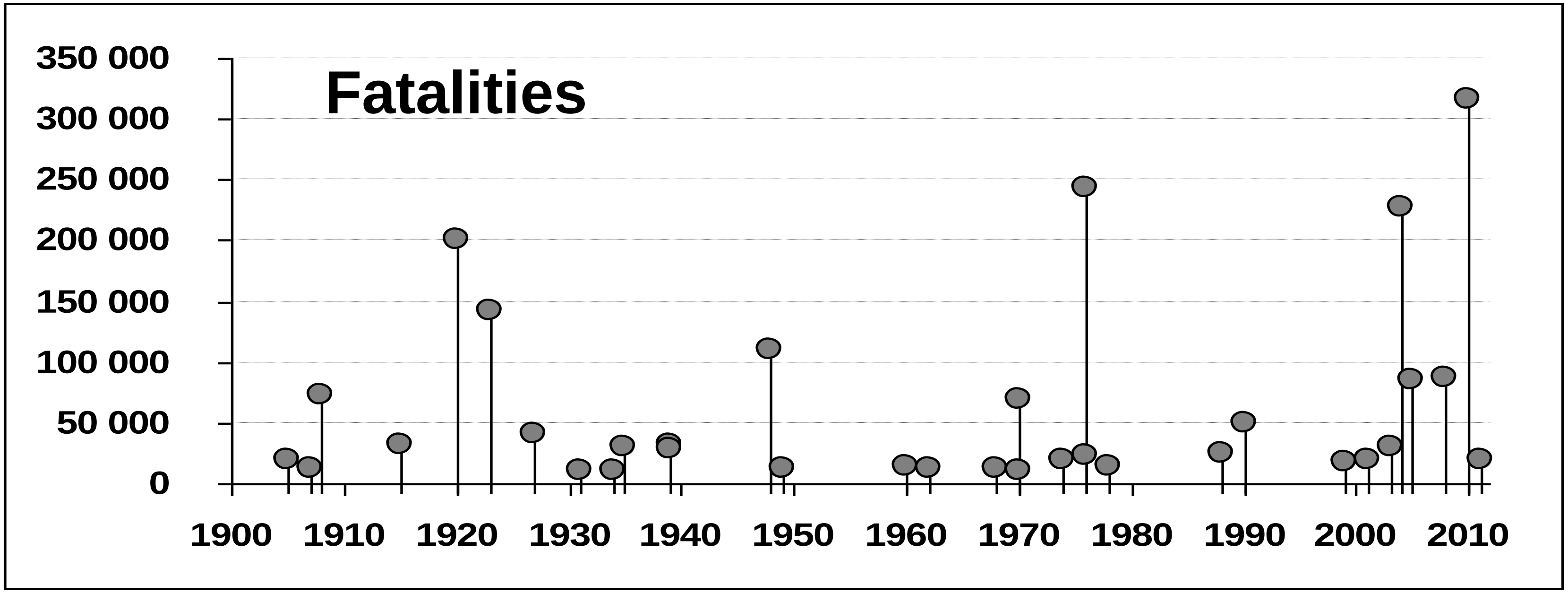
ORIGIN OF EARTHQUAKES IN AND AROUND STABLE PLATES

Christophe Vigny*

***département des Geosciences de l'ENS / UMR 8538 du CNRS**

http://www.geologie.ens.fr/~vigny

IMPACT OF EARTHQUAKES



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

6. Turkey (1948):	110 000 dead	Mw 7.3
7. Sichuan (2008):	88 000 dead	Mw 7.9
8. Pakistan (2005):	85 000 dead	Mw 7.6
9. Messina (1908):	70 000 dead	Mw 7.2
….		
21. Japan (2011):	20 252 dead	Mw 9.0

Source: USGS catalog

ECONOMIC IMPACT : GROWING !

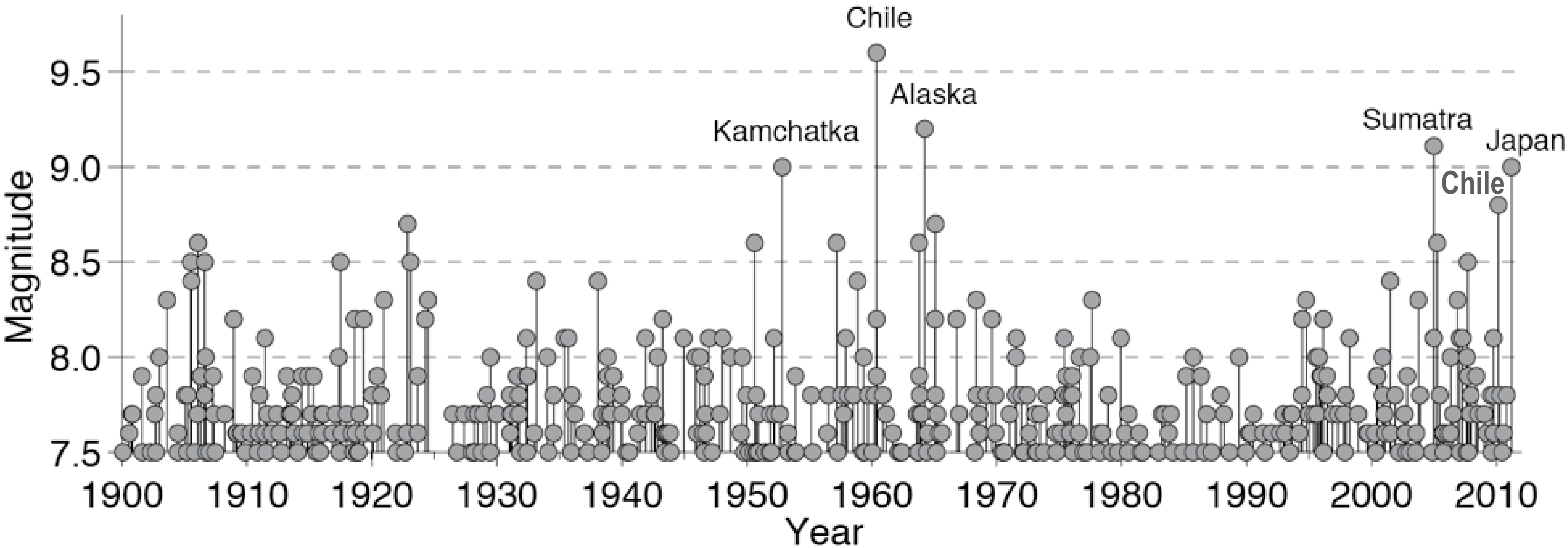
Eq	Mw	Dead	Damage (billions USD)
Valdivia, Chile, 1960	9.5	5 000	~0.5
Sumatra 2004	9.2	300 000	~10
Maule, Chile 2010	8.8	800	15 – 30
Tohoku, Japan 2011	9.0	20 000	> 200


Valdivia 1960

Tohoku 2011

Q1 : HOW MANY EARTHQUAKES ?

Large Earthquakes (> Mw 7.5)



Large ones : every year !

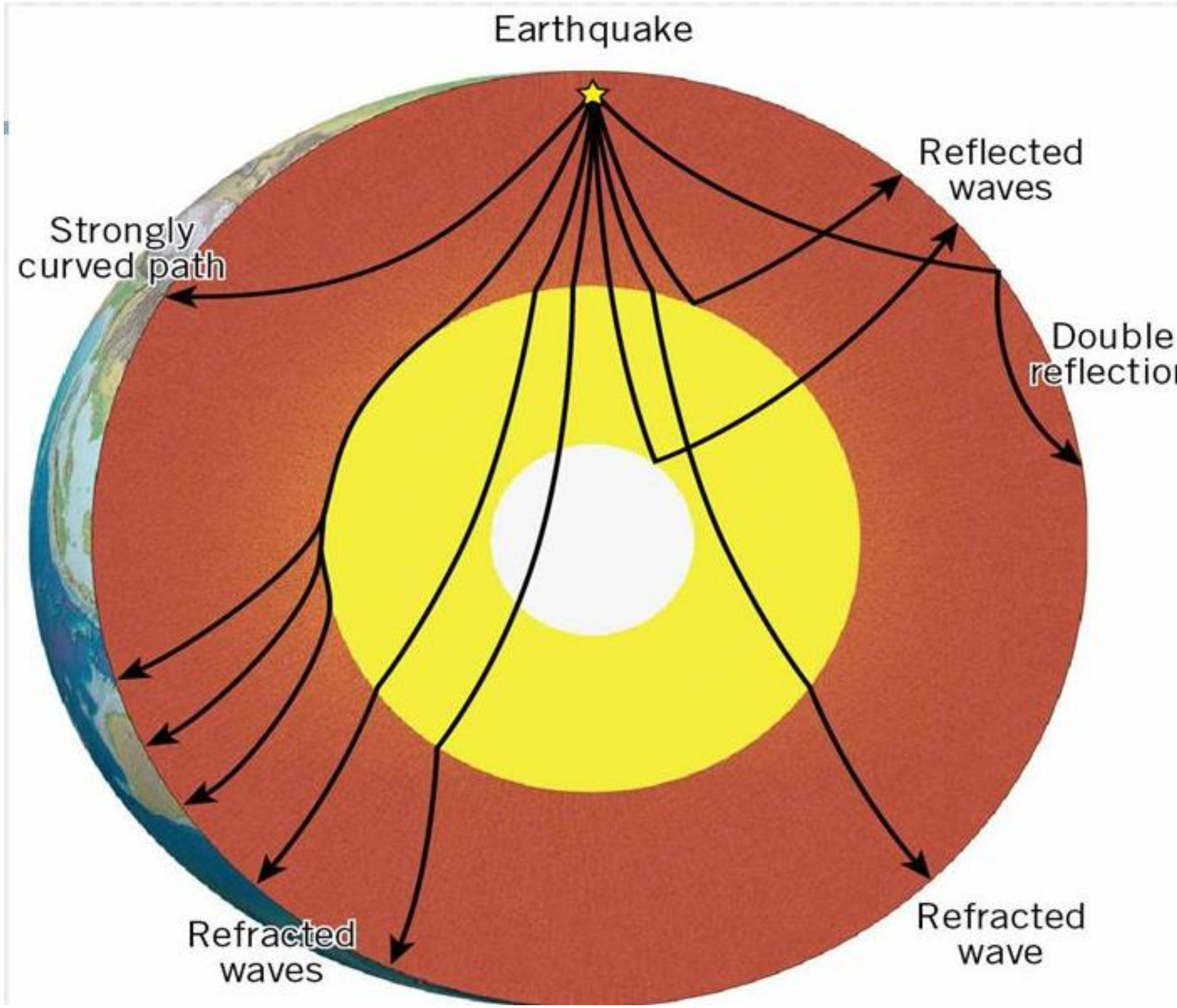
40 years
quiand

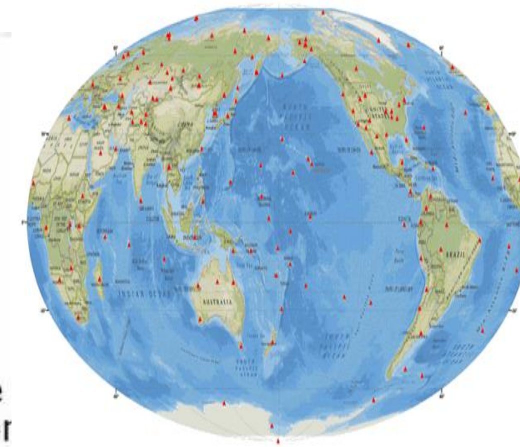
Giant ones : 8-10 within 100 years

=> 1 per decade, but irregularly

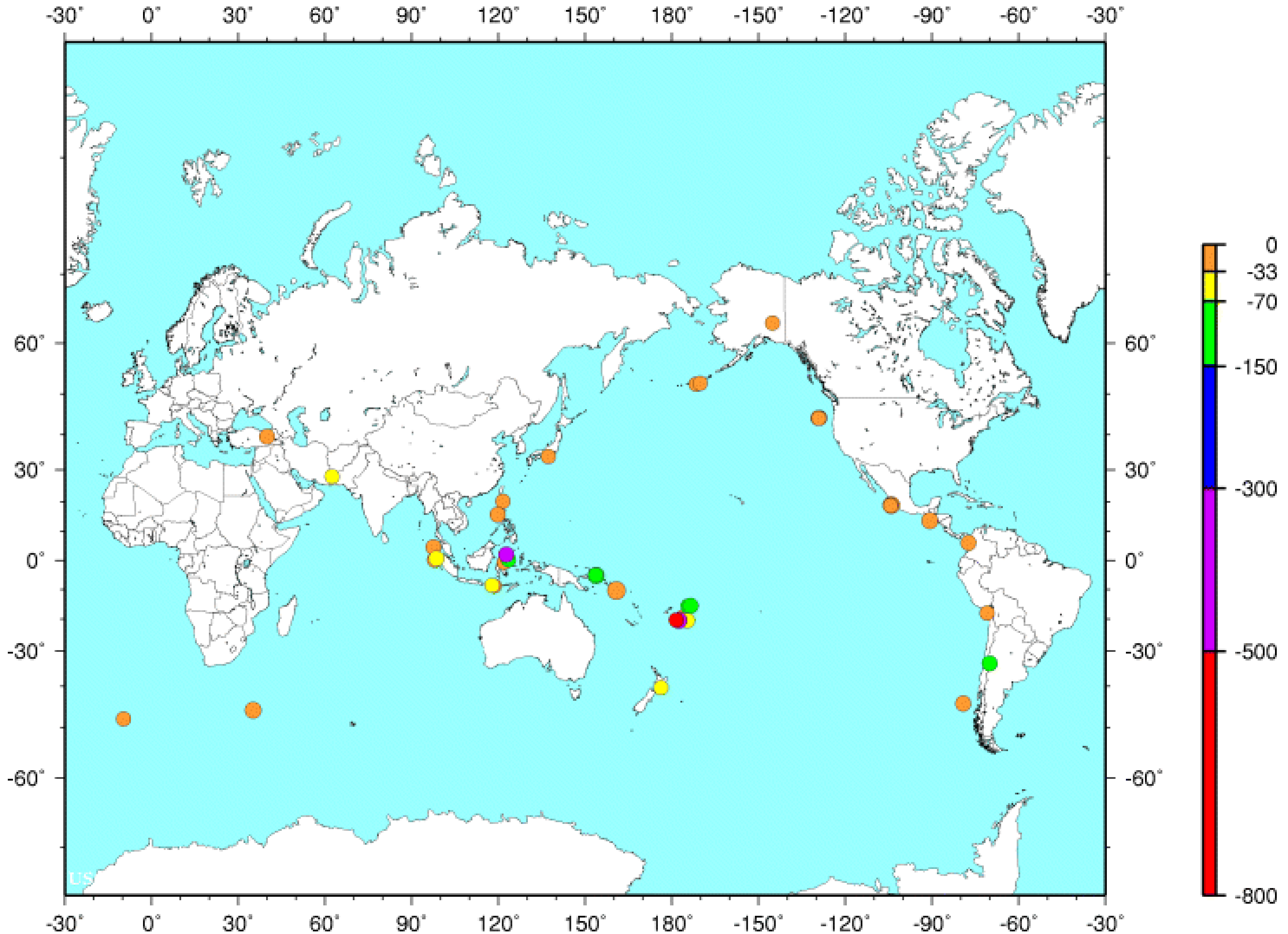
Source: USGS catalog

Earthquakes recorded by the global network of seismographs (> Mw 4.5)

