Seafloor geodetic observations in the Japan Trench subduction zone

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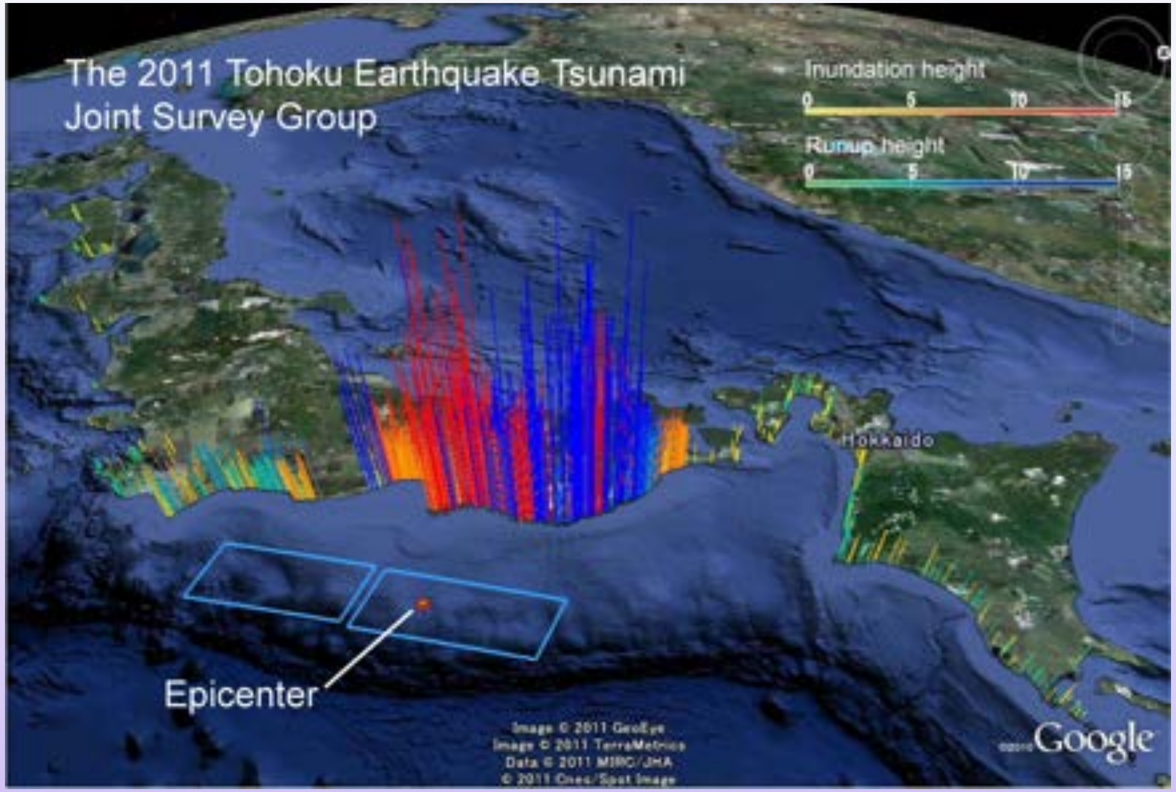
2011 Tohoku-Oki Earthquake

Japan Metrological Agency



March 11, 2011, 14:46 M9.0

Strong ground shaking (intensity 7 in JMA scale), causing severe damage in broad area

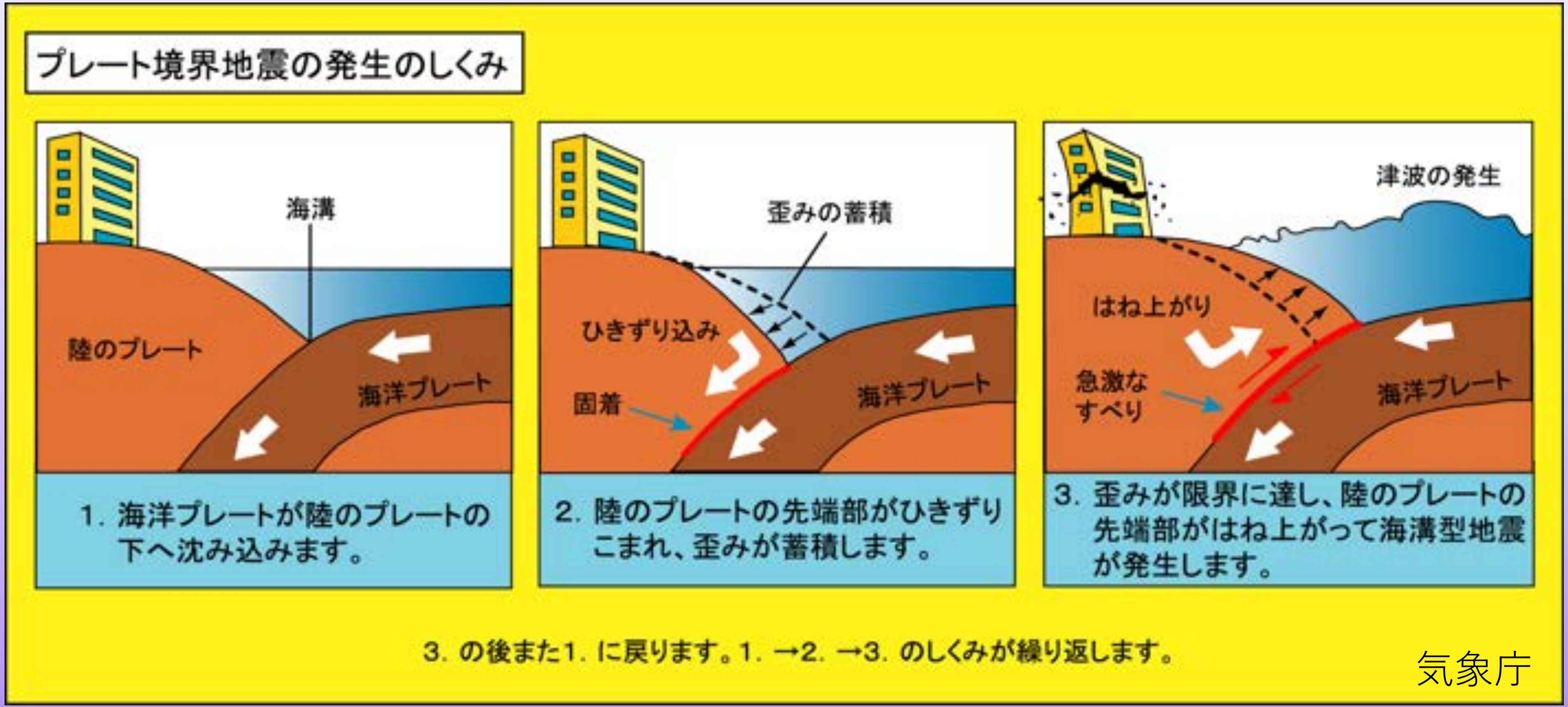
Tall tsunami (over 30 m) causing devastating damage along the coastal area

Interplate earthquake in subduction zone

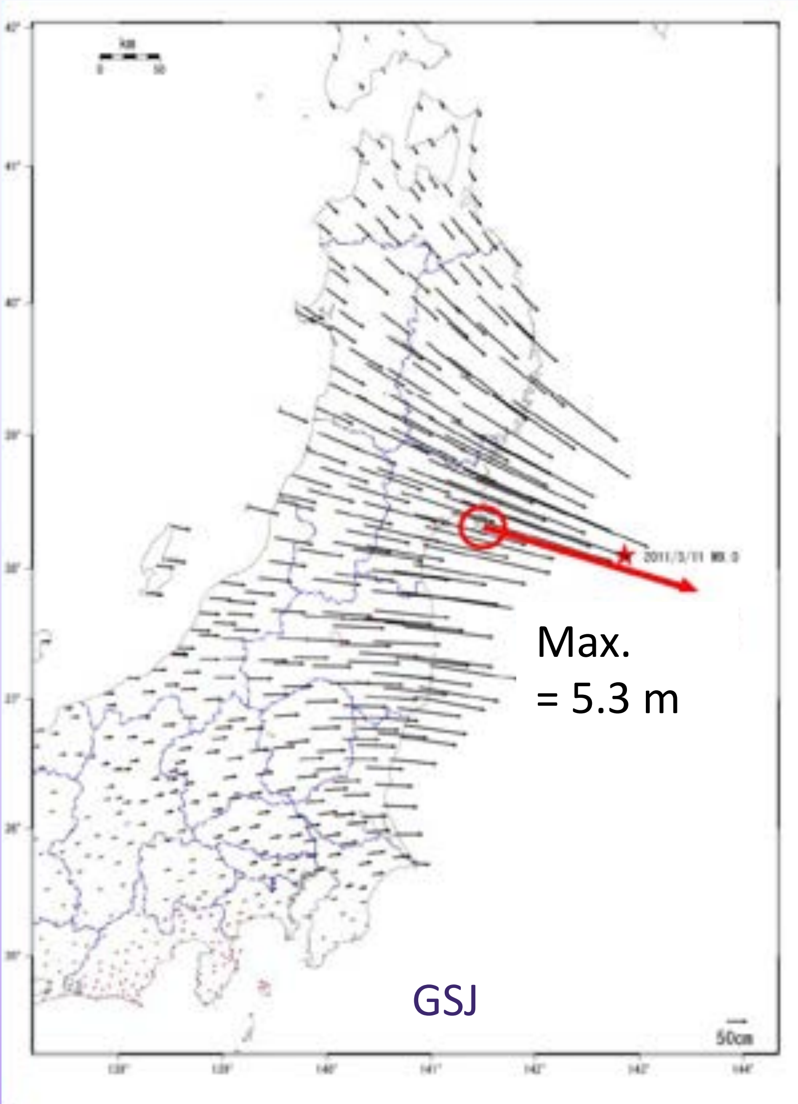
A subducting oceanic plate drags an overriding continental plate.

Shear stress builds up along the plate boundary until the stress level exceeds shear strength.

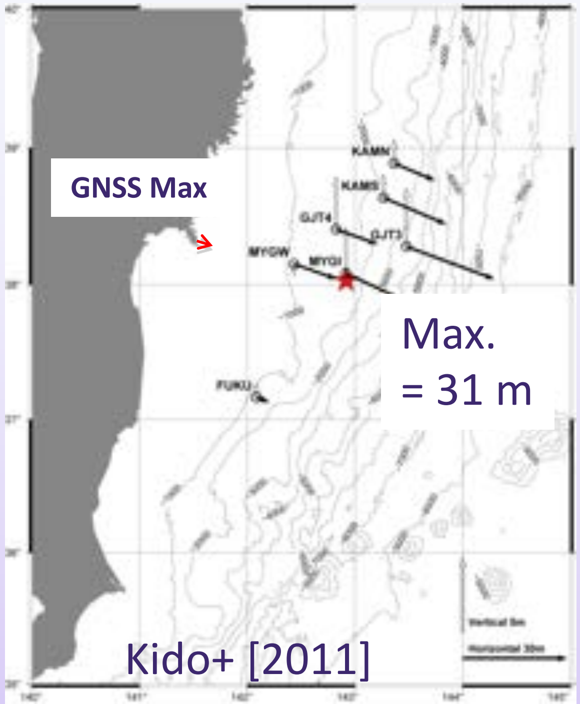
When the stress exceeds the strength, a sudden slip happens on the boundary to cause an earthquake and a tsunami.

