Geodetic contributions to studies of the physics of earthquakes

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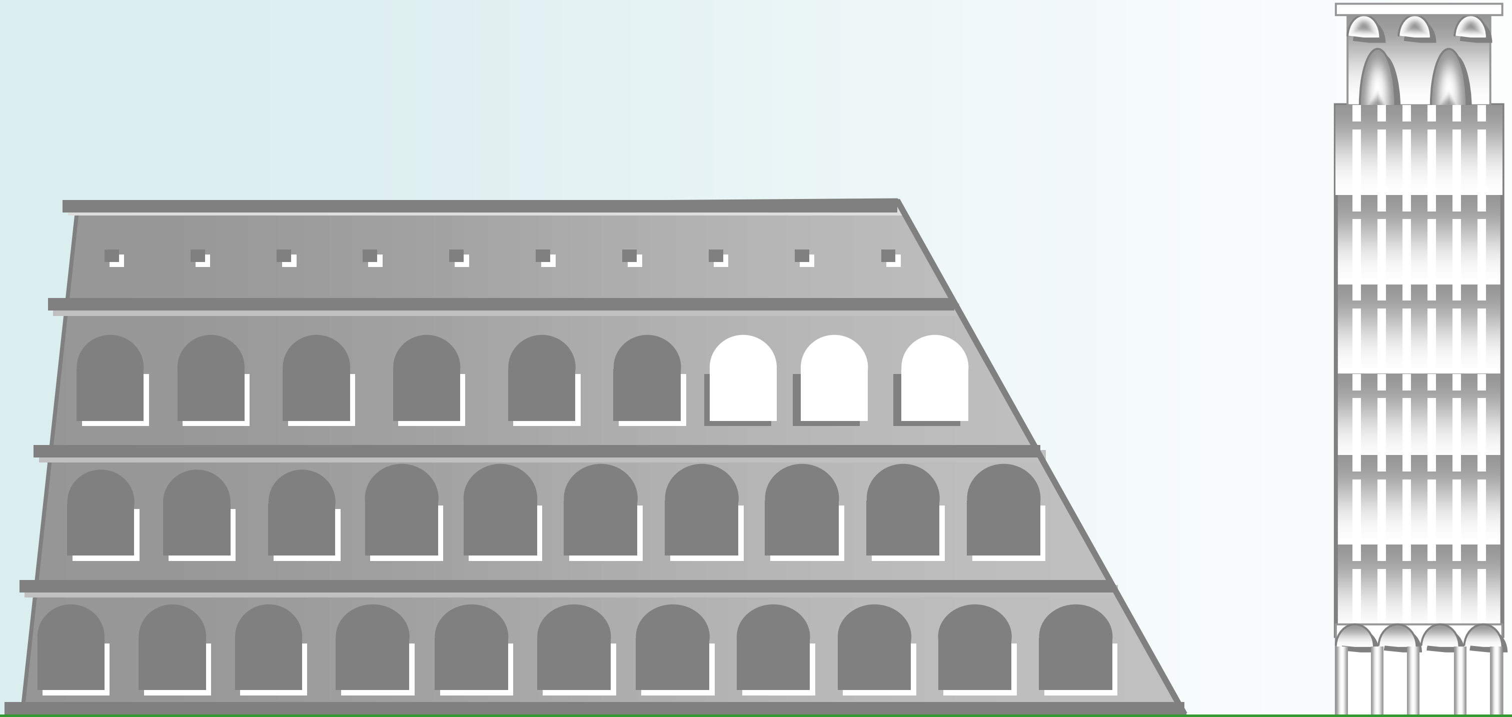
Topics of today's talk



Topic #1. Positioning : recurrence

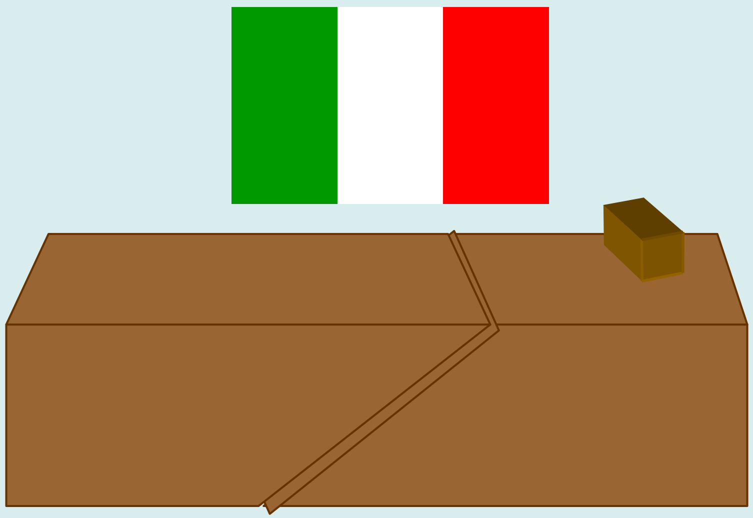
Topic #2. Gravimetry : co-/postseismic changes

Topic #3. Propagation media : coupling with atmosphere

Topic #1.
Biannual slow slip events in SW Japan

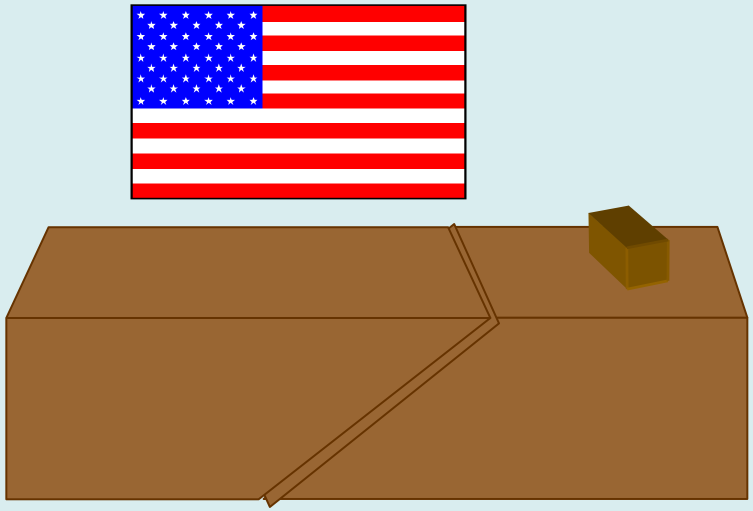
Slow earthquake

Slow Food



Fast (regular) earthquake

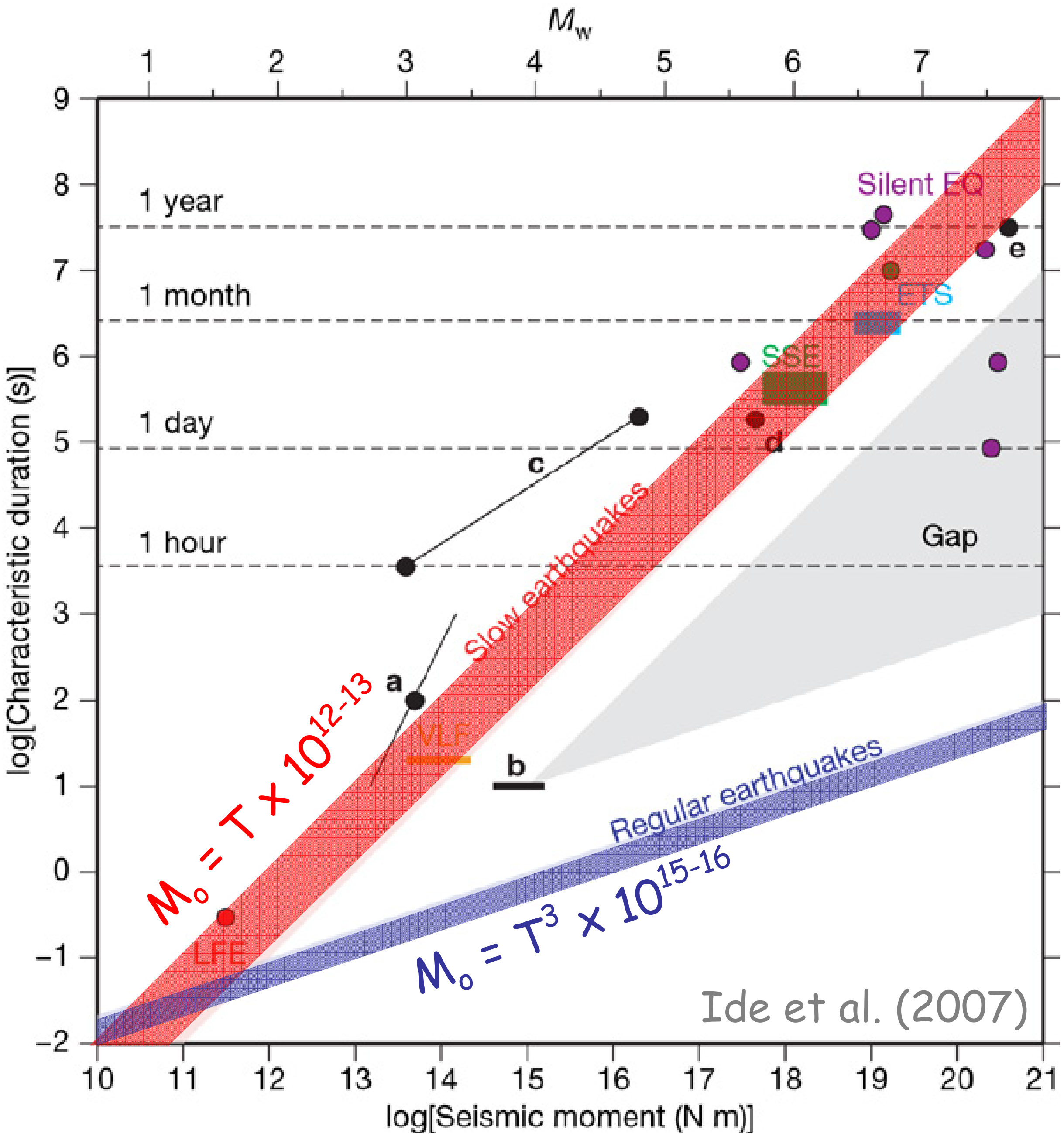
Fast Food



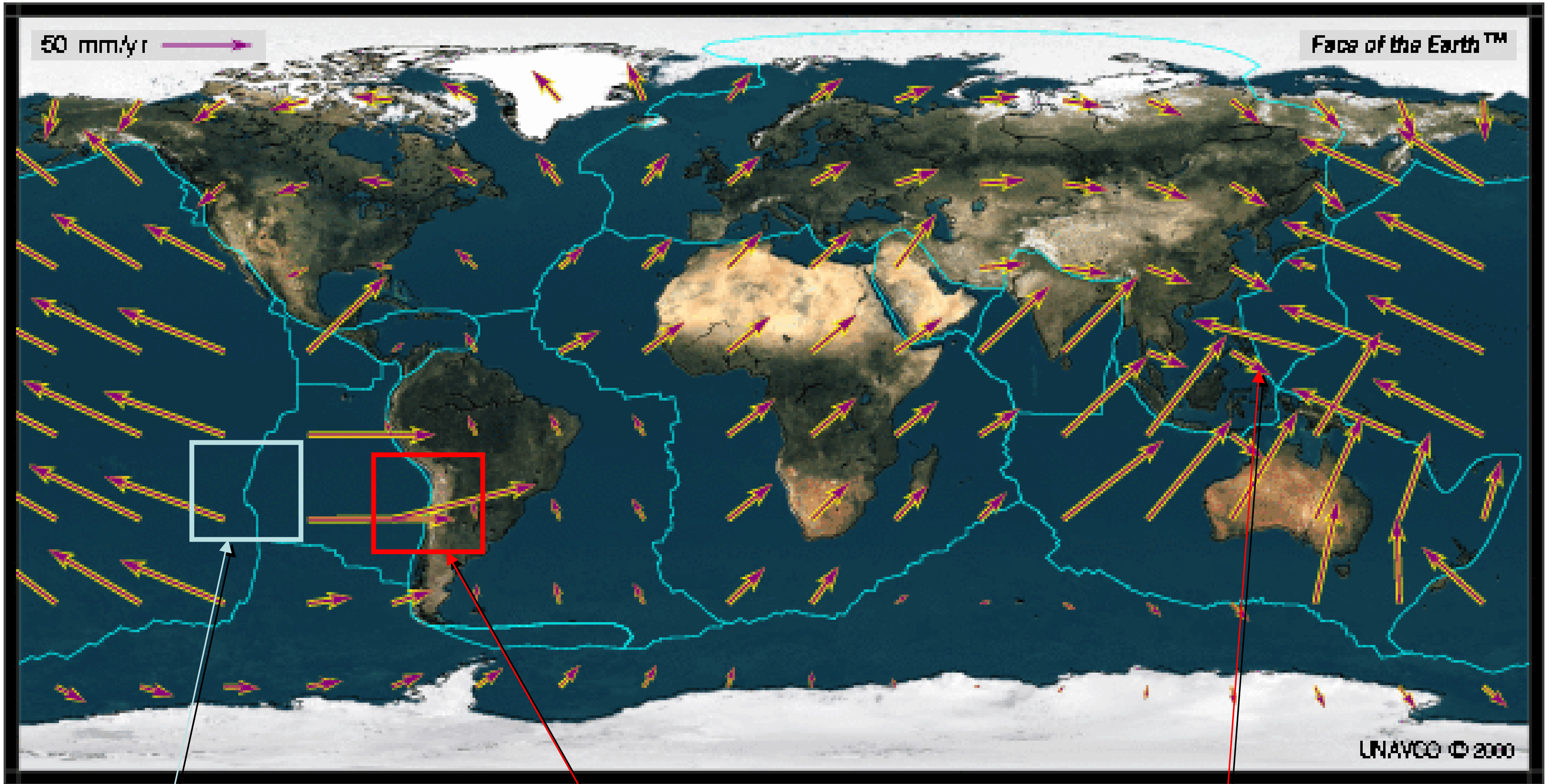
Episodic Tremor and Slip (ETS)
Slow Slip Event (SSE)
Silent Eq., Afterslip
Very Low Frequency Eq. (VLF)
Low Frequency Eq. (LFE)

A family

Scaling law: The longer it takes, the larger is the earthquake



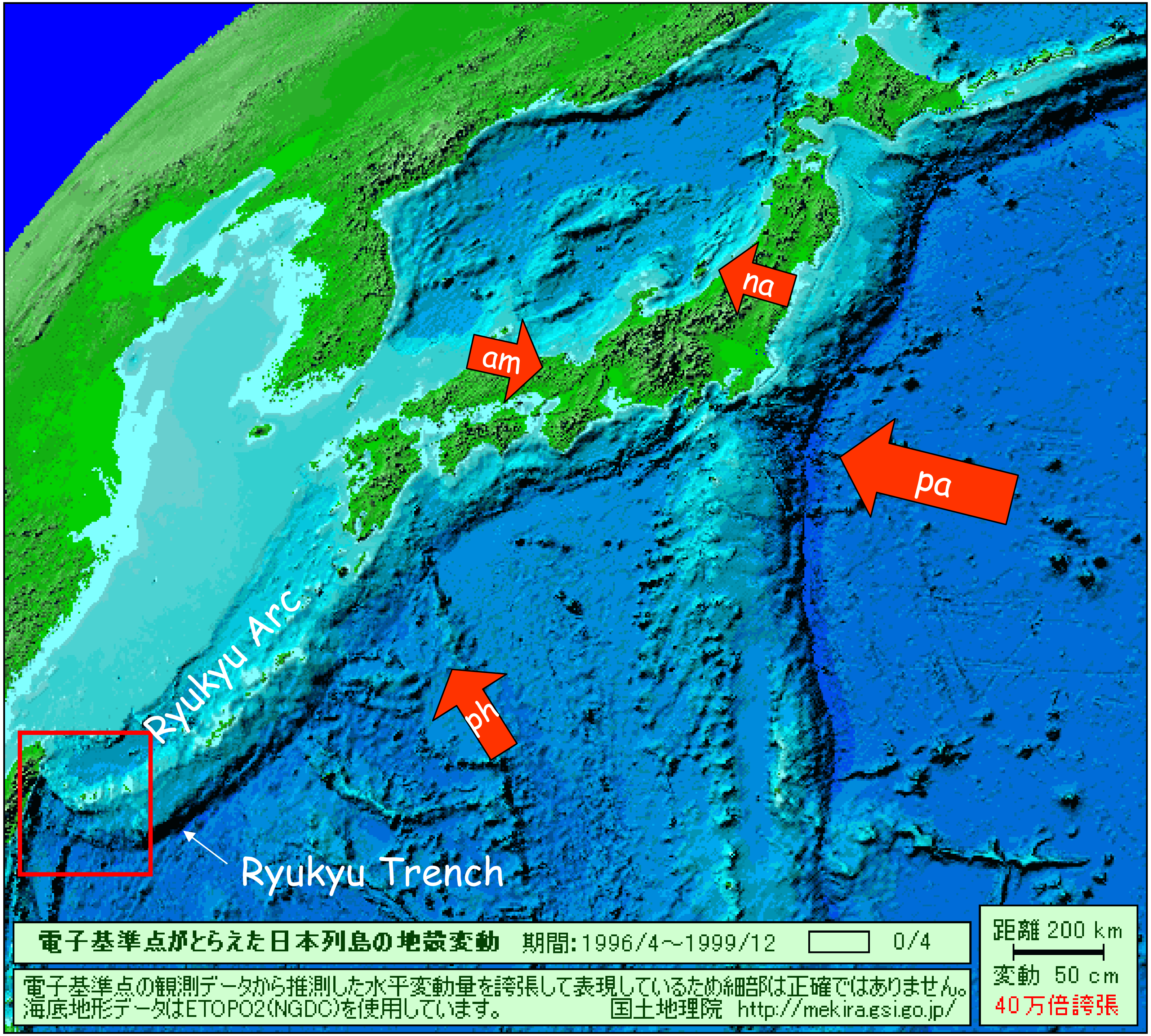
Fastest plate motion ? (UNAVCO webpage)



Fastest divergence
~17 cm/year

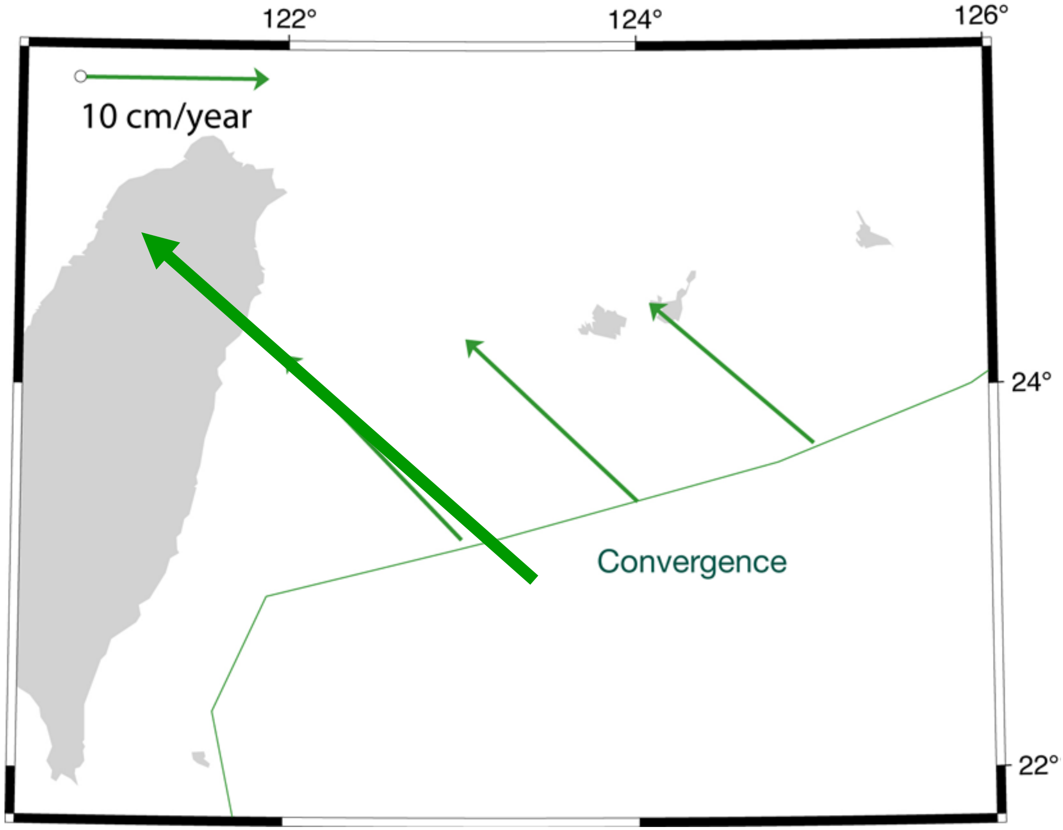
Fastest convergence?
~11 cm/year

SW Ryukyu
> 12 cm/year

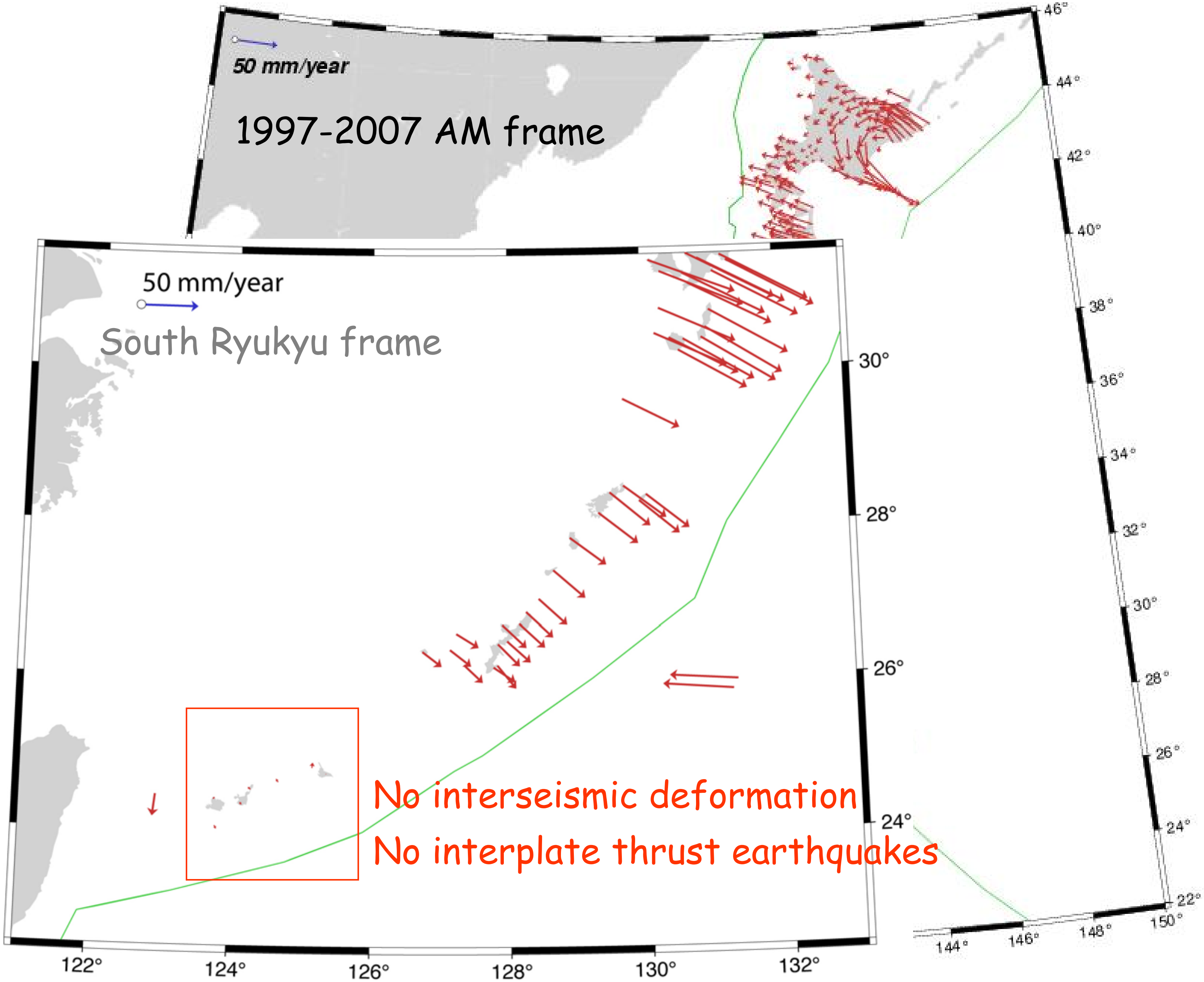


na
am
pa
ph
Ryukyu Arc
Ryukyu Trench
電子基準点がとらえた日本列島の地殻変動 期間:1996/4～1999/12 0/4
電子基準点の観測データから推測した水平変動量を誇張して表現しているため細部は正確ではありません。
海底地形データはETOPO2(NGDC)を使用しています。 国土地理院 http://mekira.gsi.go.jp/
距離 200 km
変動 50 cm
40万倍誇張

