Multiple observations and modeling of the tiny ground motions associated with coseismic gravity changes

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With inputs from Jean Paul Ampuero, Olivier Coutant, Robert Busby, Kasey Aderhold, Jean-Paul Montagner…

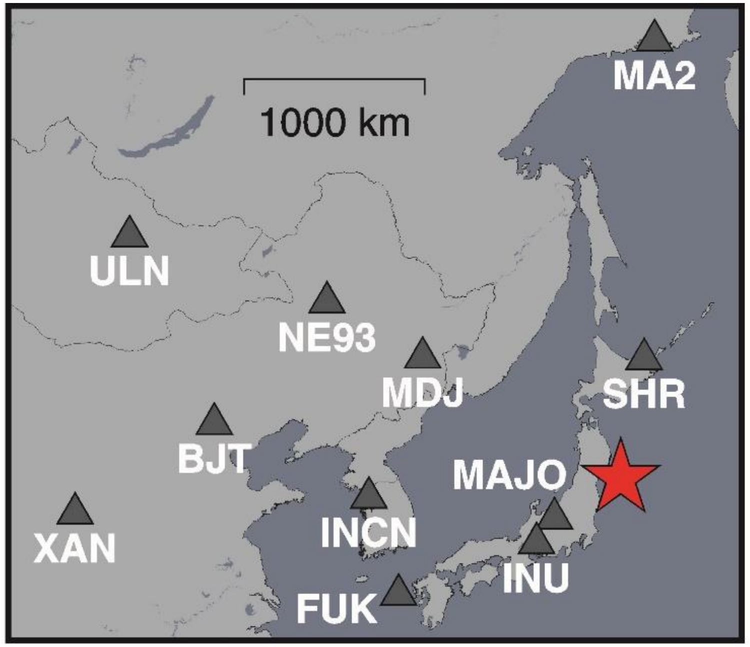
Extensive use of **publicly available broadband networks**

Numerical modeling of earthquake motions – Smolenice – July 3, 2019

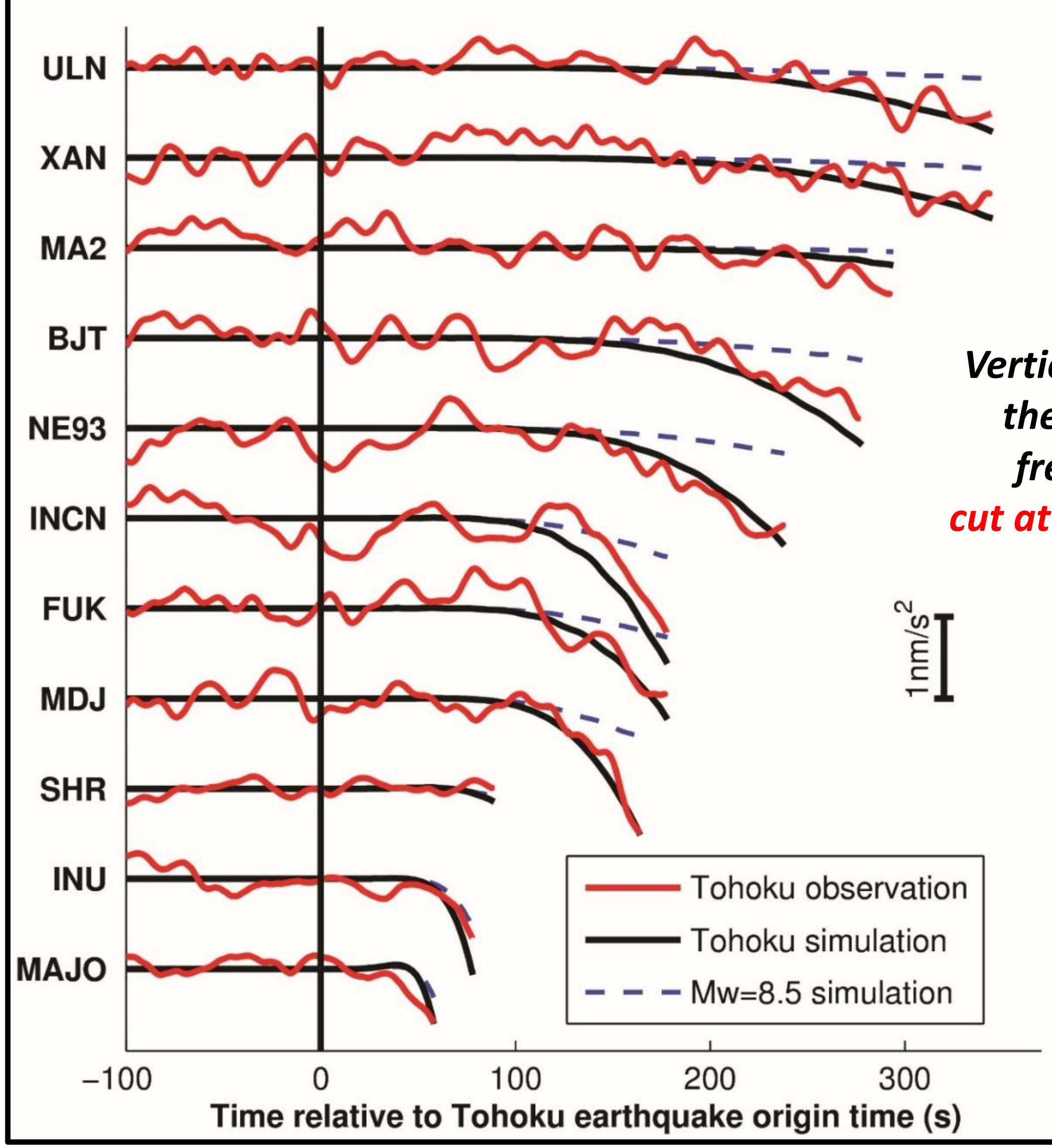
The Prompt Elastogravity Signals (PEGS)

- Use of an **unexploited** part of the seismograms : the time window **between origin time and P-wave arrival**
- High potential for **rapid determination of large earthquake source parameters**

First observed during the 2011 Mw=9.1 Tohoku earthquake [*Montagner et al., 2016; Vallée et al, 2017*]



At high-quality broadband stations, the PEGS are observed, modeled, and their amplitudes are strongly magnitude-dependent



Vertical acceleration in the [0.002-0.03Hz] frequency range, cut at the P wave arrival time

Vallée et al., Science, 2017

How do we understand and model the Prompt Elastogravity Signals ?

$$\begin{cases} \rho_0\,\ddot{\mathbf{u}} = \boldsymbol{\nabla}\cdot\boldsymbol{\sigma} + \Delta\rho\,\mathbf{g_0} + \boldsymbol{f} + \rho_0\,\boldsymbol{\Delta}\mathbf{g}\,, \\ \nabla\cdot\boldsymbol{\Delta}\mathbf{g} = -4\pi G\,\Delta\rho\,, \\ \Delta\rho = -\nabla\cdot(\rho_0\,\mathbf{u})\,, \end{cases}$$

Force balance equation (earthquake source term *f*)

Poisson equation

Continuity equation

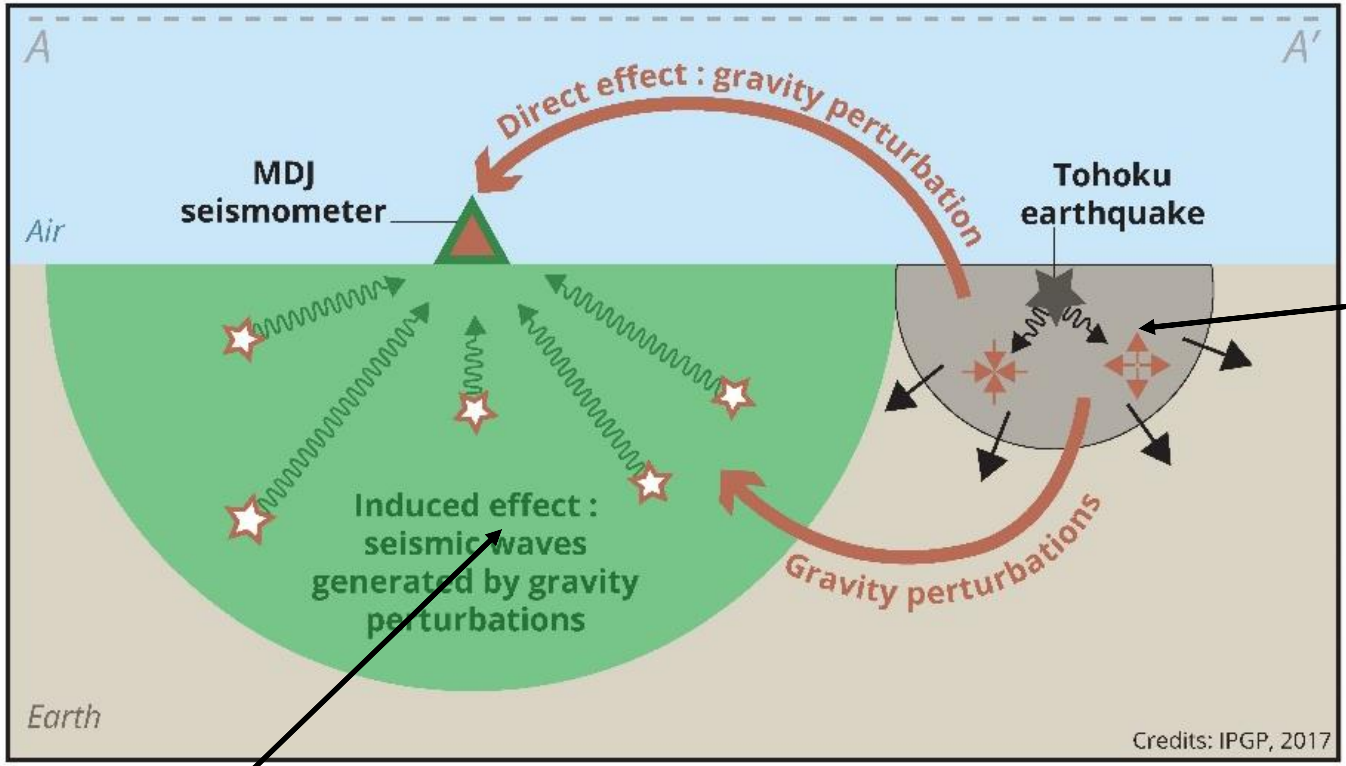
In theory, there is a **full coupling** between the gravitation perturbation **Δg** and the displacement **u**

