EGU General Assembly 2020 / 4–8 May 2020 online
EGU2020-11999 (Session SM2.5, Thu, 07 May, 14:00–15:45CEST)
https://doi.org/10.5194/egusphere-egu2020-11999

Fault modeling and stress drop estimation based on millimeter-scale tsunami records of an M6 earthquake detected by the dense and wide pressure gauge array

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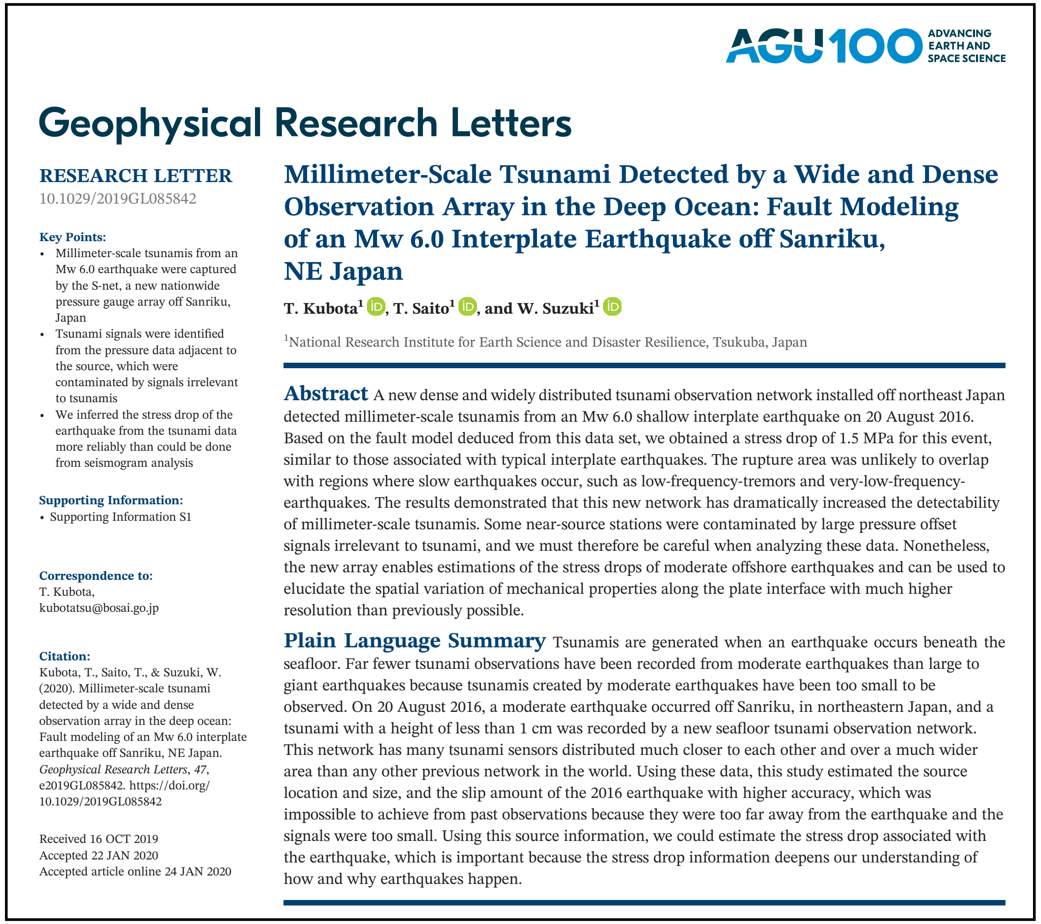
This work is published in *GRL*!
https://doi.org/10.1029/2019GL085842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Geophysical Research Letters

RESEARCH LETTER
10.1029/2019GL085842

Millimeter-Scale Tsunami Detected by a Wide and Dense Observation Array in the Deep Ocean: Fault Modeling of an Mw 6.0 Interplate Earthquake off Sanriku, NE Japan

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Key Points:
- Millimeter-scale tsunamis from an Mw 6.0 earthquake were captured by the S-net, a new nationwide pressure gauge array off Sanriku, Japan
- Tsunami signals were identified from the pressure data adjacent to the source, which were contaminated by signals irrelevant to tsunamis
- We inferred the stress drop of the earthquake from the tsunami data more reliably than could be done from seismogram analysis

Supporting Information:
- Supporting Information S1

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Citation:
Kubota, T., Saito, T., & Suzuki, W. (2020). Millimeter-scale tsunami detected by a wide and dense observation array in the deep ocean: Fault modeling of an Mw 6.0 interplate earthquake off Sanriku, NE Japan. *Geophysical Research Letters*, *47*, e2019GL085842. https://doi.org/10.1029/2019GL085842