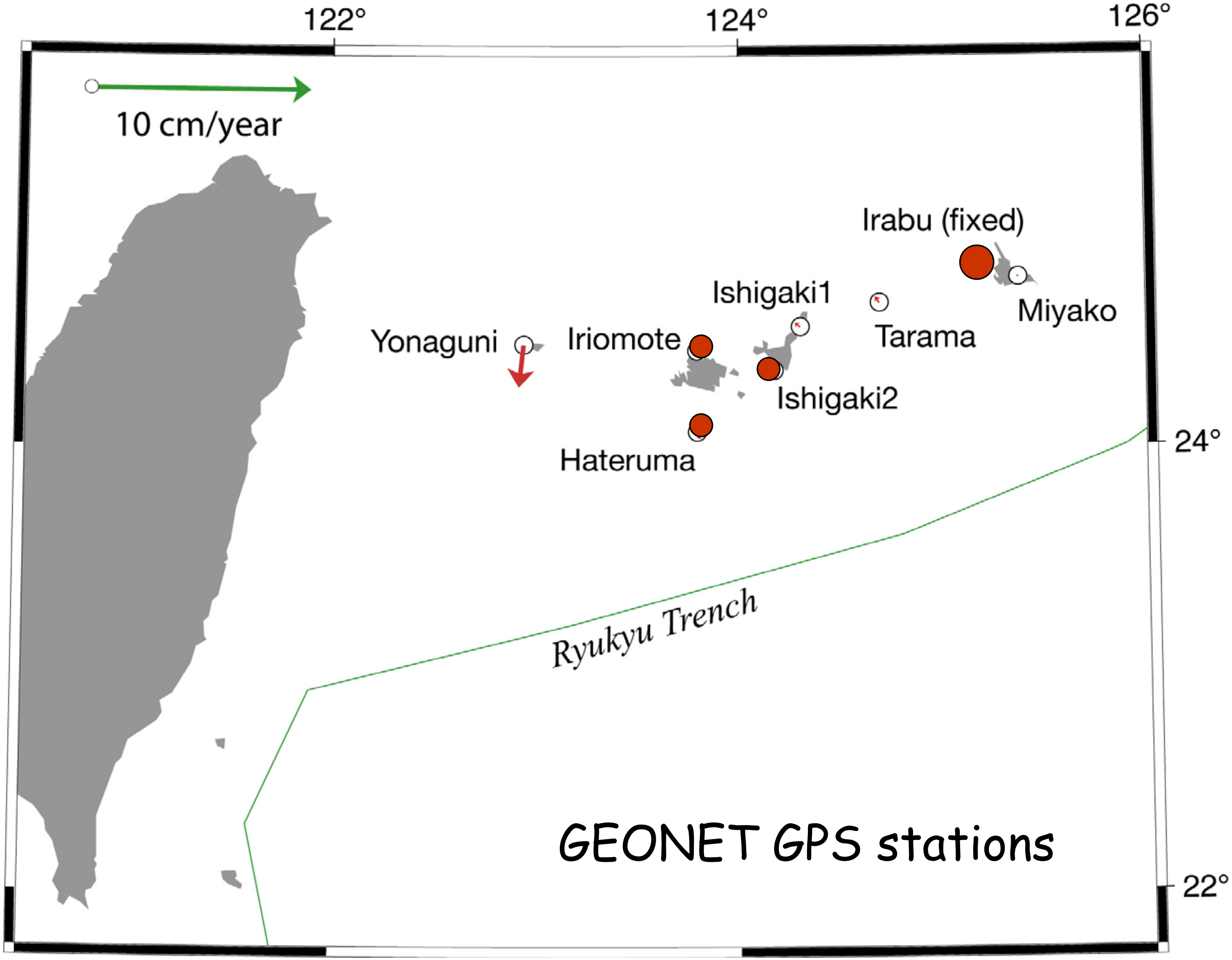
Velocity relative to the Amurian Plate



125 mm/yr (!) N46W

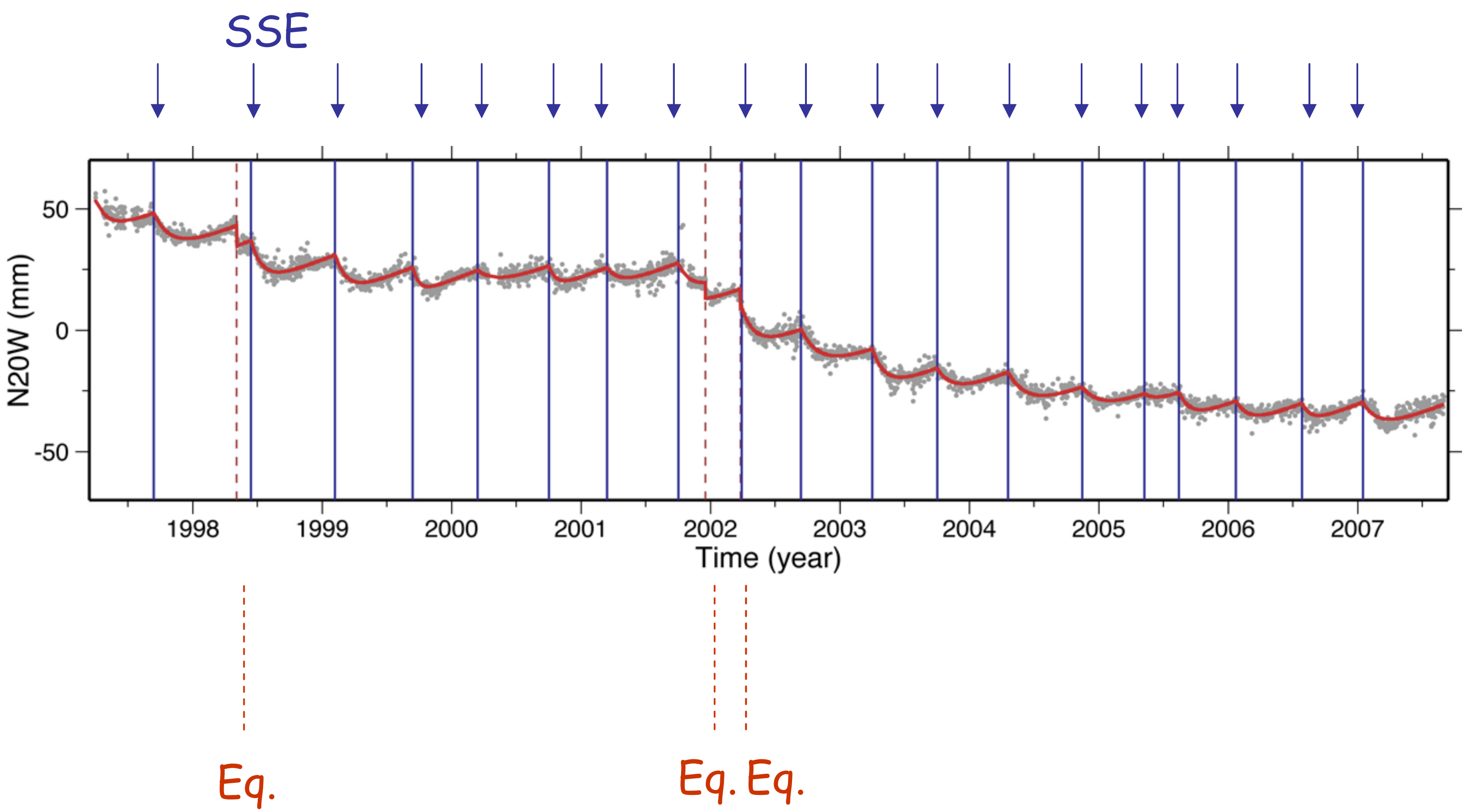


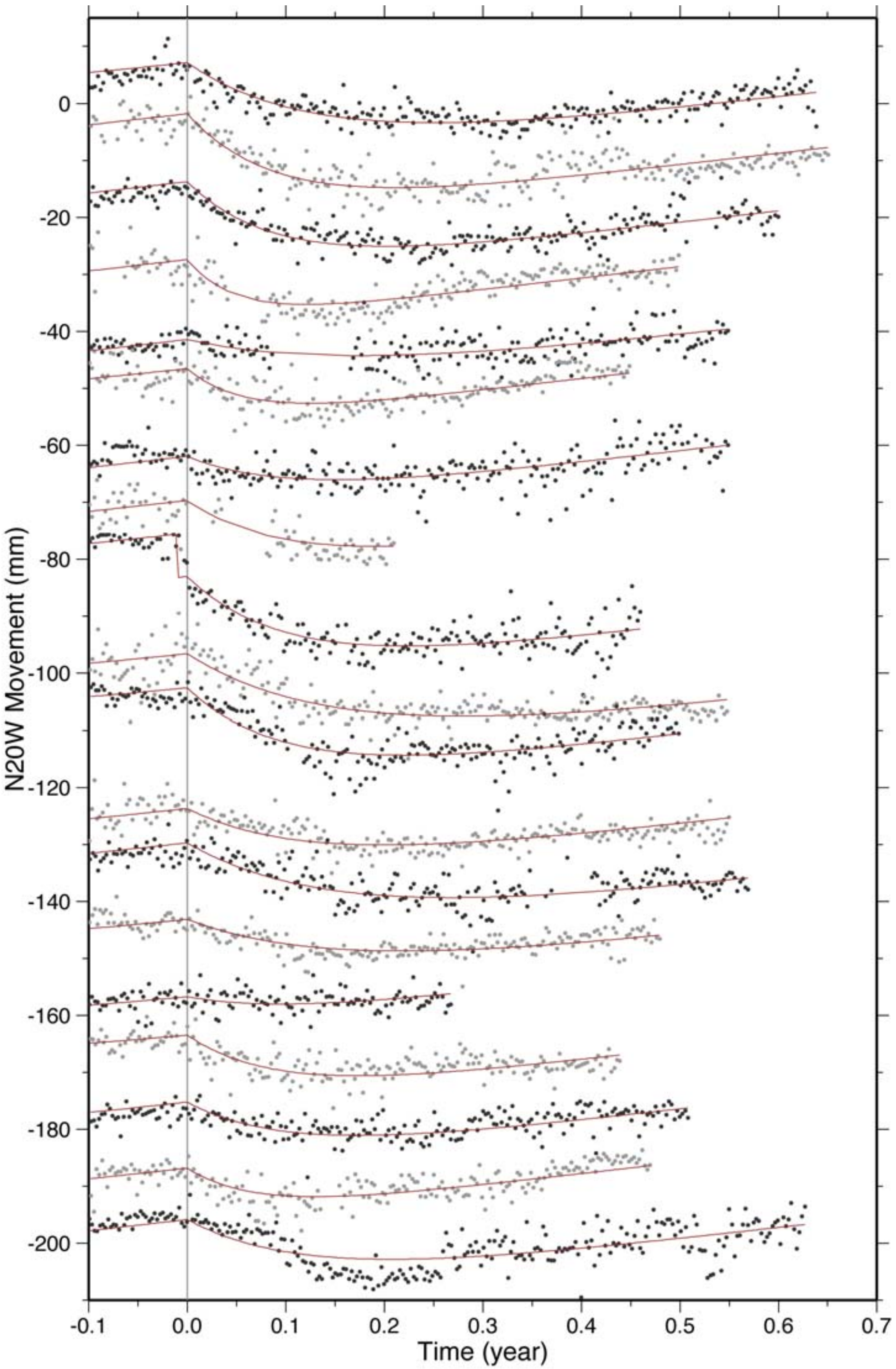
50 mm/year
1997-2007 AM frame
50 mm/year
South Ryukyu frame
No interseismic deformation
No interplate thrust earthquakes
30°
28°
26°
24°
122°
124°
126°
128°
130°
132°
46°
44°
42°
40°
38°
36°
34°
32°
30°
28°
26°
24°
22°
144°
146°
148°
150°



122°
124°
126°
24°
22°
10 cm/year
Irabu (fixed)
Ishigaki1
Miyako
Tarama
Yonaguni
Iriomote
Ishigaki2
Hateruma
Ryukyu Trench
GEONET GPS stations

Hateruma N20W

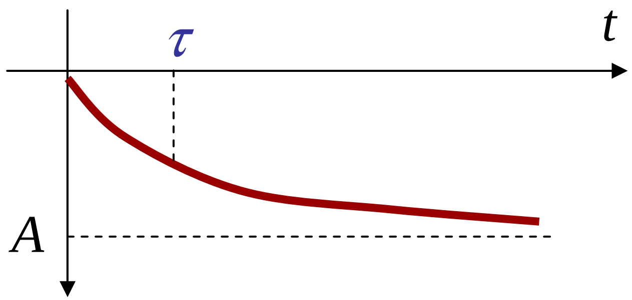




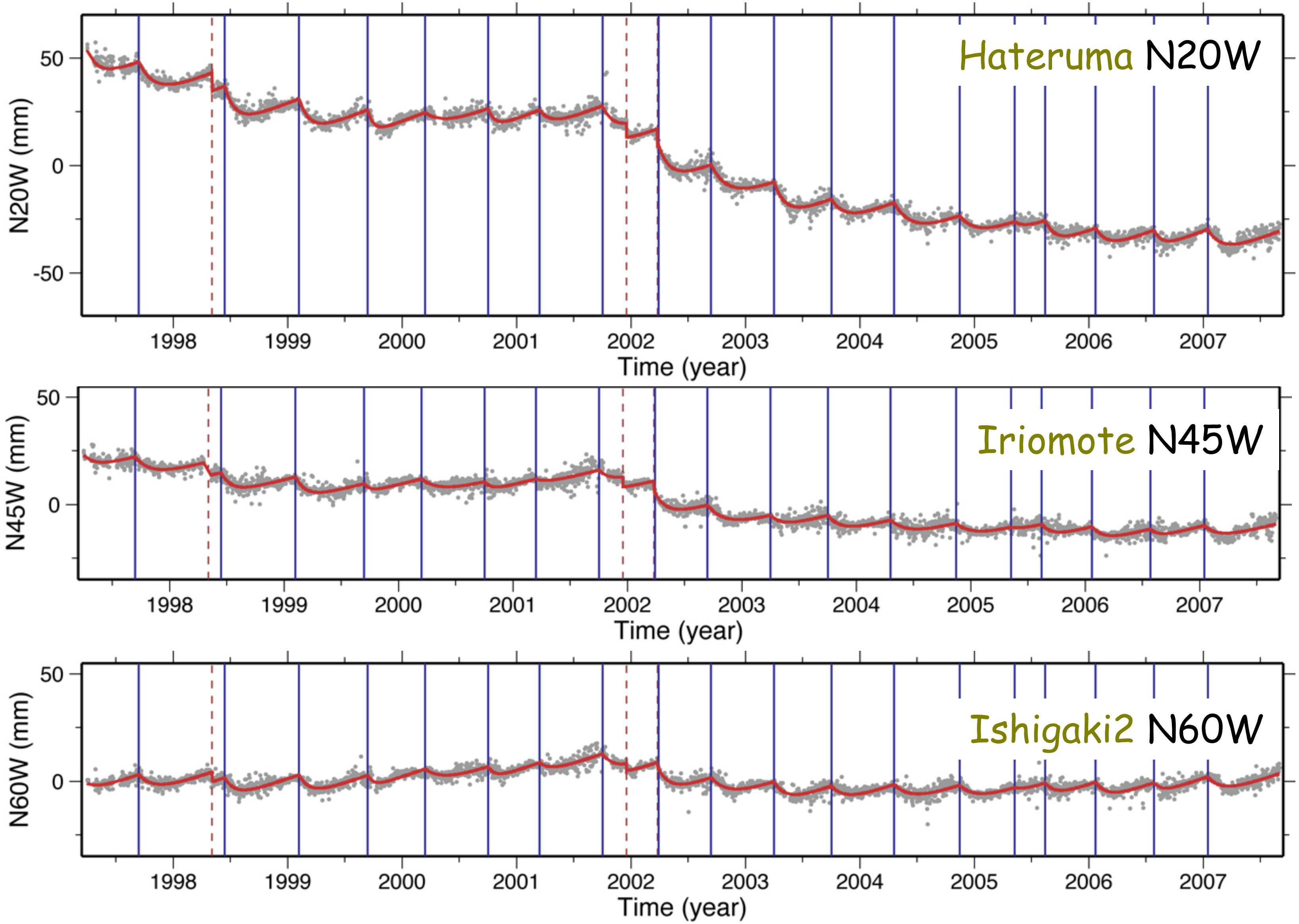
Time constants τ
0.10-0.15 year

SSE Displacement

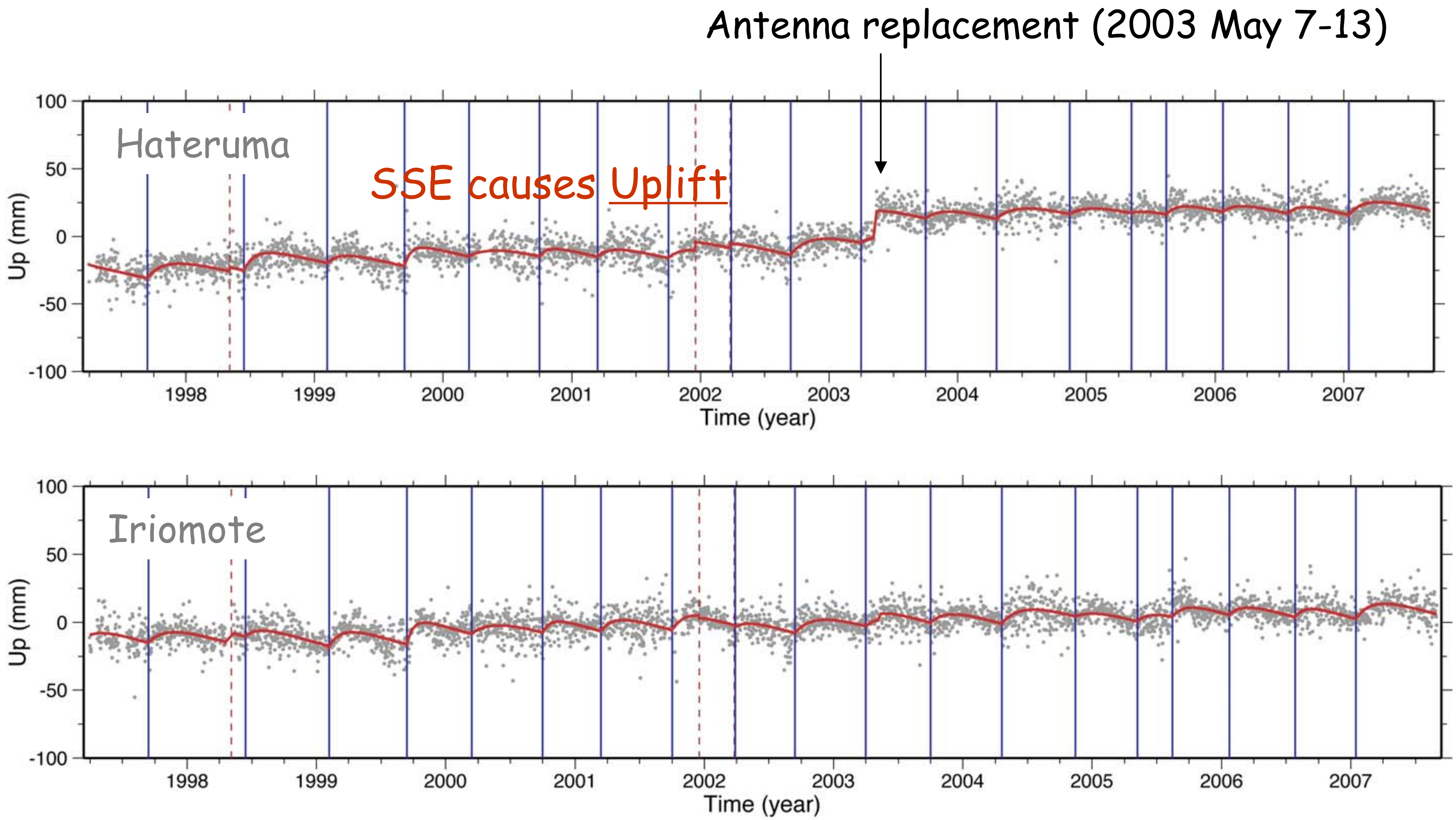
$$= A\,[1 - \exp(-t/\tau)]$$



Comparing the three islands



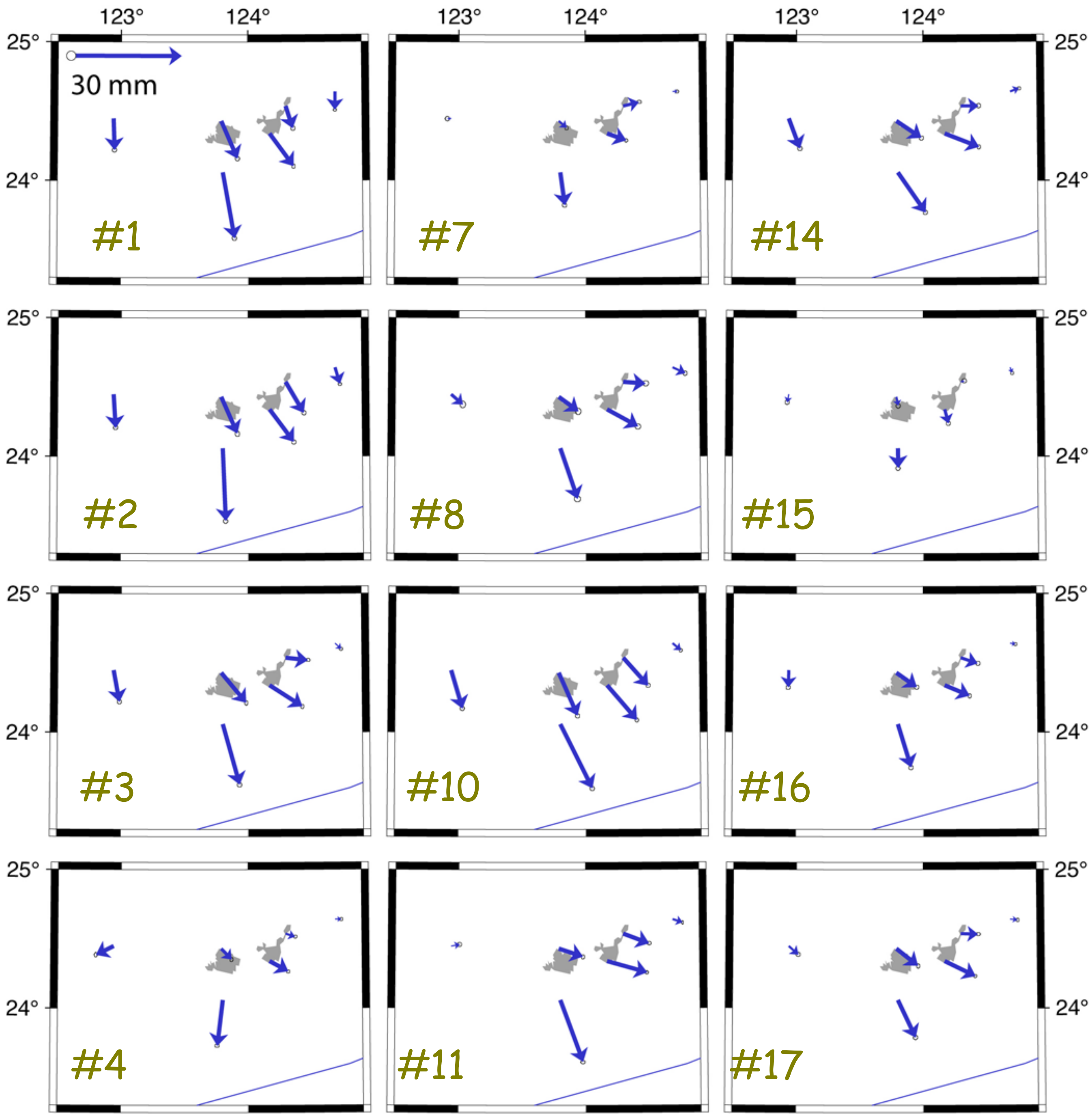
SSE in Up component



~~No interplate earthquakes at the Ryukyu Trench~~

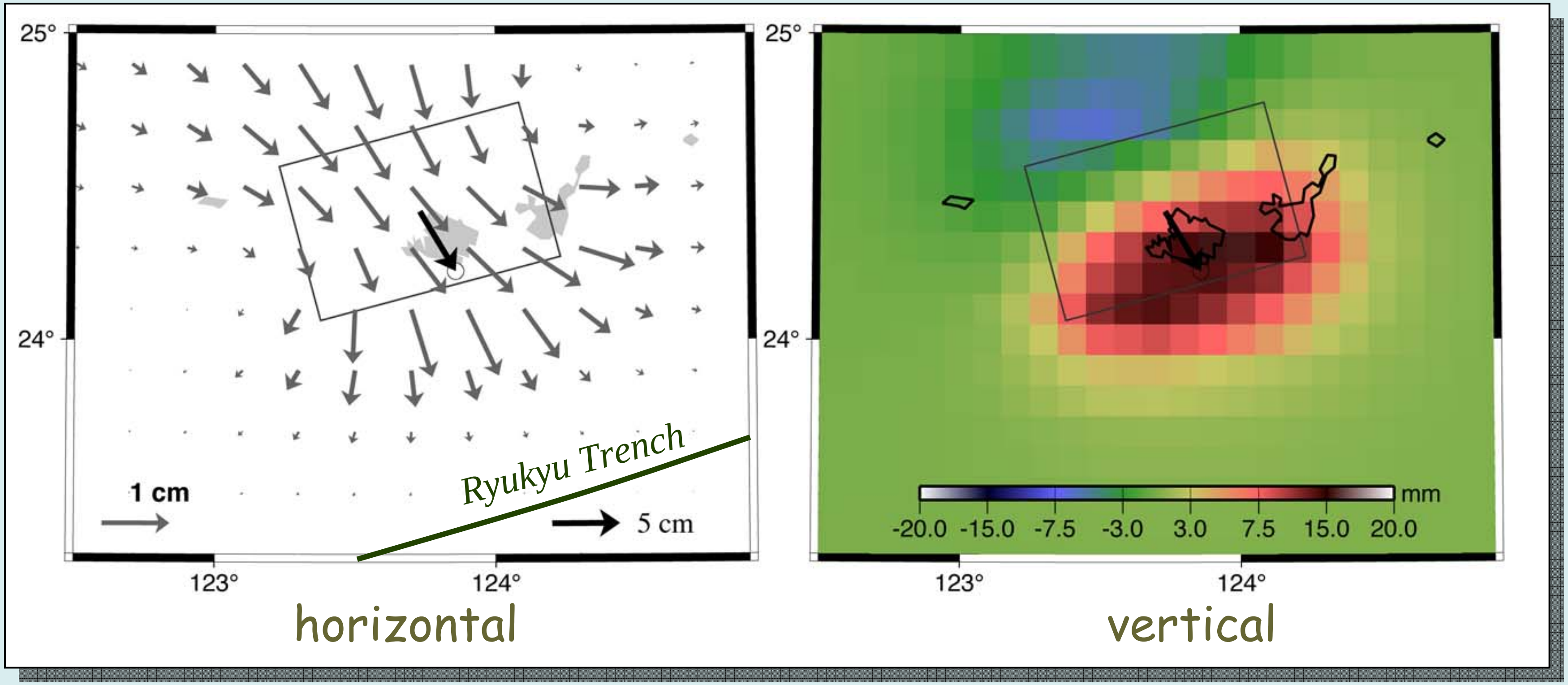
Slow slip events repeating biannually there

(too fast to be recognized in secular velocity fields)



