

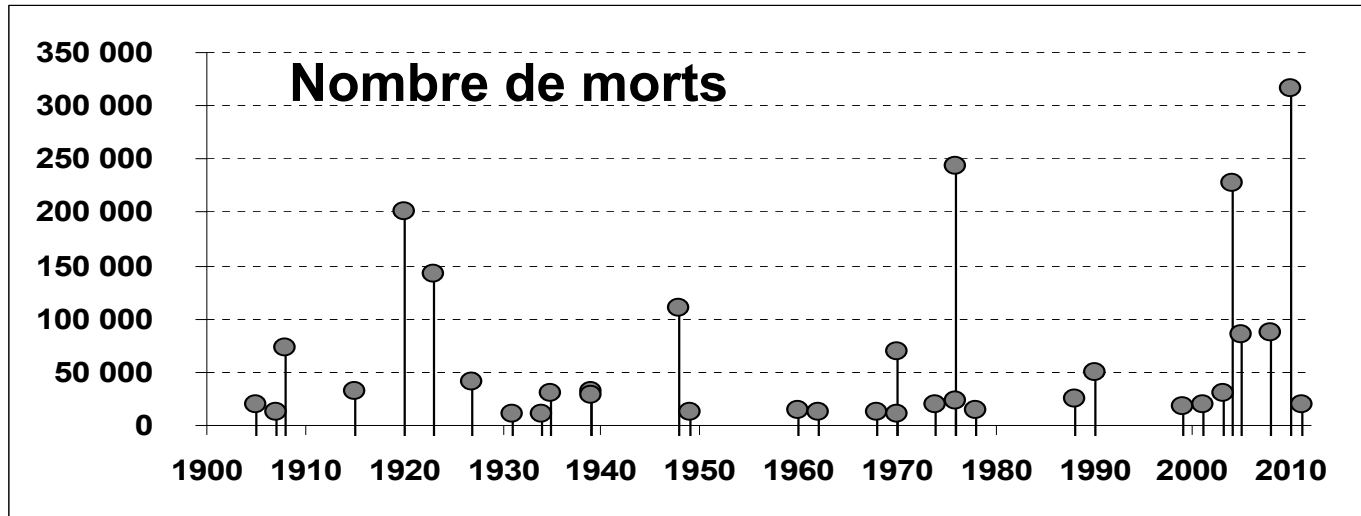
Les grands séismes mesurés par satellites

Christophe Vigny*



*département des Geosciences de l'ENS / UMR 8538 du CNRS
<http://www.geologie.ens.fr/~vigny>

Qu'est-ce qu'un grand séisme ?

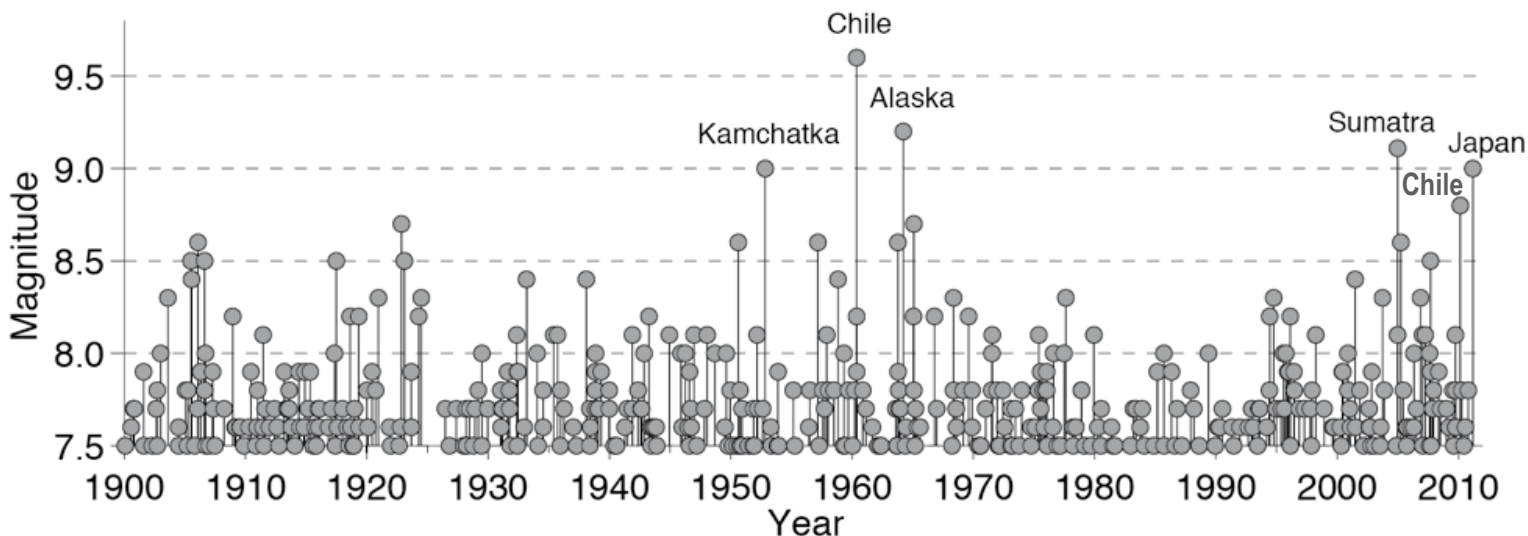


1. Haiti (2010): 316 000 morts Mw 7.0
2. Chine (1976): 243 000 morts Mw 7.5
3. Sumatra (2004): 228 000 morts Mw 9.2
4. Chine (1920): 200 000 morts Mw 7.8
5. Japon (1923): 143 000 morts Mw 7.9

6. Turquie (1948): 110 000 morts Mw 7.3
7. Sichuan (2008): 88 000 morts Mw 7.9
8. Pakistan (2005): 85 000 morts Mw 7.6
9. Messine (1908): 70 000 morts Mw 7.2
-
21. Japon (2011): 20 252 morts Mw 9.0

Source: catalogue USGS

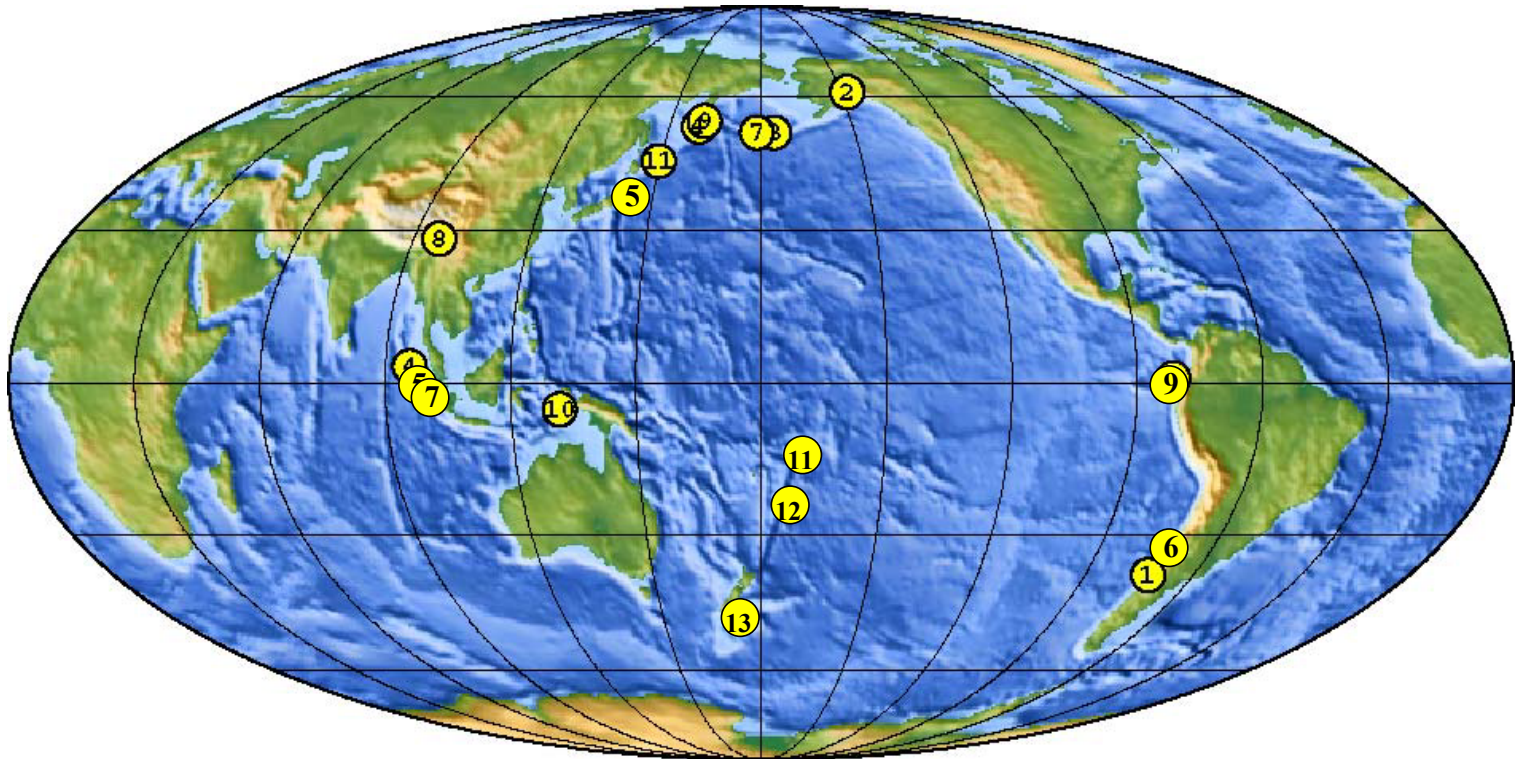
Combien de grands séisme en un siècle ?



En gros: 8-10 en 100 ans

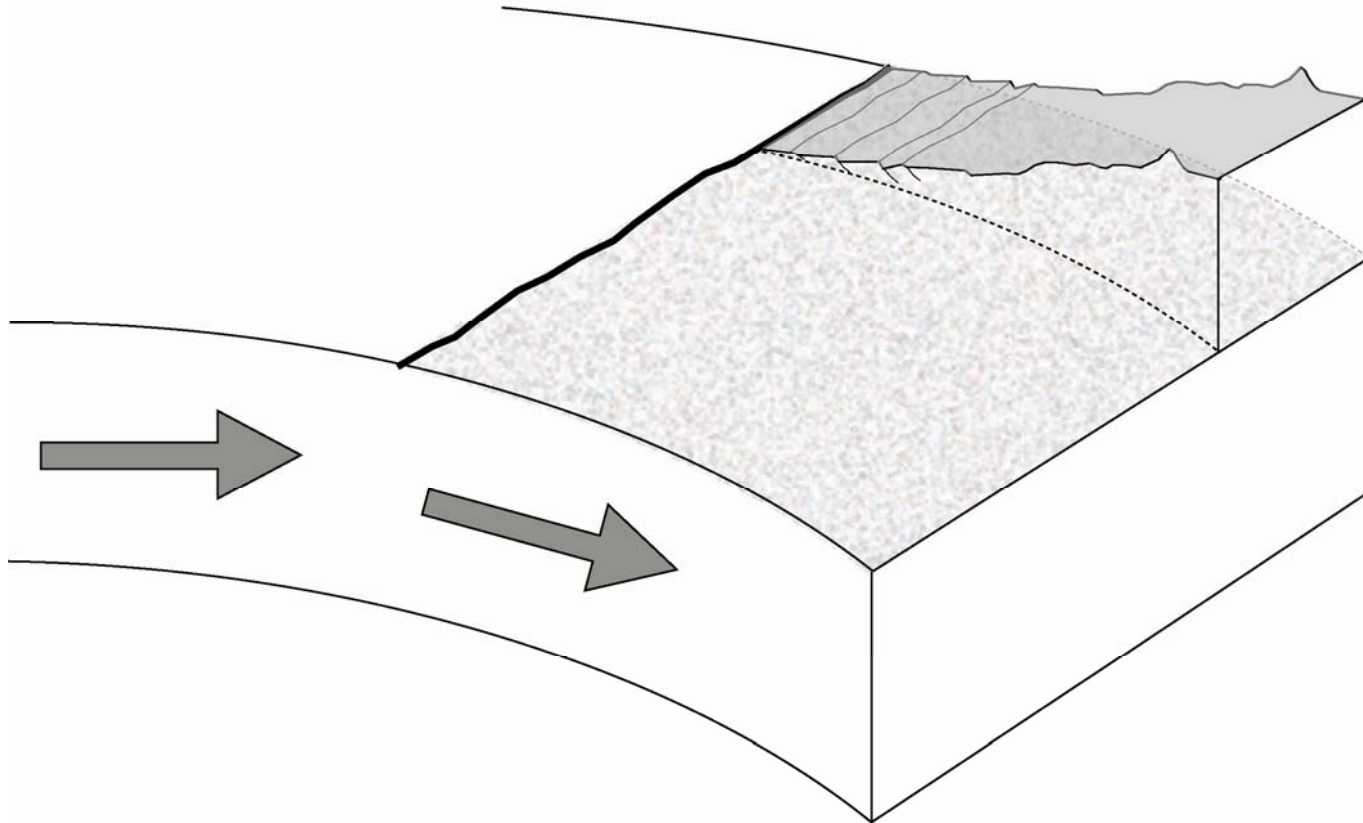
=> 1 par décennie en moyenne, mais irrégulièrement répartis

Où se produisent les plus gros séismes ?

