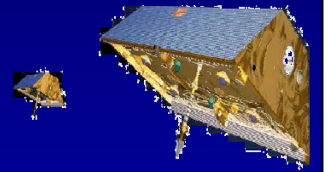
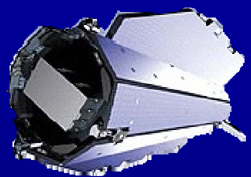
What does satellite gravity bring to the understanding and monitoring of large earthquakes ?



M. Diament[1], I. Panet [1,2], V. Mikhailov [1,3], O. de Viron[1]



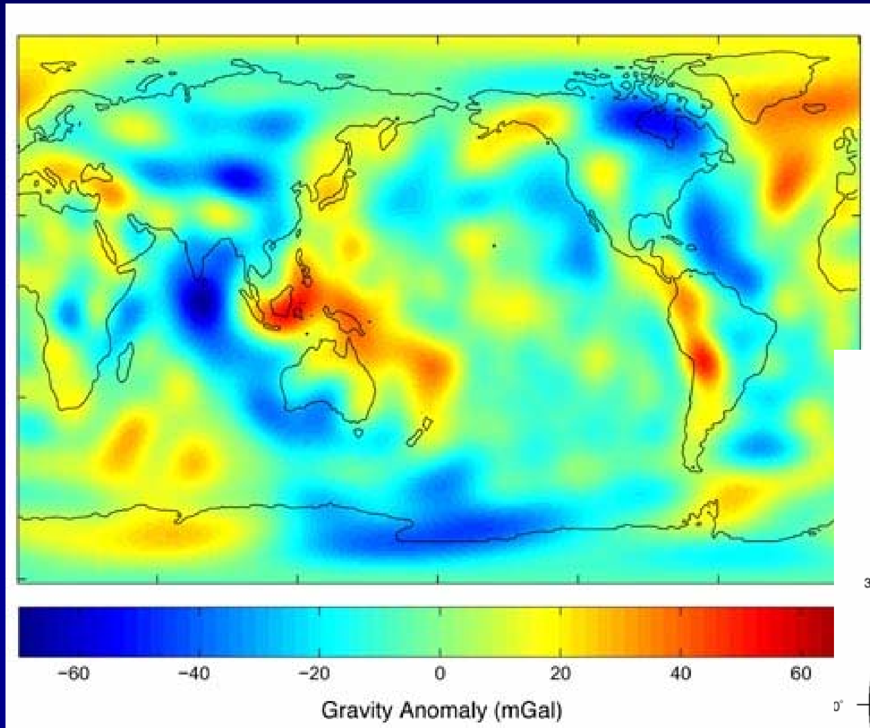
[1] Institut de Physique du Globe de Paris, France

