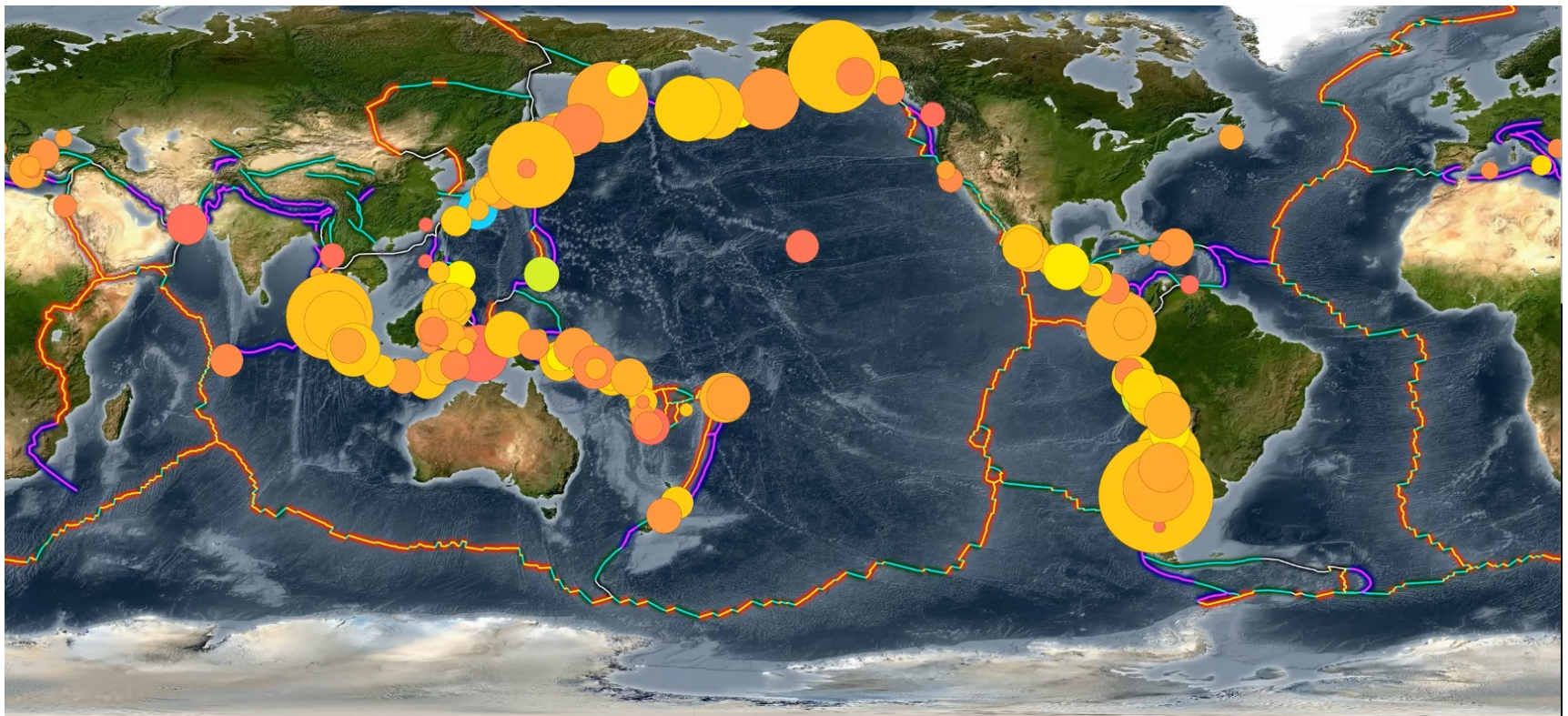
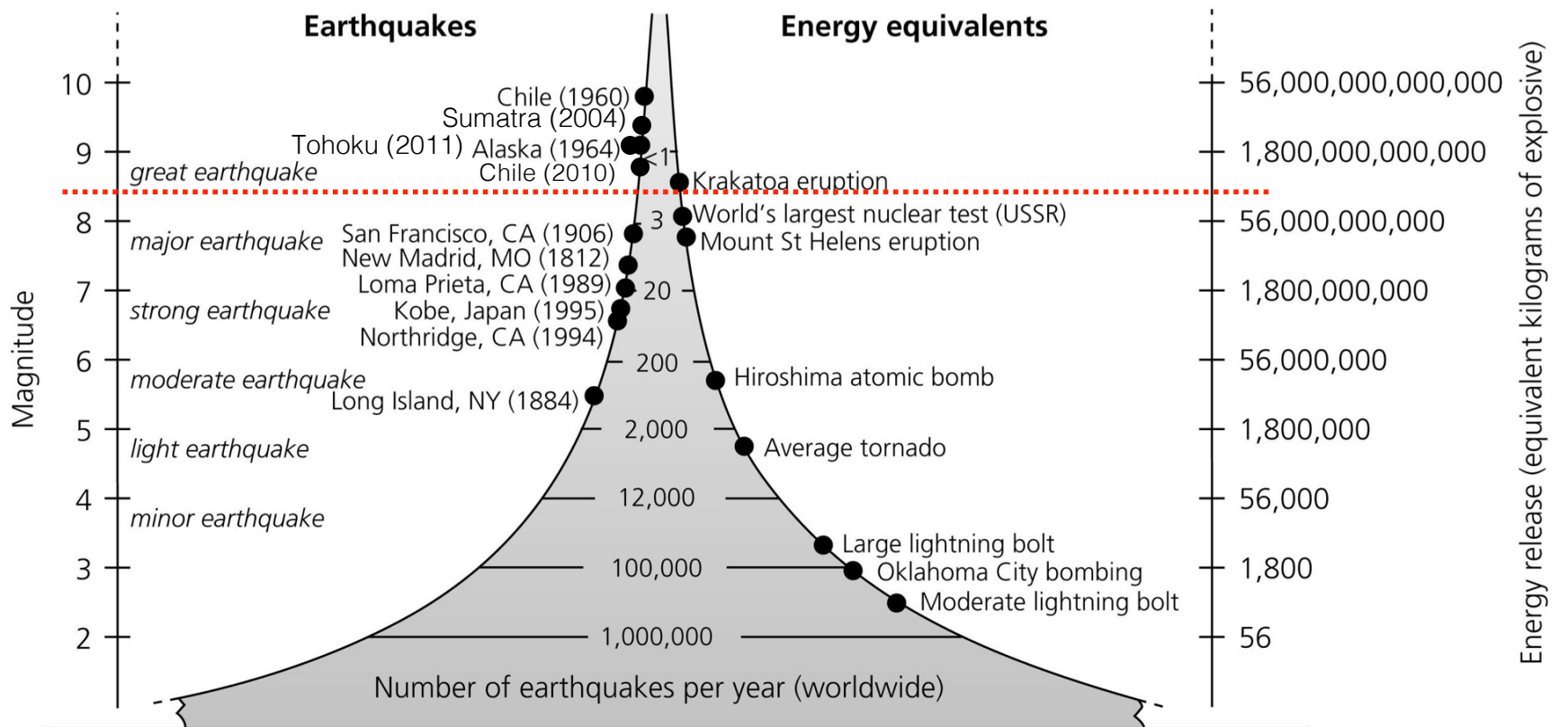


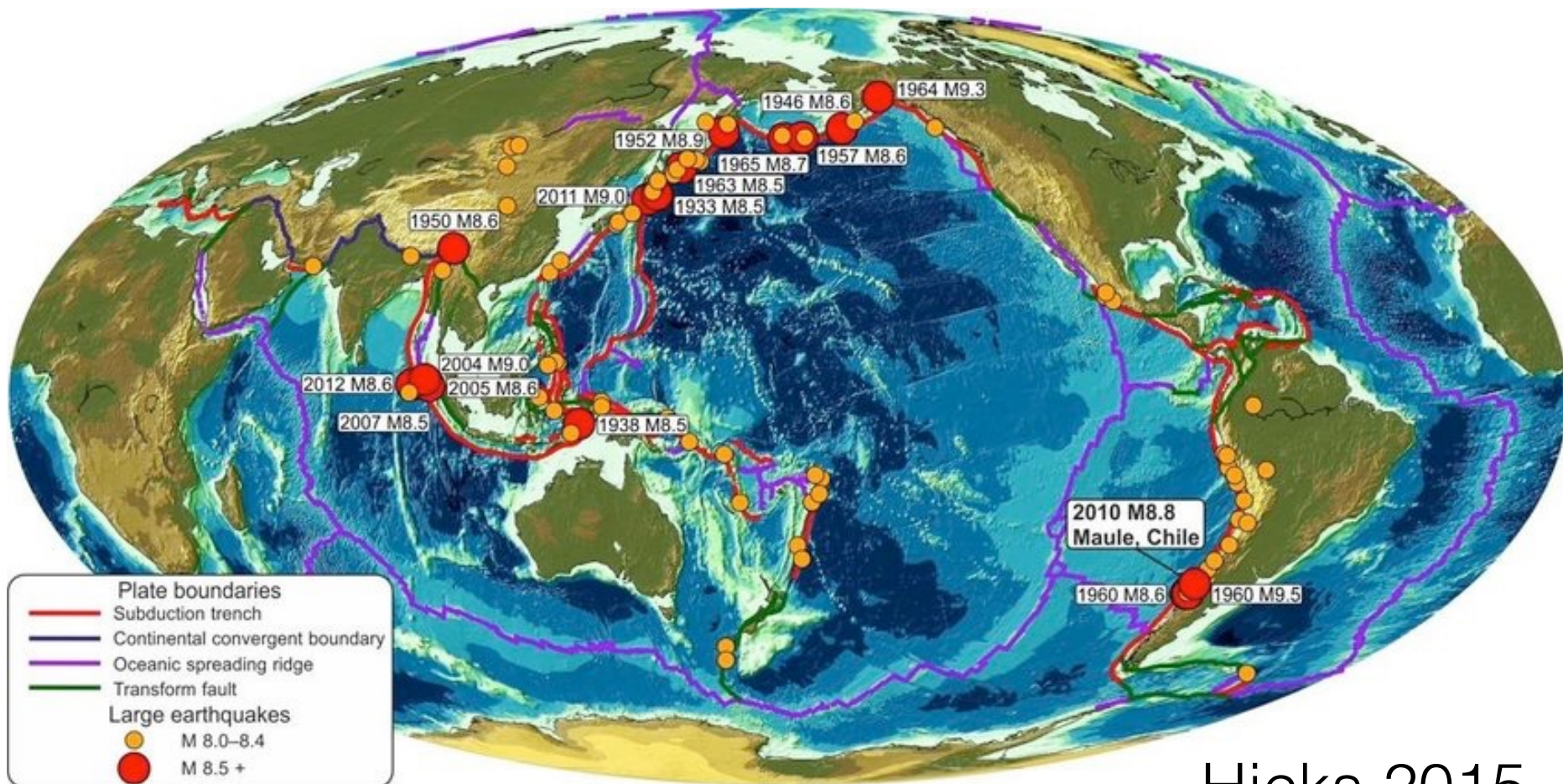
Les grands séismes



<https://www.youtube.com/watch?v=ilFEKSZQv5o>

Figure 1.2-2: Comparison of frequency, magnitude, and energy release.



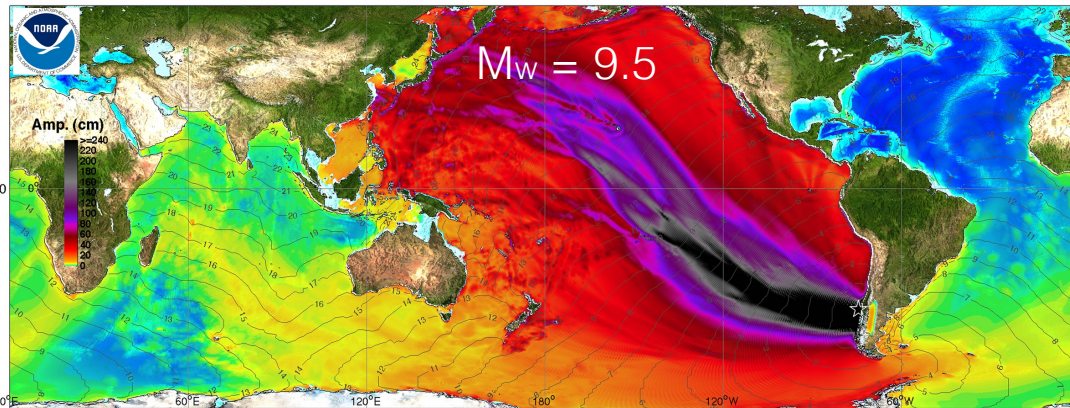


- | | |
|--|----------|
| 1. <u>Chile</u> | 1960 9.5 |
| 2. <u>Prince William Sound, Alaska</u> | 1964 9.2 |
| 3. <u>Off the West Coast of Northern Sumatra</u> | 2004 9.1 |
| 4. <u>Near the East Coast of Honshu, Japan</u> | 2011 9.0 |
| 5. <u>Kamchatka</u> | 1952 9.0 |
| 6. <u>Offshore Maule, Chile</u> | 2010 8.8 |
| 7. <u>Off the Coast of Ecuador</u> | 1906 8.8 |
| 8. <u>Rat Islands, Alaska</u> | 1965 8.7 |
| 9. <u>Northern Sumatra, Indonesia</u> | 2005 8.6 |
| 10. <u>Assam - Tibet</u> | 1950 8.6 |

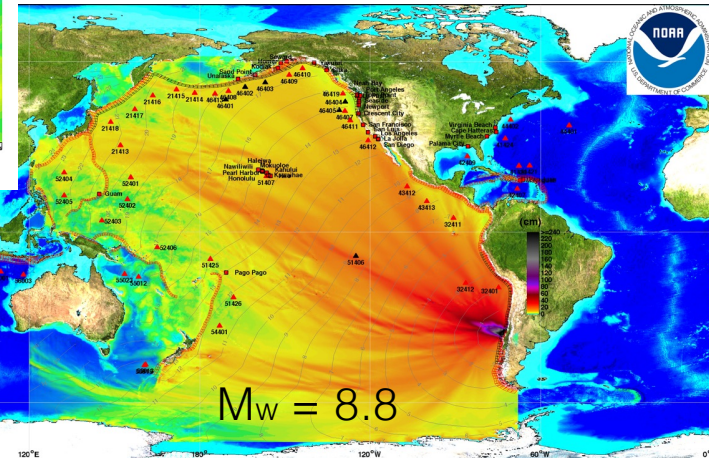
Hicks 2015

22 mai 1960 Chili M_w 9.5

3 000 à 6 000 morts



1960 Chile tsunami (earthquake magnitude Mw 9.5) Maximum amplitude plot -- for comparison with Feb 27, 2010 Chile tsunami event



