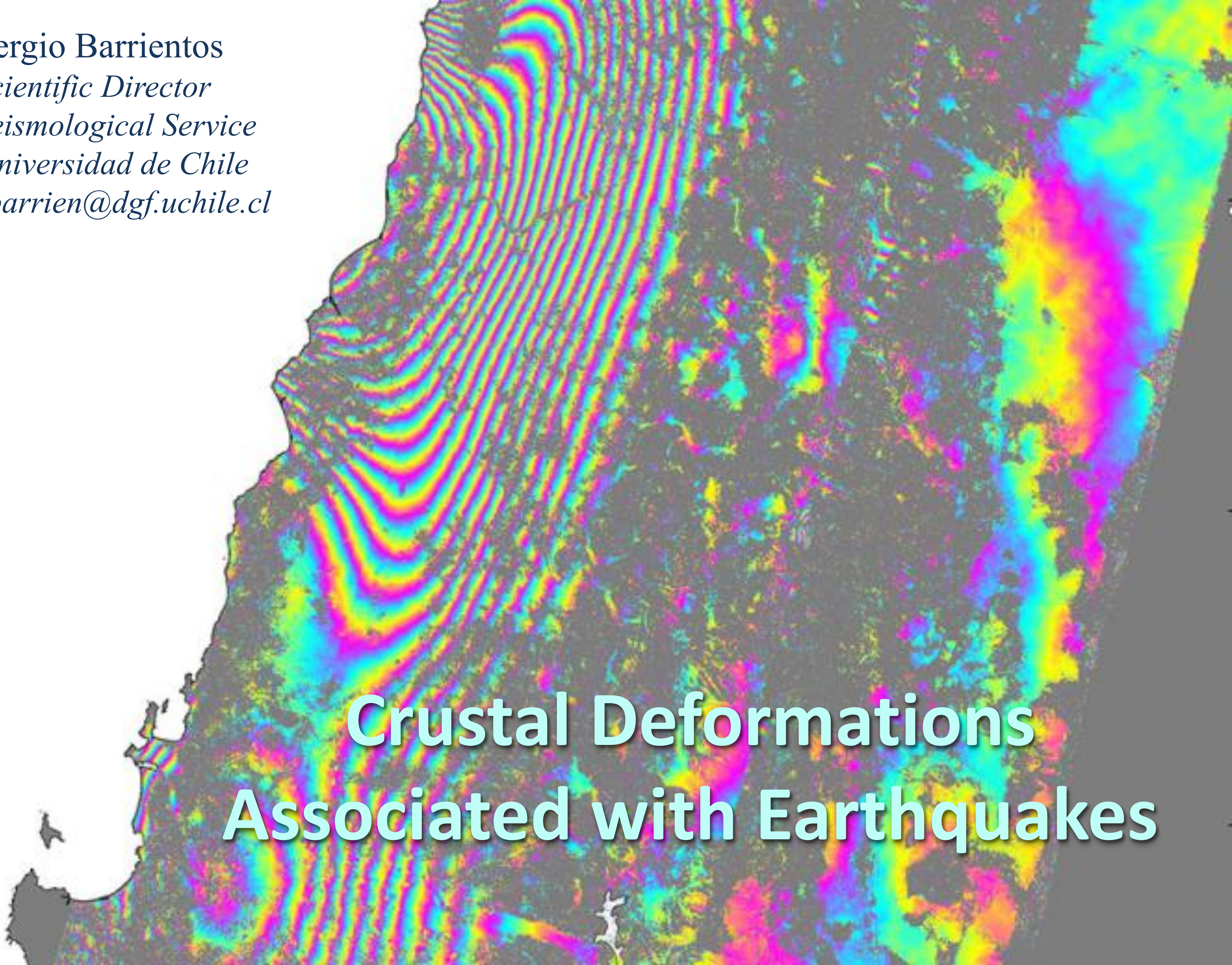
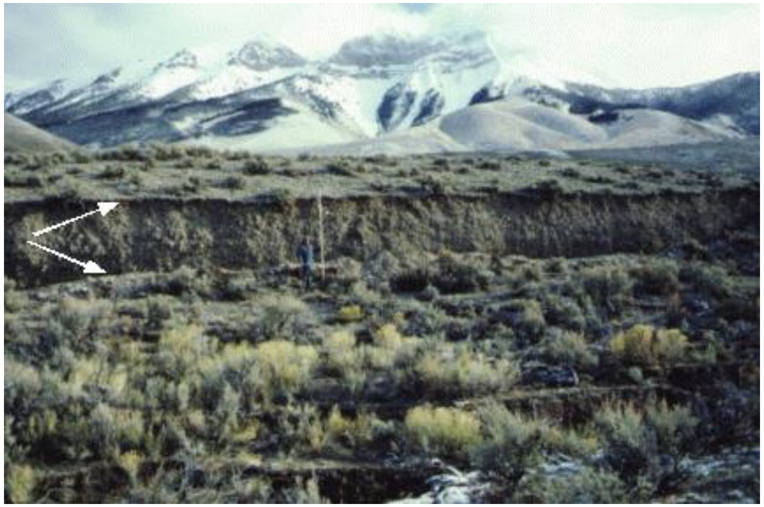
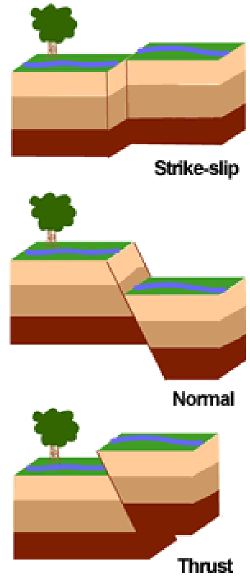
Sergio Barrientos
*Scientific Director*
*Seismological Service*
*Universidad de Chile*
*sbarrien@dgf.uchile.cl*

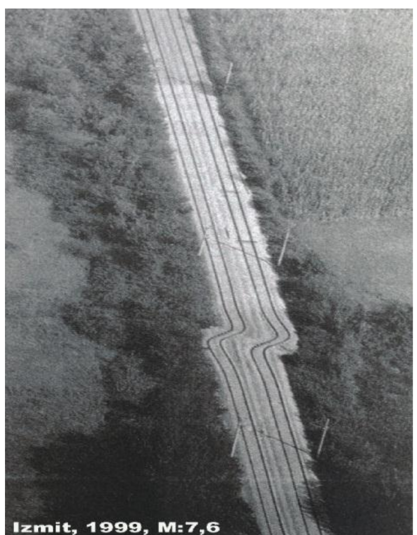


# Crustal Deformations Associated with Earthquakes

# *Example of Active Faults*

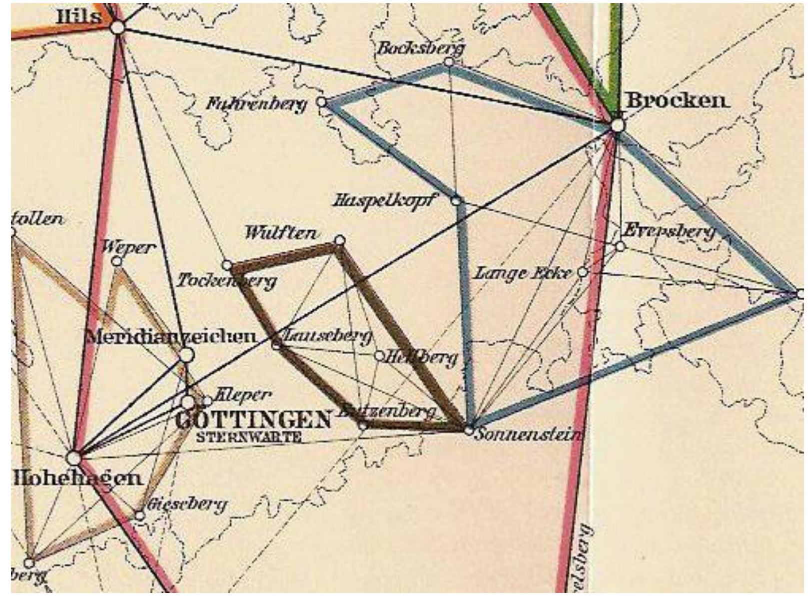




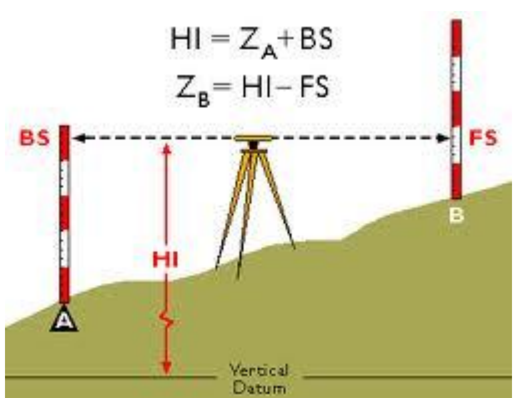



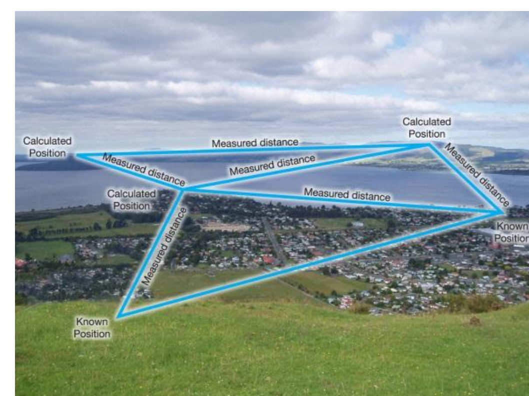

# *Triangulation, Leveling and Trilateration*


Col. Sir George Everest 1829 to 1843




A detail of the triangulation of Hanover carried out under Gauss. 1821 - 1825

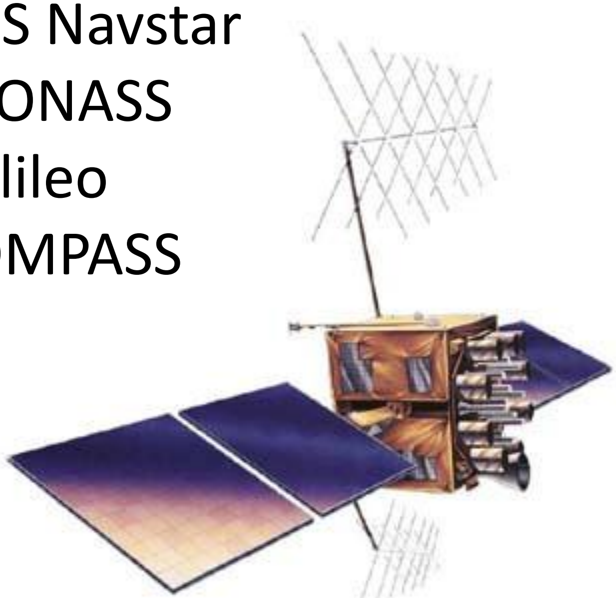


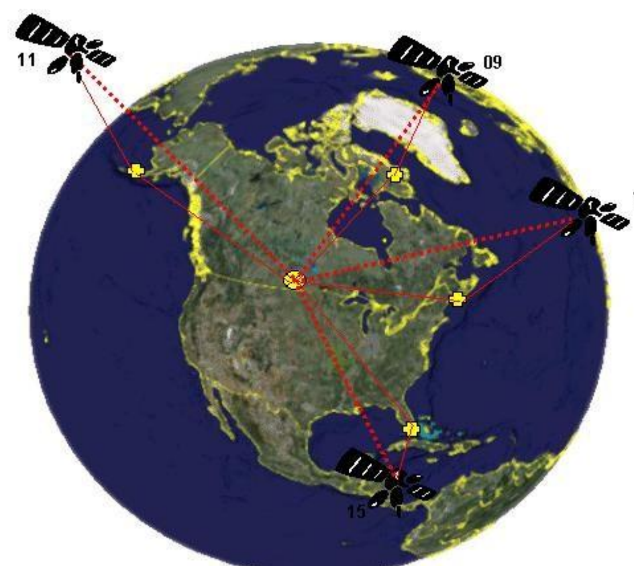



# *GPS Systems*

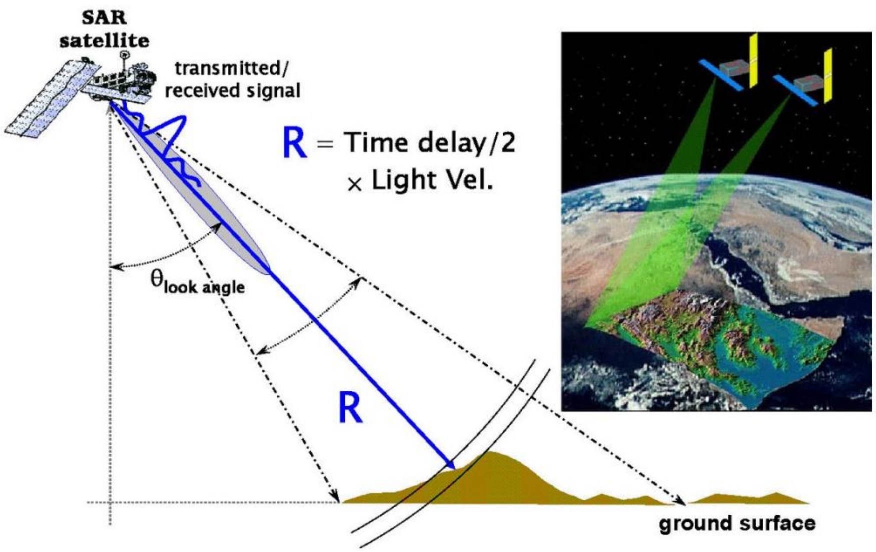
24 sat
6 orbits
20.200 km

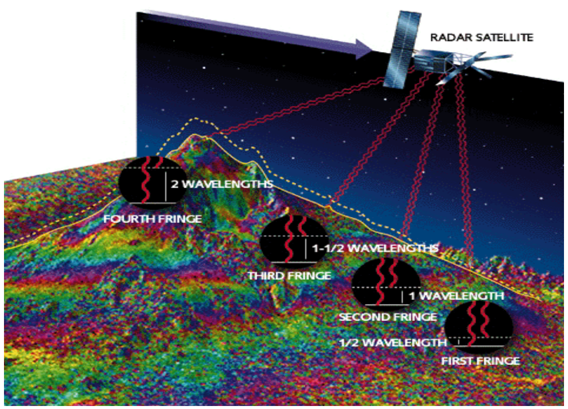
GPS Navstar
GLONASS
Galileo
COMPASS



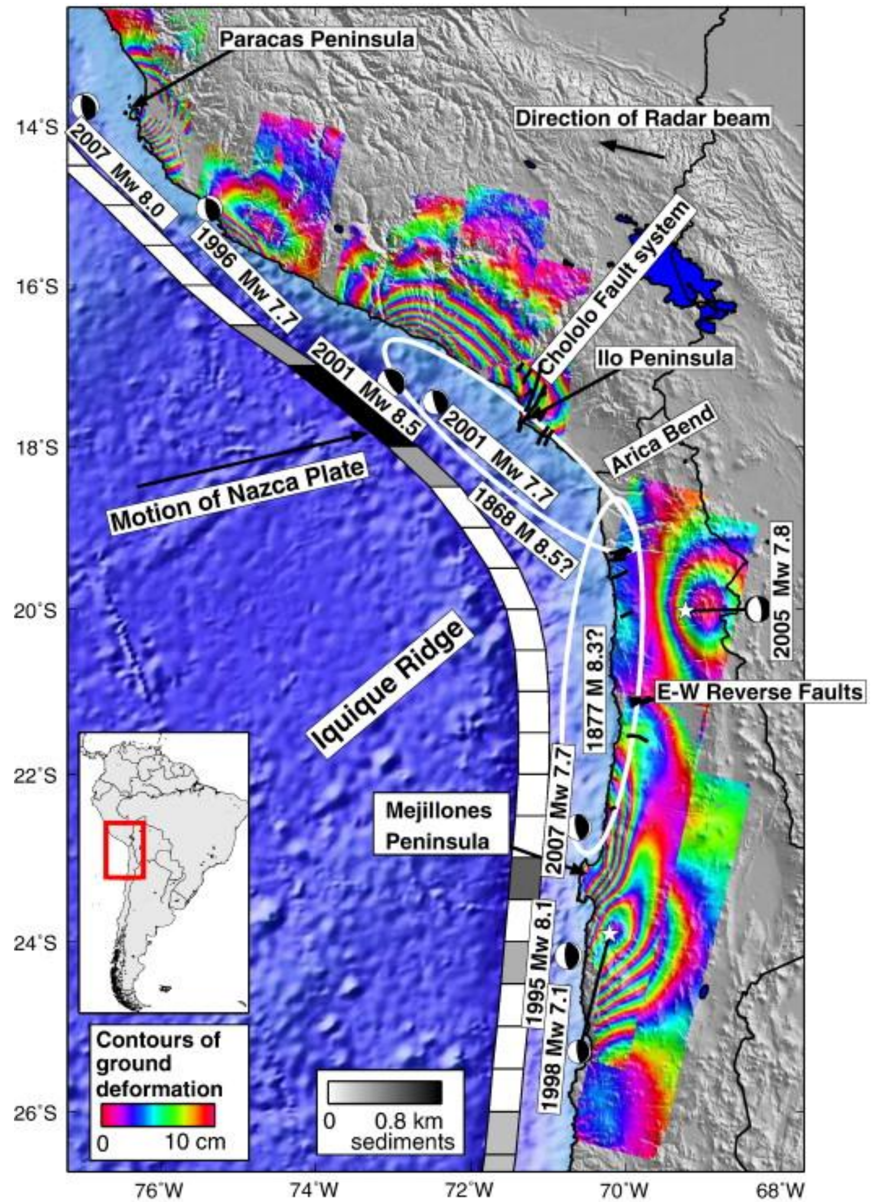
# *Interferometric Synthetic Aperture Radar*