[2] Geographical Survey Institute, Japan

[3] Institute of Physics of the Earth, Moscow, Russia

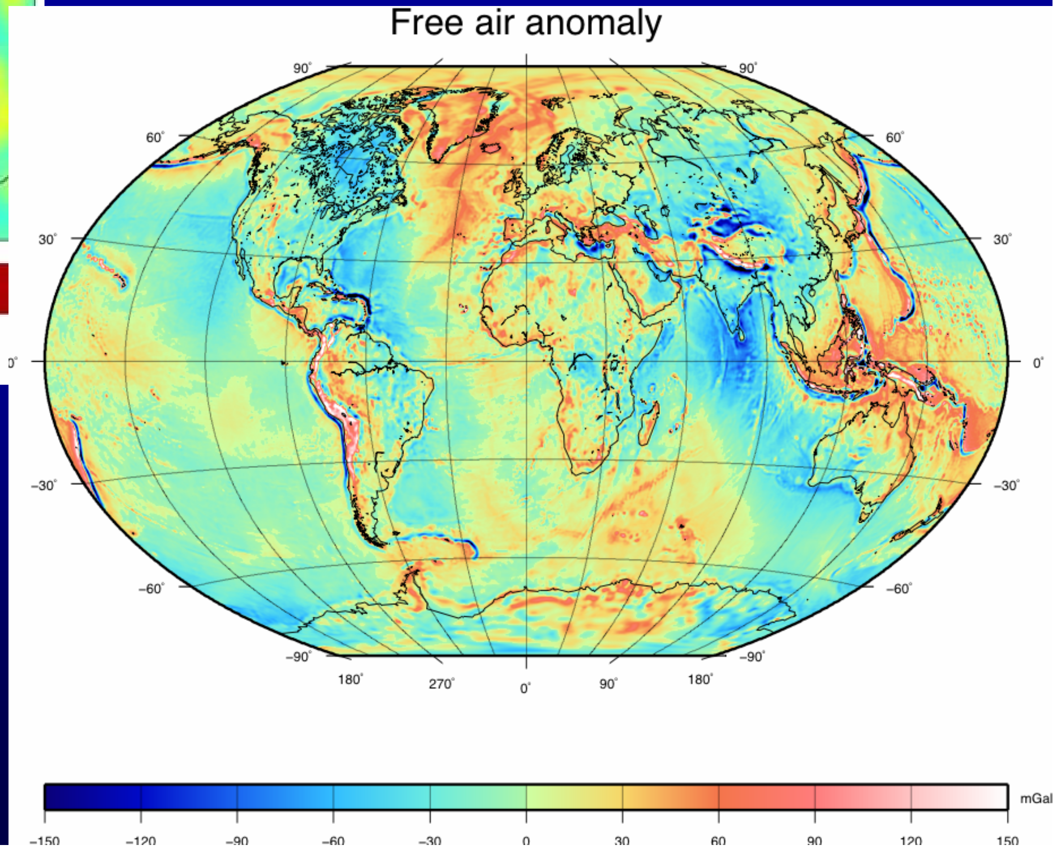
GGOS Meeting November 6, 2007 Frascati

Dedicated satellite gravity missions have dramatically increased our knowledge of the gravity field of the Earth,



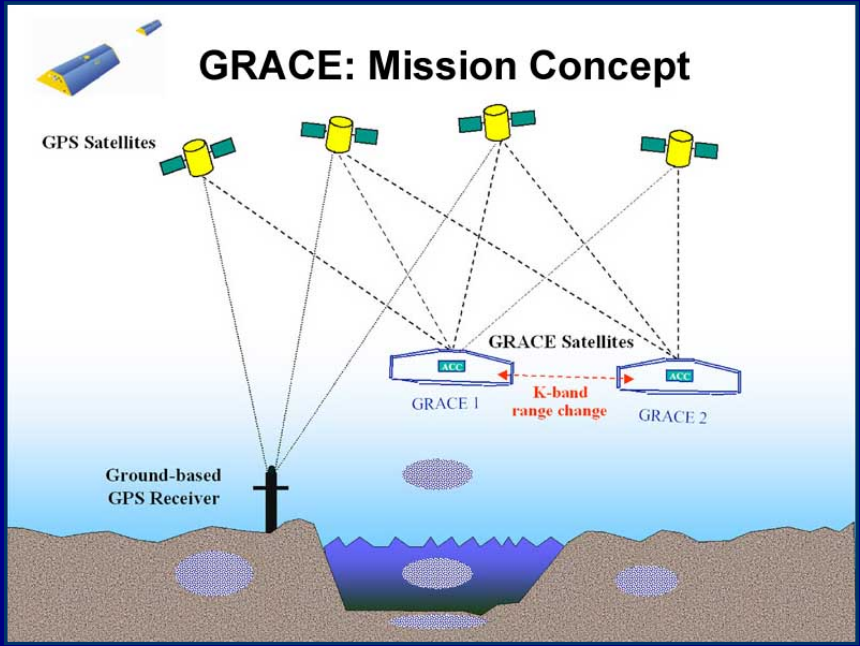
What we knew from satellite tracking by the end of last century

