Deep mass redistribution prior to the Maule earthquake revealed by GRACE satellite gravity

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Context of the study

➔ Identifying pre-seismic signals remains a key challenge in geophysics

The imaging of subduction zone motion remains incomplete :

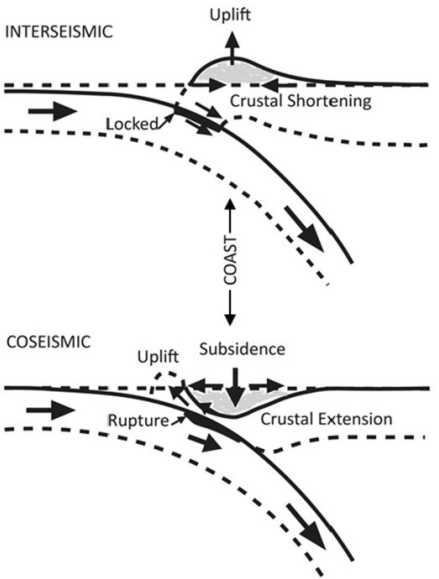
How does the motion occur at depth ?

How to link earthquakes to the regional slab movements ?

↓

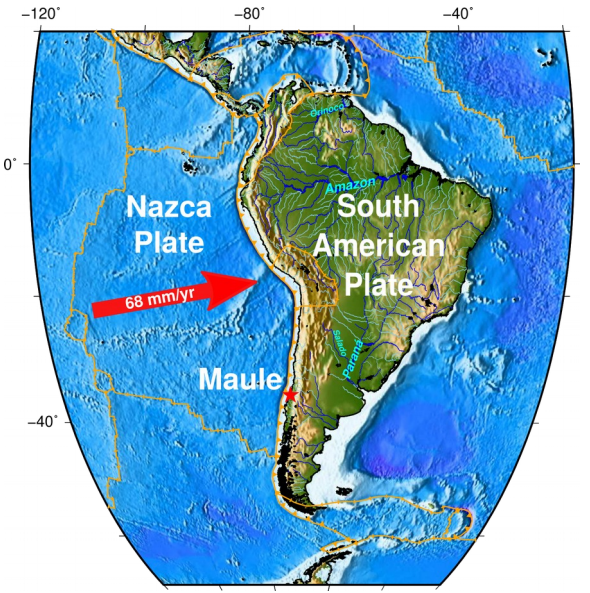
Spatial gravimetry :

Depth sensibility
Global spatial coverage



(Penserini et al., 2017)

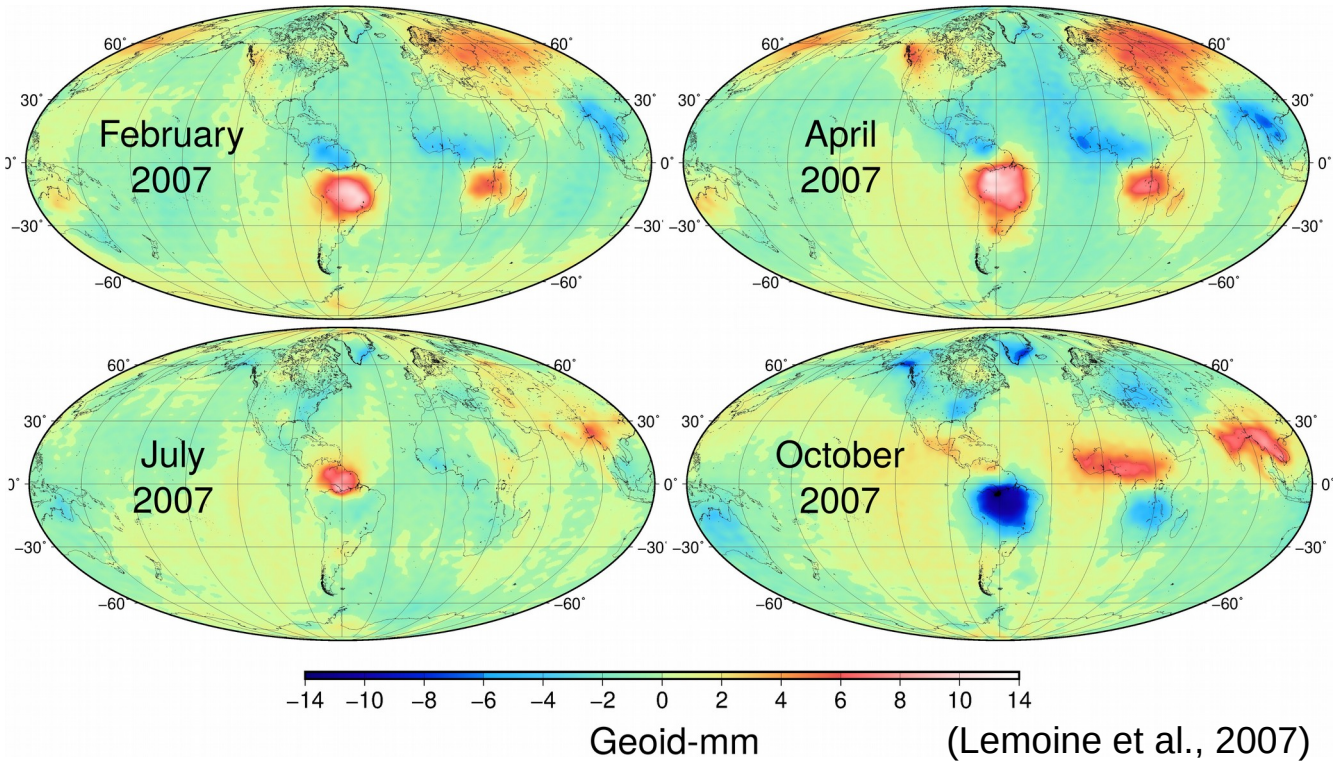
Subduction of the Nazca plate under the American plate