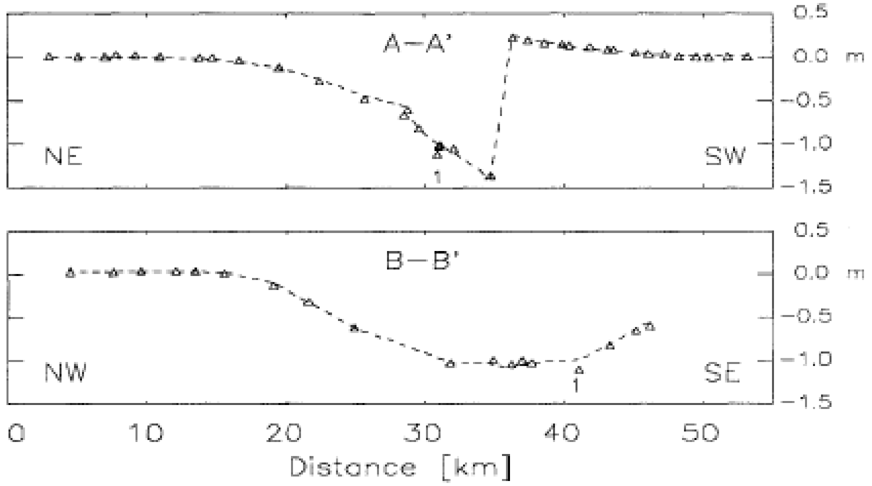

$$\Delta\rho = \frac{4\pi r B_{ort}}{\lambda R tan\theta} + \frac{4\pi h B_{ort}}{\lambda R sin\theta} + \frac{4\pi\delta\rho}{\lambda} + \Delta\Theta$$

Franges Orbitales | Topographie | Déformation | Bruit

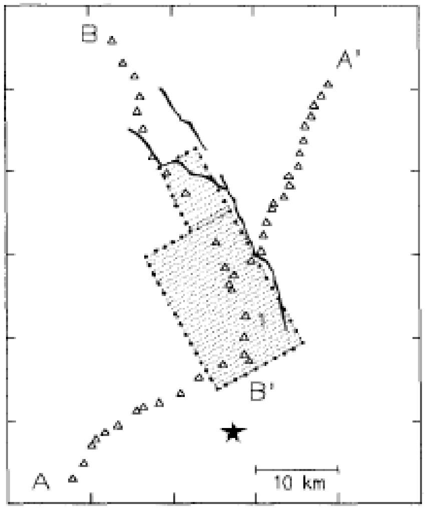


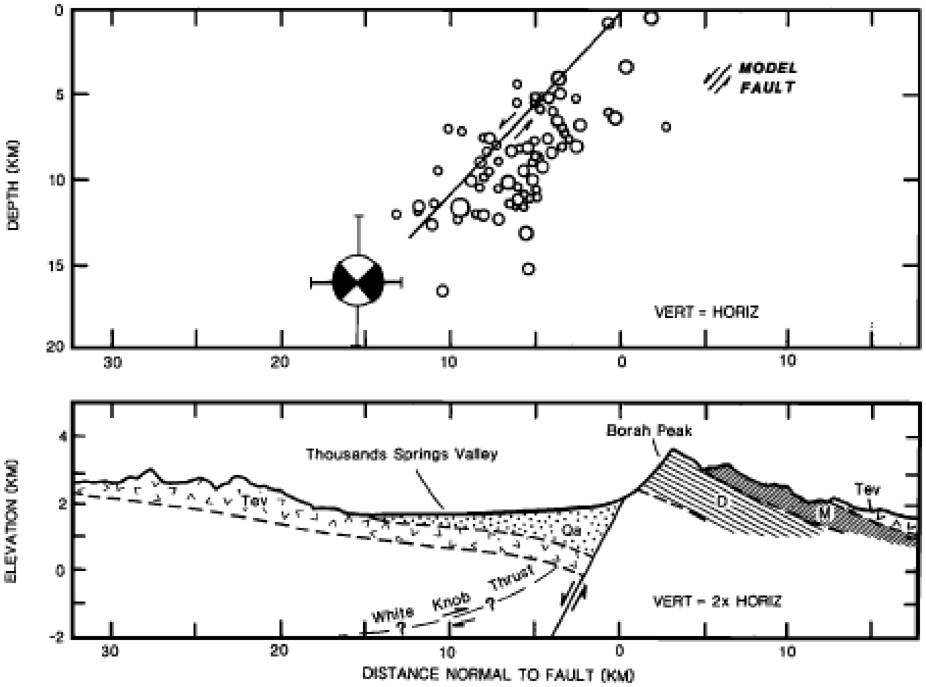

*Loveless et al, 2010*

# Borah Peak 1983 Earthquake



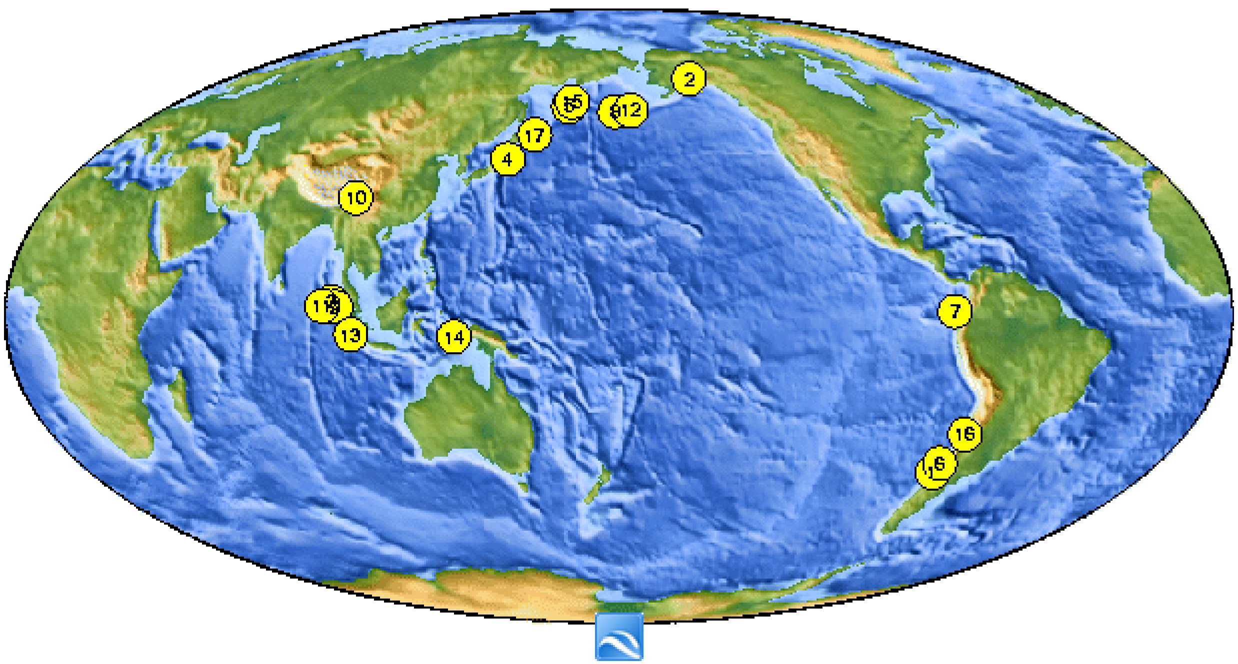

W. Arabasz



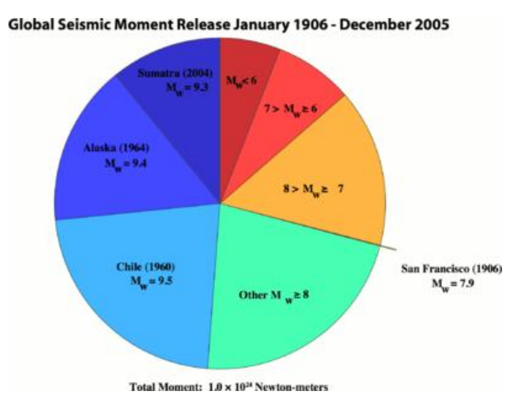



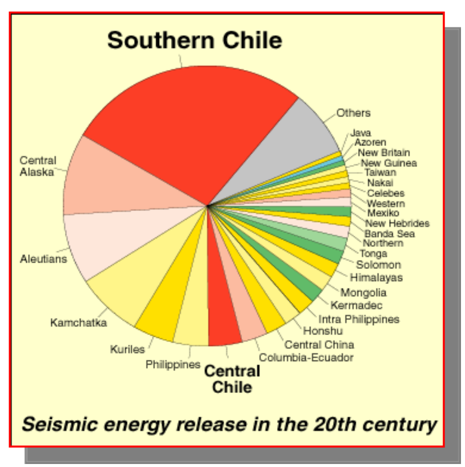

## ELASTIC !

# *Largest Earthquakes in the World Since 1900*



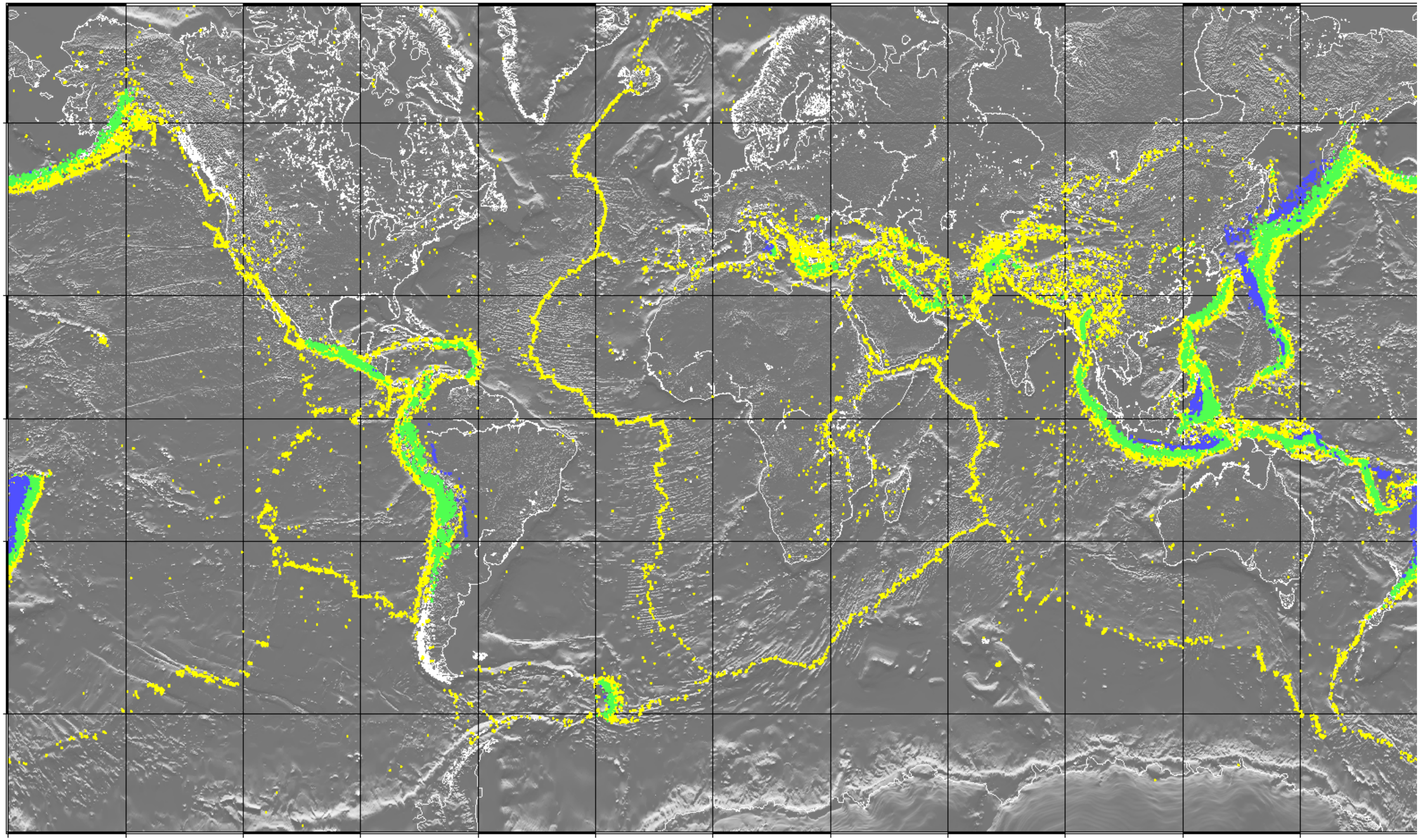

| | | | | | |
|---|---|---|---|---|---|
| **1.** | Chile | 1960 05 22 | 9.5 | -38.29 | -73.05 |
| **2.** | Prince William Sound, Alaska | 1964 03 28 | 9.2 | 61.02 | -147.65 |
| **3.** | Off the West Coast of Northern Sumatra | 2004 12 26 | 9.1 | 3.30 | 95.78 |
| **4.** | Near the East Coast of Honshu, Japan | 2011 03 11 | 9.0 | 38.322 | 142.369 |
| **5.** | Kamchatka | 1952 11 04 | 9.0 | 52.76 | 160.06 |
| **6.** | Offshore Maule, Chile | 2010 02 27 | 8.8 | -35.846 | -72.719 |
| **7.** | Off the Coast of Ecuador | 1906 01 31 | 8.8 | 1.0 | -81.5 |
| **8.** | Rat Islands, Alaska | 1965 02 04 | 8.7 | 51.21 | 178.50 |
| **9.** | Northern Sumatra, Indonesia | 2005 03 28 | 8.6 | 2.08 | 97.01 |
| **10.** | Assam - Tibet | 1950 08 15 | 8.6 | 28.5 | 96.5 |



