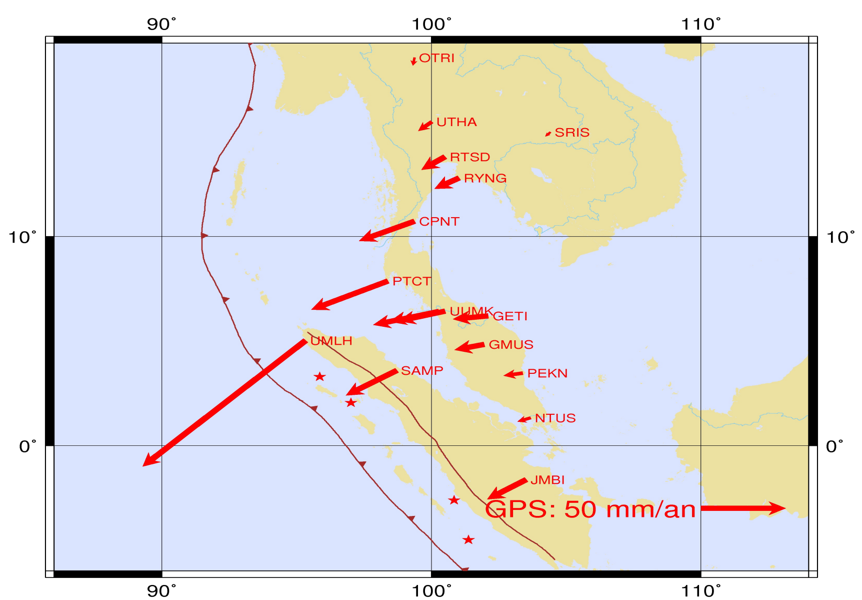
Deformations associated with megaearthquakes: rheology of the asthenosphere and of the subduction interface

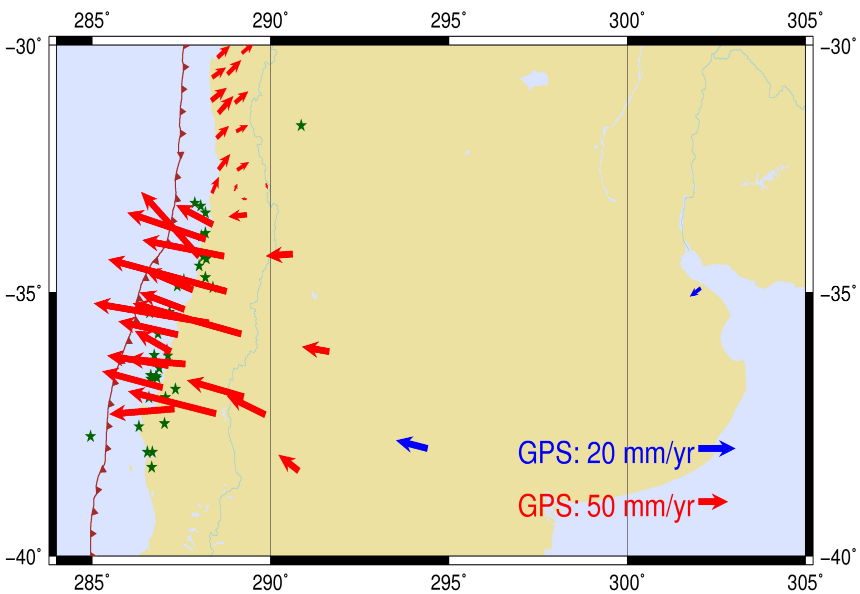
L. Fleitout, J.D. Garaud, O. Trubienko, E. Klein, and numerous 'GPS' colleagues (C. Vigny...)

Collège de France 1-12-2016

Huge velocity perturbations are observed more than 1000km away from the earthquake



Velocity perturbations 4yrs after Aceh (dec 2004)

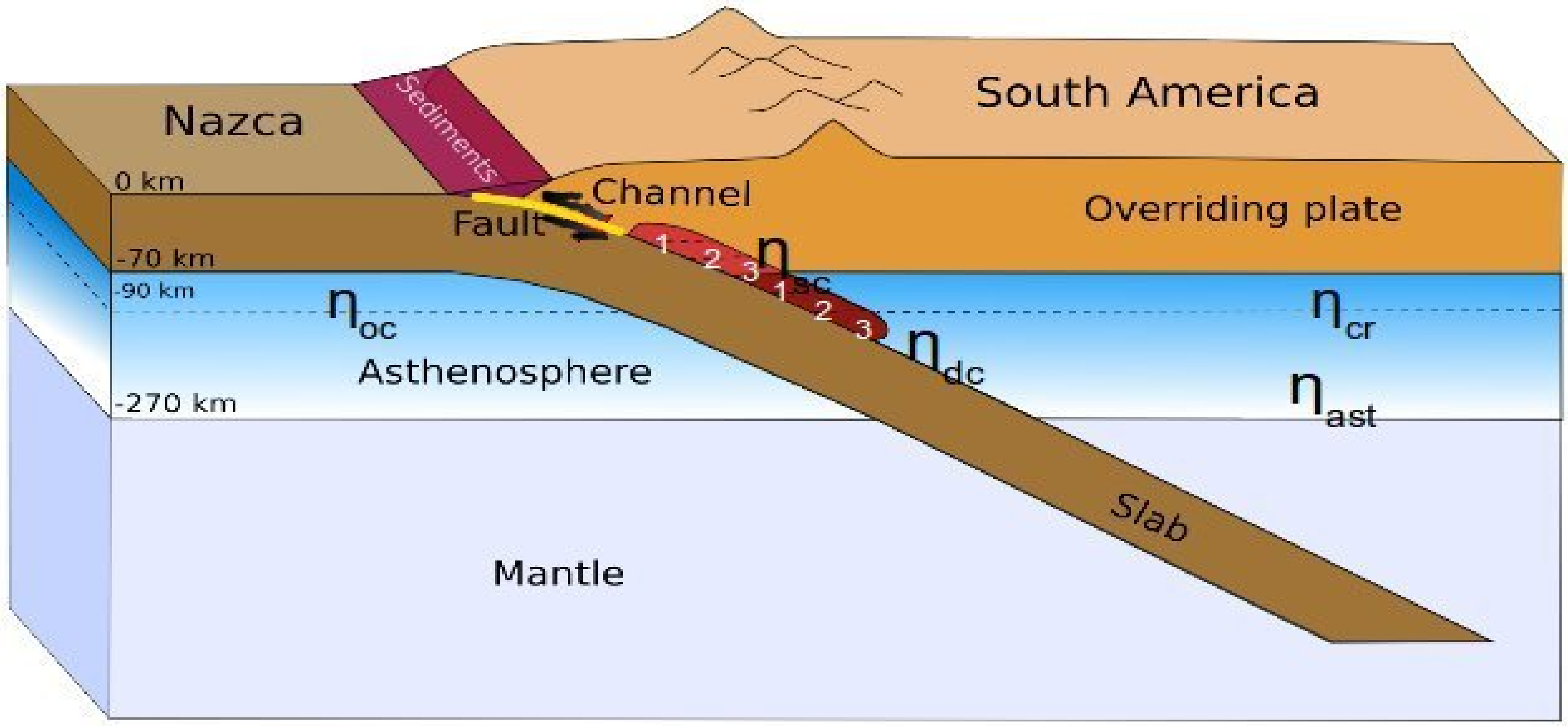


1 yr after Maule (febr 2010)

The three megaearthquakes (Aceh 2004, Maule 2010, Tohoku 2011) are the first earthquakes of magnitude around 9 since modern techniques to monitor deformation are available. They are associated with far-field, long-lasting velocity perturbations

The response of the Earth to megaearthquakes: A large-scale 'experiment'

- **To test the Earth's mechanical properties (asthenosphere, subduction channel)**
- **To explore the 'time dependence' of stress/strains**



Some of the questions that we can tackle with postseismic deformations after megaearthquakes

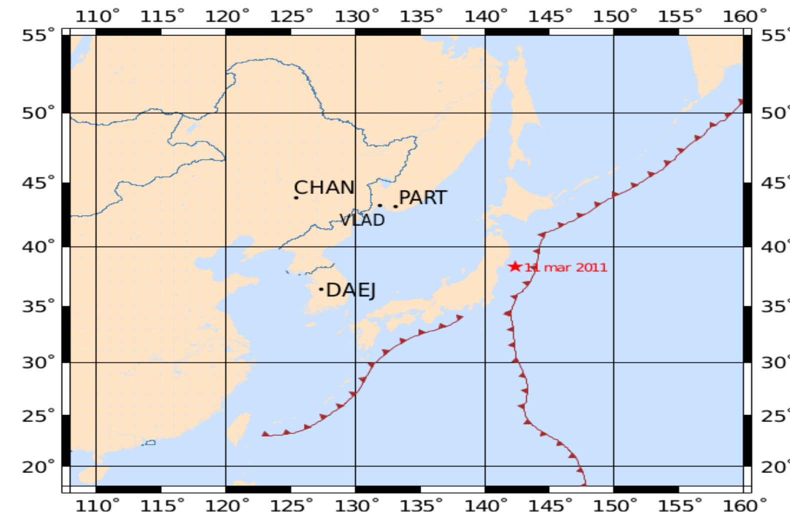
Is-there a low-viscosity asthenosphere?
What rheology (newtonian, non-linear creep), What thickness?

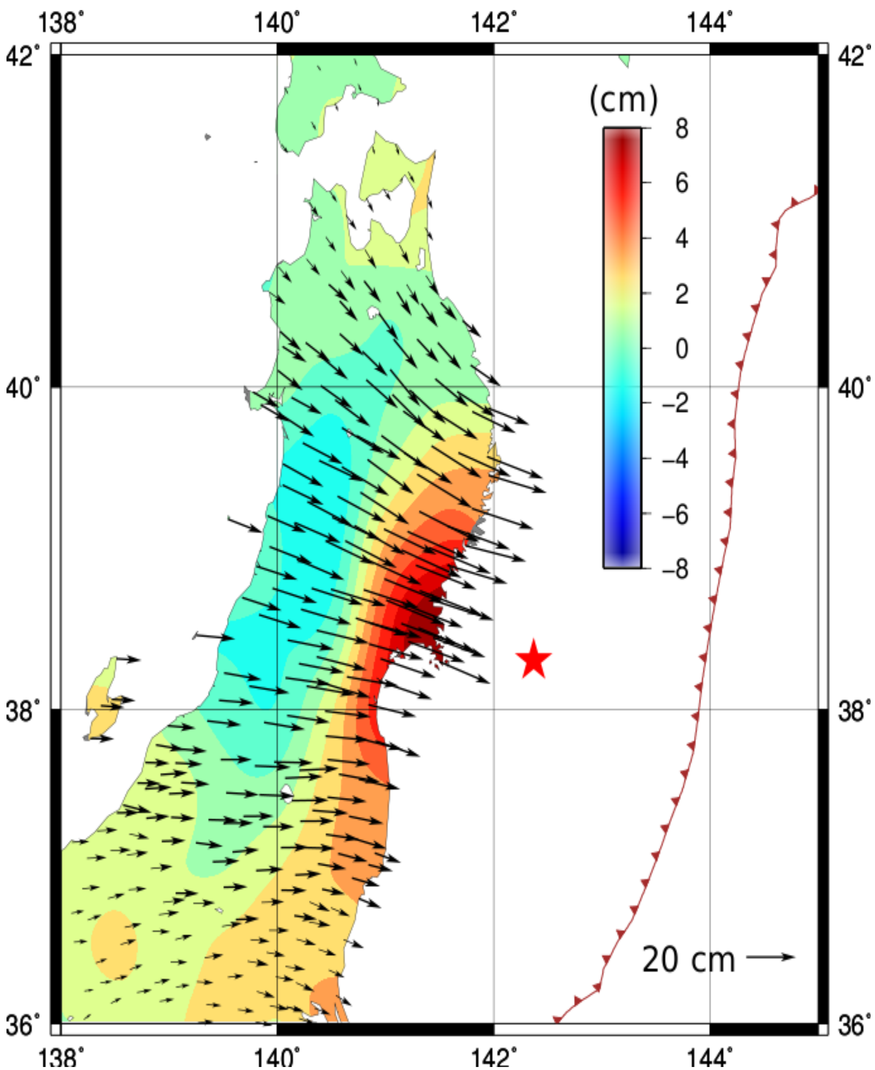
What occurs below the brittle part of the subduction interface?
Localization of the deformation in low-viscosity ductile shear zones?

This is not a new problem (Elsasser, Pollitz and coauthors...)
But we have now precise data and the numerical ability to treat the problem in 3D

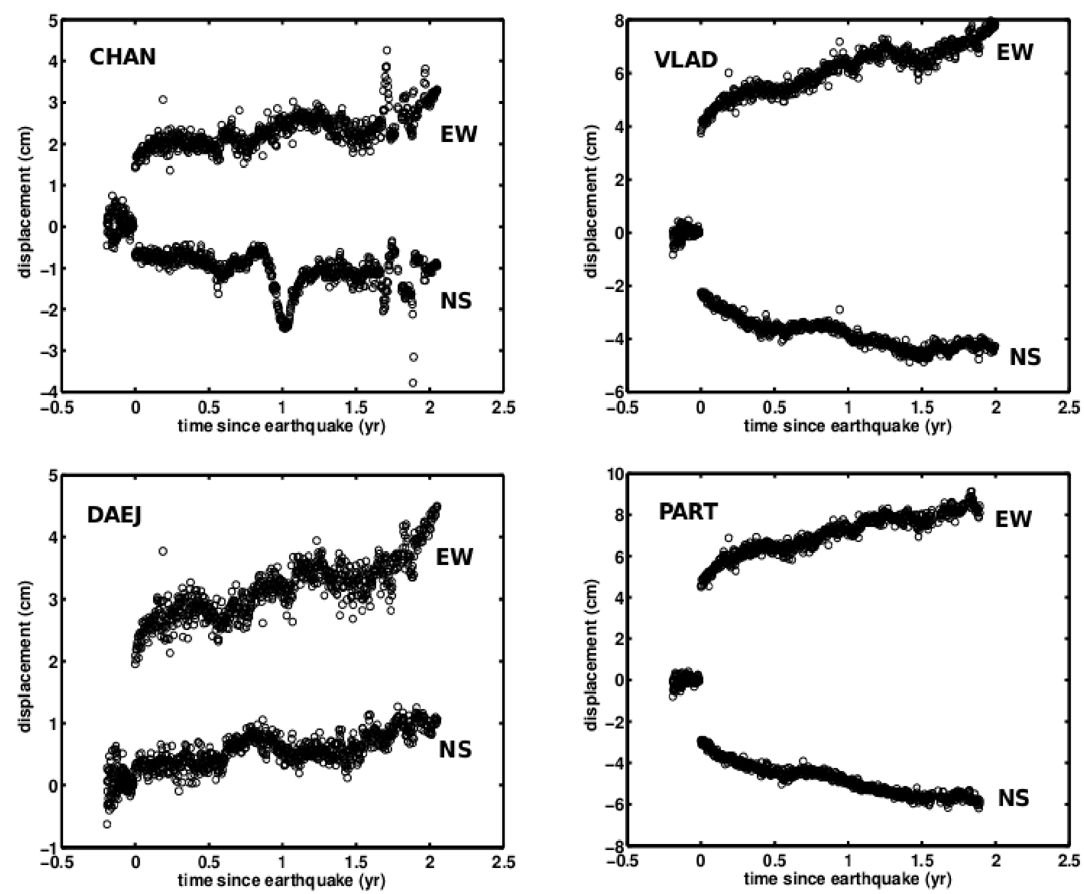
Note: The rheology obtained here will be the rheology for a time-scale of a few years. Long term rheology?

