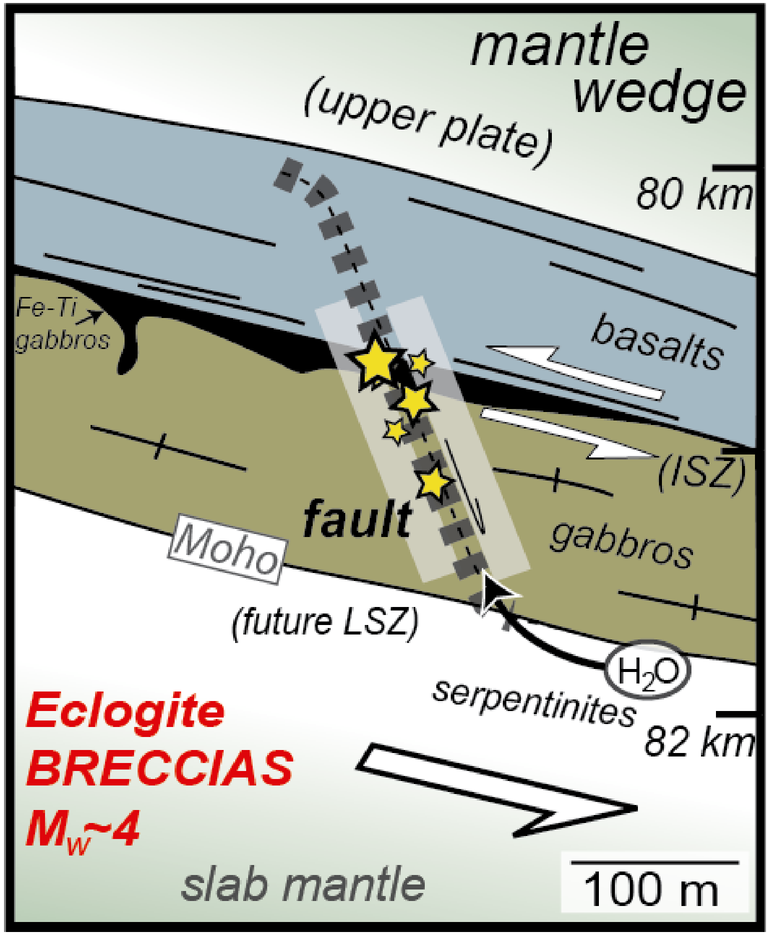
Insights on intraslab seismic activity!



The record of deep
intra-slab earthquake processes!?

Angiboust et al., *Geology, 2012*

Insights on intraslab seismic activity!



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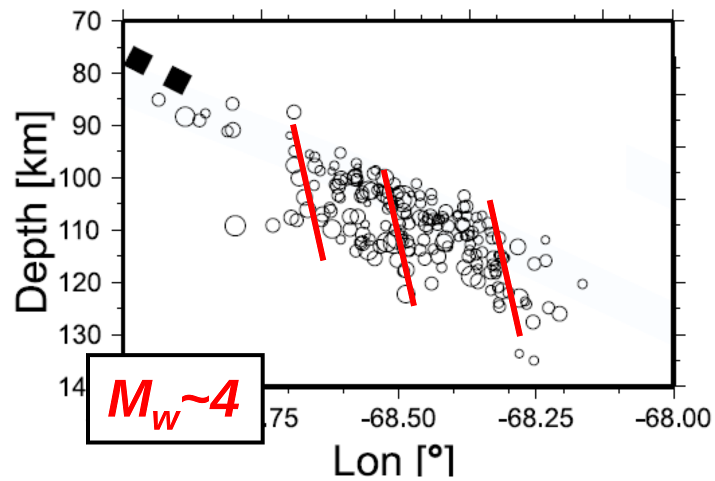
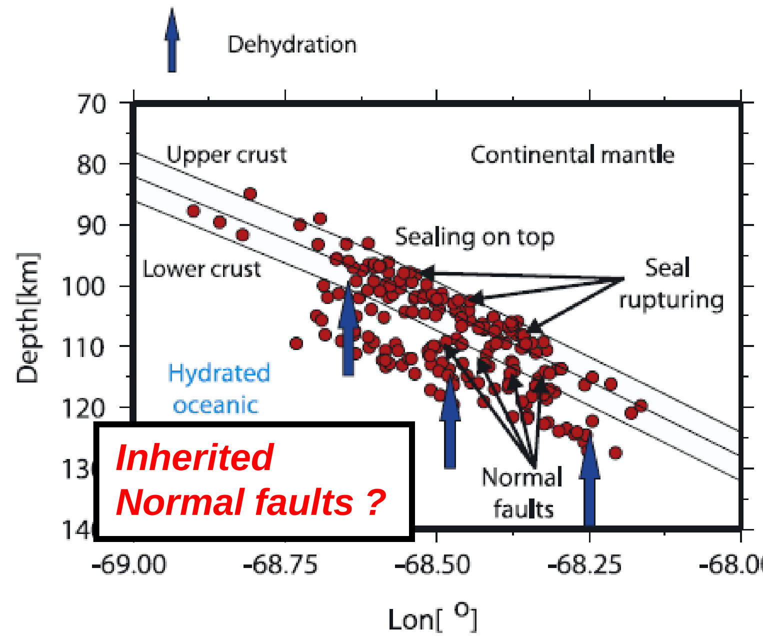
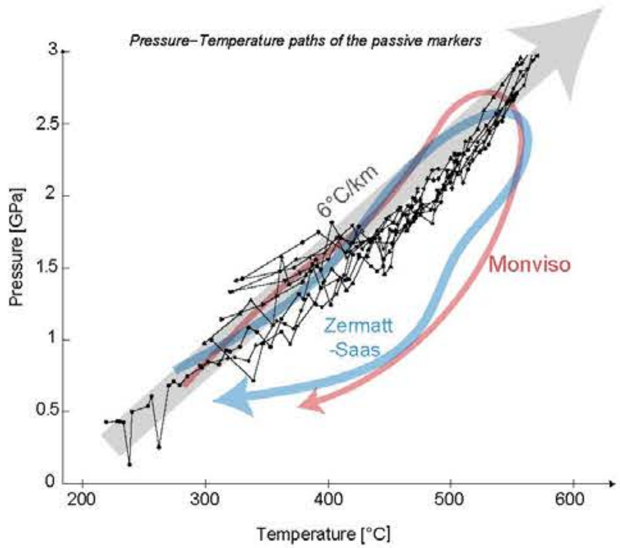


