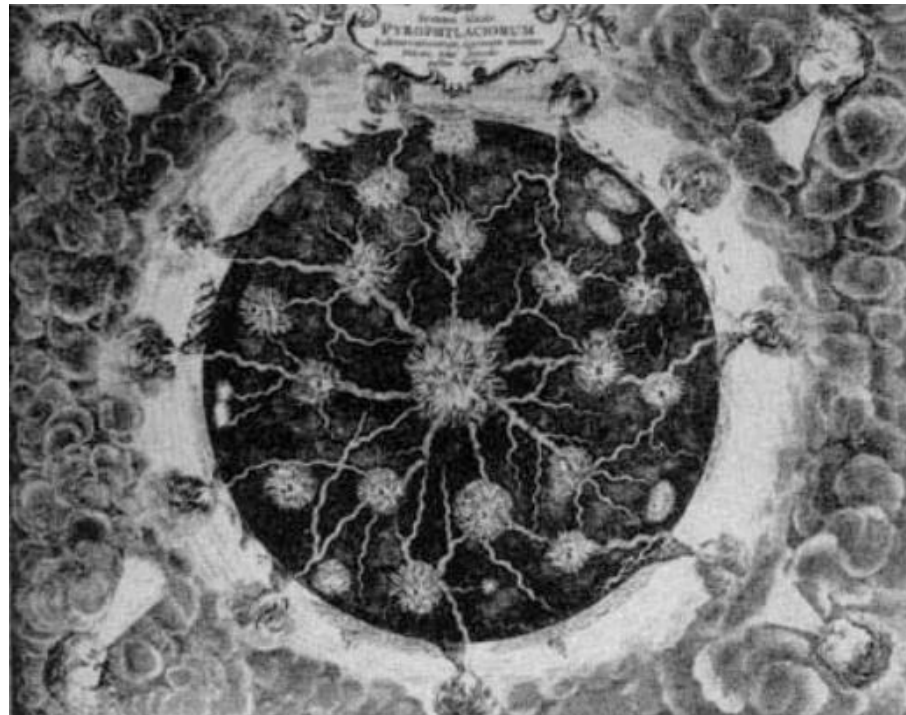


Conférences de l'Académie des Sciences
Chateau-Observatoire Abbadia
23 janvier 2019

**Du bruit de fond sismique aux
cataclysmes telluriques :
Mesures, images et théories**

Pascal Bernard, IPGP



Microséismes à Abbadia



8

PIERRE BERNARD

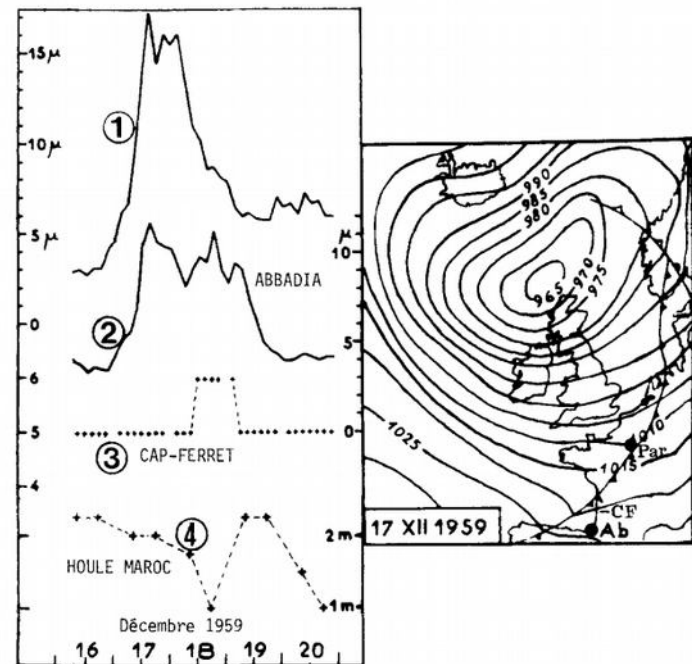


Fig. 1. Example case (Bernard, 1961) of a microseismic storm registered at Parc Saint Maur and Abbadia (Curves 1-2) with the depression responsible for it. The maximum amplitude of microseisms, December 17th, is repeated in the latter station at the same time as the swell arrives to the far end of the Bay of Biscay (curve 3: state of sea). This swell is felt on the Morocco coast the day after (curve 4).



Séisme de Haiti, 2010,

M=7.1

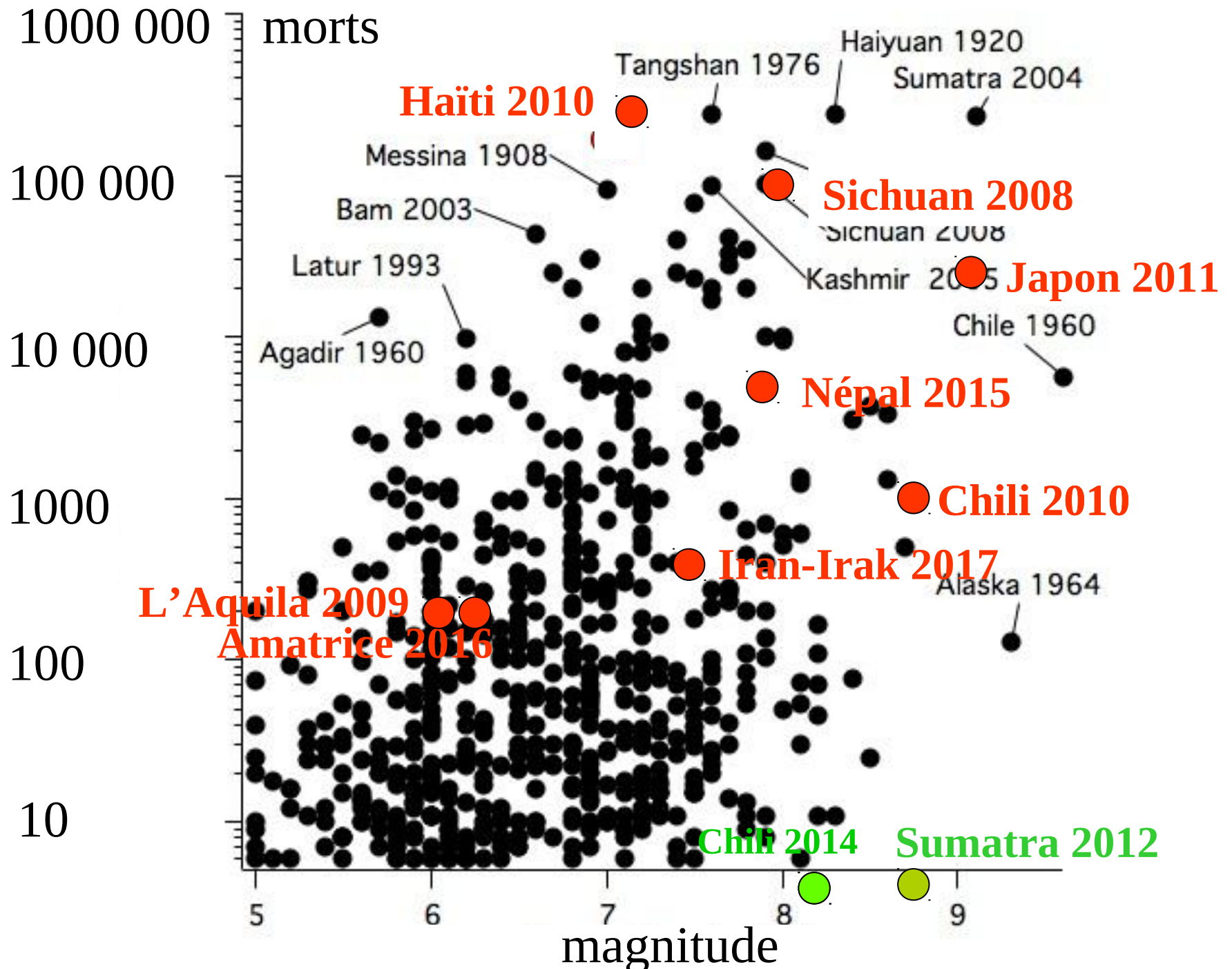
240 000 morts

Séisme de Tohoku 2011

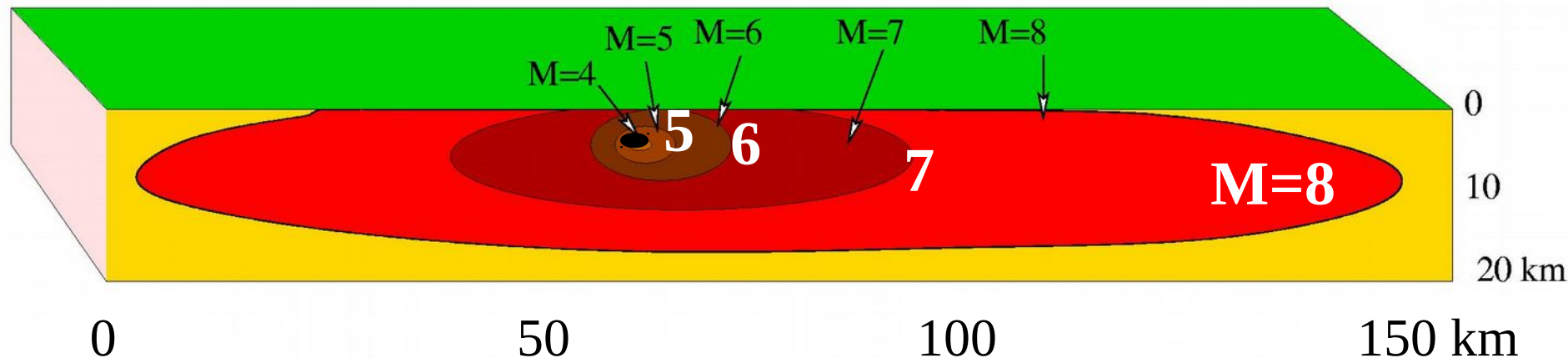
M=9.0

30 000 morts





MAGNITUDES ET LONGUEUR DE RUPTURE SUR LES FAILLES

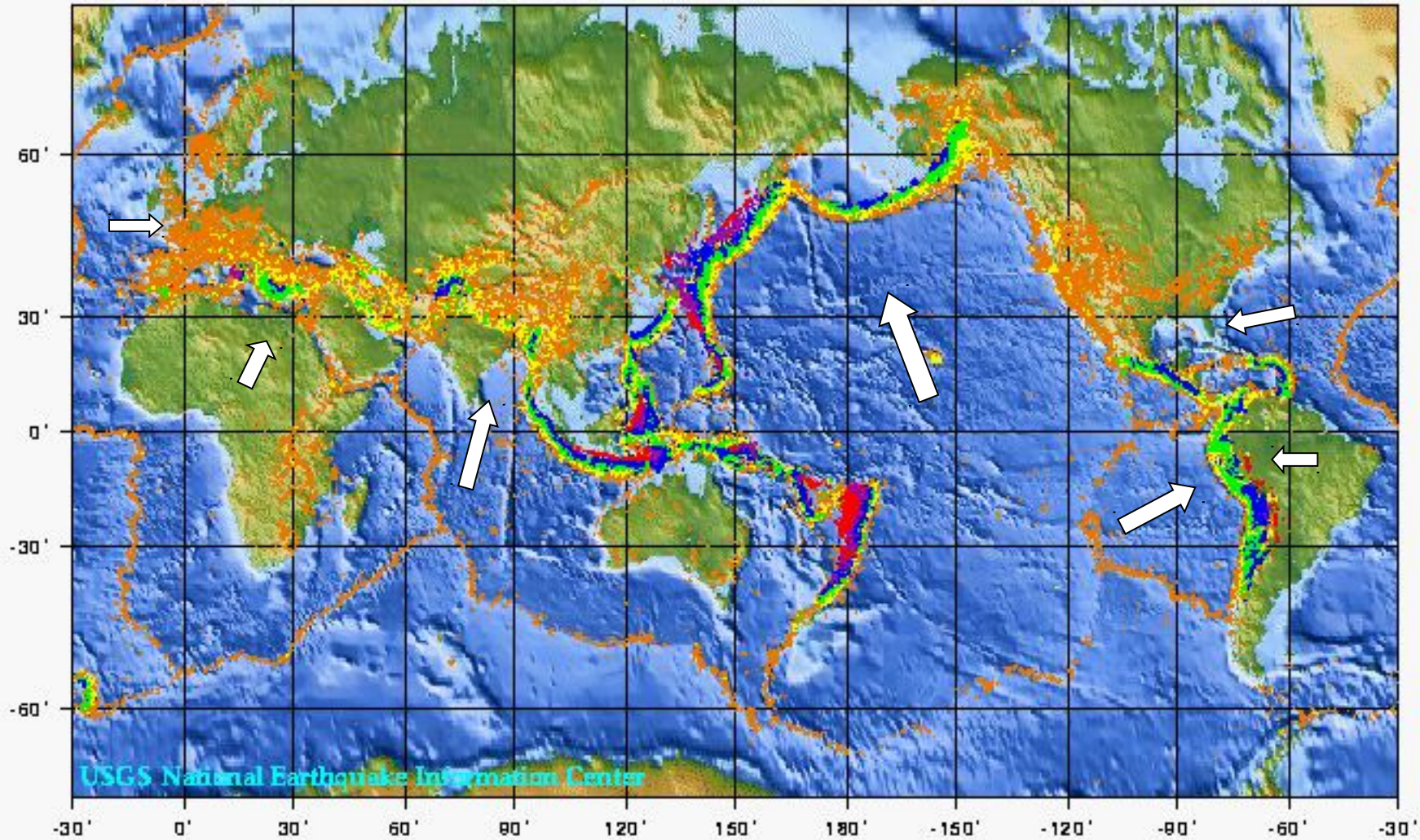


Magnitude 4 = 1 km - ressentie – pas de dommages

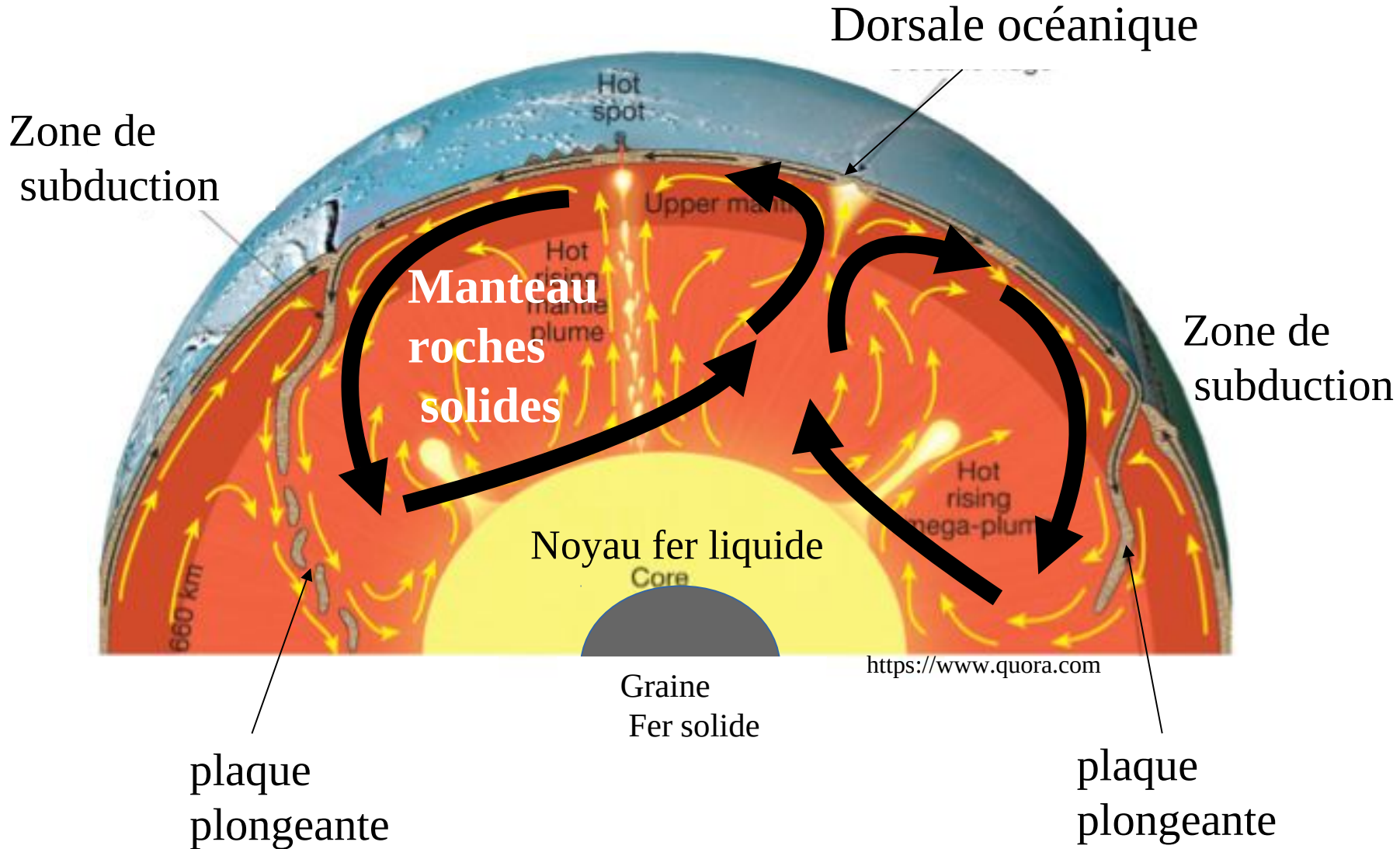
Magnitude 6 = 10-20 km – dommages aux structures