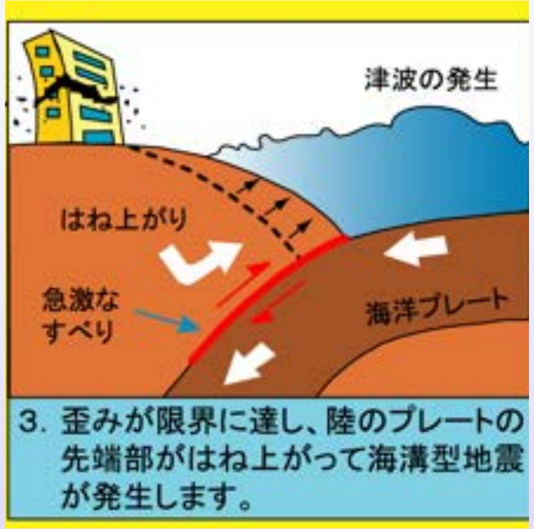


Coseismic displacement by 2011 Tohoku-Oki Earthquake



Displacements on land by GNSS



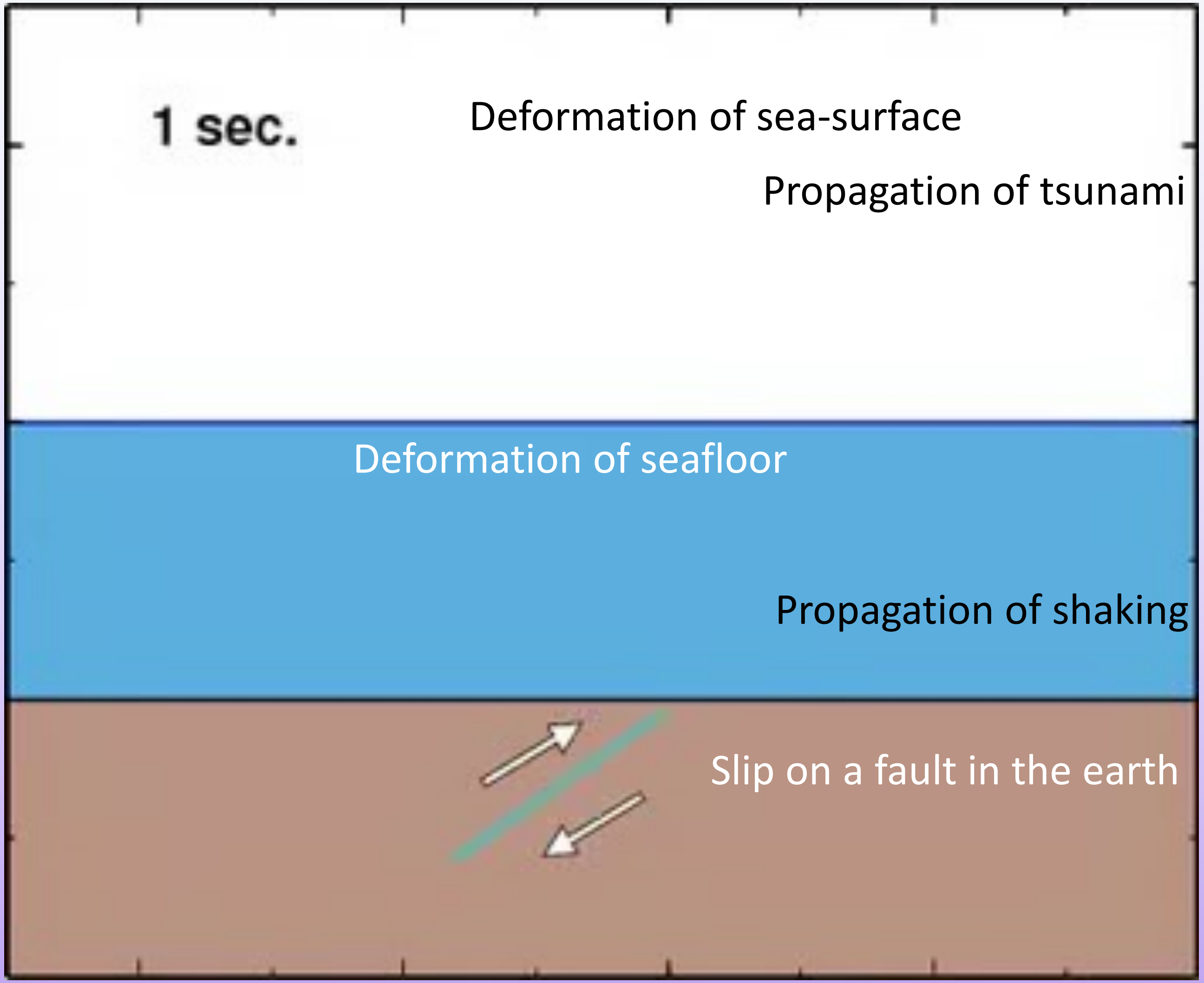


Displacements on the seafloor by GNSS-A

Observed coseismic displacements

- uniformly eastward both in on- and offshore regions
- increase monotonically toward the east
- largest at the seafloor station closest to the Japan Trench
- decrease towards the north and south, in offshore region

Earthquake & Tsunami

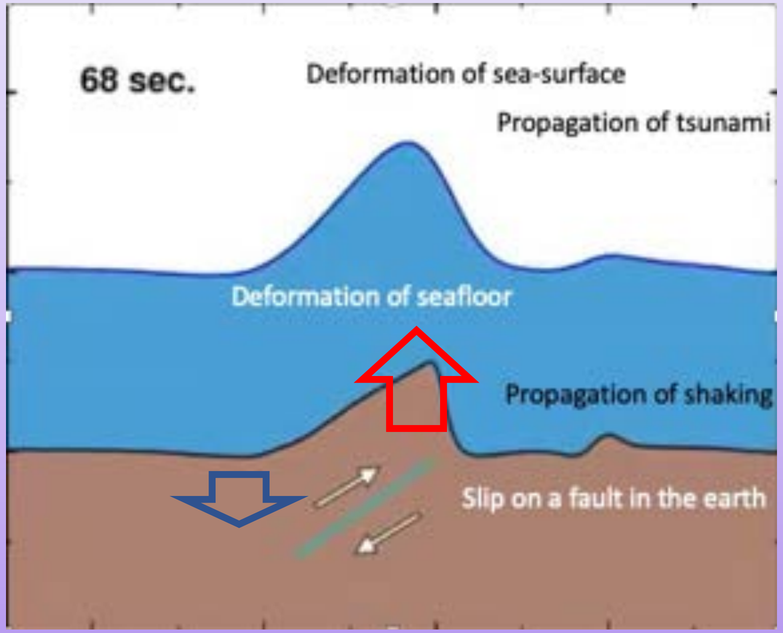


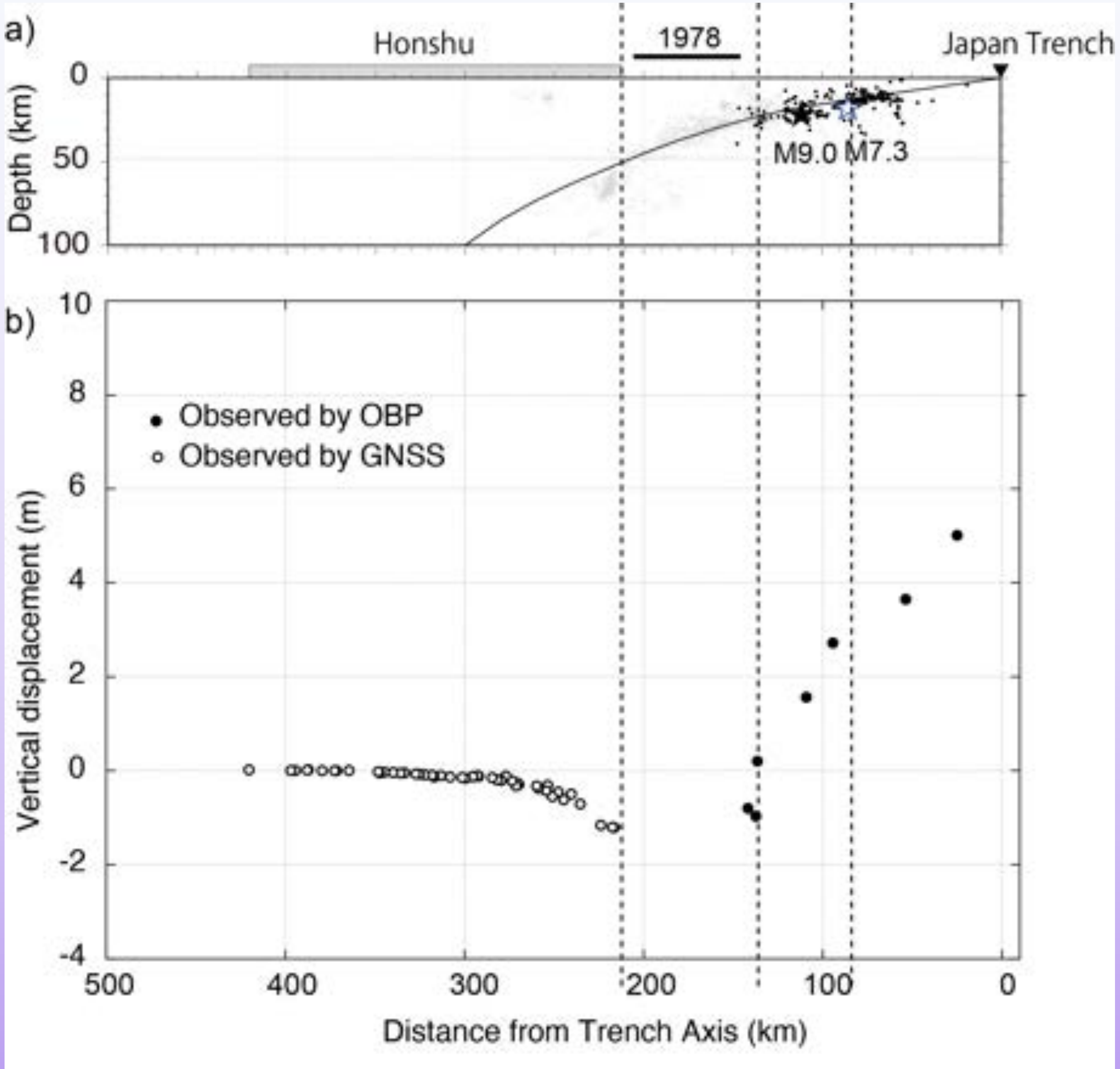
by Dr. Sato at NIED

Vertical coseismic displacement by Tohoku-Oki Earthquake

Observed coseismic displacements

- large uplift near the trench
- small subsidence on the landward side of the offshore as well as in all the onshore area

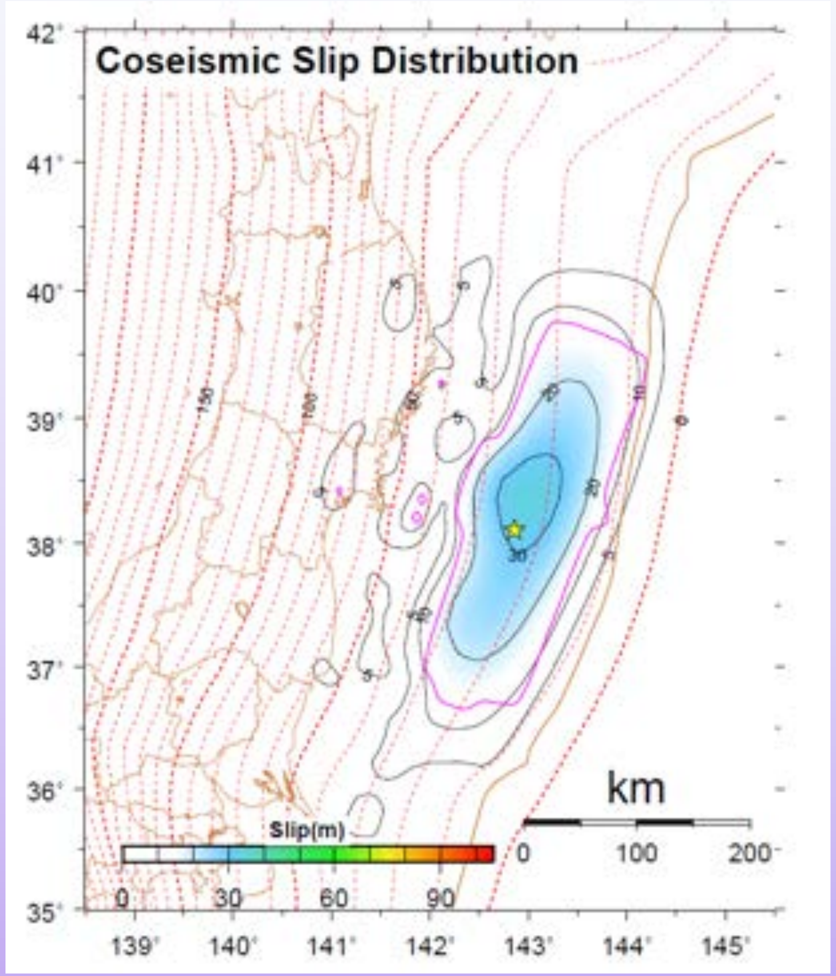




Hino [2013]

