The Calm before the Storm

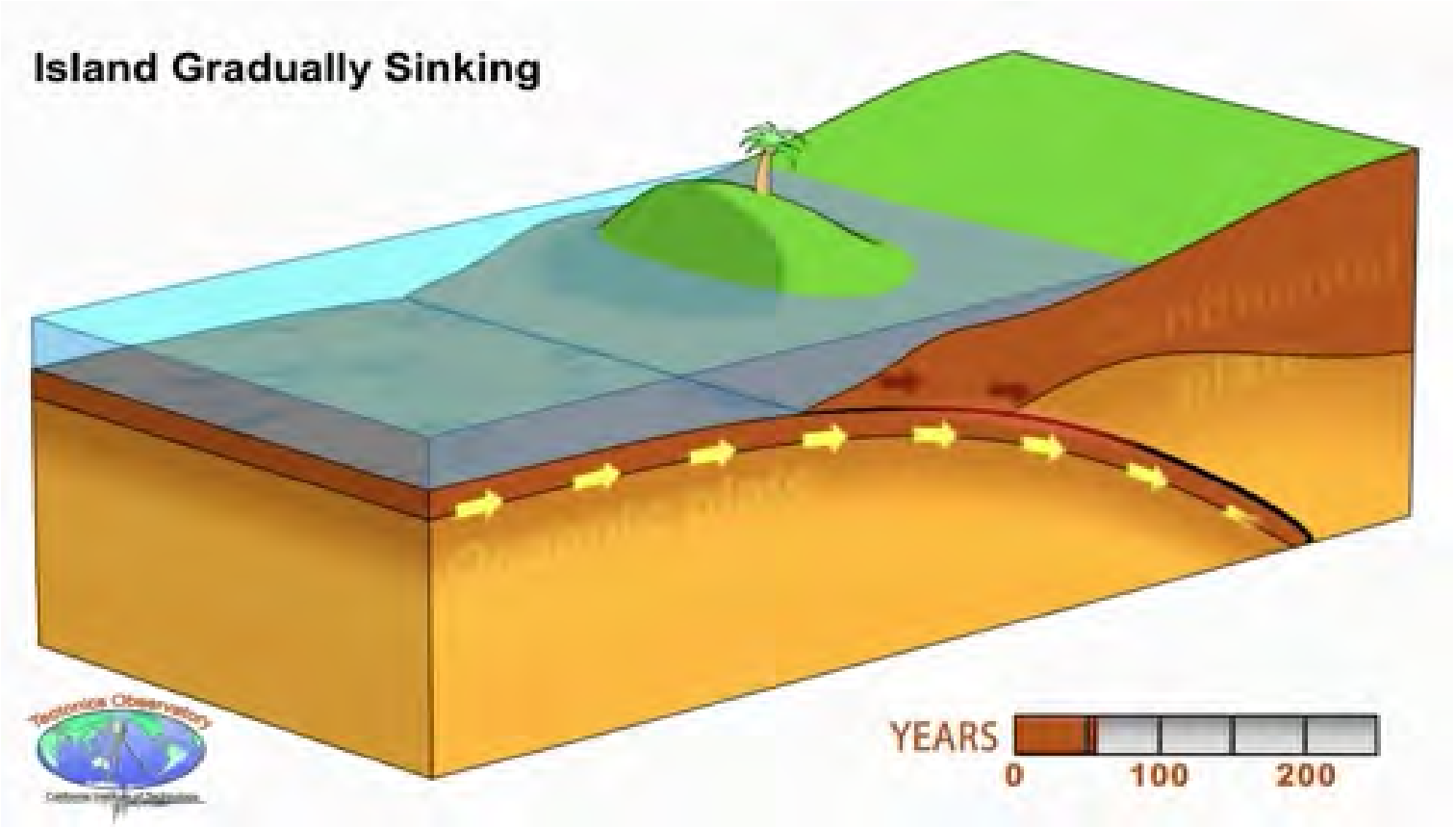
From interseismic coupling to megathrust earthquakes scenarios

case of the Chilean subduction zone

Marianne Métois

30/11/2017

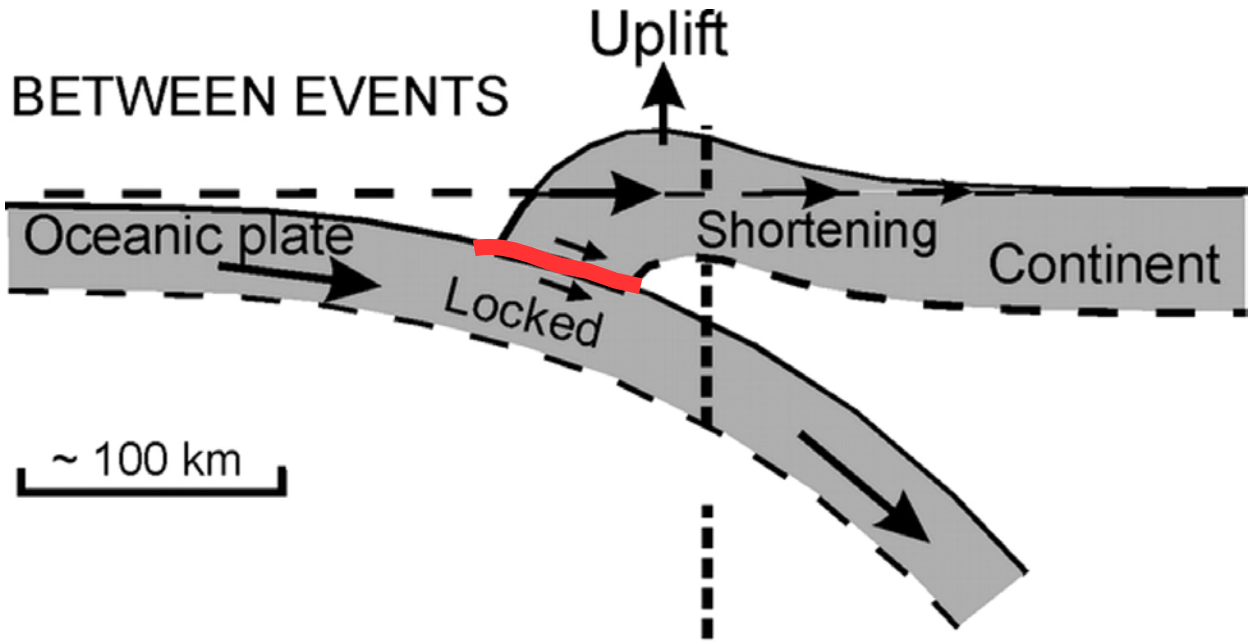
The Calm / The Storm



Principal stages of the seismic cycle on a major active fault

- Interseismic 10 - 1000 yrs
- Coseismic 1s - 10mn
- Postseismic ~100 yrs ?

The Calm / The Storm



The upper plate deformation pattern during interseismic phase gives us insights on **the degree of locking** of the interface

A purely kinematic description

$$\Phi = 1 - \frac{V_{\text{dislocation}}}{V_{\text{convergence}}}$$

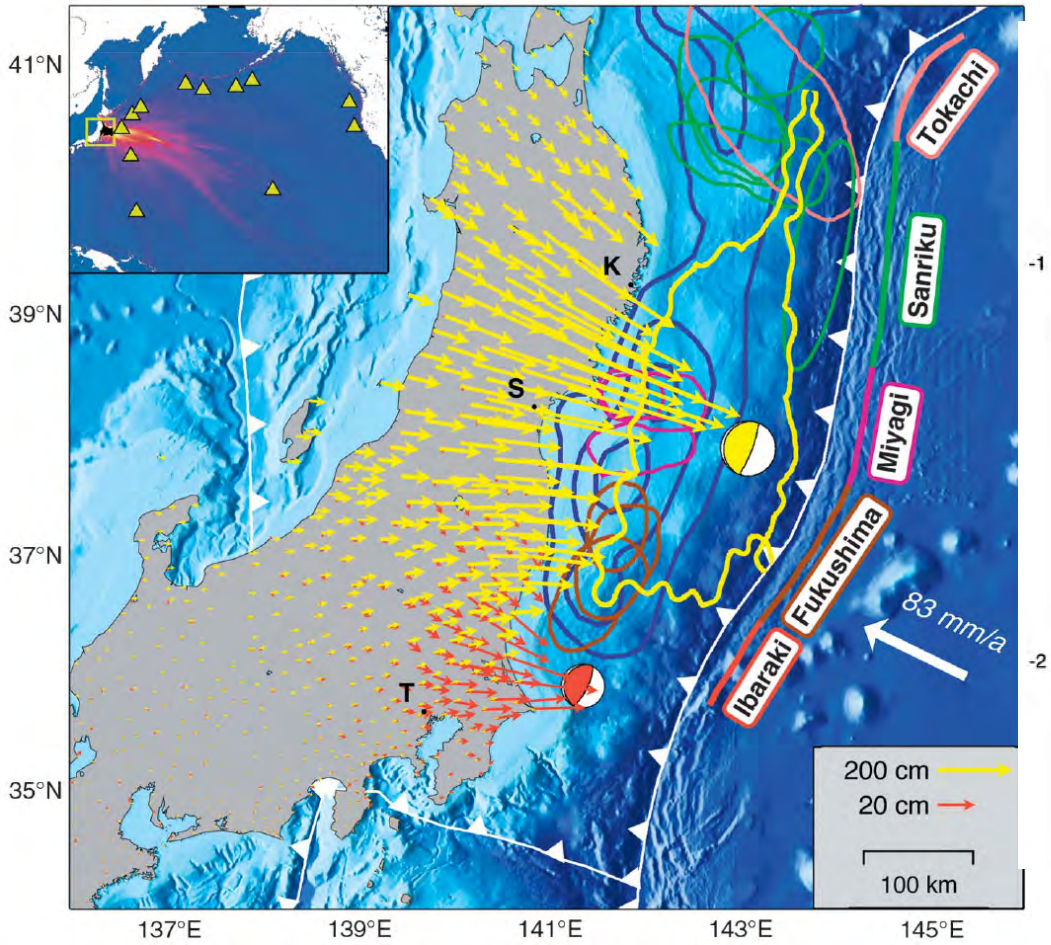
- **0 %** freely creeping interface

  Stable sliding ? Velocity-strengthening?

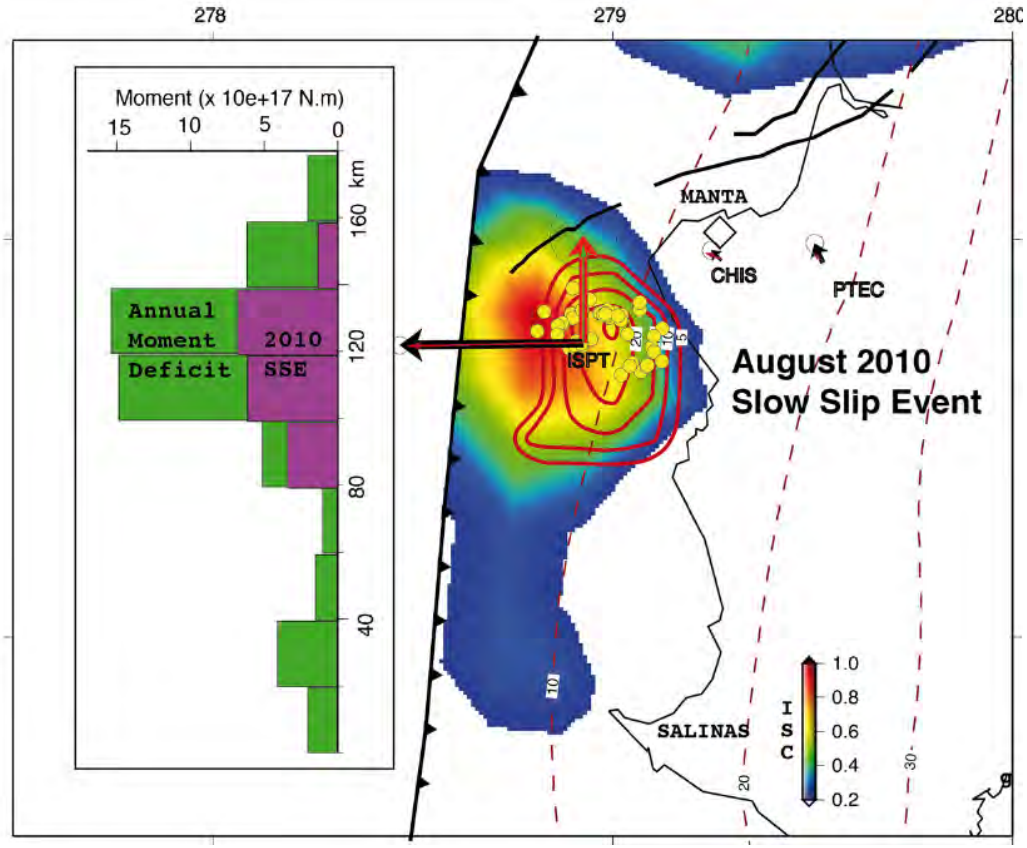
- **100 %** locked interface producing elastic deformation

  Stick-slip ? Velocity-weakening?

The Calm / The Storm



[Simons et al., 2011]



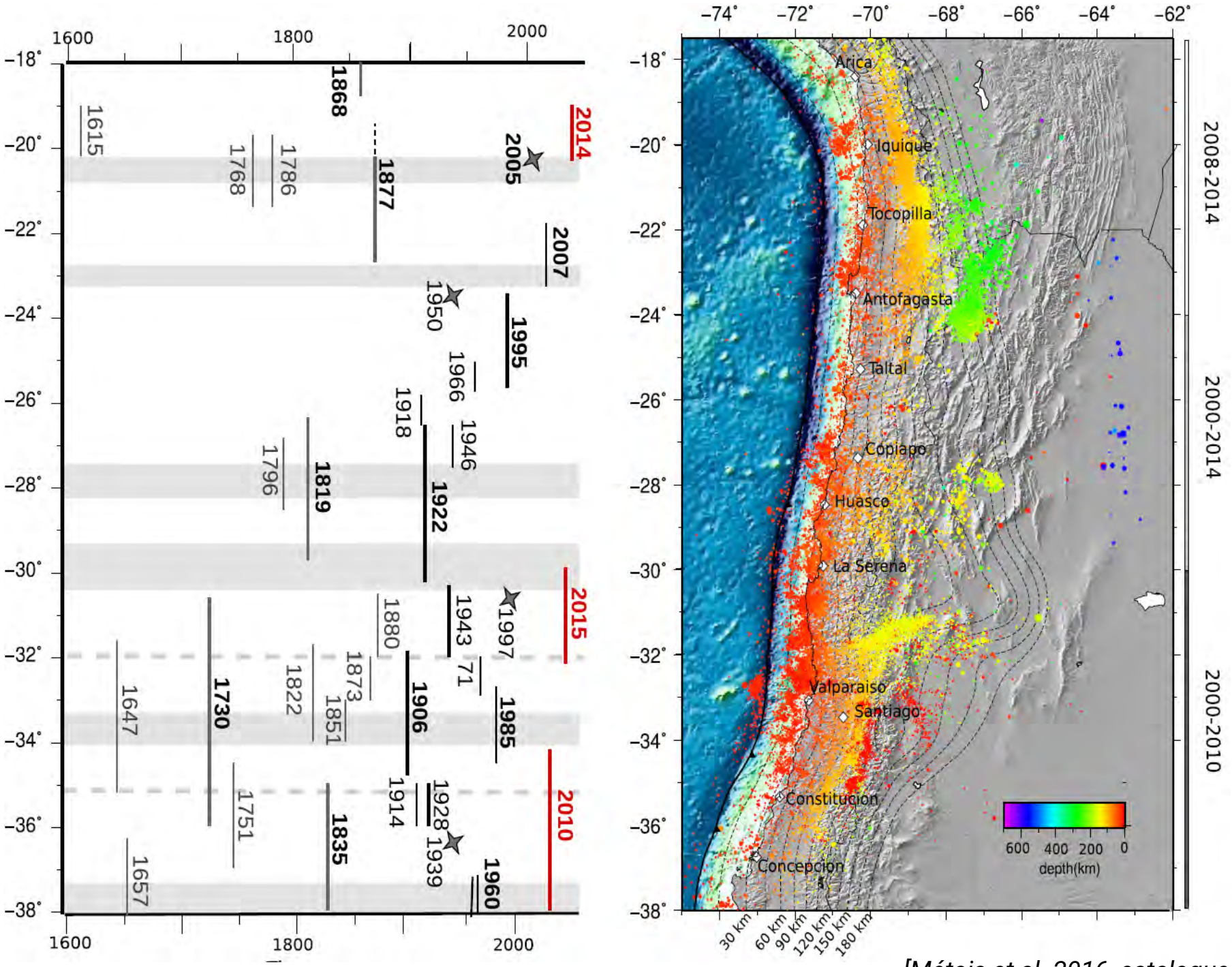
[Chlieh et al., 2014]

What is the physical meaning of coupling ?

Can we use coupling to produce consistent earthquakes scenarios ?

To what extent are the moment/slip balances reliable ?