Magnitude 8 = 100-200 km – destructions généralisées

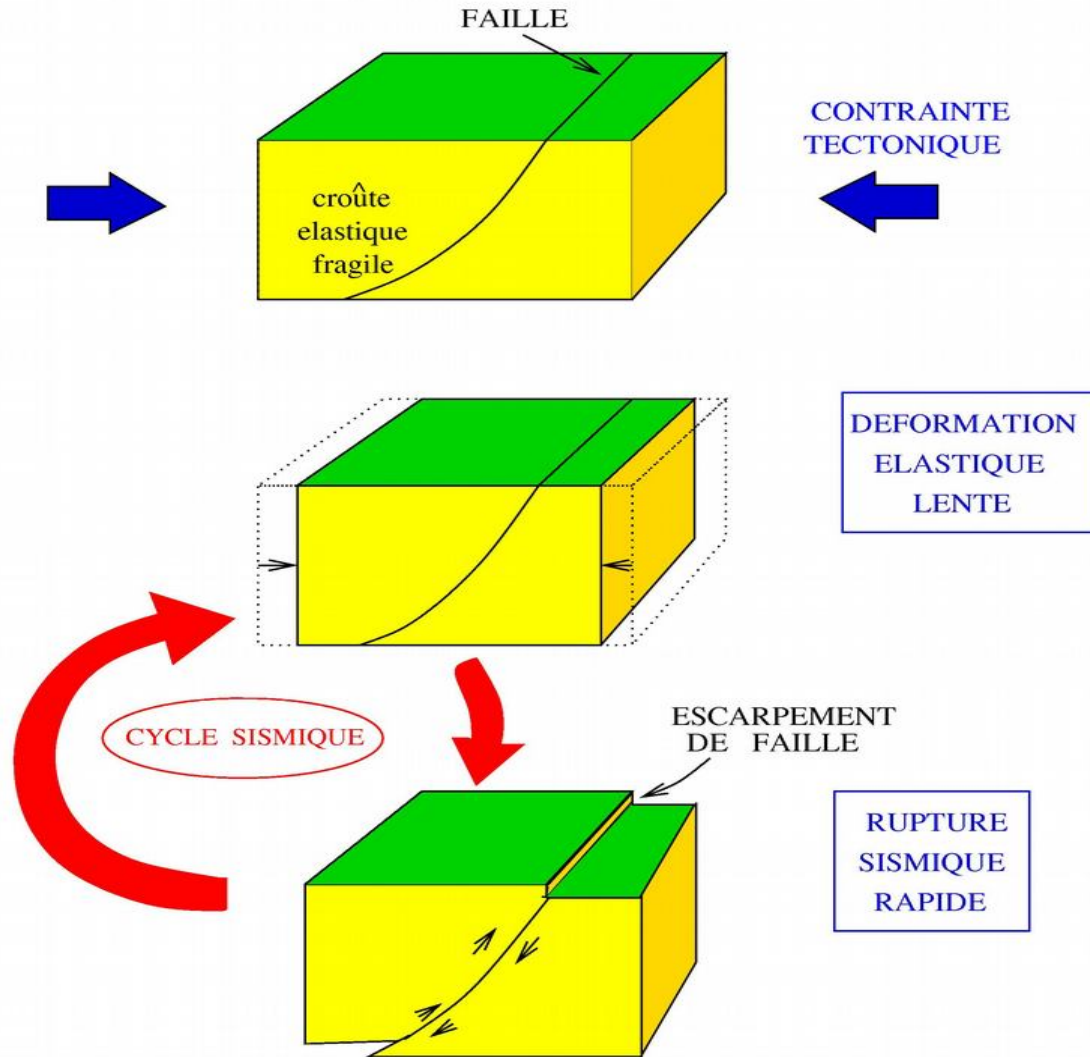
World Seismicity: 1975 - 1995



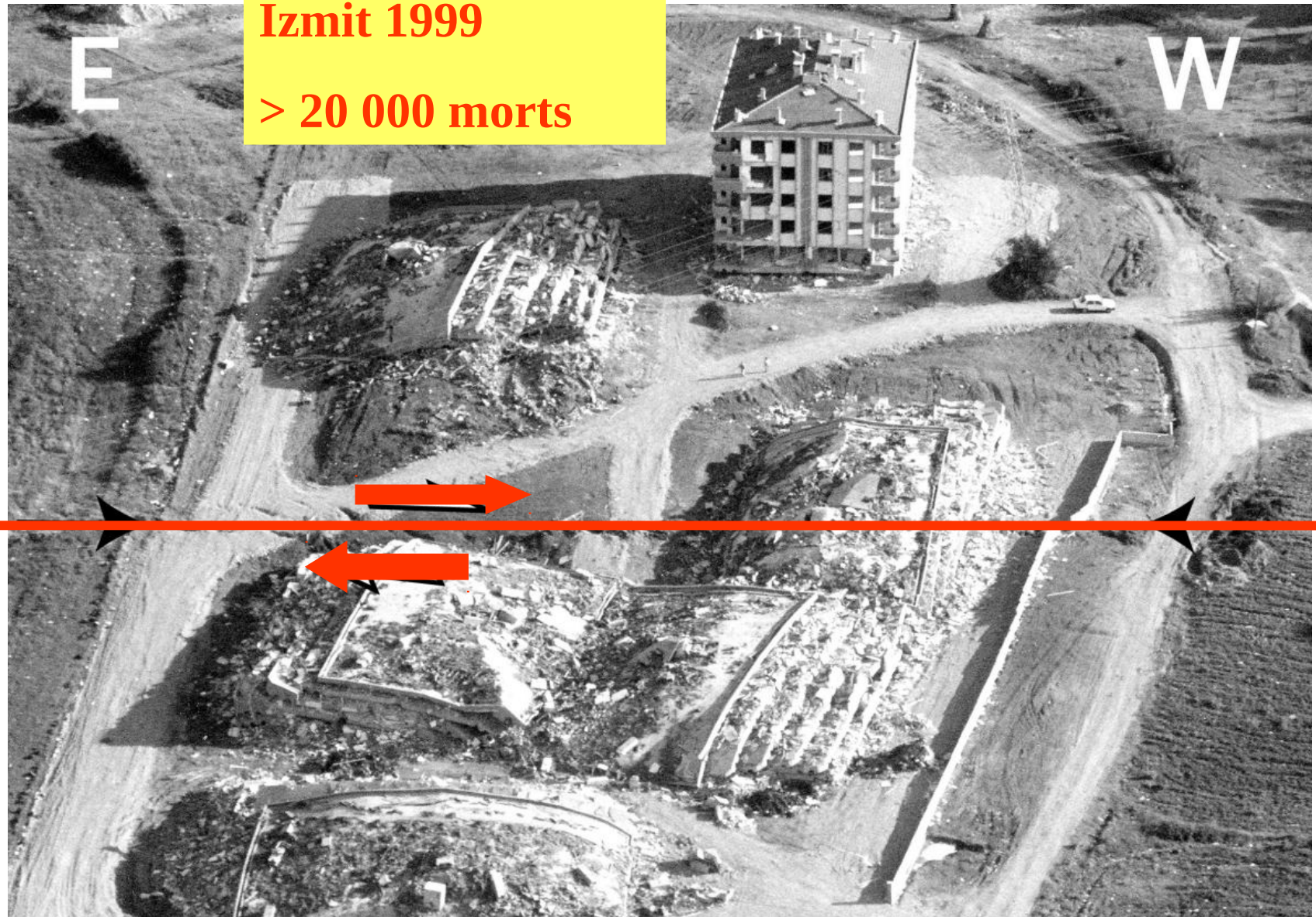
Convection du manteau terrestre



CYCLE SISMIQUE



SEISME D'IZMIT DE 1999, TURQUIE, M=7,5

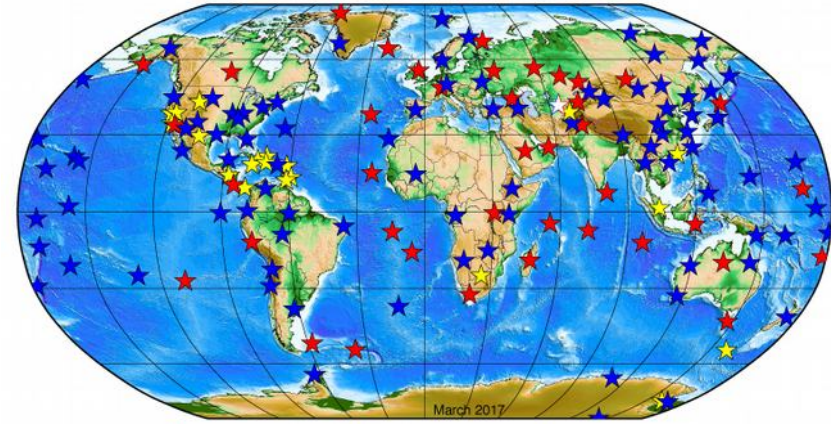


Imagerie des grands séismes

Réseaux sismologiques permanents

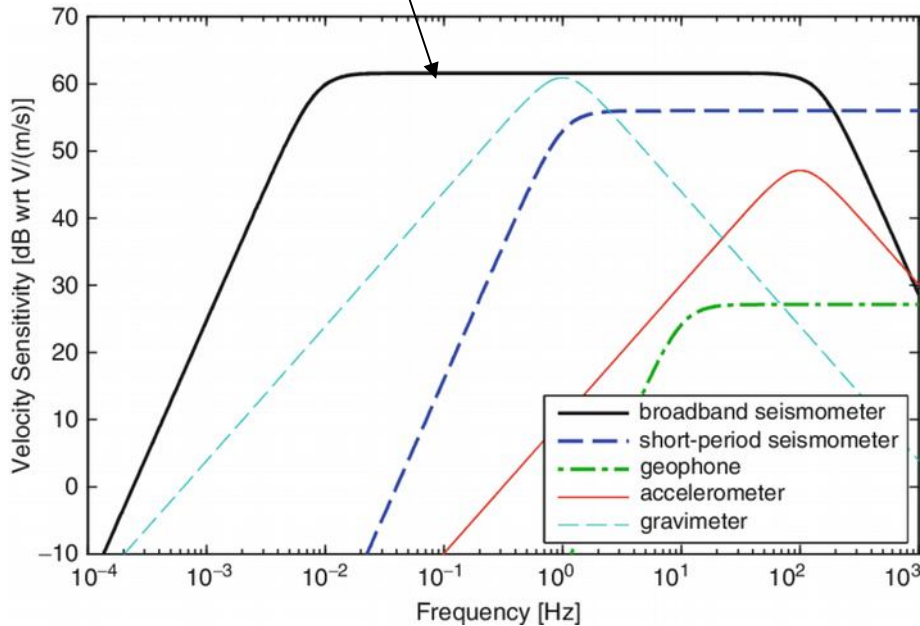


STS2



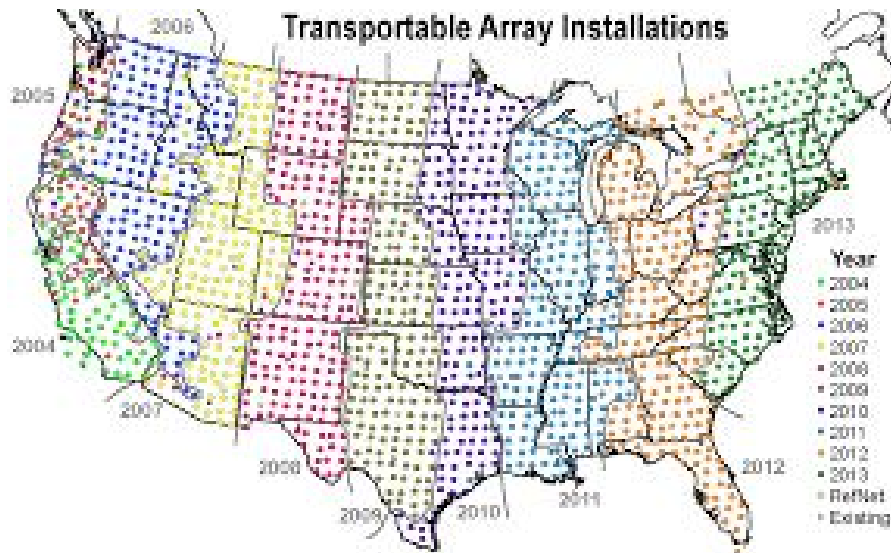
★ IRIS/IDA Stations ★ IRIS/USGS Stations ★ Affiliate Stations
★ Planned Stations

Sismomètres asservis « Large bande » spectrale

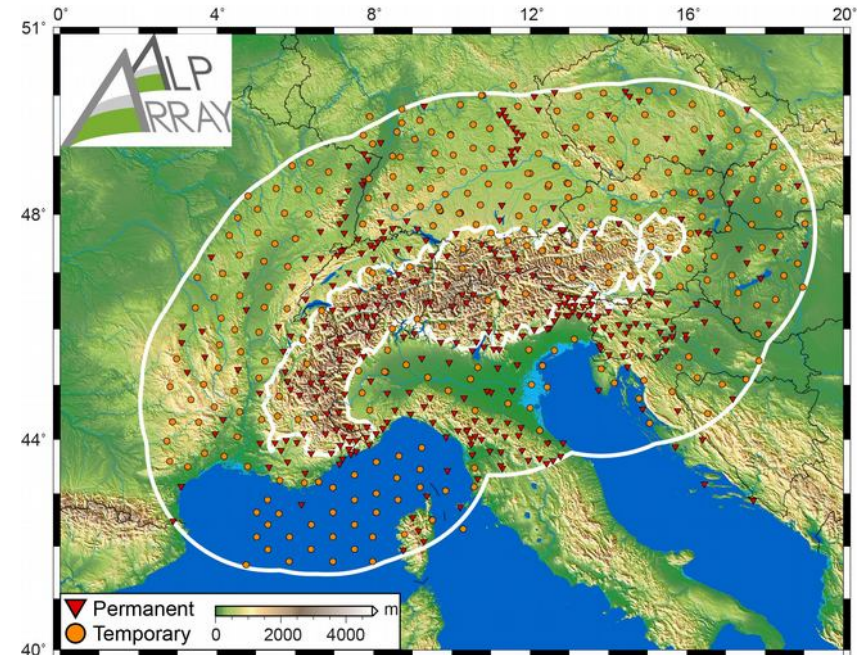


Réseaux denses temporaires

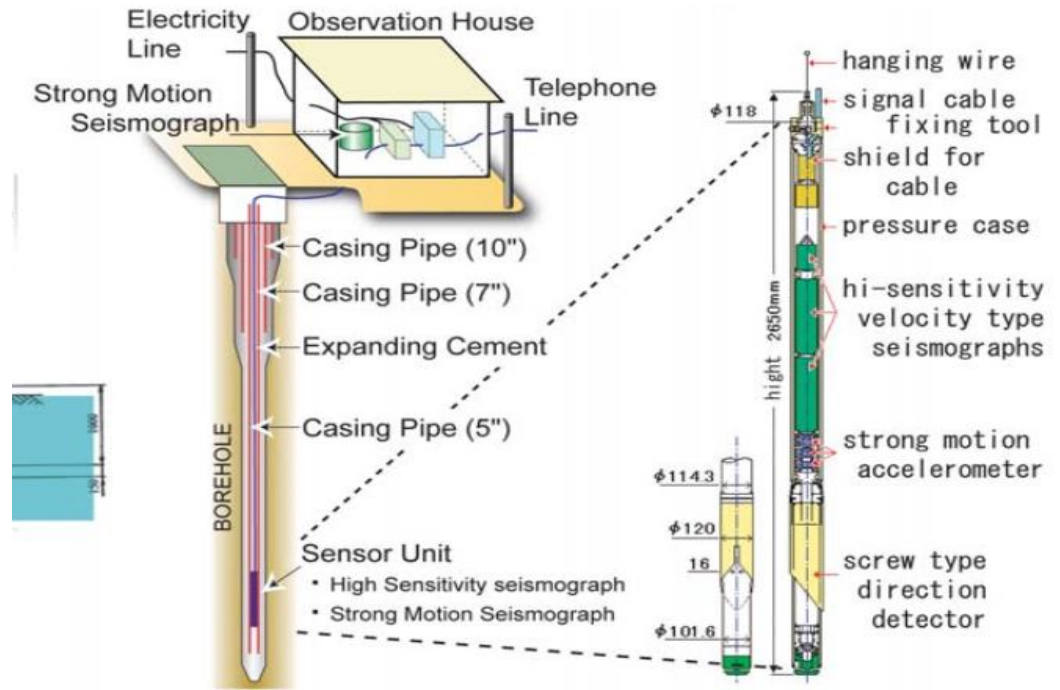
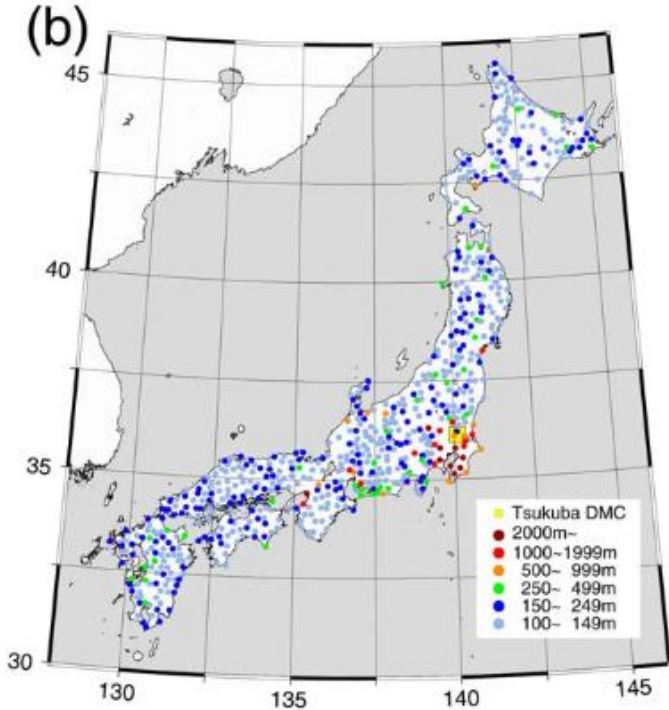
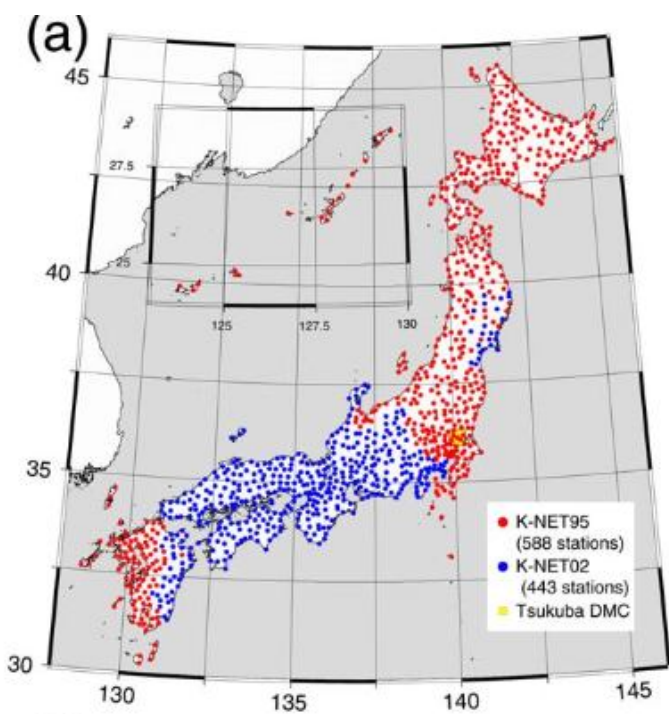
US-Array



Alp-Array



Réseaux denses d'accéléromètres : Japon

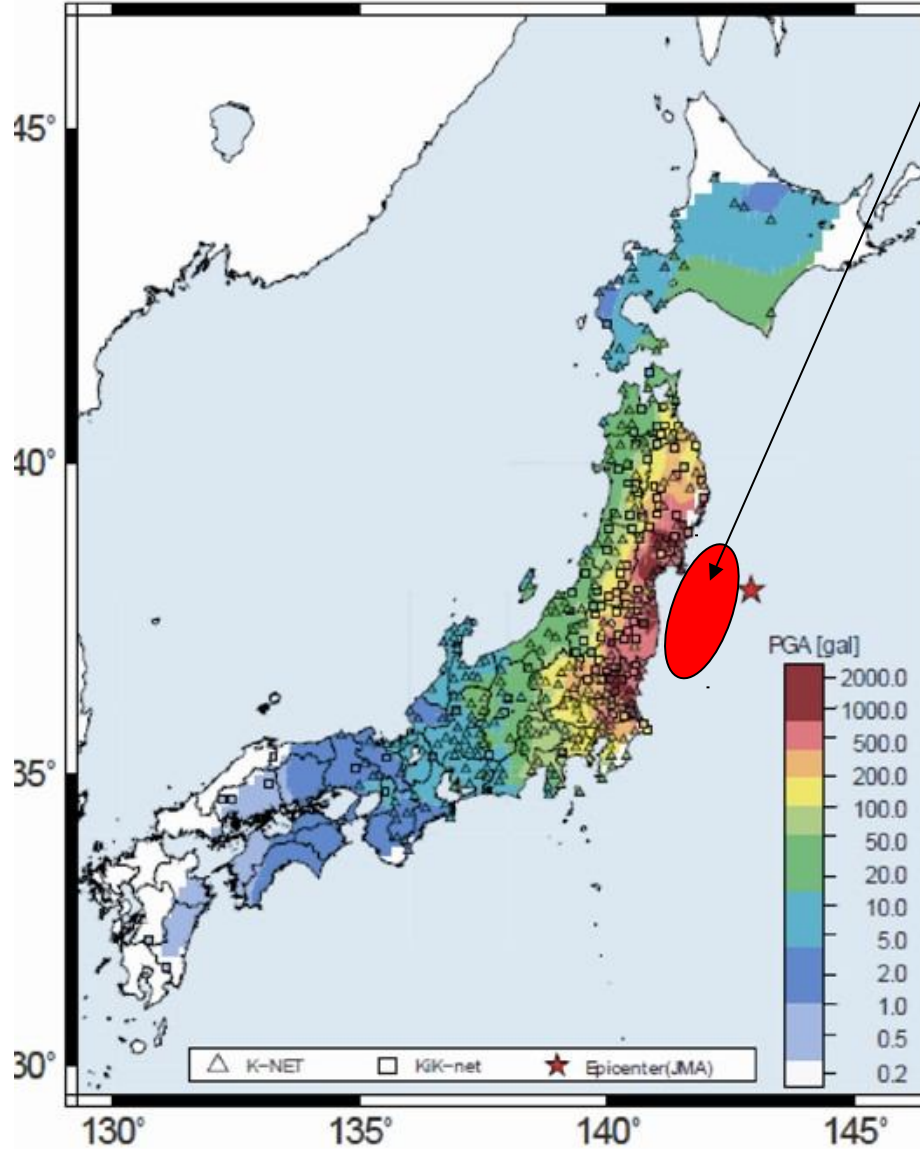


www.jaee.gr.jp

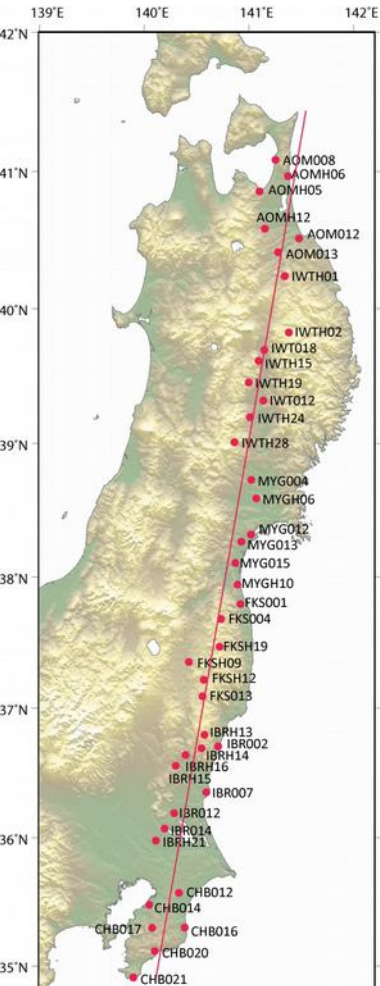
Aoi et al. 2004

Séisme de Tohoku, 11 mars 2011 , M=9.0

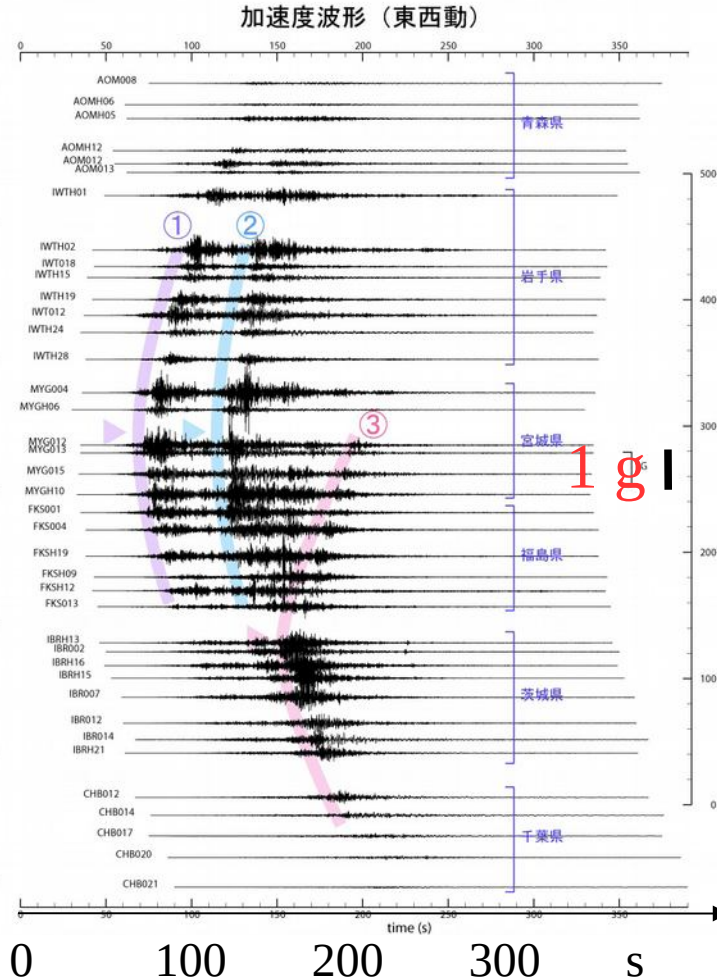
accélération → 2 g



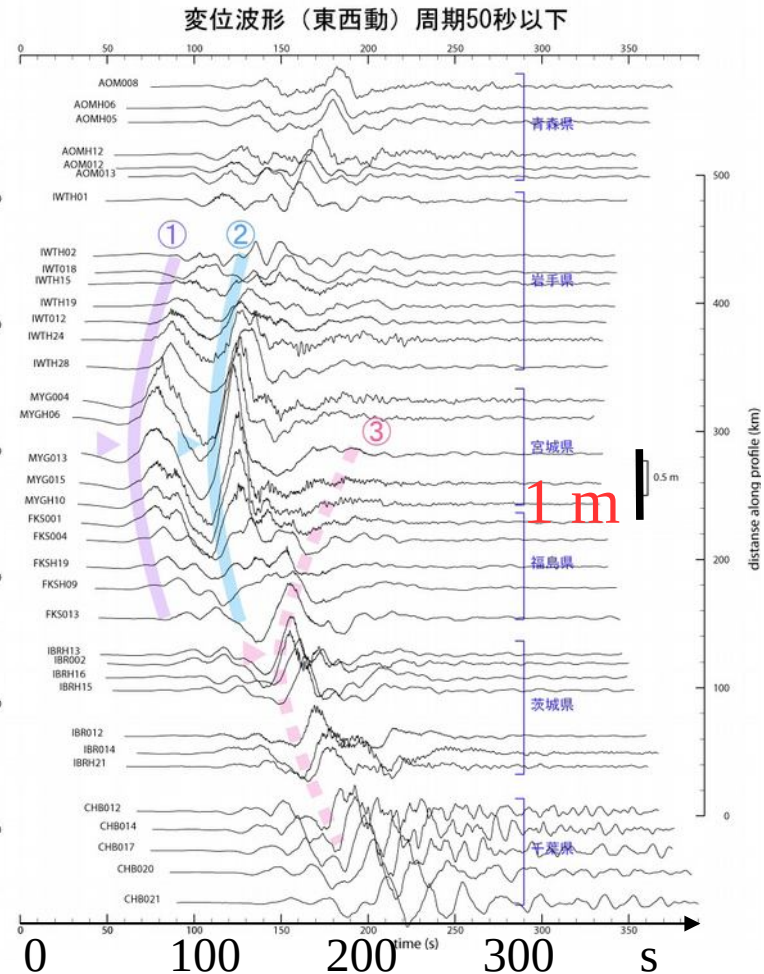
Séisme de Tohoku, Japon 2011, M=9.0



Sismomètres
« large-bande »

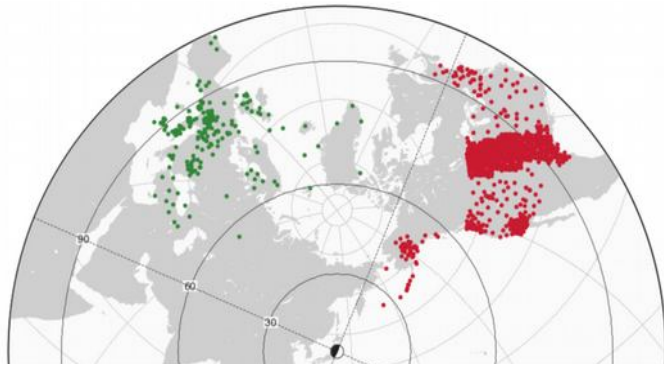


accélération

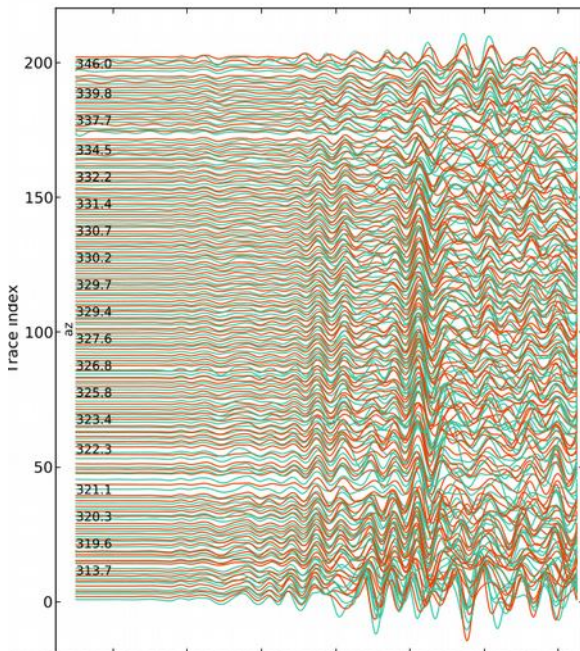


déplacement

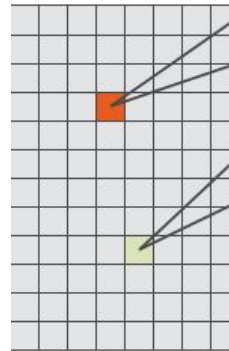
Séisme de Tohoku 2011 , M=9.0



Réseaux denses :
Analyses d'antennes

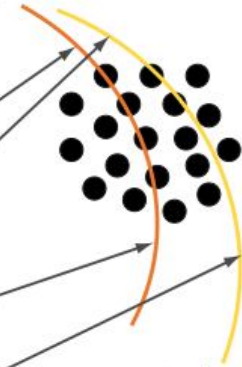


1. Grid of possible source locations

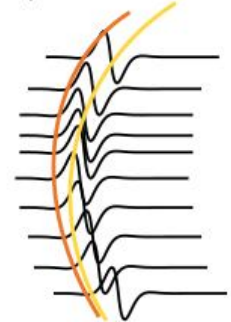


Faille source

antenne
2. Predicted P-wave travel time
at the receiver network



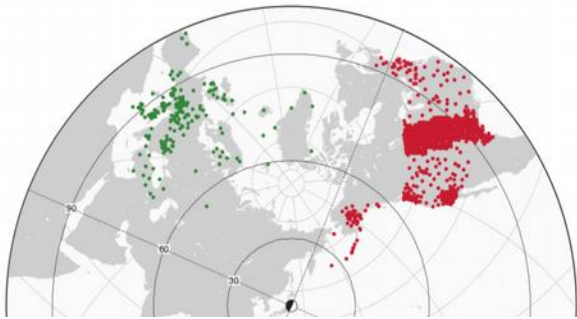
3. Stacking along the
predicted travel-time curves