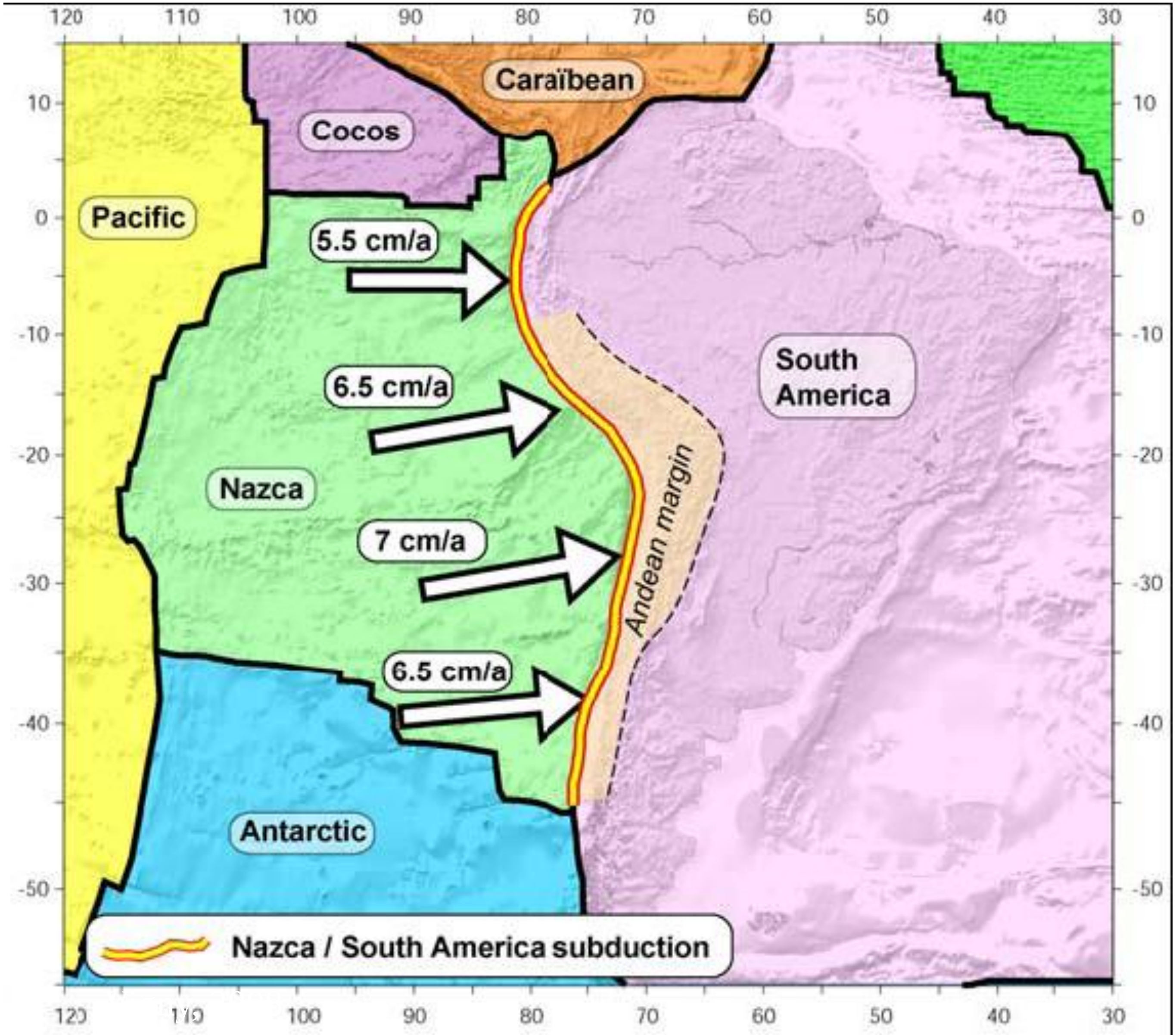



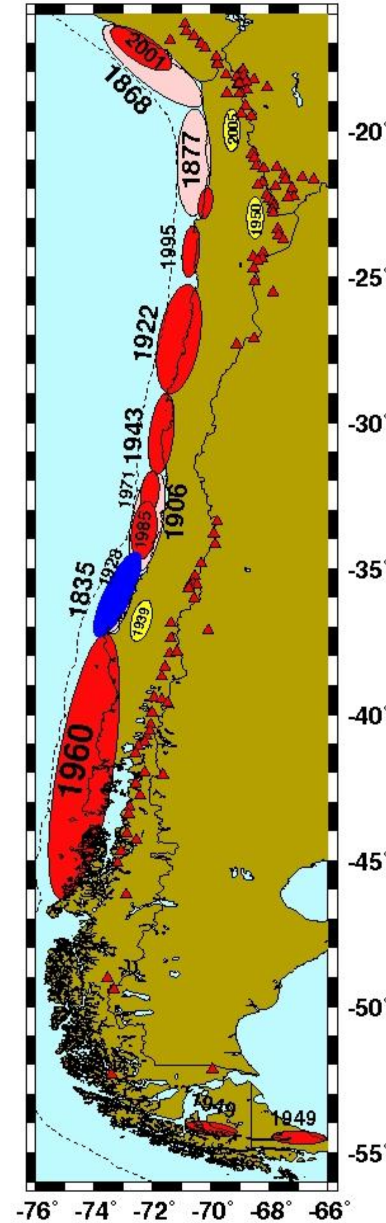
# *World Seismicity*

- 0-70 km
- 70-300 km
- 300-700 km



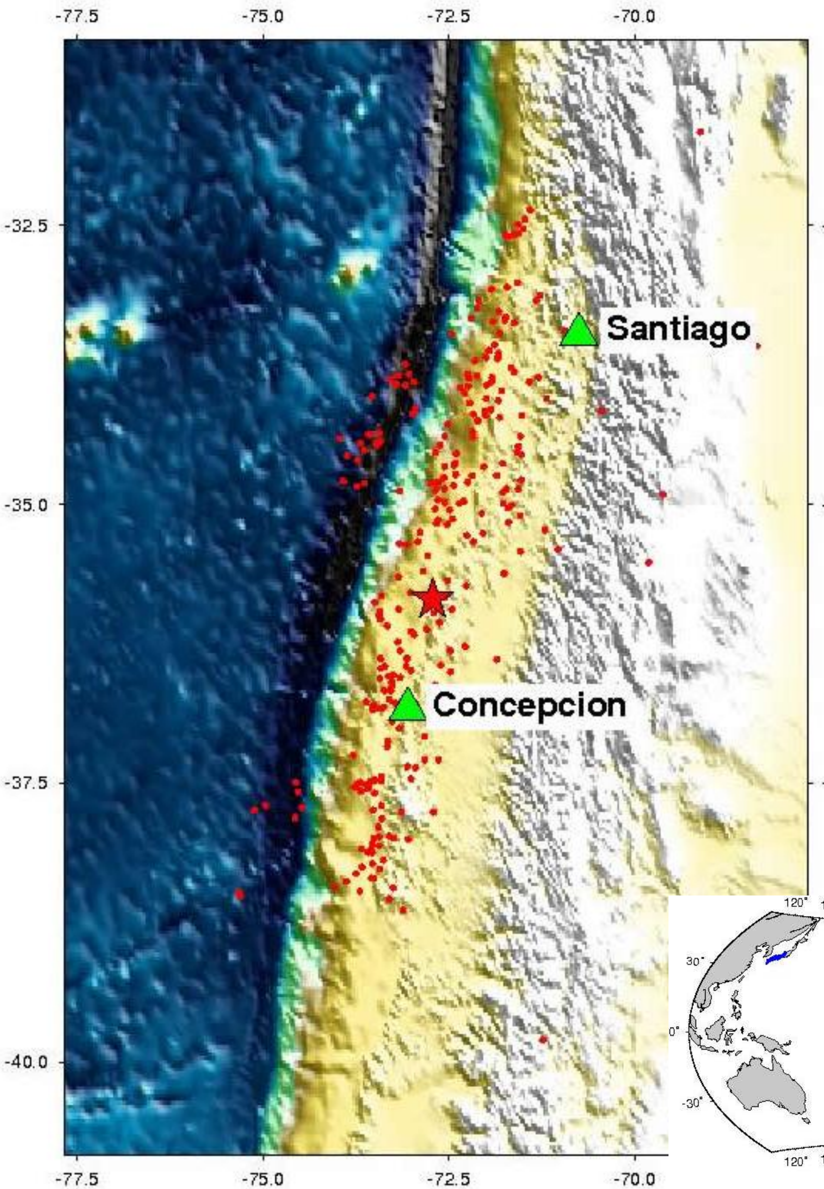
# Tectonic Framework

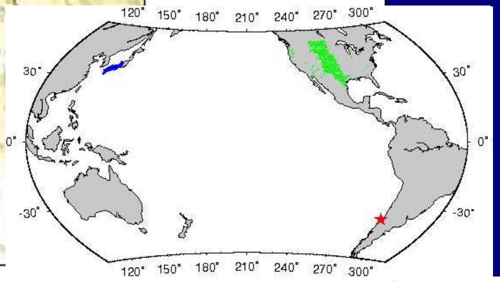


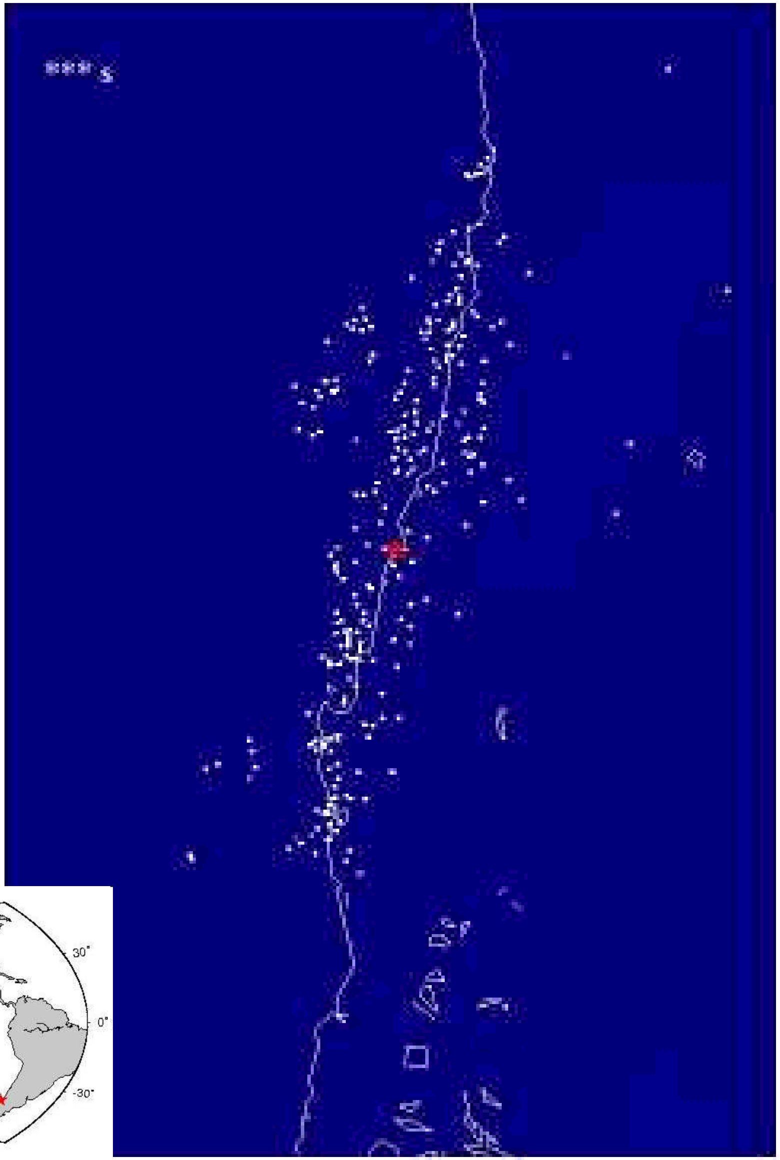




*Vigny, 2010*

# *Rupture propagation of 2010 Chile*

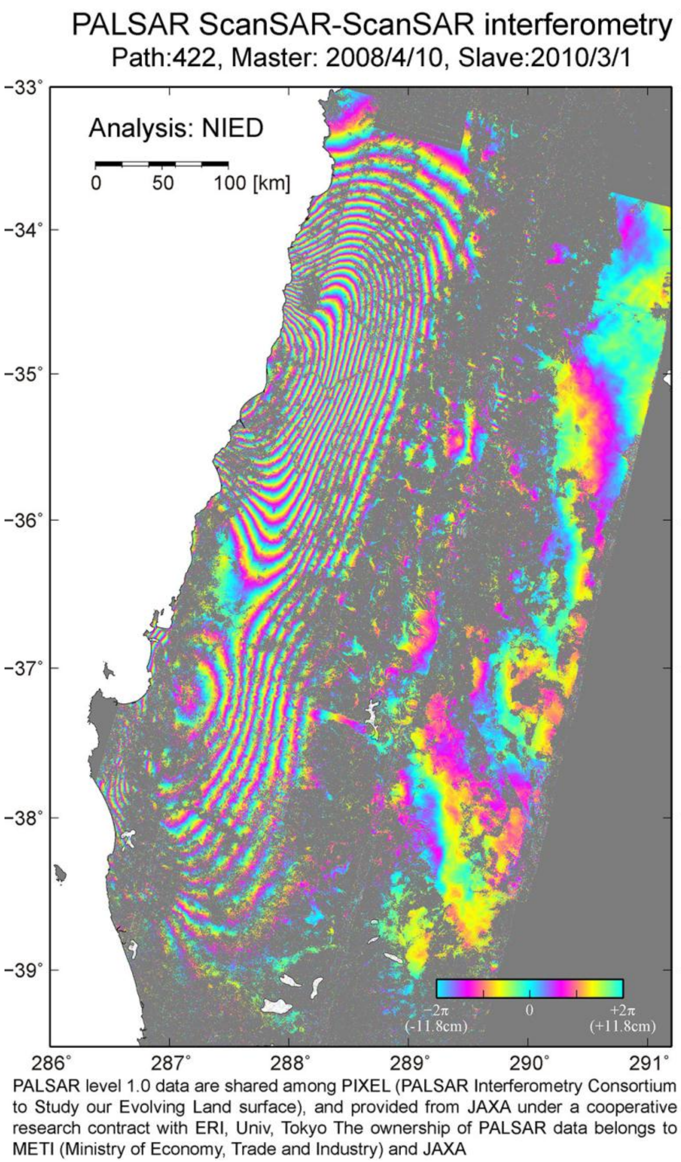


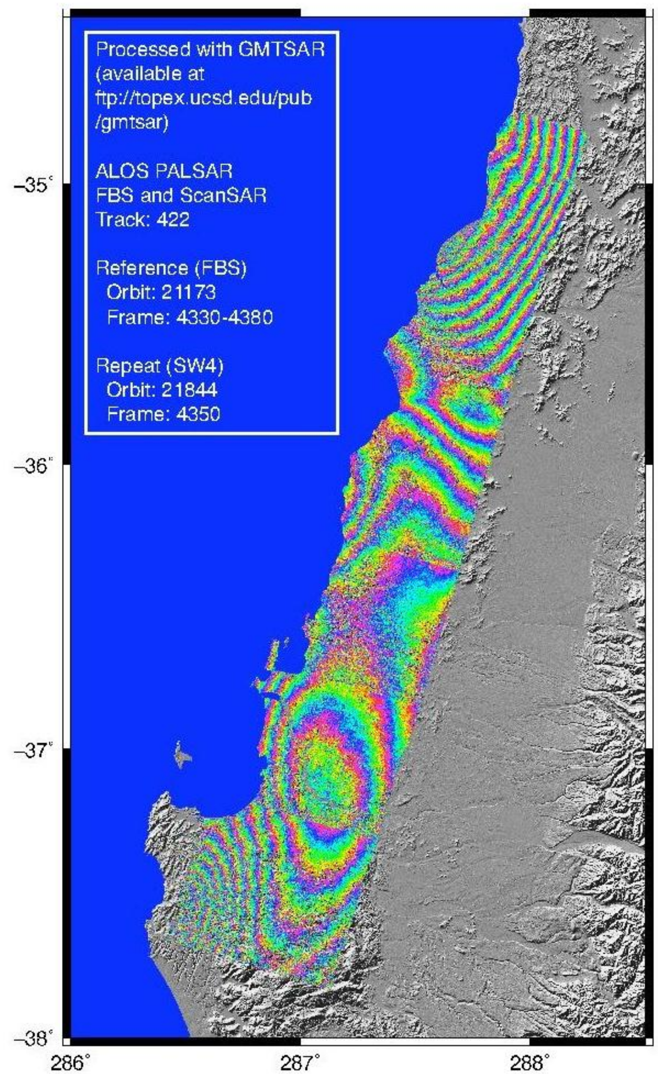



*E. Kiser, 2010*

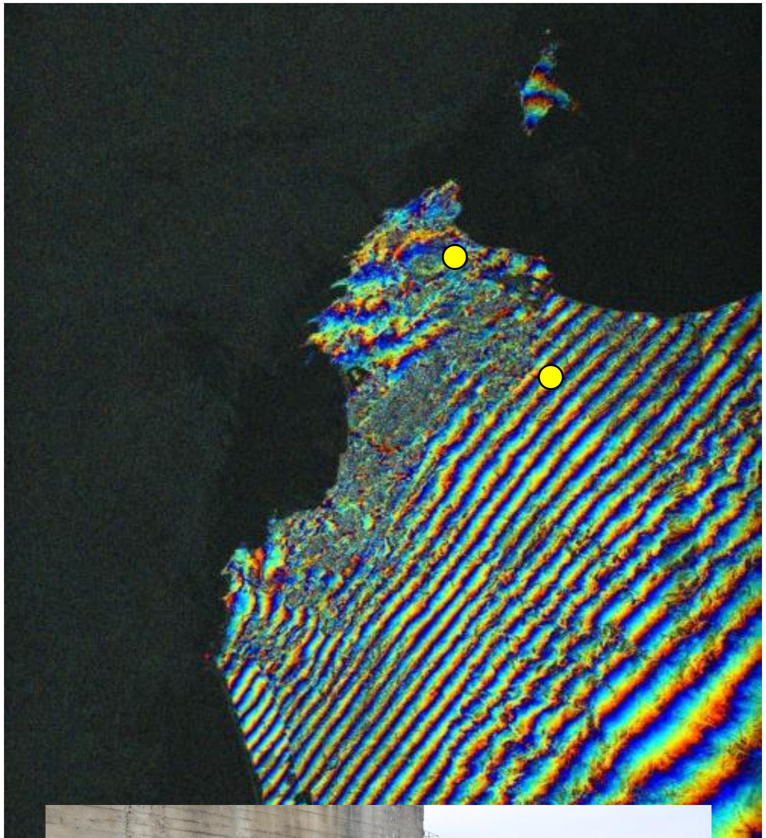
# *Crustal Deformation*



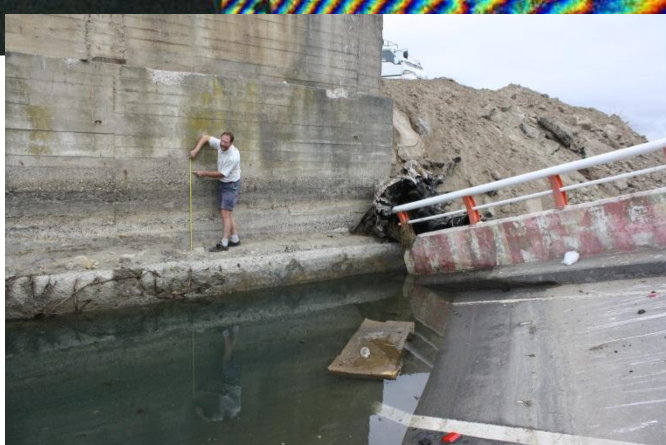




*Ando, 2010*