However, for the force balance equation :

(1) **Close from the source** (i.e. at locations where P waves already arrived), and at not-too-low frequencies (above ~0.001Hz), the source term ***f*** largely dominates over the force gravity terms

(2) **Far from the source** (i.e. where P waves did not arrive yet), the source term ***f*** has no direct influence and the density pertubation can be neglected : the only force term is $\rho_0\boldsymbol{\Delta g}$

Illustration at some time between origin time and P-wave arrival



In the volume directly affected by the elastic waves (grey area) :

$$\rho_0\, \ddot{\mathbf{u}} = \boldsymbol{\nabla}\cdot\boldsymbol{\sigma} + \Delta\rho\, \xcancel{\mathbf{g}_0} + \boldsymbol{f} + \rho_0\, \xcancel{\Delta\mathbf{g}}\,,$$

$\boldsymbol{u}$ can be known everywhere with numerical methods solving the classical elastodynamic equation (e.g. Axitra) with source term $\boldsymbol{f}$ (earthquake)

This creates a gravity perturbation everywhere

$$\begin{cases} \nabla\cdot\Delta\mathbf{g} = -4\pi G\,\Delta\rho\,, \\ \Delta\rho = -\nabla\cdot(\rho_0\,\mathbf{u})\,, \end{cases}$$

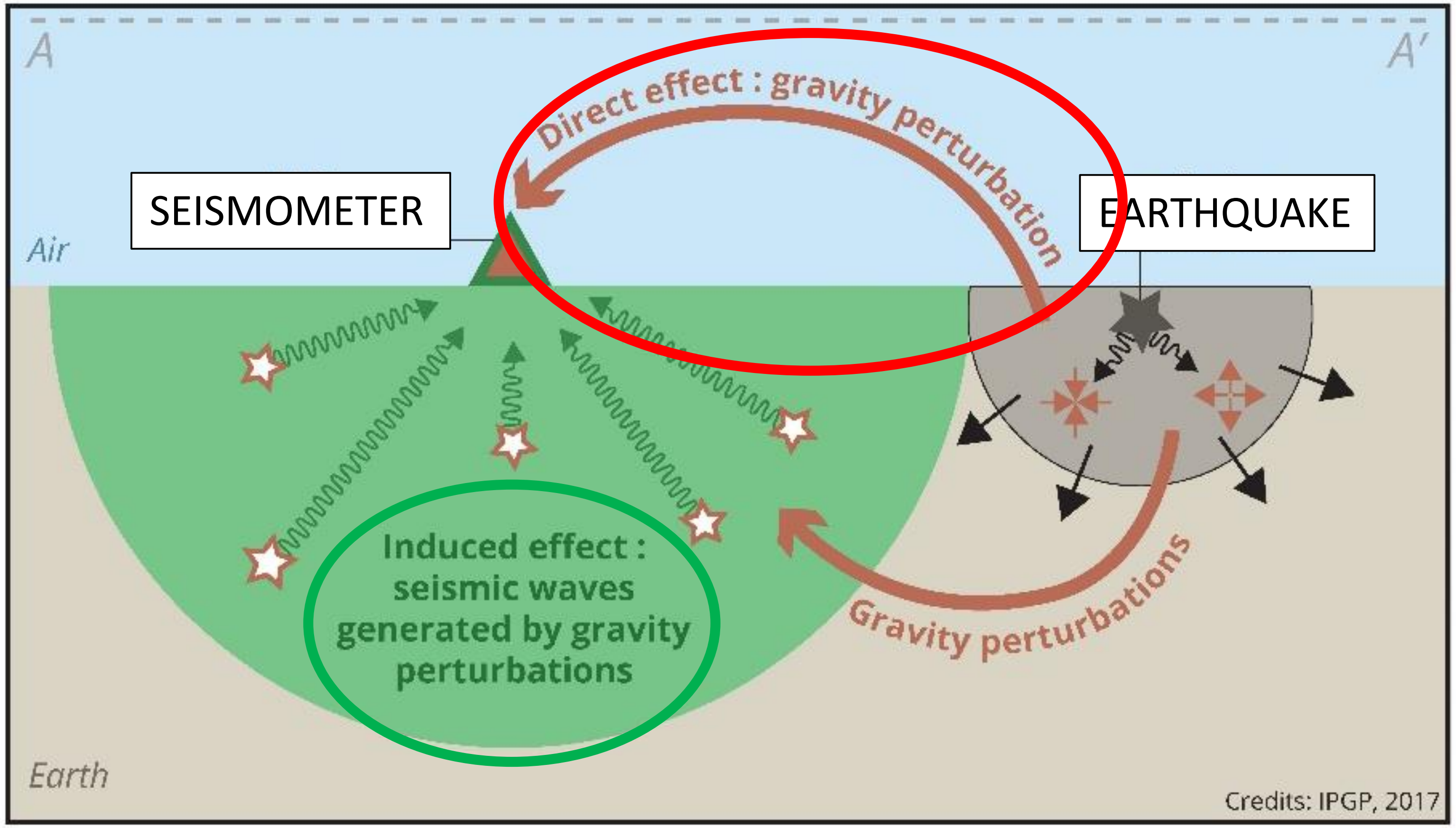
$\Delta\boldsymbol{g}$ can be known everywhere using an integral form of the Poisson equation (e.g. Dahlen &Tromp, 1998)

In the volume directly where gravity-induced elastic waves can arrive before the direct waves (green area)

$$\rho_0\, \ddot{\mathbf{u}} = \boldsymbol{\nabla}\cdot\boldsymbol{\sigma} + \Delta\rho\, \xcancel{\mathbf{g}_0} + \xcancel{\boldsymbol{f}} + \rho_0\, \Delta\mathbf{g}\,,$$

$\boldsymbol{u}$ can be known everywhere with numerical methods solving the classical elastodynamic equation (e.g. Axitra), with source term $\rho_0\Delta\boldsymbol{g}$

How do we understand and model the Prompt Elastogravity Signals ?



Schematic representation at a time between earthquake origin and P-wave direct arrival (direct elastic waves are inside the grey area)

As soon as an earthquake occurs (and **thus before the arrival of seismic waves**), a weak signal is expected to be recorded at a broadband seismometer, due to the **difference between** :

- The **gravity perturbation** induced by the earthquake rupture and elastic waves [*Harms et al., 2015, Montagner et al., 2016*] : **Direct effect**
- The **elastic relaxation** of the Earth, itself affected by the gravity perturbations [*Vallée et al., 2017, Juhel et al., 2018*] : **Induced effect**

« Prompt Elastogravity signals »