4. The value of the stack
is assigned to the corresponding
grid point

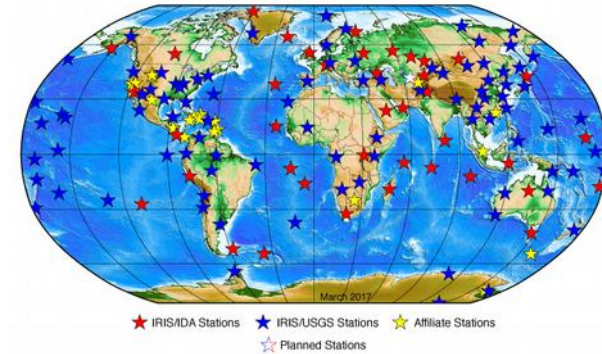
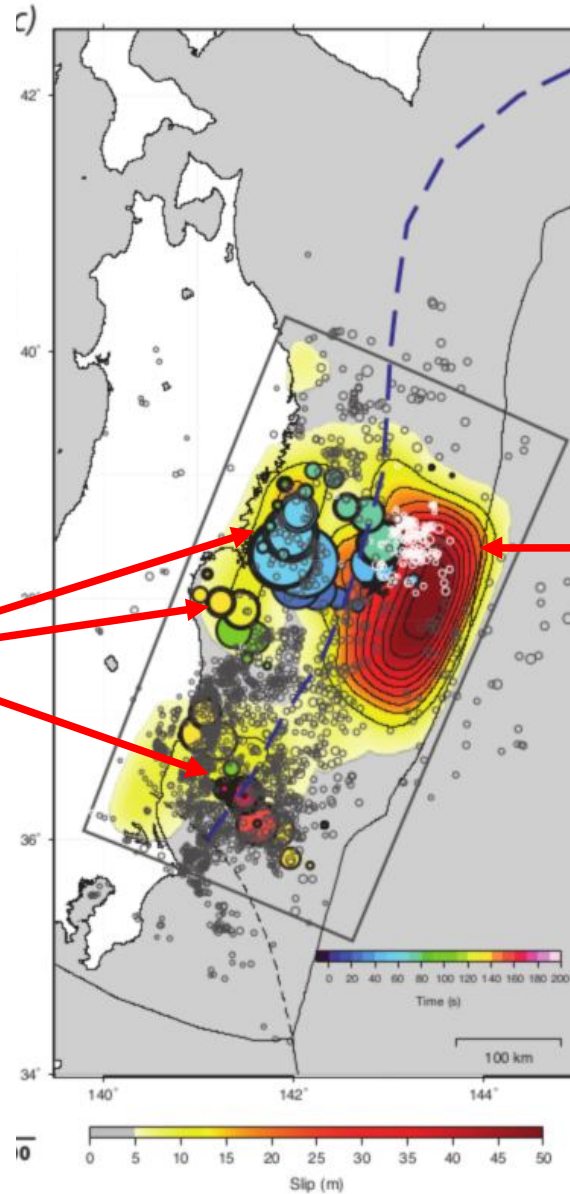
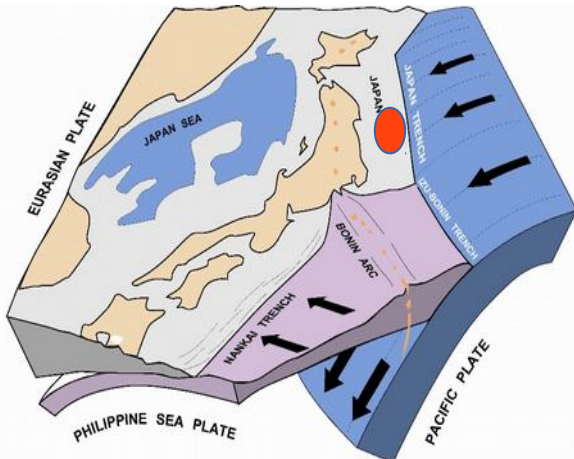
sismogrammes

Séisme de Tohoku 2011, M=9.0



Réseaux dense
= antennes

→
Sources de
Haute fréquences
→ Accélérations 2 g

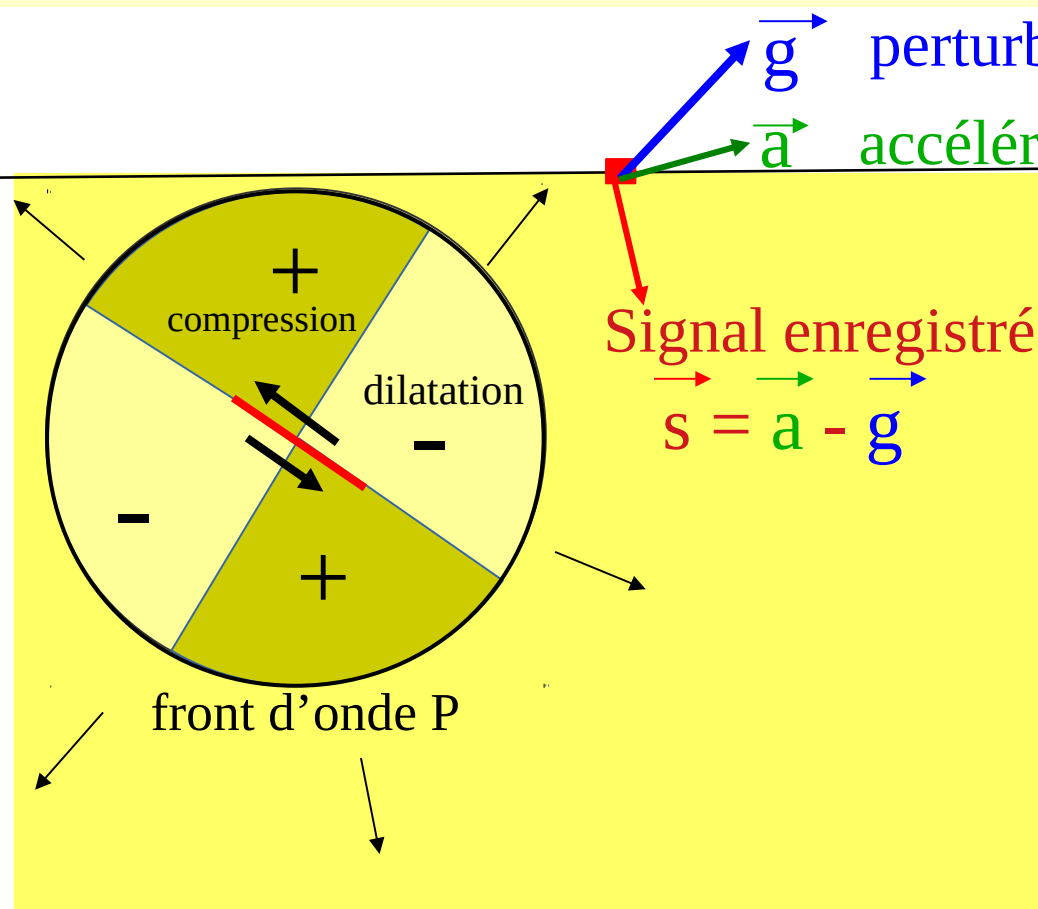


Réseau mondial

Source de
basses fréquences

Glissement de 50 m
→ tsunami

Perturbation de la gravité avant l'arrivée de l'onde P



\vec{g} perturbation de gravité

\vec{a} accélération du sol

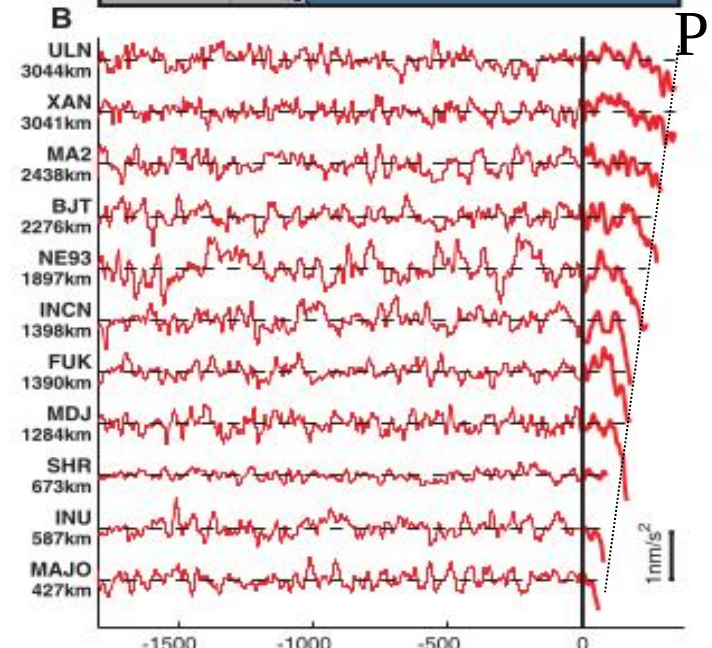
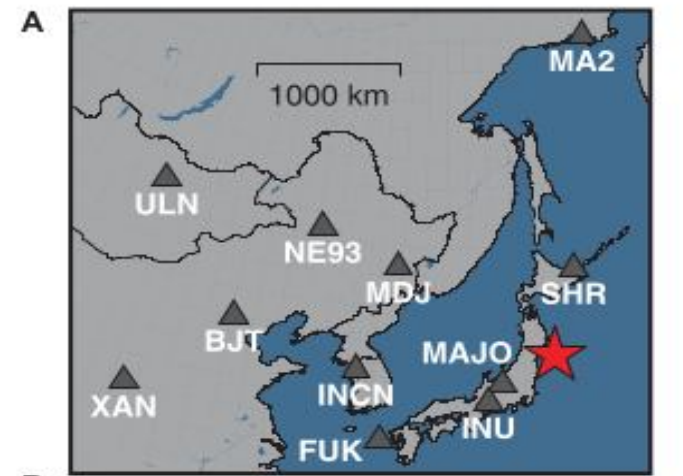
10^{-9} m/s^2

Signal enregistré:

$$s = a - g$$

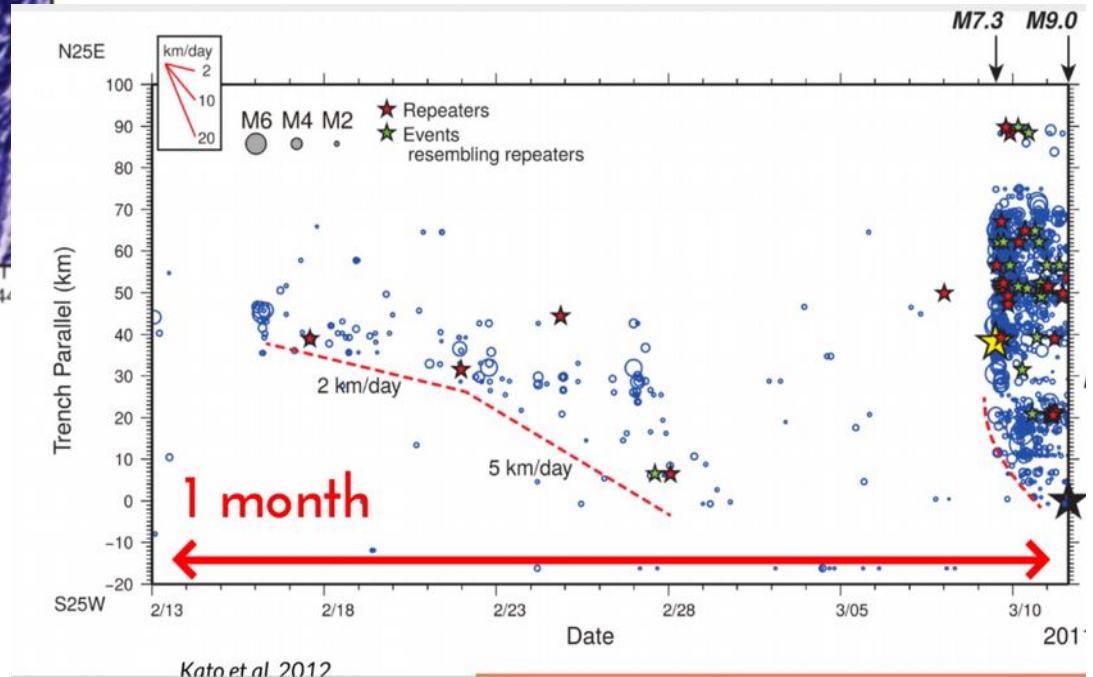
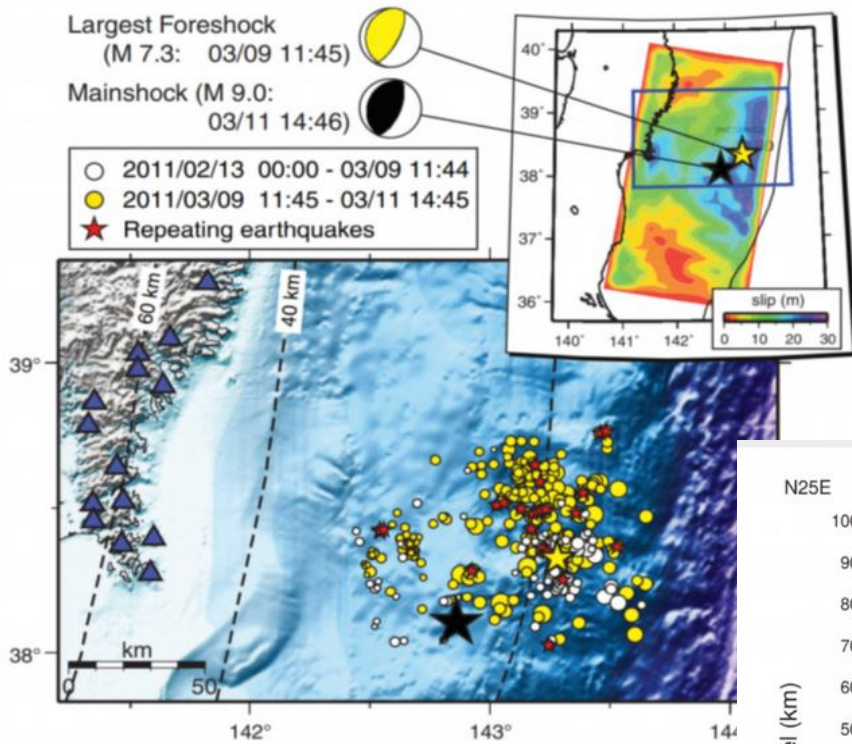
Montagner et al., 2016
Vallée et al., 2017

Séisme de Tohoku, 2010
M=9.0

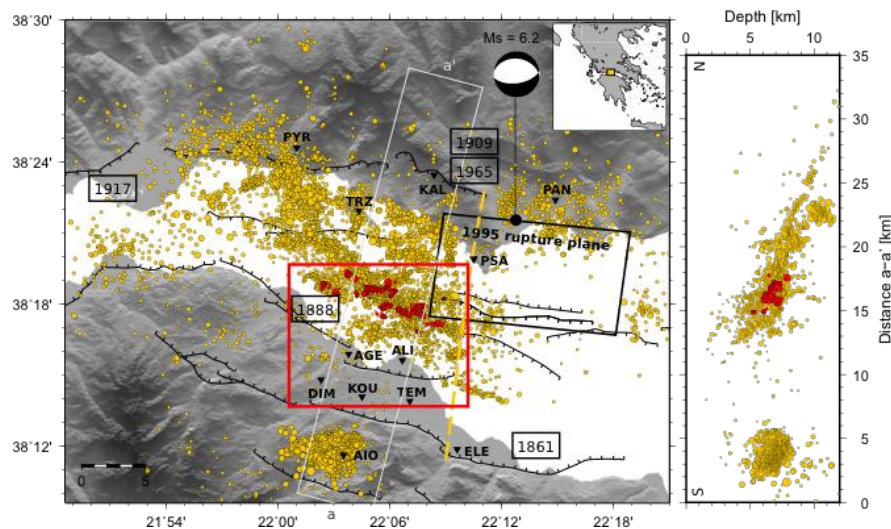


Imagerie des petits et micro-séismes

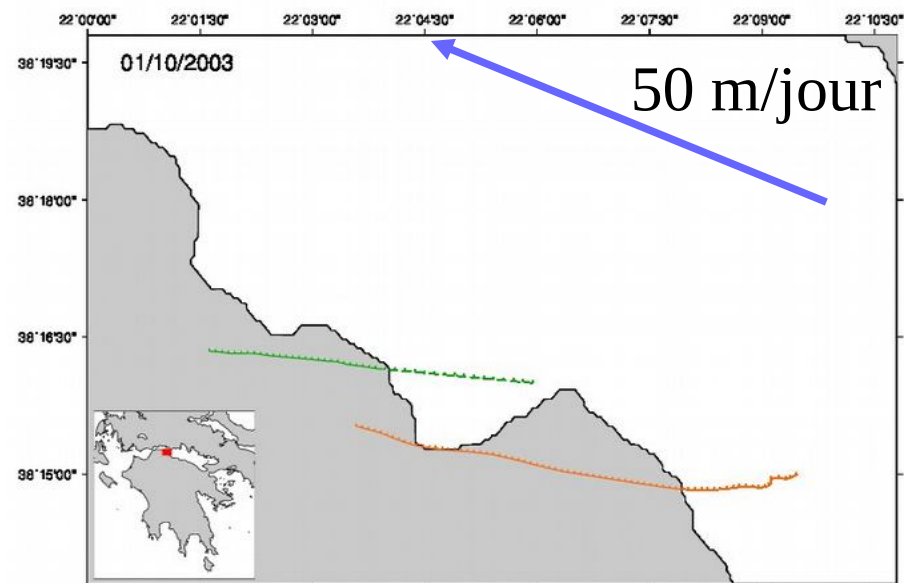
Précurseurs sismiques du séisme de Tohoku 2011



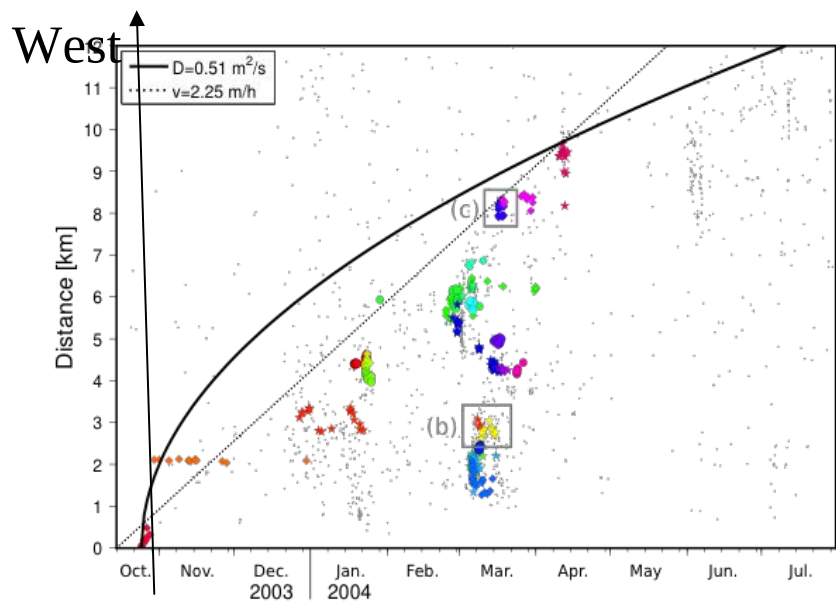
Rift de Corinthe : migration de l'essaim sismique de 2004



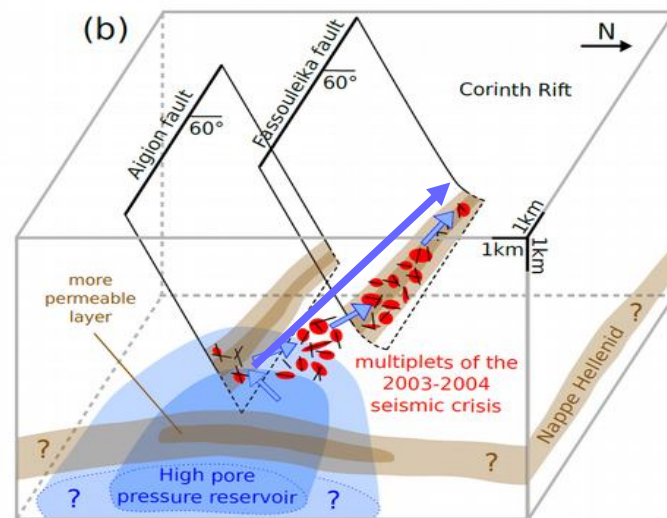
Duverger et al., 2014



pulse de pression d'eau

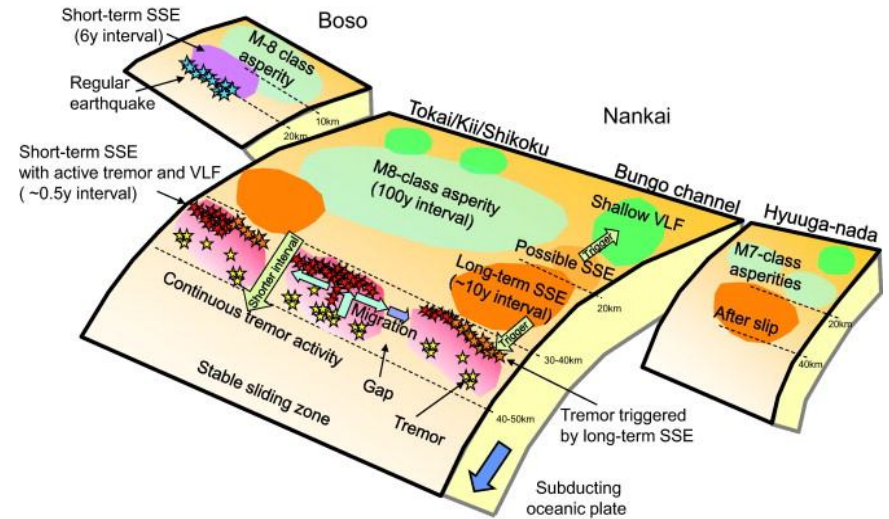
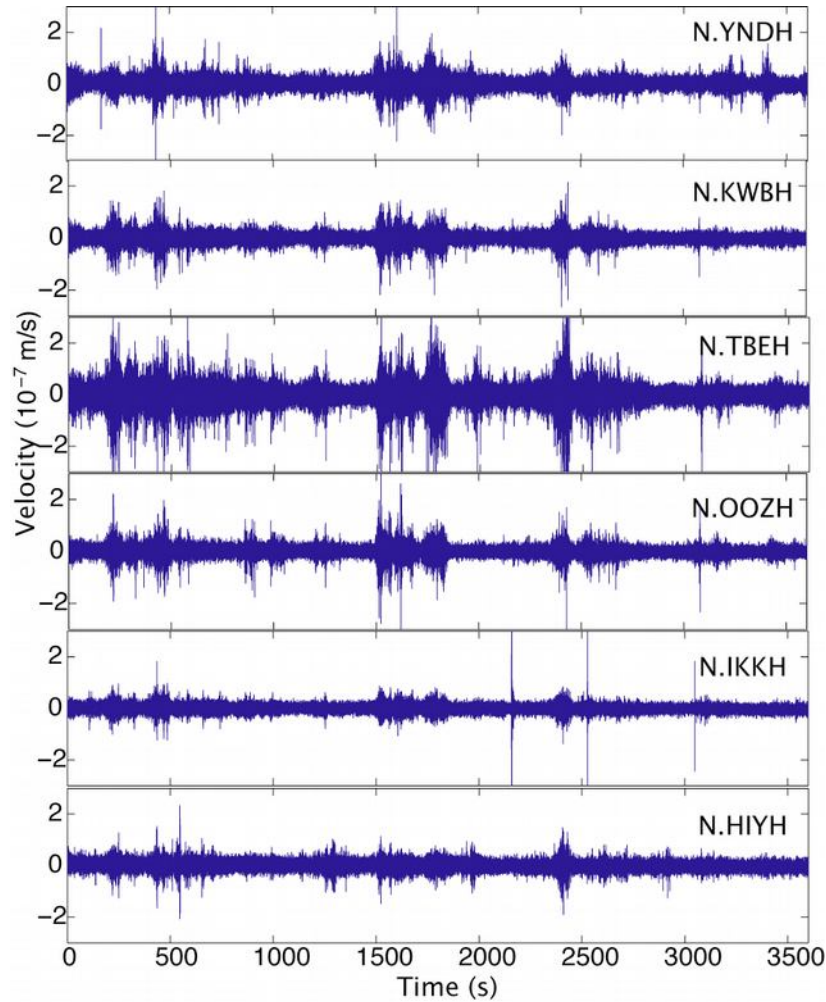