The Maule earthquake:
Mw = 8.8, February 27, 2010

The GRACE-derived geoids anomalies

- **GRACE mission :** precise measurements of **spatio-temporal variations** of the gravity field (2002-2017)
- **Multiplicity of sources:** hydrology, ice melting, aliasing, solid earth deformations

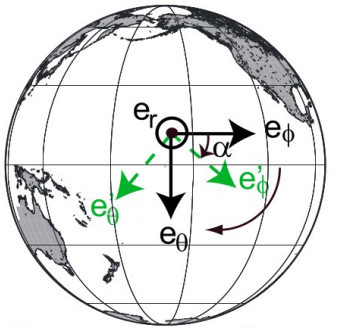


(Lemoine et al., 2007)

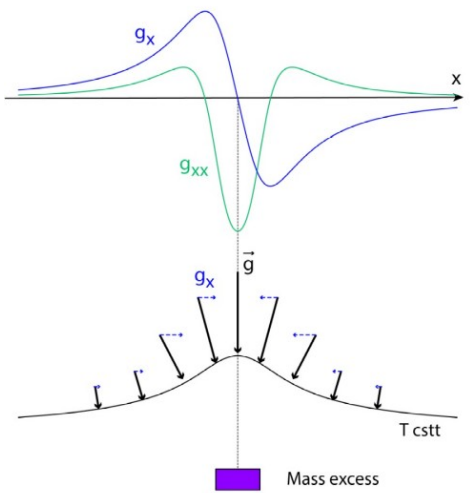
How to **separate solid earth deformations signals** from **signals associated to other sources** ?