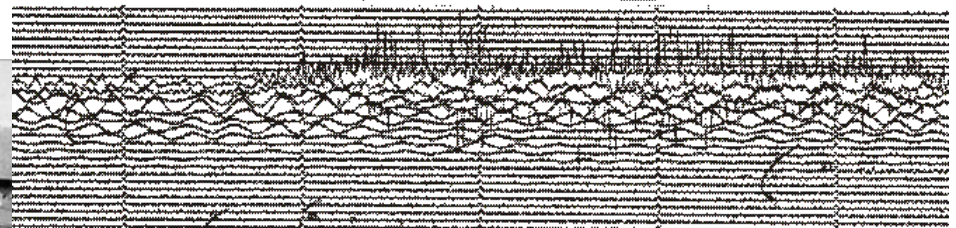
From NOAA



© NOAA



AFP



L = 800 - 1 000 km
W = 200 km
D = 20 m



27 mars 1964 - Alaska

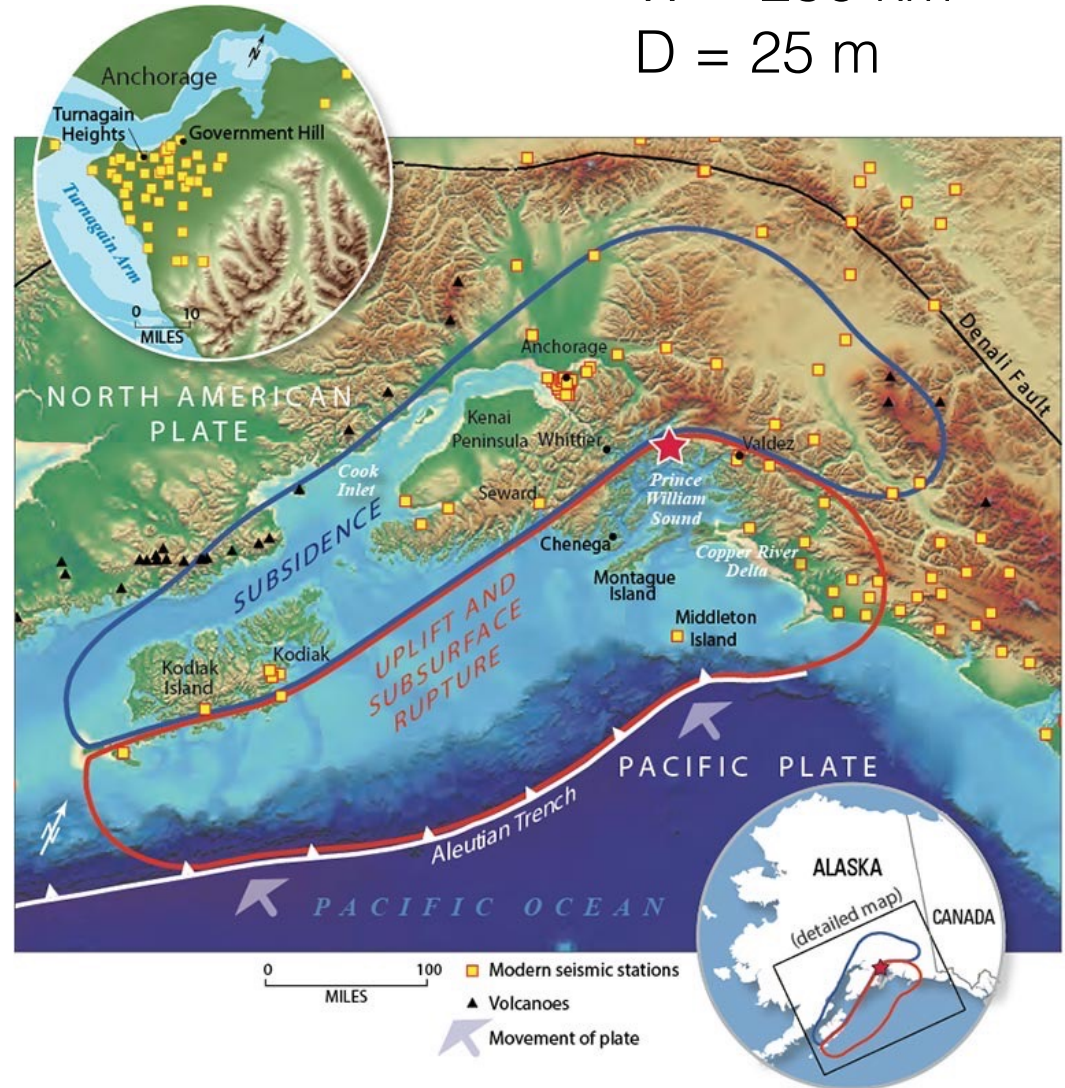
M_w 9.2

115 morts

L = 800 km

W = 250 km

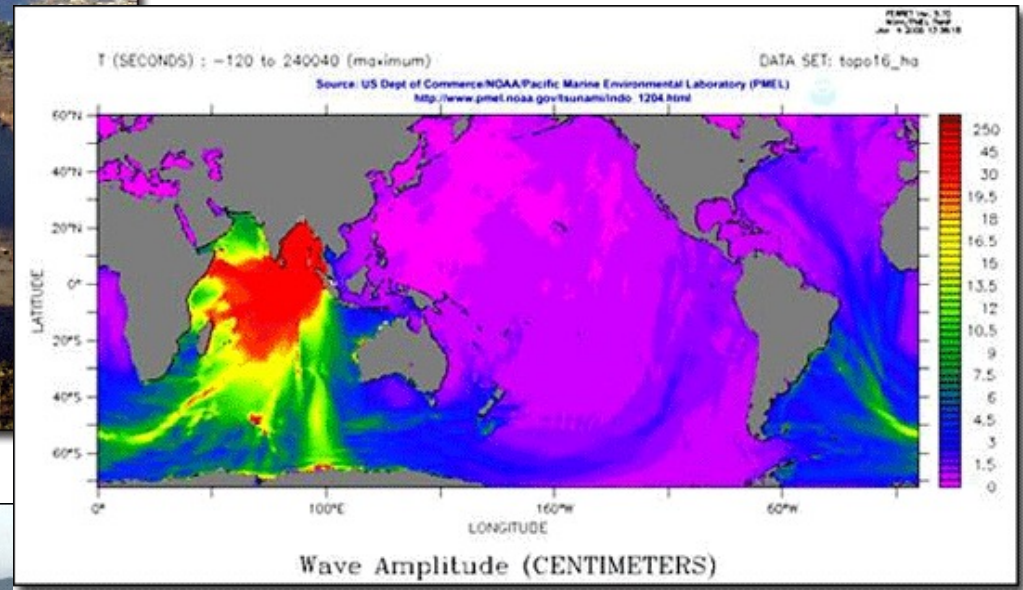
D = 25 m



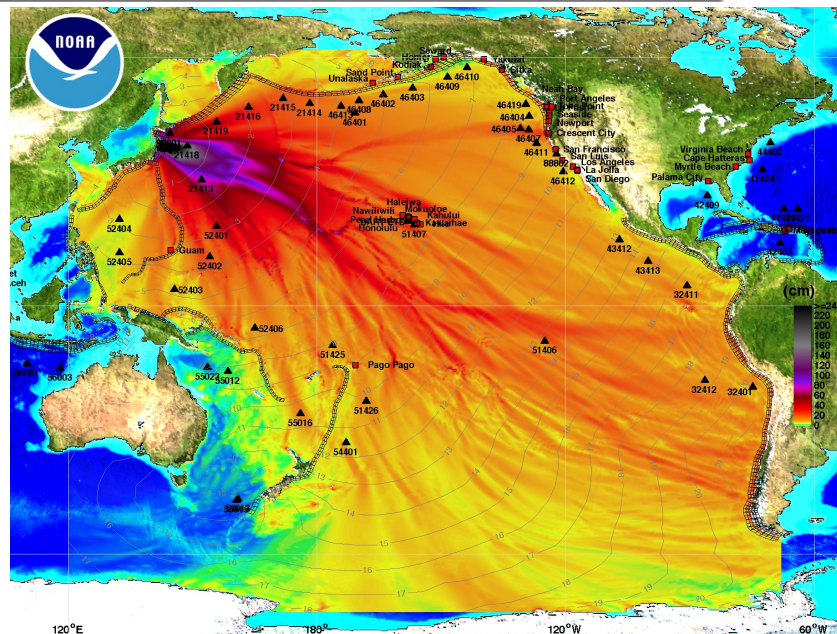
<http://pubs.usgs.gov/fs/2014/3018/>

2004, Sumatra, Mw 9.1

230 000 morts

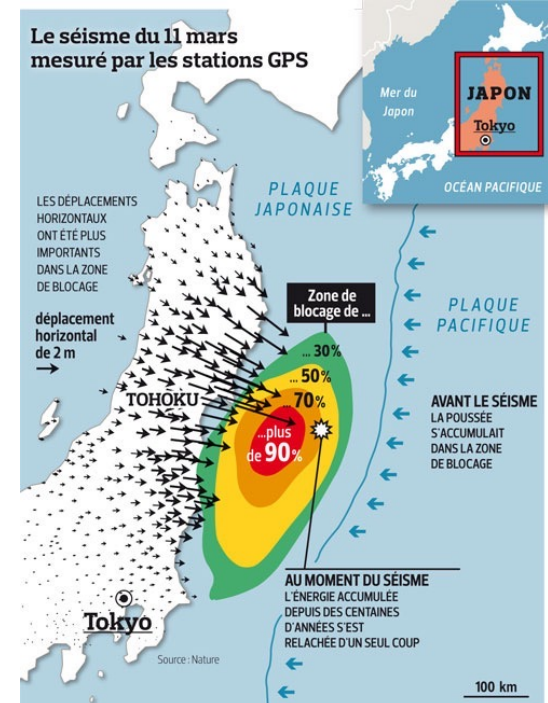


11 mars 2011, Tohoku, Mw 9.0



15 000 à
20 000 morts

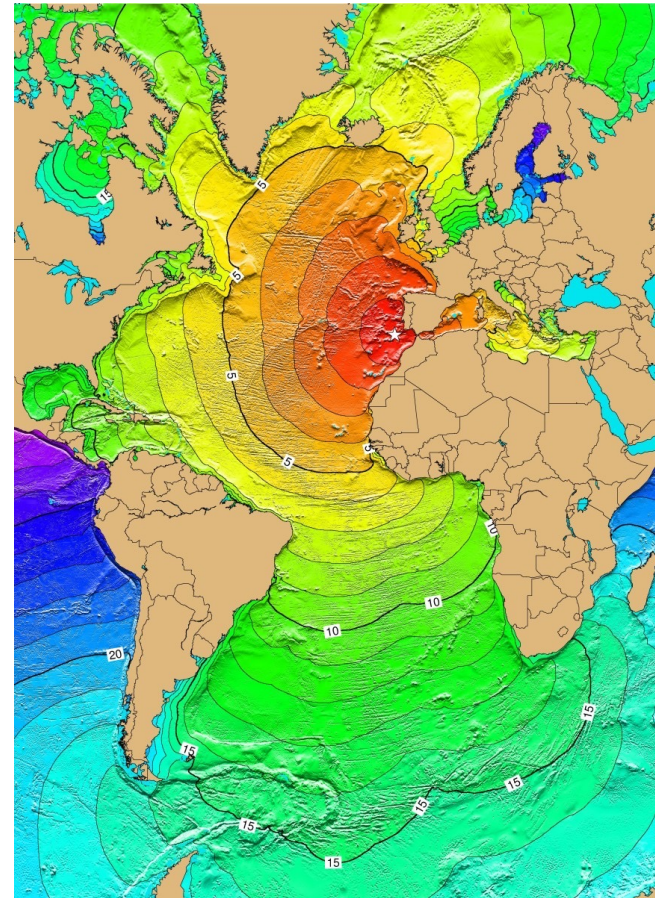
L = 500 km
W = 200 km
D = 20 m



1^{er} novembre 1755 - Lisbonne M_w 8.5 à 9.0



50 000 à 70 000 morts



Querelle Voltaire-Rousseau:
Poème sur le désastre de Lisbonne, de Voltaire
Lettre sur la providence de Jean-Jacques Rousseau

The deadliest earthquakes in human history

Mapped are the top 10 rankings of known earthquakes by death toll. Since two events are ranked equally in 8th place, a total of 11 are included. Tectonic plate boundaries are also shown in red.

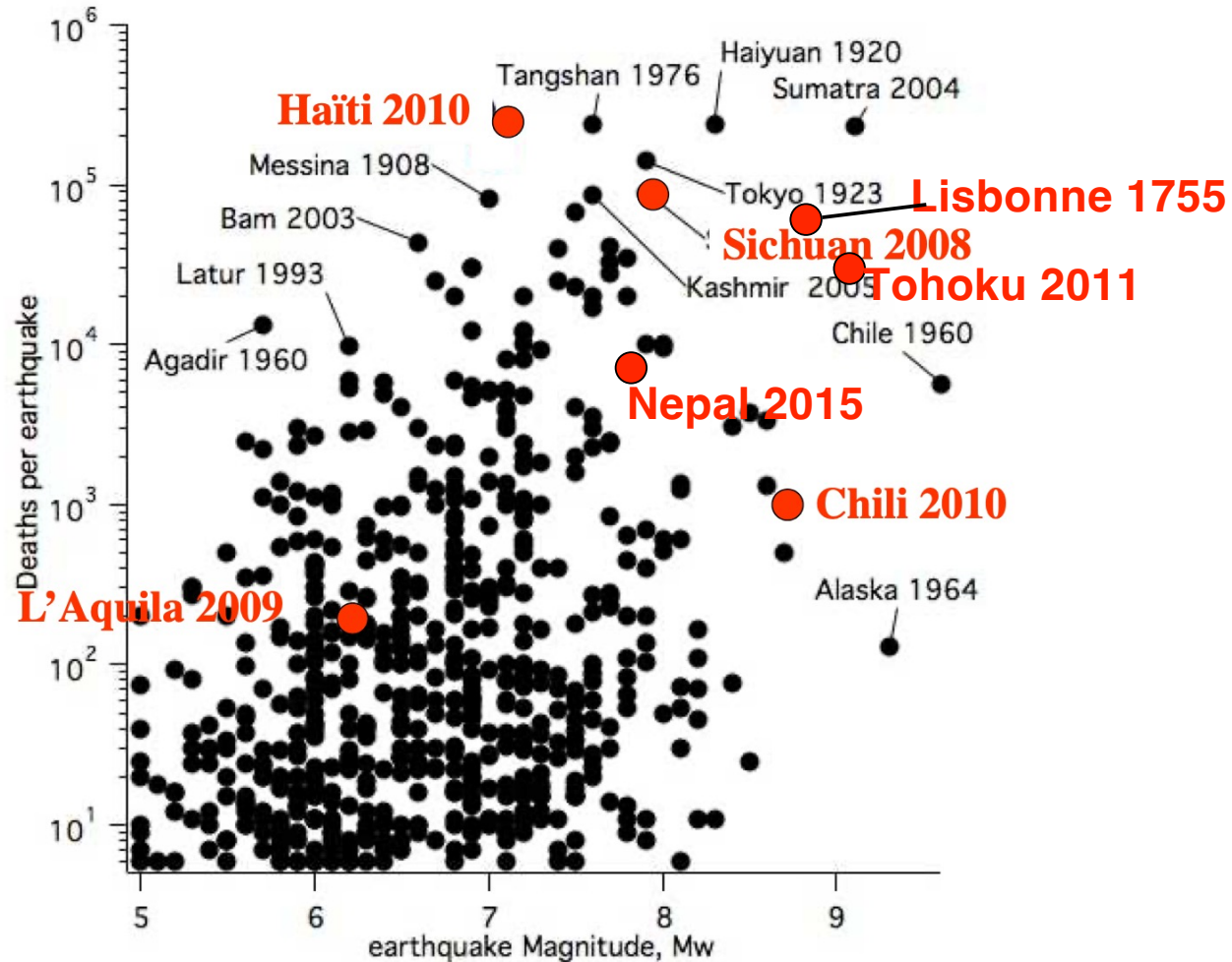


*The death toll figure for the 2010 Haitian earthquake in Port-au-Prince is still disputed. Here we present the adopted figure by the NGDC of the NOAA (for consistency with other earthquakes); this is the figure reported by the Haitian government. Some sources suggest a lower figure of 220,000. In the latter case, this event would fall to 7th place in the above rankings.

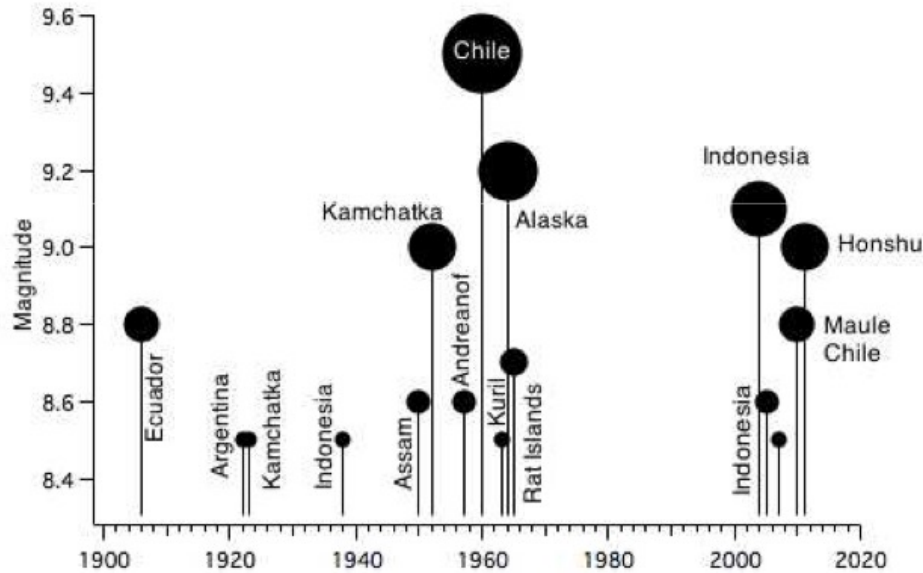
Data source: National Geophysical Data Center / World Data Service (NGDC/WDS): Significant Earthquakes Database, National Geophysical Data Center, NOAA. This is a visualization from OurWorldInData.org, where you find data and research on how the world is changing.

Licensed under CC-BY-SA by the authors Hannah Ritchie and Max Roser.

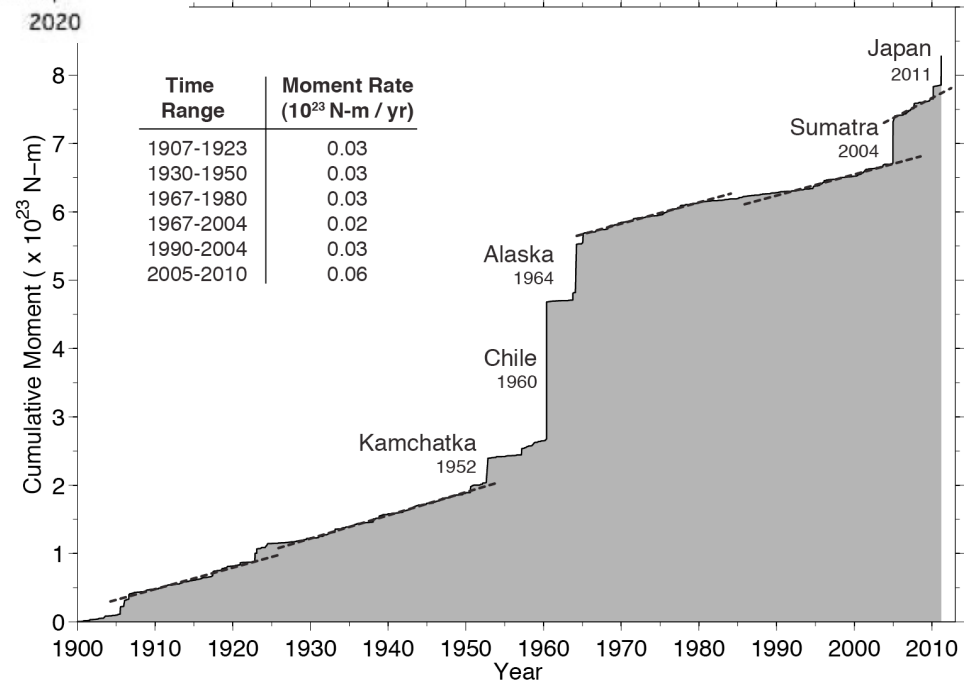
Une relation entre magnitude et dégâts?



La sismicité est aléatoire et imprévisible

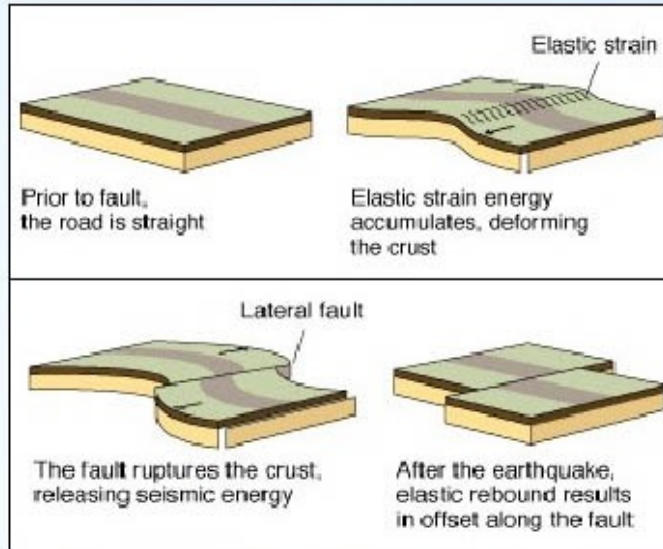


Shallow Earthquakes (Depth ≤ 100 km), Magnitude ≥ 7.0

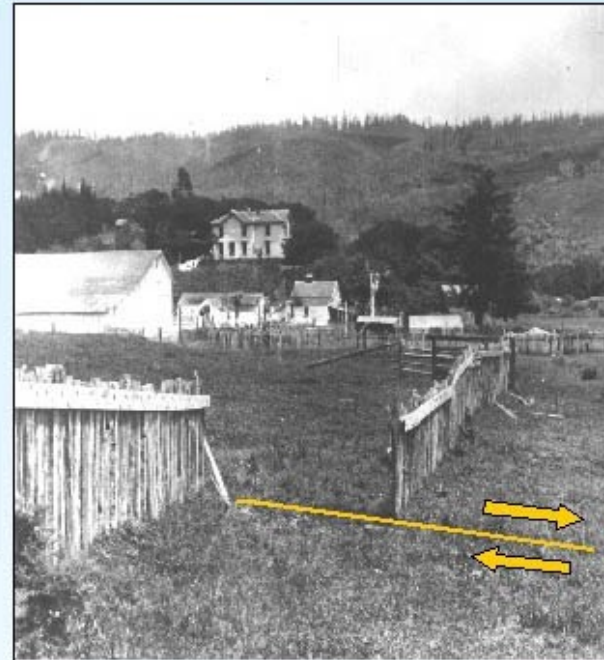


Lay 2015

À QUEL MOMENT LES SÉISMES SE PRODUISENT?



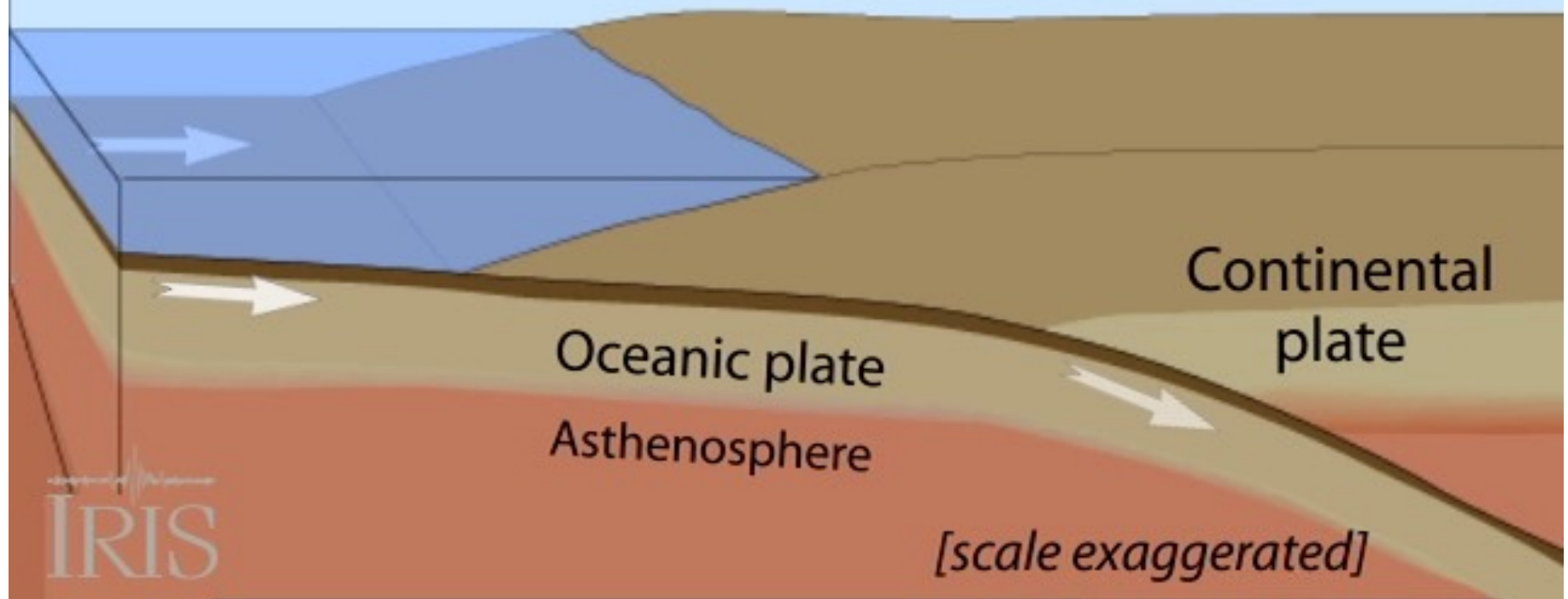
- Fence offset in 1906 quake on San Andreas Fault



Théorie du rebond élastique (Reid, 1910)

CYCLE SISMIQUE = Processus d'accumulation et de relaxation des contraintes

Elastic rebound in a subduction zone



Cycle sismique

Intersismique

Accumulation de contrainte (100-1000 ans), chargement

Présismique

comportement anormal juste avant un séisme (10mn - 10 ans)

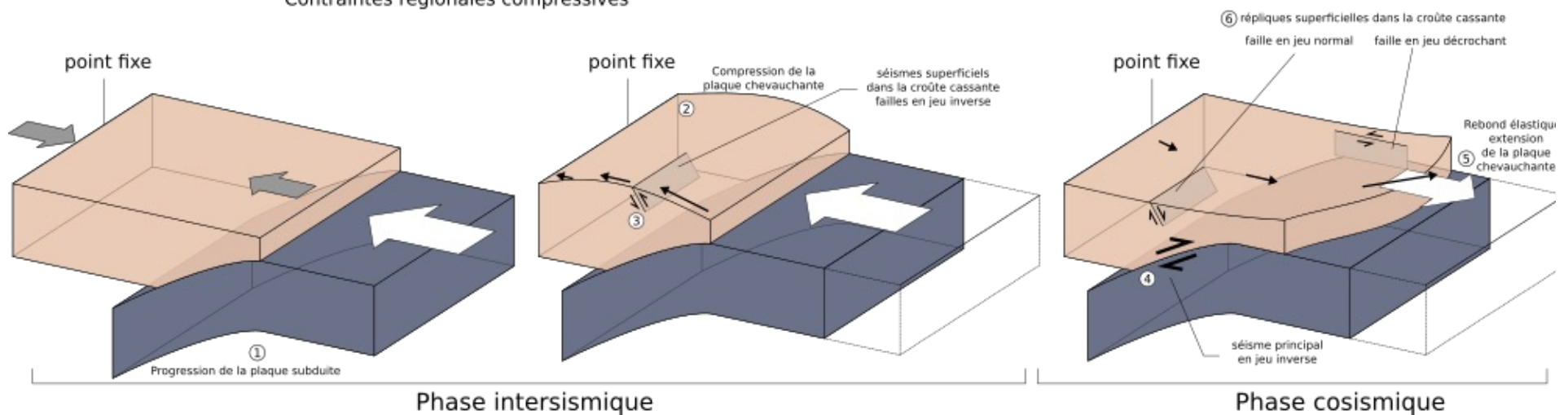
Cosismique

rupture, libération d'énergie (1-100s)

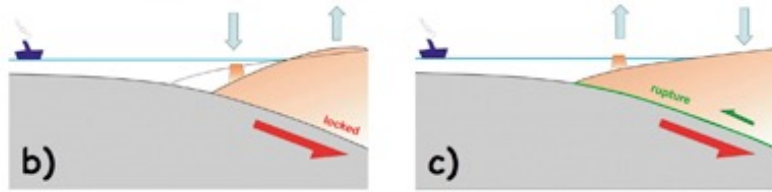
Postsismique

réajustement post-rupture (1jour - 10 ans)