Vitesse de diffusion - $v = 50 \text{ m/jour}$



Duverger et al., 2018

Trémors tectoniques : des failles qui murmurent

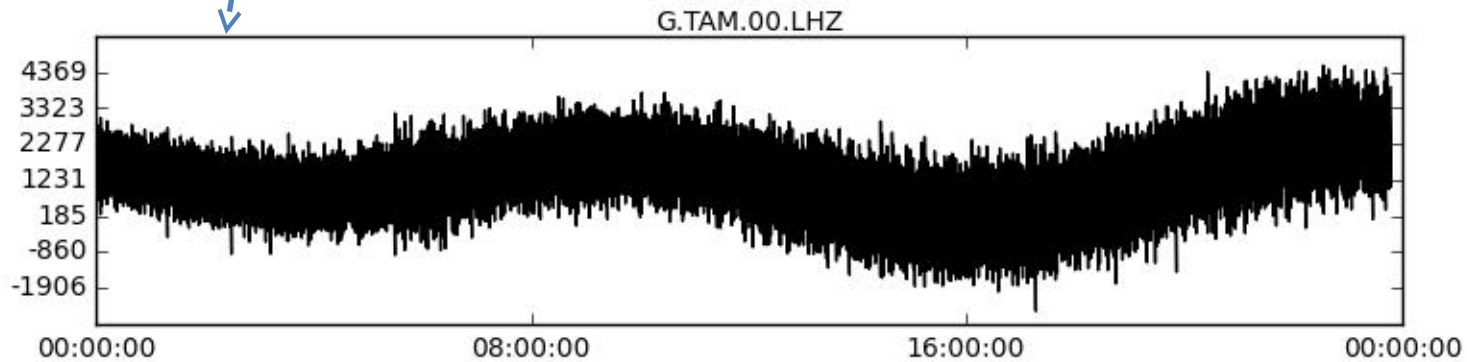
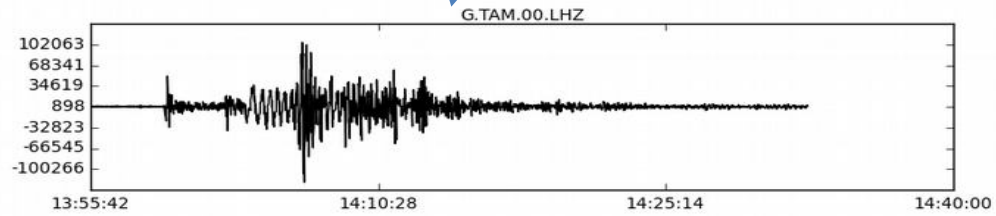
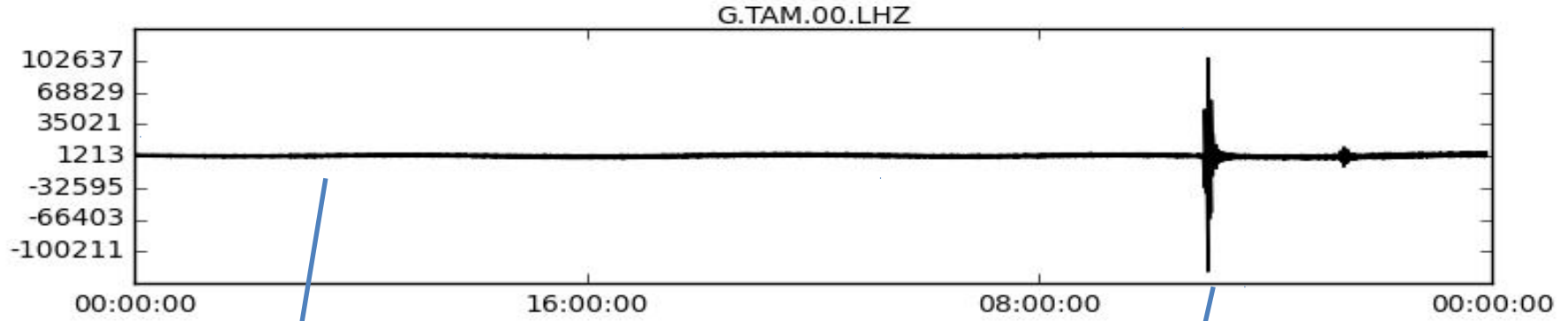


Obara 2011

Subduction de Nankai, Japon

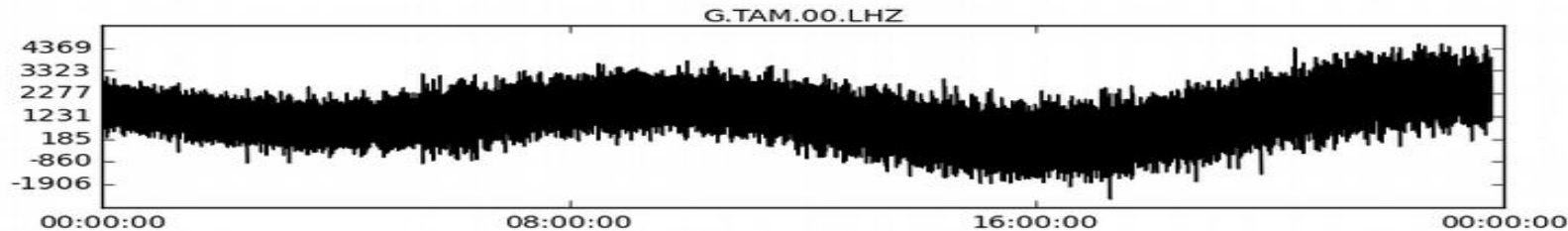
imagerie des sources du
bruit microsismique

Bruit de fond microsismique

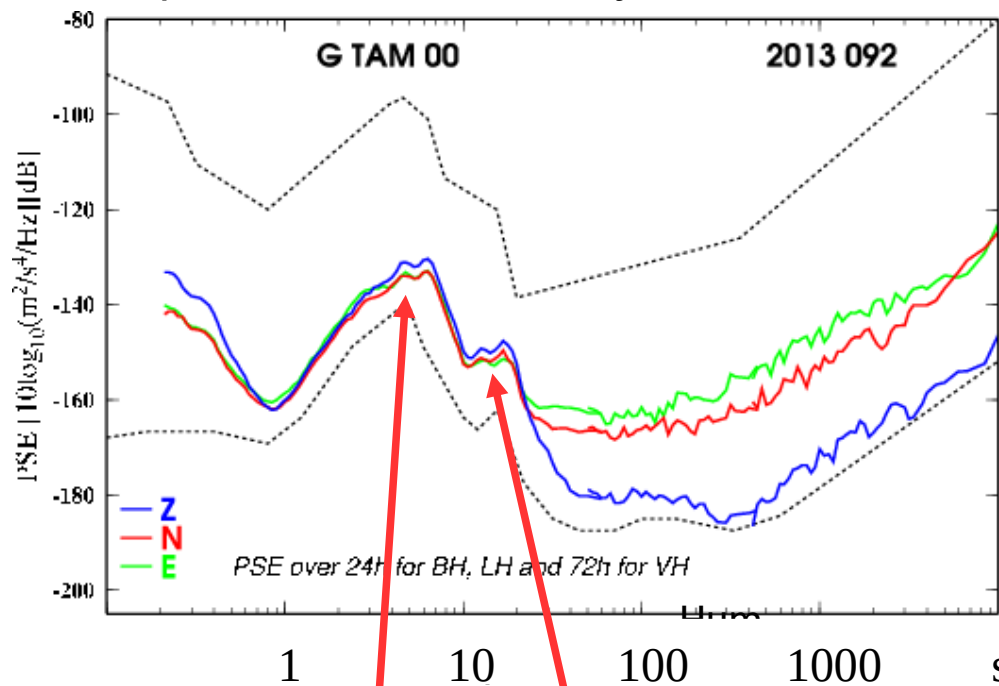


$\sim 1 \mu\text{m/s}$

Stutzman

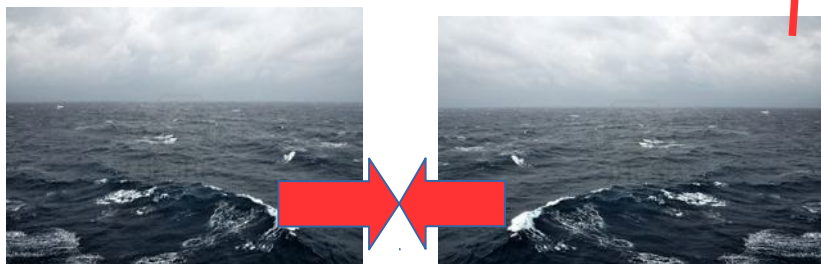


Spectre de bruit sur une journée



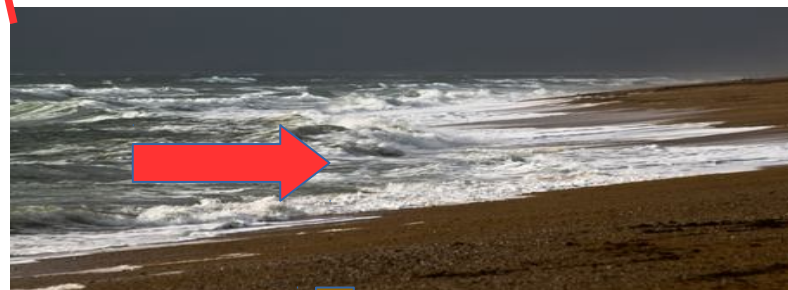
Microséismes secondaires

Microséismes primaires



4-8 s

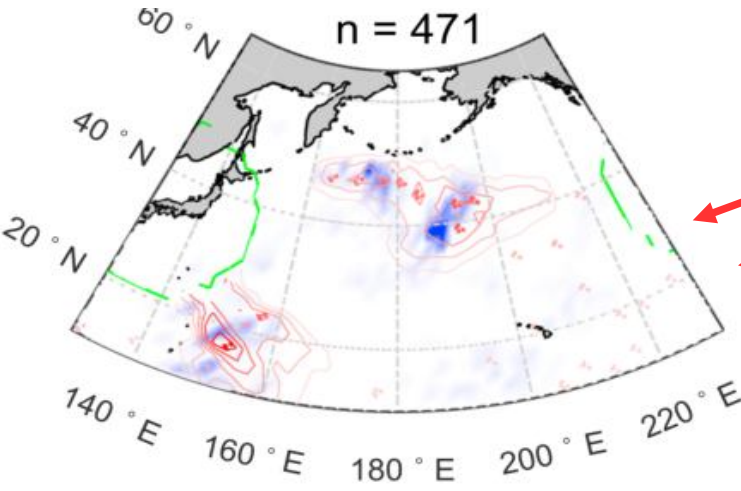
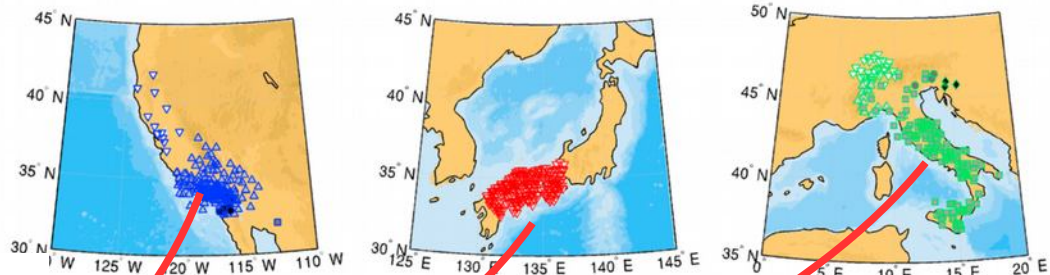
F



10-15 s

F

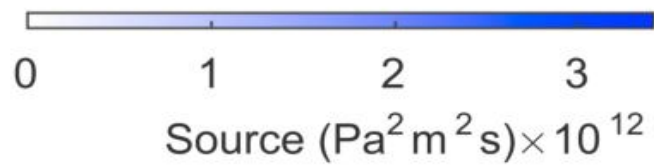
Réseaux denses de sismomètres=Antennes



Ondes P

Sources d'ondes P
d'après les hauteurs de vague

Sources d'ondes P
d'après les antennes sismiques

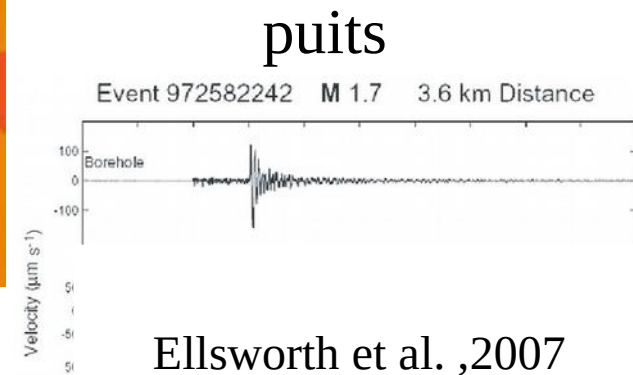
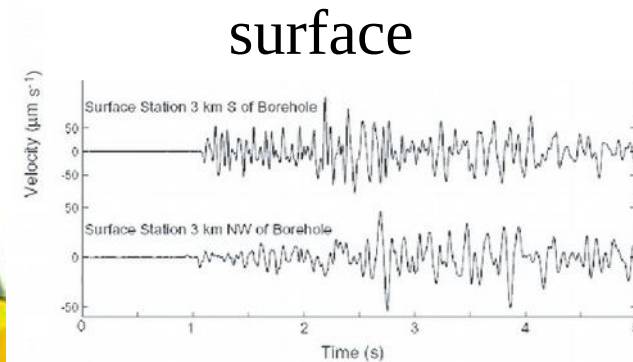
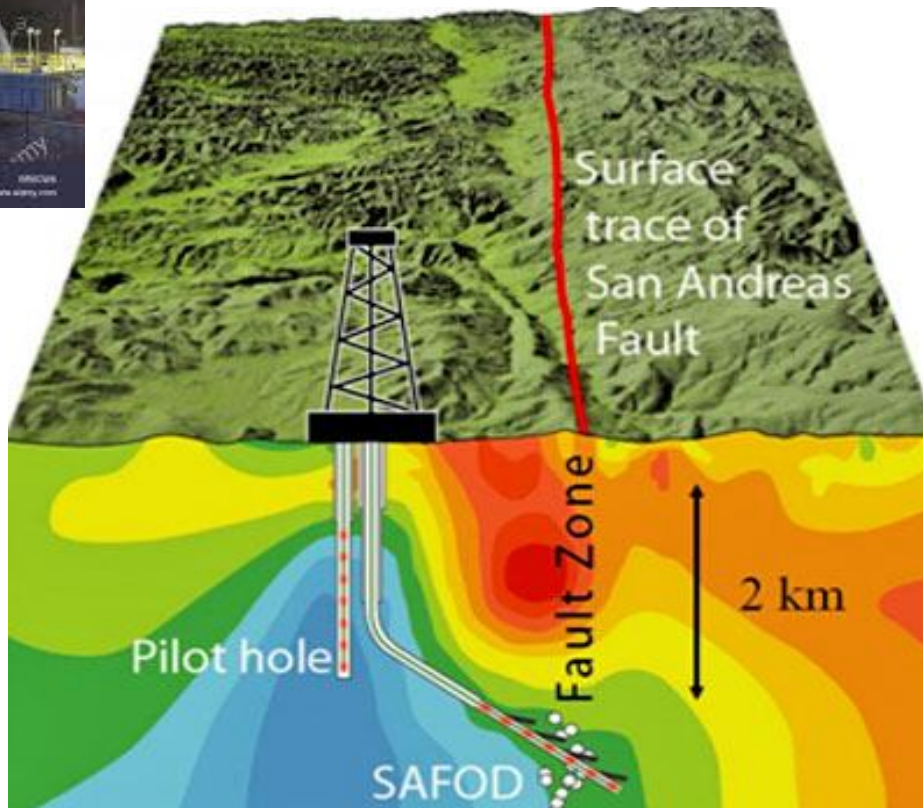


Se rapprocher des sources sismiques :

les grands défis



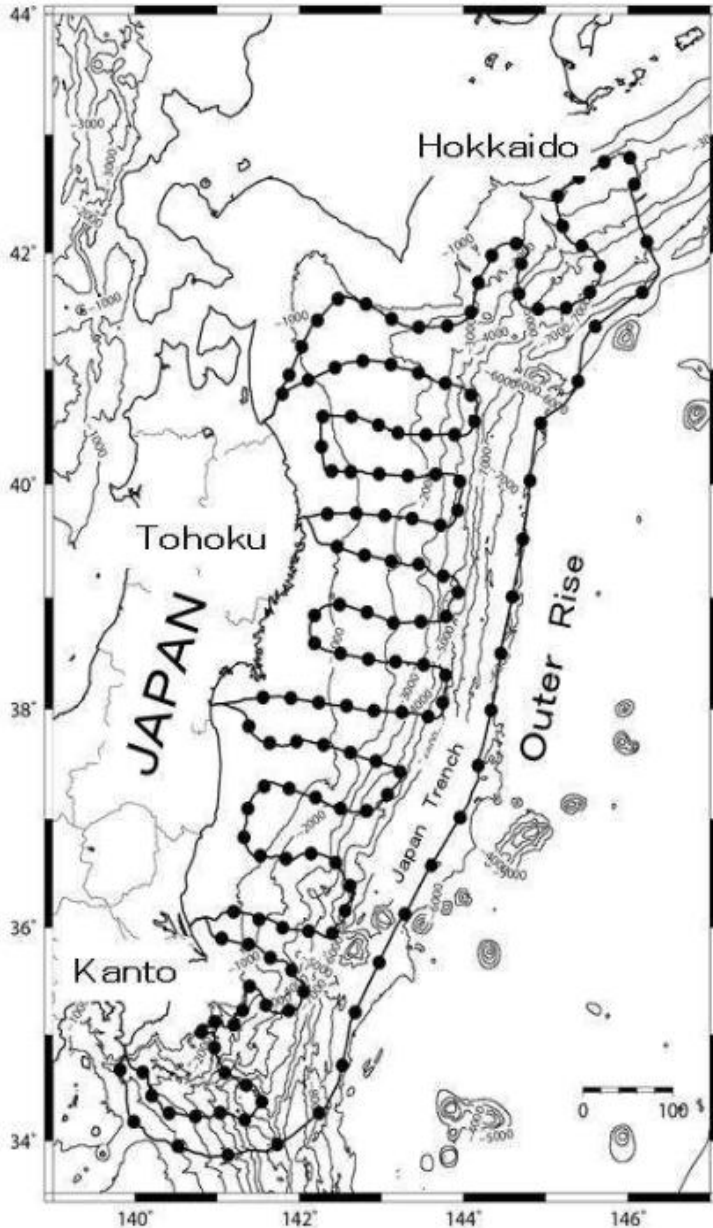
SAFOD
Observatoire profond
Faille de San Andreas
Forage profond 3.2 km



Ellsworth et al., 2007

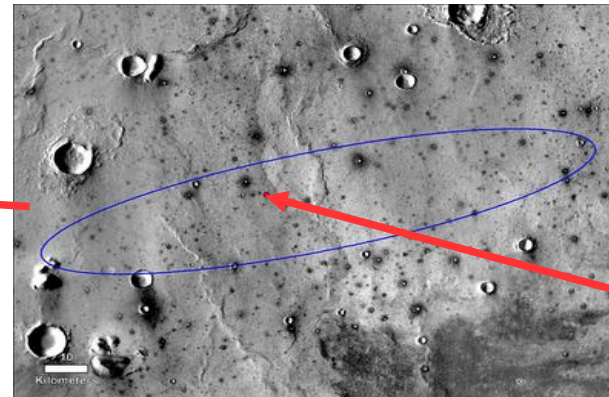
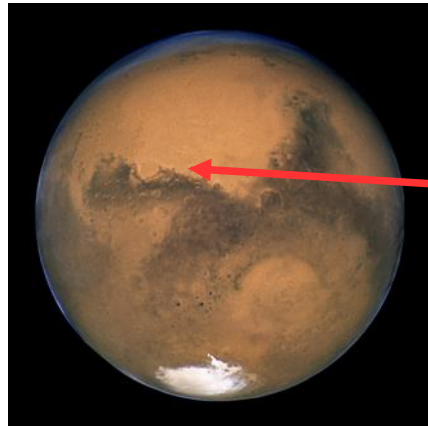
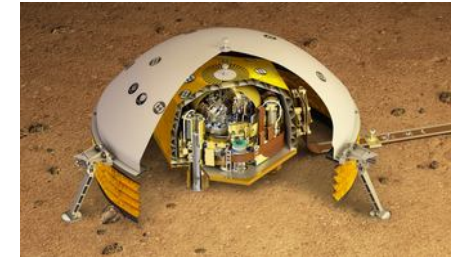
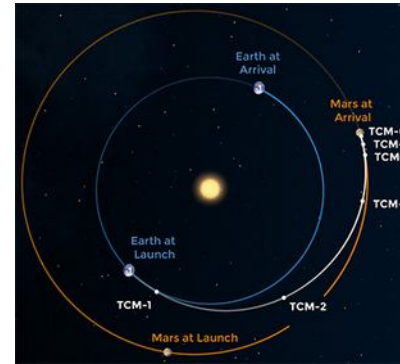
S-NET

150 observatoires sous-marin :
Sismomètres/ pressiomètres
1600 km de câble optique



Sismomètre SEIS sur Mars

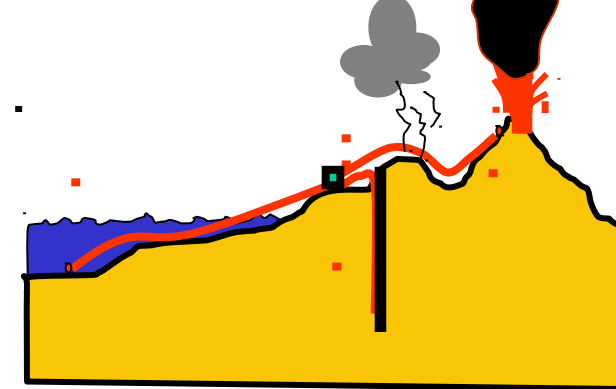
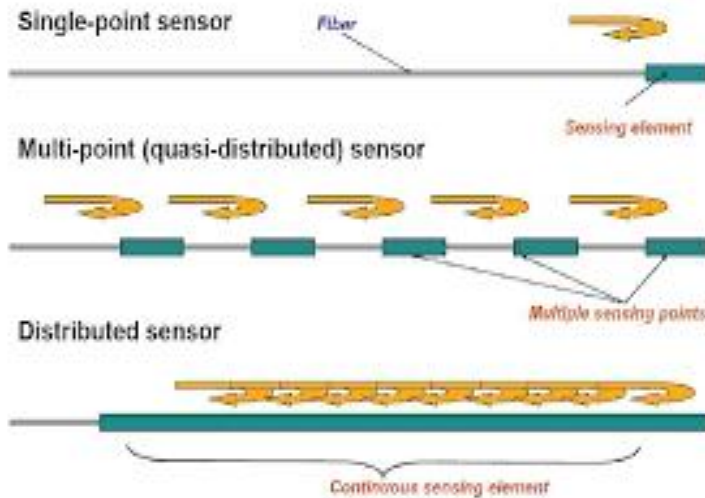
Mission INSIGHT
5 mai -26 nov 2018
0.5 Milliards de km



NASA
Lognonné et al., IPGP, CNES

Des sismomètres innovants sur fibre optique

Mesure de déplacement et déformation par interférométrie optique



- + longue fibre entre station et capteur → 50 km
- + pas d'électronique au capteur :
 - opto-mécanique simple, robuste, peu coûteux
- + fibre optique insensible au champ EM (foudre, lignes HT, ..)
- + température élevée (250°C) (pas d'électronique)

Application pour les risques naturels en environnement difficile:

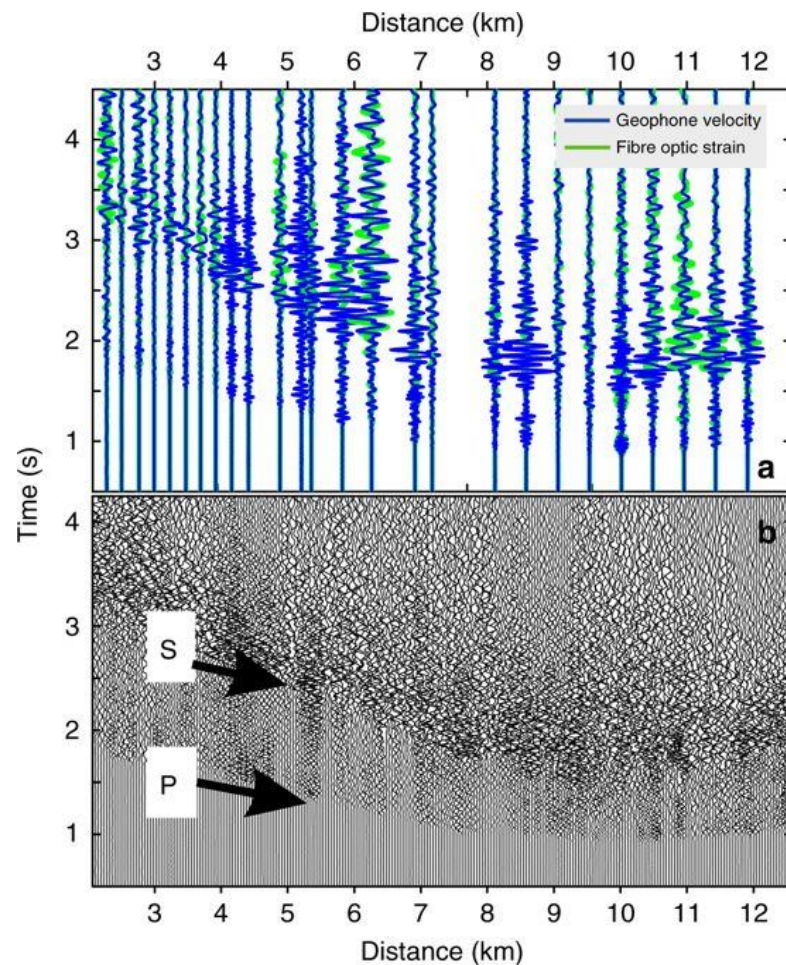
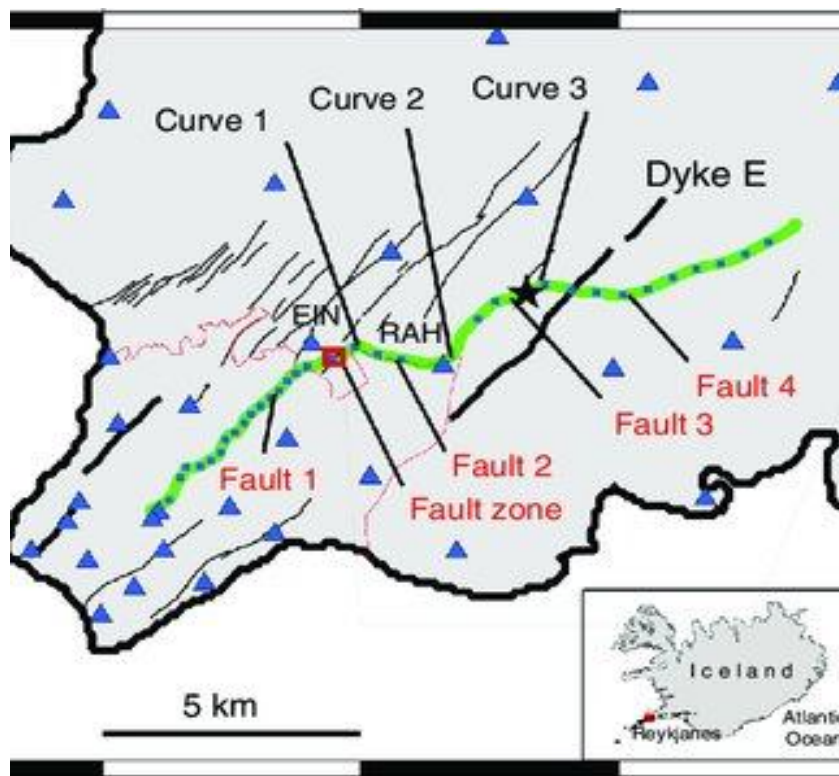
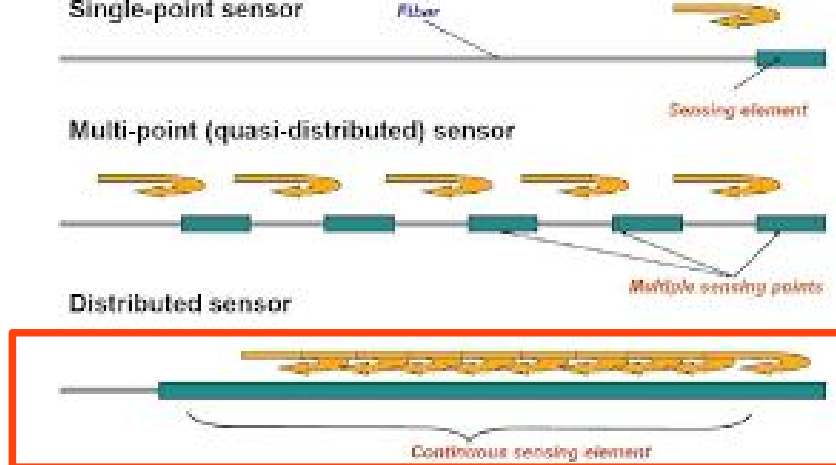
Offshore lointain, forage profond, région montagneuse, volcans,..

Systemes DAS

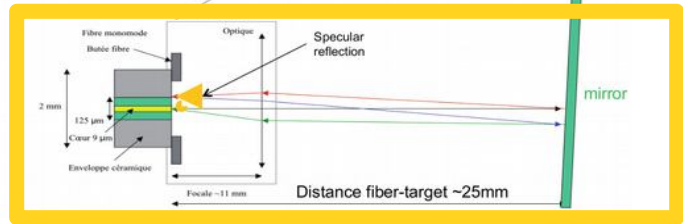
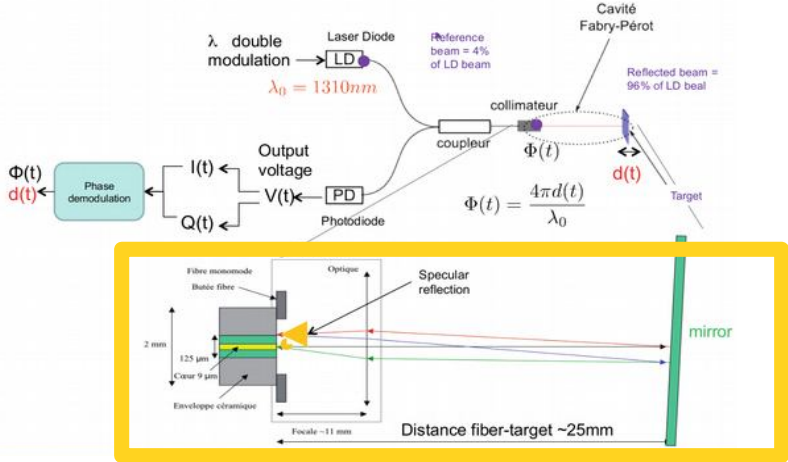
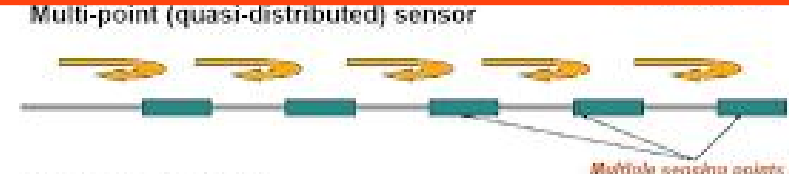
« Distributed Acoustic Sensing »

Interrogation de fibre optique

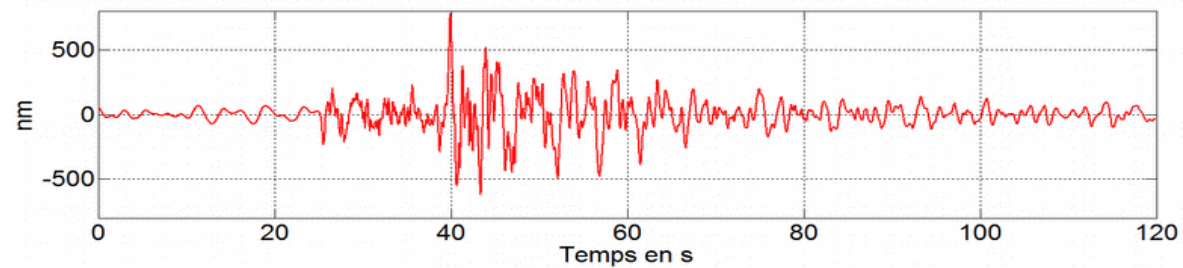
1 capteur de deformation / m !



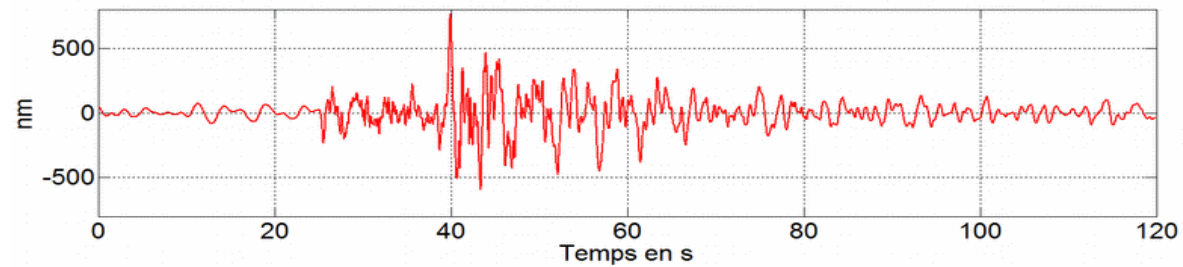
Sismomètre opto-mécanique IPGP- ESEO



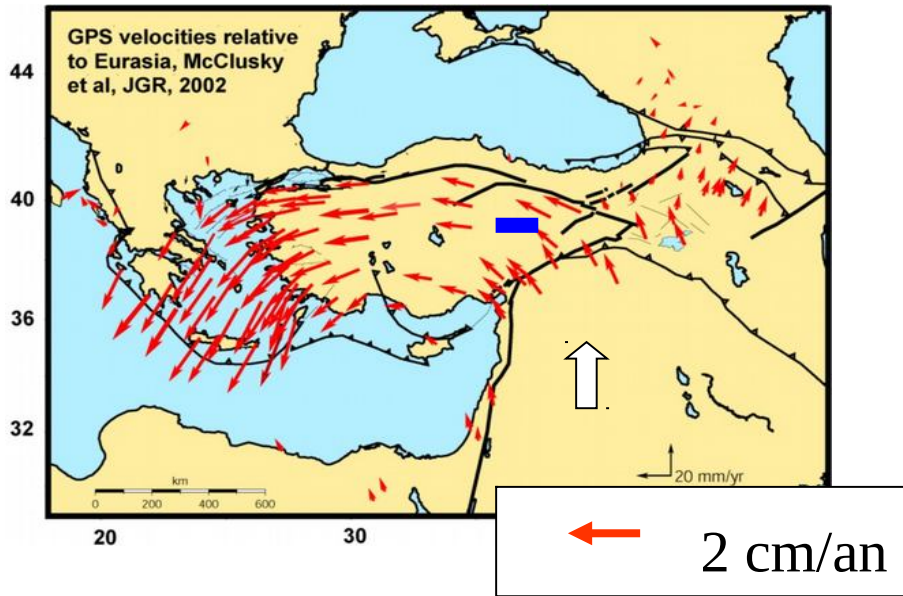
Signal $\text{Sol}_G(t)$ reconstruit par déconvolution à partir du sismo GAS dans la bande [0.1 , 20] Hz



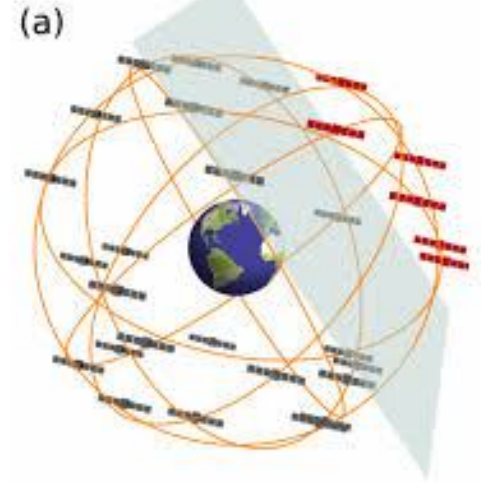
Signal $\text{Sol}_L(t)$ reconstruit par déconvolution à partir du sismo LINES dans la bande [0.1 , 20] Hz



**instruments et réseaux
pour les
observations géodésiques**



(a)



GNSS

Global Navigation Satellite System

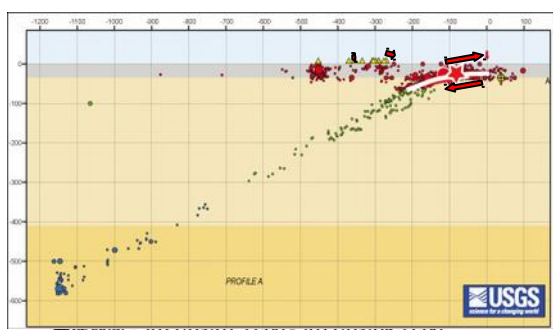
- GPS USA
- GLONASS russe
- GALILEO européen
- COMPASS Chine 2020



En 25 ans :
précision
1 cm → 1 mm

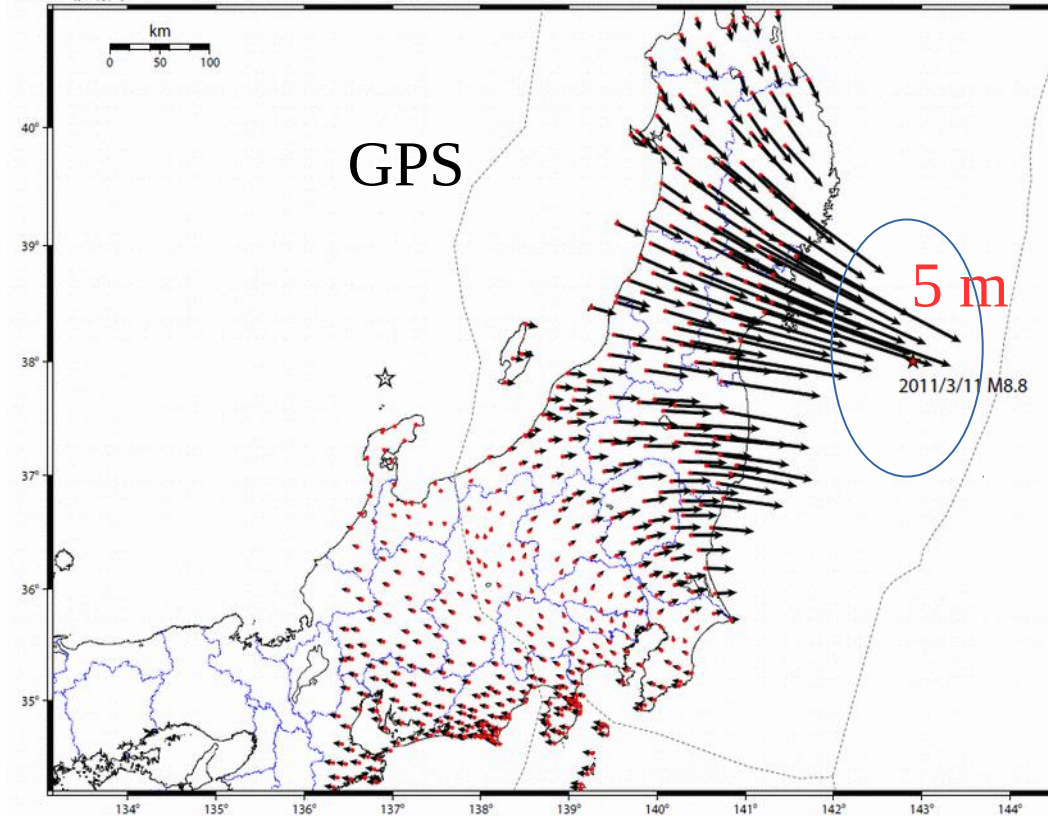


Déformation lors du séisme de Tohoku 2011



ベクトル図 (水平)

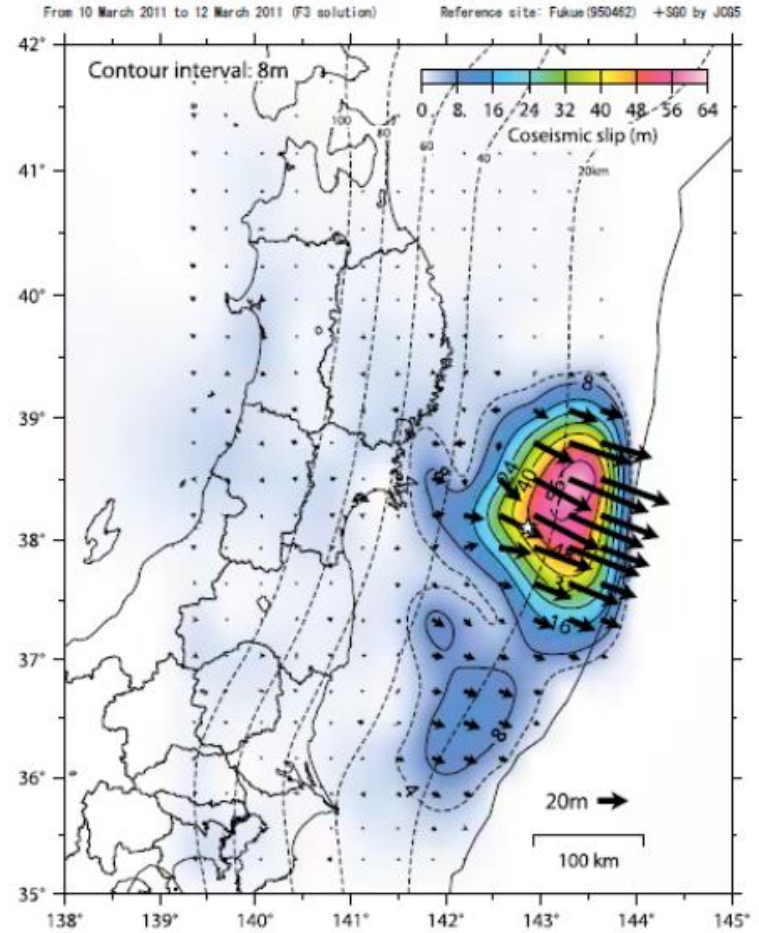
基準期間 : 2011/03/01 21:00 - 2011/03/08 21:00
比較期間 : 2011/03/11 16:30 - 2011/03/11 16:30



[基準 : R3 速報解 比較 : S3 迅速解]

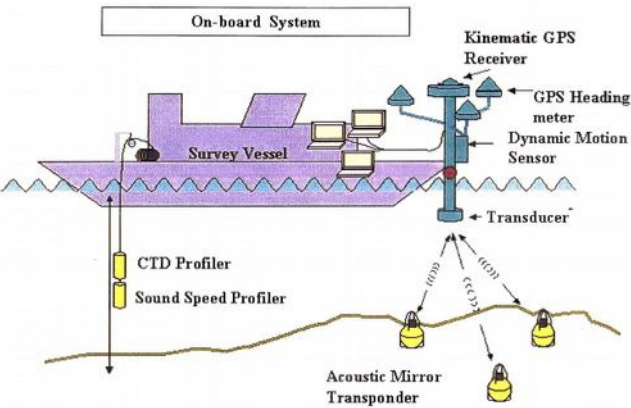
☆固定局 : 船倉島 (950252)
国土地理院

Slip distribution model based on GEONET and seafloor crustal deformation data

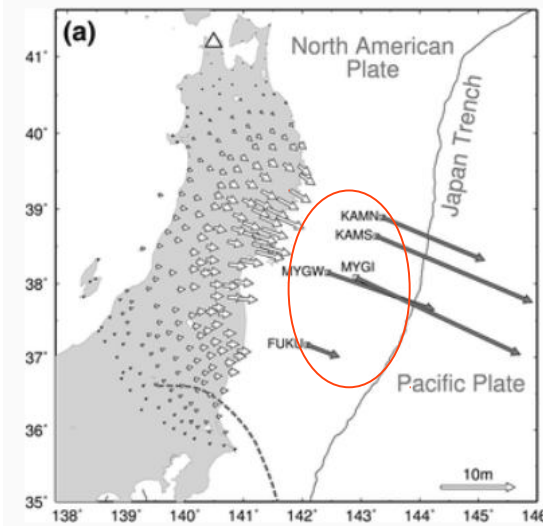


Imakiire & Kobayashi,
2011

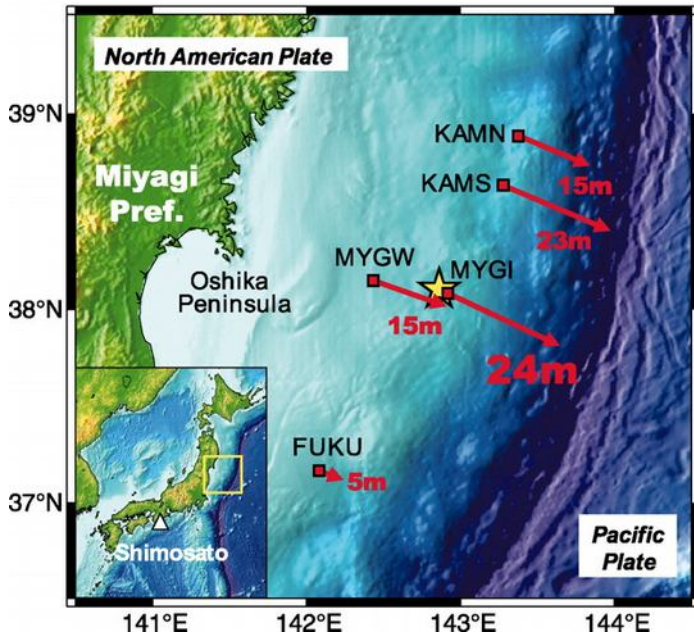
Géodésie sous-marine : GPS + Transpondeurs acoustiques