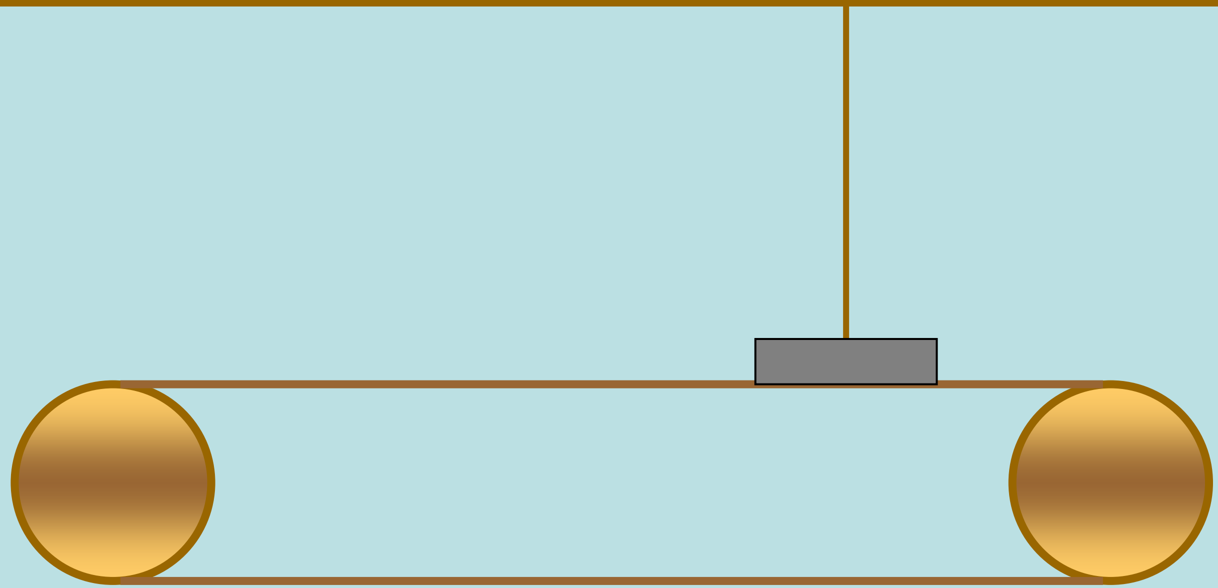
Horizontal movements by SSE

Estimating fault parameters for the 17th SSE

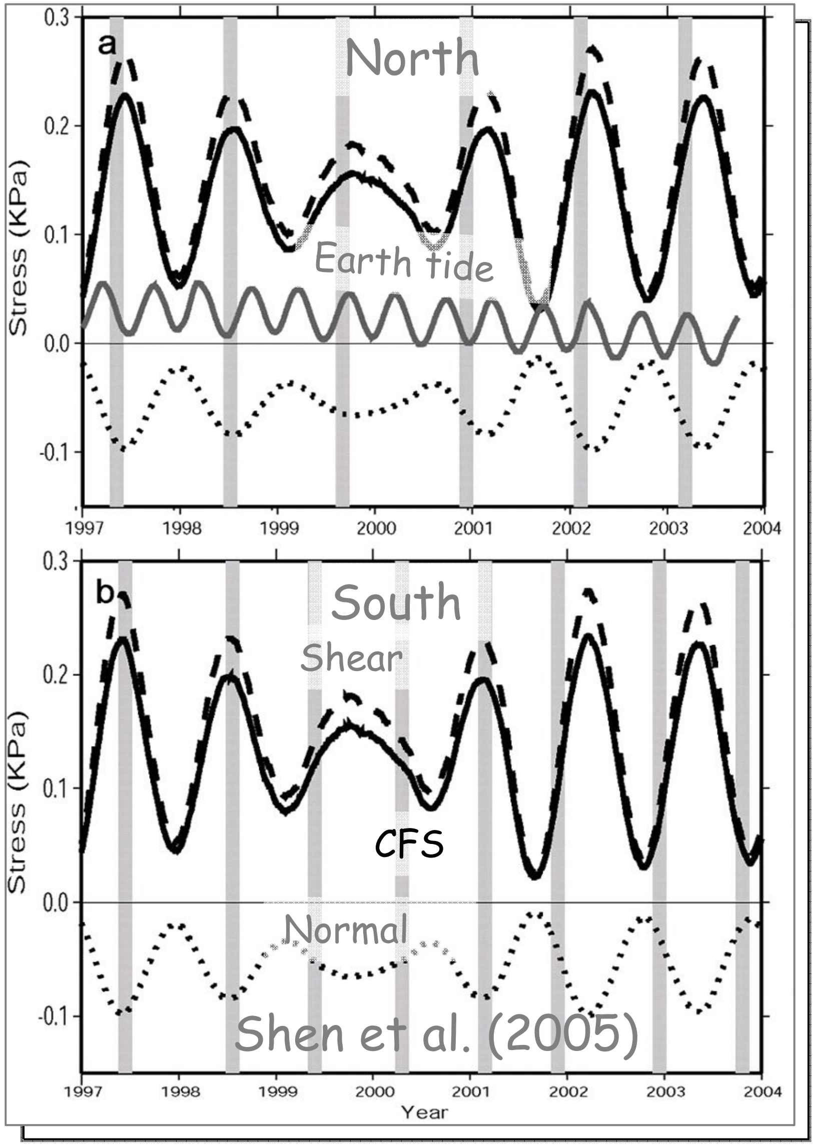


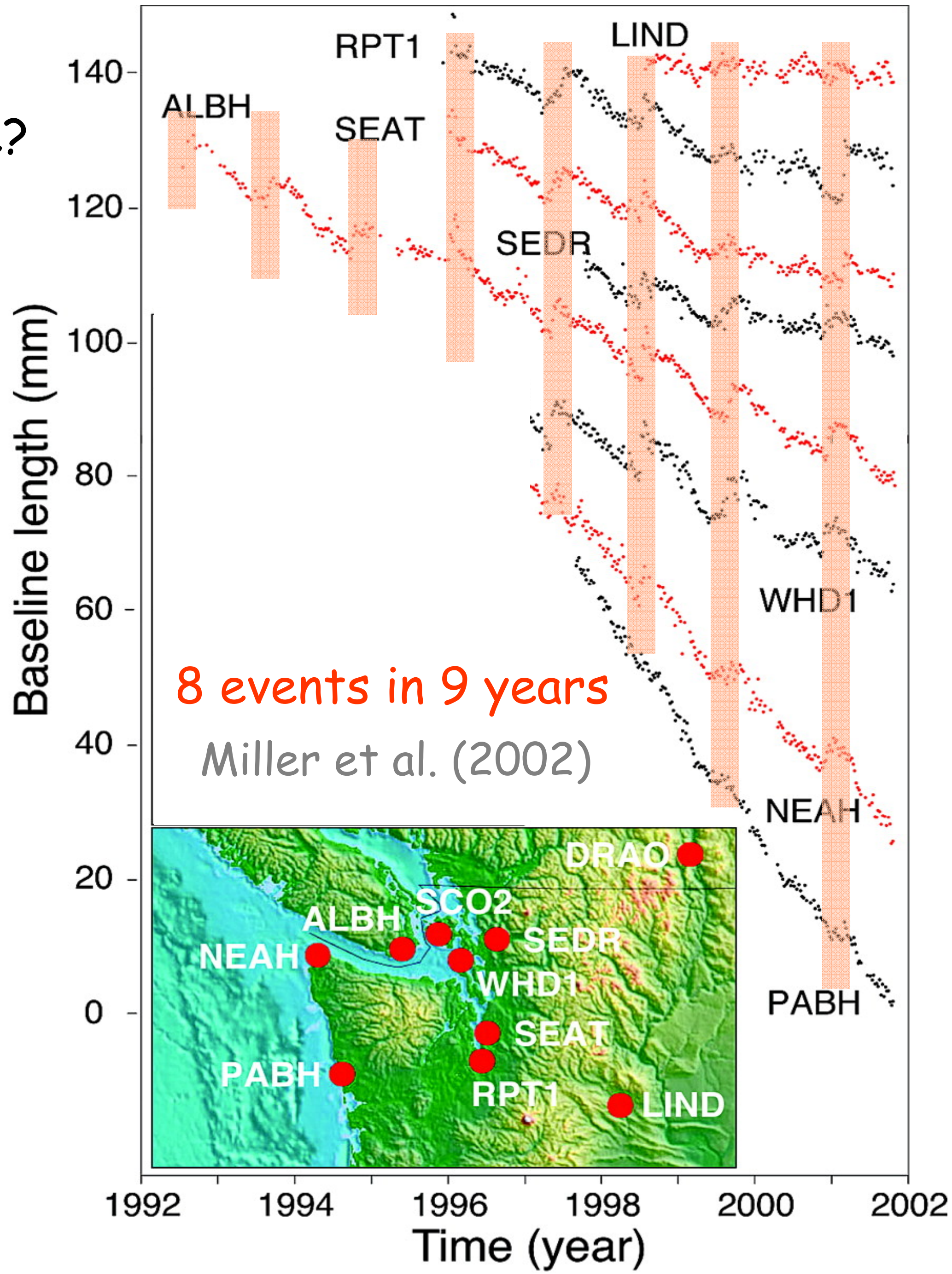
1. Slip ~ 5-6 cm consistent with convergence rate
2. ~ SE-ward close to the convergence direction
3. Depth ~ 20-40 km "transient" depth
4. Average seismic moment 1.26×10^{19} Nm (Mw ~6.7)

Stick-slip and Earthquake Recurrence



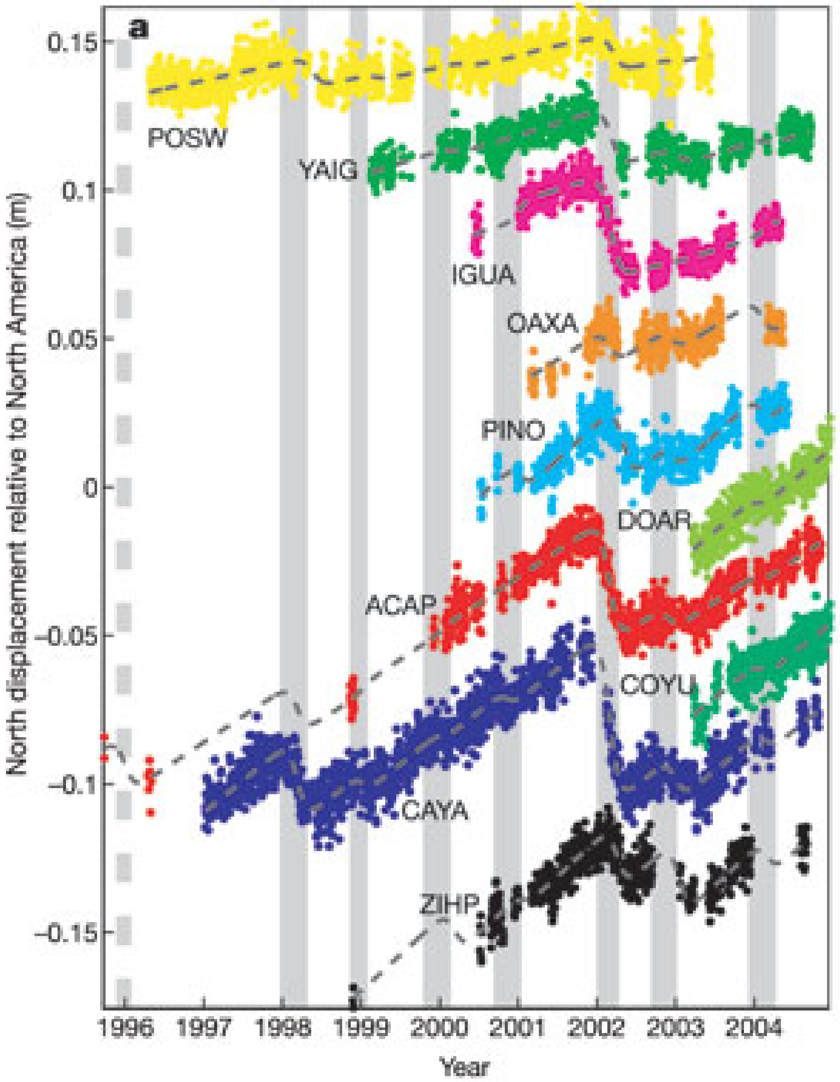
Stress perturbation by pole tide?





SSE in Guerrero, Mexico (Lowry, 2006)

7 events annually repeating in winter



Other "periodic" SSEs

Alaska ~ 1 yr interval /winter (??)
[Ohta et al., 2007]

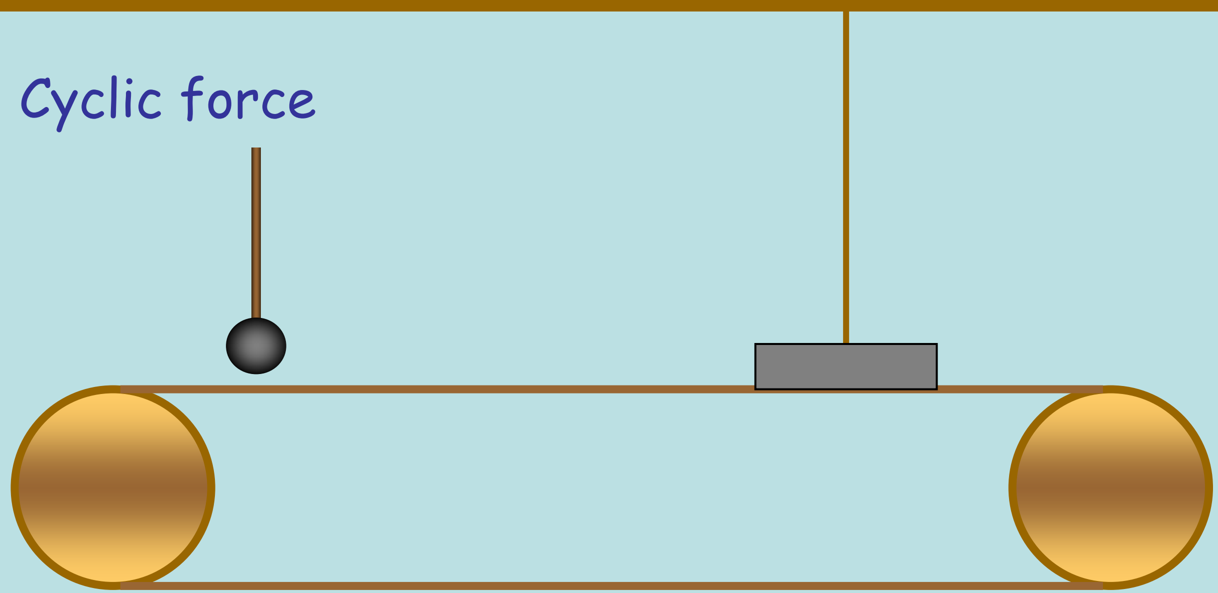
Shikoku ~ 0.5 yr interval
[Hirose & Obara, 2005]

Central Japan ~ 0.5 yr interval
[Fukuda & Sagiya, 2007]

"Commensurability" with a year

Stress perturbation by climatic load?

Stick-slip and Earthquake Recurrence

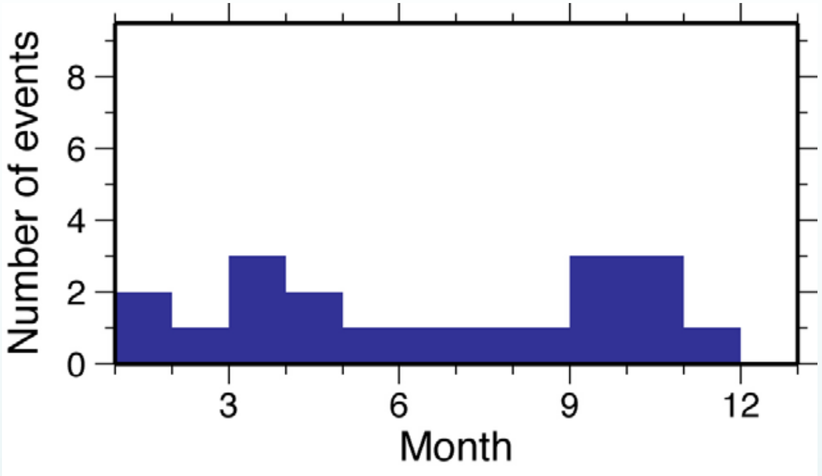


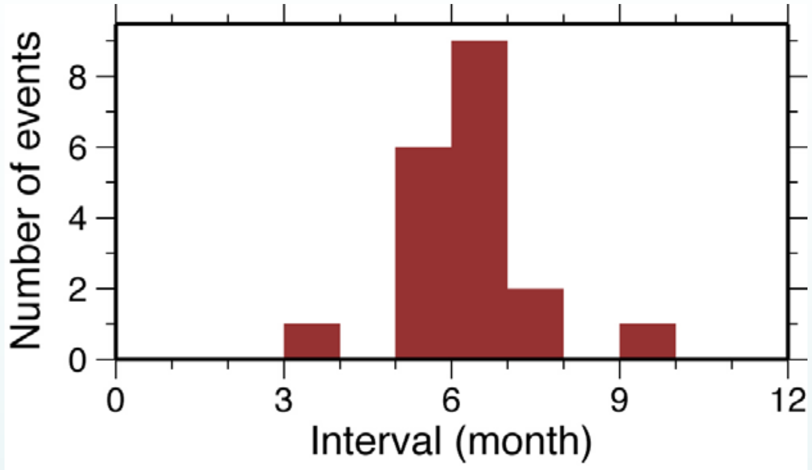
External perturbation governs the rhythm?

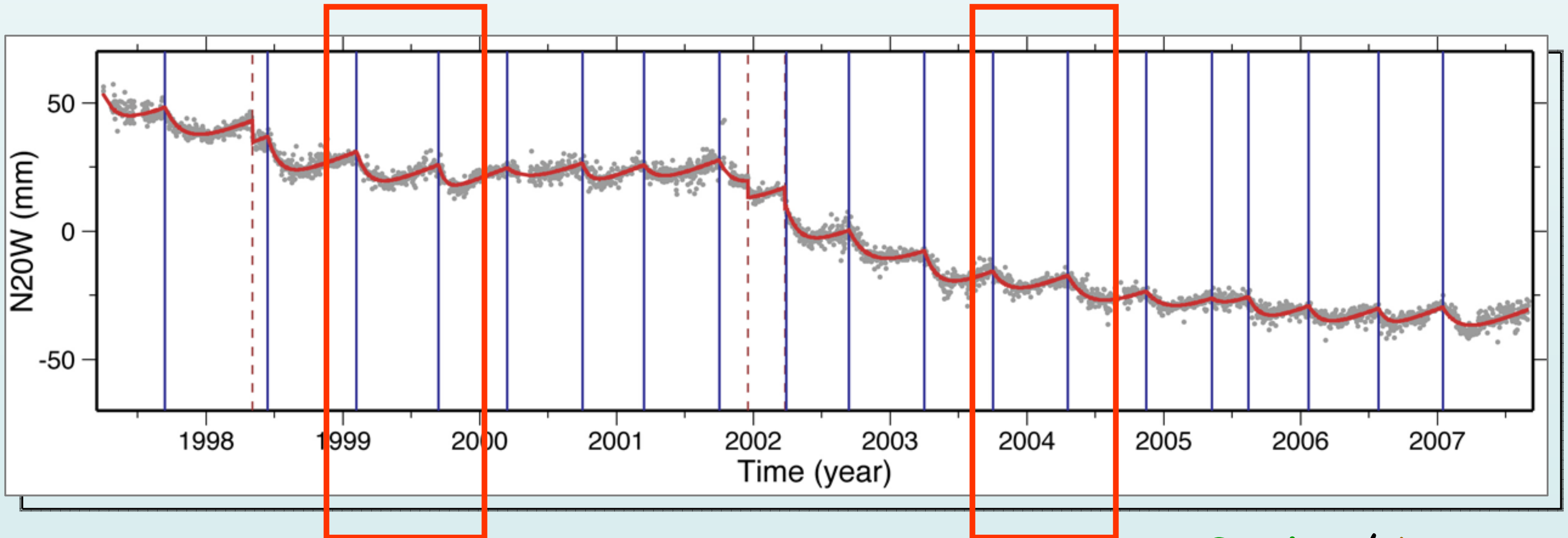
Controlled by external seasonal rhythm?

Let us compare 2 histograms.