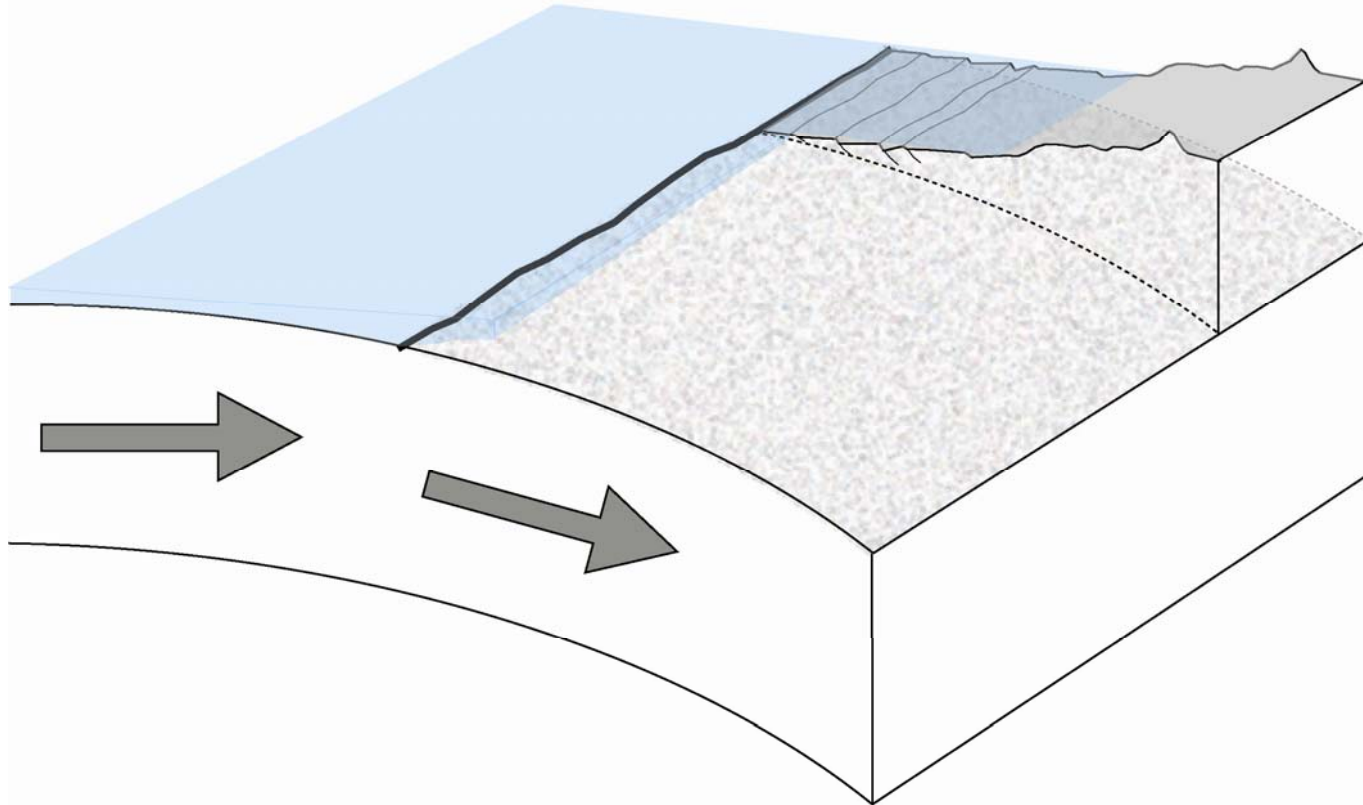


Sur les subductions

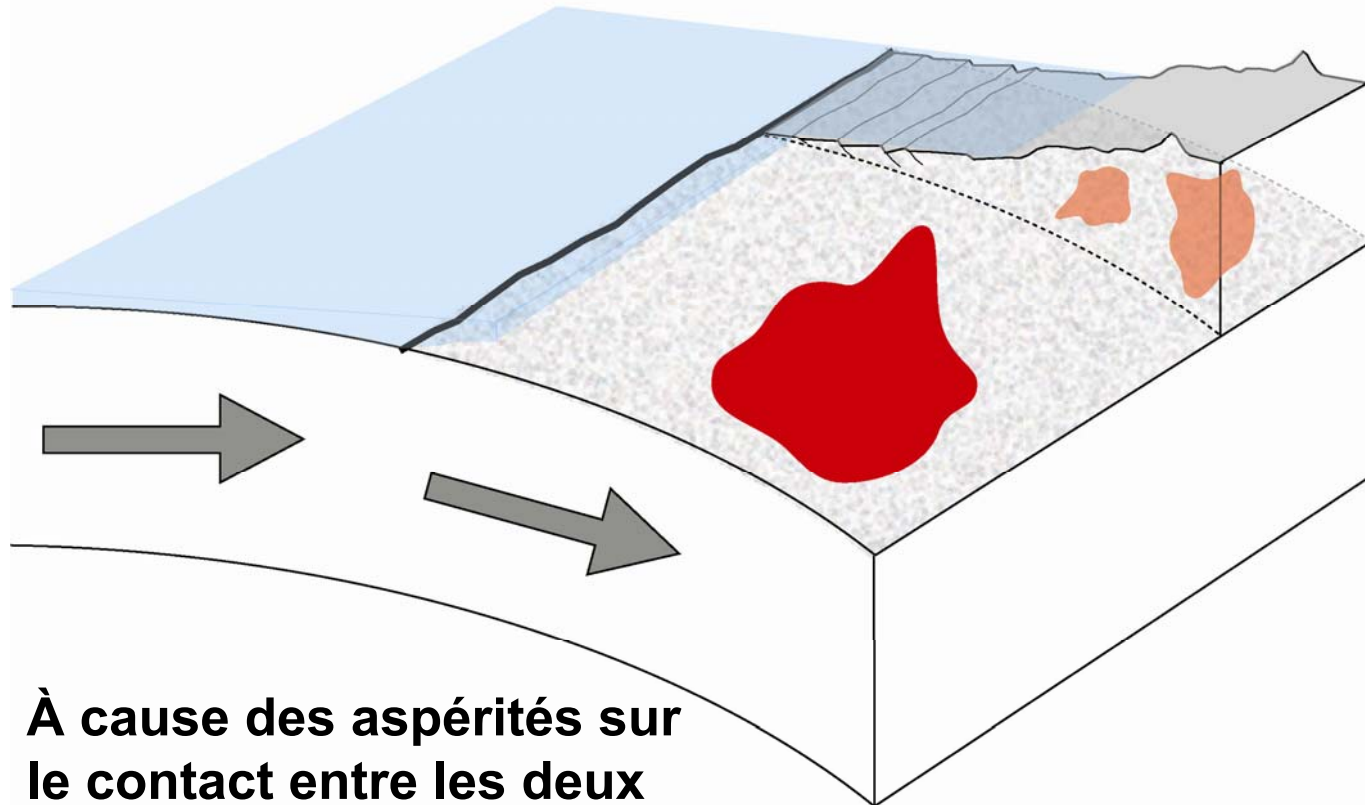
Pourquoi y a-t-il des séismes ?



Pourquoi y a-t-il des séismes ?

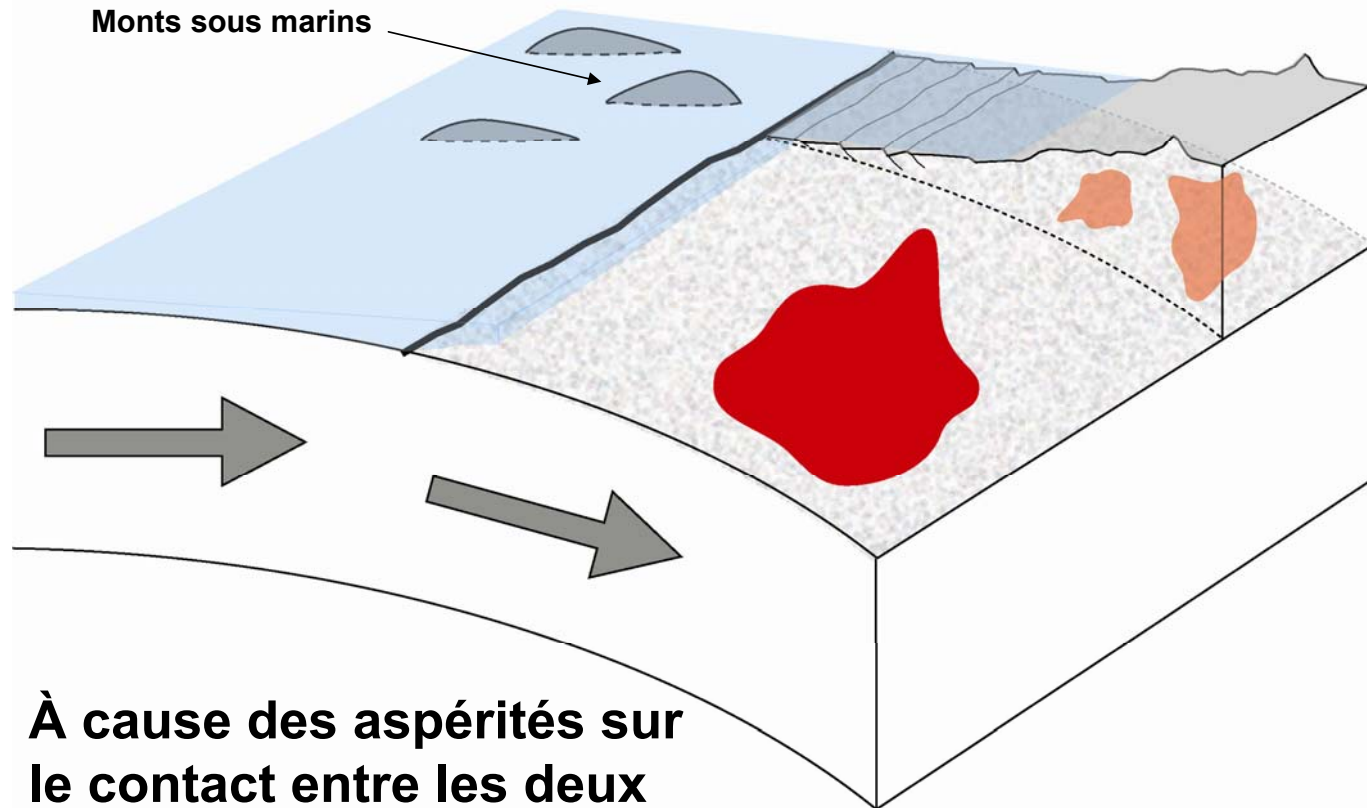


Pourquoi y a-t-il des séismes ?



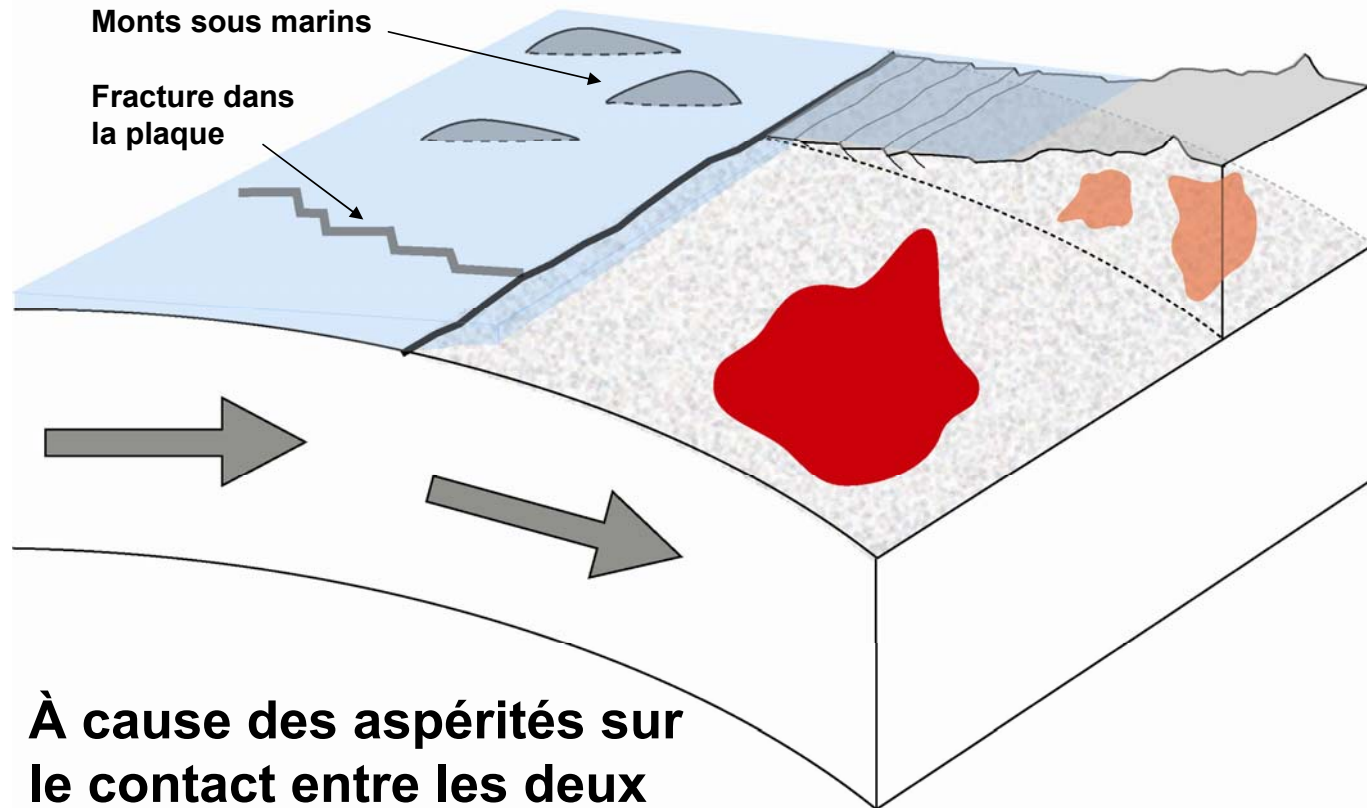
**À cause des aspérités sur
le contact entre les deux
plaques**

Pourquoi y a-t-il des séismes ?



**À cause des aspérités sur
le contact entre les deux
plaques**

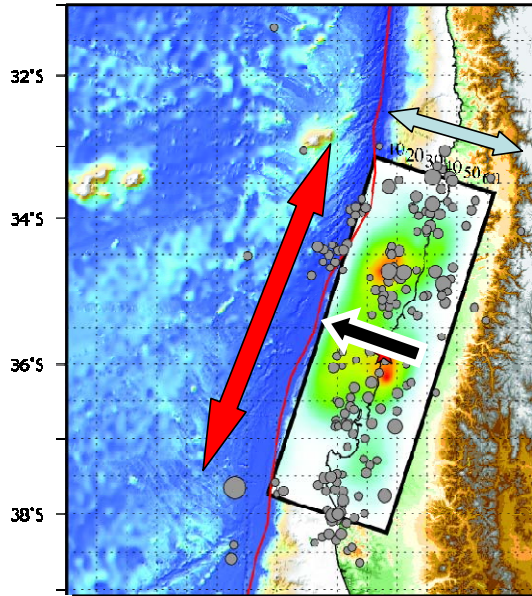
Pourquoi y a-t-il des séismes ?



**À cause des aspérités sur
le contact entre les deux
plaques**

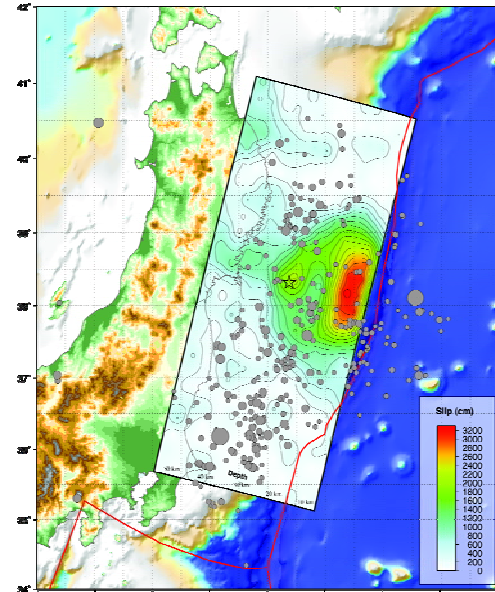
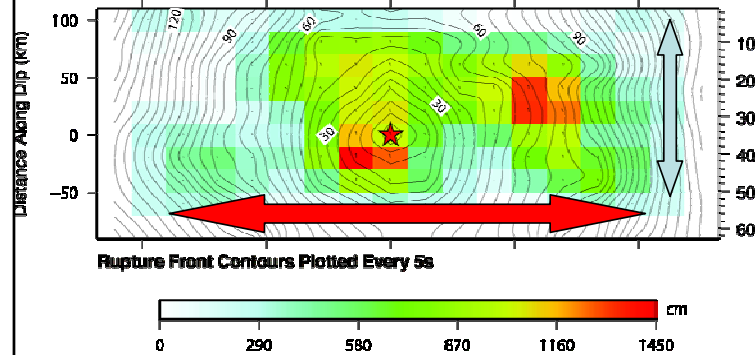
taille du séisme = surface de l'aspérité * glissement

Chili: **450 km** x **150 km** x **9 m** => Mw 8.8 Japon: 200 km * 150 km * 25 m => Mw 9.0



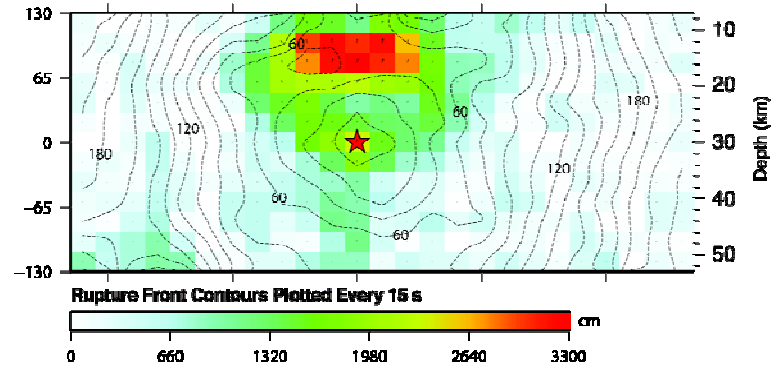
Strike = 17.5
Distance Along Strike (km)

-216 -108 0 108 216



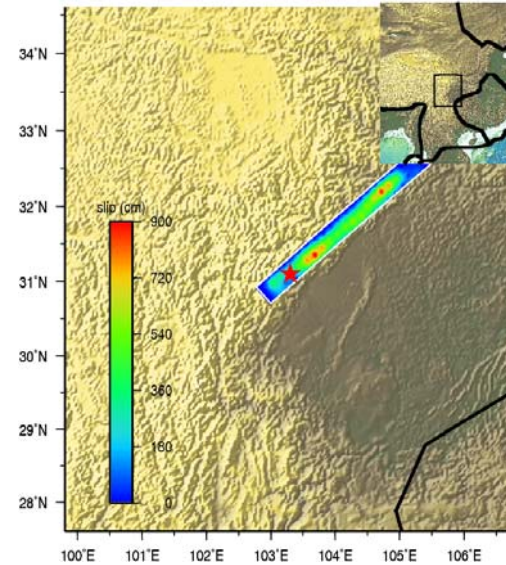
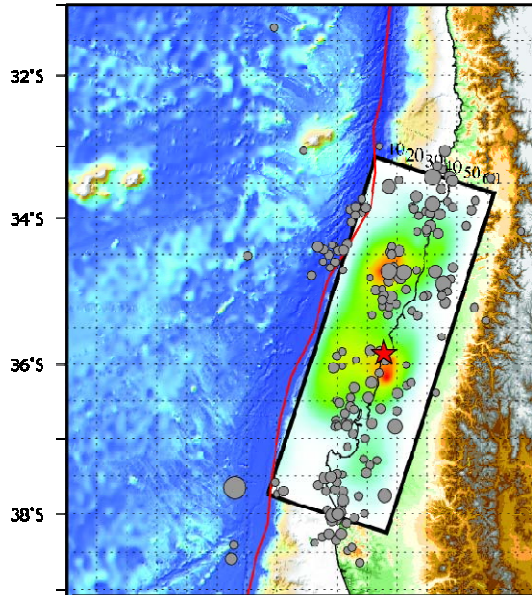
Strike = 194.4
Distance Along Strike (km)