EIGEN-GL04C

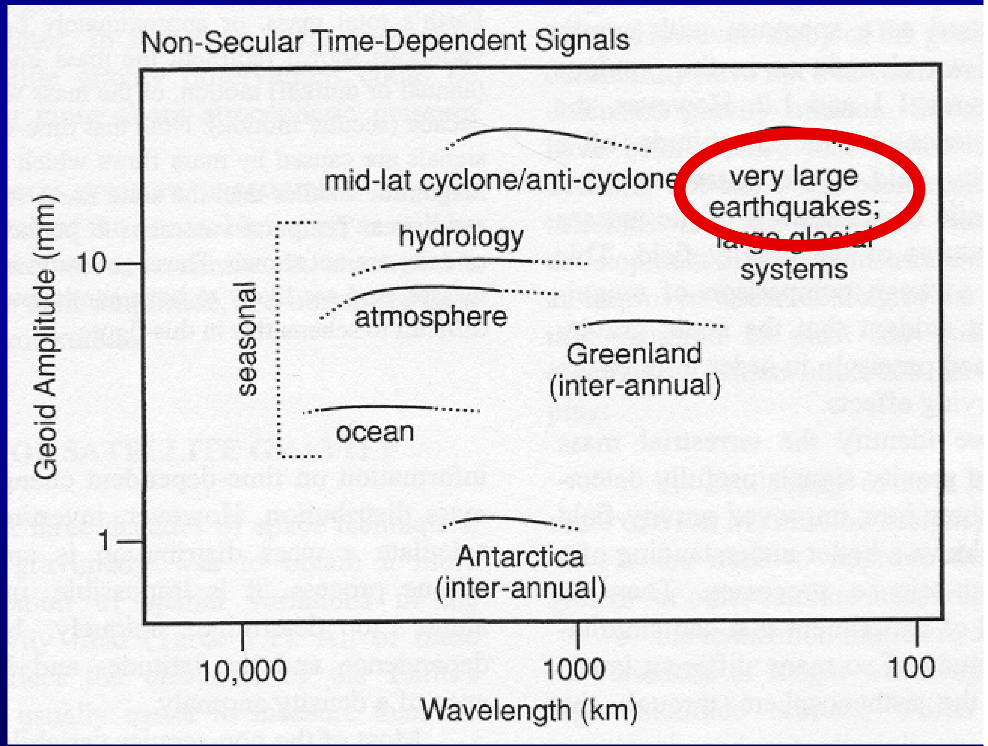


and have given acess to the globally time varying gravity field !

The GRACE mission measures the temporal variations of the gravity field



Why does the gravity field vary with time ?

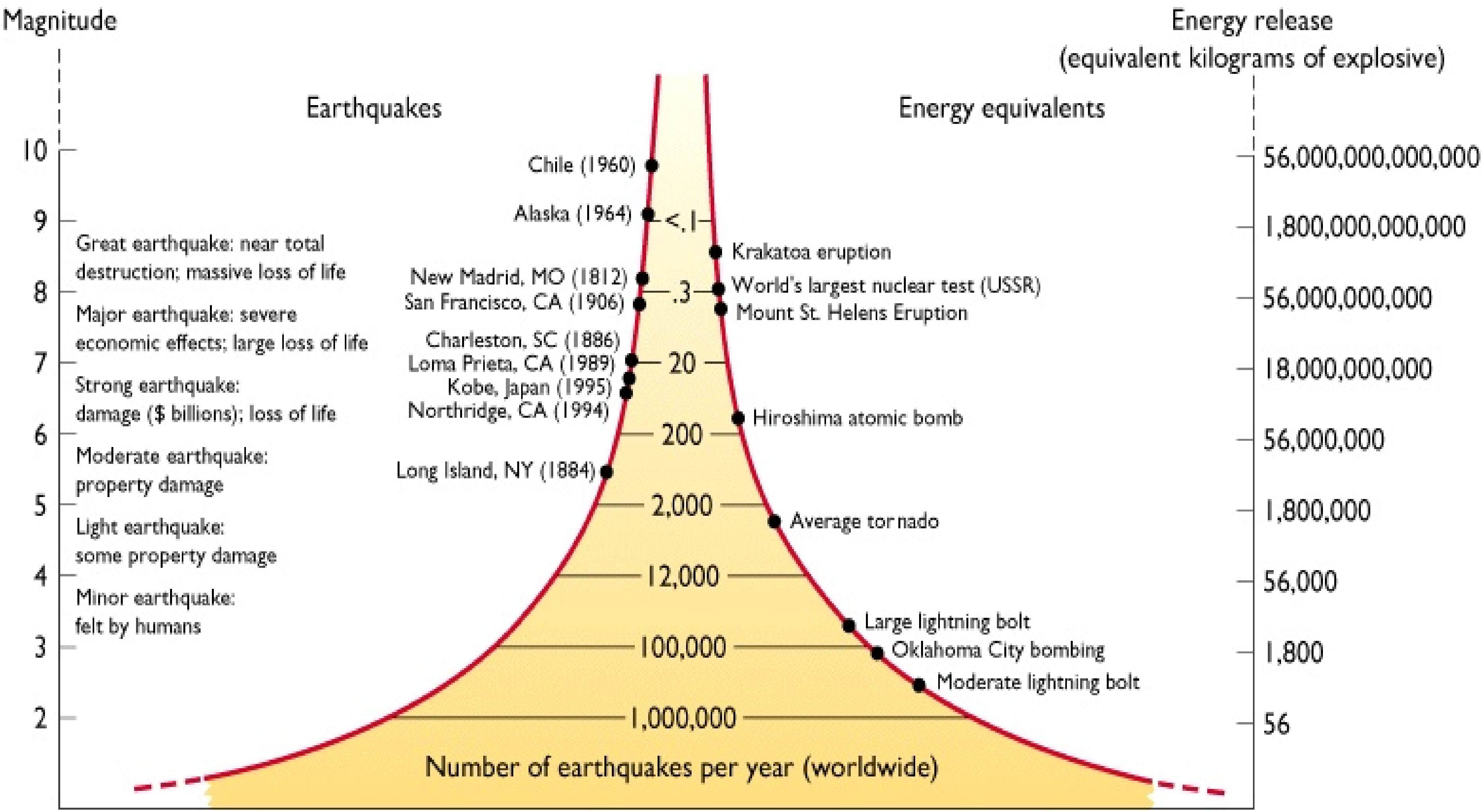


From Dickey et al., 1997

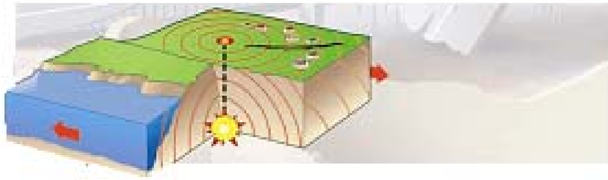
Earthquakes - a major concern for society

Kobe, Japan, 17/01/95
M_w=6.9 (t=20s)
5470 fatalities, 33000 injured

and huge economic impacts.