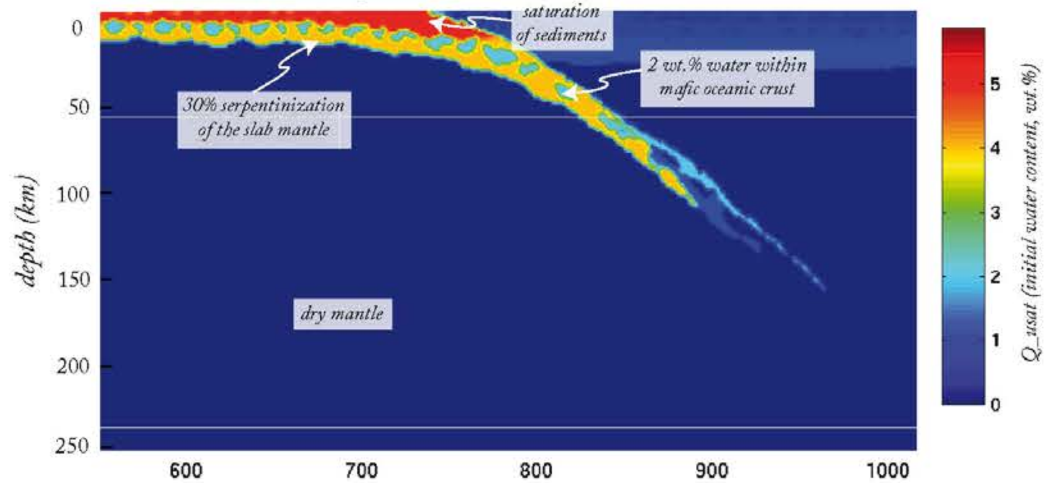


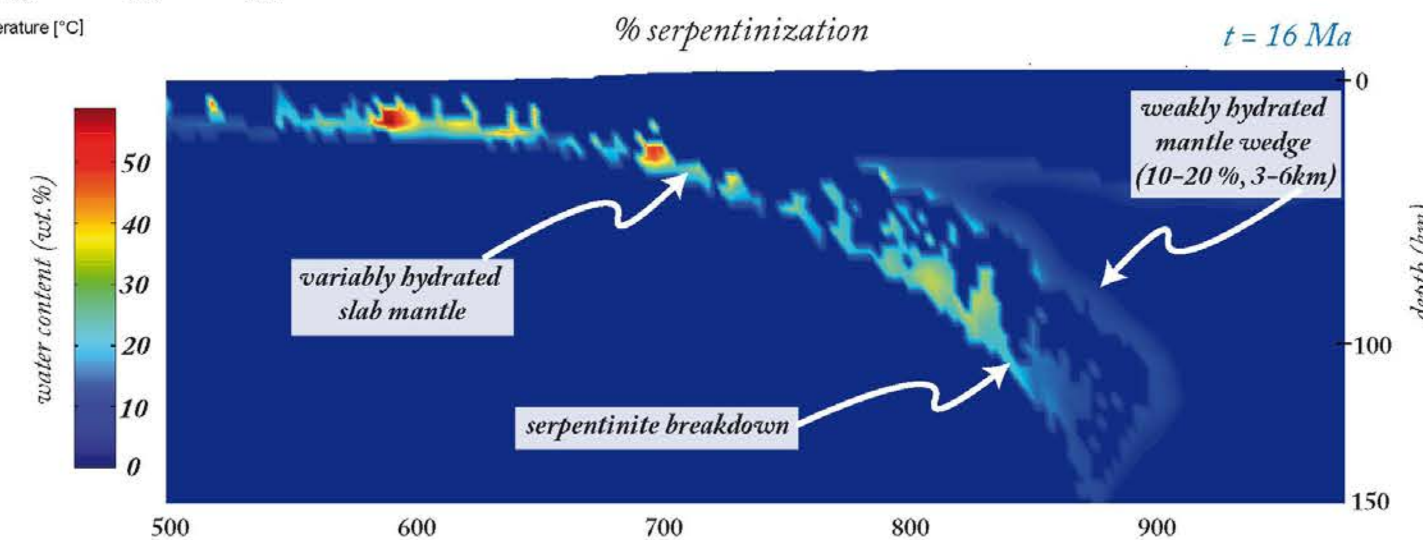
Rietbrock & Waldhauser, 2004

Linking all observations: models!



Initial water content distribution (PerpleX)
as a function of the lithology and PT conditions





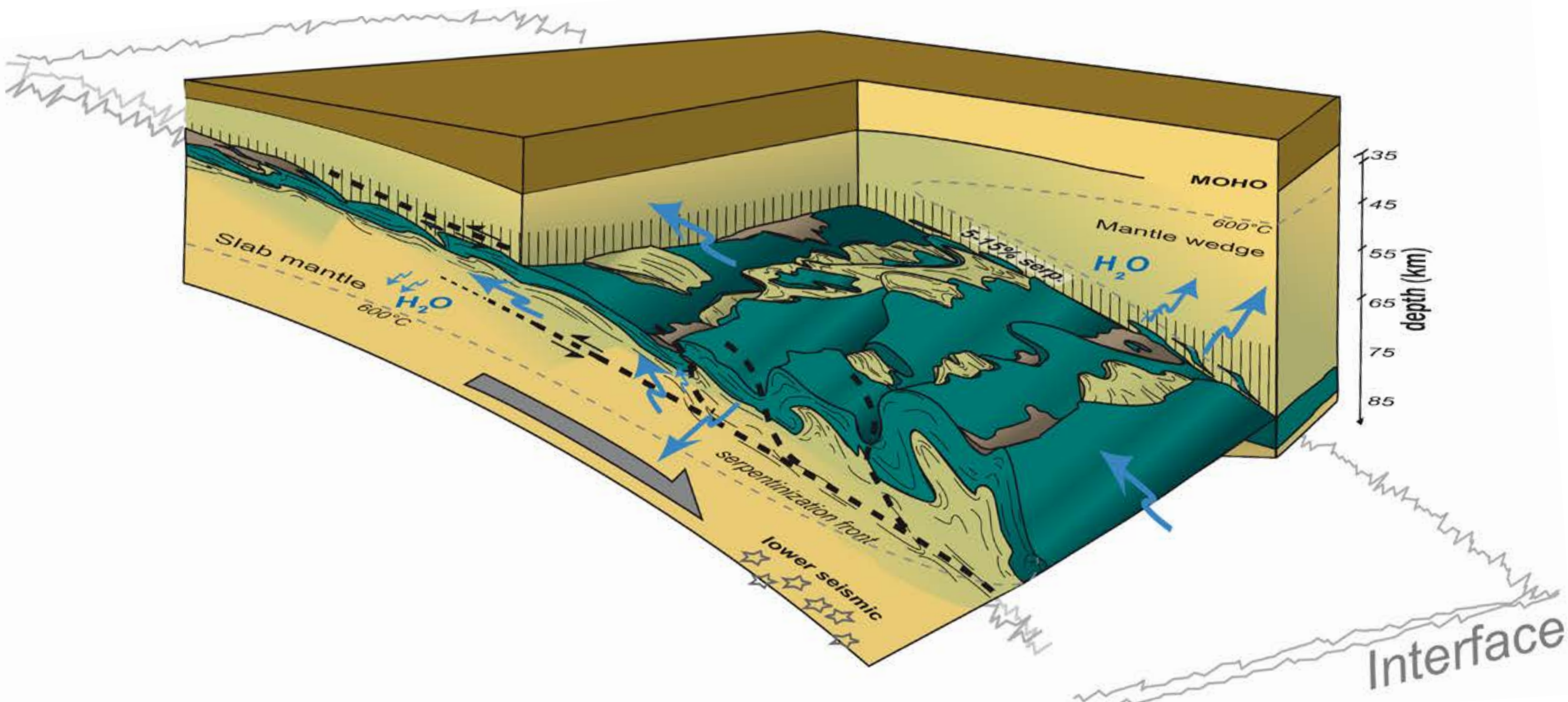
Angiboust et al., *EPSL, 2012*

What we may infer on the plate interface:

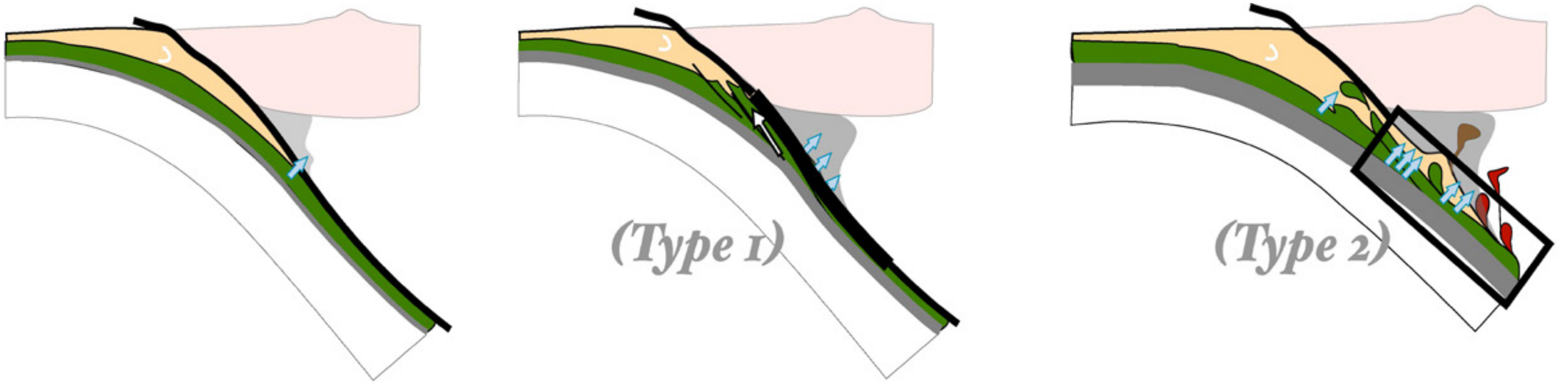
1. *Exhumation is **the EXCEPTION** rather than the rule / **short-lived** / **triggered by geodynamic pulses/events/drama***

1. HP rocks can record short-term mechanical/fluid pulses
(eclogite breccia, HP pseudotachylites,…)

***3. Large-scale slices v. blocks in mélange** — in many places? ≠ modes of coupling ?*



Work in progress…



EFFICIENT DECOUPLING AT THE PLATE INTERFACE:
no exhumation

LOCAL COUPLING AT THE PLATE INTERFACE:
exhumation of large scale slices

STRONG VISCOUS COUPLING AT THE PLATE INTERFACE:
exhumation of mafic blocks in a low viscosity channel

cold
dry → warm
wet

Agard et al., in prep.