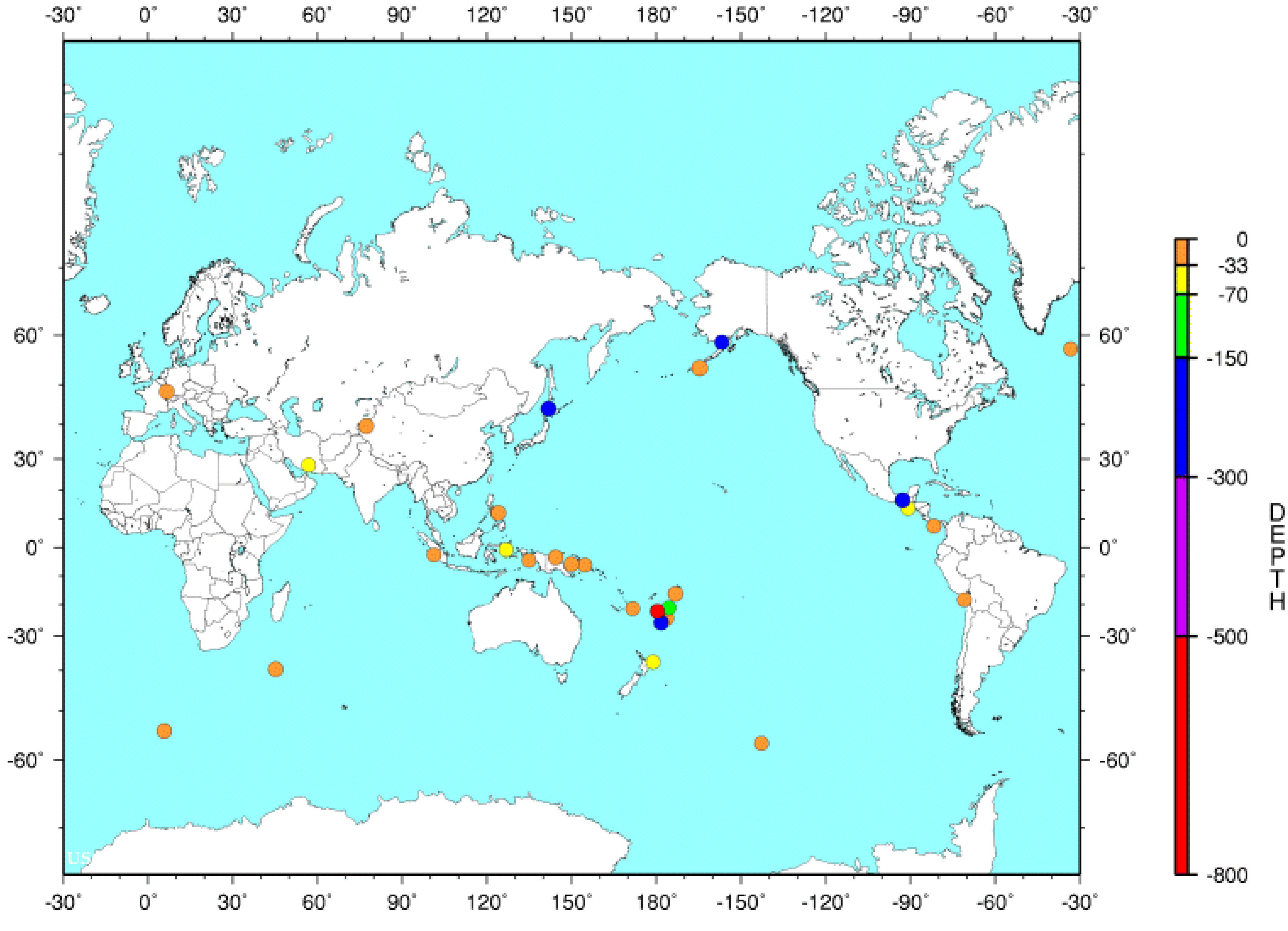




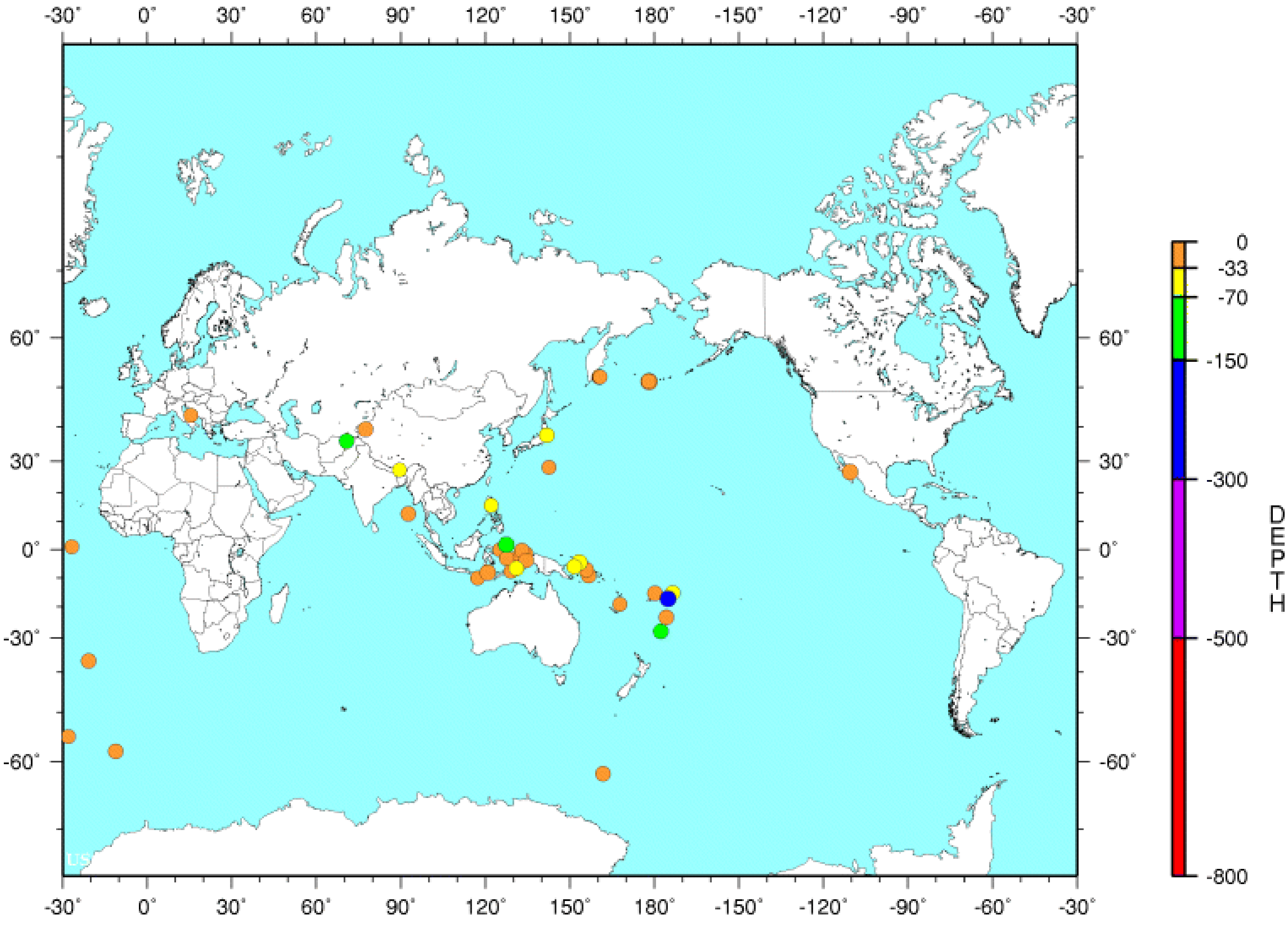
January 2003 : **40** Eq



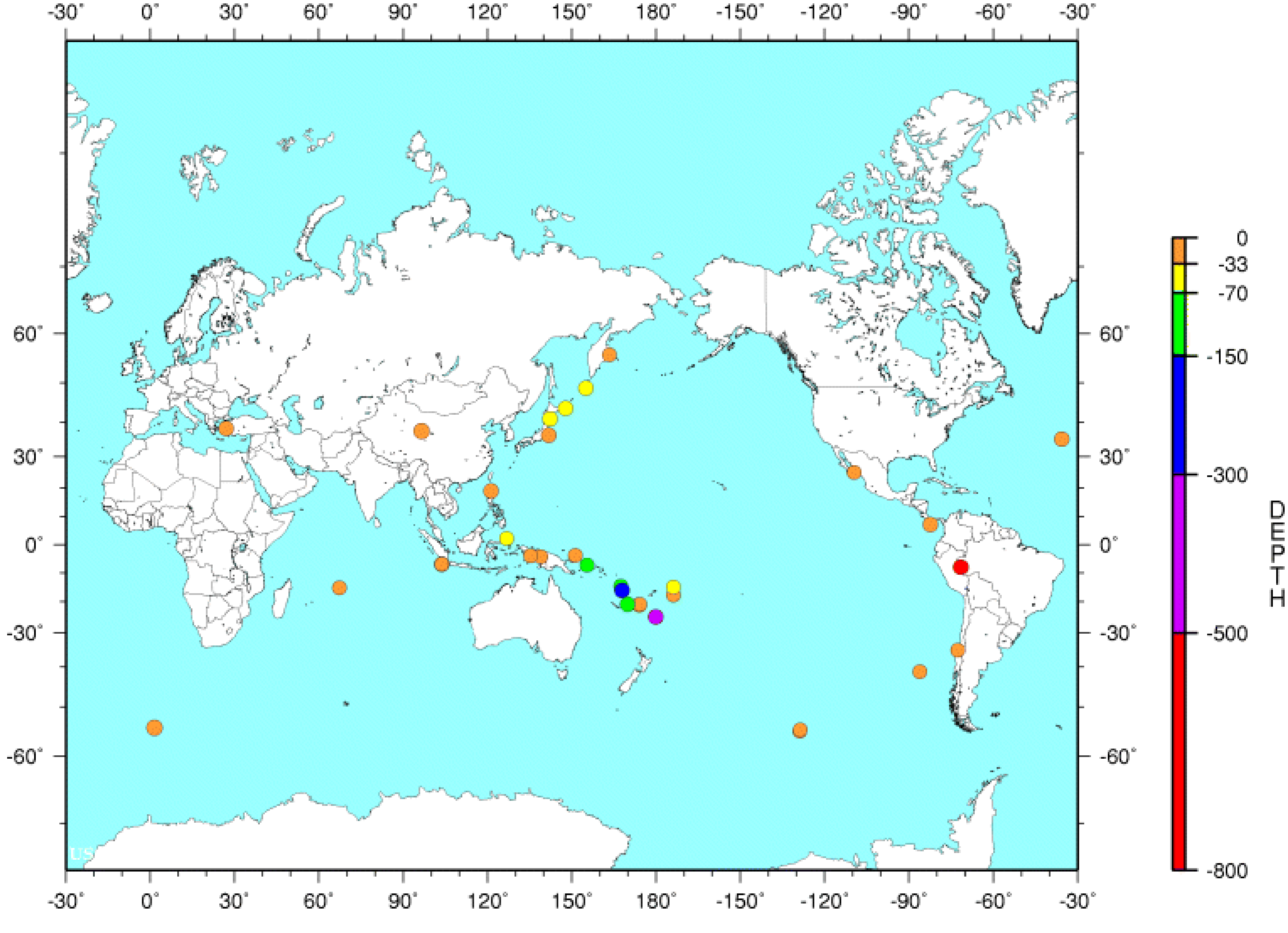
February 2003 : **29** Eq



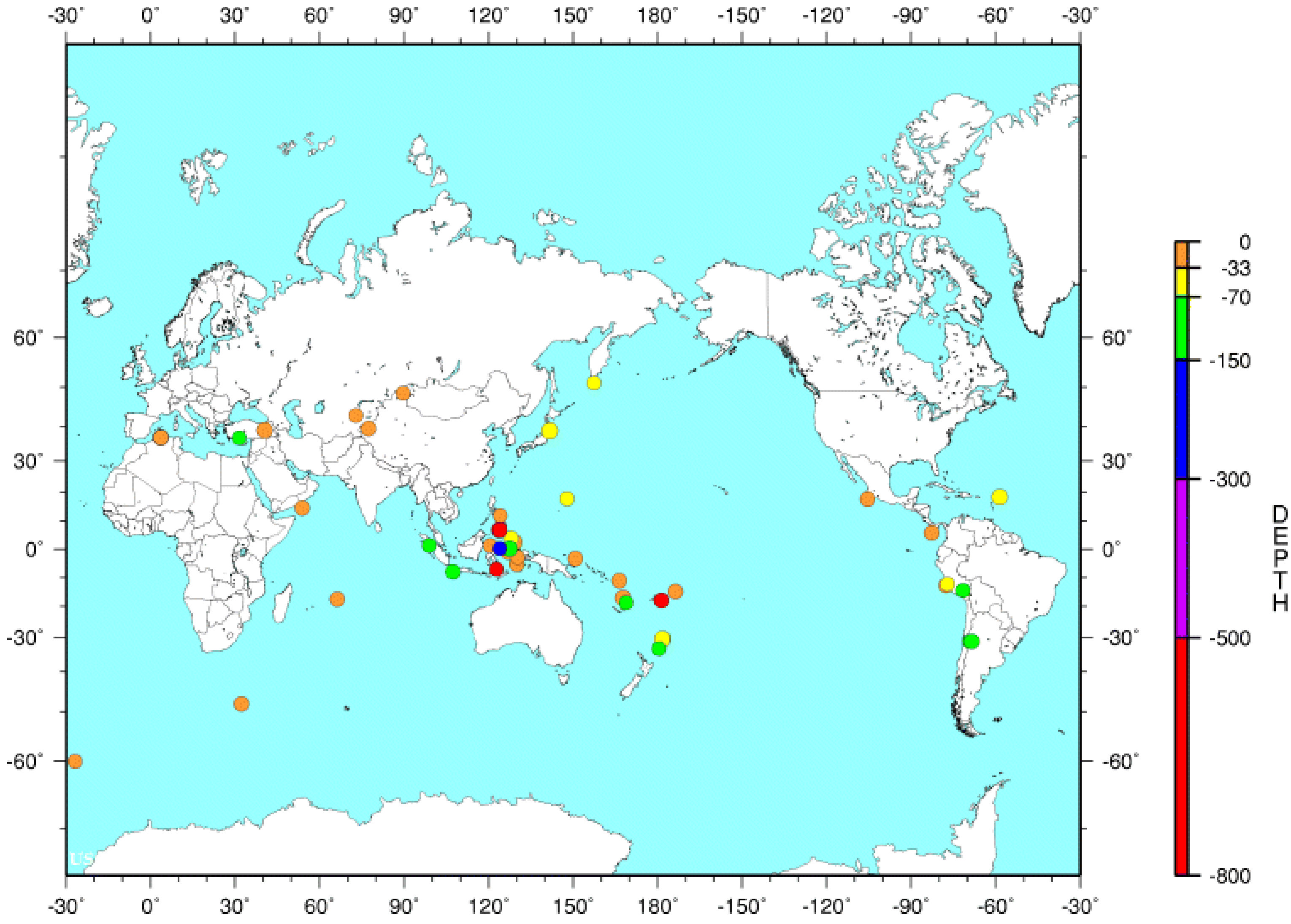
Mars 2003 : **41** Eq



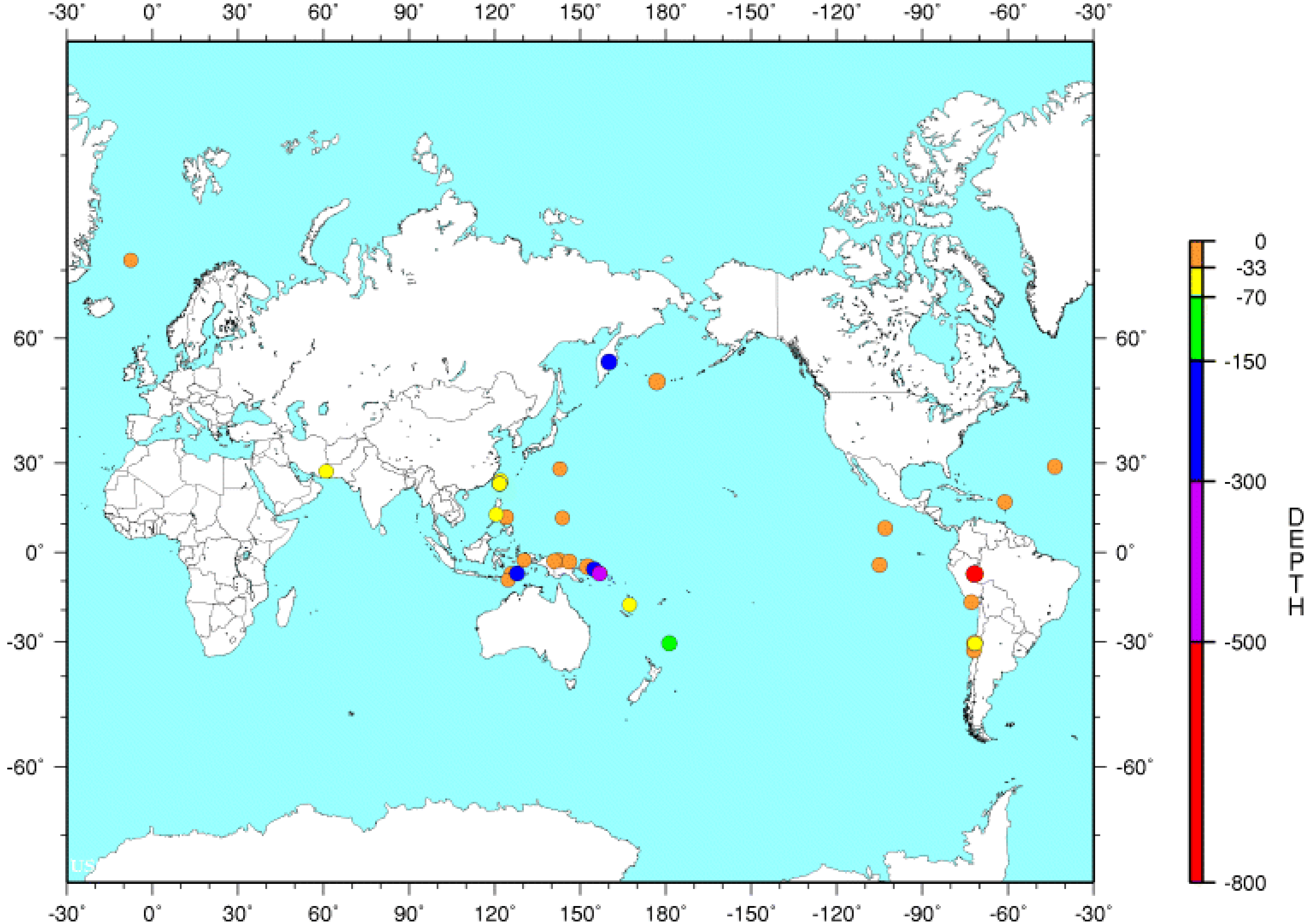
April 2003 : **33** Eq



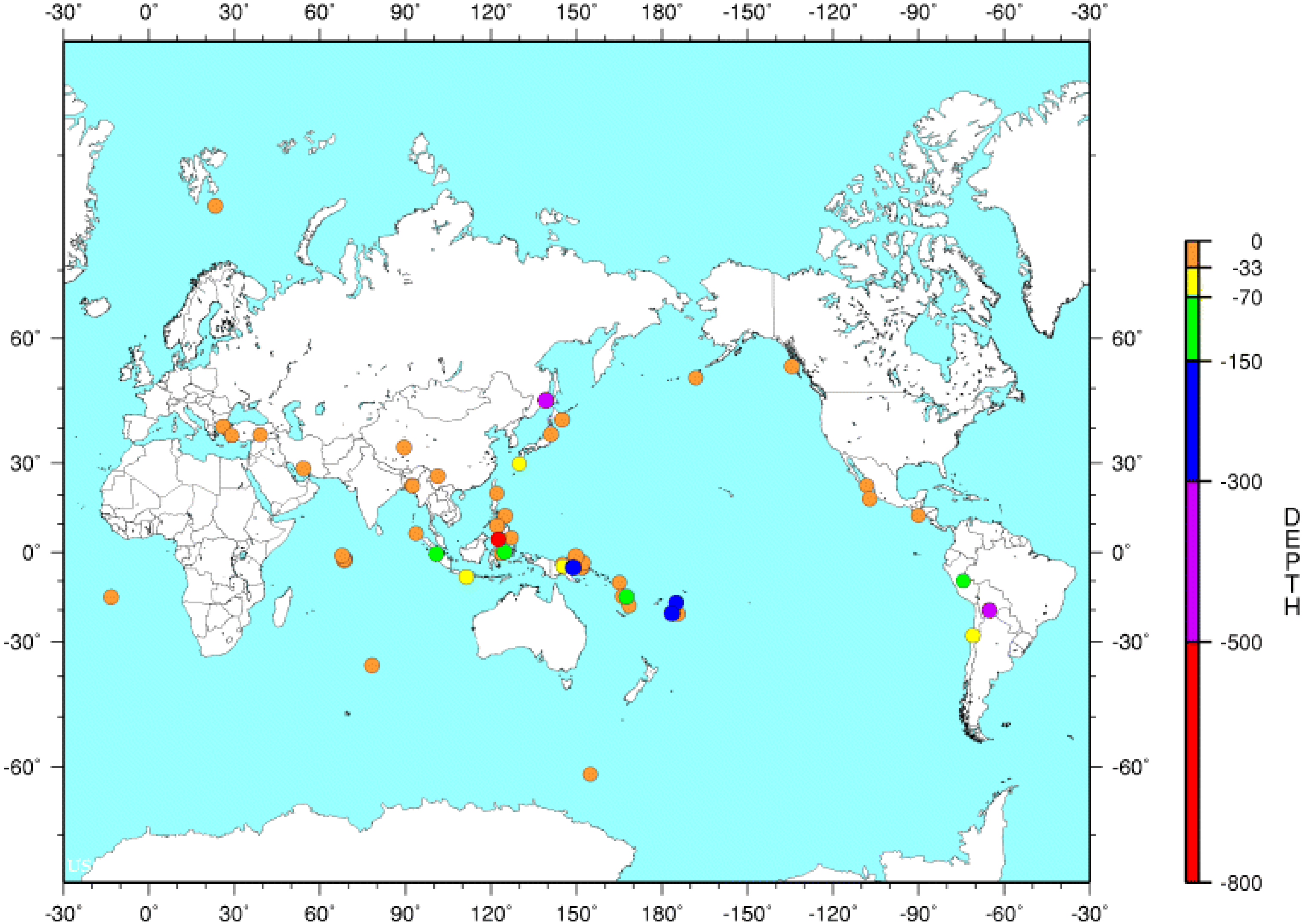
May 2003 : **46** Eq



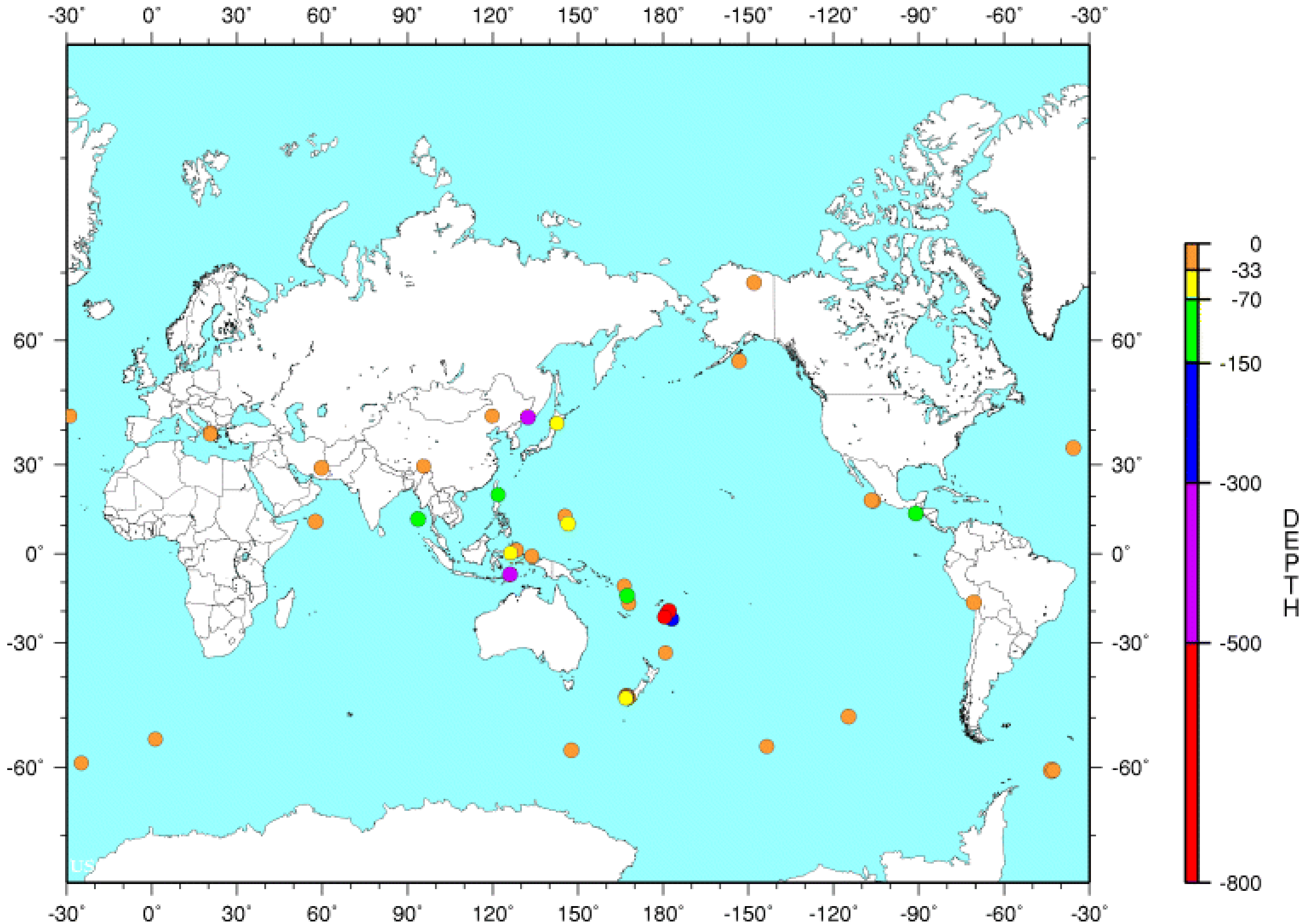
June 2003 : **33** Eq



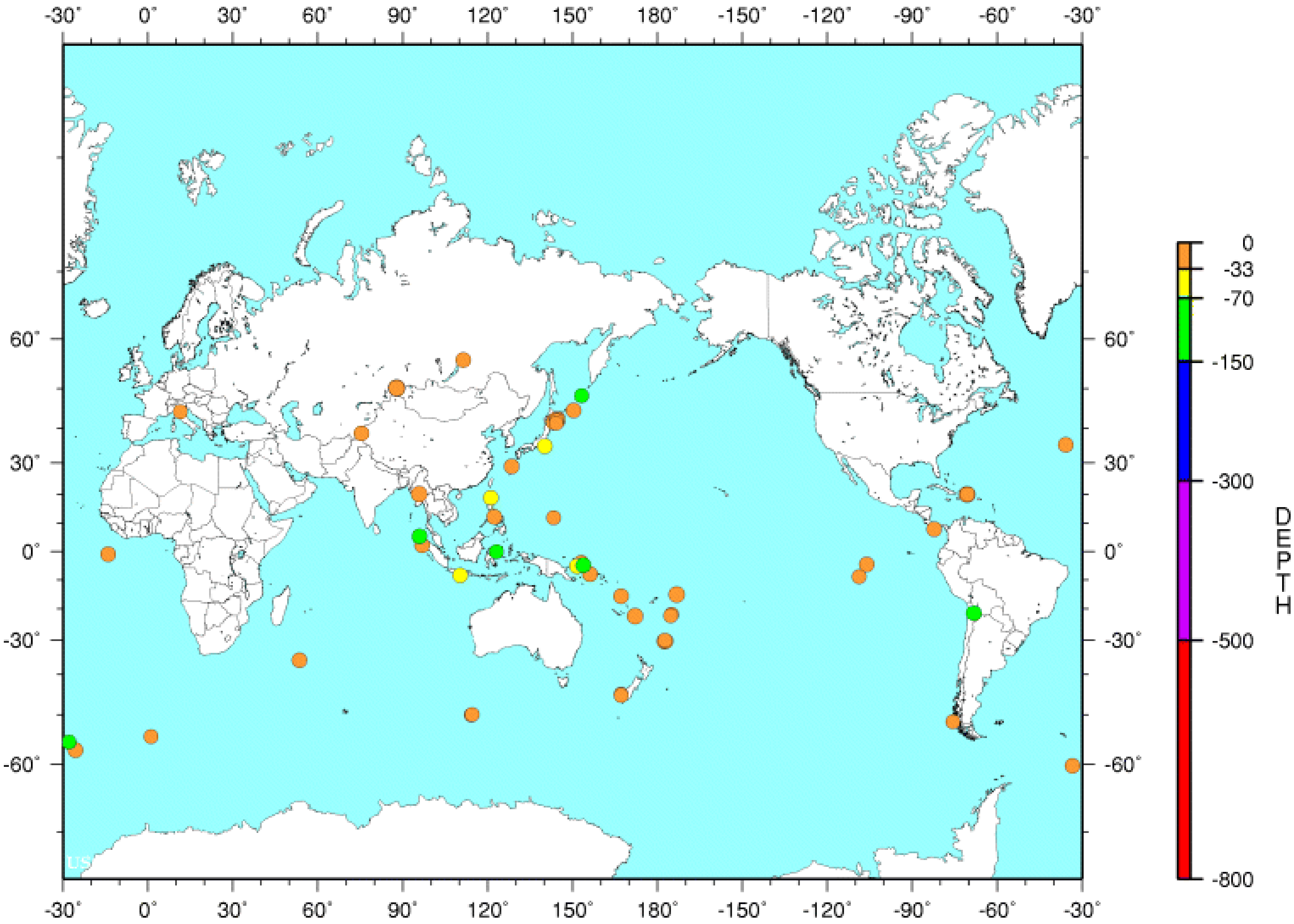
July 2003 : **53** Eq



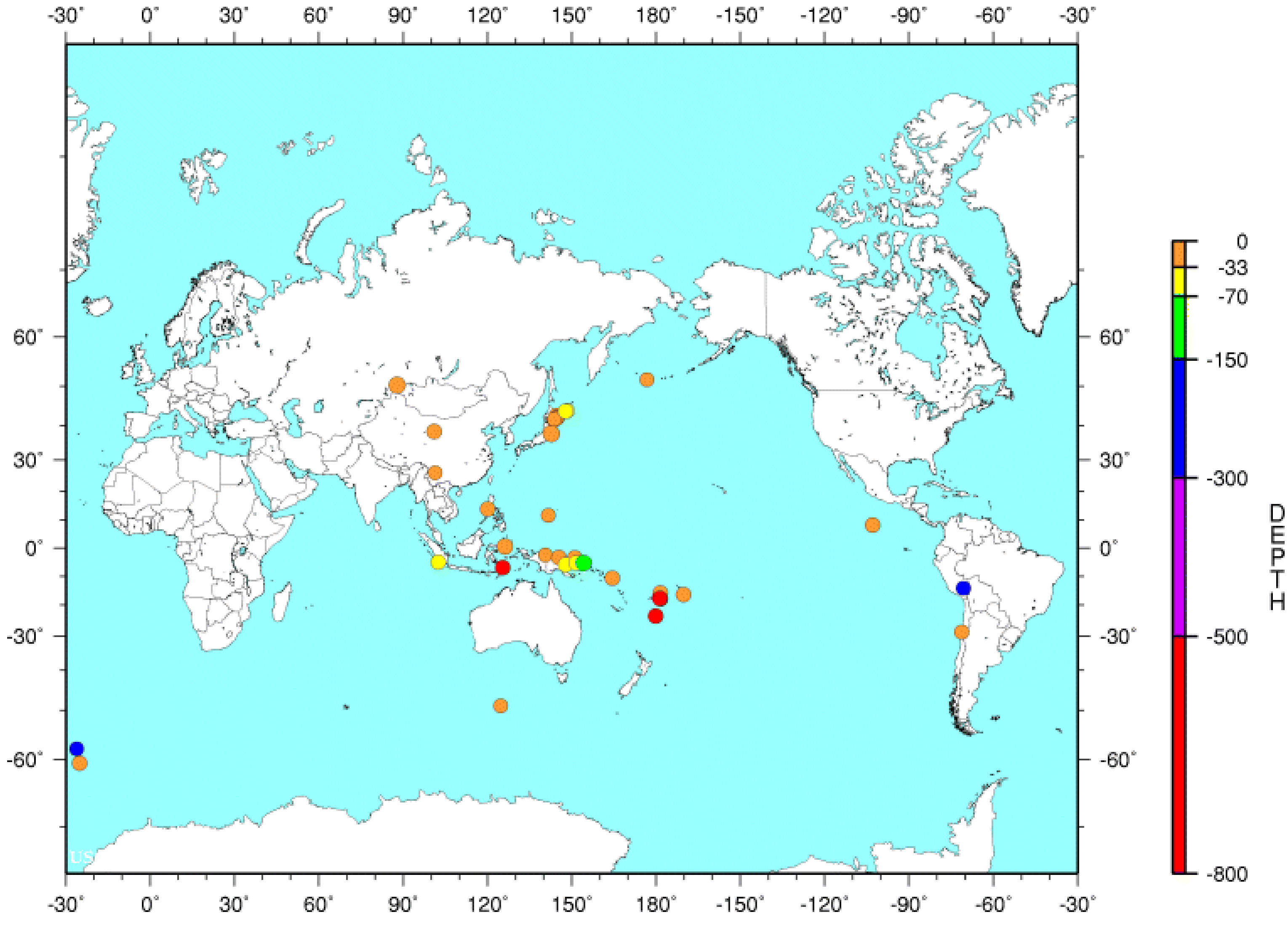
August 2003 : **47** Eq



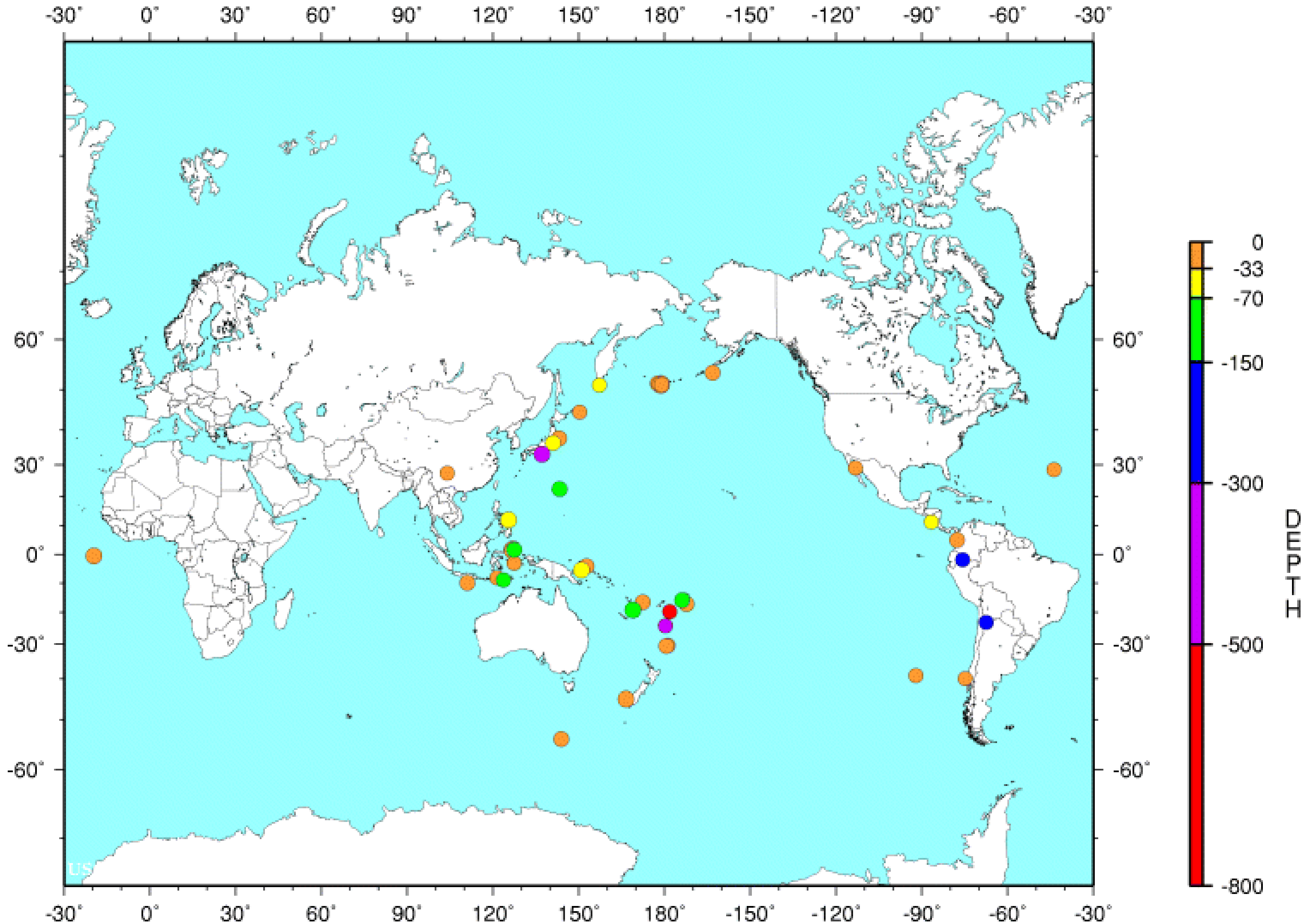
September 2003 : **63** Eq