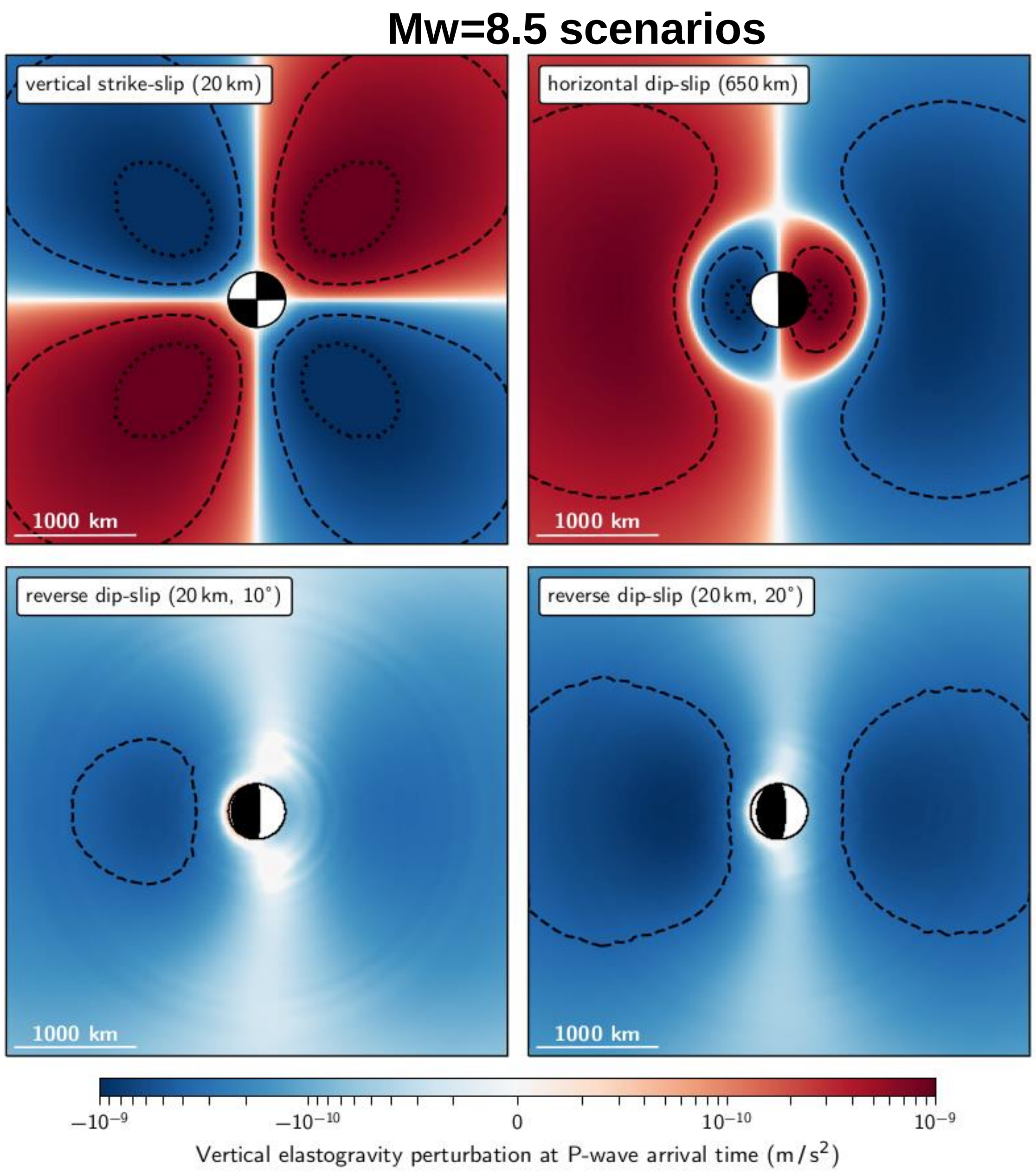
- **Questions following the first PEGS observations** made during the 2011 Tohoku earthquake, in order to **better assess the PEGS potential** for source parameter determination :

  - **What are the factors (other than magnitude) controlling the signal amplitude and detectability ?**

  - **Are such signals detectable for lower magnitude earthquakes ?**

  - **How can networks of broadband stations improve the signal detectability?**

Factors controlling the PEGS detectability



Vallée and Juhel, 2019

1) For a given magnitude and source time function (STF), **strike-slip and deep earthquakes generate larger PEGS than thrust earthquakes** on shallow dipping interfaces

2) Direct relation between STF and gravity perturbations [Harms et al., 2015] : **Rapidly growing moment rate functions increase the signal observability**

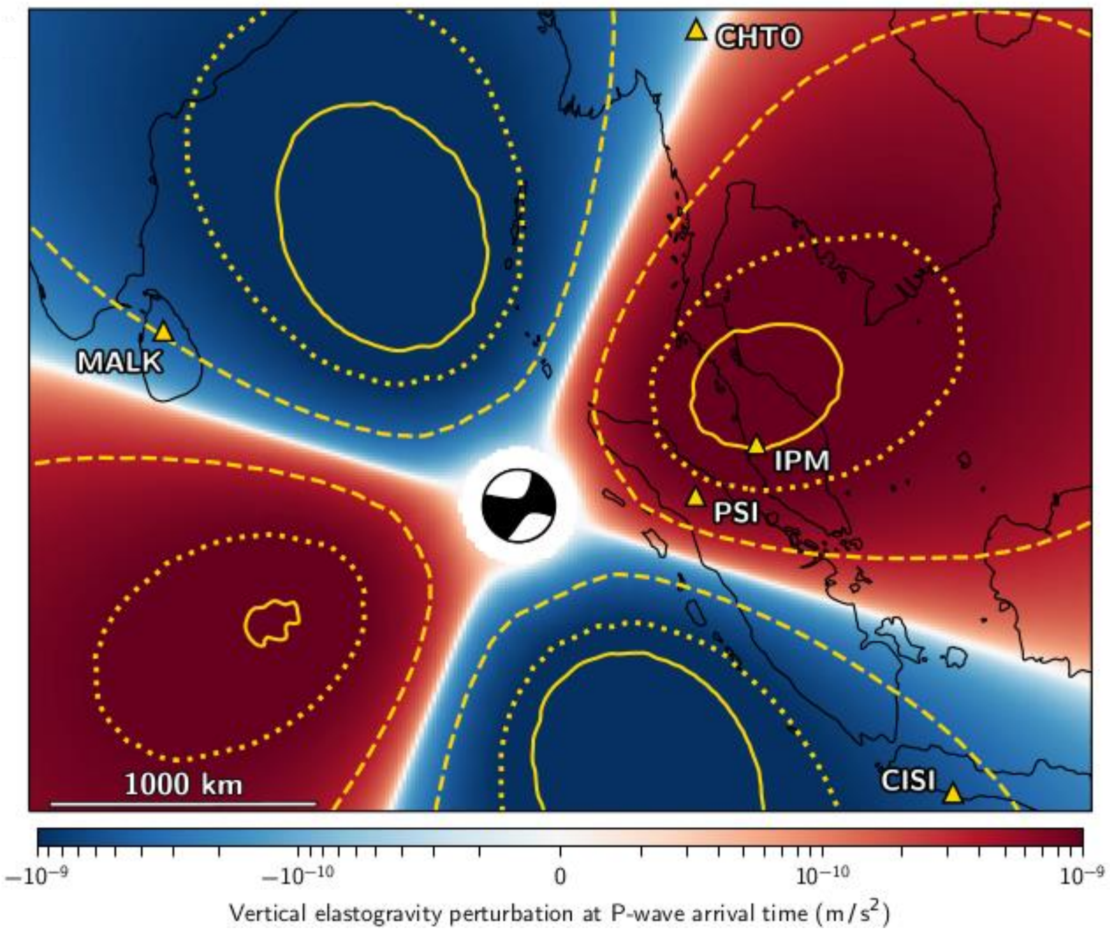
3) PEGS detection **requires the earthquakes to be recorded by good broadband stations in a relatively quiet seismic period** (e.g. not in the hours following a large earthquake)

4) For earthquakes generating PEGS close to the seismic noise, **detection can be achieved by combining the observations at several sensors** (array techniques)

Single-stations observations

The 2012/04/11 Mw=8.6 Wharton Basin earthquake

Map showing the PEGS predicted amplitude (using GCMT source parameters), and the 5 broadband stations with lowest noise in the [0.002-0.03Hz] frequency range