SCOPE

0. Introduction /geochemical-physical evidence, complex fluid/deformation processes

1. Exhumation of HP rocks: a proxy for subduction interface behavior

2. What does the subduction interface look like at ~ 80km depth?

3. **ZIP: a european ITN network / subduction plate interface** (Start. Oct. 2103)

ZIP – Zooming in between plates
a european Int. Training Network

12 PhD students + 2 Post-docs + money / travel and workshops // ~ 4 M€

INCENTIVE
Improve our resolution/understanding by one order of magnitude (down to 100s of m) by combining efforts from petrology-geophysics-modelling-rheology

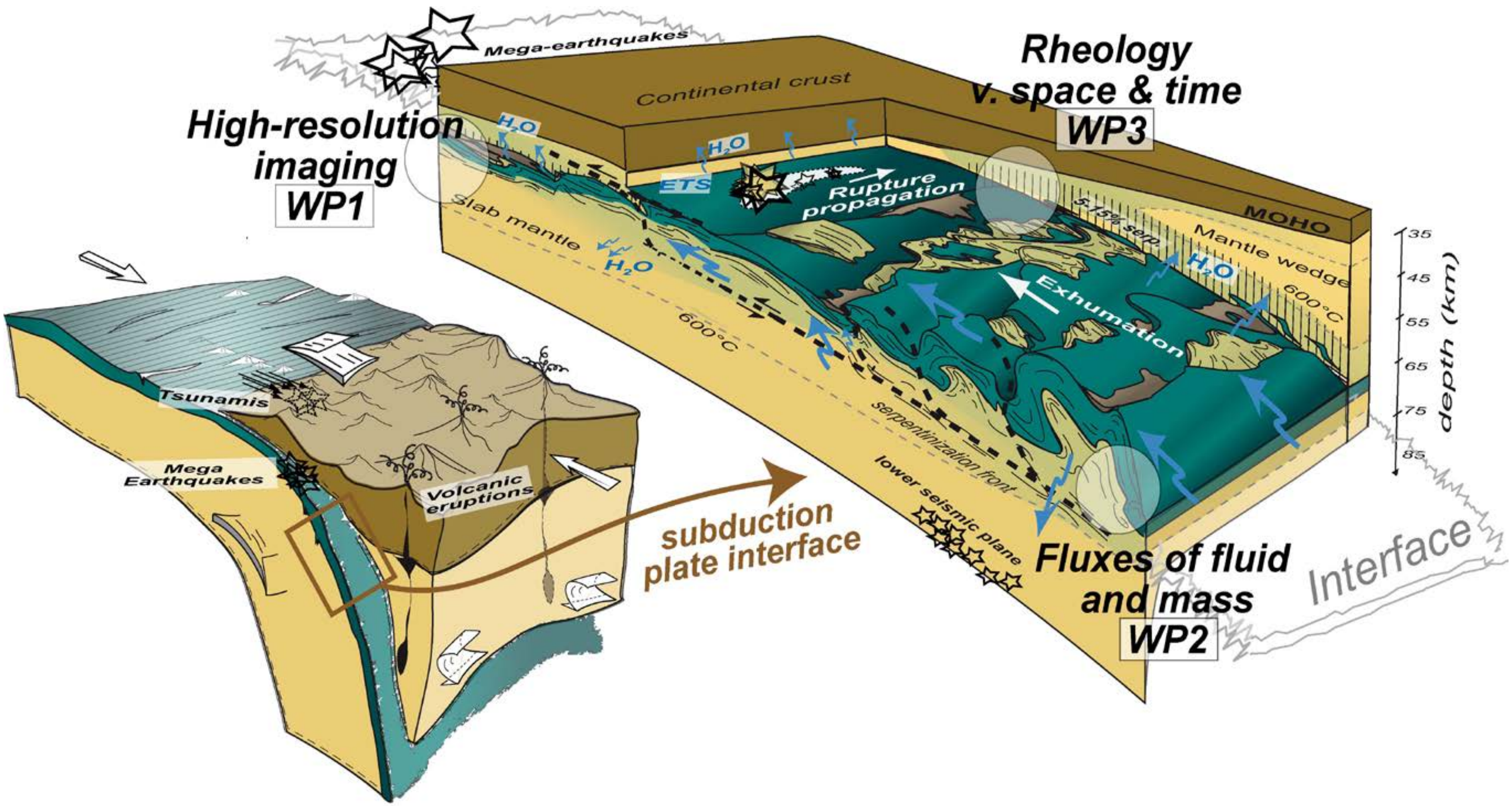
TIMELY!
- Lots of new observations/techniques on subduction zones over the past 10 years
- A number of large recent earthquakes for study (Sumatra, Chile, Japan)

AIMS
- Foster research between groups, develop new ties
- Get funds for academic-oriented research on subduction zones in Europe

Target: **Rheology and fluid behavior of the subduction interface at depths of ~10-120 km** (bridging space-time scales, for data and modelling)

ZIP – Zooming in between plates

a european Int. Training Network



w/r GEOPRISMS

4.2 **How does deformation across the subduction plate boundary evolve in space and time, through the seismic cycle and beyond?**

4.3 **How do volatile release and transfer affect the rheology and dynamics of the plate interface, from the incoming plate and trench** through to the arc and backarc?

4.4 **How are volatiles, fluids, and melts stored, transferred**, and released through the subduction system?

4.5 What are the geochemical products of subduction zones, from mantle geochemical reservoirs to the architecture of arc lithosphere, and how do these influence the formation of new continental crust?

4.6 **What are the physical and chemical conditions that control subduction zone initiation** and the development of mature arc systems?

ZIP Int. Training Network

Partnership	Country	Legal Entity Name	Department / Division / Laboratory	Scientist-in-Charge
[1] - UPMC	France	Univ. P.M. Curie **UPMC**	ISTeP	P. Agard
[2] - UM	Germany	Univ. Münster **UM**	Institut für Mineralogie	T. John
[3] - CSIC	Spain	Spanish Res. Nat. Council **CSIC**	IACT BCSI	C. Ranero
[4] - CNRS	France	Centre Nat. Rech. Scient. **CNRS**	Lab. Géol ENS UJF Grenoble	C. Vigny
[5] - UG	Italy	Univ. Genova **UG**	Dipartimento di Sc. della Terra, Ambiente e Vita	M. Scambelluri
[6] - GFZ	Germany	German Centre for Geosciences **GFZ**	Department Geodynamics and Geomaterials	O. Oncken
[7] - UB	Switzerland	University of Bern **UB**	Institute of Geological Sciences	T. Pettke
[8] - ETH	Switzerland	Eidgenössische Technische Hochschule, Zurich ***ETH***	Department of Earth Sciences	T. Gerya
[9] - CAU	Germany	Christian-Albrechts Univ. Kiel **CAU**	Institute for Geosciences	T. Meier
[10] - NOA	Greece	National Observatory of Athens **NOA**	Institute of Geodynamics	G. Papadopoulos

- **10 European leading scientific Inst.**
- **Network with large expertise***
- **Recruiting 12 PhDs + 2 PostDocs**

  (& other related PhDs)

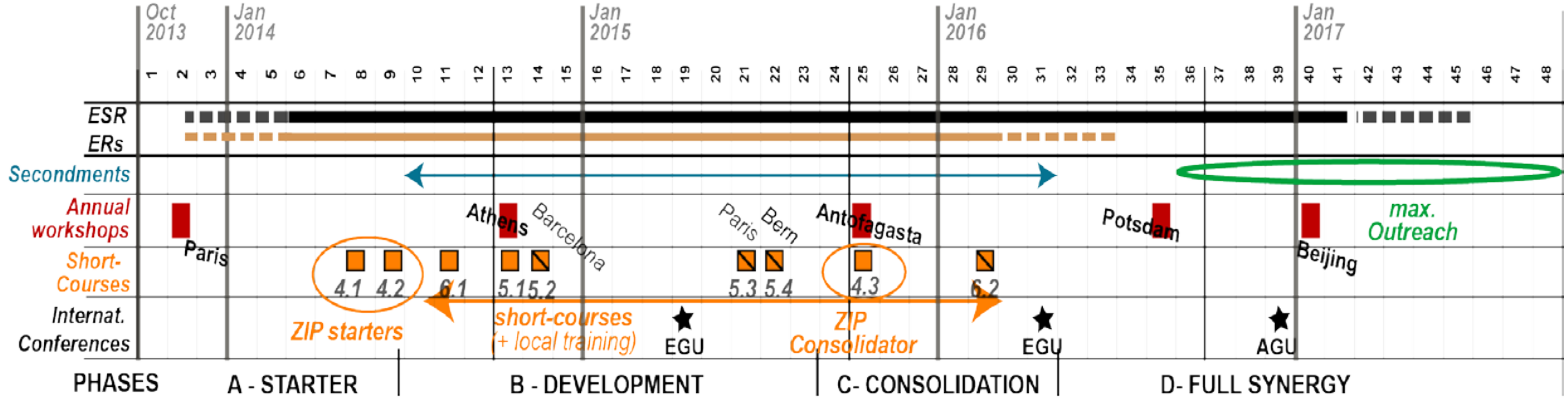
+ 9 **industrials** associated partners (modeling, geochemistry, geophysics)

+ Univ. from **China** and **Chile**

+ interactions with GEOPRISMS!