GPS velocities and displacements after Tohoku
(corrected for preseismic)

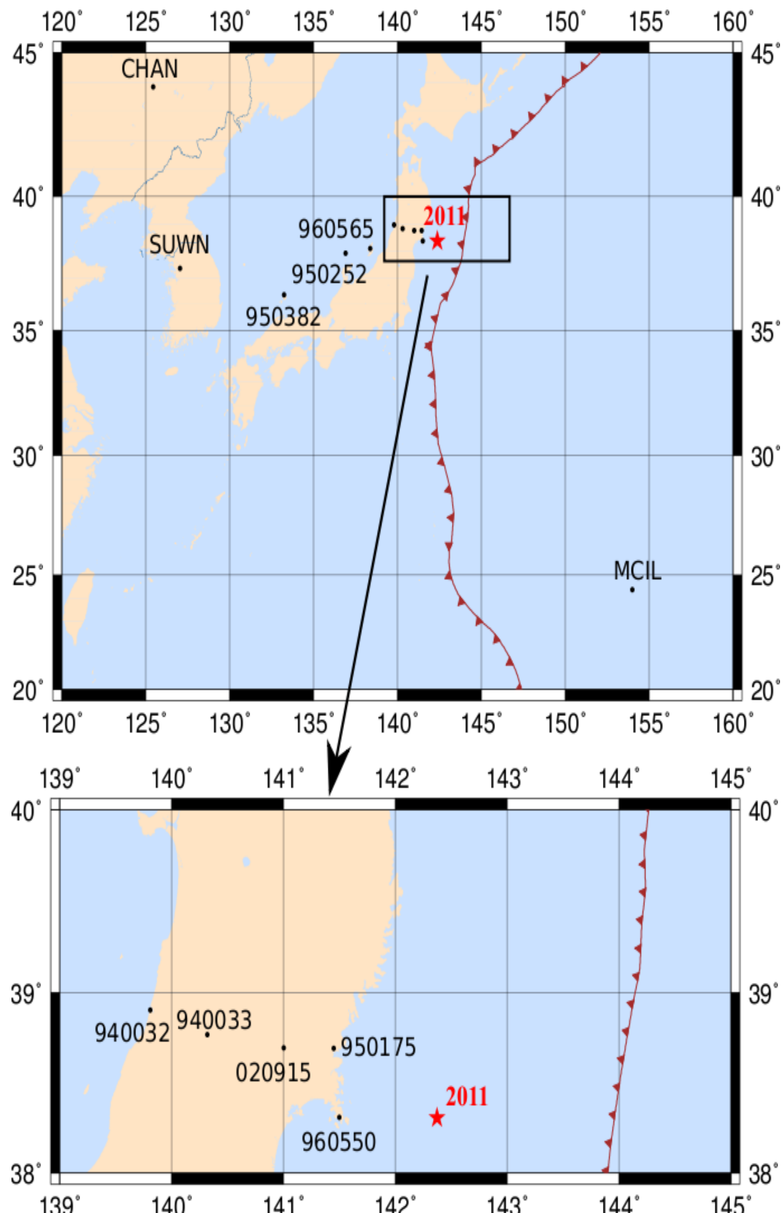


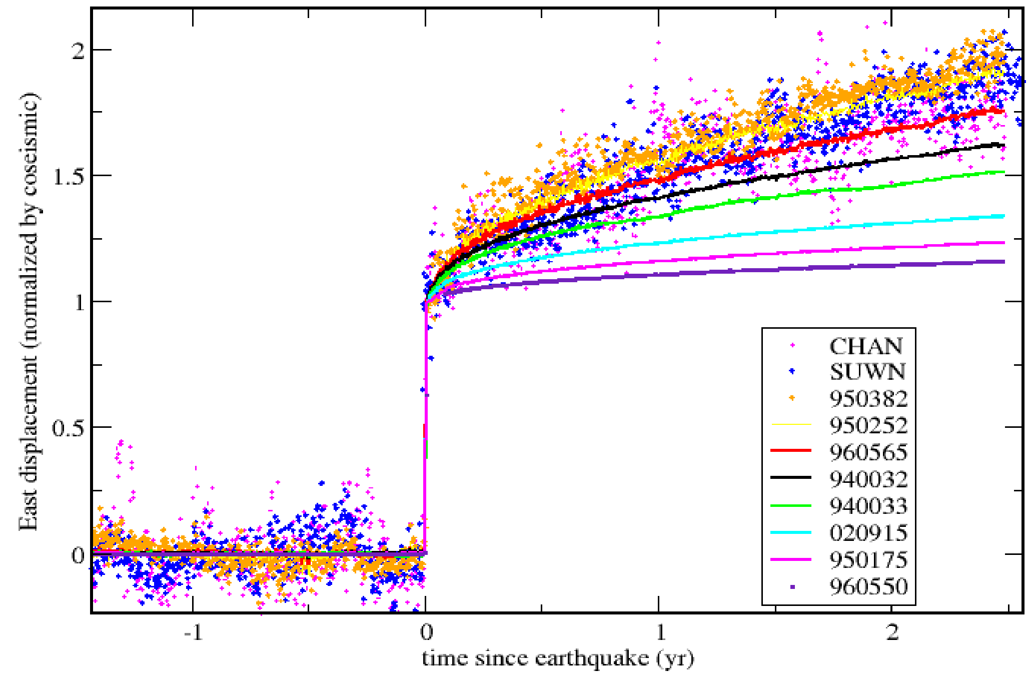


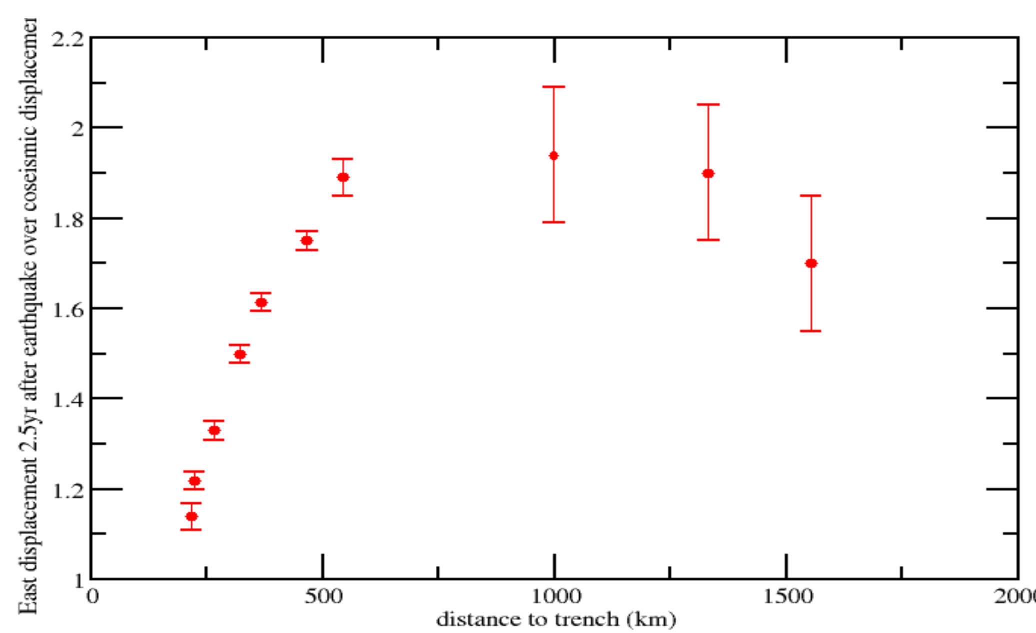
Horizontal velocities in 2012



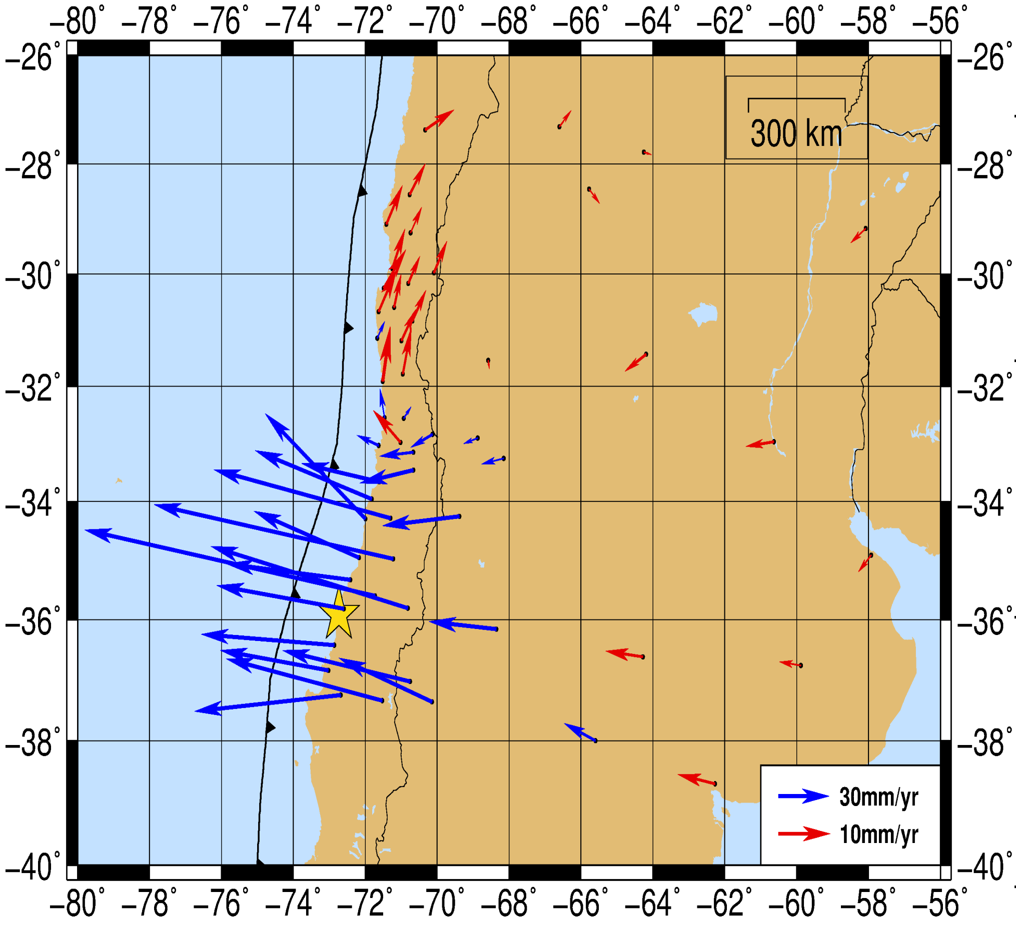
Non-dimensionalized horizontal displacements function of distance

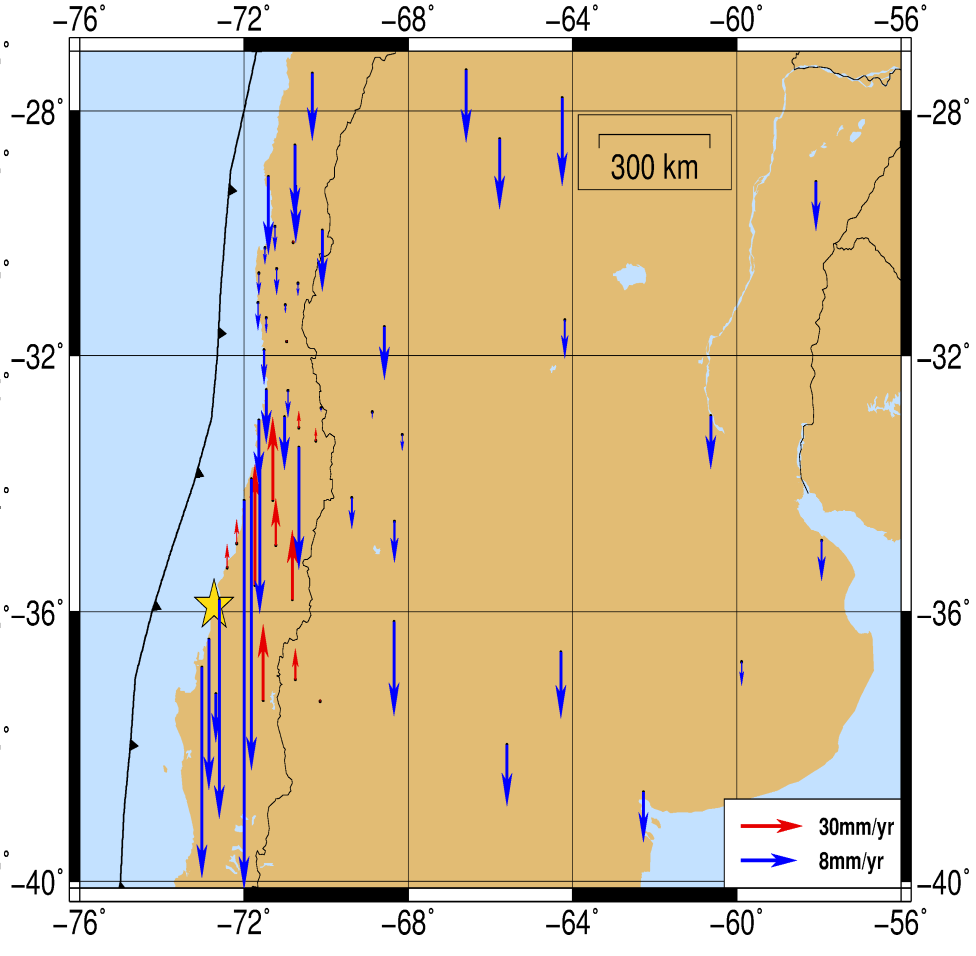






AFTER MAULE

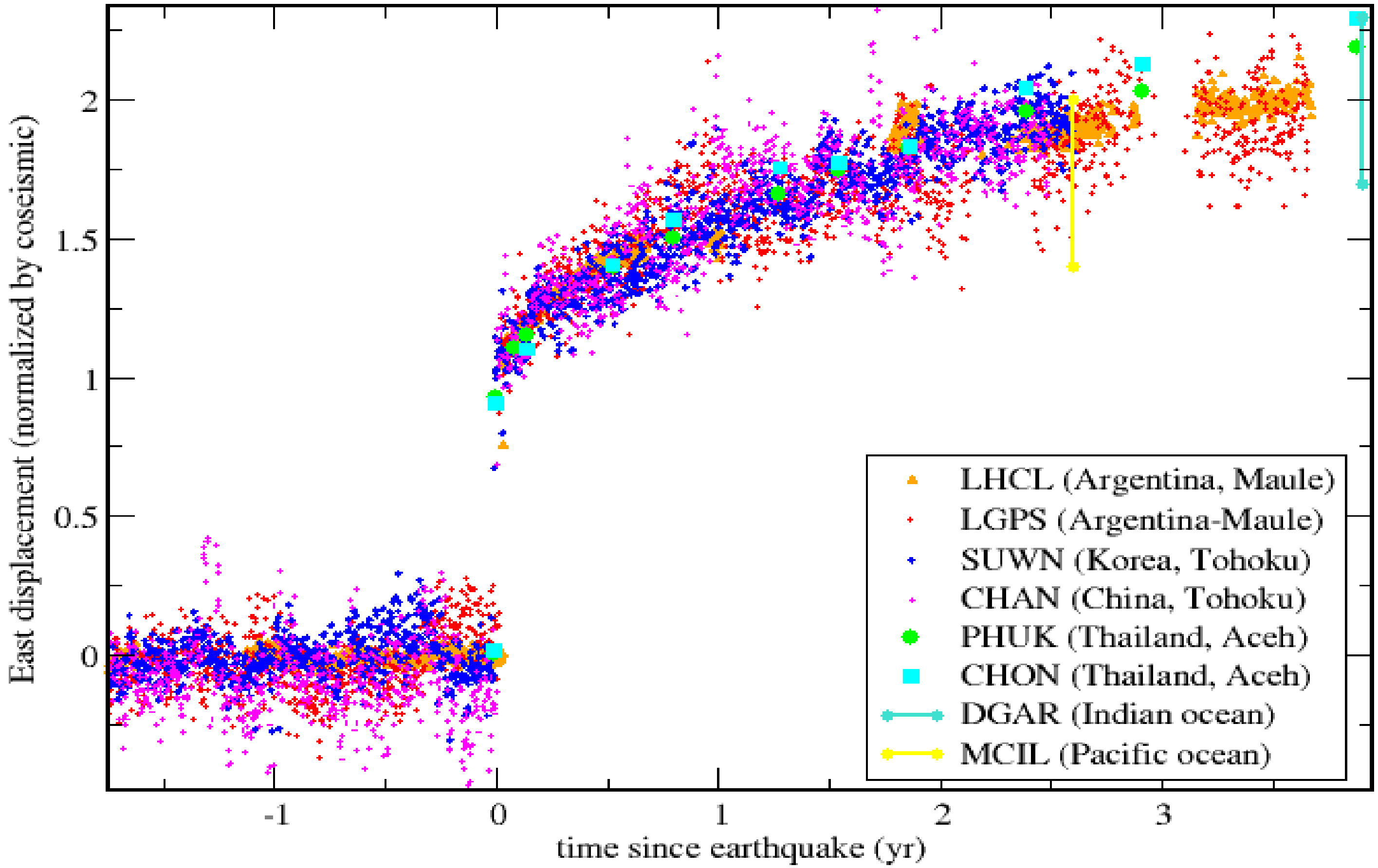


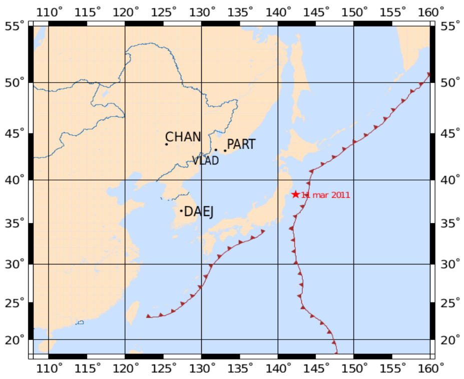


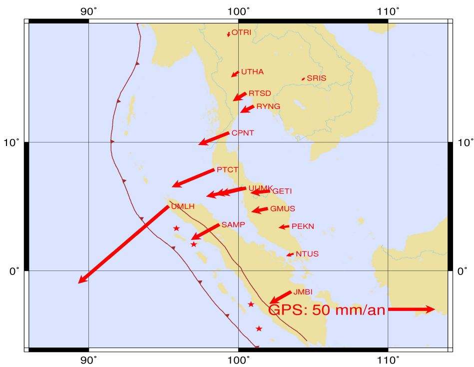
In 2012 (velocity difference between after and before Maule)

