A gravitational image of the 2011 Tohoku earthquake long-term mass transport

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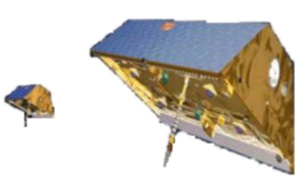
Subduction at monthly to decadal timescales from GRACE

- *Mass fluxes at scales inbetween those of local and global plate dynamics?*

→ GRACE optimal accuracy is obtained at intermediate spatial scales: let's use GRACE where it is best!

→ Take advantage of the satellites homogeneous space-time coverage and zoom out: episodic mass fluxes at the scale of the Earth's regional structure?



- *We analyze the GRGS RL03 geoids*

Lemoine et al. 2007, Bruinsma et al. 2010

- *We compare with the ITSG2016 geoids*

Mayer-Guerr et al., 2016

Performances: GRACE and beyond

Mission	Temp. res.	Performance				
		Spat. res.	Equivalent Water Height (EWH)	Geoid	Gravity anomaly	Gravity Gradient
GRACE	1 month	800 km (d/o 25)	7.5 mm / 0.75 mm/yr	0.15 mm / 0.015 mm/yr	0.25 µGal / 0.025 µGal/yr	10 µE / 1 µE/yr
		400 km (d/o 50)	25 mm / 2.5 mm/yr	0.25 mm / 0.025 mm/yr	1 µGal / 0.1 µGal/yr	0.1 mE / 0.01 mE/yr
		200 km (d/o 100)	0.5 m / 5 cm/yr	2.5 mm / 0.25 mm/yr	25 µGal / 2.5 µGal/yr	5 mE / 0.5 mE/yr
Scen. 1	1 month	800 km (d/o 25)	1.5 mm / 0.15 mm/yr	0.03 mm / 3 µm/yr	0.05 µGal / 5 nGal/yr	2 µE / 0.2 µE/yr
		400 km (d/o 50)	5 mm / 0.5 mm/yr	50 µm / 5 µm/yr	0.2 µGal / 0.02 µGal/yr	20 µE / 2 µE/yr
		200 km (d/o 100)	10 cm / 1 cm/yr	0.5 mm / 0.05 mm/yr	5 µGal / 0.5 µGal/yr	1 mE / 0.1 mE/yr
		150 km (d/o 133)	50 cm / 5 cm/yr	1 mm / 0.1 mm/yr	10 µGal / 1 µGal/yr	5 mE / 0.5 mE/yr
		100 km (d/o 200)	5 m / 0.5 m/yr	10 mm / 1 mm/yr	200 µGal / 20 µGal/yr	50 mE / 5 mE/yr
Scen. 2	1 month	800 km (d/o 25)	0.15 mm / 0.015 mm/yr	3 µm / 0.3 µm/yr	5 nGal / 0.5 nGal/yr	0.2 µE / 0.02 µE/yr
		400 km (d/o 50)	0.5 mm / 0.05 mm/yr	5 µm / 0.5 µm/yr	0.02 µGal / 0.002 µGal/yr	2 µE / 0.2 µE/yr
		200 km (d/o 100)	1 cm / 0.1 cm/yr	0.05 mm / 0.005 mm/yr	0.5 µGal / 0.05 µGal/yr	0.1 mE / 0.01 mE/yr
		150 km (d/o 133)	5 cm / 0.5 cm/yr	0.1 mm / 0.01 mm/yr	1 µGal / 0.1 µGal/yr	0.5 mE / 0.05 mE/yr
		100 km (d/o 200)	0.5 m / 0.05 m/yr	1 mm / 0.1 mm/yr	20 µGal / 2 µGal/yr	5 mE / 0.5 mE/yr

R. Pail et al., IUGG study (2015)

Objectives

Can we bring new constraints on the pre-seismic phase of giant subduction earthquakes from the GRACE satellites mapping of the Earth's gravity variations in space and time?

Improve our knowledge on the mass fluxes associated with subduction at intermediate scales.

Episodic mass changes in the regional subduction system?

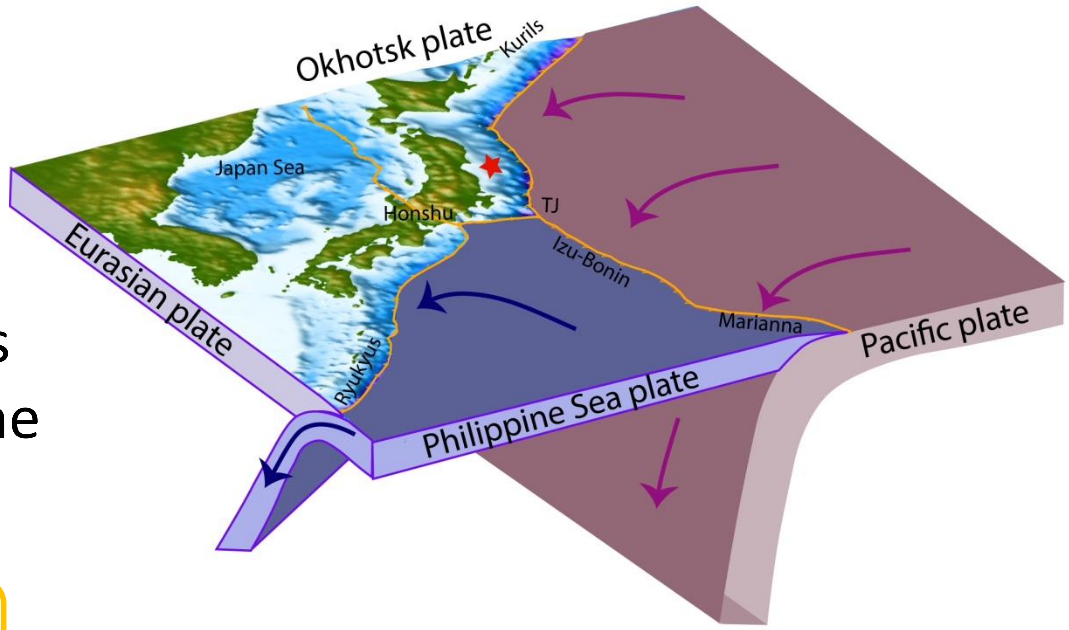
- Zoom-out and focus on the **regional scales**: 800 - 1600 km

Wavelet filtering of the potential at different scales

- Enhance the gravity signals following the geometry of the plate boundaries / slabs?

Use the direction information: orientation of the subduction.