Periodicity: internal rhythm?
No external forcing



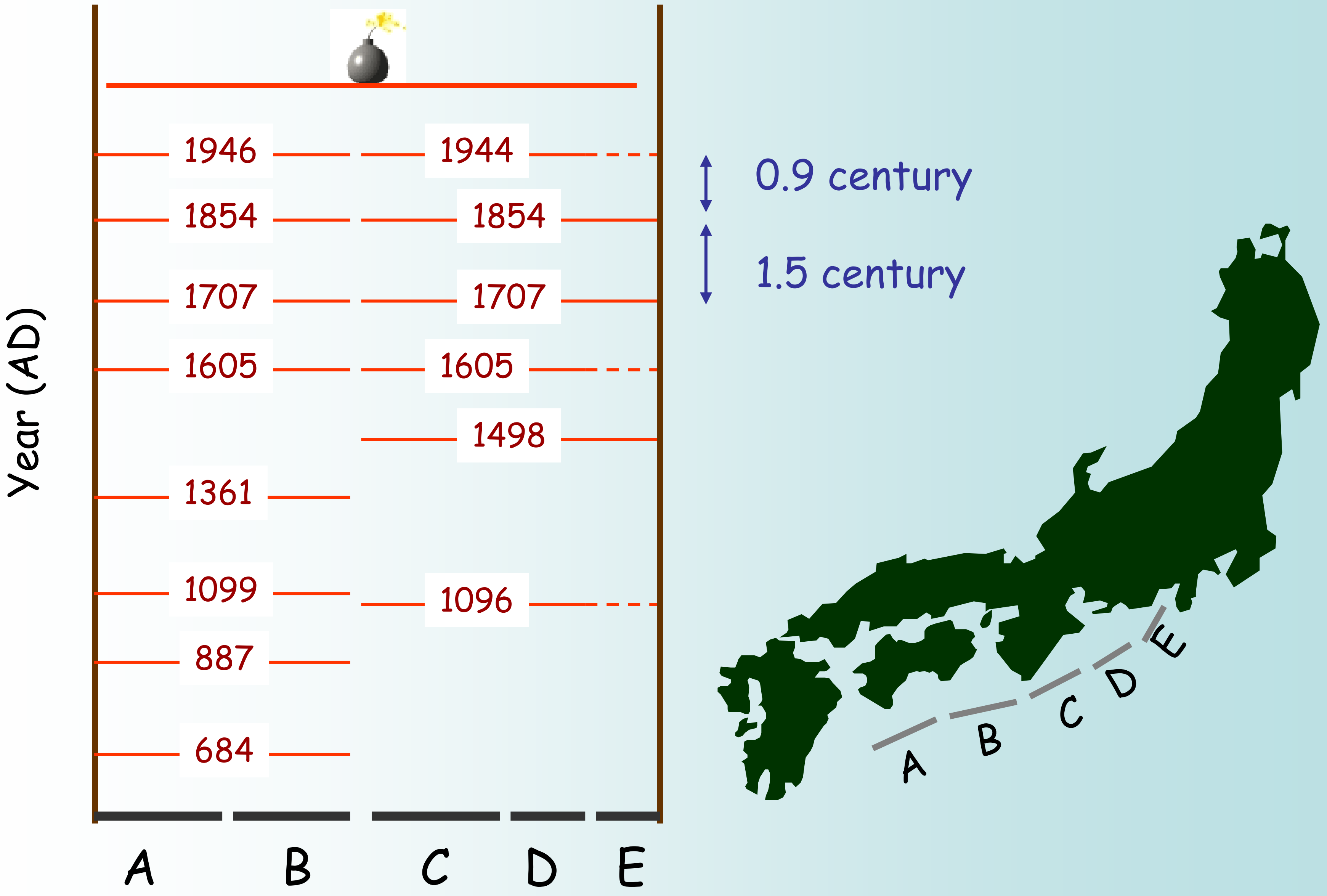




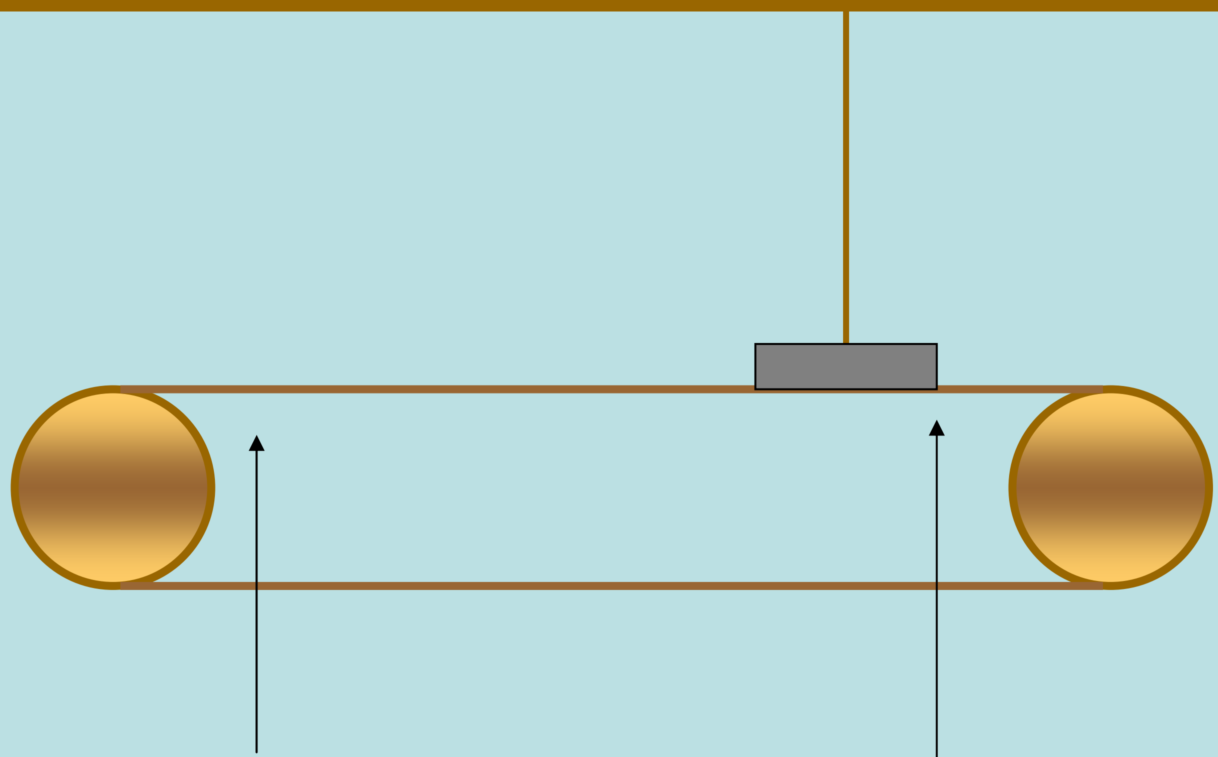
Winter/Summer

Spring/Autumn

Recurrence of interplate thrust events in the Nankai Trough

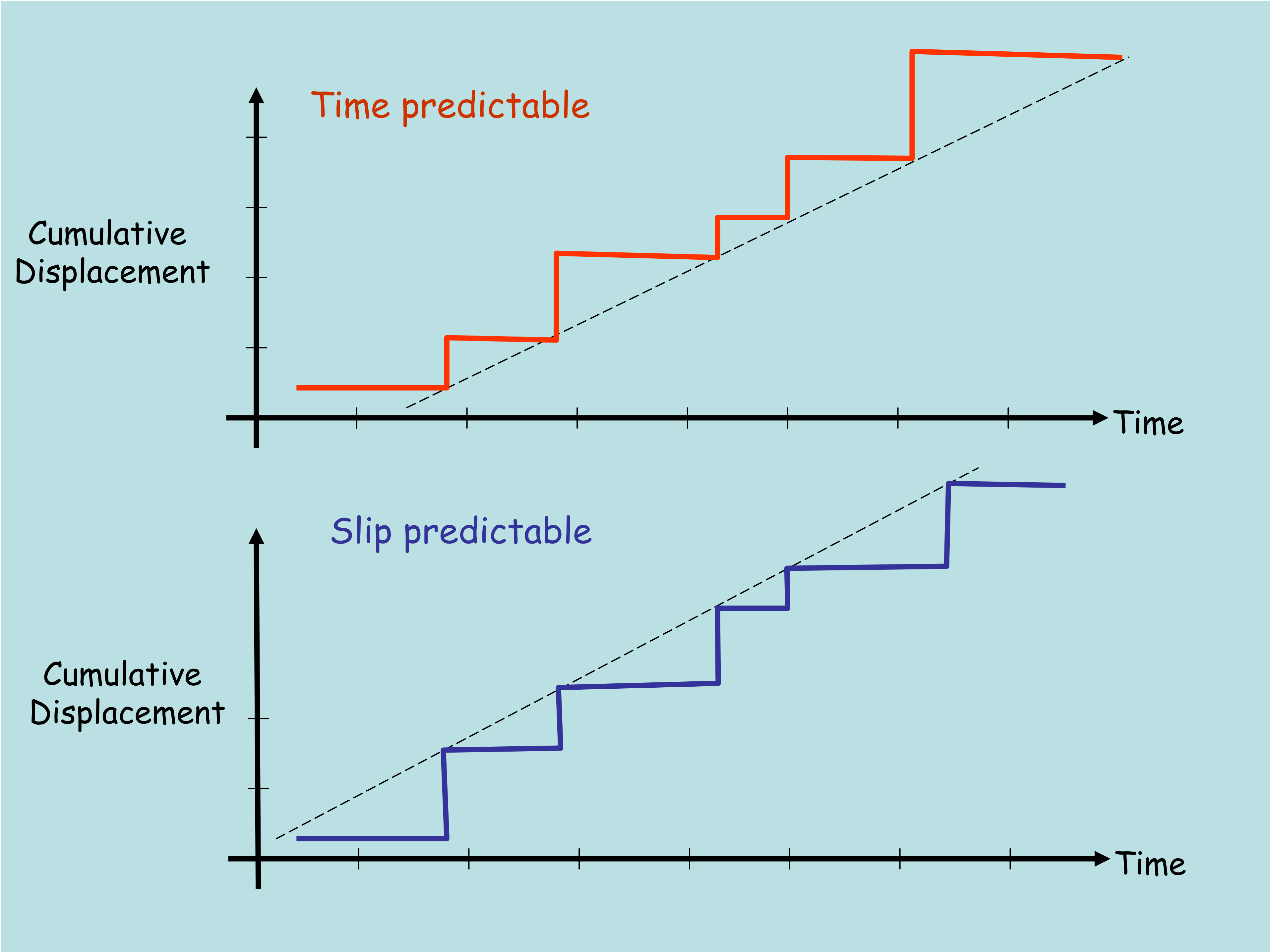


Stick-slip and Earthquake Recurrence



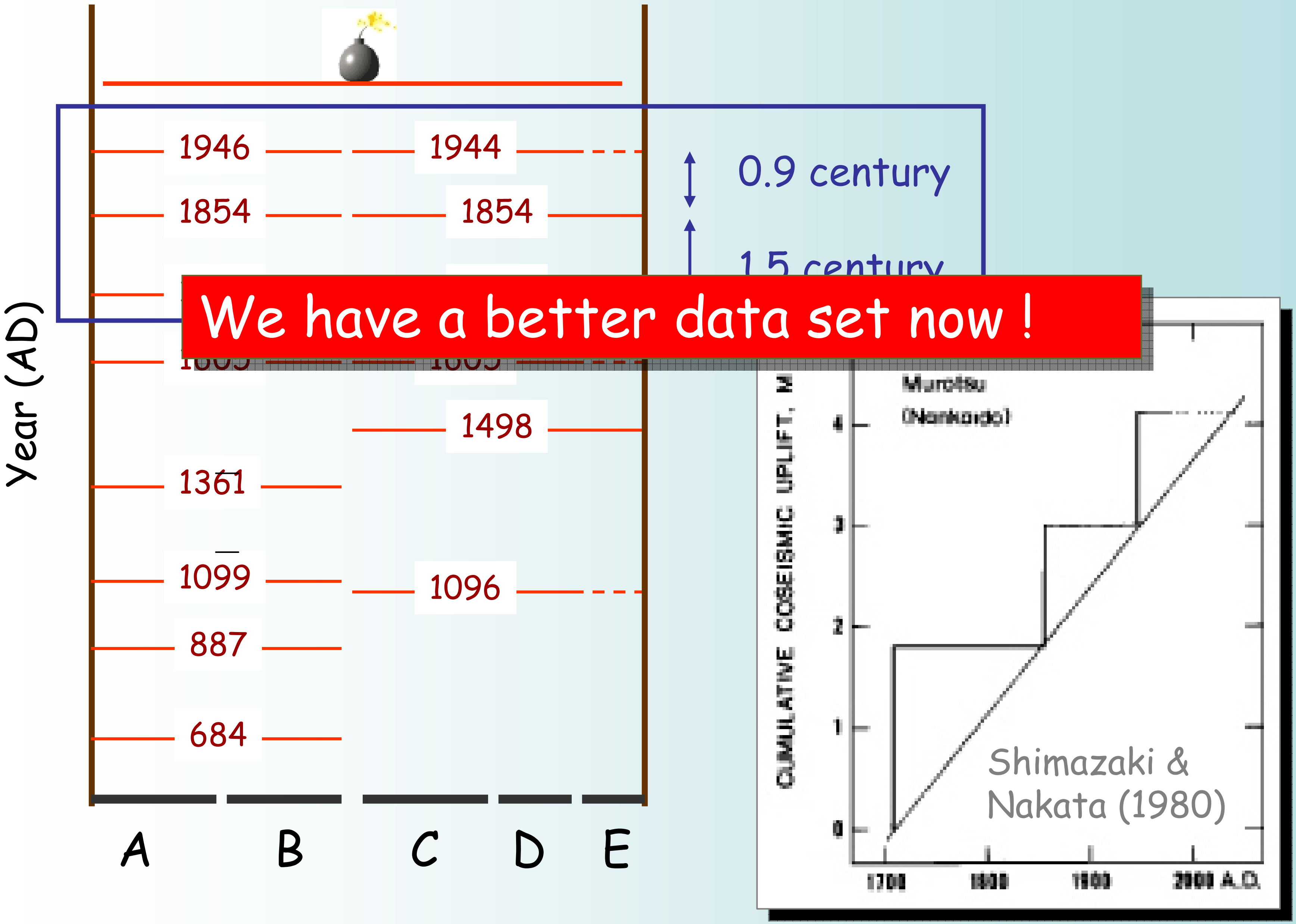
If this position is fixed, the recurrence is "time predictable"

If this position is fixed, the recurrence is "slip predictable"

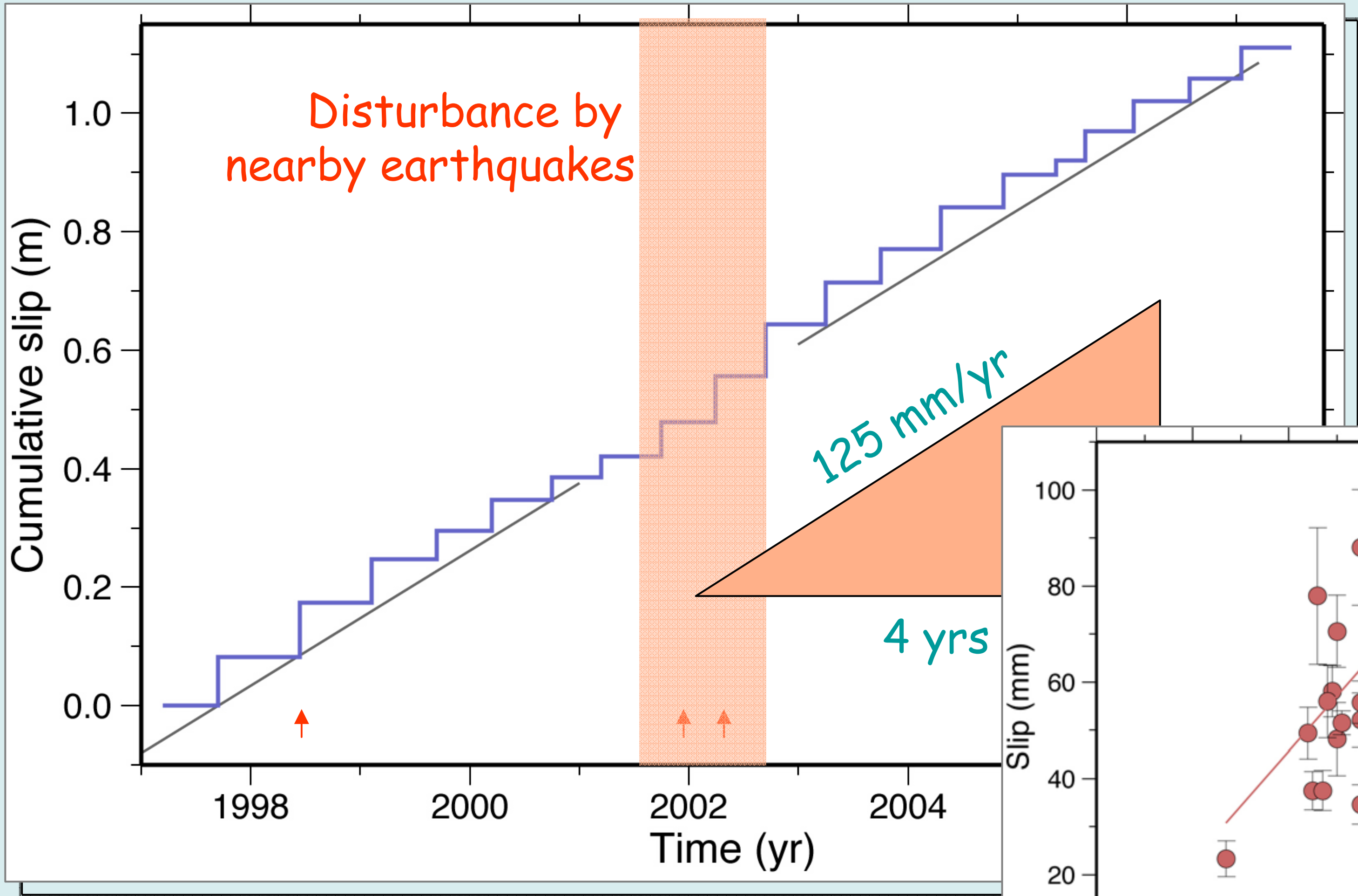


Time predictable
Cumulative Displacement
Time
Slip predictable
Cumulative Displacement
Time

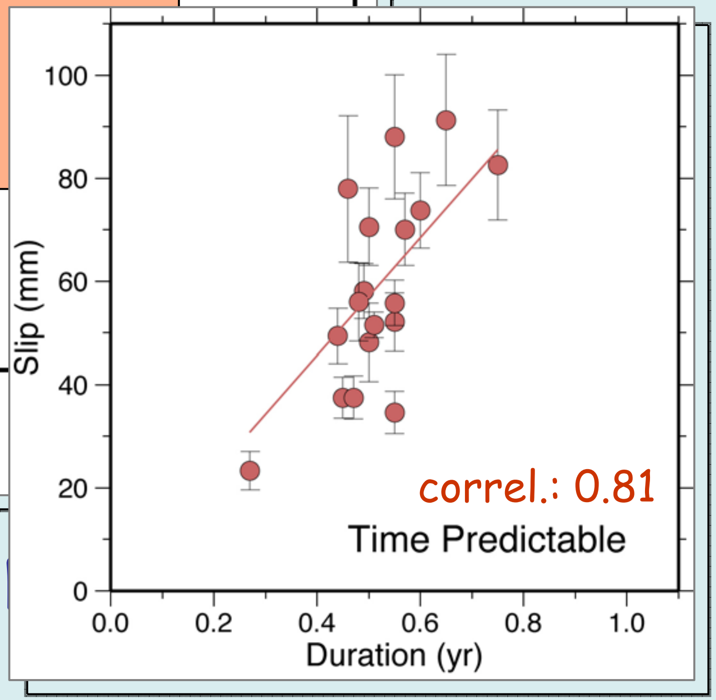
Nankaido Eqs. looks time predictable



Cumulative slip and plate convergence



100 % Cou



The larger the event, the later the next event

Topic #1 summary: TIME

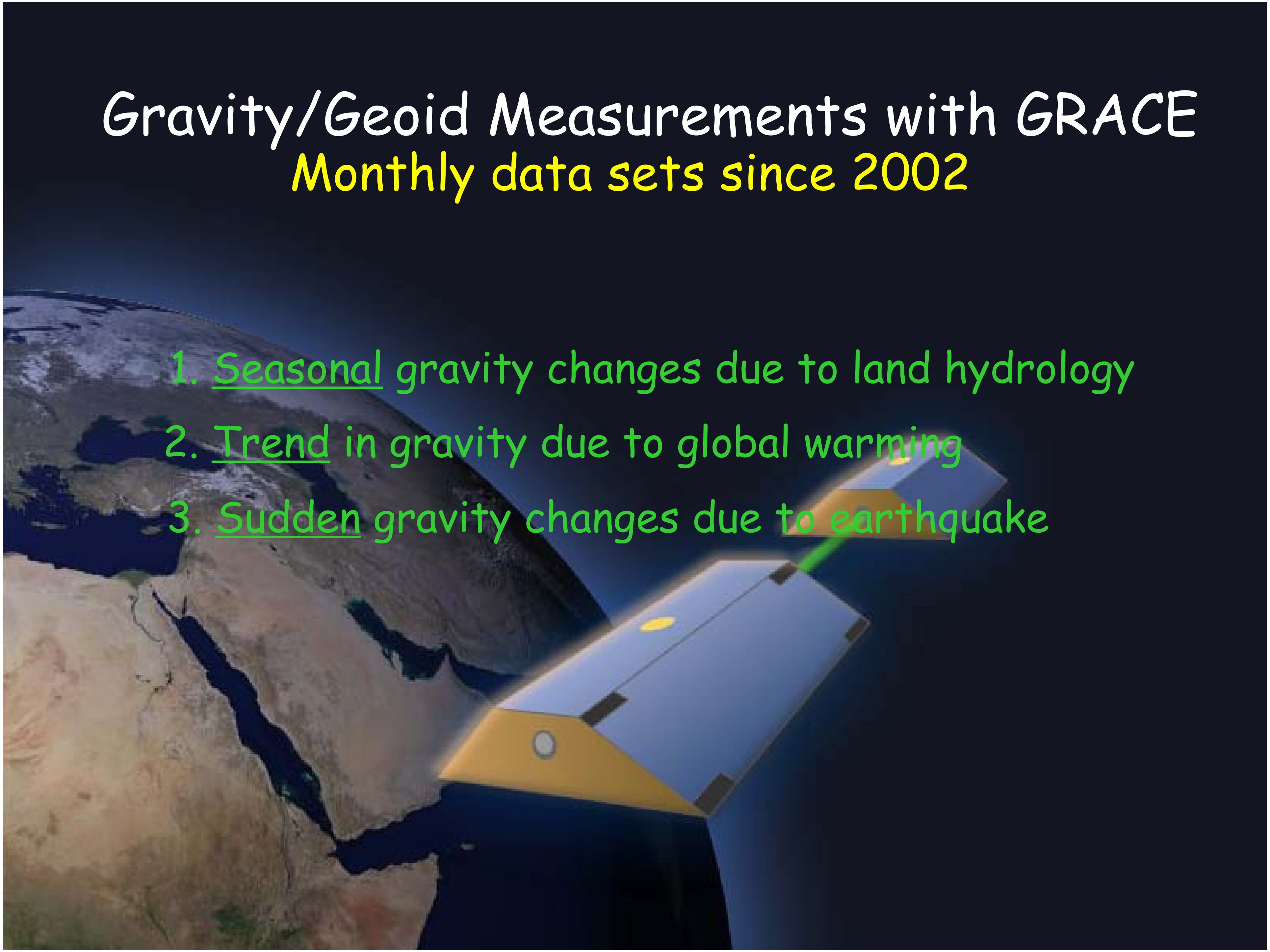
1. Recurrence of this series is time-predictable
2. - not seasonal
3. General feature?

Topic #2.
Co- & Postseismic gravity changes from GRACE

(Ogawa, R. & K. Heki, GRL, 2007 March)

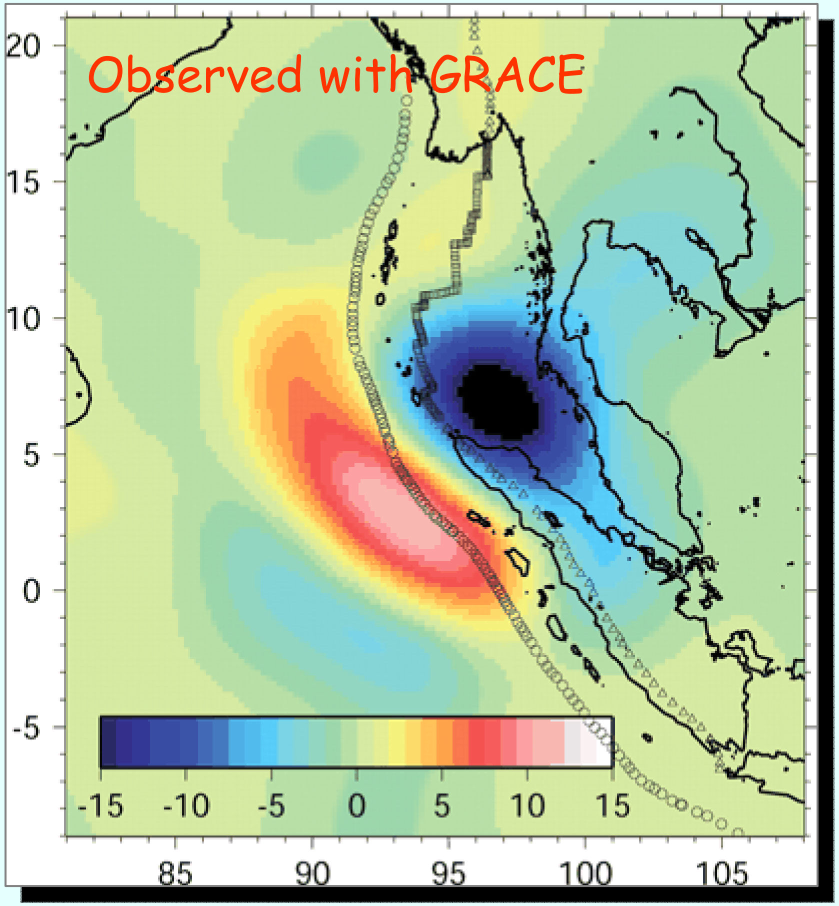
Improvements:

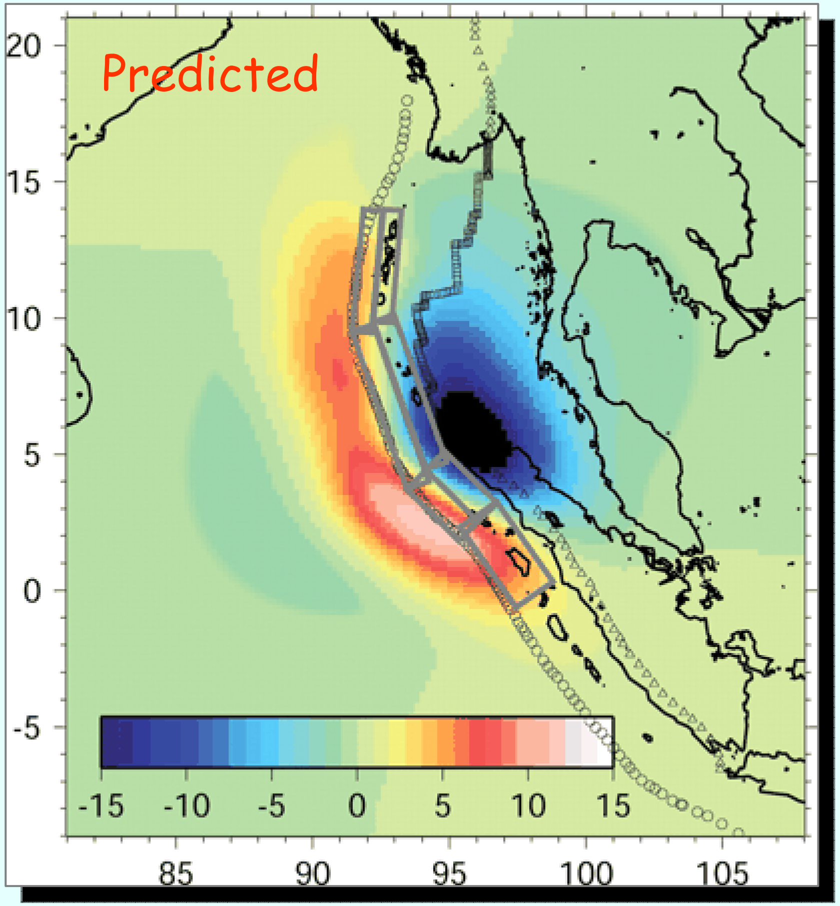
1. GRACE data from Release 01 to 04 (UT/CSR)
2. Fault model from Banerjee et al. (2005) to Banerjee et al. (2007)


Gravity/Geoid Measurements with GRACE
Monthly data sets since 2002
1. Seasonal gravity changes due to land hydrology
2. Trend in gravity due to global warming
3. Sudden gravity changes due to earthquake

Coseismic gravity change of the 2004 Sumatra Eq.

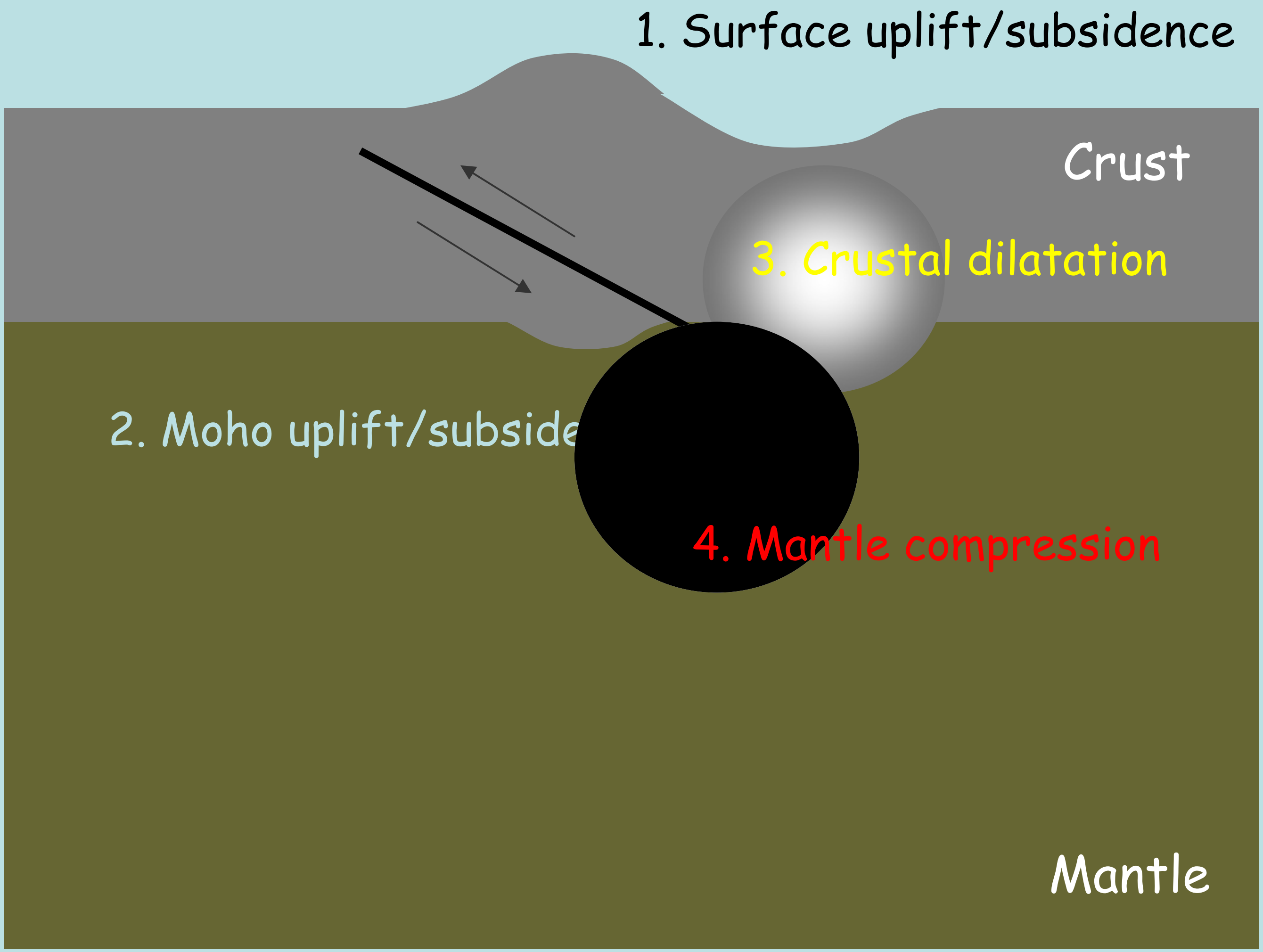
(Han et al., Science, 2006)





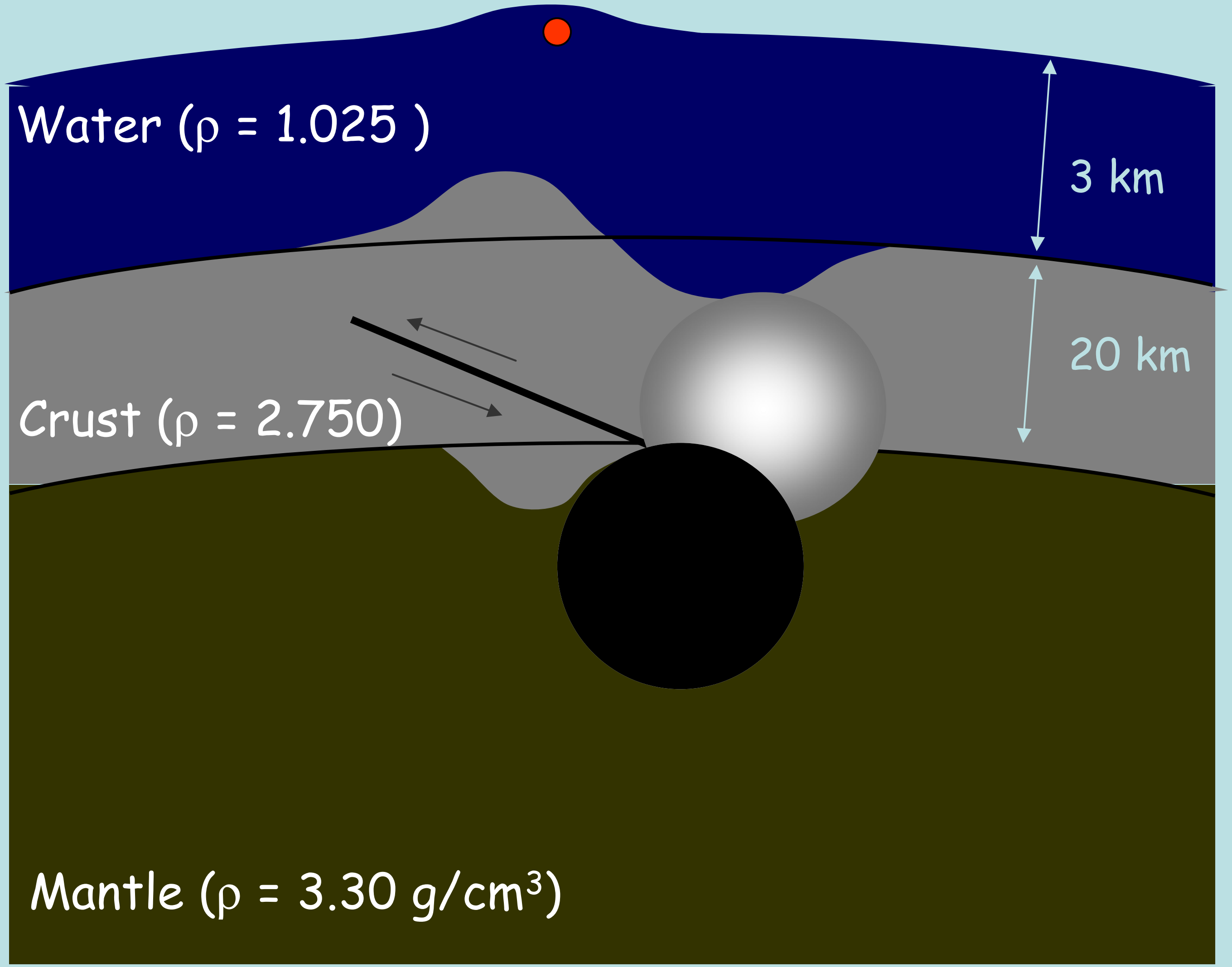
How does an earthquake change the gravity?