Notice the vertical uplift on the Andes

After the three giant earthquakes at distances between (and 1000km)



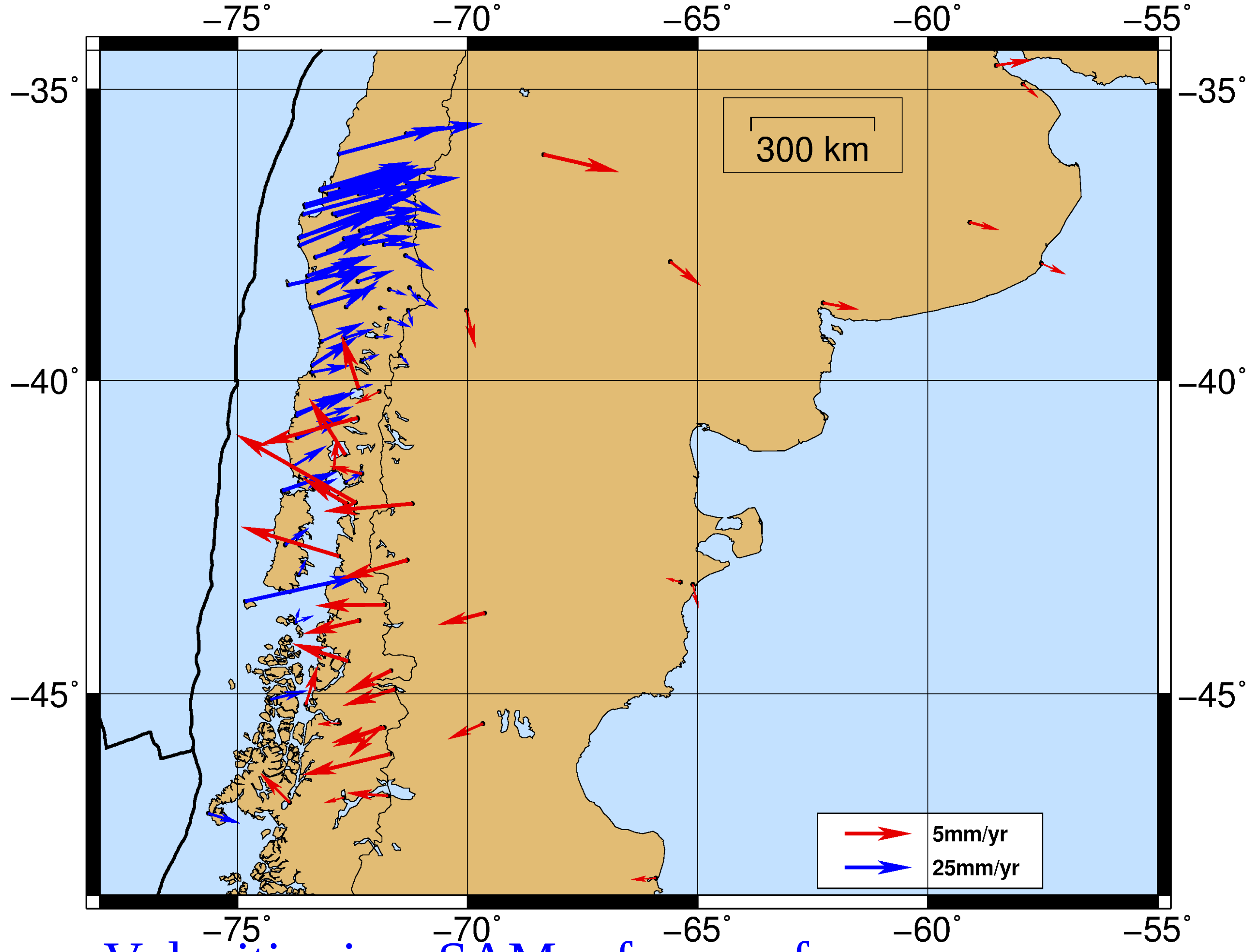




The postseismic signal non dimensionalised by coseismic is similar for the three earthquakes

The postseismic phase continues for several decenies

After Valdivia (before Maule)



Velocities in a SAM reference frame

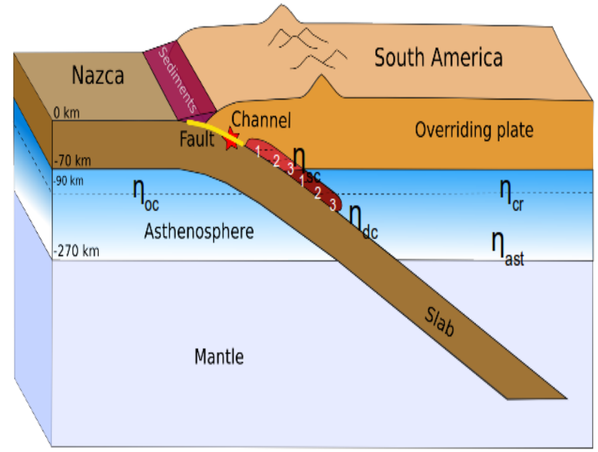
See Klotz et al. EPSL 2001
Hu et al. JGR 2004

Postseismic velocities after a subduction earthquake:

- Large perturbation of horizontal velocities. 'Bell shape' of the postseismic over coseismic velocity function of distance curve
- Similar non-dimensional curve for the far-field stations in various zones of the world
- Subsidence in the far-field, uplift on the oceanward side of the volcanic arc
- The perturbation of the velocities persists for at least several decennies

Finite element mechanical models are used to understand the origin of those postseismic velocities

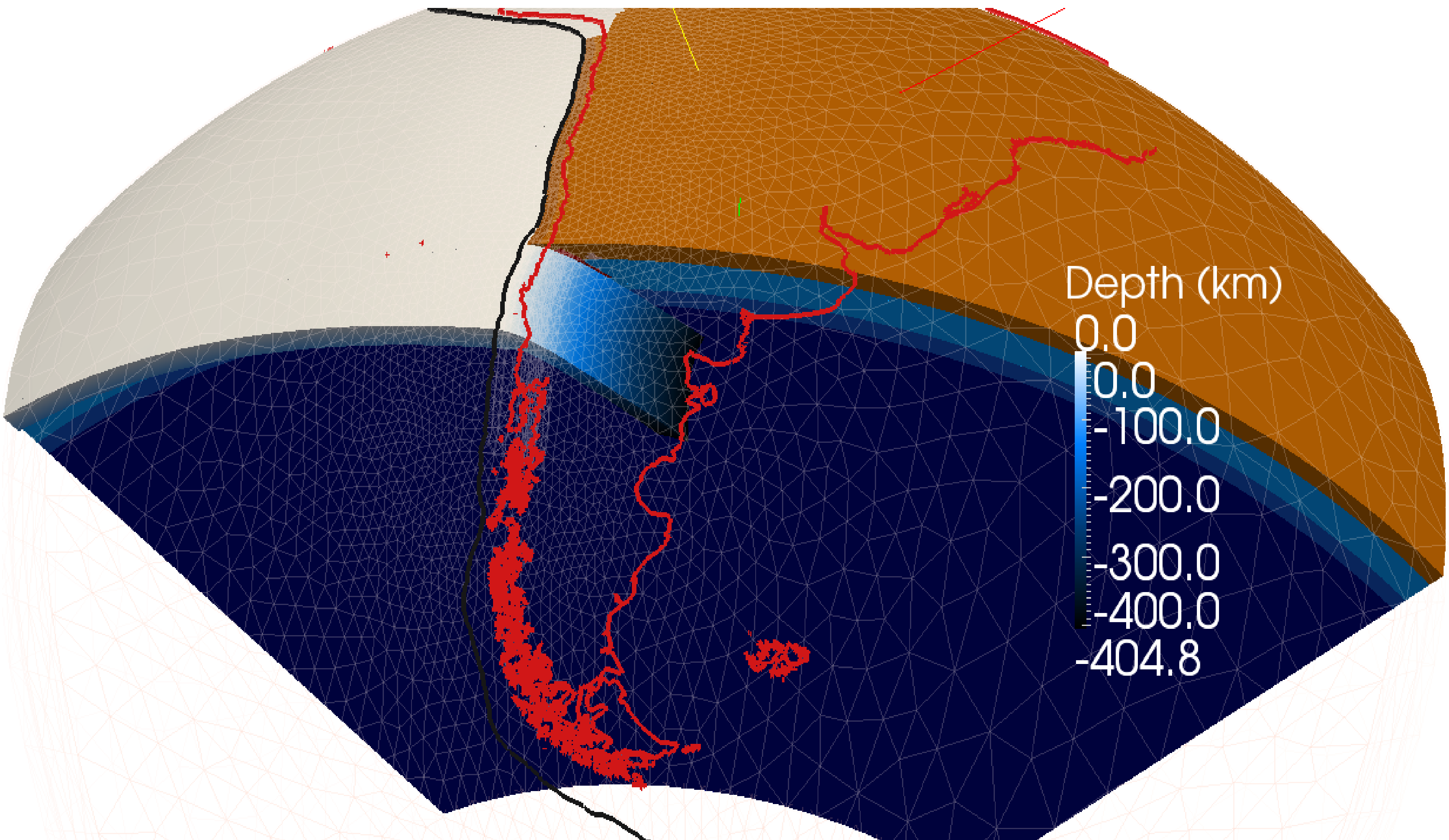
Mesh for Maule earthquake



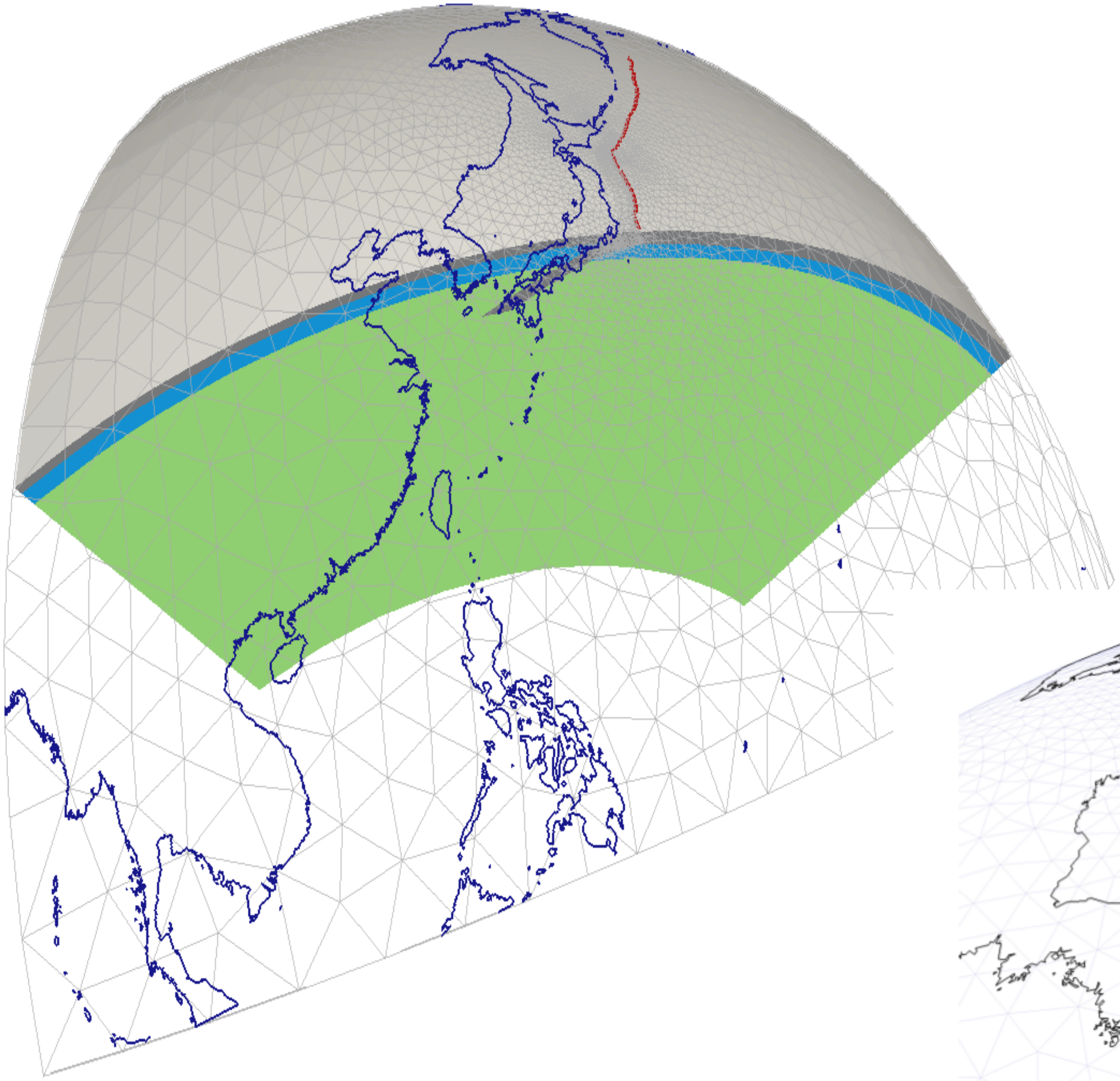
		η_1
SC1	shallow channel 1	1,85E+018
SC2	shallow channel 2	7,50E+017
SC3	shallow channel 3	5,01E+017
DC1	deep channel 1	1,86E+017
DC2	deep channel 2	5,72E+017
DC2	deep channel 3	5,72E+017
CR	crust (70-90 km)	2,00E+018
OC	ocean (70-90 km)	9,70E+018
Asthenosphere	90-200 km	3,00E+018
	200-270 km	8,40E+018