11 March 2011 Tohoku earthquake

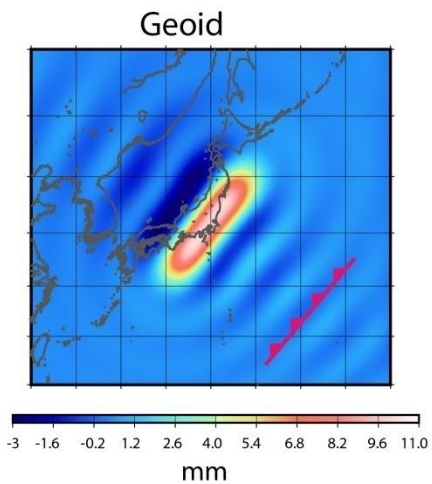


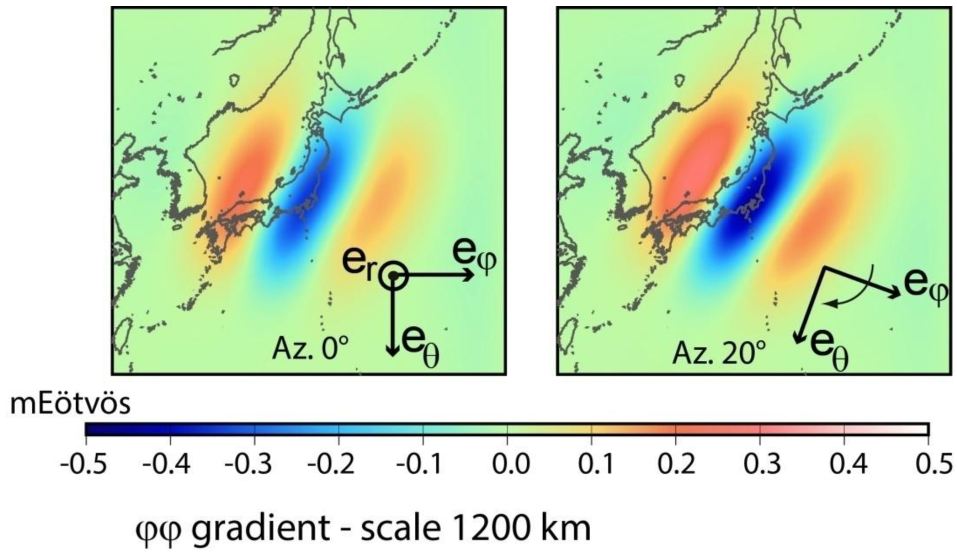
Northwest Pacific subduction

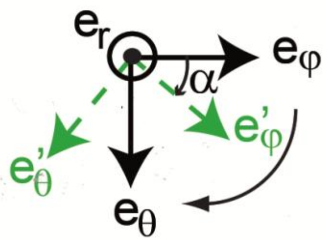
→ *Rate of change of the Earth's gravity vector in space and time*

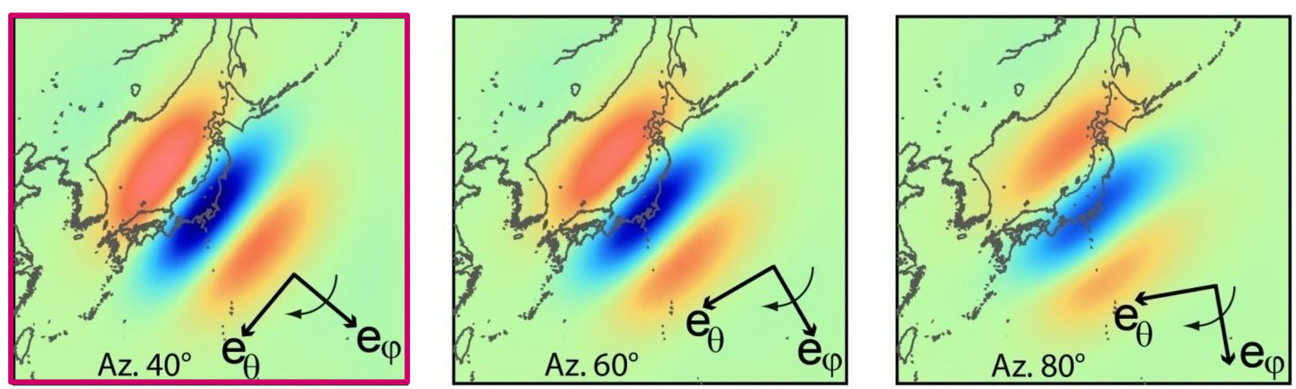
Gravity gradients in rotated frames: local slip

SH degree 80









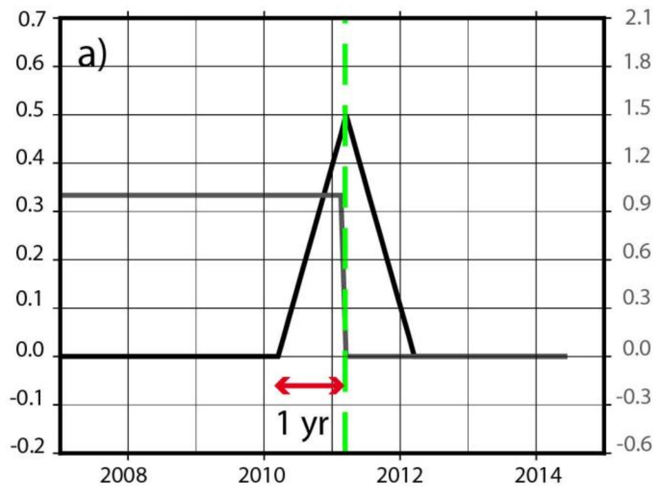
10m thrust slip, 1200-km x 100-km plane, dip 30°, strike 220°N.

Top of the fault plane: 5 km depth.

Anomalous transients near the earthquake

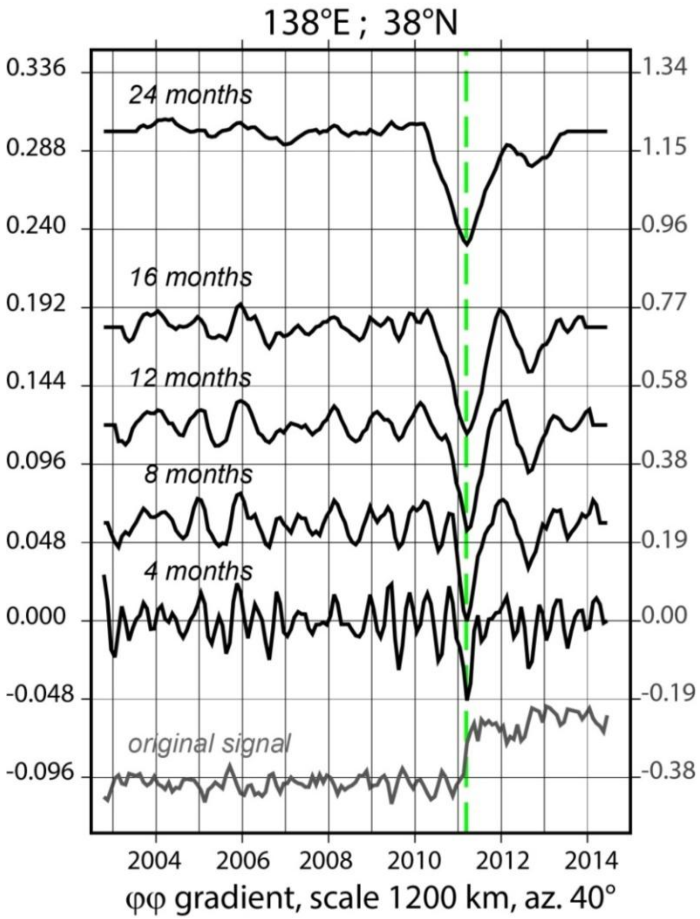
Describe the time variability over months to years, without using prior models, for each spatial scale/orientation.