Contraintes régionales compressives



Soulèvement & Subsidence

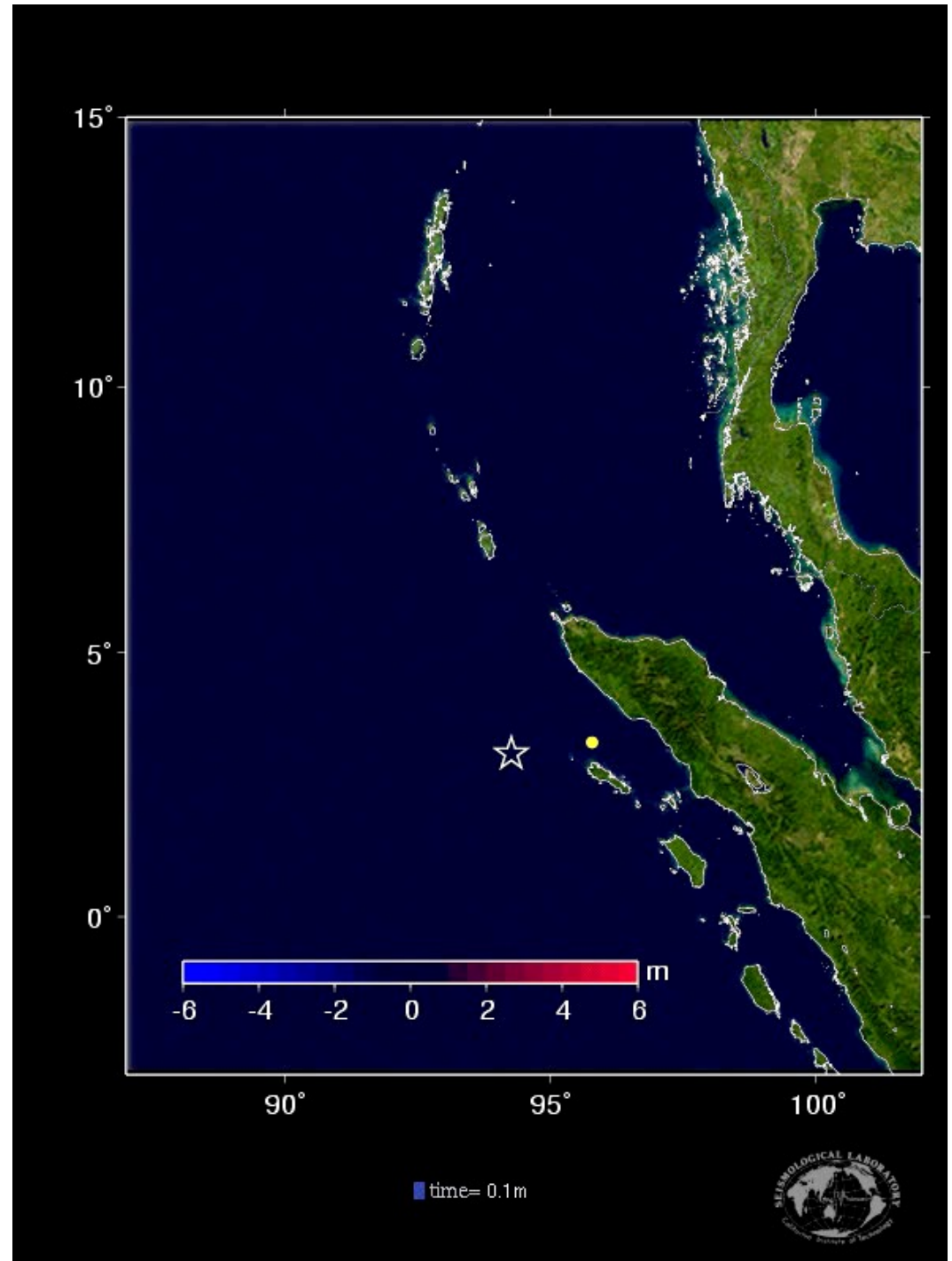


SUMATRA (MW 9.1) 2004

Déplacement en surface dû à la propagation de la rupture :

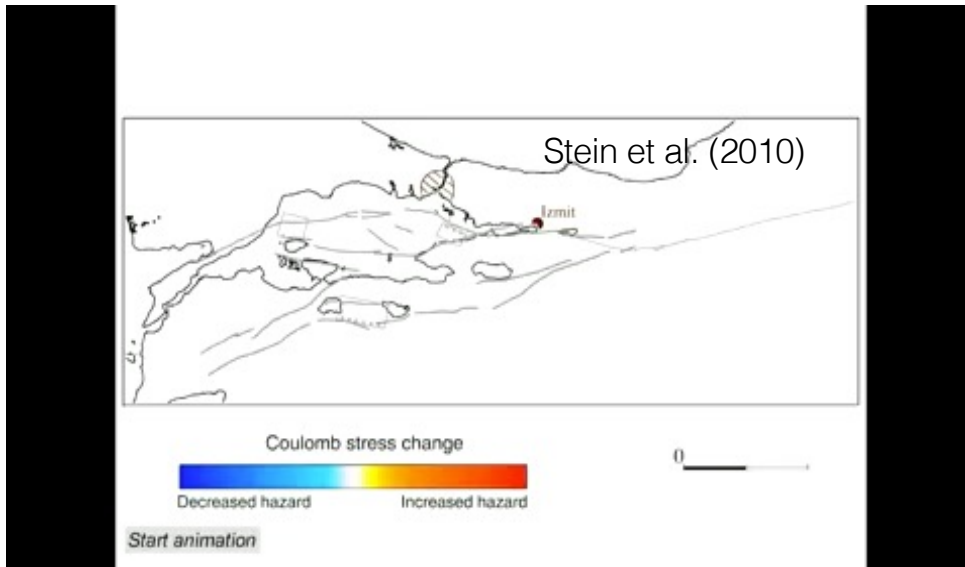
10 minutes
1500 km

Soulèvement (rouge)
Subsidence (bleu).
(source: Caltech)

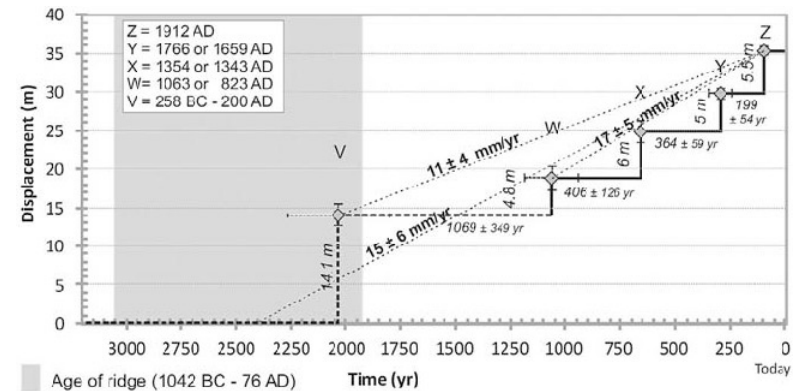


Cycle sismique

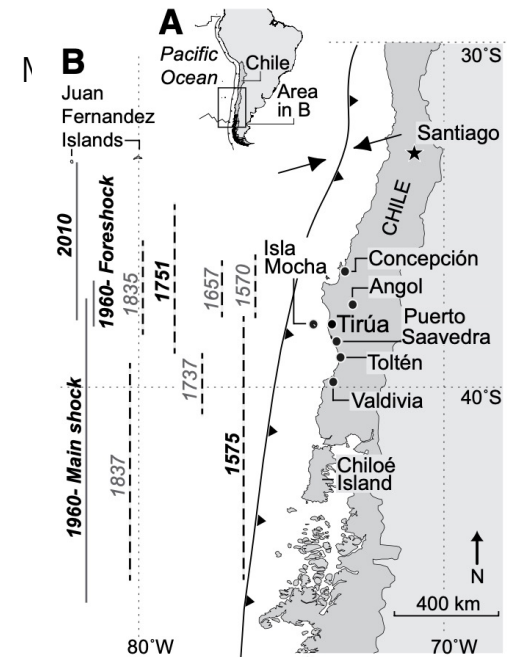
Cycle signifie-t-il périodicité et donc prévision ?



Contraintes de Coulomb



Paléosismologie
Sismologie historique



100 ans d'instrumentation...
Séismes lents, trémors,
glissement asismique...

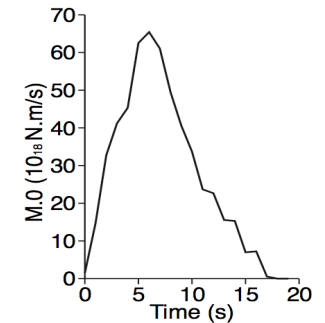
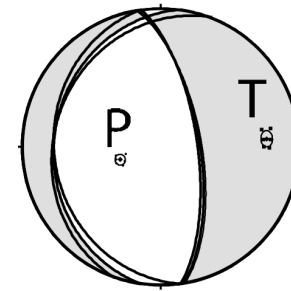
Etudes de la Source des Séismes

1) Localisation

Détermination du Moment, Magnitude

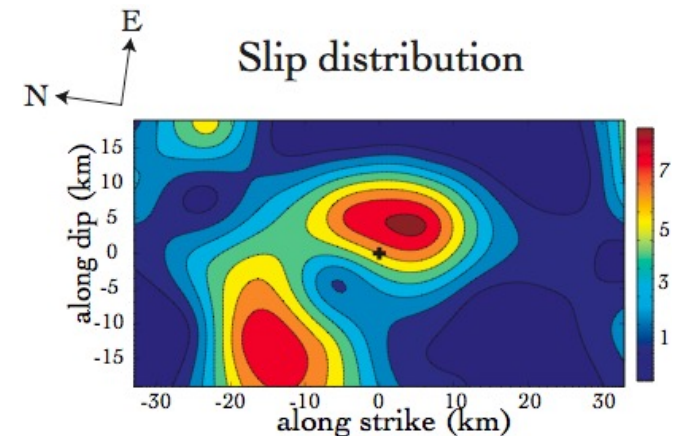
2) Mécanisme focal

Fonction Source Temporelle



3) Détails de la rupture:

Glissement et vitesse de glissement sur la faille



1st warning assumes sudden slip on a small area



IRIS

Tokyo

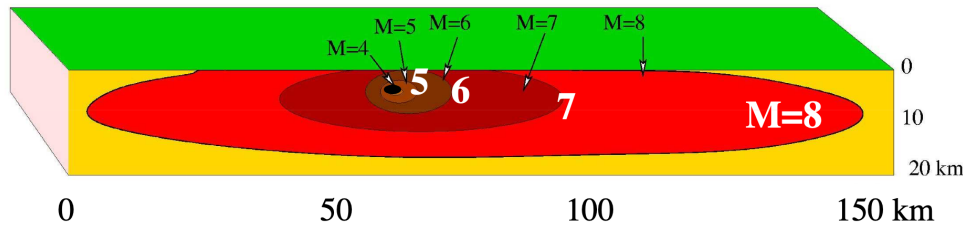
www.iris.edu/earthquake

Loi d'échelle des grands séismes

MAGNITUDES

ET LONGUEUR DE RUPTURE

SUR LES FAILLES



Magnitude 4 = 1 km - ressentie – pas de dommages

Magnitude 6 = 10-20 km – dommages aux structures

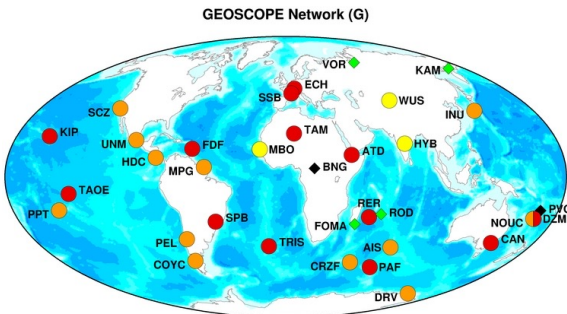
Magnitude 8 = 100-200 km – destructions généralisées

$$M_w = 2/3 \times \log(M_0) - 6$$

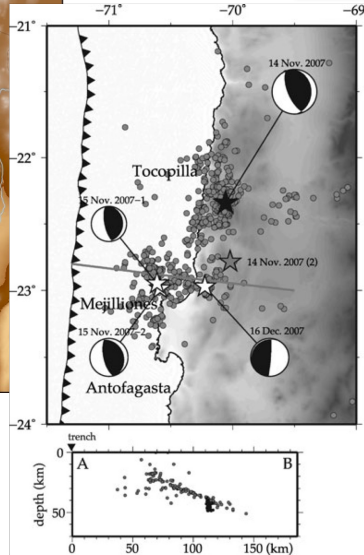
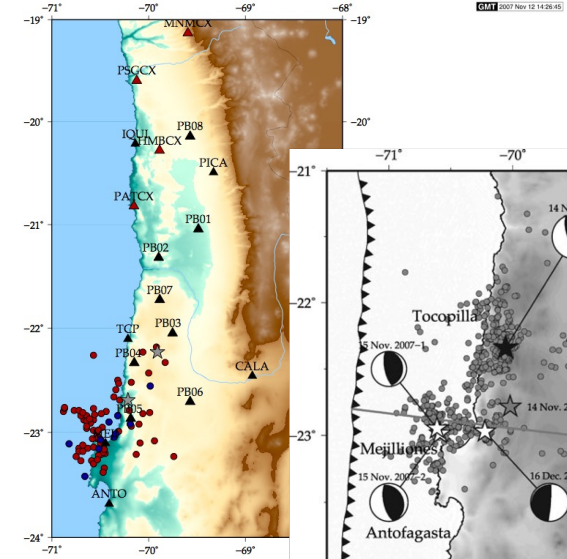
avec $M_0 = \mu \times S \times D$

- M_0 : moment sismique (en N.m)
- μ : rigidité du milieu (en N.m⁻²)
- D : glissement ou déplacement moyen sur la faille (en m)
- S : surface de la faille (en m²)

Magnitude (M_w)	Moment (Nm)	Longueur (km)	Durée (s)	Glissement (m)
10	10^{24}	1000?	300?	100?
9	3.10^{22}	300	100	30
8	10^{21}	100	30	10
7	3.10^{19}	30	10	3
6	10^{18}	10	3	1

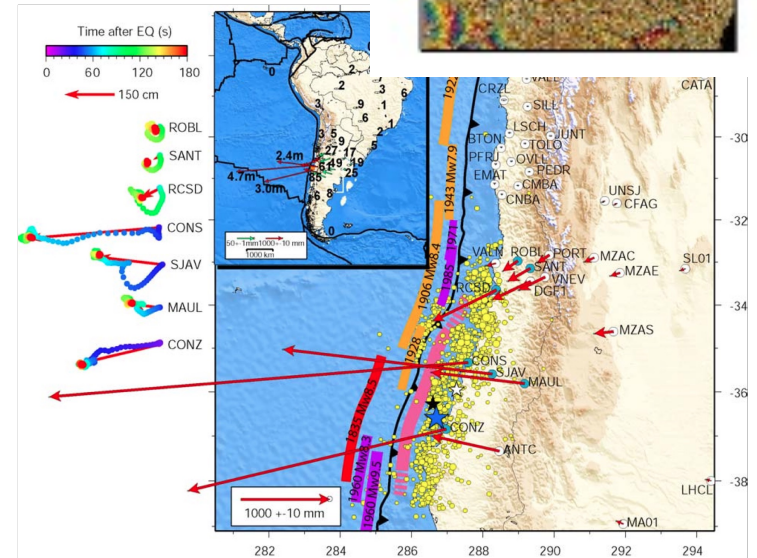
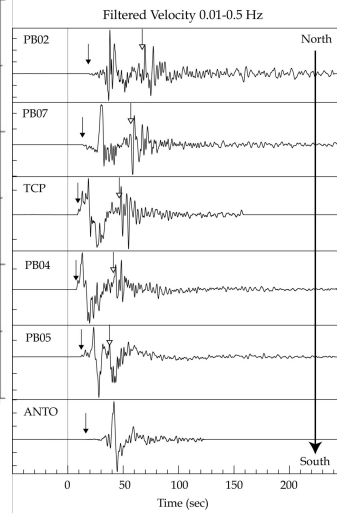


- real time / near-real time stations
- remotely accessible stations
- ◆ temporarily interrupted stations
- ◆ planned stations

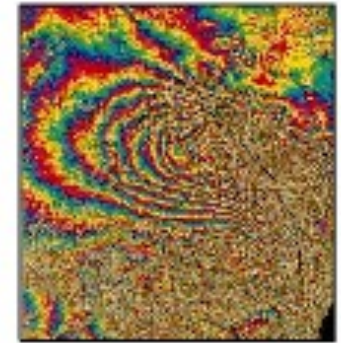


⇐ Données télésismiques

Données régionales et locales
⇐ Sismologiques, cGPS, InSAR ⇒



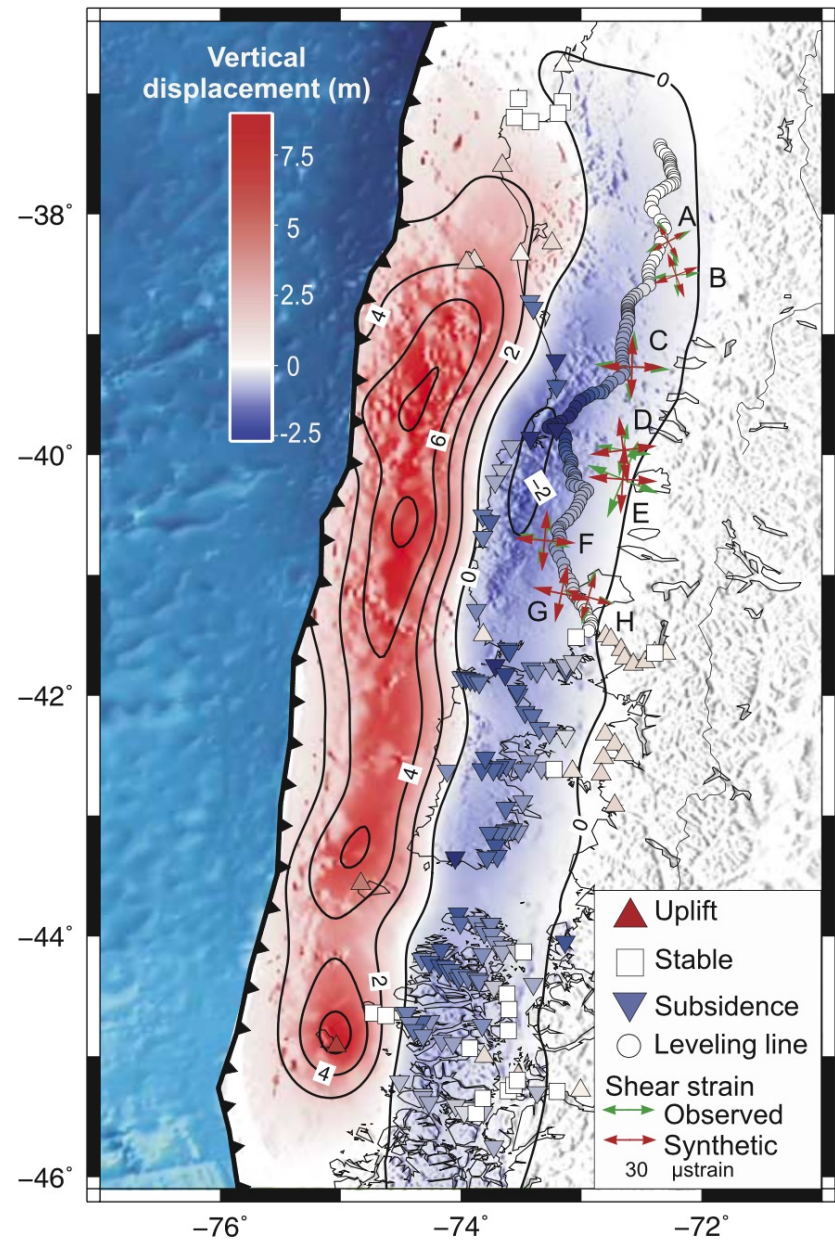
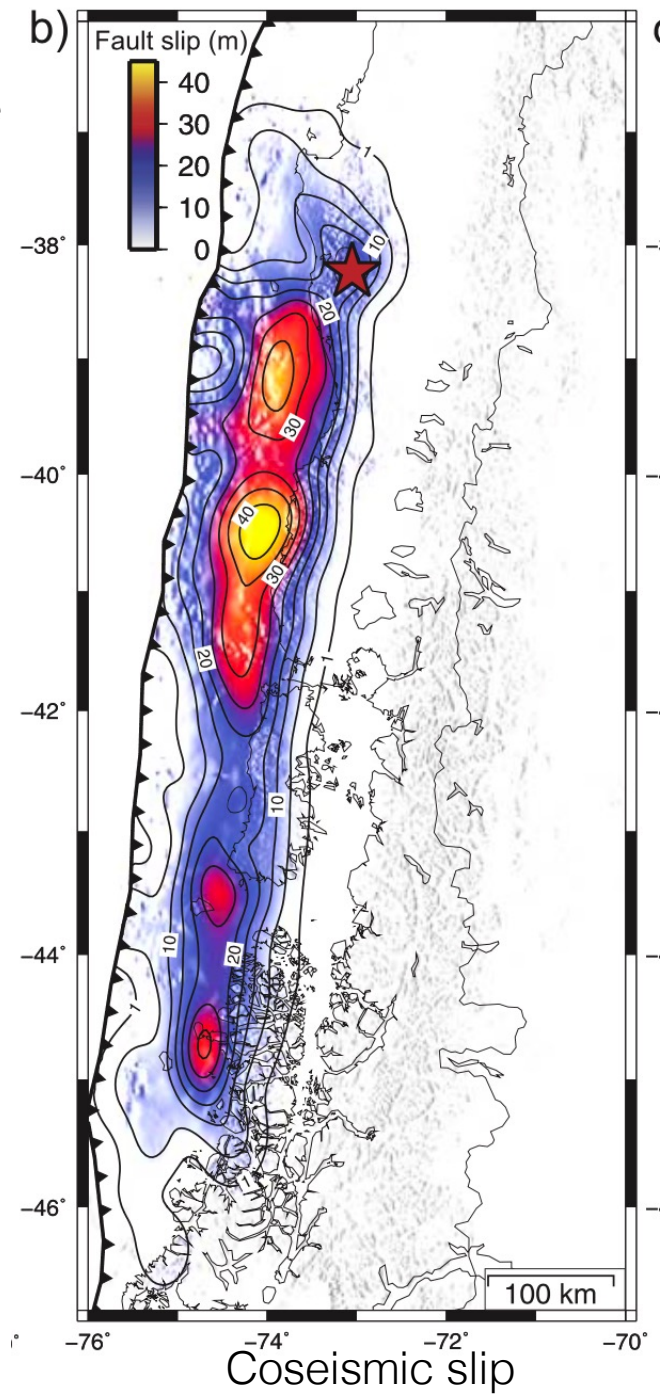
(f) Données InSAR