Interseismic coupling assessment : the Chilean context

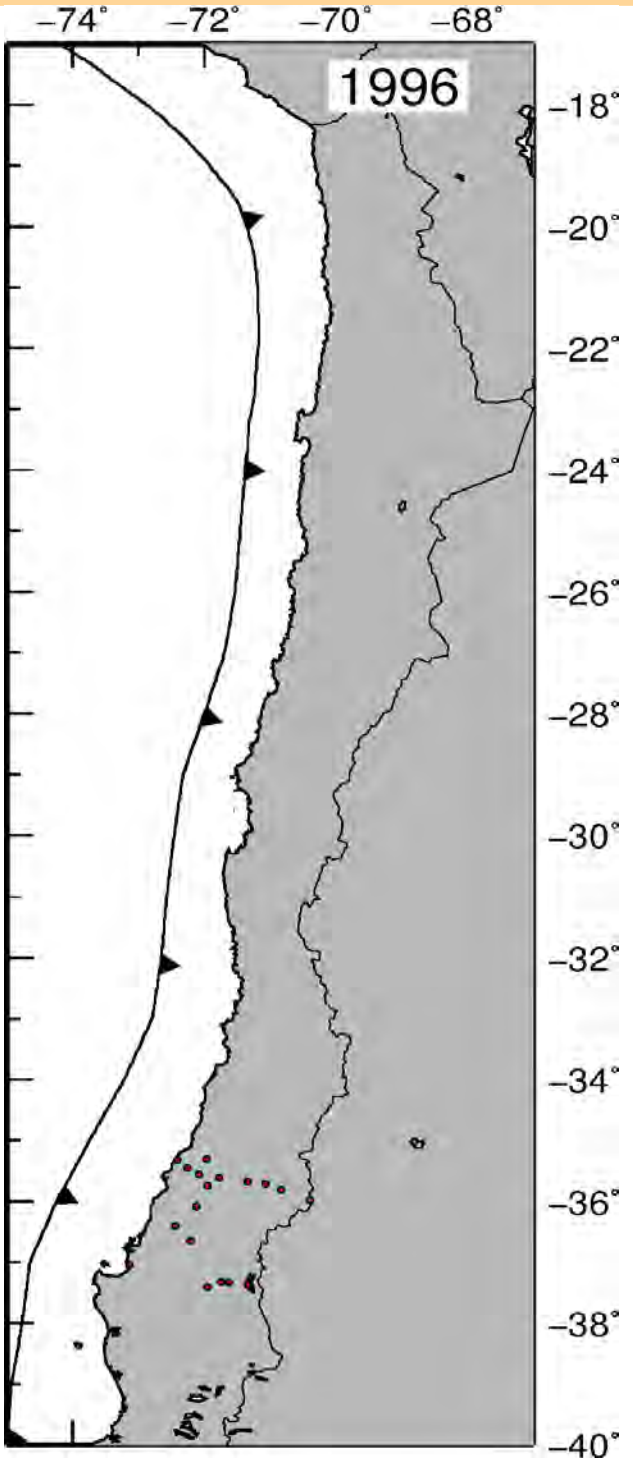


[Métois et al. 2016, catalogue du SSN]

Interseismic coupling assessment : measuring strain

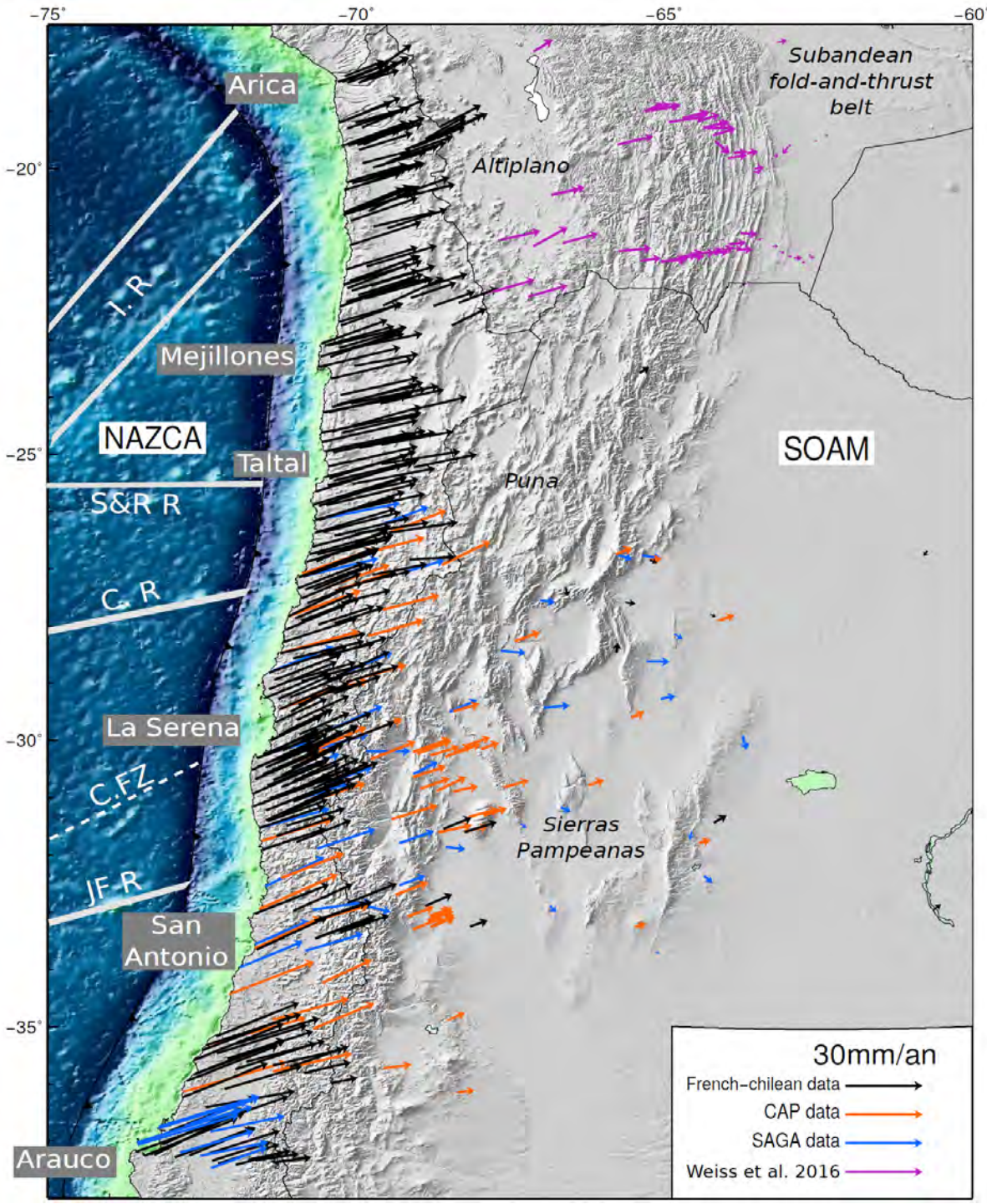
- Instrumentation of the margin started in the early 1990 (sGPS, *J.C Ruegg*)
- International effort (Chile, France, US, Germany mainly)
- Race against time to measure interseismic strain
- New chilean network of dense cGPS for early warning installed since few years

- A large part of the margin is now in a complex phase of the seismic cycle : post+interseismic



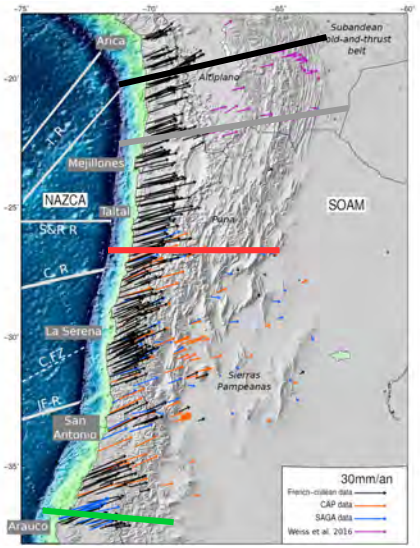
★ Megathrust earthquakes
★ Intraslab earthquakes

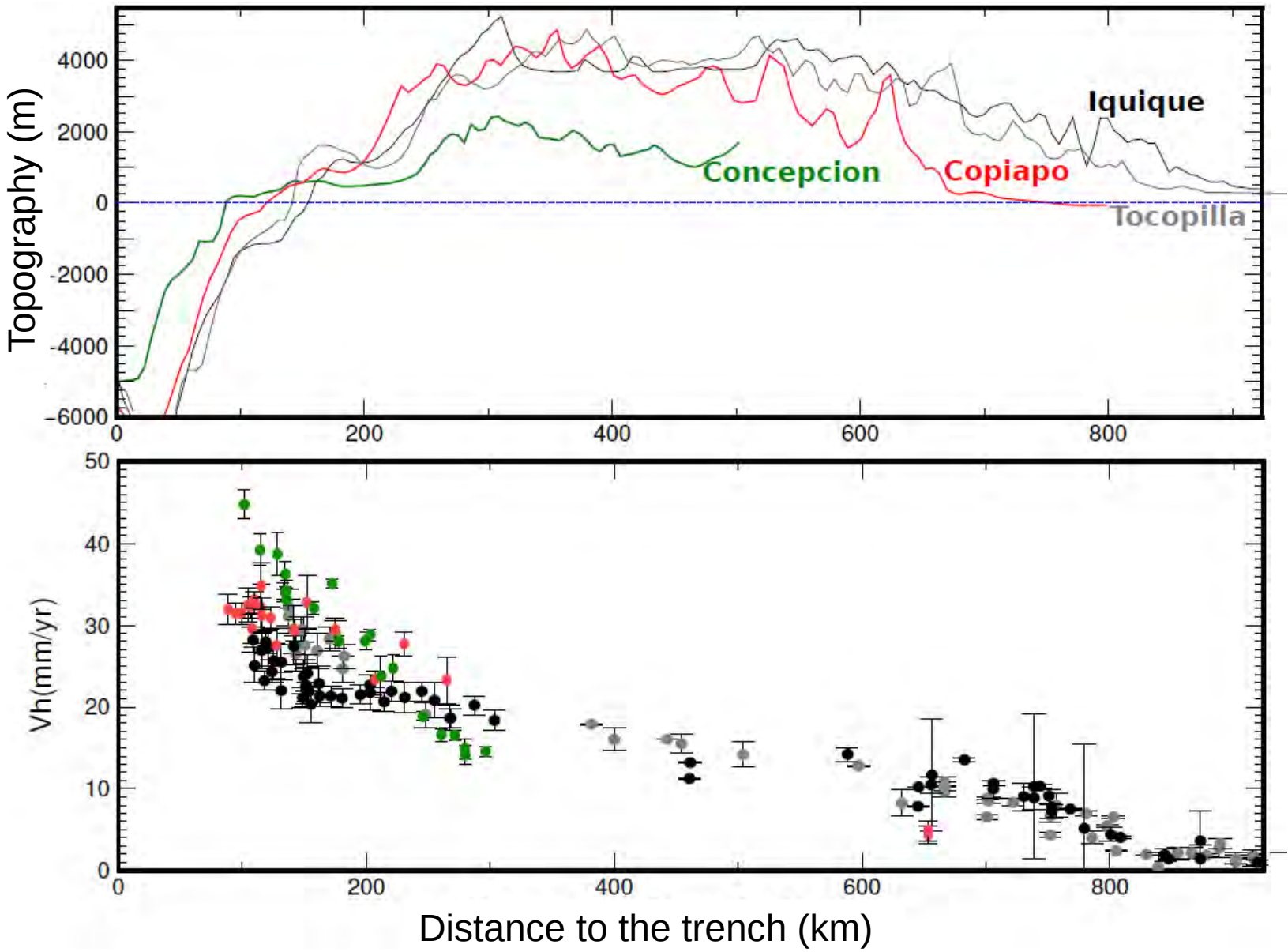
Interseismic coupling assessment : measuring strain



Most complete interseismic picture

Interseismic coupling assessment : measuring strain



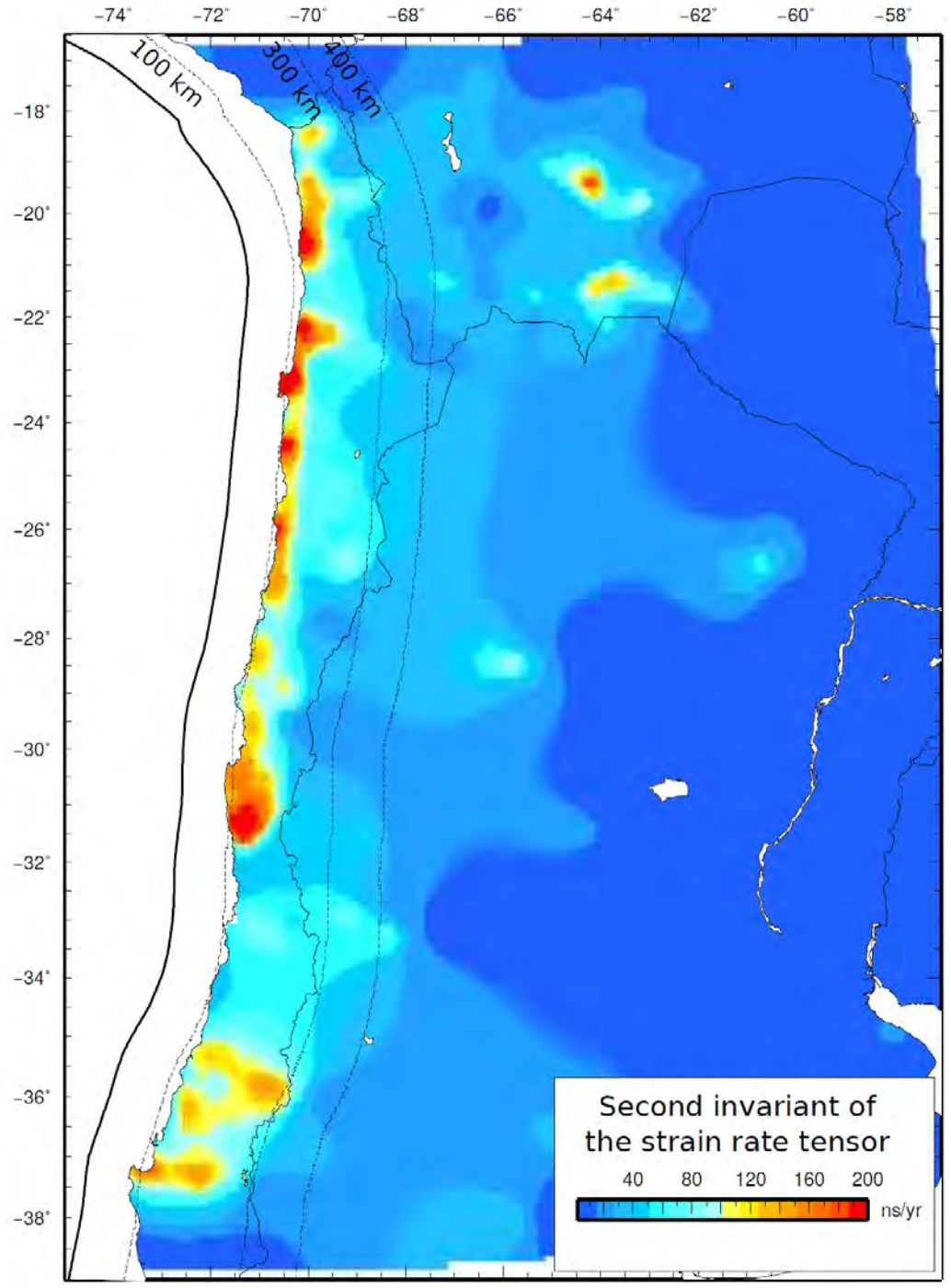


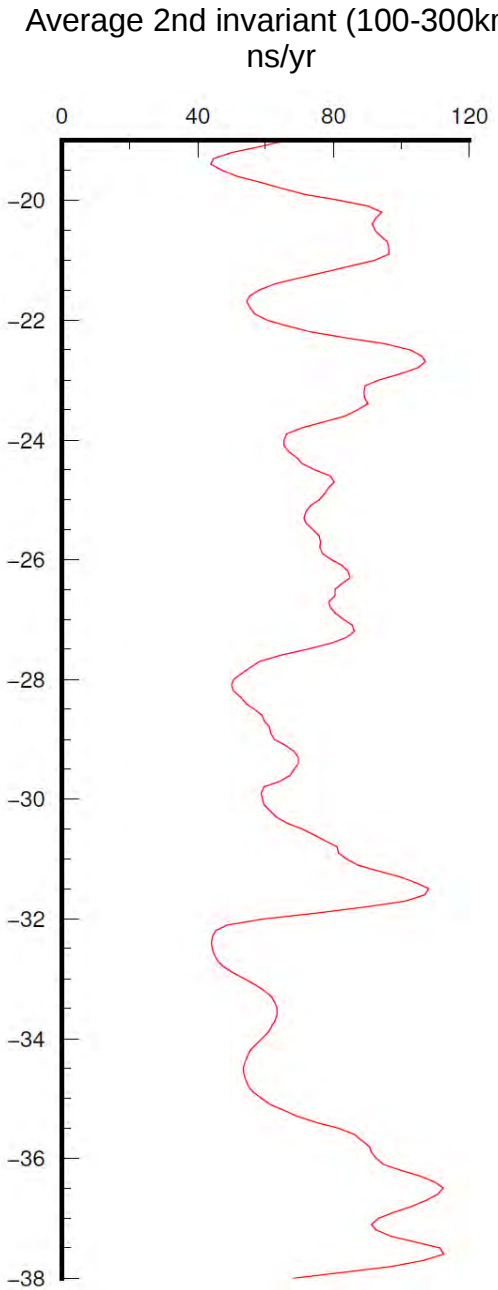
1- The Andes belt widens from South to North, the coast-trench distance generally increases

2- Few measurements across the entire belt (middle to far field)

3- Along-strike variations in the near-field strain gradient

Interseismic coupling assessment : measuring strain





Use of SPARSE software

[Haines & Holt, 1993]

Along-strike variations in the near-field strain rate draw a first kinematic segmentation

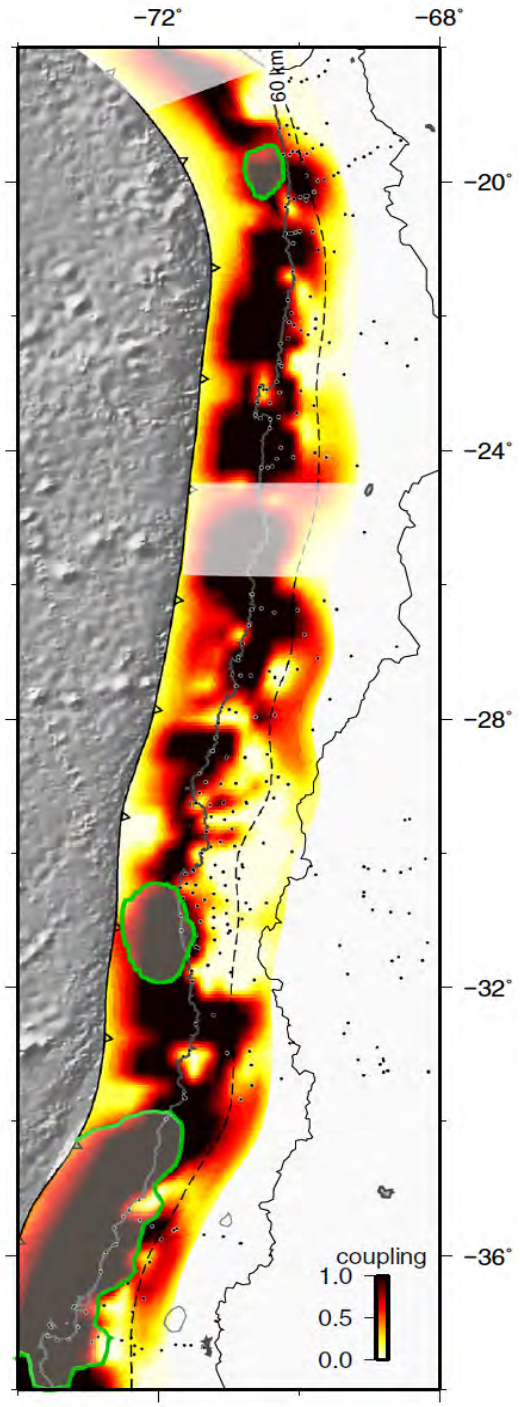
$$E = \sqrt{(\dot{\epsilon}_{xx}^2 + \dot{\epsilon}_{yy}^2 + 2\dot{\epsilon}_{xy}^2)}$$

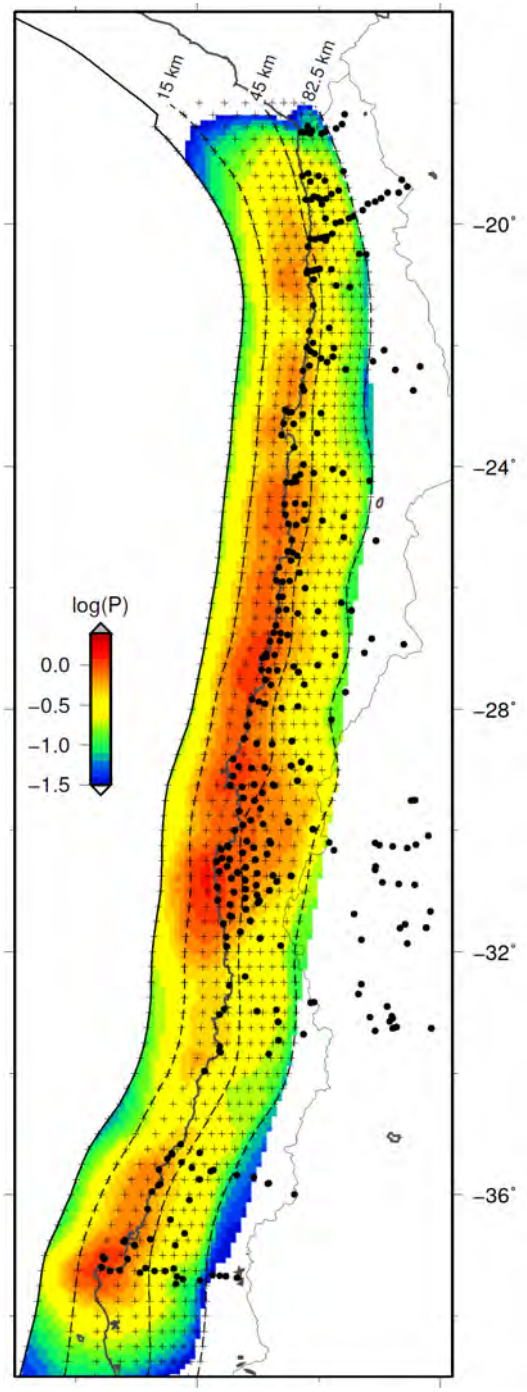
Interseismic coupling assessment : conceptual framework