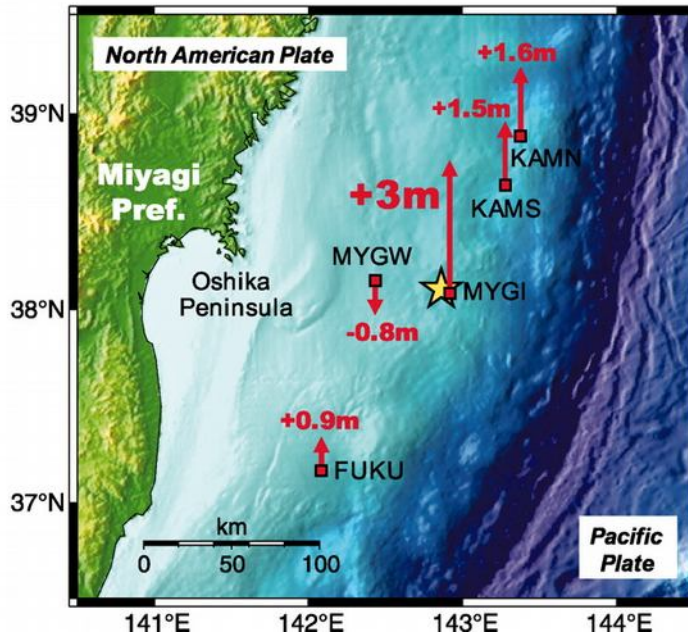
Asada & Yabuki,
2001



A Horizontal displacements



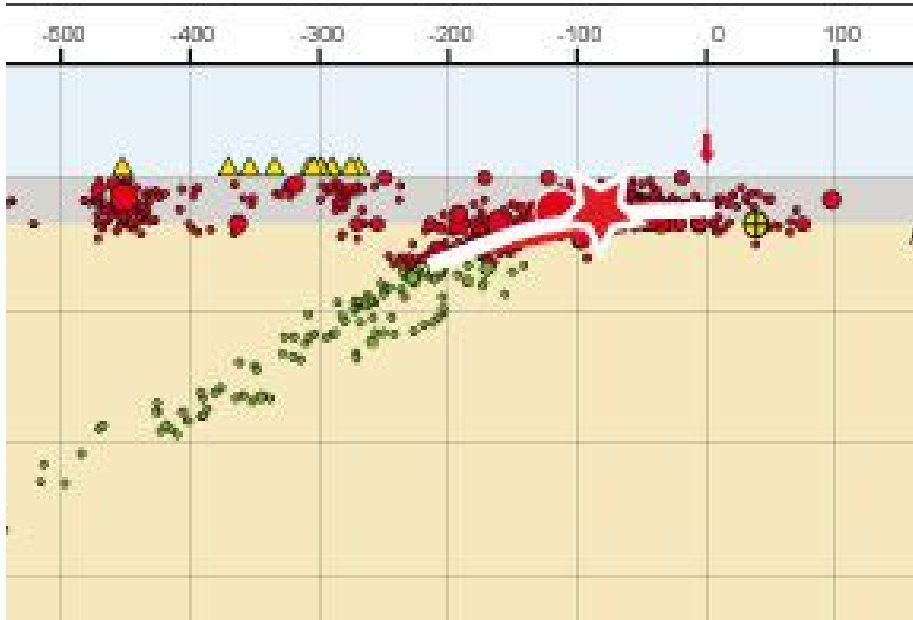
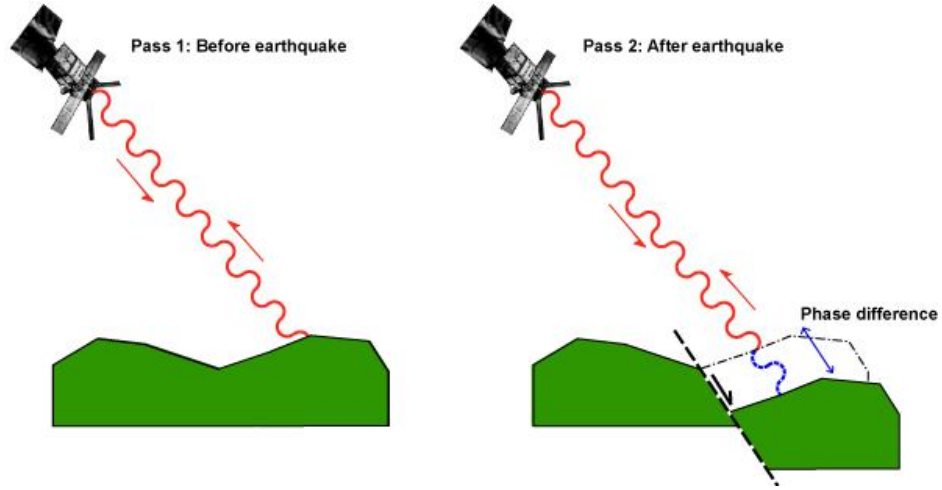
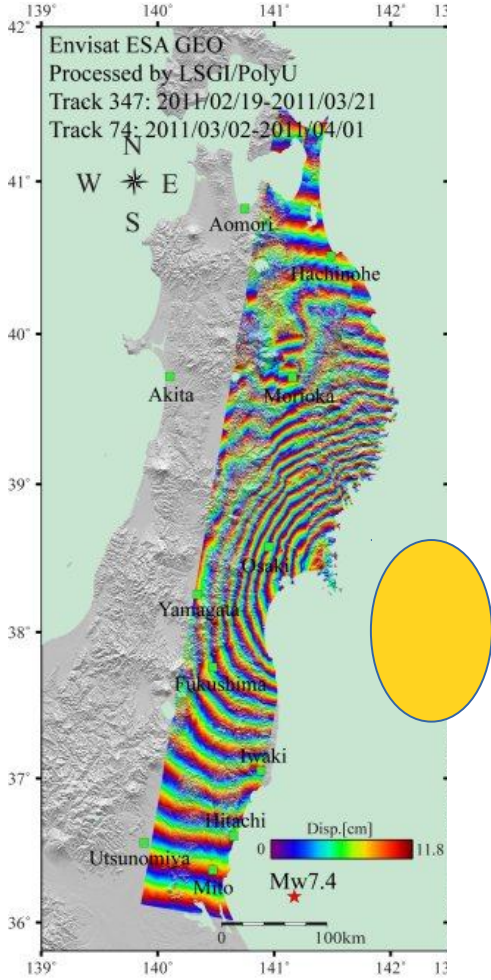
B Vertical displacements



Noda et al. 2018
Sato et al 2011

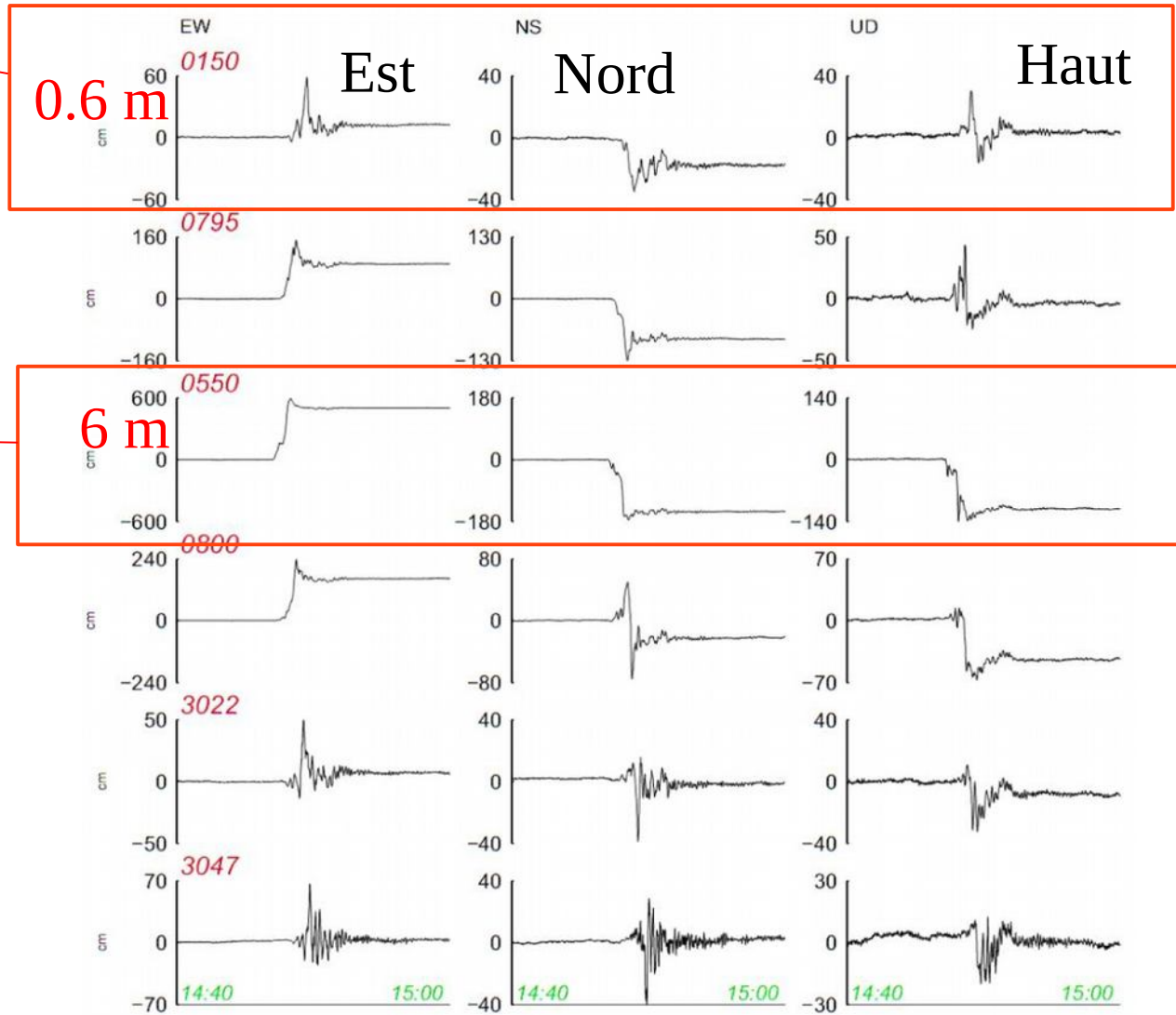
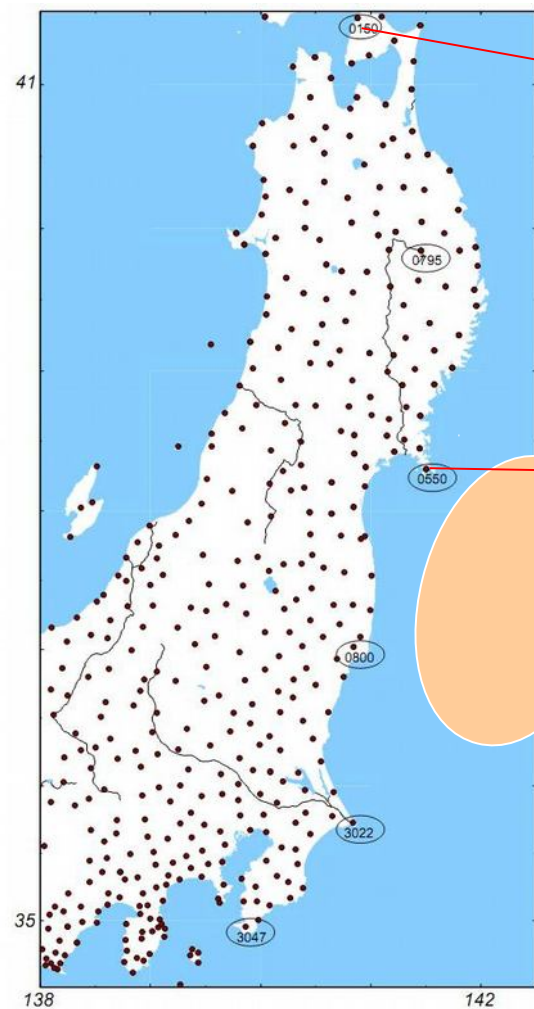
Interférométrie Radar par Satellite : InSAR

Séisme de Tohoku, 2011

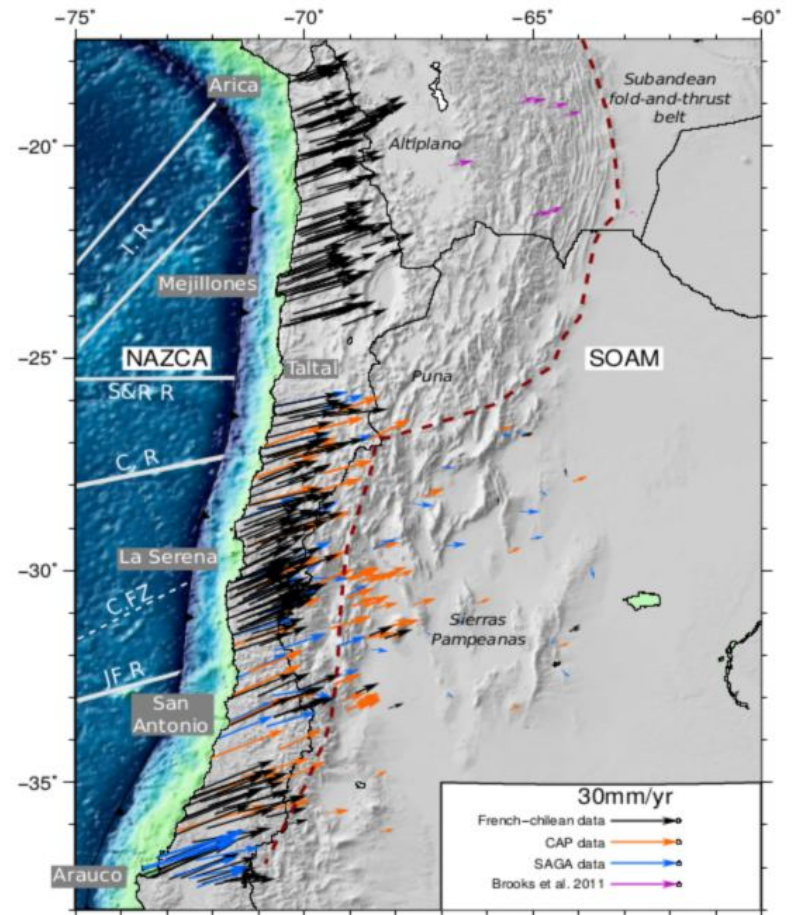
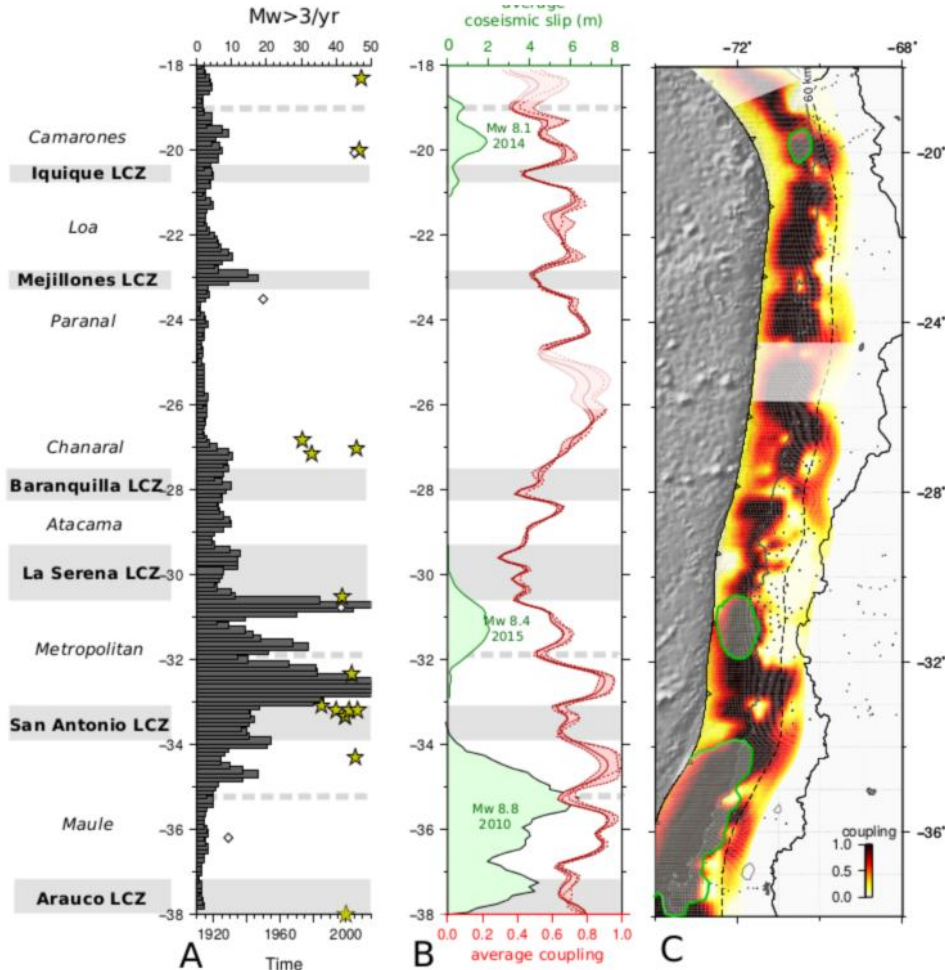
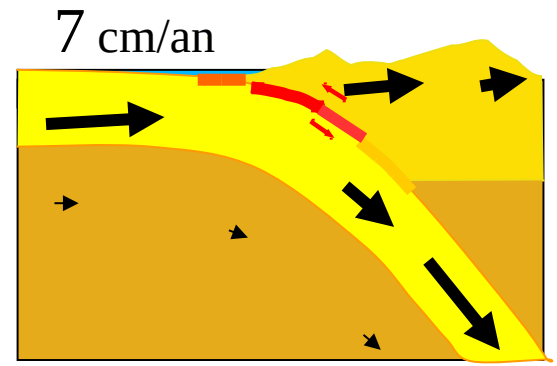


Séisme de Tohoku 2011

GPS à 10 Hz = sismomètre !



Couplage de la subduction - Chili GPS - glissement lent permanent

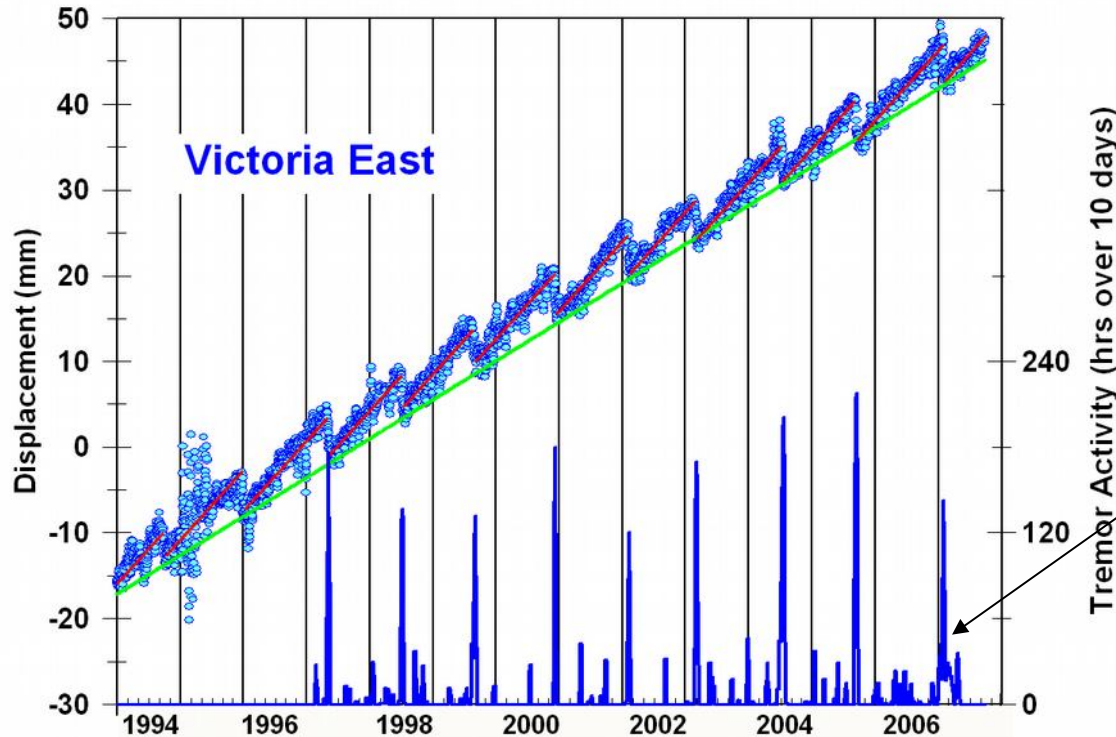
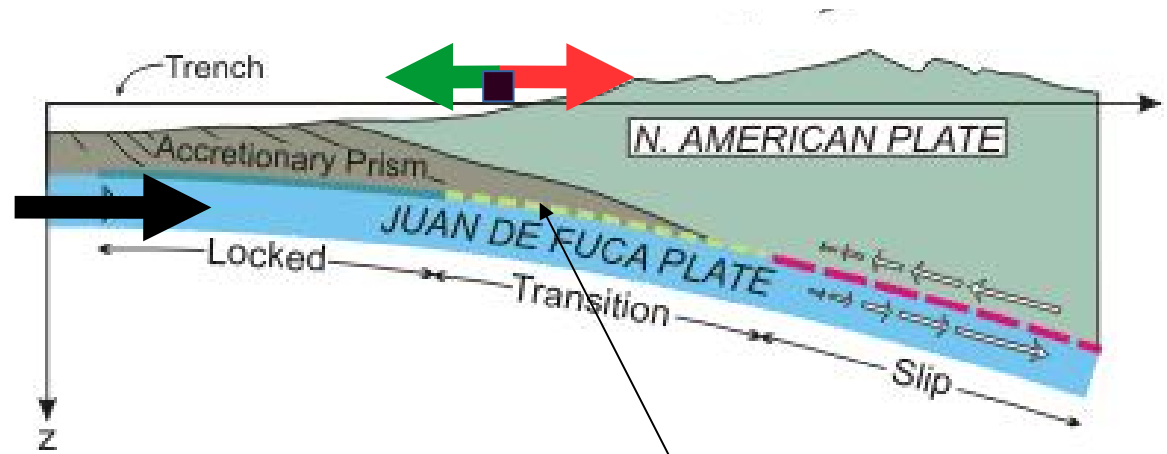


Des failles capricieuses :

Glissement lents transitoires

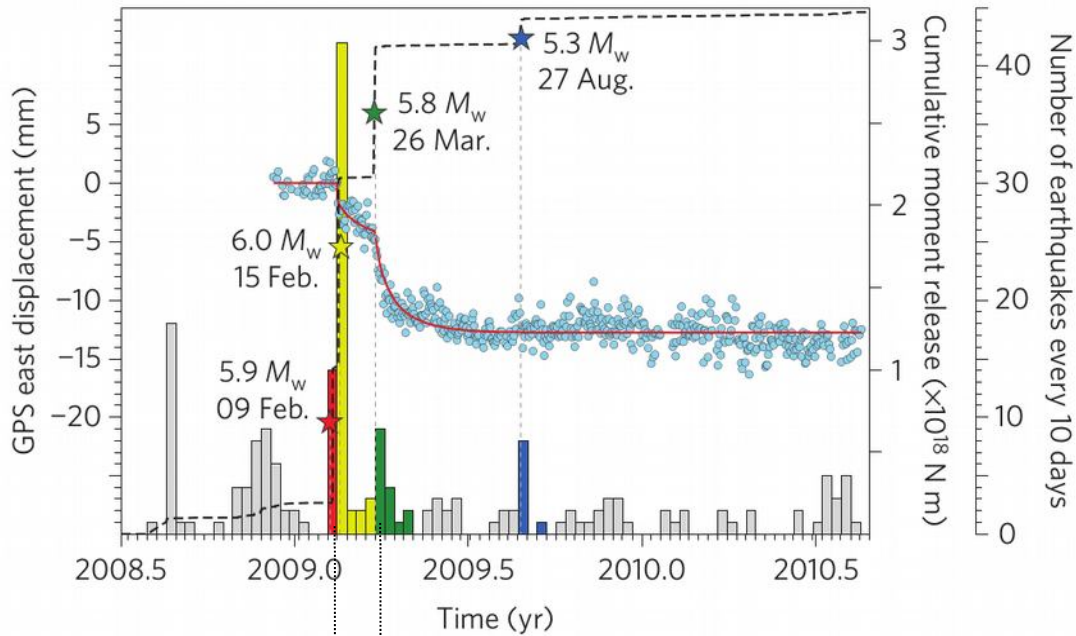
SSE = « slow slip events »