Coseismic Mass Perturbation

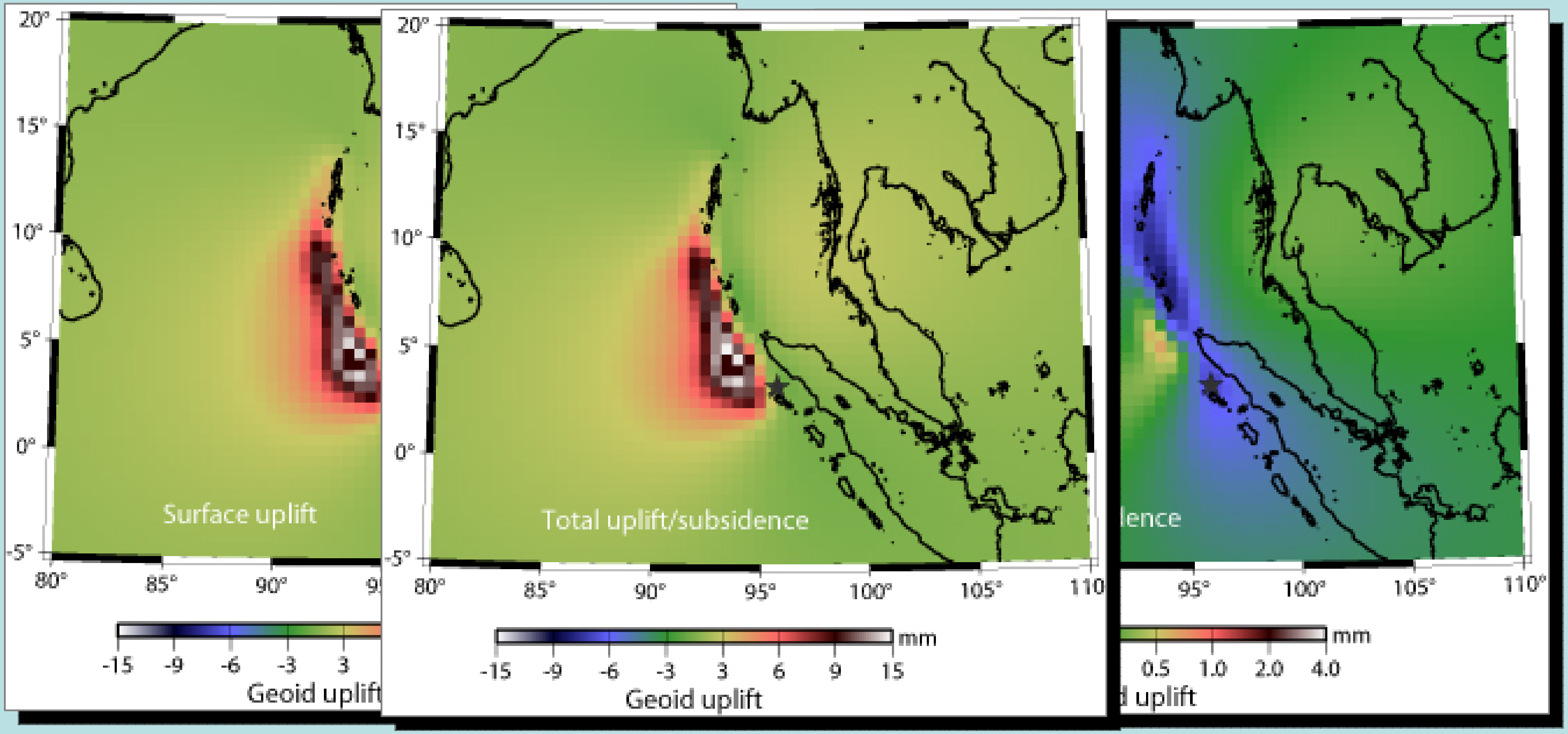


Geoid height changes

$$\Delta U = \sum_i G \Delta m_i / r_i \qquad \Delta h = \Delta U / g$$

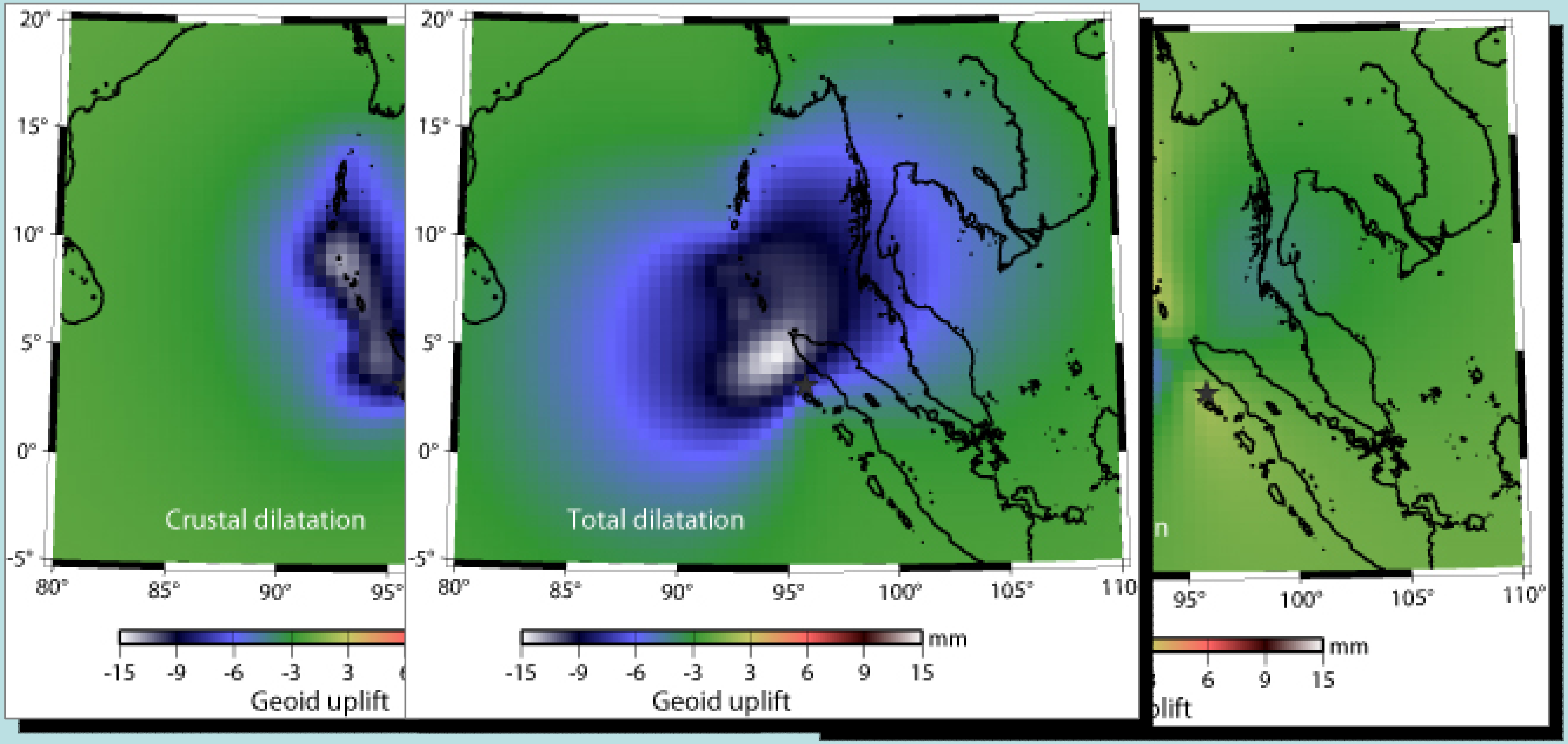


Geoid height change by uplift/subsidence

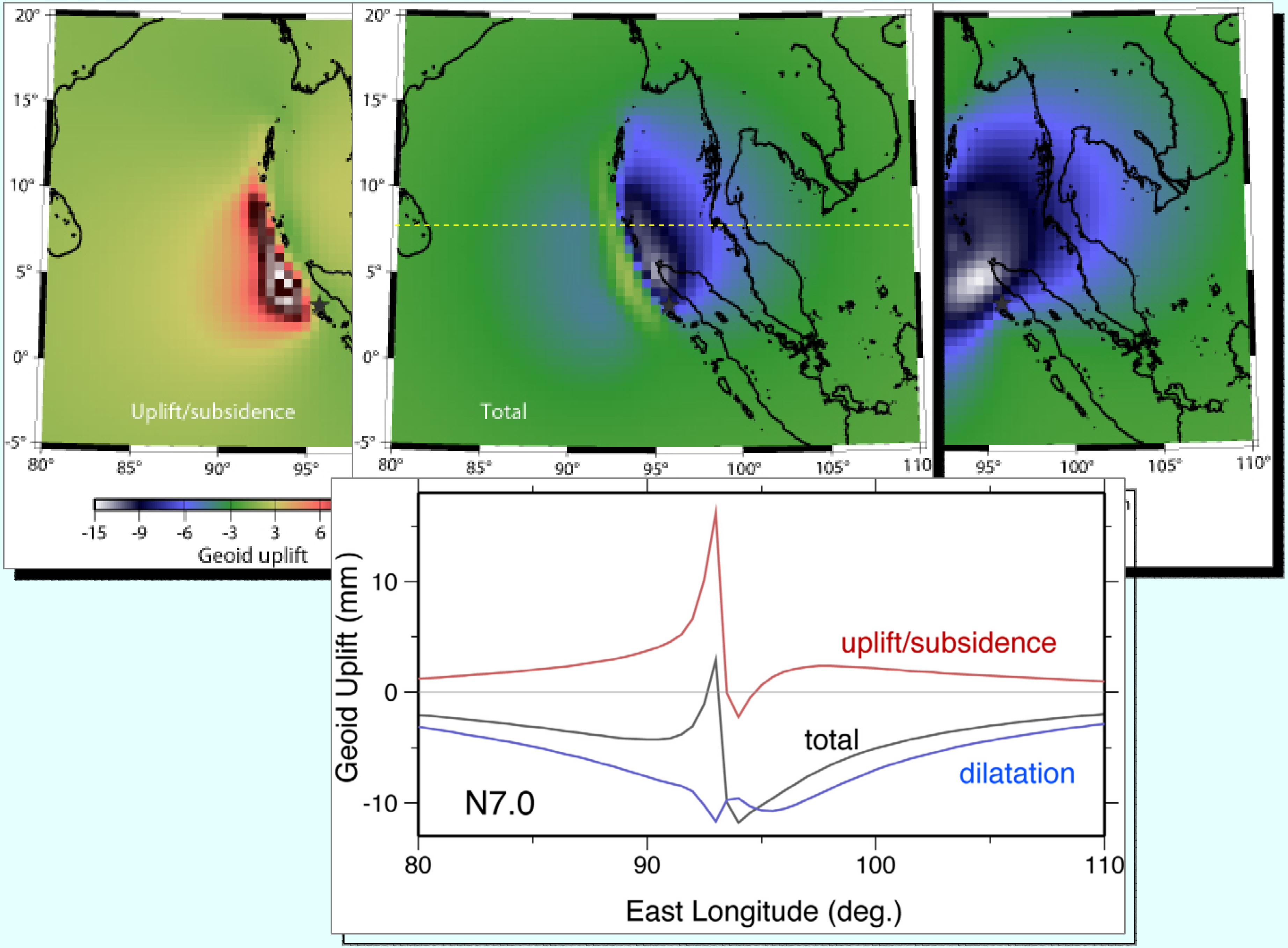


Positive in total and short in wavelength

Geoid height change by dilatation



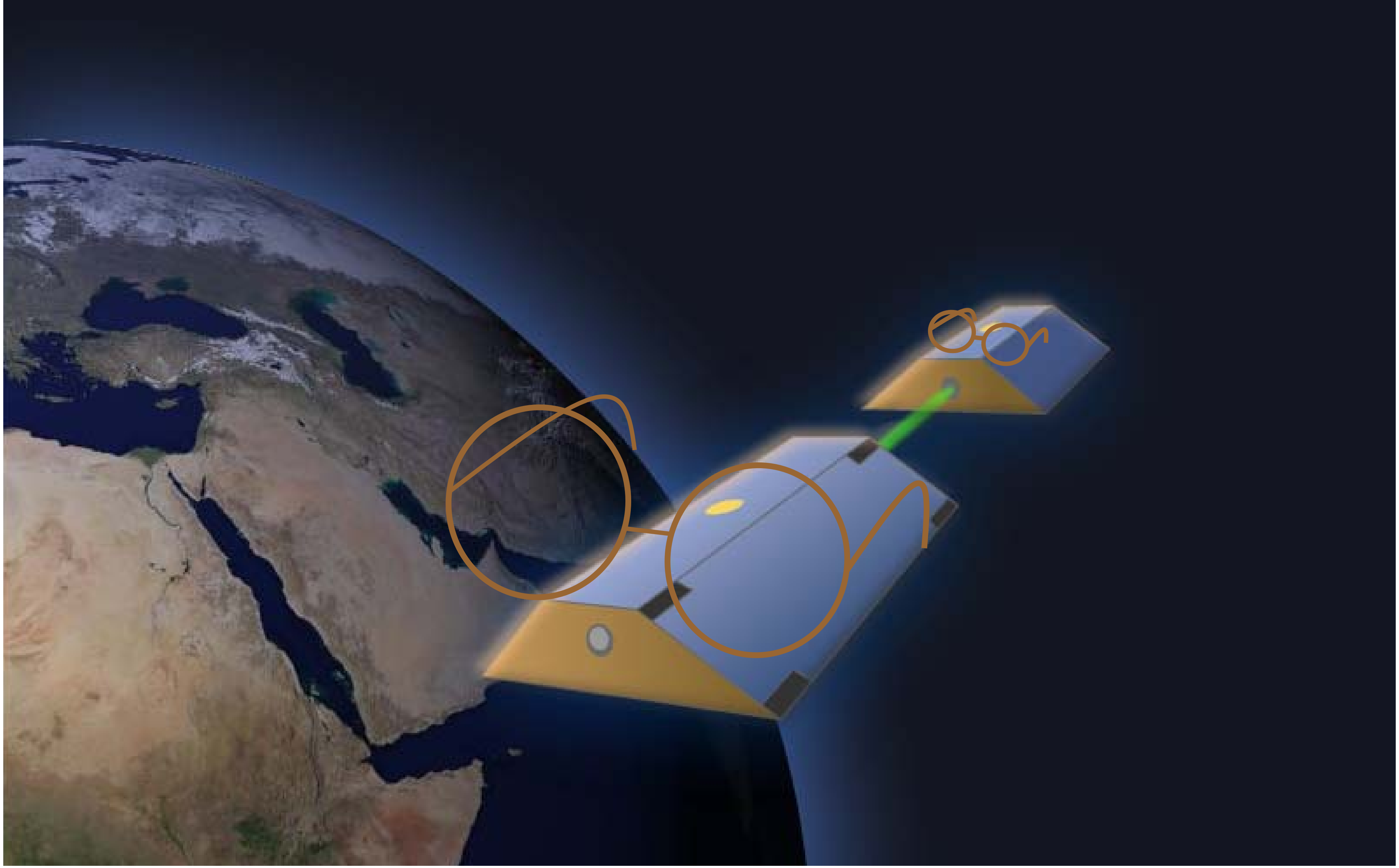
Negative in total and long in wavelength



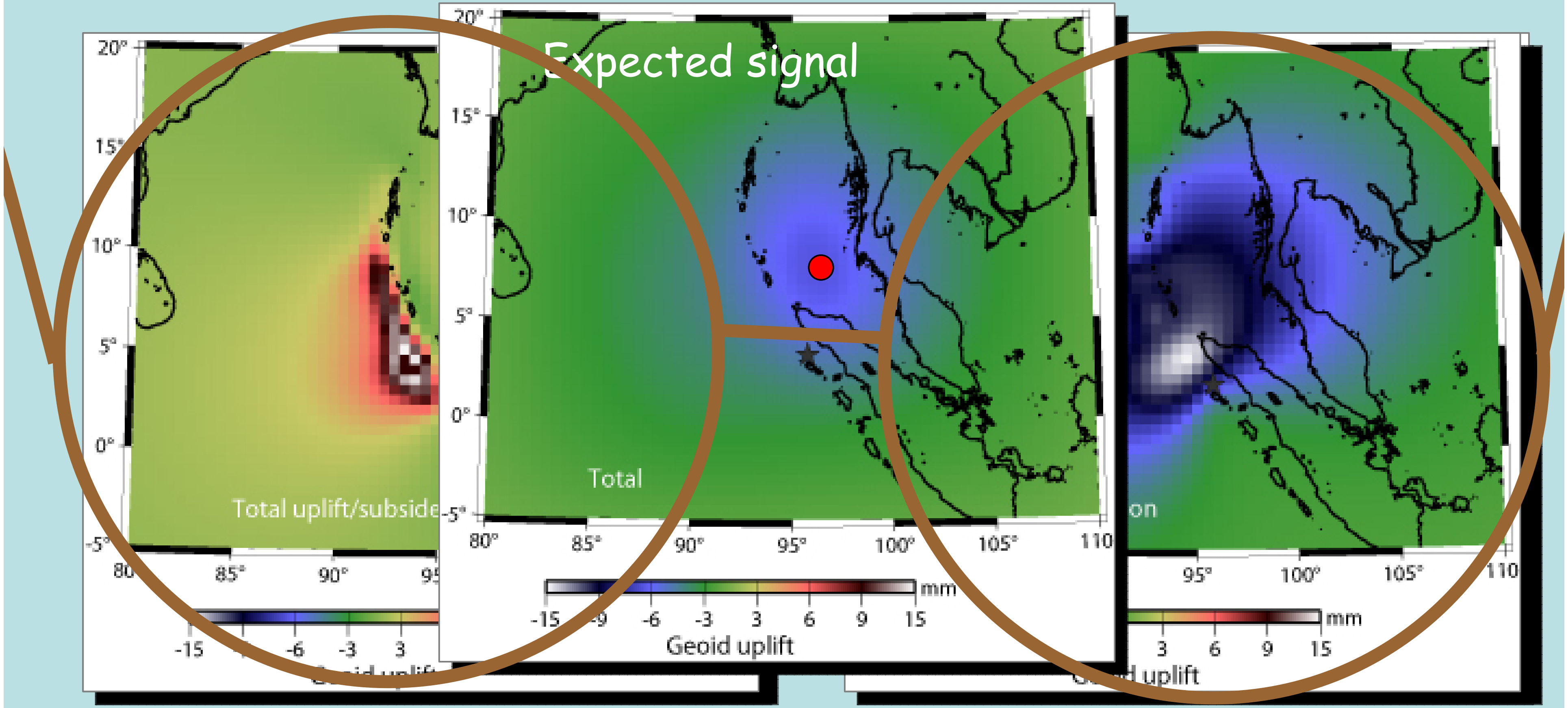
Uplift/subsidence
Total
Geoid uplift
-15 -9 -6 -3 3 6
Geoid Uplift (mm)
East Longitude (deg.)
uplift/subsidence
total
dilatation
N7.0

Subducting (downward) movement of substance makes a dent in Geoid (decrease of gravity).

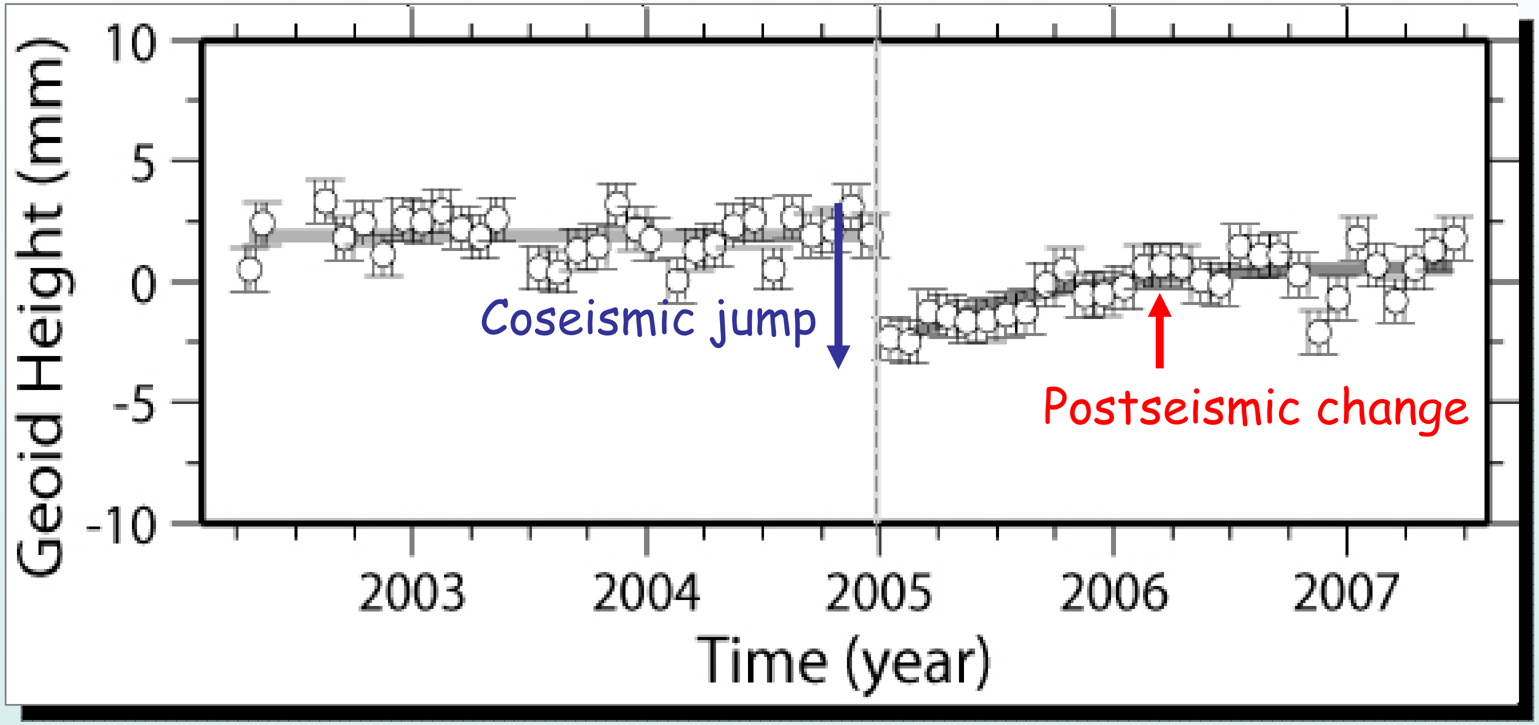
GRACE is shortsighted

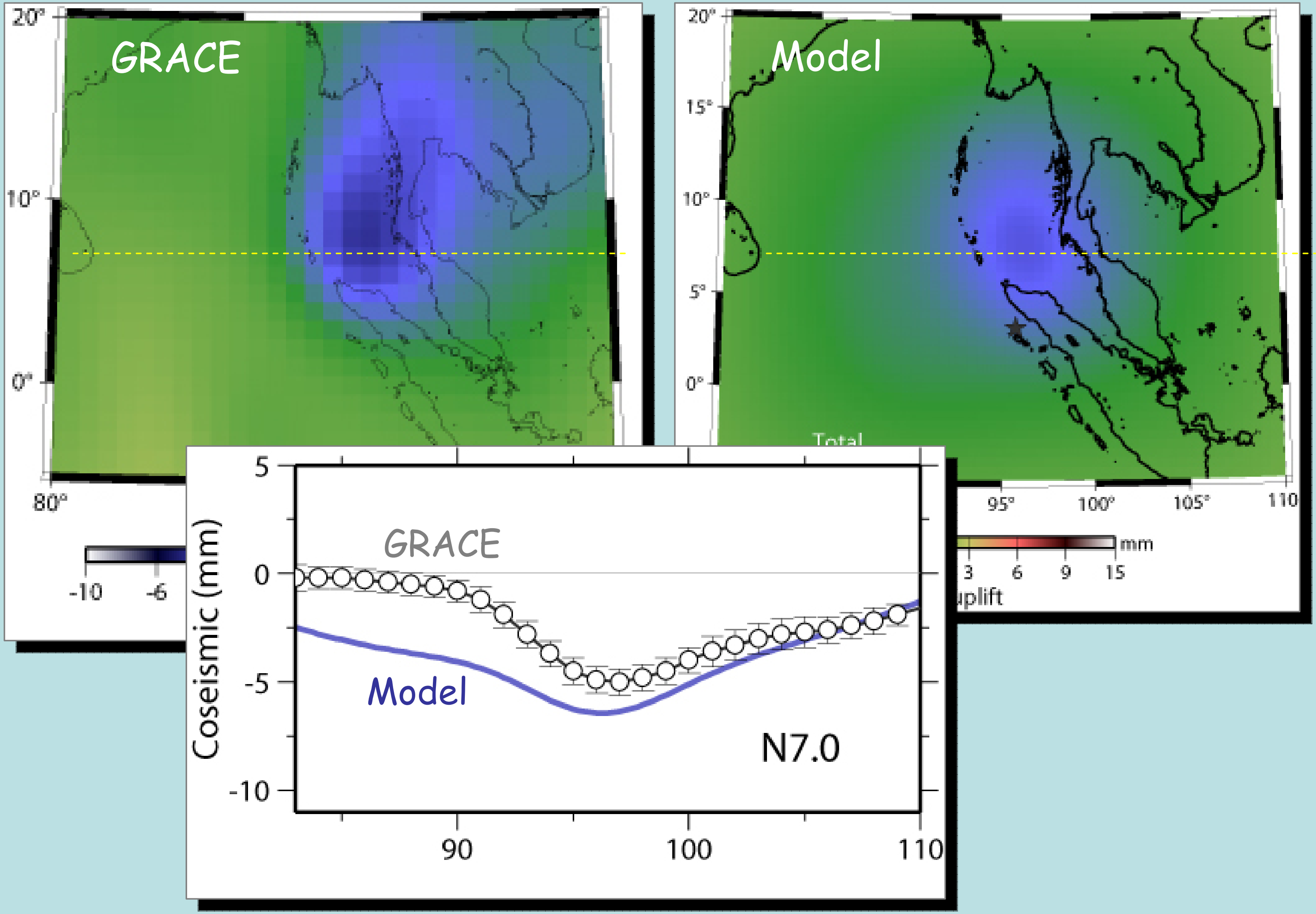


On/Off of the 350 km Gaussian filter:



Time series of Geoid height (RL04)
(N7.0, E96.5)

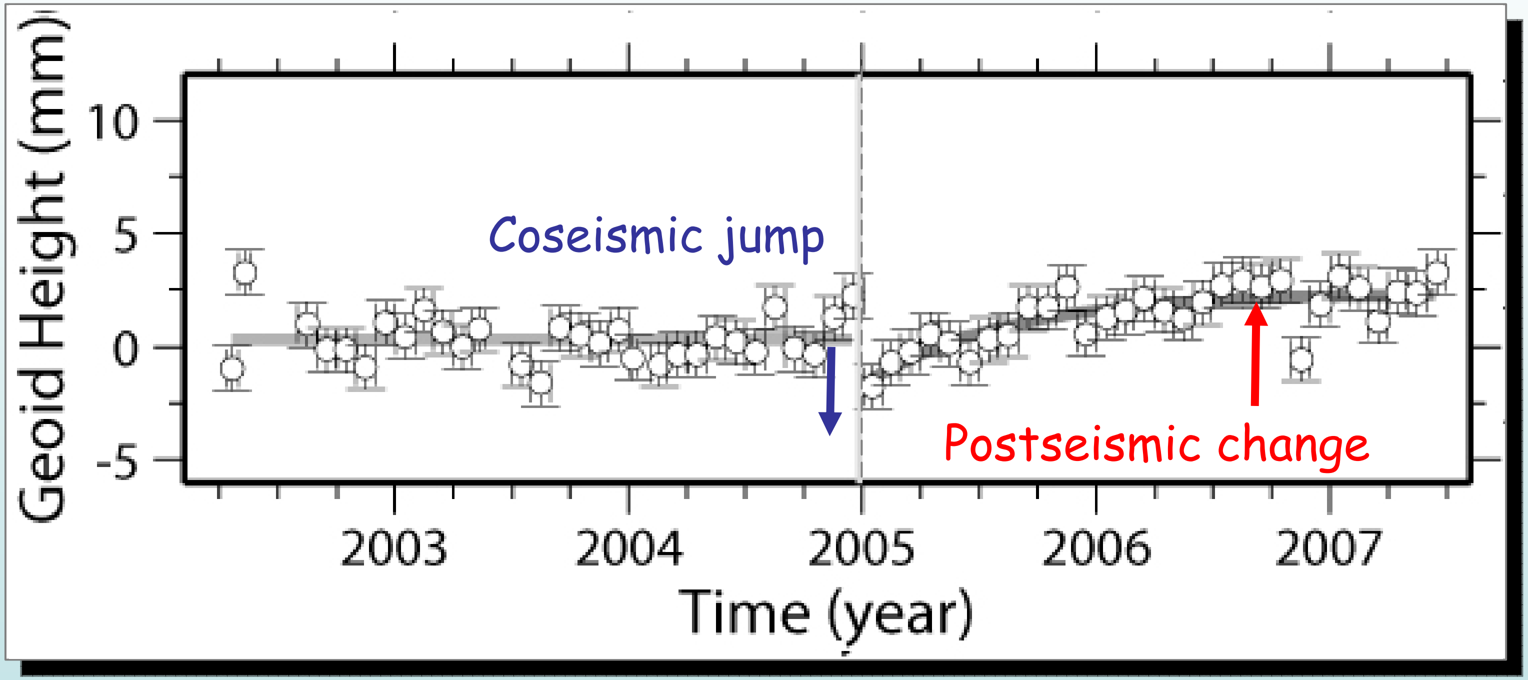




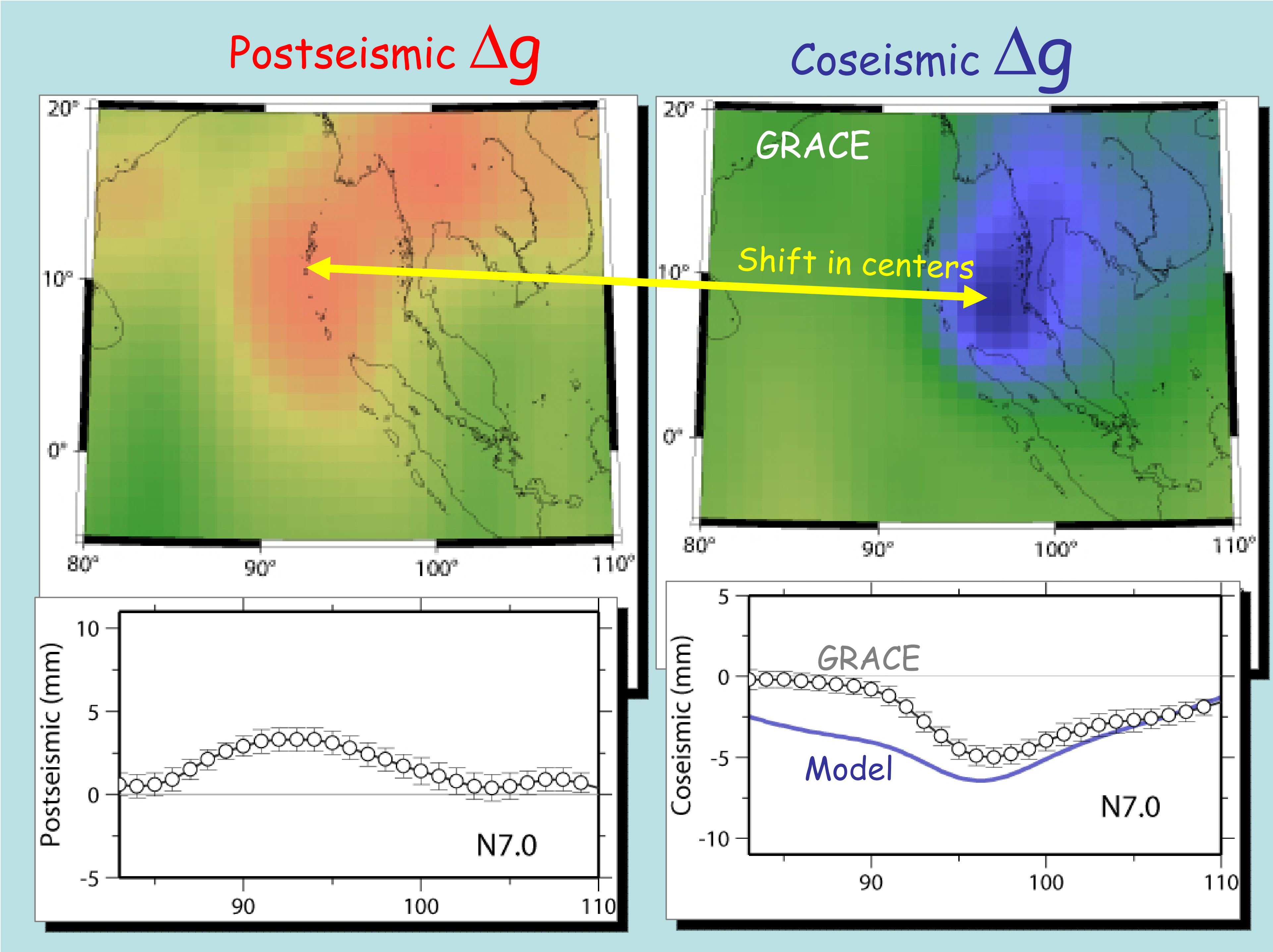
GRACE and Model are fairly similar

Postseismic changes?

Time series of Geoid height (RL04)
(N10.0, E92.0)



Time constant ~ 0.6 year



Postseismic Δg
Coseismic Δg
GRACE
Shift in centers
20°
10°
0°
80°
90°
100°
110°
Postseismic (mm)
10
5
0
-5
N7.0
Coseismic (mm)
GRACE
Model
-10

First detection of postseismic gravity/geoid changes in the world

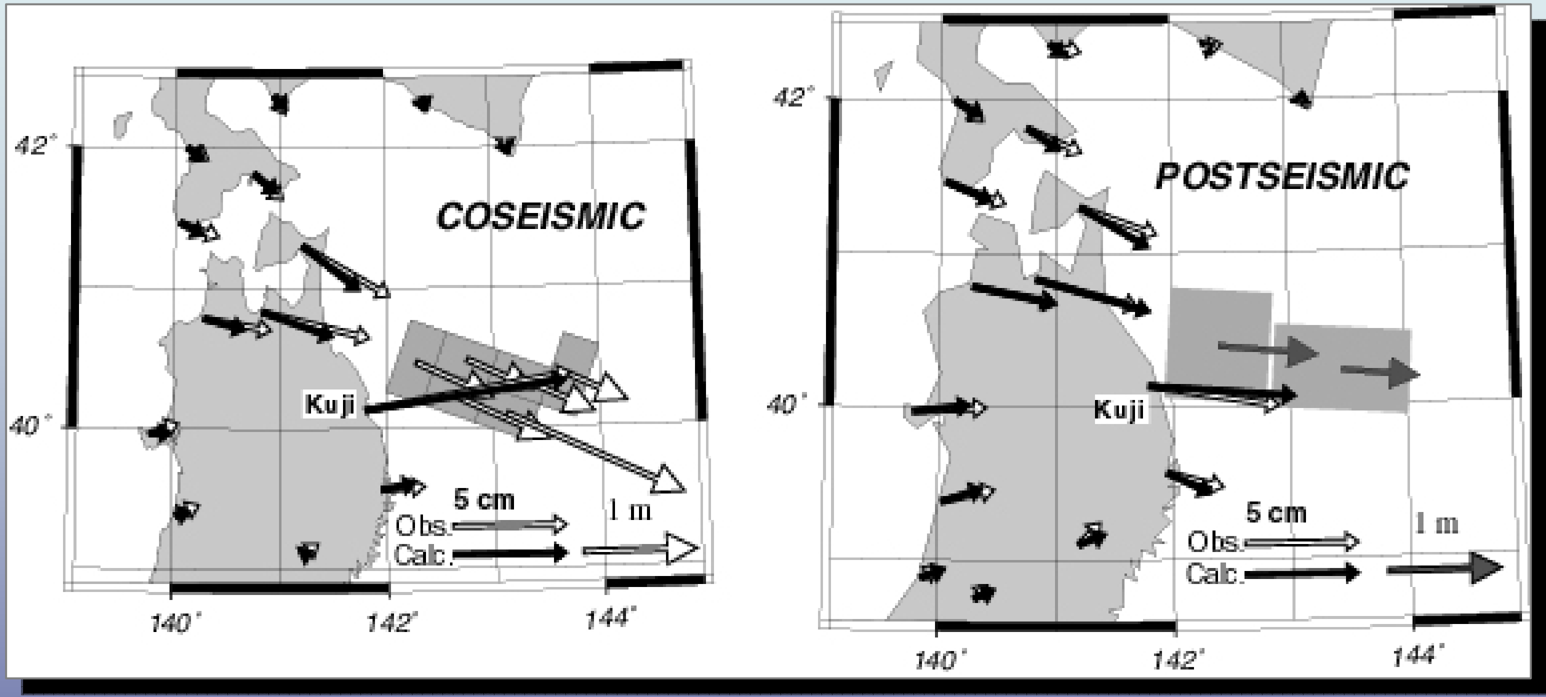
Key features

1. Opposite to coseismic
2. Rapid (τ~0.6yr)

Which of the following?

1. Afterslip
2. Viscoelasticity
3. Pore fluid diffusion

In afterslips, post- and coseismic directions are same



Heki et al. (1997)

Which of the following?

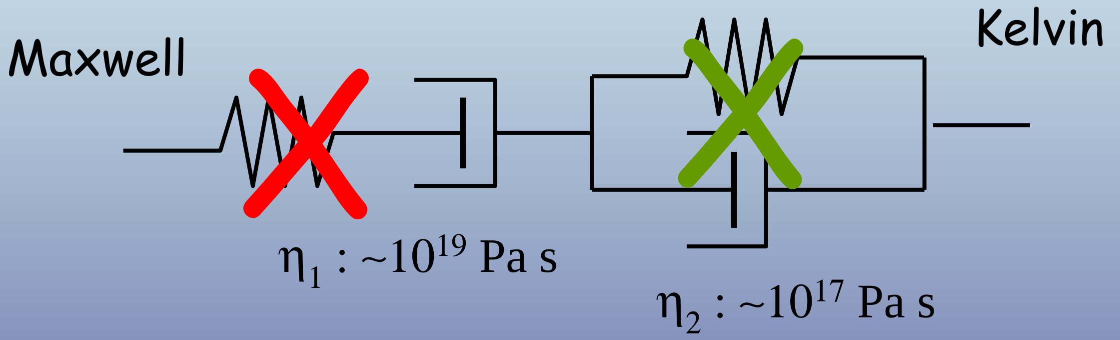
1. Afterslip
2. Viscoelasticity
3. Pore fluid diffusion

Burgers Viscoelasticity

Viscous relaxation of mantle (Pollitz et al., 2006)

Observed time constant is too short

Predicted Andaman subsidence is inconstant with GPS observations



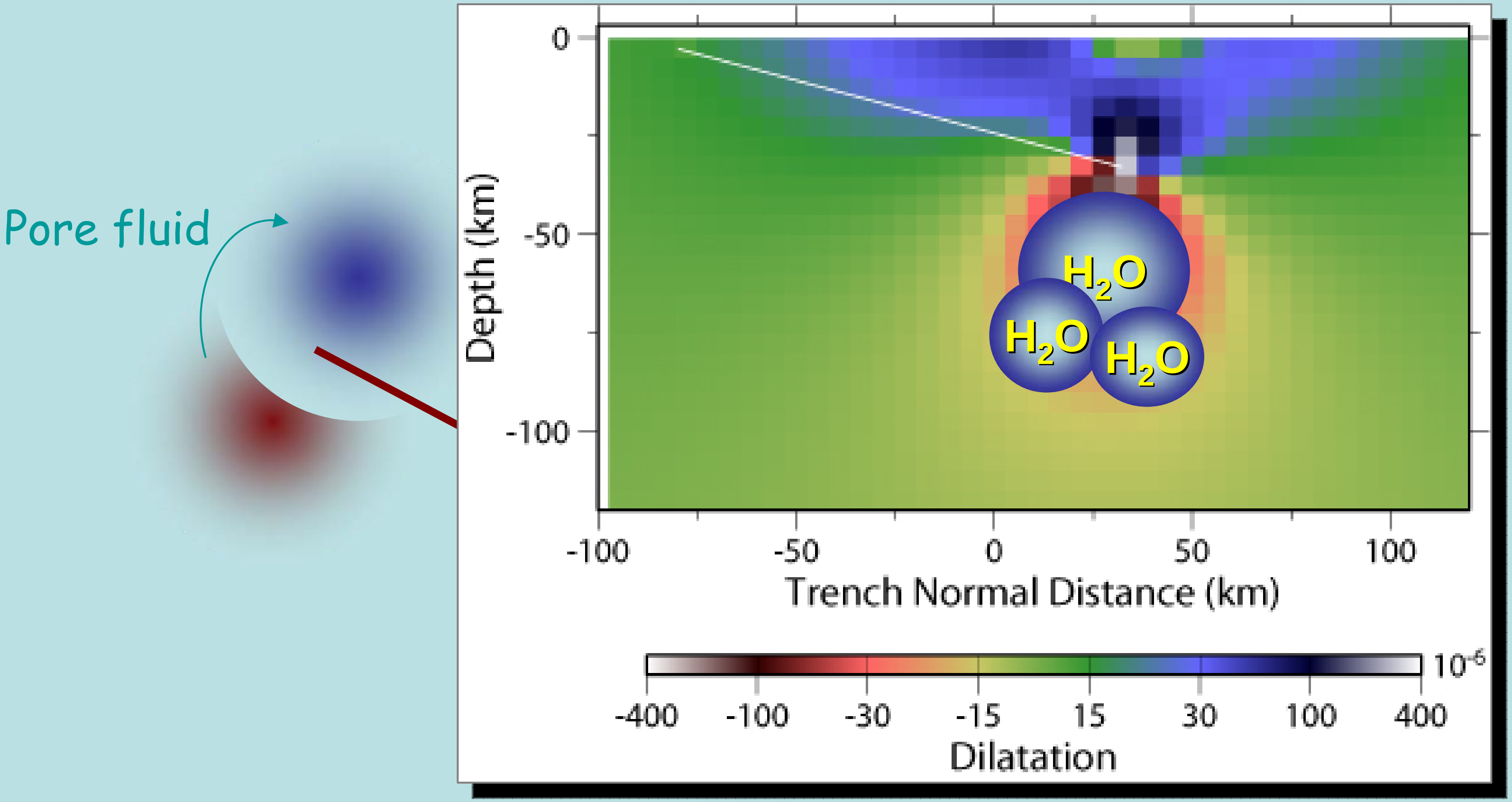
Which of the following?

1. Afterslip
2. Viscoelasticity
3. Pore fluid diffusion

Pore fluid diffusion

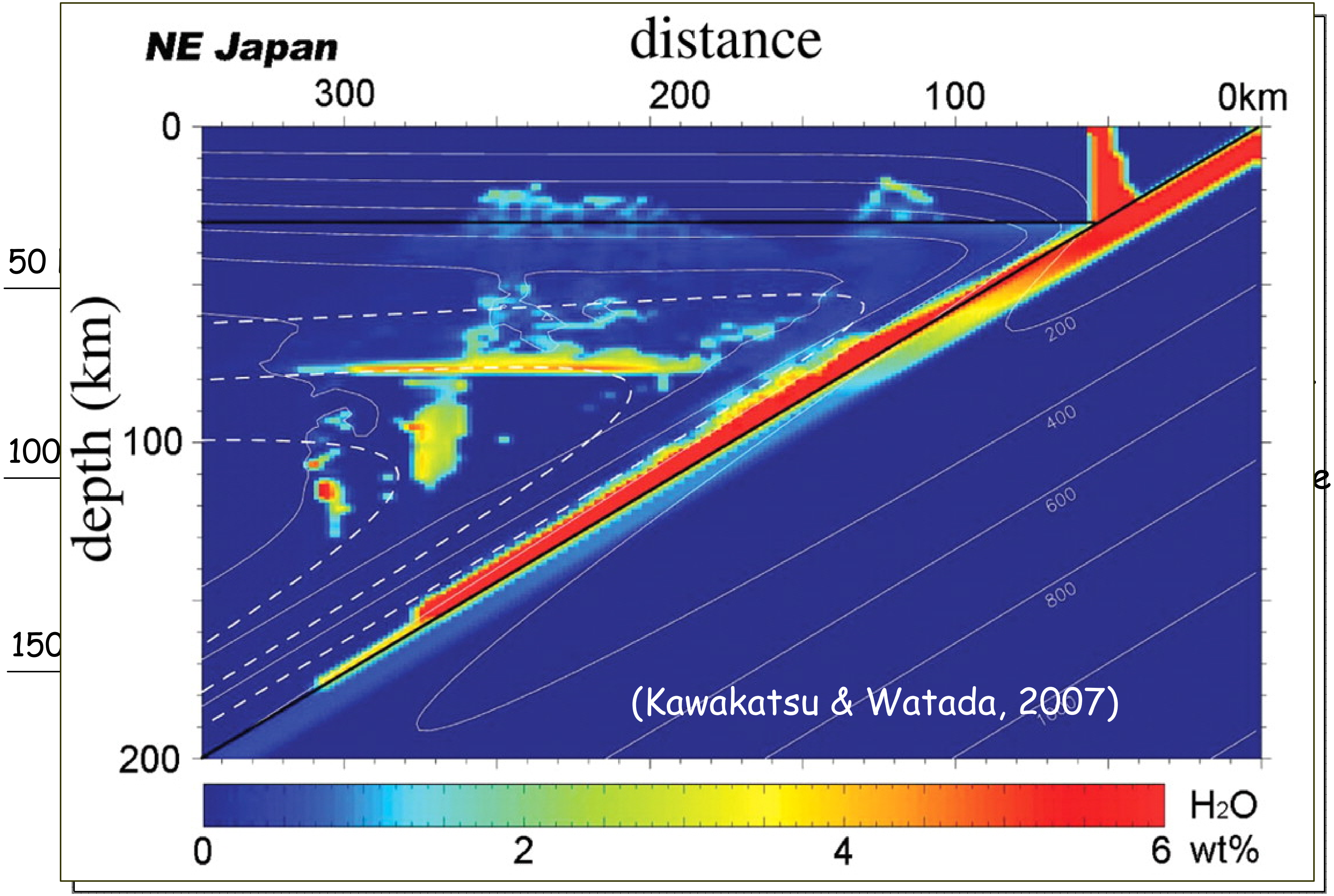
Water diffusion /pore pressure change :

opposite sense, short-term

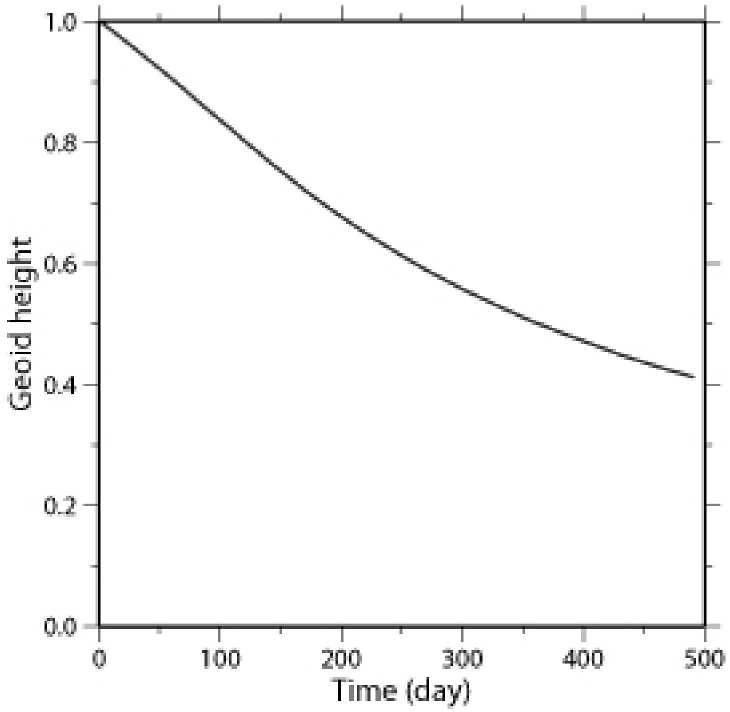


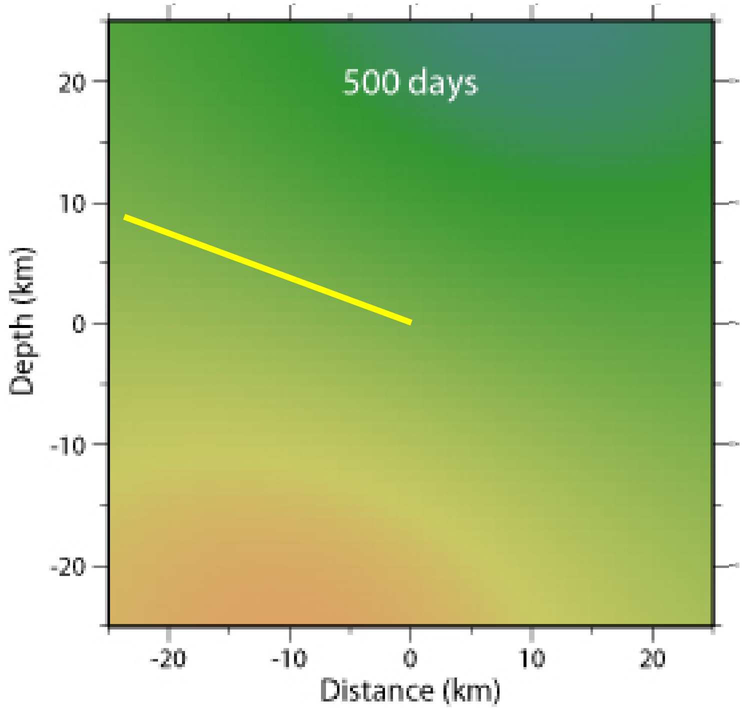
dilatation

Water in wedge mantle



Diffusion of H_2O at the Fault's End
(Nur & Booker, 1972)





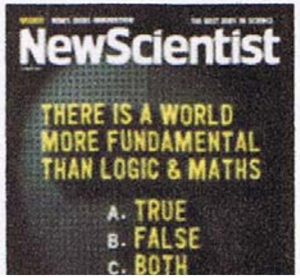
$$P(r,t) = A\,\frac{1 - \exp\left(-r^2/4ct\right)}{r}\sin\theta \qquad c = K/\eta\beta$$

K: permeabiliy
β: bulk compressibility (40 GPa)

Water volume fraction : 1 %
η: viscosity of supercritical water (10^{-5} Pa s)

Self-healing of Geoid may also suppress earthquake-induced polar motions

NewScientist Environment



Water helps earthquake-ravaged Earth to heal

17:53 10 April 2007
From New Scientist Print Edition. Subscribe and get 4 free issues
Michael Reilly

The geological scar left by the devastating earthquake off the coast of Sumatra in December 2004 has healed more quickly than expected.

Satellite measurements of Earth's gravitational field taken just after the quake show it left a depression 8 millimetres deep in the crust and shallow mantle. While this does not seem like much, the shifting mass jolted Earth's axis of rotation enough to move the poles by 10 centimetres.

In under a year, however, the depression had nearly vanished – something that surprises geologists, because according to models of how rocks in the mantle move it should have taken 20 years. "It's almost impossible for rocks to move, that quickly," says Kosuke Heki of Hokkaido University in Sapporo, Japan.

So Heki's team developed a new model to show how Earth could have healed itself in as little as seven months. The key, he says, is that the mantle beneath the 1200-kilometre fault has more water than usual – about 1% of the rock by weight. As the water is under intense heat and pressure, it behaves like a gas and can move through kilometres of solid rock in a short time.

In his model, water flows from rocks compressed by the quake into those that expanded as it released their stresses. The influx causes the de-stressed rocks to return to their original state faster. The model also suggests that the extent of permanent shifts in Earth's rotational axis due to strong quakes would be less than expected.