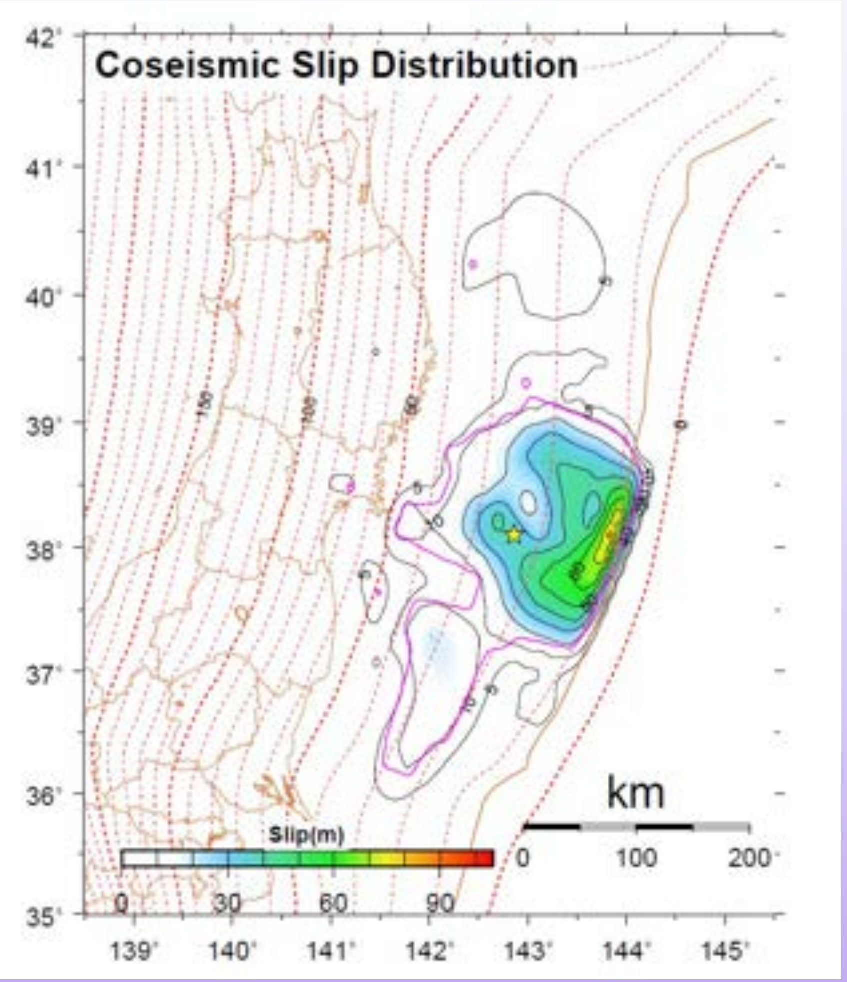
Slip distribution estimated by geodetic observations

<u>w/o offshore data</u>



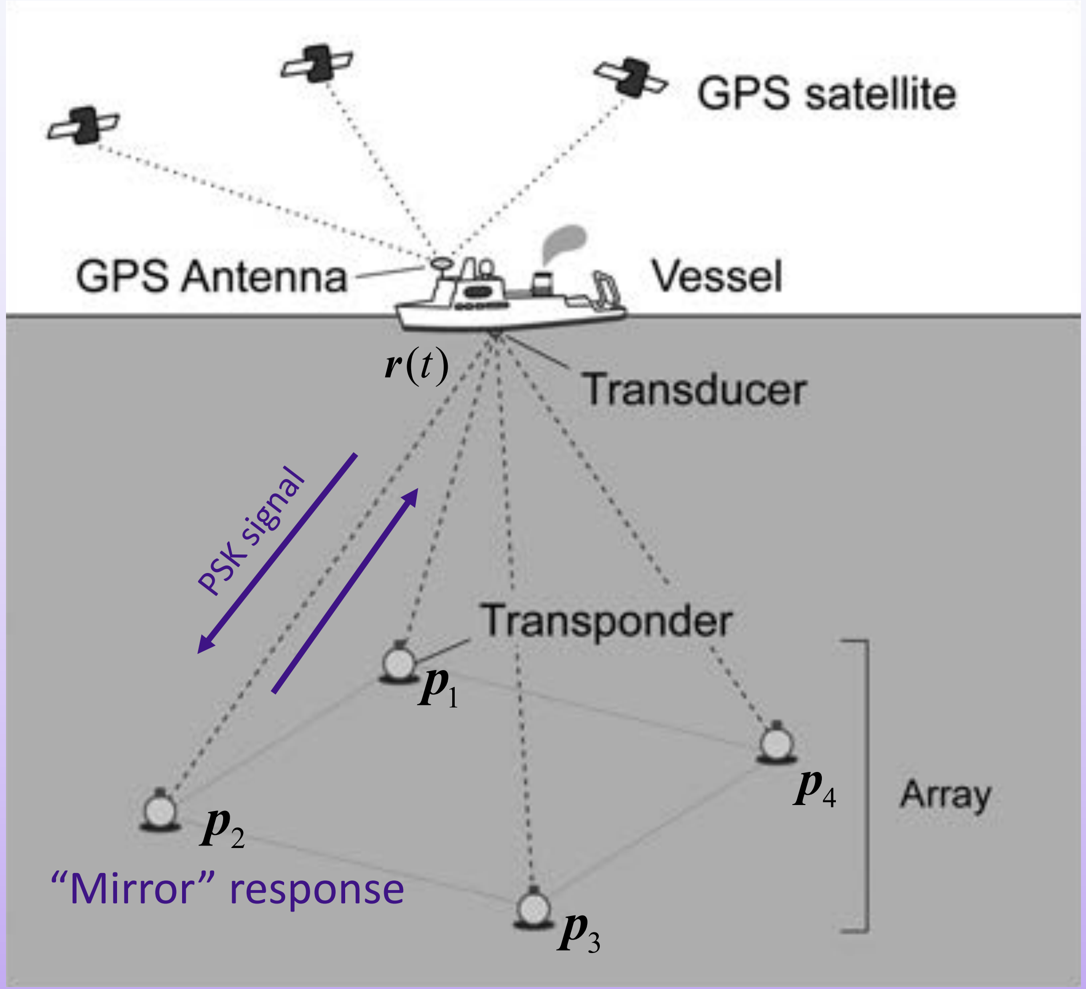
Iinuma+ [2011]

<u>With onshore data</u>



Iinuma+ [2012]

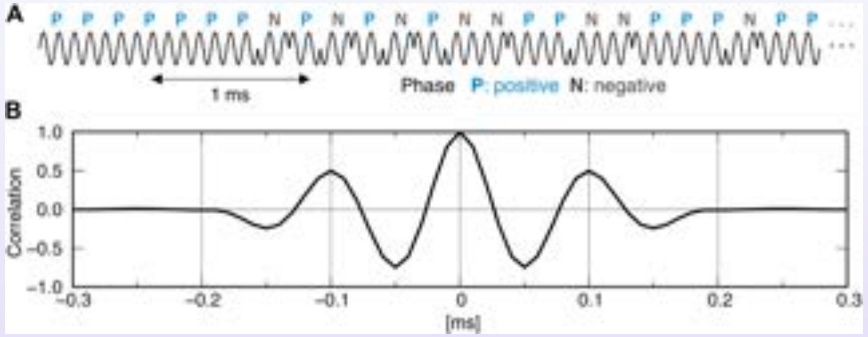
Principle of GNSS-A survey



Honsho+ [2017; 2019]

Waveform of **A**coustic signal

X-cor. of T/R waveforms



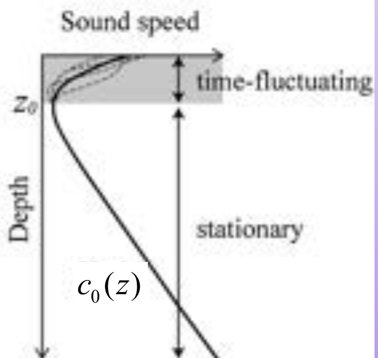
Honsho+ [2021]

Two-way time

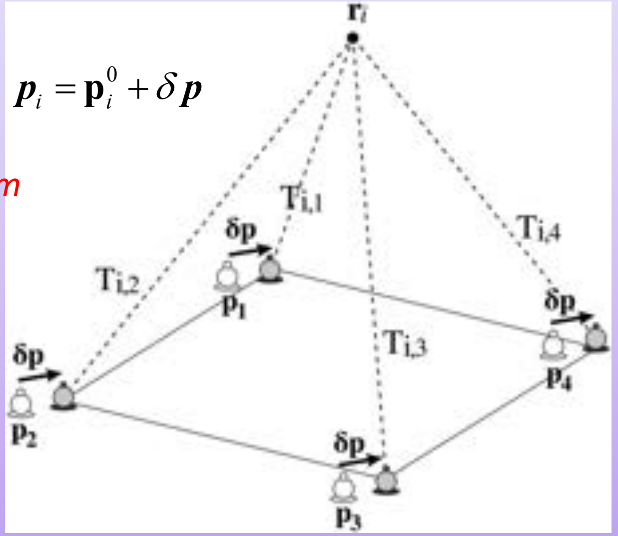
$$T(t) = f\left(\boldsymbol{p}_i, \boldsymbol{r}(t), c_0(z)\right) + \delta F(t)$$

$$T(t) = f\left(\boxed{\delta \boldsymbol{p}}, \boldsymbol{r}(t), c_0(z)\right) + \boxed{\delta F(t)}$$