Glissements transitoire : Subduction des Cascades



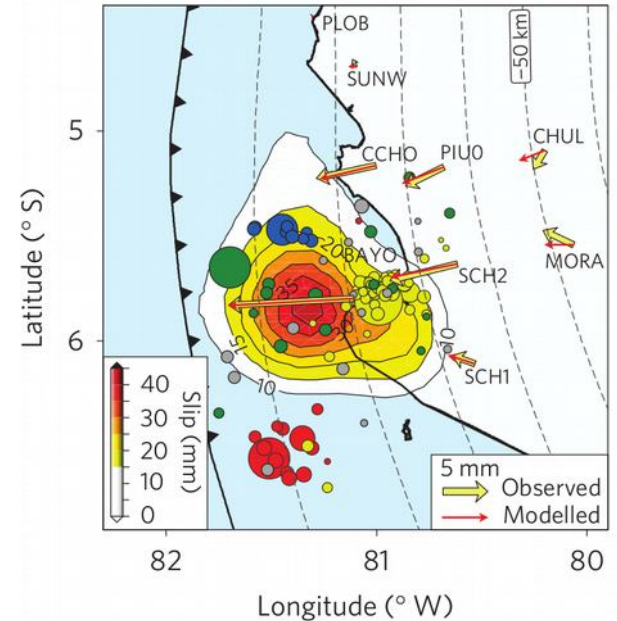
Glissement
épisodique
+
trémors

Glissement transitoire et essaim sismique au Pérou



Moment magnitude SSE: 6.7
 $\frac{3}{4}$ of total moment release

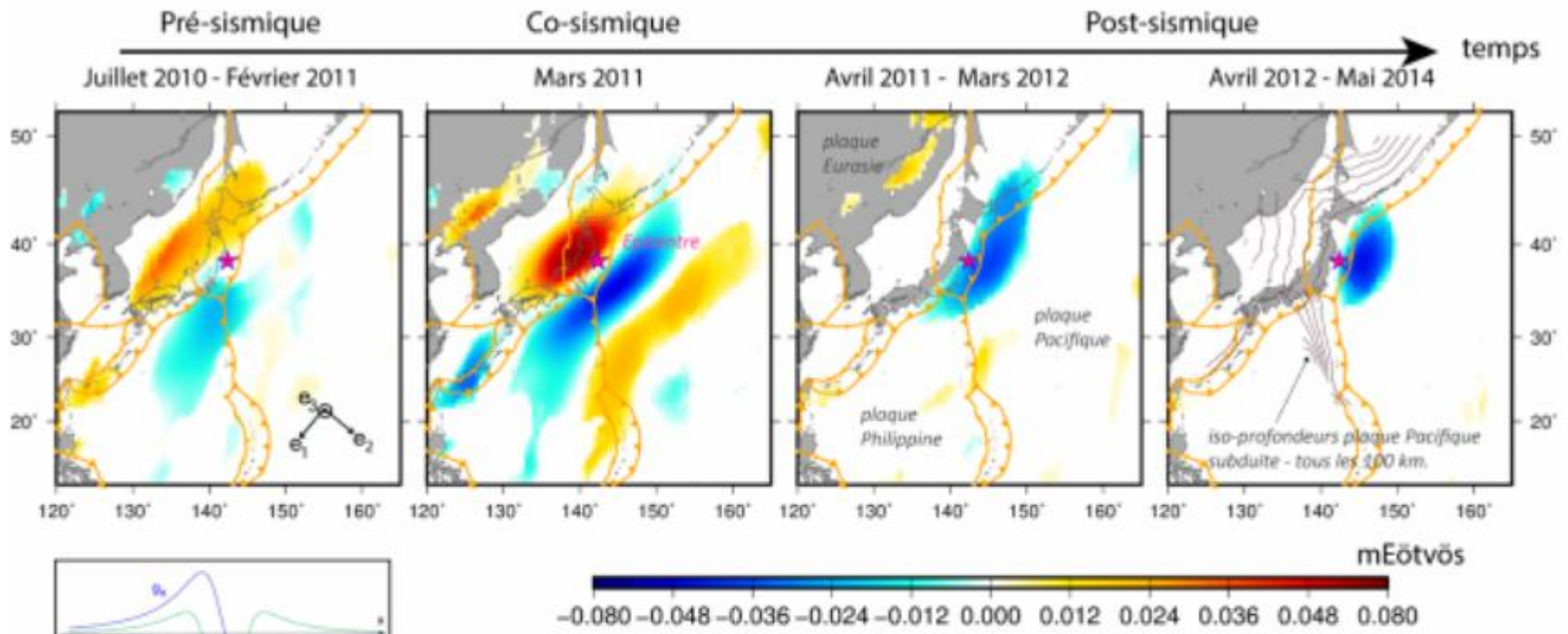
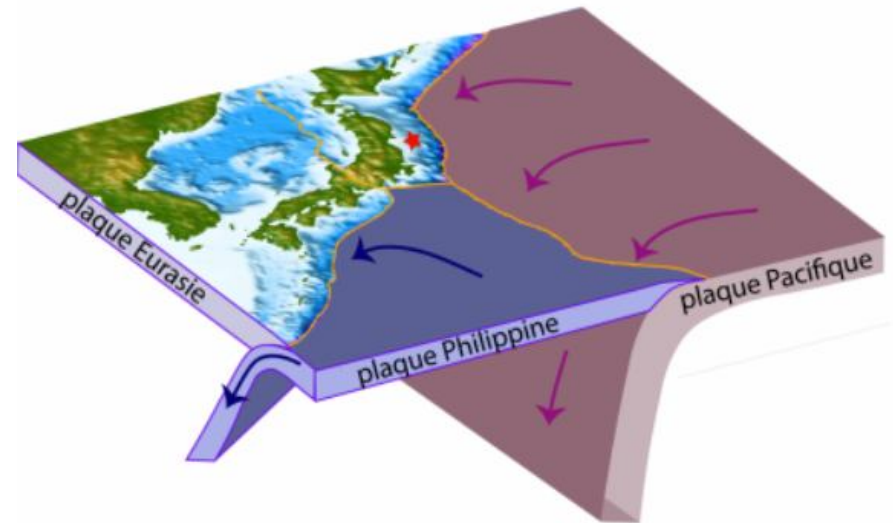
Cumulative slow slip event
from GPS



Villegas-Lanza et al. 2015

Signal de gravité présismique du séisme de Tohoku, 2011

Satellite GRACE, h=500 km

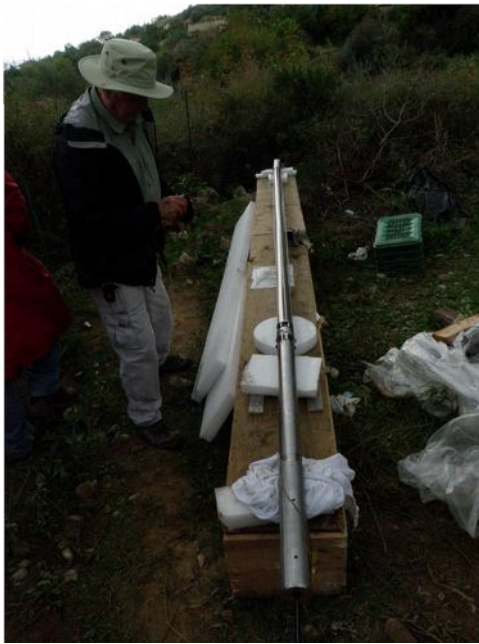


**Il n'y a pas que le GPS et l'InSAR
pour voir les failles glisser ...**

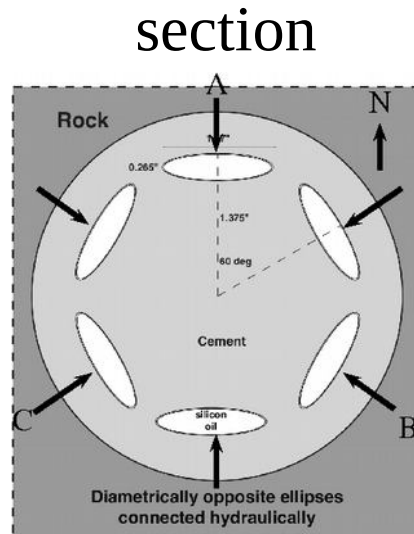
Extensomètres de puits

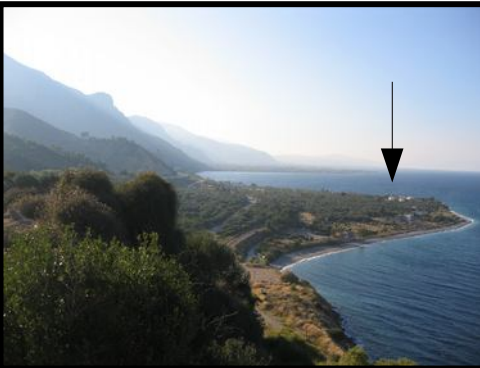
- Cylindres en acier, déformables, de 3 m de long, remplis d'huile
- Cimentés en puits – 150-300 m
- Pression des roches → pression de l'huile, détection capacité ou EM

Résolution court terme :
déformation de 10^{-10} (10^{-6} pour le GPS)



Sacks-Evertson



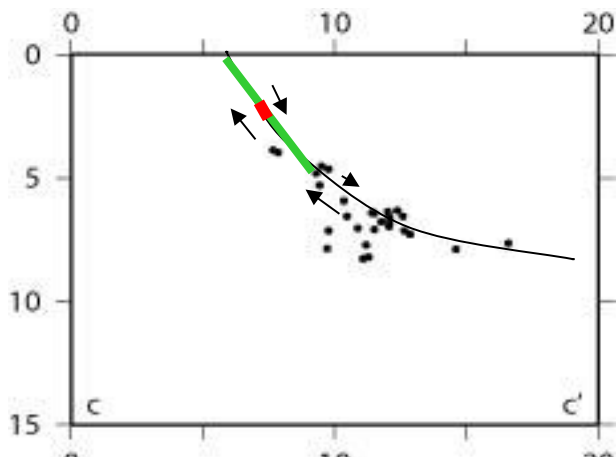
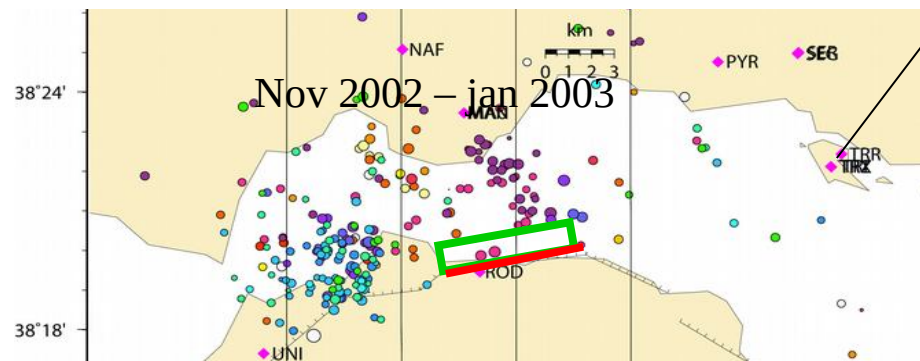
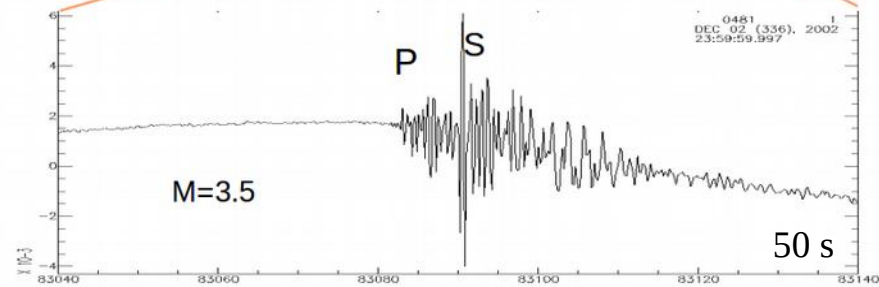
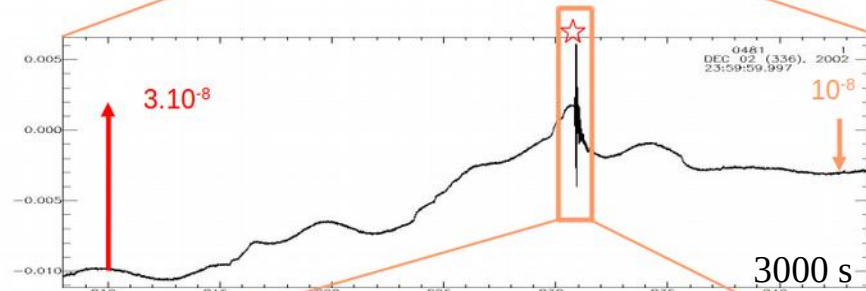
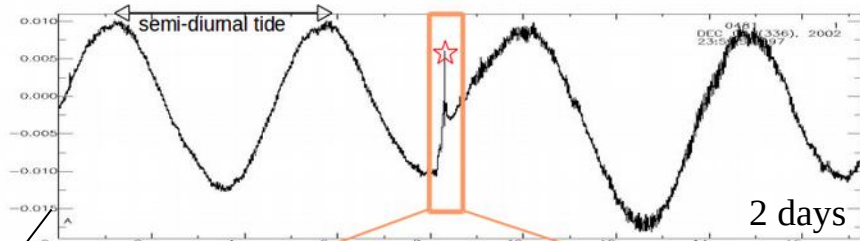


Glissement lent
 Sur la faille de
 Psathopyrgos
 Rift de Corinthe

Bernard et al. 2007

10^{-7}

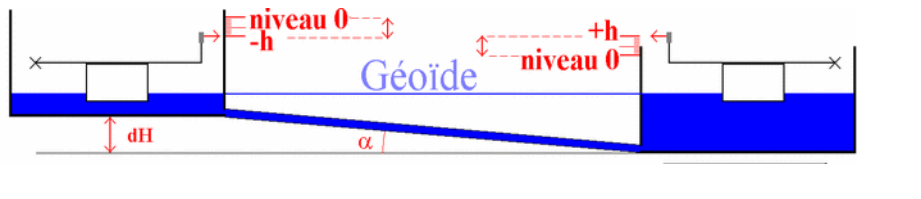
Dilatometre en puits H=150 m – TRIZ
 3 dec. 2002



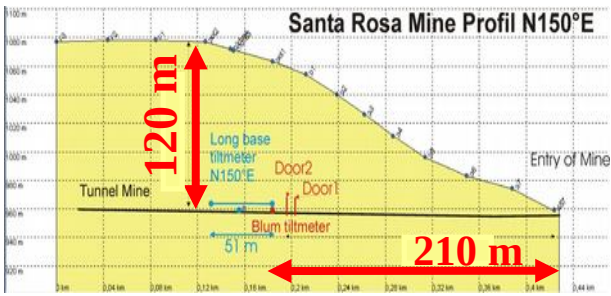
Inclinomètres hydrostatique longue base

- Niveau à eau
- Galerie souterrain, mine – longueur 50 m – 500 m
- inclinaison du sol \searrow variation de niveau d'eau aux extrémités, détection capacité, EM ou optique laser

Résolution : inclinaison de 10^{-9} radians



Glissement précurseur du séisme d'Iquique, M=8.0, 2014



Inclinomètre longue base

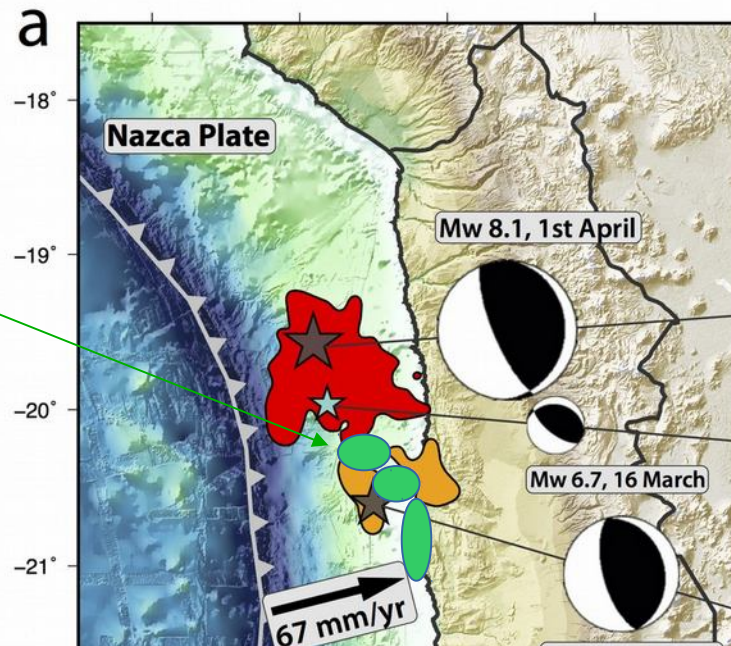
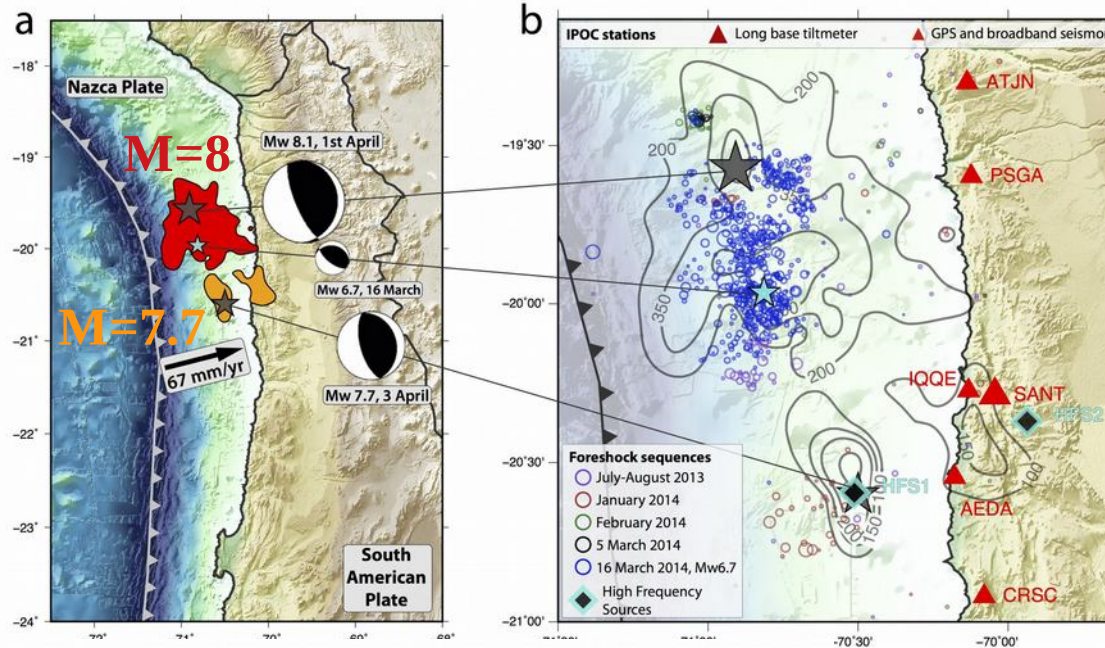


$5 \cdot 10^{-8}$ rad

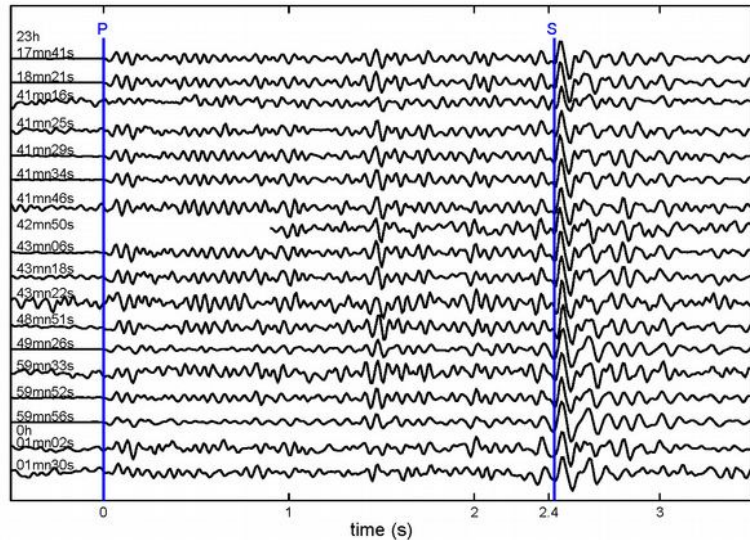


5 mm

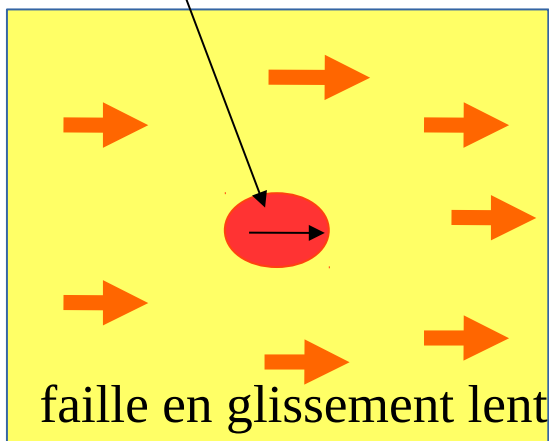
Boudin et al. , 2016



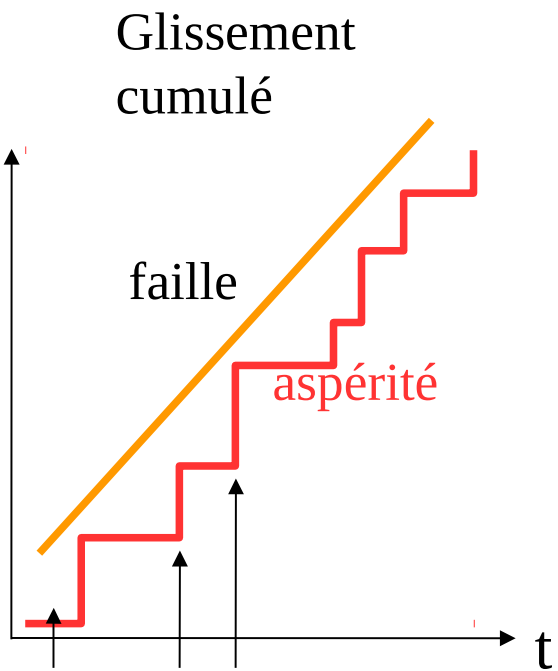
Des petits séismes répéteurs : révélateurs d'un grand glissement lent



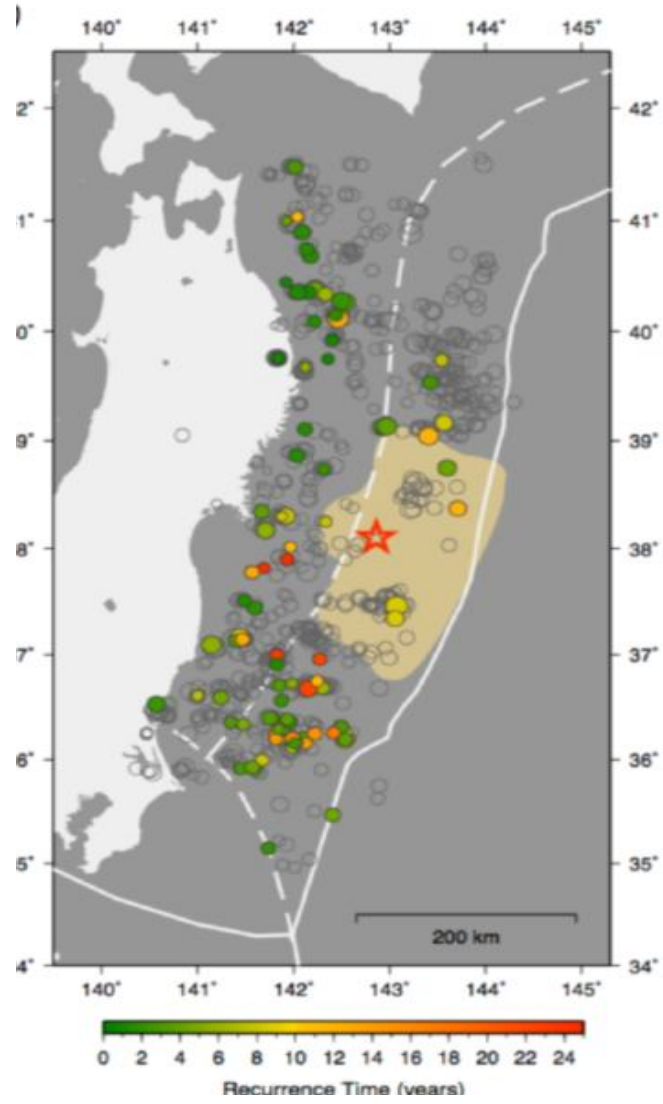
Aspérité sismique :
ruptures répétées



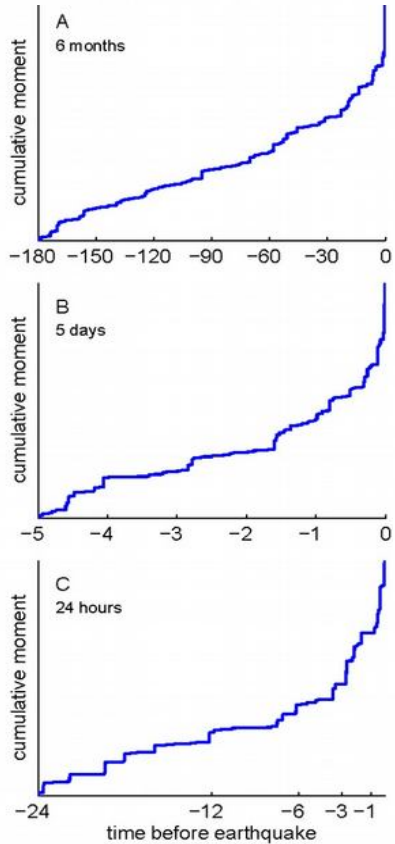
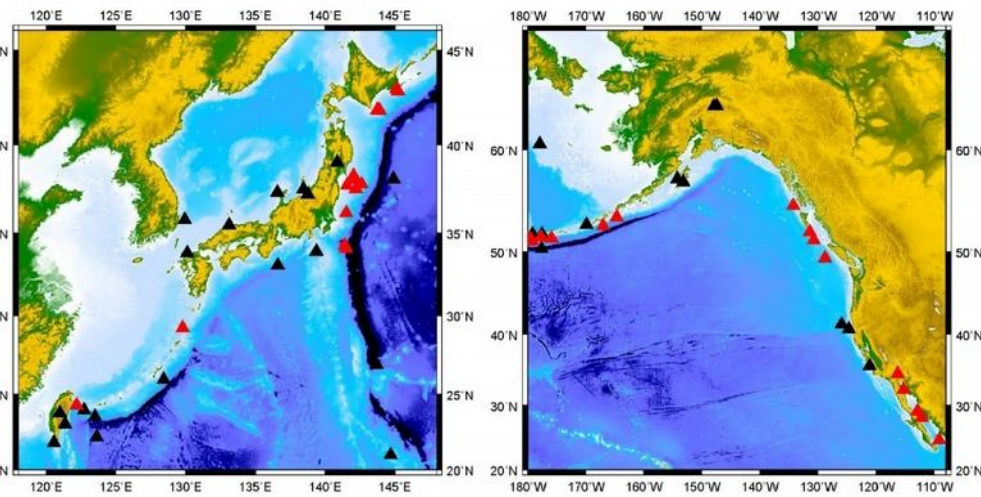
faille en glissement lent