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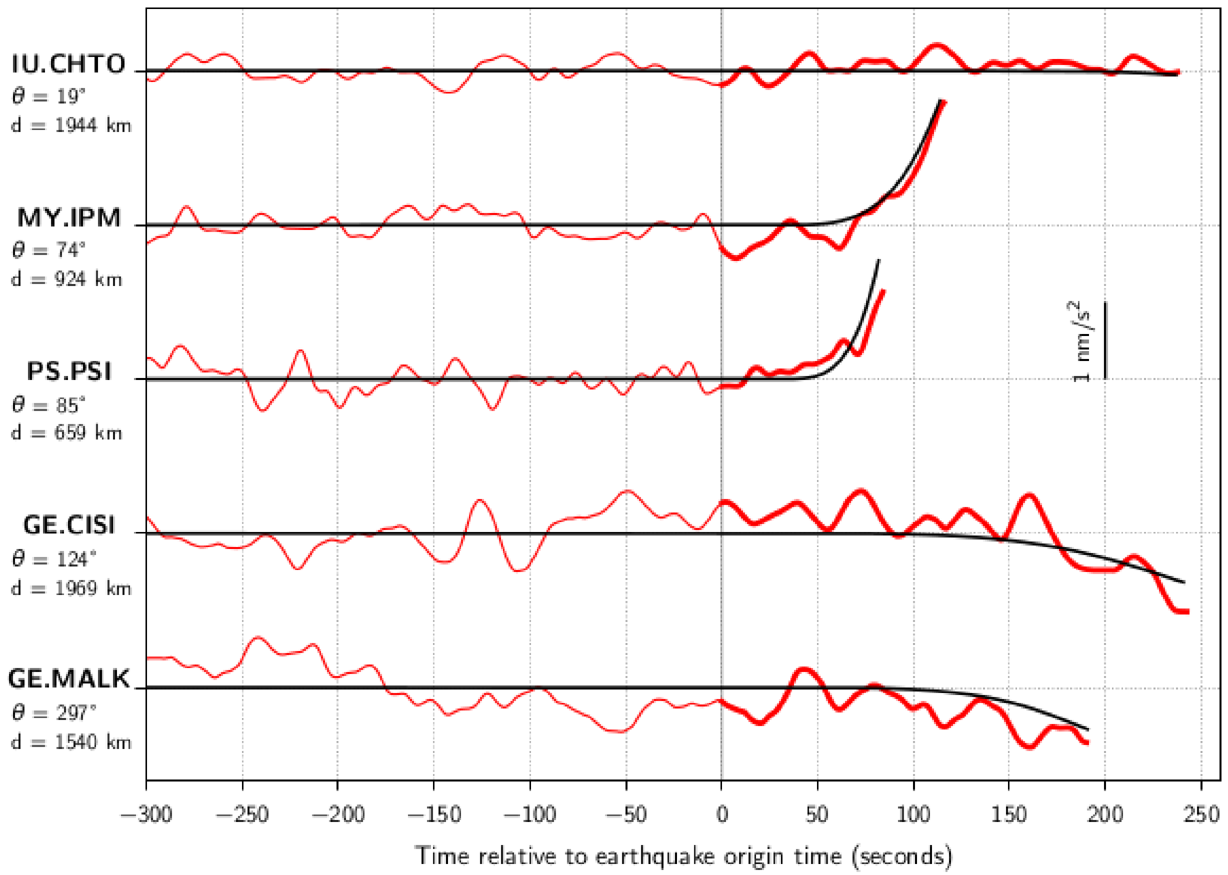
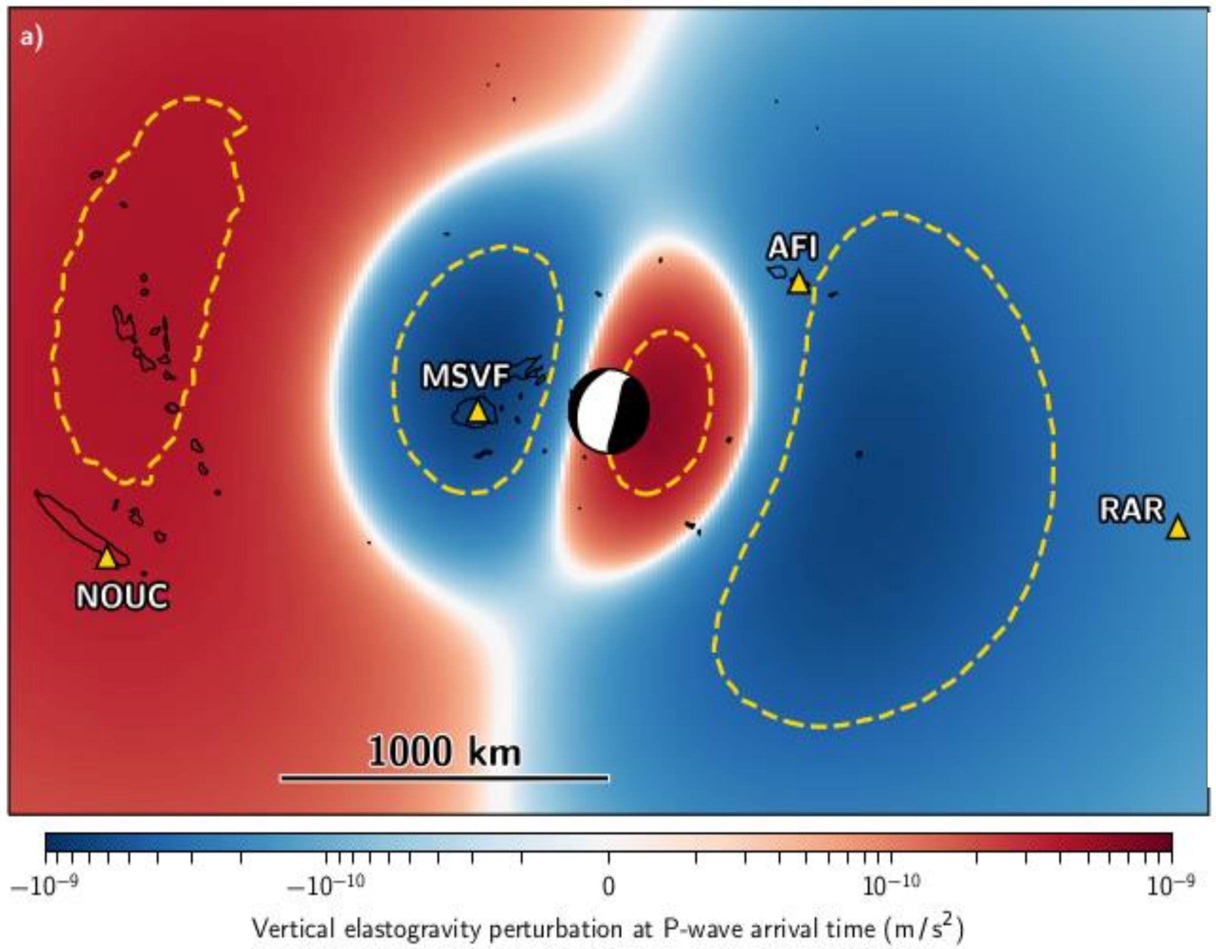
Observed (red) and modeled (black) waveforms at the 5 best stations, using an event-specific source time function (SCARDEC method)



- **Large positive signals observed at IPM and PSI**
- **Good agreement between observed and modeled PEGS**

The 2018/08/19 Mw=8.2 deep Fiji earthquake

Map showing the PEGS predicted amplitude (using GCMT source parameters), and the 4 broadband stations with lowest noise in the [0.002-0.03Hz] frequency range



Vallée and Juhel, 2019

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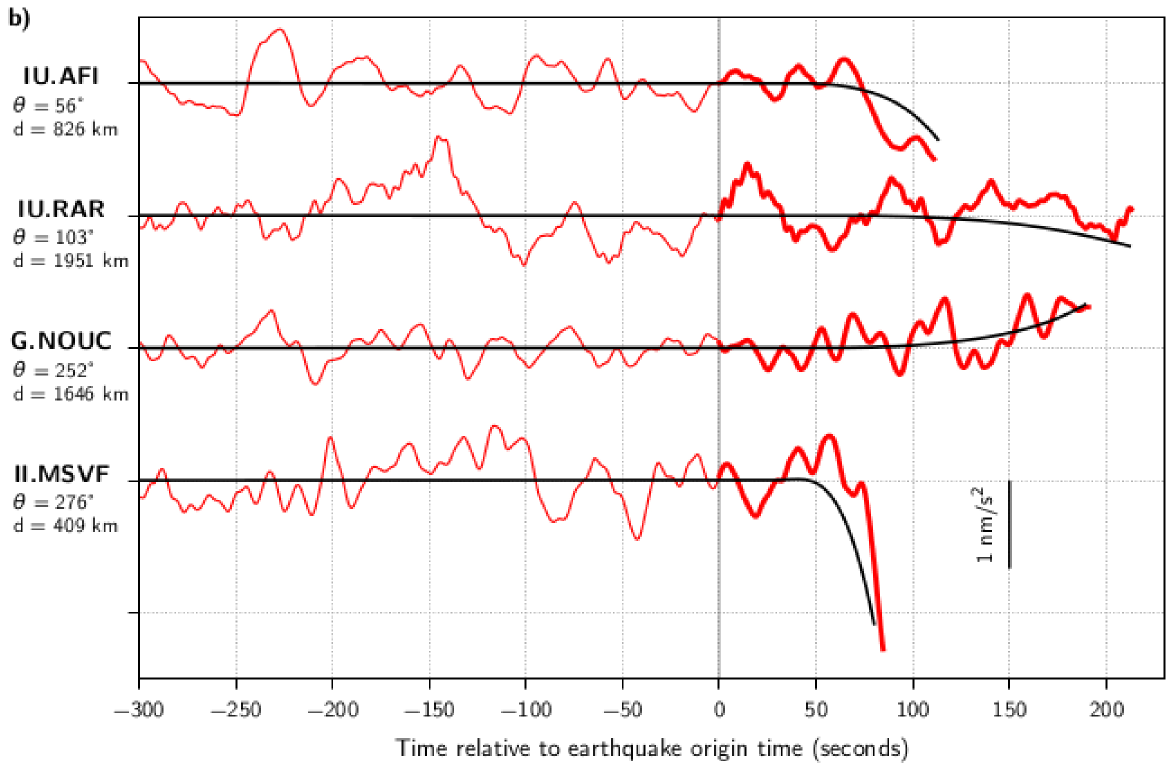
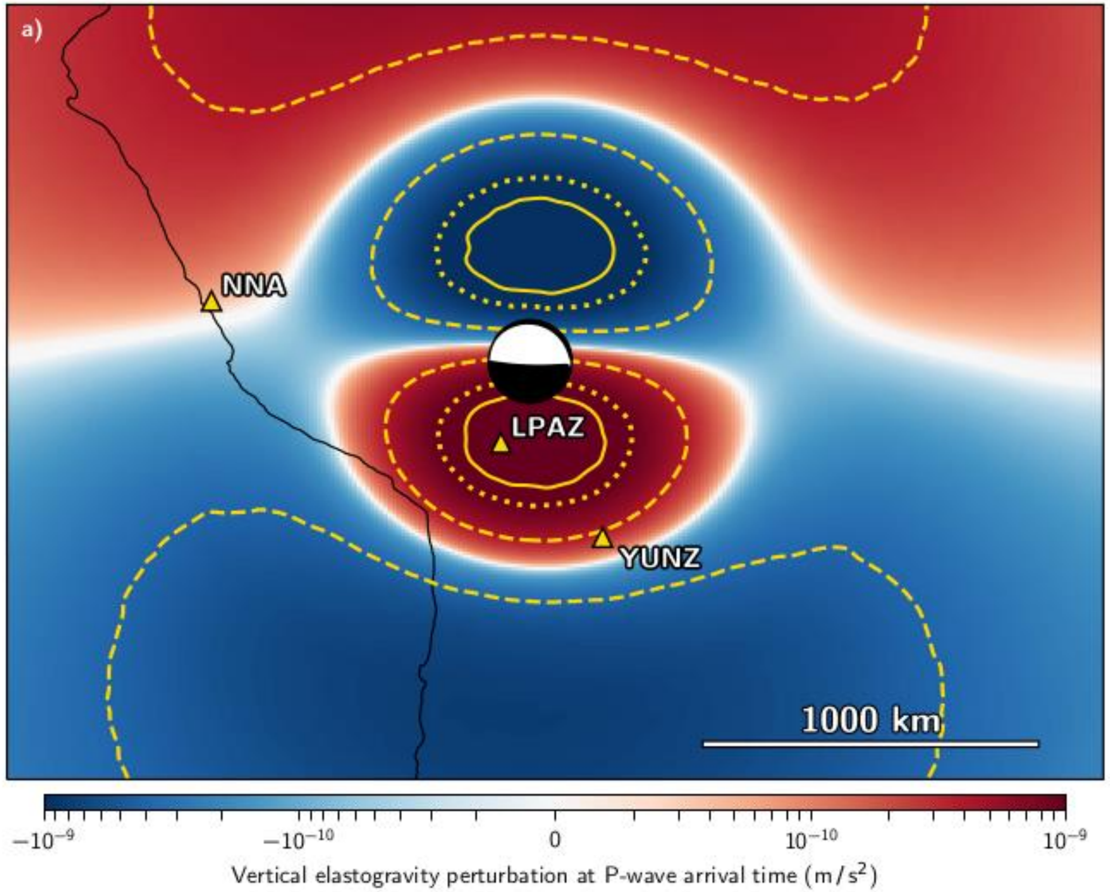