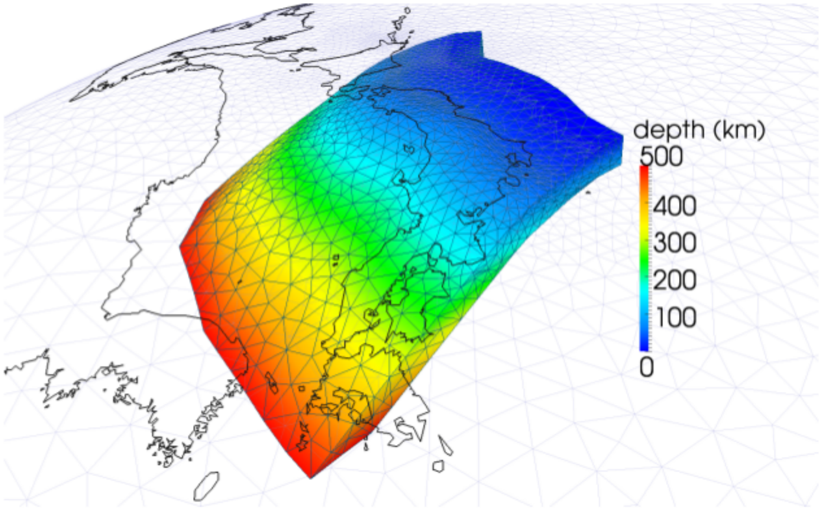
η_2/η_1 = cst = 6,5

μ_2/μ_1 = cst = 3



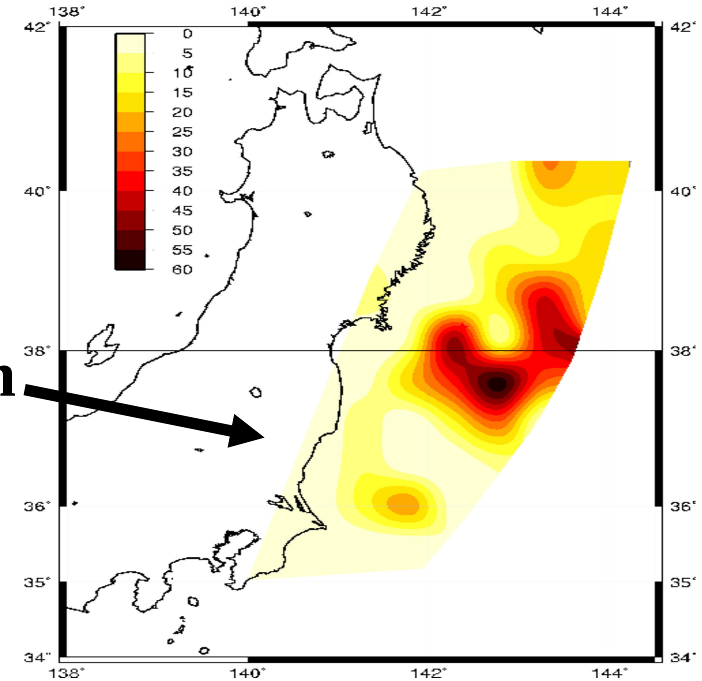
Finite element mesh for Japan computations with Zset-Zebulon

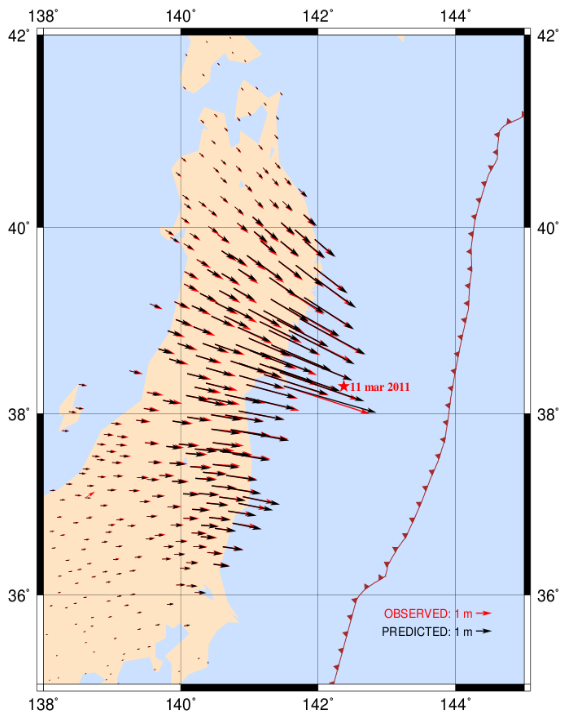


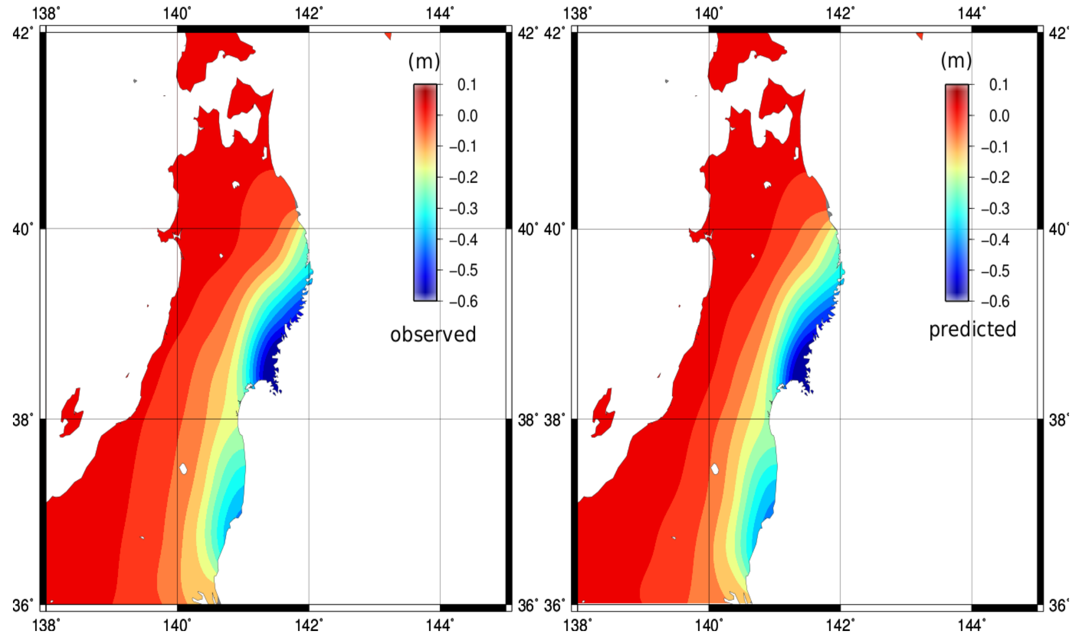


Coseismic (here example of Japan)

Predicted coseismic slip on the interface







horizontal **vertical**

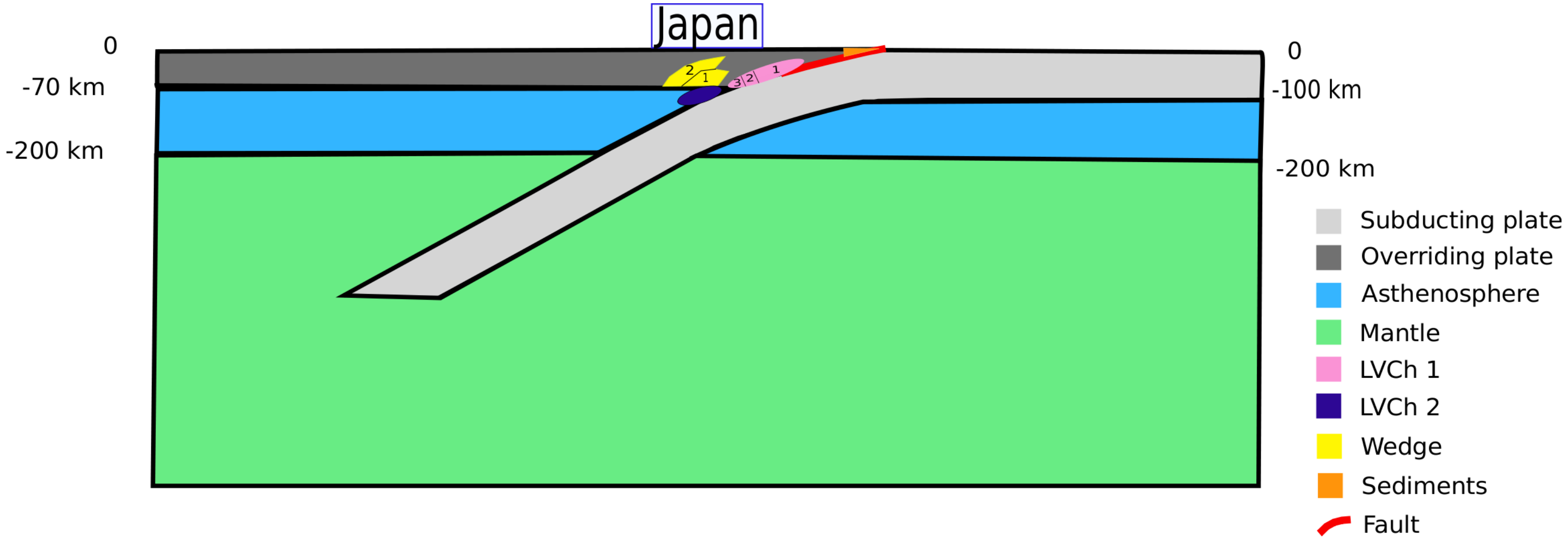
The coseismic deformation induces stresses in the mantle, and on the plate interface.

What induces postseismic deformation?

- Slip on the fault plane at shallow depths?
- Relaxation in the asthenosphere?
- Relaxation in a low viscosity channel (LVC)?

Then if there is viscoelastic deformation, what is the appropriate rheology?

Viscosities obtained from inversion (Japan)



viscosities:

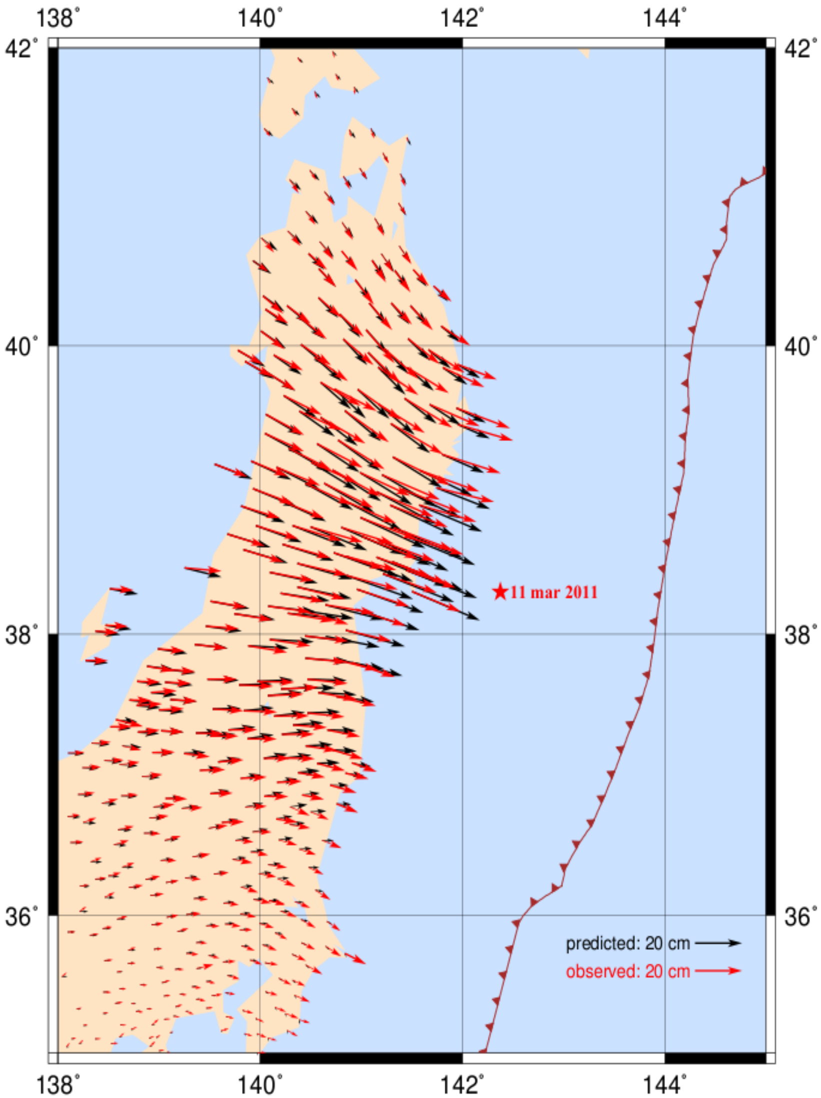
Asthenosphere (70-200km): 1.6 10^{18}Pas (a short-term viscosity?)

LVCh: from 10^{17} Pas to 6. 10^{17} Pas

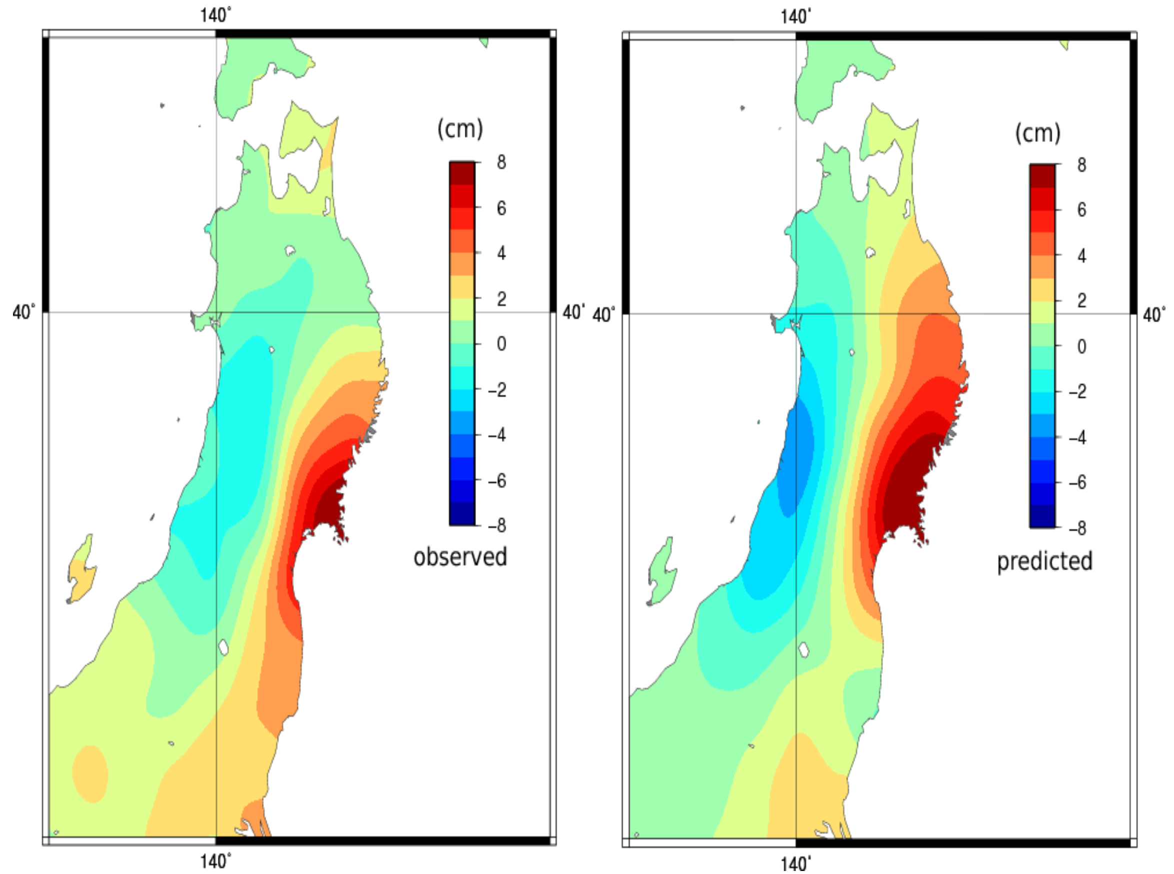
LVW1 : 4. 10^{17} Pas? (poorly constrained)

No additional postseismic slip on the interface required

Comparison between observed and predicted postseismic velocities in Japan (jan to dec 2012)