Interseismic strain
=
Elastic loading + Andean sliver eulerian motion

- Use of Tdefnode developed by R.Mc Caffrey, based on **Okada's equations (purely elastic)**
- Andean belt (from the trench to the eastern fold and thrust belt) considered as rigid. Take up to 1cm/yr in the Arica bend, few mm/yr east of Santiago

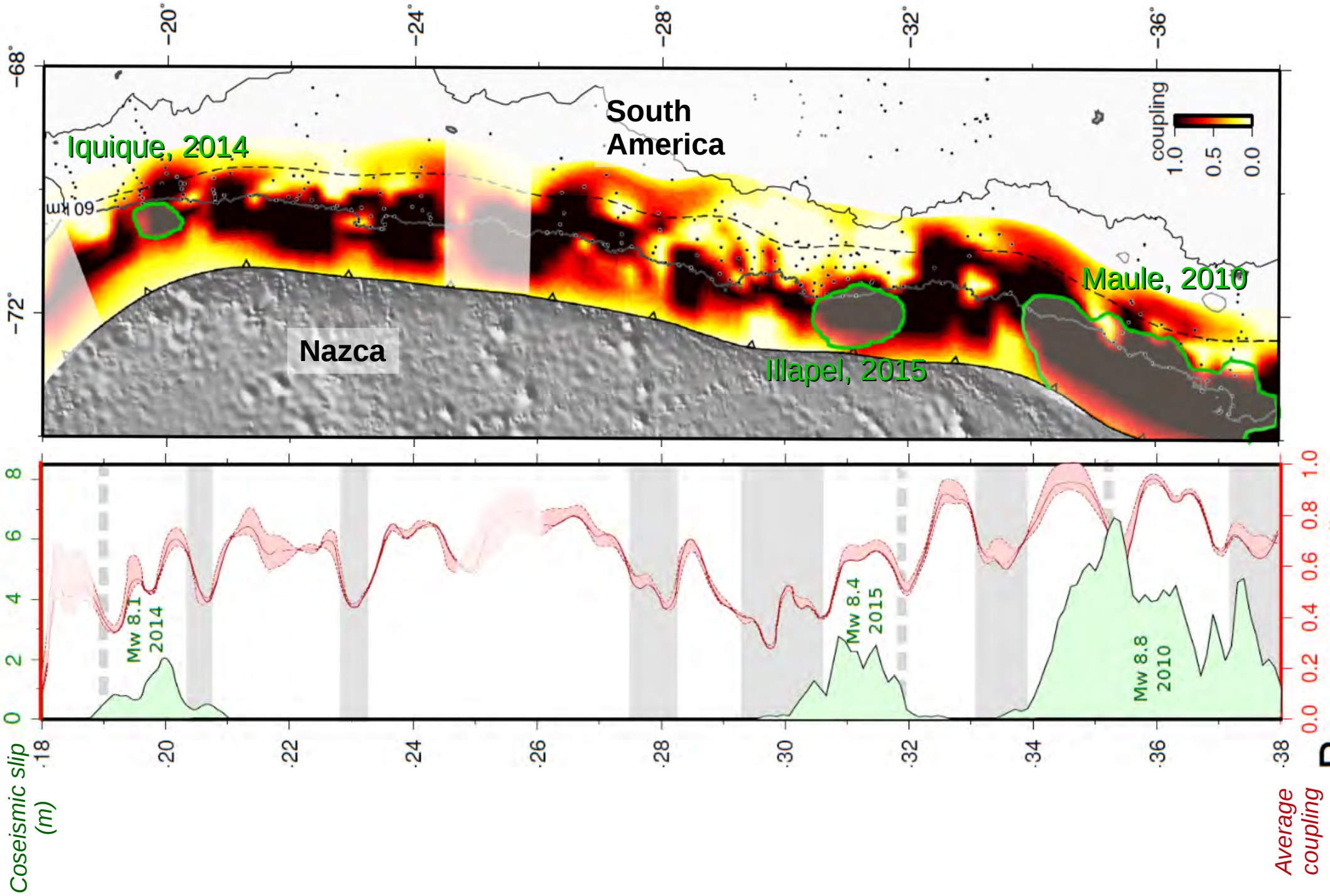
Interseismic coupling assessment



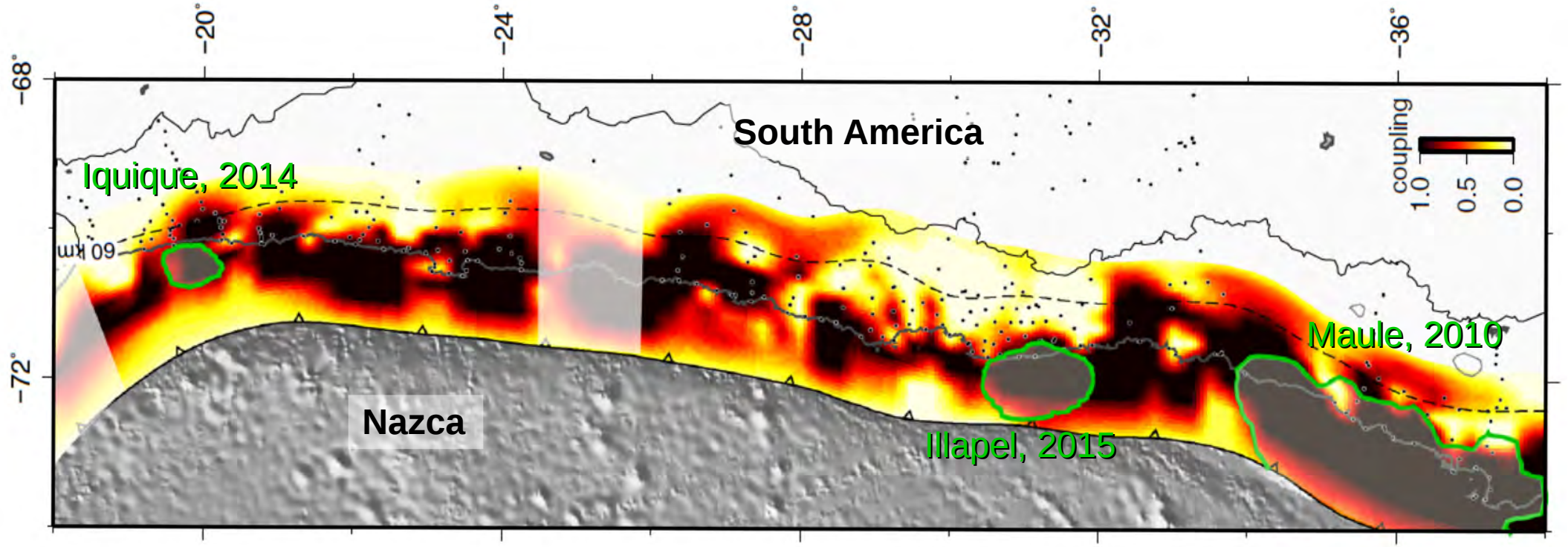


[Métois et al. 2016]

Interseismic coupling segmentation & great earthquakes



Interseismic coupling segmentation & great earthquakes

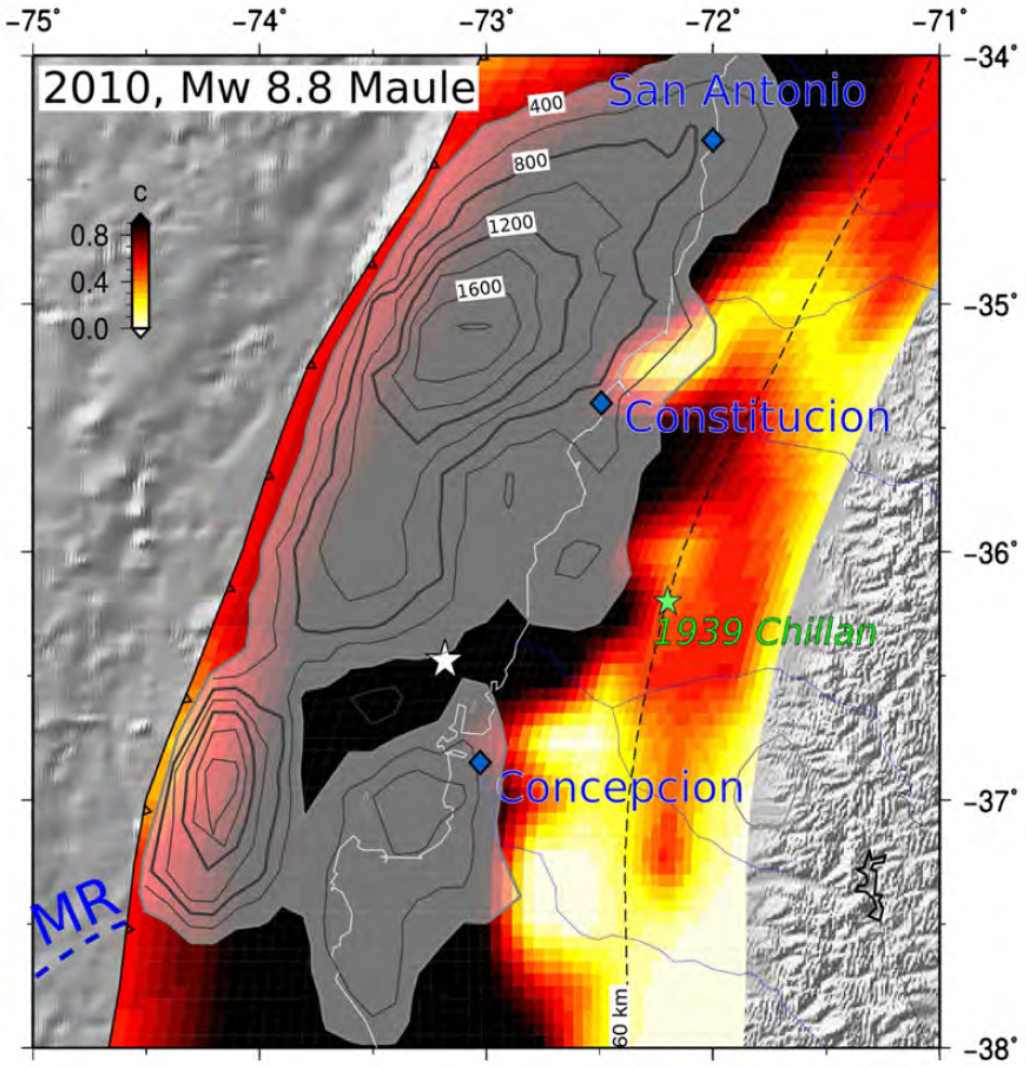


High coupling → Seismic rupture → *Stick-slip velocity-weakening*

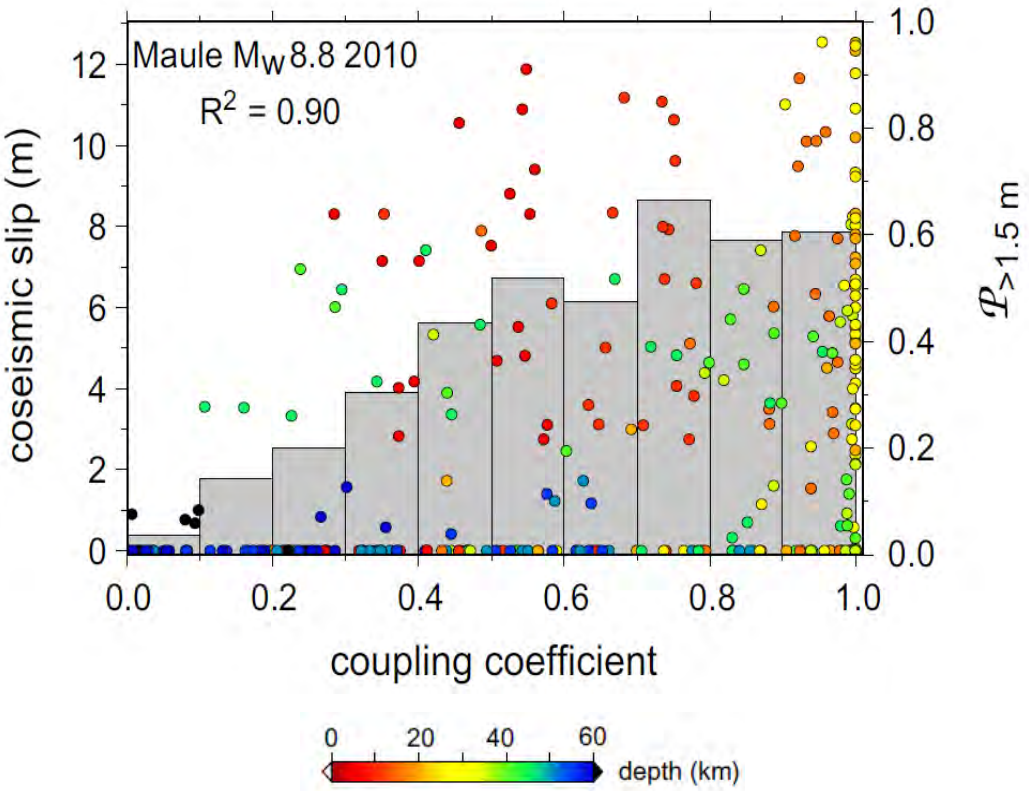
?

Low coupling → Barrier → *Creep velocity-strengthening*

Insights from Maule, Mw 8.8, 2010



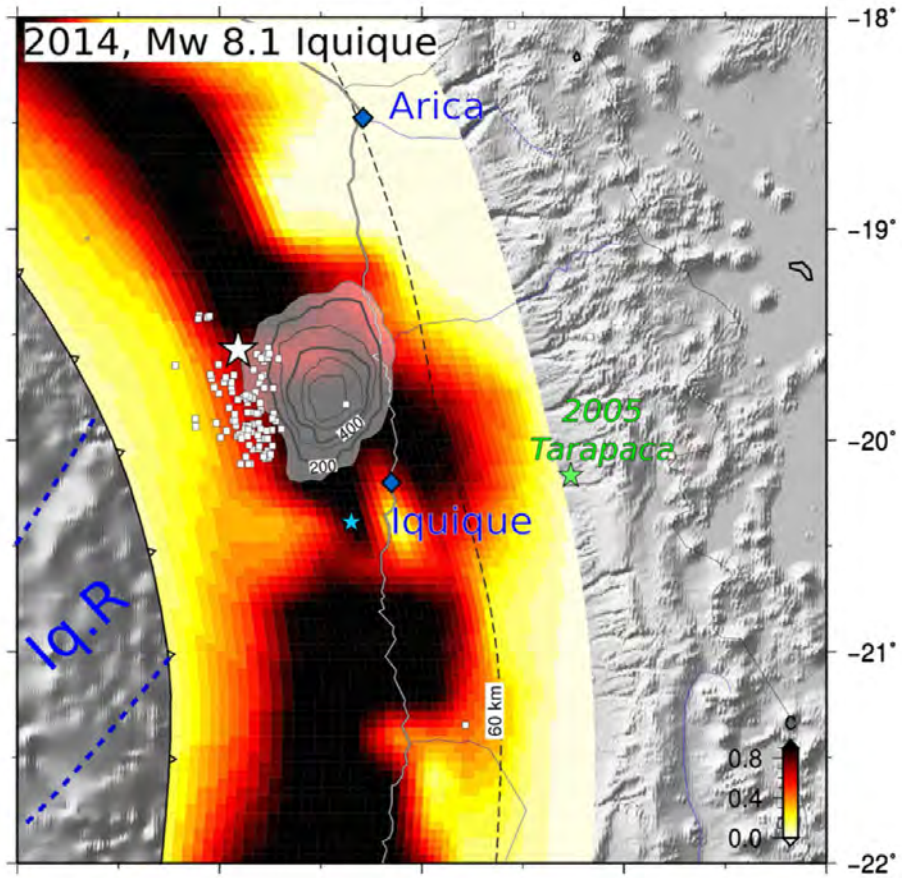
[Vigny et al. 2010, Métois et al. 2016]

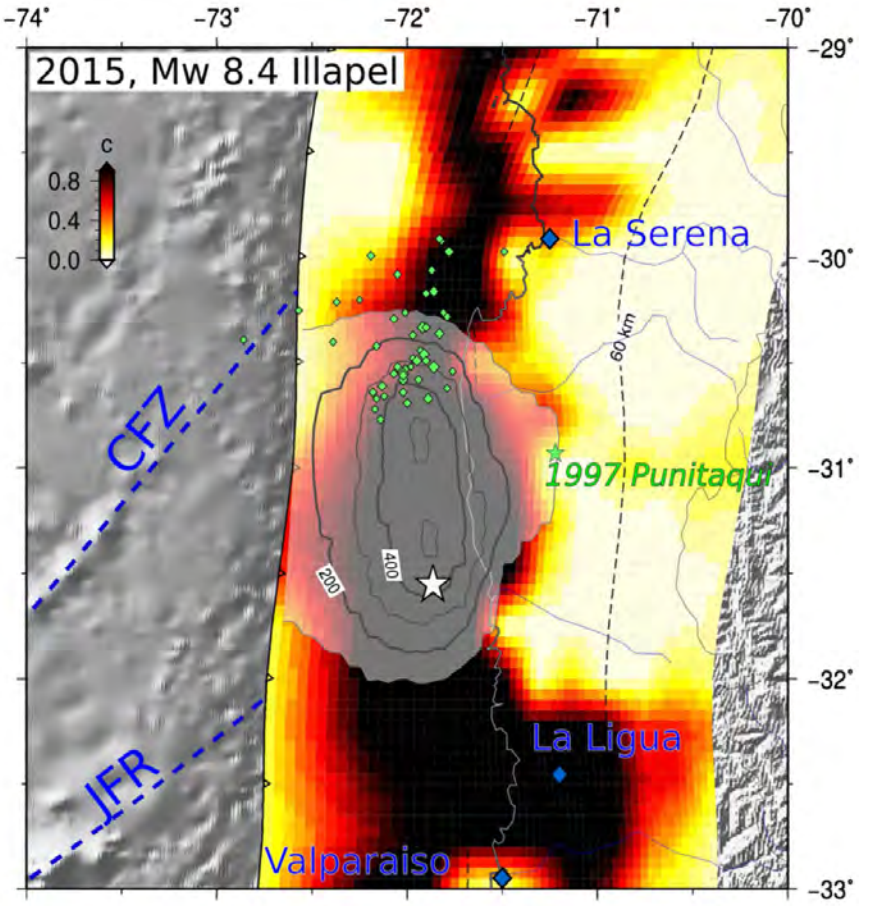


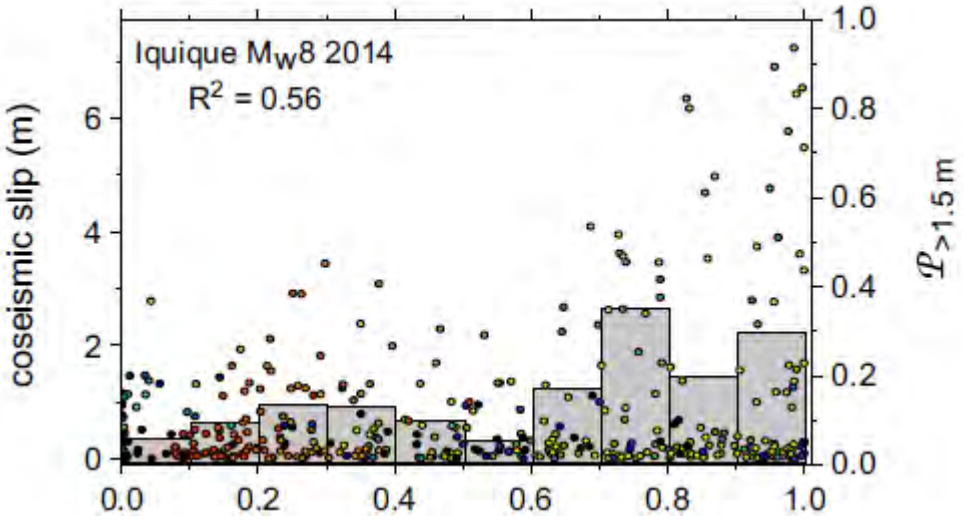
$$P_{>1.5\mathrm{m}/\Phi} = \frac{N_{\mathrm{subfaults}_{>1.5\mathrm{m}/\Phi}}}{N_{\mathrm{subfaults}_{\Phi}}}$$