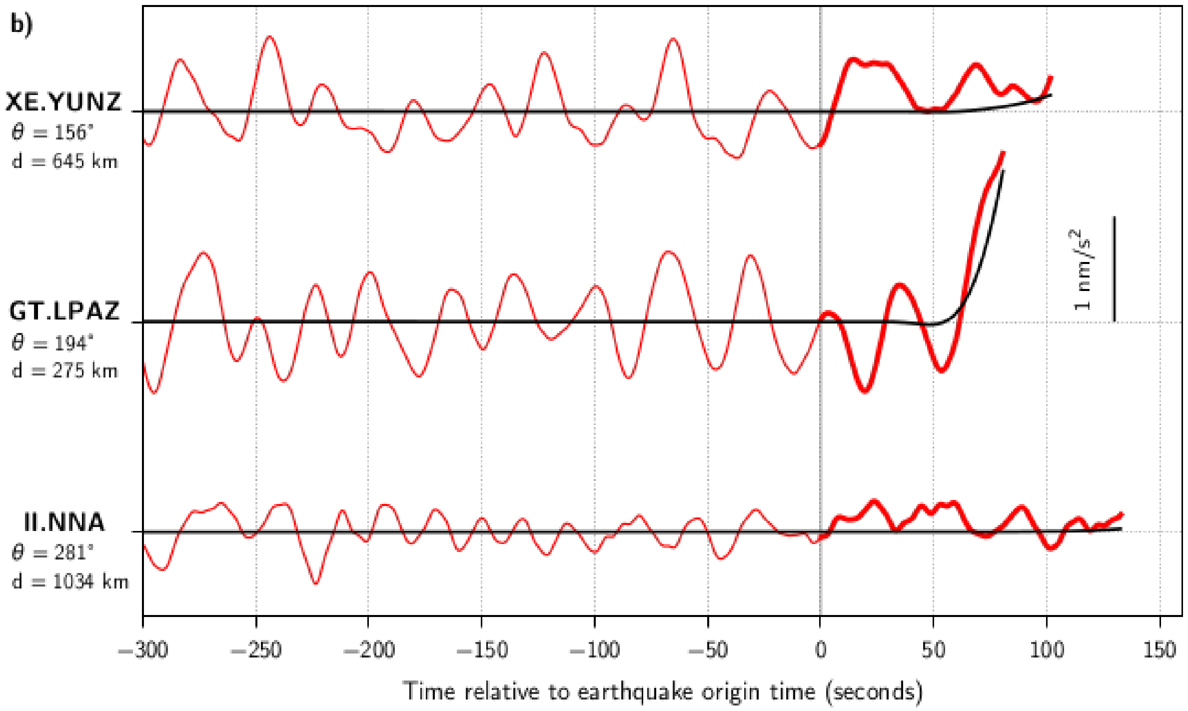
- **Large negative signal observed at MSVF (and AFI)**
- **Positive signal at NOUC**
- **Good agreement between observed and modeled PEGS**

The 1994/06/09 Mw=8.2 deep Bolivia earthquake

Map showing the PEGS predicted amplitude (using GCMT source parameters), and the 3 broadband stations with lowest noise in the [0.002-0.03Hz] frequency range



Observed (red) and modeled (black) waveforms at the 3 best stations, using an event-specific source time function (SCARDEC method)



- **Large positive signal observed at LPAZ**
- **Good agreement between observed and modeled PEGS**

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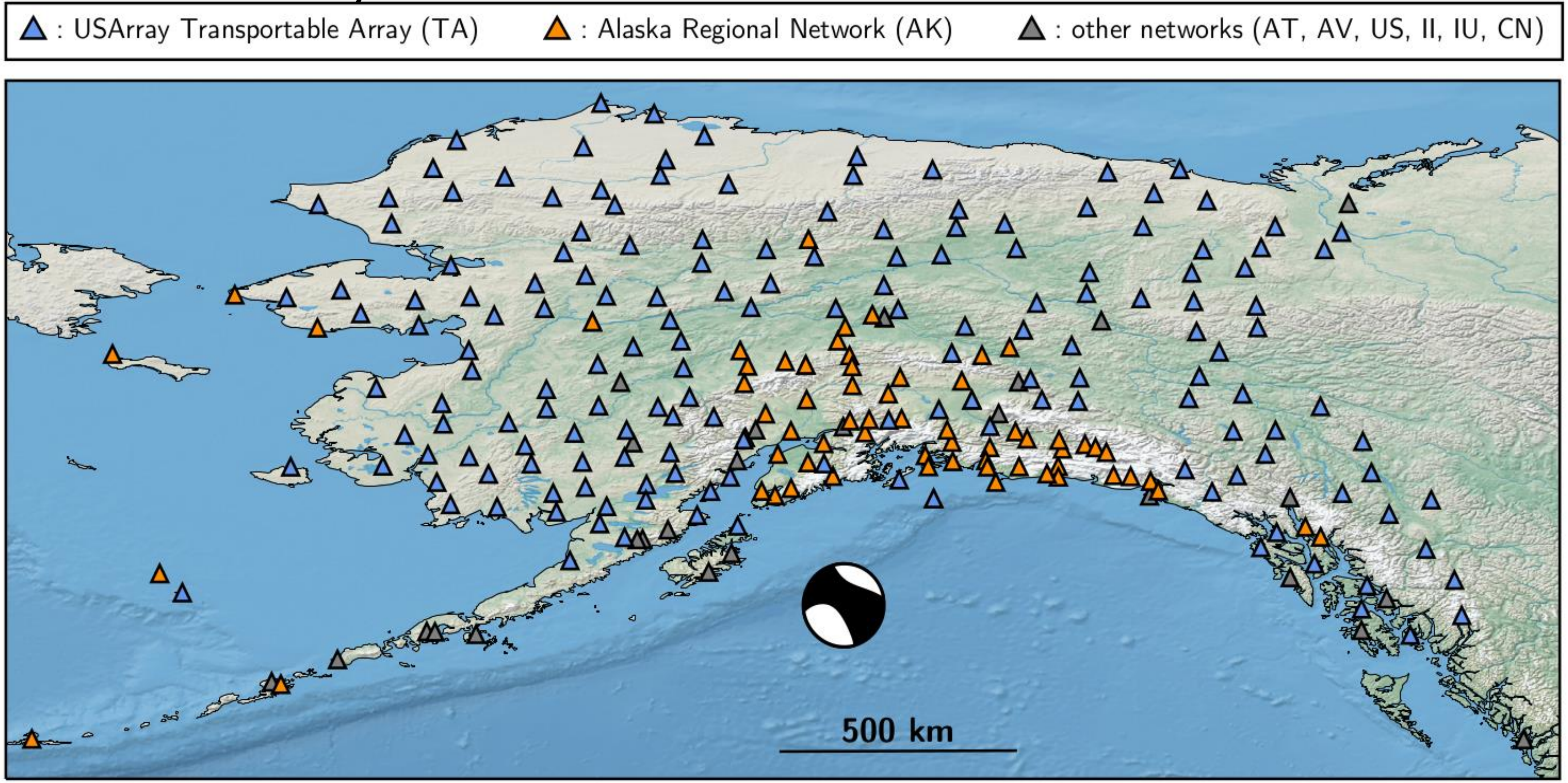
Array observations