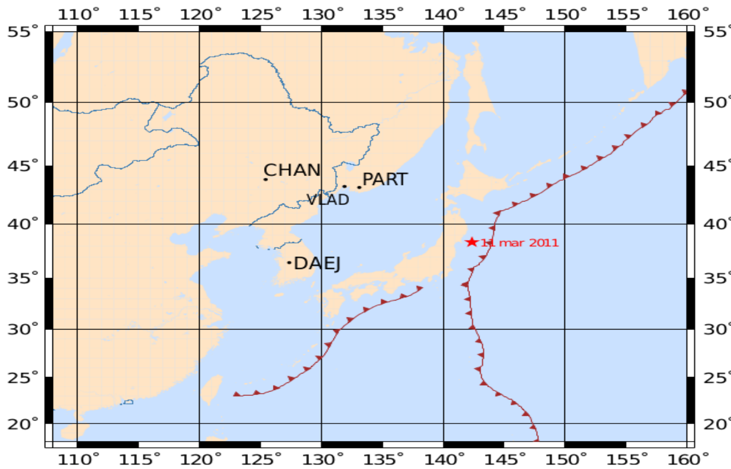


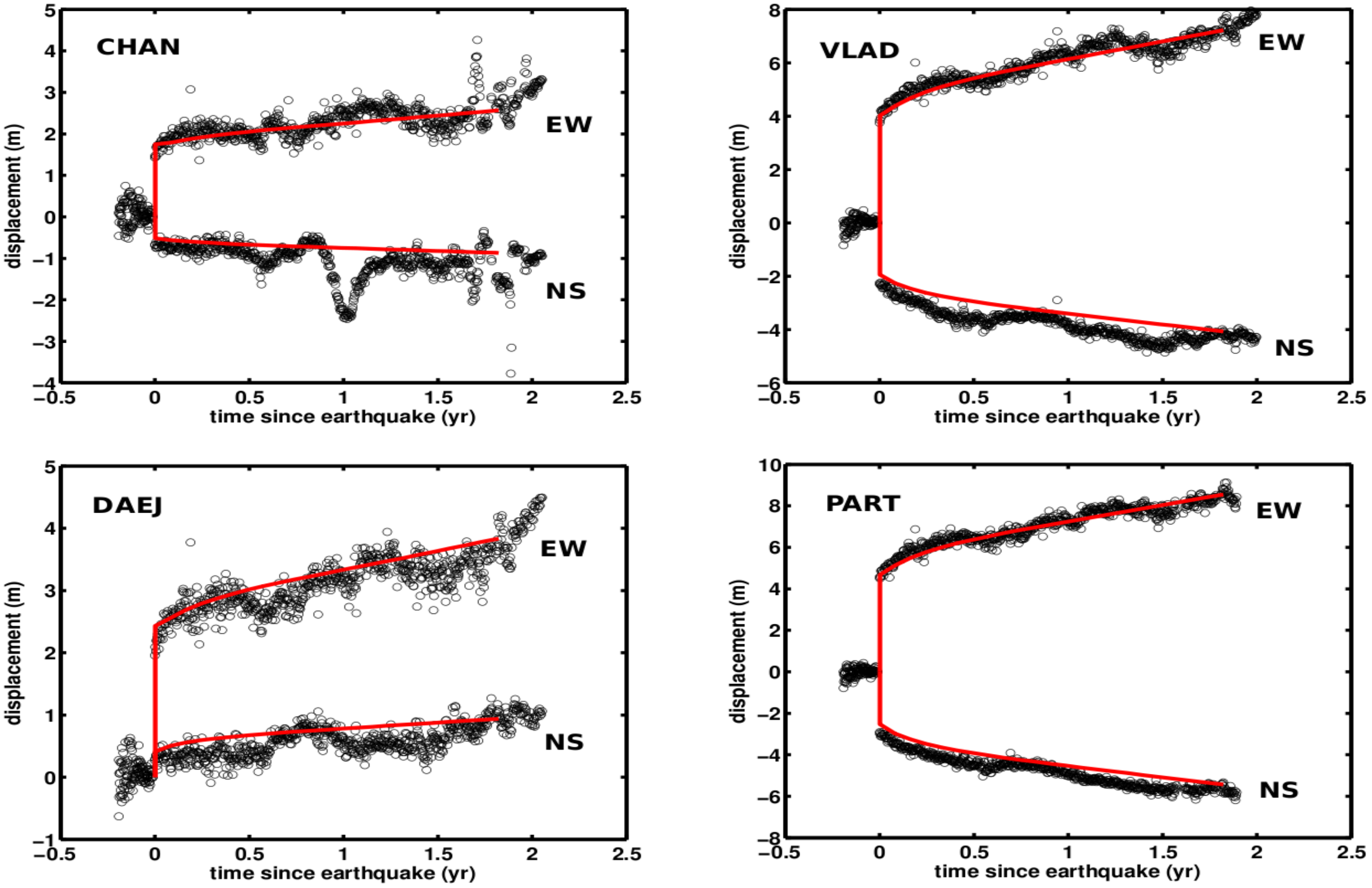
Horizontal velocities



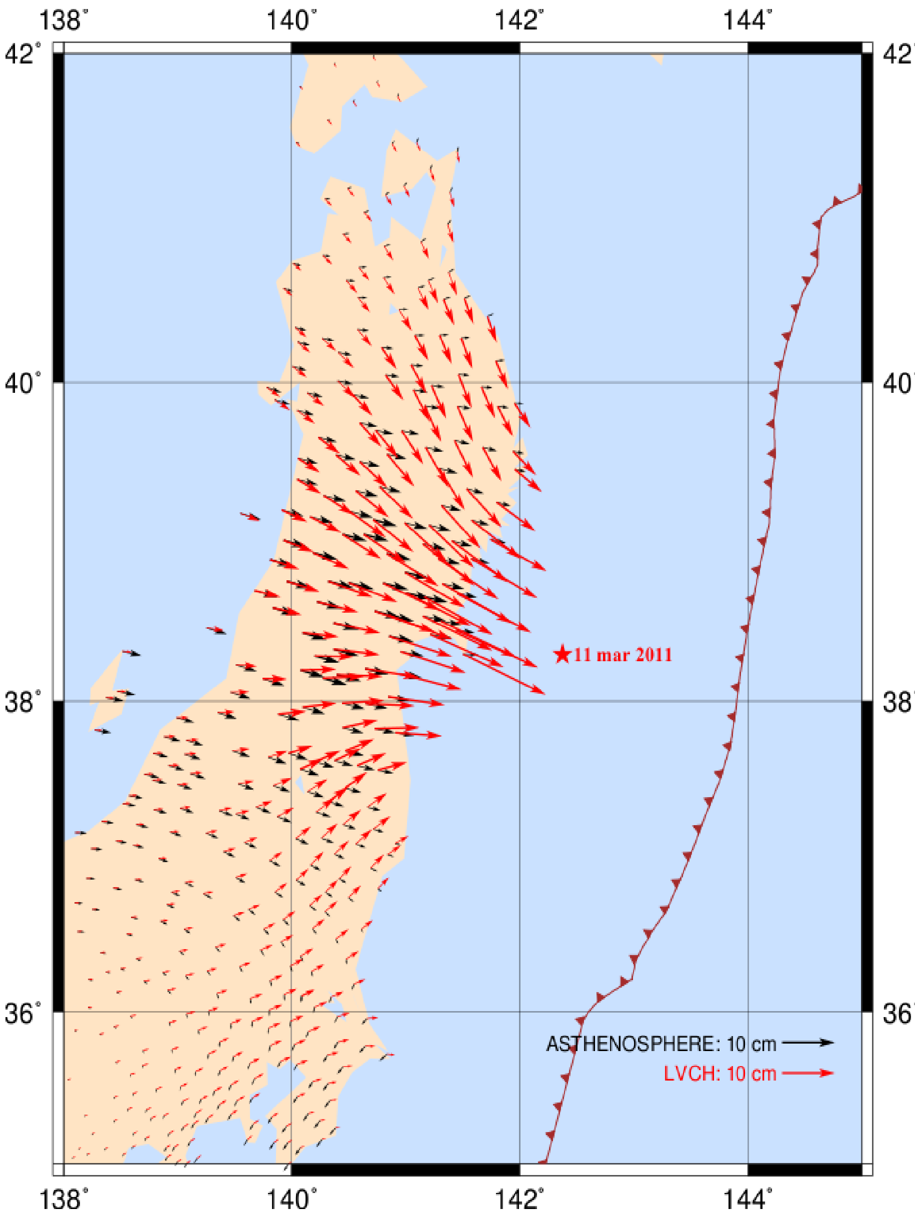
Vertical velocities

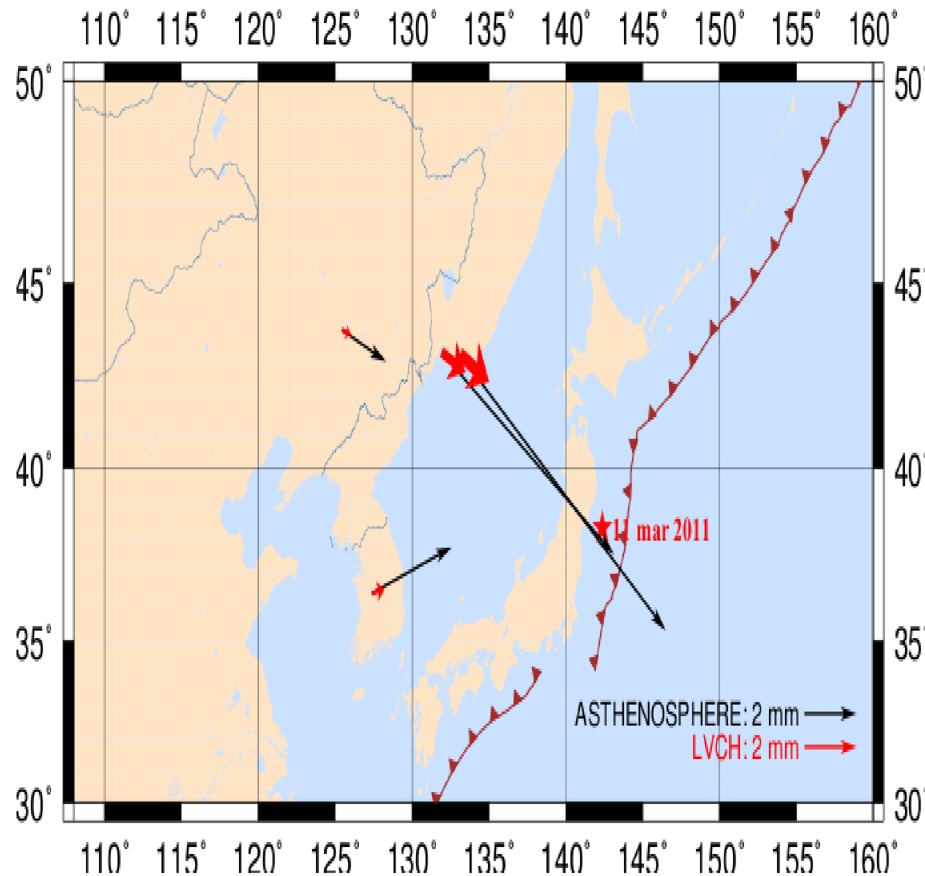
Fit to far-field stations time series





Both relaxation in the asthenosphere and relaxation in LVW or LVCh are necessary

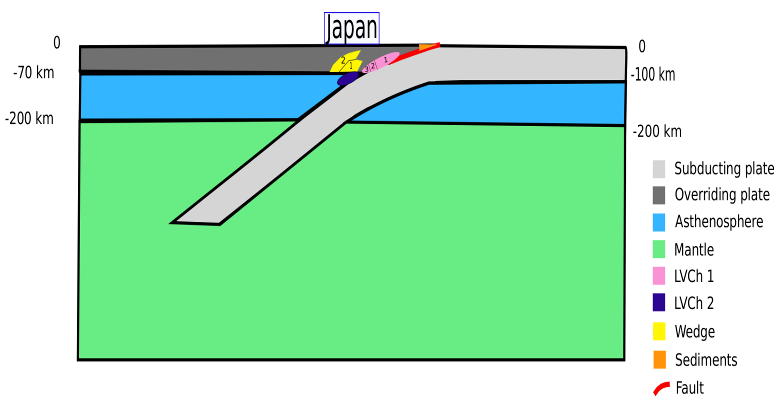


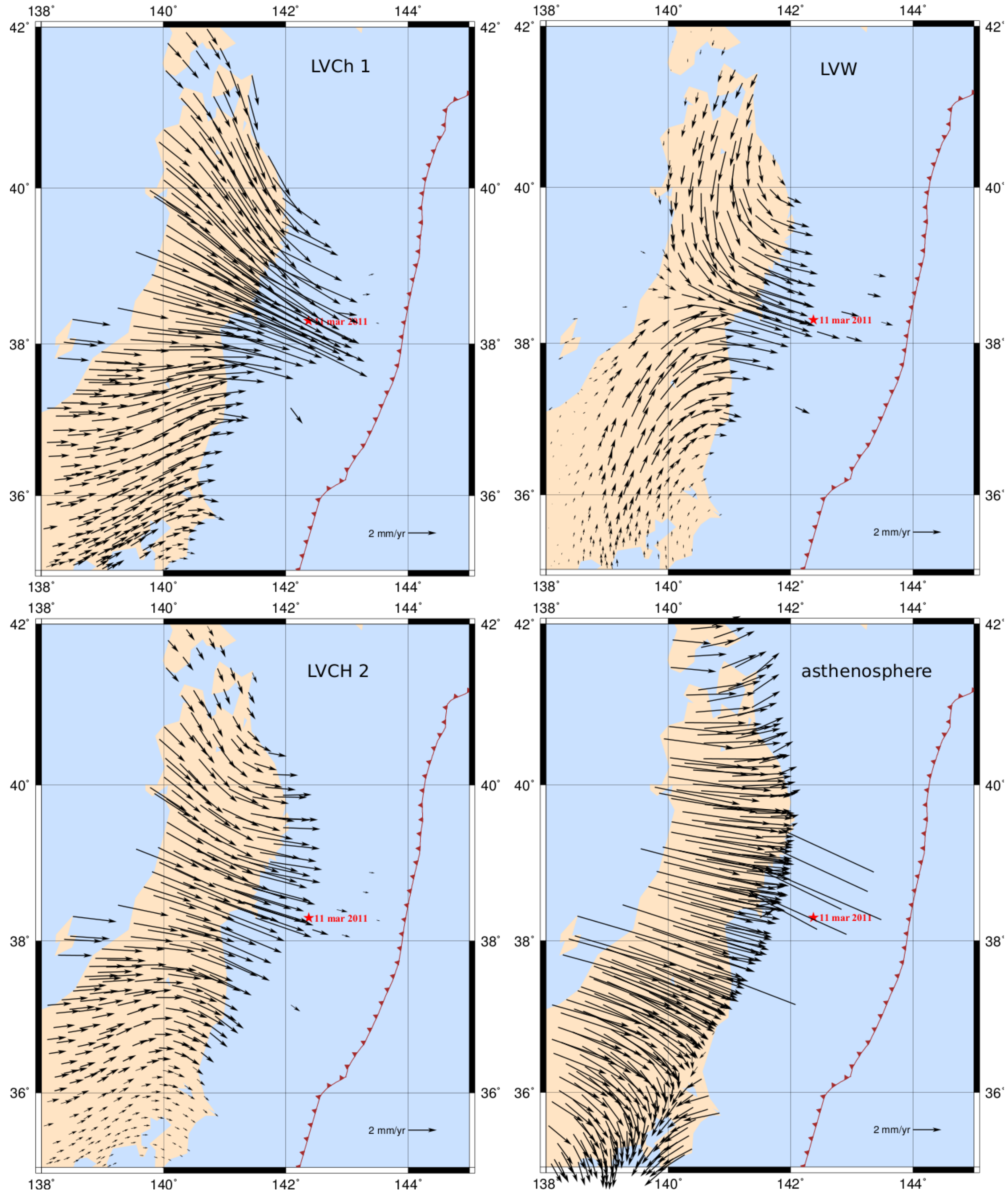


A model with only relaxation in the asthenosphere which fits the far-field velocities (black) induces negligible near-field velocities

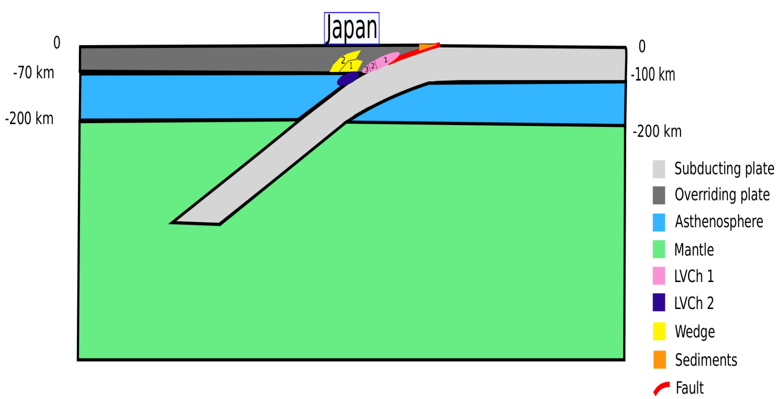
A model with only relaxation in the LVCh which fits the Japanese velocities (red) induces negligible far-field velocities.