- *Haar wavelet transform of the time series → increased rates of variations near March 2011 for the different timescales.*



Analysis of a co-seismic step, 12 months scale

→ Abrupt changes before / during/after the earthquake

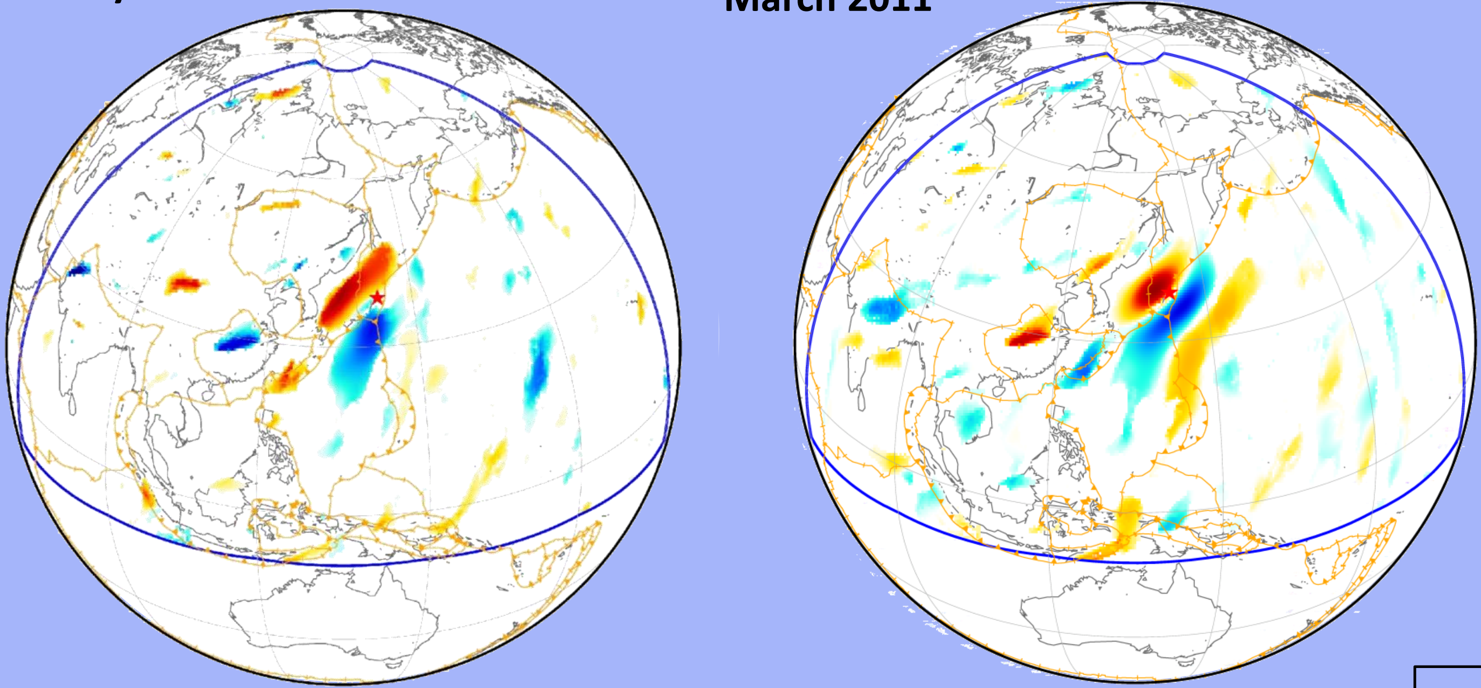


Abrupt time changes, regionally coherent

Cumulated gravity variation ($T_{\varphi\varphi}$ gradient) over:

July-February 2011

March 2011



sc. 1400 km
rot. 20-55°

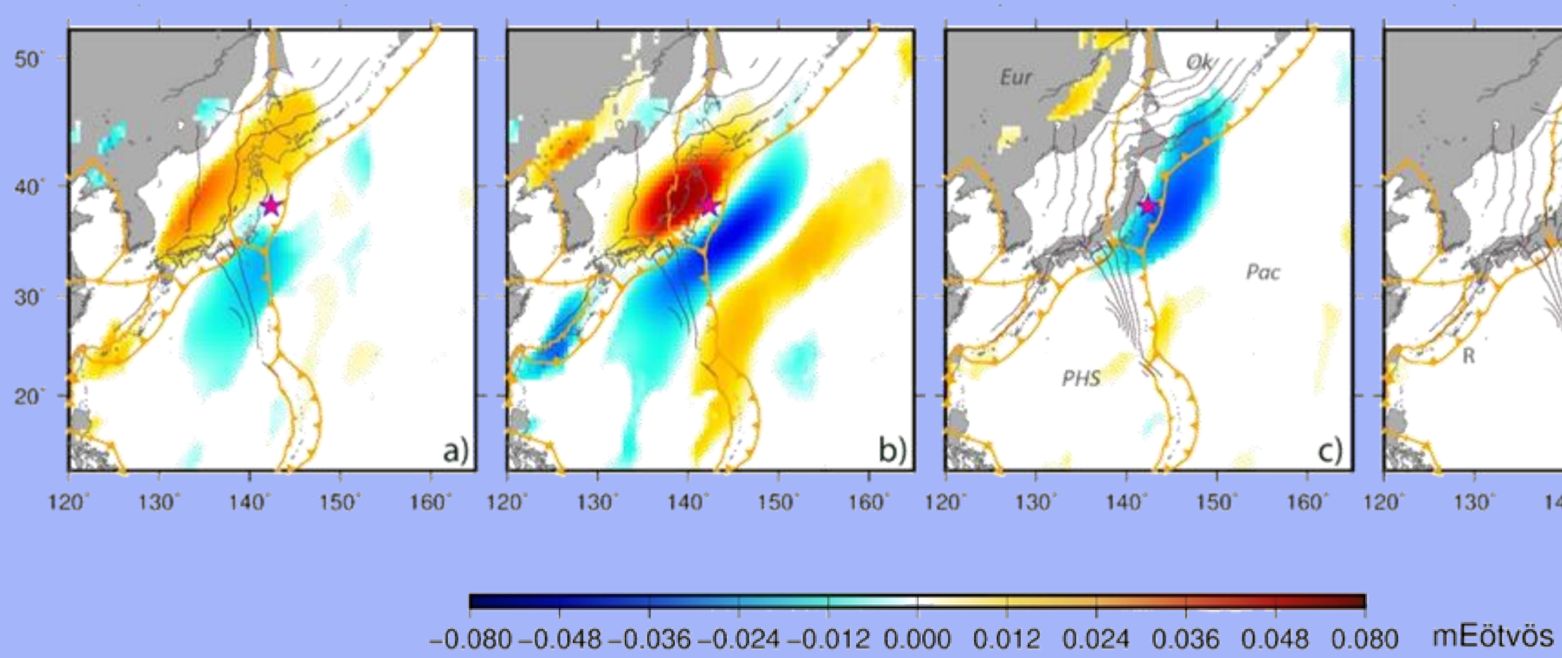
colorscale x 1

x 2

cumulated variations, mEötvös

A gravitational image of the earthquake

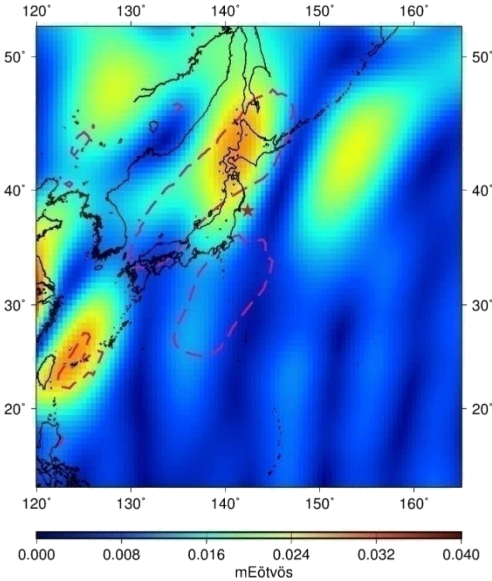
July 2010 -February 2011 | March 2011 | April 2011 – March 2012 | April 2012 – May 2014