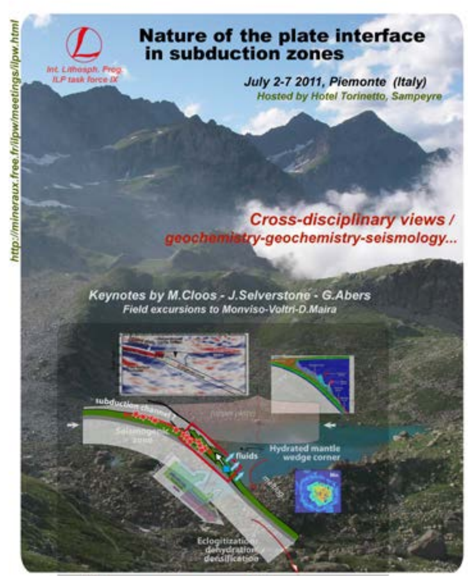
* **Field!** Metamorphic petrology, thermodynamics, fluid-rock interactions, geochemistry and geochemical reservoirs, chronometry, geochronology, tectonics, rock fabrics, geodynamics, geophysical/geodetic imaging, seismology, seismic tomography, seismic hazard, marine seismics, numerical modelling of geological, geodynamics and planetary processes,…

ZIP Int. Training Network

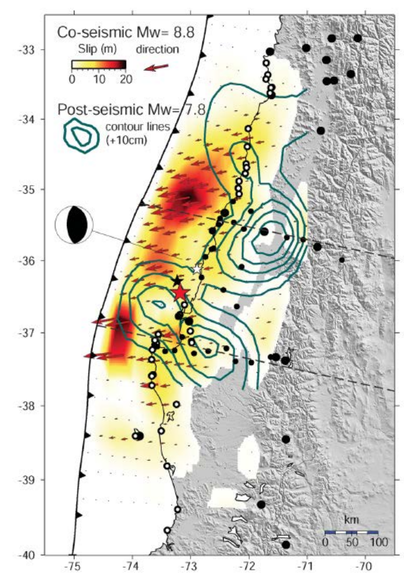


ZIP Starter 1
Hands-on marine geophysics

ZIP Starter 2
Hands-on field training
across depths [10-100 km]
...with ExTerra?



ZIP Consolidator
Hands-on monitoring



Q?...

1- **What is the dynamic behaviour within the interface?**

- How do tectonic slices / melanges migrate along the plate interface?
- How and at which depths do these rocks detach? Amount of underplated material?
- Single-pass upward flow v. continuous, extreme mixing of these rocks?
- Switches in exhumation modes v. mechanical coupling in subduction zones?
- Can we link this behaviour to seismicity and/or megathrust earthquakes?

2- **What is the rheological behaviour of the lower and upper plate boundaries?**

- Is there a permeability seal and, if so, downto to which depths?
- Rheology of the mantle wedge as a function of depth: from strong to increasingly weak?
- Deformation/fracture mechanisms v. frictional mechanical coupling?
- Exact link between fluid flow and seismic coupling during the seismic cycle?

3- **What is the extent of material transfer along the interface?**

- Element recycling v. fluid fluxes into and out of the mantle wedge and into the deep mantle?
- Fluids channelized within the mantle and/or along the plate inferface and at which time scale(s)?
- What is the rock record of ETS and associated fluid fluxes?

…

(plenty left…)

ZIP – Zooming in between plates

A european Initial Training Network

WELCOME ZIP PROJECT JOB OPPORTUNITIES PEOPLE TRAINING PUBLICATIONS & OUTREACH

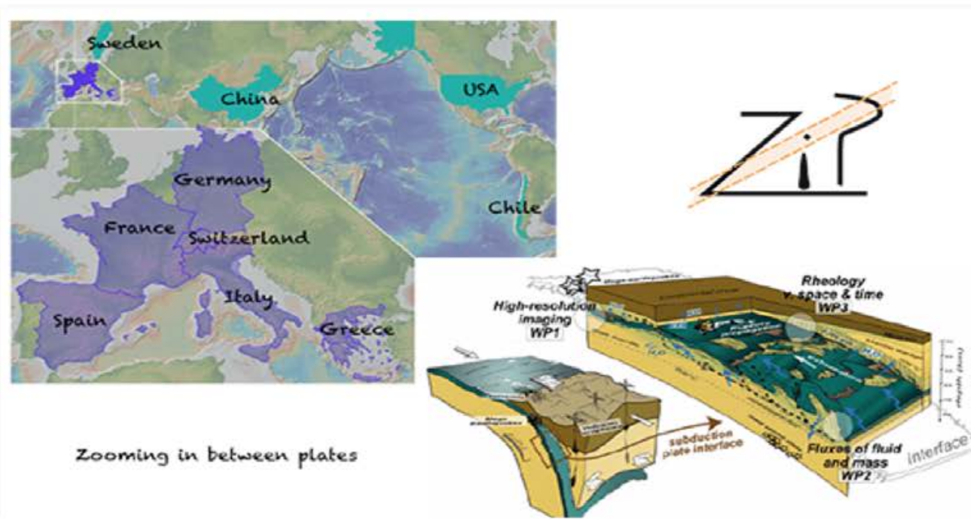
Welcome

Recherche

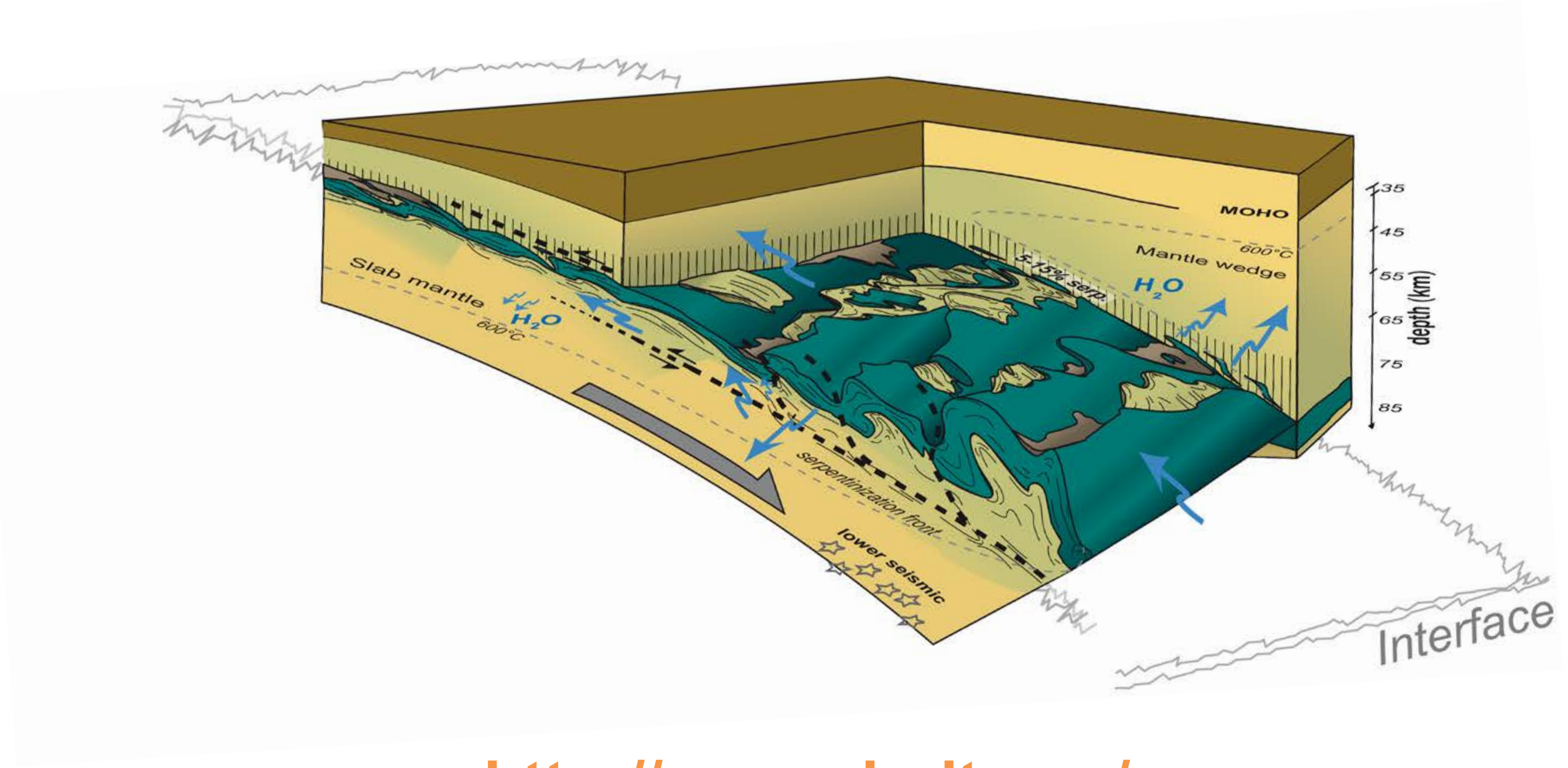
Tectonic plates sinking over millions of years? Megaearthquakes & tsunamis? Global fluxes of elements?... How do stresses and energy release, via earthquakes and fluid-mediated mass transfer, interact on such varied spatial and temporal scales (from 10^{-4} to 10^{6-7} yr)? **Time to ZIP** (Zoom In between Plates)**, into the subduction plate interface!**

[We are hiring NOW!]