-250 -125 0 125 250

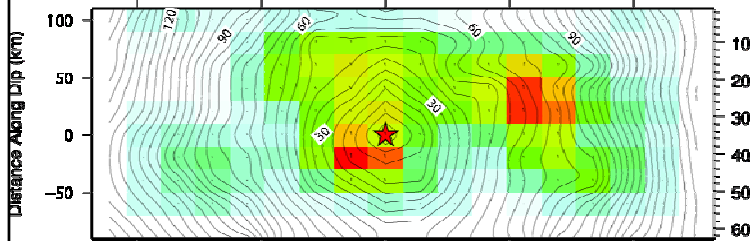


taille du séisme = surface de l'aspérité * glissement

Chili: 450 km * 150 km * 9 m => Mw 8.8 Sichuan: 200 km * 20 km * 5 m => Mw 7.8



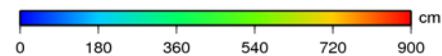
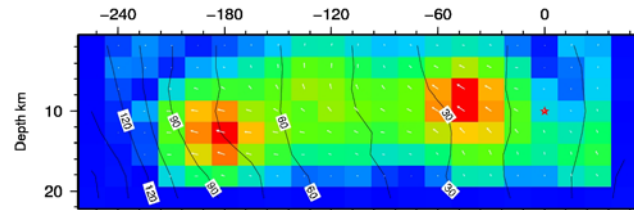
Strike = 17.5
Distance Along Strike (km)



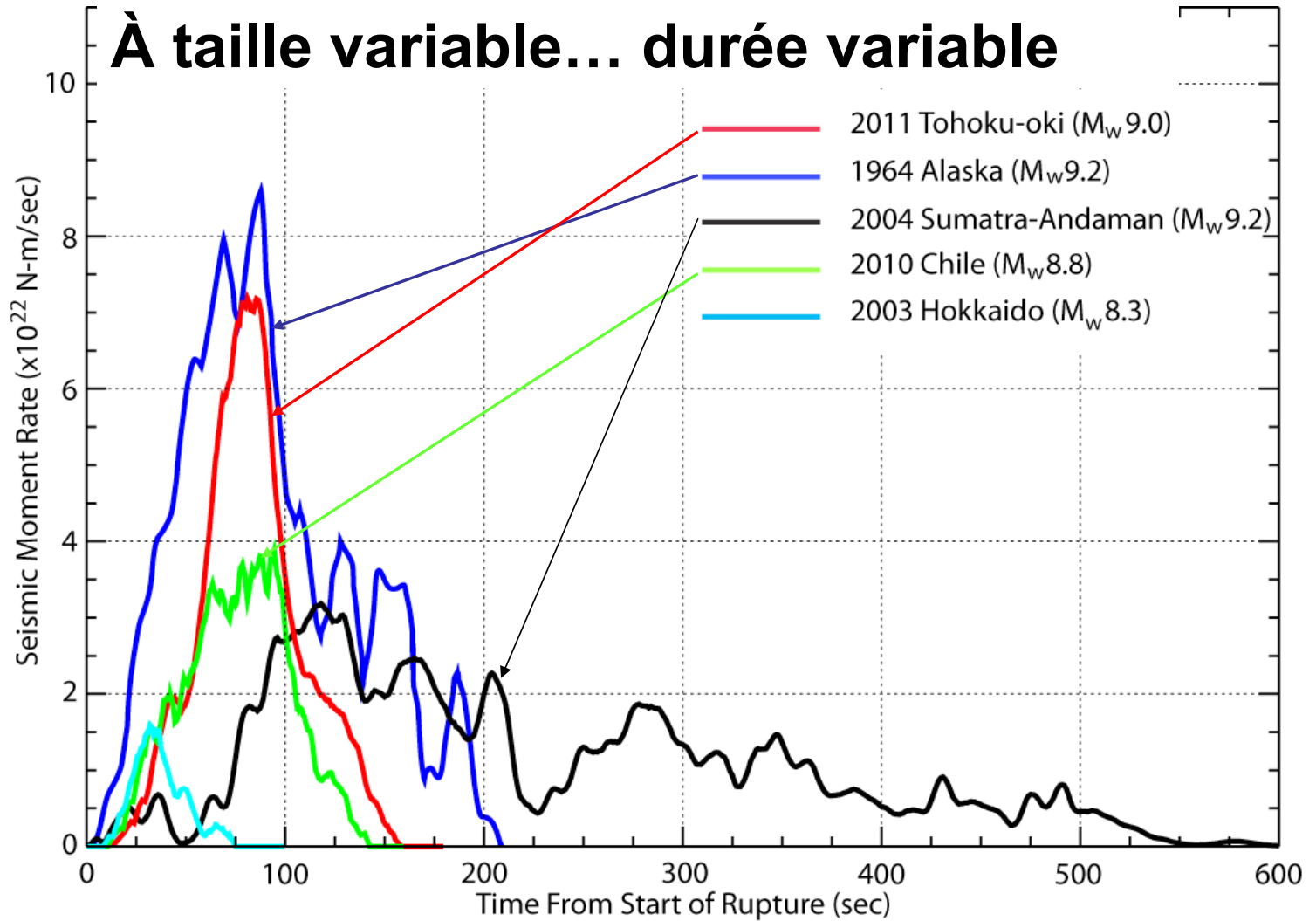
Rupture Front Contours Plotted Every 5s



Strike = 229 deg



À taille variable... durée variable

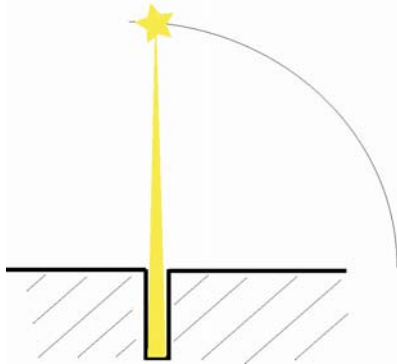


Comment sait-on tout ça ?

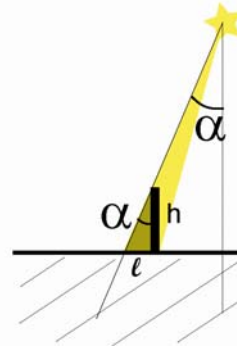
Depuis longtemps grâce à la sismologie, mais depuis 10-15 ans la géodésie spatiale a permis des avancées majeures

La géodésie a été inventée par les Grecs (Eratosthene, 300 bc)

$$\text{Taille de la Terre : } \text{circ} = 360^\circ / \alpha * d_{12} = 40000 \text{ km}$$

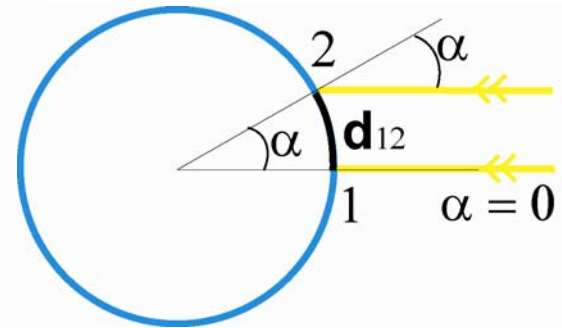


At one place on Earth, the Sun is vertical (lights the bottom of a well) only once a year



At the same time, at a different place, the Sun is not vertical

The angle can be measured from the length of the shadow of a vertical pole



The angle α of the sun light direction depends on the **local vertical** direction

=> Depends on the **latitude** of the site

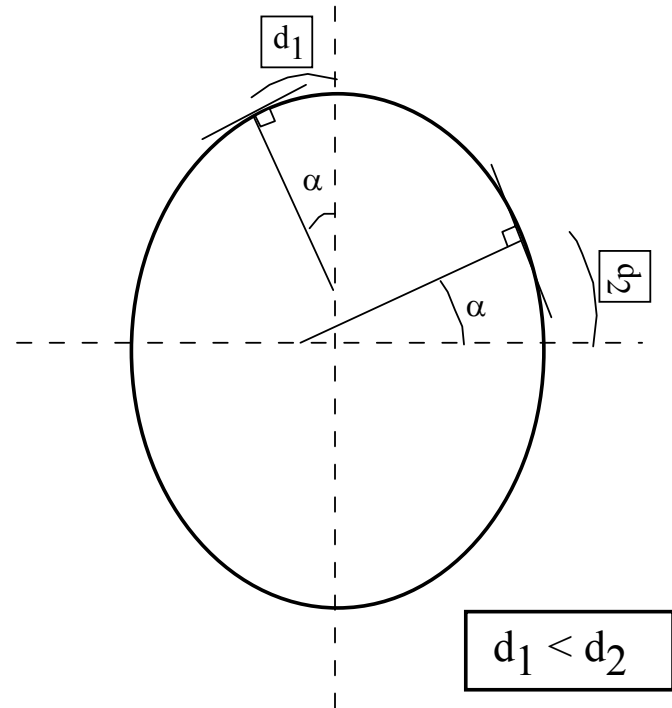
La forme de la Terre (18^{ème} siècle)

Making those measurements, different people find different values for the length of an arc of 1° at different places in Europe

- Snellius (1617) : 104 km
- Norwood (1635) : 109 km
- Riccioli (1661) : 119 km

In France, **Picard** finds :

- **108 km** in the **north** of France
- **110 km** in the **south** of France

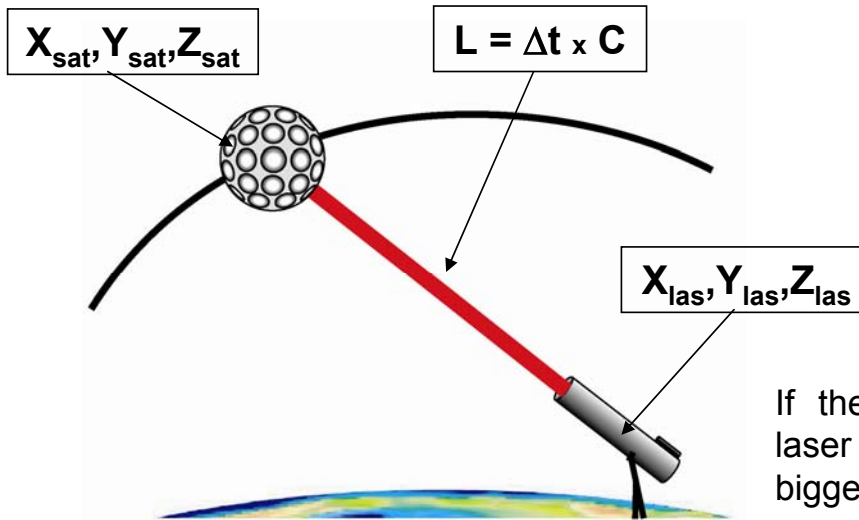


La déformation de la Terre

Satellite Laser Ranging (SLR)



High energy laser firing at satellites enable to determine the position of the satellite and then the Geoid, assuming the station position is know. On reverse, assuming one knows the satellite position (i.e. the earth gravity field), then by measuring the satellite-station distance one can determine the station position. The time is measured with a precision of about **0.1ns to 0.3 ns** ($3 \cdot 10^{-10}$ sec), which give a precision of about **3 to 10 cm** on the measured length, hence on the station position.



$$X_{las} = X_{sat} - L_x$$

$$Y_{las} = Y_{sat} - L_y$$

$$Z_{las} = Z_{sat} - L_z$$

$$\text{pos}_{las} = \text{pos}_{sat}(t_i) - L(t_i)$$

With : t_i = time of i^{th} measurement along the orbit

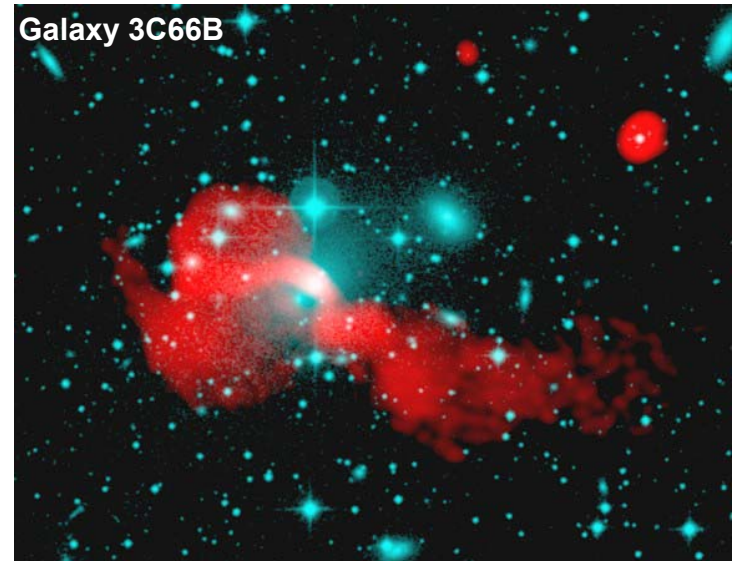
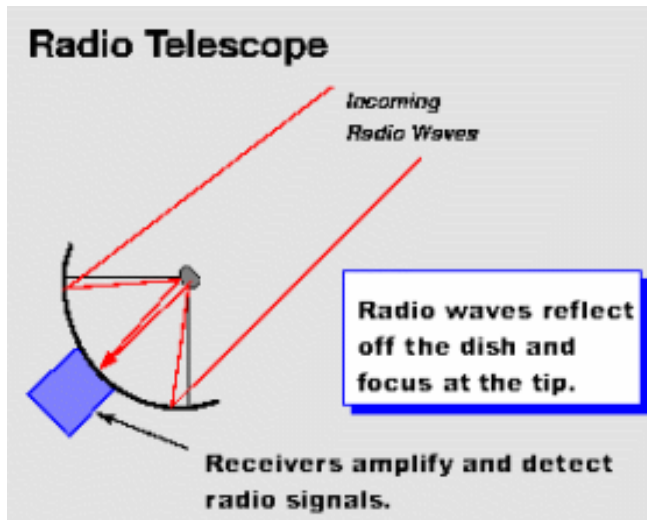
If the earth surface deforms, then the laser station moves. If this motion is bigger than a few cm, then the measurement detects it !