# *Interferometric Syntetic Aperture Radar (InSAR)*

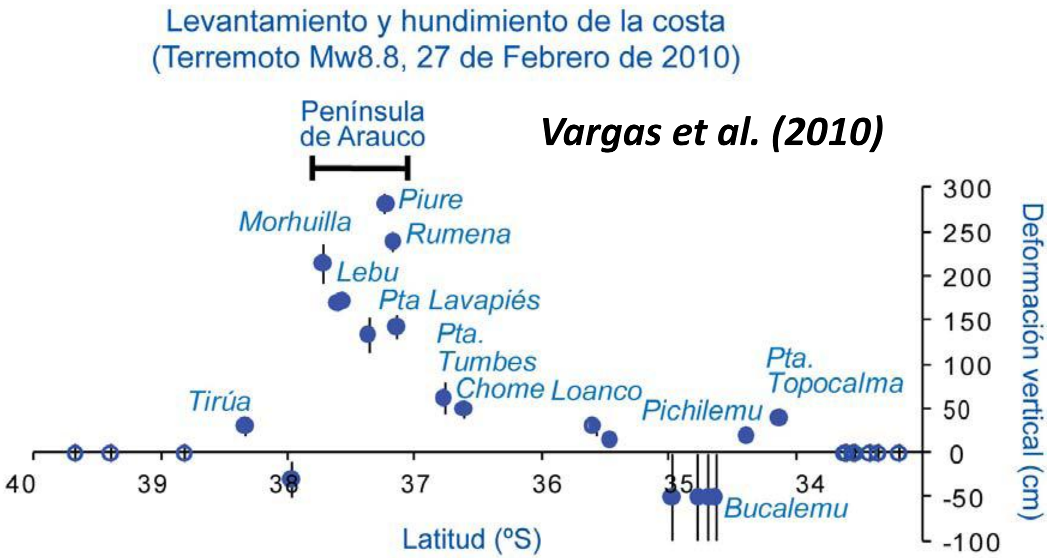




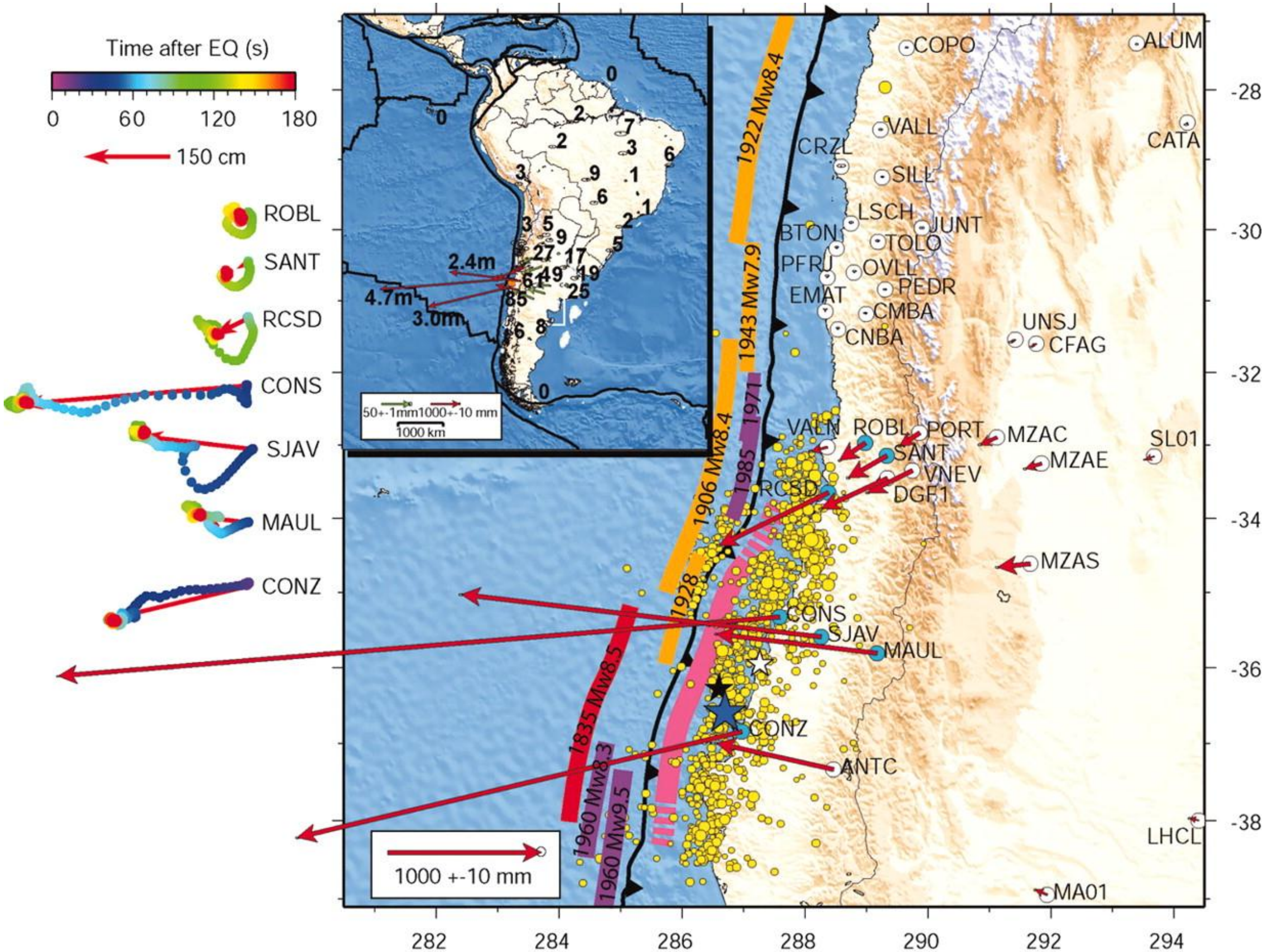


1.32 ± 0.05 m

# Coastal Uplift

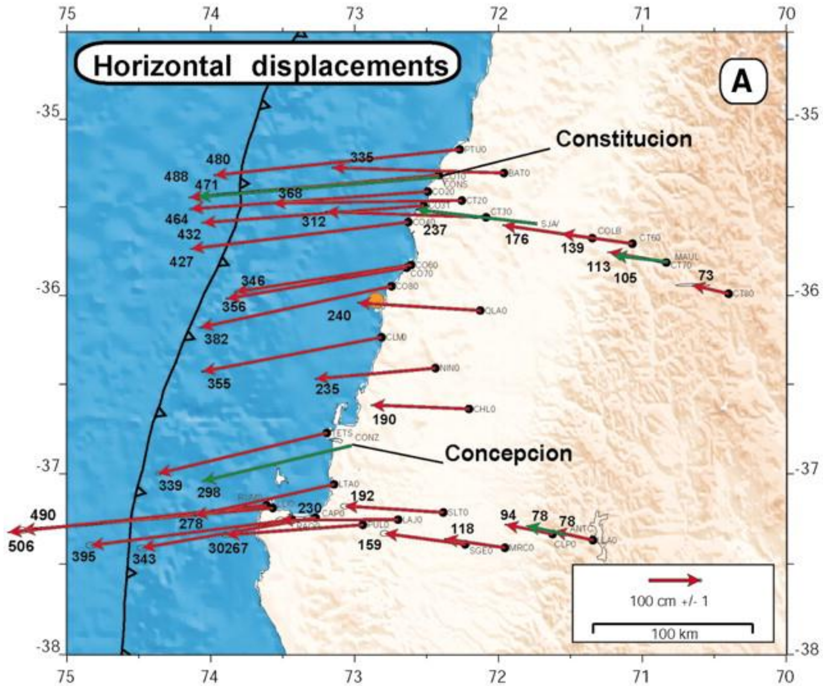


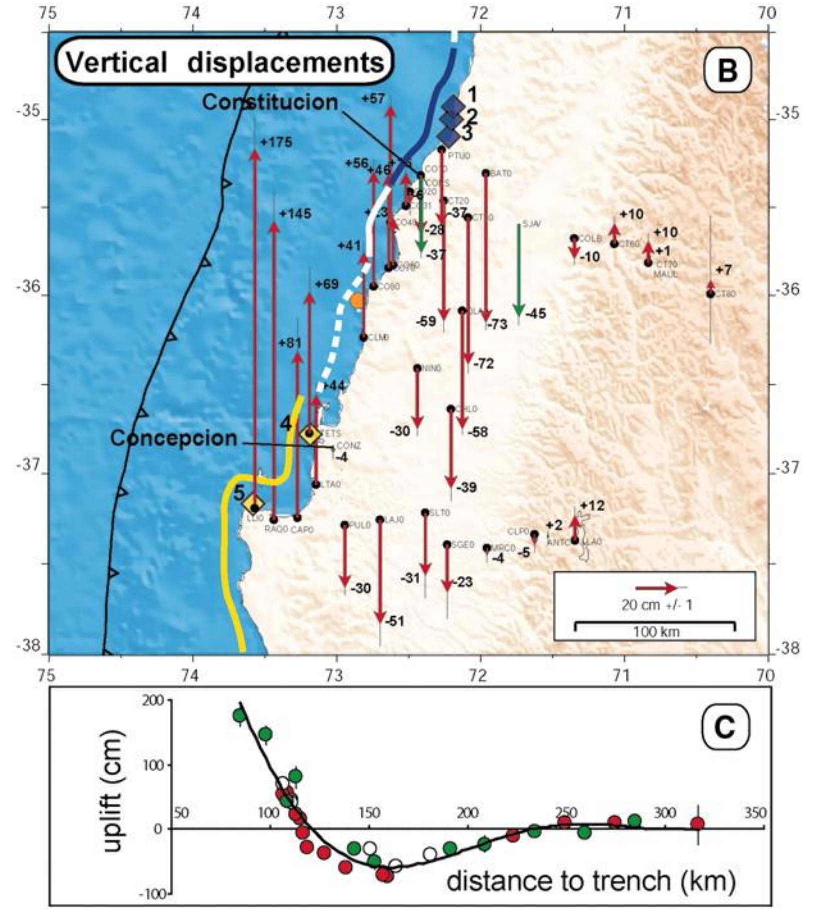

# 1 Coseismic static displacement field derived from cGPS sites.

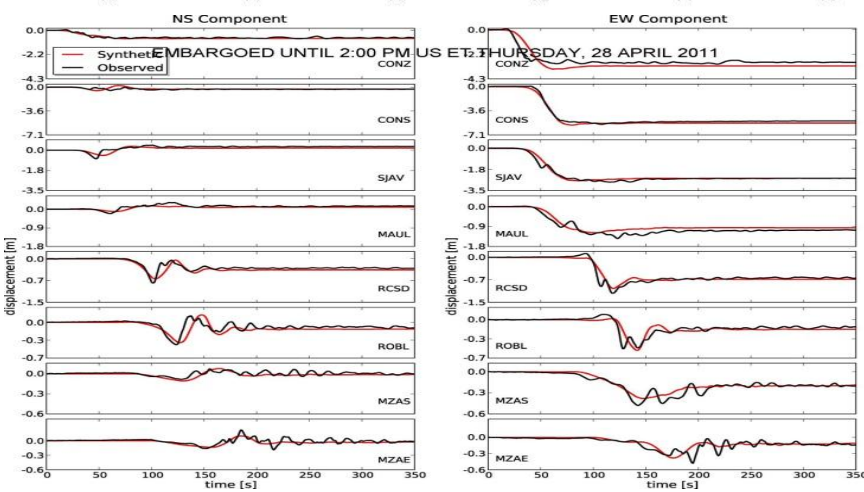



*C Vigny et al. Science 2011;332:1417-1421*

**Coseismic static displacement field for survey sites (red arrows) and cGPS sites (green arrows) in the epicentral area (A) horizontal component and (B) vertical component .**