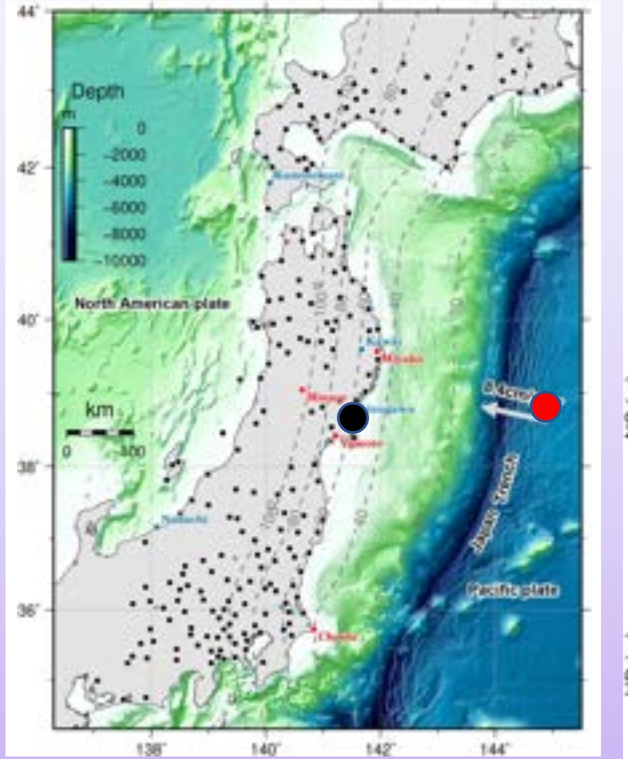
Motion of array *correction term*



Sound speed profile

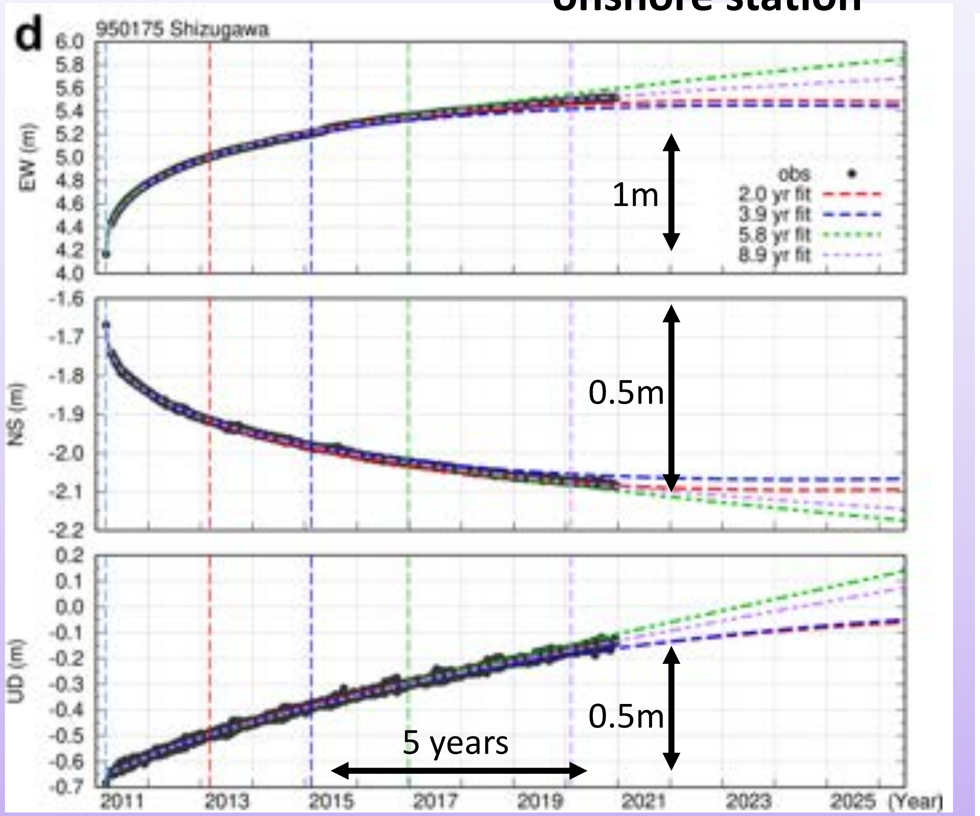


Displacement time series
onshore GNSS vs offshore GNSS-A

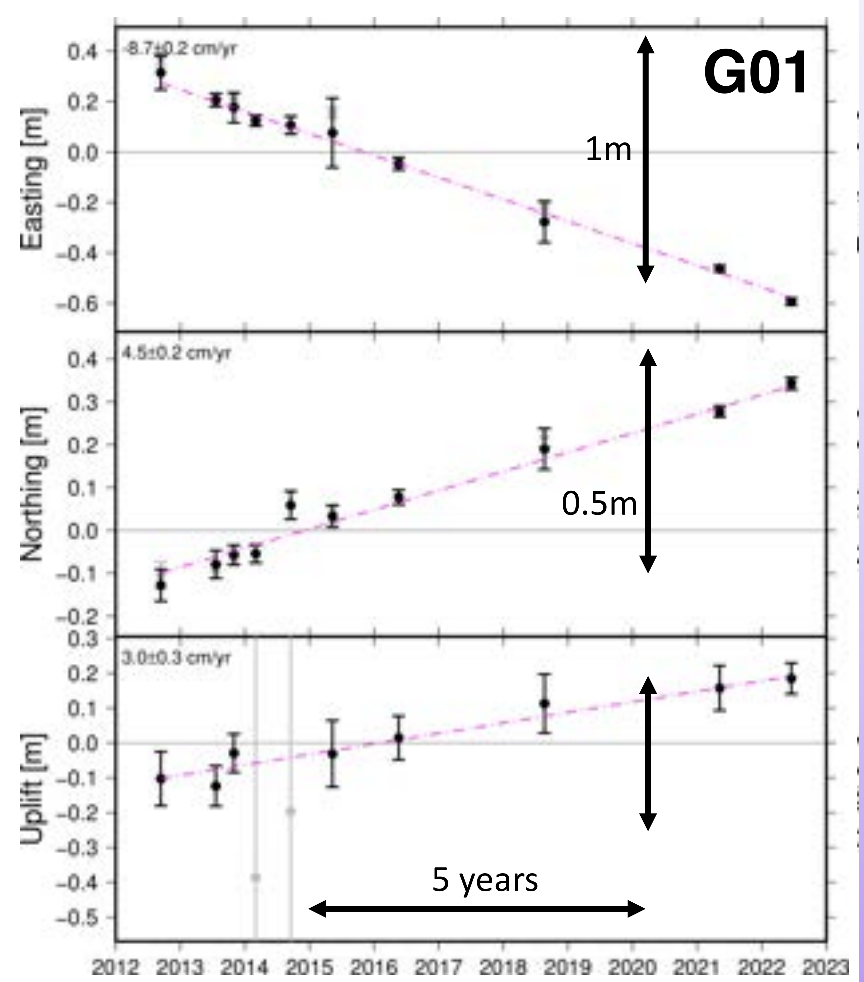


Fujiwara+ [2022]

onshore station

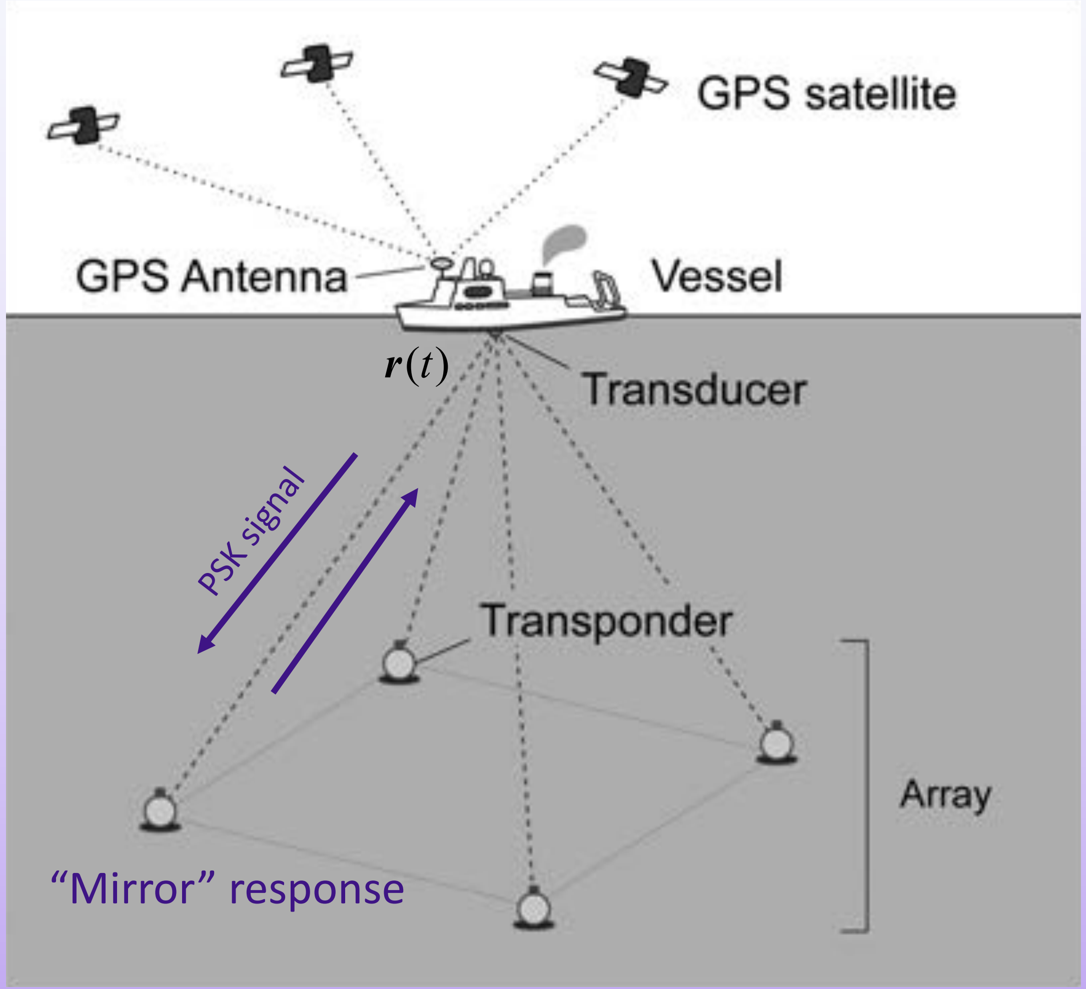


offshore station



Tomita+ [2022]

Causes of accuracy degradation in GNSS-A



Honsho+ [2017]

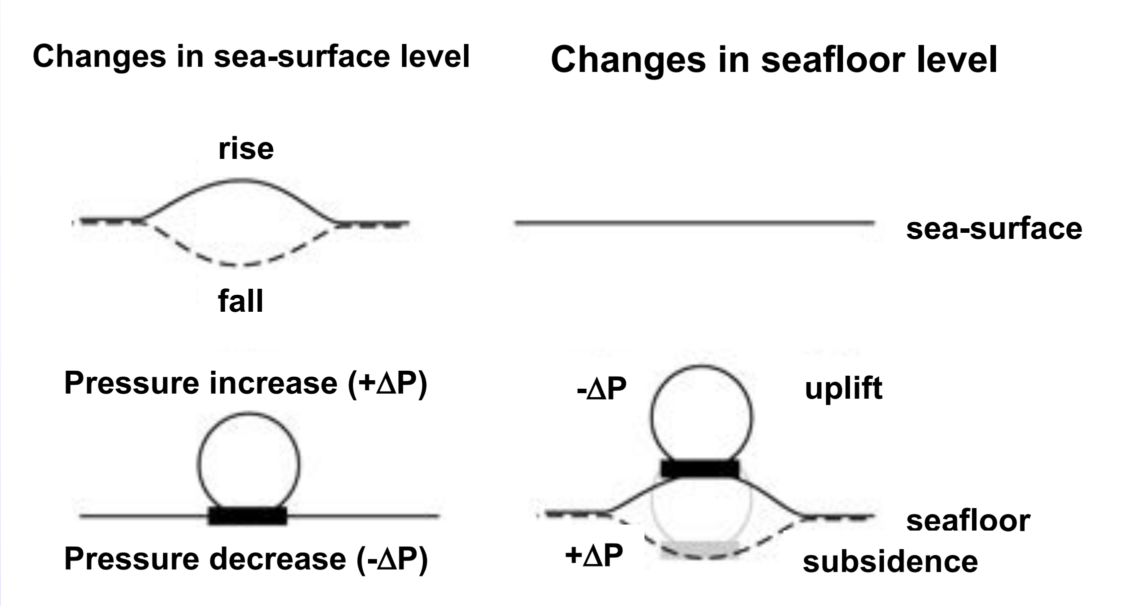
$$T(t) = f\left(\boldsymbol{p}_i, \boldsymbol{r}(t), c_0(z)\right) + \boxed{\delta F(t, \boldsymbol{p}_i, \boldsymbol{r}(t))}$$

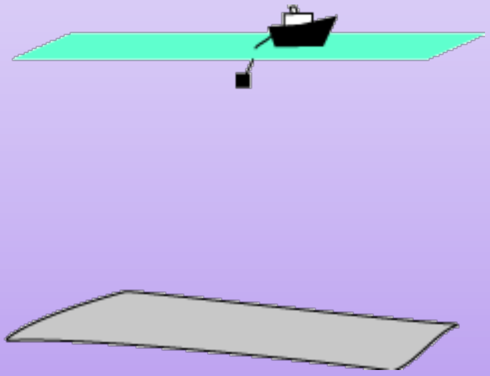
Correction term δF depends also on the positions of the ship and the transponders.

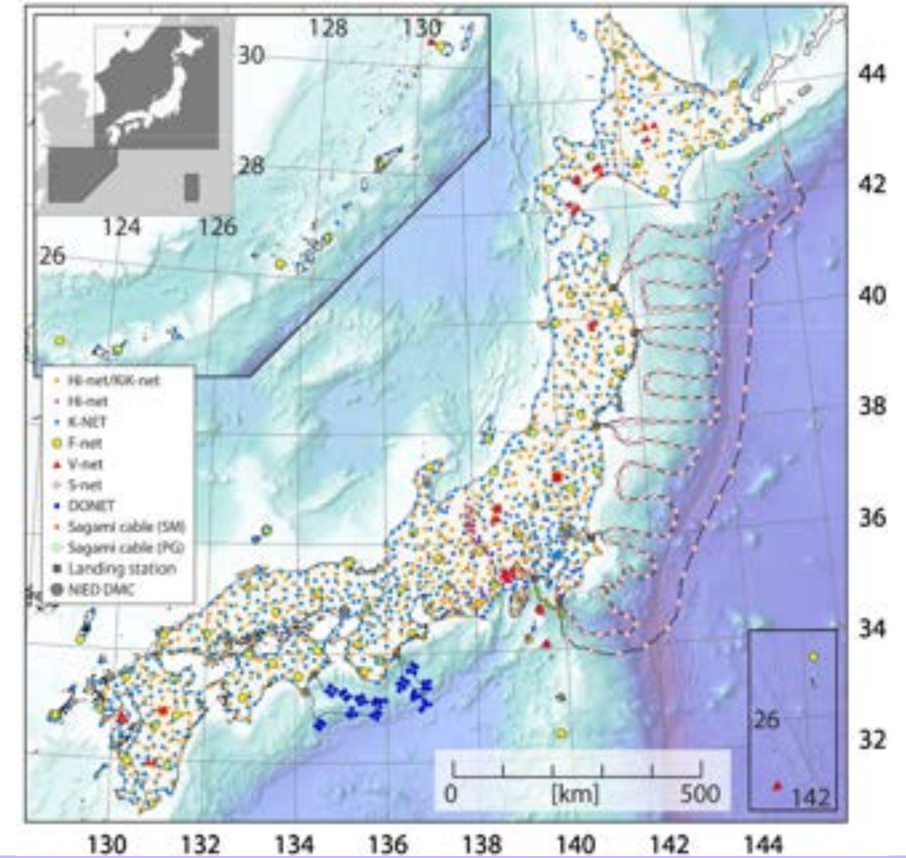
The trade-off between $\boldsymbol{p}_i$ and δF is inevitable in GNSS-A observations with limited ray coverage.

In GNSS, 3-D atmospheric structure can be estimated owing to dense satellite/observatory networks.