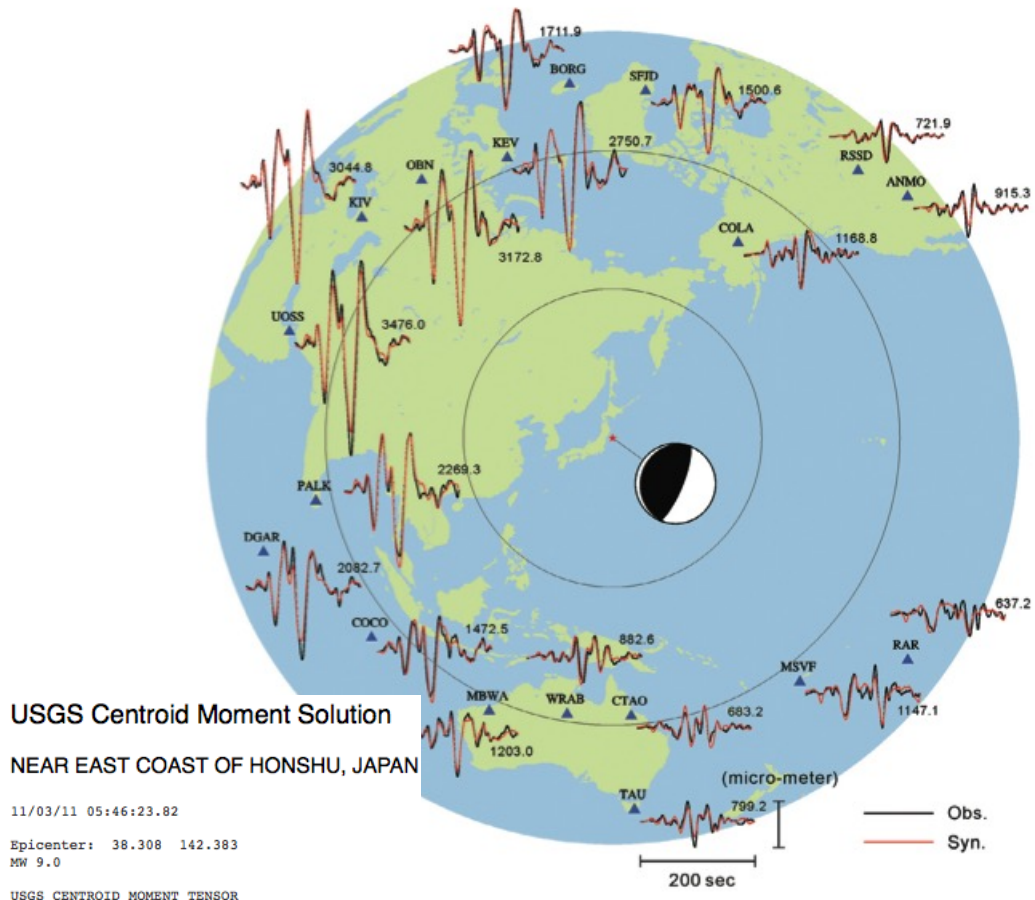
Données géologiques
(Trace en surface) ⇒



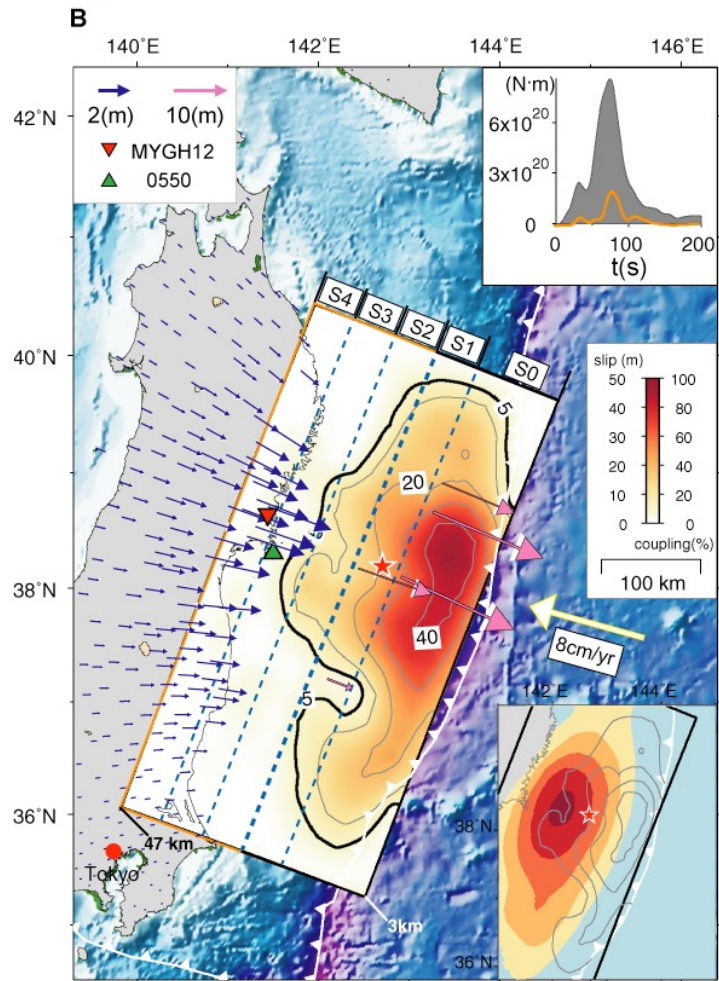
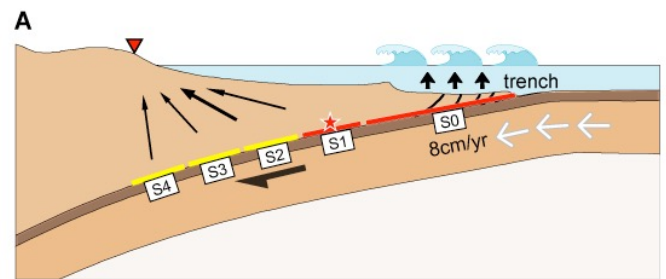
Chile
1960

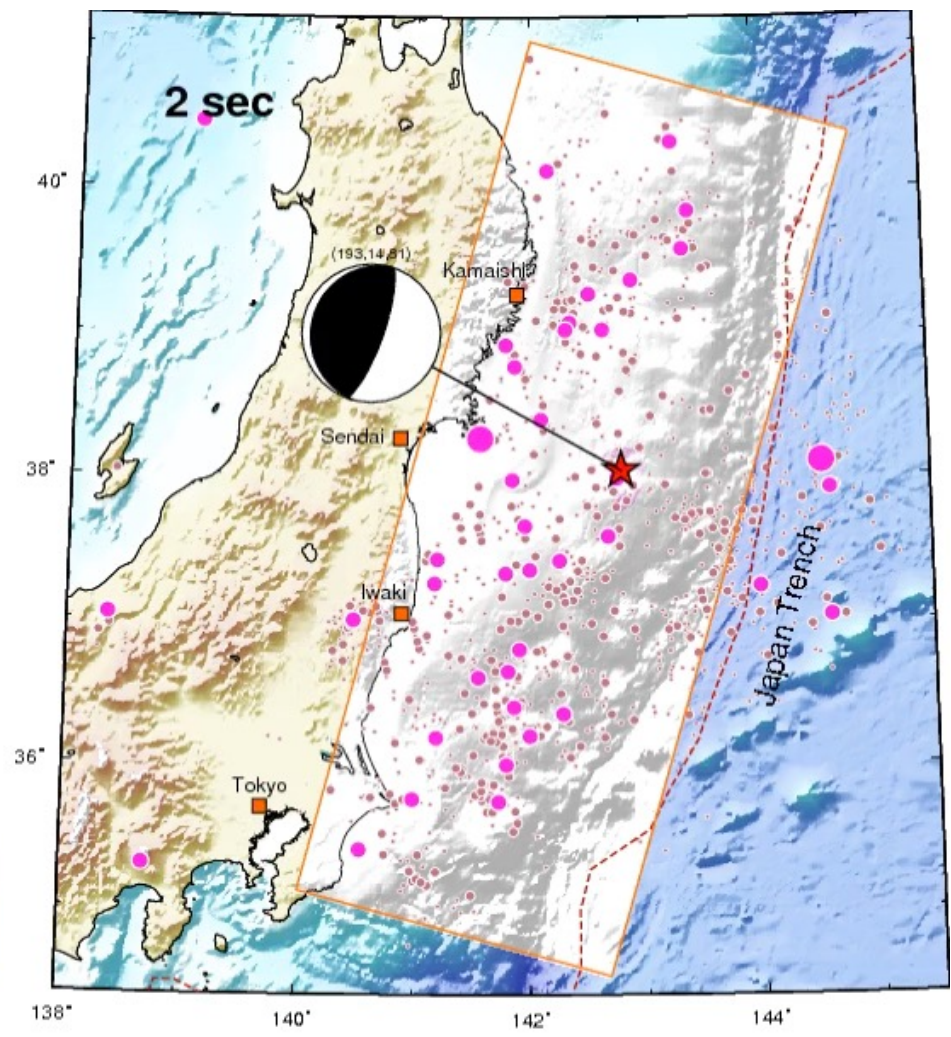
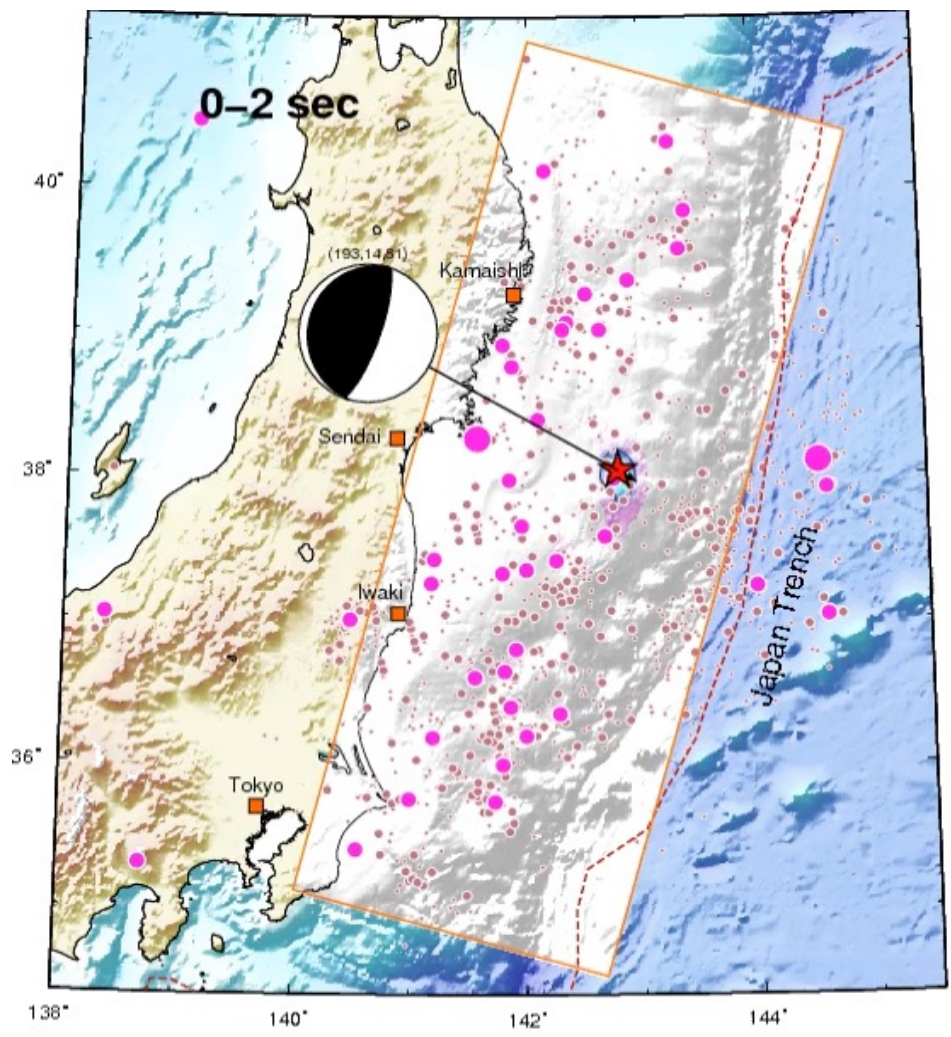


Coseismic surface deformation



Séisme de Tohoku (Japon 2011) Mw=9



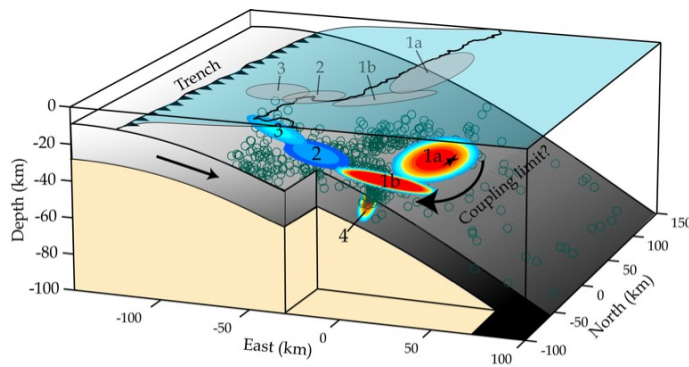


Ingrédients pour faire un mega-séisme

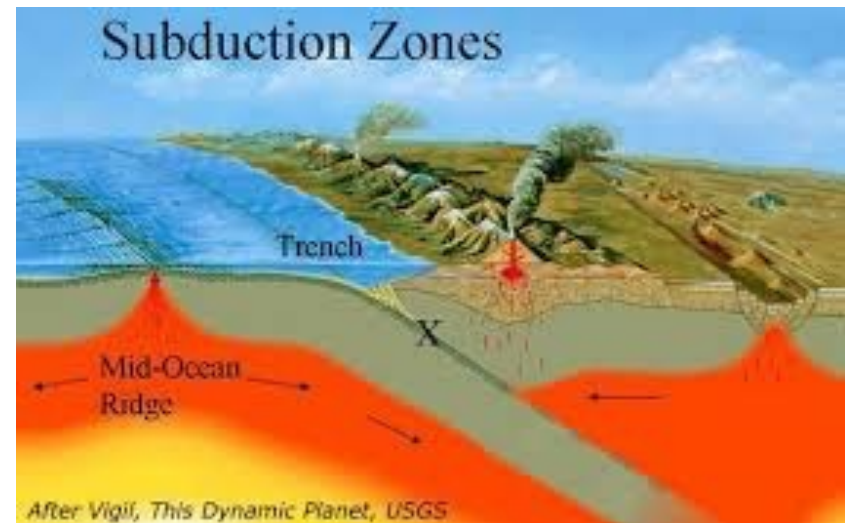
$M_w > 8.5$ si:



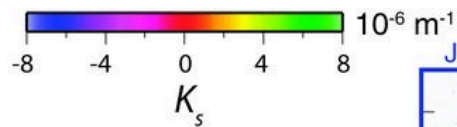
- grande surface de rupture
- déplacement important



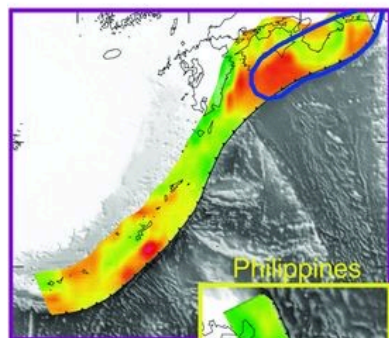
Glissement généré lors du séisme de Tocopilla (Chili 2007) et de ses plus grosses répliques



Décrochement ?

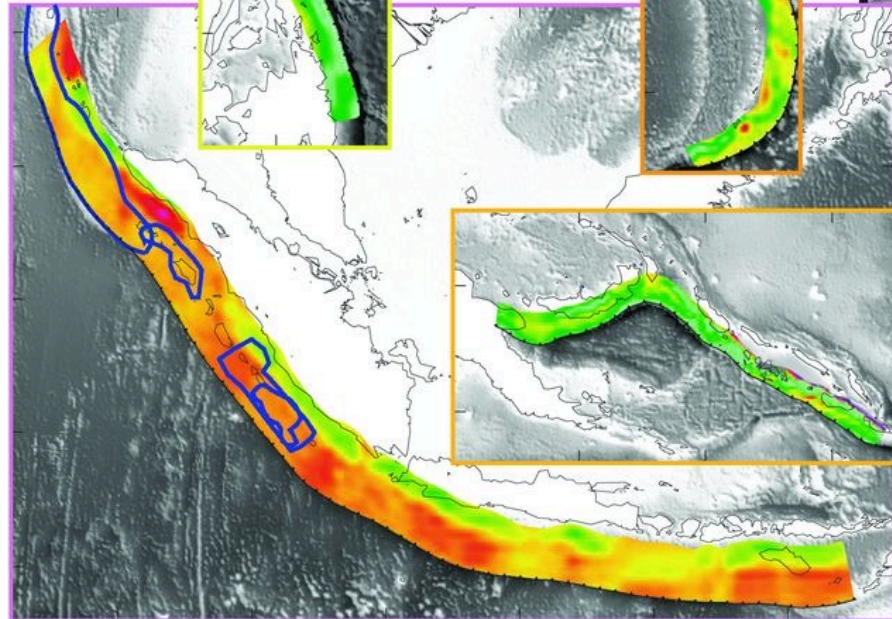


○ Historical $M \geq 8.5$ earthquake contours

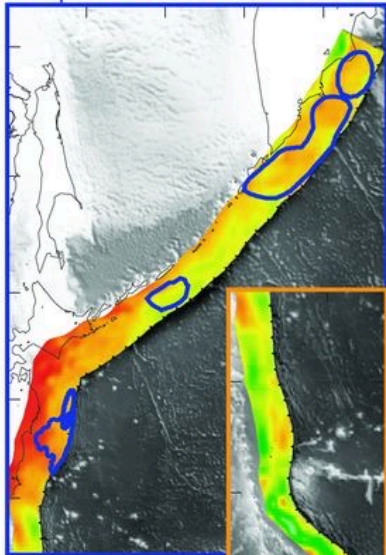


Ryukyu - Nankai

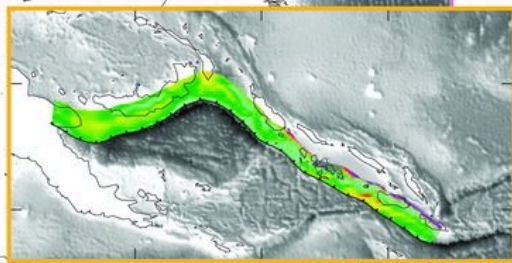
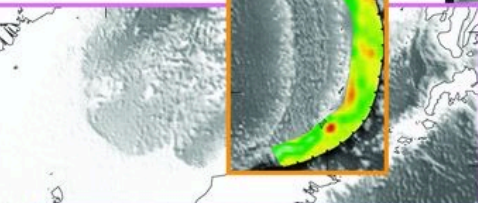
Sumatra - Java



Japan - Kuriles - Kamchatka



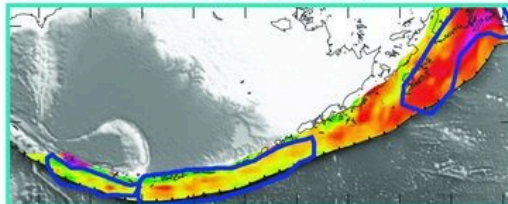
Izu - Bonin



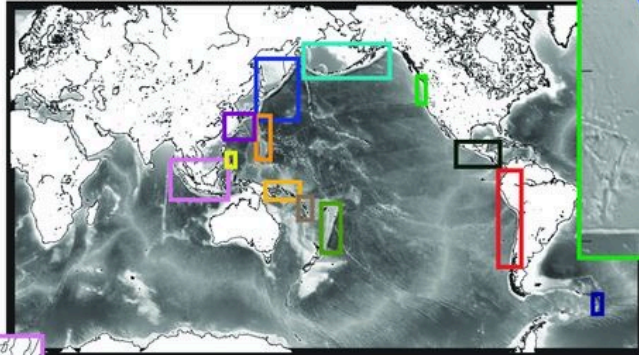
Solomon islands

Tonga - Kermadec

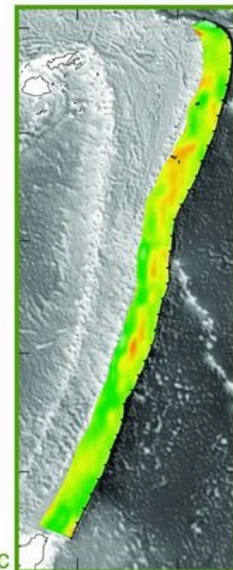
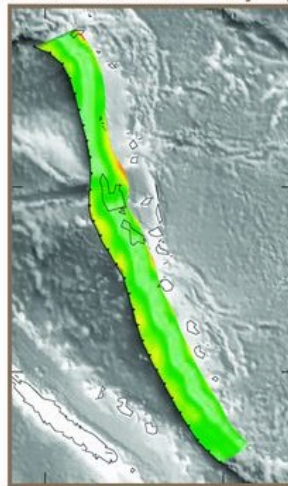
Alaska - Aleutians



