Intraplate deformations: short versus long time-scales

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In collaboration with:
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E. Calais, C. Vigny and numerous 'GPS' colleagues

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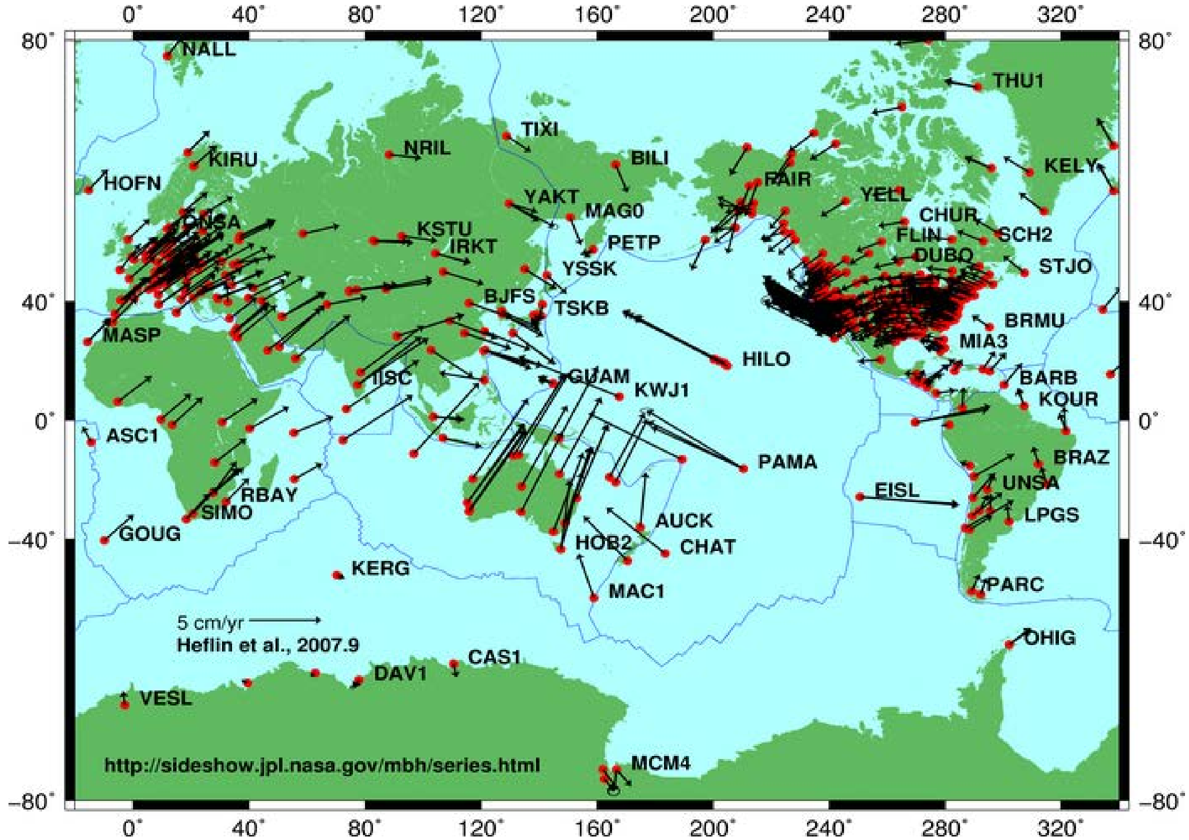


Plate-tectonics describes the rotation of **rigid** plates
'Tectonic' zones characterized by more diffuse plastic deformation have been identified.

Precise modern GPS measurements reveal deformations inside 'stable' plate interiors of a few mm/yr

What is the origin of those deformations within ‘stable plate interiors’?

Slow viscous or plastic deformation ?

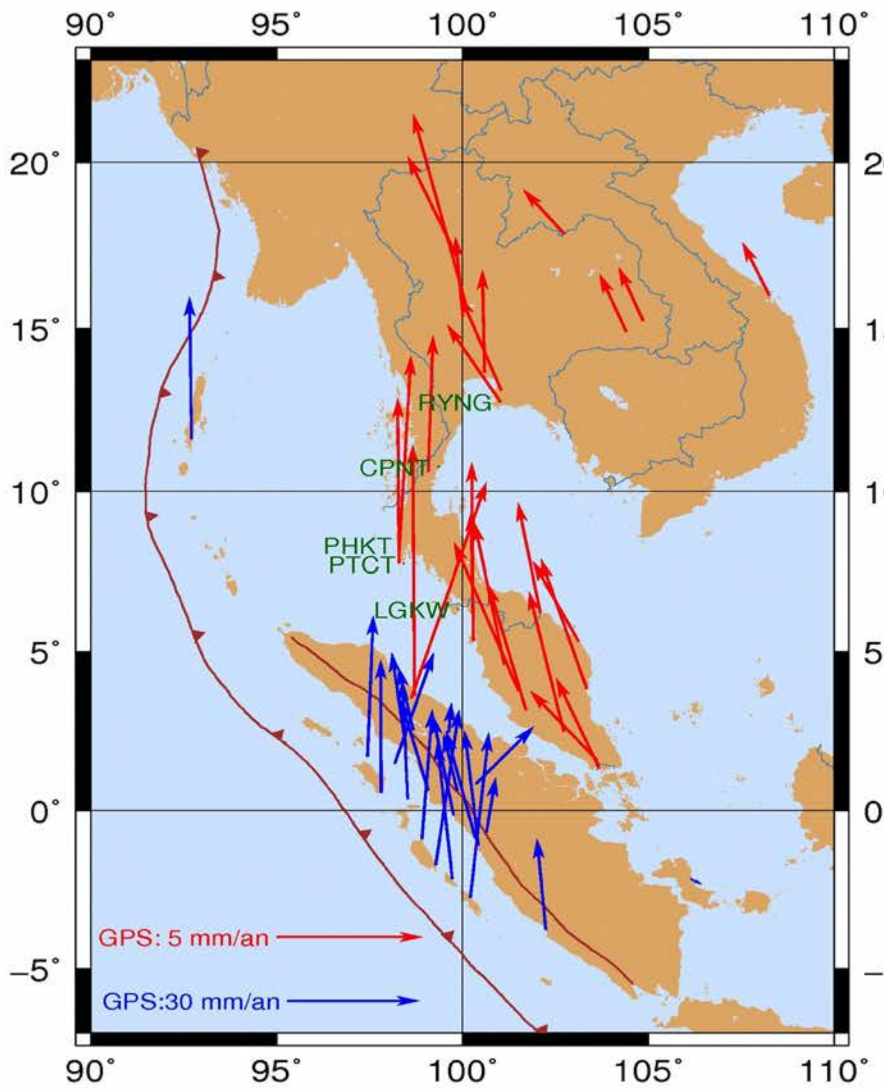
Then, they reflect the state of stress in the plates and are a precious indicator of the ‘forces which move the plates’

Elastic deformation ?

Then, they reflect time derivatives of stresses induced by ‘short time-scale’ processes :

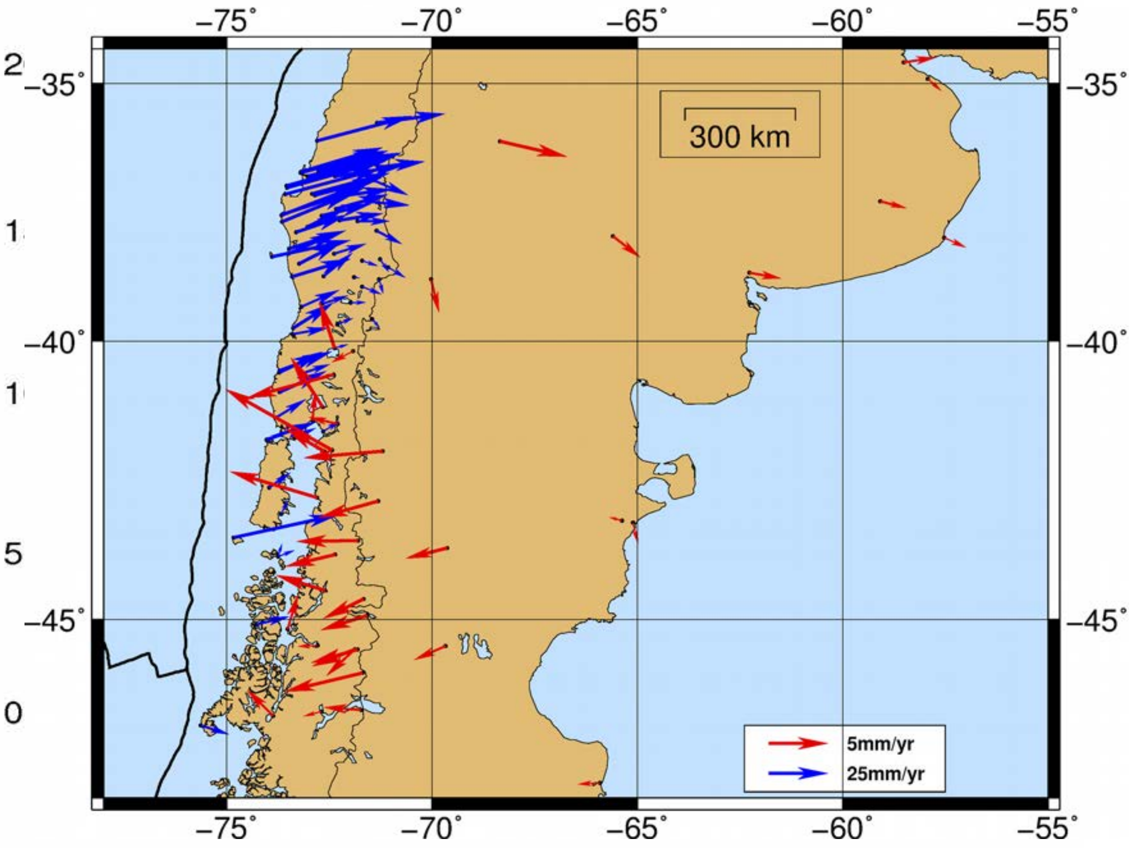
- Earthquakes
- Readjustment of the Earth after the last glaciation
- Response to present-day hydrological loads
- ‘Internal strains’ within the top meters of the Earth induced by temperature variations or pressure variations within aquifers

Megaearthquakes and the far-field deformation through the seismic cycle



Trubienko et al. Tectonophy 2013

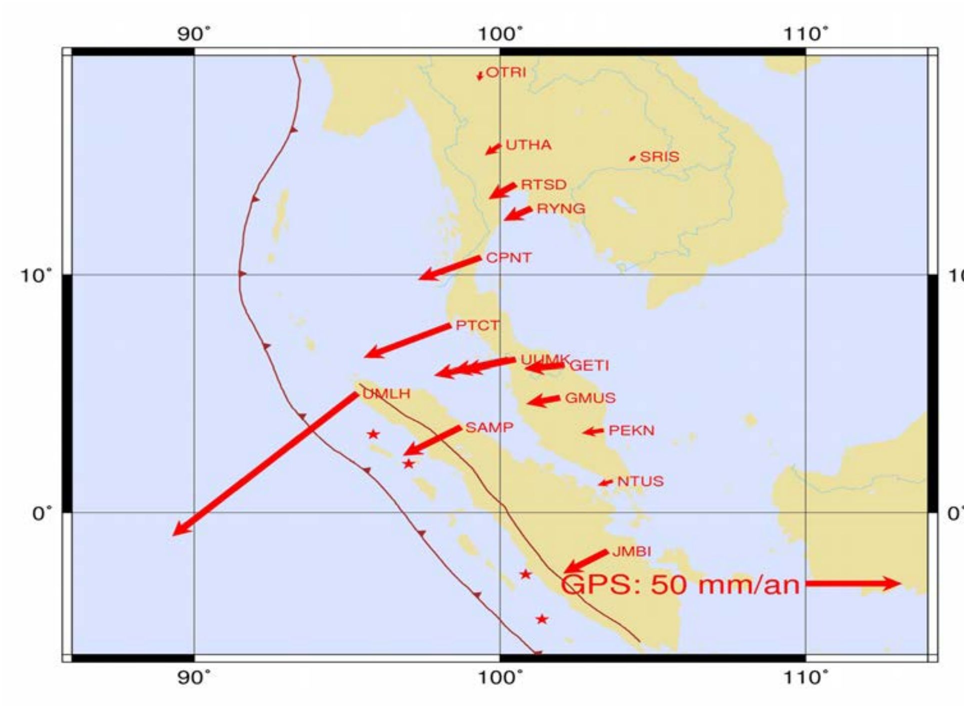
Observed velocities with respect to south China before 2004