Magnitude
Energy release
(equivalent kilograms of explosive)
Earthquakes
Energy equivalents
10
9
8
7
6
5
4
3
2
56,000,000,000,000
1,800,000,000,000
56,000,000,000
18,000,000,000
56,000,000
1,800,000
56,000
1,800
56
Great earthquake: near total destruction; massive loss of life
Major earthquake: severe economic effects; large loss of life
Strong earthquake: damage ($ billions); loss of life
Moderate earthquake: property damage
Light earthquake: some property damage
Minor earthquake: felt by humans
Chile (1960)
Alaska (1964)
New Madrid, MO (1812)
San Francisco, CA (1906)
Charleston, SC (1886)
Loma Prieta, CA (1989)
Kobe, Japan (1995)
Northridge, CA (1994)
Long Island, NY (1884)
<.1
.3
20
200
2,000
12,000
100,000
1,000,000
Krakatoa eruption
World's largest nuclear test (USSR)
Mount St. Helens Eruption
Hiroshima atomic bomb
Average tornado
Large lightning bolt
Oklahoma City bombing
Moderate lightning bolt
Number of earthquakes per year (worldwide)

Seismic cycle

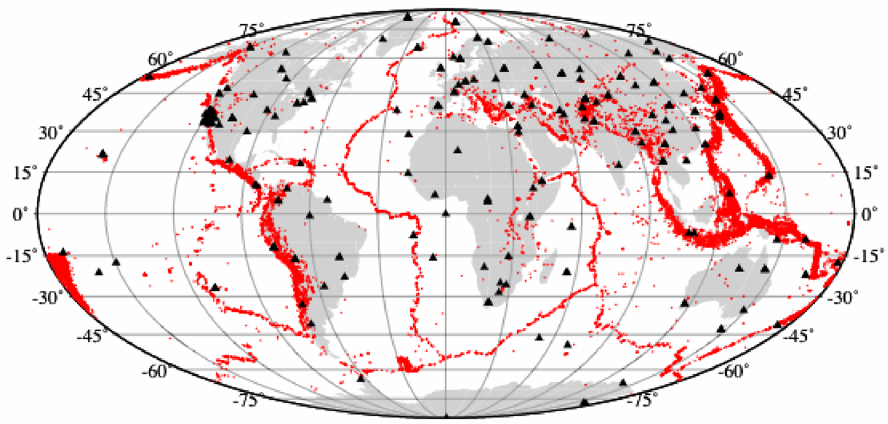


Co-seismic, post seismic phases

Inter seismic, pre-seismic phases

To study the seismic cycle (pre-seismic, co-seismic, post-seismic and inter-seismic phases) long time series of geophysical and geodetic observations are mandatory

Réseau IRIS GEOSCOPE et sismicité générale (Mb > 5.0 1977-1996)



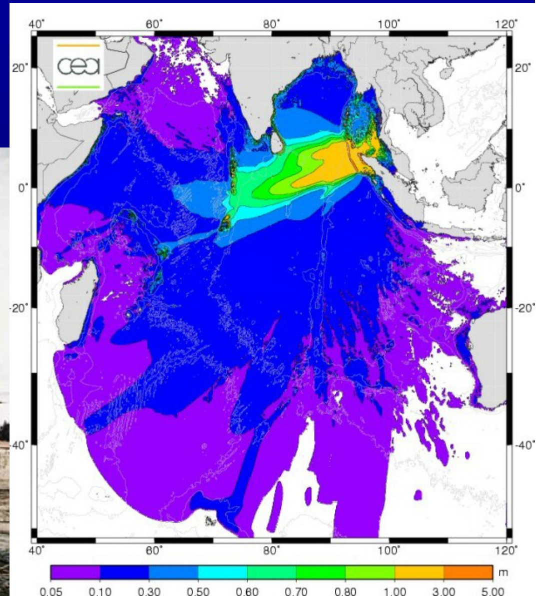
Largest earthquakes generally occur in subduction zone areas, thus in zones partly or totally covered with oceans, very poorly monitored with geodetic or geophysical instruments.

Therefore purely space based techniques can contribute to study the seismic cycle : one possibility is satellite gravity.