La déformation de la Terre

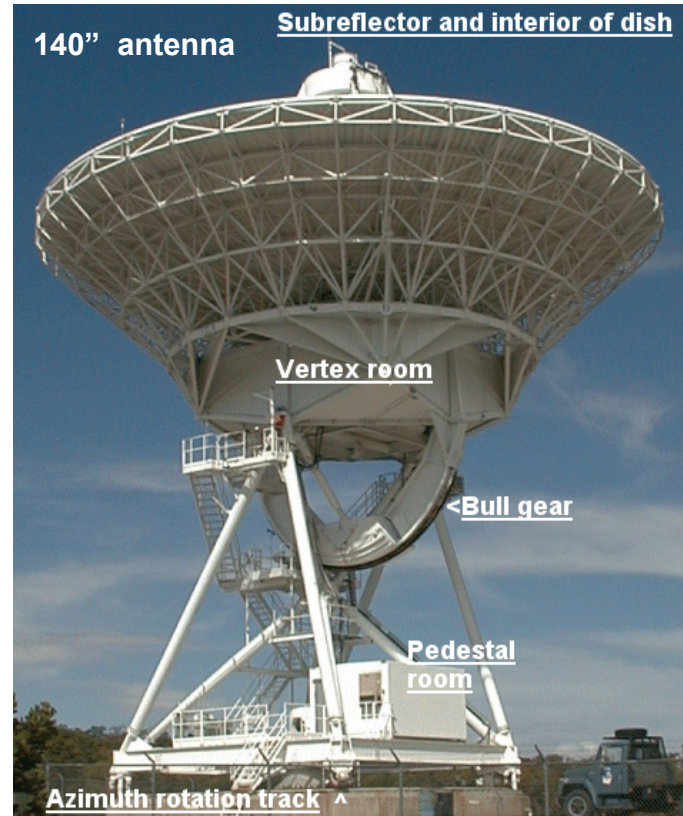


Radio Telescope principle

Radio telescopes are used to study naturally occurring radio emission from stars, galaxies, quasars, and other astronomical objects between wavelengths of about 10 meters (30 megahertz [MHz]) and 1 millimeter (300 gigahertz [GHz]). At wavelengths longer than about 20 centimeters (1.5 GHz), irregularities in the ionosphere distort the incoming signals. Below wavelengths of a few centimeters, absorption in the atmosphere becomes increasingly critical. the effective angular resolution and image quality **is limited only by the size of the instrument.**



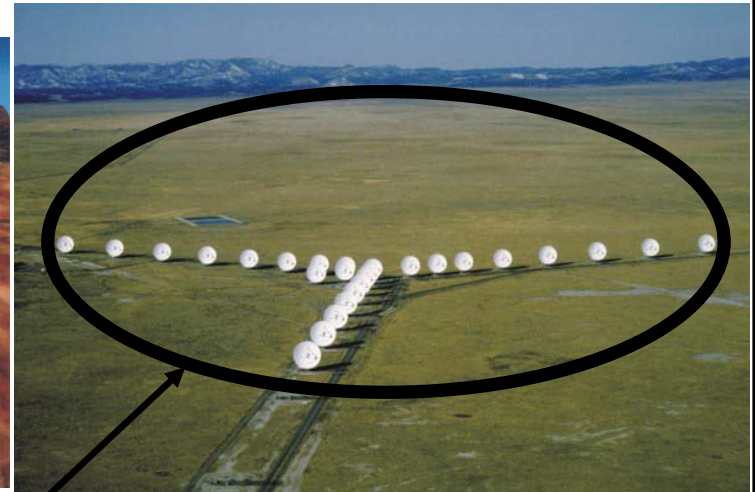
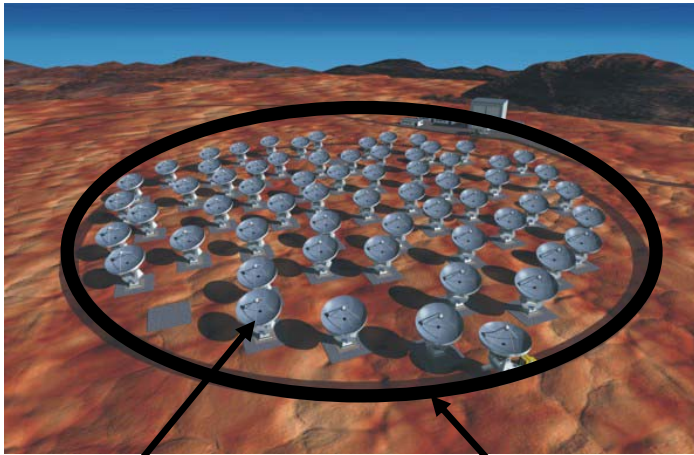
Bigger antennas



Very Large Base Interferometry (VLBI)



It is extremely difficult to built antennas bigger than 20-30 meters diameter...
But, one **single large** mirror (or antenna) can be replace by **many small** mirrors (or antenna). The size of the image will be equivalent. Thus, an array of small antennas make a **virtual** big antenna of equivalent size the size of the array.



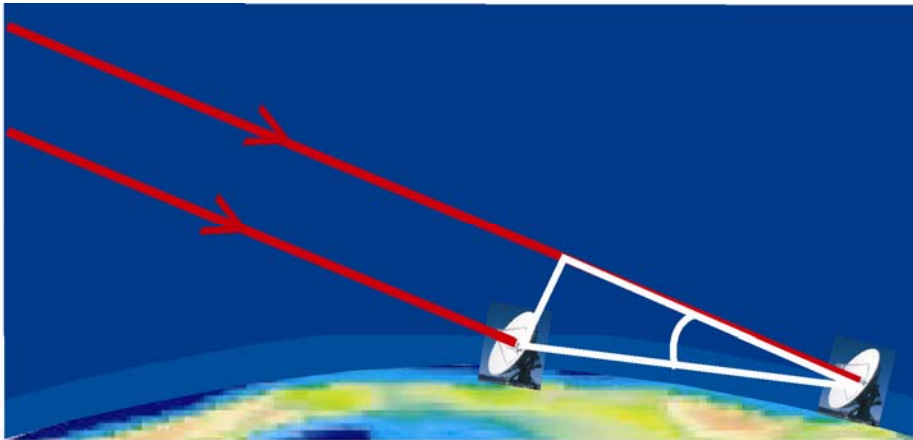
Single small antenna

virtual antenna

Very Large Base Interferometry (VLBI)



One can reconstruct a precise image of the observed object, knowing precisely the distances between the individual antennas. If these distances are not well known, then the image is fuzzy. Again, reversing the problem, focusing a known image allow to determine the distances between stations.



The obtained precision is around **1 millimeter** !

The radio wavelength arrives at first antenna at time t , and at the second antenna at time $t + \Delta t$.

The additional distance is :
 $\Delta t \cdot c$

Which we can easily convert into distance between stations (knowing the angle=difference in latitude)

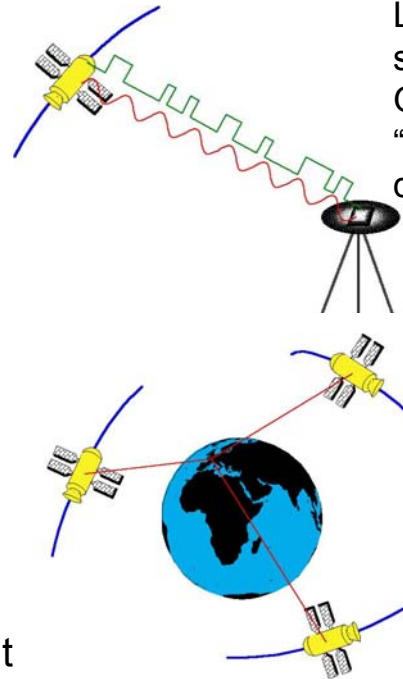
Les systèmes de positionnement **précis** par satellite (GPS, GLONASS, GALILEO)

GPS (Global Positioning System)

Le GPS a été créé dans les années 80 par le D.o.D. des USA pour une utilisation militaire. L'objectif est de pouvoir positionner précisément **n'importe quoi** (un avion, un navire, un char d'assaut, un missile, un commando), **n'importe quand** (rapidement) et **n'importe où** à la surface de la Terre.



Constellation de satellites bien répartis
⇒ mesure possible à toute heure / partout
⇒ précision 'diabolique' de quelques mm



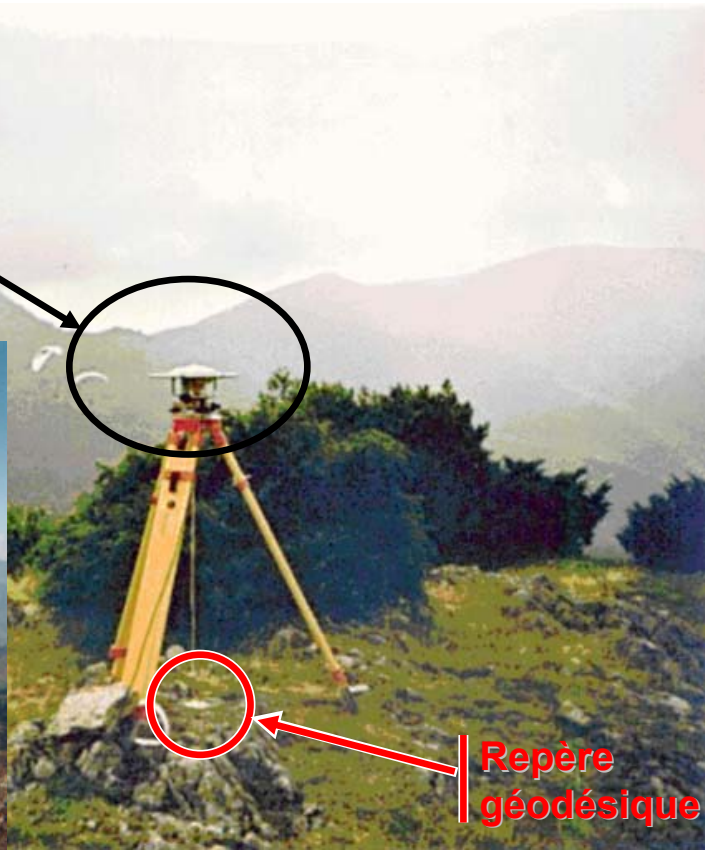
Les satellites envoient un signal, reçu par l'antenne GPS. La mesure du "temps de vol" donne la distance satellite-station.

Avec un minimum de 3 satellites visible simultanément, il est possible de calculer sa position instantanément. La précision est **millimétrique**.

GPS (Global Positioning System)



Antenne GPS sur trépieds



Repère
géodésique

GPS (Global Positioning System)



Stations permanentes



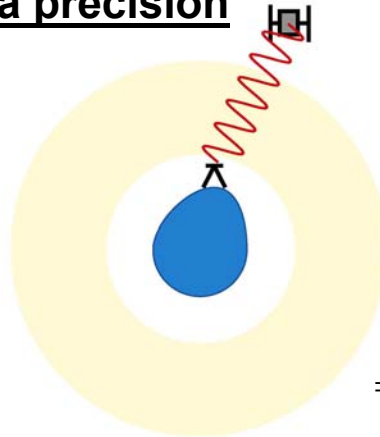
GPS (Global Positioning System)



Limitations de la précision

PROPAGATION

Ionosphère



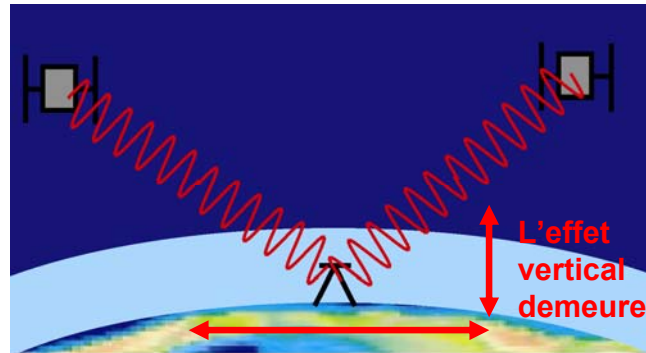
Résolu grâce au bi-fréquence

$$\tau_{ion_1} = \alpha Ne / f_1^2$$

$$\tau_{ion_2} = \alpha Ne / f_2^2$$

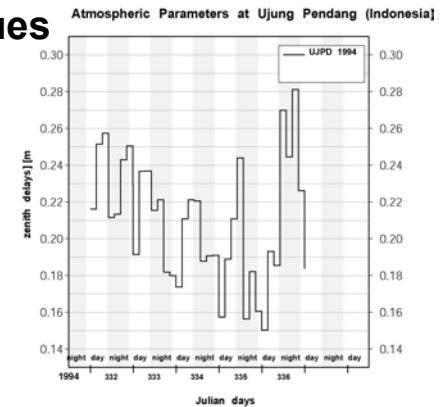
$$\Rightarrow Ne = \left[\tau_{ion_2} - \tau_{ion_1} \right] / \alpha (1/f_2^2 - 1/f_1^2)$$

troposphère



L'effet horizontal s'auto compense

Résolu grâce à des mesures longues



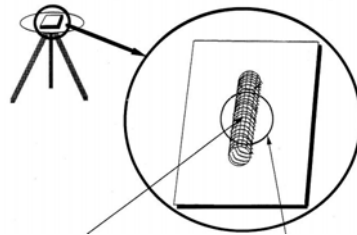
GPS (Global Positioning System)



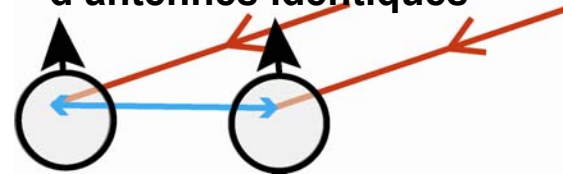
Limitations de la précision

TECHNIQUE

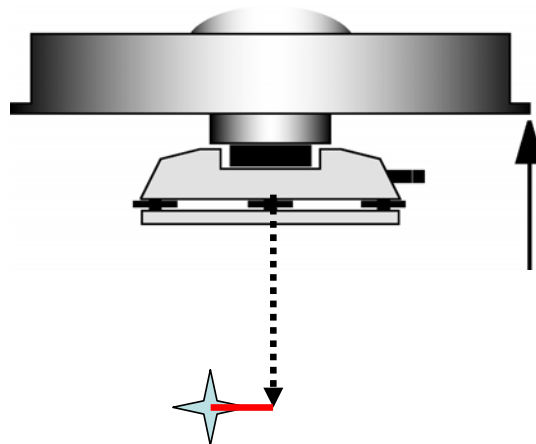
centre de phase
des antennes



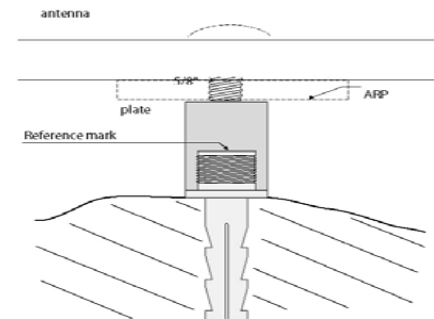
Résolu grâce à l'utilisation
d'antennes identiques



Centrage des embases



Résolu grâce au centrage forcé

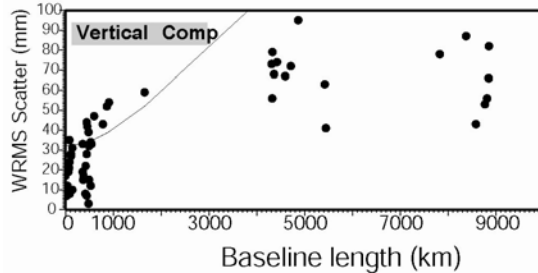
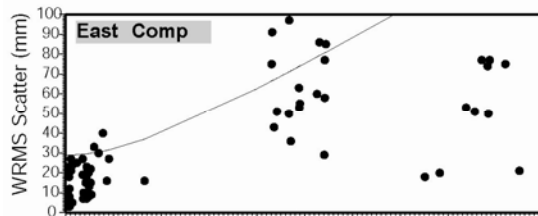
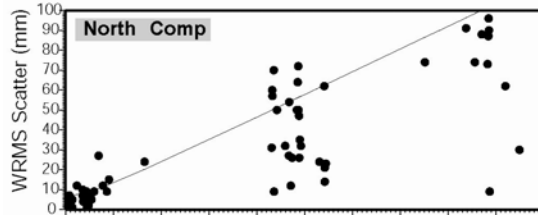


GPS (Global Positioning System)

Précision obtenue

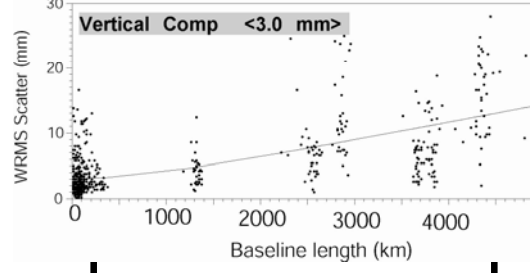
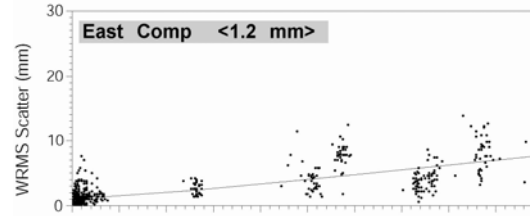
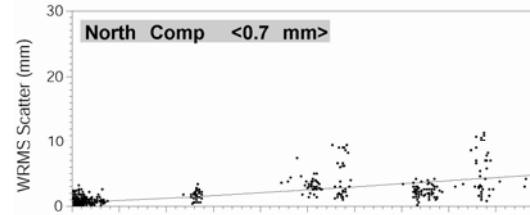