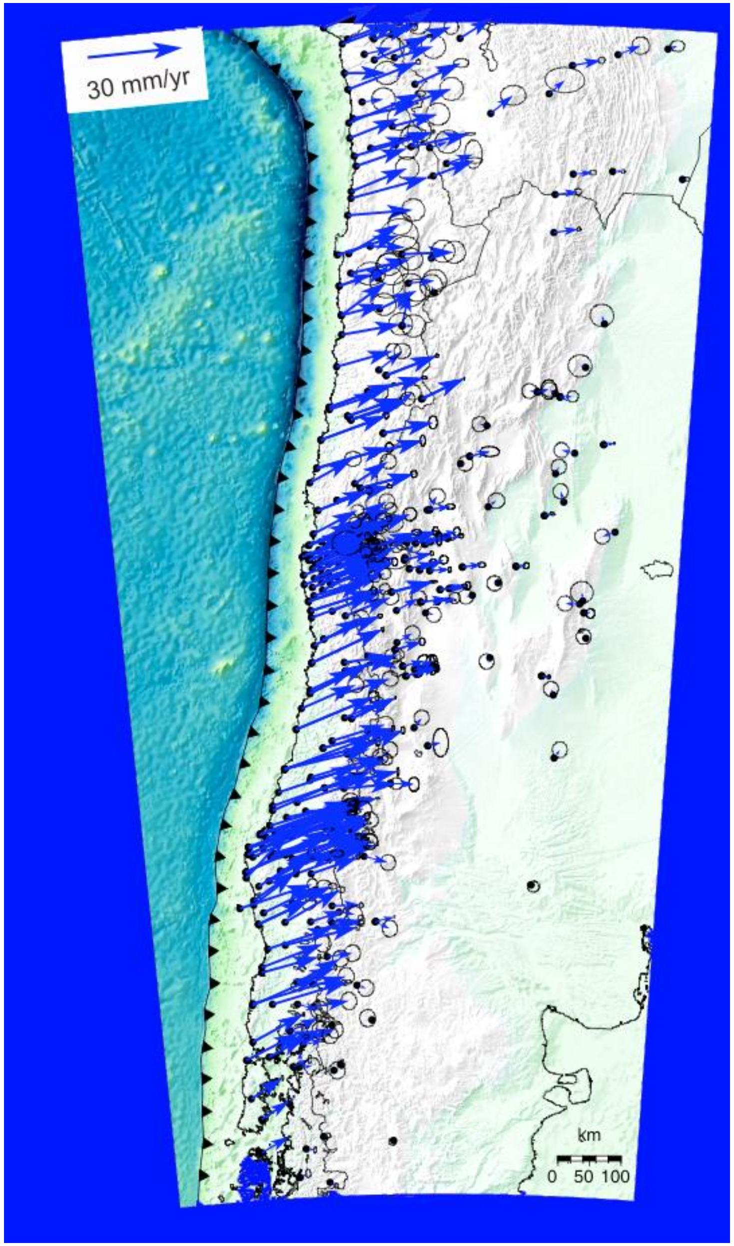


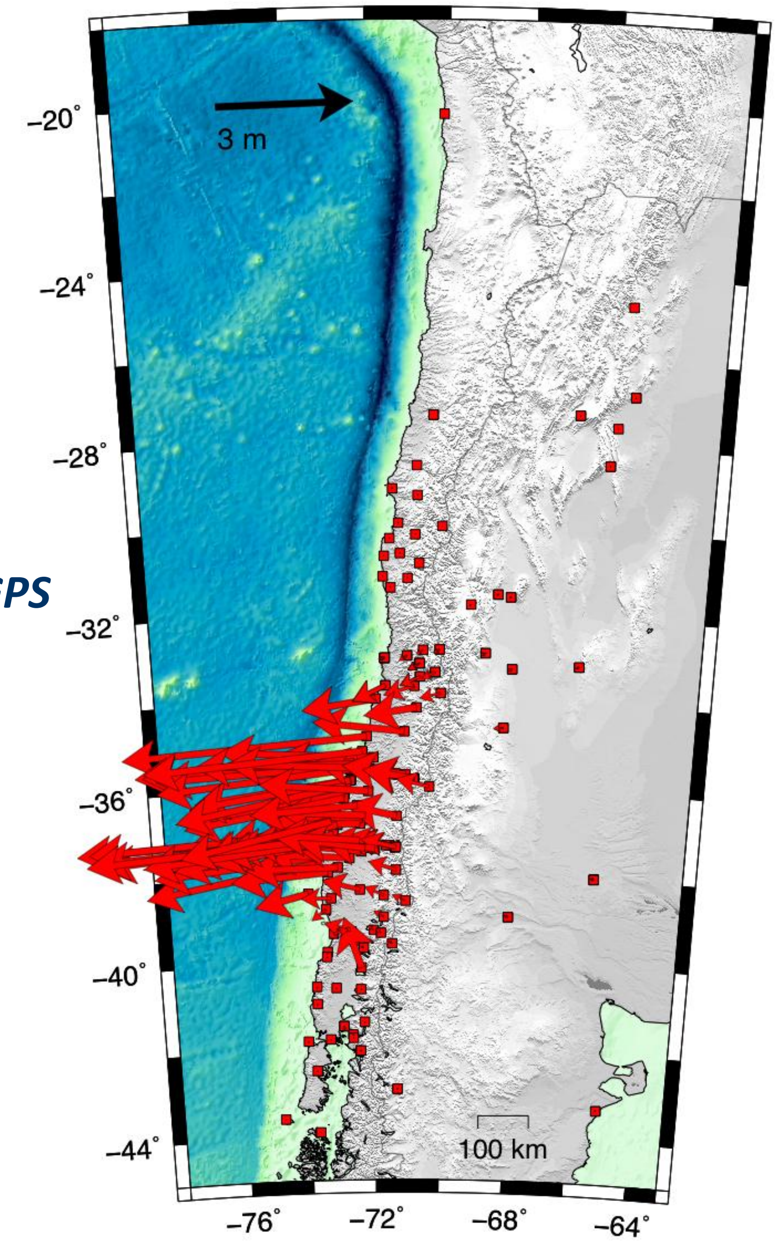




*C Vigny et al. Science 2011;332:1417-1421*

# GPS Displacements

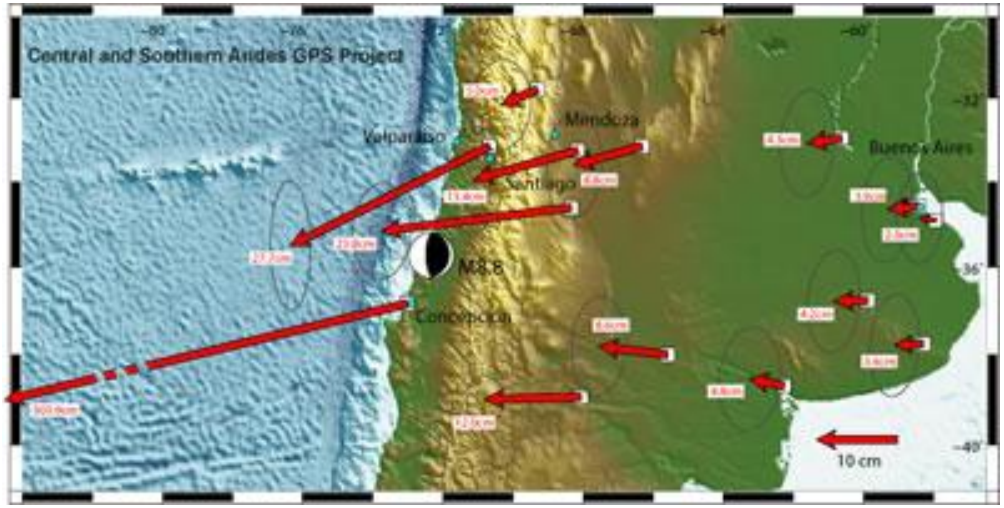


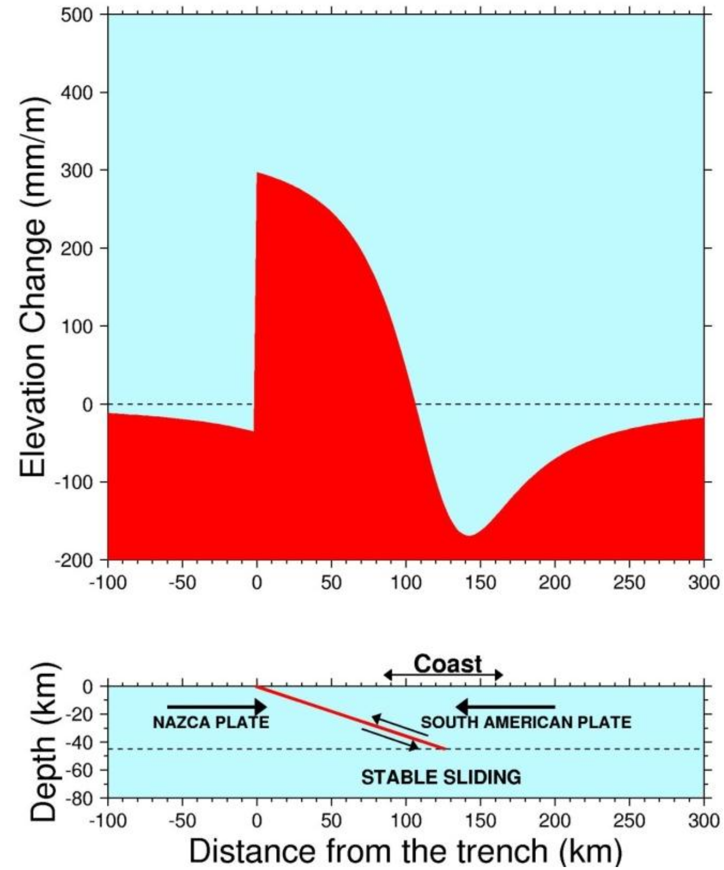

GPS



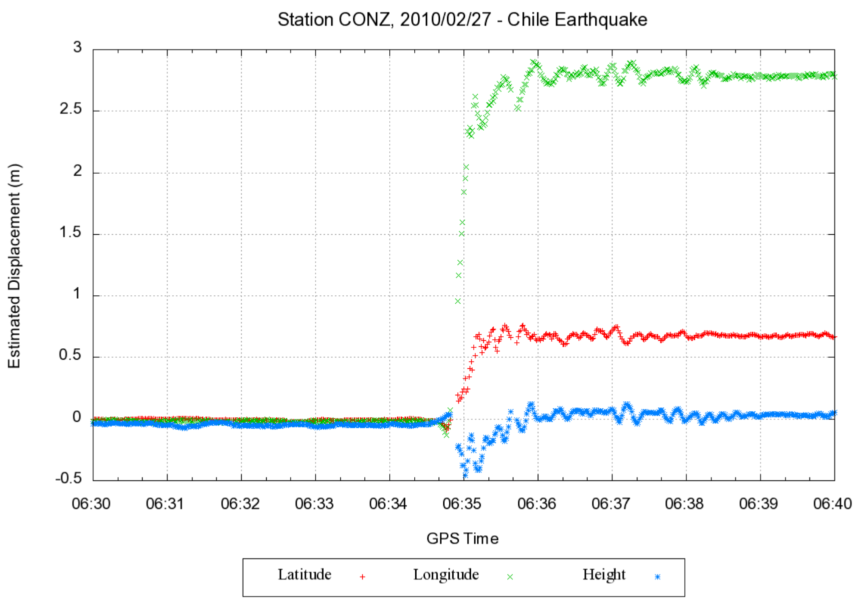

M. Moreno

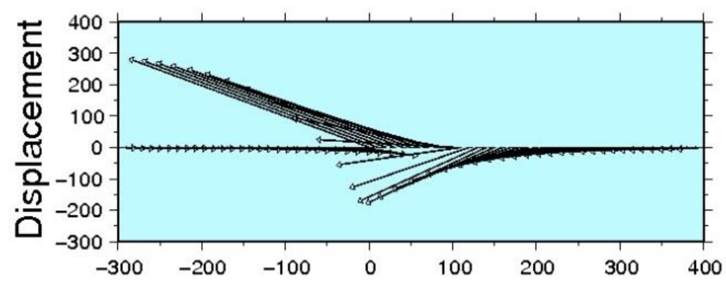
# *Crustal Deformation*



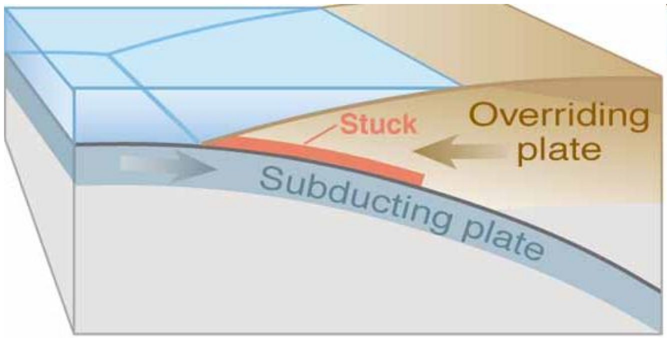

CAP



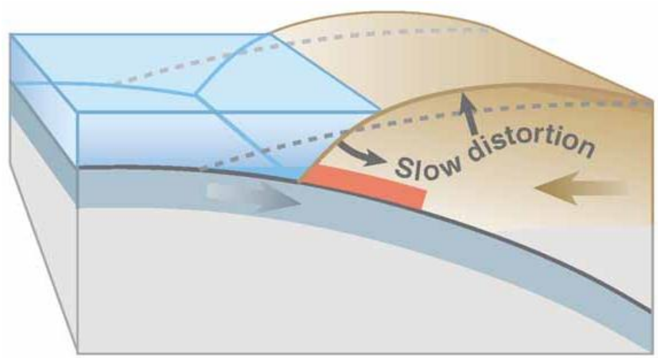




Fault

# *Tsunami Generation*




Accumulation of stresses over centuries




Overriding plate bulges under strain, causing uplift

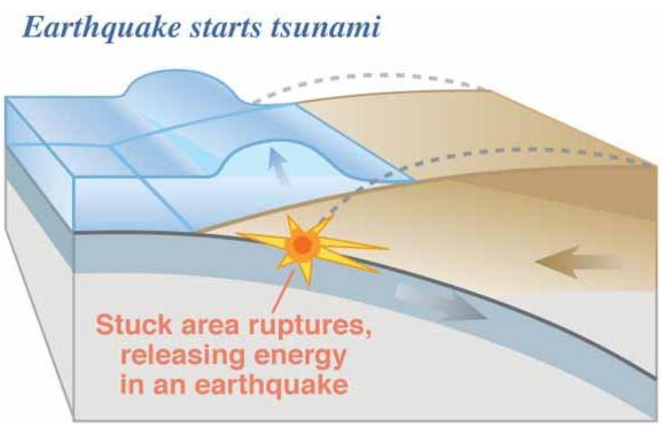
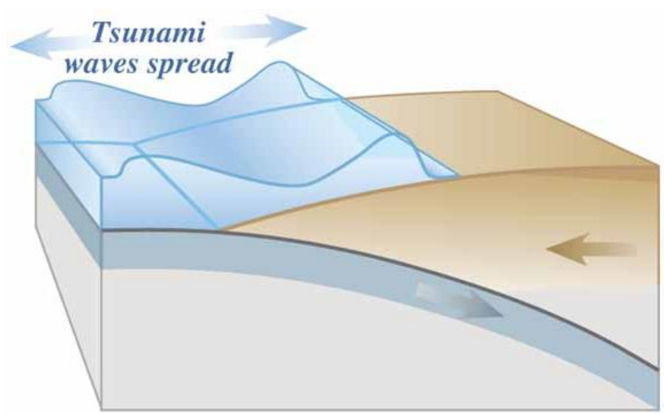


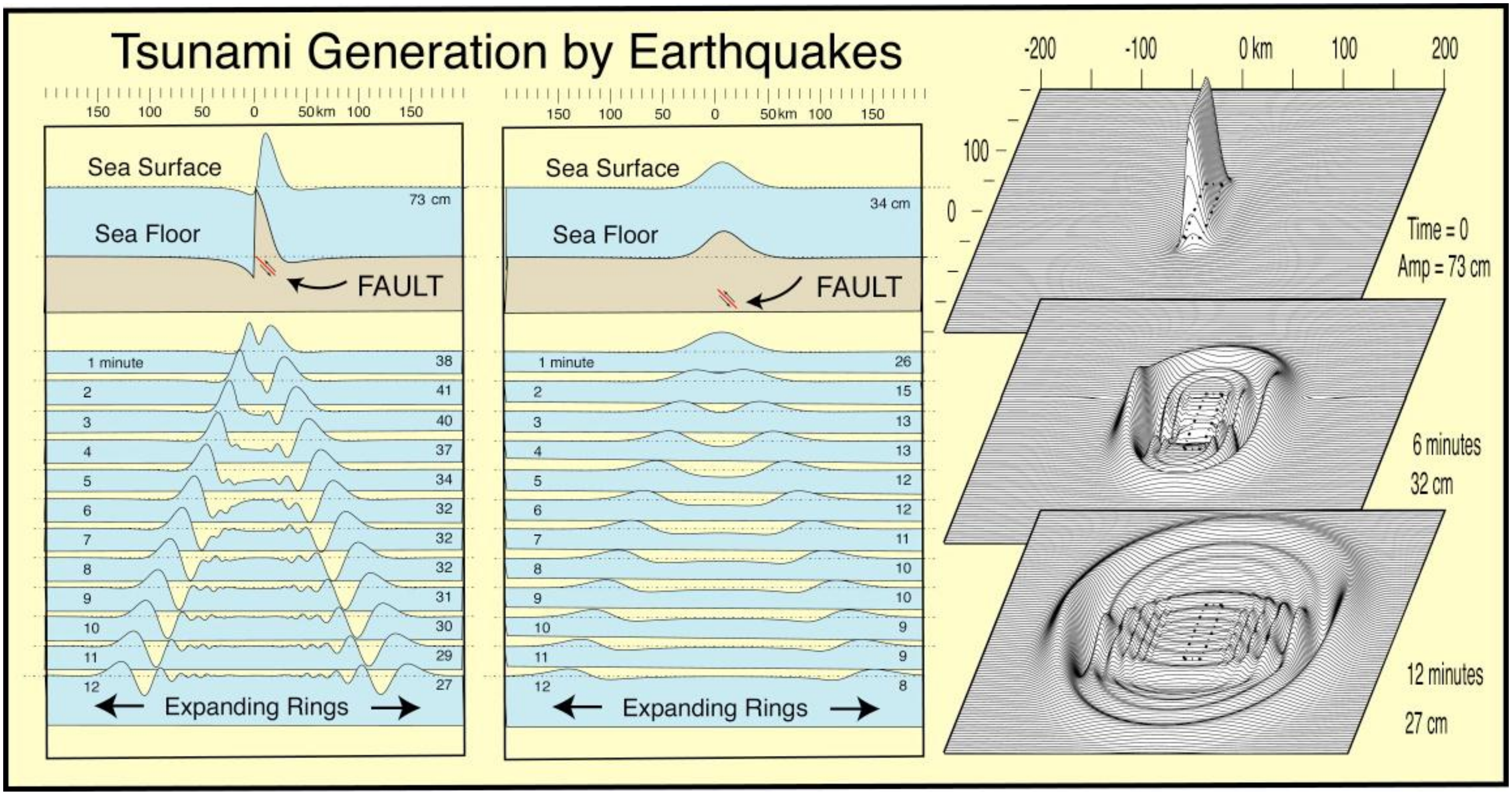

Plate slips, causing subsidence and releasing energy into water.




displaces a large enough volume of water.