Sources separation

Separation according to source **size and orientation**

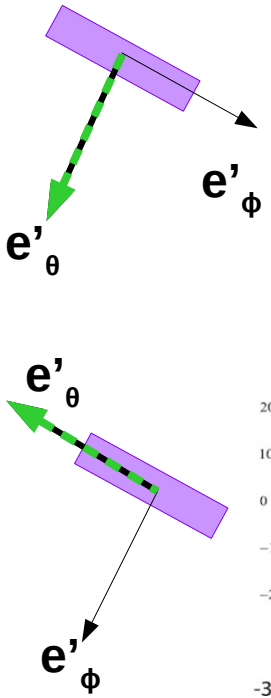


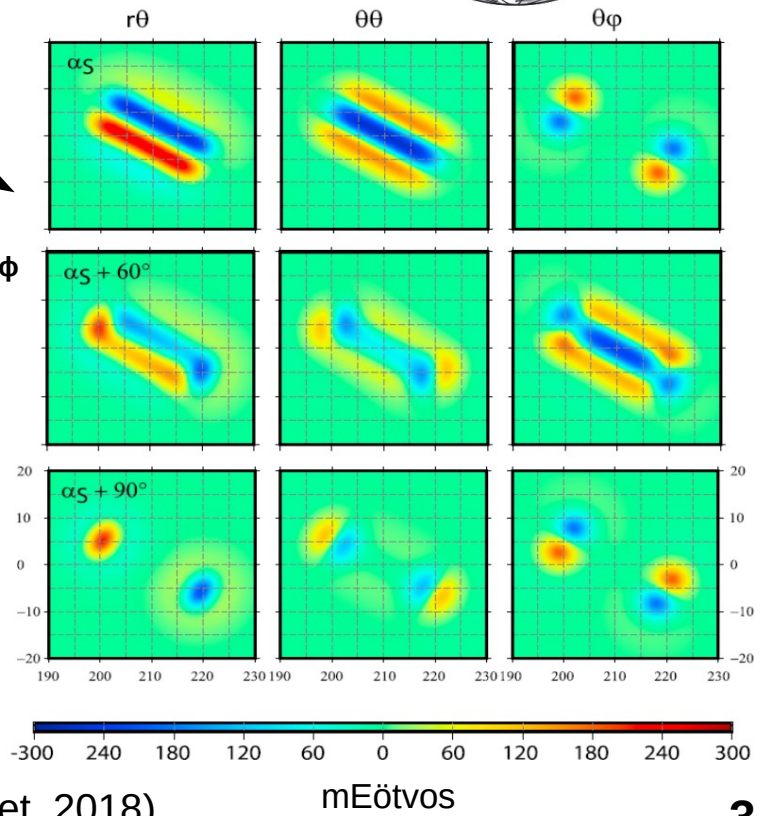
- **Wavelet filtering :** separate the signals based on their **sizes**
- **Gravity gradients :** characterize the **geometry and orientation** of the gravity signal and its sources



Gravity gradient
=
Second directional derivative of the gravity potential

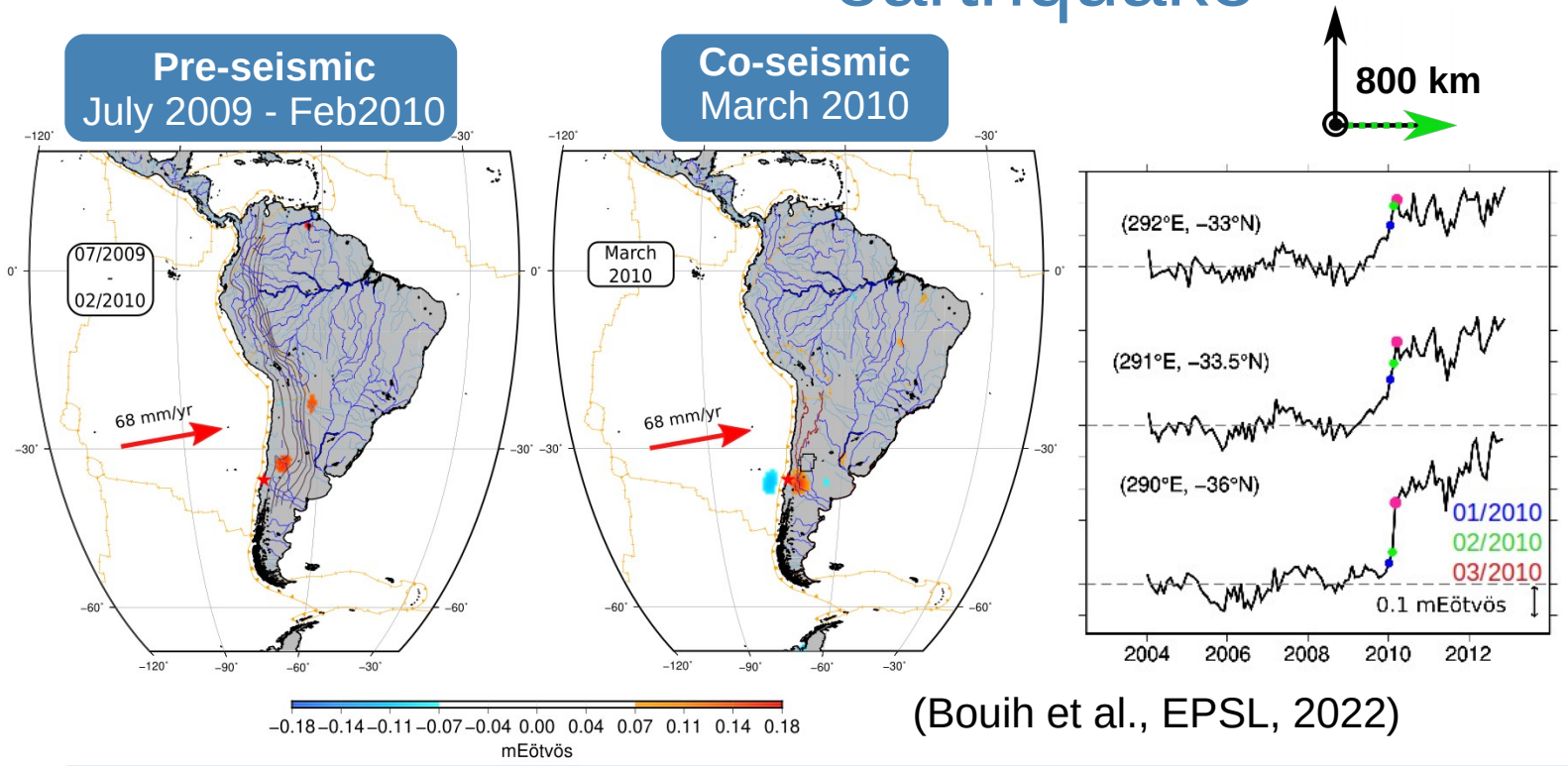
Green arrow represents the differentiation direction