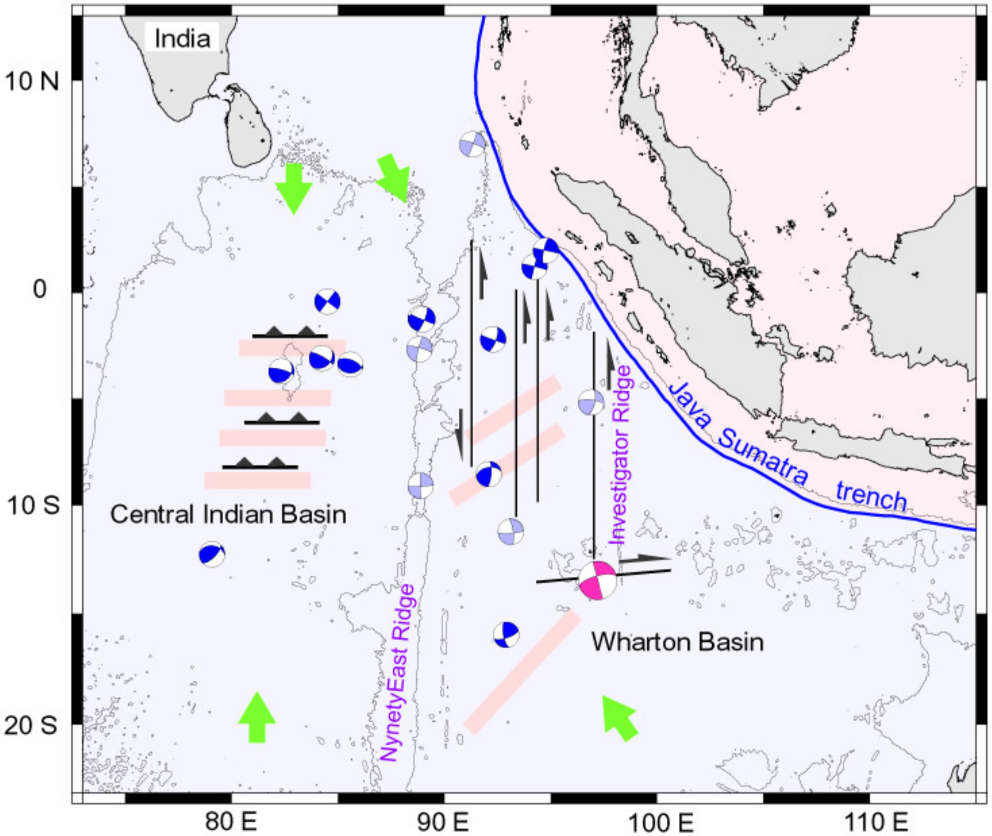
Indeed, studies published in 2004 theoretically showed that Grace type mission should register signal linked with very large earthquakes, typically Mw ≈ 8.5, 9 (depending upon the effective Grace data accuracy).

After the Mw 9.3 December 26, 2004 Sumatra-Andaman event, several groups analyzed Grace data using different data sets and approaches.

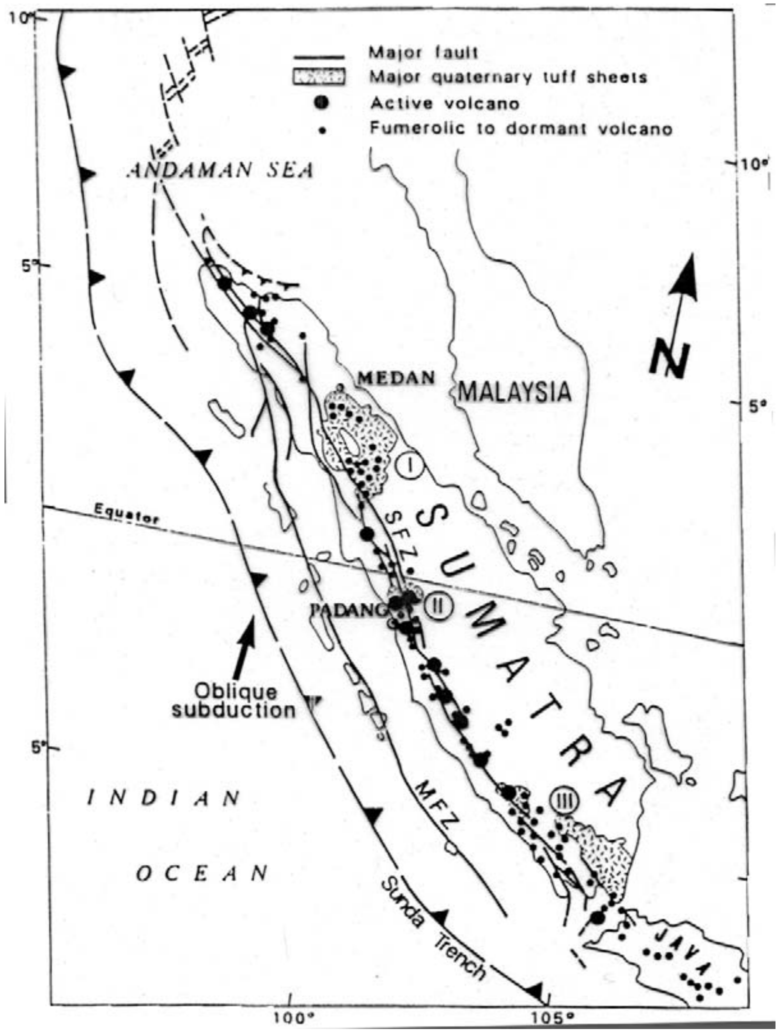
We used the GRACE and LAGEOS based gravity field models expressed as normalized spherical harmonic coefficients from degree 2 to degree 50, produced and delivered by our colleagues from CNES/GRGS (R. Biancale et al.).
We studied the December 2004 and March 2005 events.