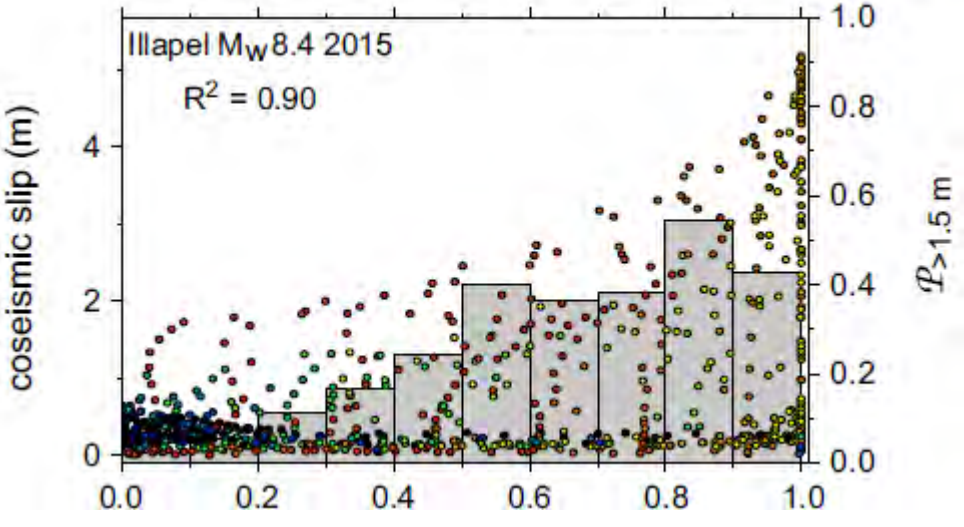
- The higher the interseismic coupling, the higher the probability of rupturing coseismically
- Along-strike kinematically defined LCZ control the rupture length

Insights from Iquique (8.1) and Illapel (8.4)

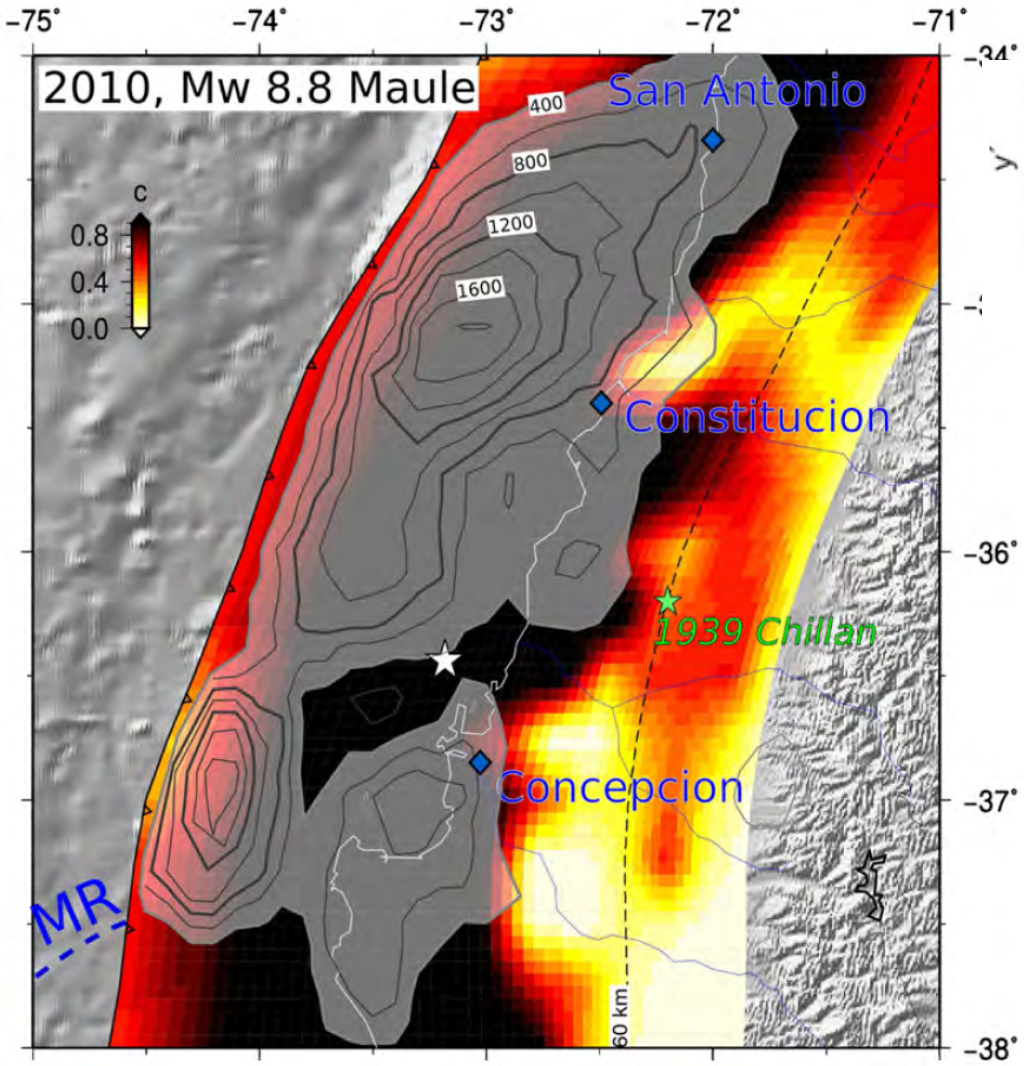




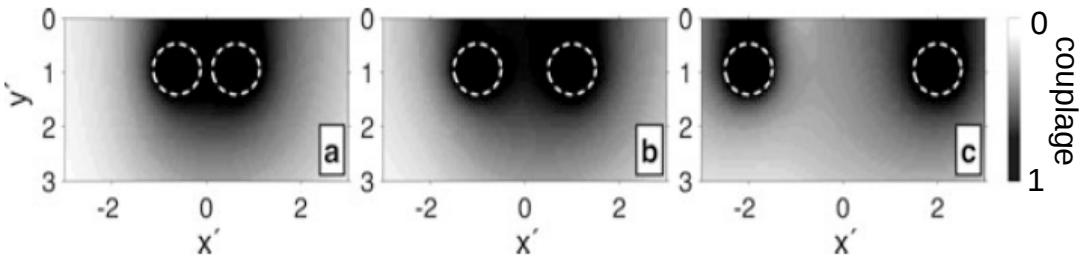




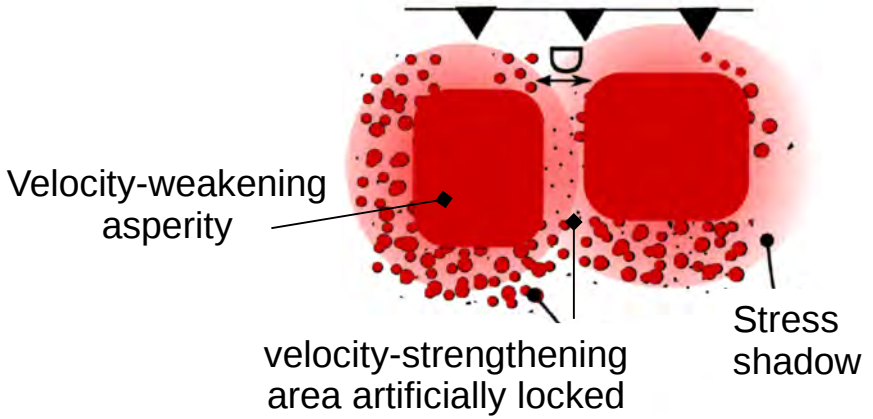
Insights from Maule, Mw 8.8, 2010



[Vigny et al. 2010, Métois et al. 2016]

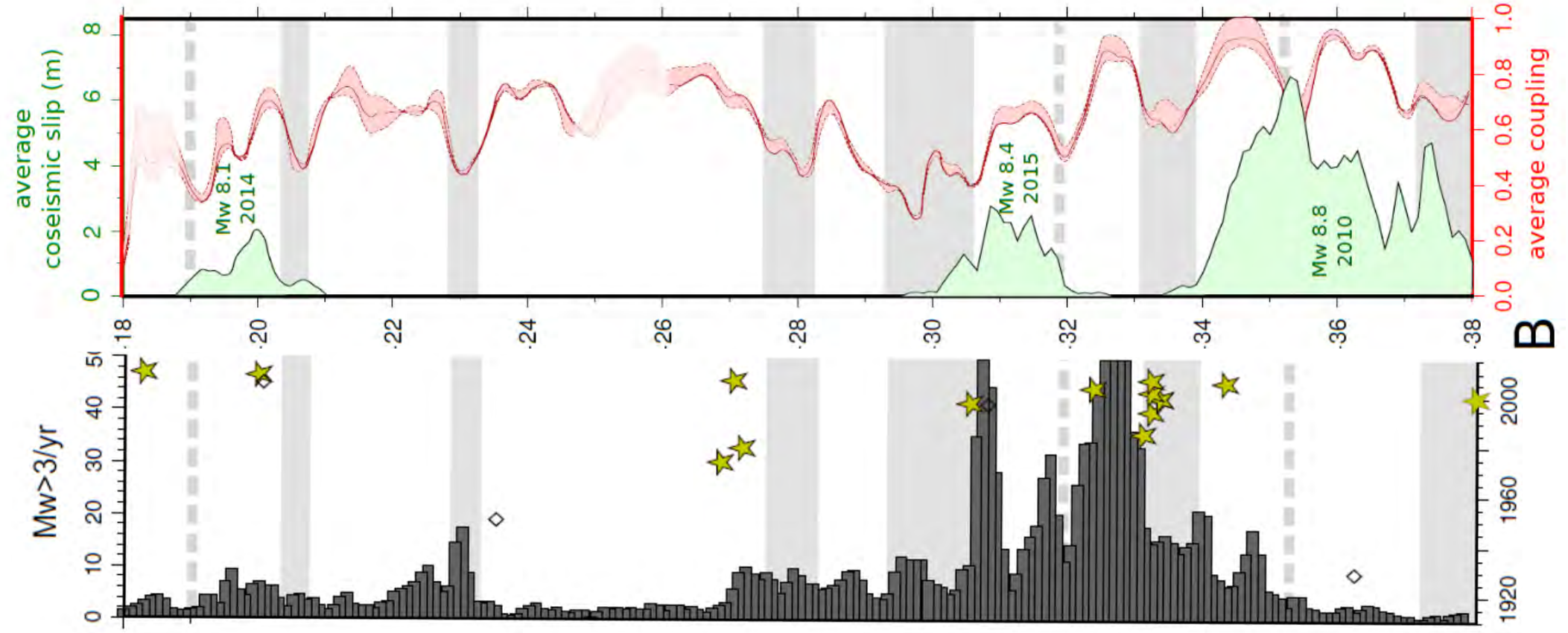


[*Hetland et al. 2010*]



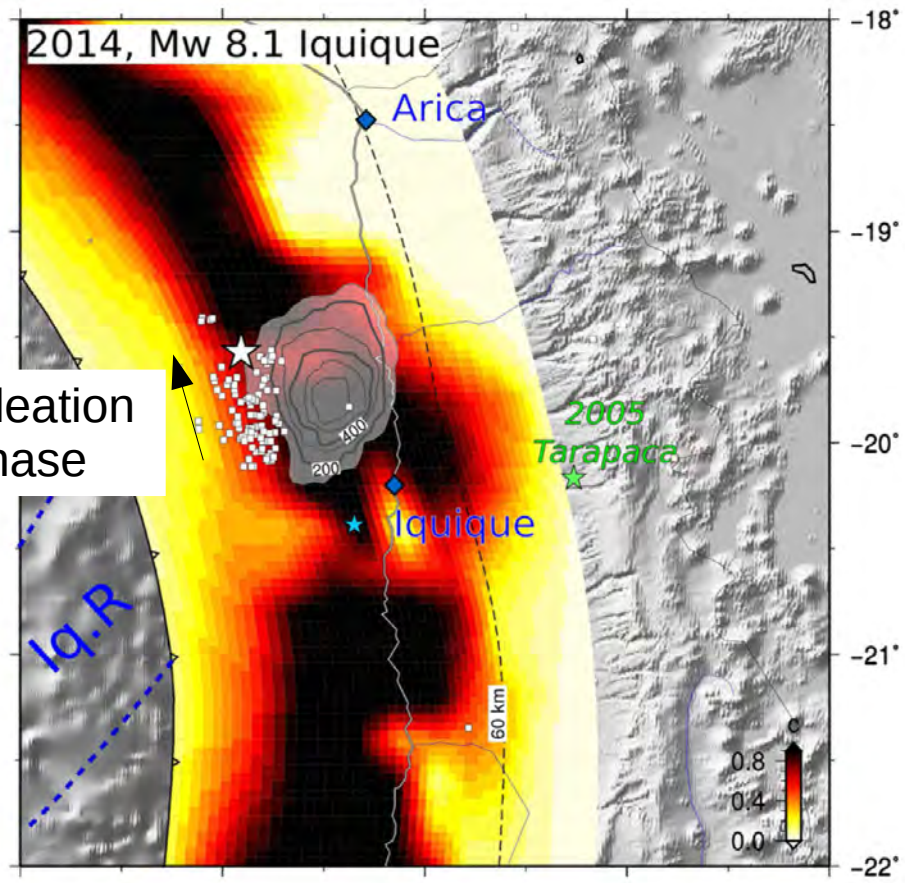
- Blurry vision of velocity weakening / strenghtening asperities on the fault : **apparent coupling**
- **Mapping coupling is not sufficient to anticipate the rupture dynamics**
- We need to link coupling coefficient to frictional parameters of the interface and reconstruct the segment history to better assess the initial conditions

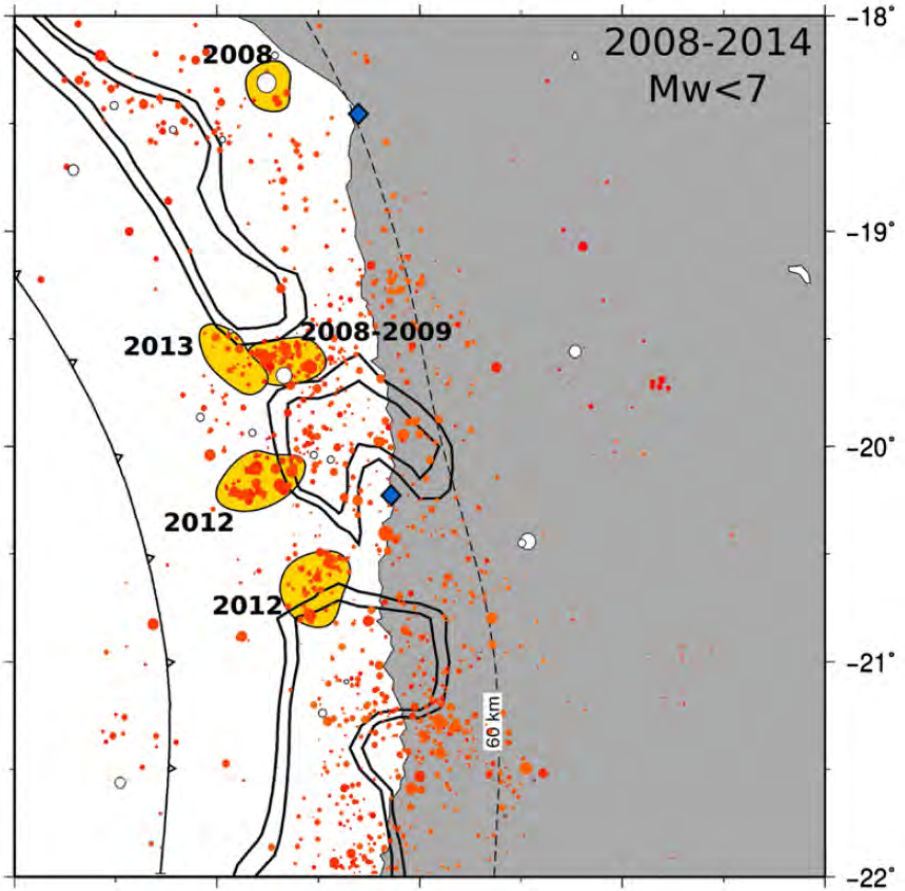
The not so calm interseismic phase



- First order correlation between detected swarms and intermediate coupling zones