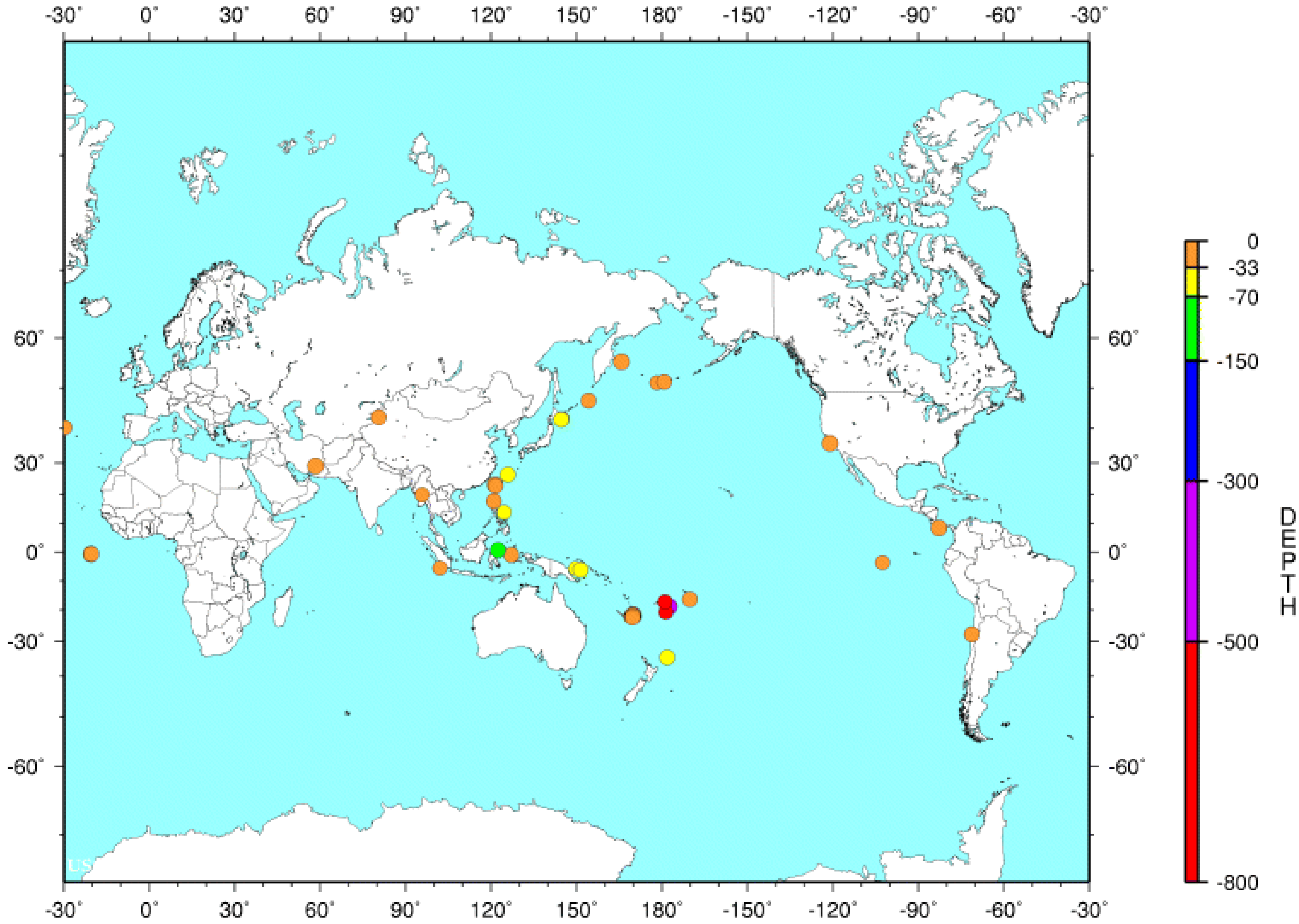
October 2003 : **38** Eq



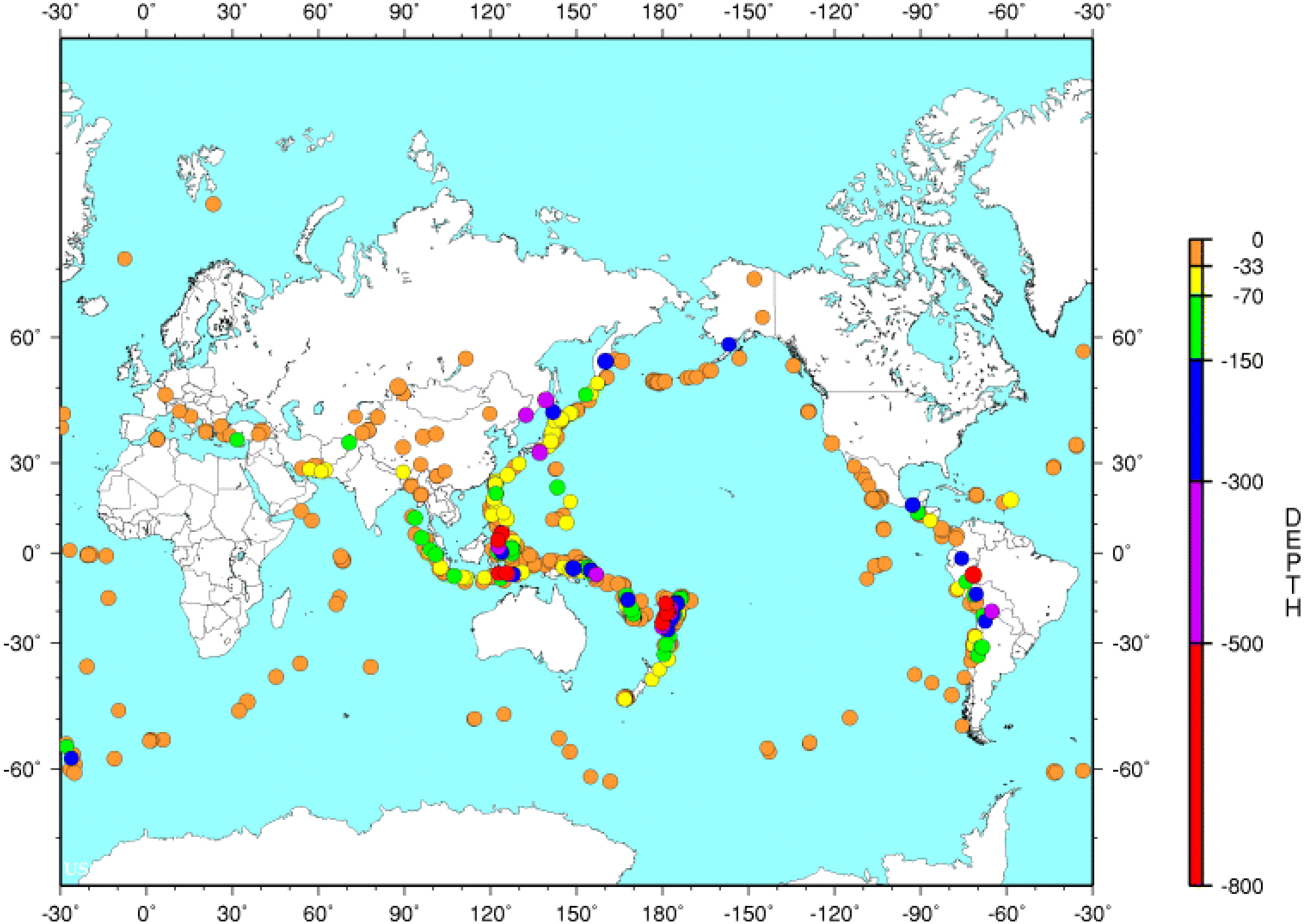
November 2003 : **43** Eq



December 2003 : **46** Eq



YEAR 2003 : **512** Eq



Q1 : HOW MANY EARTHQUAKES ?

ANSWER : it really depends on size !

small (magnitude between 4 and 5) : **1 / hour**

medium (magnitude between 5 and 6) : **1 / day**

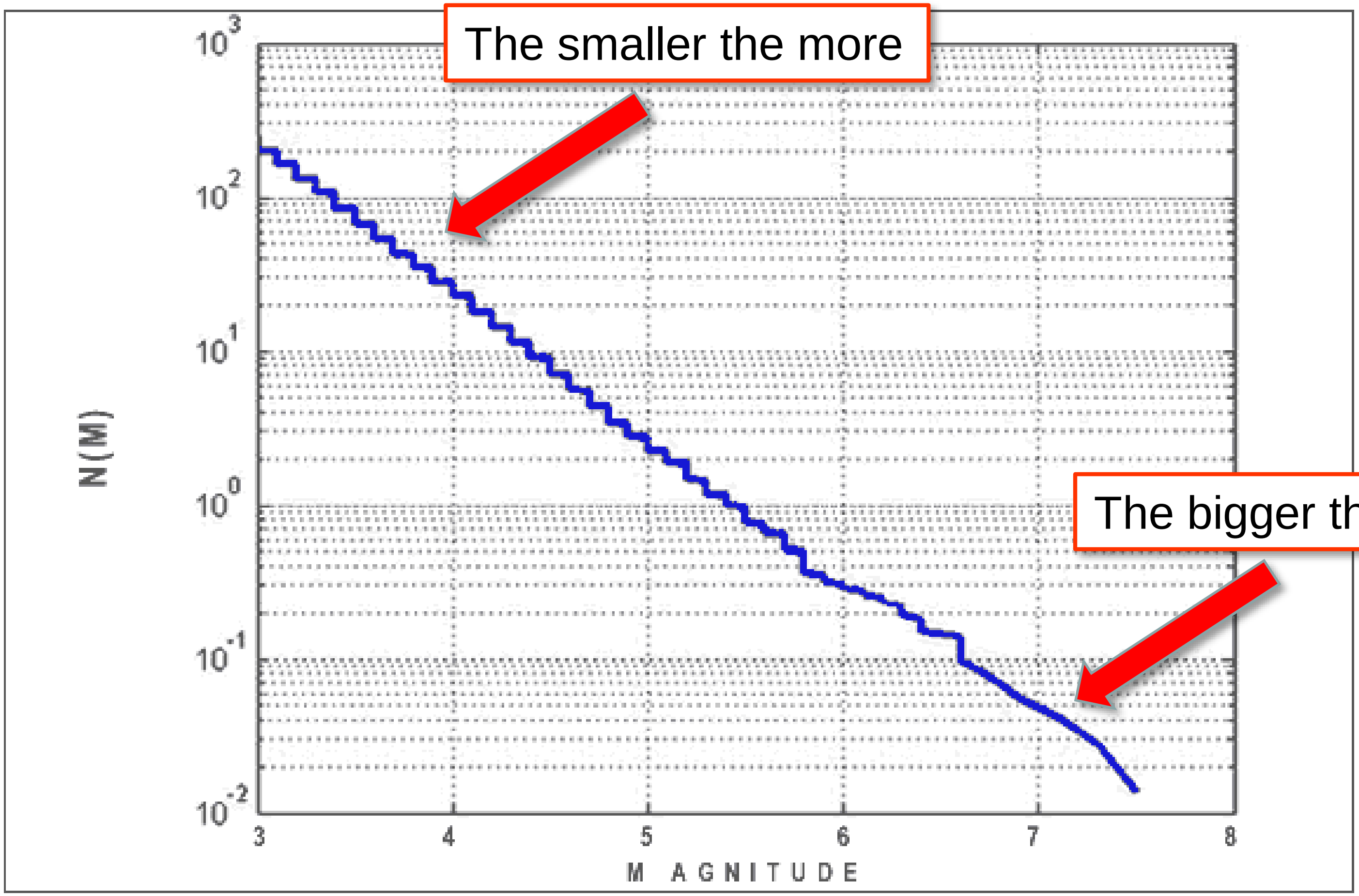
big (magnitude between 7 and 8) : **1 / month**

very big(magnitude between 8 and 9) : **1 / year**

giants (magnitude > 9) : **1 every decade**

Q1 : HOW MANY EARTHQUAKES ?

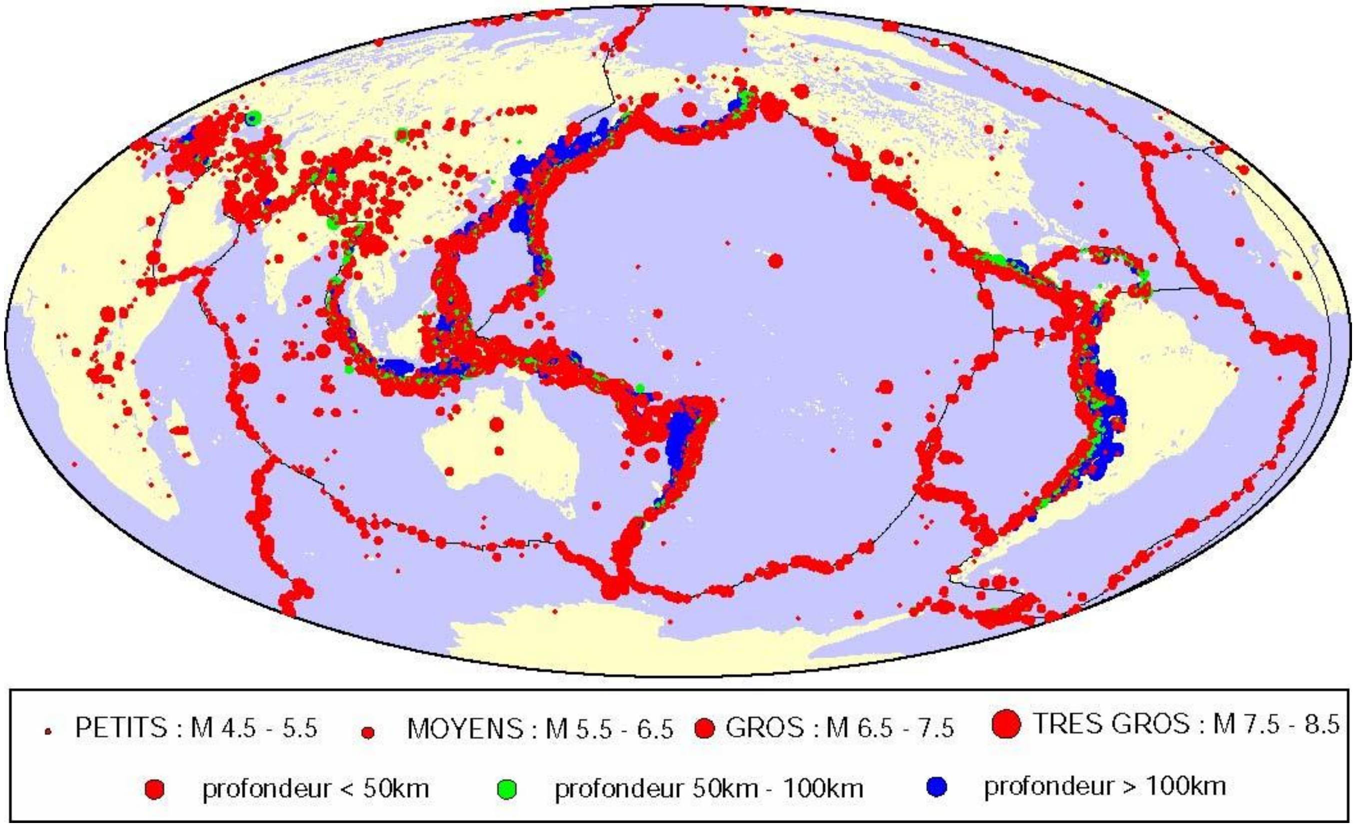
Gutenberg & Richter law



Q2 : WHERE DO EARTHQUAKES OCCUR ?