Journal reference: *Geophysical Research Letters* (vol 34, p L06313)

Tools
digg

Topic #2 summary: New sensor

1. Seismometer
2. GPS (positioning)
3. GRACE (gravity)

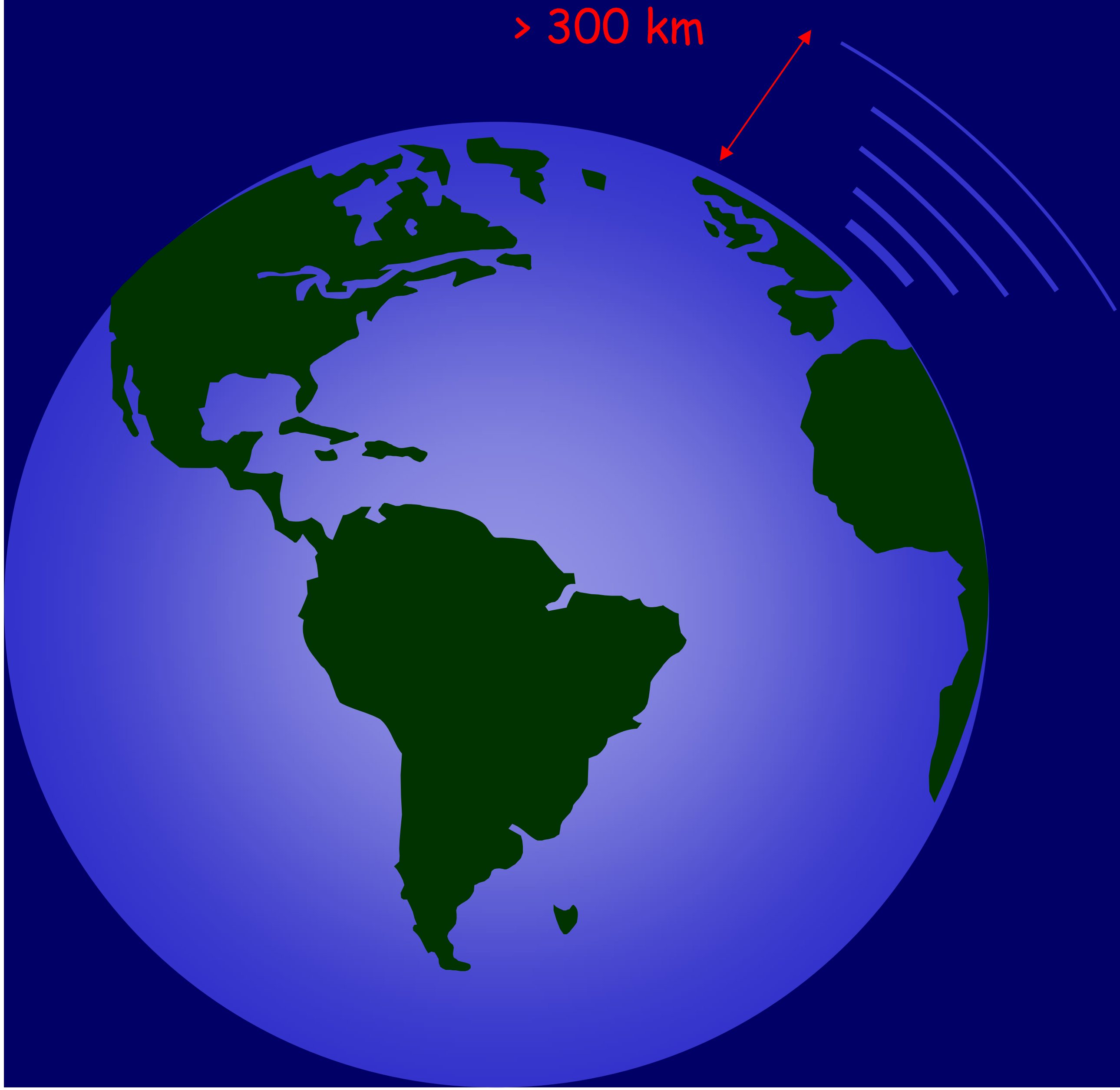
A talk in a similar topic later in this session

Diament et al., What does satellite gravity bring to the understanding and monitoring of large earthquakes?

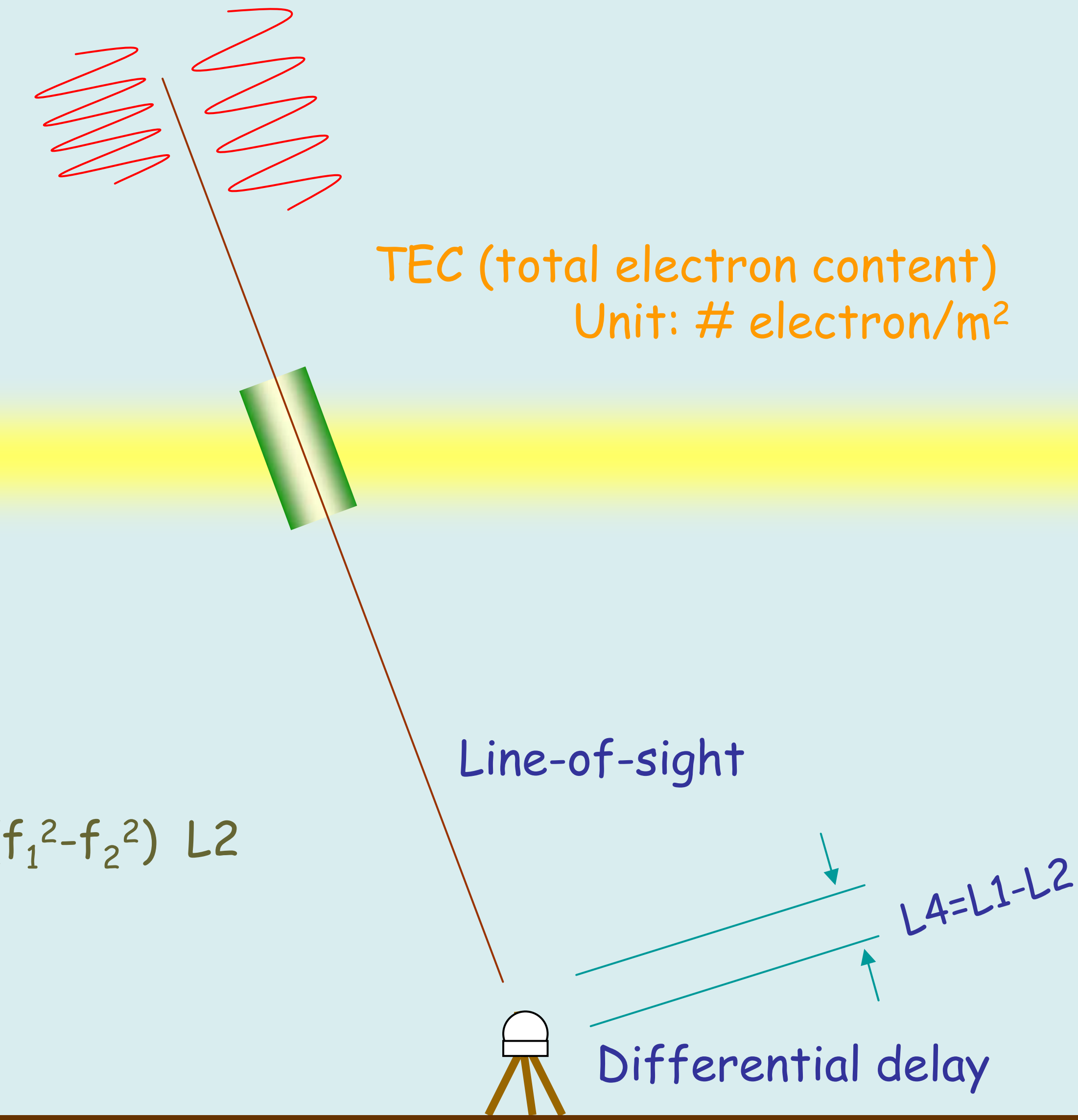
Topic #3.
Studying Earthquakes by GPS -TEC

Seismic waves propagating upward

They reach the space



Measuring ionosphere with GPS



To remove ionosphere

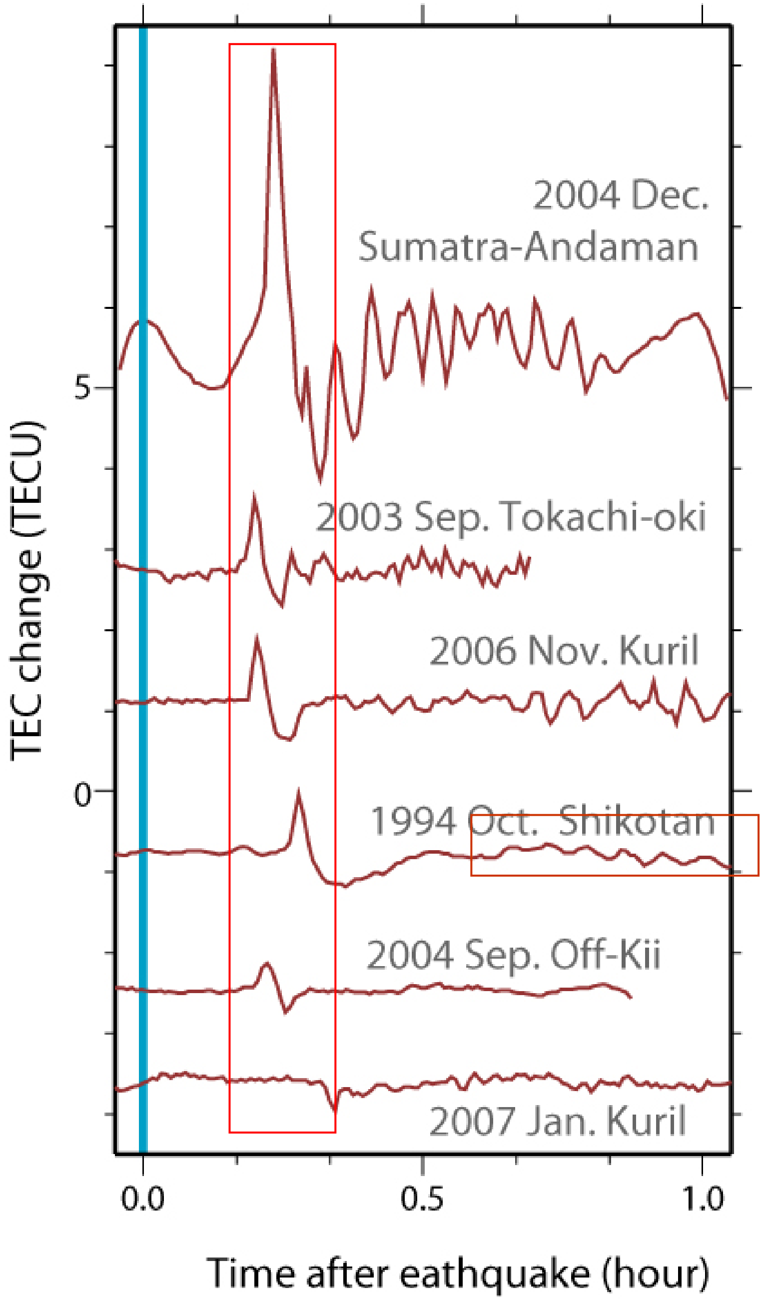
$L3=f_1^2/(f_1^2-f_2^2)\ L1 - f_2^2/(f_1^2-f_2^2)\ L2$

To isolate ionosphere

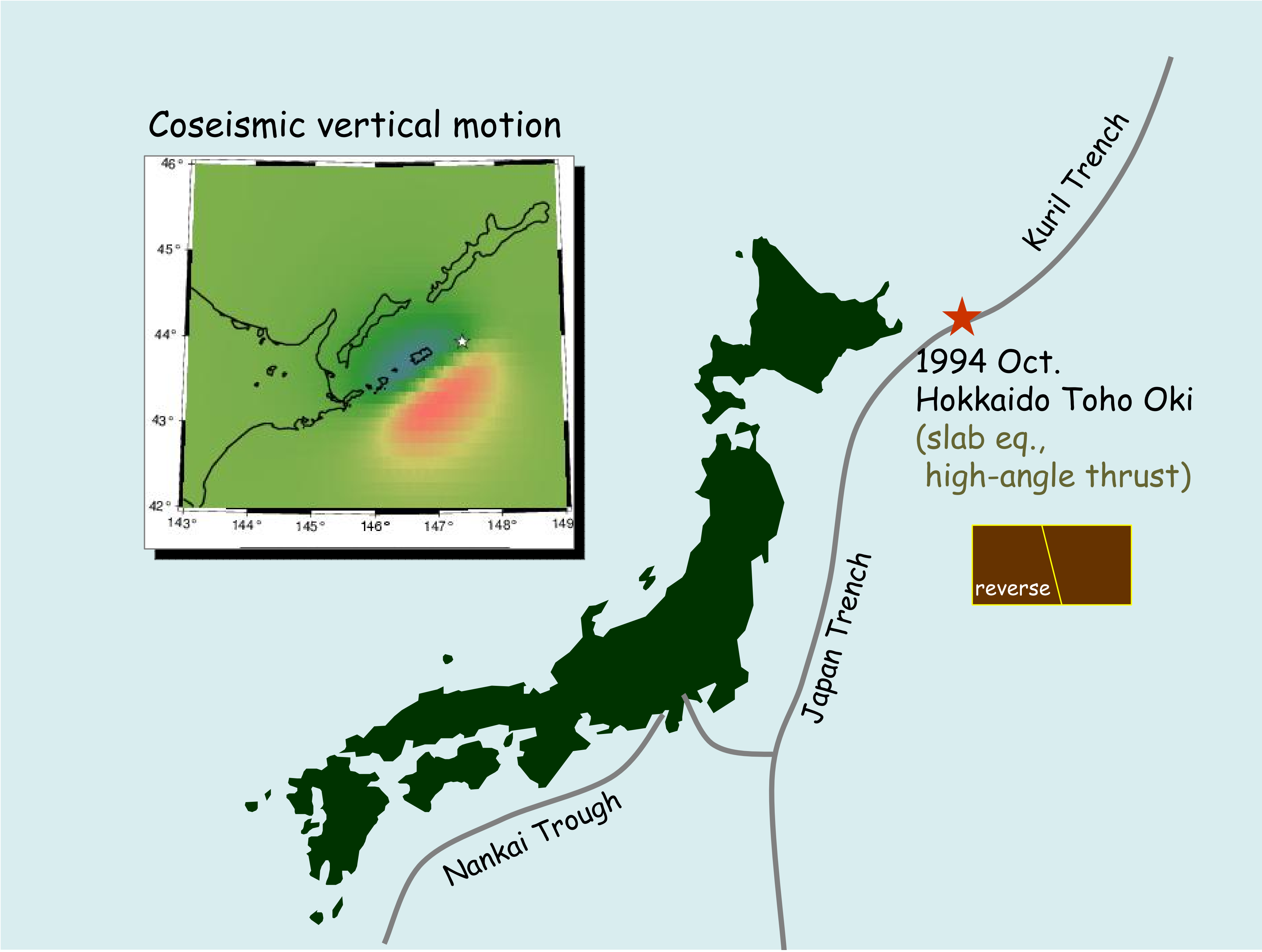
$L4=L1-L2$

Examples of past coseismic ionospheric disturbances
(Heki, 2007)

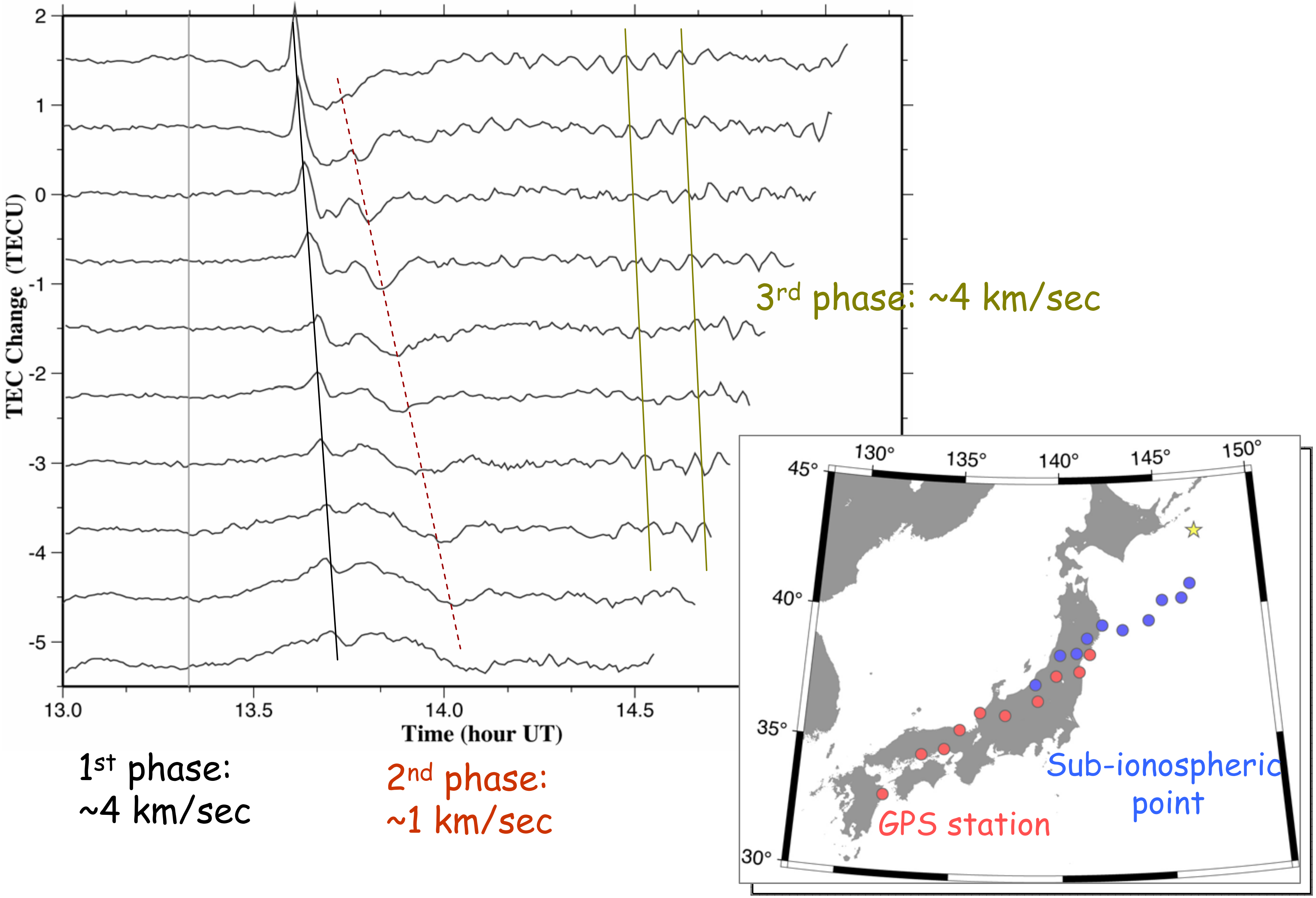
Coseismic disturbance ~10 min. after eq.



Monochromatic oscillation


Coseismic vertical motion
46°
45°
44°
43°
42°
143°
144°
145°
146°
147°
148°
149
Kuril Trench
1994 Oct.
Hokkaido Toho Oki
(slab eq.,
high-angle thrust)
reverse
Japan Trench
Nankai Trough

1994 Hokkaido-Toho-Oki (Shikotan) Eq. Satellite 20



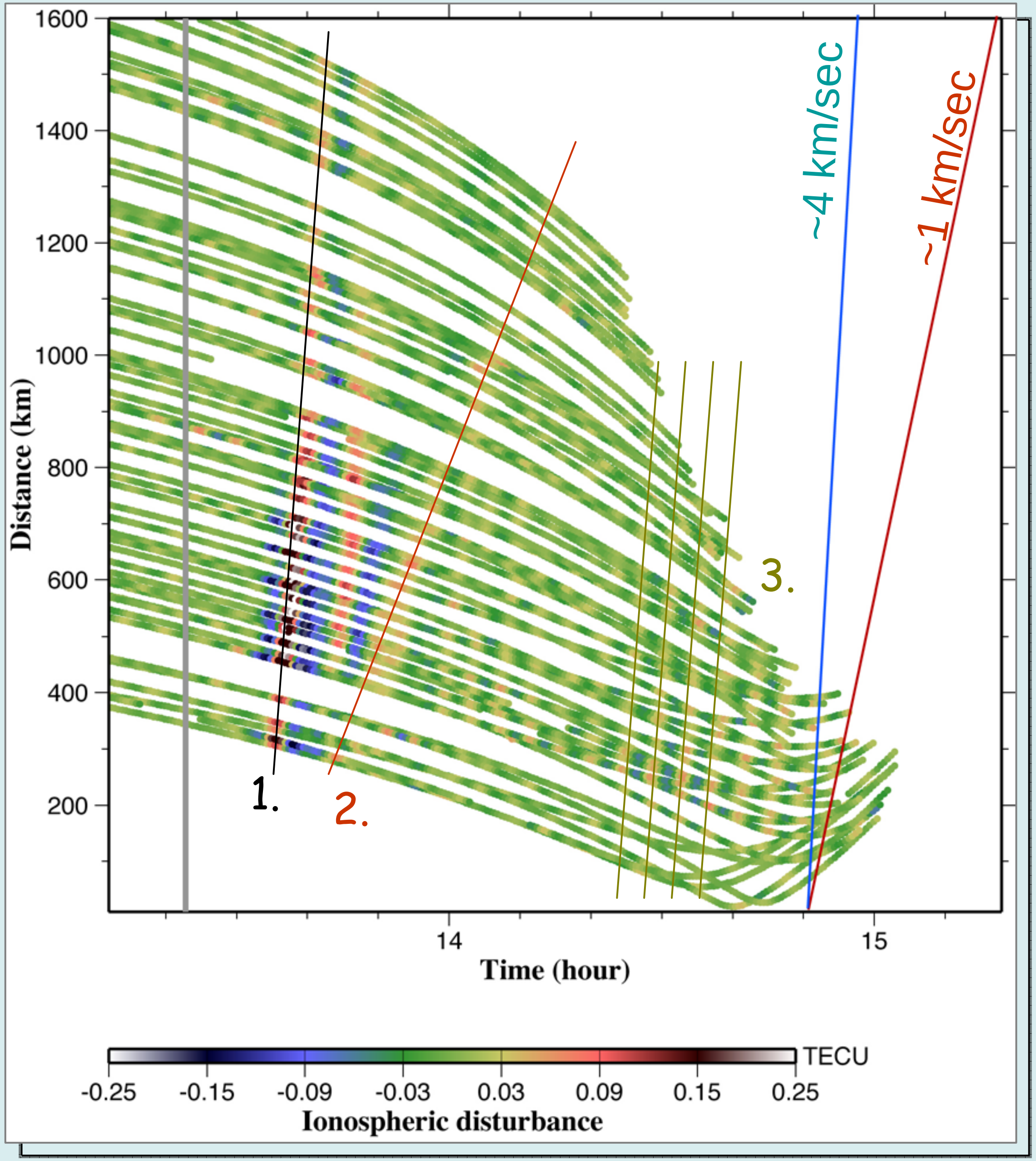
1st phase:
~4 km/sec

2nd phase:
~1 km/sec

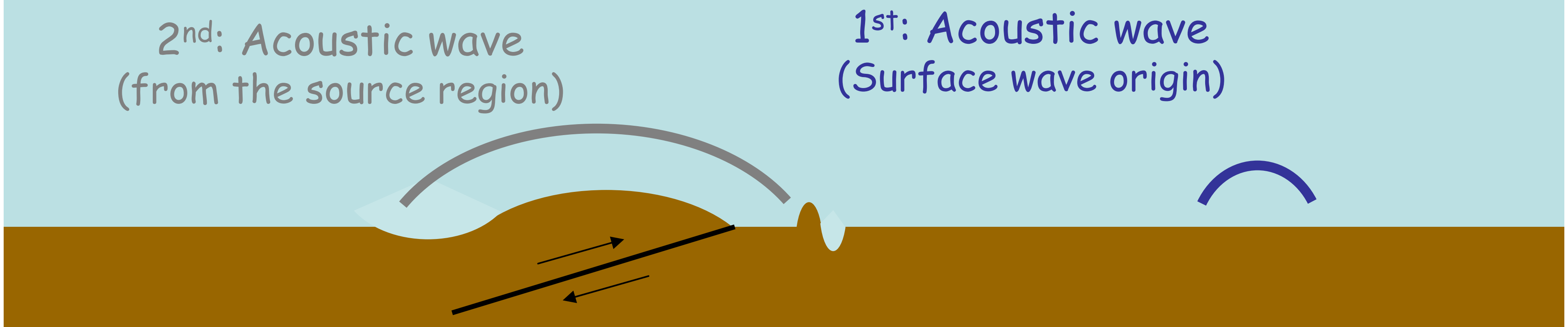
Time-distance diagram of the disturbance

1994 Hokkaido-Toho-Oki

Satellite 20



1st and 2nd phases
Rayleigh surface wave and acoustic wave

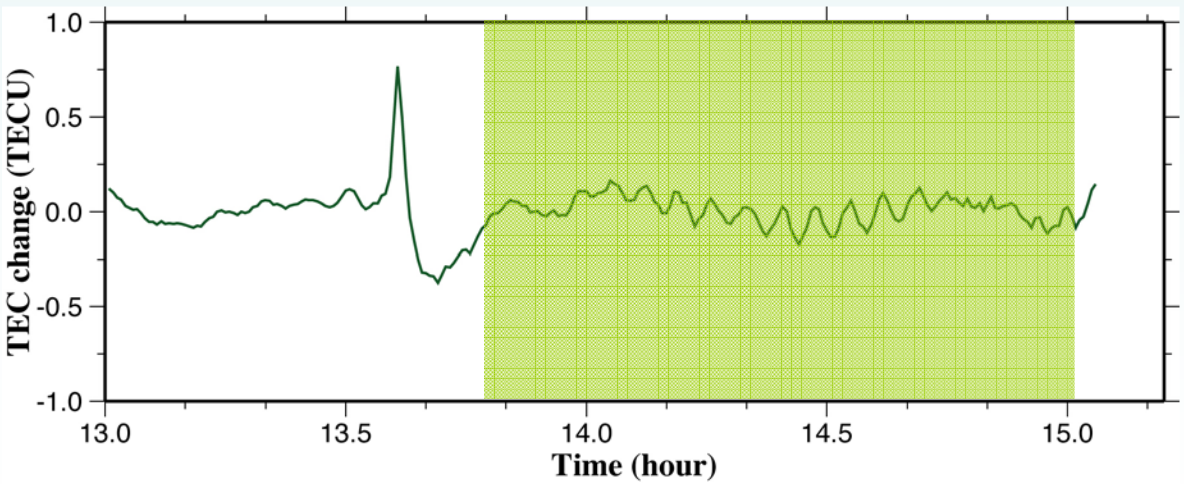


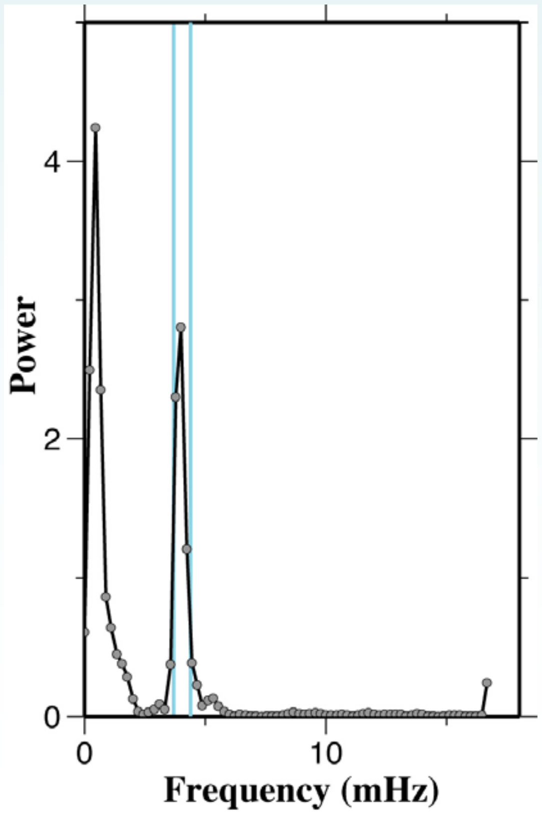
What is the 3rd phase ?