Tφφ
sc. 1400 km
rot. 20-55°

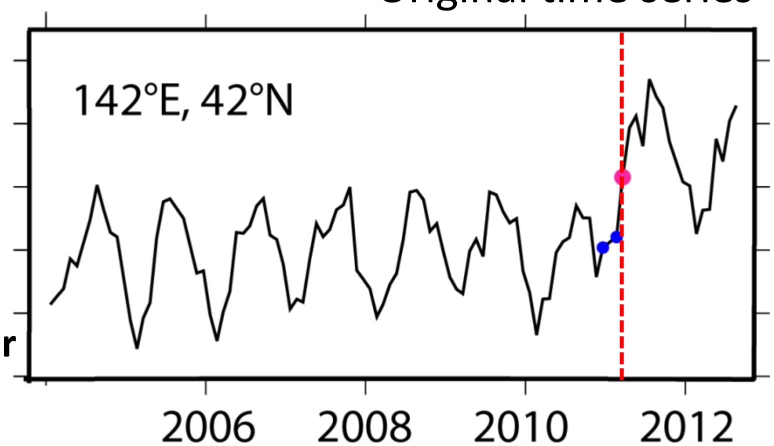
Pre-seismic trend changes

Amplitude of the annual cycle fitted in the GRACE data



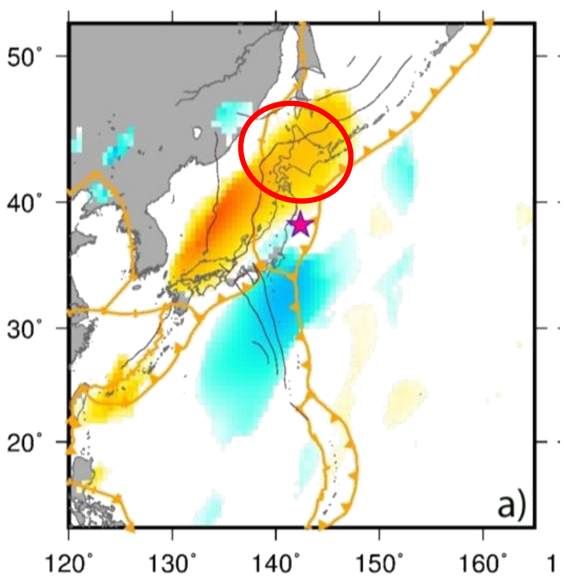
A regular annual cycle (winter snow).

Original time series

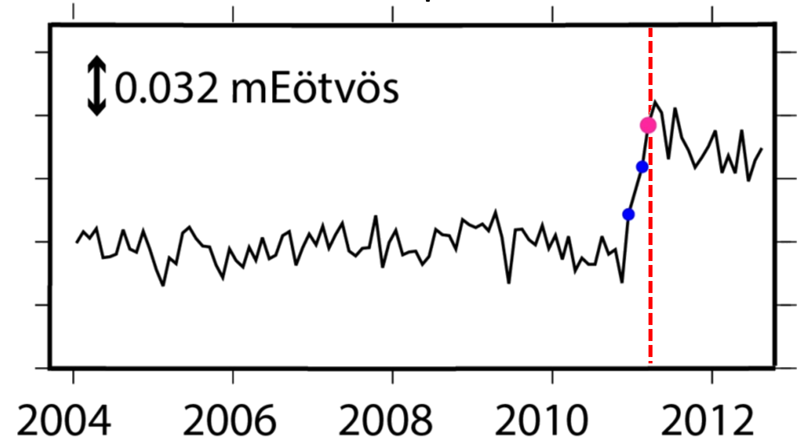


Winter 2010/2011: A large, continued gravity increase over 4 months near the annual minimum