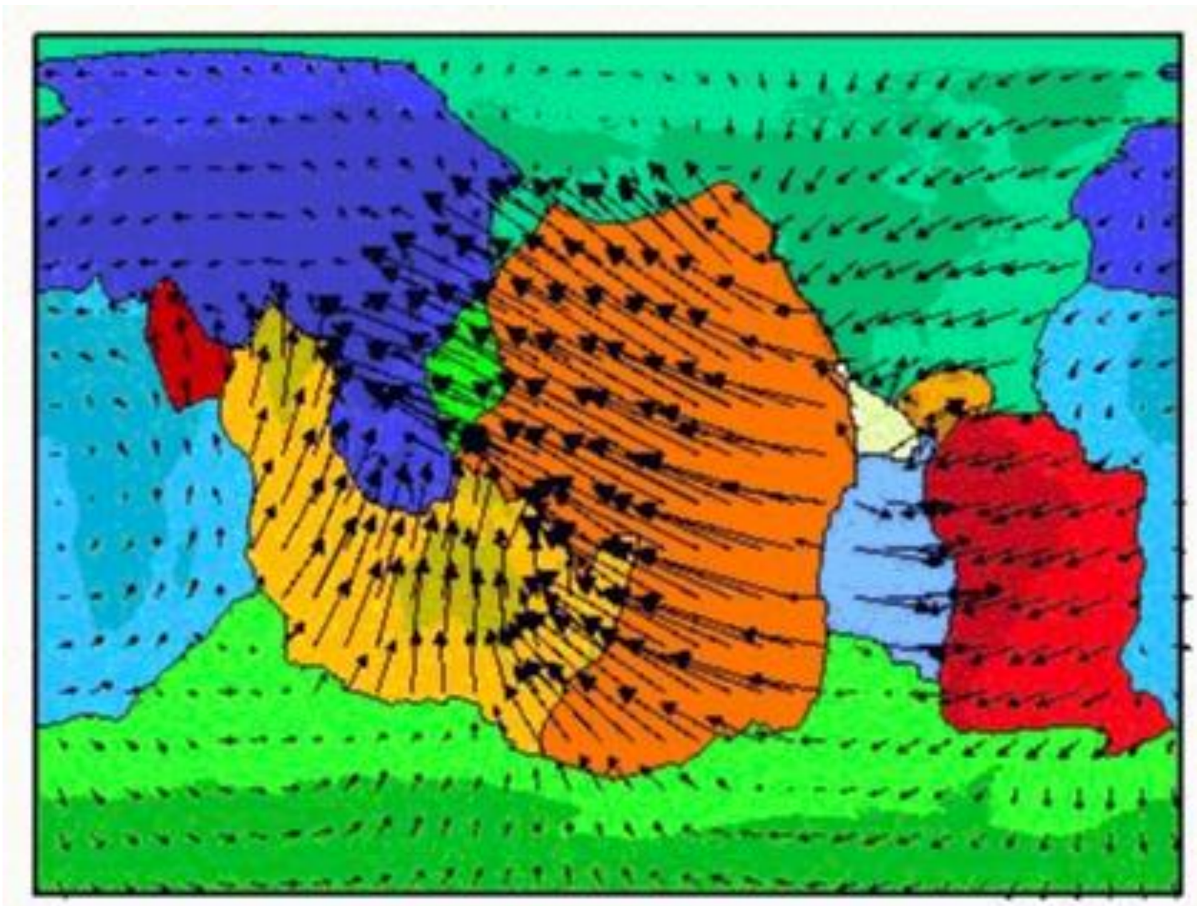
ANSWER : Not everywhere !

World sismicity : 30 years – 17 000 events of magnitude larger than 4.5



Q3 : WHY DO EARTHQUAKES OCCUR ?

ANSWER : mostly(*) because of plate tectonics

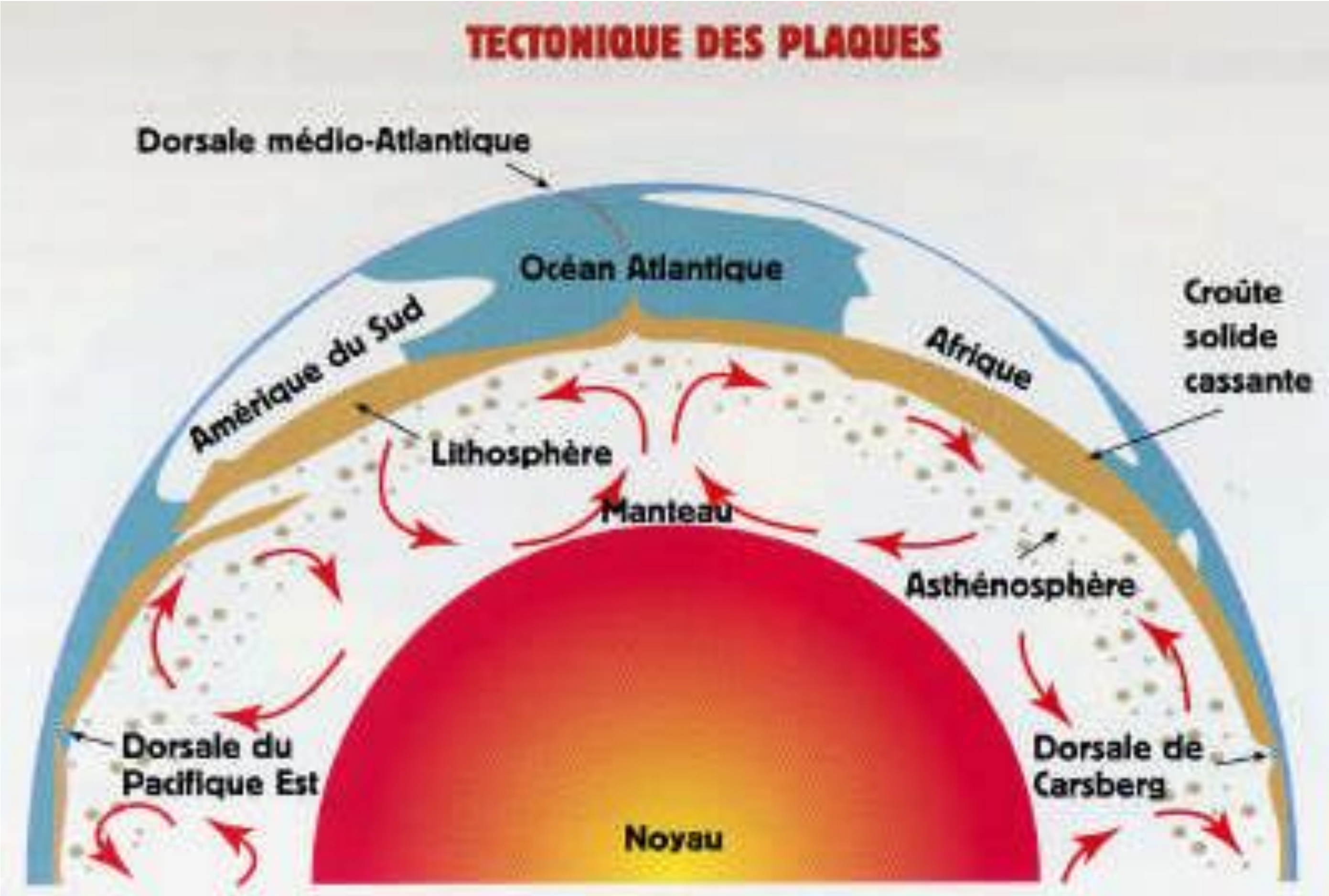


- Pacifique
- Eurasie
- Amérique du N
- Amérique du S
- Afrique
- Antarctique
- Indie-Australie
- Nazca
- Philippine
- Arabie
- Caraibes
- Coco

There are 12 major plates …and they move ! **Plate tectonics**

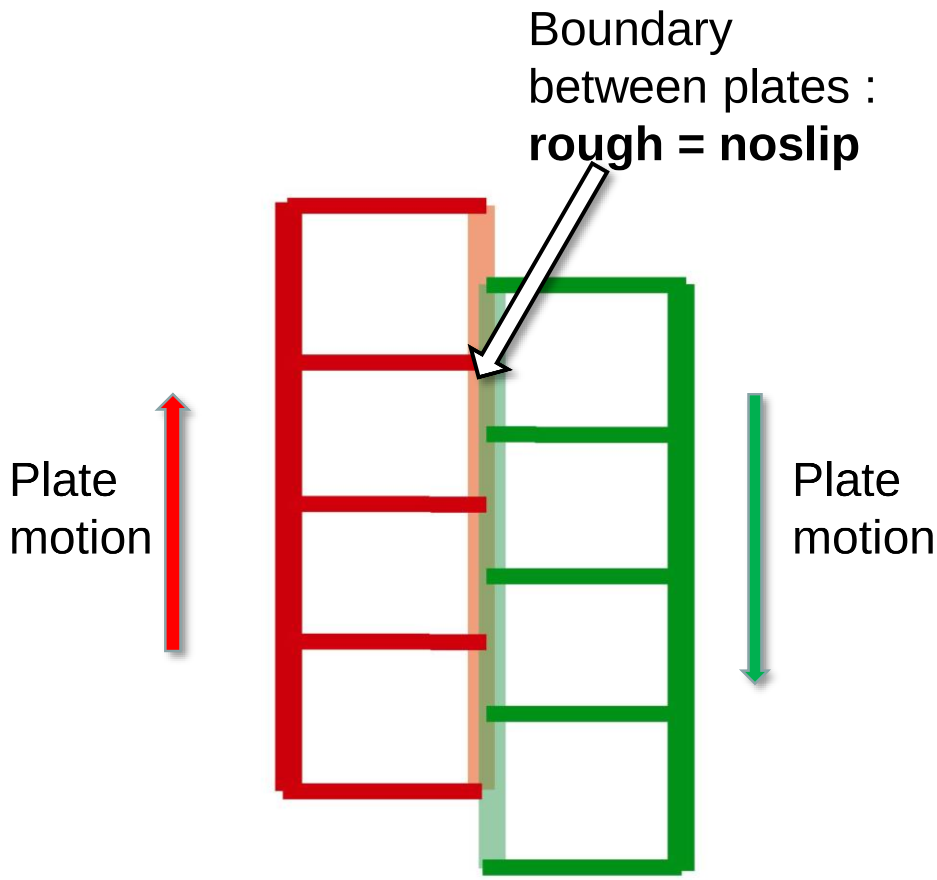
** Will get back to that later*

The engine of plate tectonics is mantle convection its fuel is rocks natural radio-activity



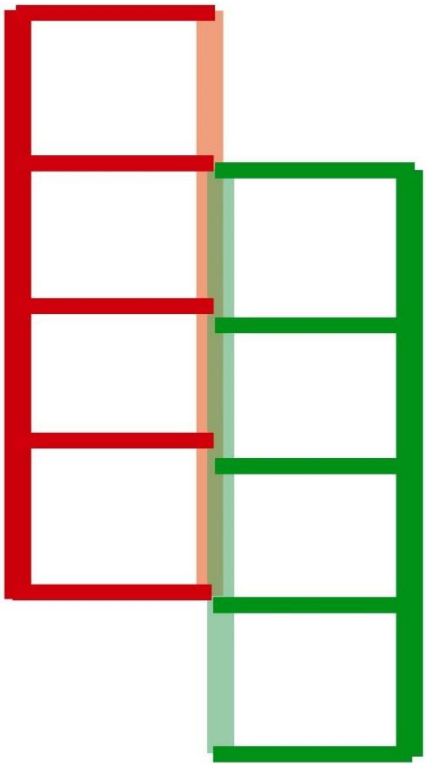
Q4 : HOW DO EARTHQUAKES OCCUR ?

Answer : because of friction, It rubs and it brakes !



Earthquake

When strain > fault resistance

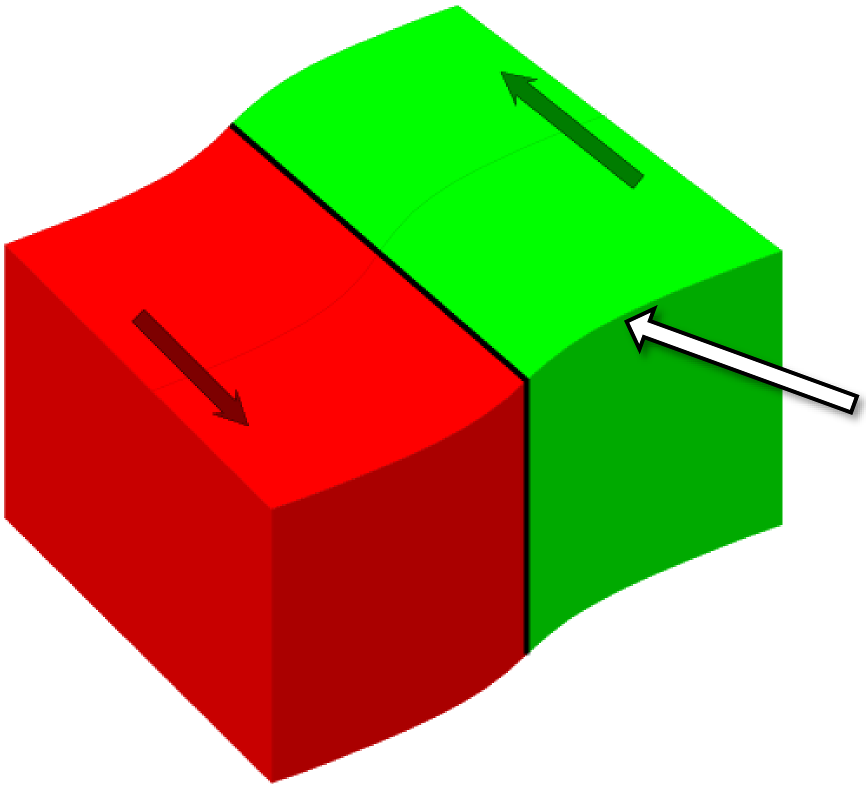


Earthquake

Larger: fault resisted longer

Q5 : ANTICIPATE EARTHQUAKE size ?

Answer : possible, measure deformation before…

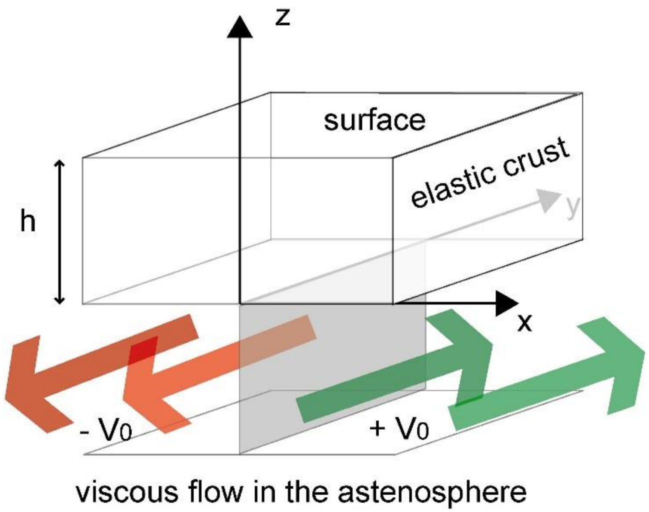


This curve is not any curve

Inter-seismic deformation obeys elastic medium formulation

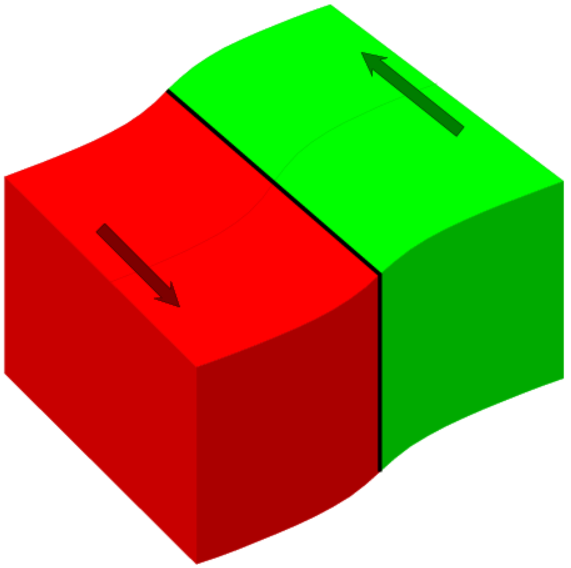
Mathematical formulation : screw dislocation model

$$U_y = K \arctan g\,(x/z)$$



At the surface (z=h)

$$U_y = 2 . V_0/\Pi \arctan g\,(x/h)$$

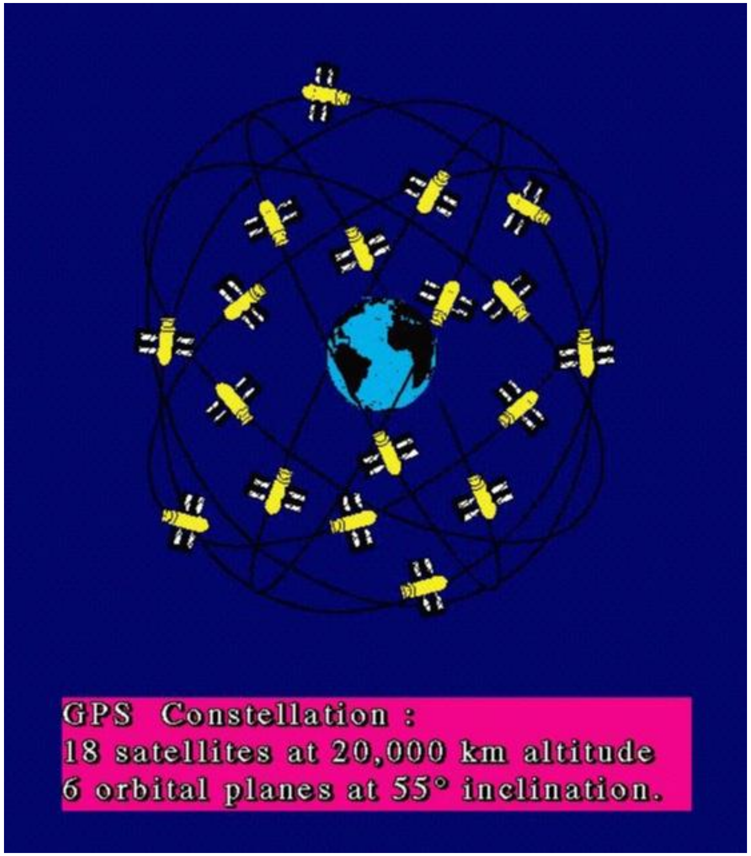


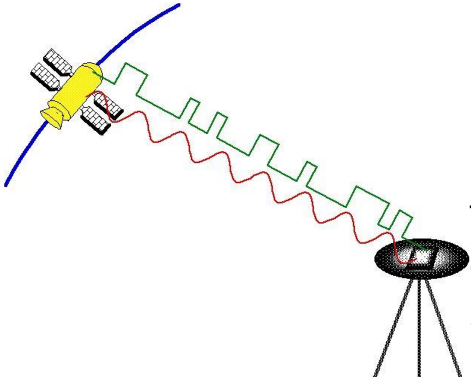
(*) Weertman & Weertman 1964; Savage & Burford 1973; Okada 1985

Q6 : HOW MEASURE pre earthquake deformation ?

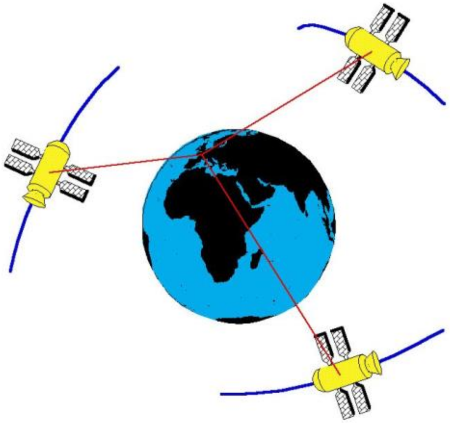
Answer : Geodesy, now space born : GPS

GPS was created in the 80s' by the US Department of Defense for military purposes. The objective was to be able to get a precise position anywhere, anytime on Earth.