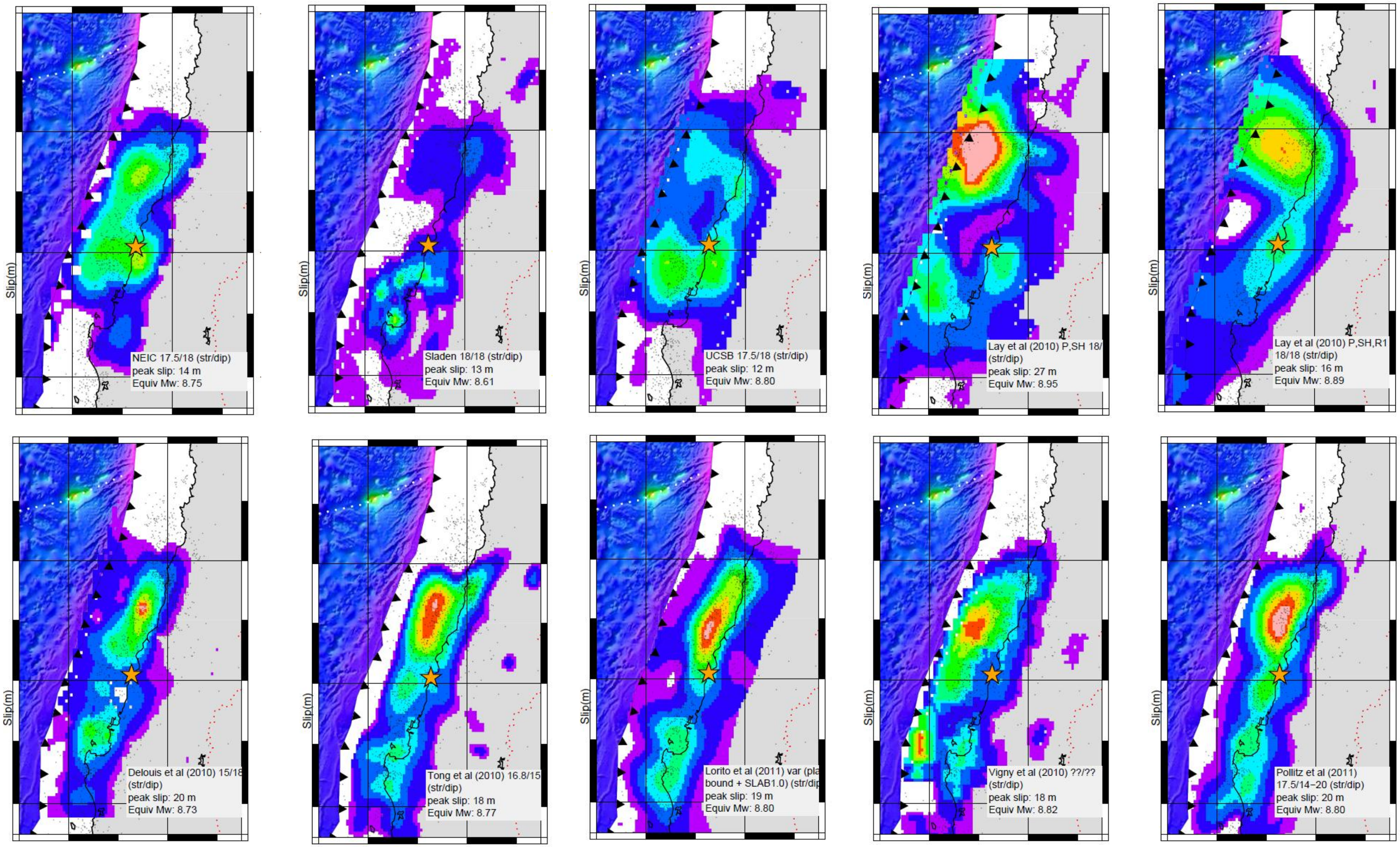
[Tsunami]




$$u_z^{surf}(\mathbf{r},t) = \int_0^\infty k\,dk\,\frac{\cos\omega(k)t}{2\pi\cosh(kh)}\left[A\Delta u\mathbf{M}_{ij}\varepsilon_{ij}\right]$$

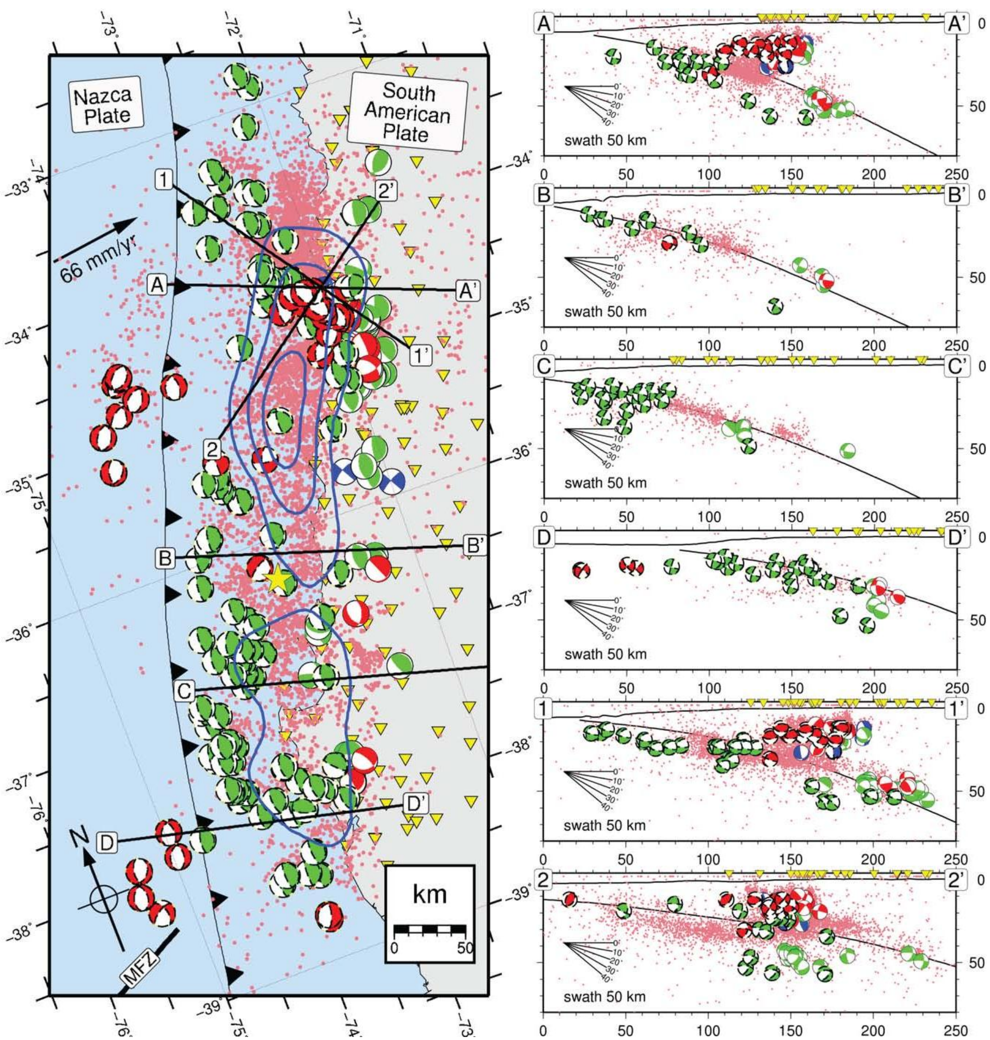
*S. Ward, 2010*

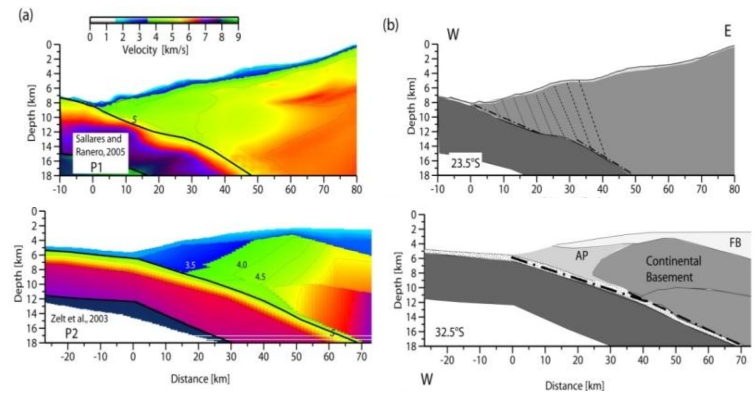
# 2010 Slip Distribution (Compiled by F. Tilmann, 2012)

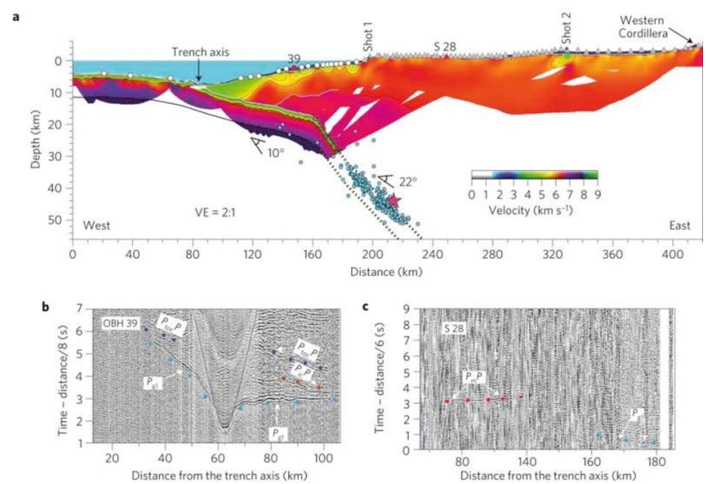



a) NEIC (2010), basado en ondas internas y superficiales, máximo desplazamiento 14m, b) Sladen (2010), en ondas internas y GPS de campo lejano, 13 m, c) Shao (2010), ondas internas, 12 m, d) Lay et al. (2010), ondas internas, 27 m, e) Lay (2010), ondas internas y superficiales, 16 m, f) De Louis et al., (2010), ondas internas, GPS, InSAR, 20 m, g) Tong, (2010), GPS, InSAR, 18 m, h) Lorito et al. (2010), GPS, InSAR, formas de ondas de tsunami, 19 m, i) Vigny et al. (2011), GPS cinemático en campo cercano, InSAR, 18 m, j) Pollitz et al. (2011), GPS, InSAR, 20 m.