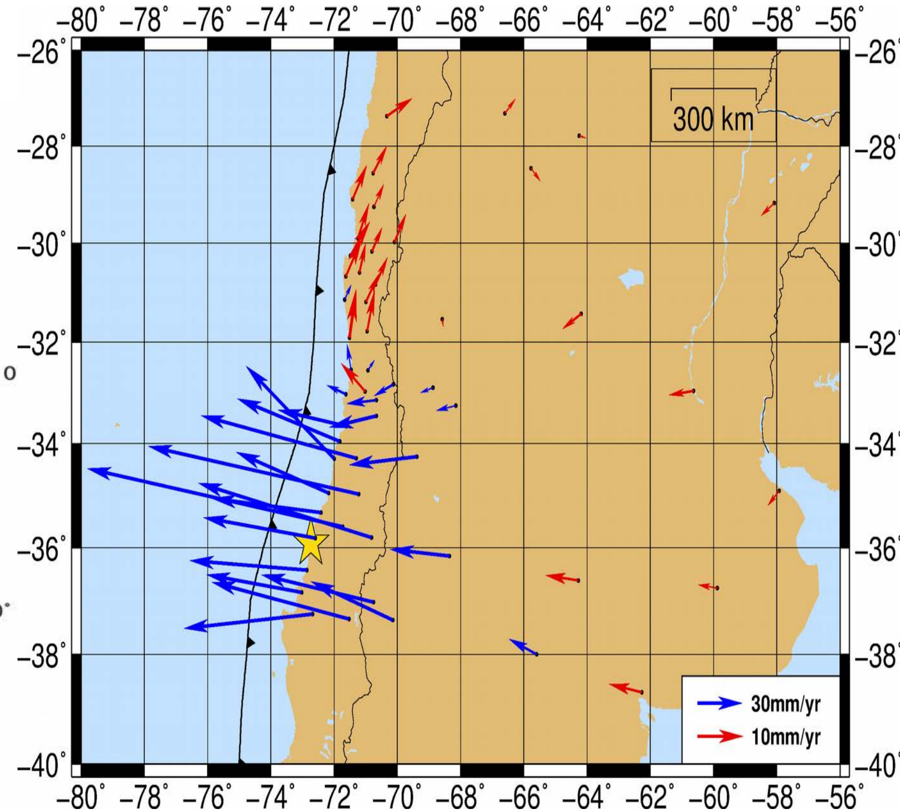
Deduced from Klein et al. GJI 2016-See also Klotz et al. EPSL 2001, Hu et al. JGR 2004

Observed velocities in a SAM reference frame with respect to stable South-America

1) Postseismic deformation



Velocity perturbations 4yrs after Aceh (dec 2004)

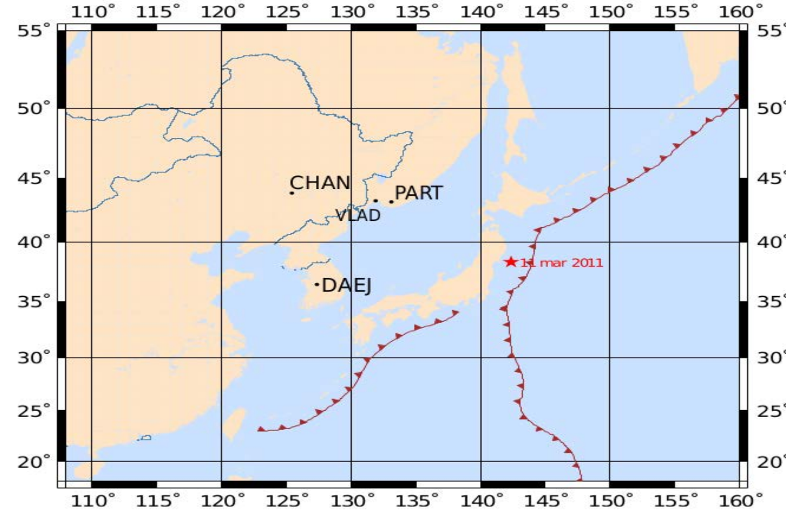


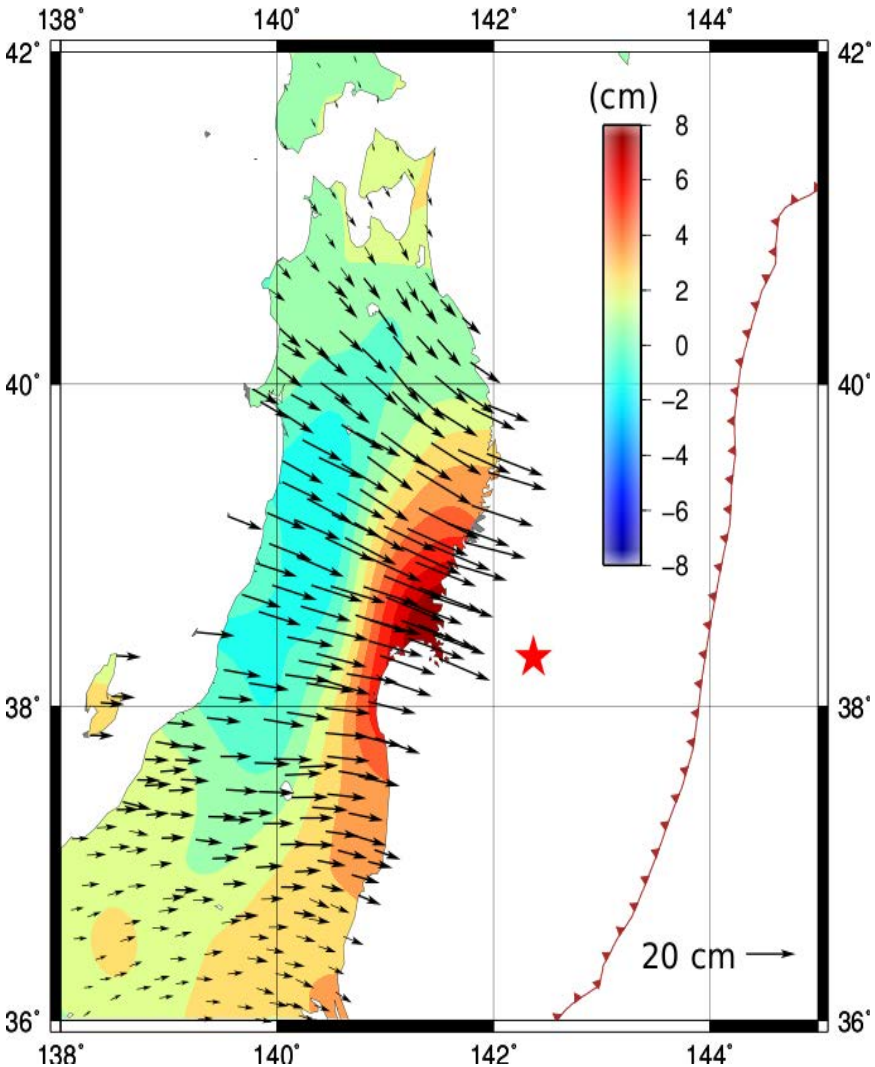
2 yr after Maule (febr 2010)

Klein et al. GJI 2016

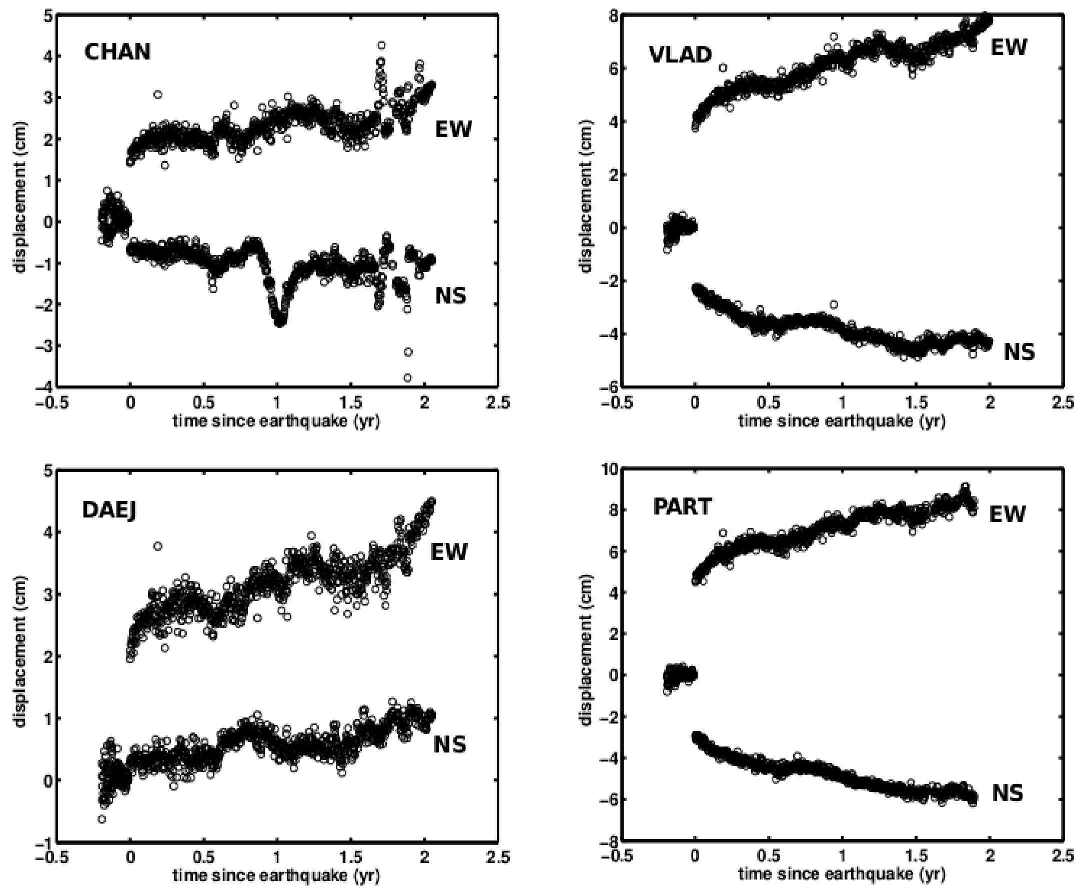
The three megaearthquakes (Aceh 2004, Maule 2010, Tohoku 2011) are the first earthquakes of magnitude around 9 since modern techniques able to monitor deformation are available. They are associated with huge, far-field, long-lasting velocity perturbations

GPS velocities and displacements after Tohoku
(corrected for preseismic)