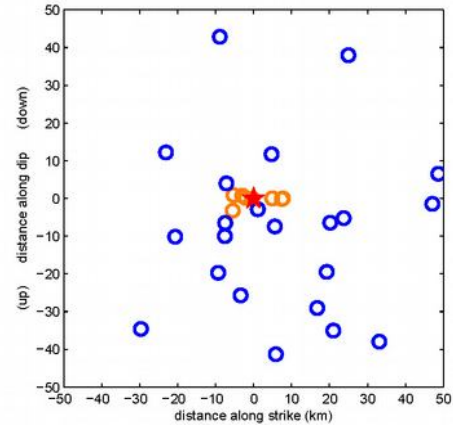
Ruptures sismiques
de l'aspérité



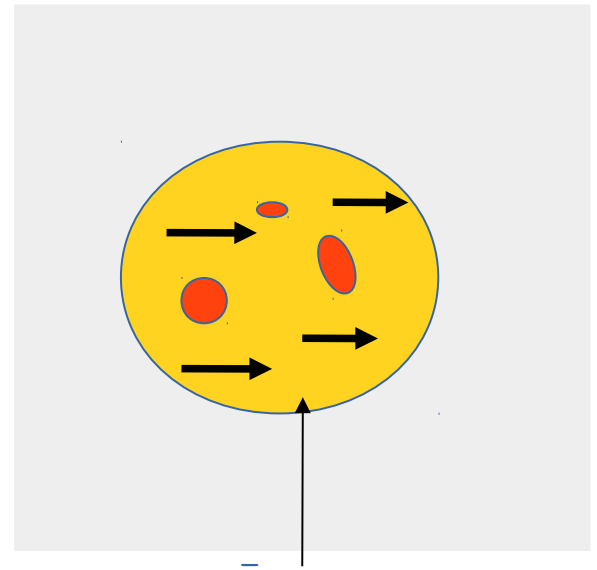
Glissement accéléré des failles avant les grands séismes déduits de la microsismicité



1999-2011
M>6.5



Interplate earthquakes:
subduction
transform



Zone de glissement lent avant le grand séisme

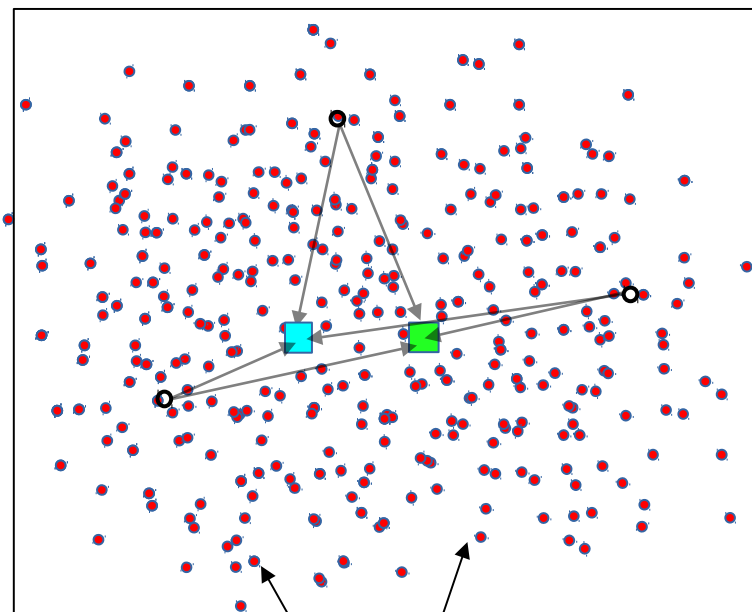
**Comment voir la Terre
se déformer
en analysant le
bruit microsismique ambiant**

Corrélation de bruit

Duvall et al. ,1993

Weaver & Lobkis, 2001

Campillo et Paul, 2003

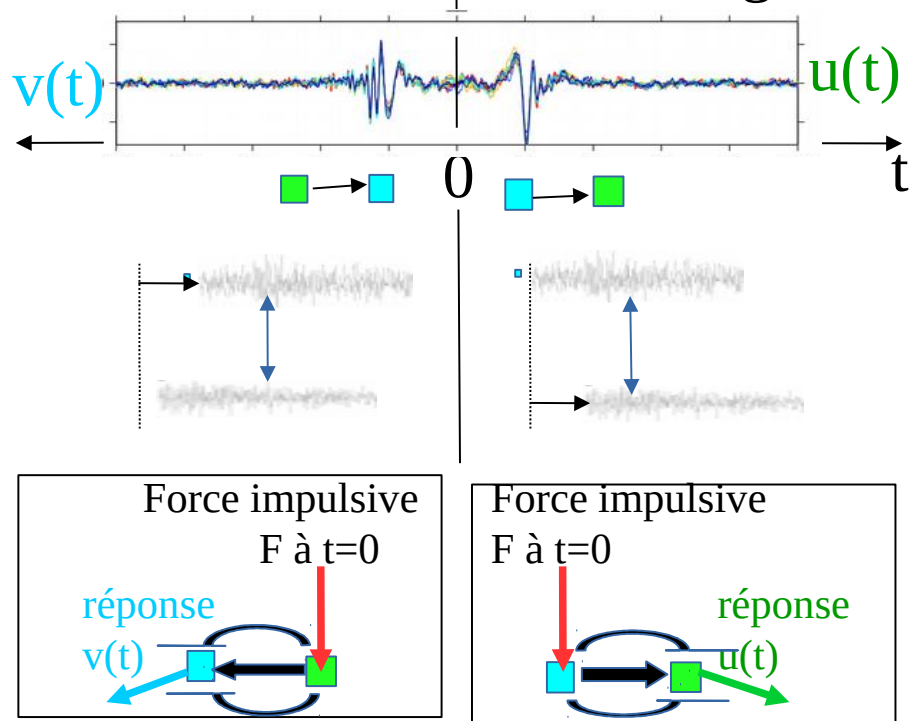


sources aléatoires

sismogrammes de bruit

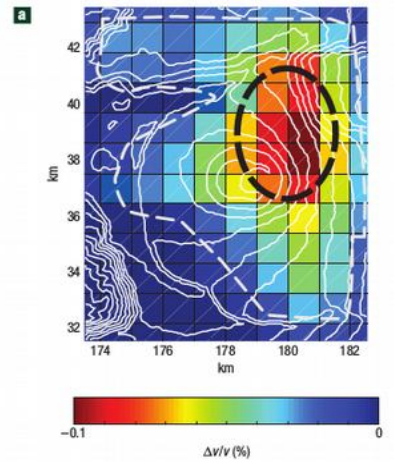
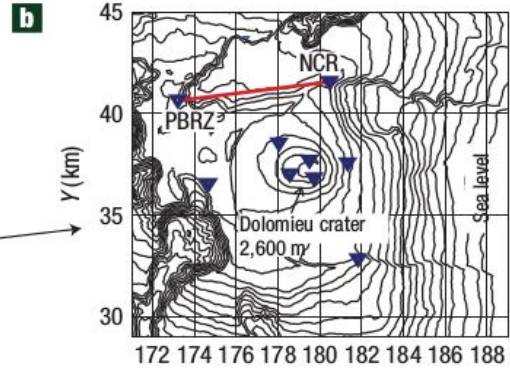
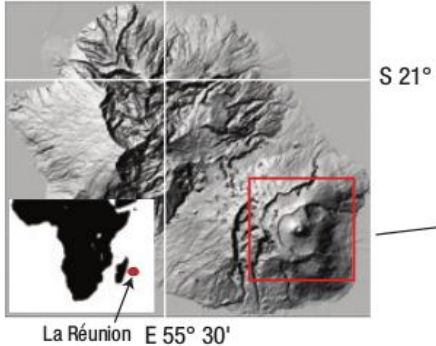


Corrélation entre les sismogrammes

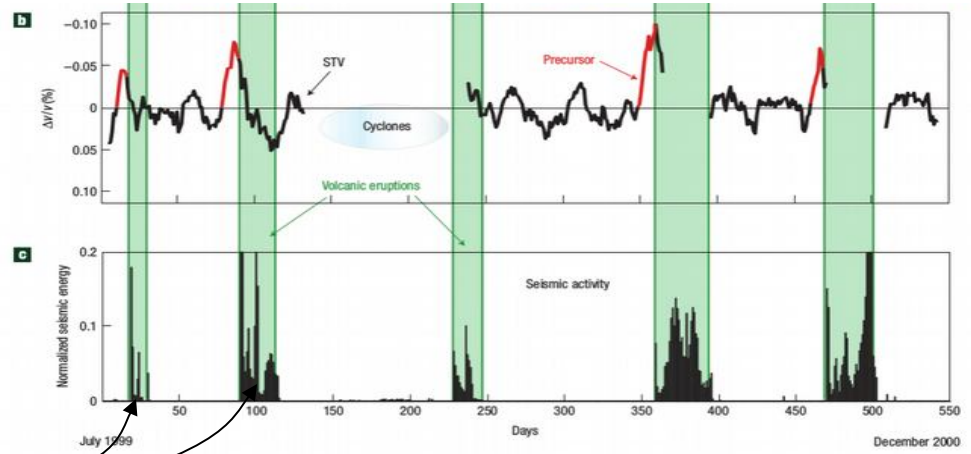
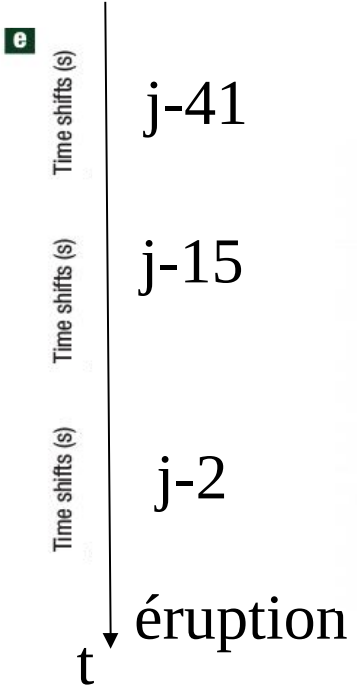
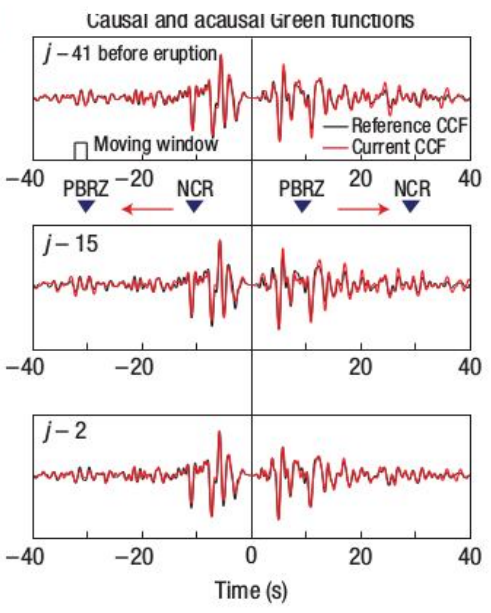


→ ~ réponse impulsionnelle du milieu ~ vitesses sismiques

Variation temporelle de la corrélation de bruit au Piton de La Fournaise

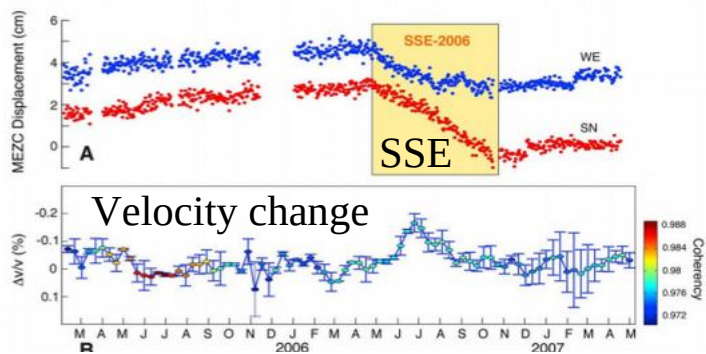


Corrélation entre PBRZ et NCR



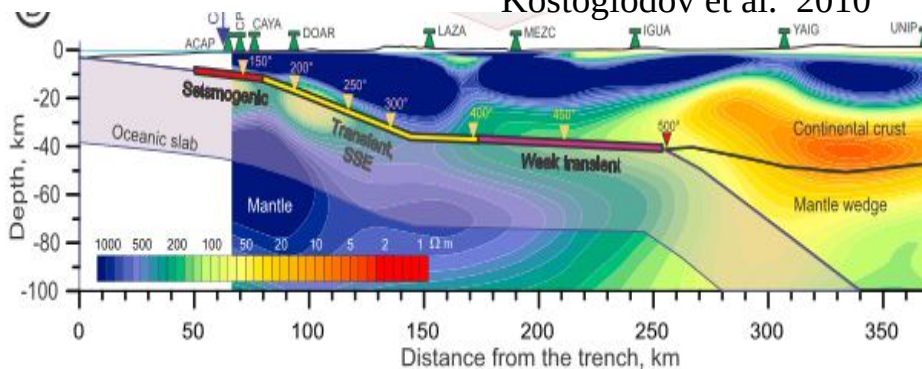
Séisme lent (SSE) 2006, Mexico

Rivet et al., 2011

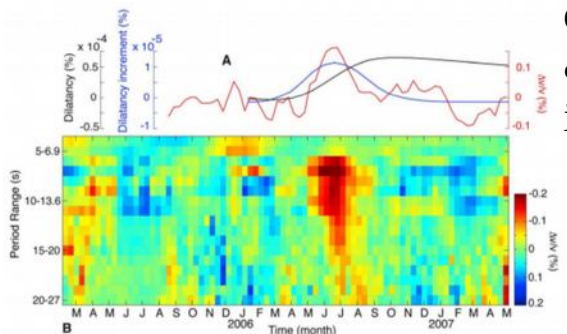


11-15 s

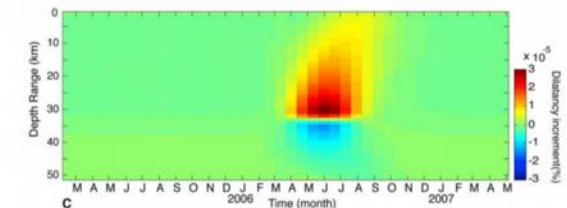
Kostoglodov et al. 2010



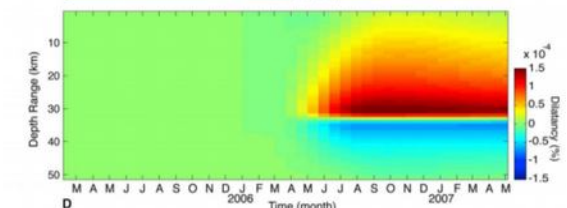
dilatancy & dilatancy increment



velocity change

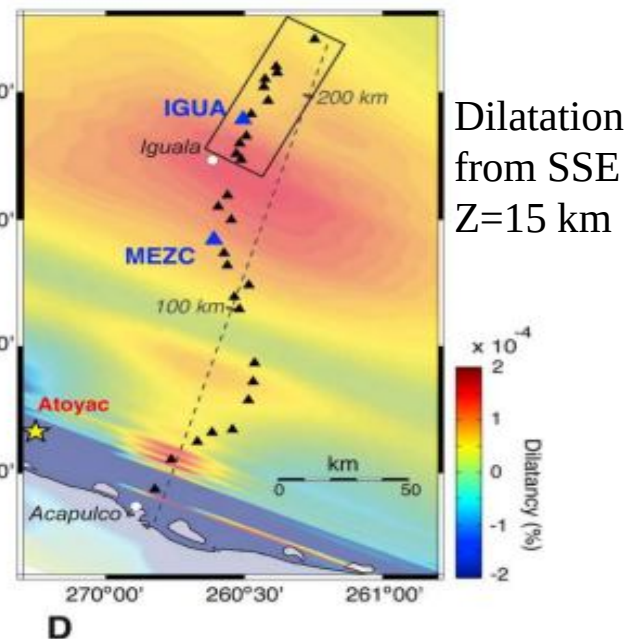


dilatancy increment



dilatancy

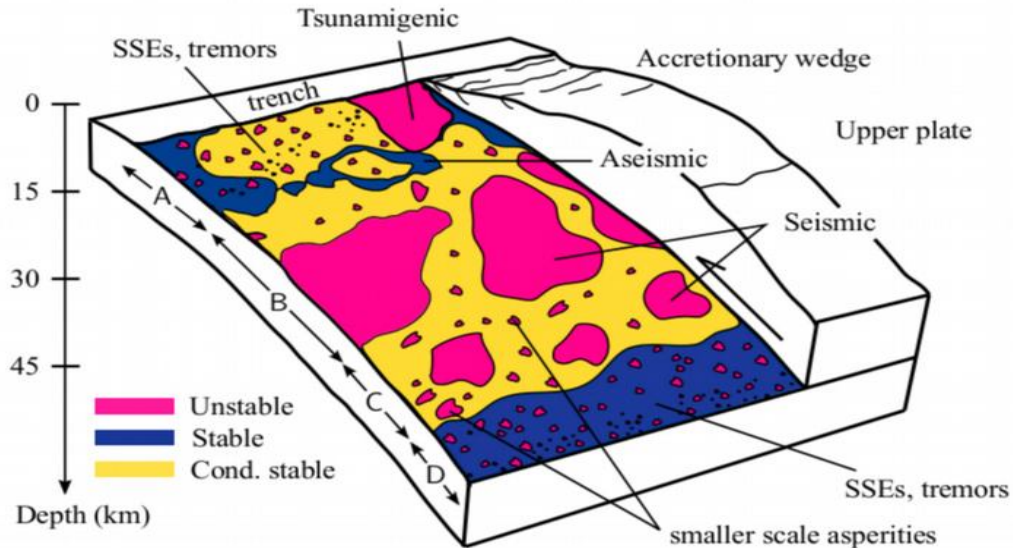
Time



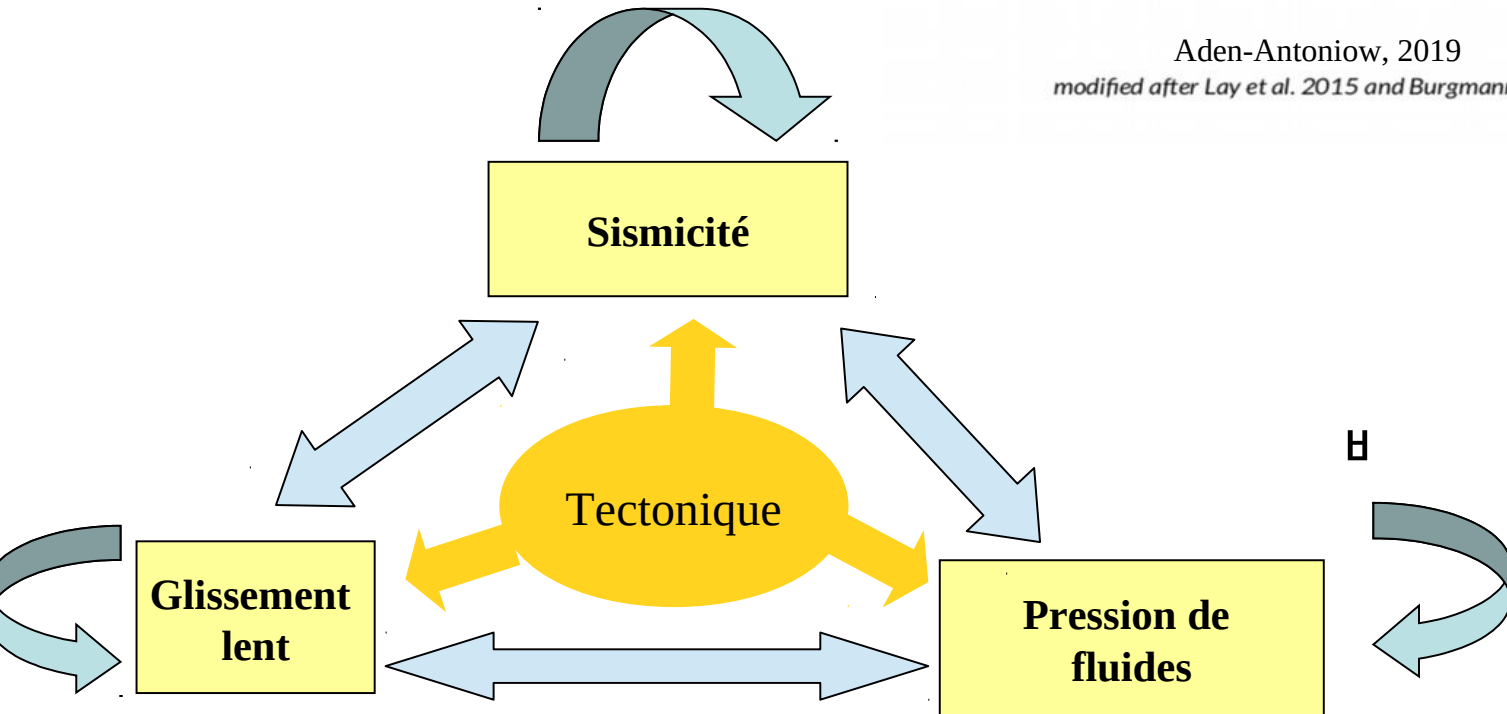
Dilatation from SSE
Z=15 km

Conclusion

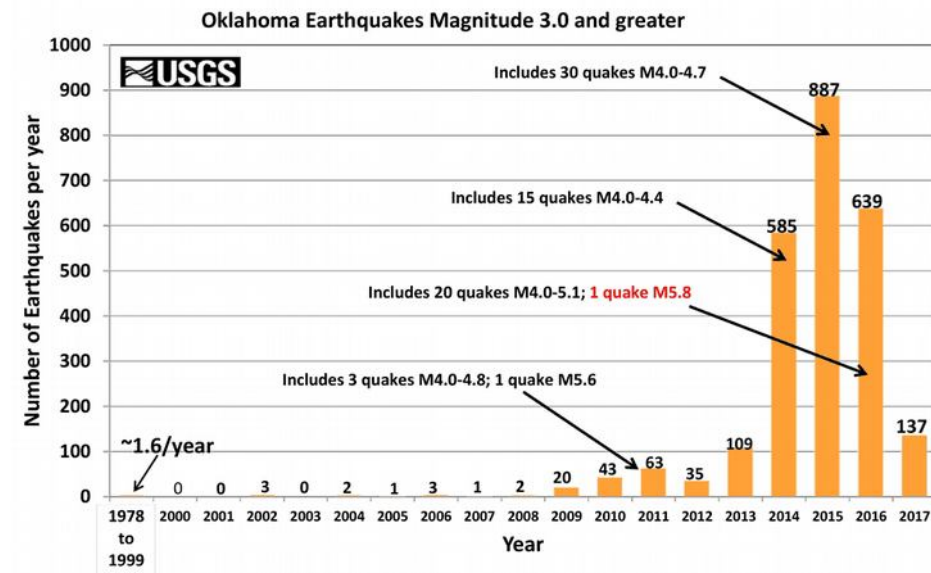
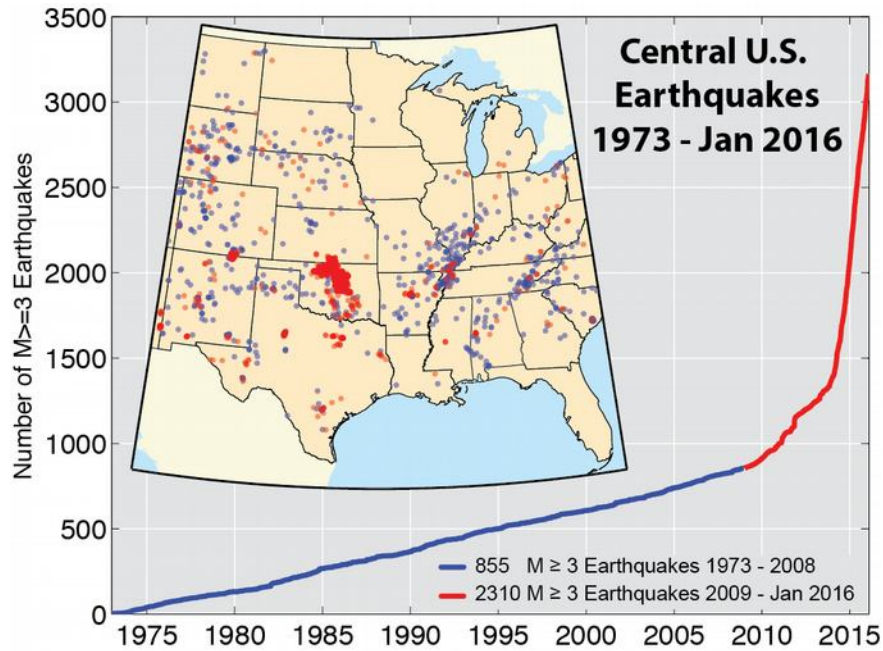
Déformations transitoires dans la croûte terrestre



Aden-Antoniow, 2019
modified after Lay et al. 2015 and Burgmann 2018



Epilogue : Sismicité induite au centre des USA



Source: USGS-NEIC ComCat & Oklahoma Geological Survey; Preliminary as of July 4, 2017

La cause :
 Injection à grande profondeur
 des eaux usées de la production
 de gaz ou de pétrole