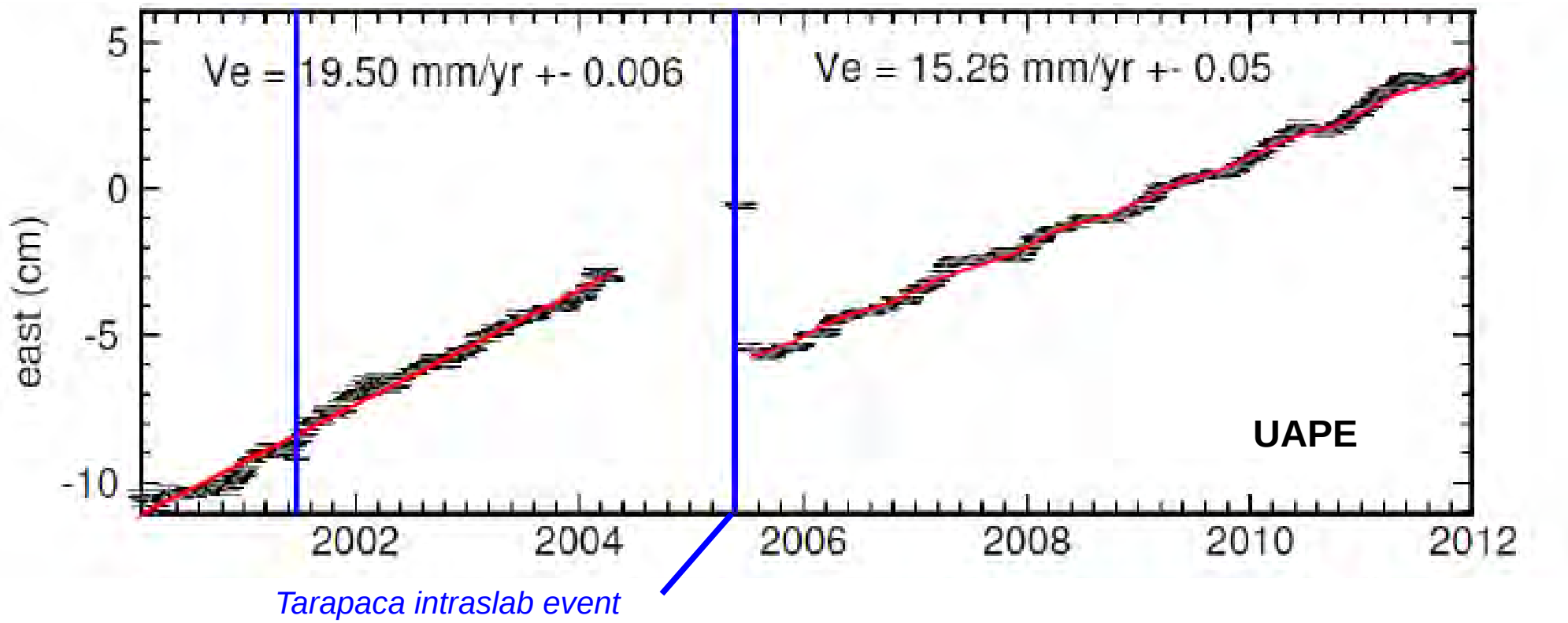
The not so calm interseismic phase





- First order correlation between detected swarms and intermediate coupling zones
  - **Coupling helps detecting possible candidates for future nucleation**

The not so stable interseismic phase

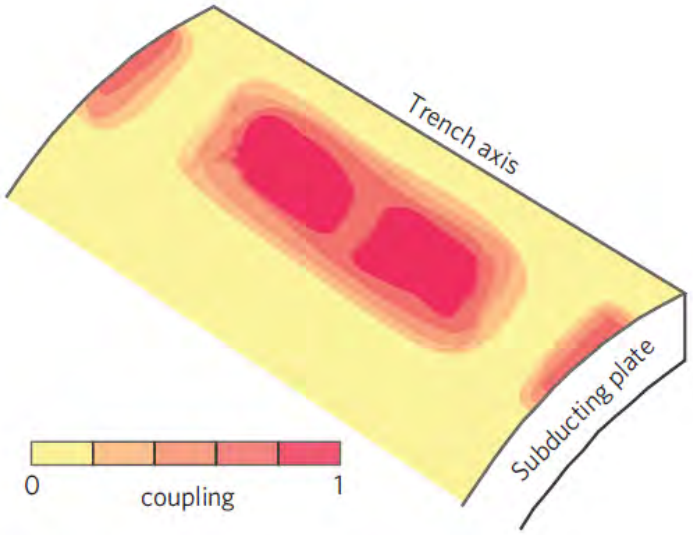


- Does coupling vary during the interseismic period ?
- No large SSE in Chile so far : maybe detected by tiltmeters ?

[Boudin et al. In prep]

Lessons from the Chilean case

Kinematic coupling

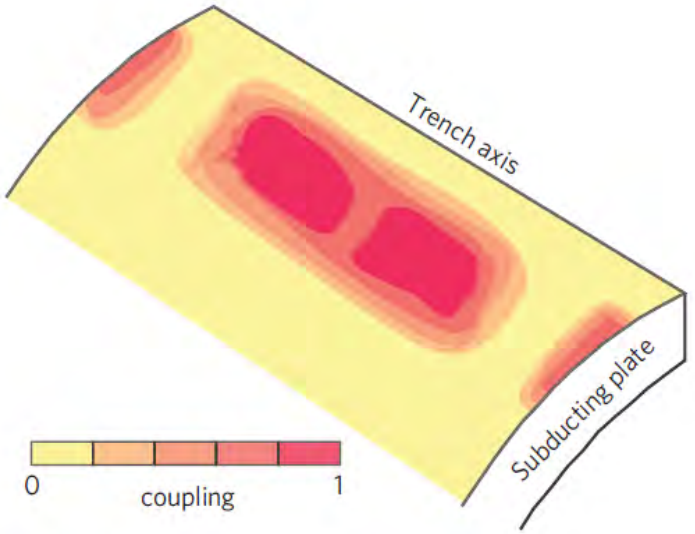


[Kaneko et al. 2010]

- Length of segments : good apriori idea of earthquake length and magnitude
- Help constraining the dynamics of coming earthquakes
- Location of swarms and nucleation phases in intermediate coupling zones

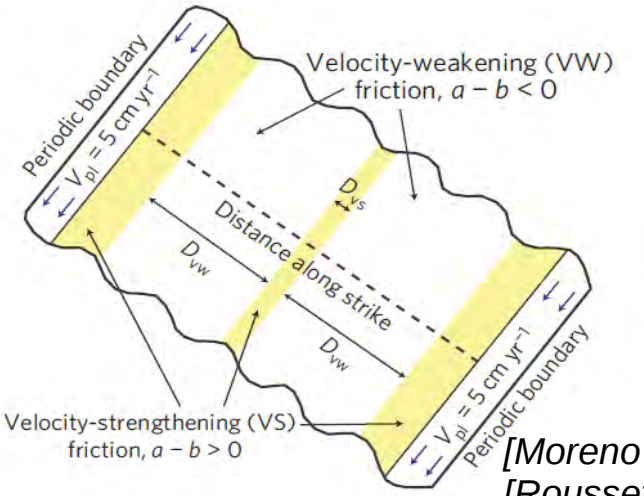
Lessons from the Chilean case

Kinematic coupling



[Kaneko et al. 2010]

Frictional parameters

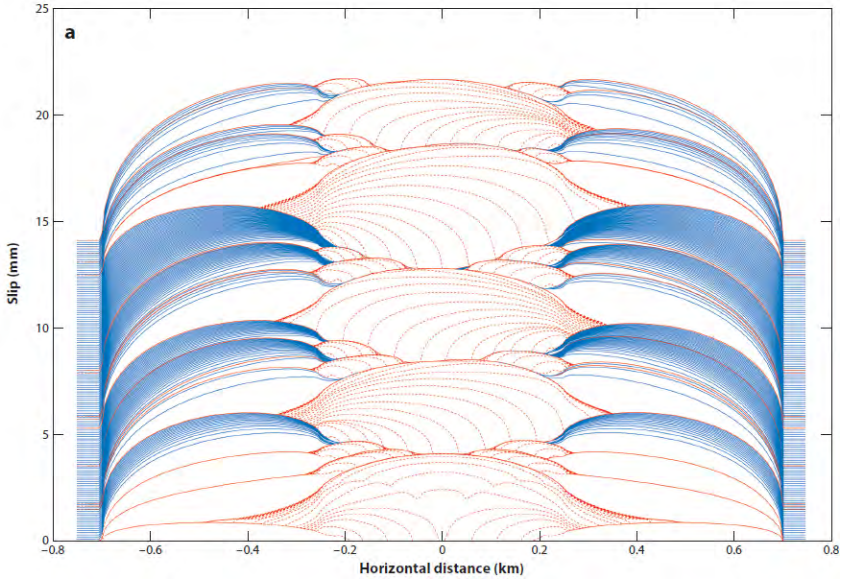


[Moreno et al. 2014]
[Rousset et al. 2016]
[Cubas et al. 2013]

?

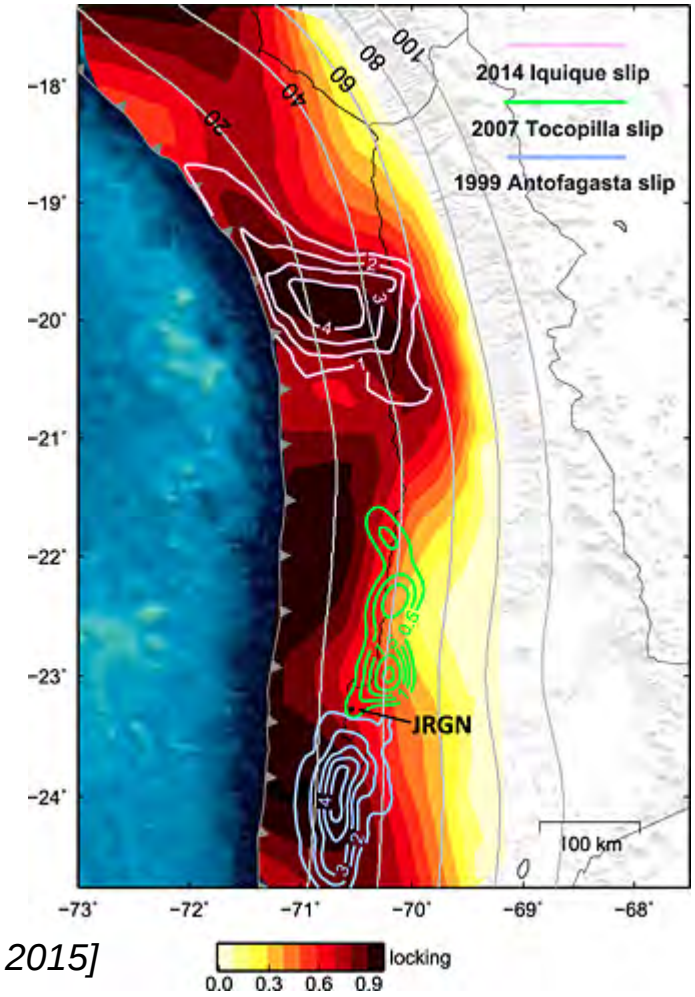
Initial conditions (stress state and seismic history)

Rupture scenarios (stress state)



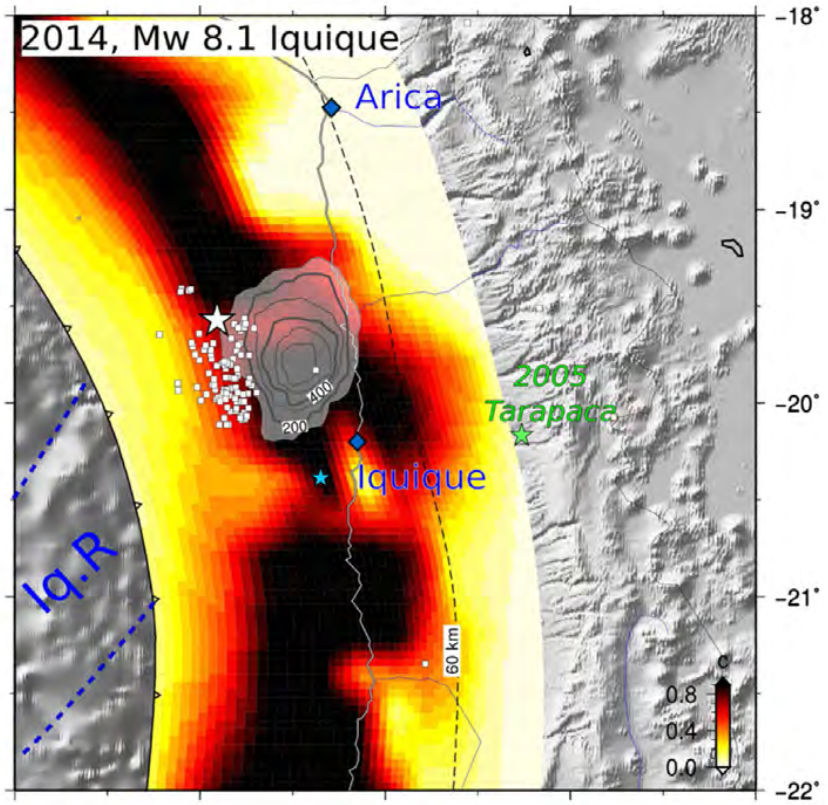
Moment balances

Visco-elastic model, no sliver



[Li et al. 2015]

Elastic model, 1 cm/yr sliver



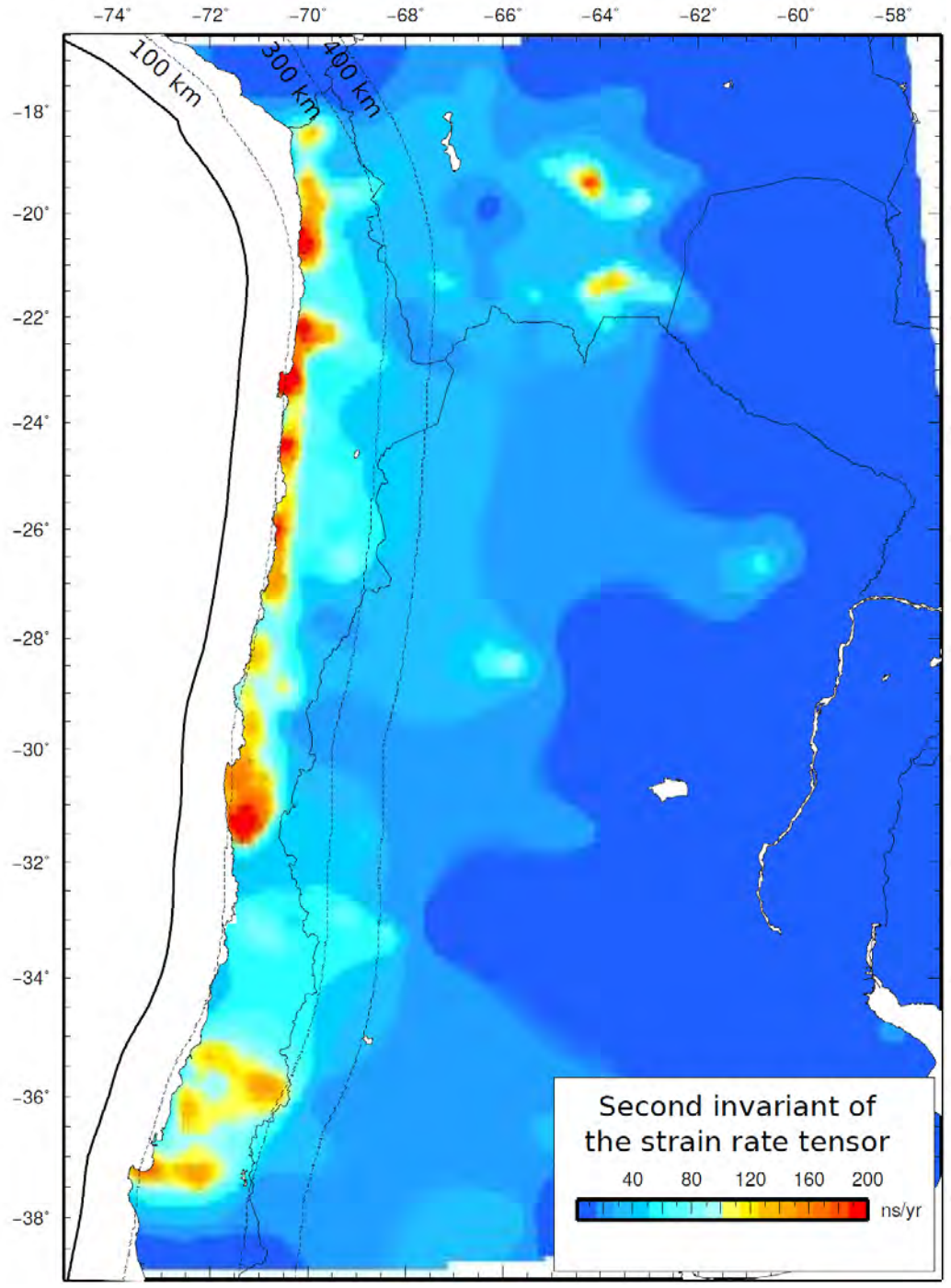
- Calculation of accumulated moment highly **depends on the Andean sliver velocity**
- If part of this far-field deformation is due to **visco-elastic deformation**, interseismic accumulated moment is largely under-estimated !

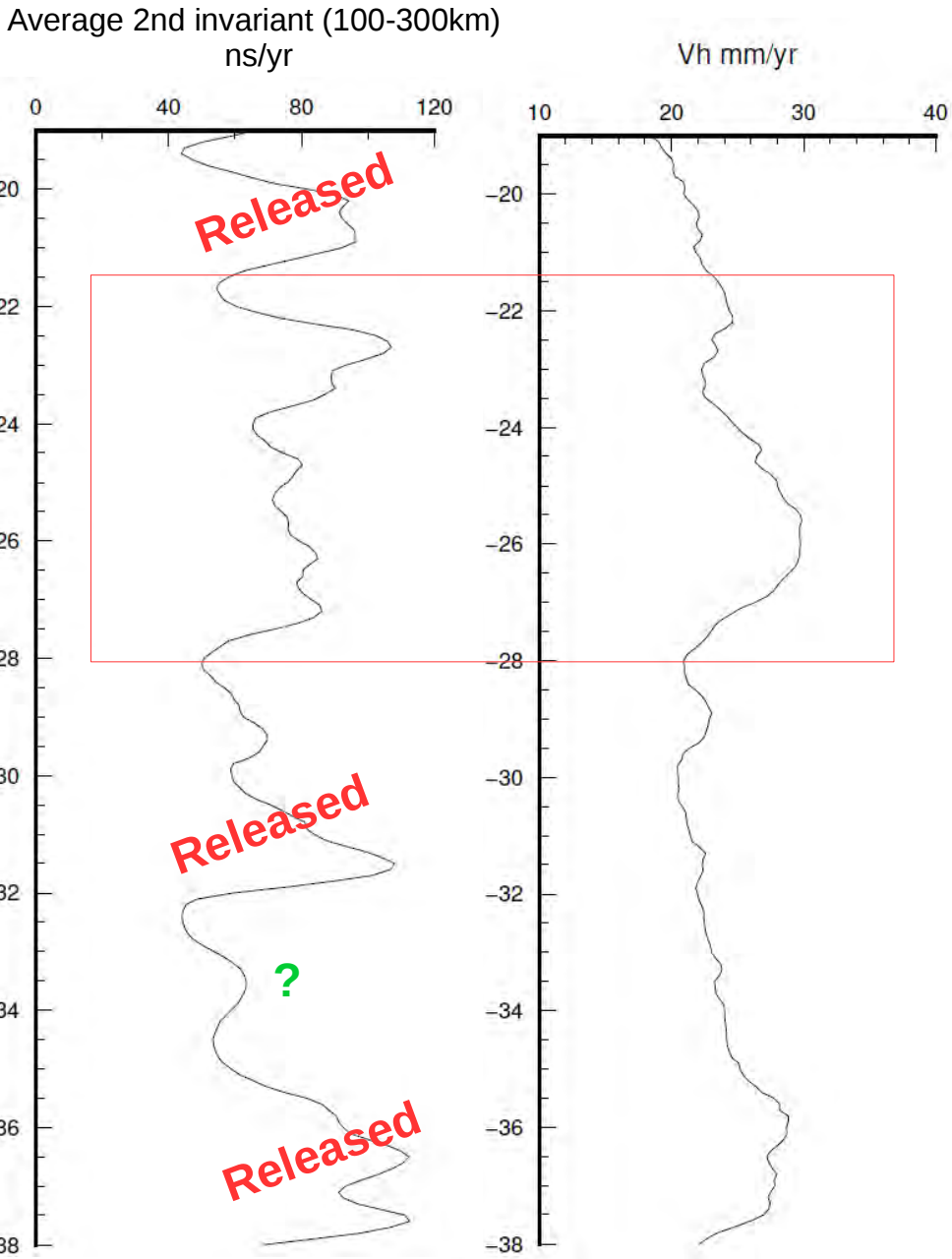
Interseismic coupling can help

- Assessing the size and location of future megathrusts
- Constraining the dynamics of coming earthquakes (but not alone !)
- Identifying swarm prone areas where nucleation phases could occur
- Give insights on moment balances over seismic cyles ?? still unsure