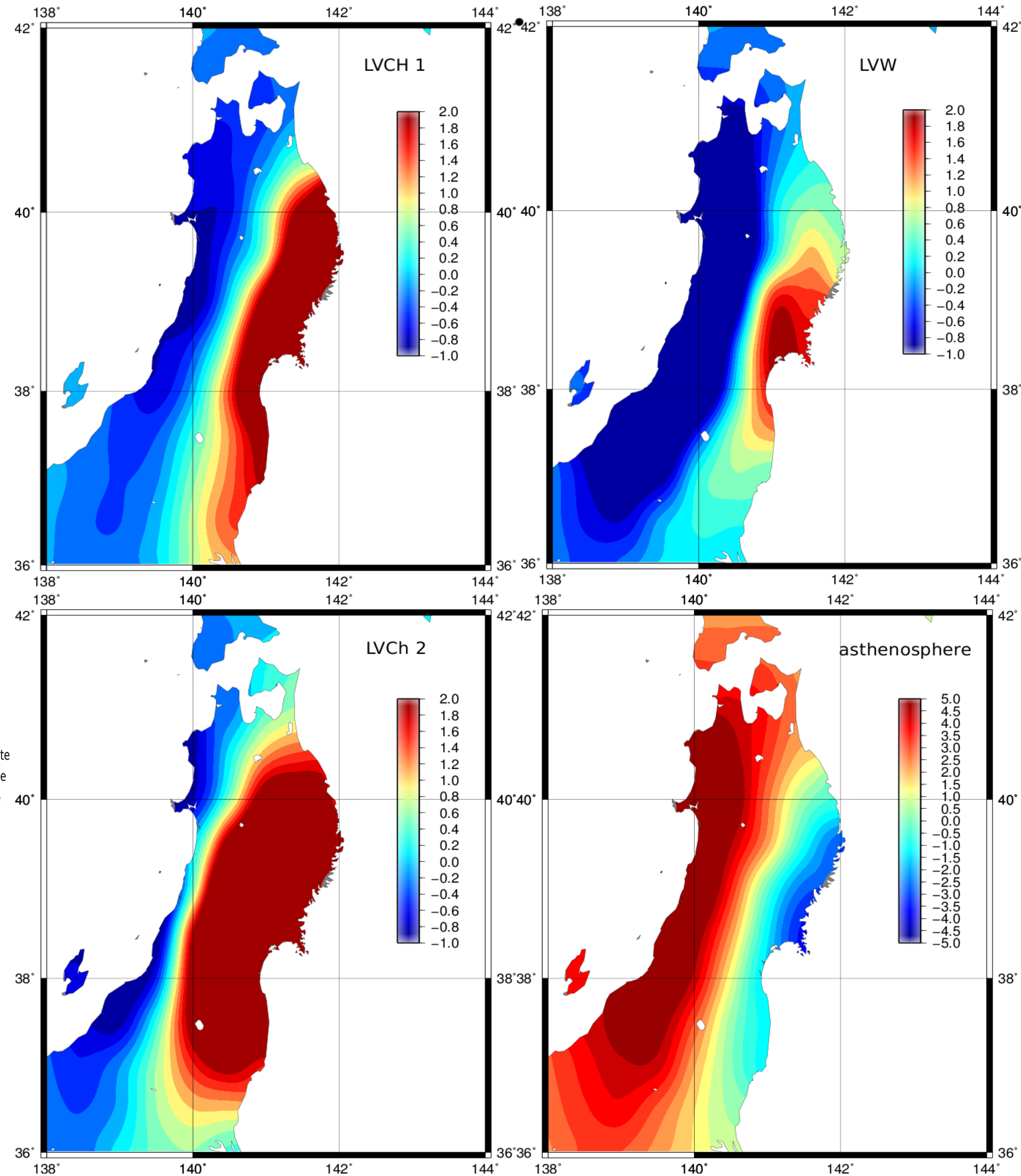
Impact of the viscosity in various zones on horizontal velocities ('partial derivatives')



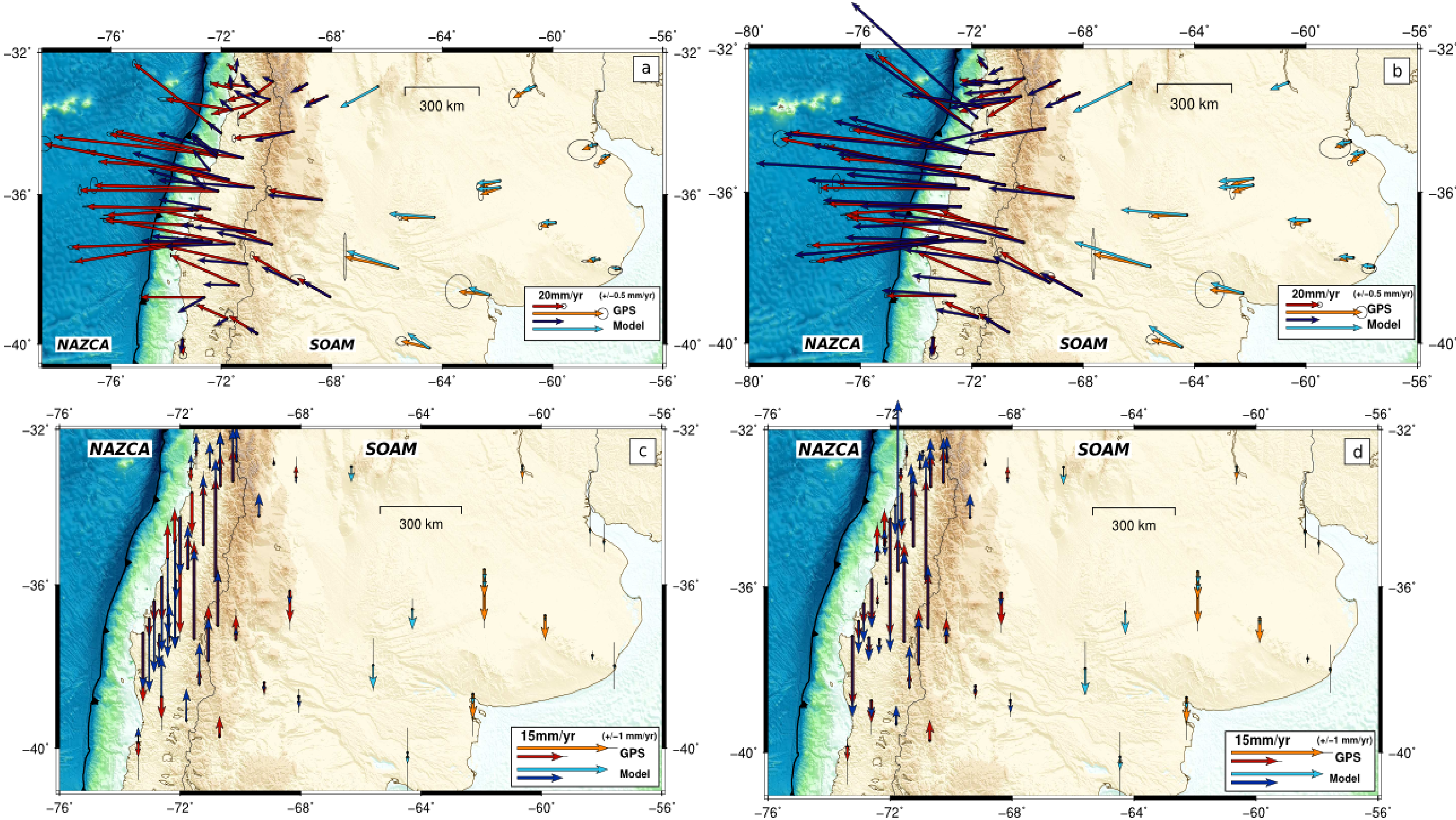


Impact of the viscosity in various areas on vertical velocities ('partial derivatives')



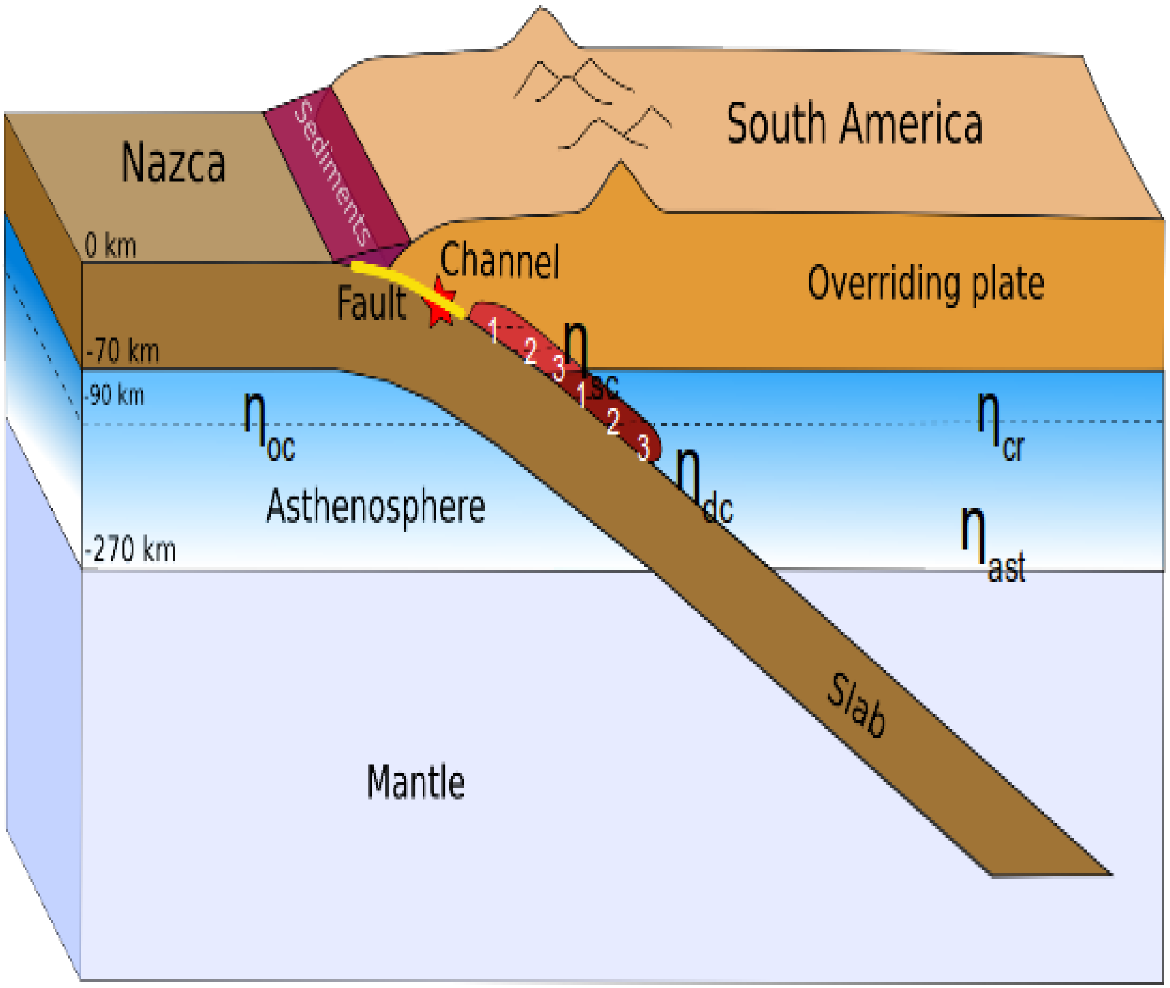


In Chile, additional slip on the interface is required



Modeled vs measured mean velocities over the 2nd year after the earthquake :
a) horizontal vel. in the case of a pure viscoelastic relaxation model
b) vertical vel. in the case of a pure viscoelastic relaxation model
c) horizontal vel. in the case of a viscoelastic relaxation + afterslip model
d) vertical vel. in the case of a viscoelastic relaxation + afterslip model

Klein et al. GJI 2016



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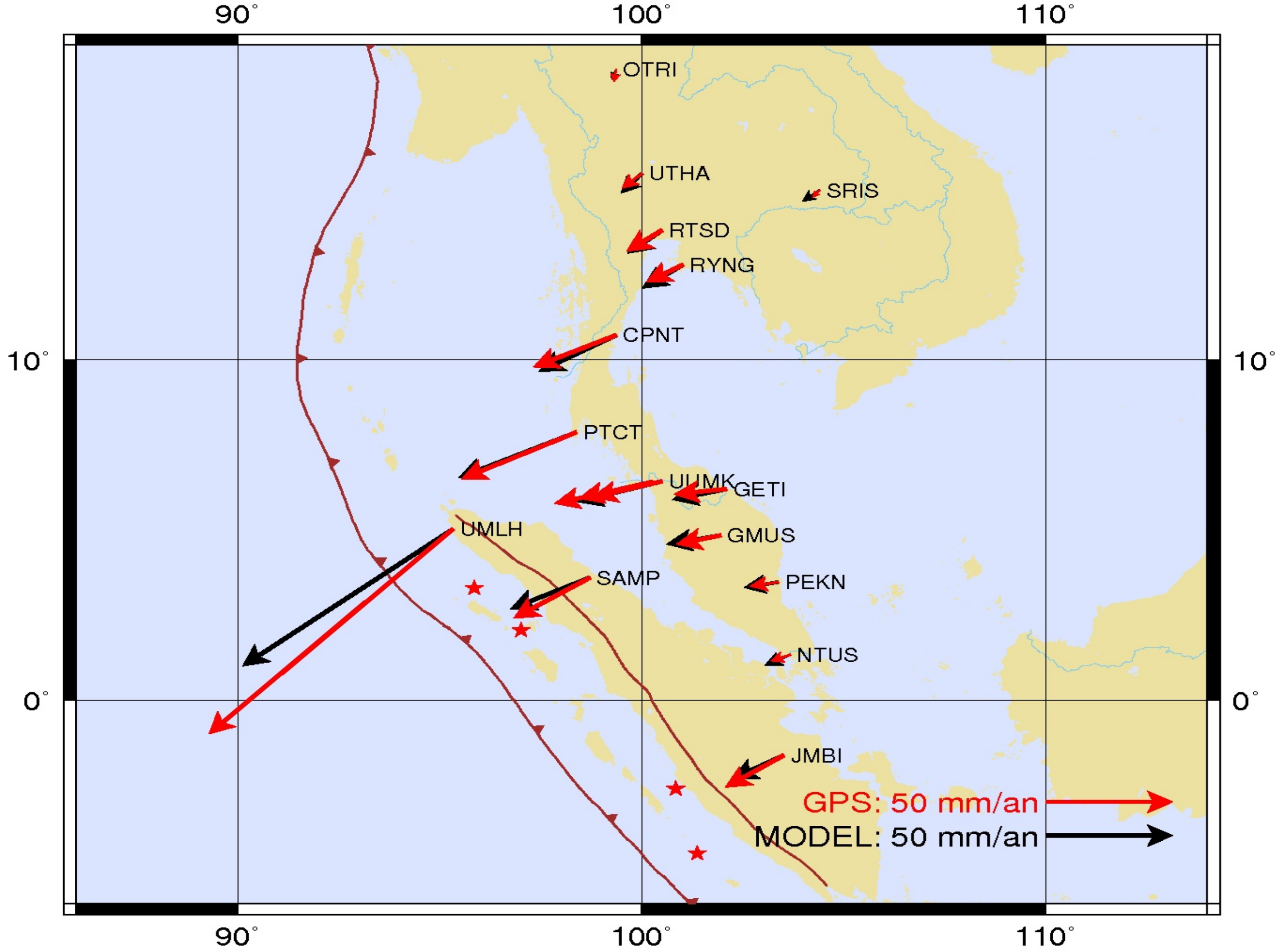
$\eta_2/\eta_1 = cst = 6,5$