(Panet, 2018)

Gravitational signals before and during the Maule earthquake



(Bouih et al., EPSL, 2022)

Spatial representation of **highly anomalous signals** showing :

- a **trend** from July 2009 to Feb 2010 **(preseismic)**
- a **jump** between Feb and March 2010 **(coseismic)**

Progressive gravity gradient increase North of Maule between July 2009 and February 2010.

Stabilization in March 2010

Signal **consistent in 3 geoid solutions:** GRGS03, CSR06 and ITSG2016

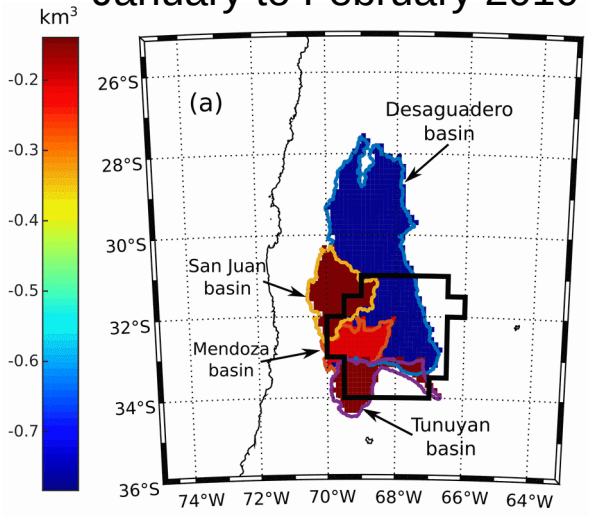
A signal of hydrological origin?

Comparison between GRACE and :

- **in-situ data** (evaluation of water storage variations)
- **4 different hydrological models**

Water storage variations

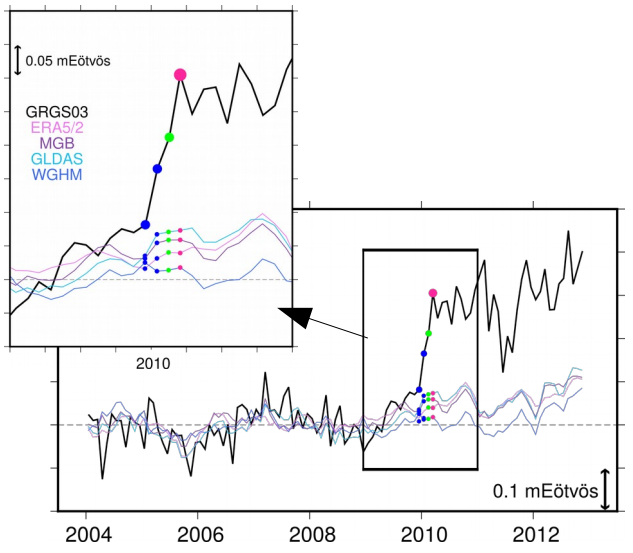
January to February 2010 :