July 2010 - February 2011



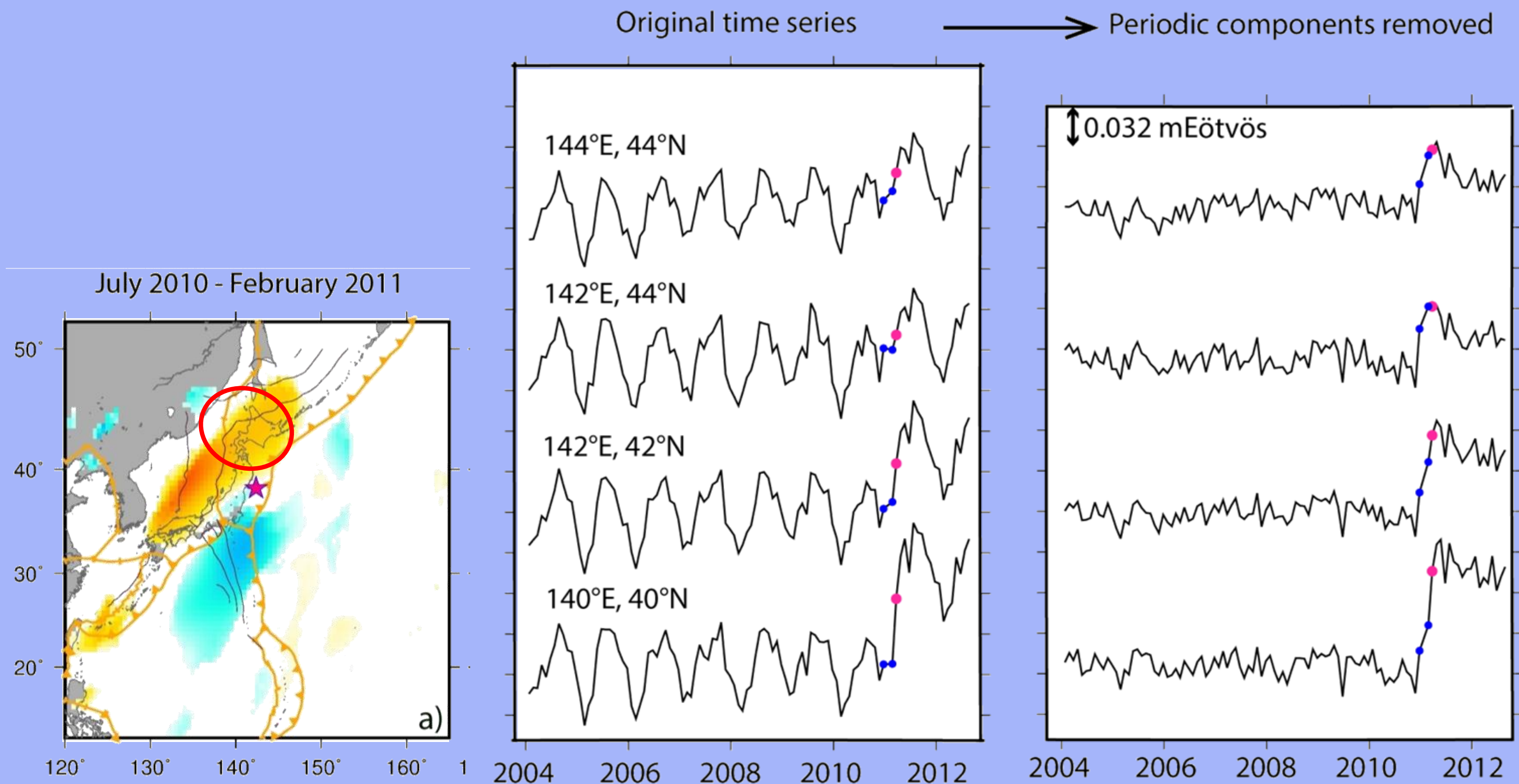
Periodic components removed



Previous years: A constant, slow trend

● Dec. 2010, February 2011; ● March 2011

Time series: Northern Japan



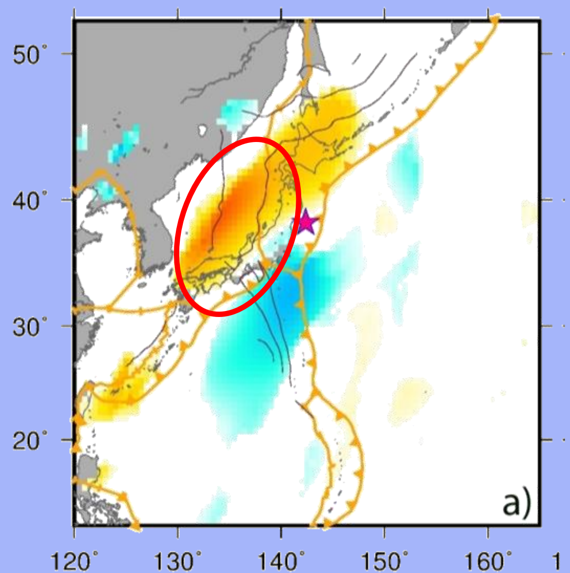
Tφφ
sc. 1400 km
rot. 20-55°

● Dec. 2010, February 2011; ● March 2011

Time series: Sea of Japan

GRACE dealiasing ocean model added back

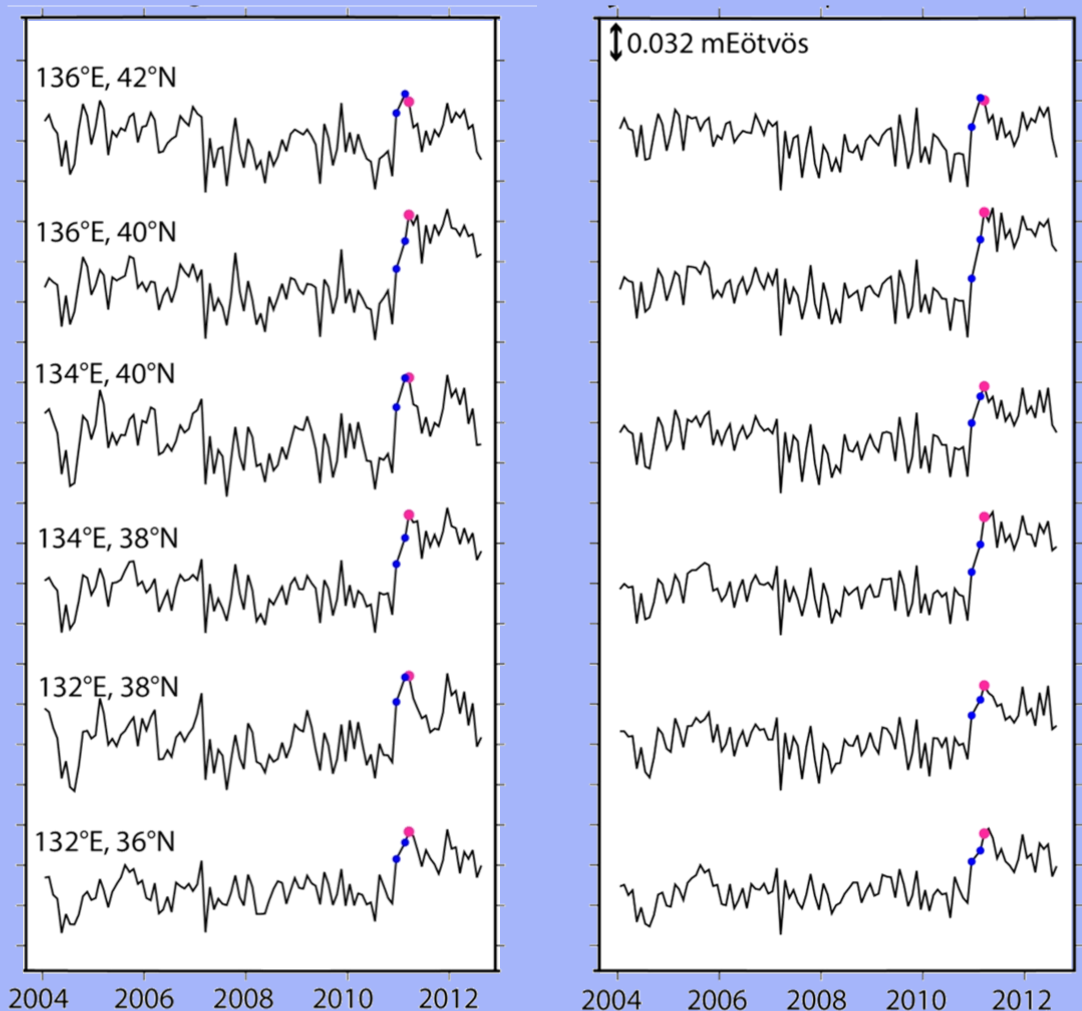
July 2010 - February 2011



Tφφ
sc. 1400 km
rot. 20-55°

Original time series

Periodic components removed

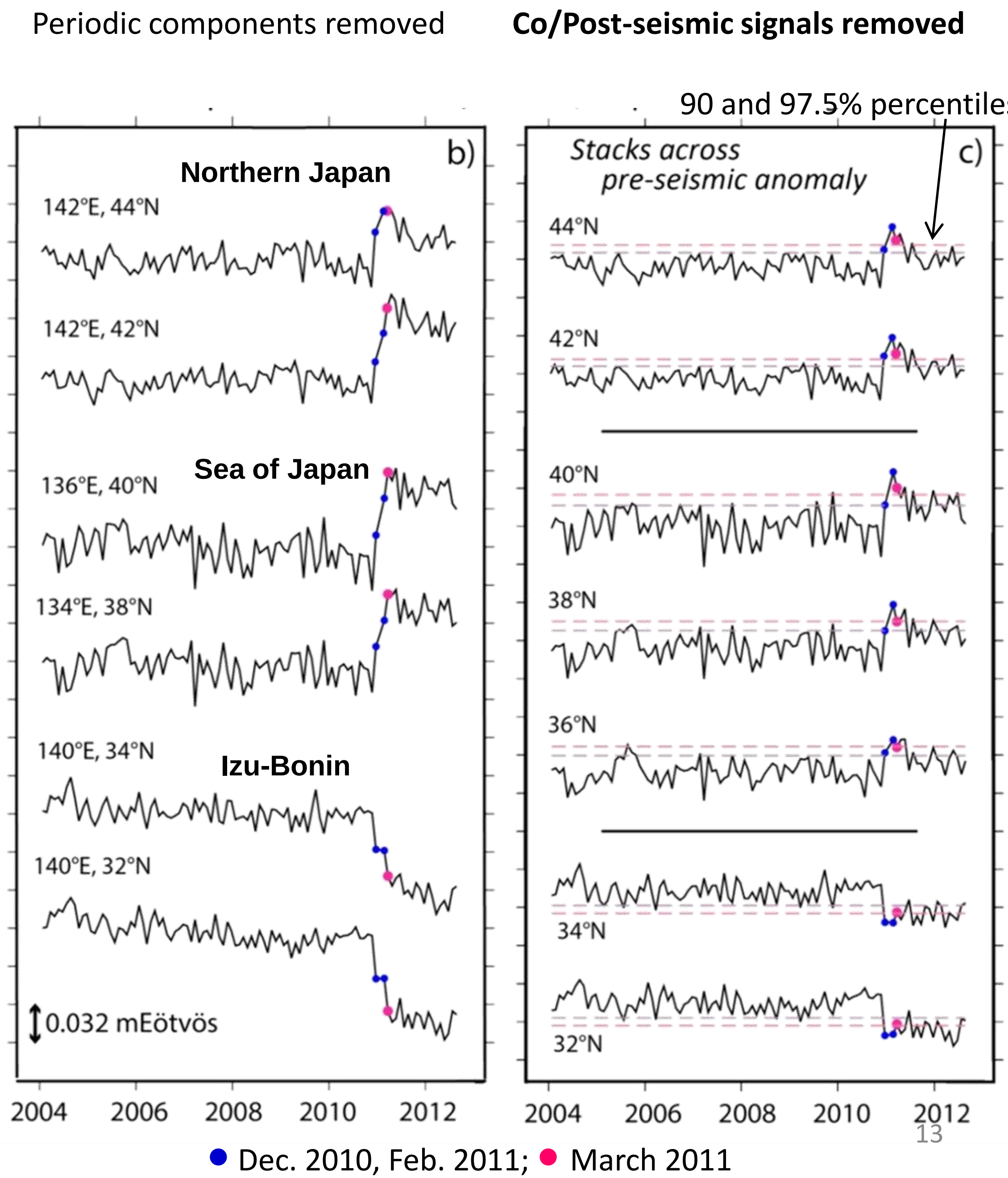


● Dec. 2010, February 2011 ; March 2011

A step-like temporal signature

Contrasting with other large sudden deviations, the pre-seismic signal does not vanish.