$\mu_2/\mu_1 = cst = 3$

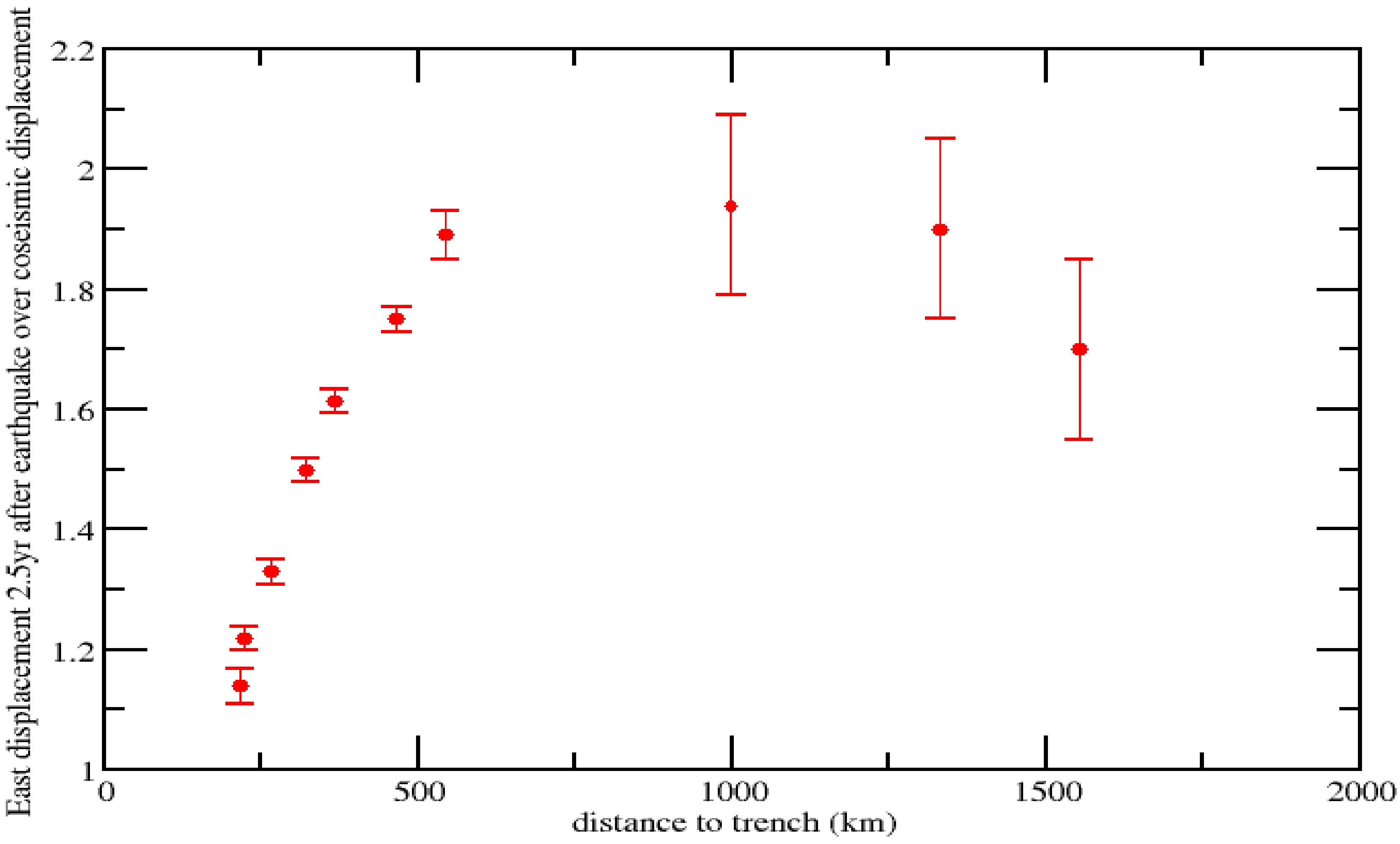
Far-field horizontal postseismic velocities after 2004 Sumatra earthquake

2008 velocities- predicted vs observations. asthe:3. 10**18 Pas

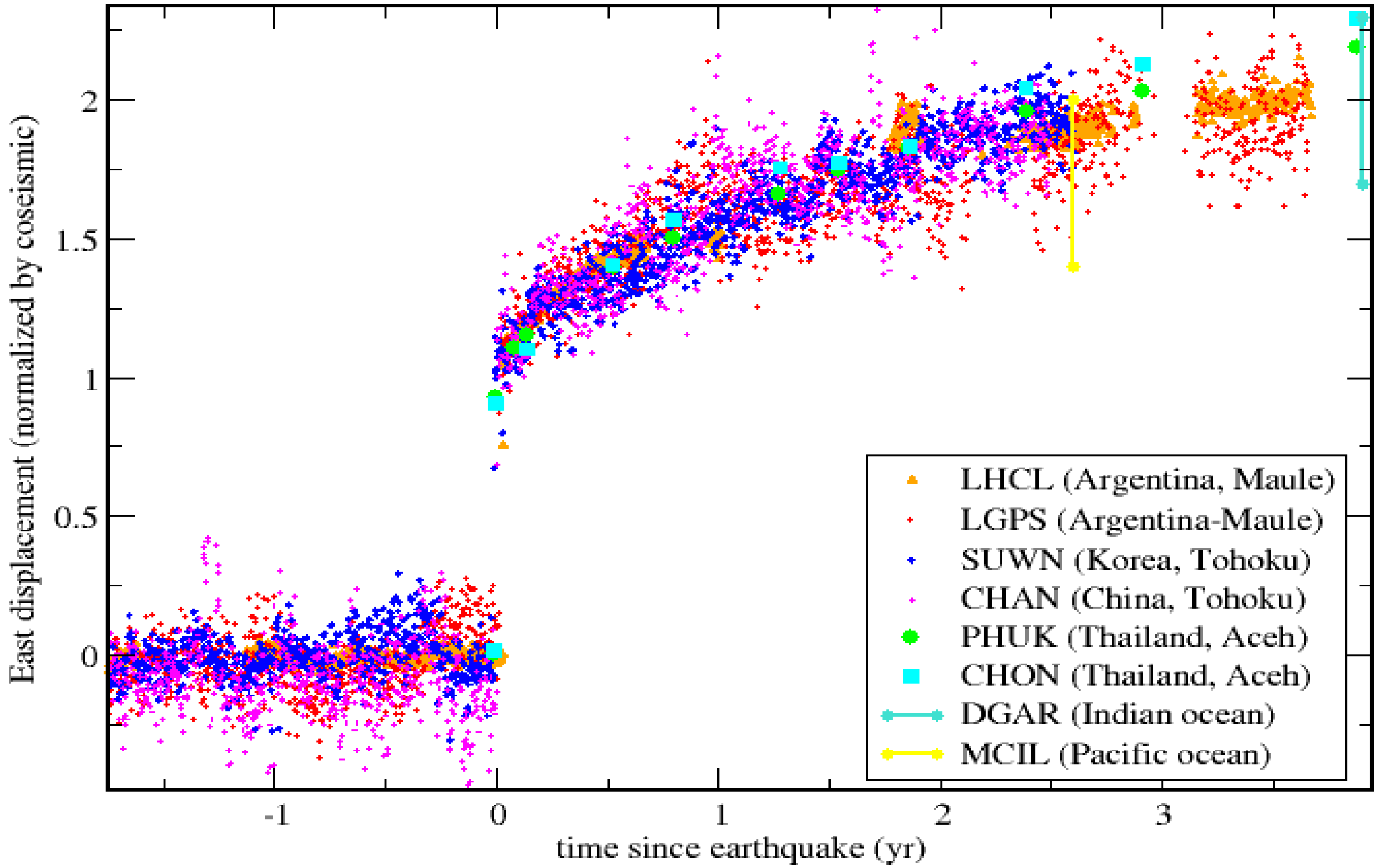


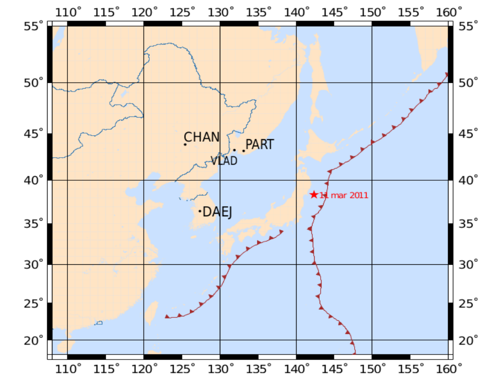
An asthenosphere of finite thickness:

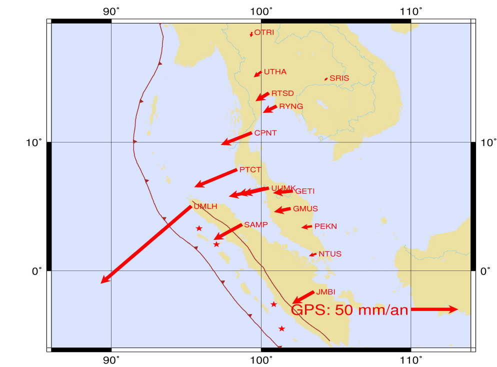
This curve keeps on increasing in case of low viscosity
in the whole upper mantle



After the three giant earthquakes at distances between (and 1000km)







The postseismic signal non dimensionalised by coseismic is similar for the three earthquakes but the deviatoric stresses differ by a factor 5!!!

Summary of the results from models of postseismic deformation after large subduction earthquakes:

Relaxation in the asthenosphere: Necessary for explaining far-field horizontal and vertical velocities. Viscosity around 2 to 4 10^{18} Pas (likely a long-term 'transient'). Asthenosphere 150-200km thick;

Relaxation in a 'low viscosity channel': necessary for explaining middle-field velocities (uplift).

Slip on the interface at shallow depths: Important for Aceh and Maule. Less for Tohoku

What we have learnt from the deformations following megaearthquakes:

Is-there a low-viscosity asthenosphere? What rheology (newtonian, non-linear creep), what thickness

Asthenosphere (200km thick?) with a viscosity around 3.10^{18} Pa.s. Transient creep but not power law rheology

What occurs below the brittle part of the subduction interface? Localization of the deformation in low-viscosity ductile shear zones?

A low viscosity channel is clearly identified: serpentine; hydrated material?

Other tectonic implications:

What are the ingredients of the stress/strain-field?

Stresses and strains vary in time: Only close to megaearthquakes?

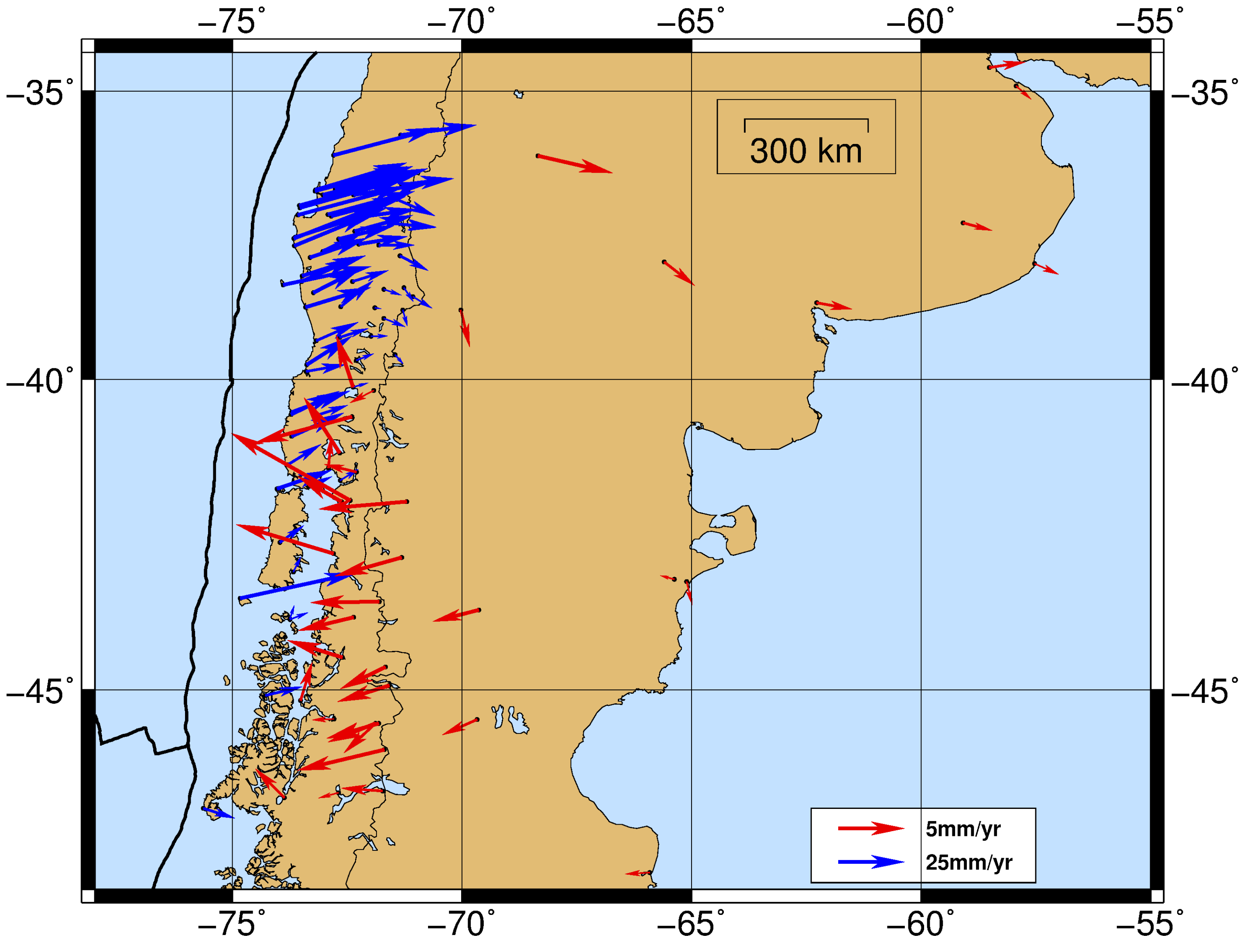
Implications concerning the stress evolution along the slab interface and within the overiding and subducting plates

What occurs on longer time-scales?