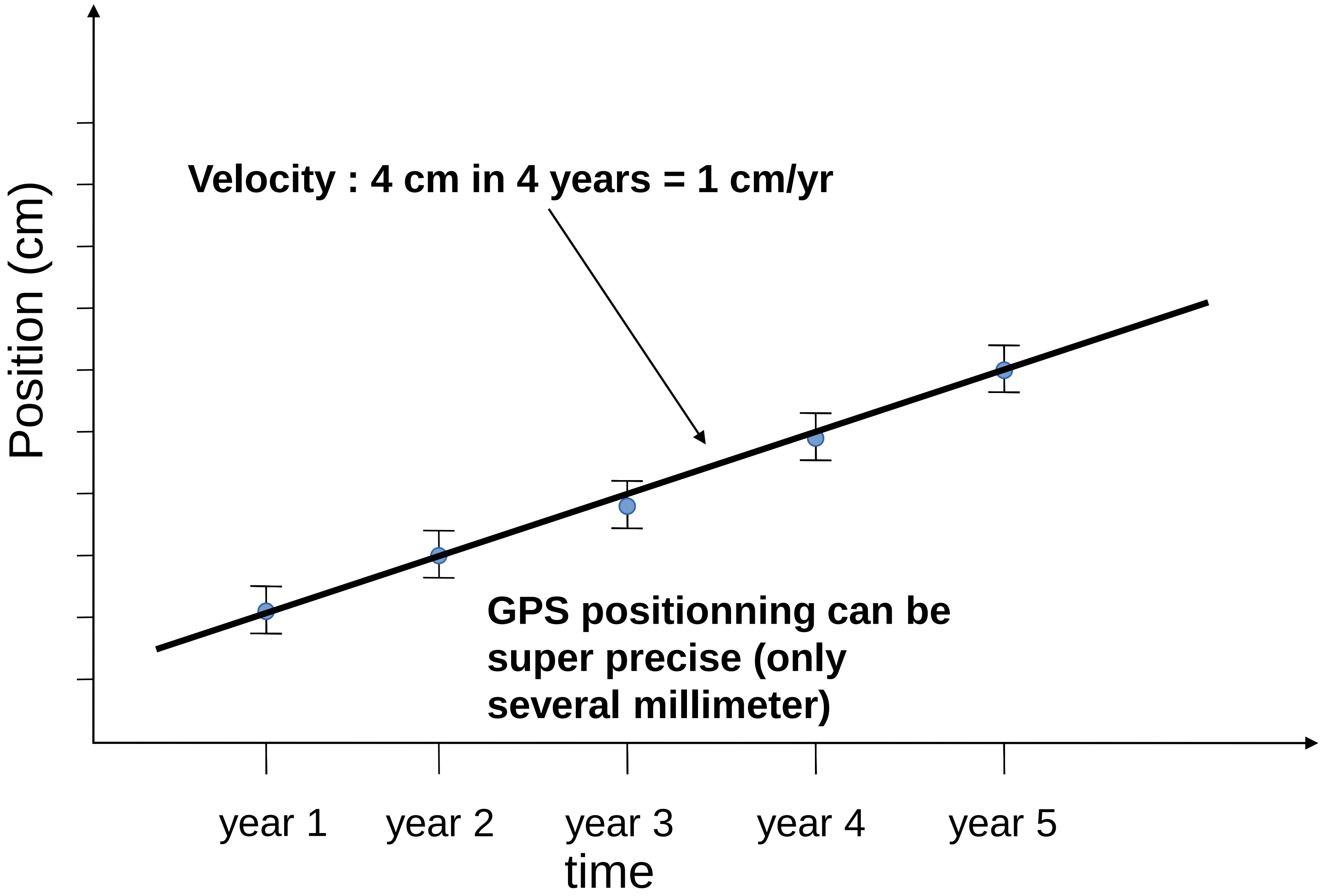


Satellites send signal to Earth.
Receiver records and this allows to determine distance between satellite and receiver



With 3 satellites, one can triangulate and determine the receiver position

GPS (Global Positioning System)

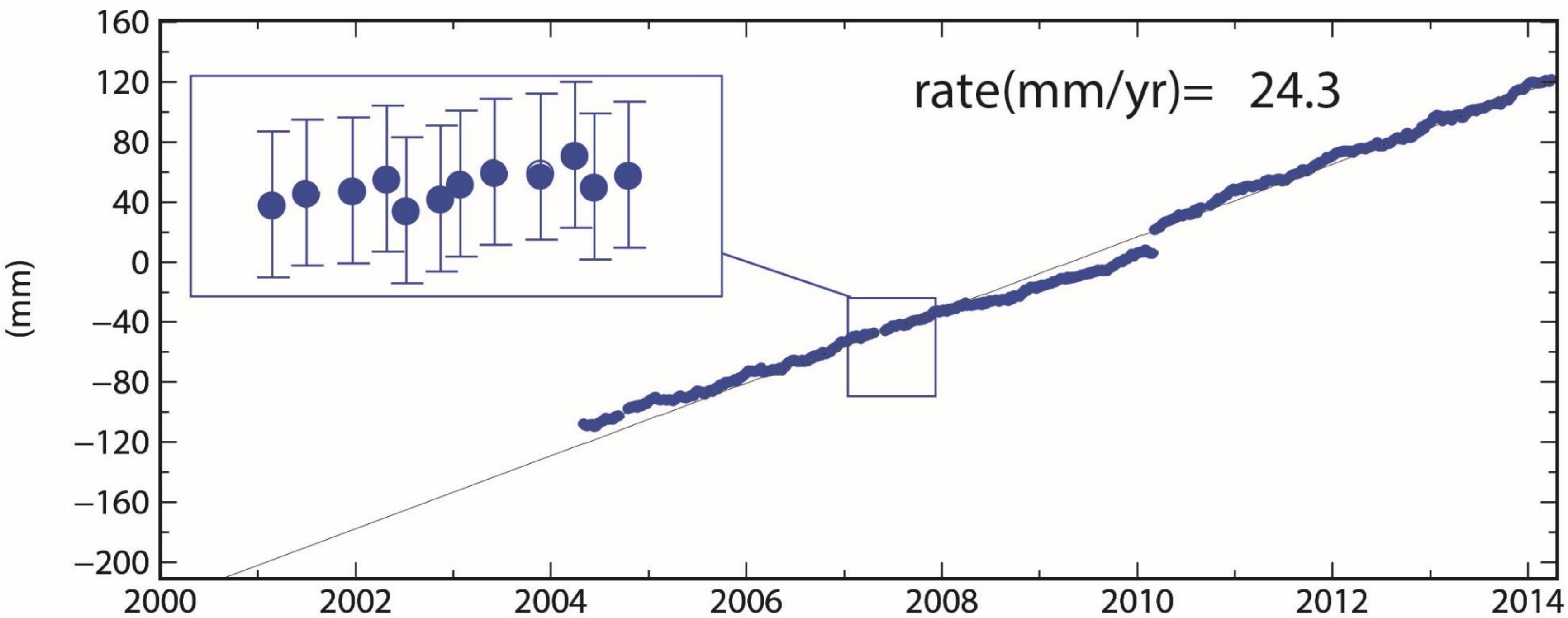


Velocity : 4 cm in 4 years = 1 cm/yr
Position (cm)
GPS positionning can be super precise (only several millimeter)
year 1
year 2
year 3
year 4
year 5
time

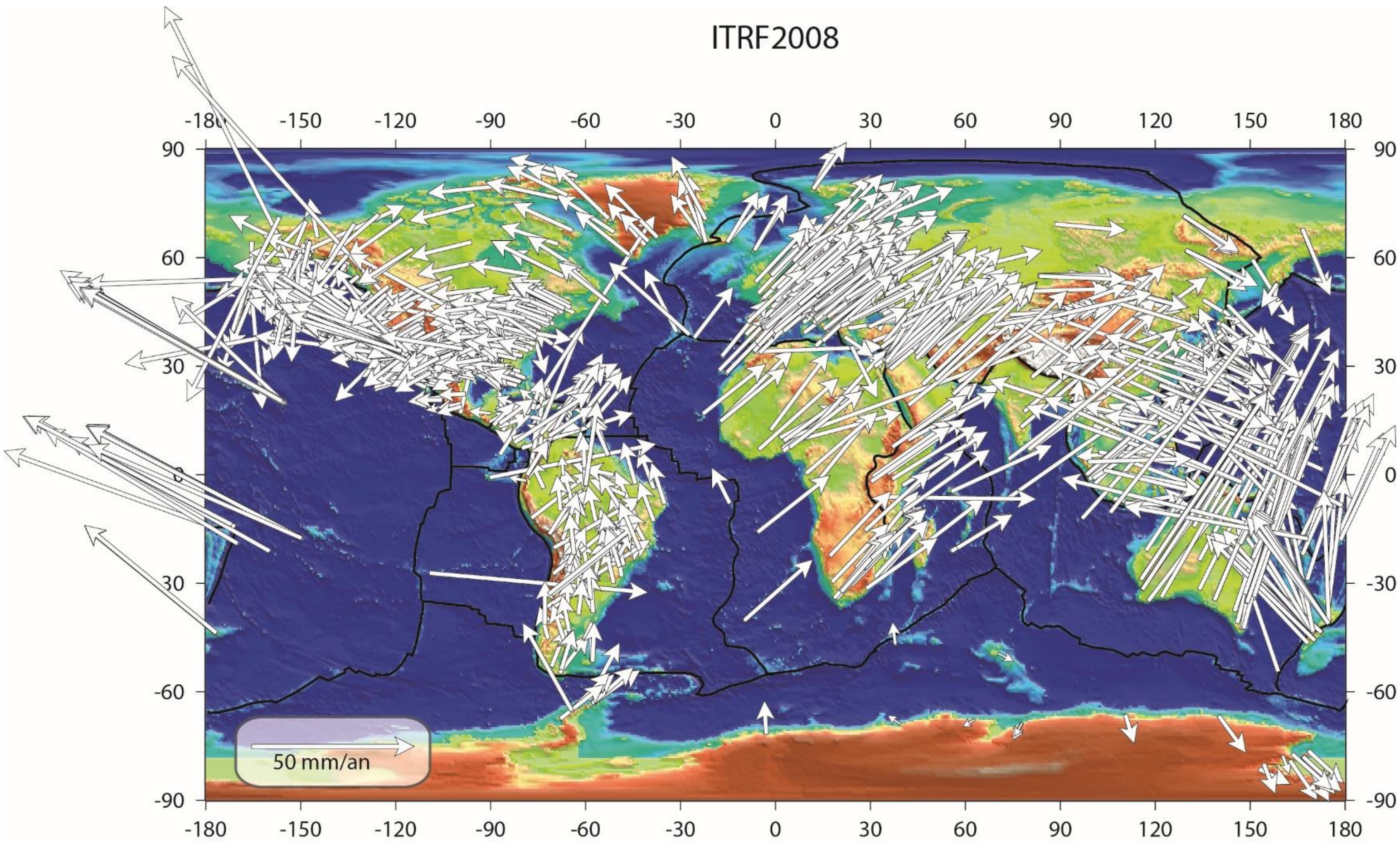
GPS (Global Positioning System)

Permanent stations

Continuous GPS (cGPS) : time series

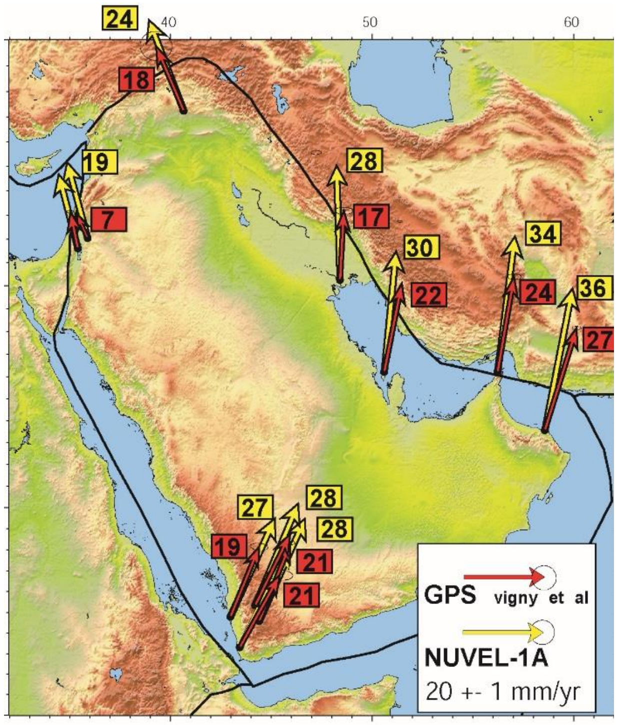


A spectacular application of GPS:
Measurement and quantification of plate tectonics

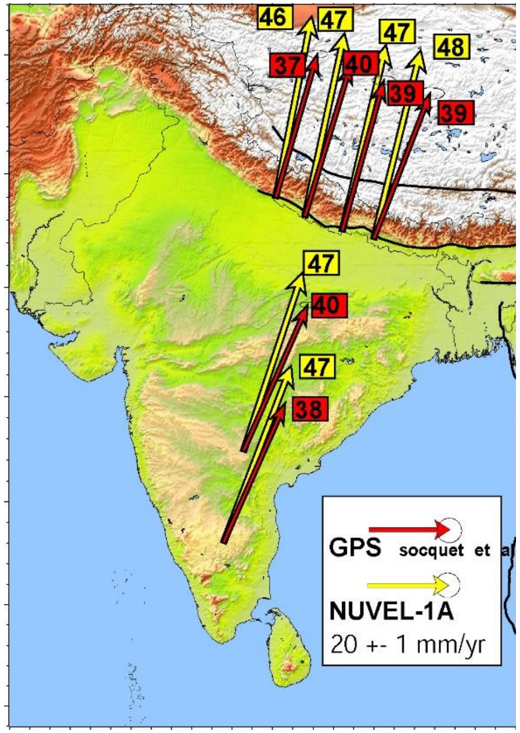


GPS velocities compare well with "geological" velocities: ITRF = Nuvel
⇒ plate motions are stable : 10 km in 1 Myr = 1 cm/yr

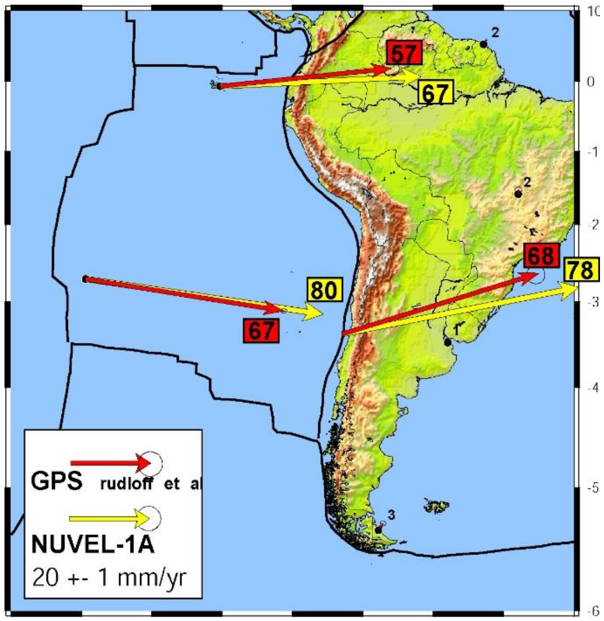
Confirmation of plate tectonics : direct measurement from space



ARABIA

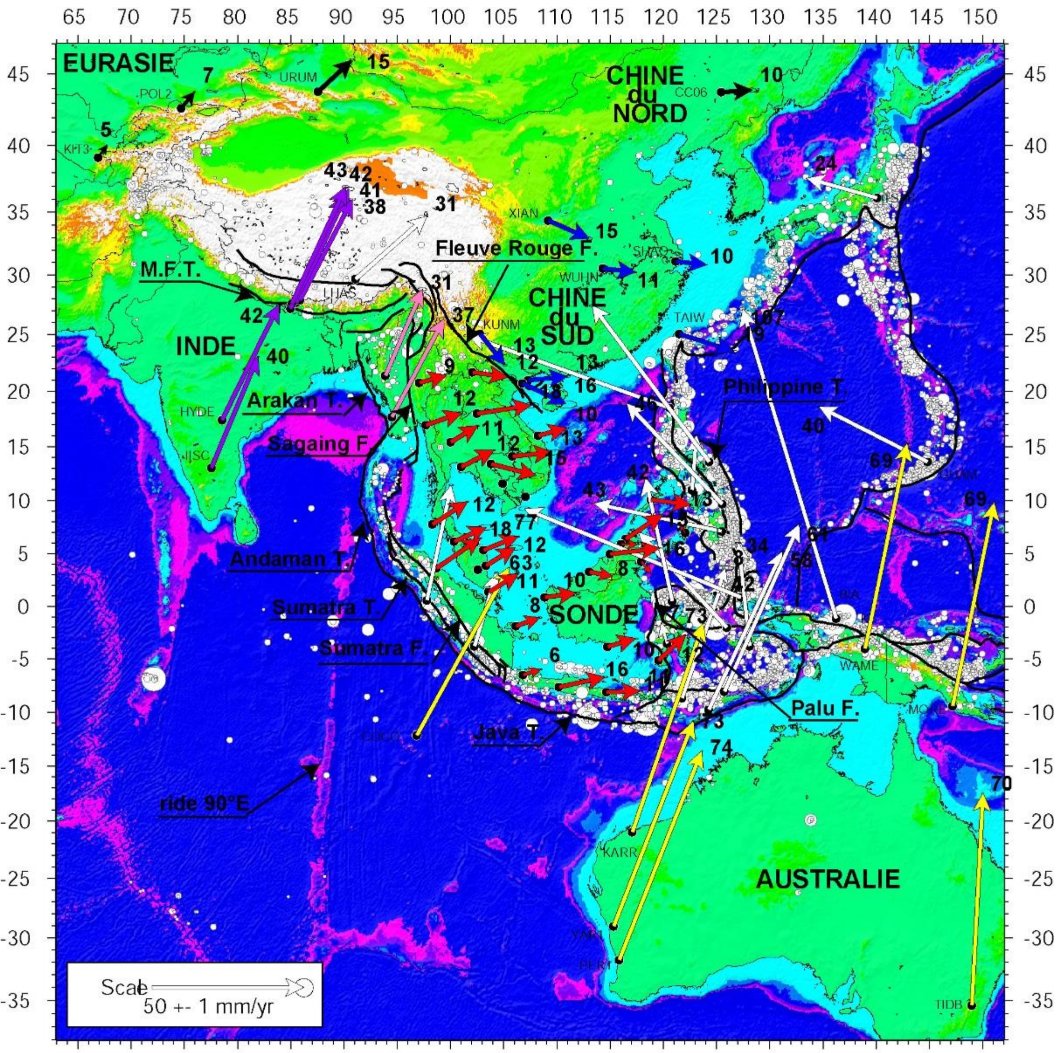


INDIA



SOUTH AMERICA

Discovery of platelets : Sundaland (1997)



SUNDA plate:
60 GPS sites
12 years of measurements

independent from Eurasia and moves 1 cm/yr Eastward

INDIA plate:
6 GPS sites
10 years of measurements

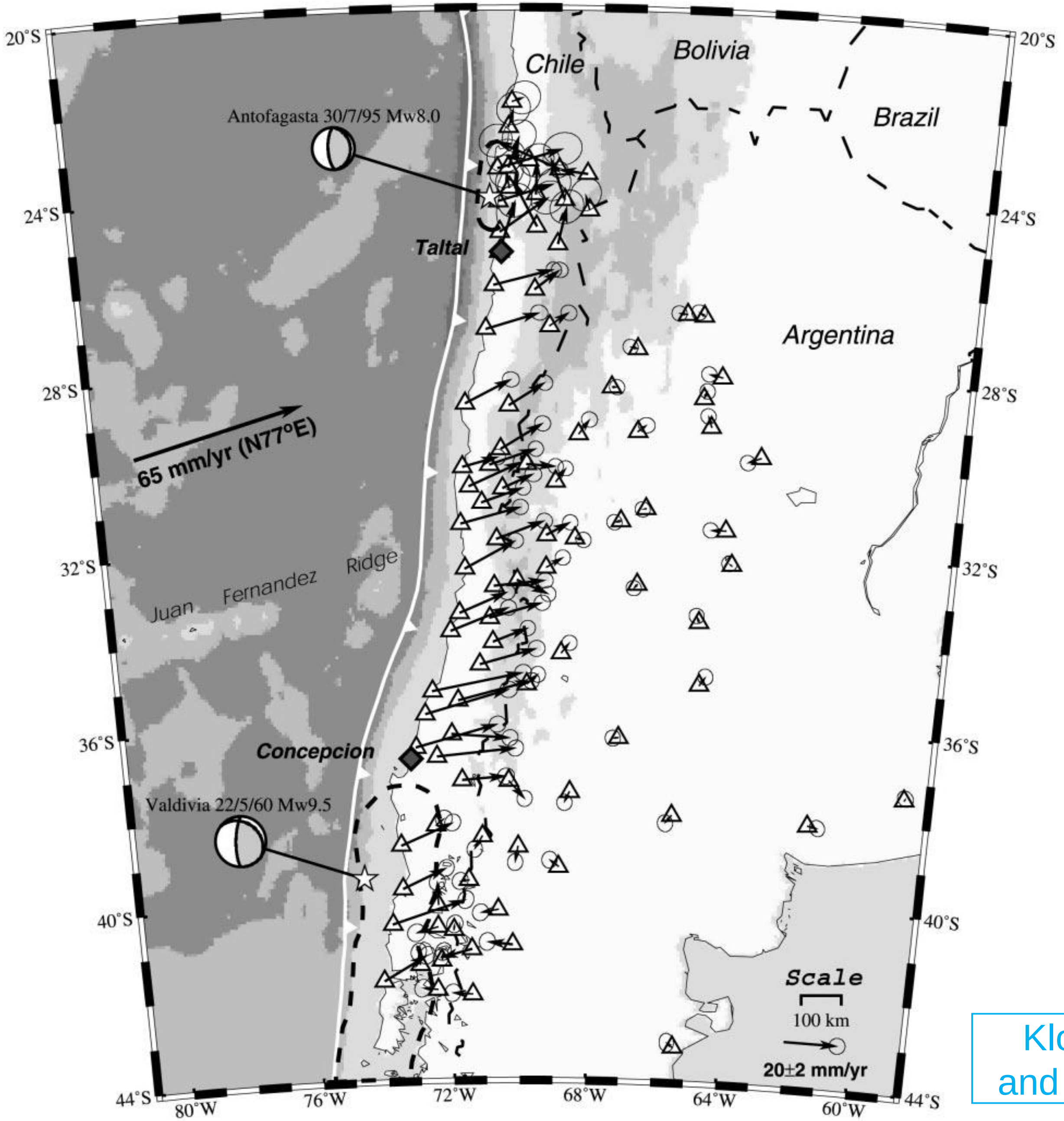
only <u>4 cm/yr</u> wrt GPS Eurasia even less (3.5 cm/yr) wrt Sunda

BURMA platelet (or sliver):
22 GPS sites
2 years of measurements

Nor India, nor Eurasia, not even Sunda

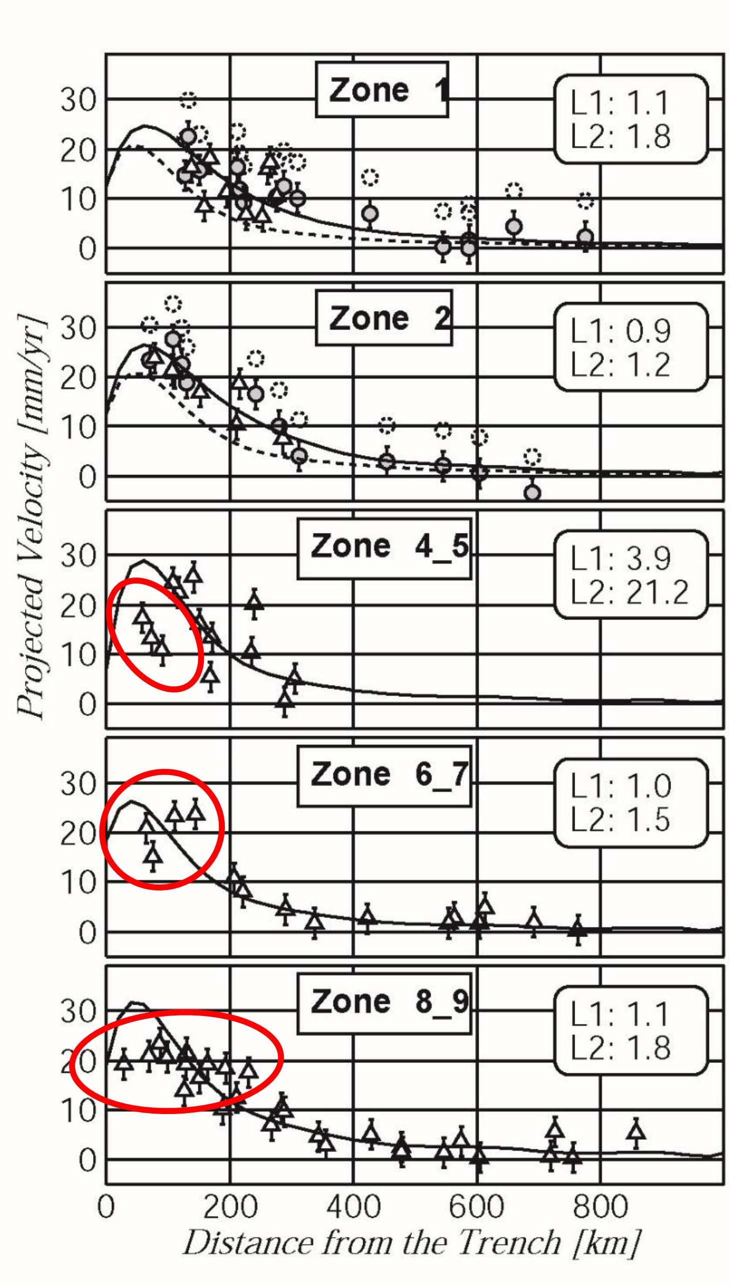
South China ????