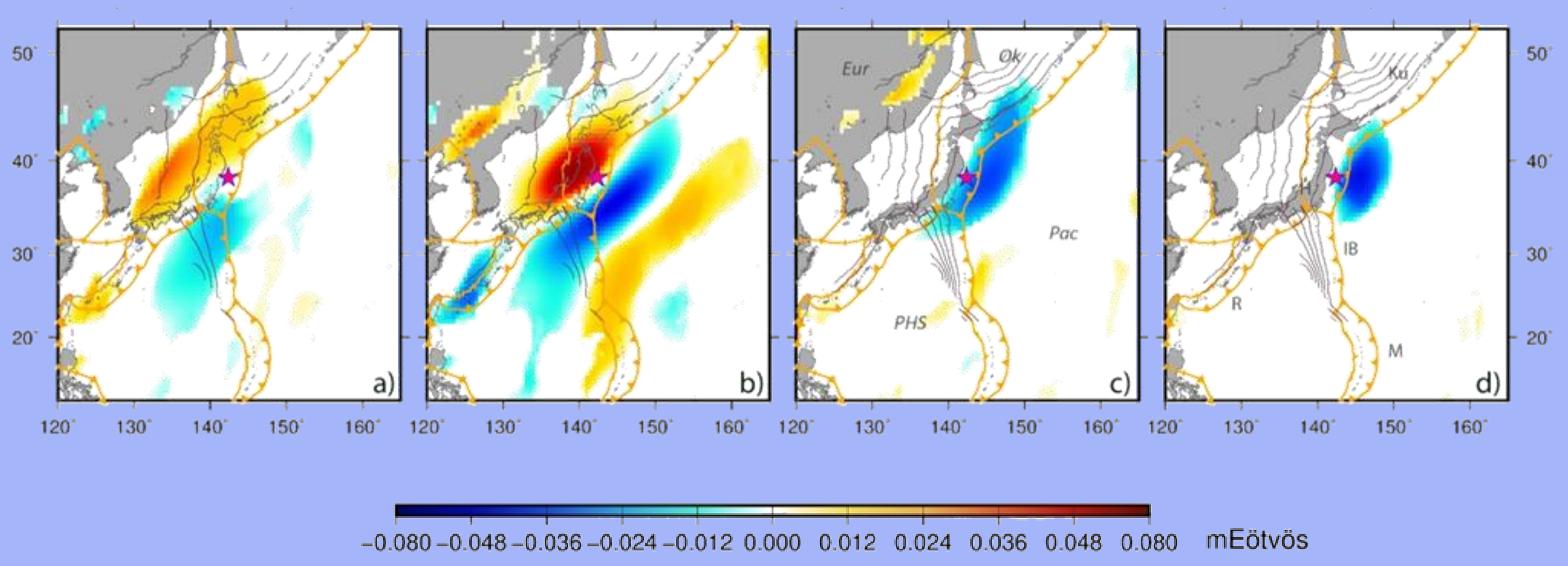
- *persistent fingerprint in the gravity field,*
- *large amplitude with respect to usual water signals & noises,*
- *sea/ocean/island spatial pattern.*



Tφφ
sc. 1400 km
rot. 20-55°

❶ Regional orientation, persistent from pre-seismic to co-seismic (March 2011) phases

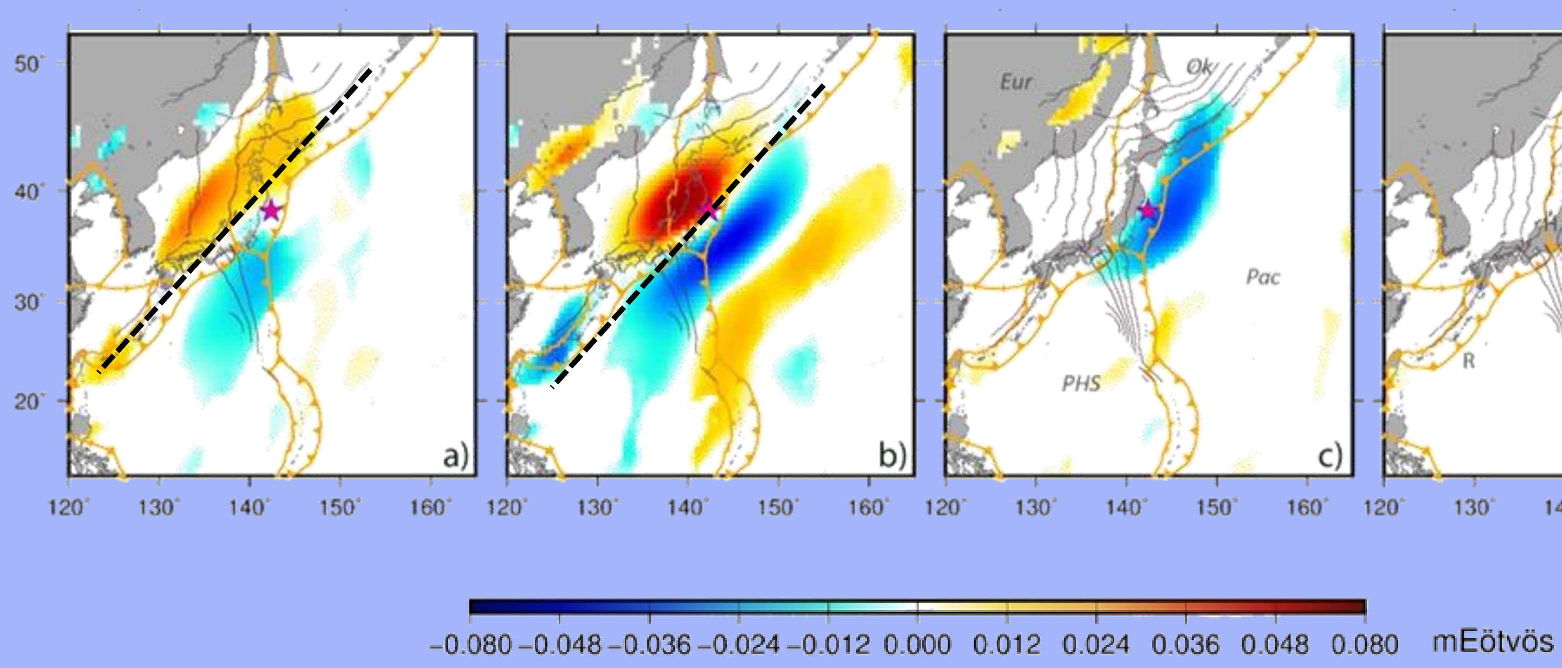
July 2010 -February 2011 | March 2011 | April 2011 – March 2012 | April 2012 – May 2014



Signals follow the geometry of the regional subduction

❶ Regional orientation, persistent from pre-seismic to co-seismic (March 2011) phases

July 2010 -February 2011 | March 2011 | April 2011 – March 2012 | April 2012 – May 2014