The 2018/01/23 Mw=7.9 Gulf of Alaska earthquake

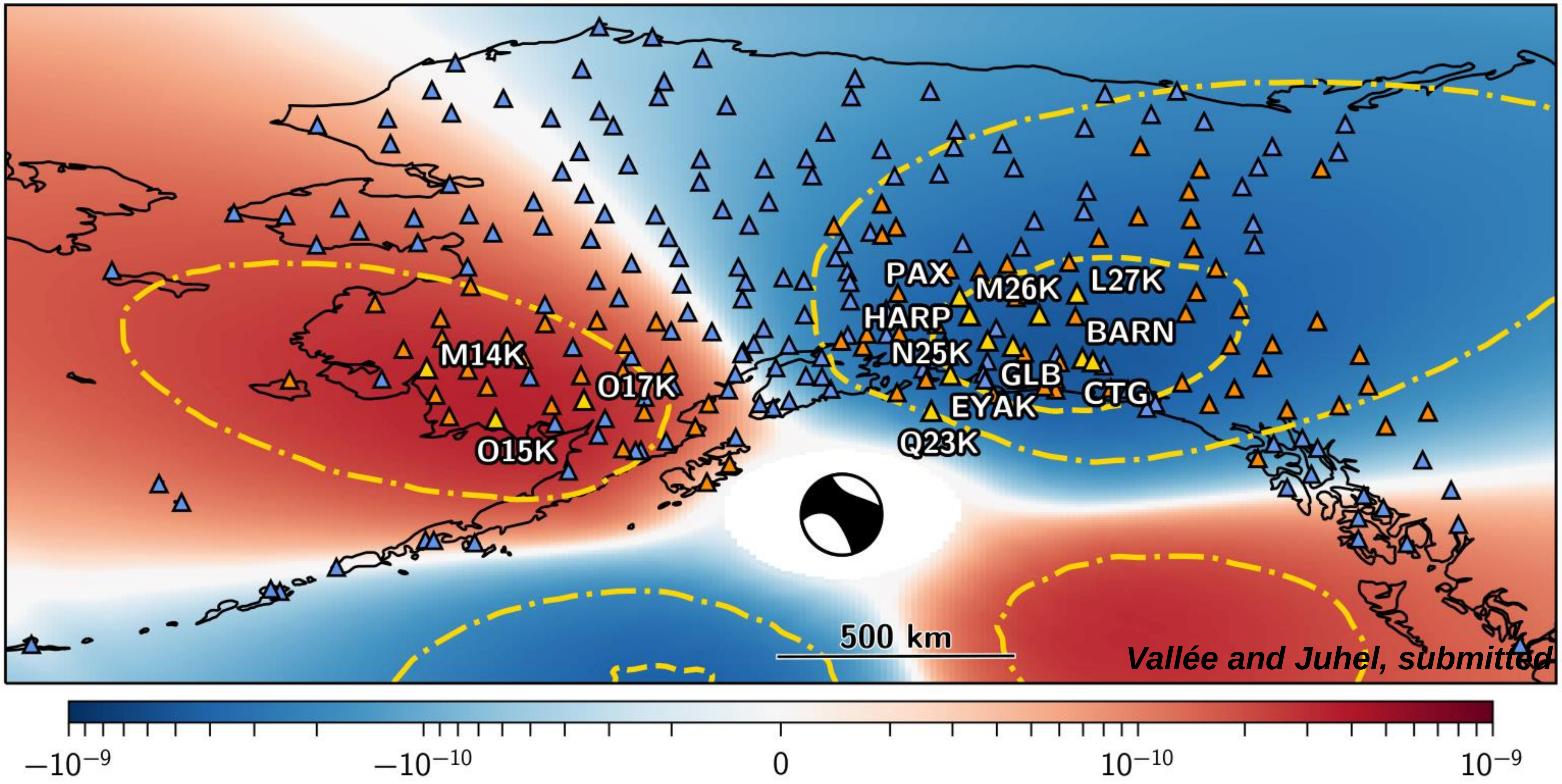
Seismic moment is about 50 times smaller than the Tohoku earthquake, but :

- **Strike-slip mechanism**
- **Excellent coverage provided by USArray (and complemented by the other permanent networks)**



During the Gulf of Alaska earthquake, ~250 broadband stations in the Alaska region can contribute to the PEGS detection

Predicted PEGS amplitudes



Vertical PEGS amplitude (at the P-wave arrival time)

Dashed-dotted : +/- 0.2 nm/s²

Dashed : +/- 0.4 nm/s²

The areas with largest predicted PEGS are well sampled by broadband stations… But due to the expected amplitudes (max ~ 0.5nm/s²), direct detection is unlikely

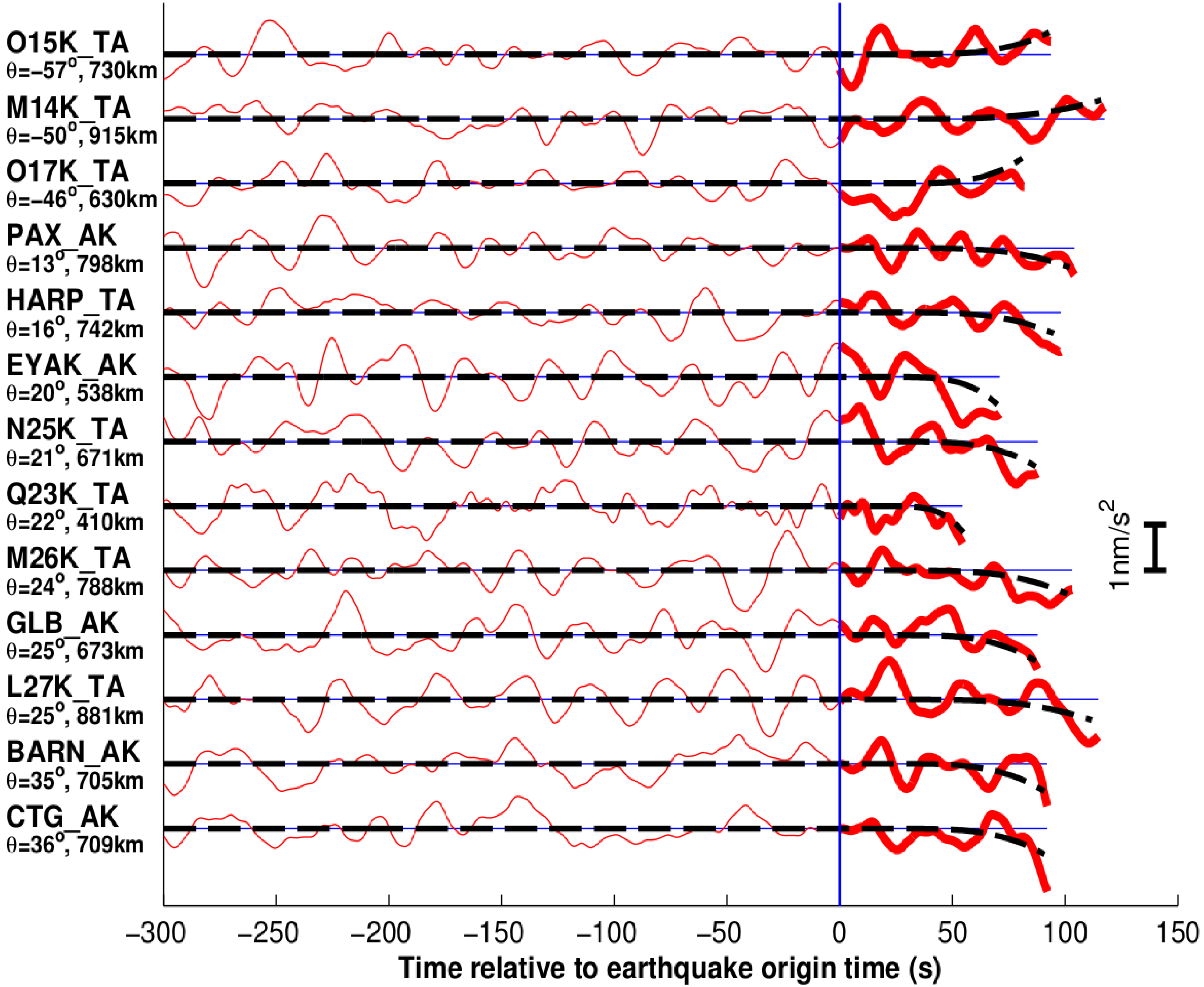
A sensor *i* has a **good detection potential** if :

- At this location, the **expected PEGS is large**
  [quantified by the value of $\boldsymbol{s_i(T_i^P)}$, expected amplitude at the P-wave arrival time T_i^P]