Welcome
Contact us
MEMBER LOGIN



Thanks for your attention!



http://www.zip-itn.eu/

ESR1 — Tracing trajectories and geochemical evolution of subducted oceanic lithosphere [WP1]
Supervisors: Scambelluri (UG) / Mezger (GFZ)
Objectives: Characterization of rock diversity on the subduction interface at all scales / Methods: field mapping; petrological/geochemical characterization of rocks/minerals by SEM, microprobe, ICP-MS laser ablation and TIMS; geochemical modelling of fluid/rock exchange, element partitioning and fractionation

ESR2 — Imaging and characterizing deformation patterns on plate interfaces [WP1]
Supervisors: Oncken (GFZ) / Agard (UPMC)
Objectives: Petrophysical properties, fluid circulations, permeability estimates / Methods: seismic tomography, field mapping, models of fault slip, pore elastic deformation, viscous response and thermo-mechanical processes

ESR3 — Monitoring of the subduction interface by GPS and InSAR [WP1]
Supervisors: Vigny (CNRS) / Moreno(GFZ)
Objectives: Correlation of geodetic/geophysical and petrological/petrophysical data / Methods: integration from high-end, dense monitoring networks (LIA and IPOC observatories, Chile) across a fully continental upper plate with continuous GPS stations, seismological stations, tilt meters, geodetic benchmarks.

ESR4 — High resolution imaging of the subduction interface using microseismicity [WP1]
Supervisors: Meier (CAU) / REPSOL
Objectives: Transients and microseismicity (v. space/time and the seismic cycle) / Methods: seismology, data processing of clusters of highly similar microseismic events

ESR5 — Structure and physical properties of the subduction plate boundary [WP1]
Supervisors: Ranero (CSIC) / REPSOL
Objectives: Seismological and physical nature of the interplate boundary / Methods: processing and numerical modelling of marine seismic data, combined seismic and gravity modeling

ESR6 — Non-lithostatic fluid (thermo)dynamics of subduction interface dehydration reactions [WP2]
Supervisors: Garrido (CSIC) / Connolly (ETH)
Objectives: Numerical modeling of dehydration reactions within thermo-mechanical models / Methods: field mapping, petrology, geochemistry, thermodynamic modelling

ESR7 — Fluid liberation from the down-going slab: chemistry and fluid pathways [WP2]
Supervisors: Pettke (UB) / THERMOFISHER
Objectives: Fluid/mass transfer and source contributions through space and time / Methods: link careful petrography with bulk rock and in-situ geochemistry (XRF, ICP-MS, TIMS, LA-ICP-MS, SIMS) of trace elements and isotopes, fluid characterization

ESR8 — Time scales of deformation and fluid-mediated interactions along the plate interface [WP2]
Supervisors: John (FUB) / Agard (UPMC)
Objectives: Links between fluid flow patterns and rock chemical-petrophysical changes / Methods: tectonics, field mapping, metamorphic petrology, fluids, chemical gradients, diffusion modelling, geochronology

ESR9 — Experimental-numerical constraints on the rheological impact of metamorphic reactions [WP3]
Supervisors: Schubnel (CNRS) / John (FUB)
Objectives: Testing the rheological impact of metamorphic reactions / Methods: experimental rheology, fluid-rock experiments, modelling. Linked to ESRs 2, 3 and 10 and to ER2

ESR10 — Paleoseismicity (pseudotachylites, eclogite breccia): from the field to experiments
Supervisors: Verlaguet (UPMC) / Federico (UG)
Objectives: Rock deformation experiments at HP-HT and ongoing fluid release / Methods: field mapping, tectonics, petrology, rheology

ESR11 — Big or small quakes along the subduction interface: impact on natural hazard [WP3]
Supervisors: Papadopoulos (NOA) / Weidle (CAU)
Objectives: Post-seismic deformation and hazard after large earthquakes / Methods: modelling of seismic instabilities

ESR12 — Rheological timescales, from geodynamics to the seismic cycle [WP3]
Supervisors: Gerya (ETH) / LePourhiet (UPMC)
Objectives: Upscaling the rheological behavior of the plate interface versus depth and time through numercial models / Methods: numerical modelling, rheology, seismology

ER1 — Physics of multiscale fluid-melt migration across the deforming subduction interface [WP3]
Supervisors: May (ETH) / AF CONSULT
Objectives: Testable numerical models for fluid/melt transport / Methods: numerical modelling, rheology, thermodynamics and kinetics of fluid/melt-rock interactions

ER2 — Impact of composite rheologies for mixing processes at the plate interface [WP2]
Supervisors: Burov (UPMC) / Sallares (CSIC)
Objectives: Rheological/geodynamical/geochemical/seismological/2D-3D numerical thermomechanical / Methods: modelling, mechanical mixing

FLAMAR (Burov)

- $$\rho g_i + \frac{\partial \sigma_{ij}}{\partial x_j} = \rho \frac{\partial V_i}{\partial t}$$ dynamic law (Newton)
- $$\frac{DT}{Dt} = \frac{\partial}{\partial x_i}\left(\chi \frac{\partial T}{\partial x_i}\right) + \frac{H_r}{\rho\, C_p} - V_i \frac{\partial T}{\partial x_i}$$ Heat equation
- $$\frac{\partial h}{\partial t} = k_{ero} \frac{\partial^2 h}{\partial x^2}$$ erosion sedimentation
- $$\frac{D\sigma}{Dt} = F\left(\sigma, \mathbf{u}, \mathbf{V}, \nabla\mathbf{V}, ..., T, ...\right)$$ Constitutives laws

$$\dot{\varepsilon} = A \exp\left(-\frac{E}{RT}\right) \sigma^n$$

$$\sigma_{ij} = \lambda\, \delta_{ij} \sum_k \varepsilon_{kk} + 2\mu\varepsilon_{ij}$$