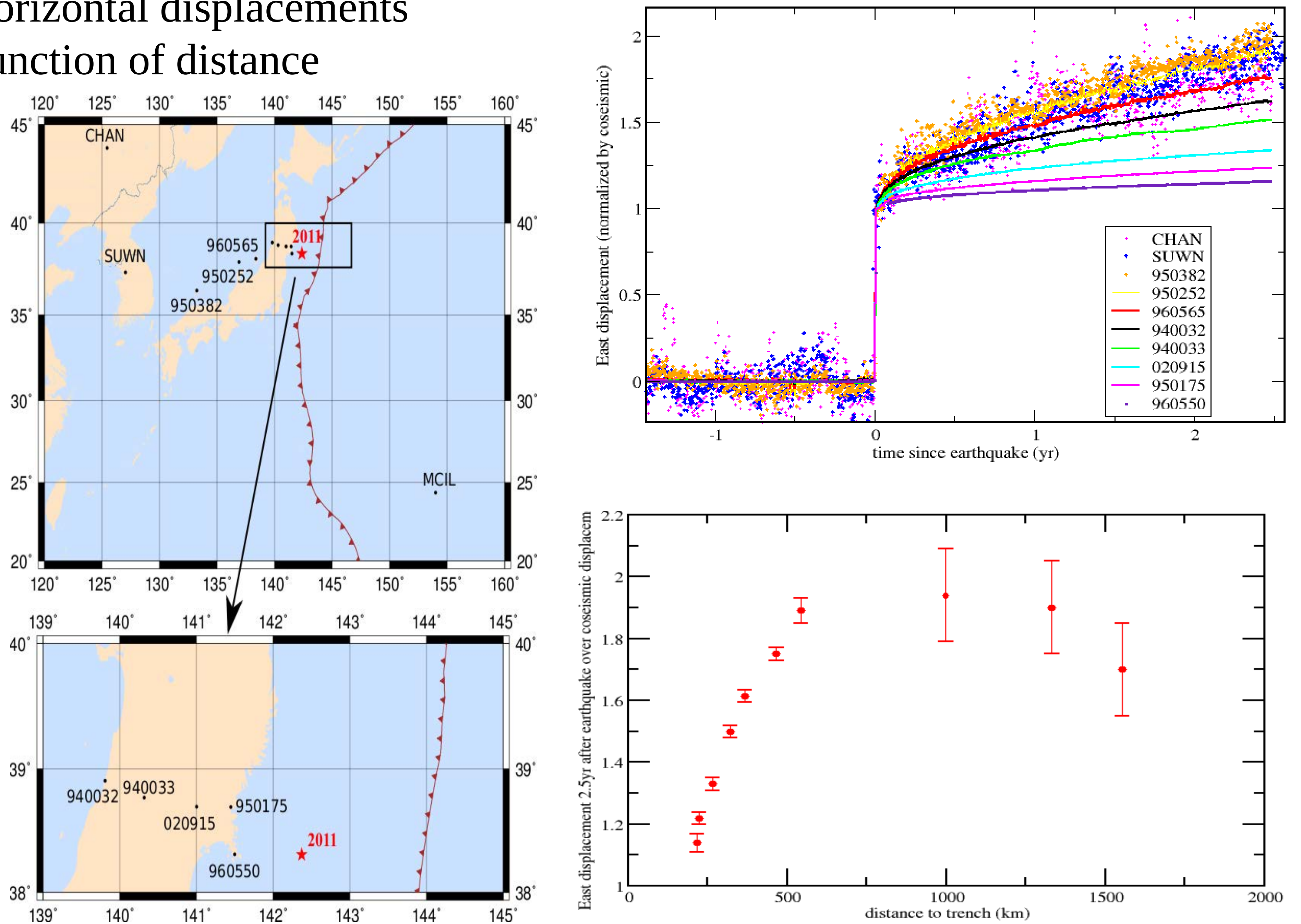


Horizontal velocities in 2012



Non-dimensionalized horizontal displacements function of distance

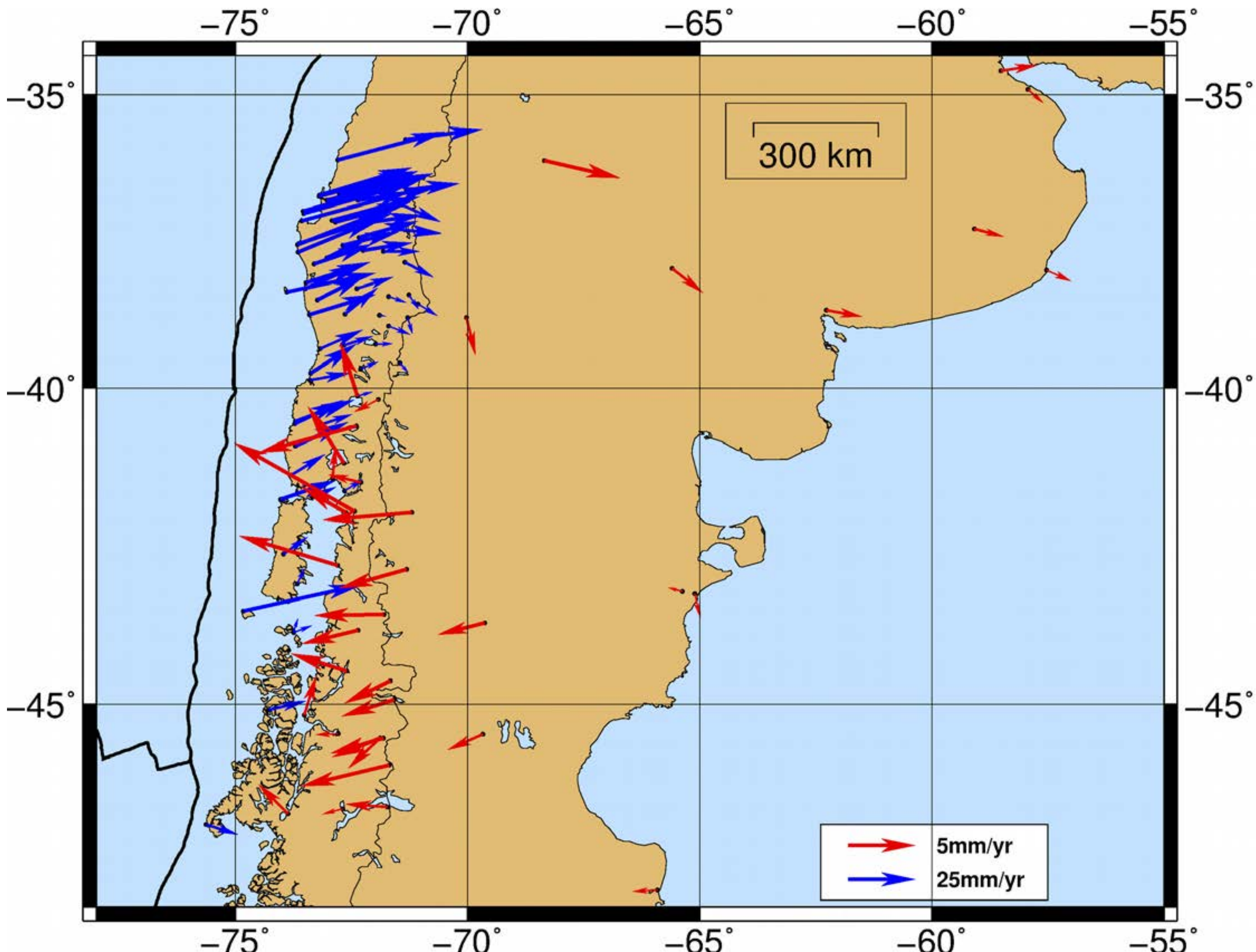
Coseismic and postseismic:different pattern



Trubienko et al. Solid Earth discuss 2014

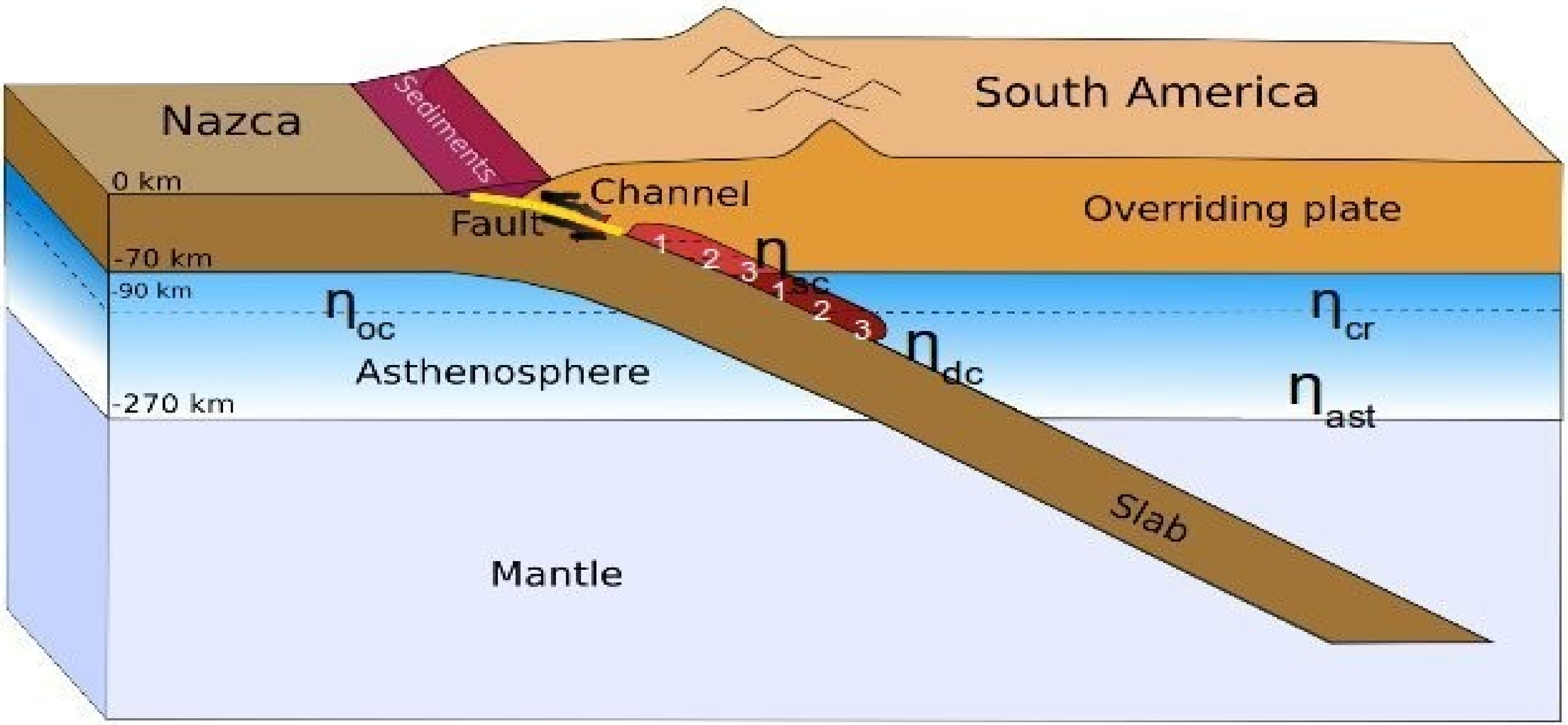
The postseismic phase continues for several decenies

After Valdivia (before Maule)



Velocities in a SAM reference frame

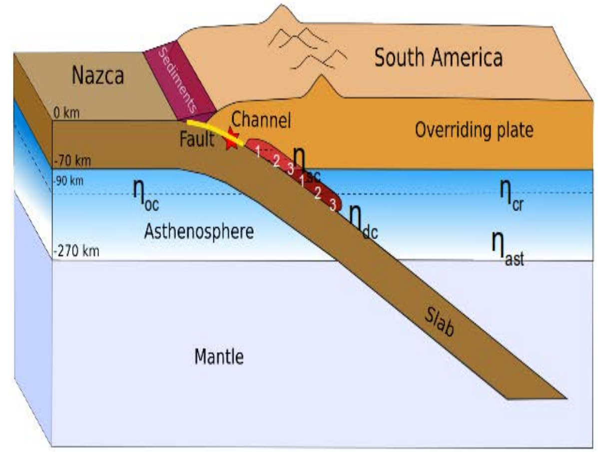
See Klotz et al. EPSL 2001
Hu et al. JGR 2004



The response of the Earth to megaearthquakes:

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

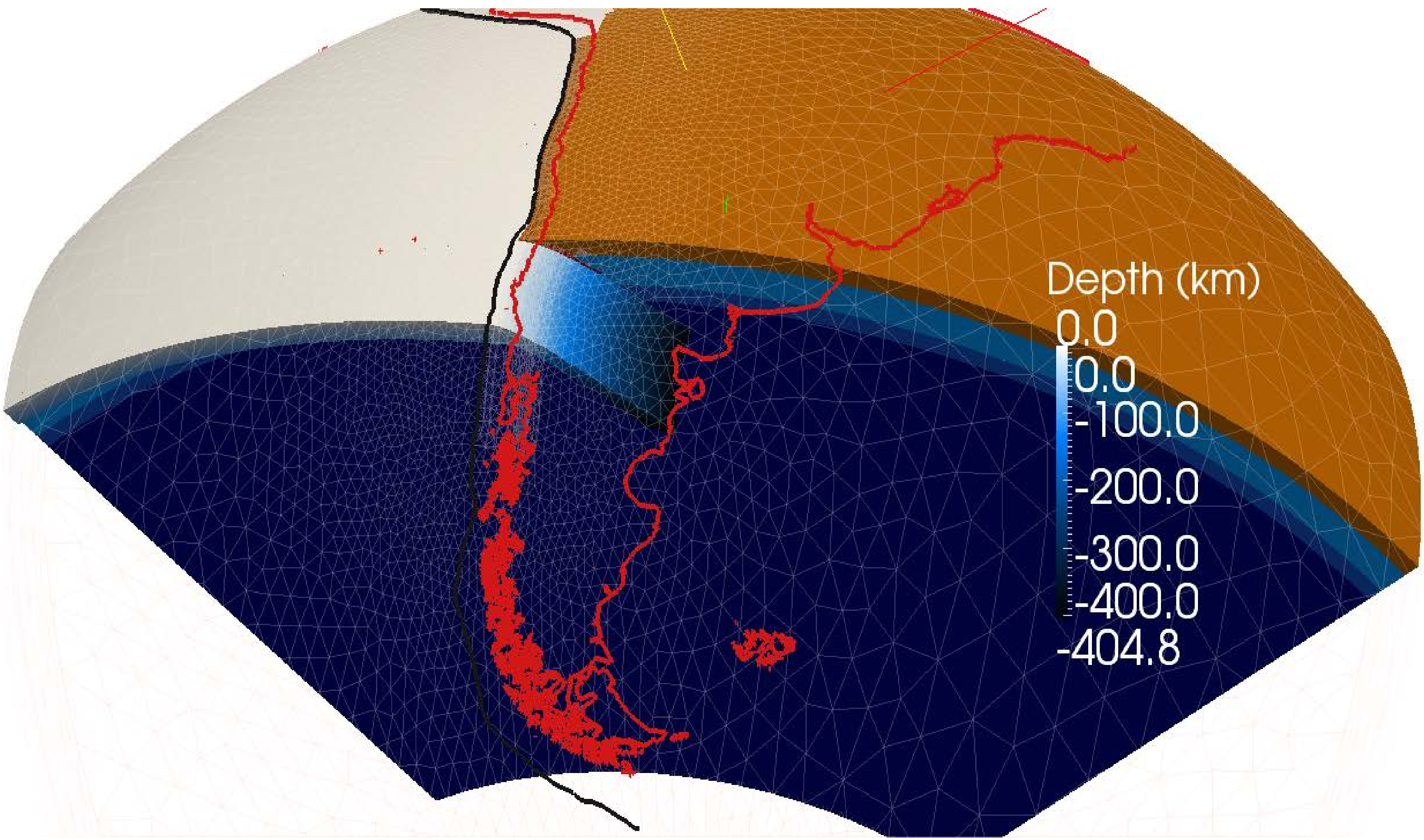
Mesh for Maule earthquake



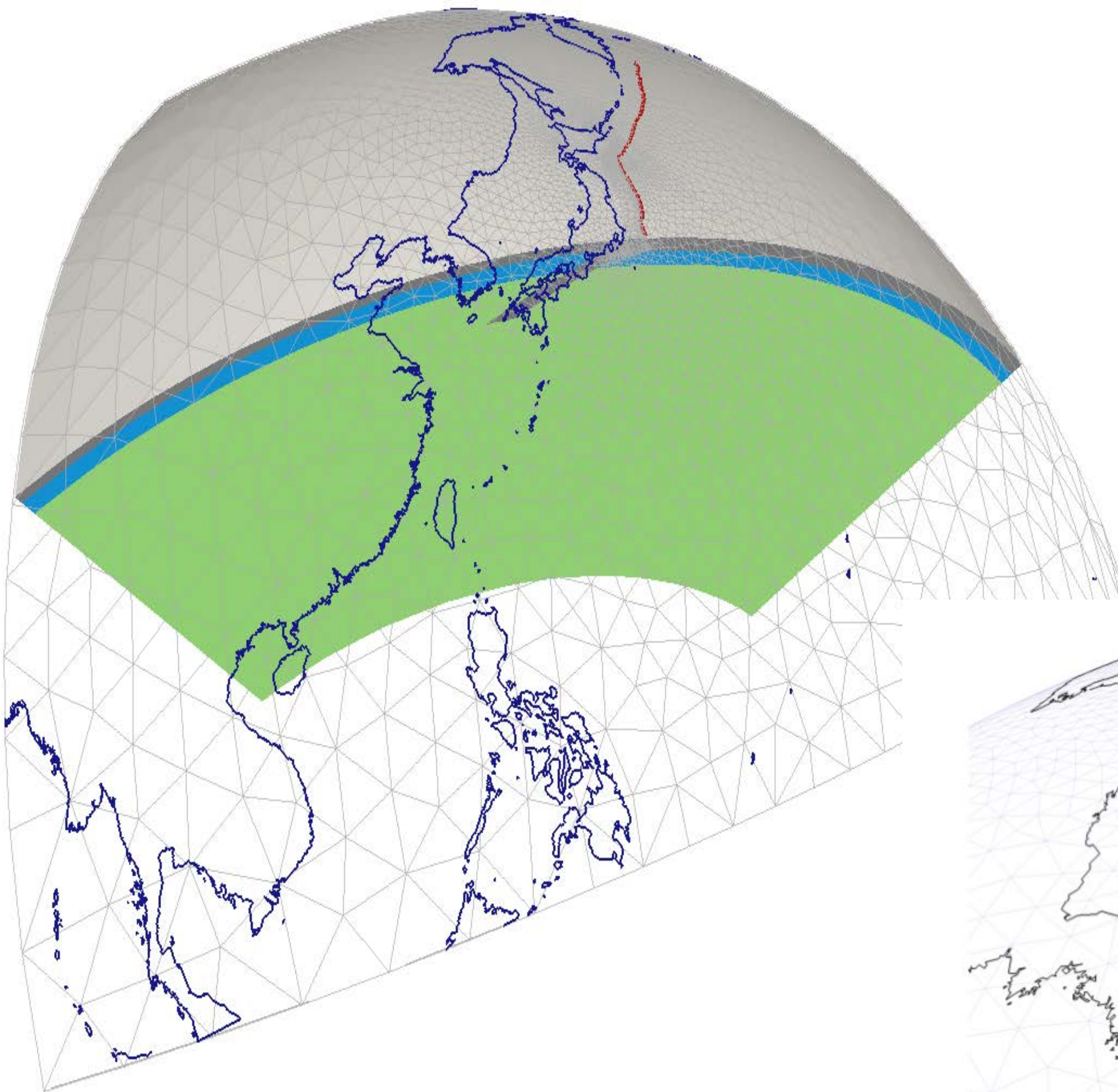
		η_1
SC1	shallow channel 1	1,85E+018
SC2	shallow channel 2	7,50E+017
SC3	shallow channel 3	5,01E+017
DC1	deep channel 1	1,86E+017
DC2	deep channel 2	5,72E+017
DC2	deep channel 3	5,72E+017
CR	crust (70-90 km)	2,00E+018
OC	ocean (70-90 km)	9,70E+018
Asthenosphere	90-200 km	3,00E+018
	200-270 km	8,40E+018

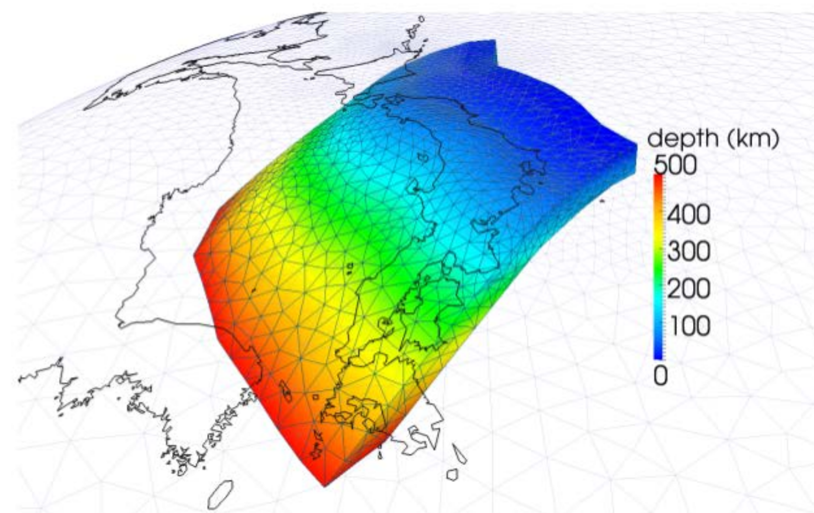
η_2/η_1 = cst = 6,5

μ_2/μ_1 = cst = 3

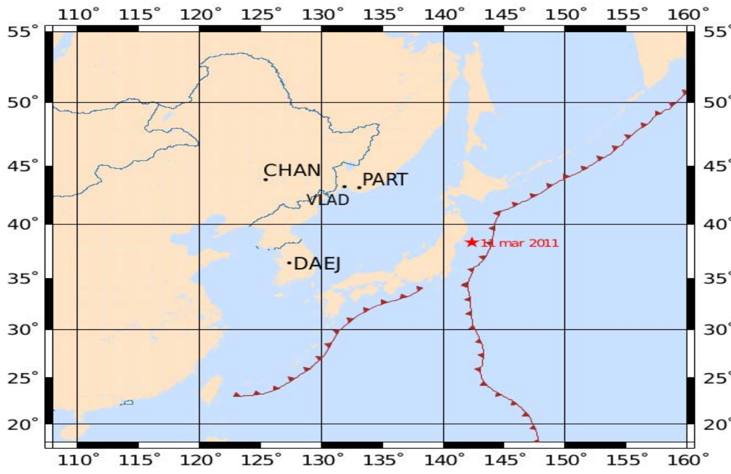


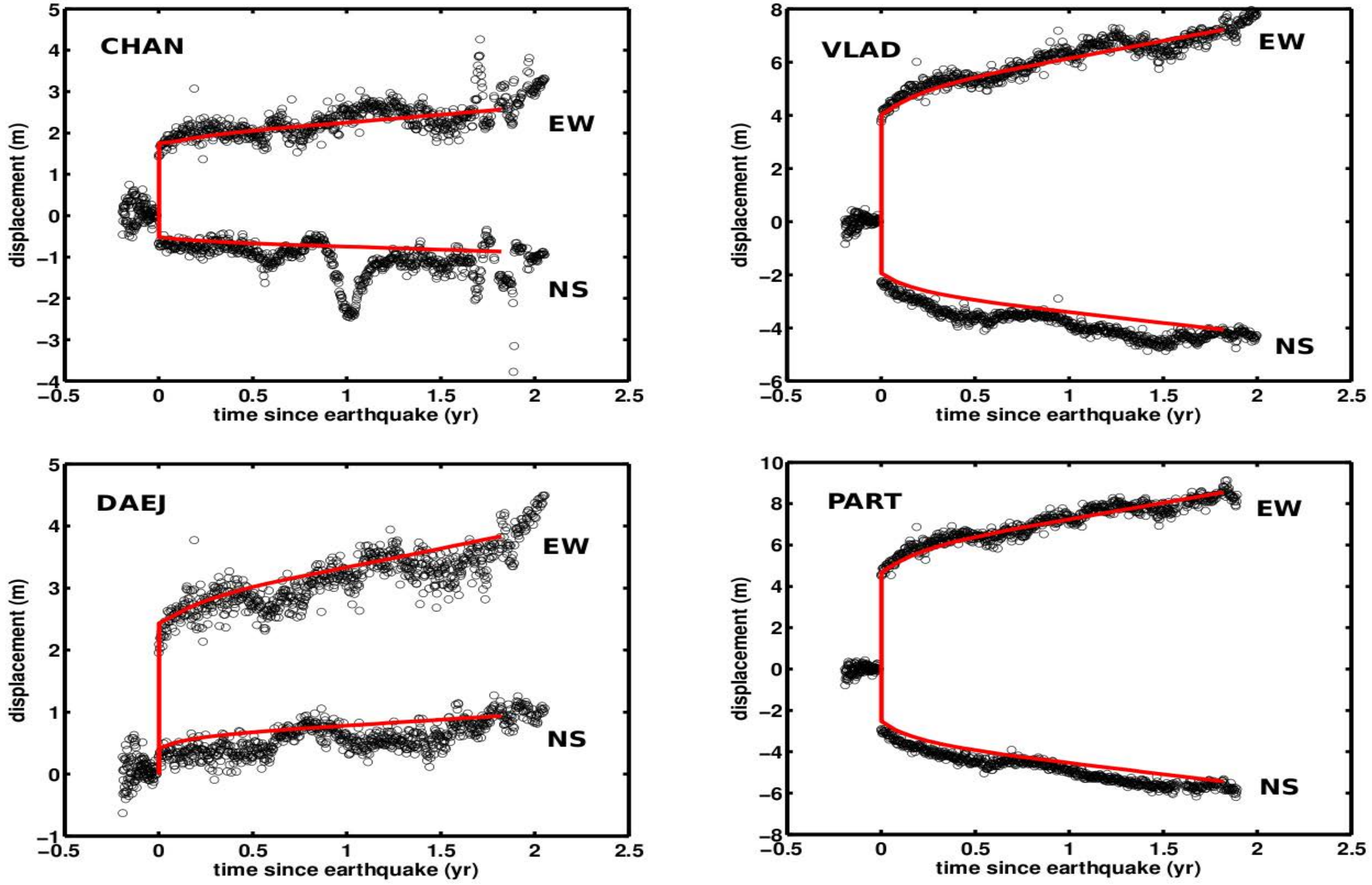
Finite element mesh for Japan computations with Zset-Zebulon