Afar 1991 - bias fixed- pggg orbits



1-2 cm 1-10 cm

Chili 2006 - biases fixed - IGS orbits

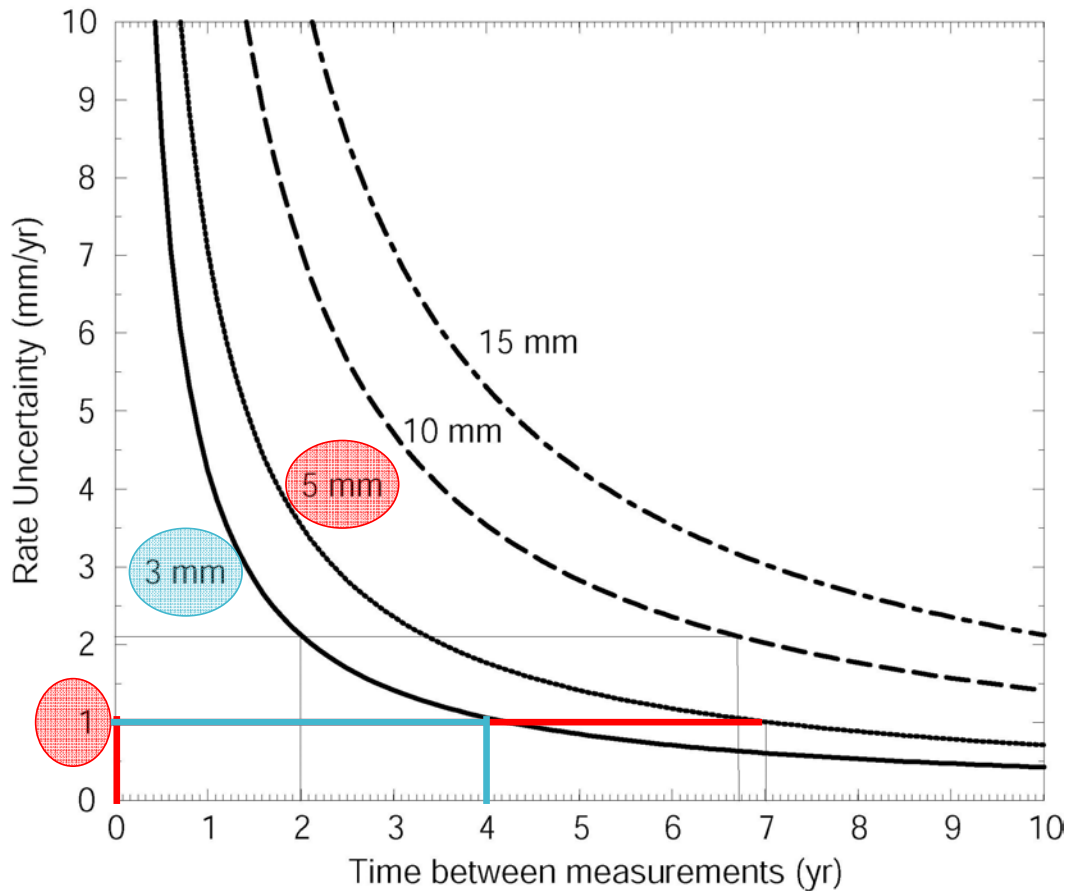


1-2 mm 1-10 mm

GPS (Global Positioning System)



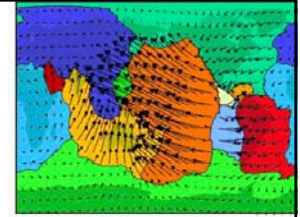
Déterminer des vitesses



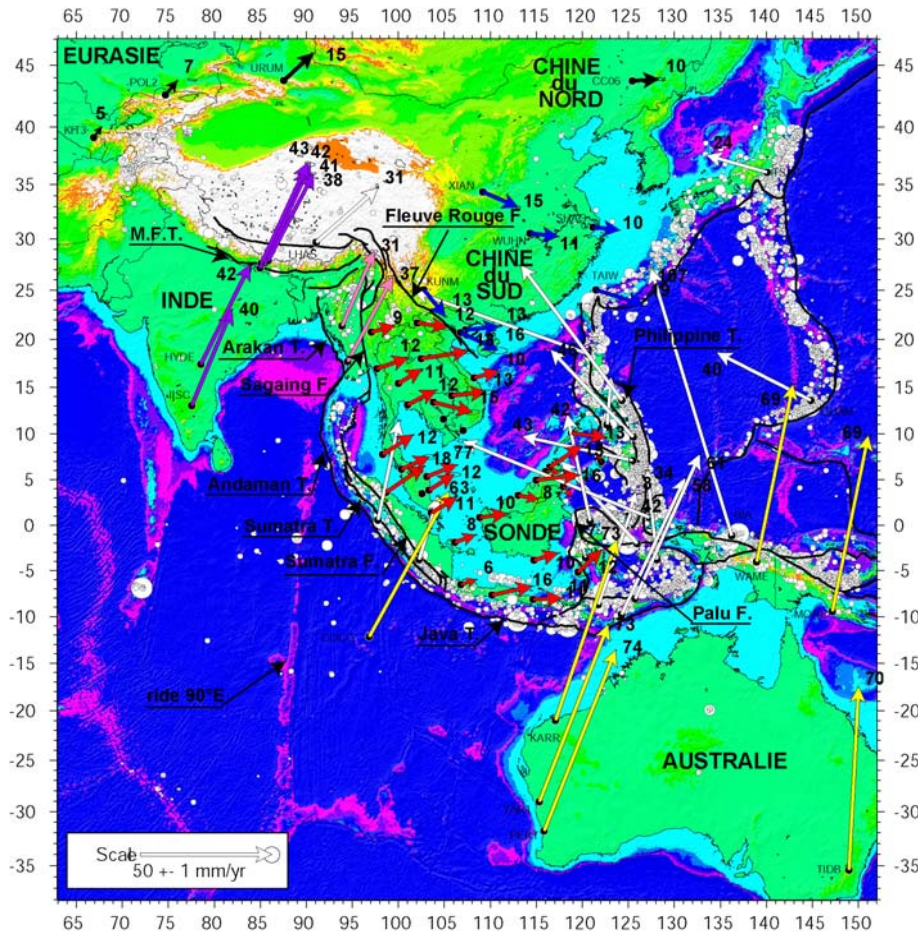
Il suffit d'attendre un certain temps entre deux mesures de position pour en déduire des vitesses de déformation

Plus le temps est long, plus la vitesse est précise

GPS : la tectonique des plaques



À grande échelle: les micro-plaques ou blocs



Le bloc de la sonde:

=> ce bloc est indépendant de l'Eurasie et s'en éloigne à ~1cm/an vers l'Est

La Chine du Sud:

=> est aussi indépendante de l'Eurasie et s'en éloigne à ~1cm/an vers l'Est également.

L'INDE:

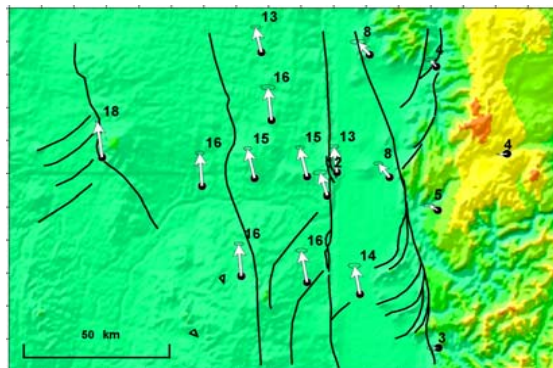
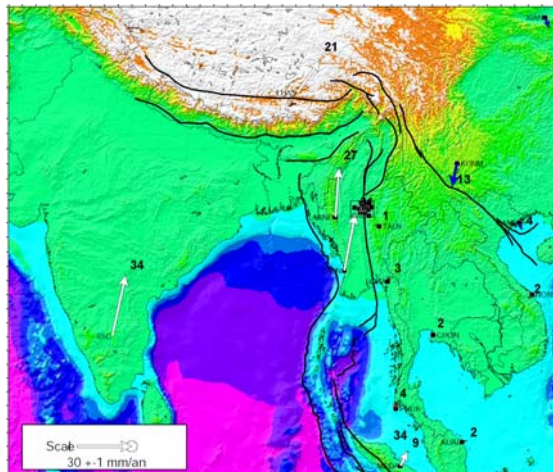
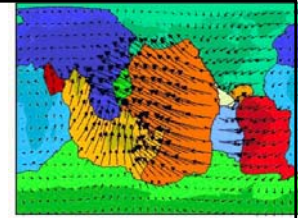
=> Seulement 4 cm/a par rapport à l'Eurasie et seulement 3.5 cm/an par rapport à Sunda

BURMA platelet (or sliver):

=> Ni Inde ni Sonde (encore moins Eurasie)

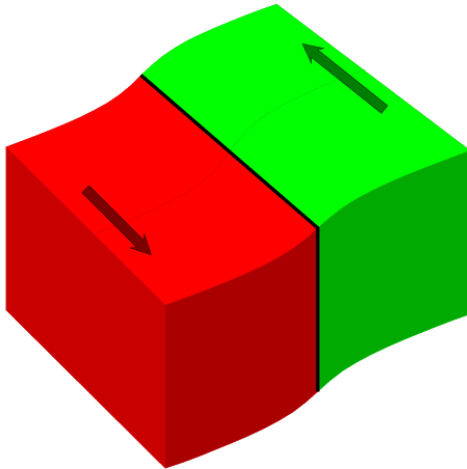
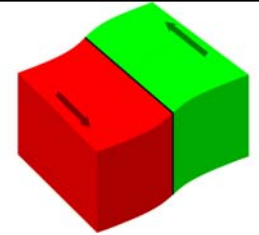
GPS : déformation localisée sur les failles

La faille de Sagaing en Birmanie



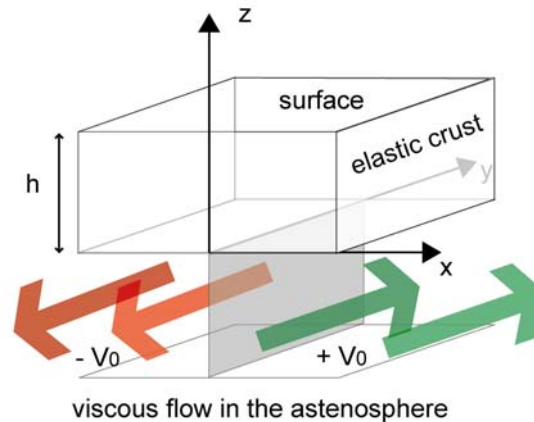
GPS : la tectonique des plaques

La déformation autour des frontières de plaques



Le concept:
déformation élastique
à cause du frottement

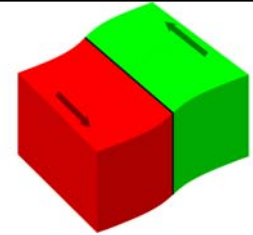
⇒ **La solution analytique:**
une courbe en arctangente



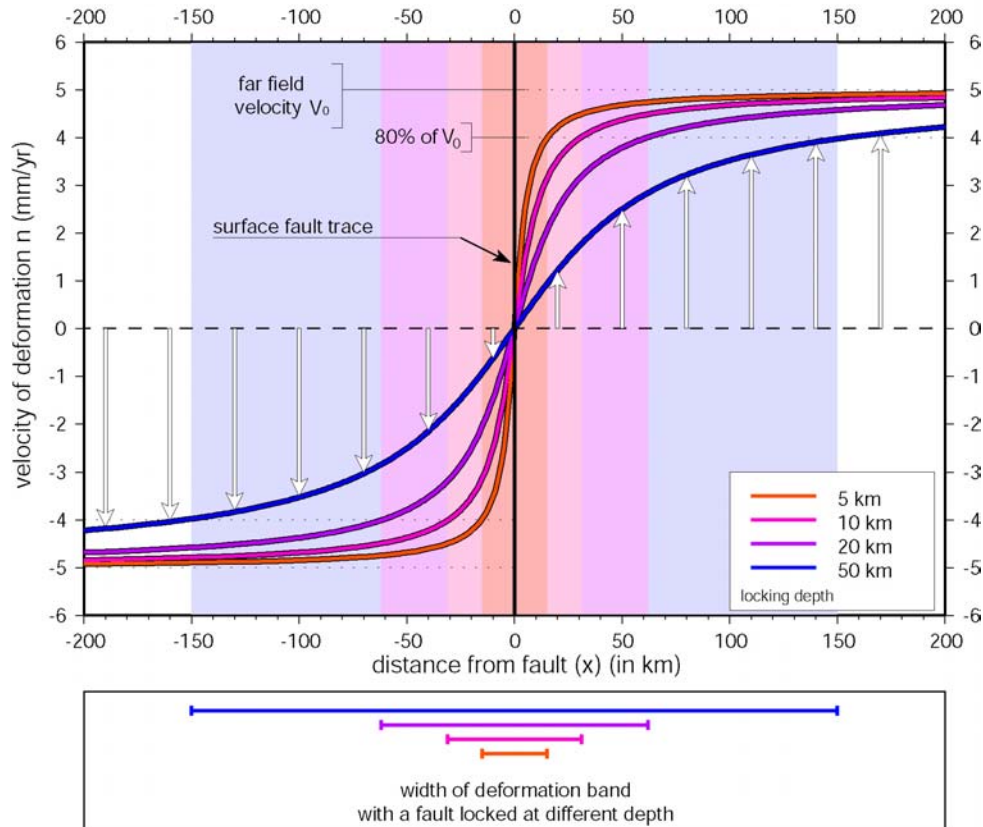
Le modèle:
le flux mantellique localise la
déformation sous une plaque élastique

$$U_y = 2 \cdot V_0 / \pi \arctang(x/h)$$

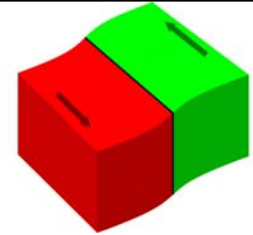
profils de déformations autour d'une faille



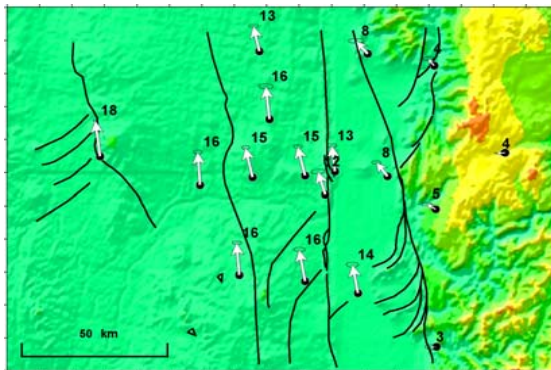
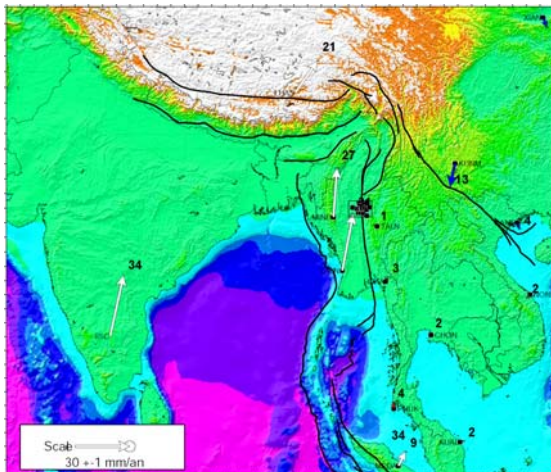
$$U_y = 2 \cdot V_0 / \pi \arctang(x/h)$$



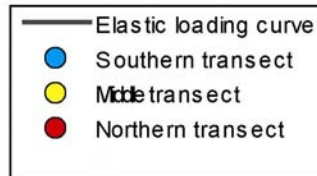
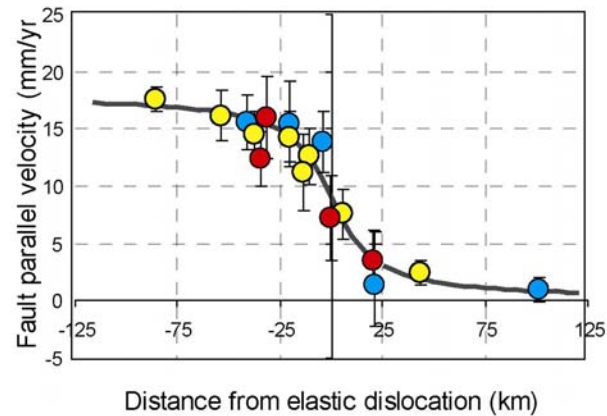
GPS : déformation localisée sur les failles