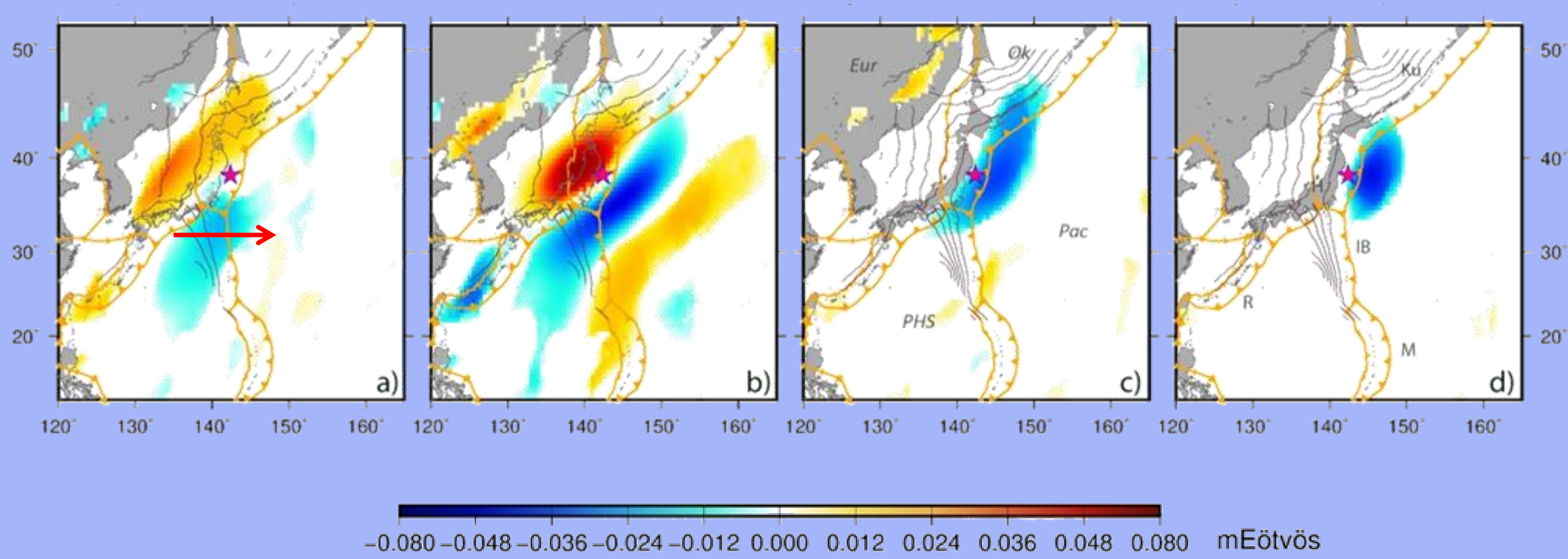


Signals follow the geometry of the regional subduction

Tφφ
sc. 1400 km
rot. 20-55°

❷ Eastward propagation of the gravity signals

July 2010 -February 2011 | March 2011 | April 2011 – March 2012 | April 2012 – May 2014



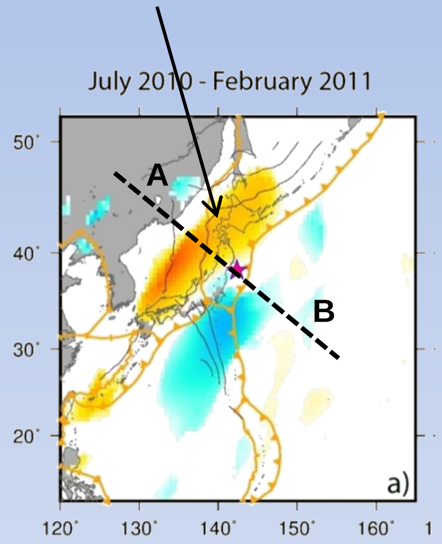
The rupture is part of a broad, depth-to-surface sequence of motions

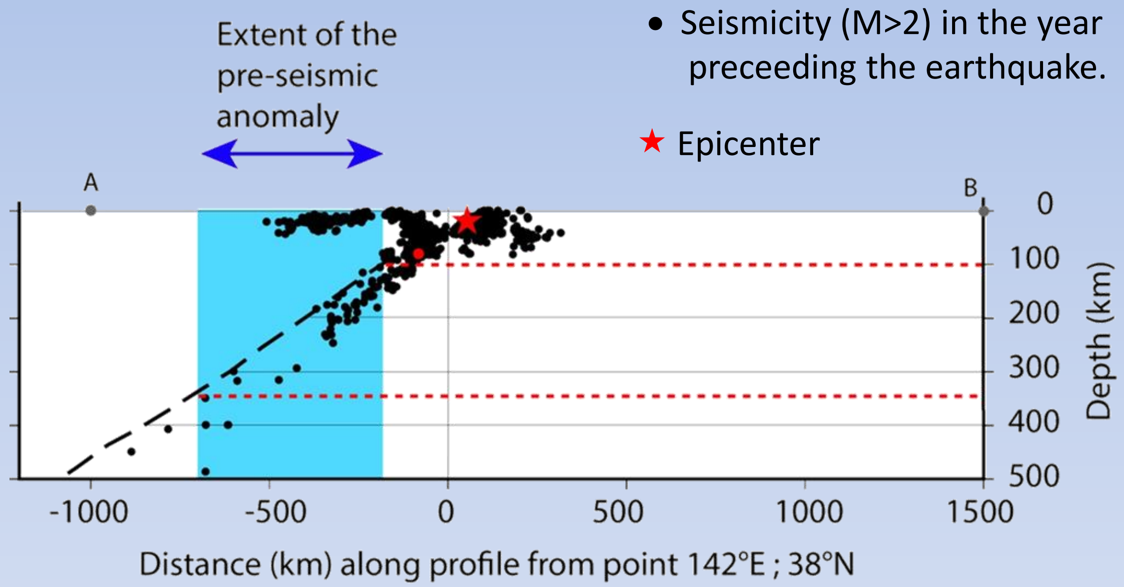
❶ + ❷ → A subduction episode at regional scale

Before the rupture

Large-scale gravity gradient high (no detection at smaller scales)

→ Mass decrease; a broadscale source.





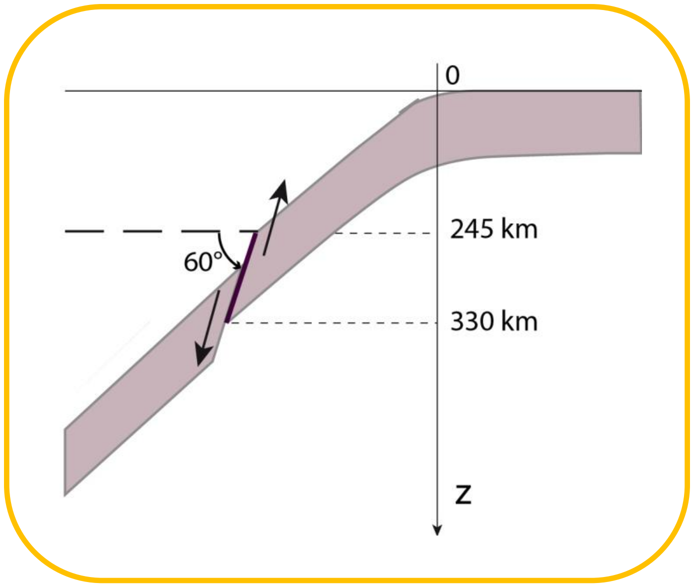
Mass decrease in the slab → Slab extension at regional scale