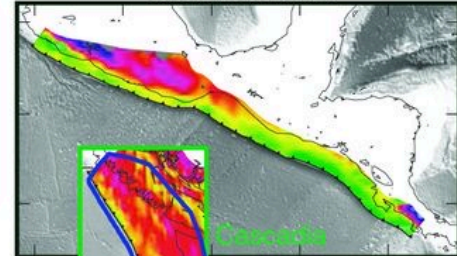
Subduction zones locations



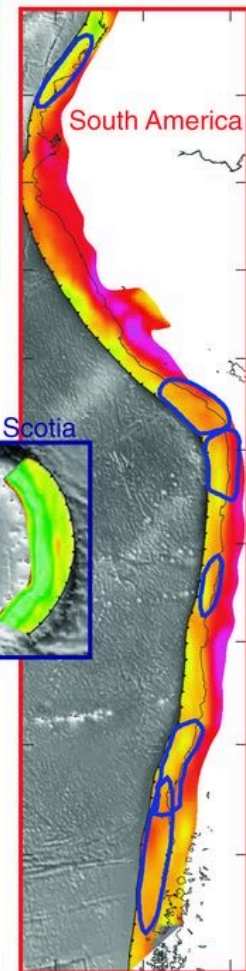
Santa Cruz - Vanuatu - Loyalty



Central America



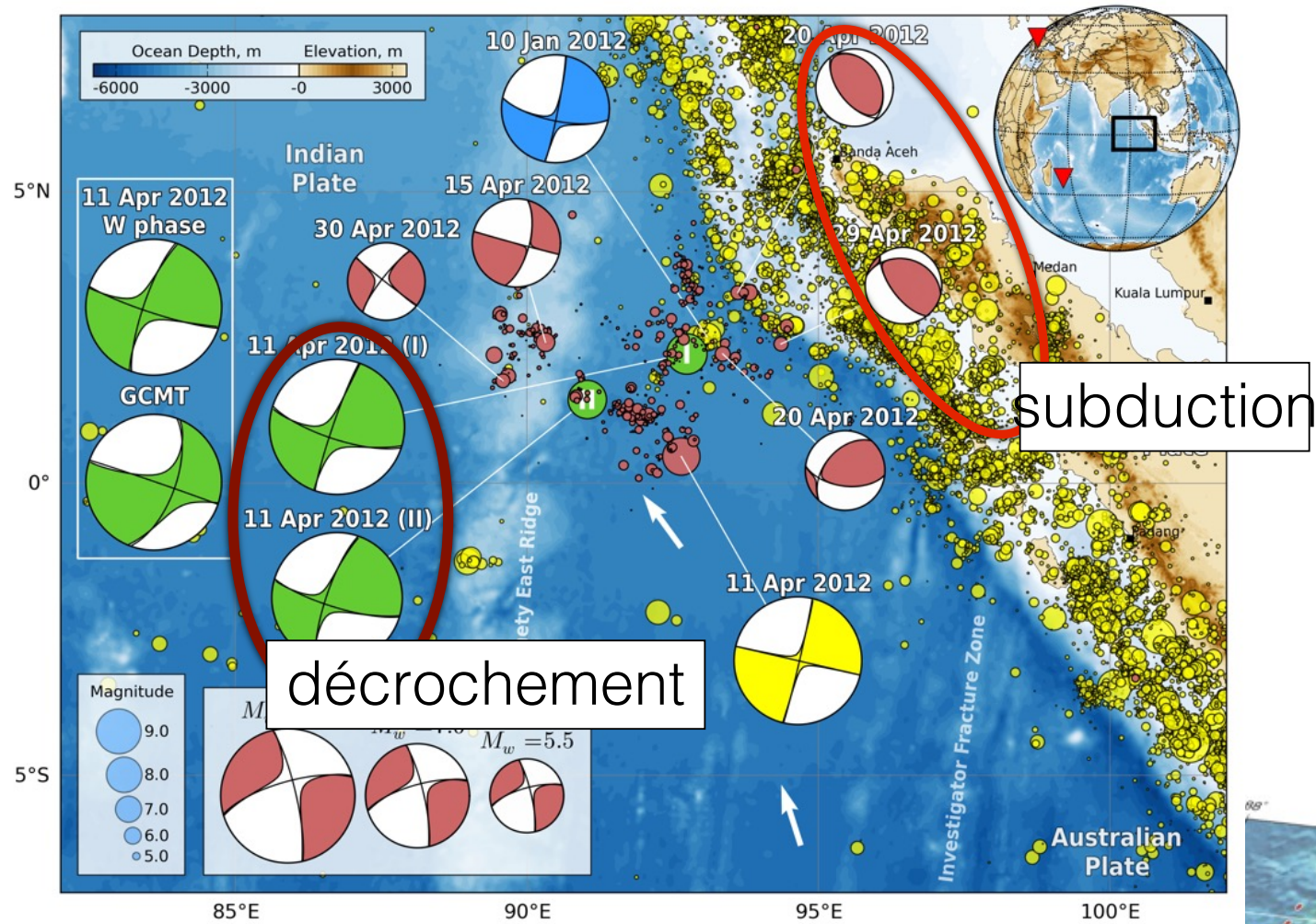
South America



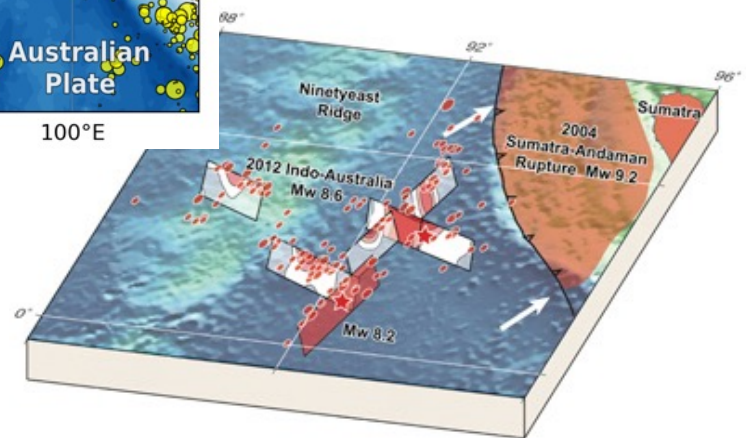
Scotia

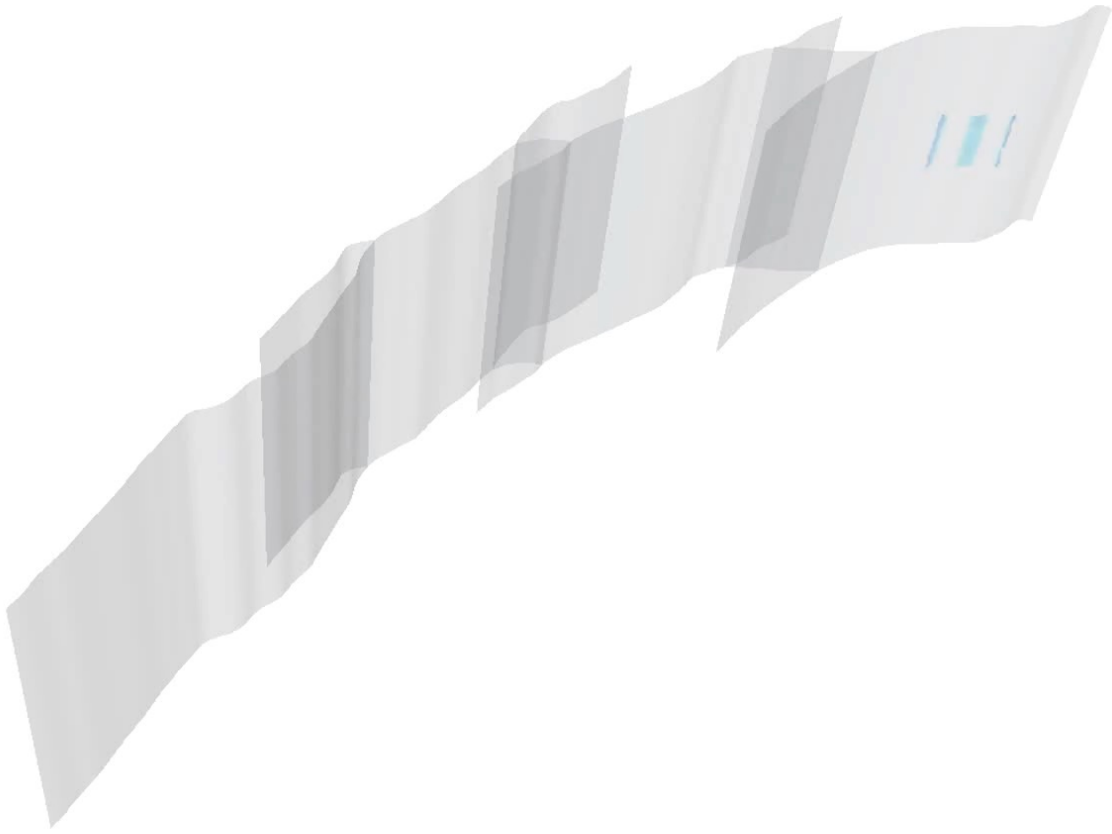


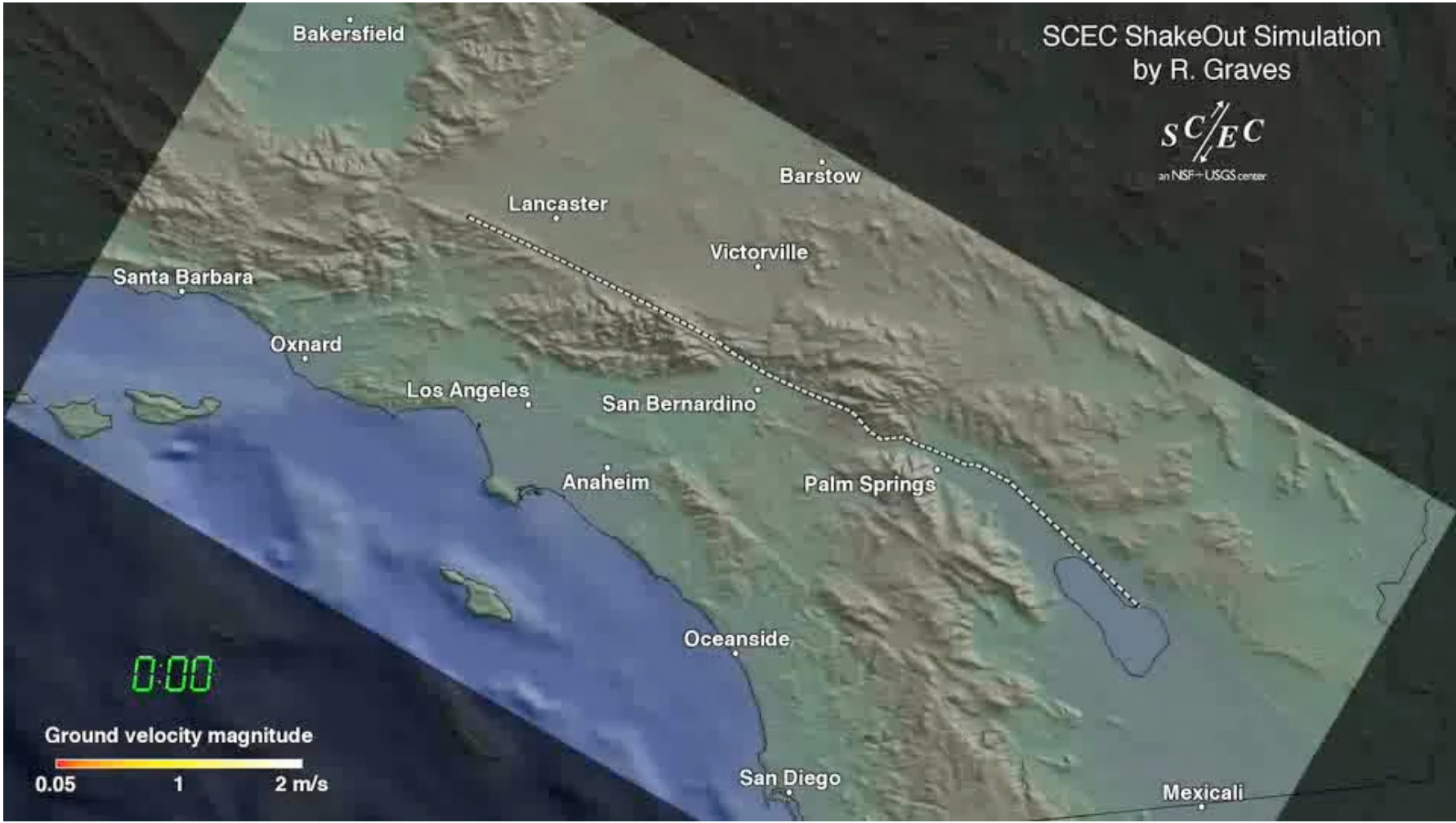
Exemple: les séismes de Sumatra le 11/04/2012, Mw 8.6



Duputel et al, 2012

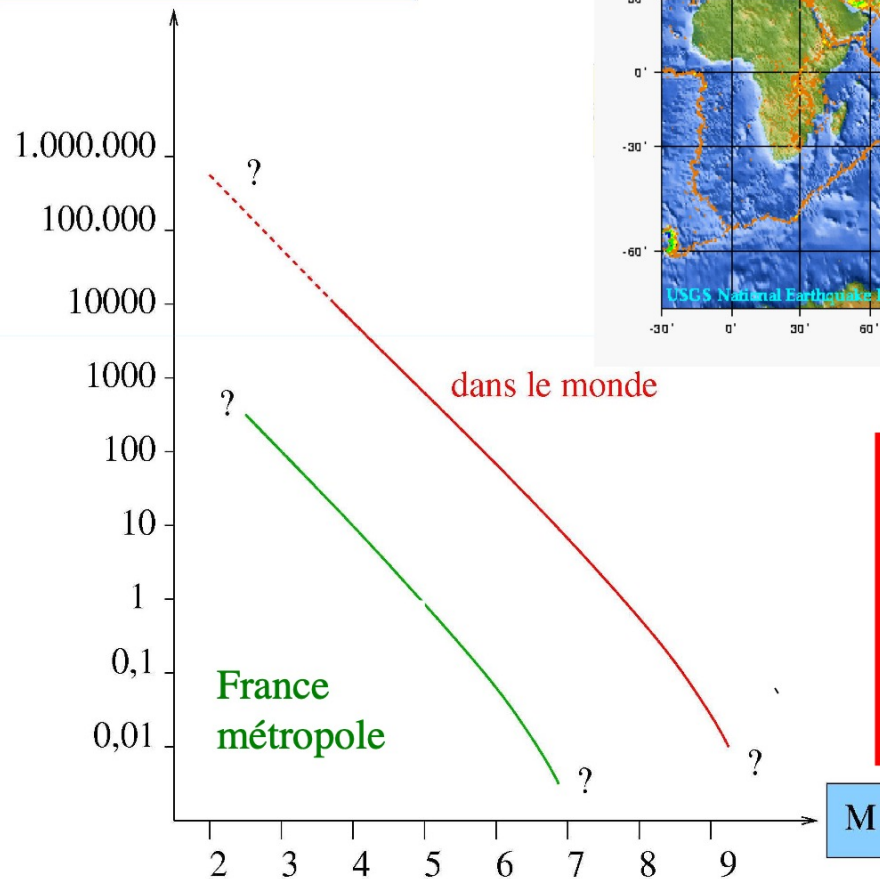




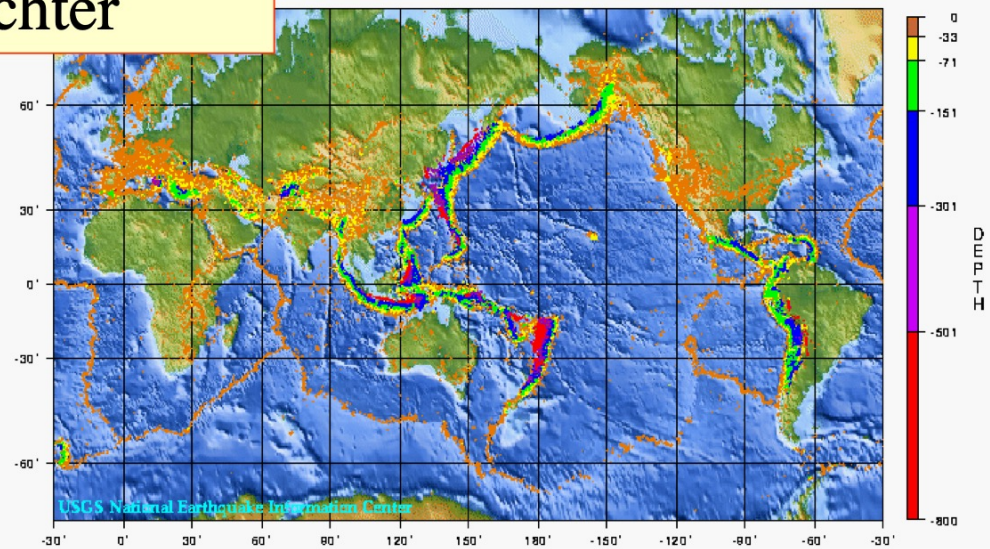


Loi de Gutenberg-Richter

Nombre de Séismes par an
magnitude > M



World Seismicity: 1975 - 1995



$$\text{Log} (N_s (>M)) = a - bM$$

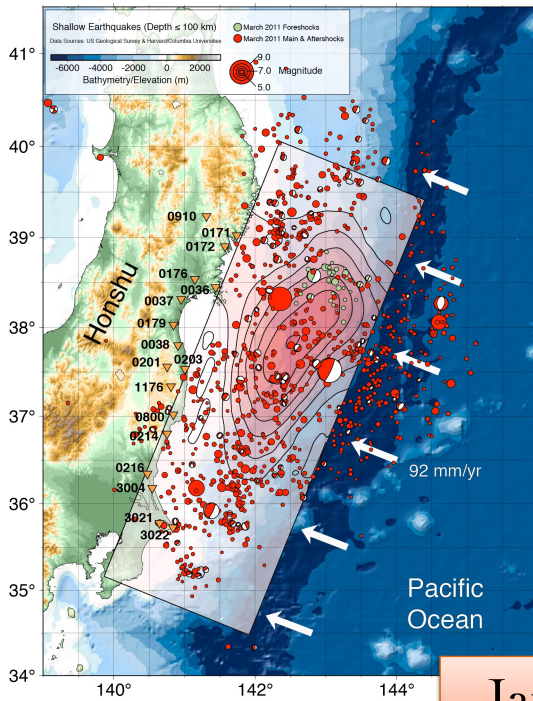
$$b = 1 \quad (0.5-1.5)$$

a dépend de la région étudiée

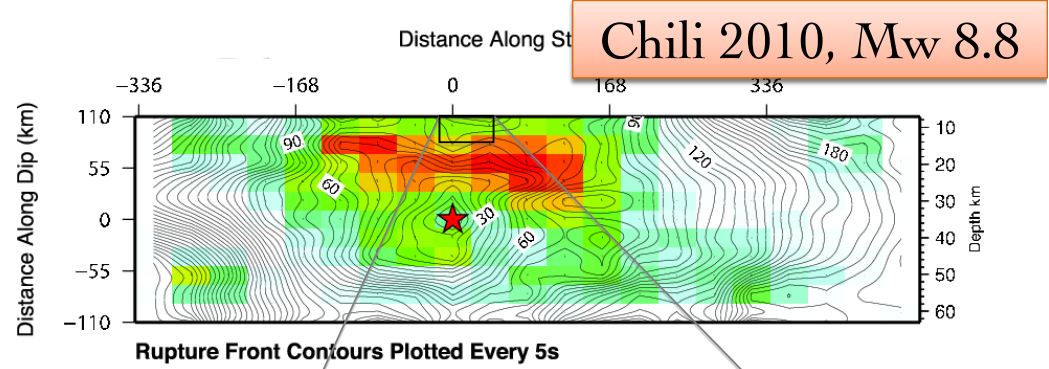
“CARTES”

DES GLISSEMENTS SUR LES FAILLES

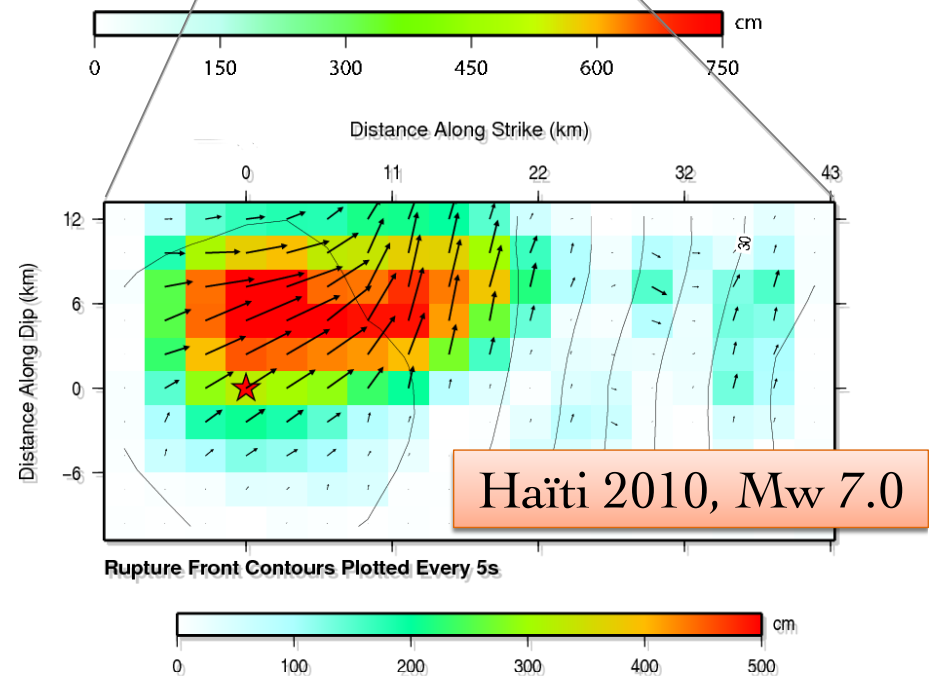
Glissement au chili seulement 50% plus grand, mais la faille est beaucoup plus grande 500 x plus d'énergie au Chili