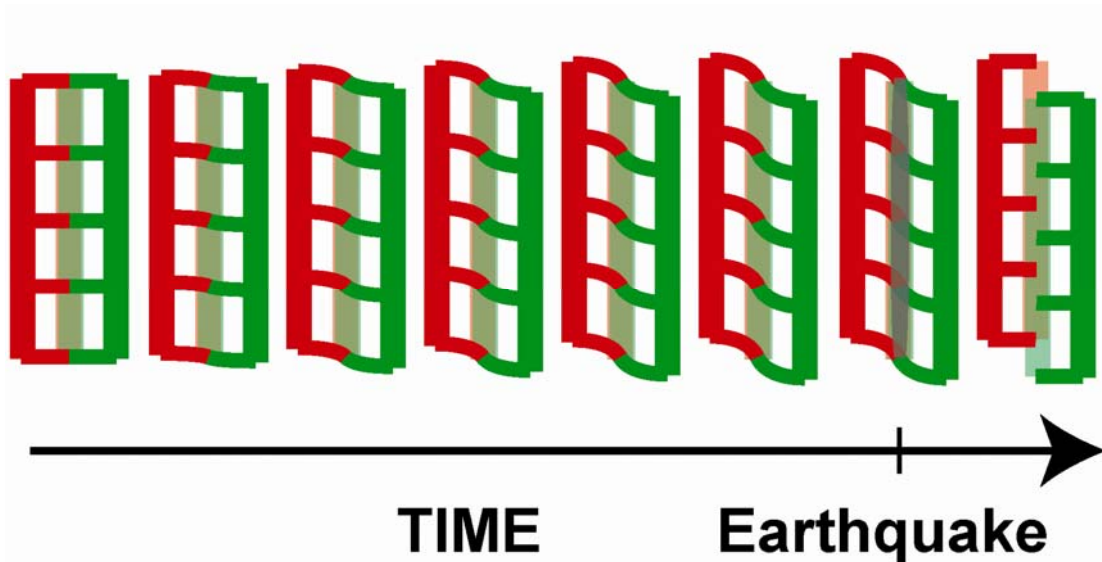
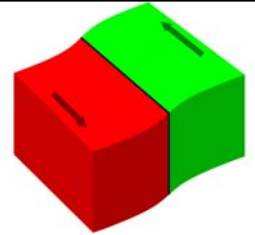
La faille de Sagaing en Birmanie



Dislocation long. = 96.12° E
Locking depth = 15.0 km
Far field velocity = 18 mm/yr

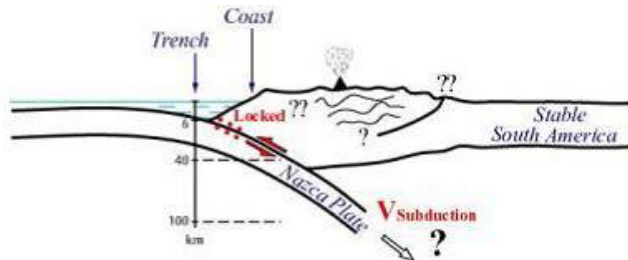


Elastic accumulation and rupture



Because the fault is locked, and the 2 plates want to move, they will deform. Deformation will accumulate (arctangent shape) until the accumulation is too much for the fault to resist. It then brakes : **it is an earthquake**

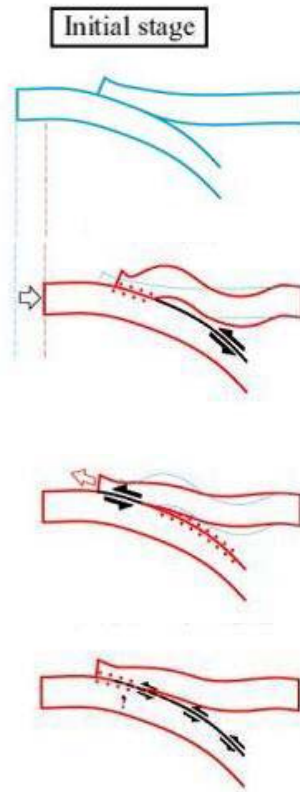
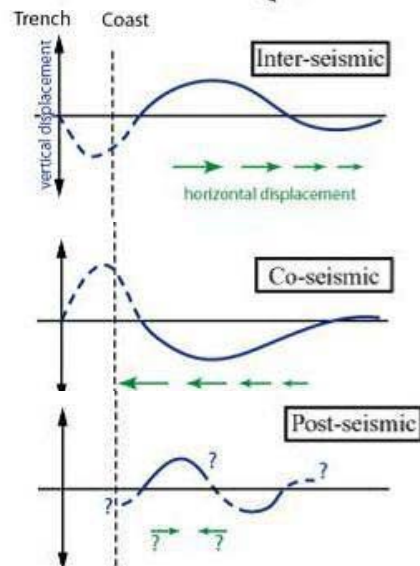
Seismic cycle in subduction context



Géométrie du slab et physique de la friction

Modèle de rupture: répartition du glissement

Viscosité du manteau

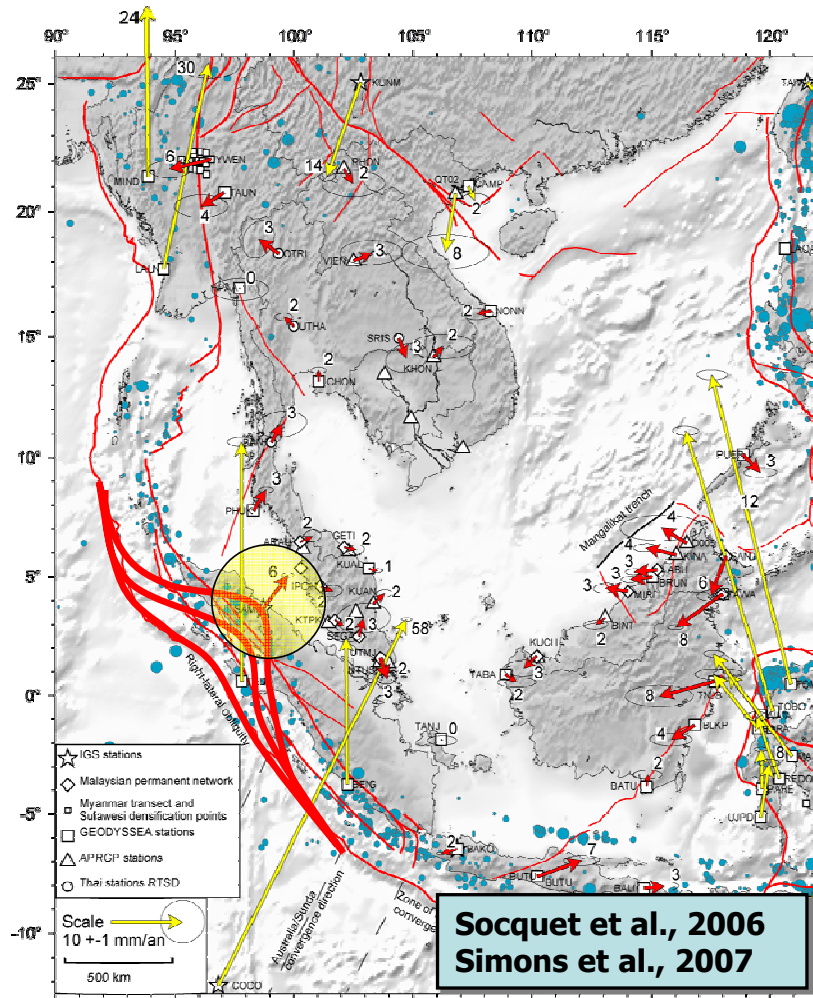


100^s years

seconds -> minutes

months- -> years

Couplage elastique subduction Sumatra



An earthquake in
this region was
inevitable

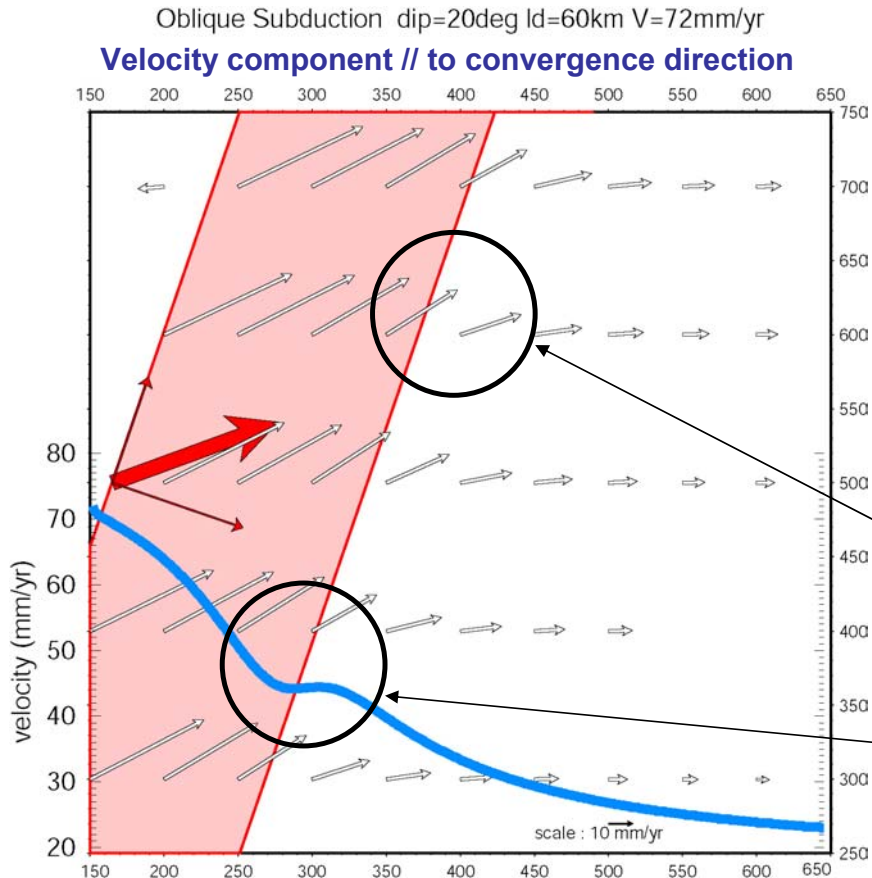
GEODYSSEA
+
SEAMERGES

~100 sites



Deformation of
Sundaland Platelet
boundaries, in
particular near
Sumatra and Borneo

Subduction modeling



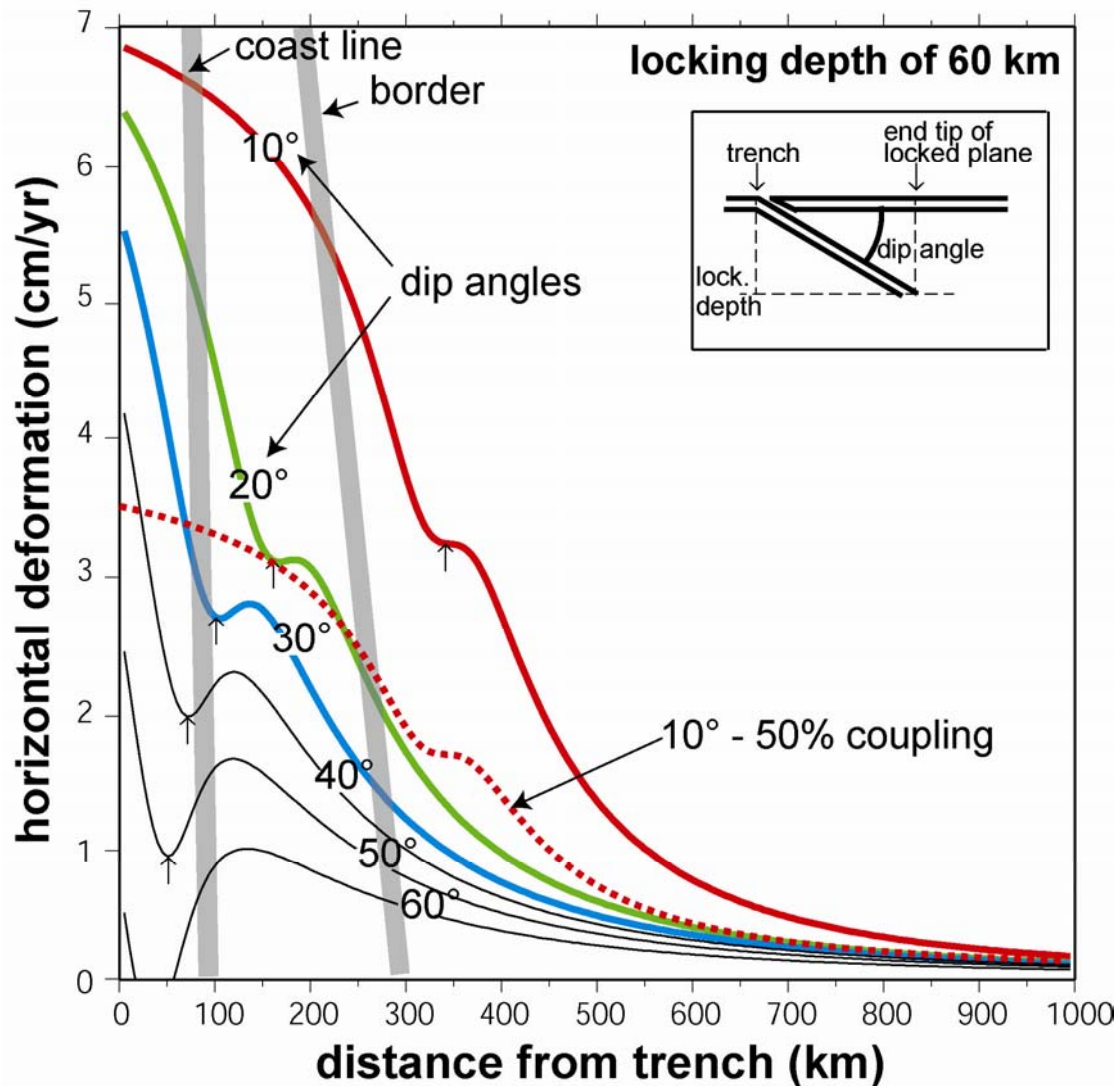
In the case of a subduction (dipping fault with downward slip) we use Okada's formulas.

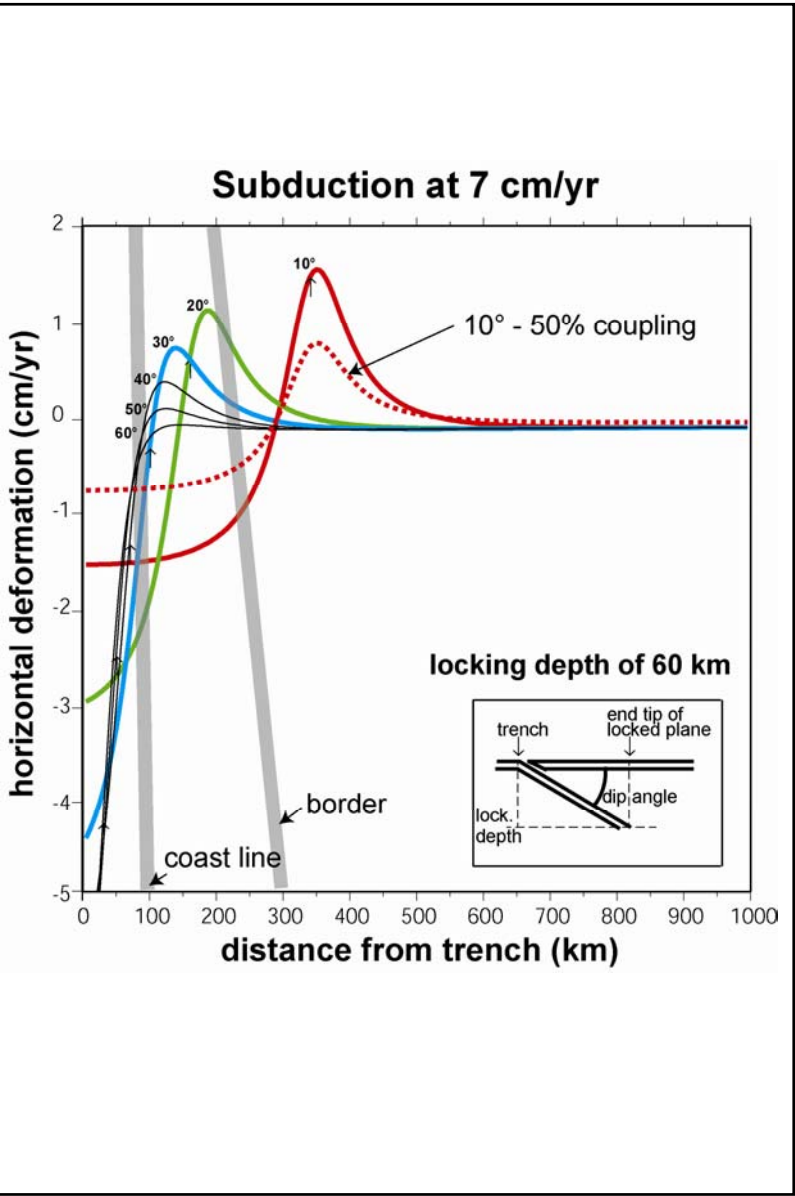
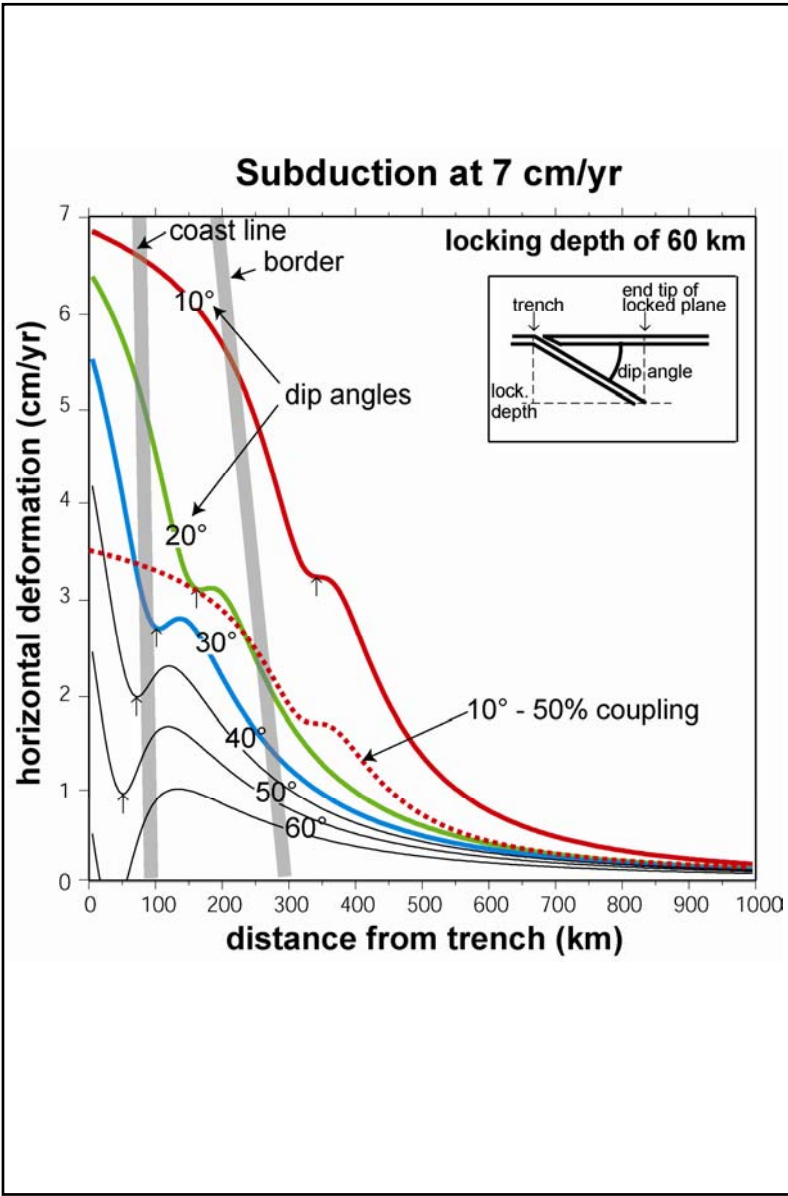
We find a very large deformation area (> 500 km) because the dipping angle is only 22°