$$\tau = (\tan\varphi)\, \sigma_n + C_0$$

- Progressive densities changes: PerpleX (

$$\sigma = F\,(\mathrm{P}, \mathrm{T})$$

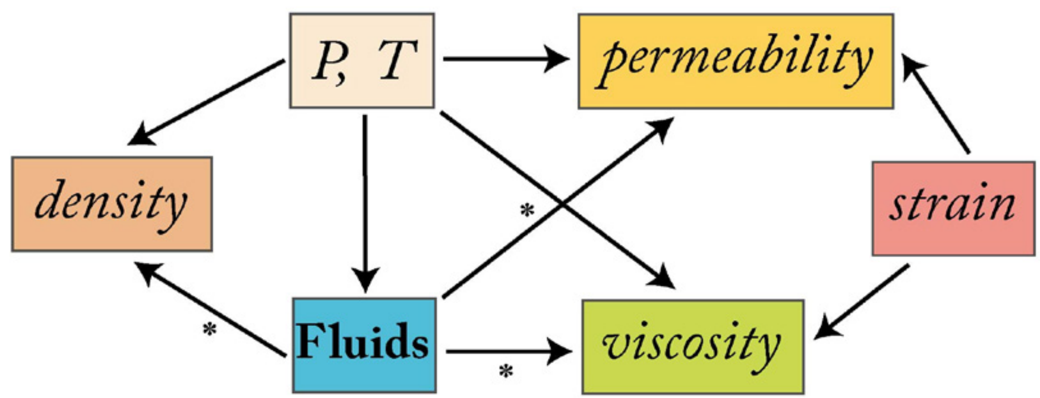
$$\vec{q} = -K \nabla P^*_{fl}$$

$$P^*_{fl} = (P_{total} - P_{litho}) \times \frac{[H_2O]_{usat}}{[H_2O]_{sat}}$$

$$K = \frac{k}{\mu} \times \varepsilon^*$$: calculated diffusion coefficient

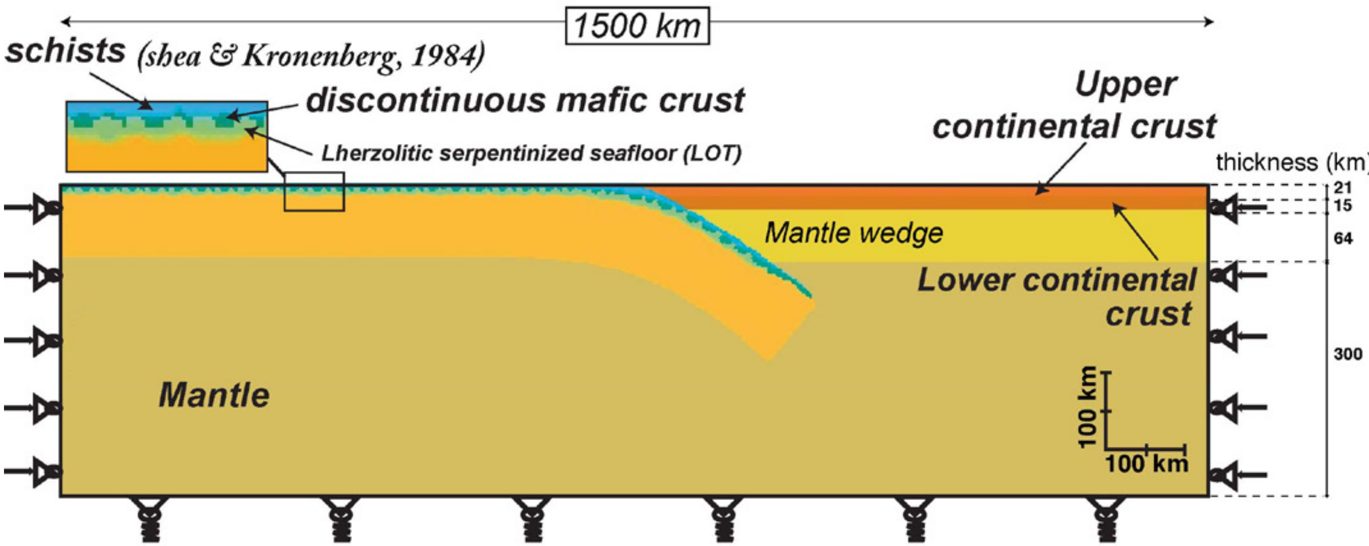
k : intrinsic permeability (m^2) as a function of depth (Manning & Ingebritsen, 1999)
μ : dynamic viscosity of the fluid (Pa.s) as a function of T (Seeton, 2006)

$$\varepsilon^* = \frac{\dot{\varepsilon}}{\bar{\varepsilon}}$$ ← instaneous strain rate / ← average model strain rate

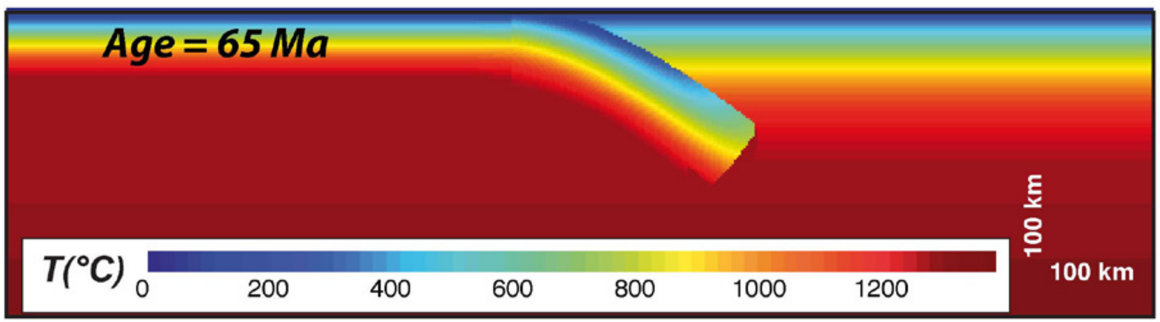


*: only for mantle phases

Oceanic subduction experiments

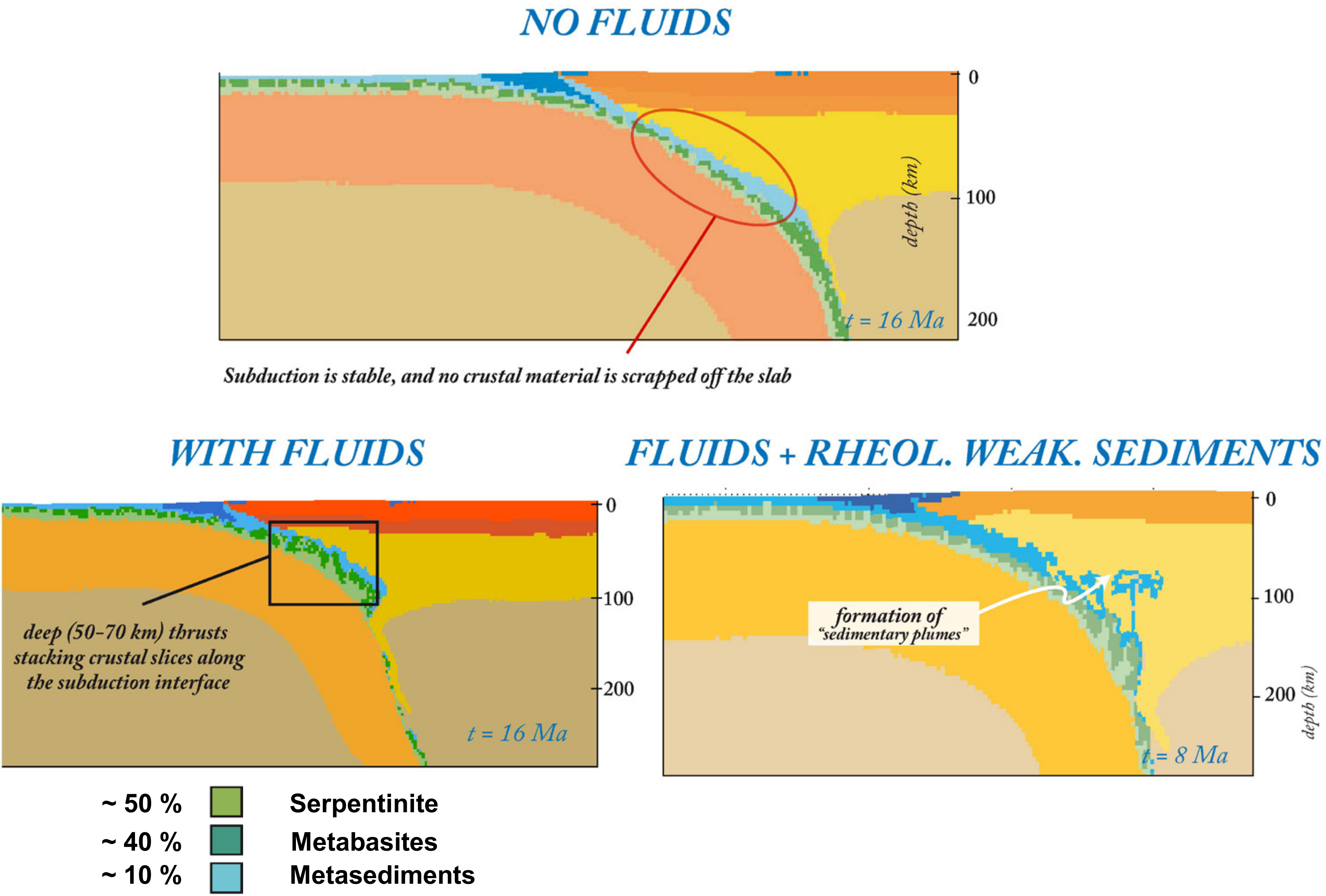


Initial lithological structure



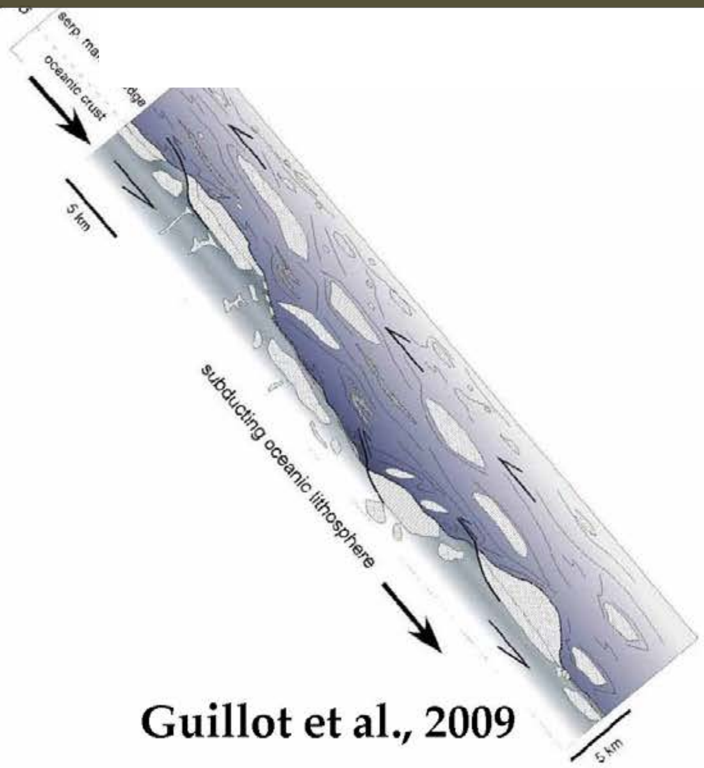
Initial thermal structure

« garbage in, garbage out!... »