# *Maule 2010 Aftershocks*



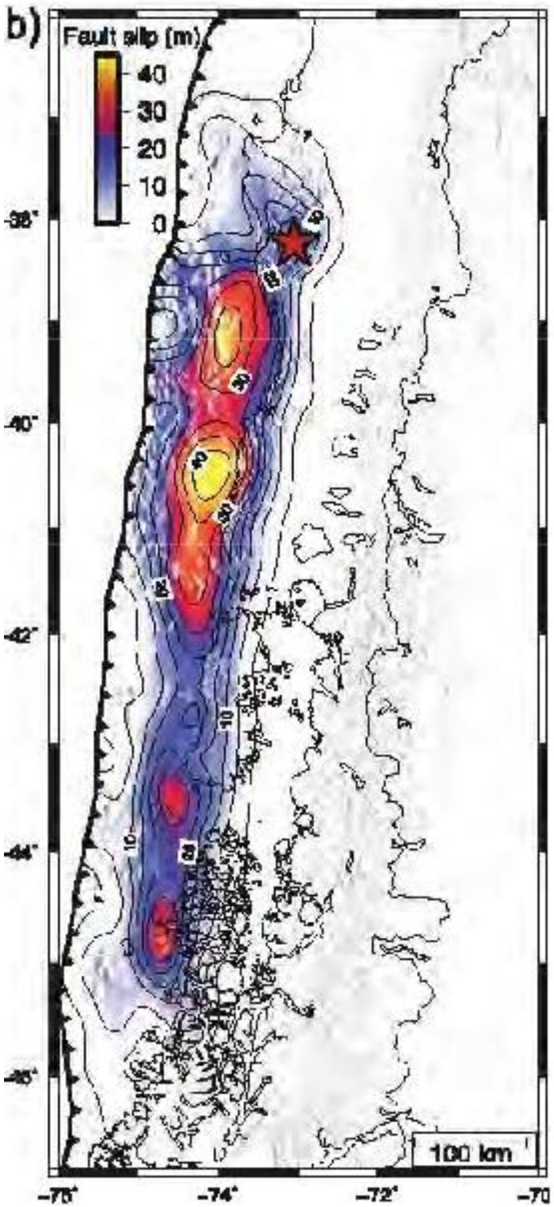



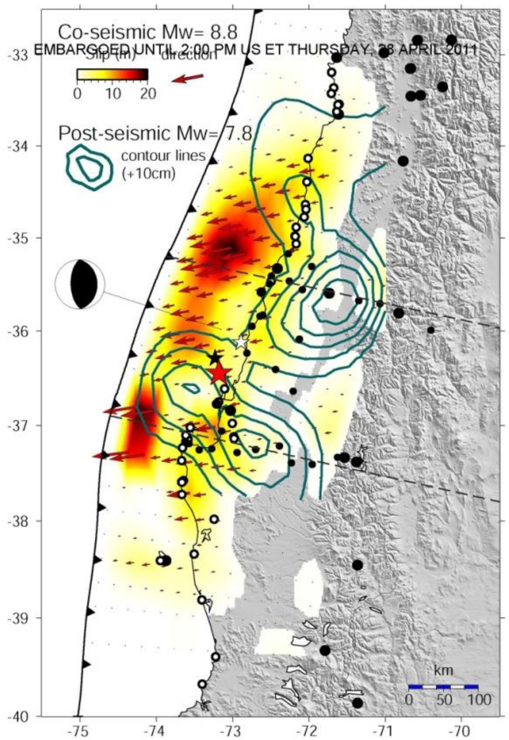




*Lange et al (2012)*

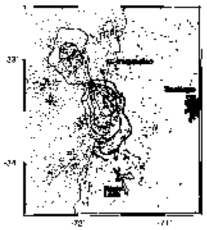
*Contreras-Reyes et al. (2012)*

# *1960, 1985 y 2010  Rupture zones*




*Vigny et al. (2011)*



*Barrientos (1997)*

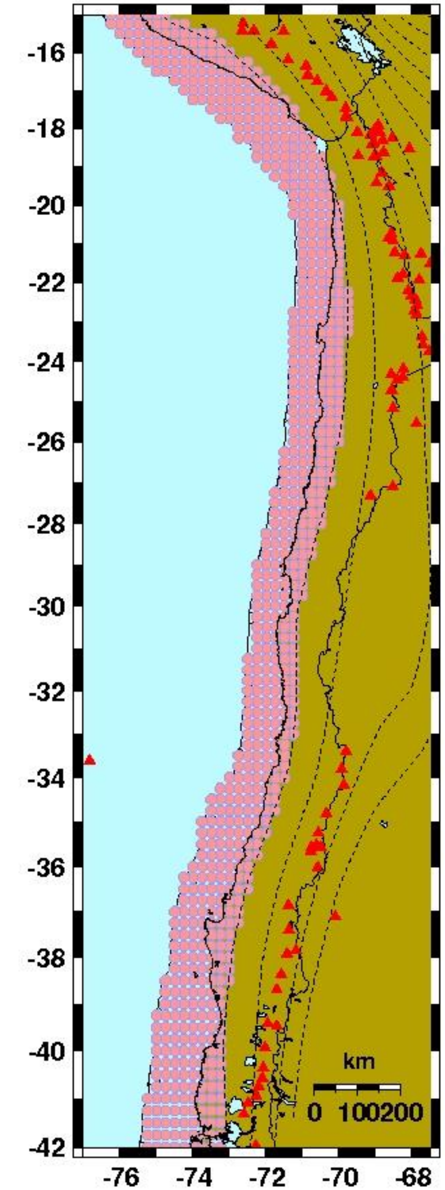
*Compararison  (Mw)*

*M = 9.5*

*M = 8.8*

*M = 8.0*

*Moreno et al.  (2009)*

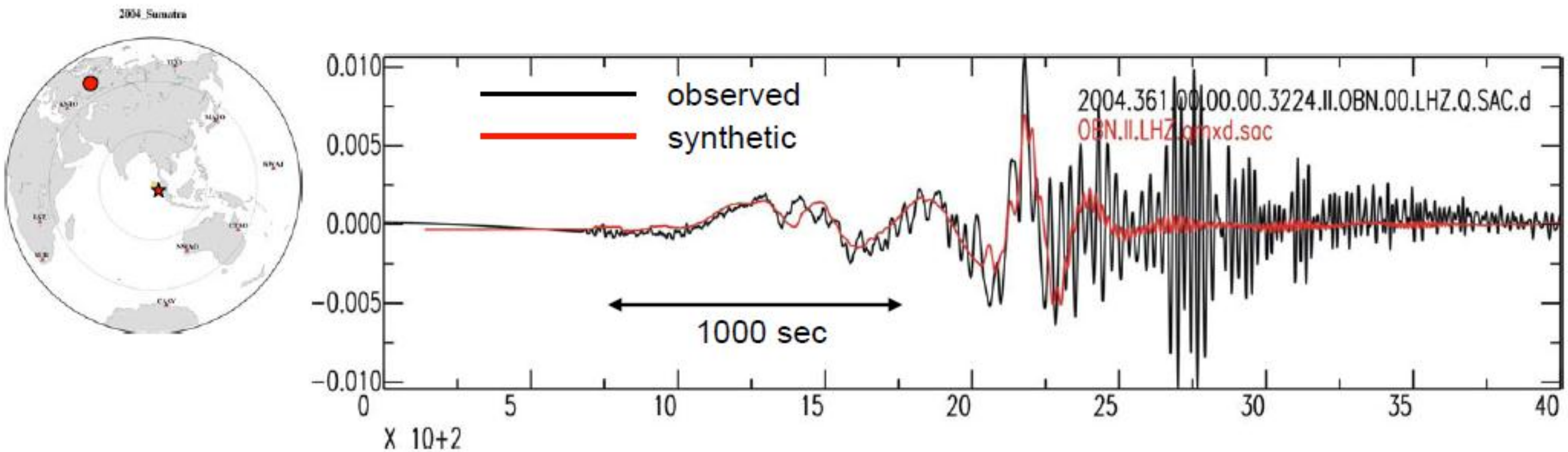


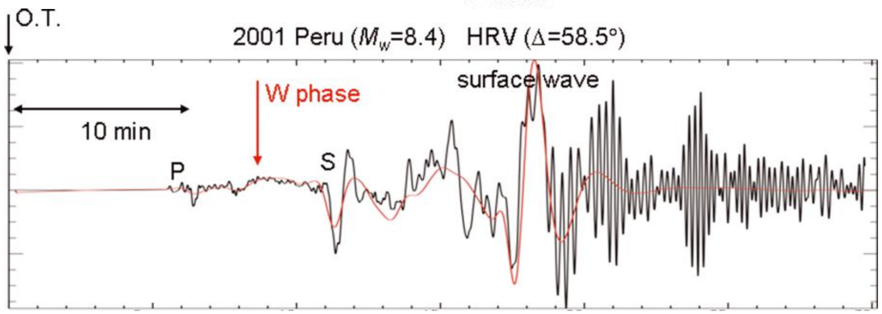
# Magnitude and Fault Size

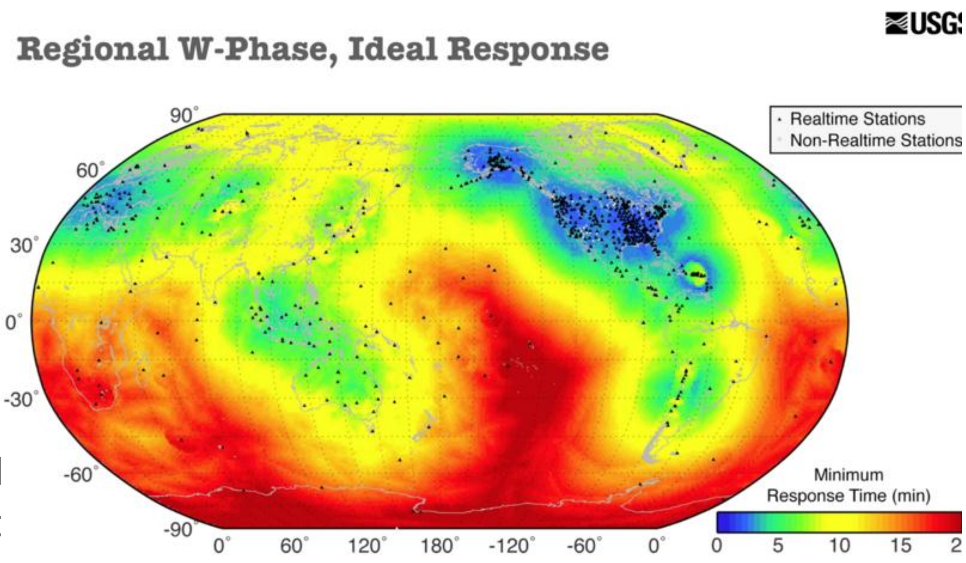
| Magnitude $M_w$ | Moment $M_0$ (Nm) | Area $A$ ($km^2$) | Length $L$ (km) | Width $W$ (km) | Slip $\Delta u$ (m) |
|---|---|---|---|---|---|
| 6.5 | $6.3 \times 10^{18}$ | 224 | 28 | 8 | 0.56 |
| 7.0 | $3.5 \times 10^{19}$ | 708 | 50 | 14 | 1.00 |
| 7.5 | $2.0 \times 10^{20}$ | 2,239 | 89 | 25 | 1.78 |
| 8.0 | $1.1 \times 10^{21}$ | 7,079 | 158 | 45 | 3.17 |
| 8.5 | $6.3 \times 10^{21}$ | 22,387 | 282 | 79 | 5.66 |
| 9.0 | $3.5 \times 10^{22}$ | 70,794 | 501 | 141 | 10.0 |
| 9.5 | $2.0 \times 10^{23}$ | 223,872 | 891 | 251 | 17.8 |

**Table 1**. Relationship between earthquake magnitude and moment with values of fault area, length and mean slip for typical tsunami-generating earthquakes. This paper assumes $\log(L)=0.5M_w-1.8$, $\Delta u = 2\times10^{-5}L$, and $\lambda=\mu= 5\times10^{10}$ Pa

# Magnitude and Moment Tensor: W-phase



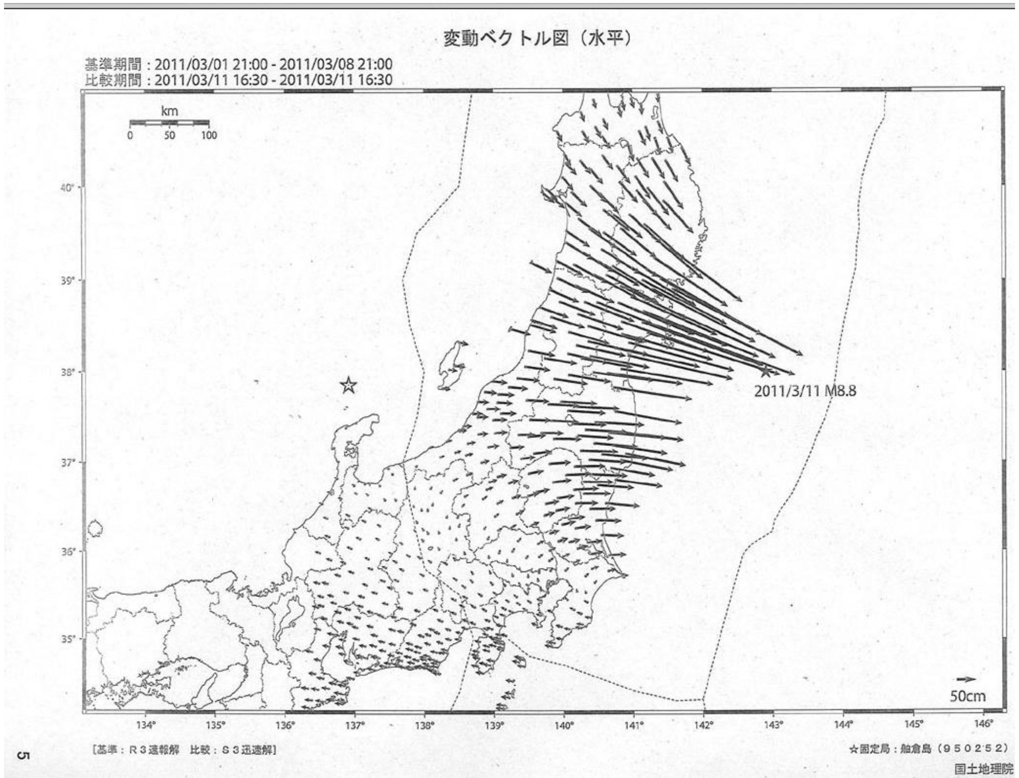

This is a theoretical, idealized response (assumes immediate trigger). Nevertheless, this shows that in most places globally stable magnitudes are possible in **under 25 mins**; and **within 5-10 mins** for many places in the US and Europe.

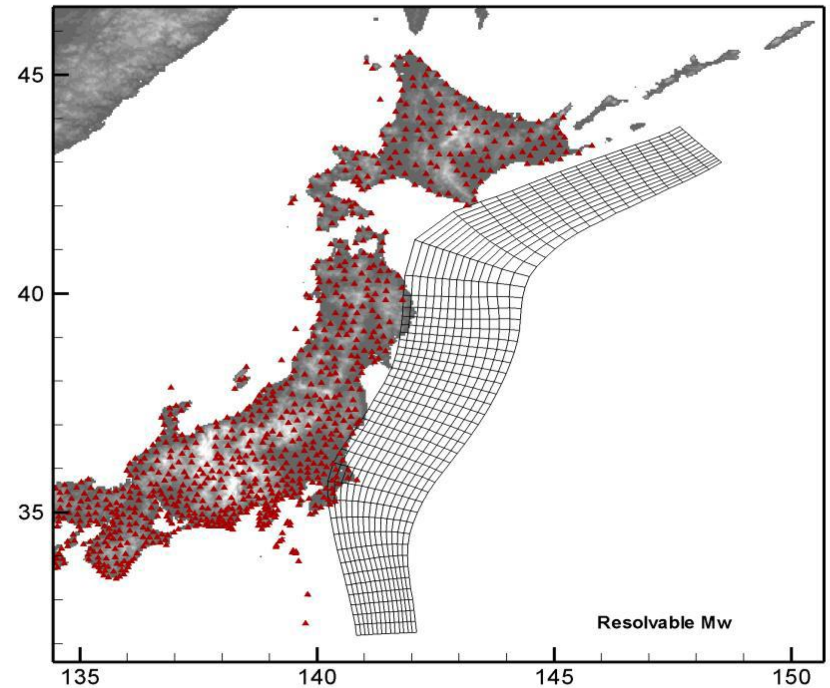
H. Kanamori, 1993, W Phase, Geophys. Res. Lett., v. 20, 1691-1694.

H. Kanamori and L. Rivera, 2008. Source inversion of W phase: speeding tsunami warning, Geophys. J. Int v. 175, 222-238.

*G. Hayes, 2012*

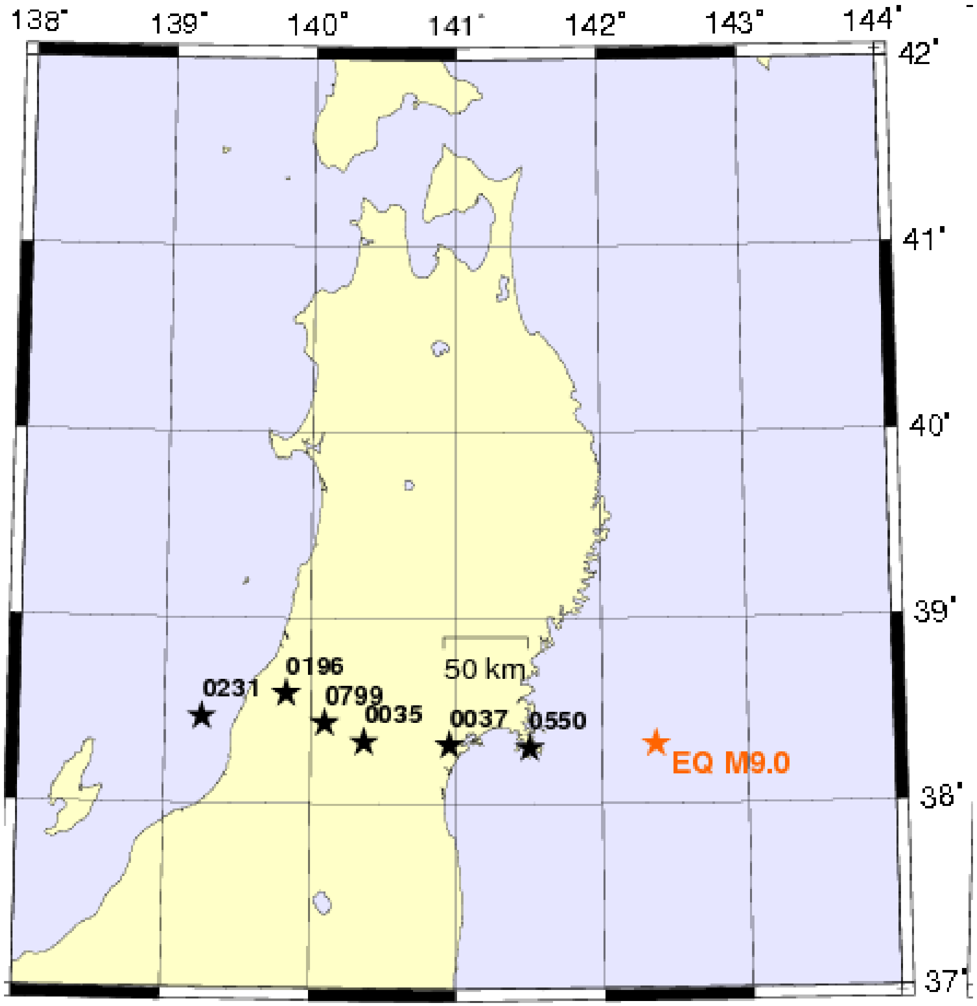
# *Global Positioning System*

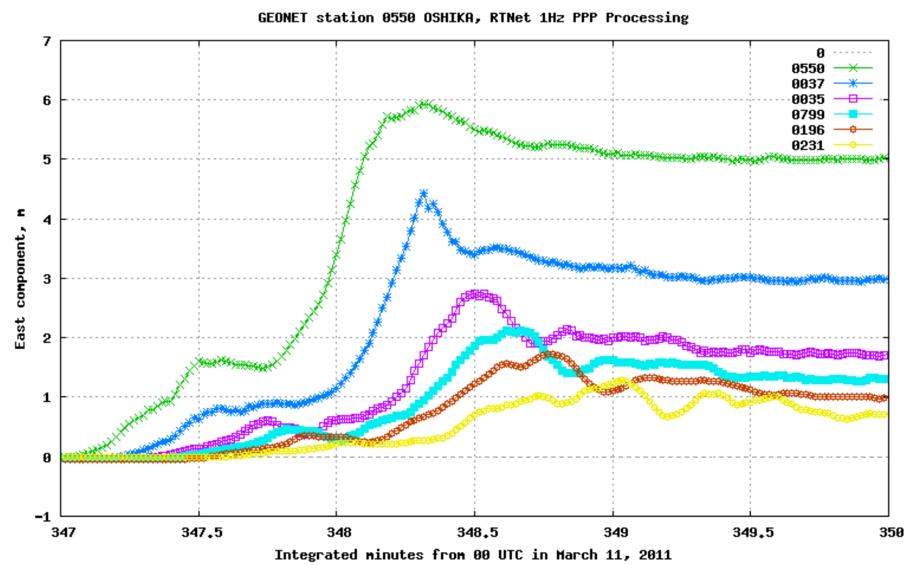


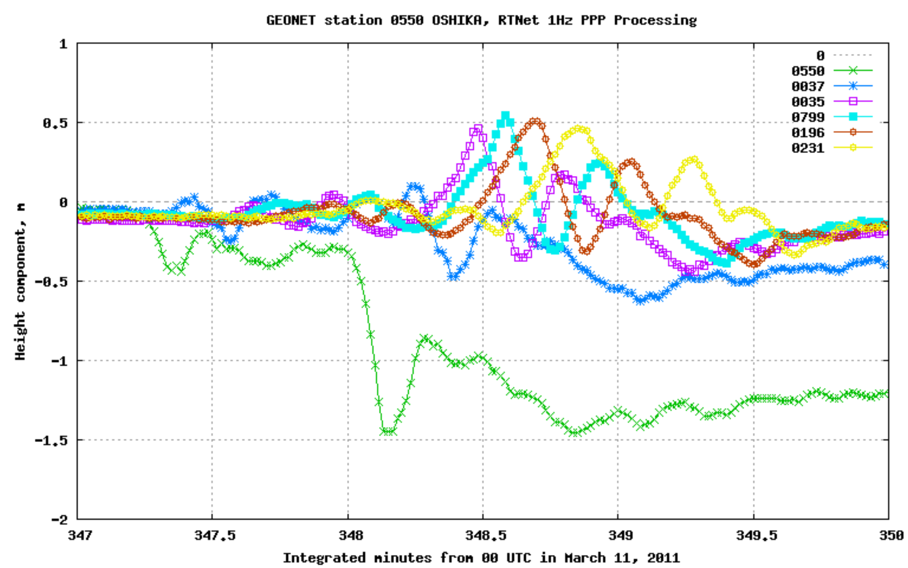




[Tohoku I](#)　　　　[Tohoku II](#)