GRACE signal correspond to a loss of **60 km³** of water

Estimation from **in-situ data** = **1,2 km³** of water

Hydrological models



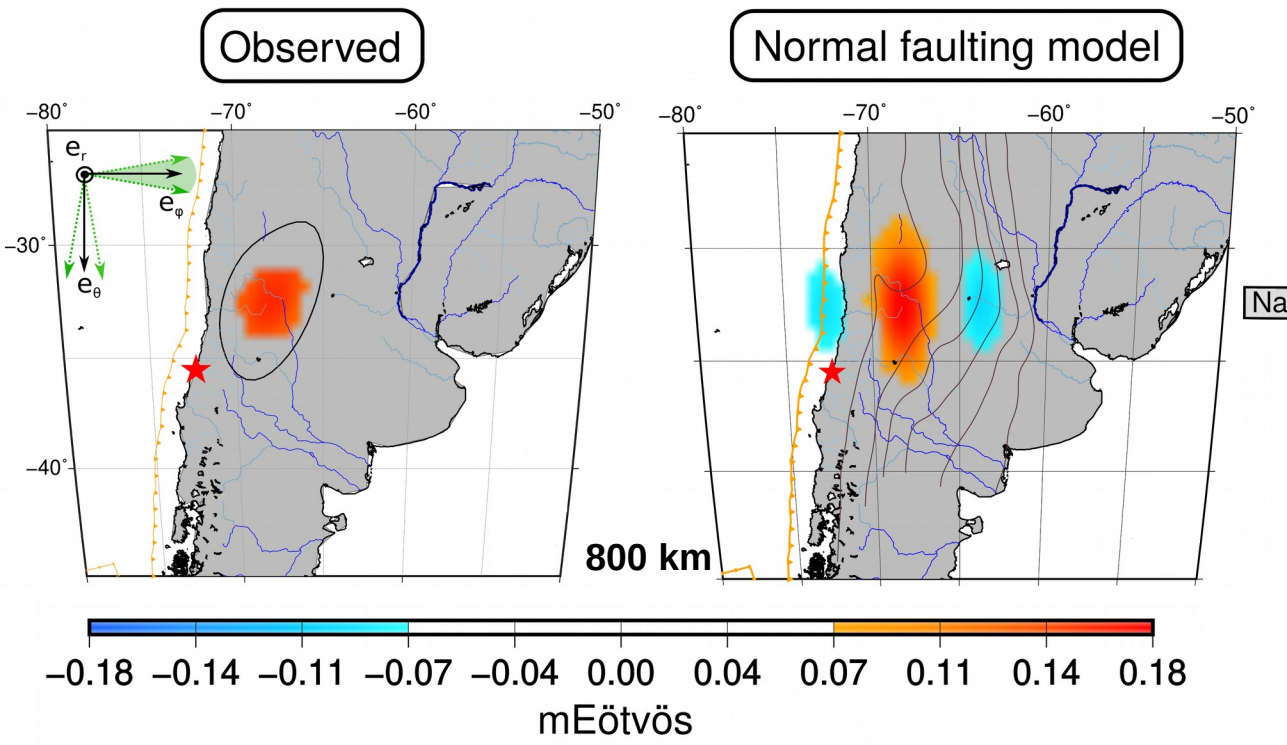
2004 - 2009: Good agreement

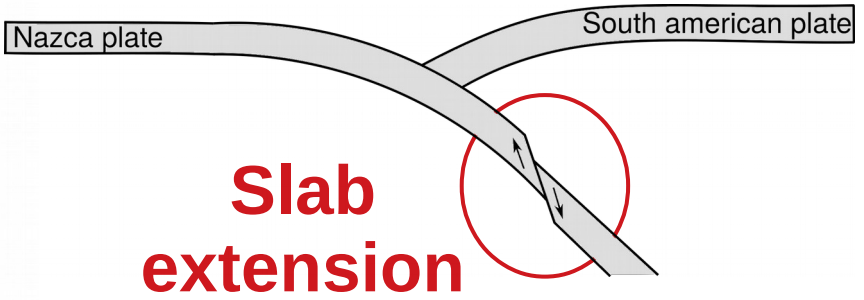
2 months before the earthquake: Disagreement