With oblique slip we predict the surface vector will start to rotate at the vertical of the end of the subduction plane

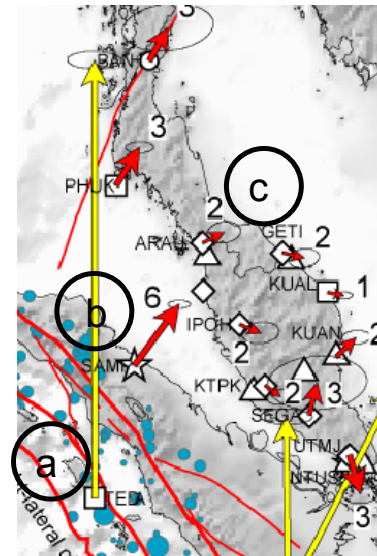
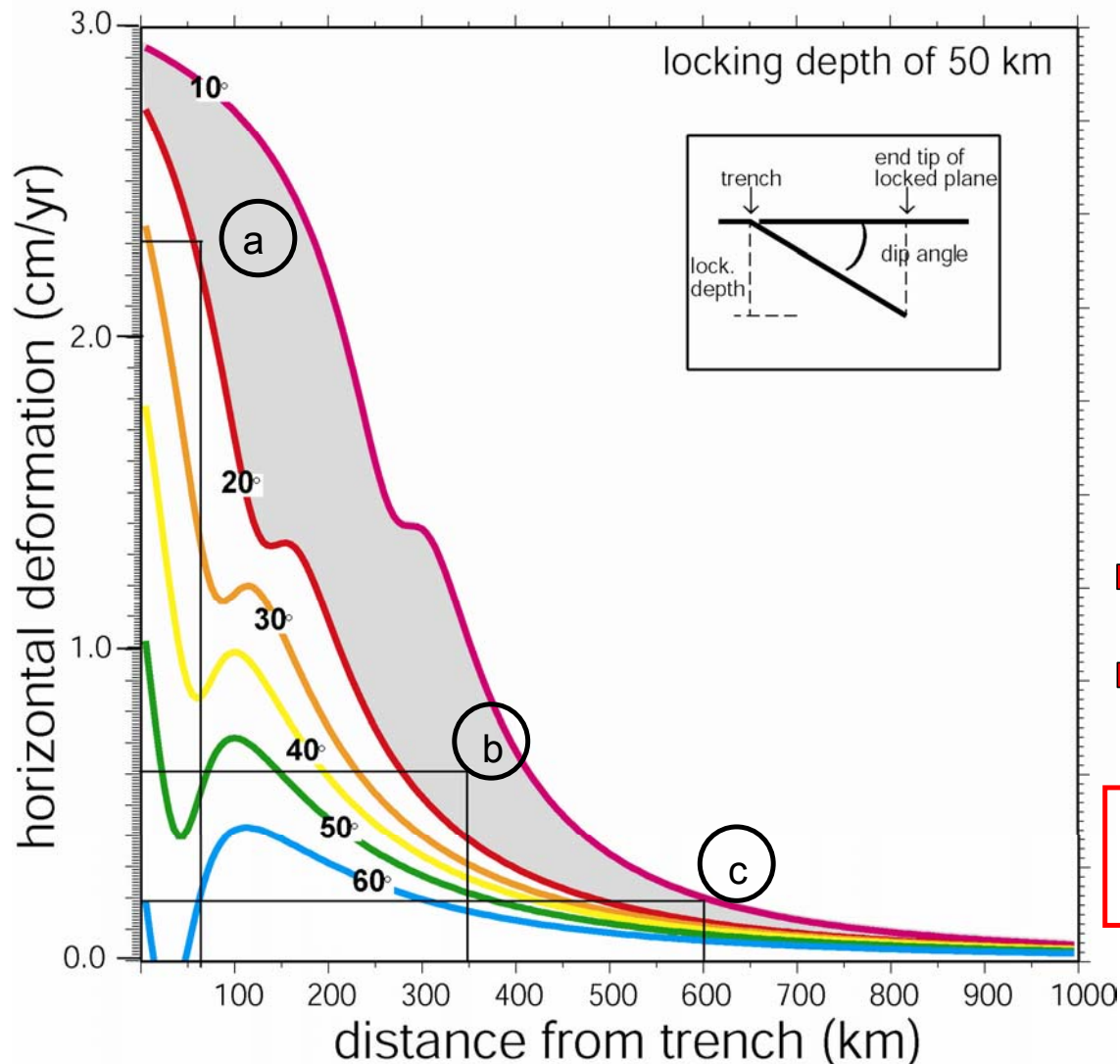
The profile of the velocity component // to the convergence shows this with a flat portion at this location

Subduction at 7 cm/yr





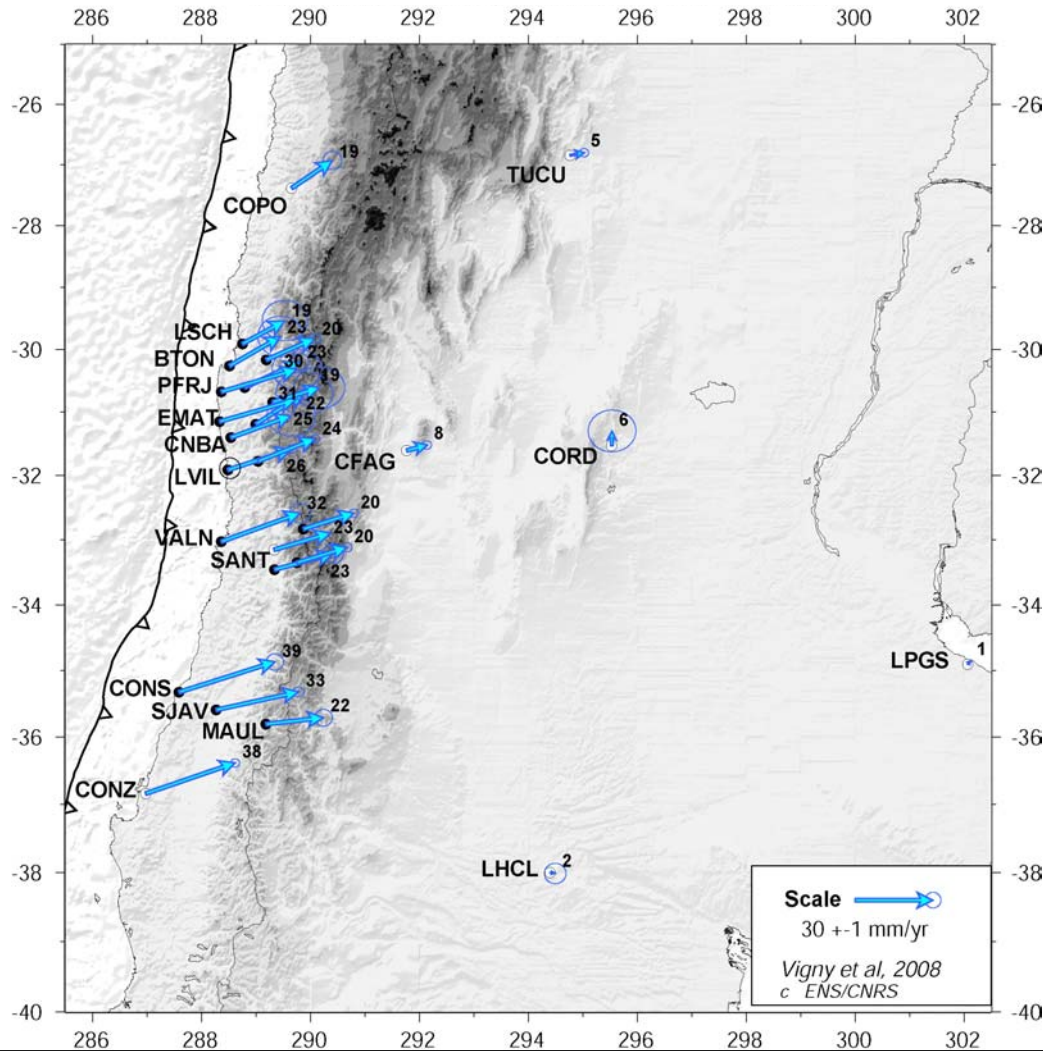
Subduction = 3 cm/yr



- Dip ~15°
- W ~200 km

200km x 200km x 3m
= Mw 8 every 100 yr

GPS measures deformation of S America

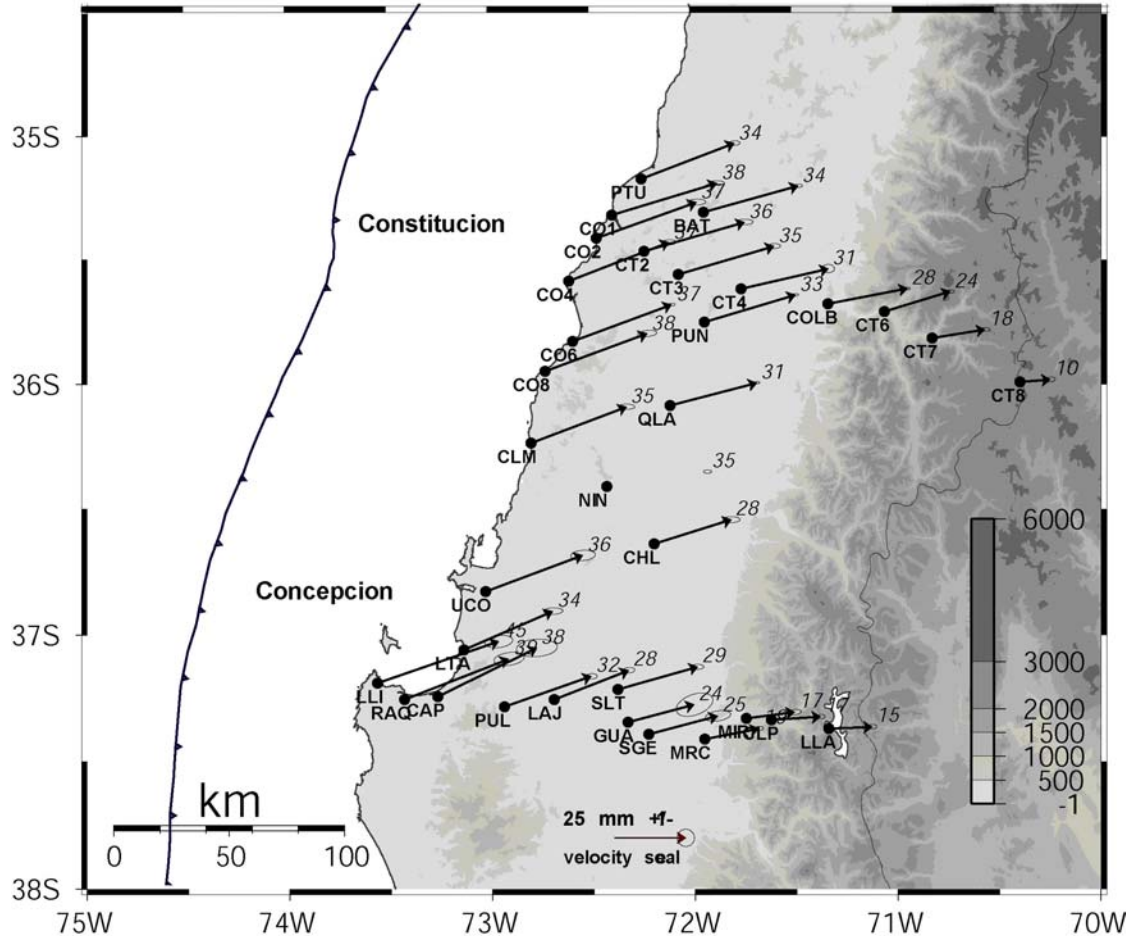


Deformation (elastic def. induced by coupling on the subduction) is visible in Chile

And

reaches far inland: TUCU (Tucuman) and CFAG (Coronel Fontana) in Argentina show deformation more than 400 km away from the trench

Zoom along high density profiles in Concepcion/Constitution area

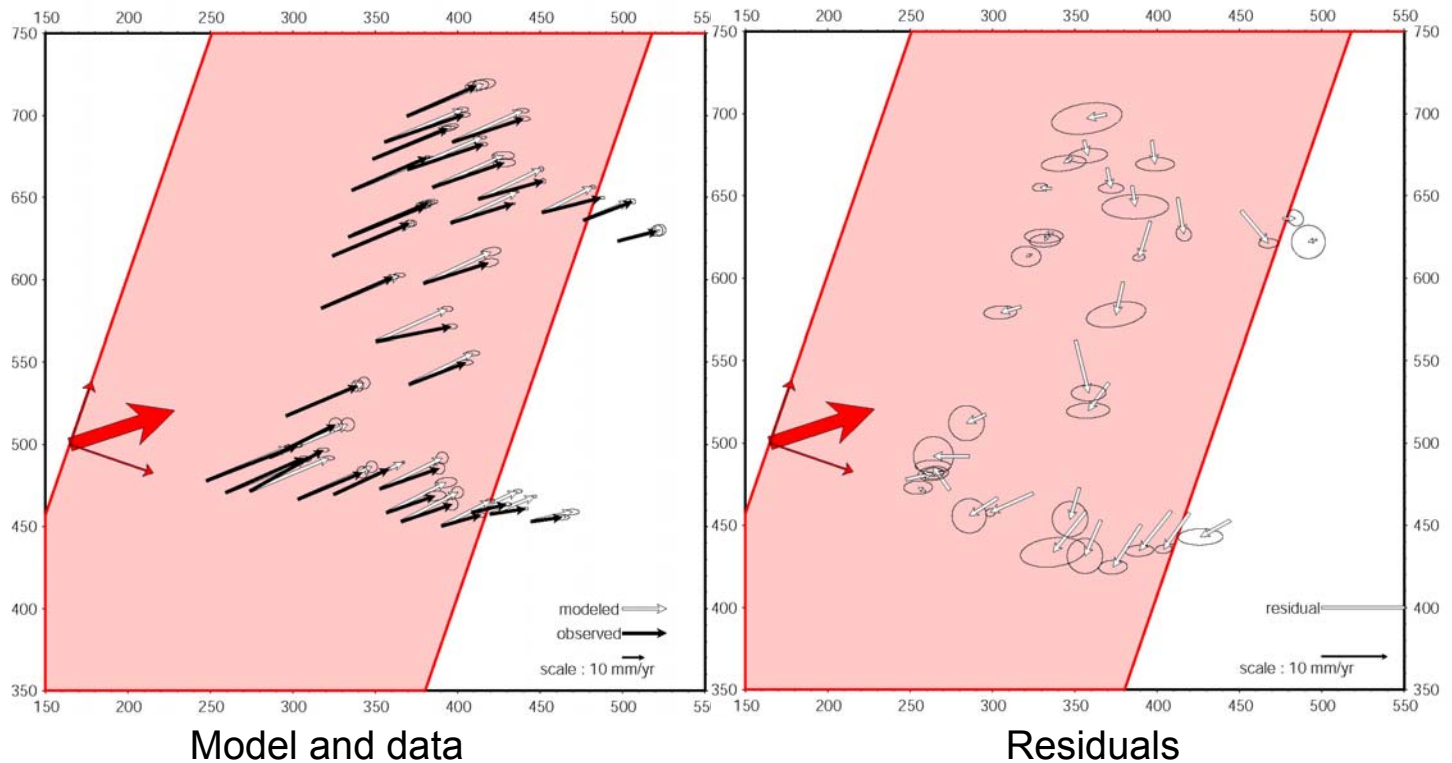


As expected from elastic coupling, velocities **decrease** Eastward (from 35-45 mm/yr along the coast to 10-15 mm/yr at the cordillera) and vector directions **rotate** from a direction // to plate convergence to East-West trending.