Japon 2011, Mw 9.0



Chili 2010, Mw 8.8

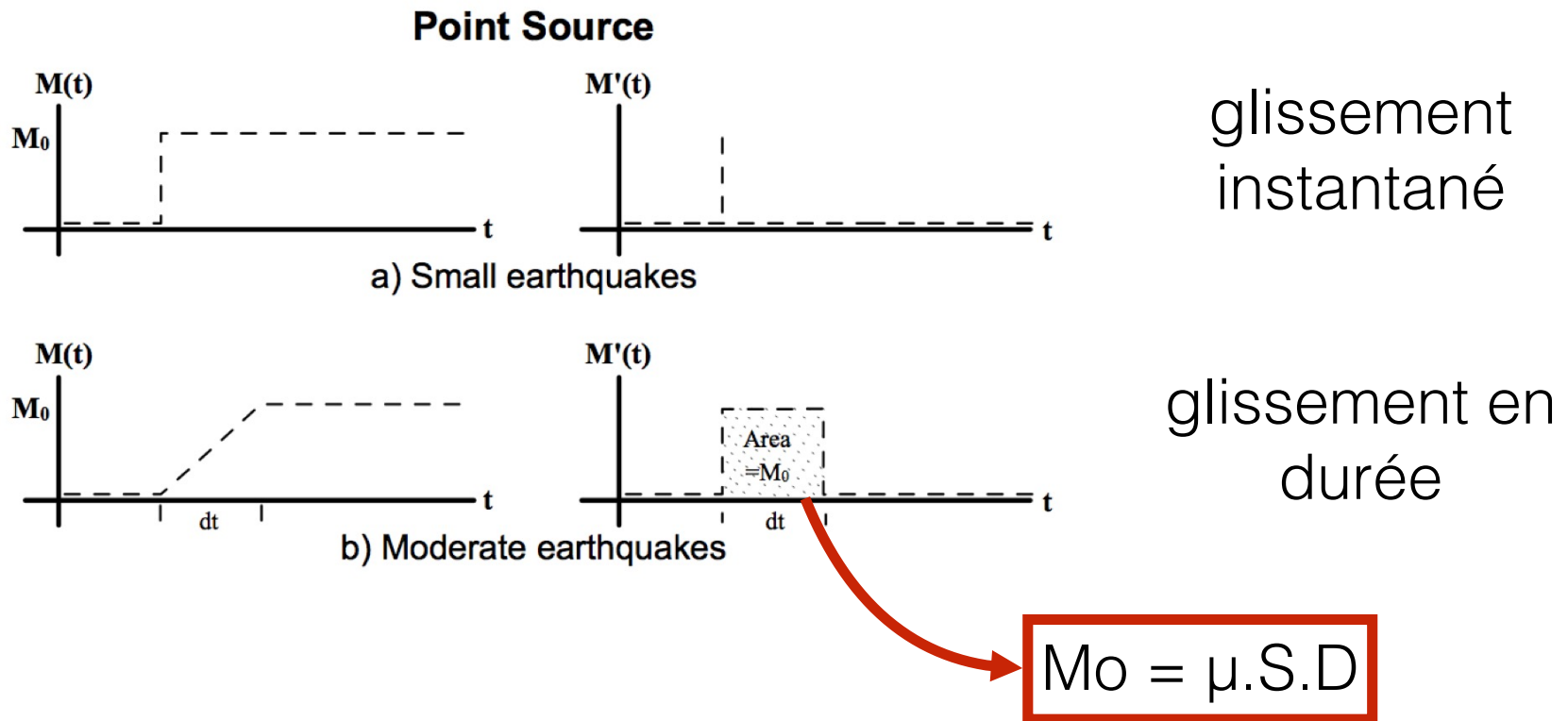


Haiti 2010, Mw 7.0

Images courtesy of the U.S. Geological Survey

Les mega-séismes sont-ils différents des petits?

Comment les failles glissent-elles ?



Propagation de la rupture

Les mega-séismes sont-ils différents des petits?

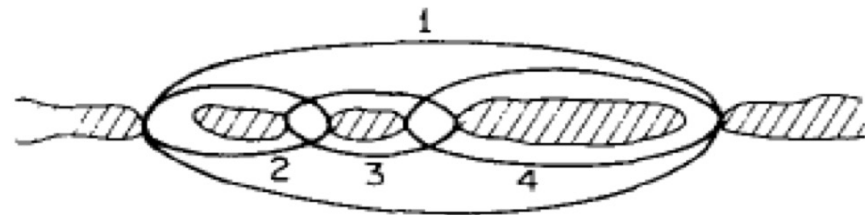
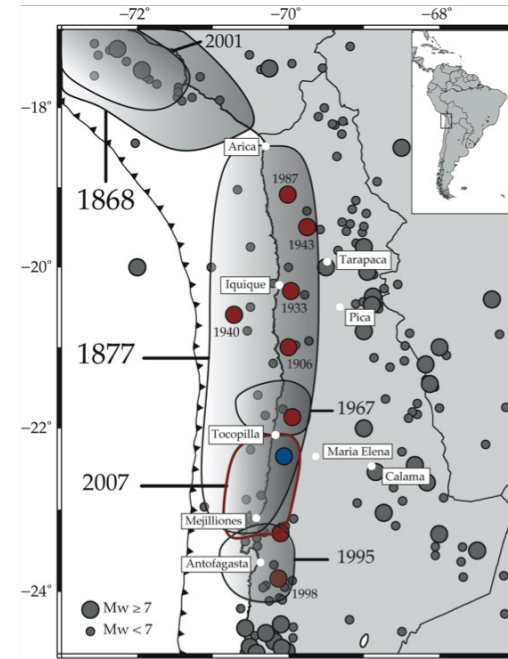
MODÈLE D'ASPÉRITÉ DANS LES ZONES DE SUBDUCTIONS

ANALYSE DE LA SISMICITÉ ET MODÈLE D'ASPÉRITÉ

Un explication simple est que les longueurs de la rupture et les glissements varient d'un cycle à l'autre:

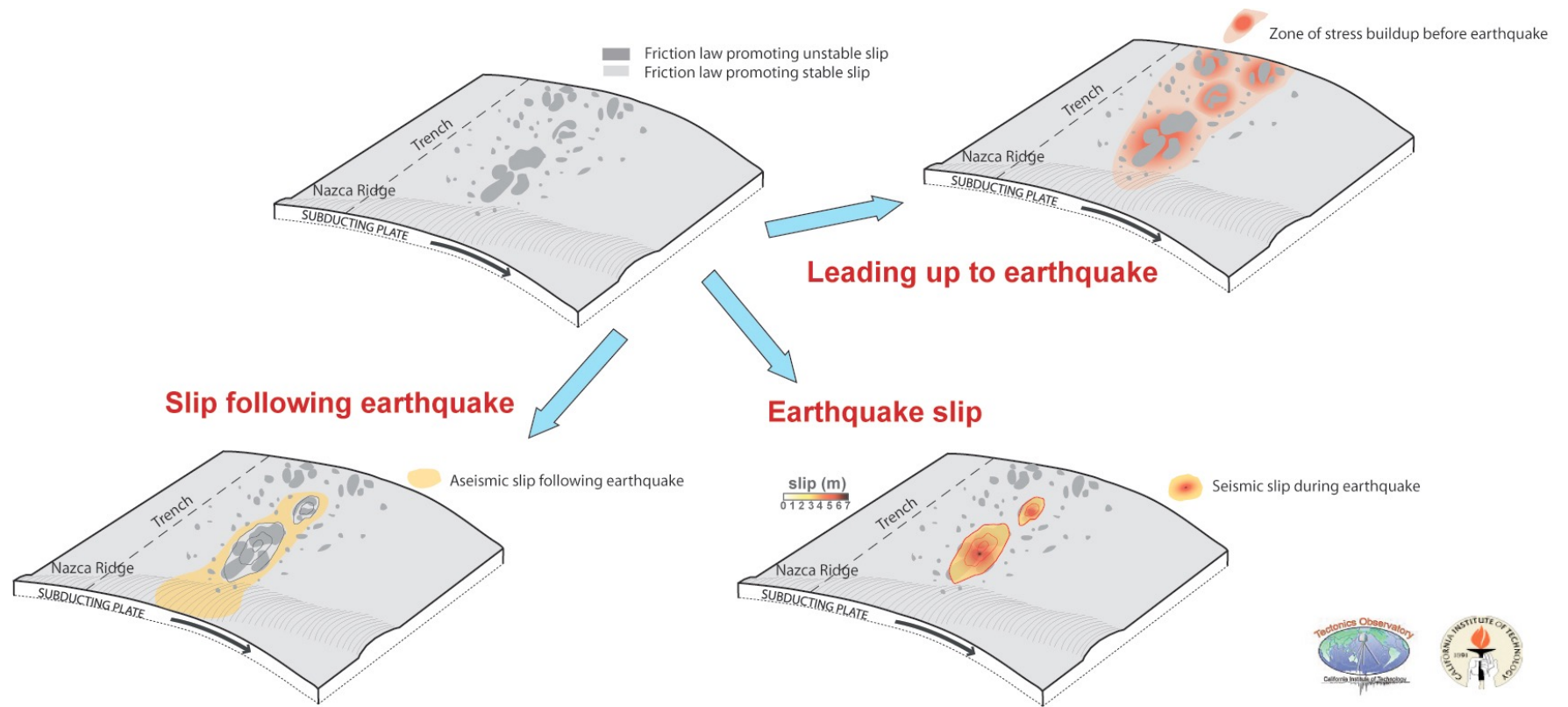
Petit séisme -> une aspérité.

Grand séisme -> plusieurs aspérités selon leur degré d'interactions.

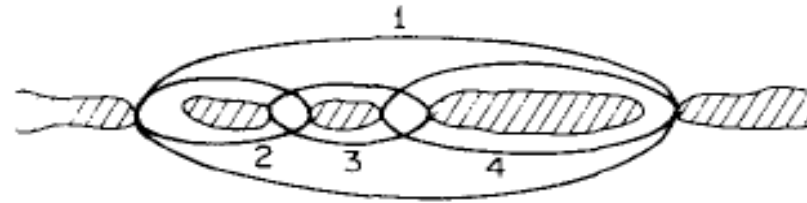


$$M_1 > M_2 + M_3 + M_4, \quad D_1 > D_i, \quad i = 2, 3, 4$$

Kanamori and McNally, 1982



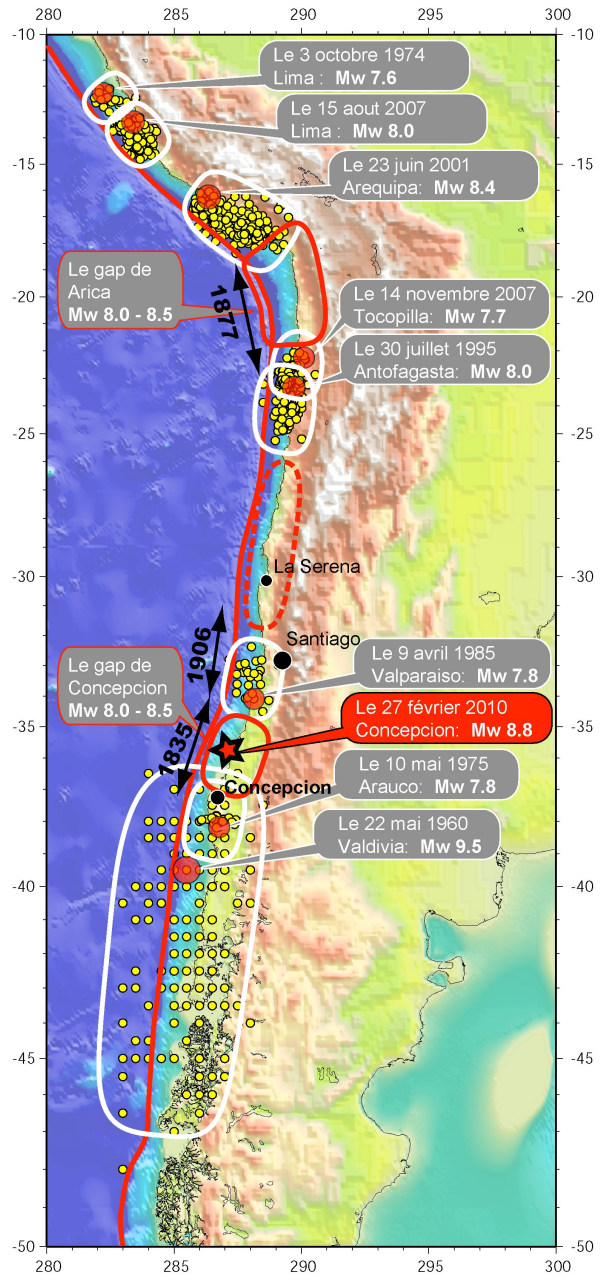
MODÈLE D'ASPÉRITÉ



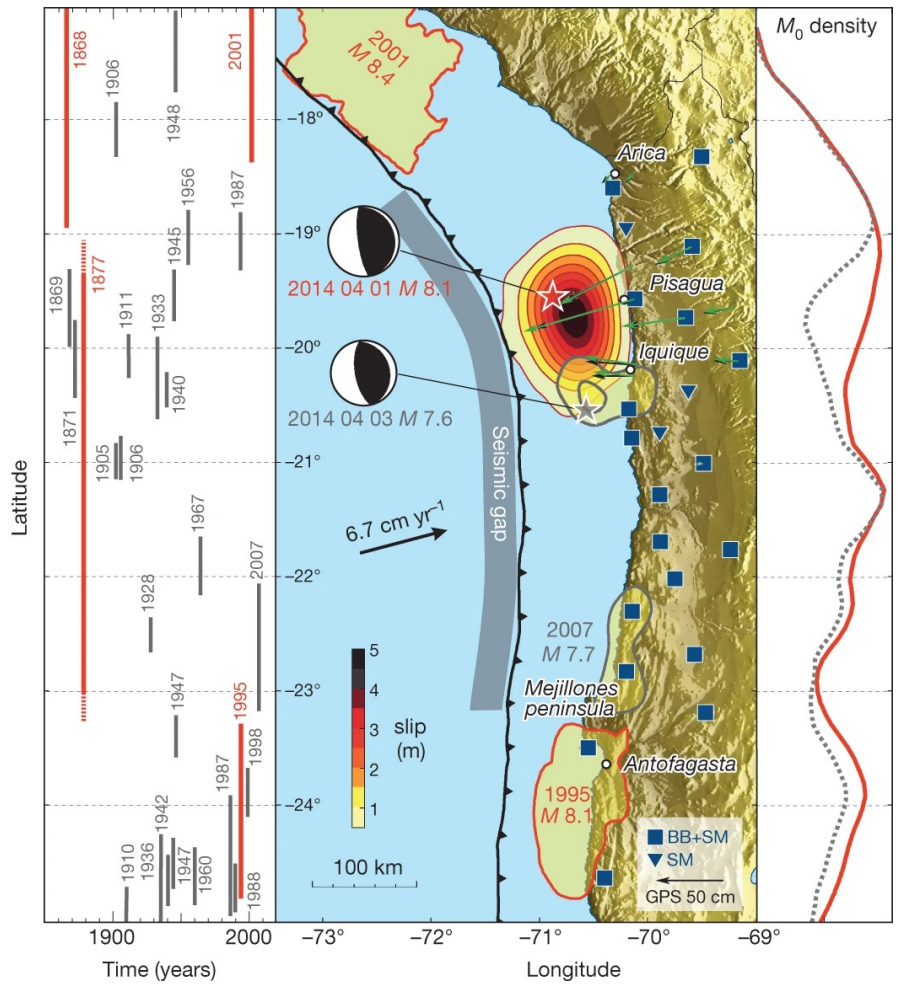
$$M_1 > M_2 + M_3 + M_4, \quad D_1 > D_i, \quad i = 2, 3, 4$$

Kanamori and McNally, 1982

Les mega-séismes sont-ils différents des petits?

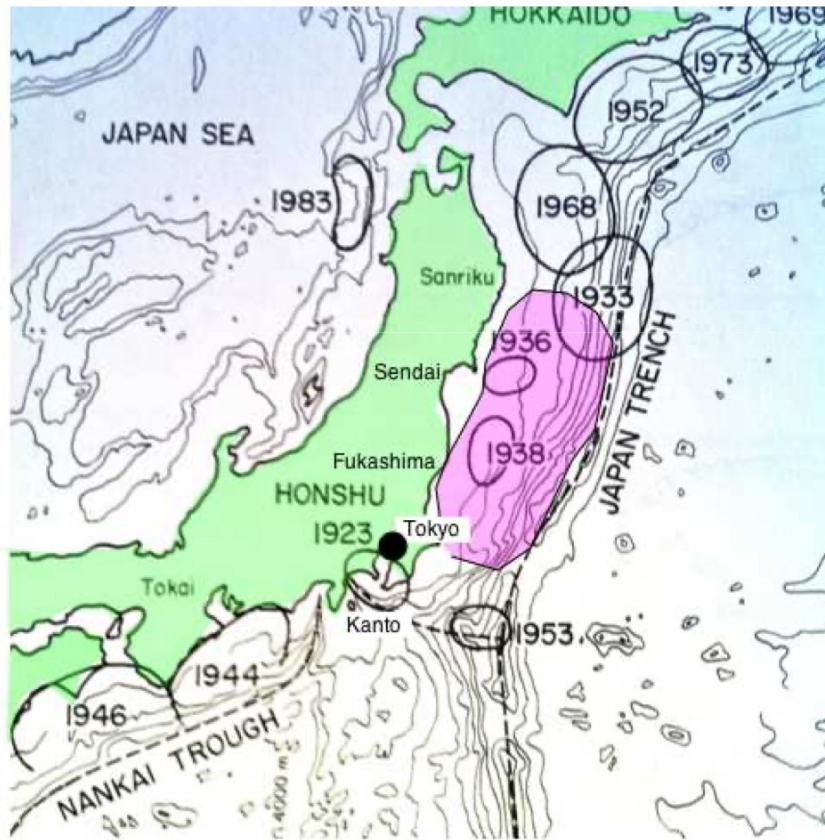


Modèle d'aspérités ?



Les mega-séismes sont-ils différents des petits?

Modèle d'aspérités ?

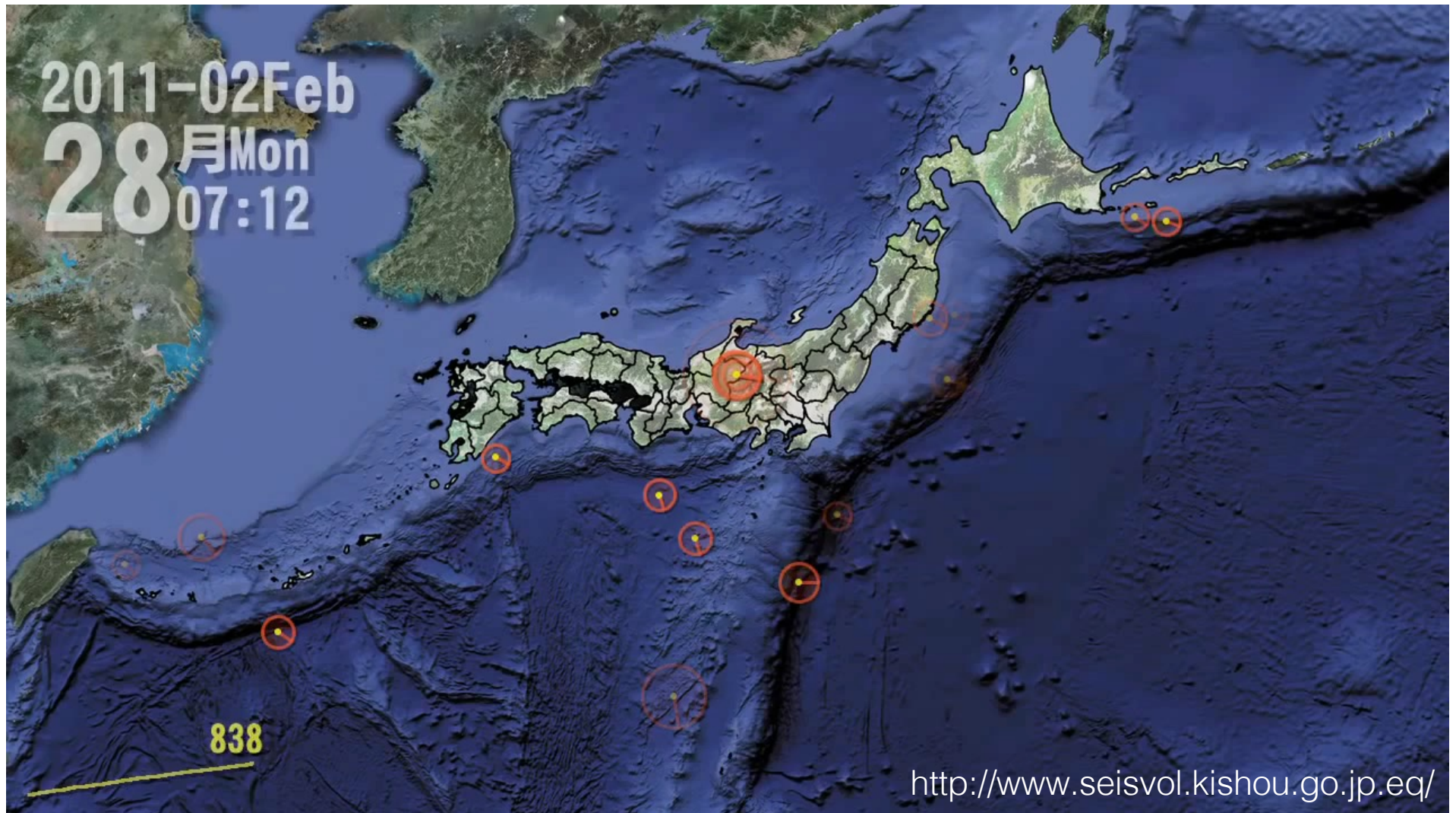


Surface de rupture $M_w > 8.0$
depuis le XXème siècle

Séisme de Tohoku (2011, $M_w = 9.2$) reprend des zones ayant déjà rompu...

Les mega-séismes sont-ils différents des petits?