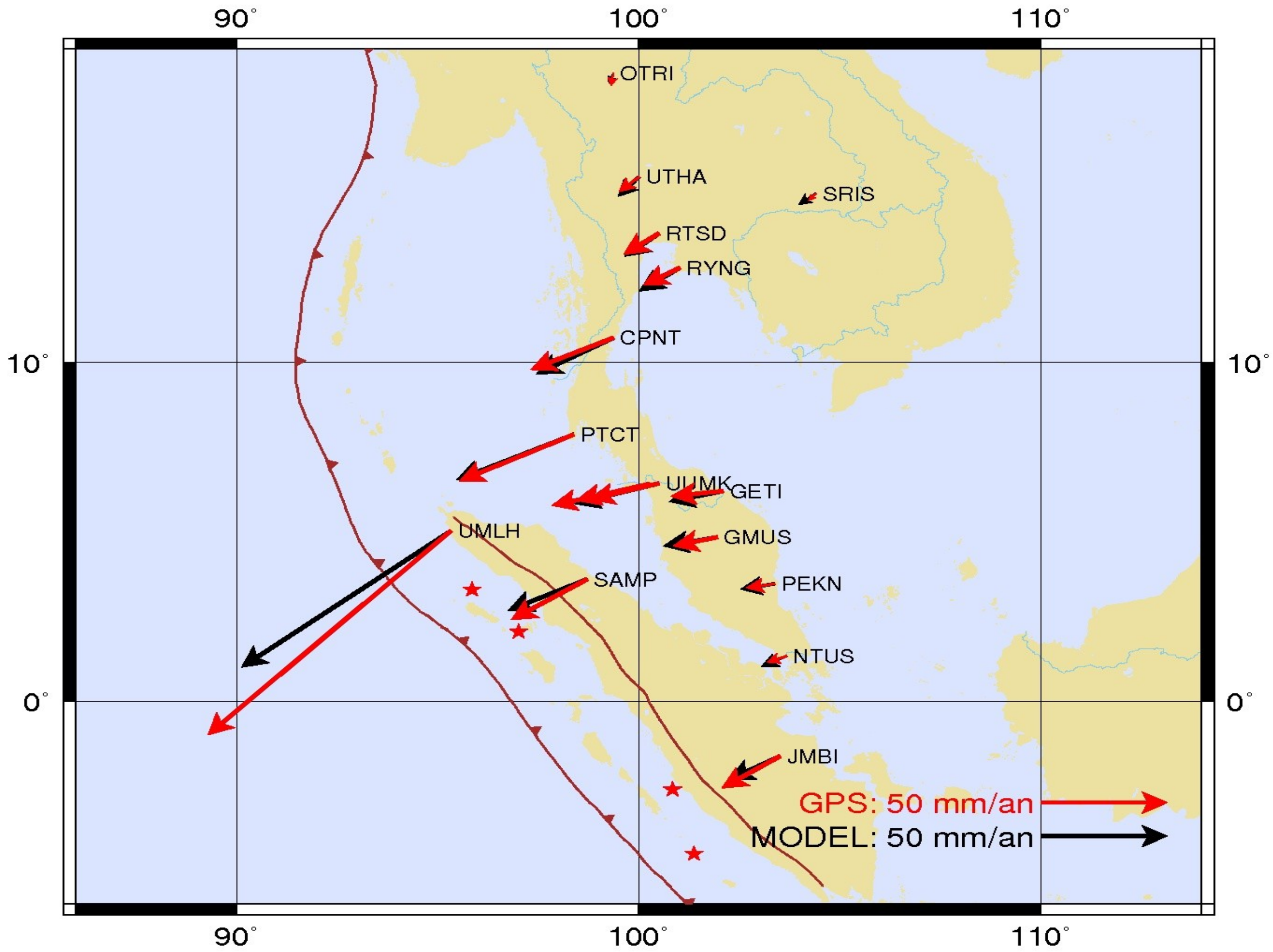
Fit to far-field stations time series



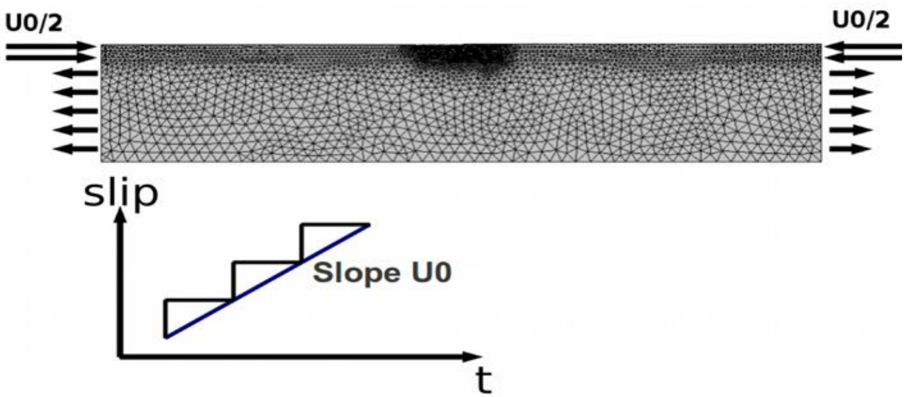


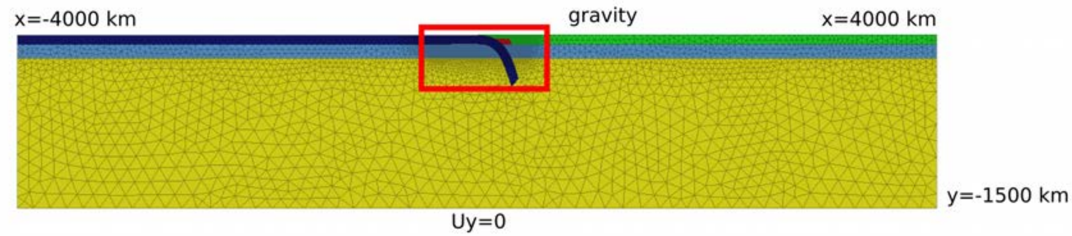
Far-field horizontal postseismic velocities after 2004 Sumatra earthquake

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

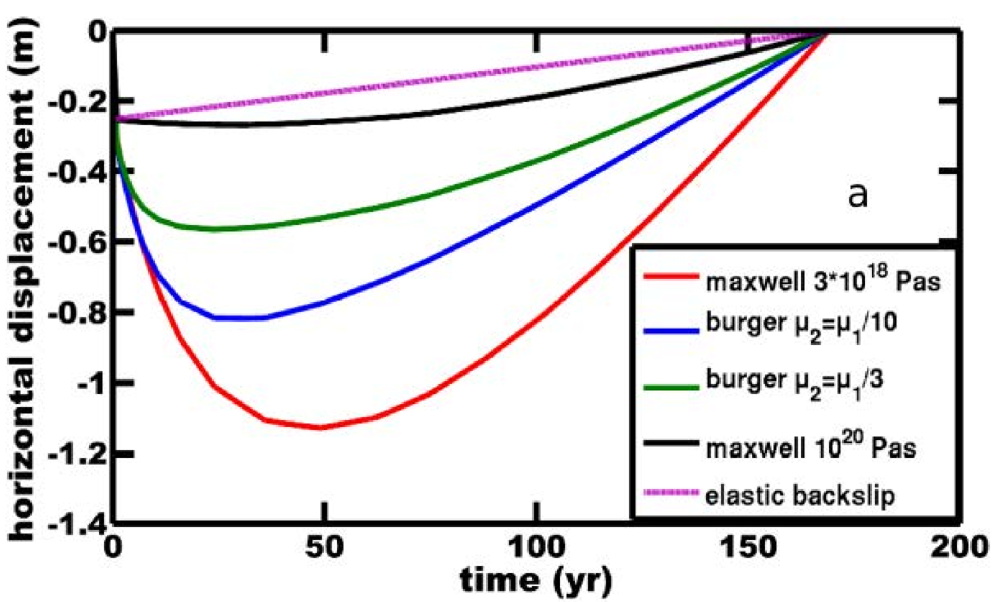


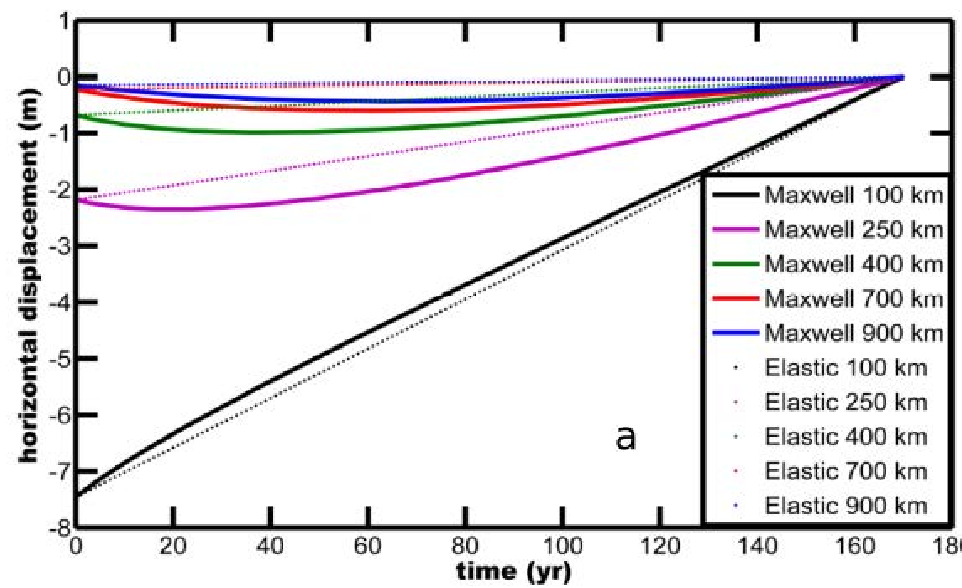
Trubienko et al. Tectonophy 2013





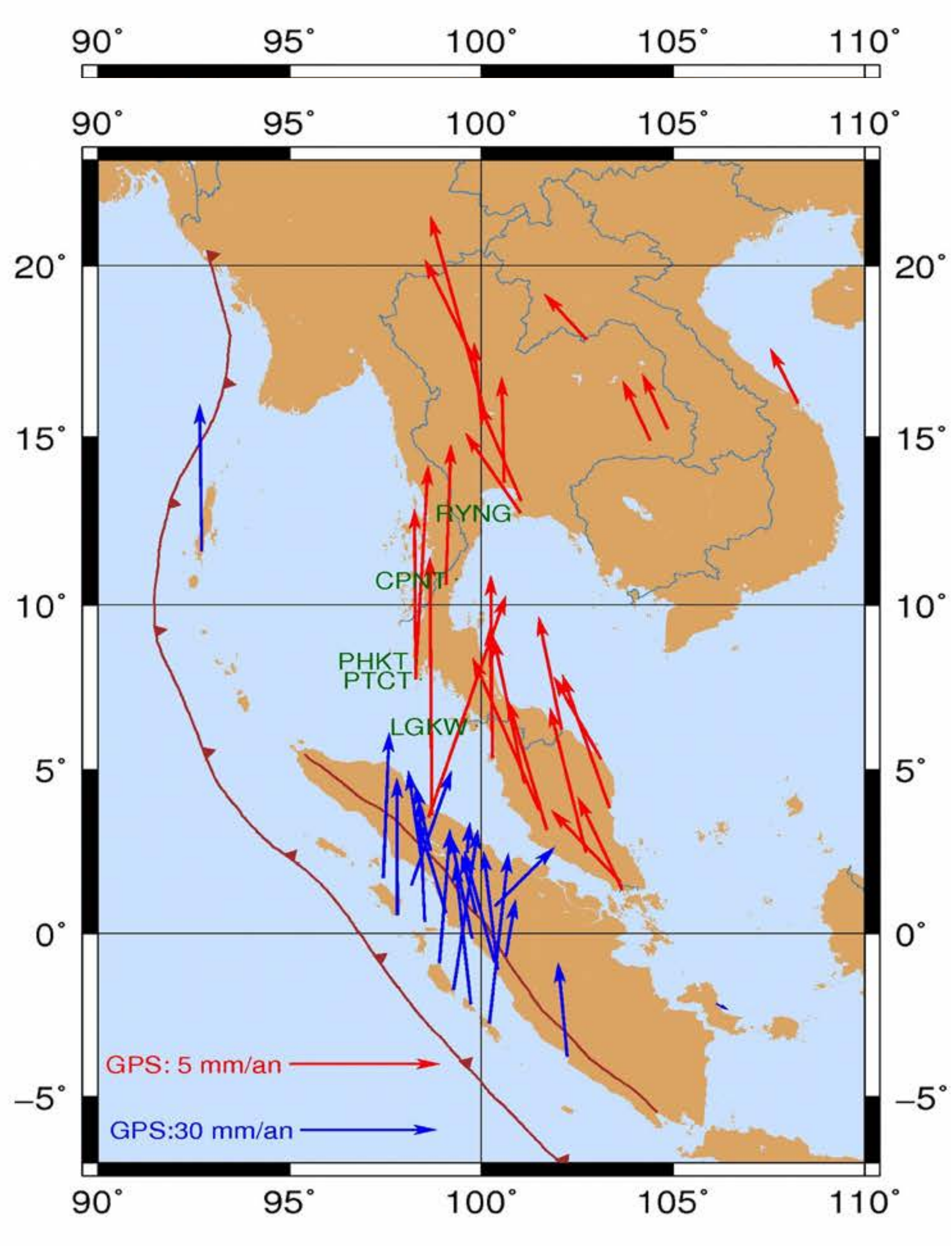
Viscosity 10^{19}Pas

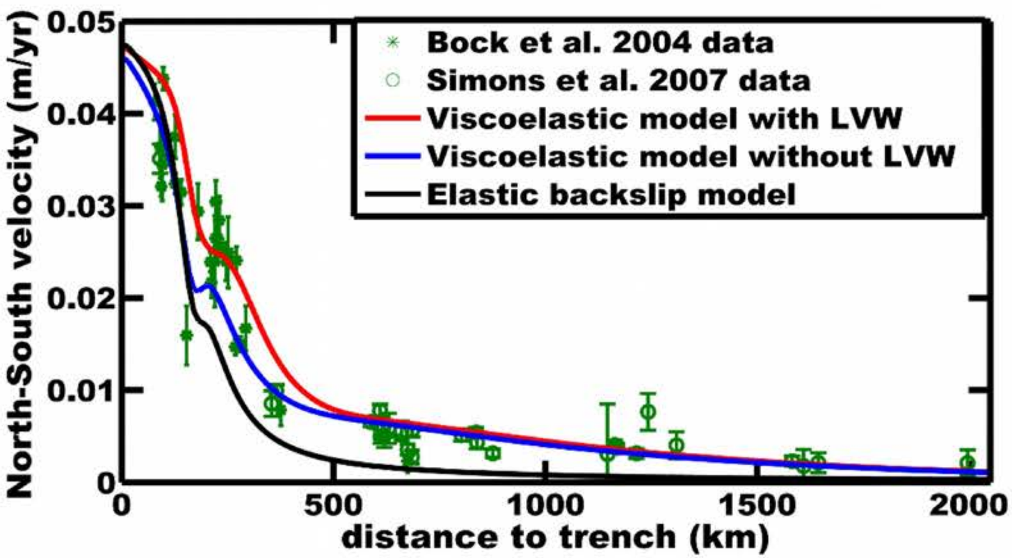




Because of the viscoelastic relaxation in the asthenosphere, the far-field motion associated with megaearthquakes is, in the far-field, much larger than anticipated from elastic models (elastic backslip)