- The **instrumental/physical noise is low**
  [quantified by the signal variance in the pre-event period $\boldsymbol{\sigma_i^2}$]

We show on the right the **13 best sensors in terms of detection potential**, i.e. the 13 first sensors when ordered by **decreasing order of the coefficient** $\left|\frac{s_i(T_i^P)}{\sigma_i^2}\right|$

Single-station observations **are not sufficient for PEGS detection**



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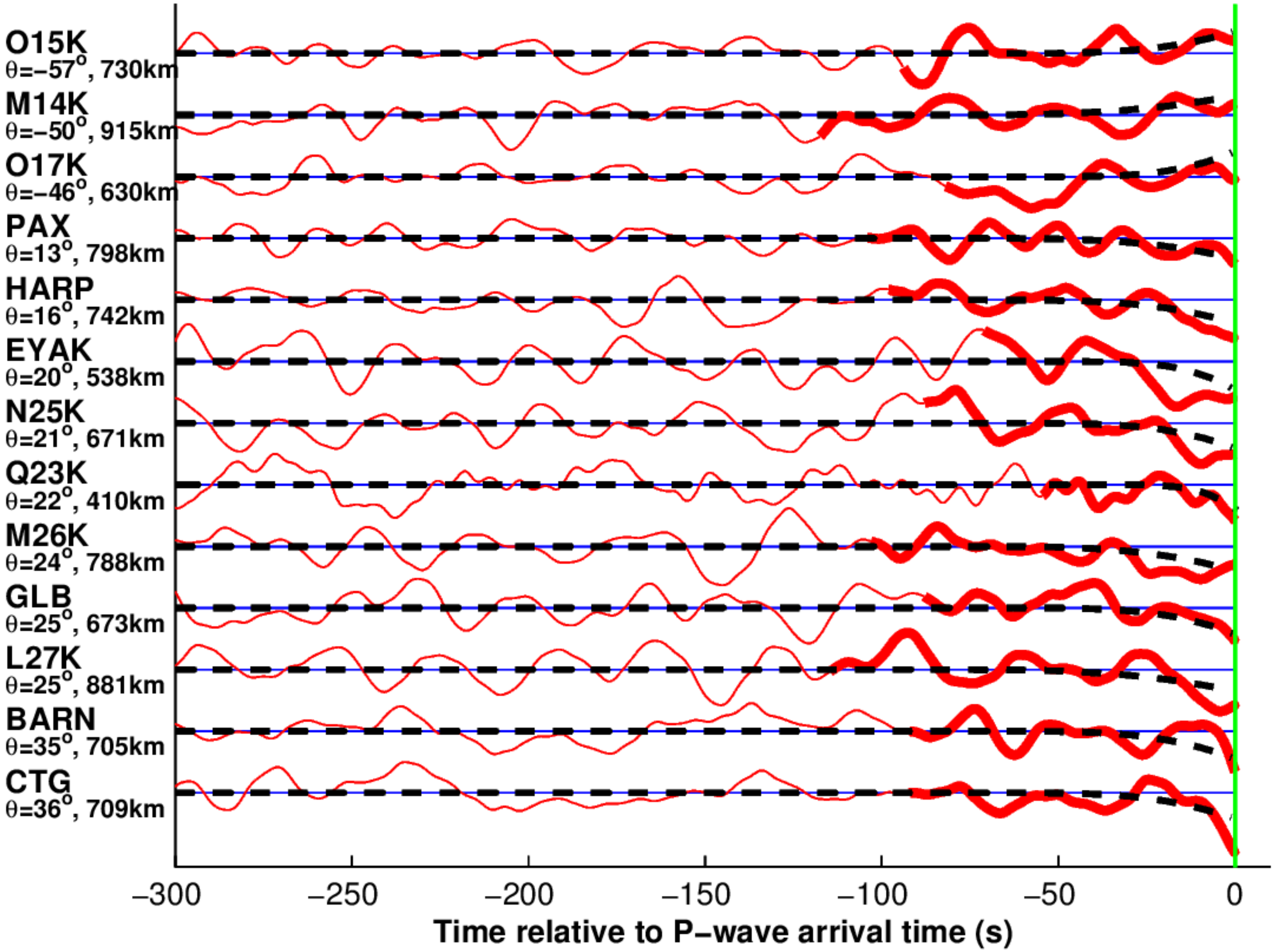
Strategy for array stacking

1) Change the reference time of the waveforms a_i from absolute time **to P-wave reference time**
(as maximum expected amplitudes occur at the P-wave arrival)

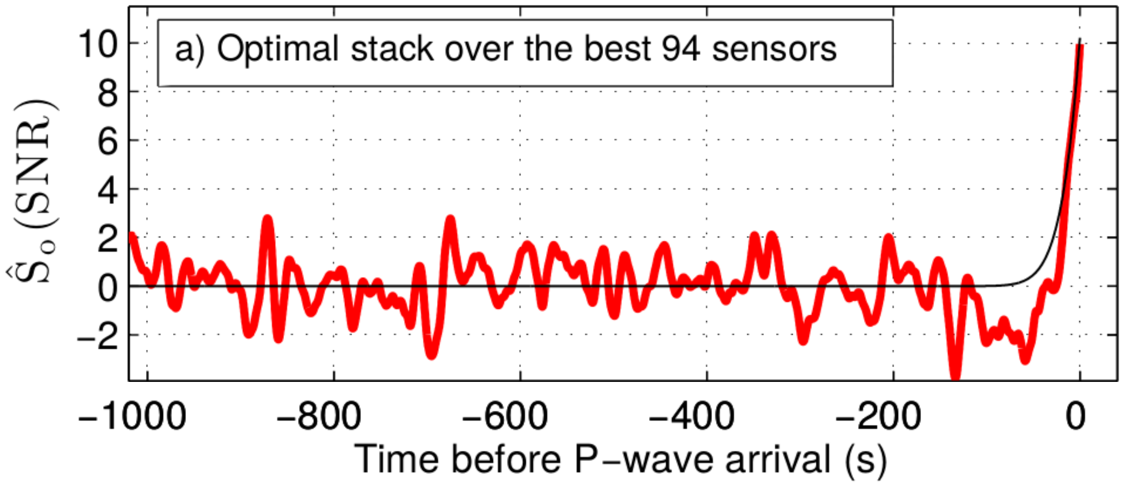


2) Optimal stack, with **weights equal to** $\frac{s_i(T_i^P)}{\sigma_i^2}$:

$$S_o(t) = \sum_{i=1}^{N} \frac{s_i(T_i^P)}{\sigma_i^2} a_i(t + T_i^P)$$

Assumes noise to be Gaussian and stationary
[*Tyapkin and Ursin, 2005; Robinson, 1970*]

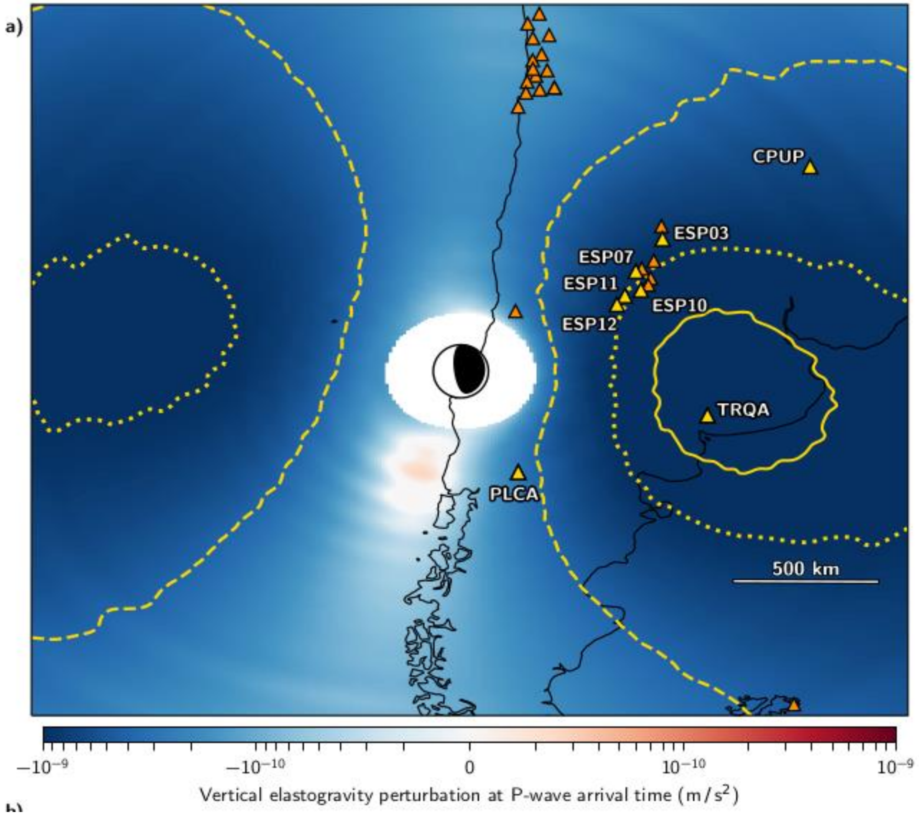
3) Normalization to the the pre-event noise (-> SNR)