The signal observed by GRACE **is not explained by a water mass redistribution** predicted by the models or recorded from in-situ data

A deep pre-seismic mass redistribution

- The signal could be explained by a **slab extension ~150 km deep**





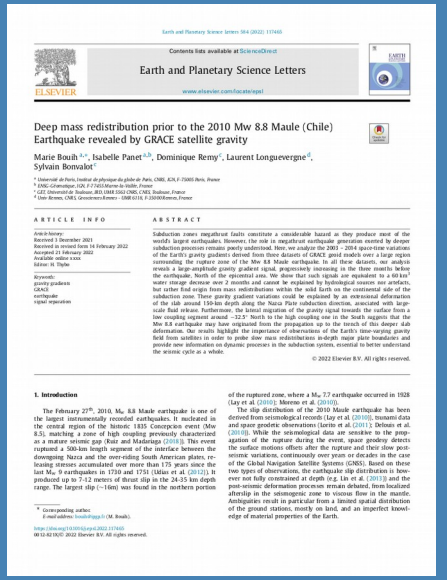
- Normal fault slip model
- Deformation equivalent to a **Mw 8.2** earthquake over ~2 months

Conclusion

From the end of 2009 and March 2010 : the signal migrates from depth to the surface.

The Maule earthquake may have originated from the propagation up to the surface of this deep deformation.

For more details : Bouih et al., EPSL, 2022



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Deep mass redistribution prior to the 2010 Mw 8.8 Maule (Chile) Earthquake revealed by GRACE satellite gravity

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ABSTRACT

Subduction zones megathrust faults constitute a considerable hazard as they produce most of the world's largest earthquakes. However, the role in megathrust earthquake generation exerted by deeper subduction processes remains poorly understood. Here, we analyze the 2003 – 2014 space-time variations of the Earth's gravity gradients derived from three datasets of GRACE geoid models over a large region surrounding the rupture zone of the Mw 8.8 Maule earthquake. In all these datasets, our analysis reveals a large-amplitude gravity gradient signal, progressively increasing in the three months before the earthquake. North of the epicentral area. We show that such signals are equivalent to a 60 km³ water storage decrease over 2 months and cannot be explained by hydrological sources nor artefacts, but rather find origin from mass redistributions within the solid Earth on the continental side of the subduction zone. These gravity gradient variations could be explained by an extensional deformation of the slab around 150-km depth along the Nazca Plate subduction direction, associated with large-scale fluid release. Furthermore, the latent migration of the gravity signal towards the surface from a low coupling segment around −32.5° North to the high coupling one in the South suggests that the Mw 8.8 earthquake may have originated from the propagation up to the trench of this deeper slab deformation. Our results highlight the importance of observations of the Earth's time-varying gravity field from satellites in order to probe slow mass redistributions in-depth major plate boundaries and provide new information on dynamic processes in the subduction system, essential to better understand the seismic cycle as a whole.

1. Introduction

The February 27th, 2010, M_w 8.8 Maule earthquake is one of the largest instrumentally recorded earthquakes. It nucleated in the central region of the historic 1835 Concepcion event (Mw 8.5), matching a zone of high coupling previously characterized as a mature seismic gap (Ruiz and Madariaga (2018)). This event ruptured a 500-km length segment of the interface between the downgoing Nazca and the over-riding South American plates, releasing stresses accumulated over more than 175 years since the last M_w 9 earthquakes in 1730 and 1751 (Ulloa et al. (2012)). It produced up to 7–12 meters of thrust slip in the 24-35 km depth range. The largest slip (~16m) was found in the northern portion of the ruptured zone, where a M_w 7.7 earthquake occurred in 1928 (Lay et al. (2010); Moreno et al. (2010)).