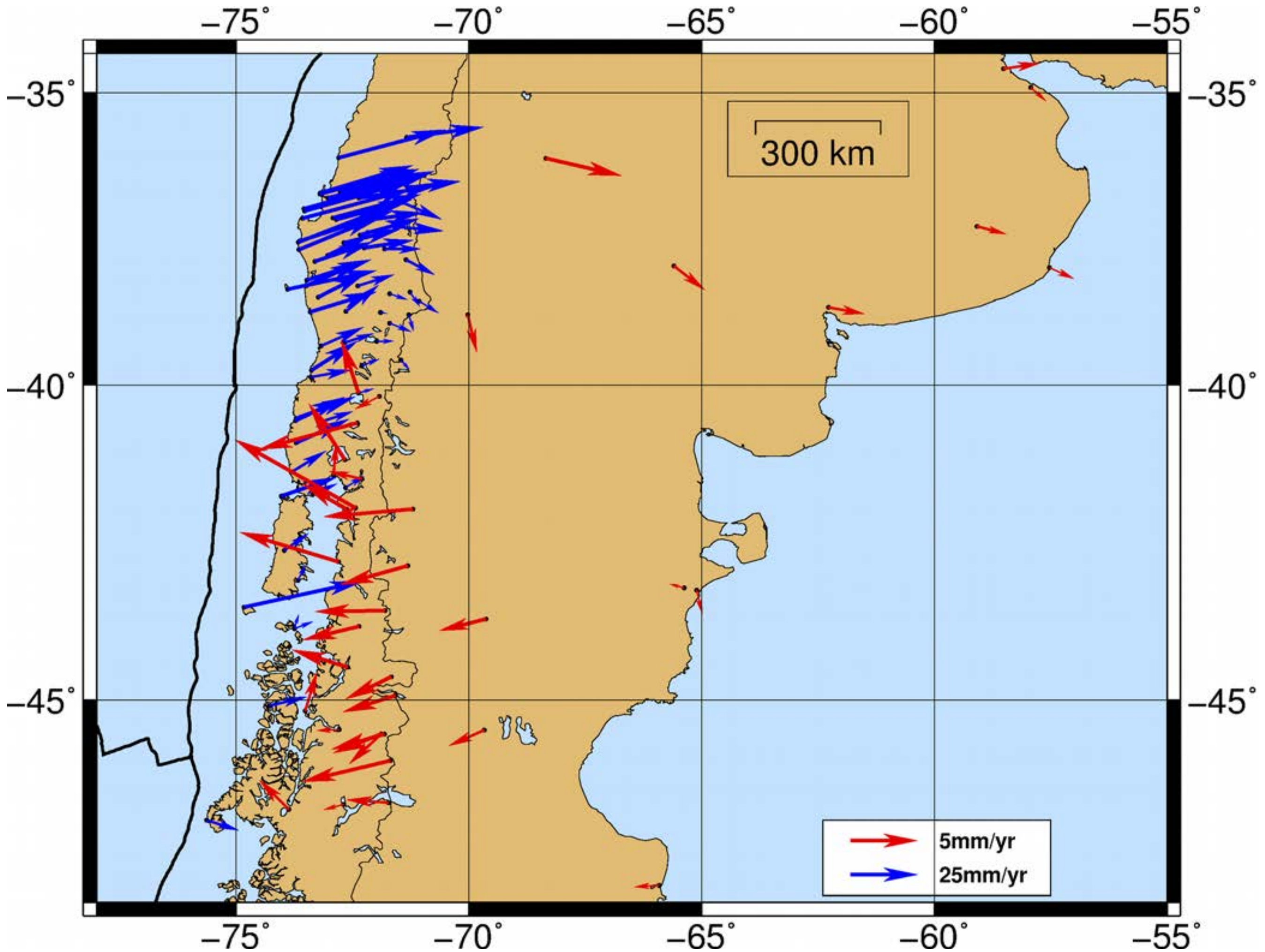
Are the present-day strains 'Geologic' strains or effect of the seismic cycle?





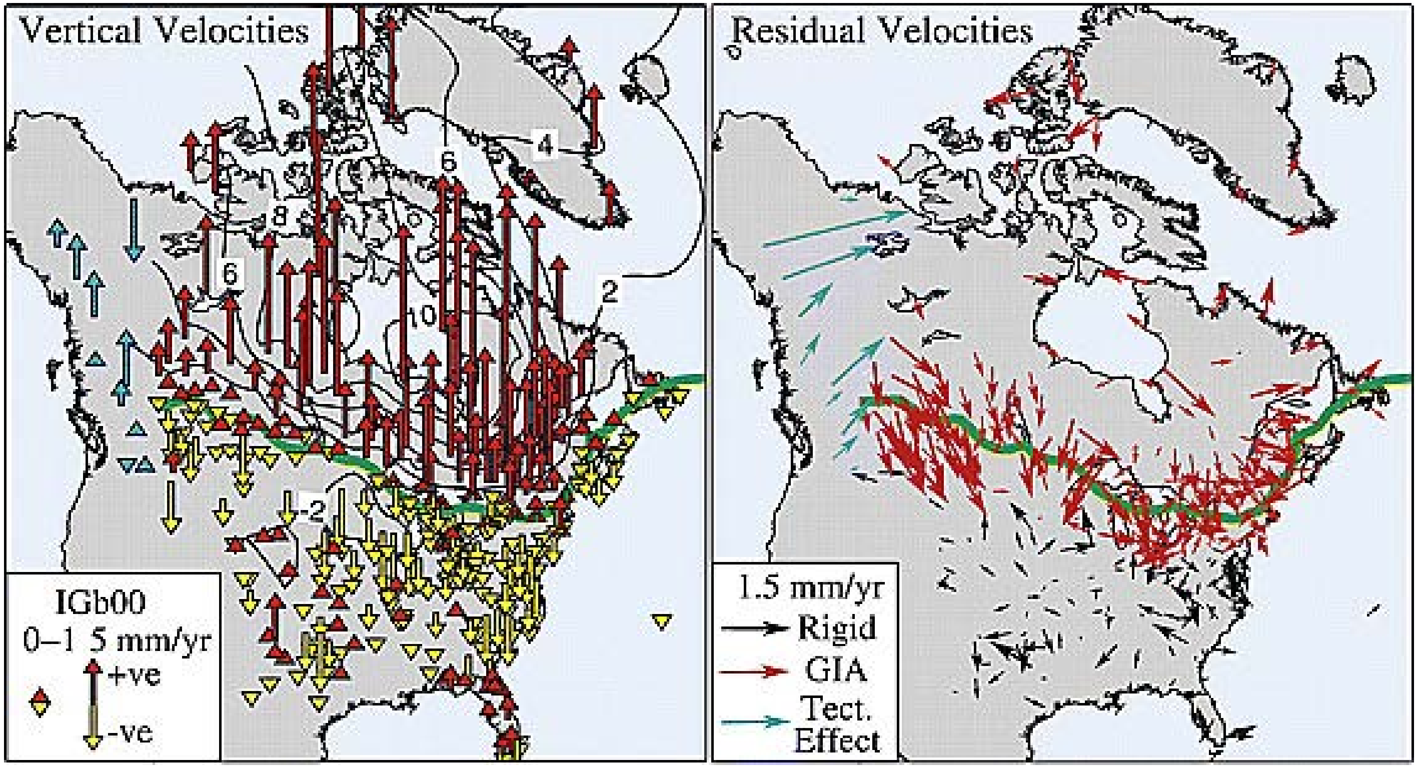
Trubienko et al. Tectonophy 2013

to south China before 2004

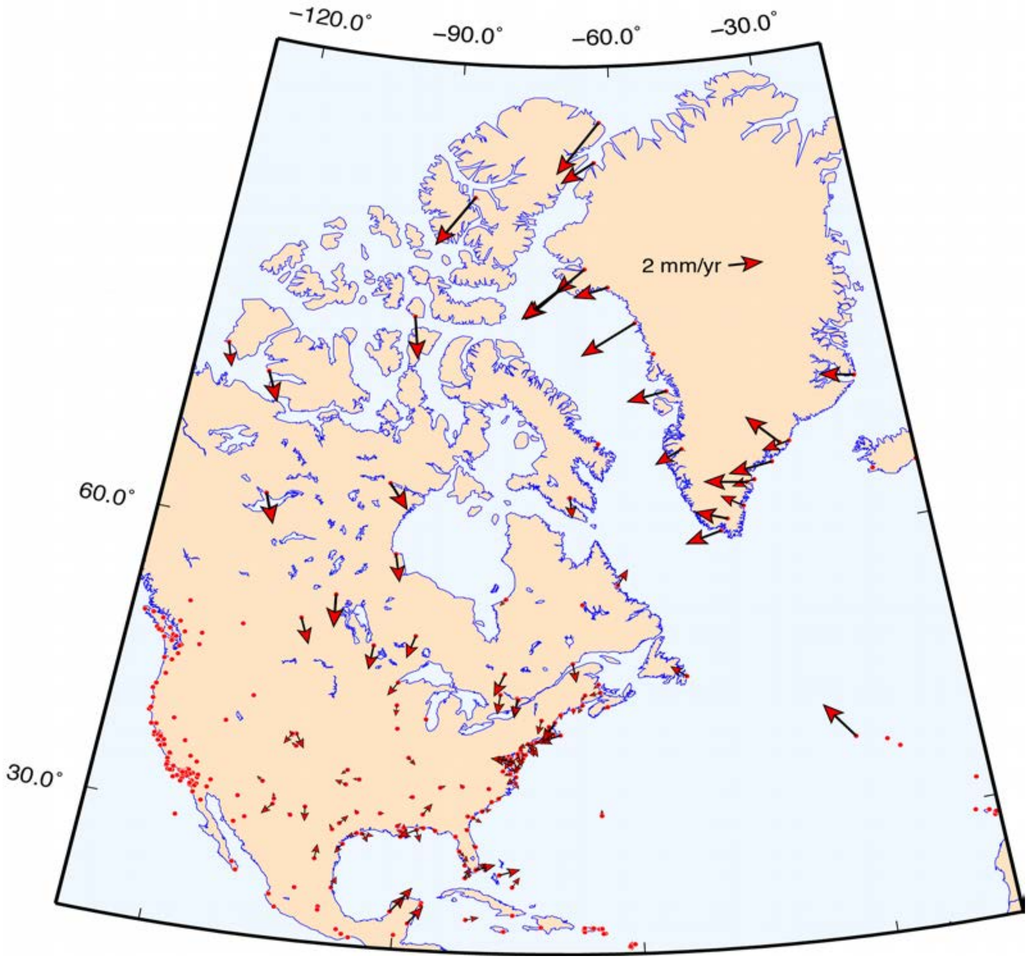


In broad areas (several thousands of km) around the zones prone to megaearthquakes, the plate velocities are perturbed, not only during the postseismic period but through the whole seismic cycle