Un gros séisme est suivi par une succession de plus petits événements : les répliques



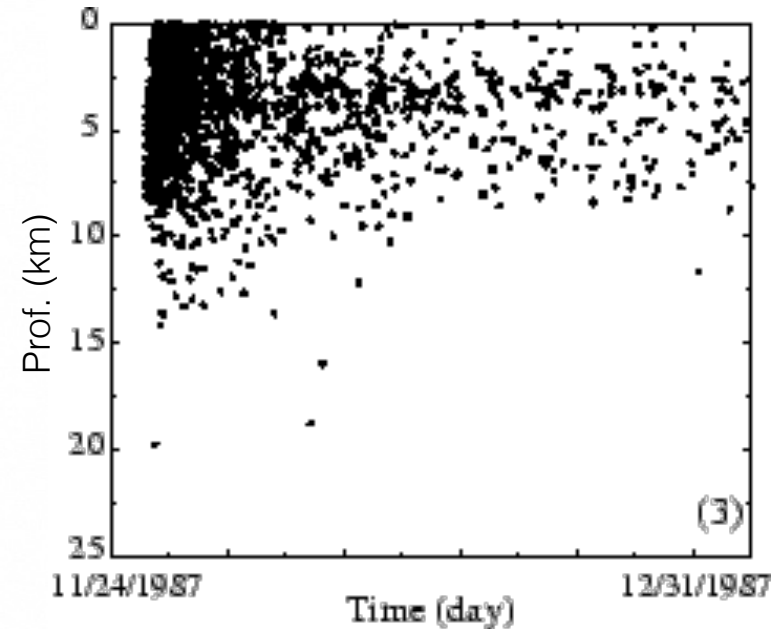
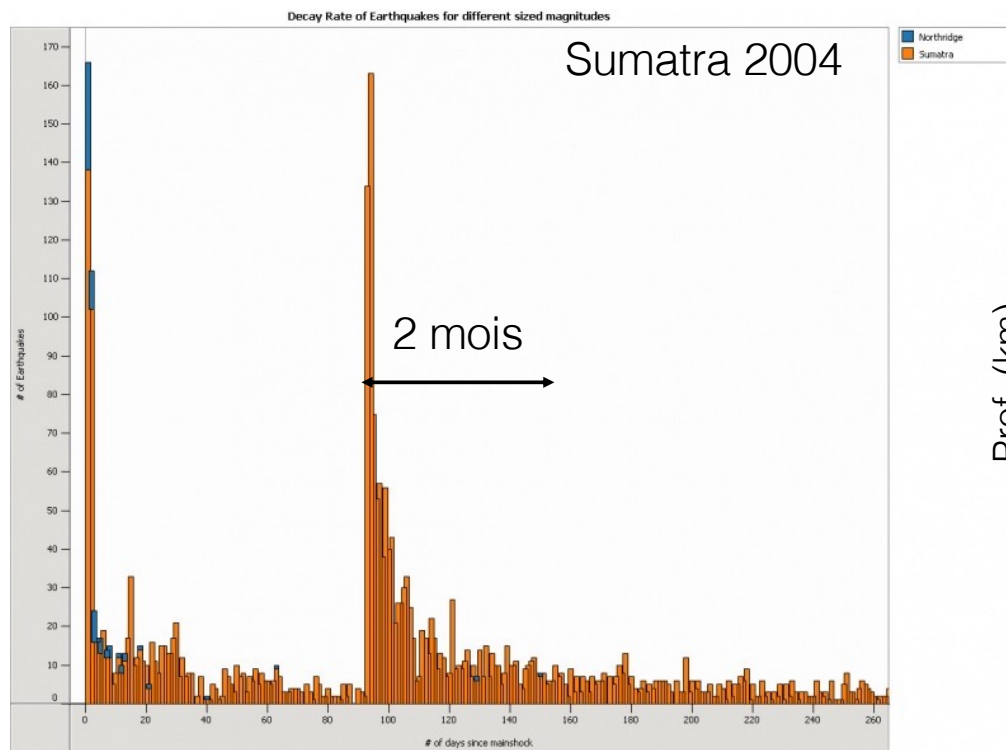
Les mega-séismes sont-ils différents des petits?

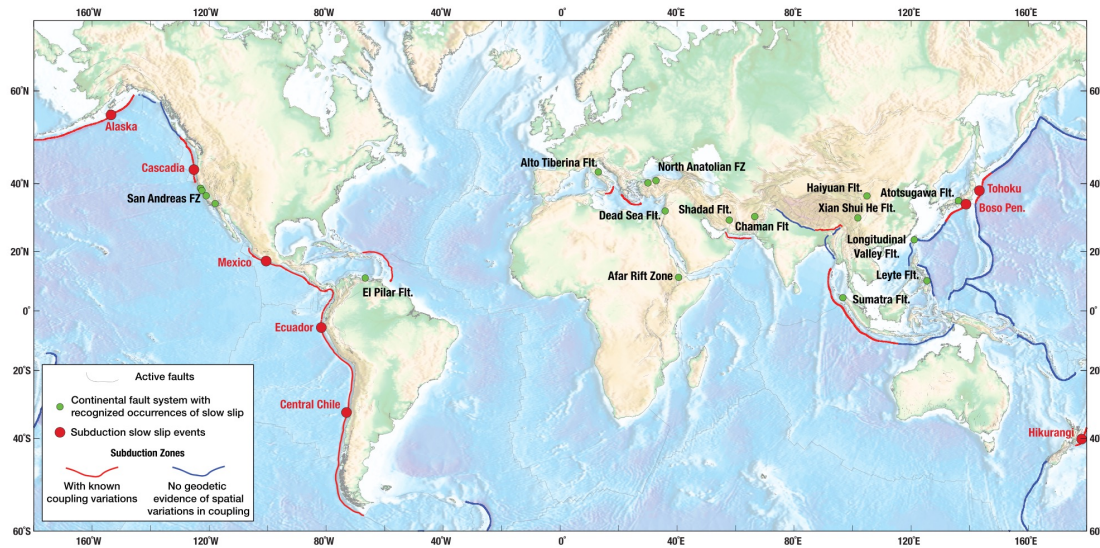
Un gros séisme est suivi par une succession de plus petits événements : les répliques

Le nombre de répliques $N(t)$ suit une décroissance régulière :

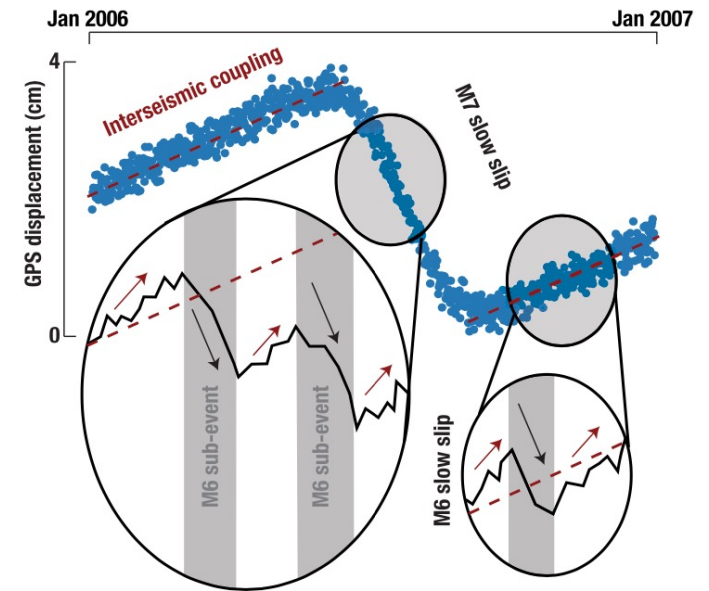
$$N(t) = \frac{K}{(t + c)^\theta}$$

Loi d'Omori





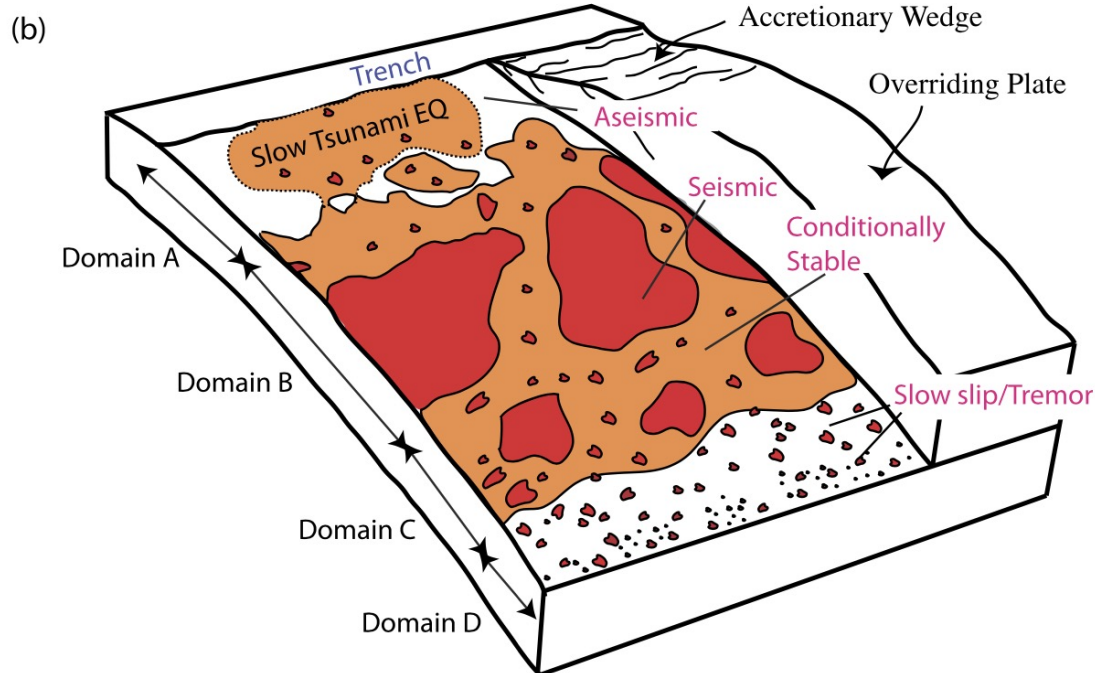
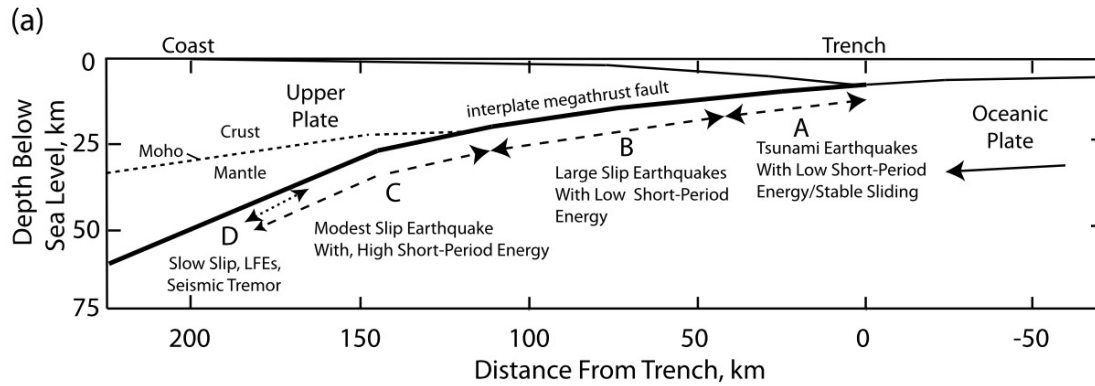
Nouveaux
phénomènes
identifiés:
Séismes lents,
tremors....



A: Subduction Megathrust

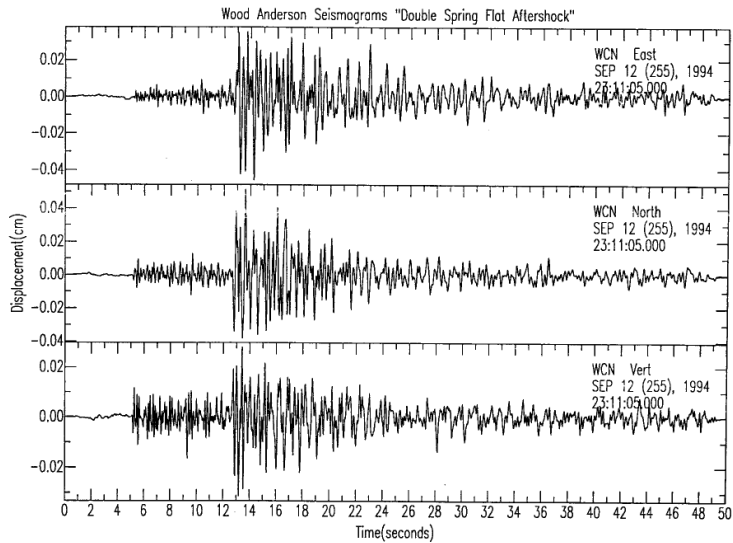
Nouveaux phénomènes identifiés: Séismes lents, tremors....

T. Lay / *Earth and Planetary Science Letters* 409 (2015) 133–146



TD Source des Séismes

SISMOGRAMMES OBSERVÉS
À LA SURFACE

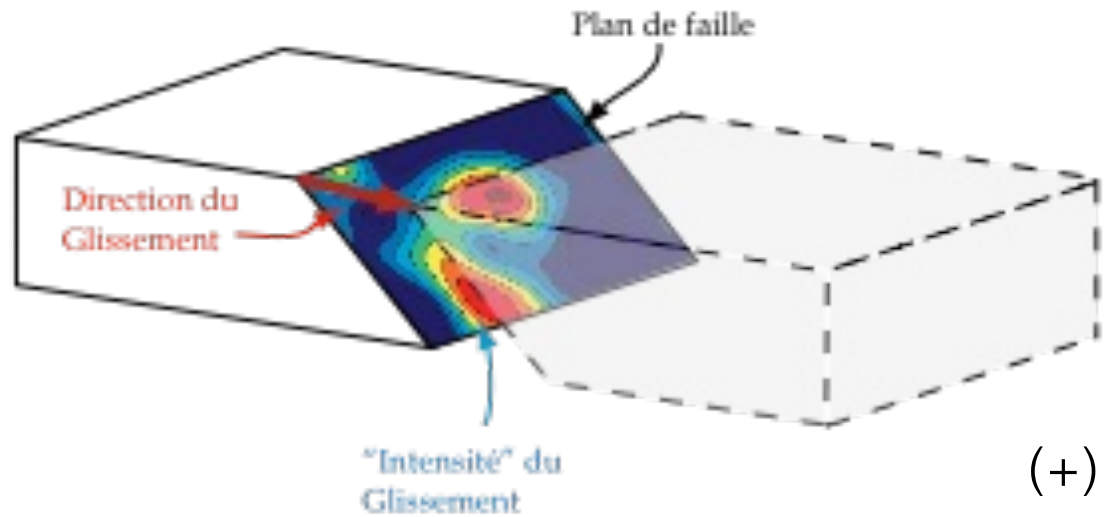


Problème
Inverse

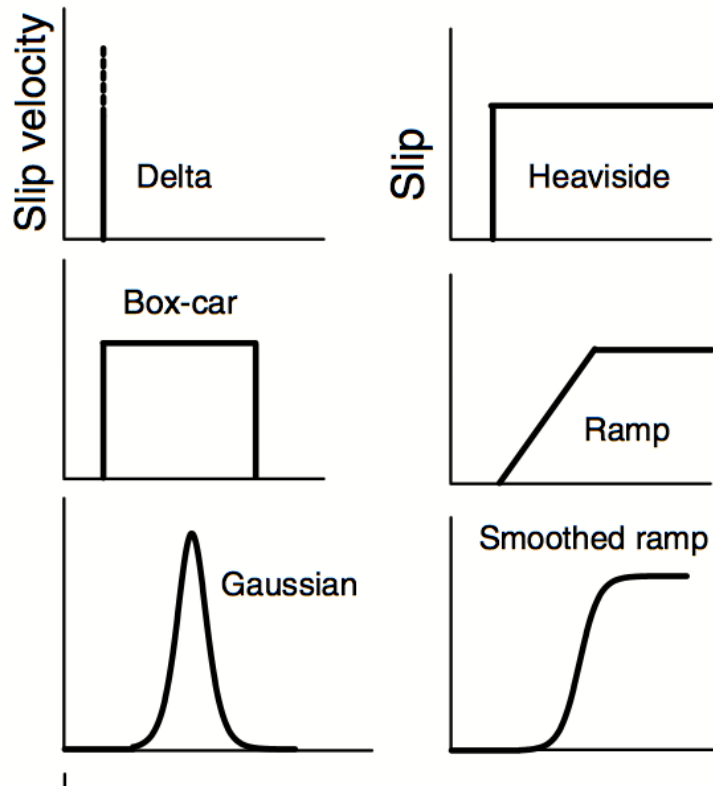
DÉPLACEMENTS ET VITESSES
SUR LA FAILLE

ONDES
GÉNÉRÉES

(Problème Direct)



Comment les failles glissent-elles ?



glissement instantané

glissement en durée

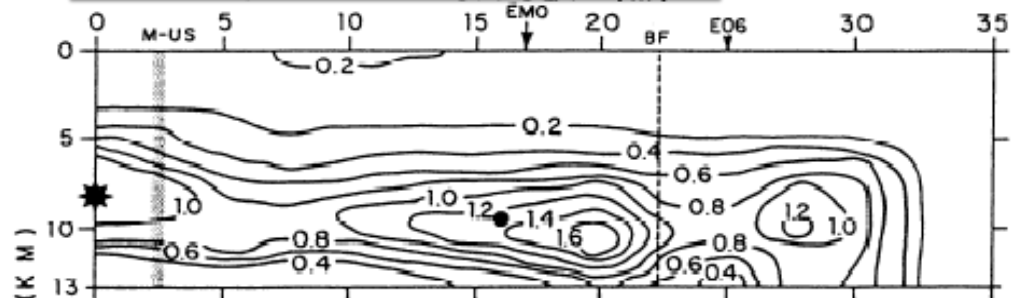
$M_0 = \mu \cdot S \cdot D$

Propagation de la rupture

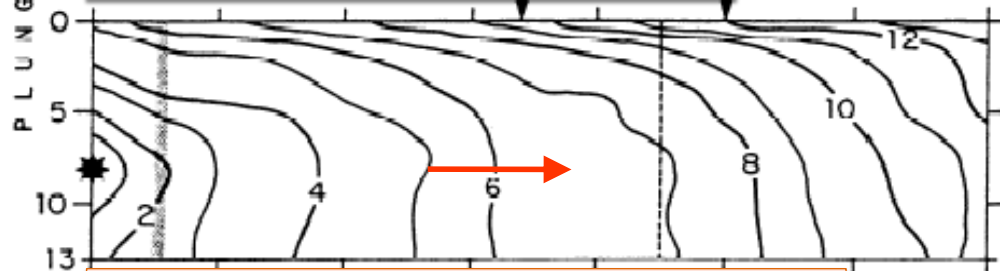
Paramètres cinématiques de la

Fig. 11

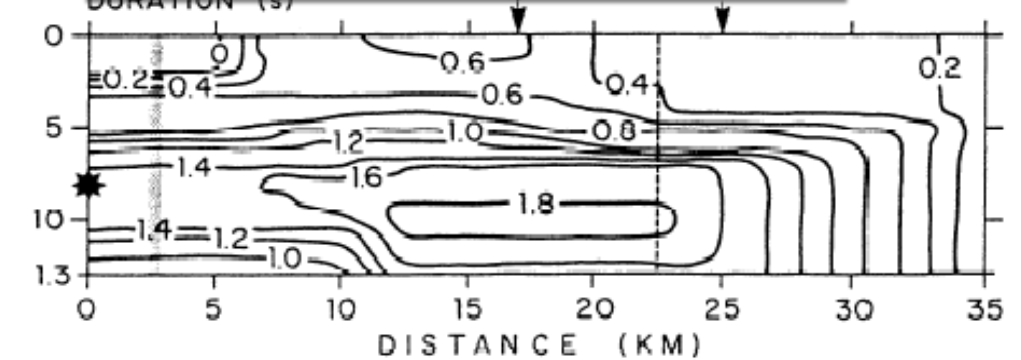
GLISSEMENT FINAL (M)



TEMPS DE RUPTURE (SEC)



DURÉE DE LA RUPTURE (SEC)

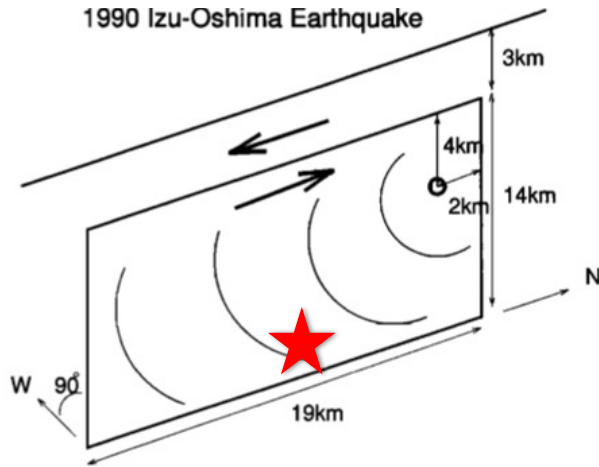


Modèle de rupture du
séisme d'Imperial Valley
1979

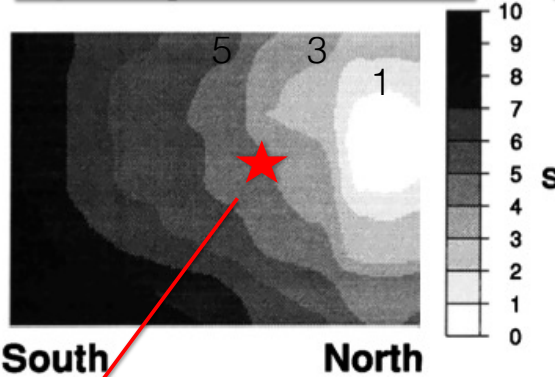
Inversion par essai-erreur
(R. Archuleta, 1984)

1)