The slip distribution of the 2010 Maule earthquake has been derived from seismological records (Lay et al. (2010)), tsunami data and space geodetic observations (Lorito et al. (2011); Delouis et al. (2010)). While the seismological data are sensitive to the propagation of the rupture during the event, space geodesy detects the surface motions offsets after the rupture and their slow post-seismic variations, continuously over years or decades in the case of the Global Navigation Satellite Systems (GNSS). Based on these two types of observations, the earthquake slip distribution is however not fully constrained at depth (e.g. Lin et al. (2013)) and the post-seismic deformation processes remain debated, from localized afterslip in the seismogenic zone to viscous flow in the mantle. Ambiguities result in particular from a limited spatial distribution of the ground stations, mostly on land, and an imperfect knowledge of material properties of the Earth.

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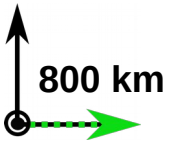
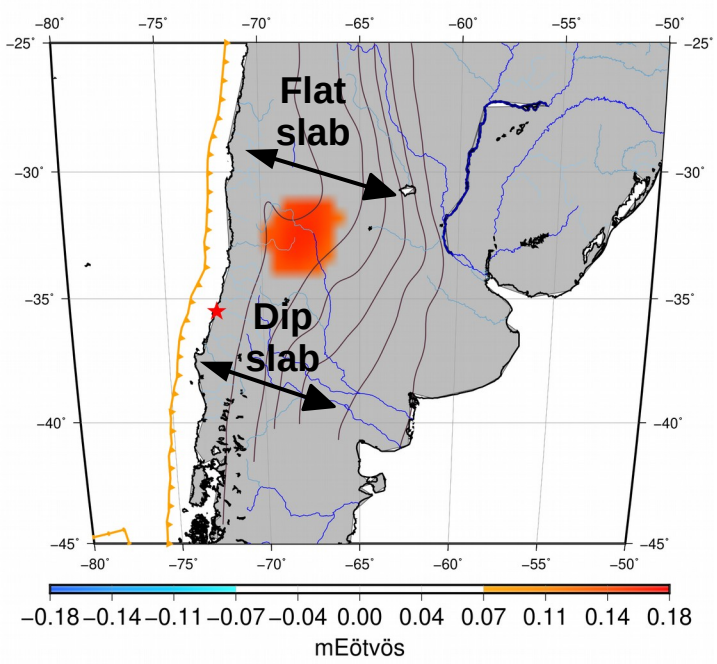
Interpretation



Pre-seismic signal

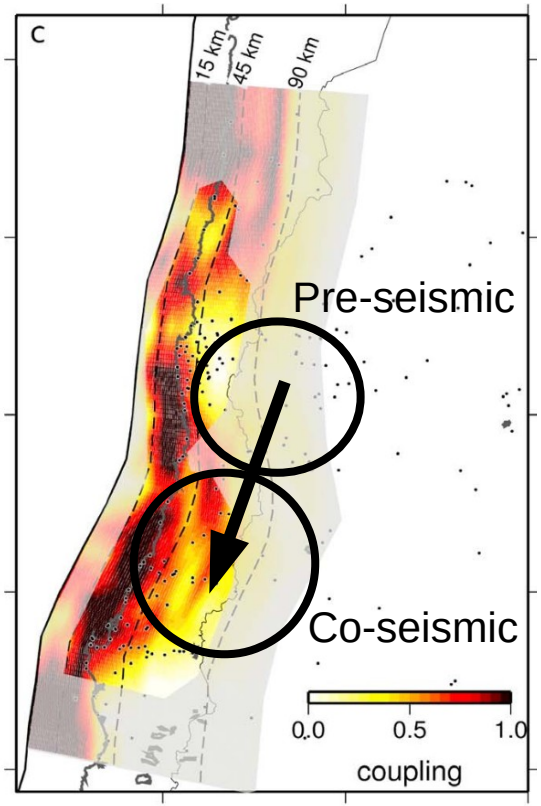


Anomaly localized in an area of **change in slab dip** (Anderson et al., 2007)
→ **Strong extensional stresses**

Migration of the gravity signal **from the deeper side** of the subduction **to the shallower side :**

- ***Deep*** *deformation* ***propagating to the surface***
- *Propagation in-depth of* ***low coupled to high coupled*** *sections of the subduction*

Coupling distributions



(Métois et al., 2012)