Deformations induced by GIA



Sella et al. GRL 2007



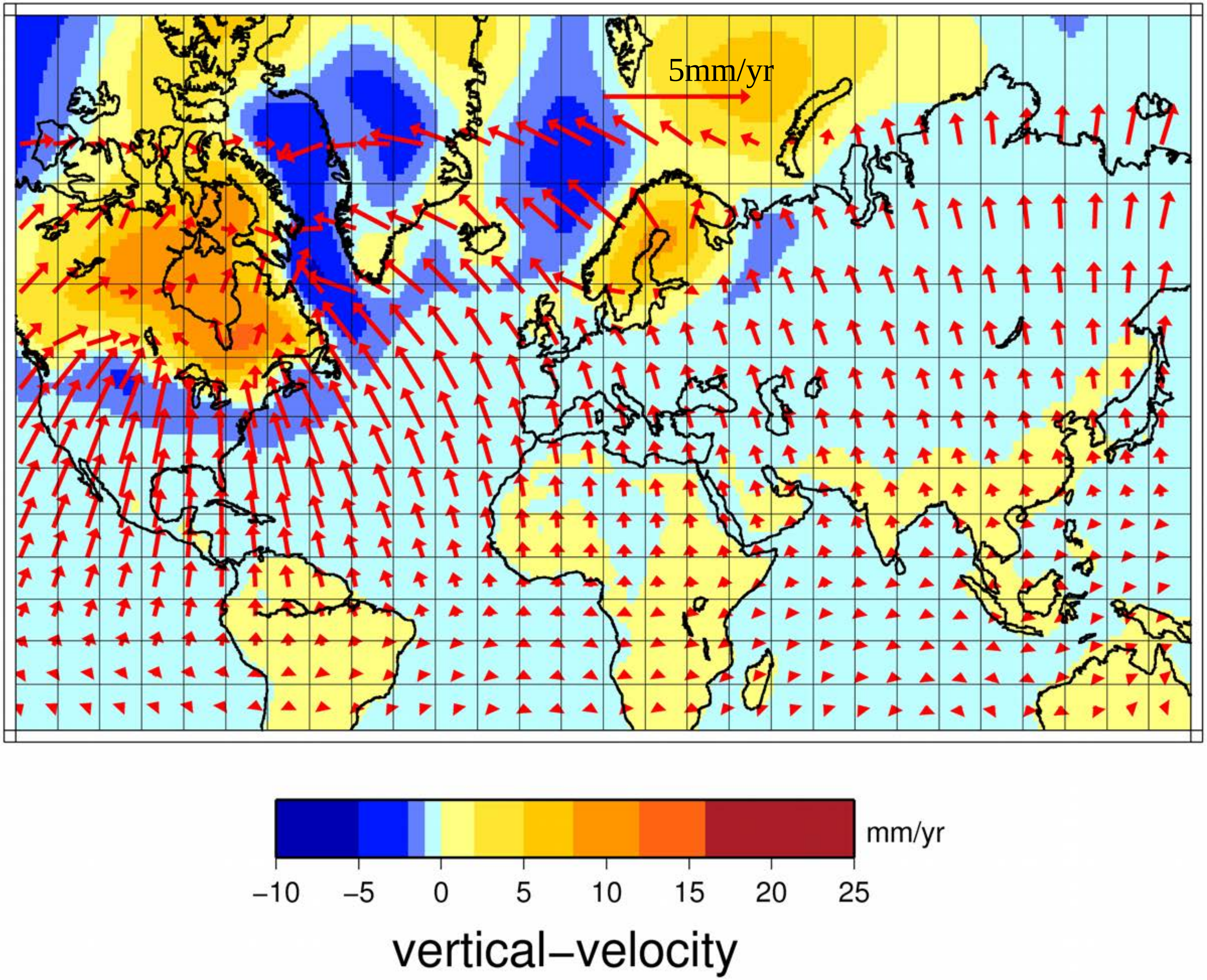
Calais et al. EGU 2018

Residual velocities after estimating angular rotation without sites "affected by Glacial Isostatic Adjustment" (GIA)

The present-day pole of rotation of the NA-Eurasia plates is situated in NE Asia close to the point where the focal mechanisms of earthquakes on the plate boundary switch from extensional to compressive.
When the rotation of NA plate is deduced from GNSS data in ‘stable’ Eastern USA, the pole of rotation is predicted to be several hundred of km away from the observed pole.

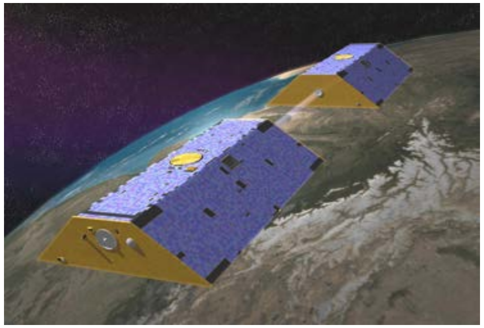
The velocities in the whole NA plate and in the Eurasia plate are then corrected from the horizontal deformations predicted using various classes of GIA models which induce appropriate present-day vertical velocity and paleo sea-level. Two types of models predict also simultaneously well the pole of rotation NA-Eurasia and reduce significantly the residual horizontal velocities over both the NA and Eurasia plates.

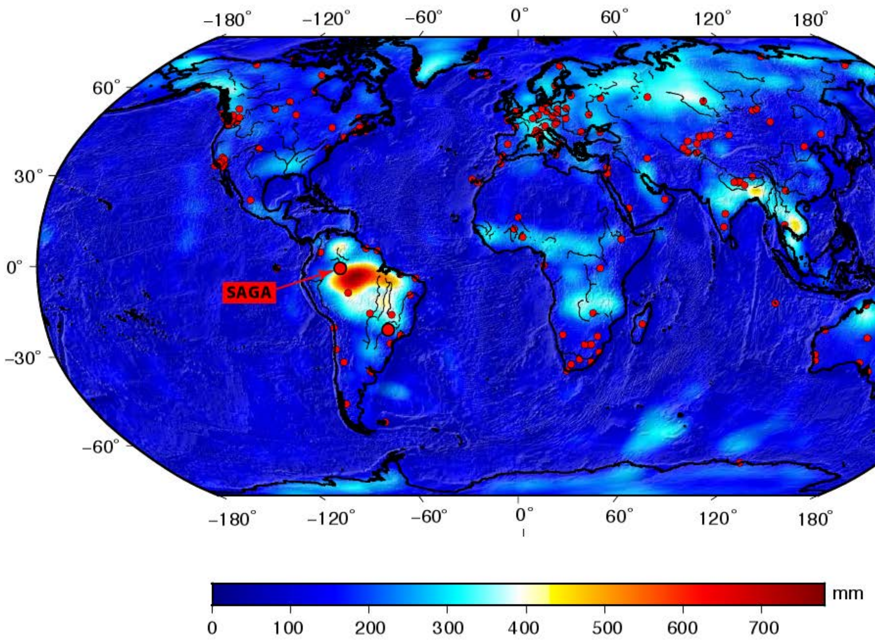
- One is close to the profile VM5 (Ice6G)
- The other features a high viscosity lower mantle and a Burger rheology



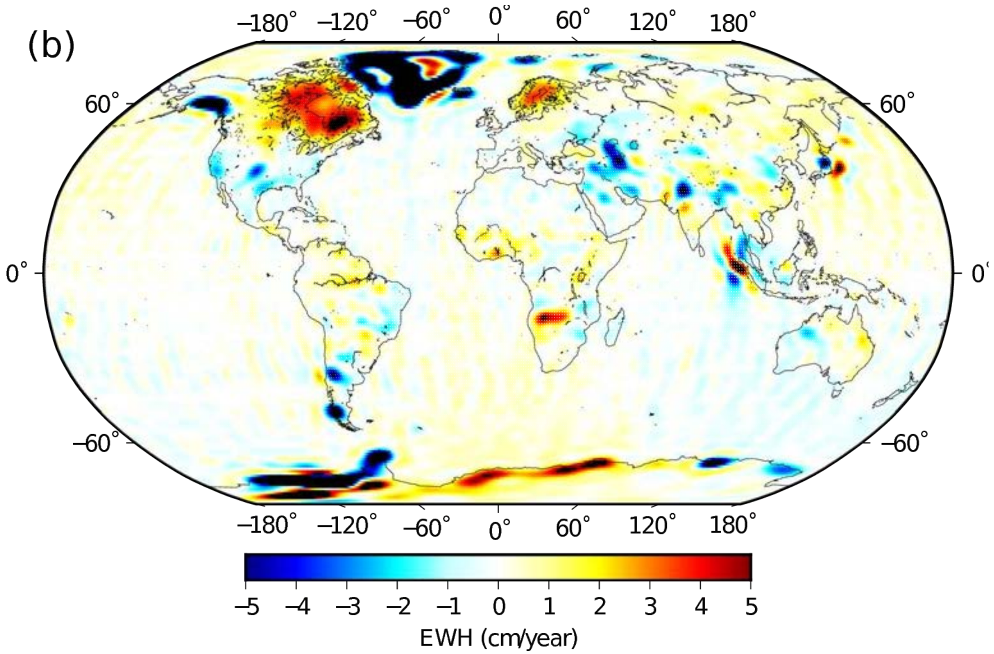
Model B17- GIA induces broadscale horizontal deformations of a few mm/yr

Deformations induced by hydrological loads





Amplitude of the annual signal (EWH)

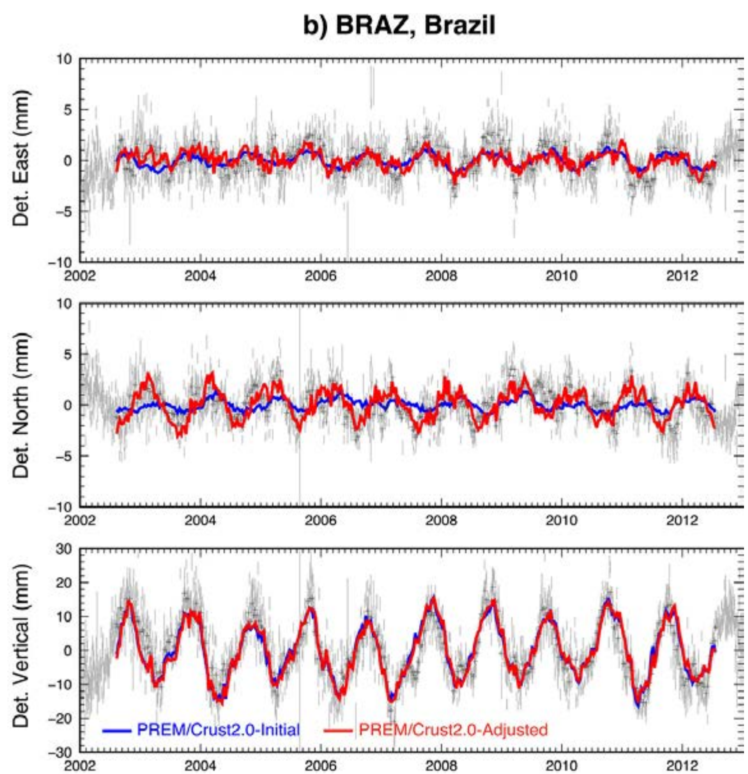


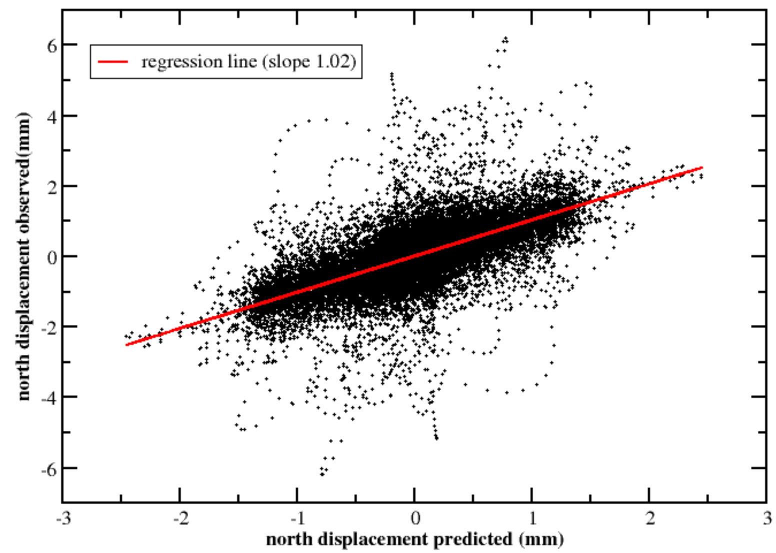
Gravity trend (EWH)