Ocean bottom pressure (OBP) observations

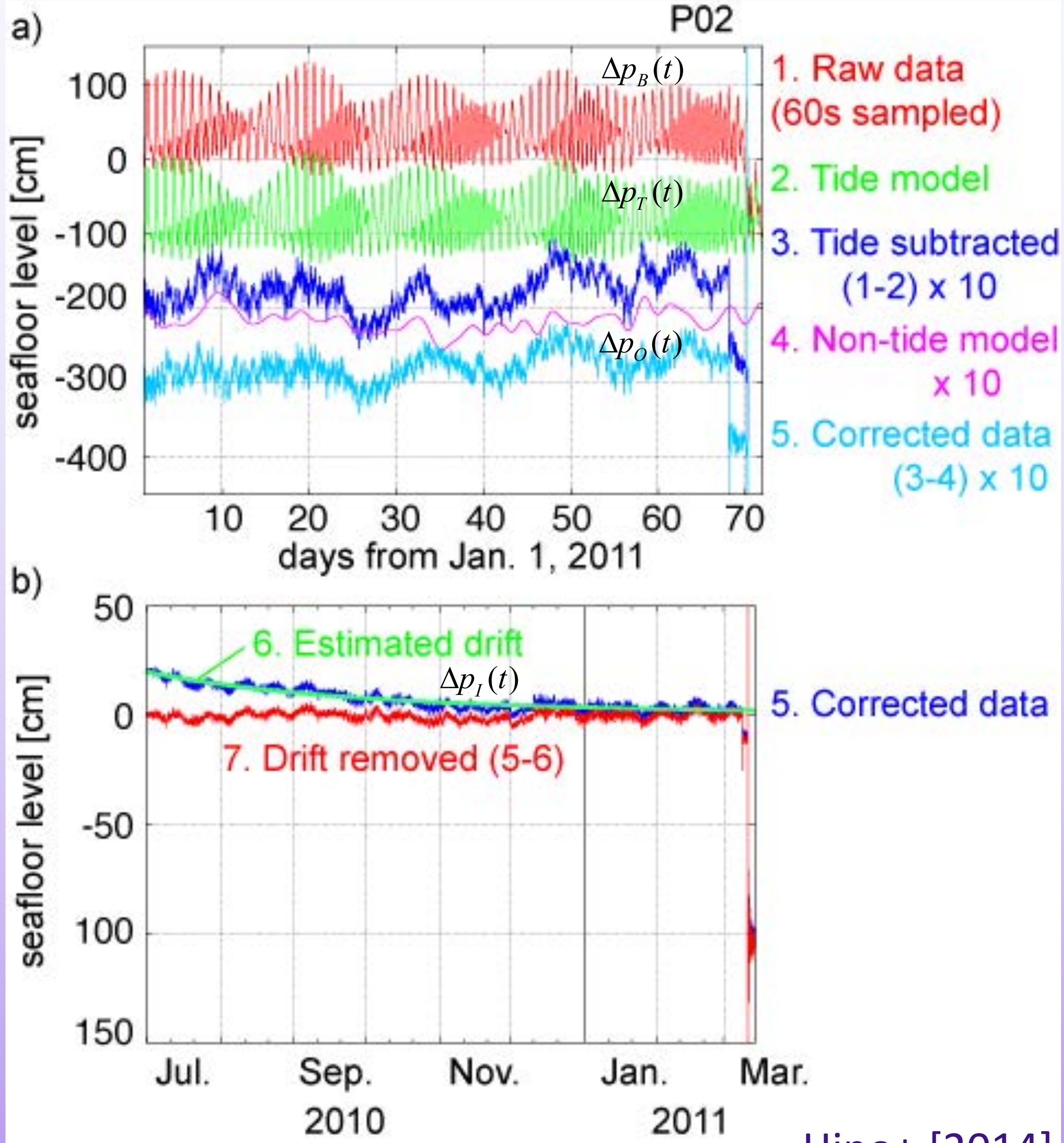






Aoi+ [2021]

Constituents of OBP records



Hino+ [2014]

1 hPa ～ 1 cm H_2O

$$p_B(t) = \bar{p}_B + \Delta p_B(t)$$

mean

~ 10^5 hPa

($\propto$ depth of deployment)

$$\Delta p_B(t) = \Delta p_C(t) + \Delta p_O(t) + \Delta p_I(t)$$

geodetic signal	non-tidal fluctuation	instrumental drift
~ 1 hPa	~ 10 hPa	~ 10 hPa/year

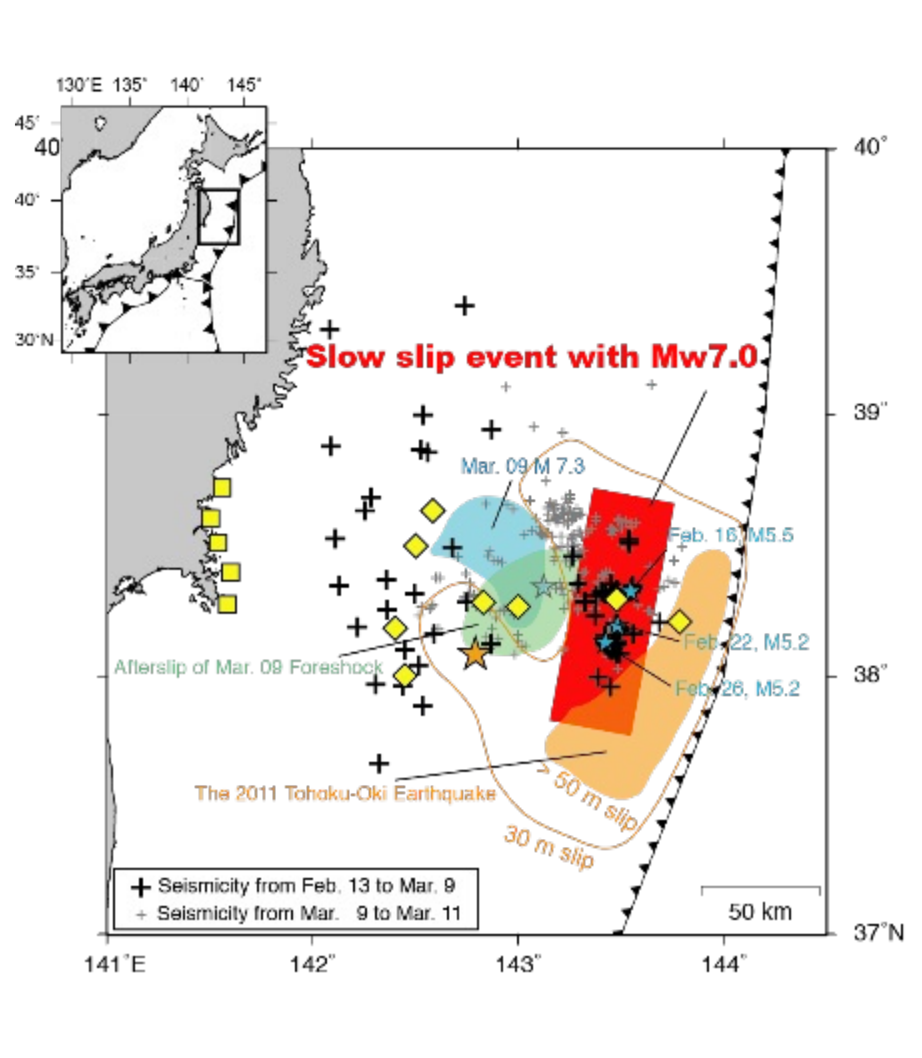
$$+\Delta p_T(t) + \Delta p_A(t)$$

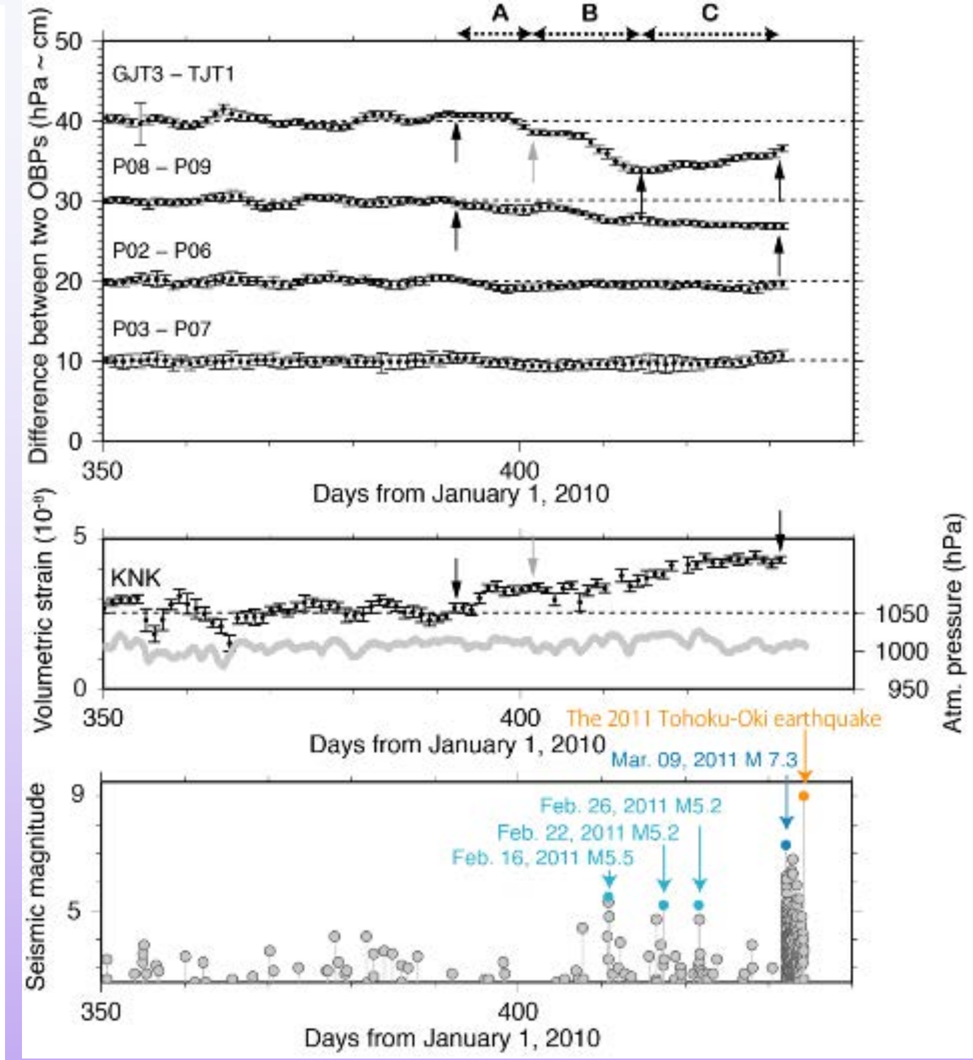
tidal fluctuation	atmospheric pressure
~ 100 hPa	*= 0* *(IB assumption)*

$$\Delta p_c(t) \big/ \bar{p}_B$$ ~ 10 ppm

→ Required resolution < 1 ppm (~ 1 mm)

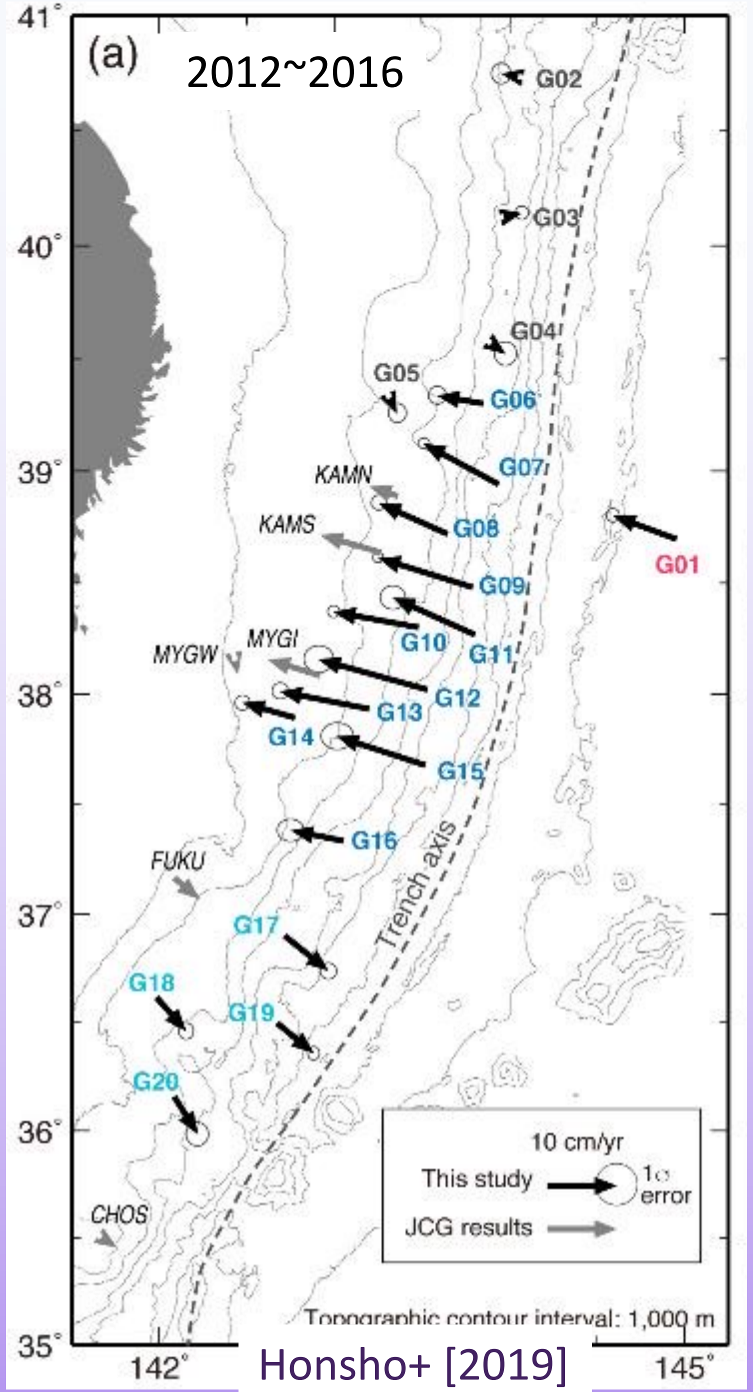
Slow slip preceding 2011 Tohoku-Oki Earthquake