Some elements on the geodynamic context

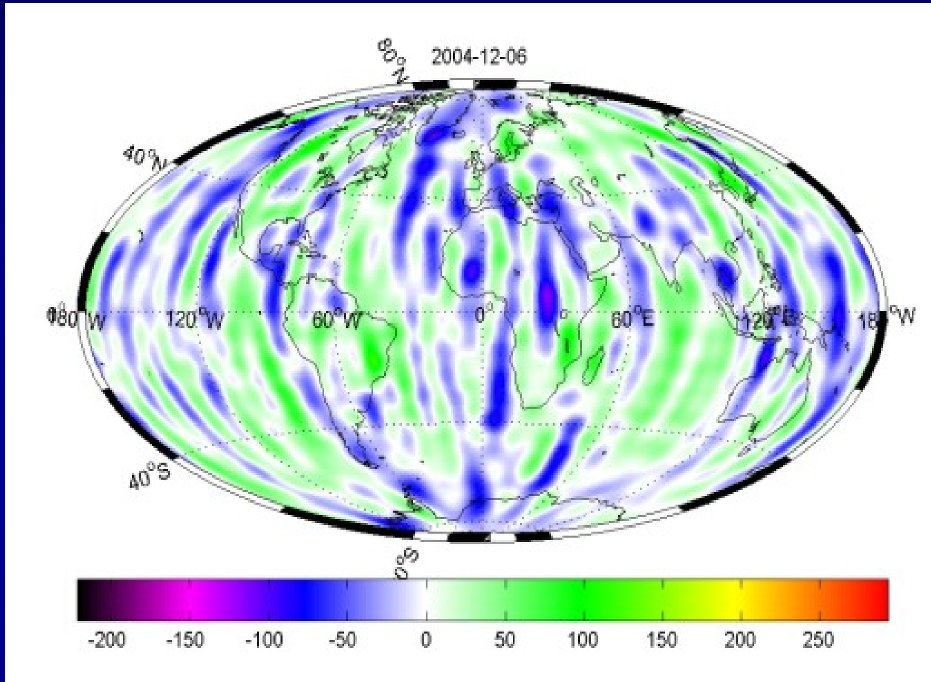


From Deplus, 2001

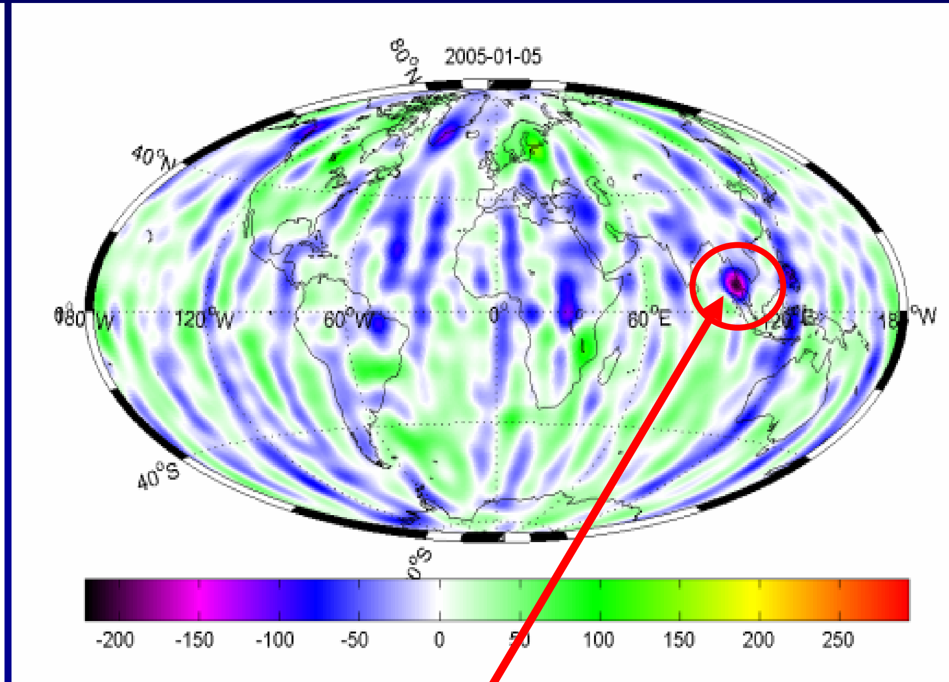


From Devi Zen,1993

Comparison of 2 geoid models covering one month period before (left) and after (right) the Andaman-Sumatra earthquake.



December 2004



January 2005

Stripes are due to aliasing and must be treated here as artefacts.

There are hydrology effects (for example in Amazonia)

A strong negative signal appeared over the Andaman Sea after the earthquake.

Comparable anomalies were not observed before

Continuous wavelet analysis coefficients at 500 km scale of the geoid difference between 2005 and 2004, stacked over 9 months (right panel), and of the geoid difference between 2004 and 2003, stacked over 9 months (left panel).

What do we learn from GRACE about this event ?

*Panet et al., Geophys. J. Int., **171**,177-190, 2007*

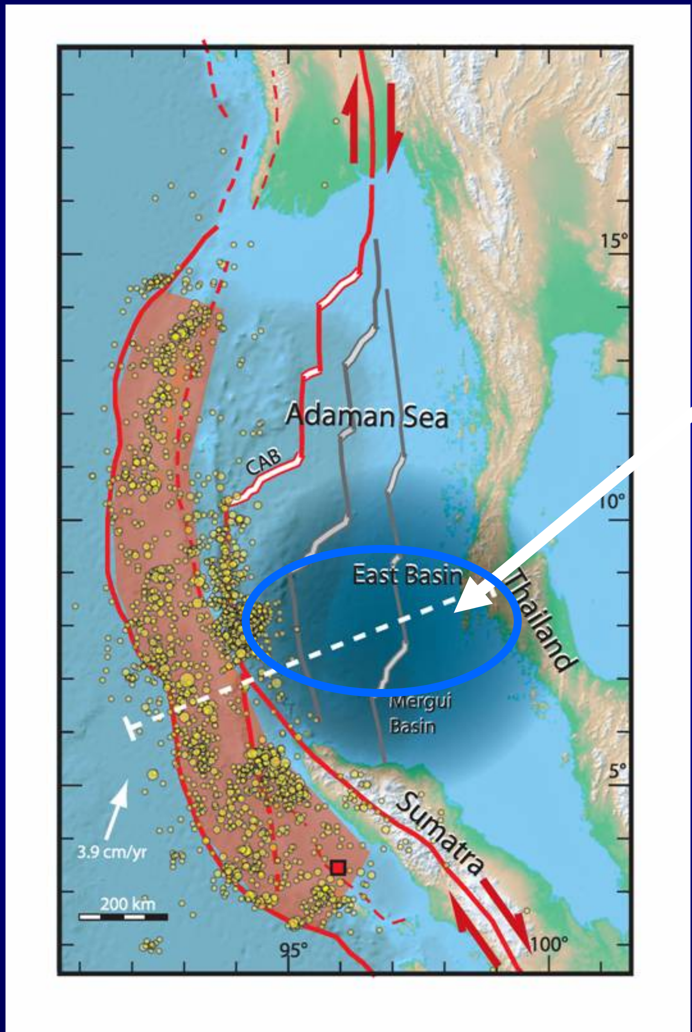
Continuous wavelet analysis coefficients at 1000 km scale of the geoid anomaly

a: resulting from Banerjee *et al.* (2005) model of the Andaman December 2004 earthquake. A self-gravitating, spherically layered, compressible Earth model (Pollitz, 1996) is used.

c: Observed GRACE geoid difference between January 2004 and January 2005

b: Inhomogeneous lithosphere. Additional 15 cm subsidence in the Andaman Sea.

Our co-seismic observations and the geodynamic context



- Accomodation of co-seismic stresses creates subsidence in the Mergui basin : a compliant block.

But what about post-seismic signal ?

Continuous wavelet analysis coefficients at 1000 km scale of the geoid 2005/2004 differences stacked over *n* months, with *n* between 1 and 9.

On the upper left subplot, the co-seismic signal (*n* = 1: January 2005 – January 2004) is represented. It has been subtracted from the other subplots (*n* = 2 to 9). The value of *n* is indicated on each subplot. Note stable growth of the signal with stacking interval (i.e. with time).