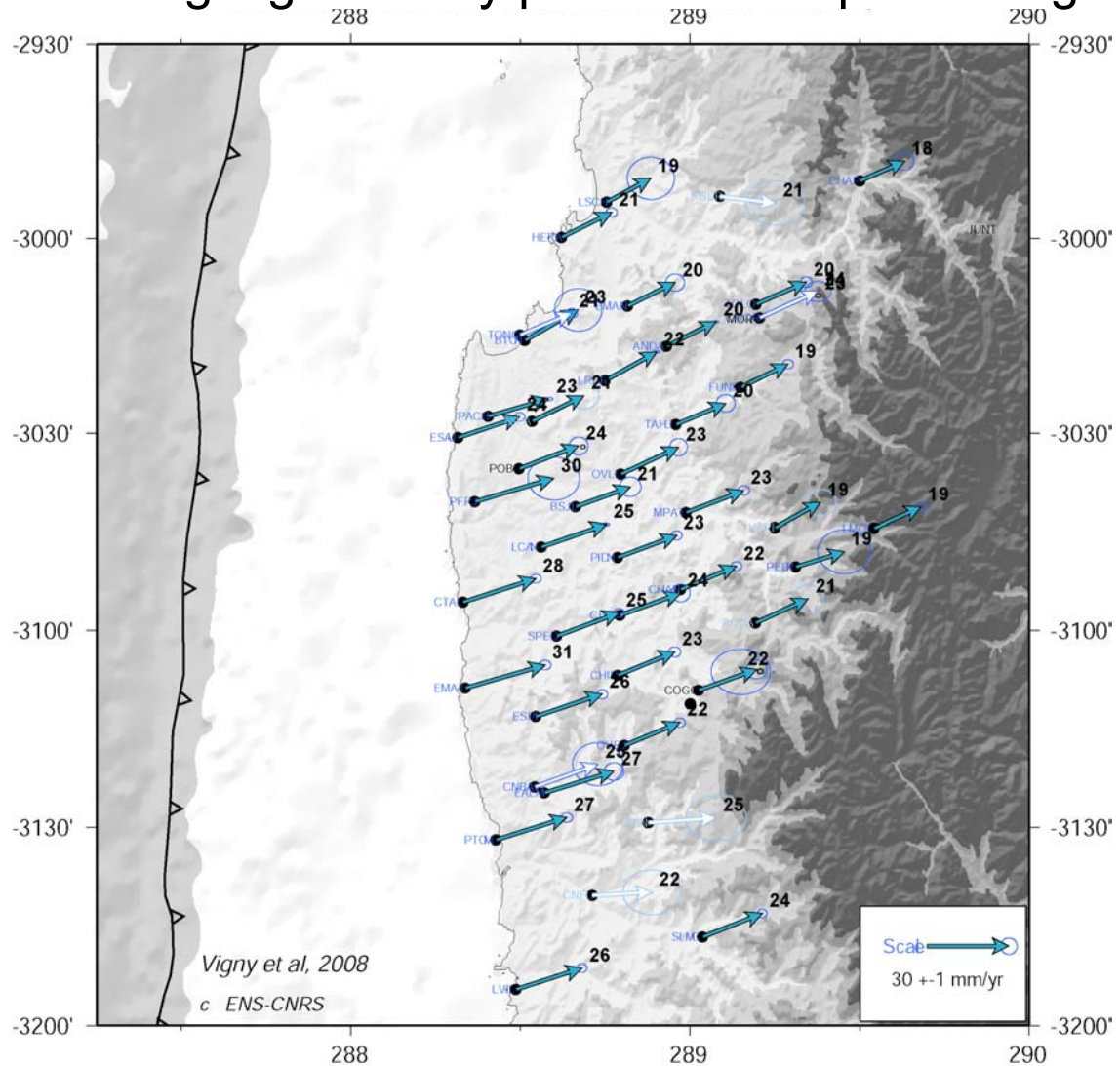
Subduction parameter adjustments

Oblique Subduction dip=13deg $L_d=60\text{km}$ $V=50.2\text{mm/yr}$ N72

Oblique Subduction dip=13deg $L_d=60\text{km}$ $V=50.2\text{mm/yr}$ N72



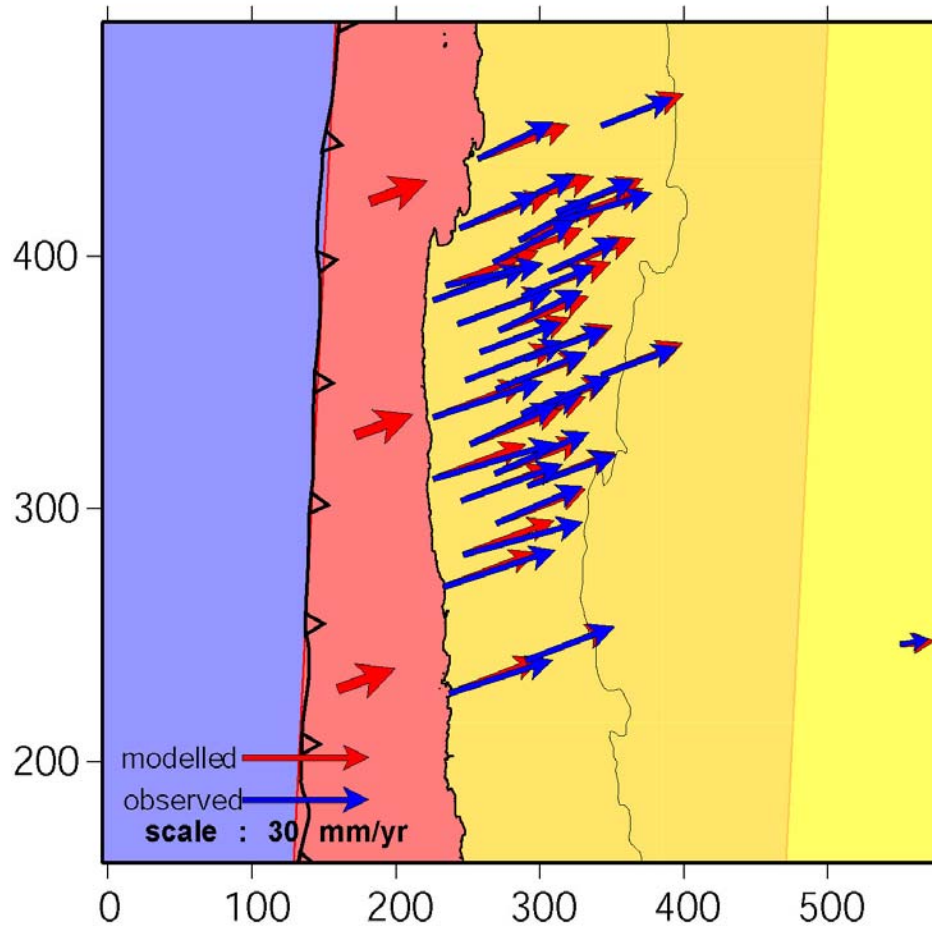
Zoom along high density profiles in Coquimbo region



Patial coupling model

observed/modelled Velocities

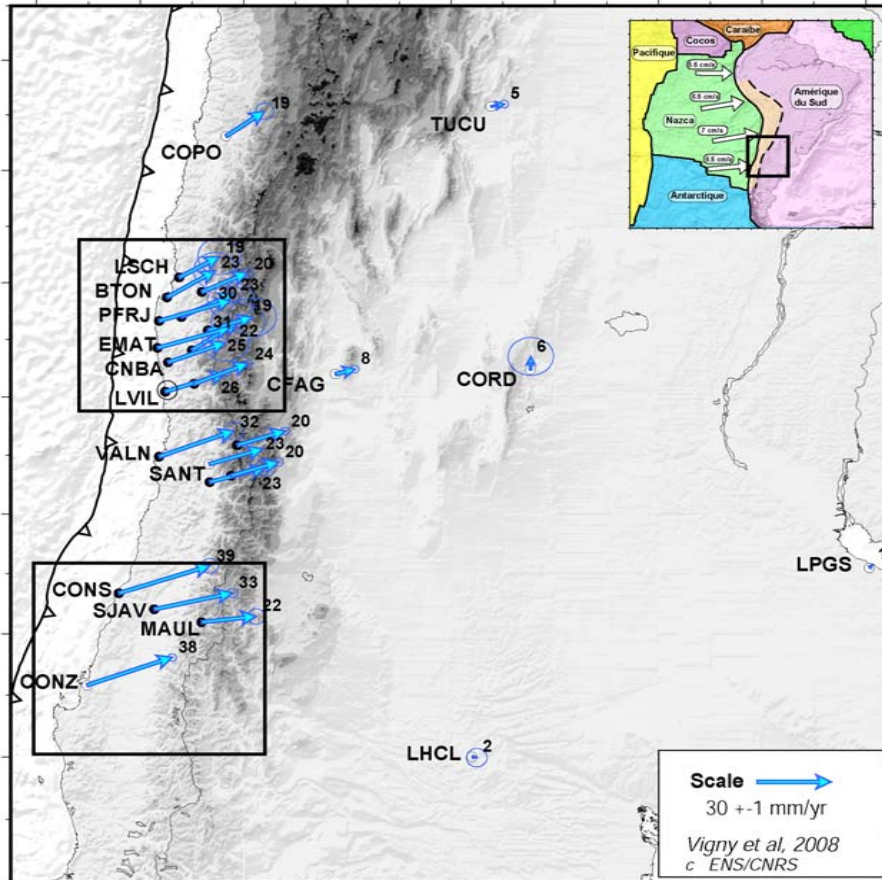
model parameters



Subduction strike: 5°N
Dislocation strike: 71°N
Locking Depth: 60 km
Plane Dip: 10°
Slip: 27 mm/yr
(41% coupling)

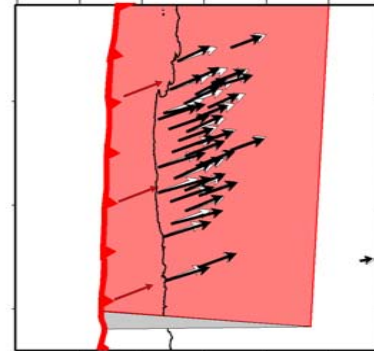
mean residual
2.6 mm/yr
over 34 points

Coupling is not always 100%

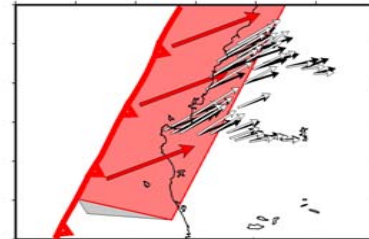


Elastic "back-slip" models

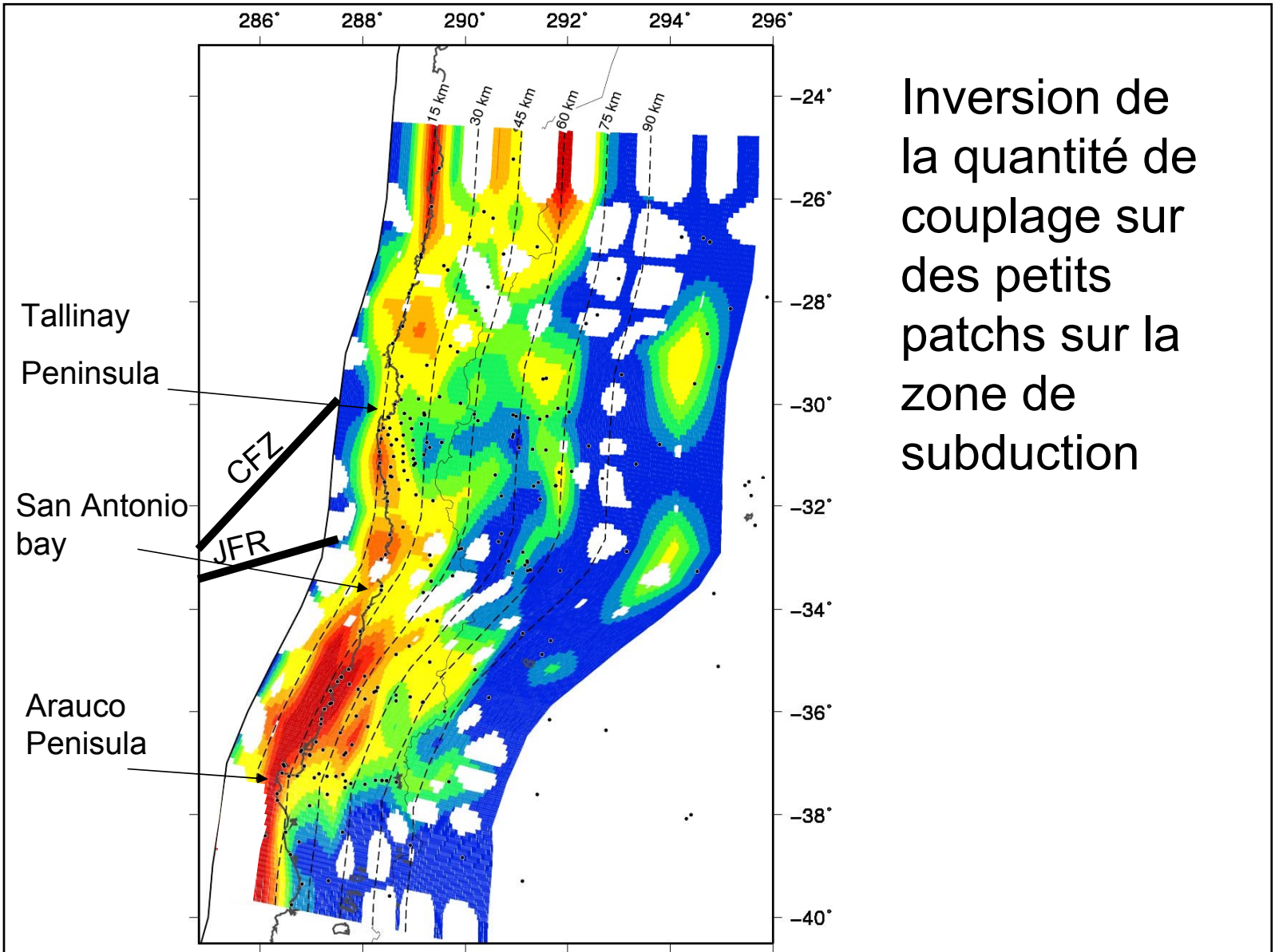
30° S : flat slab & 40% cpl



37° S : normal slab & Full cpl



modelled \rightarrow
observed \rightarrow
scale : 30 mm/yr



Inversion de la quantité de couplage sur des petits patchs sur la zone de subduction