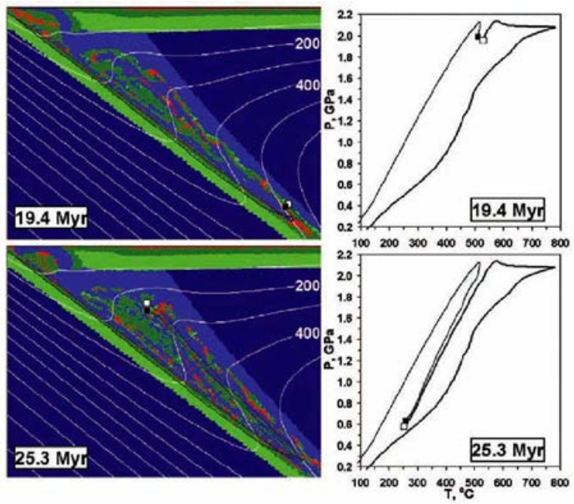


NO FLUIDS
0
100
200
depth (km)
t = 16 Ma
Subduction is stable, and no crustal material is scrapped off the slab
WITH FLUIDS
0
100
200
deep (50-70 km) thrusts stacking crustal slices along the subduction interface
t = 16 Ma
FLUIDS + RHEOL. WEAK. SEDIMENTS
0
100
200
depth (km)
formation of "sedimentary plumes"
t = 8 Ma
~ 50 % Serpentinite
~ 40 % Metabasites
~ 10 % Metasediments

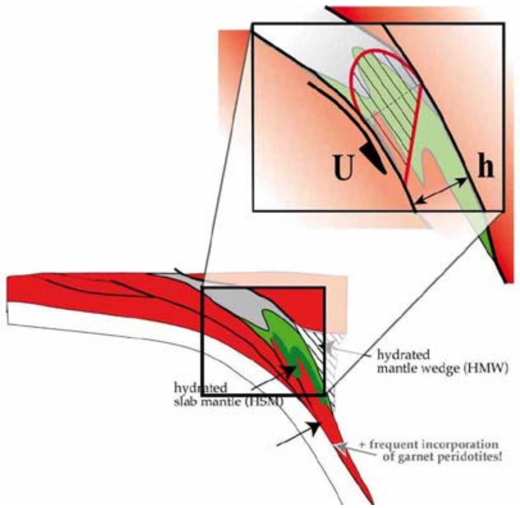
ZIP Int. Training Network



Guillot et al., 2009



Gerya et al., 2002

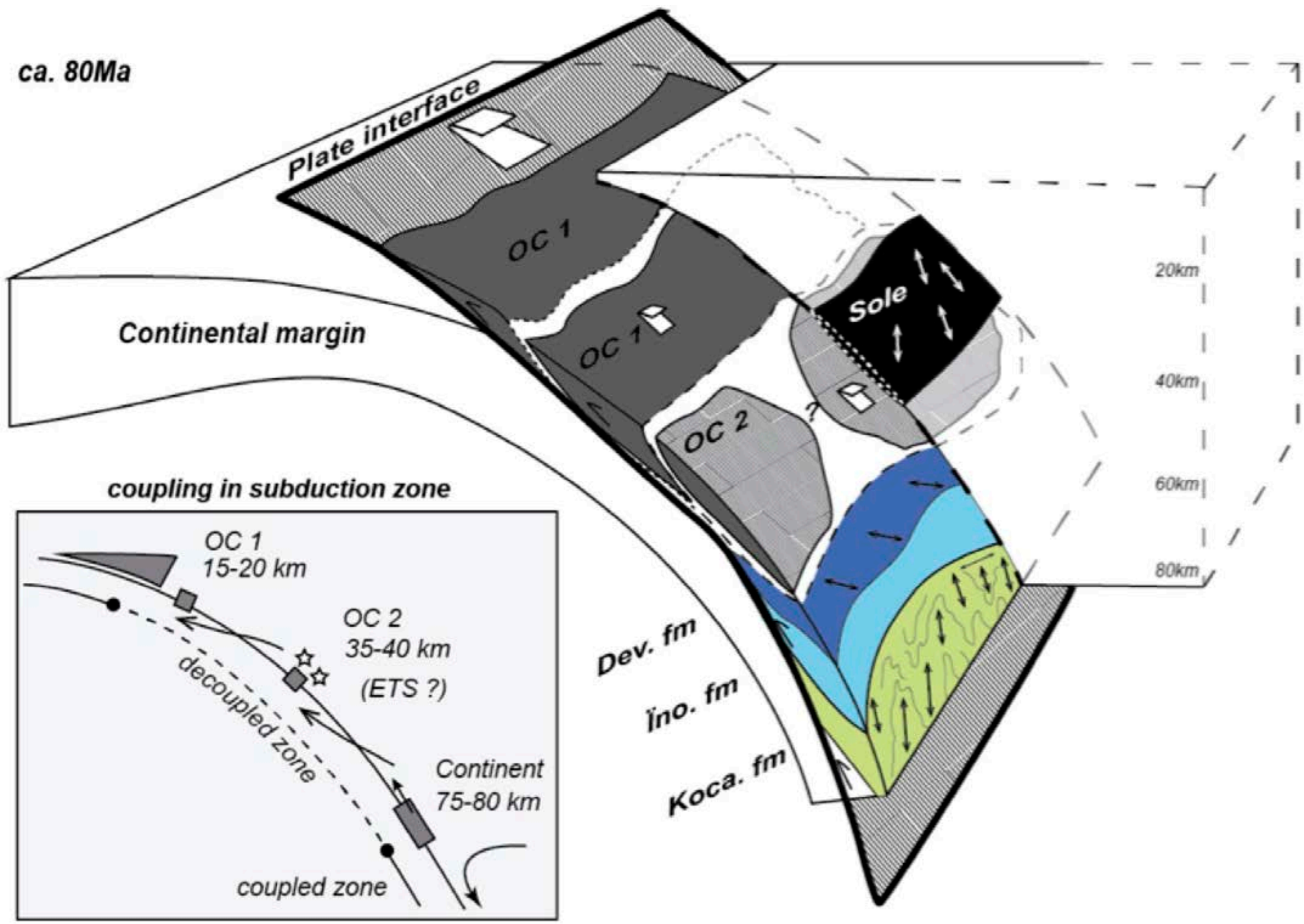


Raimbourg et al., 2007

?

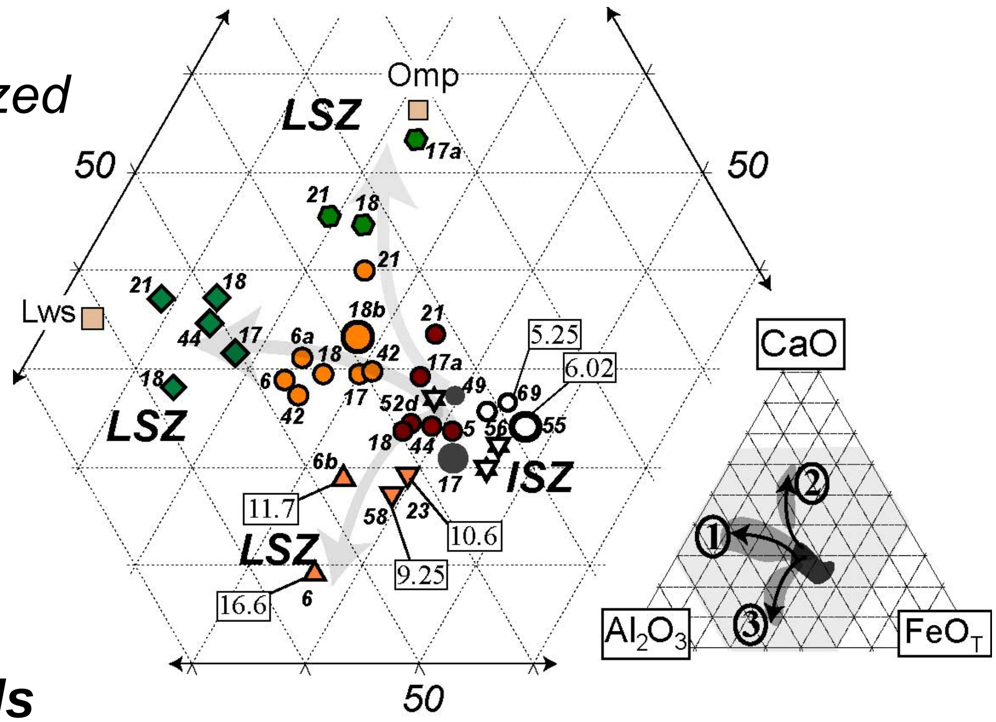
Plate interface (subduction channel):