SAGA network (GFZ-Potsdam) since ~1990



Klotz, Khazaradze and co-authors, 2002

Klotz, Khazaradze and co-authors



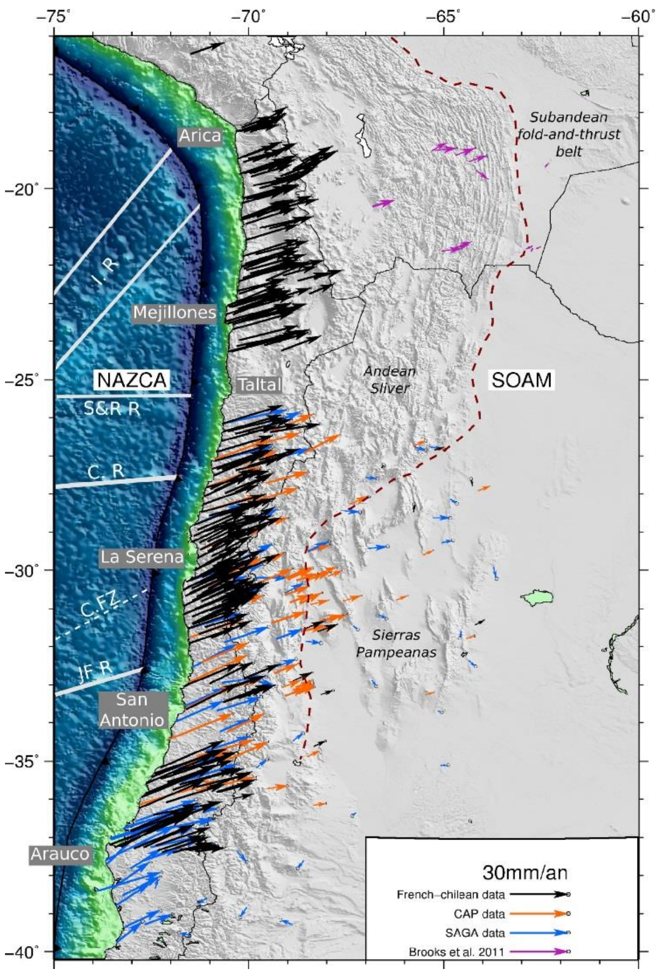
Curves show elastic deformation prediction according to sandard model (Full Coupling, …)

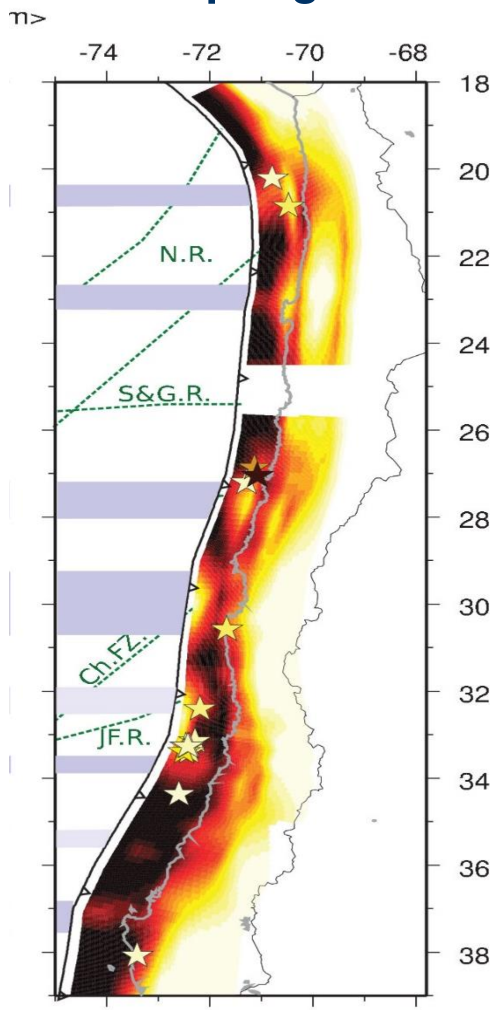
But ……

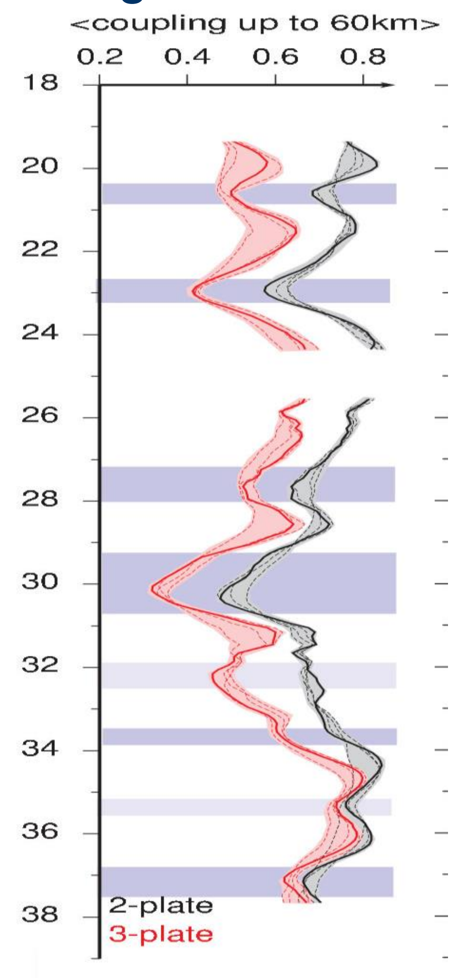
Intra-plate deformation during inter-seismic loading…

25 years of GPS measurements in Chili => coupling maps

Deformation → **coupling** → **segmentation**





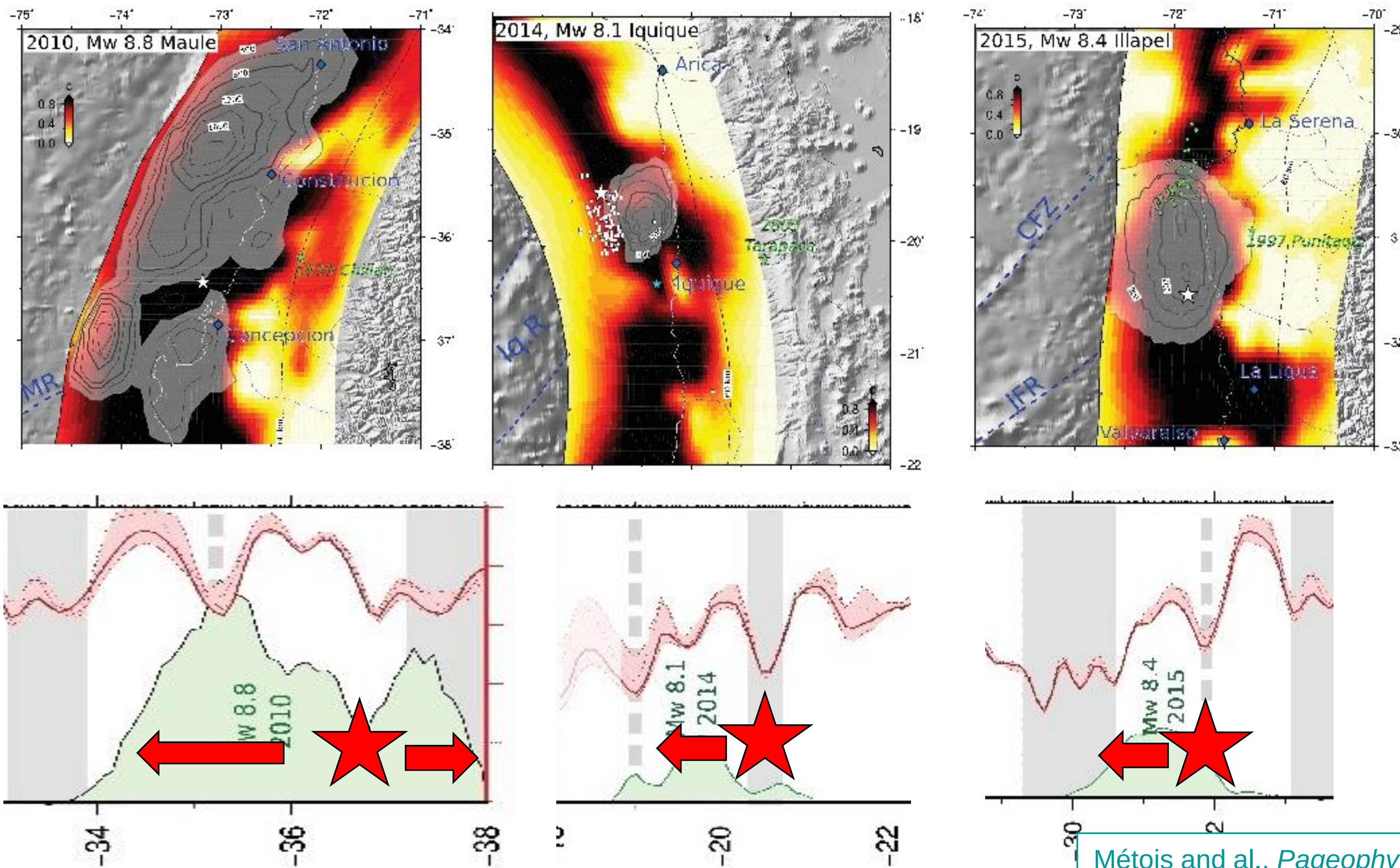


Métois et al., pageophy, 2016

FINDING1 : Earthquakes occur in high coupling areas

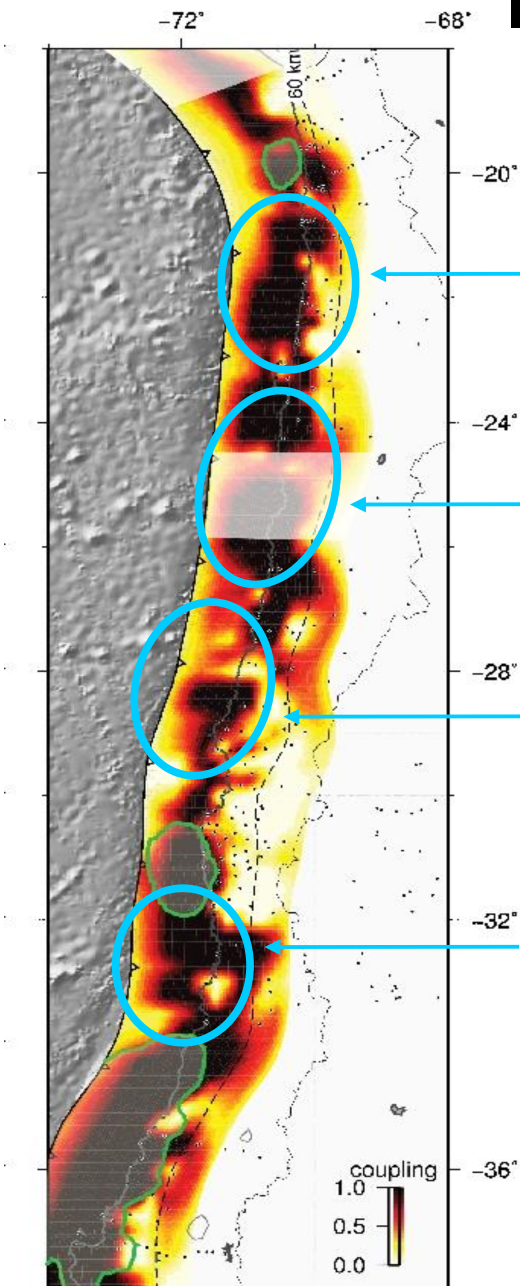
interesting : epicenters seem located in lower coupling areas….

Maule 2010 8.8 **Iquique 2014 8.1** **Illapel 2015 8.4**



Métois and al., *Pageophy*, 2016

Plausible ~~predictions~~ scenarios



1877 north Chile Gap :

Coupled but not mature

Unlikely to break soon with Mw ~9 (like 1877

but could produce *several "smaller magnitude(s)" Mw 8.?*

Taltal ????

1922 Copiapo Gap :

Coupled and mature and triggered

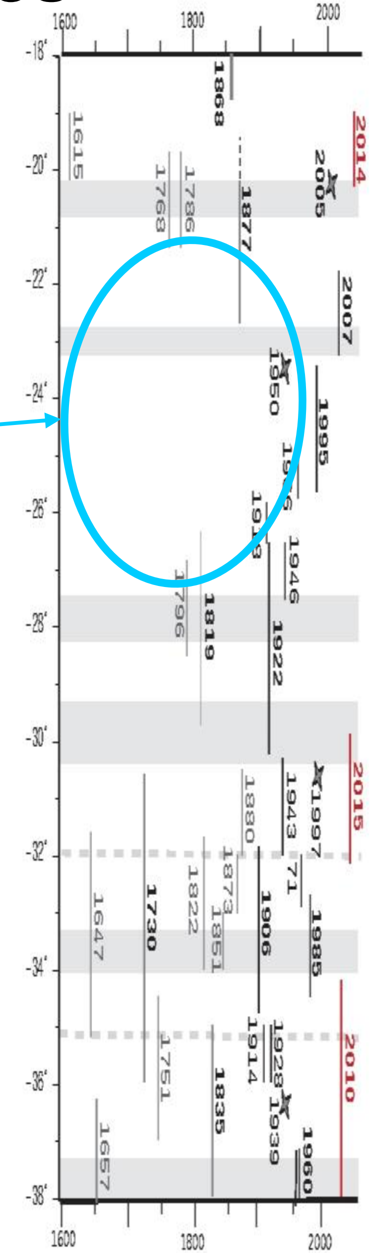
likely to break soon with Mw ~8.5 (like 1922)

But complex gap (segmented ?)

1906 Valparaiso Gap :

Coupled, may be mature but delayed by relax.

Unlikely to break soon with Mw > 8.5 (like 1906)

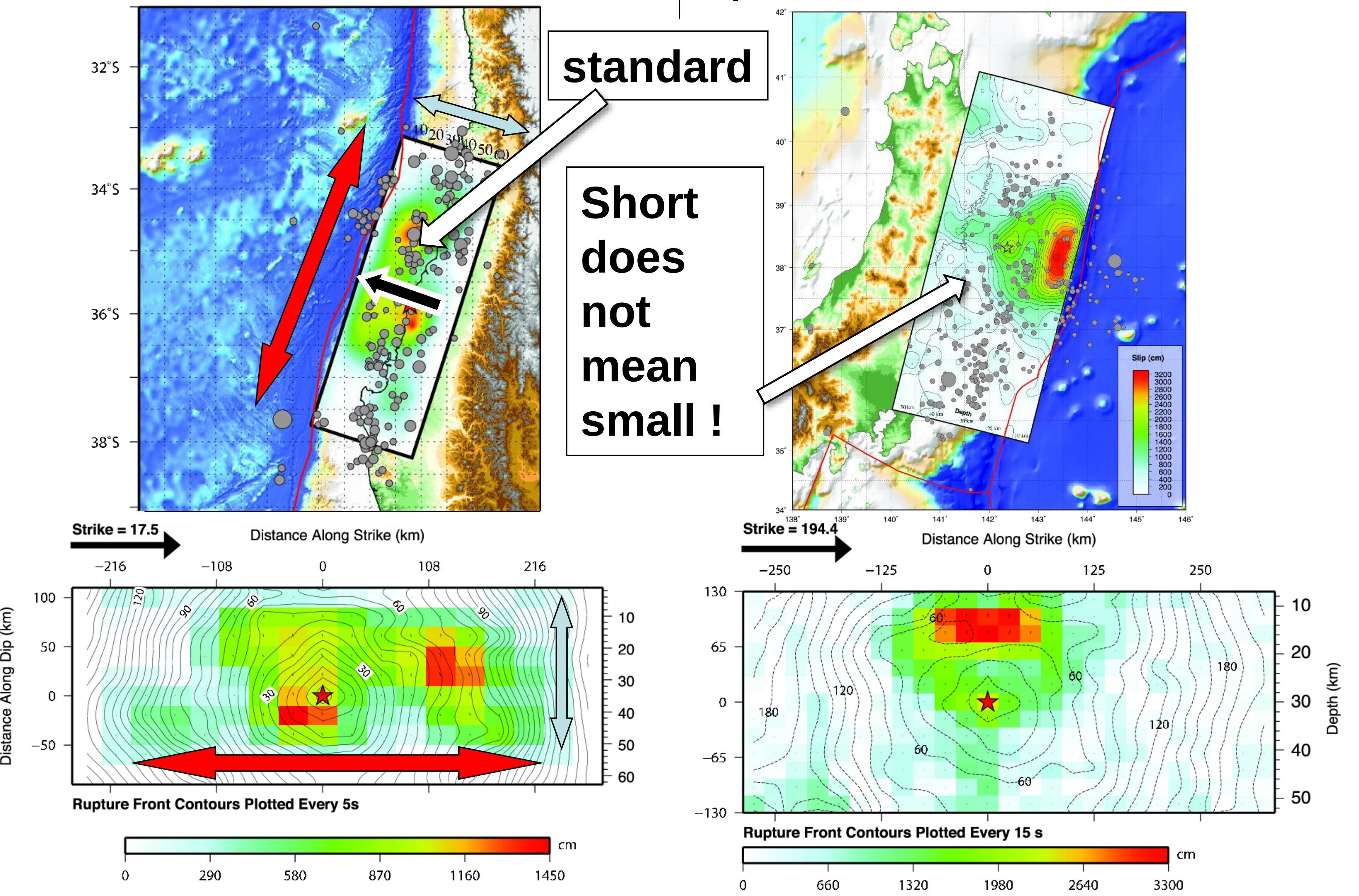


Surprises !!!

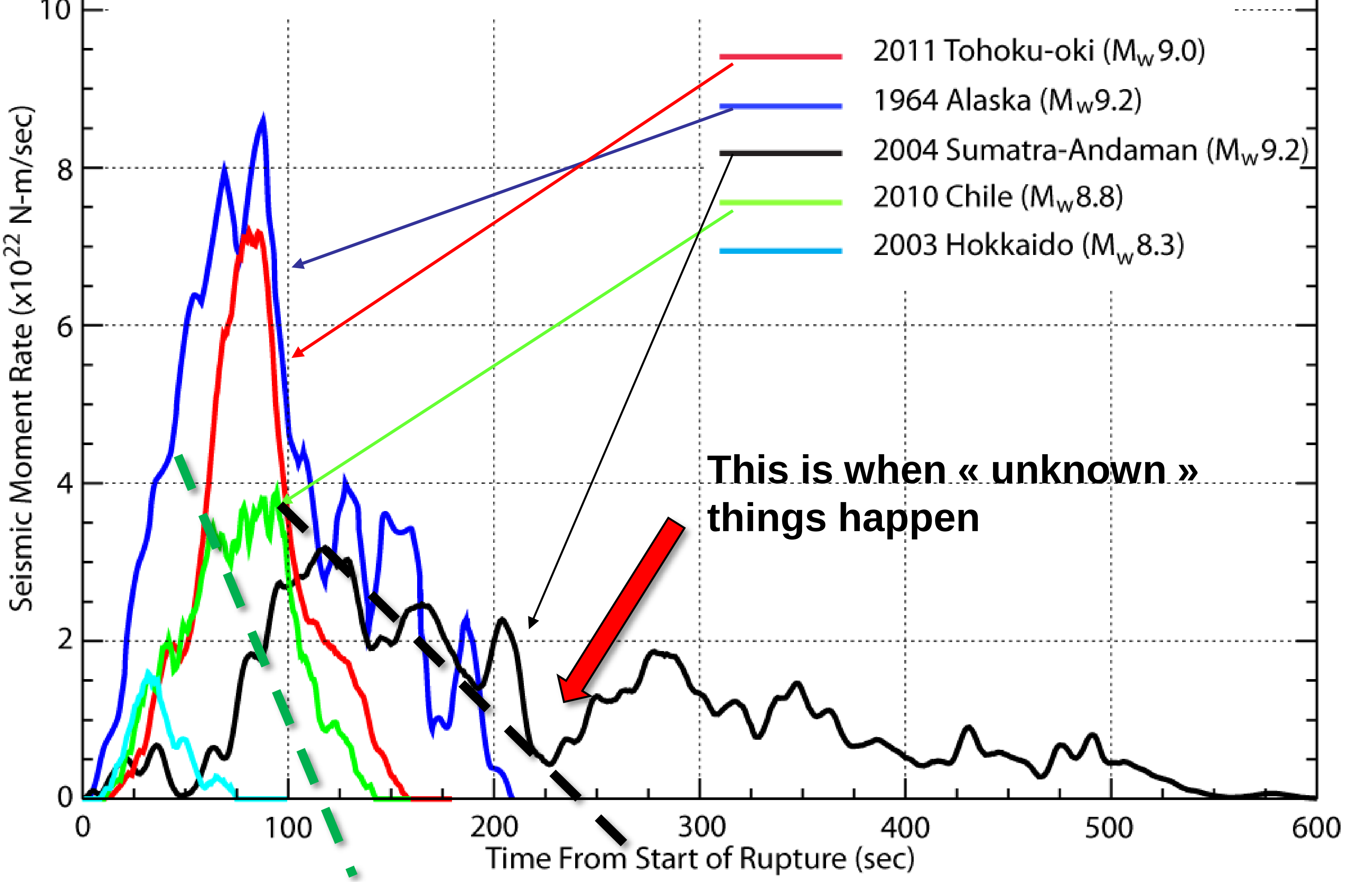
Things to learn from….