The seismic cycle

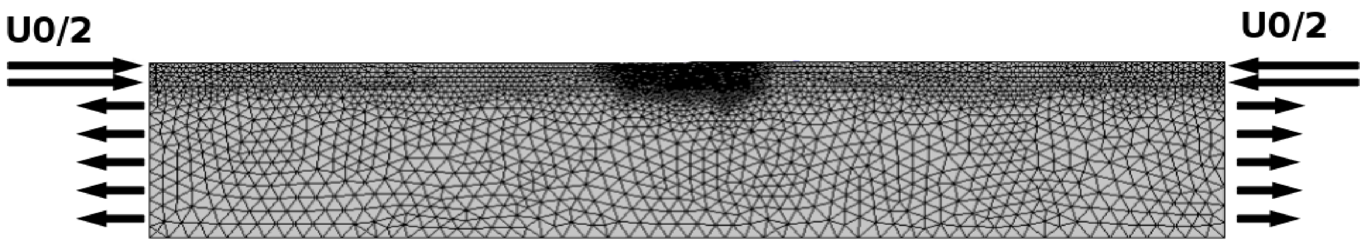
Viscoelastic versus elastic backslip...
Observations and models

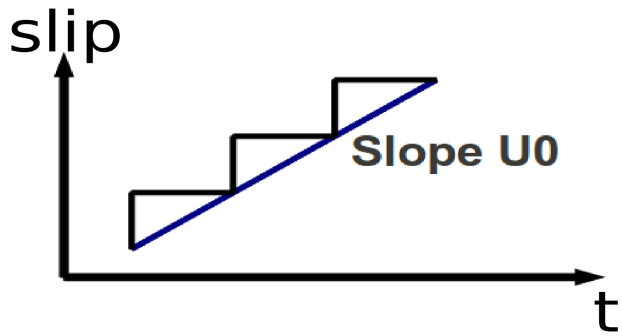
40yrs after Valdivia, before Maule (referential of North-East South America)



Notice eastward velocities far inland in front of Maule

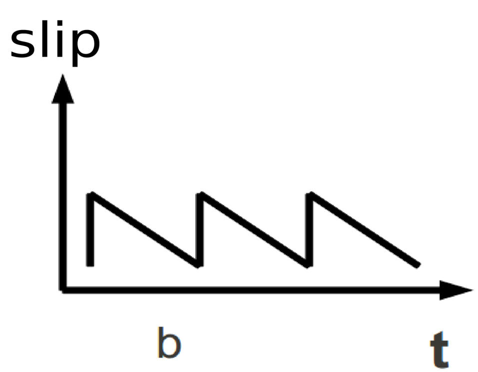
Back-slip

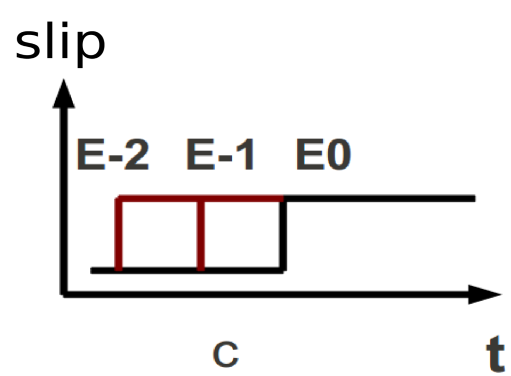




realistic

backslip

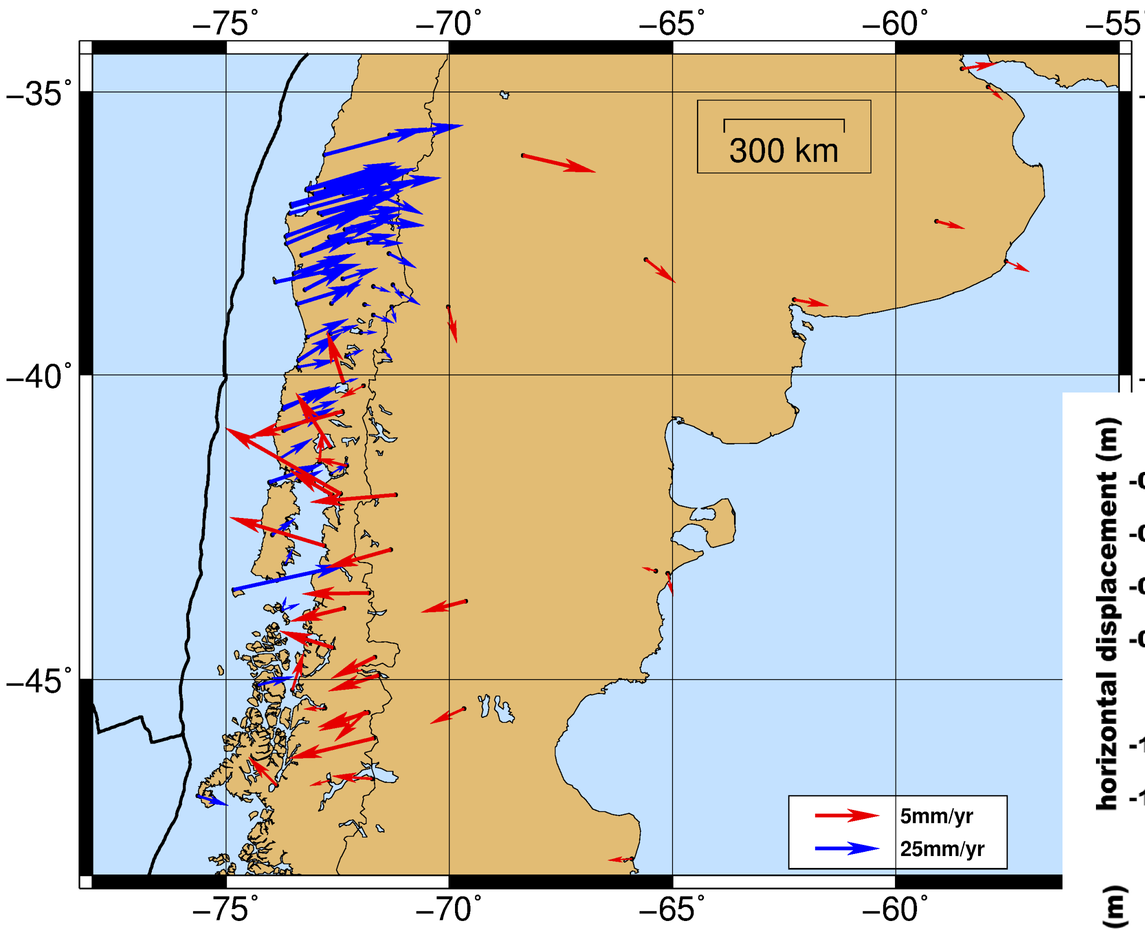




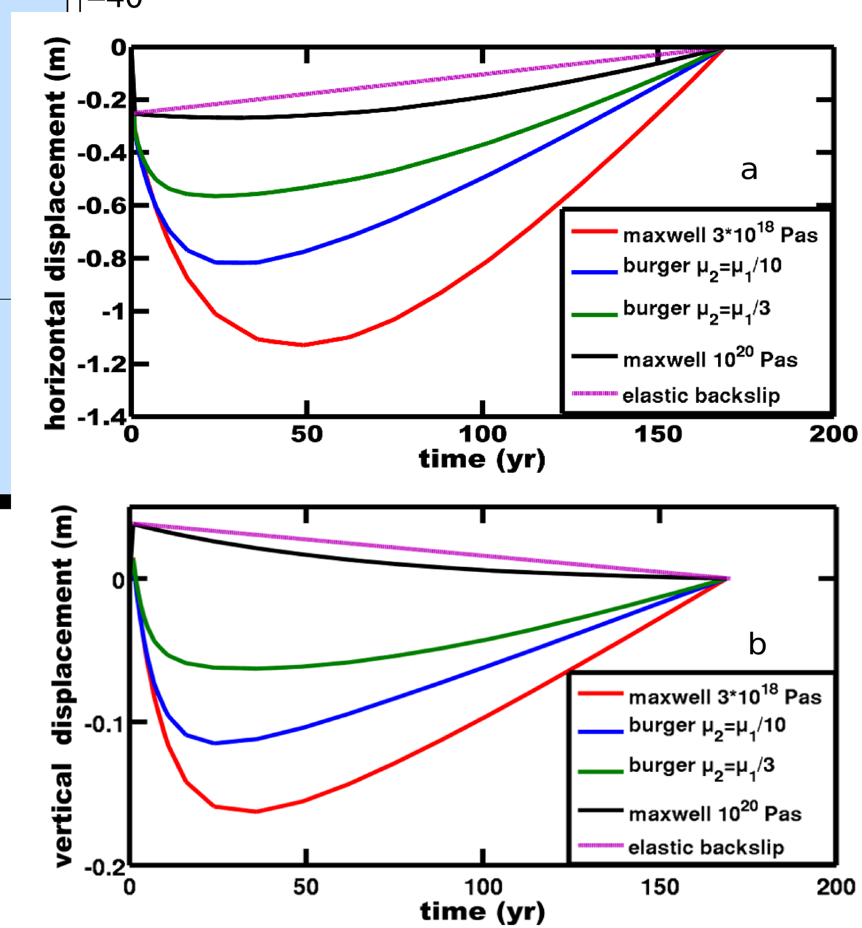
superposition

There are several equivalent methods to model the seismic cycle
Elastic backslip implicitely assumes a large viscosity (>10^{21} Pas)
But the asthenosphere has a low viscosity....

Observed 40yrs after Valdivia, before Maule (referential of North-East South America)

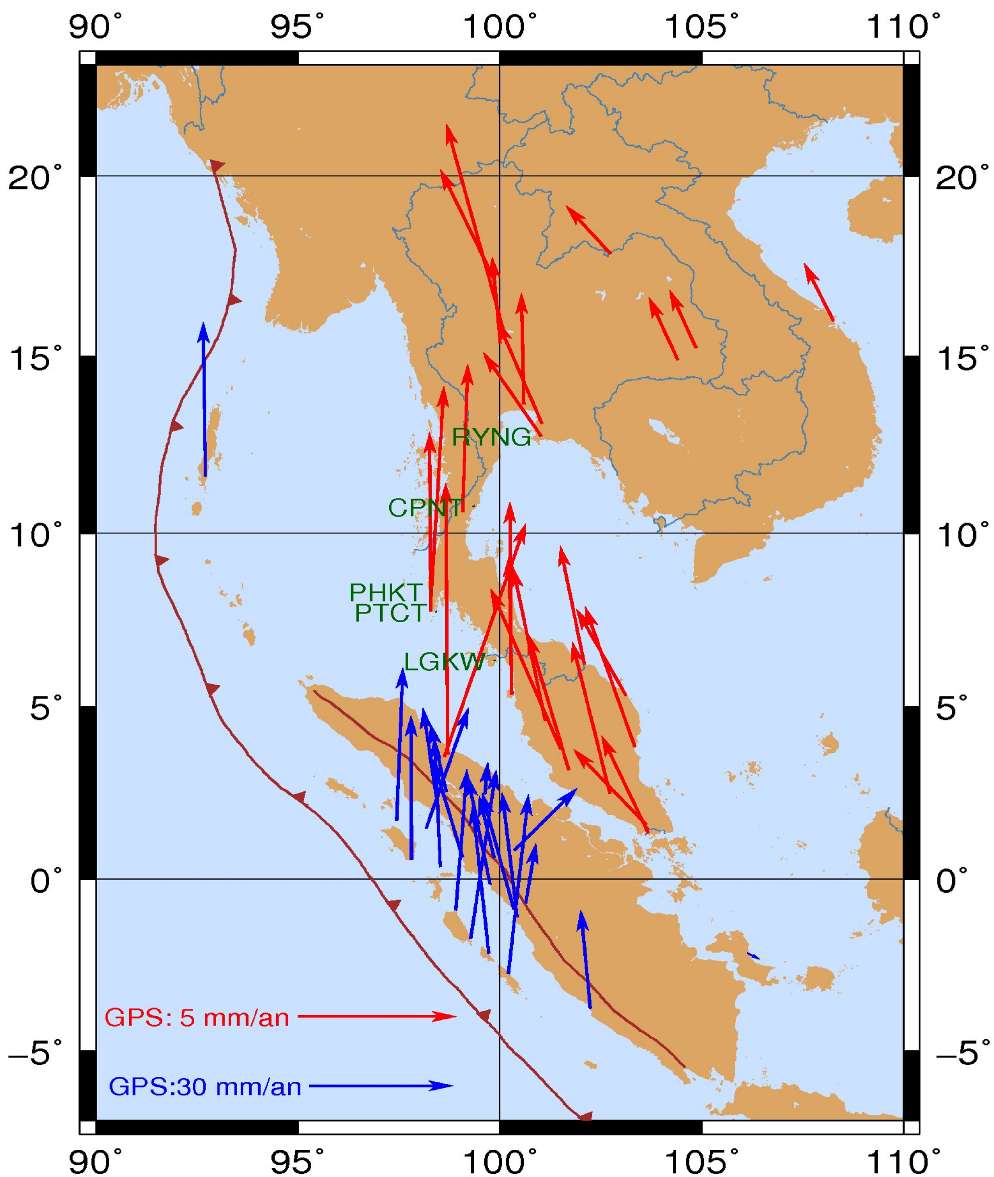


Predicted displacements at a distance of 700km



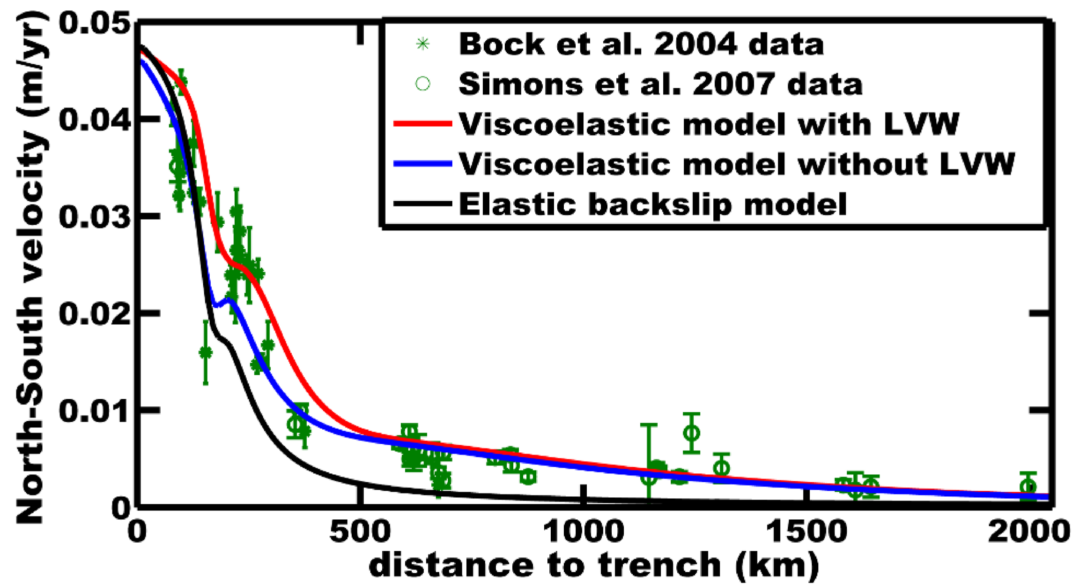
The velocity and strains are almost never equal to the long-term average

Are the present-day strains 'Geologic' strains or effect of the seismic cycle?



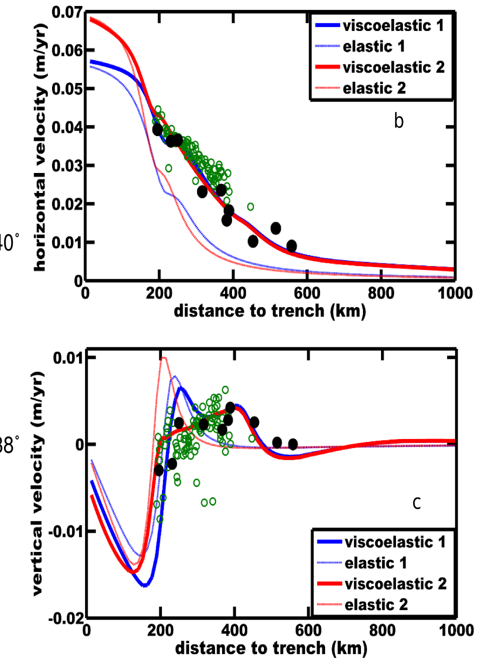
Observed velocities with respect to south China before 2004

Is there a Sunda plate distinct from South-China?



What is the long-term convergence? velocity between the Okhotsk and Amour plates?

East West



Westward velocities in Japan before Tohoku

- Before Tohoku Earthquake, Western Japan moves westward /Amour plate
- After Tohoku, Western Japan moves eastward/Amour plate

Deformations within continental Asia?