Ito+ [2012]

Horizontal motions after 2011 Tohoku-Oki Earthquake



Honsho+ [2019]

<u>Northern part (not ruptured by the 2011 mainshock)</u>

Slow deformation rate

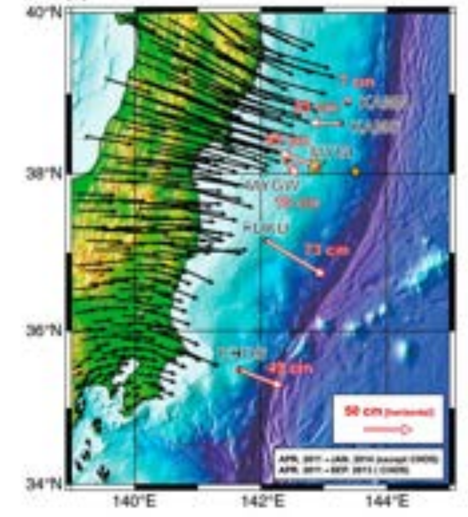
<u>Middle part (large coseismic slip during the 2011 MS)</u>

Rapid landward motion

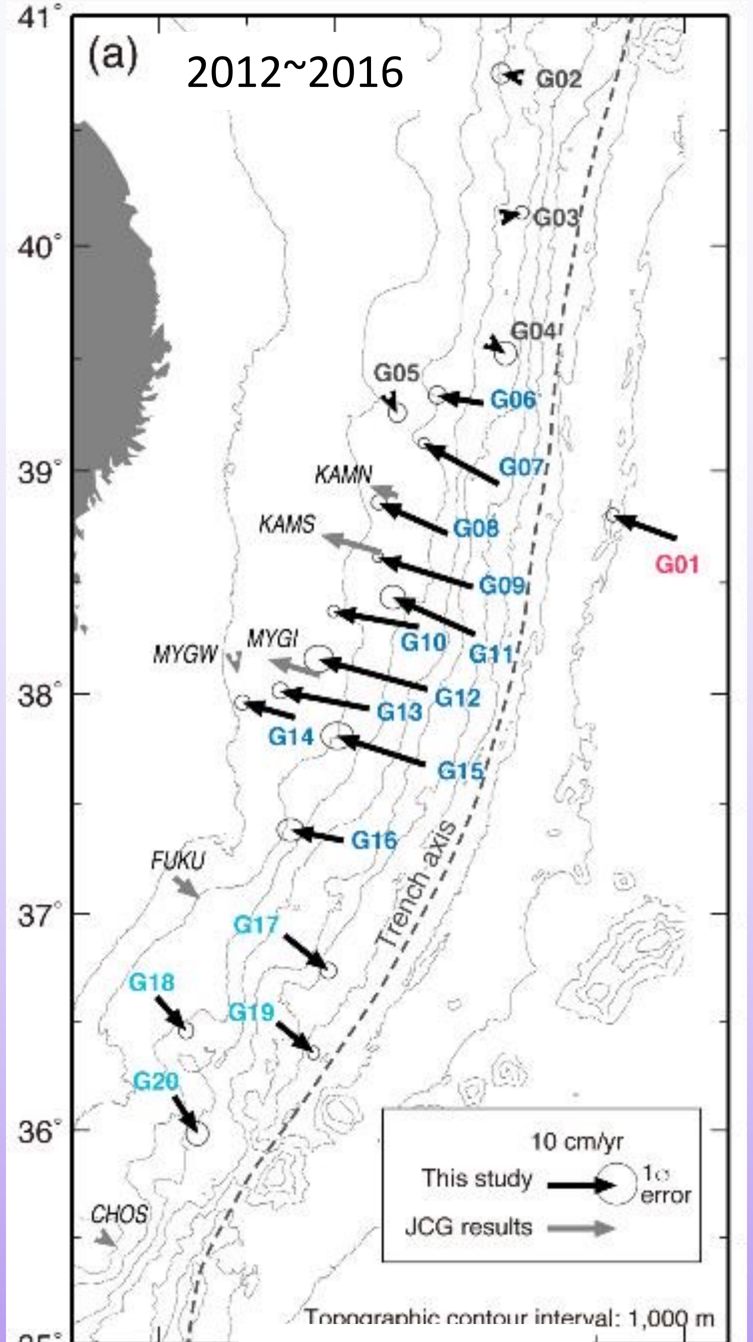
<u>Southern part (not ruptured by the 2011 mainshock)</u>

Rapid oceanward motion

Onshore GNSS observations show little spatial variations



Complex behavior in and around the rupture area of Tohoku-Oki Eq.



Honsho+ [2019]

Horizontal motions after 2011 Tohoku-Oki Earthquake

<u>Northern part (not ruptured by the 2011 mainshock)</u>

Slow deformation rate ? (balancing ① and ③)

<u>Middle part (large coseismic slip during the 2011 MS)</u>

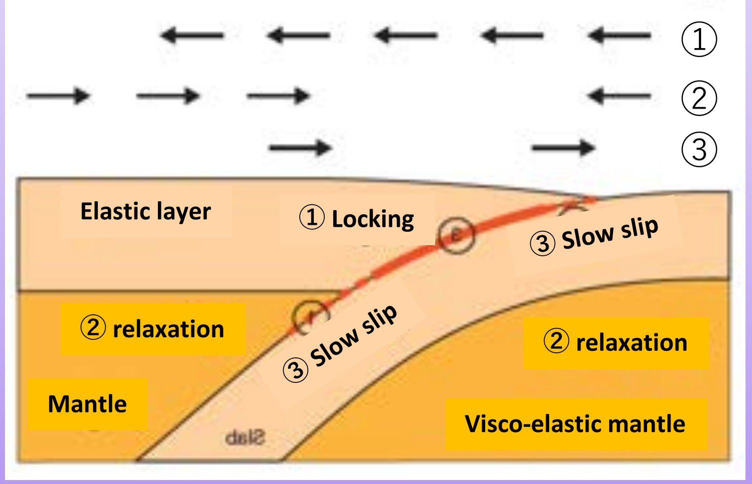
Prevalence of VE-relaxation ②

<u>Southern part (not ruptured by the 2011 mainshock)</u>

Prevalence of slow slip (afterslip) ③

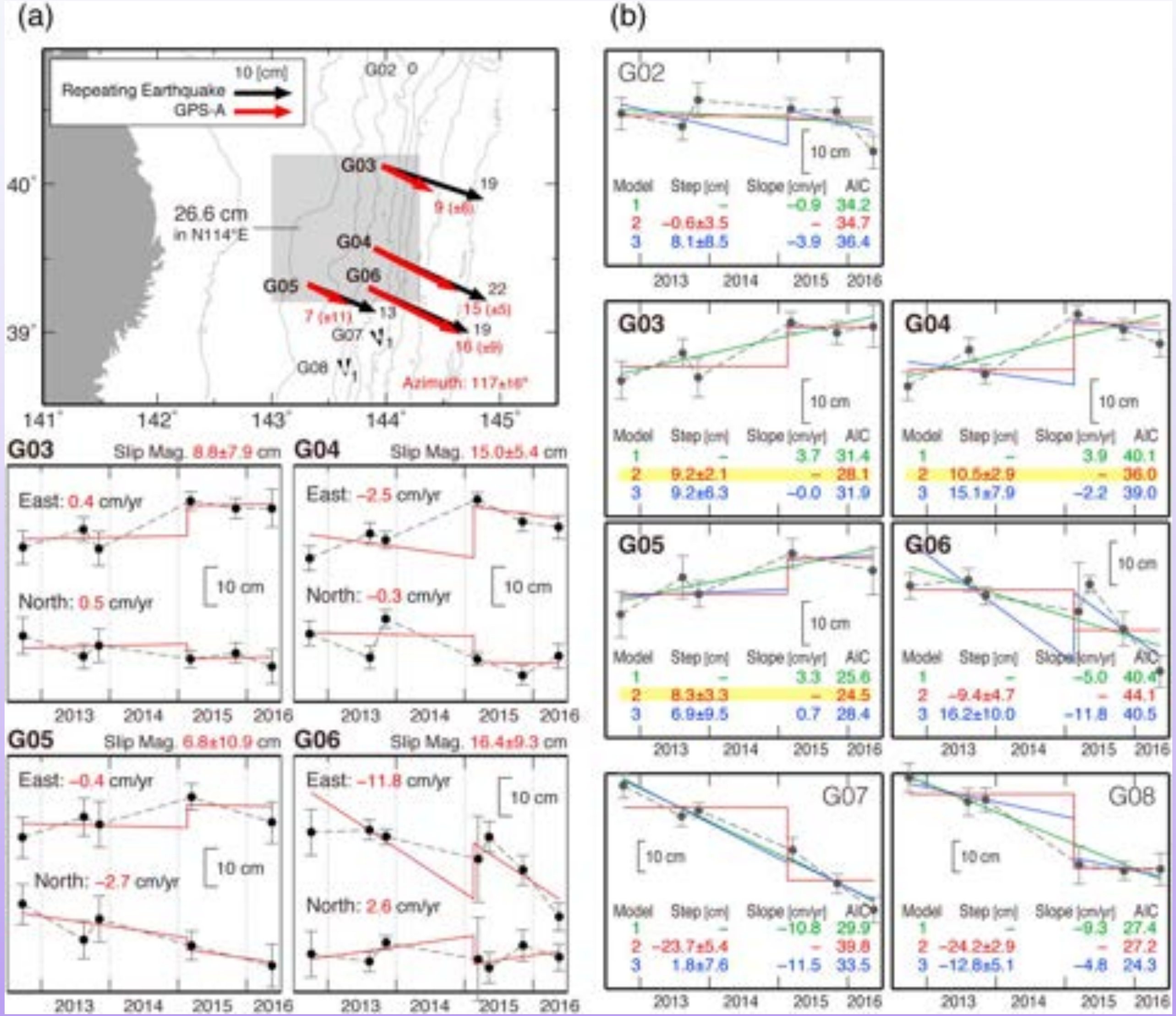
Onshore deformation:
combination of ② and ③

① Locking between the plates
② Viscoelastic relaxation
③ Slow slip on the plate boundary



Wang+ [2012]

SSE detected by GNSS-A observation in 2015



Frequent SSEs have been pointed out by seismicity [Uchida+, 2016]

SSE-related seismicity change was observed in 2015.

GNSS-A displacement time series at several stations seem to show “step” in 2015.

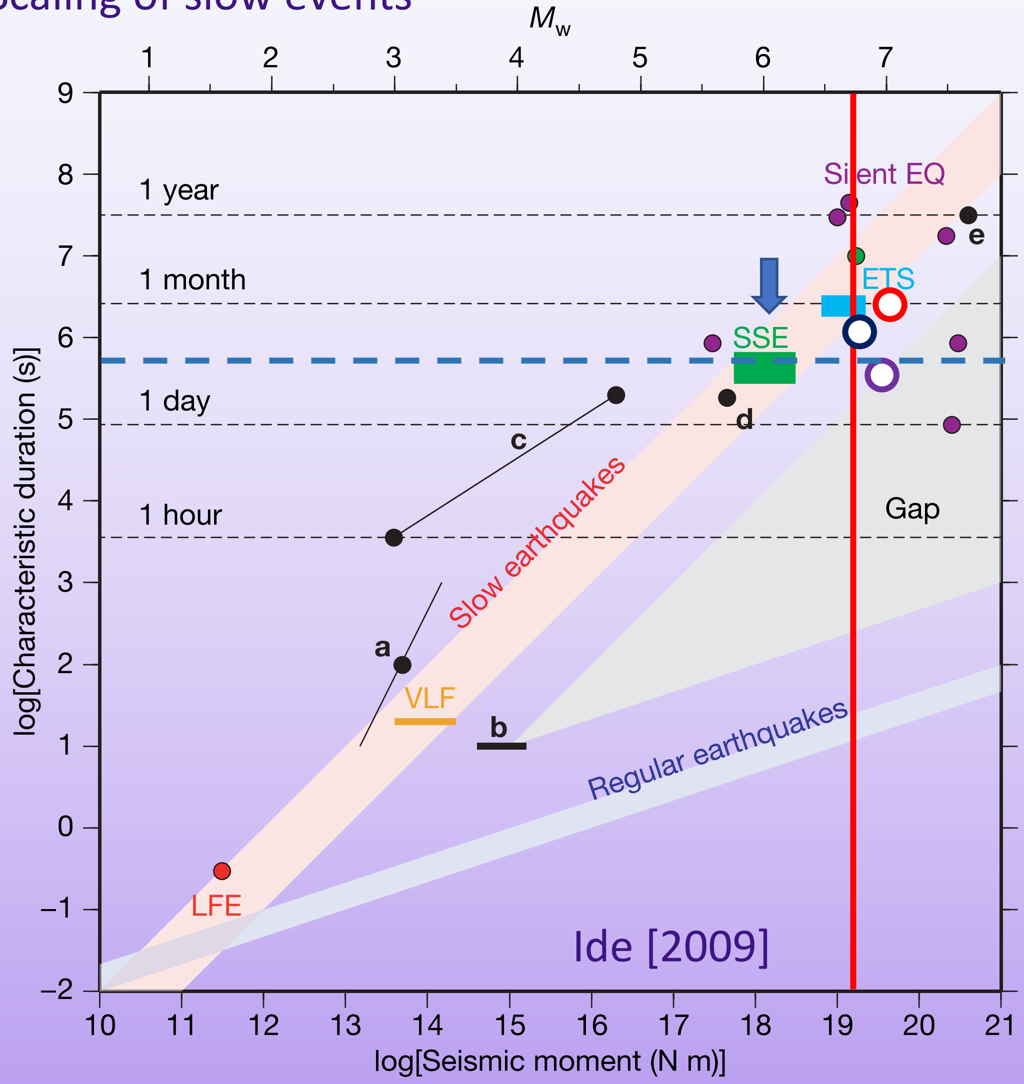
The steps were statistically significant.