Earthquake size = surface of asperity x slip

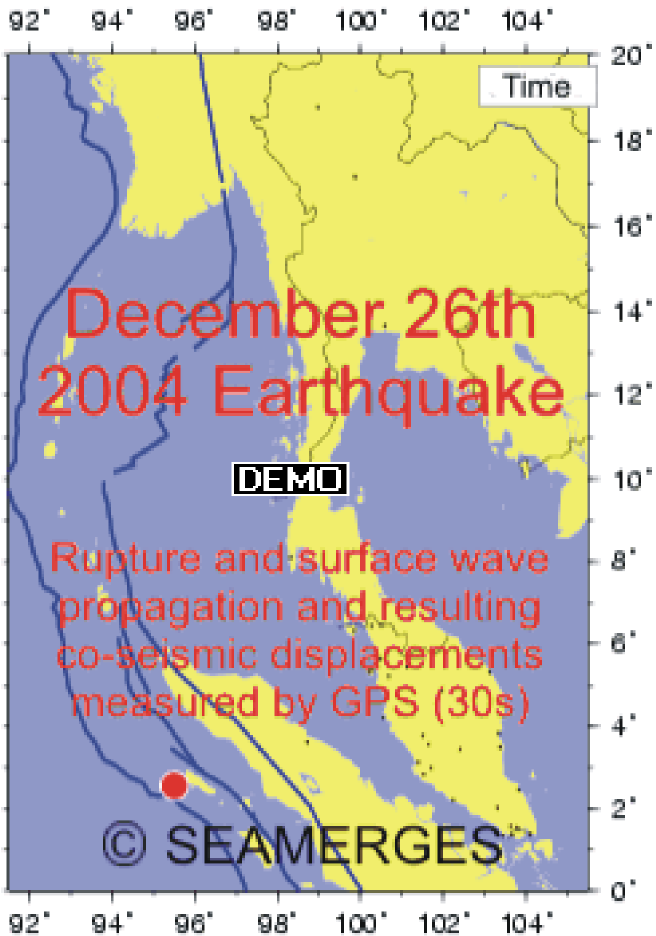
Chile: **450 km** x **150 km** x **9 m** => Mw 8.8 | **Japan**: **200 km** * **150 km** * **25 m** => Mw 9.0



Variable size… variable duration



Lay and Kanamori, Physics Today, 2011



http://www.deos.tudelft.nl/seamerges

rupture

Seismic **surface** waves propagation

(3.7 km/s)

GPS stations displacements

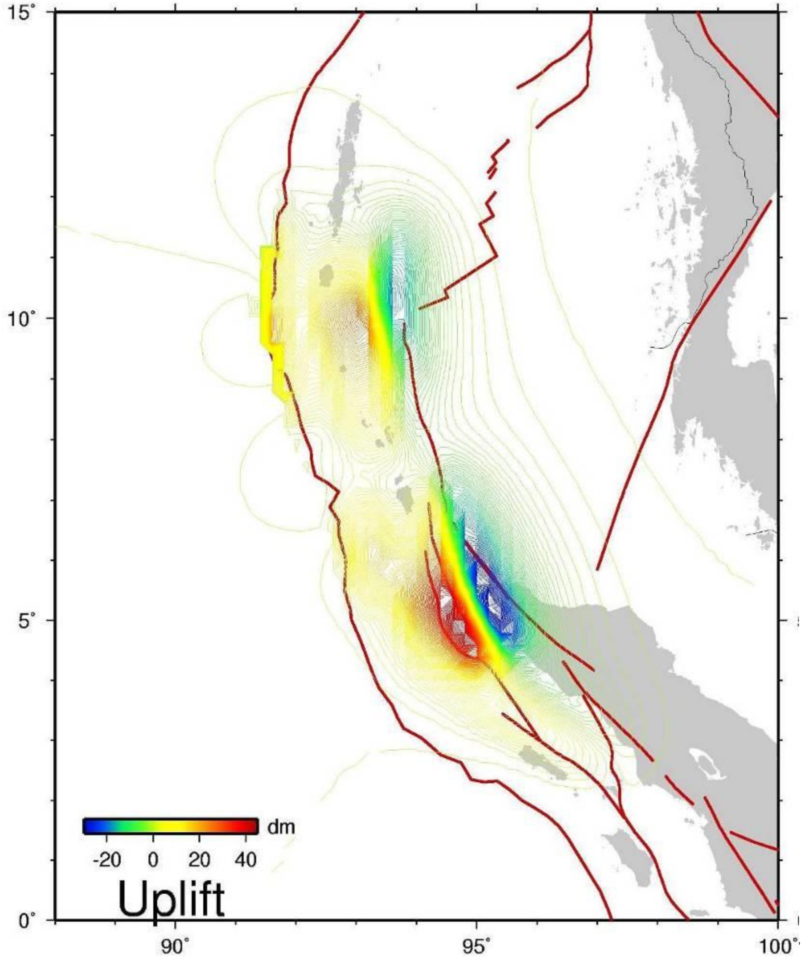
<u>Rupture Propagation:</u>

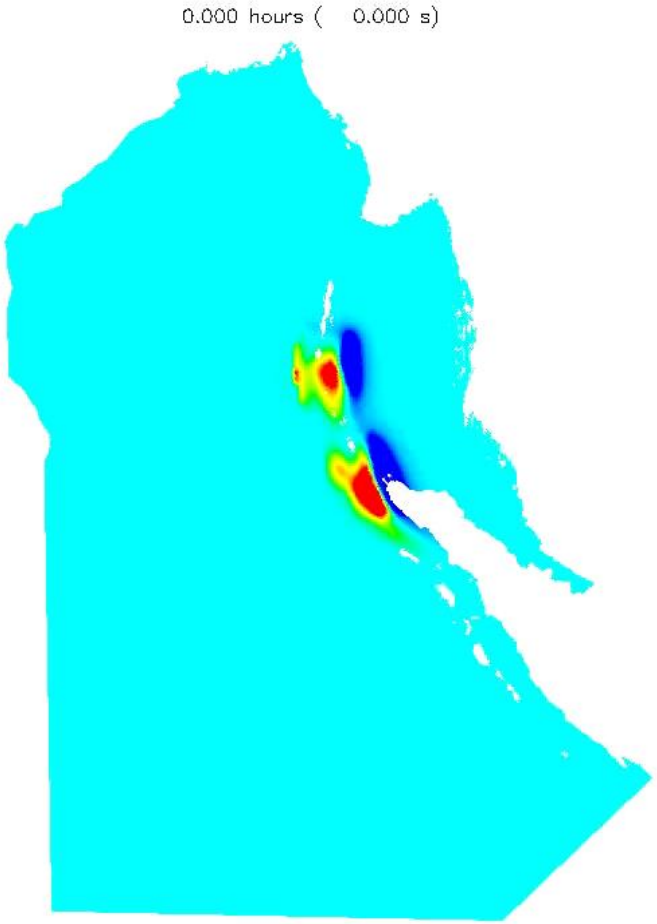
3.7 km/s initially (South)

30s stop ~ 8° lat

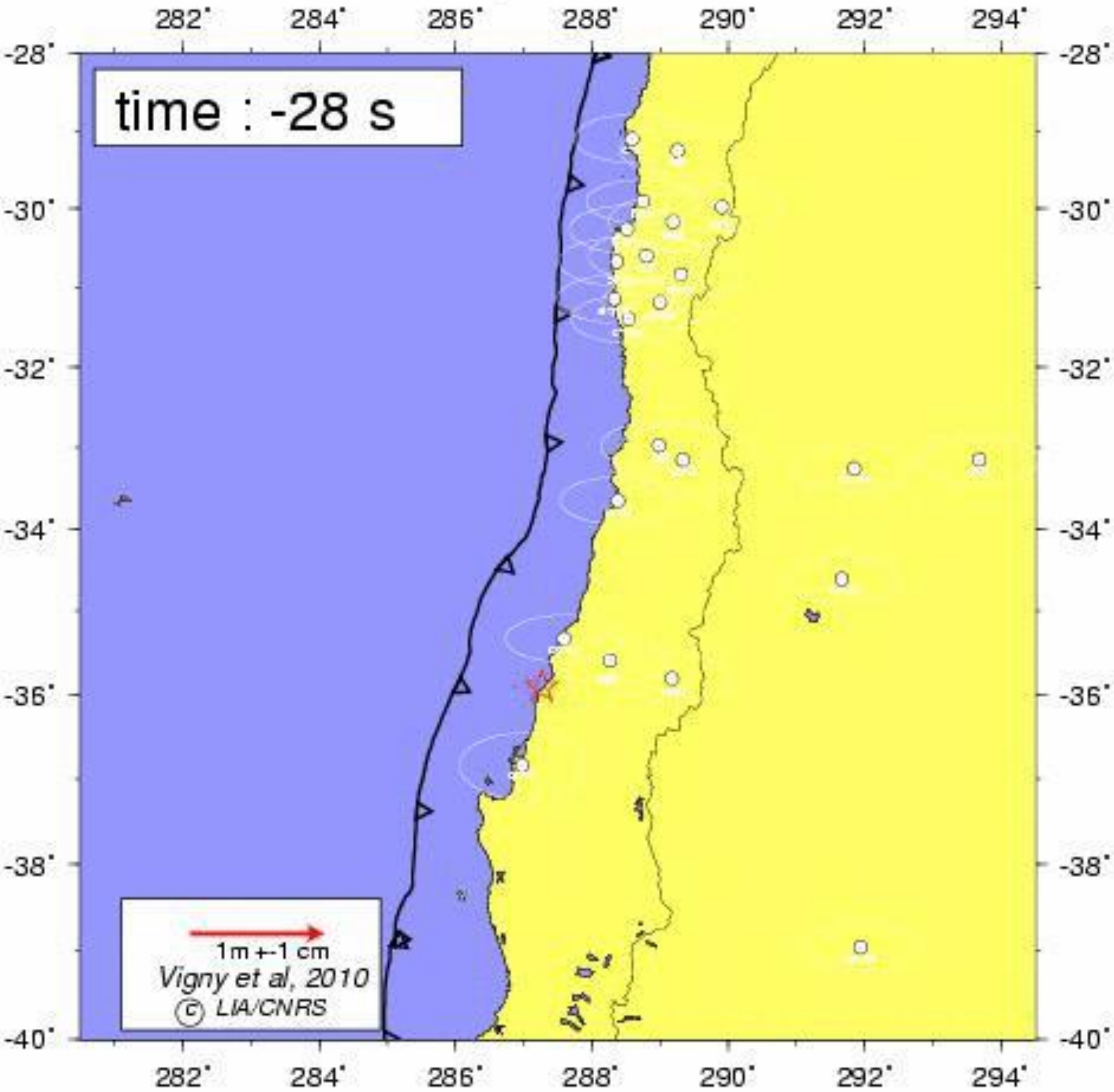
1.8 km/s onward (North)

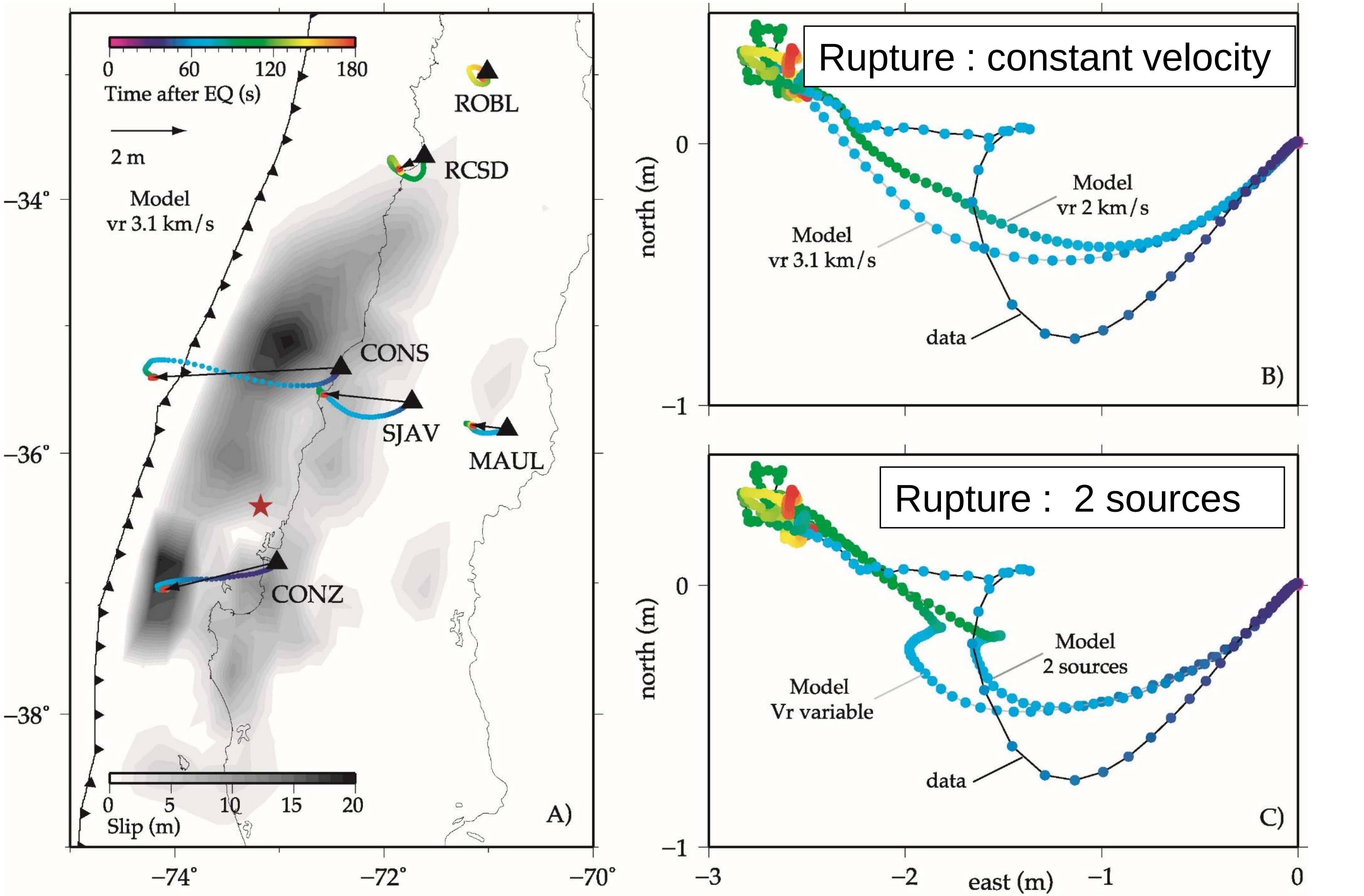
Underwater ground motion => Tsunami





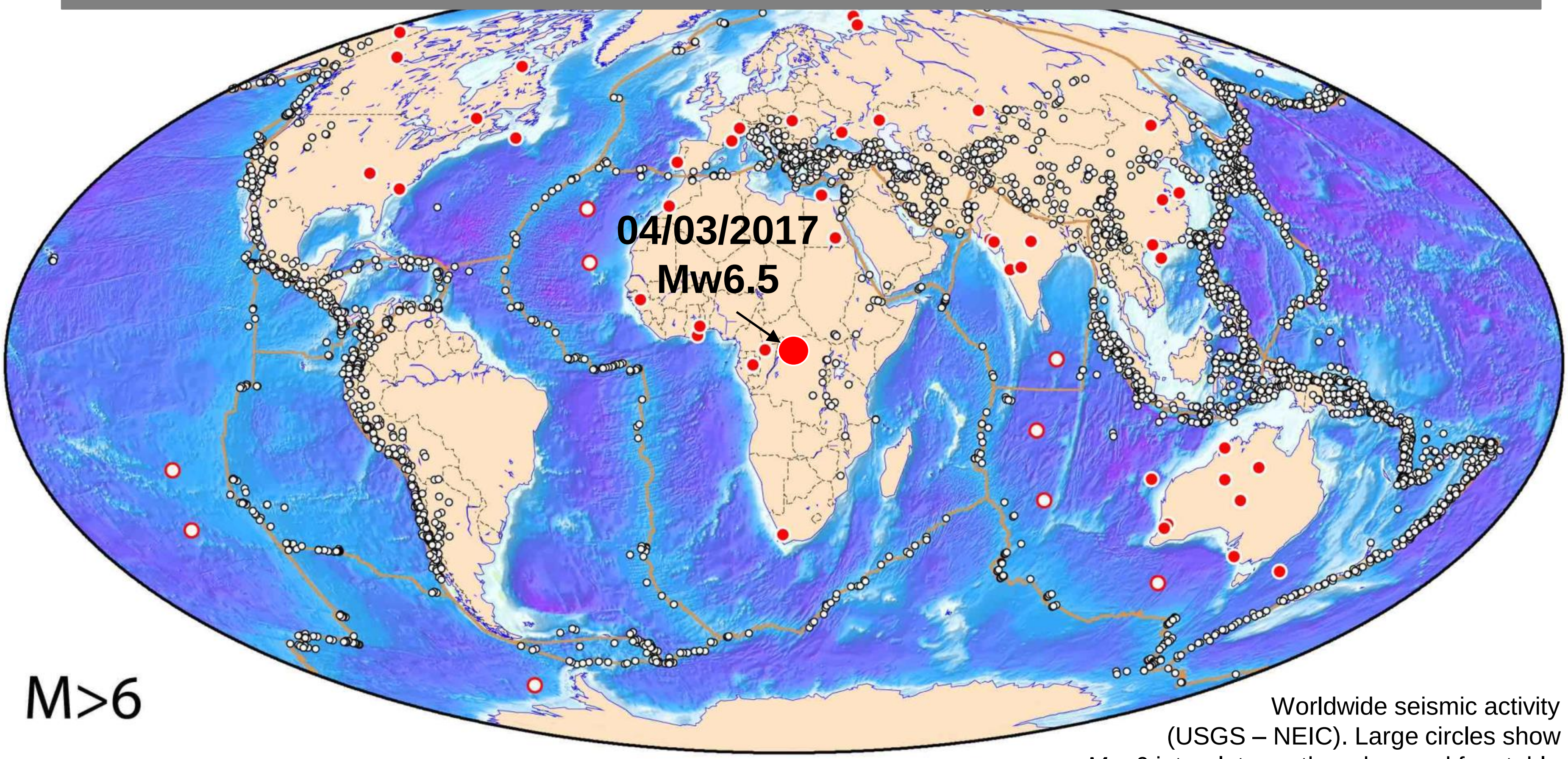
Maule Eq 27-Feb-2010





0 60 120 180
Time after EQ (s)
2 m
Model
vr 3.1 km/s
ROBL
RCSD
CONS
SJAV
MAUL
CONZ
0 5 10 15 20
Slip (m)
A)
−34°
−36°
−38°
−74°
−72°
−70°
Rupture : constant velocity
Model
vr 2 km/s
Model
vr 3.1 km/s
data
B)
north (m)
0
−1
Rupture : 2 sources
Model
2 sources
Model
Vr variable
data
C)
north (m)
east (m)
−3
−2
−1
0

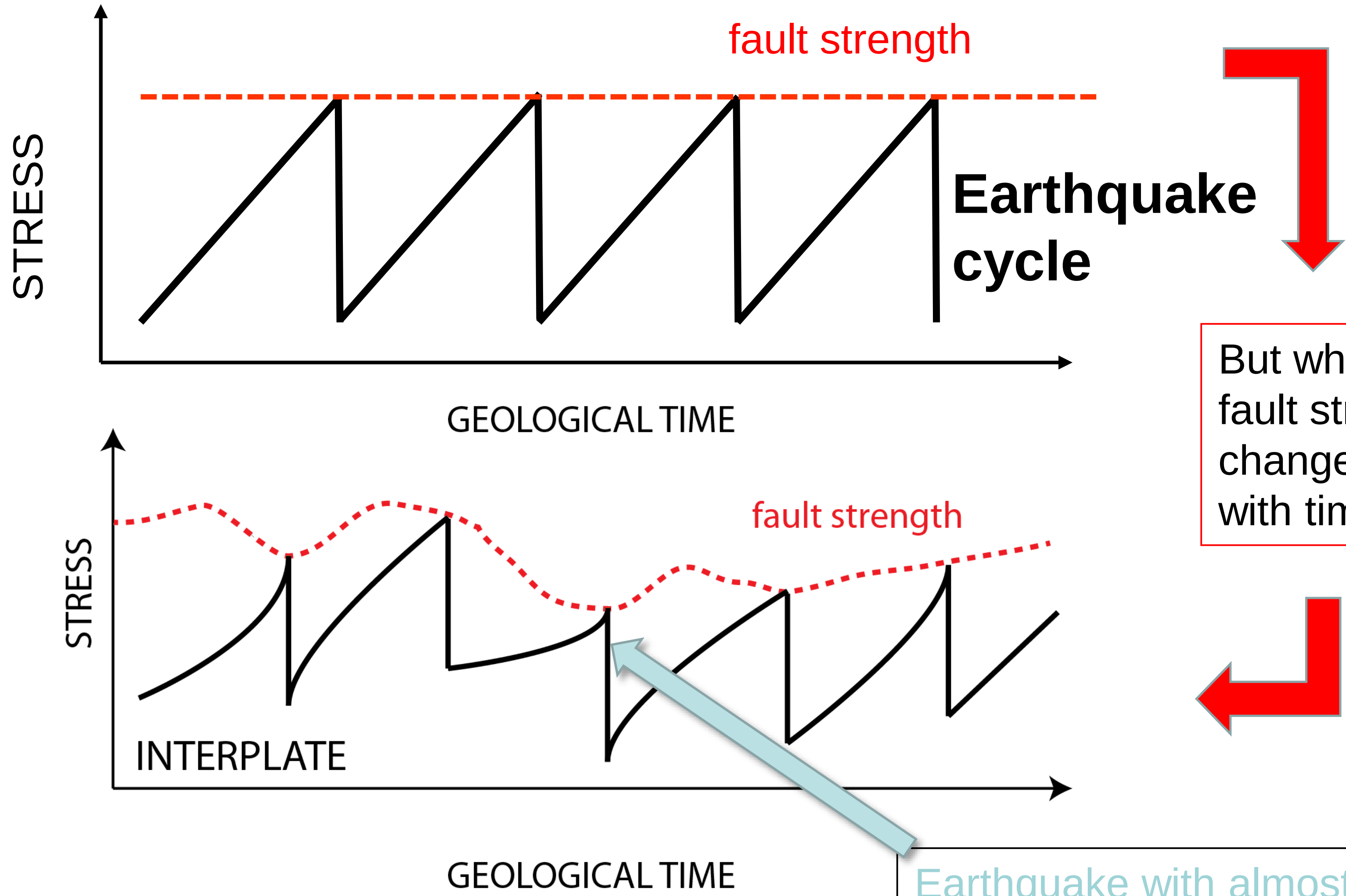
Large Earthquakes in Plate Interiors: A Challenge to Plate Tectonics



Worldwide seismic activity (USGS – NEIC). Large circles show *M* > 6 intraplate earthquakes: red for stable continental regions, white for stable oceanic regions.