→ **Depths 100-350 km**

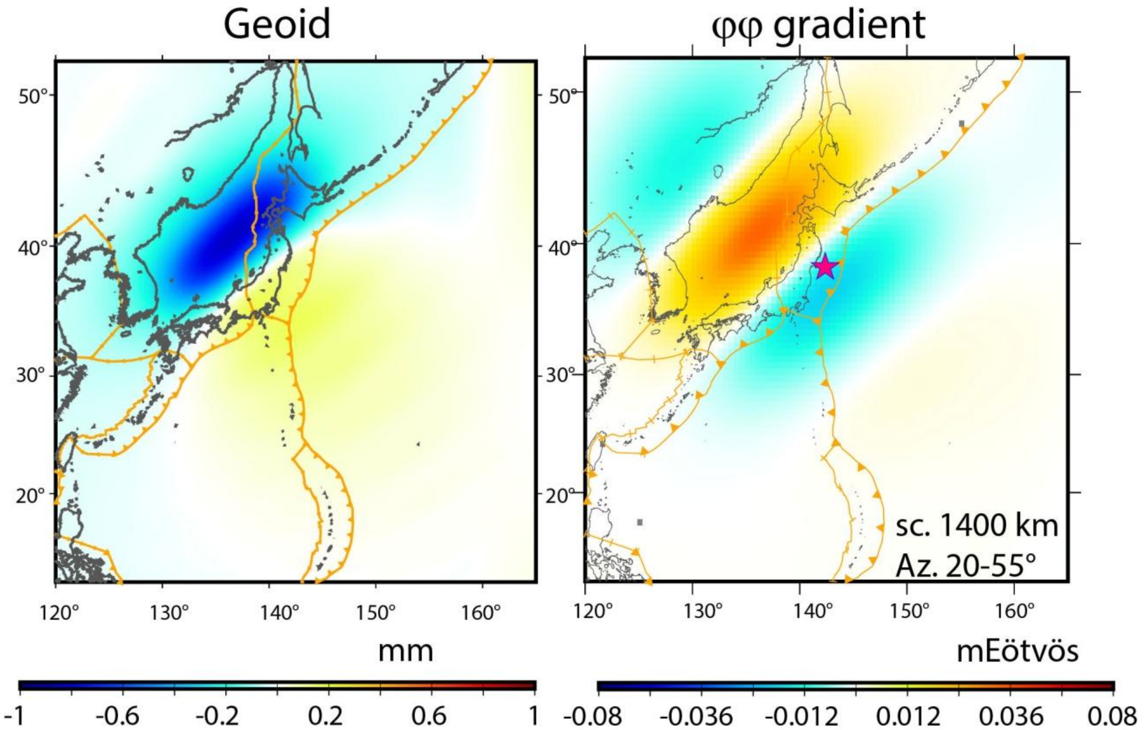
→ Precedes at depth the shallower acceleration of the seismic release reported before the rupture (Bouchon *et al.*, 2016).

Precursory slab extension

Equivalent quasi-static slip model, normal faulting:
a M_w 8.4 event over a few months.



Slip 40 cm
100 x 1200 km^2 plane



→ Subduction acceleration at depth

Tφφ
rot. 20-55°

Co-seismic signals: gravity vs geodesy

Co-seismic slip model: Minson et al. (2014), based on: surface and seafloor geodesy, tsunami data

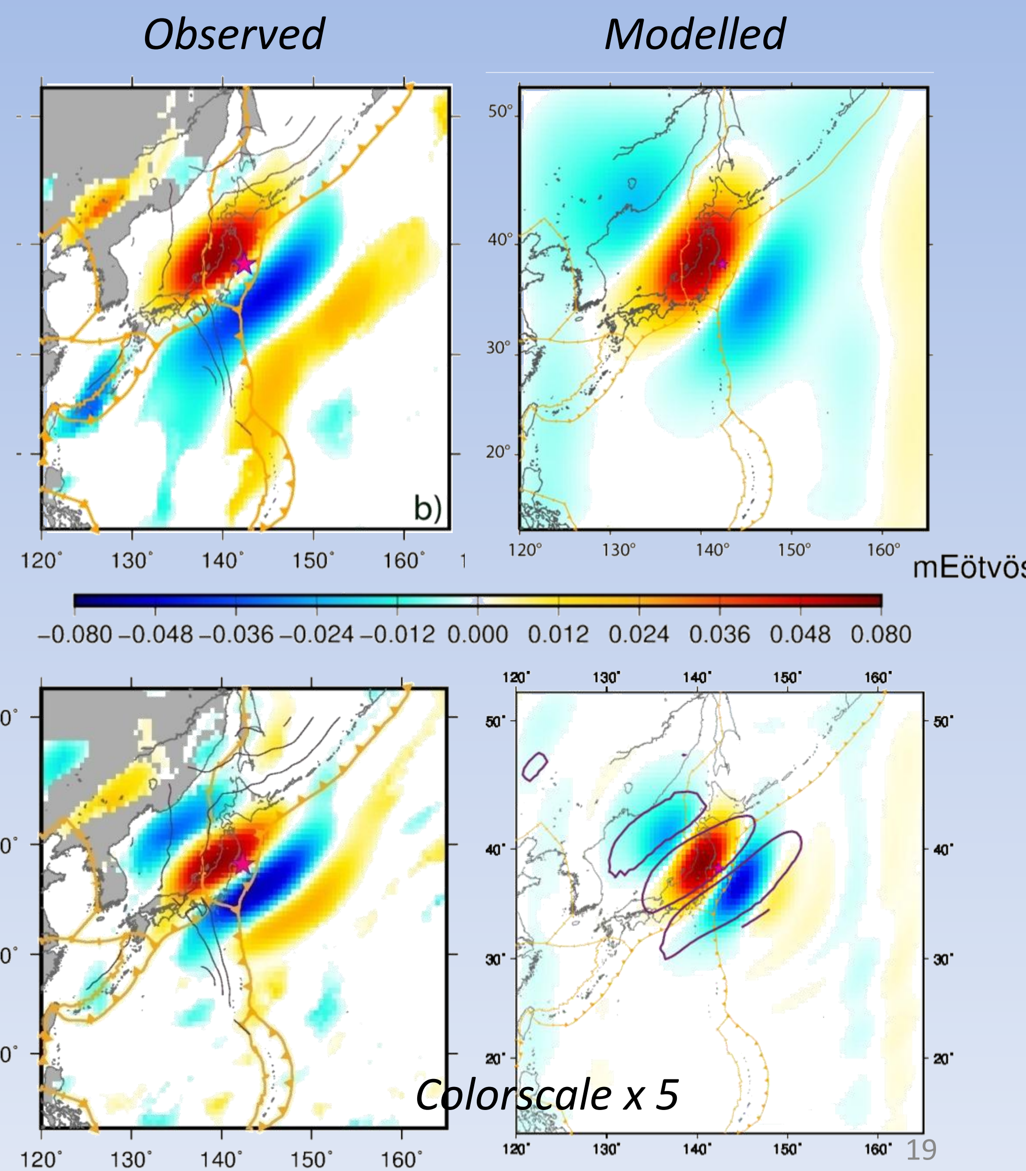
- **Orientation**: local versus regional strike of the subduction.

- **Spatial extent**: gravity indicates motion of both oceanic plates across the triple junction.

GRACE: a larger deformation pattern near the rupture than detected from geodesy.

1400-km

Zoom at 800-km



Conclusions

- From gravity, episodic mass transfers at timescales of months are detected within the entire subduction system.
- Deep precursors are thus found for the Tohoku earthquake; need to perform the analysis for other giant events.
- Highly deformable layers in the slab and at its boundaries are needed to enable pre-seismic deformation rates of 10^{-12} s^{-1}.
- Such layers decouple deep motions from the surface $\rightarrow$ no crustal deformation.
- Time-varying satellite gravity provides unique information on the dynamics of mass redistributions related to giant events, including in the pre-seismic phase.