Continuous wavelet analysis coefficients at 570 km scale of the geoid 2005/2004 differences stacked over *n* months, with *n* between 1 and 9.

On the upper left subplot, the co-seismic signal (*n* = 1: January 2005 – January 2004) is represented. It has been subtracted from the other subplots (*n* = 2 to 9). The value of *n* is indicated on each subplot.

Zoom over the area affected by the Nias (march 2005) earthquake

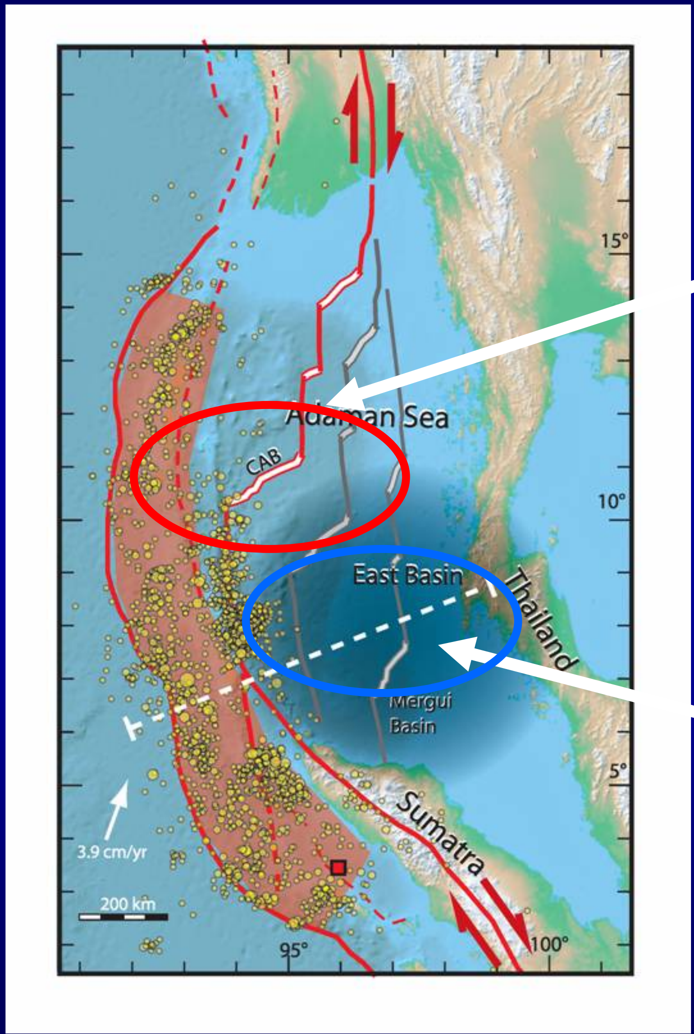
This shows that wavelet analysis permits to detect earthquakes with a magnitude as “low” as 8.7 with the present-day accuracy of GRACE data.

The style and rate of gravity signal relaxation is consistent with a bi-viscous model (a harder matrice with softer inclusions, e.g. Ivins, 1996).

This model explains well the post-seismic deformation registered by GPS stations in Sumatra area (Pollitz et al., 2006) .

Relaxation over a few months as observed at the 570 km scale could indicate the presence of material with viscosities of the order of 10^{17} Pa·s below the Central Andaman ridge.

Our observations and the geodynamic context

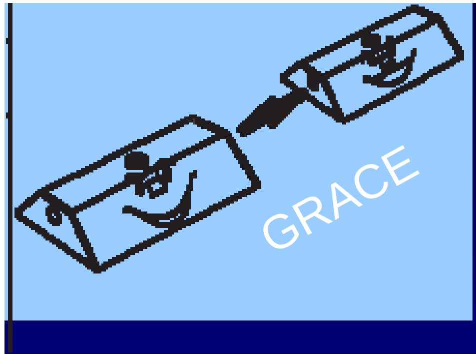


- Strong post-seismic signal in the central Andaman sea where rifting is present

rift ➔ hot and superficial mantle, non linear viscous response.

- Accomodation of co-seismic stresses creates subsidence in the Mergui basin : a compliant block.

Next challenge : pre-seismic phase...



Conclusions:

1. We evidence a strong signal in GRACE data associated with the Sumatra 2004 and 2005 earthquakes. Our analysis allowed us to localize a co-seismic gravity low in the Andaman Sea and to evidence post-seismic relaxation.
2. To explain these observations, we take into account the specific structure of the Andaman Sea crust and mantle. Interpretation requires to include information about local geodynamics.
3. Combination of gravity, deformation (GNSS, INSAR...) and seismological data allows to get full picture of active processes.
4. These observations show broad perspectives of the satellite gravity for understanding and monitoring the seismic cycles, especially in locked subduction zones : GRACE-GOCE follow on missions (with sharper eyes to avoid glasses !!) ?