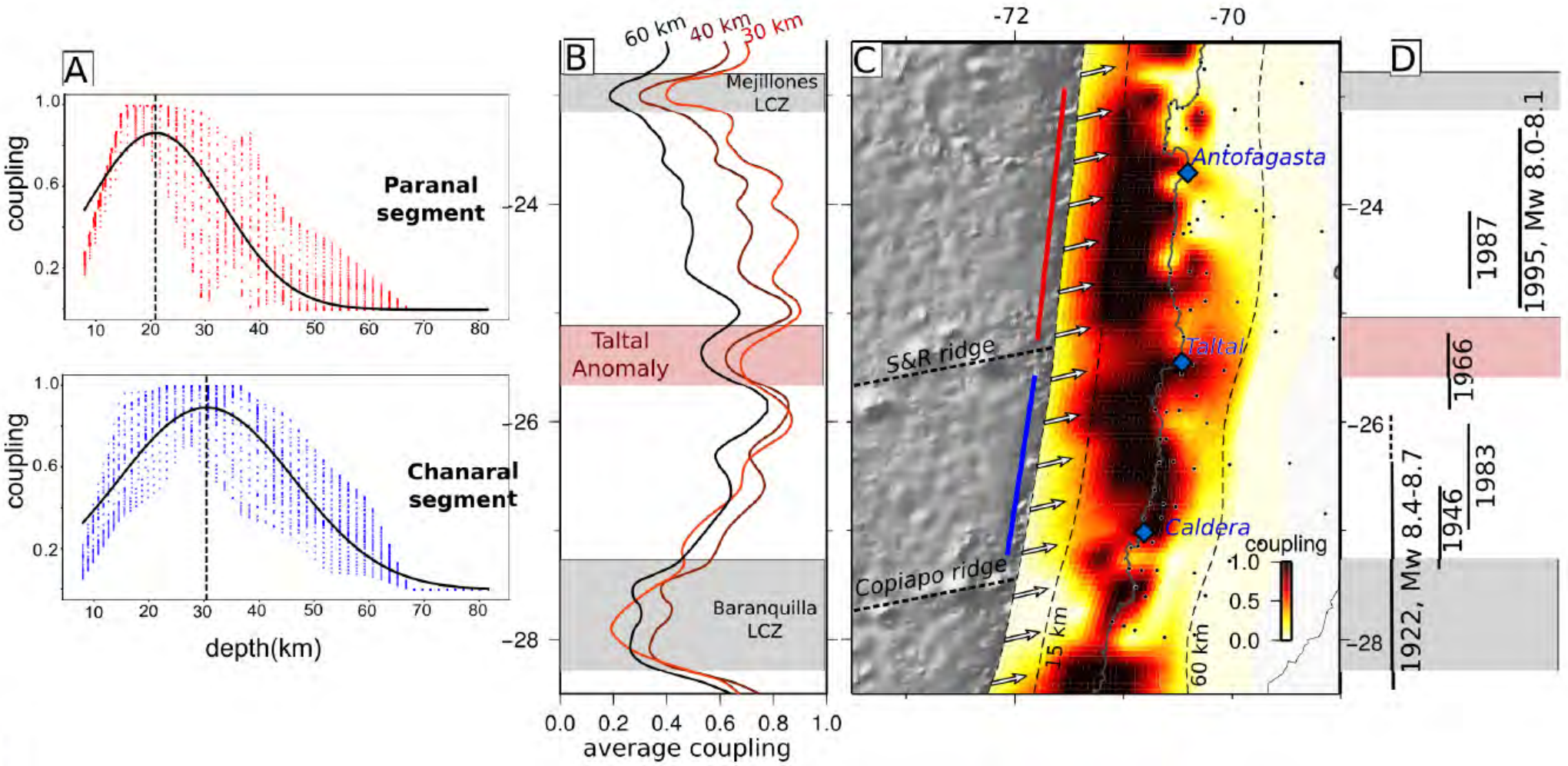
Thank you for your attention

What's next ?


100 km
300 km
400 km
Second invariant of
the strain rate tensor
40 80 120 160 200
ns/yr


Average 2nd invariant (100-300km)
ns/yr
Vh mm/yr
Released
Released
?
Released

What's next ?



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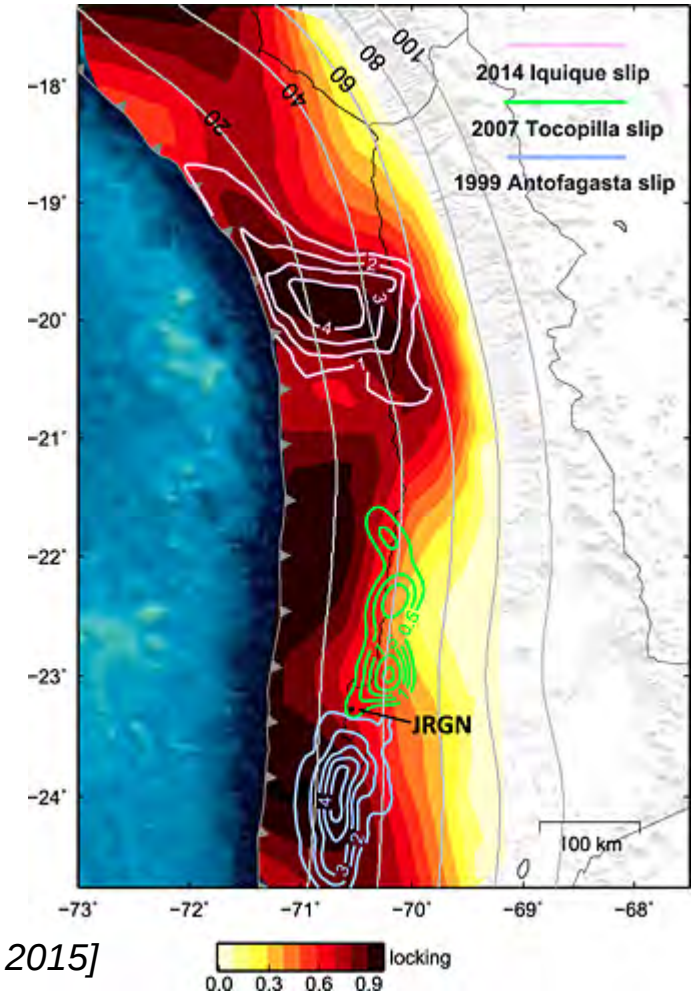
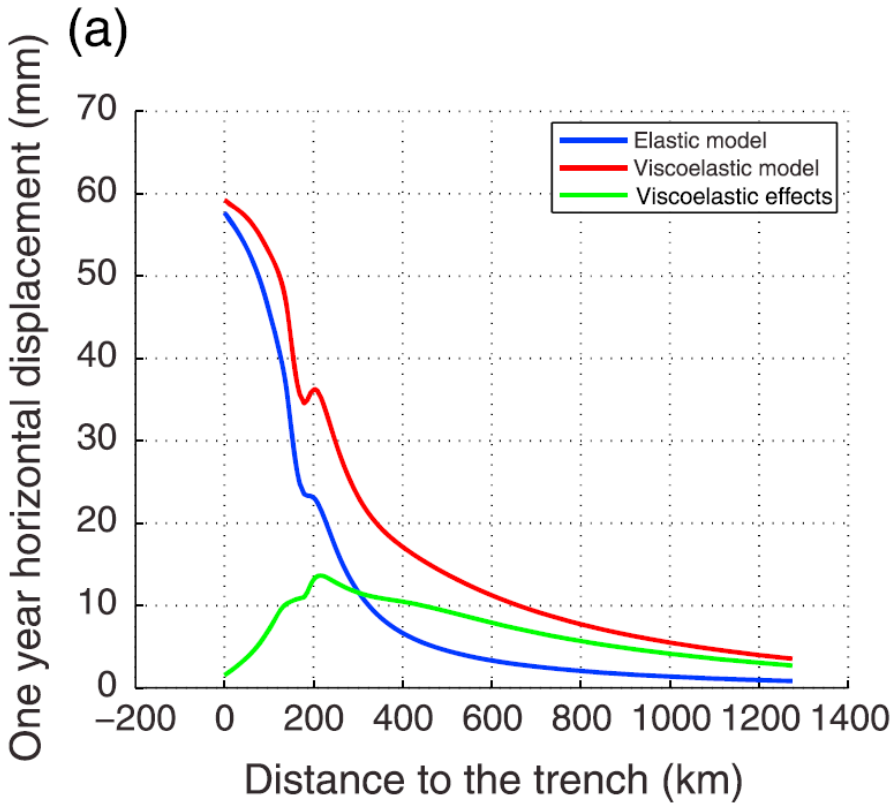
Moment balances

Visco-elastic model, no sliver



[Li et al. 2015]



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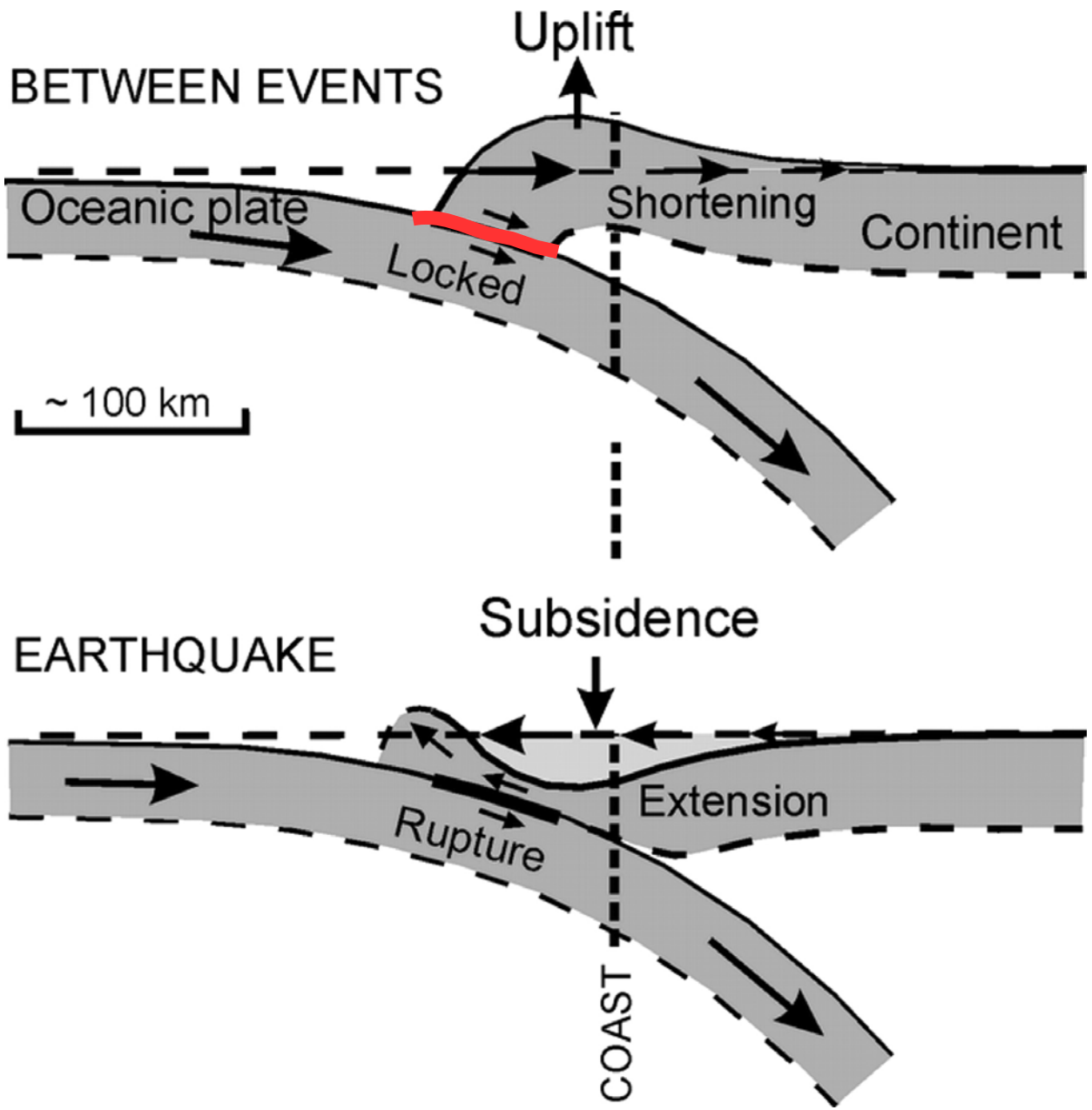
The Calm / The Storm



The upper plate deformation pattern during interseismic phase gives us insights on **the degree of locking** of the interface

- **Assessing kinematic interseismic coupling in Chile**
- **From kinematic to dynamics : insights from the three recent megathrust earthquakes**
- **Issues and unknowns**

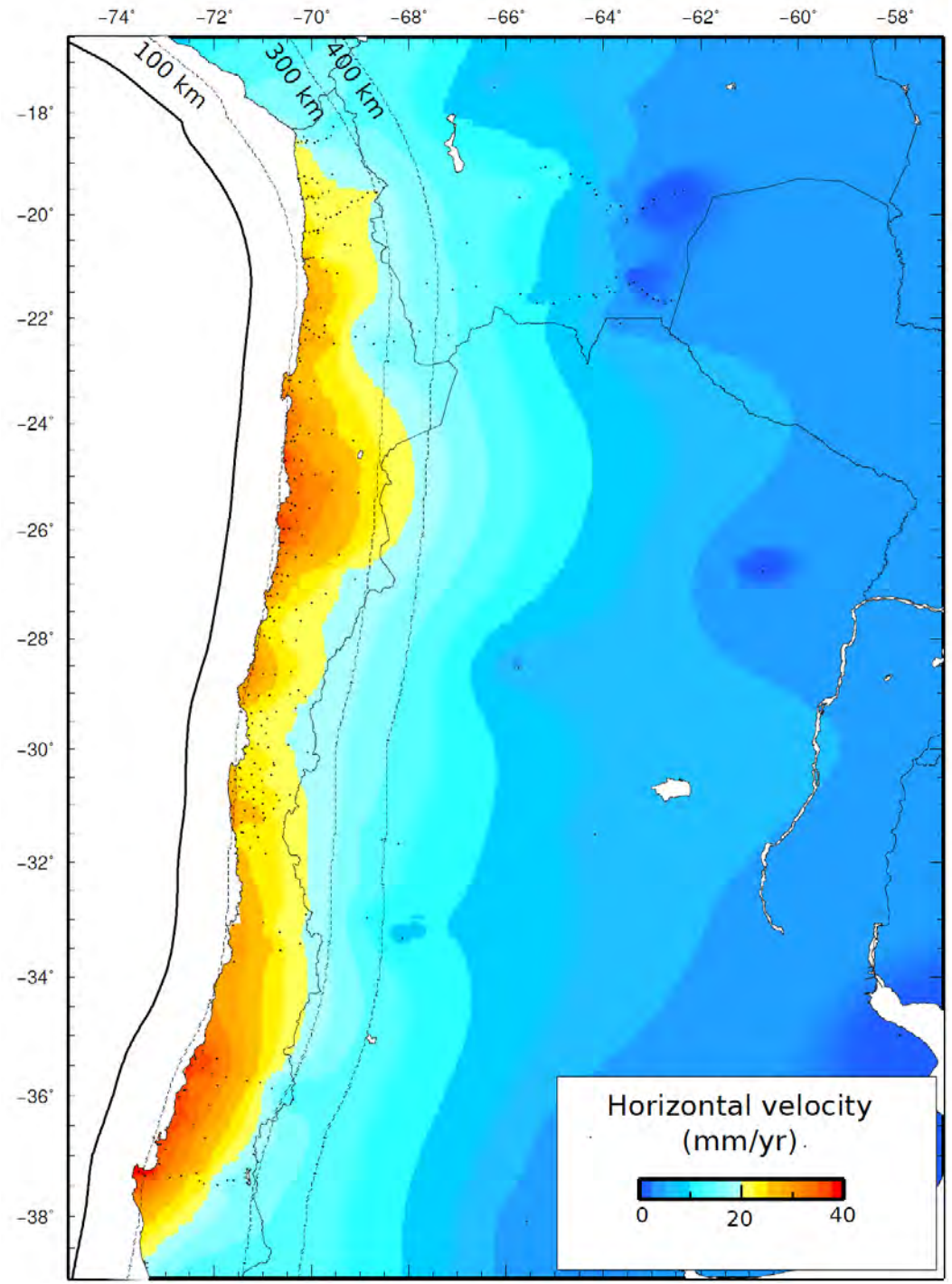
Interseismic coupling assessment : the Chilean context

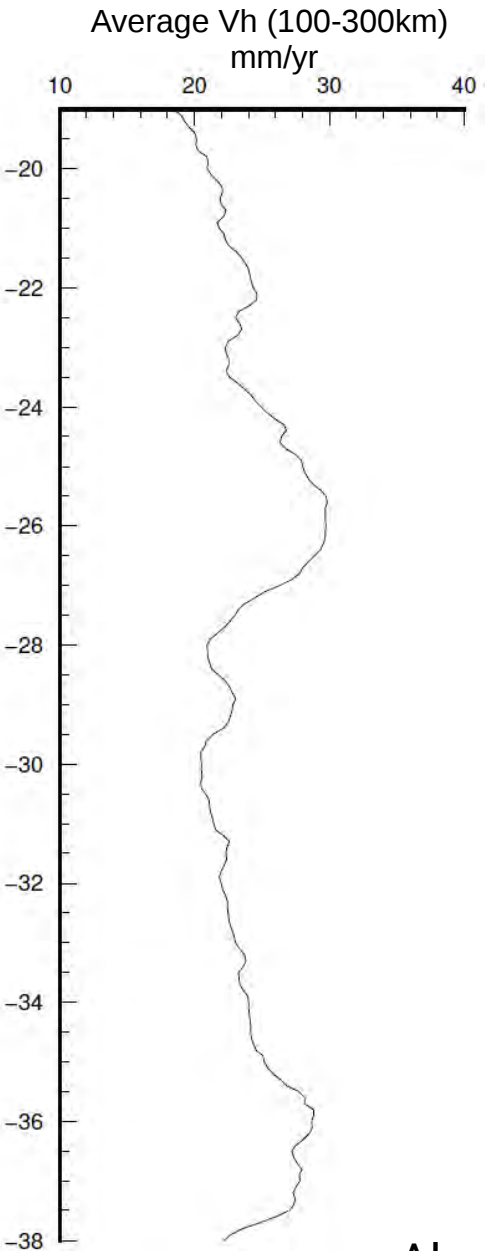
Nazca-South America rapid and oblique convergence ~7cm/yr

Stable South American Craton

[Armijo et al., 2016]