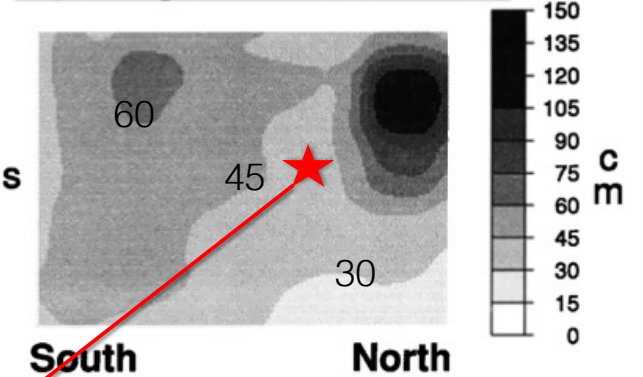
1990 IZU-OSHIMA, JAPAN, EARTHQUAKE (M-6.5) (FUKUYAMA AND MIKUMO, 1993)



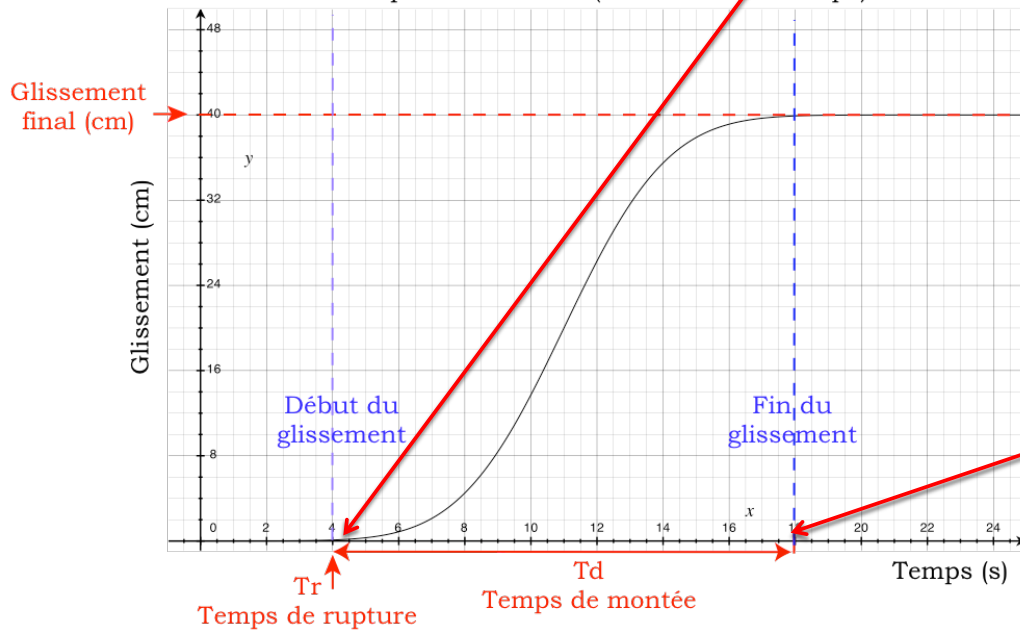
Temps de rupture (s)



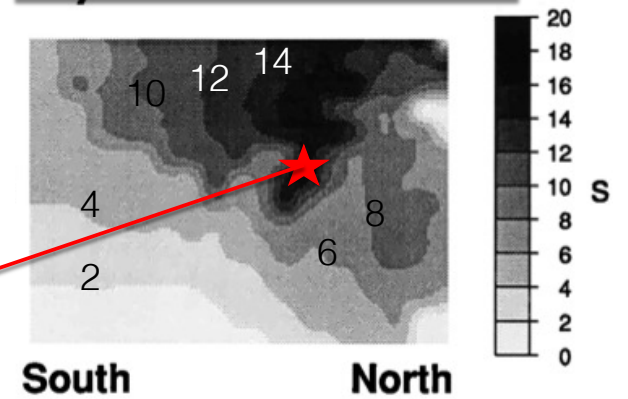
Glissement (cm)

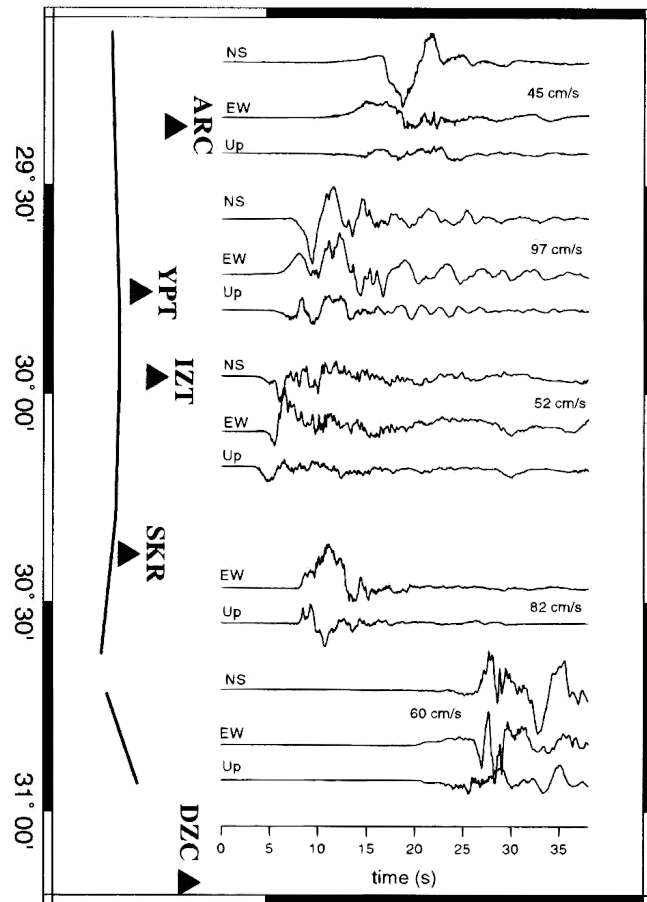
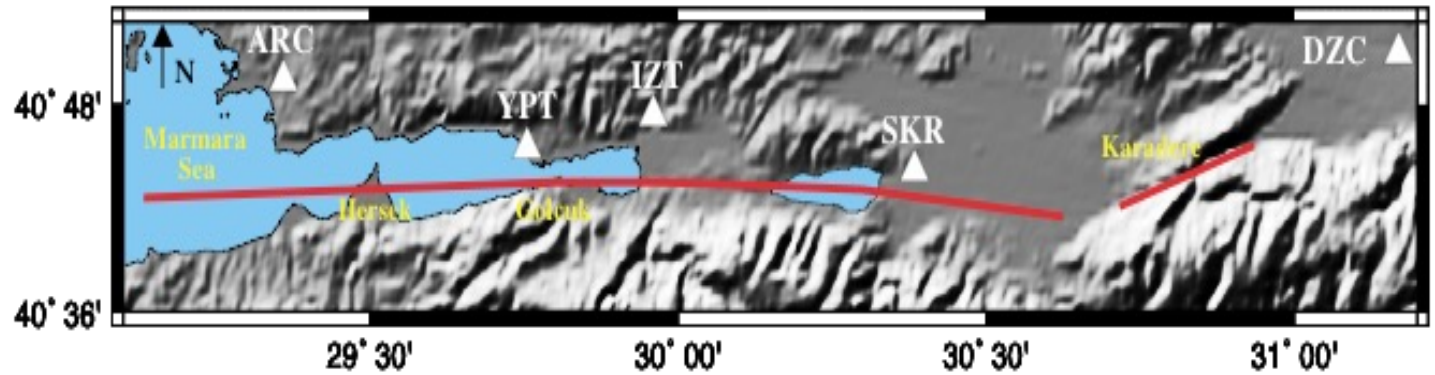


Histoire du glissement (ou déplacement)
en 1 point de la faille (en fonction du temps)



Temps de montée (s)





2) IZMIT (1999)

(BOUCHON ET AL BSSA 2002)

Vitesse

2) IZMIT (1999) (BOUCHON ET AL BSSA 2002)

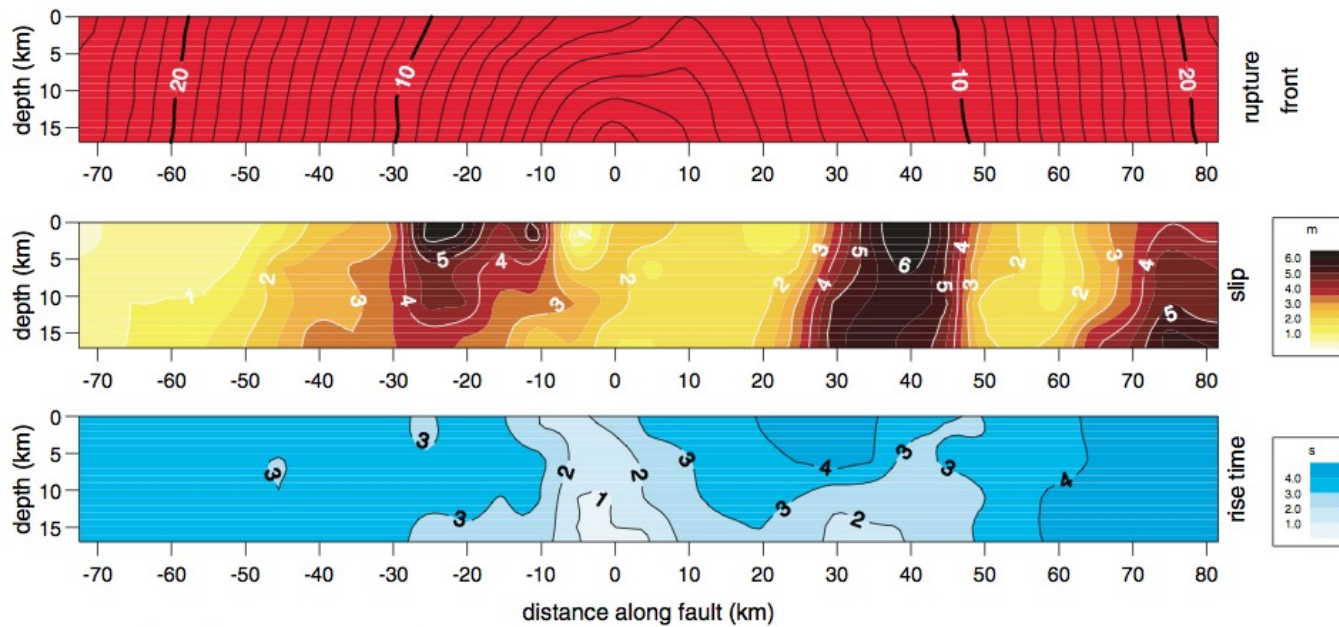
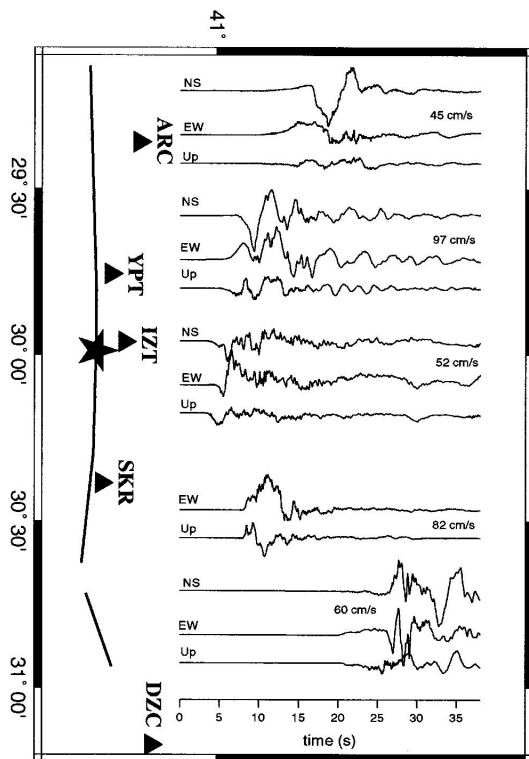
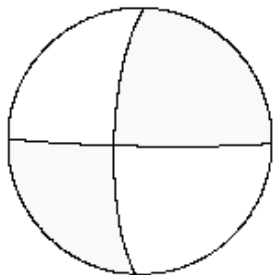


Figure 3. Top: Map of the surface rupture of the İzmit earthquake (red line). The geometry of the fault model used in the inversion follows the red line but is continuous across the junction with the eastern segment. The symbols indicate the location of the epicenter (red star) and of the recording stations (triangles). Middle and bottom: Images of the rupture front, slip, and rise time on the fault. The position of the rupture front is shown at 1-sec intervals from the beginning of the rupture.

Strike 91 Dip 87 Slip 164



Point	Profondeur (km)	Distance le long de la faille (km)	T rupt	Gliss	T mont
P1	15	0	1	1.5	1
P2	5	+25	6	2	4
P3	5	-25	9	5	3
P4	10	-60	20	1	3.5

2) IZMIT (1999) (BOUCHON ET AL BSSA 2002)

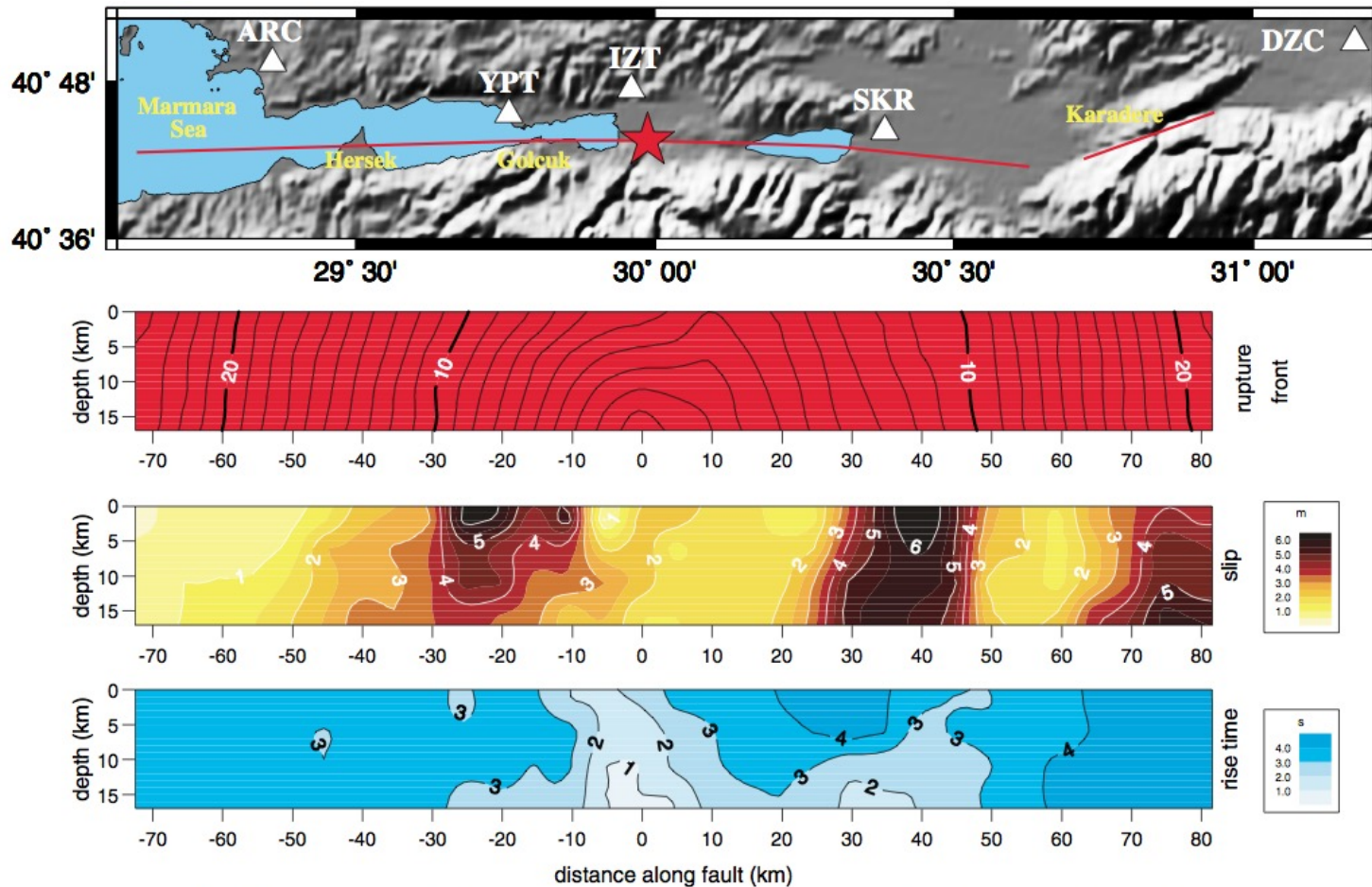
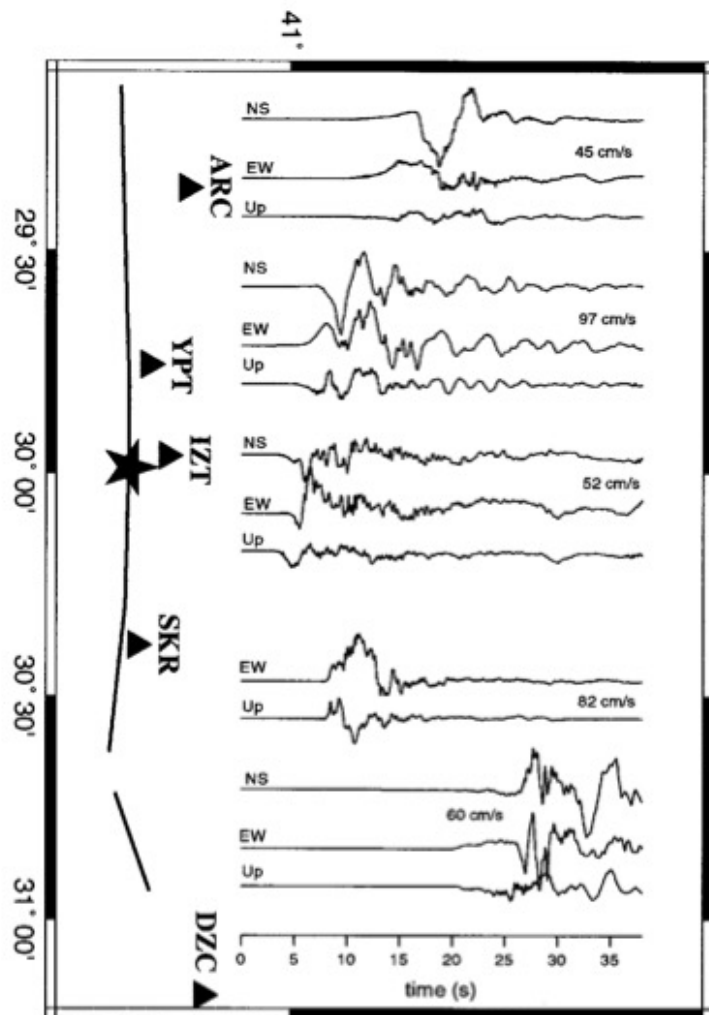
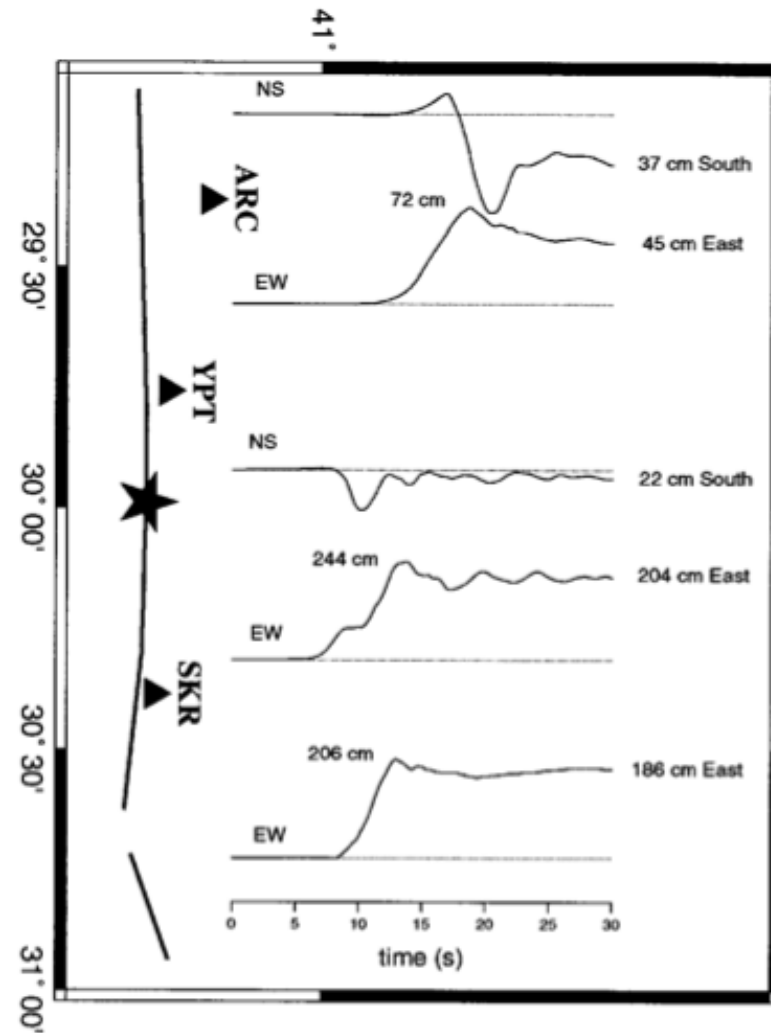


Figure 3. Top: Map of the surface rupture of the İzmit earthquake (red line). The geometry of the fault model used in the inversion follows the red line but is continuous across the junction with the eastern segment. The symbols indicate the location of the epicenter (red star) and of the recording stations (triangles). Middle and bottom: Images of the rupture front, slip, and rise time on the fault. The position of the rupture front is shown at 1-sec intervals from the beginning of the rupture.

2) IZMIT (1999) (BOUCHON ET AL BSSA 2002)



Vitesse enregistrée à la surface



Déplacement