The motions are consistent with the SSE fault model derived from seismicity analysis.

Honsho+ [2019]

Possible size of SSEs in the Japan Trench

Scaling of slow events



OBP

SSEs previously detected by seafloor observations

- SSE starting Feb., 2011 [Ito+, 2014]
- Afterslip of the M7 foreshock of 2011 Tohoku Eq. [Ohta+, 2012]
- Spontaneous SSE in Hikrangi, NZ [Wallace+, 2016]

GNSS-A

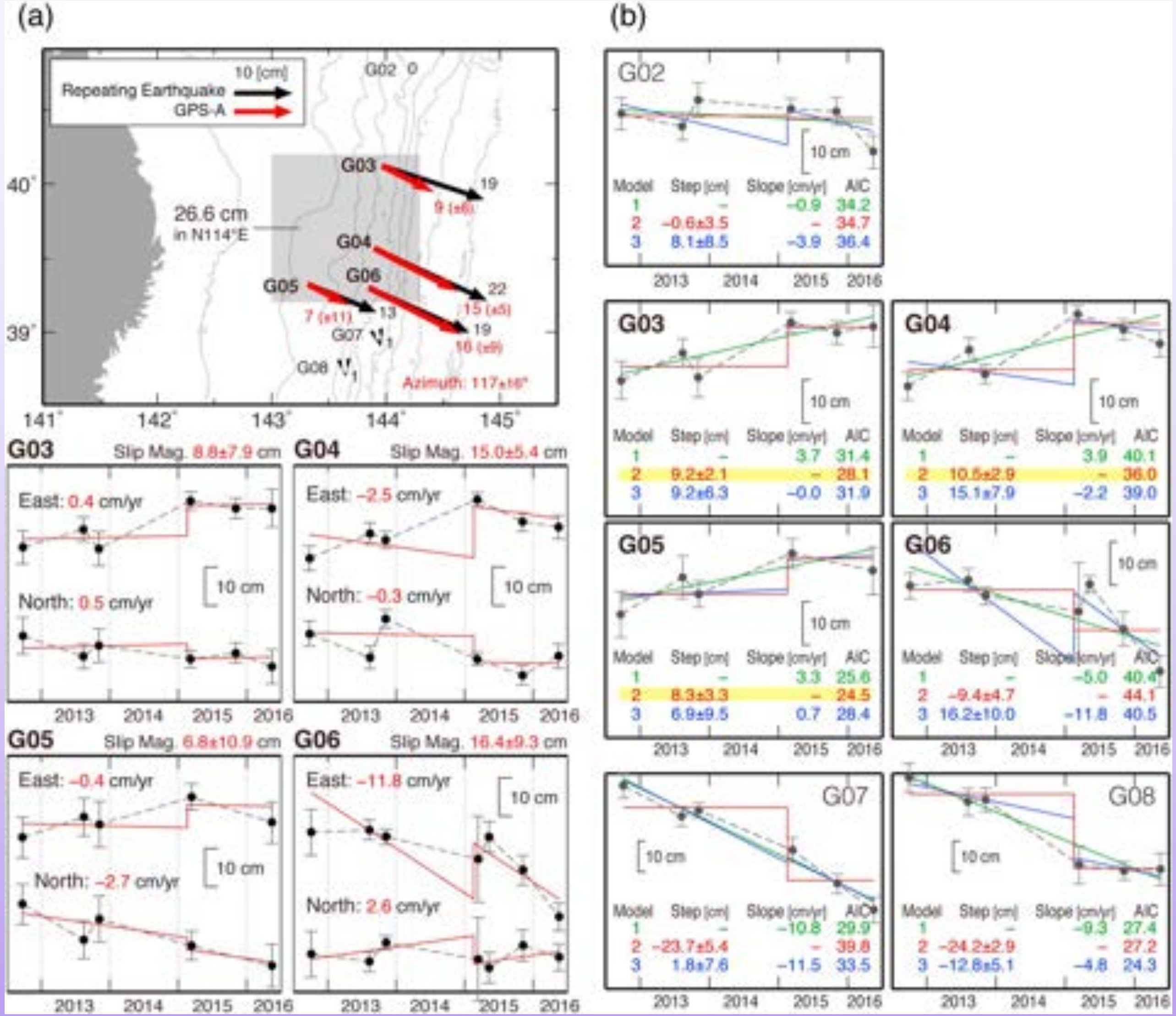
- SSE in northern Japan Trench [Honsho+, 2019] (duration was not constrained)

Possible SSEs in northern Japan Trench

Duration: ~ 10 days (based on tectonic tremor activity)
Frequency: ~ 5 events/year (based on tremor activity)
Estimated size: ~ M6+ (based on scaling relation)

Expected displacement
< 10 cm in horizontal
< 2 cm in vertical

SSE detected by GNSS-A observation



Horizontal displacements of ~10 cm are expected to be detected by GNSS-A,

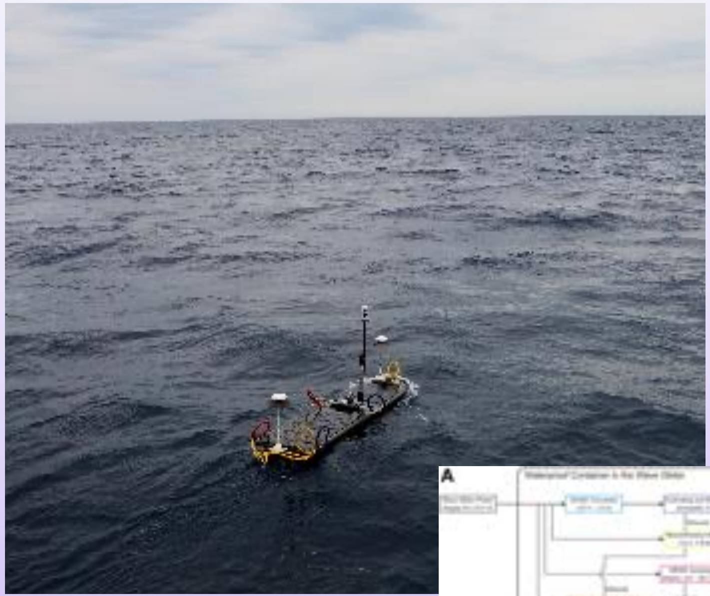
but are not convincing enough because
the **sampling intervals are too coarse**.

Systematic biases, if included, are difficult to
be identified from the **coarsely sampled time series**.

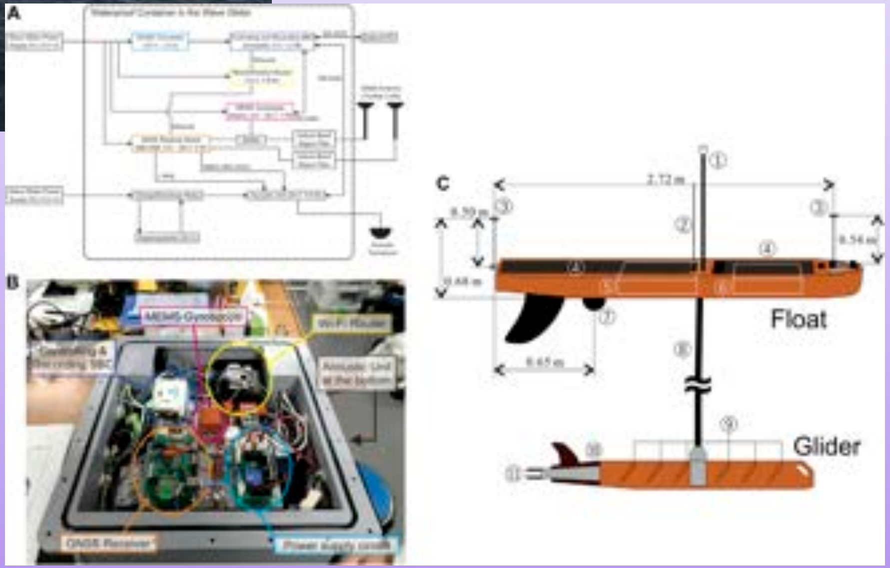
Challenges:
1) Increase time intervals of repeating surveys
2) Reduce the chances of systematic biases

Improvement of detectability of SSEs by GNSS-A

Increase mobility by using unmanned vehicles

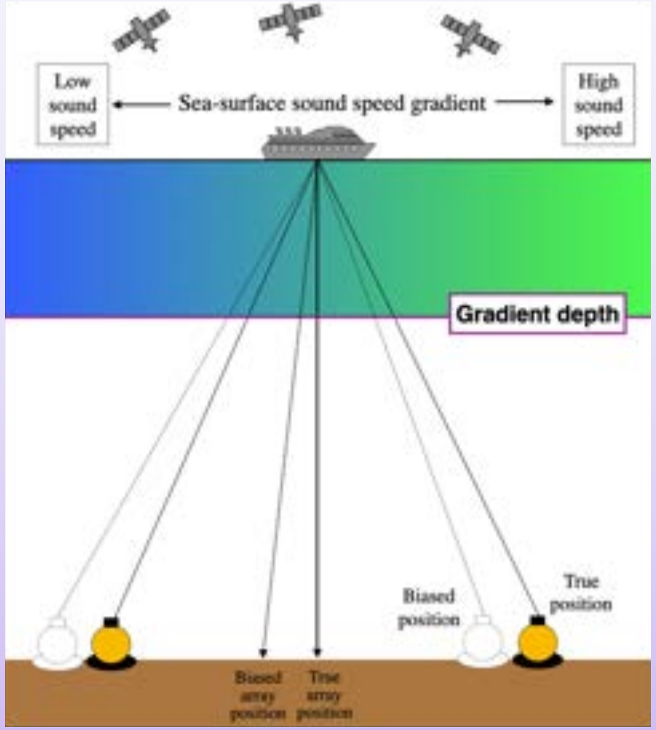


Wave glider



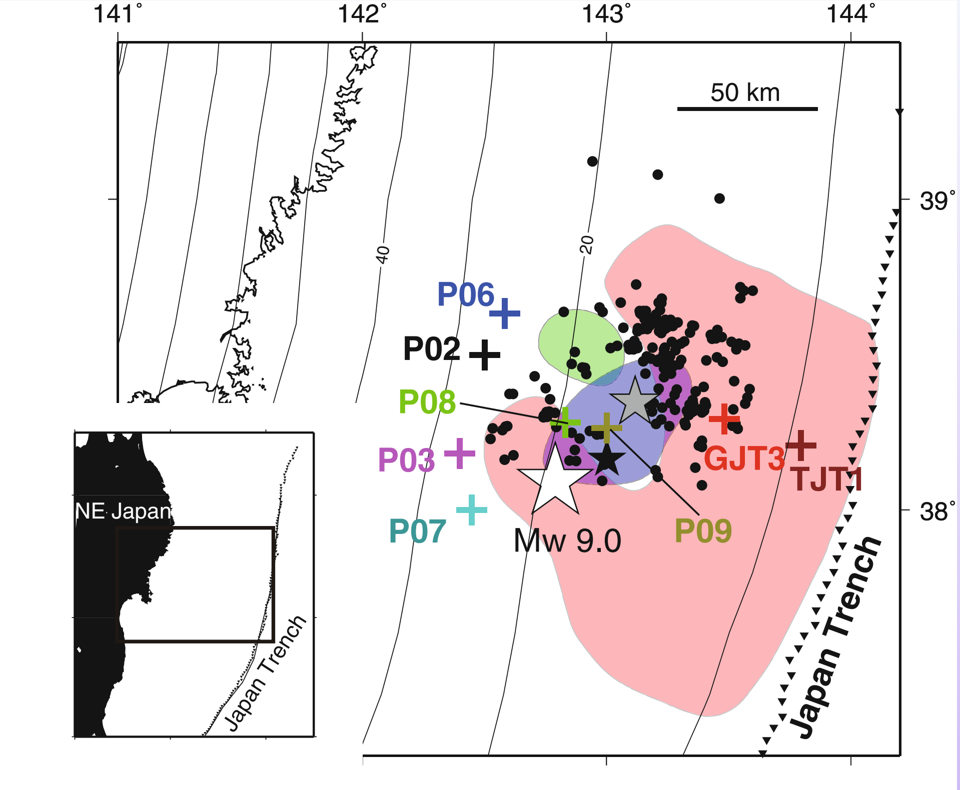
Iinuma+ [2021]