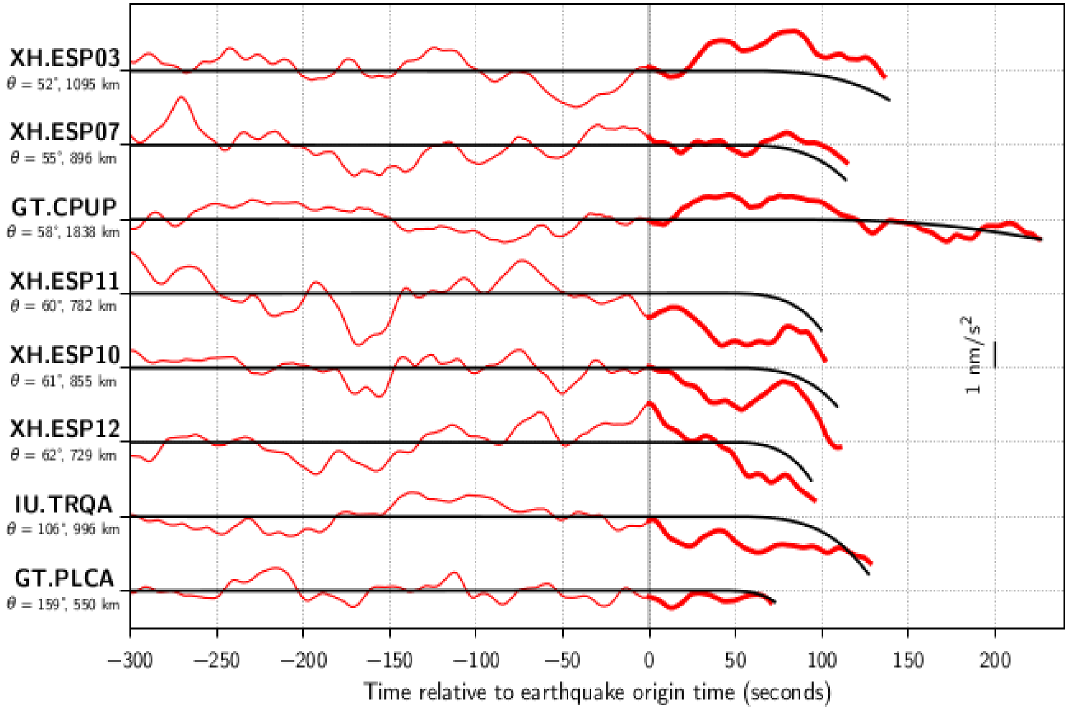
PEGS are detected with a high Signal to noise ratio (~10)

The 2010/02/27 Mw=8.8 Maule (Chile) earthquake

Predicted PEGS amplitudes

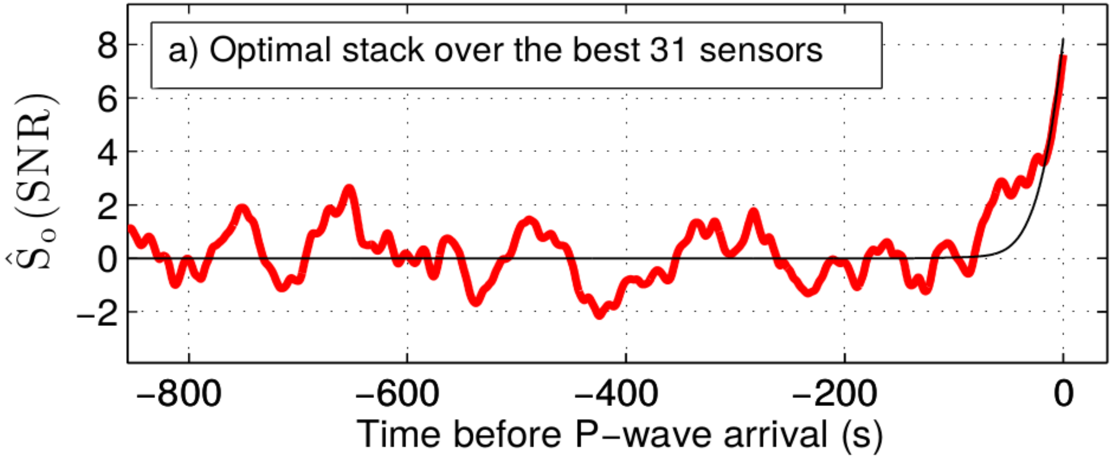


Observed (red) and modeled (black) waveforms at the best located and best quality sensors. Sensor quality is affected by a Mw7 earthquake, 10 hours before in Japan



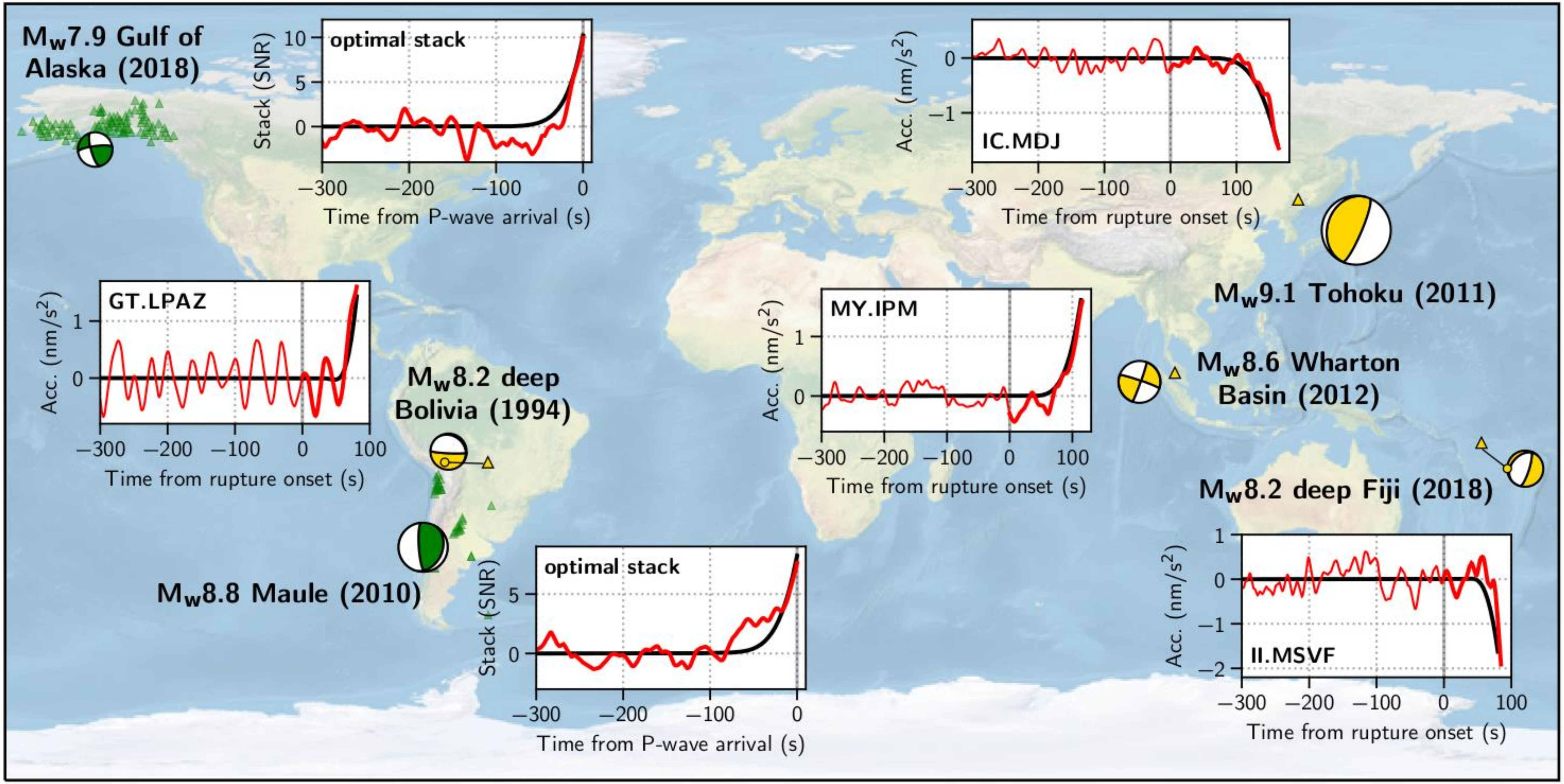
+

Waveform stack, in P-wave arrival reference-time, weighted by sensor quality and expected amplitude



PEGS are detected with a high Signal to noise ratio (~7.6)

Summary of the PEGS observations to date



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Discussion and perspectives

- **In addition to the 2011 Tohoku earthquake, we show 5 earthquakes in the [7.9-8.8] magnitude range with unambiguous PEGS observations**

- For **earthquake types generating efficient PEGS** (strike-slip or deep-focus, rapidly growing source time function) and **recorded in favorable configurations**, **PEGS can be observed for magnitudes lower than 8**

- Based on their **sensitivity to key source parameters** (magnitude, focal mechanism, source time function), the use of **PEGS can become a new powerful tool for earthquake monitoring and anticipated tsunami alert.**

- **In well-instrumented areas with large earthquake hazard (e.g. Alaska, Japan, Cascadia), such approaches can today be tested without additional sensor installation**