# Tohoku Earthquake and GPS



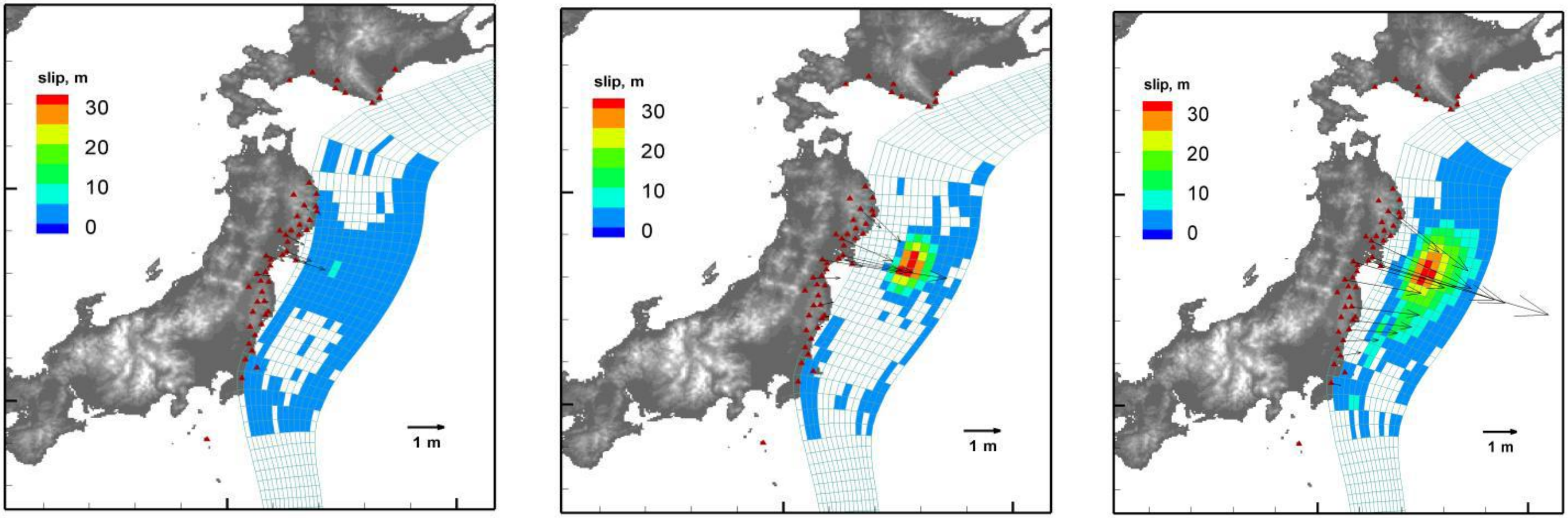




O.T.: 346min 24 sec

# *Early Warning*

60 s + Δt p | 90 s + Δt p | 180 s + Δt p

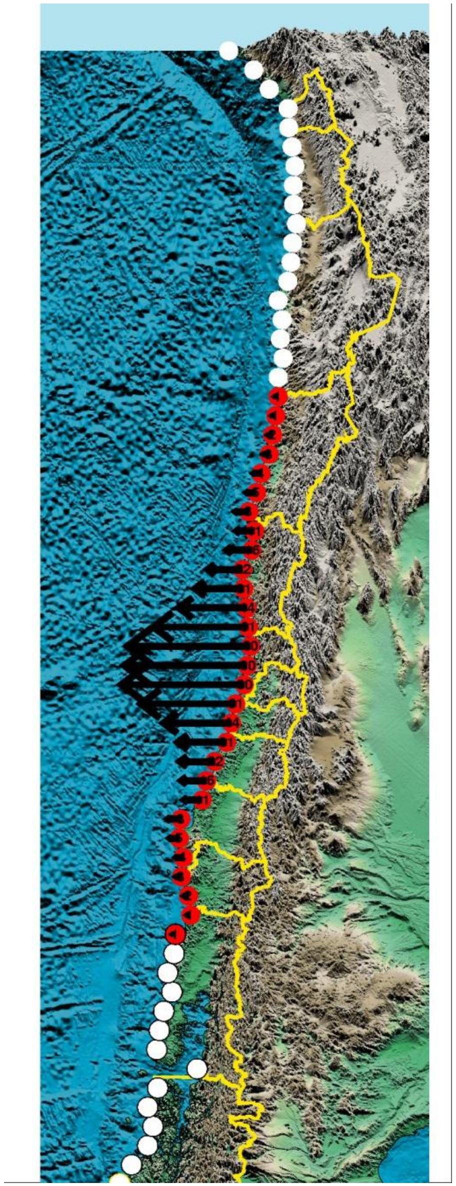


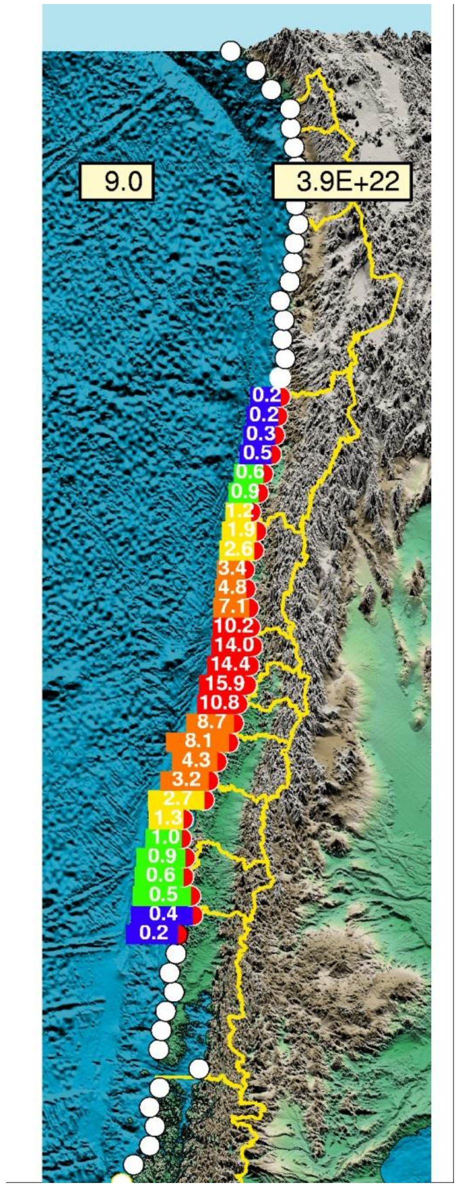

Mw=8.5 | Mw=8.7 | Mw=9.0

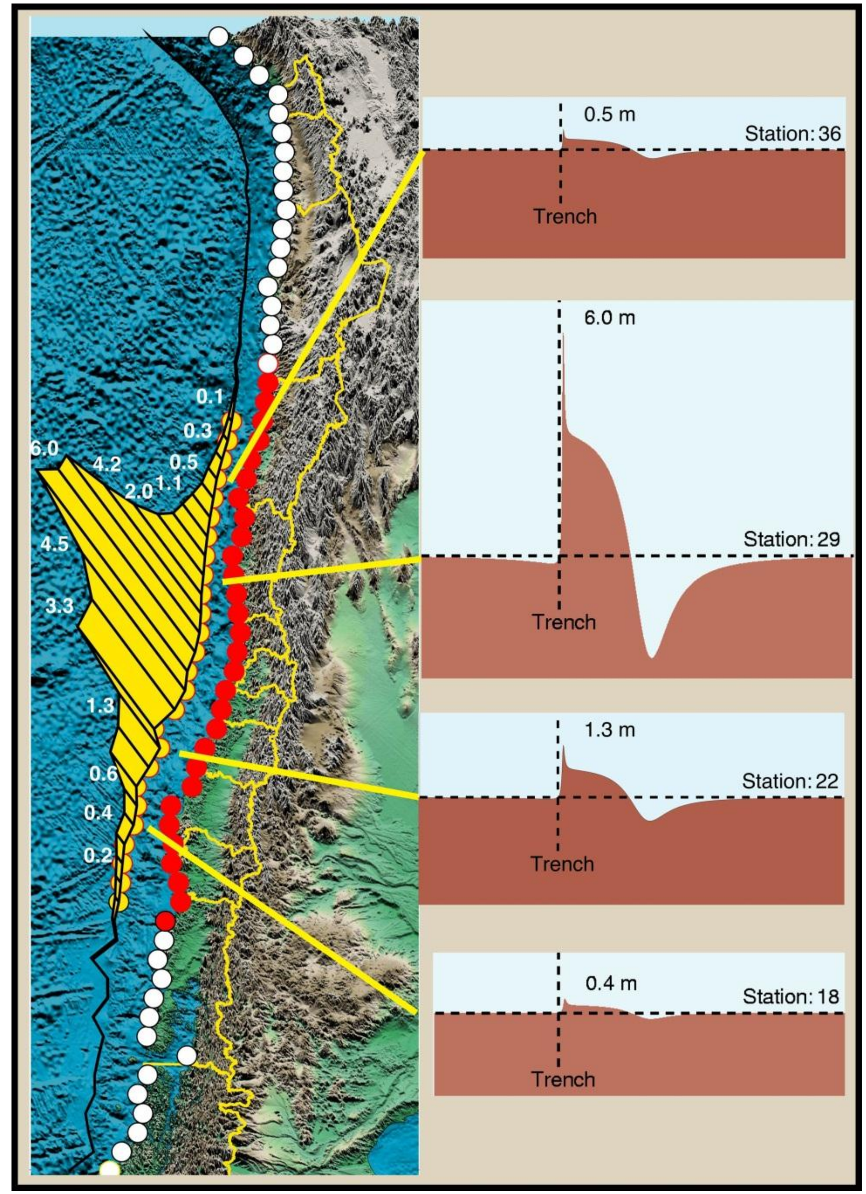
GPS-data: by courtesy of Geospatial Information Authority of Japan (GSI)
Processing time currently 30 to 90 sec

Babeyko, GFZ Group, 2012

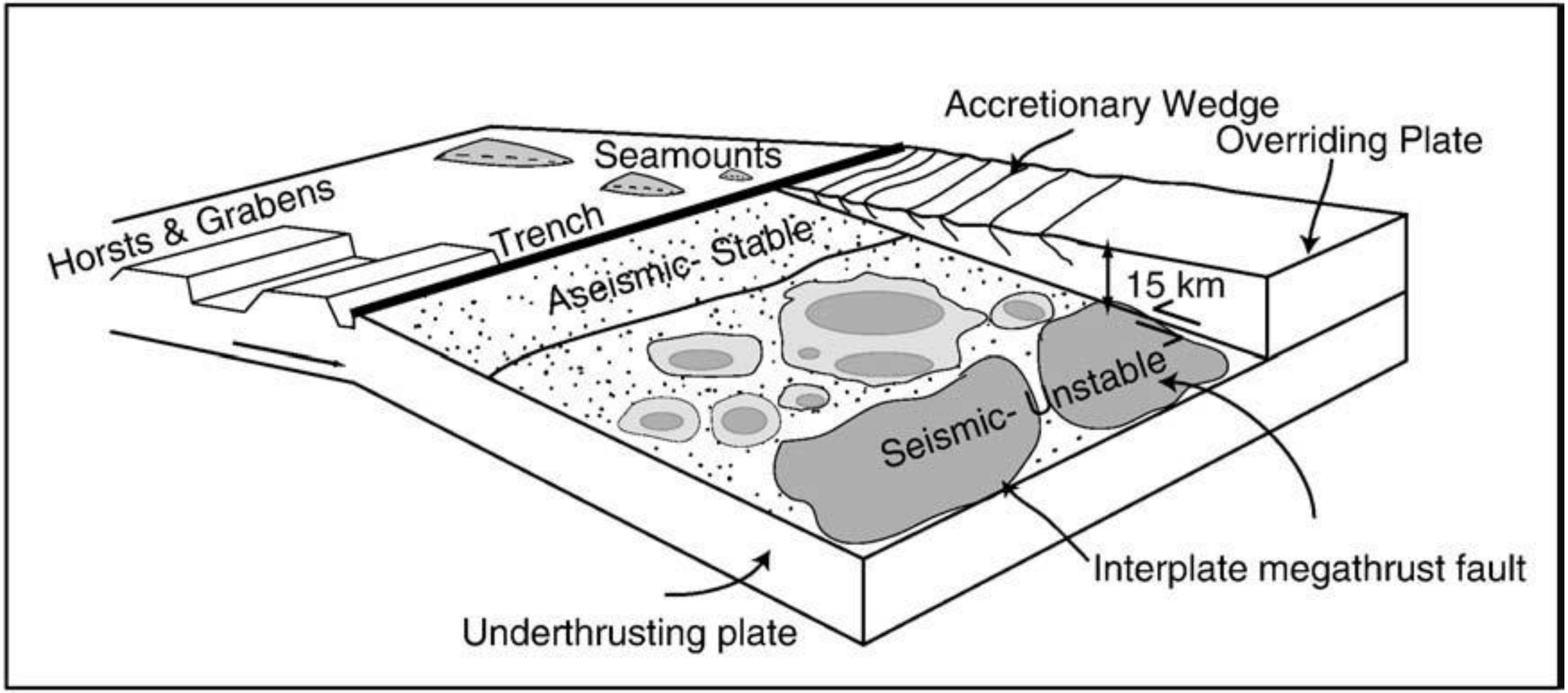
# *Tsunami Warning: GPS Concept*





# *Interpretation: Asperities*



# Crustal Deformation: Early Reports

**1822 19 November 10:15 PM Valparaiso M= 8 to 8.5** (Lomnitz,2004)
The alteration of the level at Valparaiso was about three feet, and some rocks were thus newly exposed, on which the fishermen collected the scollop-shell fish, which was not known to exist before the Earthquake. At Quintero, the elevation was about four feet . No significant tsunami
**Maria Graham**
Henry Warbuton published in *Trans. Geol. Soc. London* in 1823
Discussion with Greenough, Pres. of the Soc., (to attack Lyell's ideas)

**1835 20 February 11:30 AM Concepcion M = 8 to 8.5** (Lomnitz,2004)
The island of Quiriquina was uplifted 8 feet, Santa Maria Island 8 to 10 feet, Talcahuano 4 to 5 feet, Tubul 6 feet-- according to Darwin's own estimates, based on the level of dead shellfish as a reference. Subsidence was reported in the Maule estuary. Large tsunami.
**Charles Darwin**

# Continuous Fight of Cai-cai and Tren-tren