Simultaneous estimation of sound speed heterogeneity

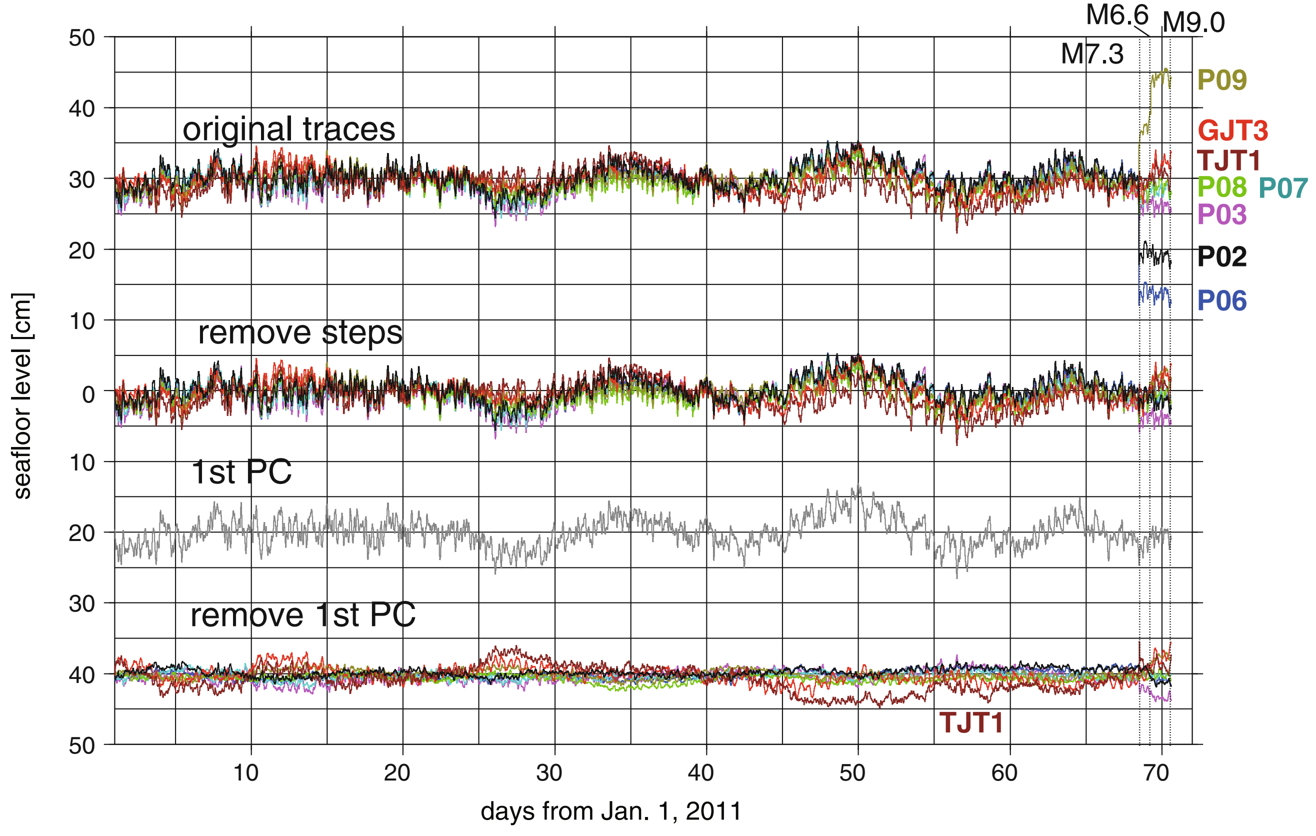


Tomita+ [2022]

Improvement of detectability of SSEs by OBP



Hino+ [2014]

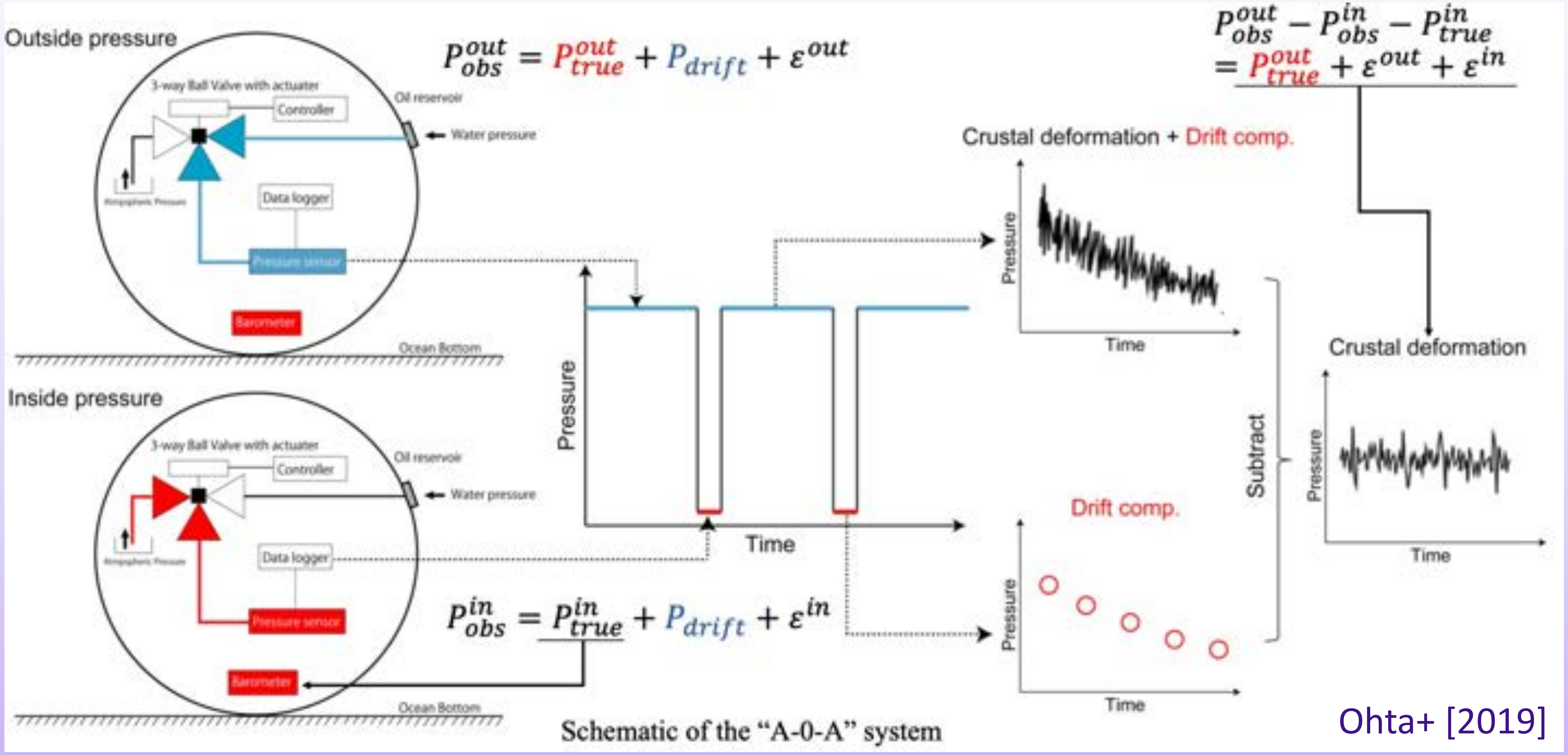


$$\Delta p_B(t) = \Delta p_C(t) + \boxed{\Delta p_O(t)} + \Delta p_I(t)$$

oceanographic fluctuation

Challenges:
3) Reduce noise components included in OBP records

Improvement of detectability of SSEs by OBP

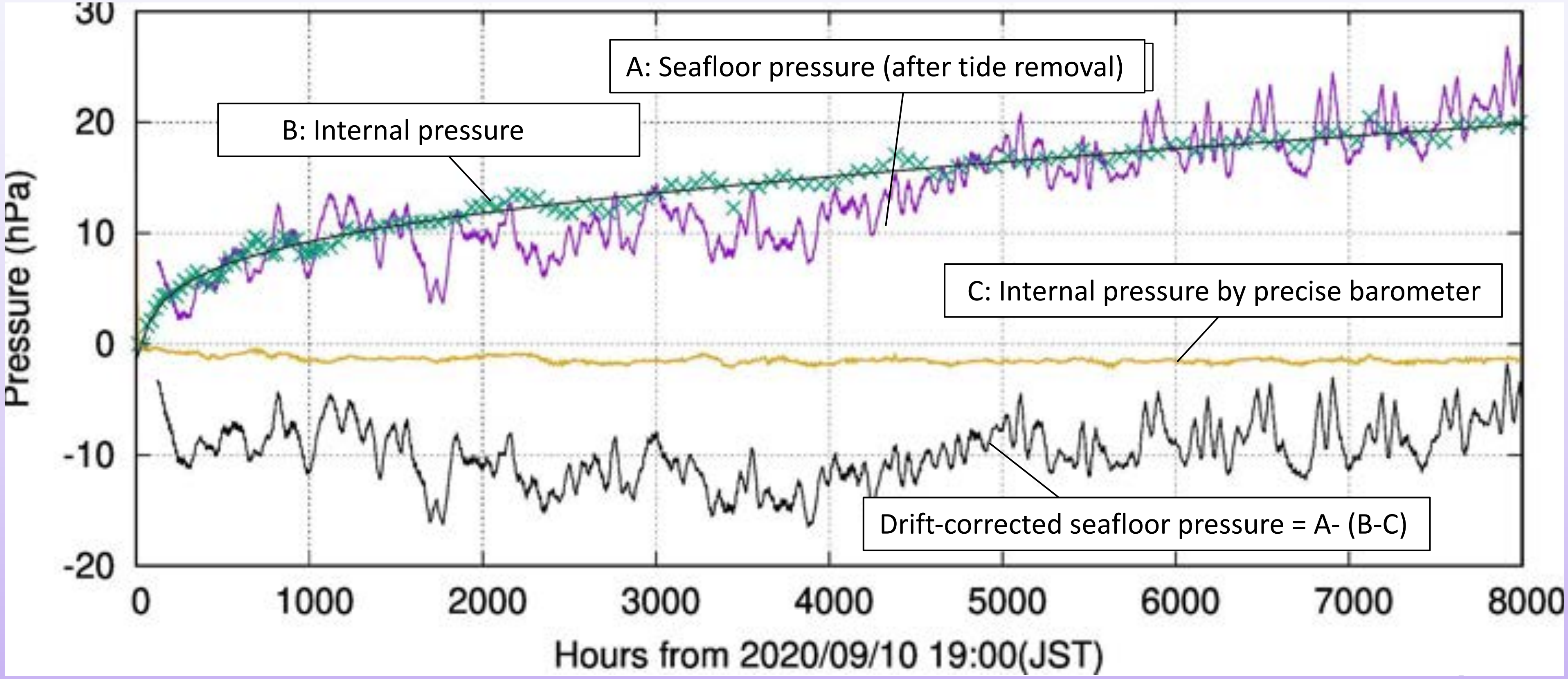


$$\Delta p_B(t) = \Delta p_C(t) + \Delta p_O(t) + \boxed{\Delta p_I(t)}$$

instrumental drift

Challenges:
3) Reduce noise components included in OBP records

Self-calibrating system for drift correction



Ohta+ [2021]

Summary

- The importance and effectiveness of seafloor geodetic observations were proven by capturing various important aspects of the 2011 Tohoku-oki earthquake.
  - Seismic slip monotonically increased towards the trench
  - SSE preceded the main shock
  - Postseismic deformation shows significant regional variations
- Efforts are underway to improve observation techniques to detect smaller SSEs
  - GNSS-A observation using unmanned vehicles
  - New methods to reduce the noises due to oceanographic fluctuations
  - Developing self-calibration pressure recorders