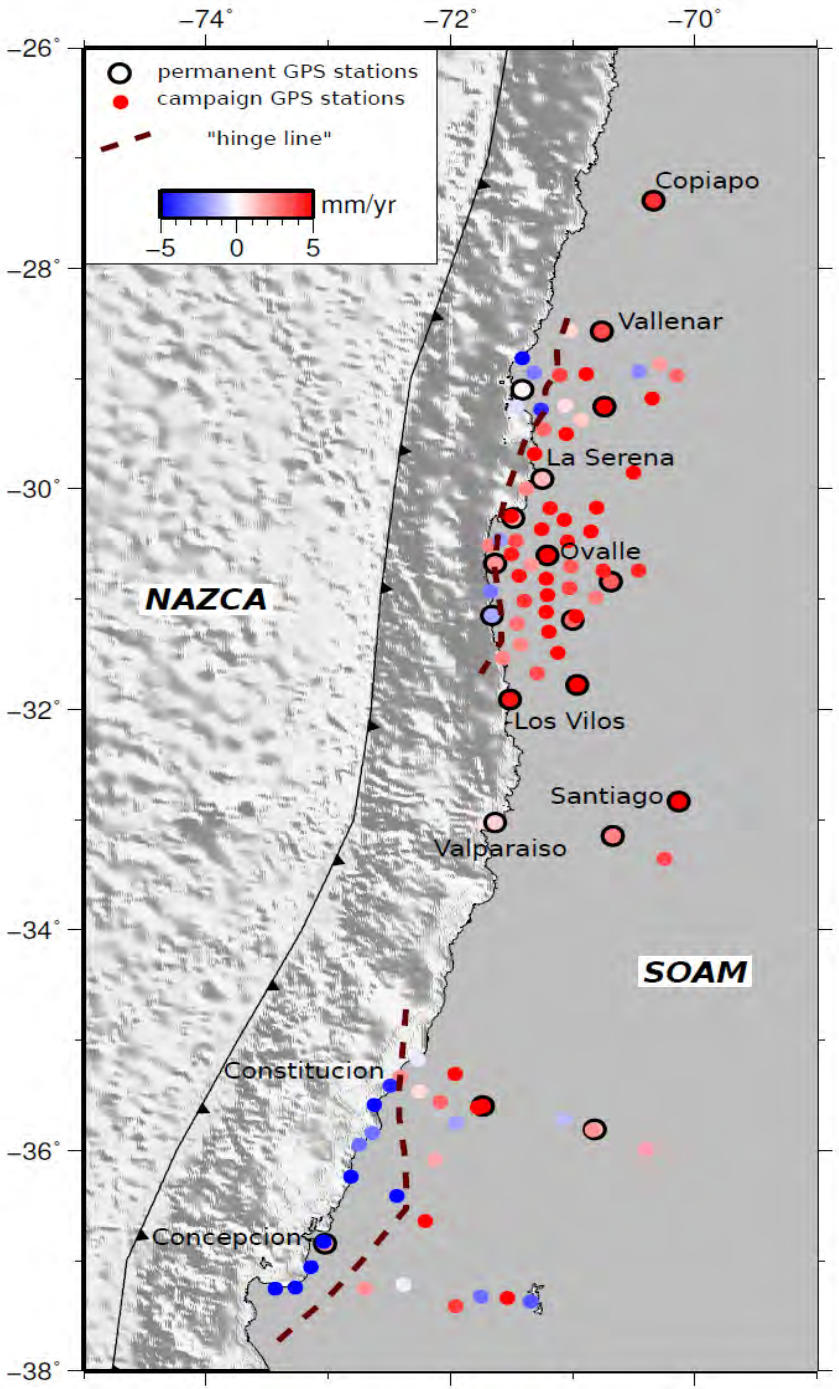
Interseismic coupling assessment : measuring strain



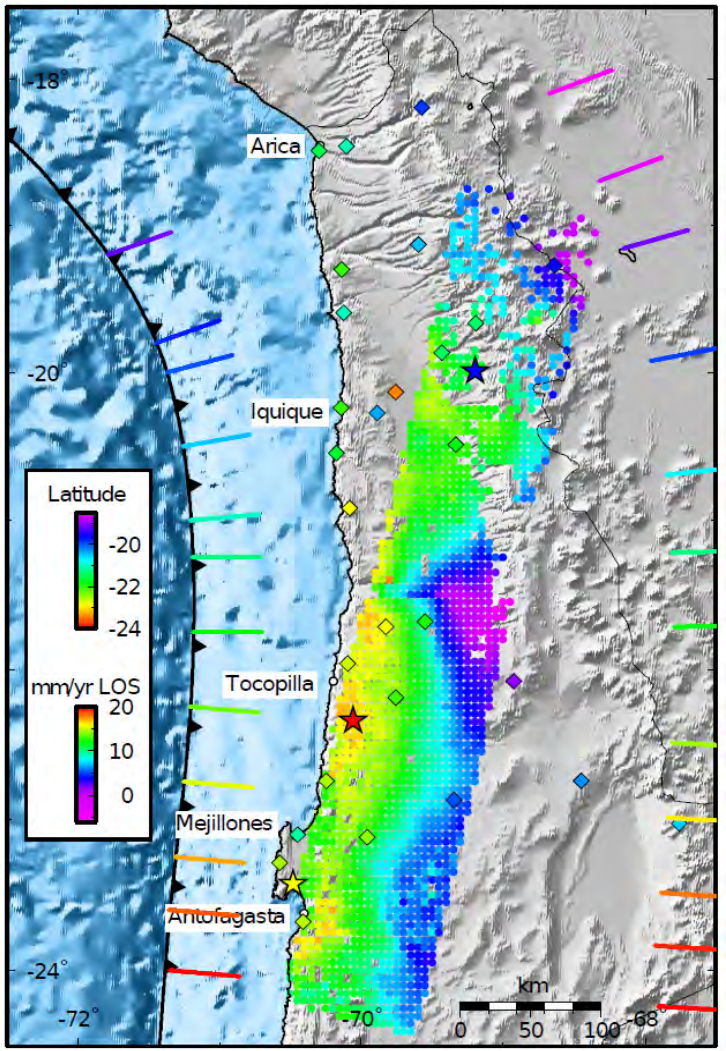


Along-strike variations in the near-field horizontal velocities

Interseismic coupling assessment : measuring strain



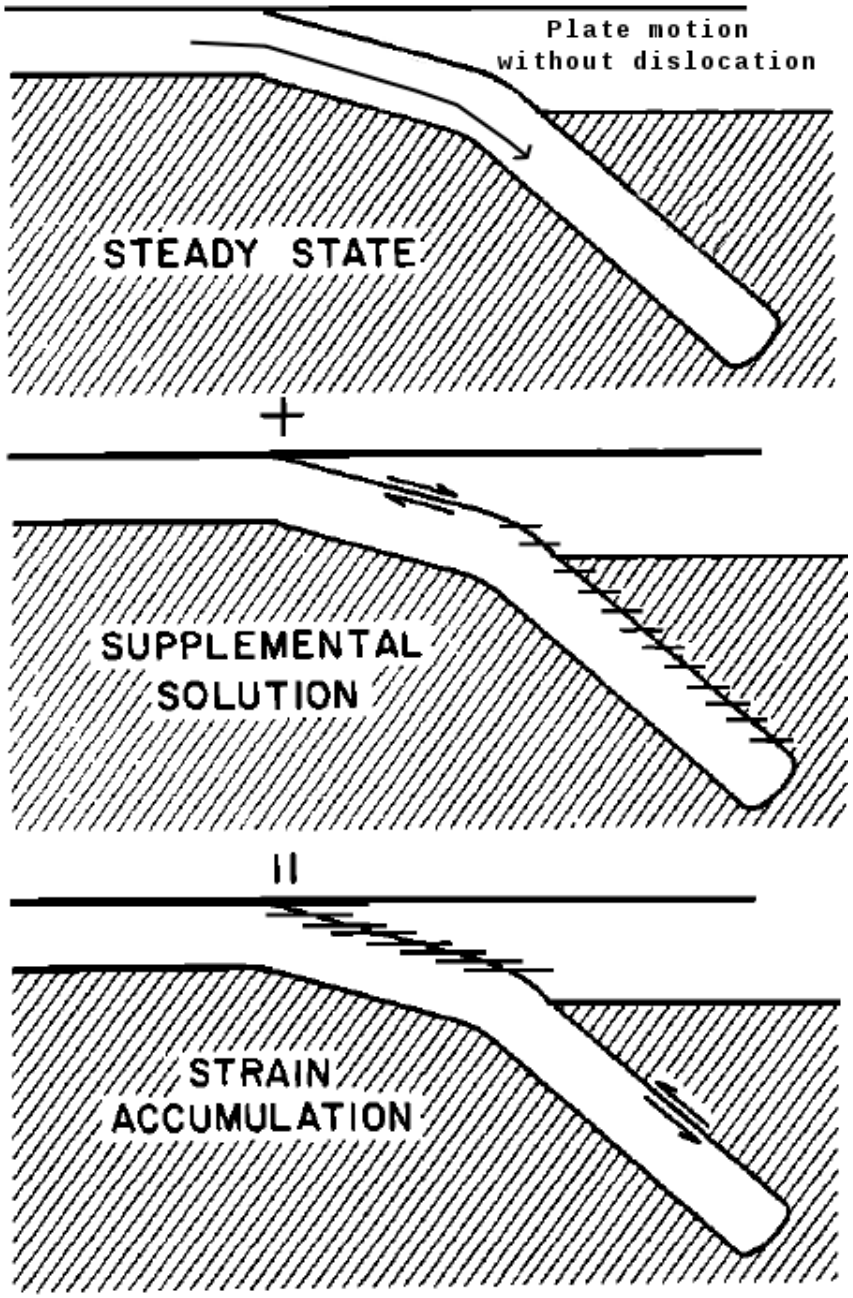
[Métois et al. 2016]



[Bejar et al. 2013]

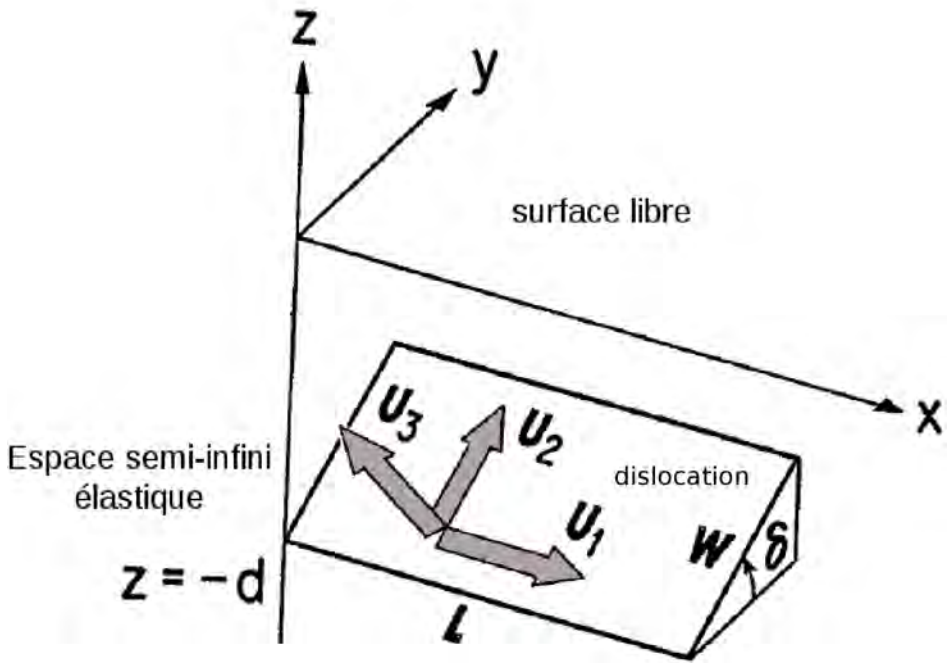
- Needed to constrain along-dip extent of coupling
  - Poorly constrained by GPS
  - Some attempts using INSAR

Interseismic coupling assessment : conceptual framework



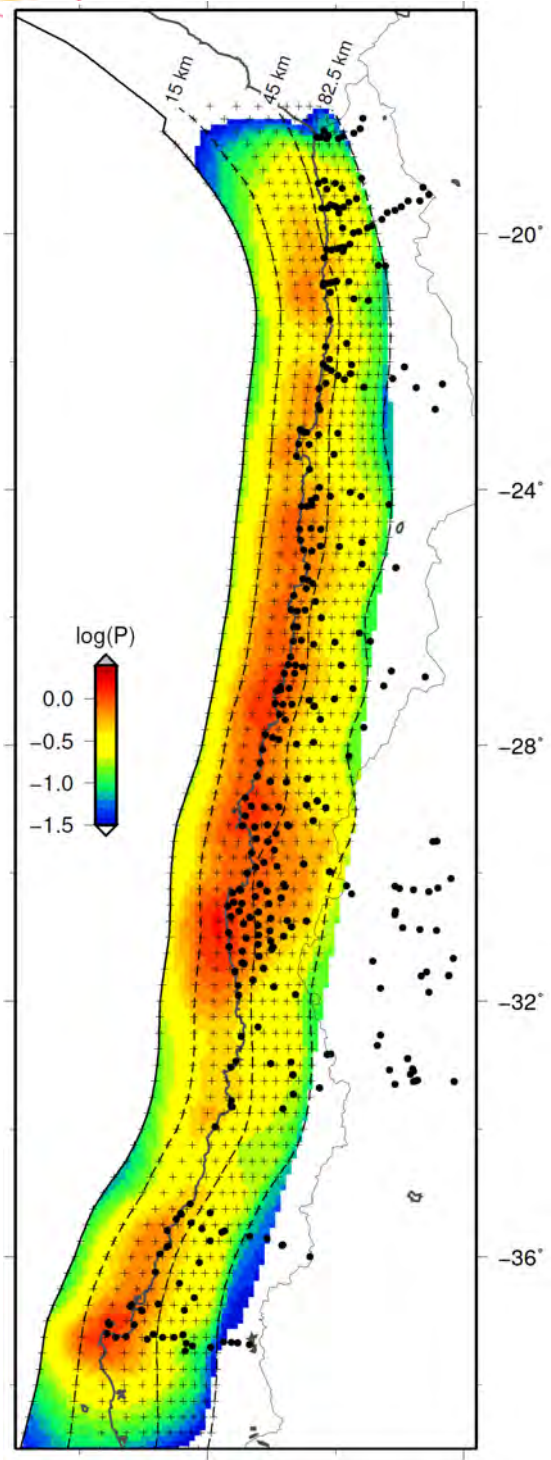
[Savage, 1983]

The upper plate strain field during interseismic phase can be modeled with **Okada's equations (purely elastic) and Savage backslip hypothesis**

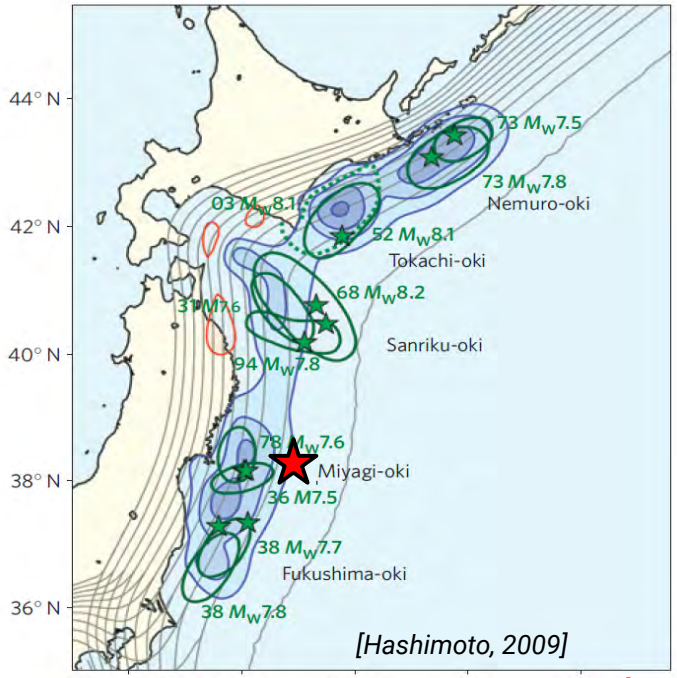


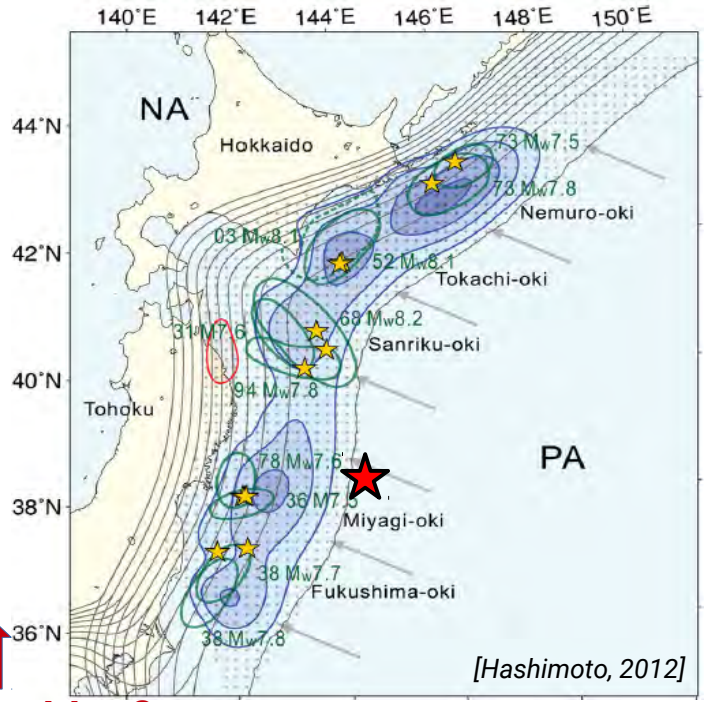
[Okada, 1985]

Interseismic coupling assessment



- Interseismic coupling models are commonly unresolved in the shallowest part of the slab
- In Chile, resolved from ~10 to 50 km depth along-dip