Stable continental regions (SCRs): “areas where the continental crust is largely unaffected by currently active plate boundary processes” (Johnston, 1989)

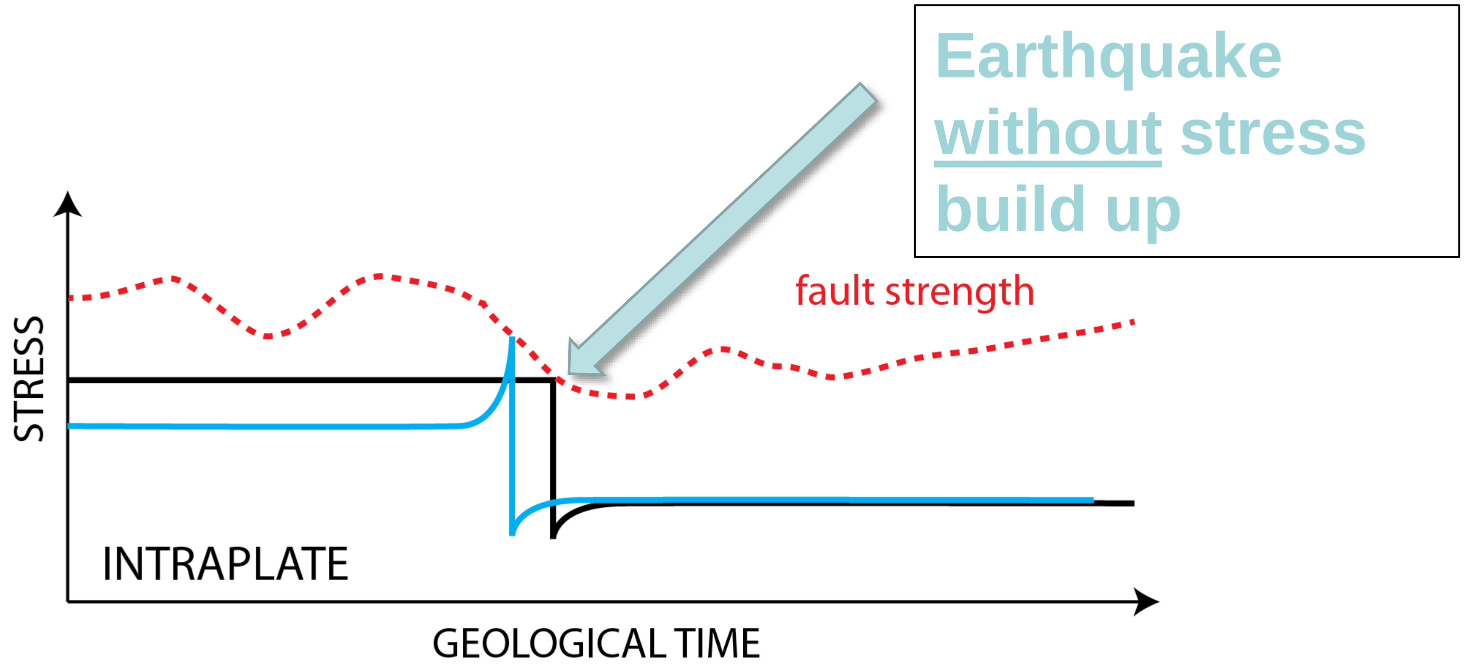
"Earthquakes occur as a result of global plate motion"
(Kanamori and Brodsky, Rep. Prog. Phys., 2004)



But what if fault strength changes with time ?

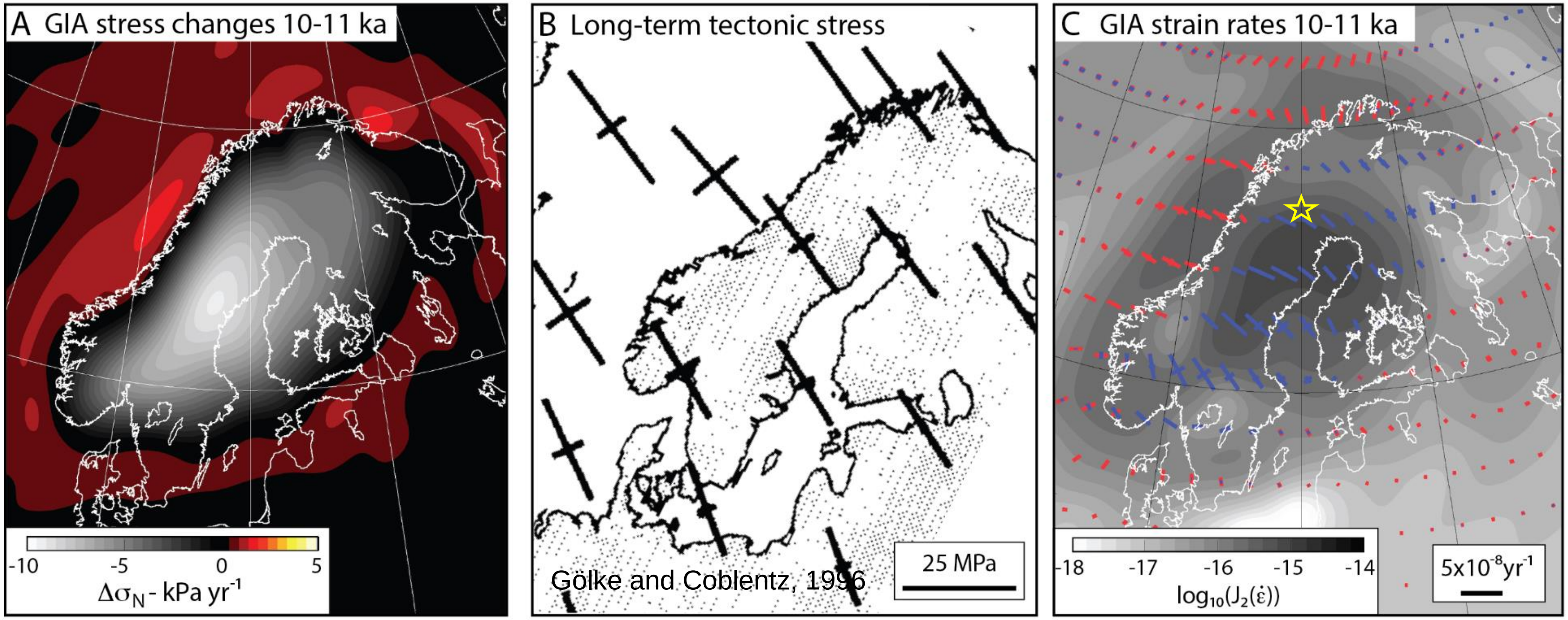
Earthquake with almost no stress build up

While long-term tectonic stress provides the energy that is released during large SCR earthquakes, they are **triggered by** transient perturbations of local stress that release elastic energy from **a pre-stressed crust** where faults are at failure equilibrium.



SCR earthquakes occur as a result of transient stress/strength perturbations and release elastic energy from a pre-stressed crust.

Current release of paleo stress in Fenoscandia => new seismic hazard



End-glacial faults did not release strain building up at the time

=> SCR crust stores elastic energy over time scales that are longer than observable by geodesy or paleoseismology

Craig, Calais, Fleitout, Bollinger, Scotti, GRL, 2017

…more [difficult] work ahead..

Thanks for attention

Size of an Earthquake

Earthquake « size » or released Moment M_0, is proportional to :

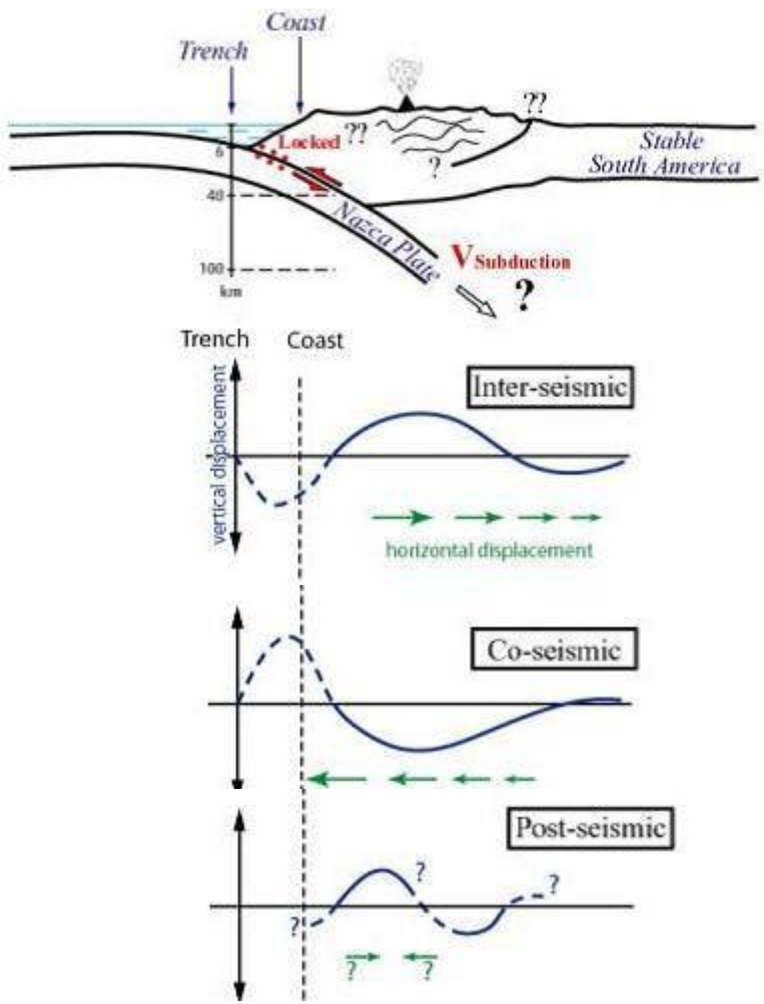
- Quantity of slip (U)
  - ↳ fault velocity (V) x time between earthquakes Δt
- Size of ruptured surface (S)
  - ↳ Length of rupure (L) x Locking depth of fault (d)

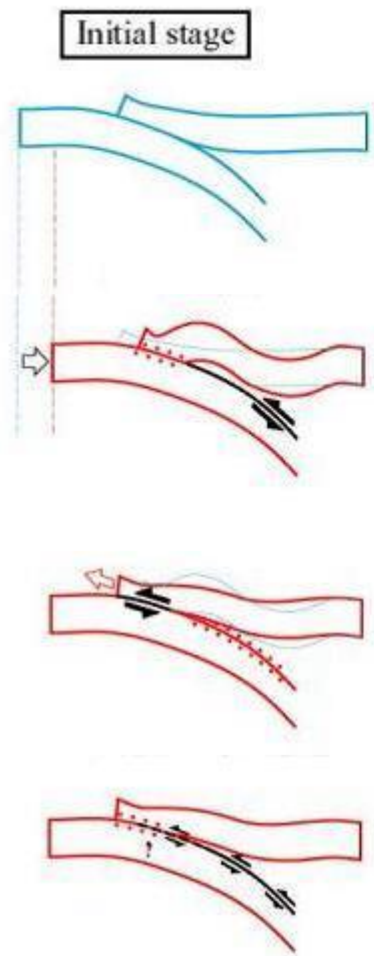
$$\Rightarrow M_0 = \mu \times S \times U = \mu \times L \times d \times V \times \Delta t$$

Magnitude of an Earthquake (Hanks & Kanamori):

$$M_W \sim Log\,(M_0) = 2/3\,Log\,(M_0) - 10.7$$

La Subduction : Un très très gros ressort !!!





Centaines d’années

Quelques secondes
quelques minutes

Des mois

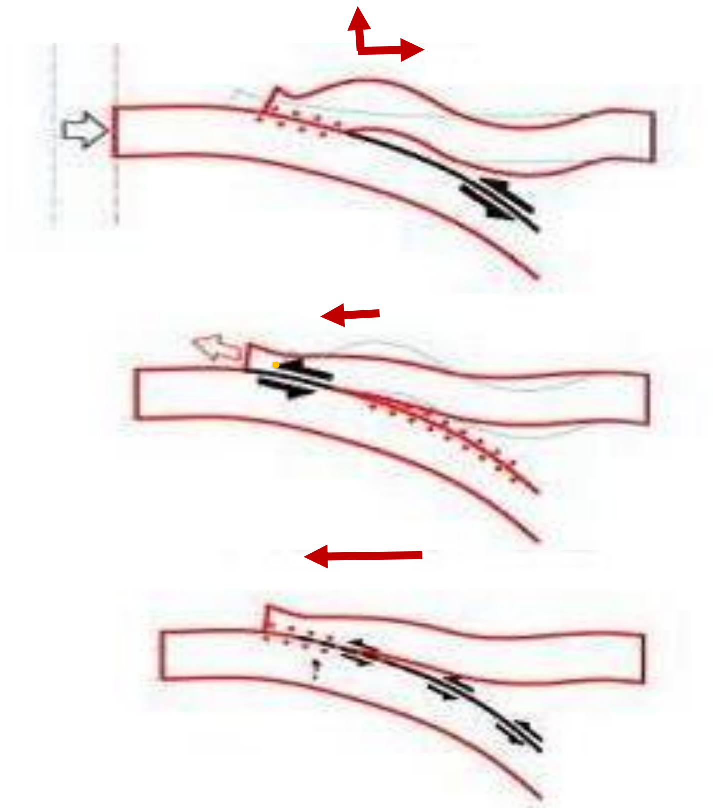
des années

Seismic cycle on subduction zone

Interseismic stage :
Interface locked over several decades
Strain accumulation *over decades to century*

Coseismic stage : **The earthquake**
Sudden stresses release *in a few seconds/minutes*

Postseismic stage :
Response of coseismic stresses transfert on deep layers *over decades*



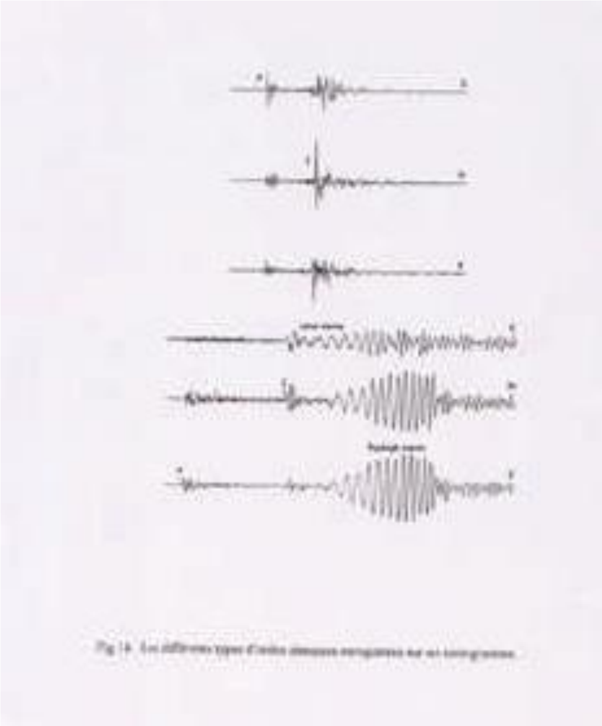
Modified from Chlieh *et al.*, 2004

Different mechanisms:

- **Poroelastic rebound** → < 50km from the trench / several months
- **Elastic afterslip** → first hundreds km / few months to few years
- **Viscoelastic relaxation** → very large scale / few decades

Pourquoi un séisme produit il des dommages ?

À cause de l'énergie rayonnée sous forme d'ondes sismiques



L'énergie émise est bien sur reliée à la taille de la rupture (au moment sismique), *mais pas seulement*. Elle dépend aussi de la vitesse à laquelle la « déchirure » se propage……….

Kobé, Japon (17/01/1995) – Mw 7.5

- dommages au bâti sont surtout causés par mouvements horizontaux du sol (ondes S) dans la gamme de période de 1seconde à 0,1 seconde qui correspond aux résonnances de la plupart des batiments

- La chute opposée de deux rangées de vélos permand de déterminer la demi longueur d’onde du mouvement horizontal (onde S)

- Effands indirects : liquéfaction du sol
- Caracas, Venezuela 29/07/1967 Mw 6.6

Phénomène de liquéfaction responsable du basculement et de l'enfoncement d'un immeuble à Caracas (Vénézuela), lors du séisme du 29 juillet 1967 (magnitude 6,6). (Collection NOAA)

Risque sismique = Aléa x Vulnérabilité

- Aléa sismique:

Probabilité pour un site de subir un séisme donné (localisation, profondeur, taille, type, andc…) à un instant donné

- Vulnérabilité:

Dépend 1/ des personnes and 2/ des biens exposés à l'aléa:

1/ De la Population :

- De son niveau d'éducation
- De son niveau économique and social
- De l'existence ou non d'une "culture sismique" des individus and des pouvoirs publics (réflexes, organisation, secours, andc…)

2/ Des constructions:

- Du type and de la qualité des matériaux
- Du mode de construction
- De la qualité du sol

- Dans le désert, le risque sismique est négligeable même si l'aléa est élevé.
  Exemple: le séisme des î Balleny, Antarctique, 2004.

- Dans régions à forte densité de population (and aux constructions précaires), le risque sismique est très élevé même si l'aléa est modéré.
  Exemple séismes de Bâle (Suisse) au 16eme siècle ou de Lisbonne au 17eme siècle.

- La vulnérabilité, **donc le risque**, est en augmentation constante dans pays en voie de développement (surpopulation and paupérisation).

Séisme d'El Asnam (Algérie), le 10 octobre 1980
M = 7,3

Risque sismique négligeable

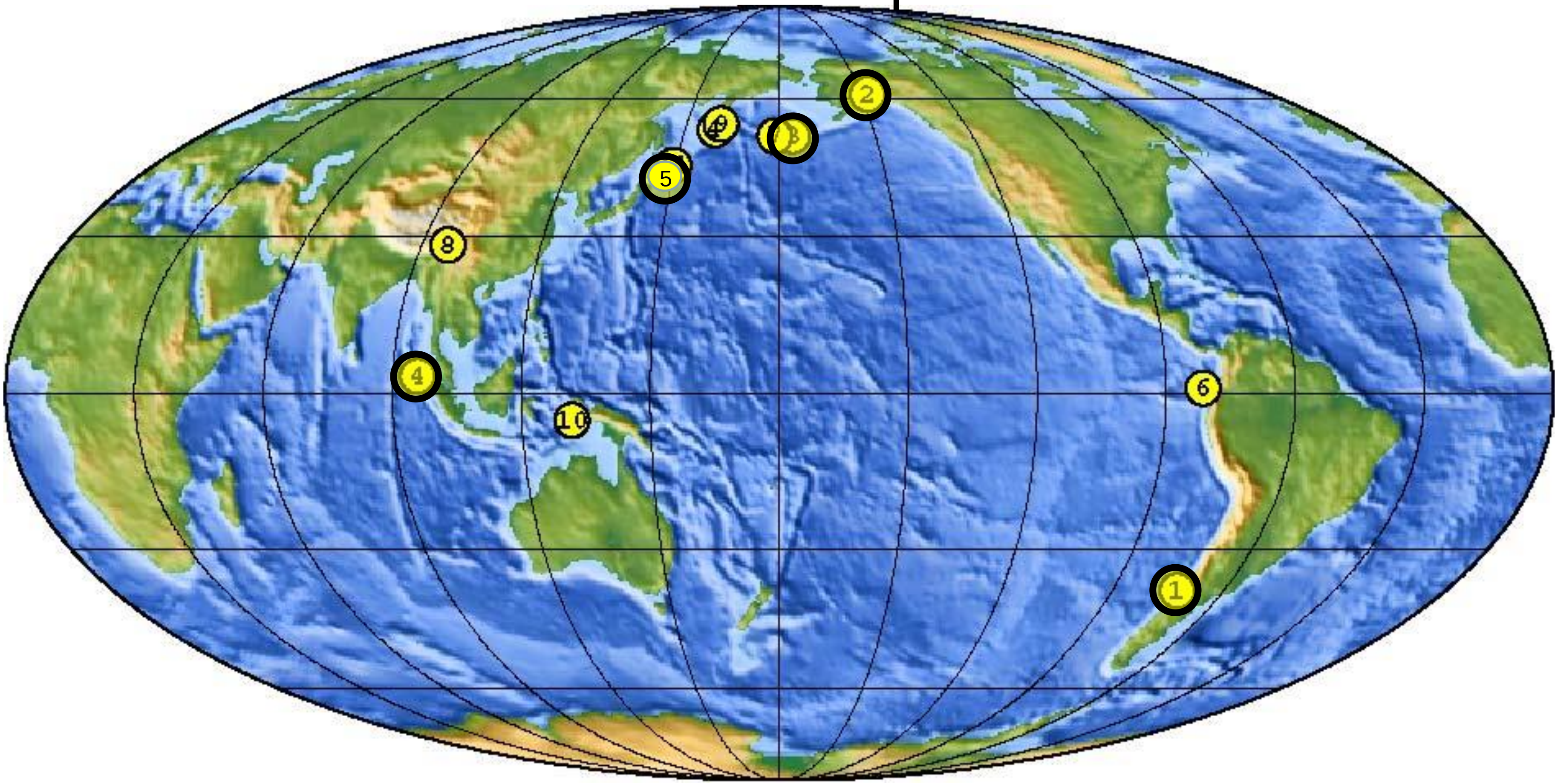
Risque sismique élevé

Exemp de vulnérabilité du bâti: étage souple, piliers sous dimensionnés, maçonnerie non chaînée….

Zémmouri-Boumerdes, Algérie Mai 2003 Mw 6.5

plus gros séismes en 50 ans

5: c’est bien environ 1 par décennie



1 : Valdivia 1960: 9,6

2 : Alaska 1964: 9,4

3 : I Aléoutiennes 1957: 9,2

4 : Sumatra 2004: 9,2

5 : Japon 2011: 9,0

Chili : Déjà 4 séismes majeurs en quelques années

20eme siècle (10)				**21eme siècle (4) and counting**		
Antofagasta	1995	8.0		Tocopilla	2007	7.8
Valparaiso	1985	8.0		Maule	2010	8.8
Valparaiso	1971	7.8		Iquique	2014	8.2
Valdivia	1960	9.6		Illapel	2015	8.4
Antofagasta	1950	8.2				
Coquimbo	1943	8.1				
Chillan(*)	*1939*	*7.8*				
Copiapo	1922	8.3				
Atacama	1918	7.8				
Valparaiso	1906	8.2