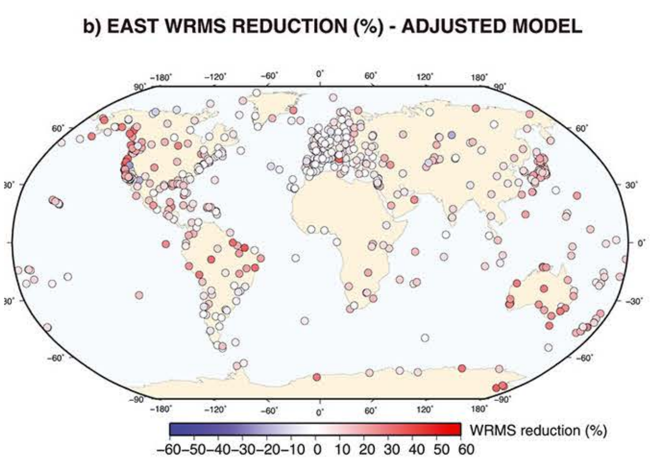
Prevost et al. EGU 2018

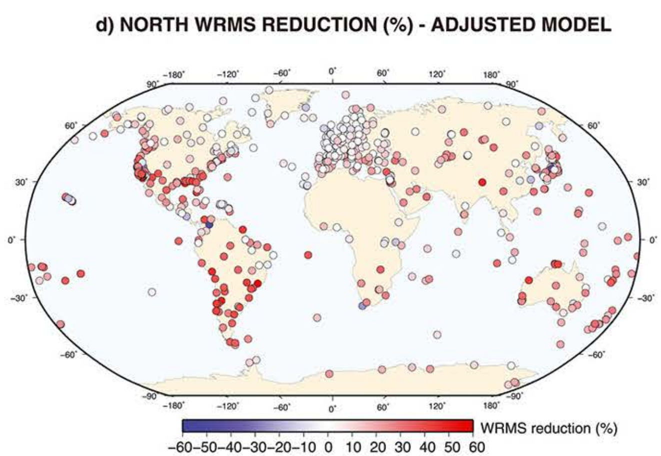
Seasonal variations

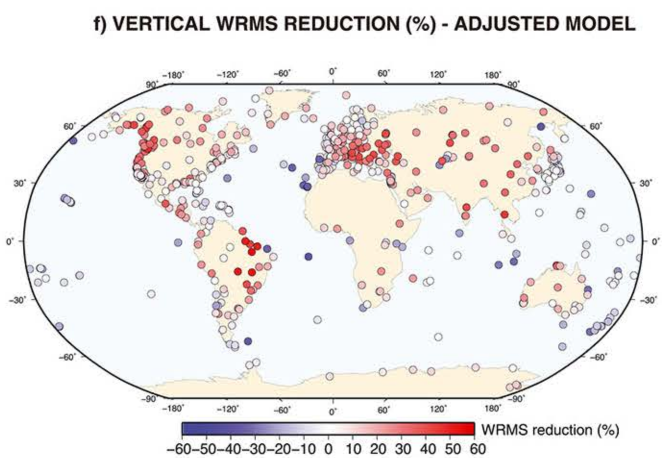
A standard elastic Earth model provides the best fit to the horizontal and vertical data





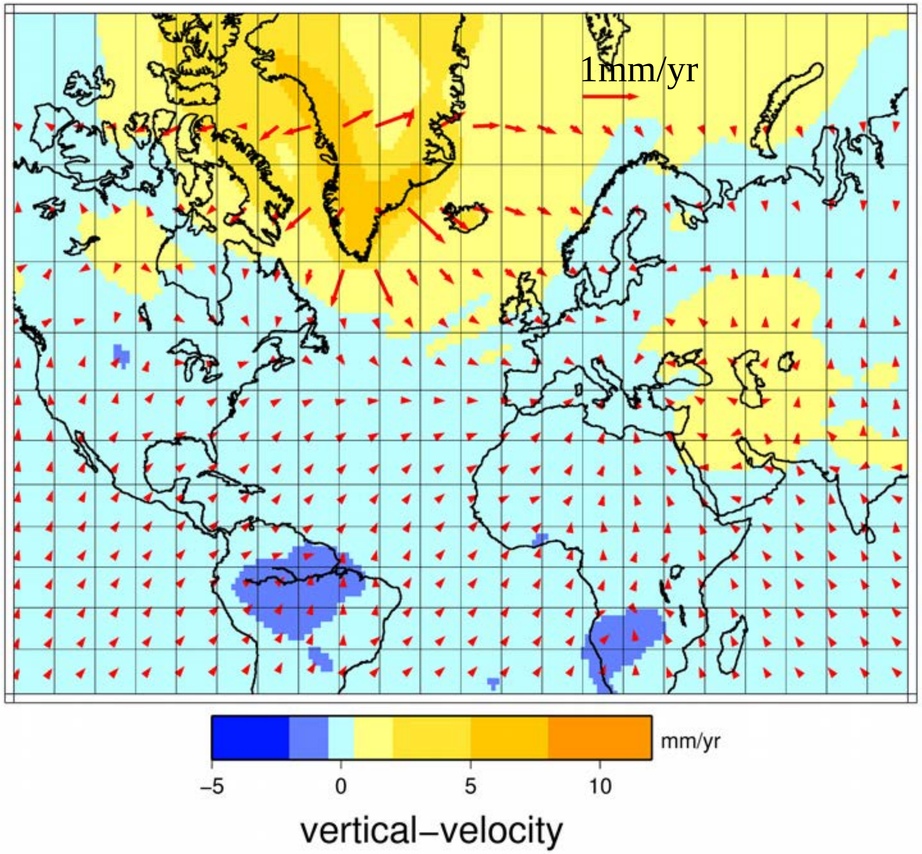




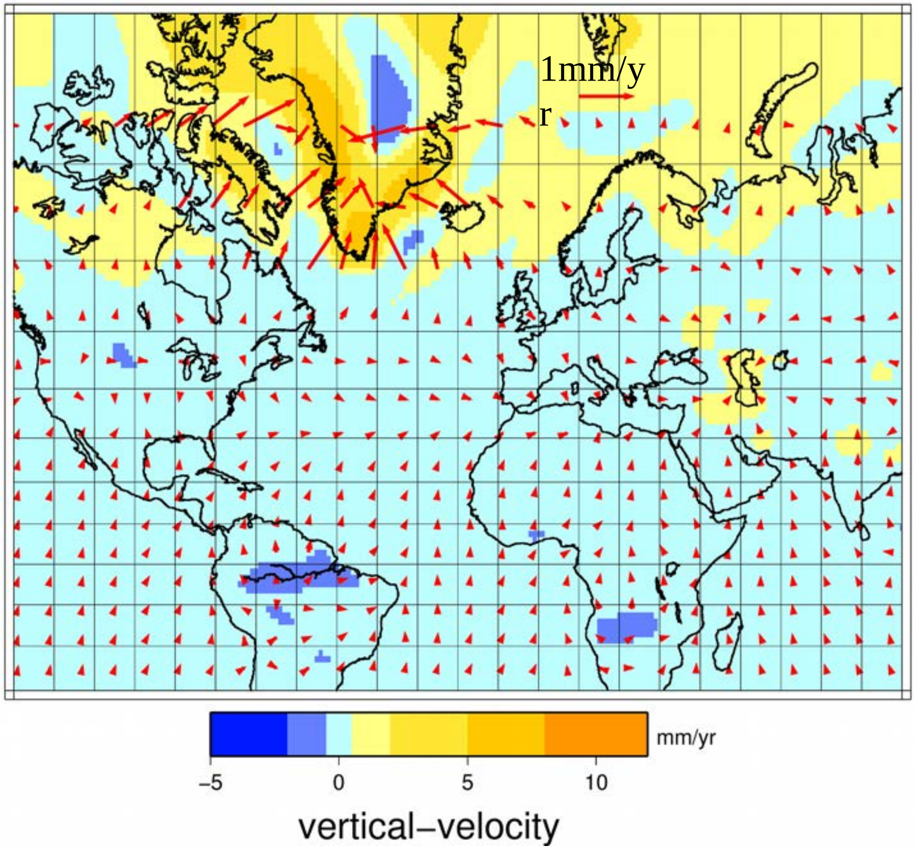


From Chanard et al. JGR 2018

Concerning the decadal variations (computed from GRACE trends)



Purely elastic

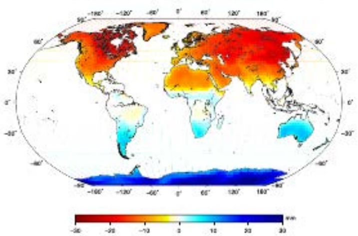


Viscoelastic asthenosphere

The ‘decadal’ velocities are modest even with a low-viscosity asthenosphere except close to the melting ice-sheets

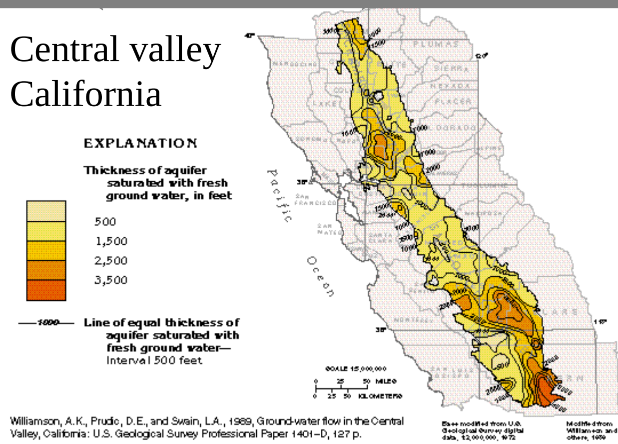
Internal strains induced by surficial temperature variations and variations of pore pressure in aquifers (same formalism)

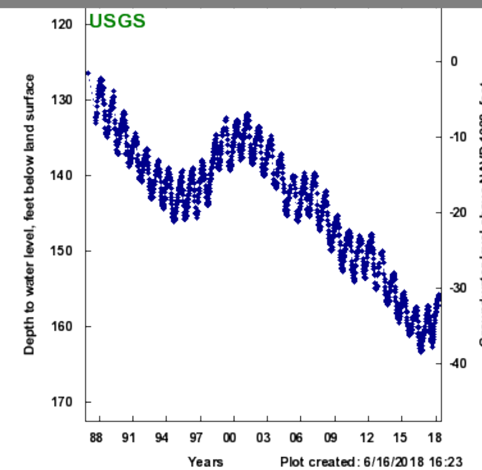
Mean Temperature
January – Annual mean



(Land surface temperature
https://esrl.noaa.gov/)

Central valley
California





Temperature induces internal strains in the top few meters
Poroelasticity induces internal strains over the thickness of saturated zone of aquifers (meter to kilometer)
But these shallow 'internal strains' induce much deeper deformation.

Load	displacement α (load.λ)	stress α load
Temperature	displacement α (T.E)	stress α (T.E)/λ
Poroelastic	displacement α (dp.h)	stress α (dp.h)/λ

T Temperature variation, E Young modulus in surficial layers,
dp variation of pore pressure, h thickness of the saturated zone
λ characteristic wavelength of load or of (T.E) or of (dp.h)

Surficial internal strains are mainly important at short wavelength (tens of km) (noise in GPS data): mm for seasonal signal, mm/yr for decadal signal near some aquifers.
Stress variations induced at depth

Megaearthquakes :

- Velocity perturbations from cm/yr to mm/yr several thousands of km around the zones prone to megaearthquakes.
- Postseismic extension
- Compression during the last part of the seismic cycle.

GIA :

- 'Long-term' velocities of a few mm/yr affecting the whole planet

Present-day hydrological loads :

- Conspicuous annual millimetric term over the whole Earth.
- Small decadal amplitude except near melting ice-sheets.
- Both short and large wavelengths.

Surface temperature and poroelasticity :

- Mainly important at short wavelengths.
- Millimetric amplitude for the seasonal term.
- Potential mm/yr decadal horizontal motions close to deep aquifers

Conclusion

Plate tectonics is a slow, regular, process damped by the viscosity of the mantle. However, under the lens of modern GNSS, plate motion does not appear only as ‘a long calm river’ readjusting over million years time-scales: Sizable, large-scale elastic intraplate deformations are induced by short-term processes (large earthquakes, surficial recent or present-day load variations)

- These short-term strains in ‘stable areas’ do not reflect ‘the forces which drive plate-tectonics’.
- The presence of elastic ‘recoverable’ deformation within the plates must be kept in mind when interpreting GNSS data or other short-term indicators of present-day strain-rate in terms of geological deformation (epidemy of microplates?)

However, these intraplate strains provide useful constraints:

- On the mechanical properties of the mantle (megaearthquakes, GIA, hydrological loads)
- On present-day redistribution of hydrological loads (environmental implications).

A lot remains to be done for:

-Disentangling the effects of the various short-term processes over the major plates

-Understanding the interaction of these ‘short-term’ processes with:

- intraplate seismicity
- plate-boundary deformation and seismicity