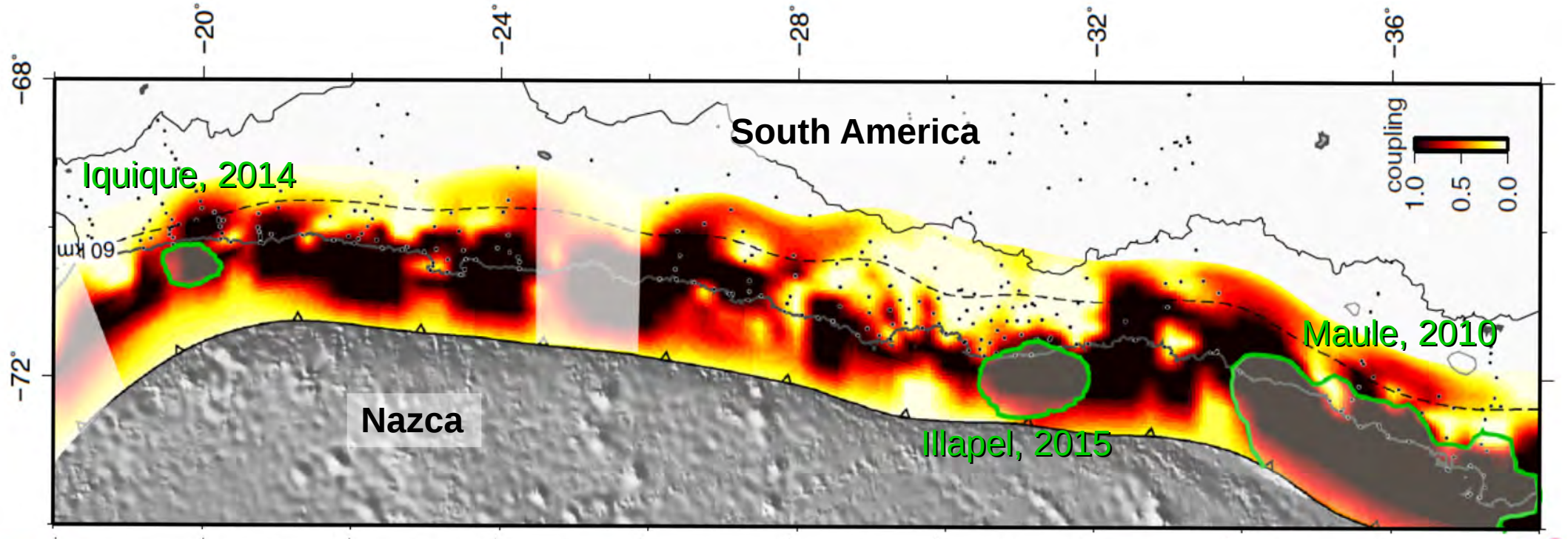


Tohoku, Mw 9

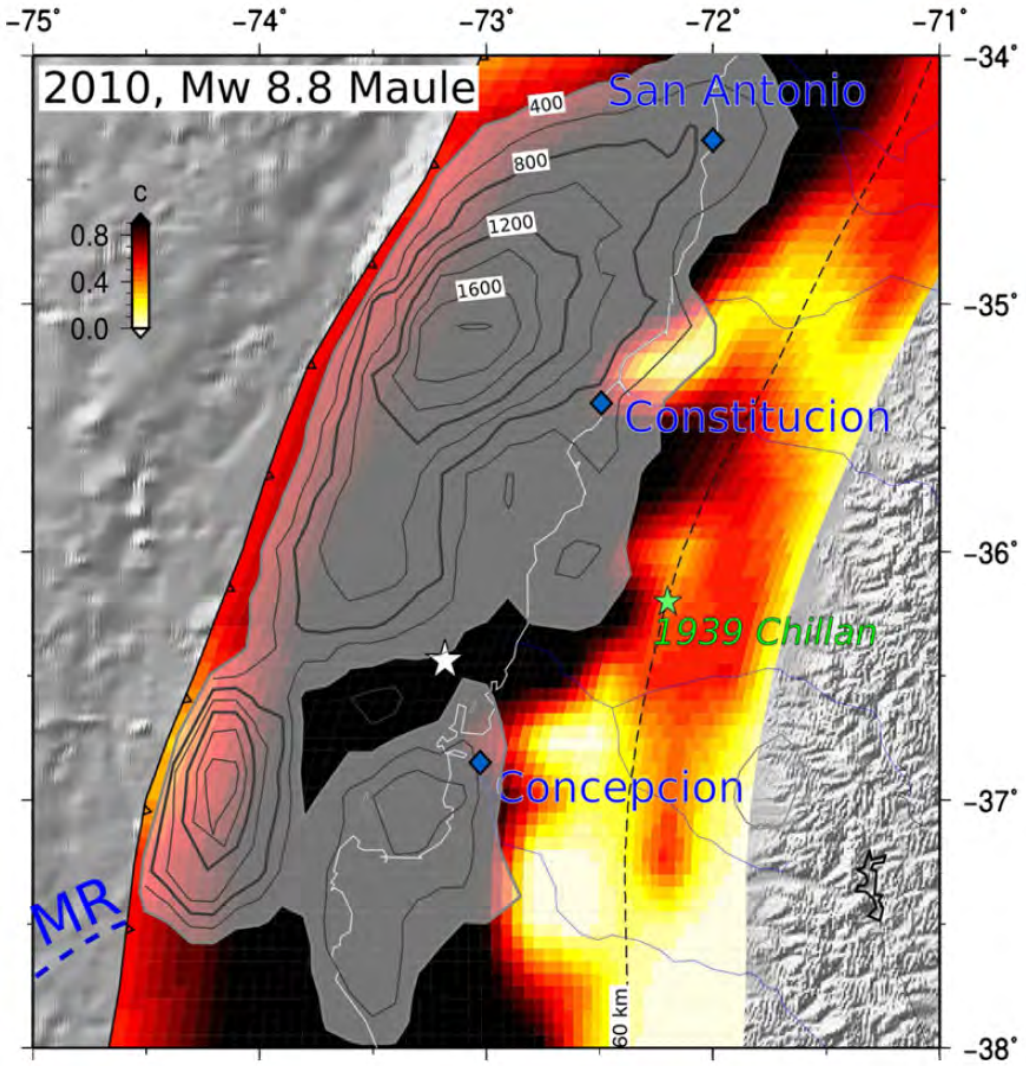
Superficial coupling fixed to zero

No constrain on superficial coupling

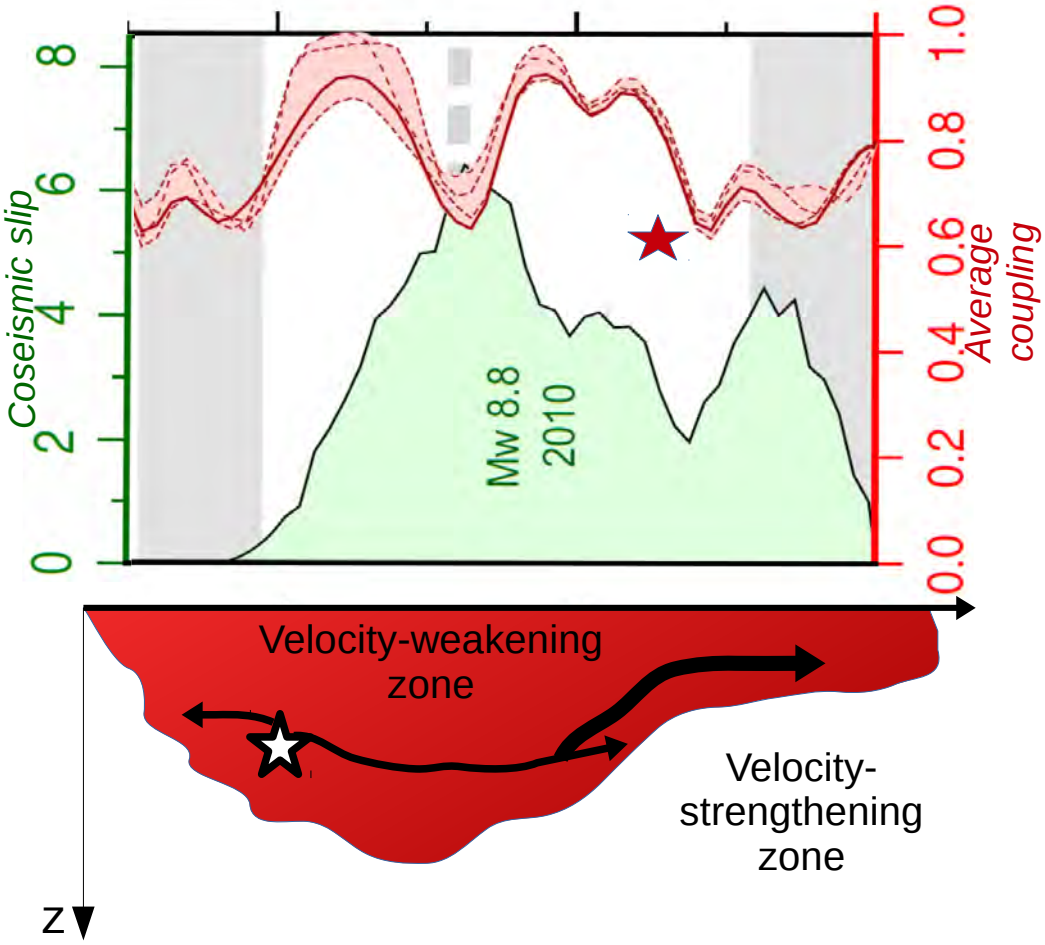
Interseismic coupling segmentation & great earthquakes



Insights from Maule, Mw 8.8, 2010

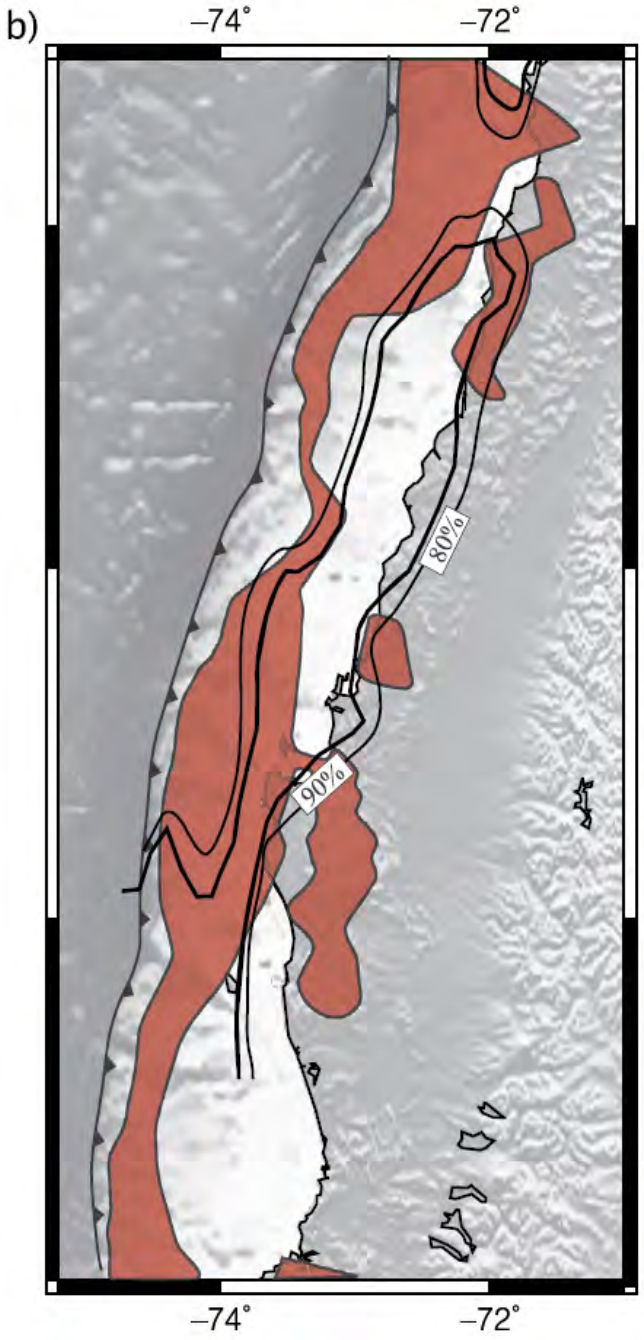


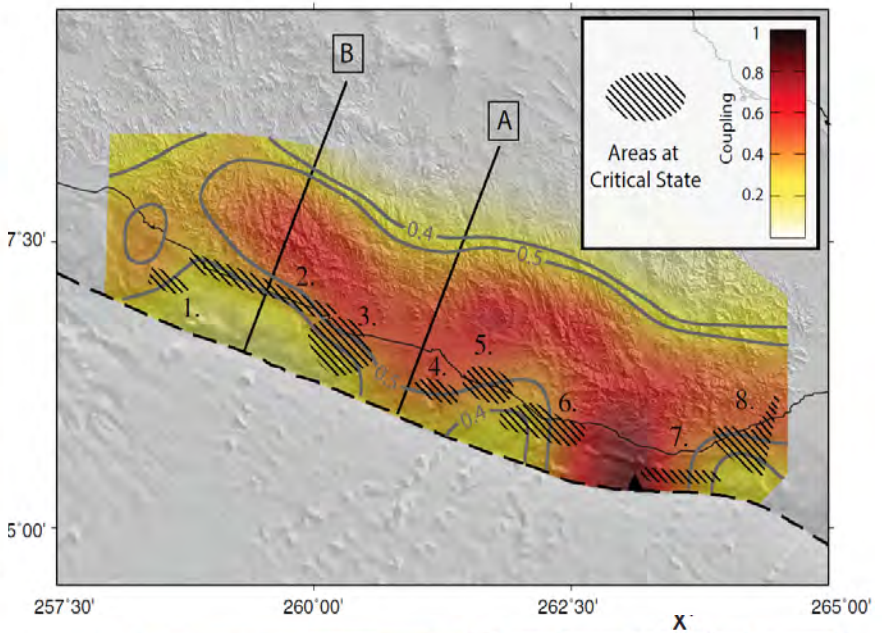
[Vigny et al. 2010, Métois et al. 2016]

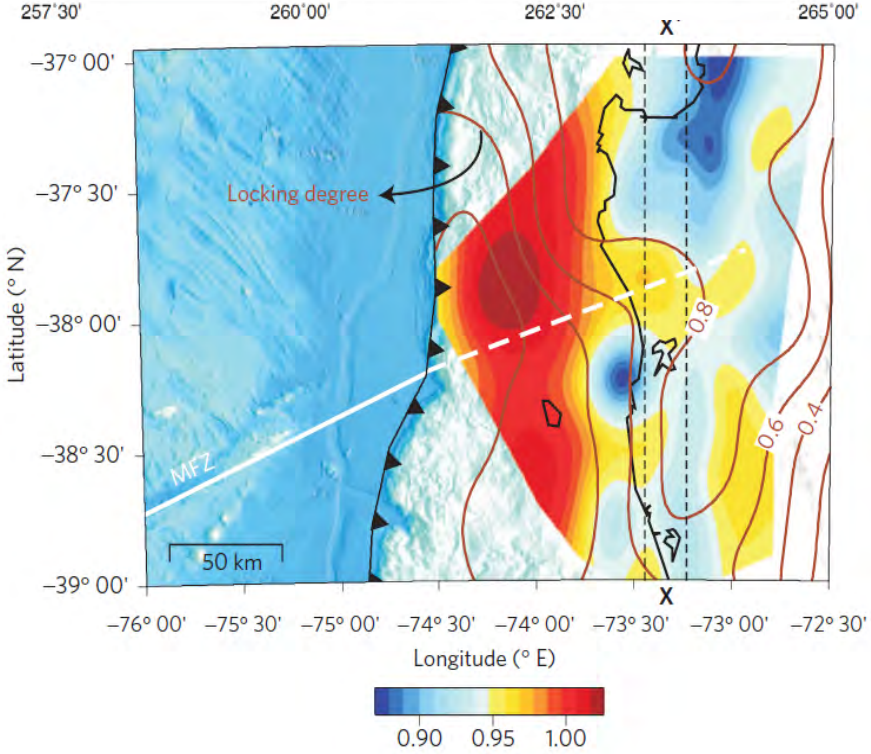


- **Mapping coupling is not sufficient to anticipate the rupture dynamics**
- We need to link coupling coefficient to frictional parameters of the interface and reconstruct the segment history to better assess the initial conditions

Looking for frictionnal properties



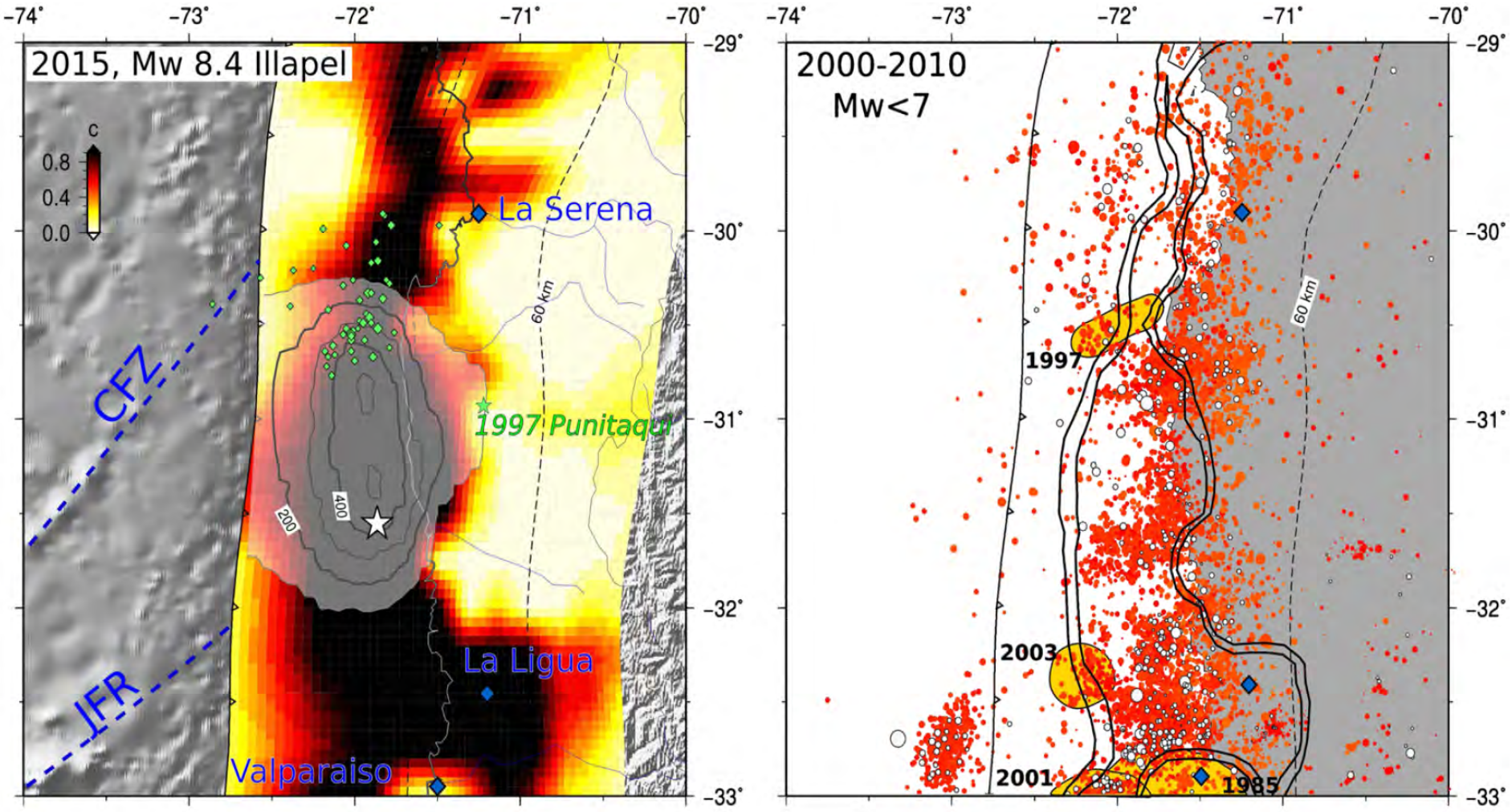




[Moreno et al. 2014]
[Rousset et al. 2016]
[Cubas et al. 2013]

Pore pressure / lithostatic pressure

The not so calm interseismic phase



Insights from Iquique (8.1) and Illapel (8.4)

Dire on sest plus focalisé sur la compréhension des phases pré-earthquake.
Est-ce que la phase intersismique est si calme que ça.
qu'est ce qu'on peut encore apprendre pour aider à contraindre les séismes ?
- detection slow slips
- raffiner image de l'interface + suivi temporel
- améliorer la connaissance du glissement absolu pour faire de vrais bilans