- Nature of the interface : mélange (which lithologies?) / slivers?
- Decoupling : when (key reactions?)/ where (+- 1km) / volumes?
- Evolution of the units: residence time, underplating?
  - => rheology of the subducting plates
  - => rocks/elements fluxes (geochem recycling, arc volcanism,…)

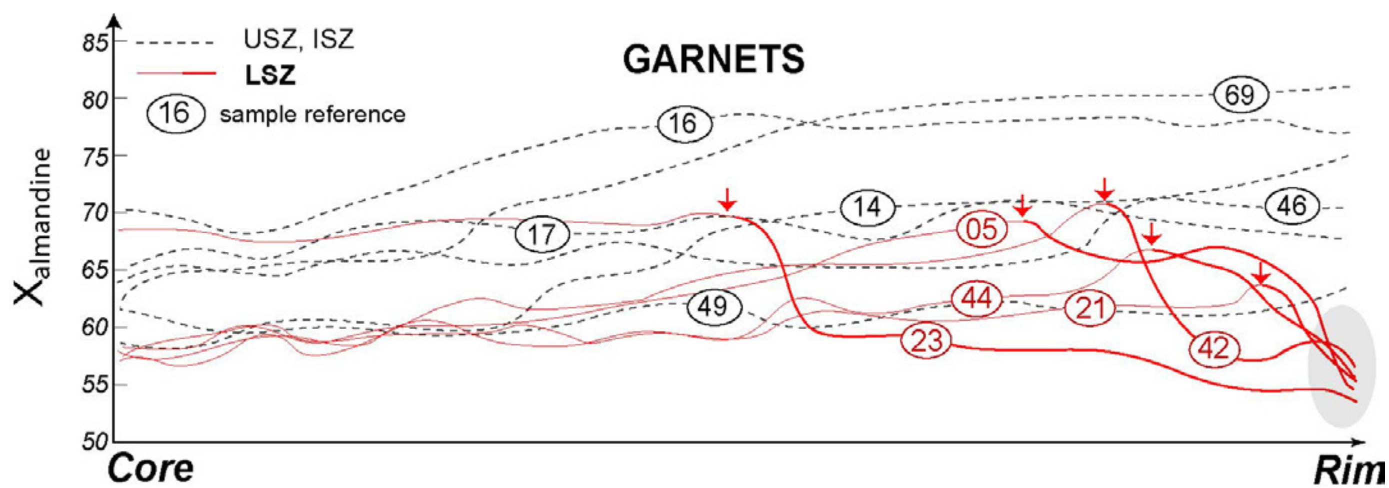

ca. 80Ma
Plate interface
OC 1
OC 1
OC 2
Sole
Continental margin
20km
40km
60km
80km
Dev. fm
İno. fm
Koca. fm
coupling in subduction zone
OC 1
15-20 km
OC 2
35-40 km
(ETS ?)
decoupled zone
Continent
75-80 km
coupled zone

Evidence for fluid ingression in the LSZ

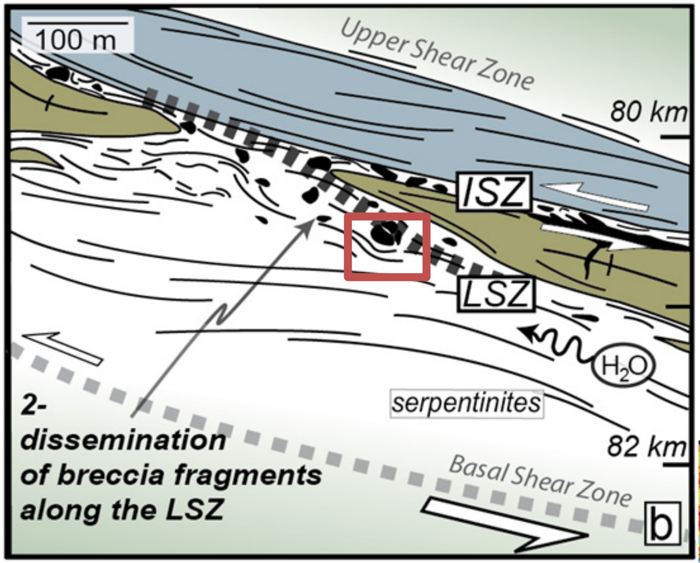
*Chemical changes in mylonitized & **brecciated** eclogite blocks*



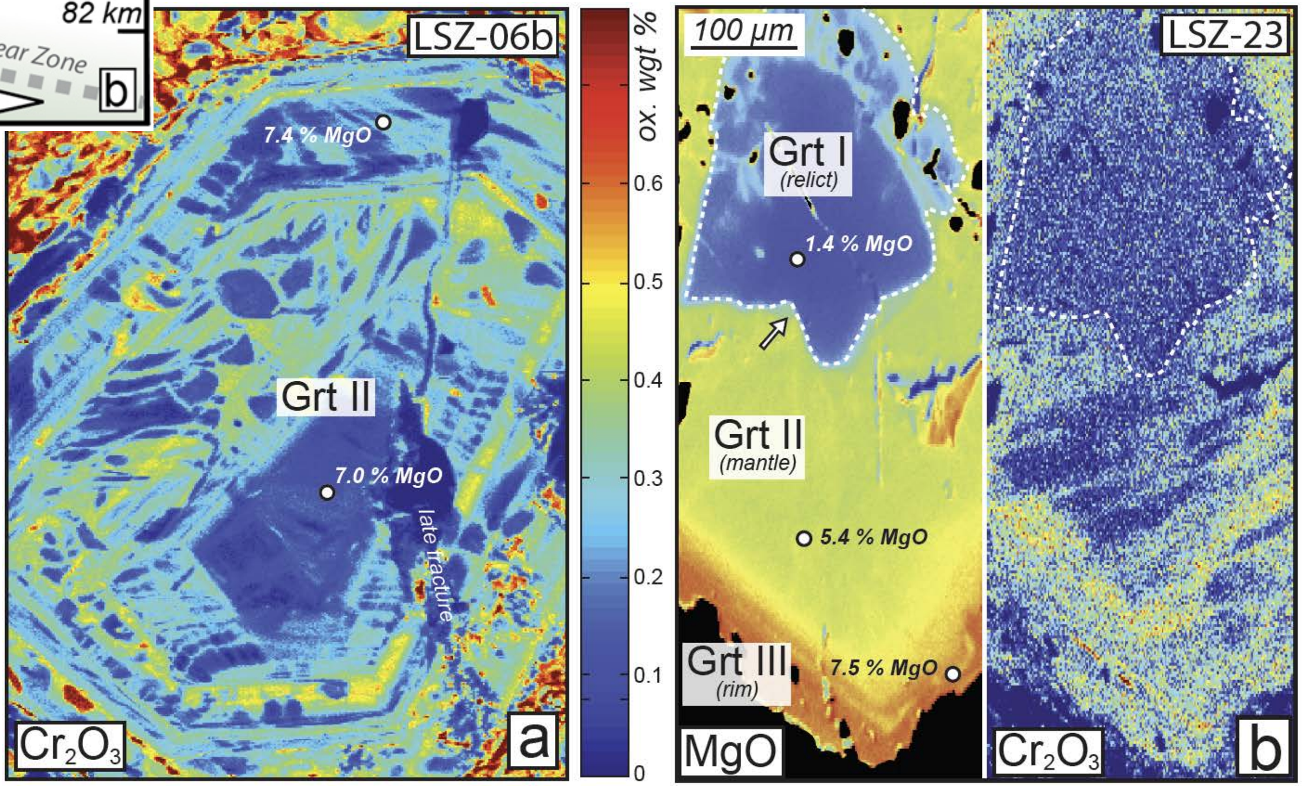
*Buffering of garnets by **serpentinite-derived fluids***



Evidence for fluid/rock interaction along the LSZ



→ *Growth of **metasomatic hydration rinds** around the blocks in the Lower Shear Zone*



Angiboust et al., in prep.