Power spectrum of the 3rd phase

3.7mHz 4.4mHz

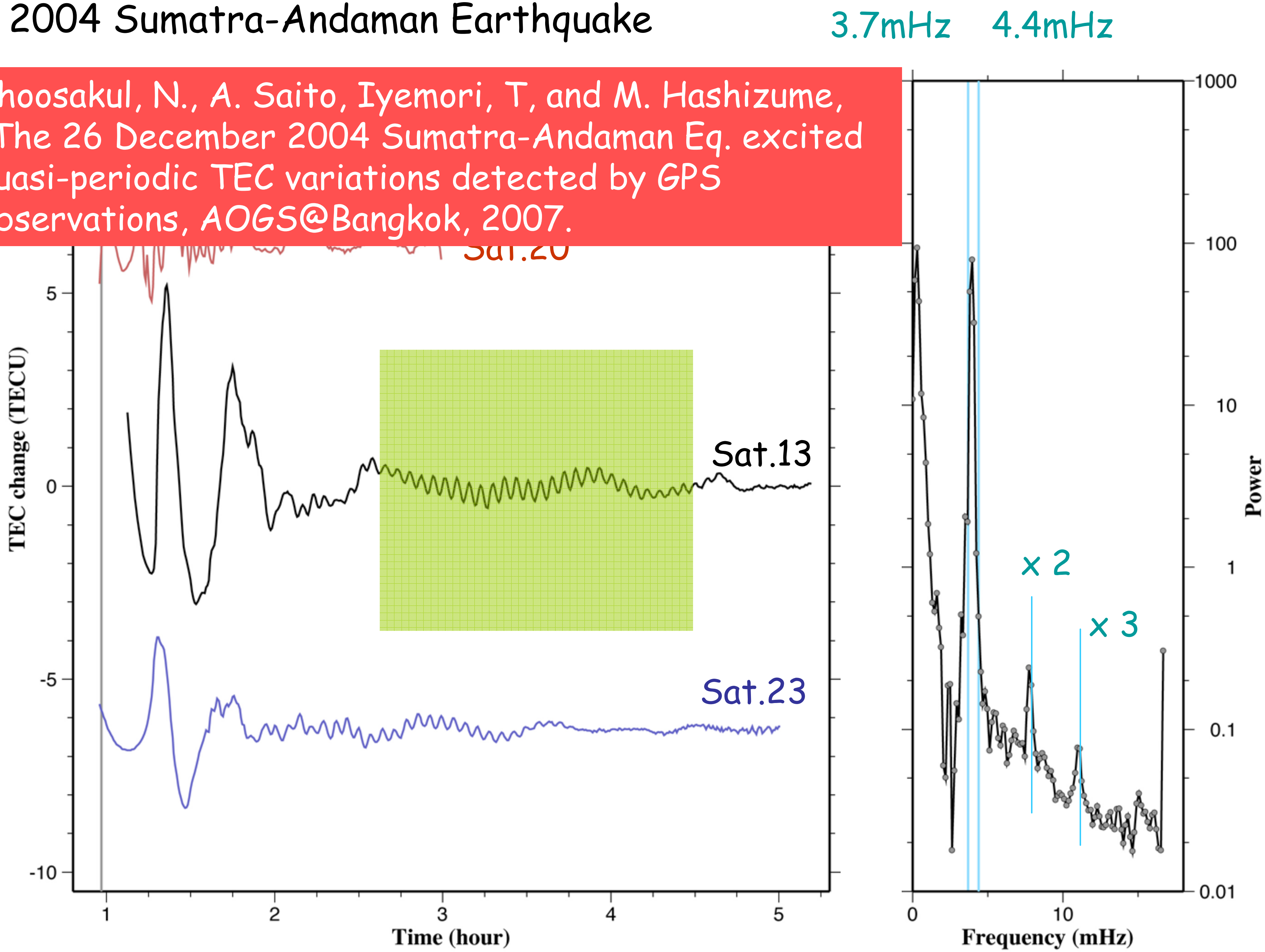
940036 Satellite 20





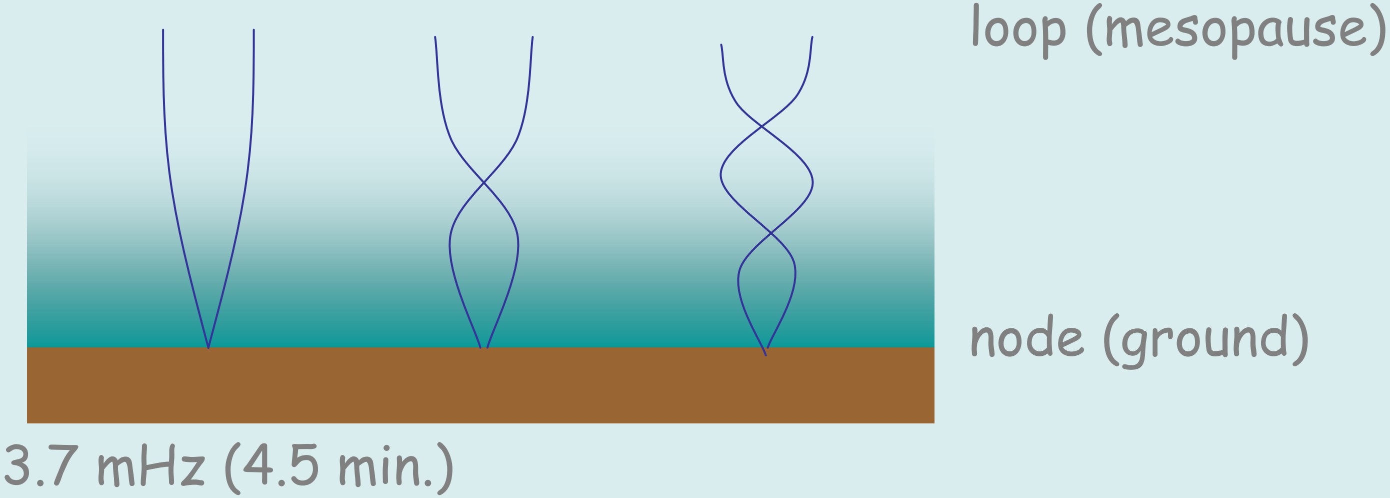
2004 Sumatra-Andaman Earthquake

Choosakul, N., A. Saito, Iyemori, T, and M. Hashizume, "The 26 December 2004 Sumatra-Andaman Eq. excited quasi-periodic TEC variations detected by GPS observations, AOGS@Bangkok, 2007.

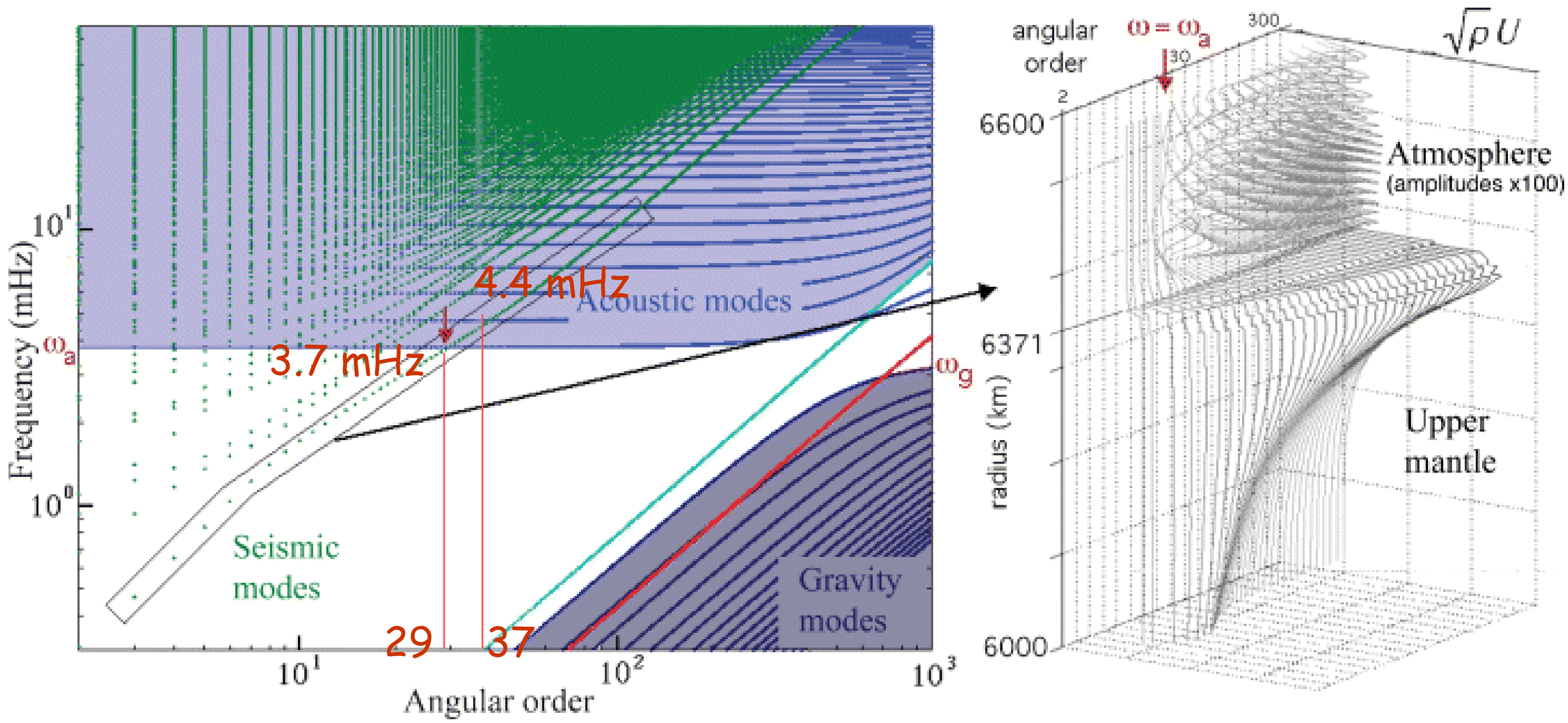


Solid Earth

Atmosphere (standing acoustic wave)

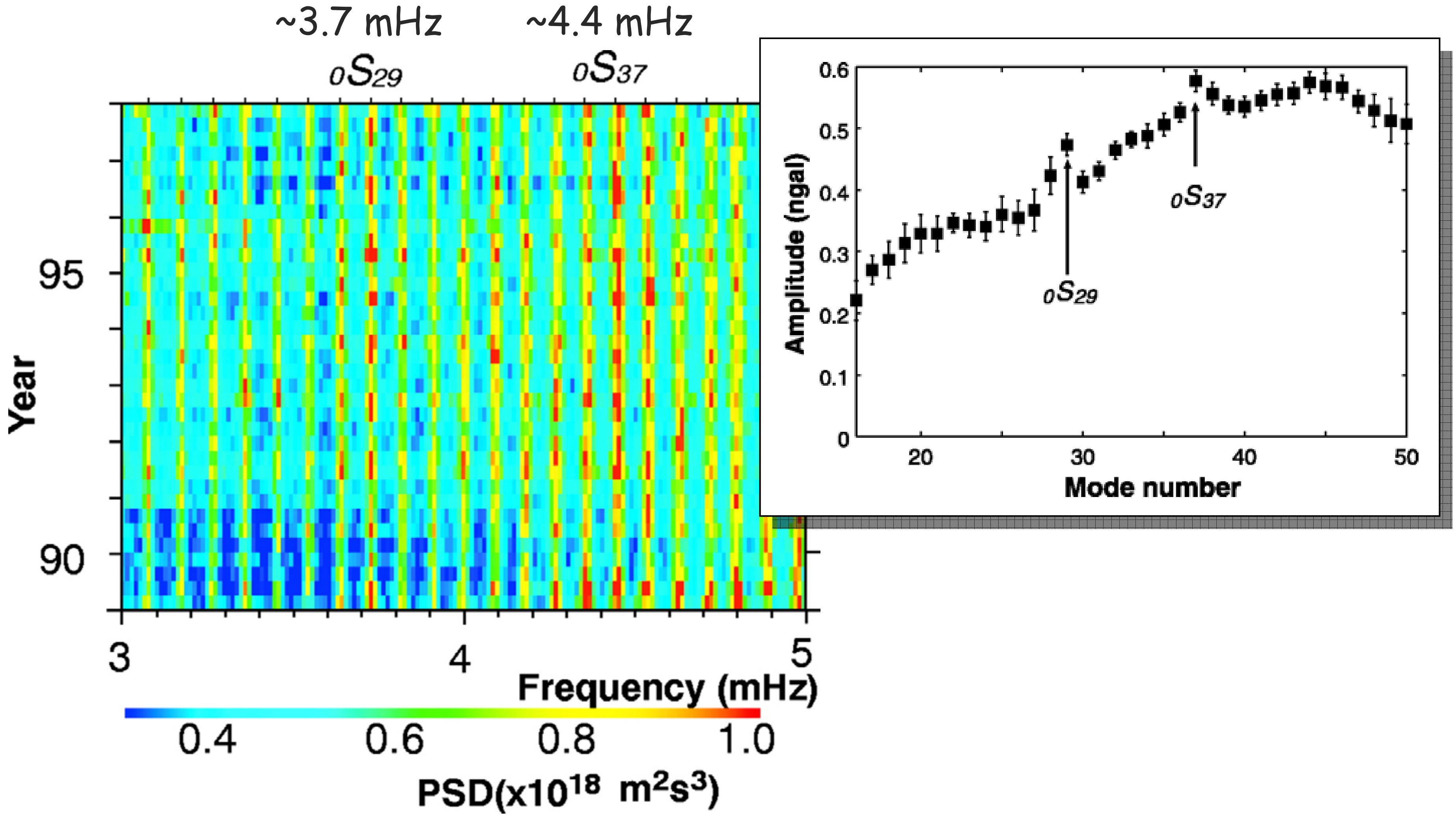


Normal Modes of the solid earth and atmosphere



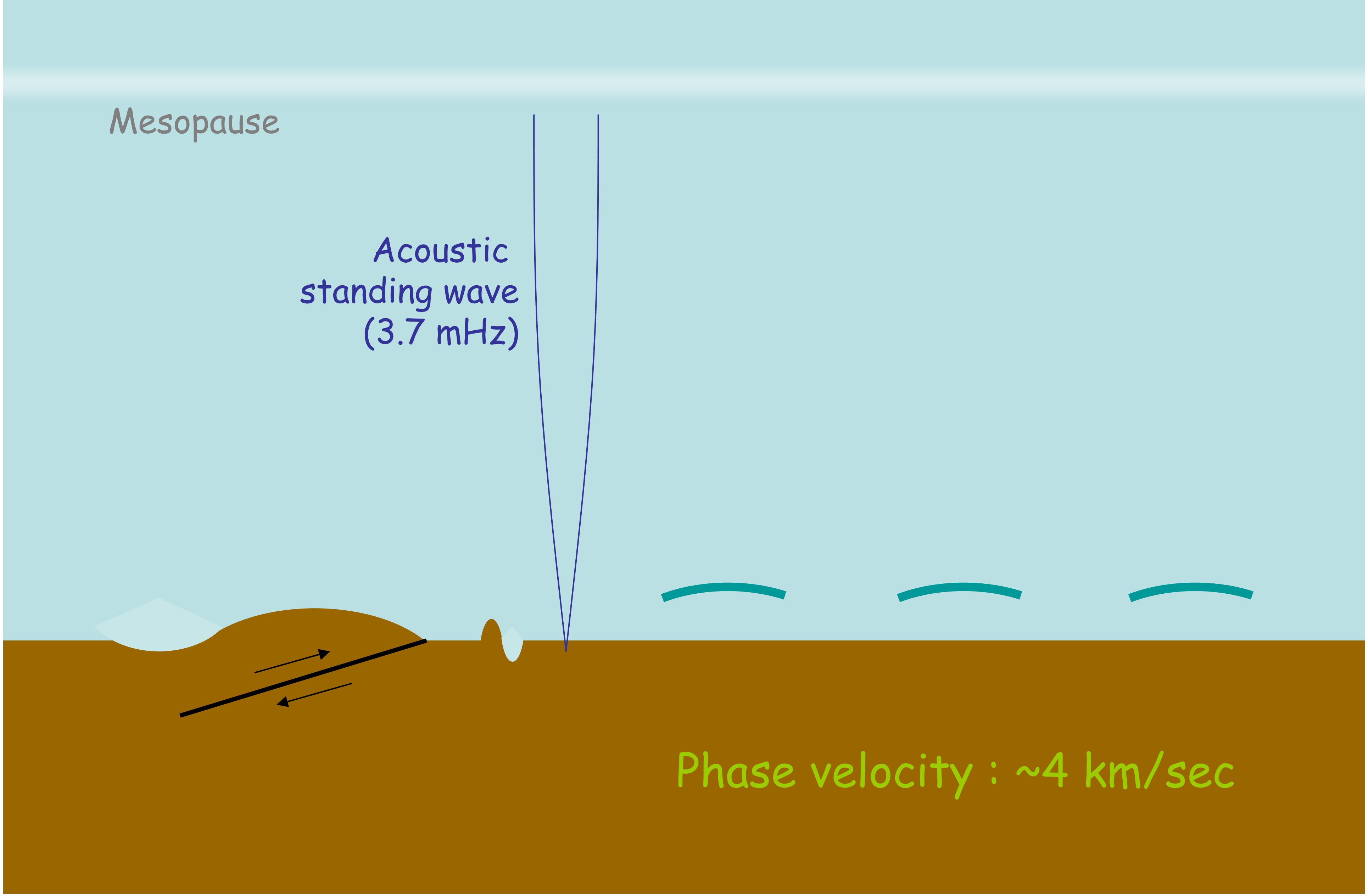
Artru et al. (GJI 2004)

Solid earth – atmospheric resonance in the background free oscillation

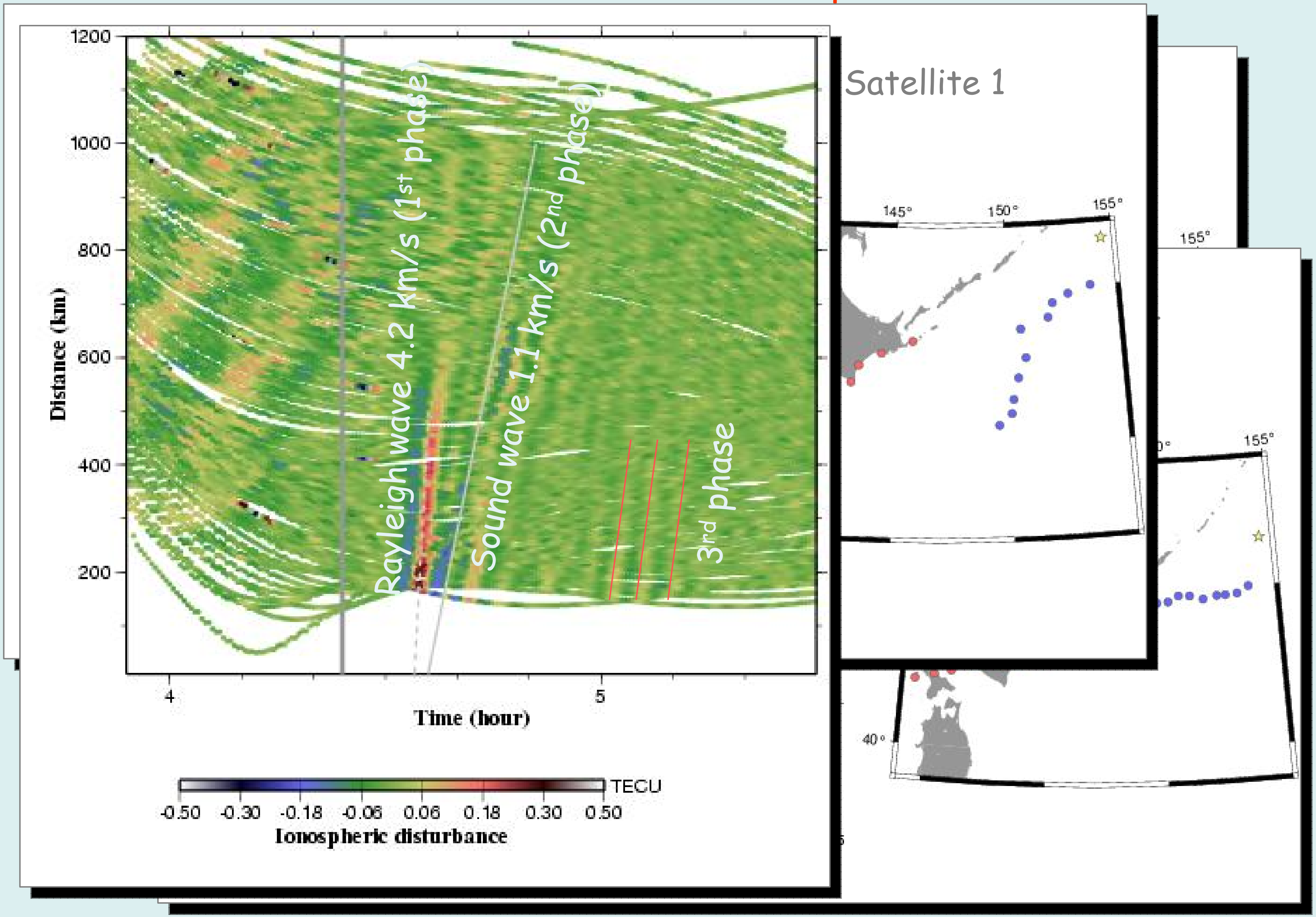


Nishida, K. et al., Resonant oscillation between the solid earth and the atmosphere, Science, 287, 2244, 2000.

3rd phase : Atmospheric standing wave



2007 Jan. Outer rise earthquake

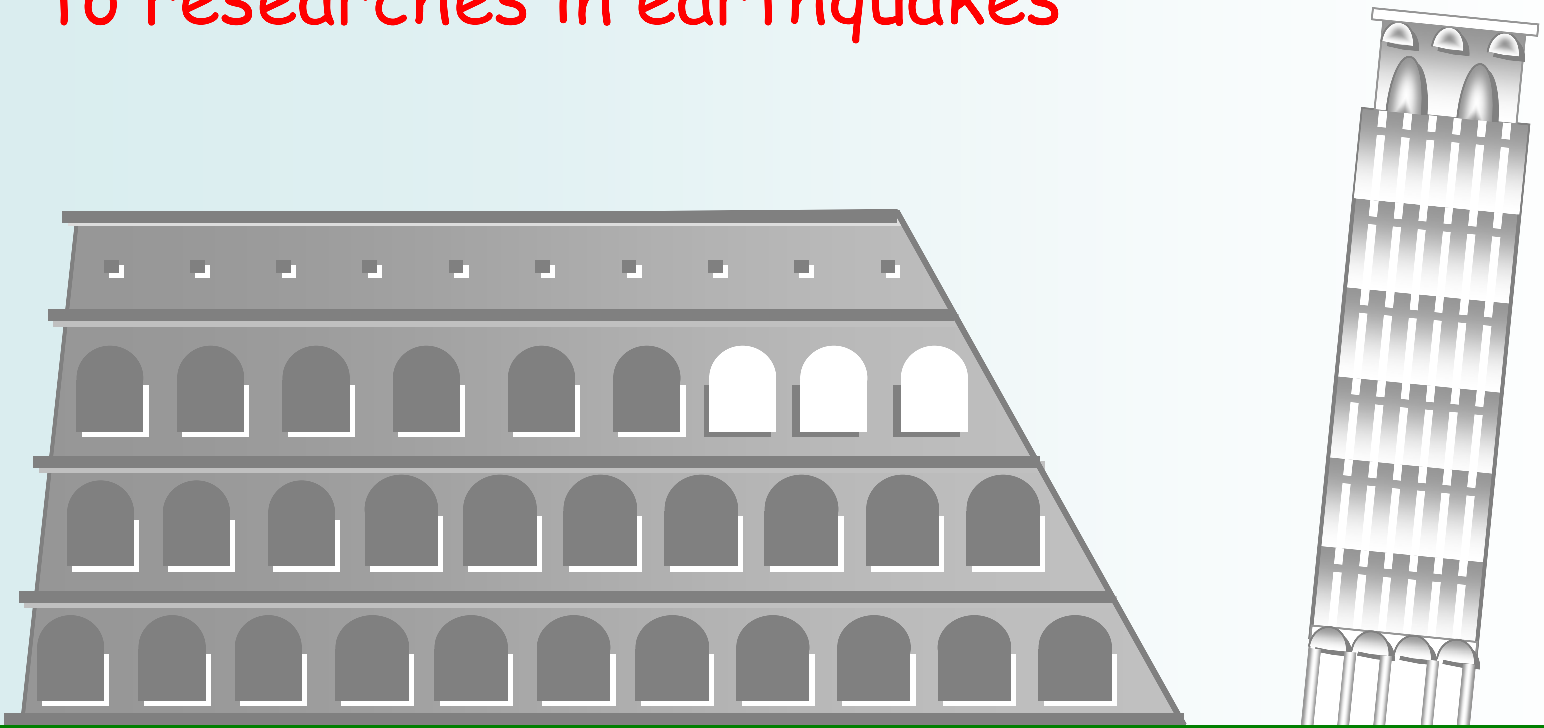


Topic #3 summary: New seismology

1. Crust/Mantle
2. Core
3. Atmosphere/ionosphere

A talk in a similar topic later in this session
Lognonné et al., Ionospheric seismology : a new perspective in earth observation

Recent contributions of space geodesy to researches in earthquakes



Joint work with

Topic #1. GPS : Takeshi Kataoka (MSc student)

Topic #2. GRACE : Ryoko Ogawa (PhD student)

Topic #3. GPS-TEC : Naoki Kobayashi (Tokyo Inst. Tech.)

Thank you

Hokkaido University
SPACE GEODESY