Received 16 OCT 2019
Accepted 22 JAN 2020
Accepted article online 24 JAN 2020

Abstract A new dense and widely distributed tsunami observation network installed off northeast Japan detected millimeter-scale tsunamis from an Mw 6.0 shallow interplate earthquake on 20 August 2016. Based on the fault model deduced from this data set, we obtained a stress drop of 1.5 MPa for this event, similar to those associated with typical interplate earthquakes. The rupture area was unlikely to overlap with regions where slow earthquakes occur, such as low-frequency-tremors and very-low-frequency-earthquakes. The results demonstrated that this new network has dramatically increased the detectability of millimeter-scale tsunamis. Some near-source stations were contaminated by large pressure offset signals irrelevant to tsunami, and we must therefore be careful when analyzing these data. Nonetheless, the new array enables estimations of the stress drops of moderate offshore earthquakes and can be used to elucidate the spatial variation of mechanical properties along the plate interface with much higher resolution than previously possible.

Plain Language Summary Tsunamis are generated when an earthquake occurs beneath the seafloor. Far fewer tsunami observations have been recorded from moderate earthquakes than large to giant earthquakes because tsunamis created by moderate earthquakes have been too small to be observed. On 20 August 2016, a moderate earthquake occurred off Sanriku, in northeastern Japan, and a tsunami with a height of less than 1 cm was recorded by a new seafloor tsunami observation network. This network has many tsunami sensors distributed much closer to each other and over a much wider area than any other previous network in the world. Using these data, this study estimated the source location and size, and the slip amount of the 2016 earthquake with higher accuracy, which was impossible to achieve from past observations because they were too far away from the earthquake and the signals were too small. Using this source information, we could estimate the stress drop associated with the earthquake, which is important because the stress drop information deepens our understanding of how and why earthquakes happen.

[Acknowledgments]
This study used the pressure gauge data recorded by JAMSTEC (KPG1 and KPG2) and DART (21346 and 21347). This study was financially supported by JSPS KAKENHI 19K14818 and the Sasakawa Scientific Research Grant by Japan Science Society 2019-2037. The GMT software (Wessel & Smith, 1991) is used for preparing the figures.

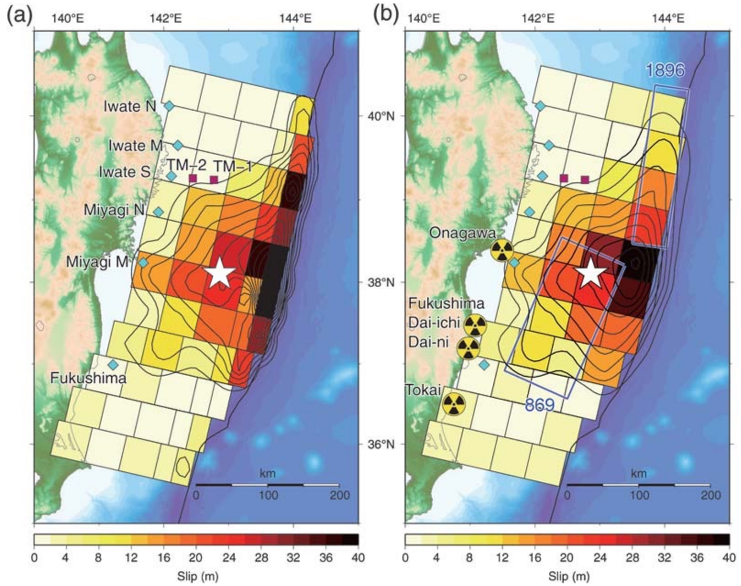
M>~7 EQ modeling using offshore pressure gauge (PG) tsunami data

M >~7 tsunamis have been detected by offshore PGs and used for fault modeling.

- However it is challenging to observe M<~6 tsunami
  - Typical offshore PG networks contain too few stations and remote from the source.

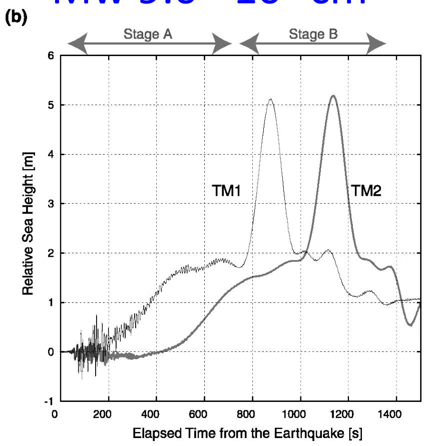
Mw 7.2 ~10^1cm

Mw 6.5 ~10^0cm

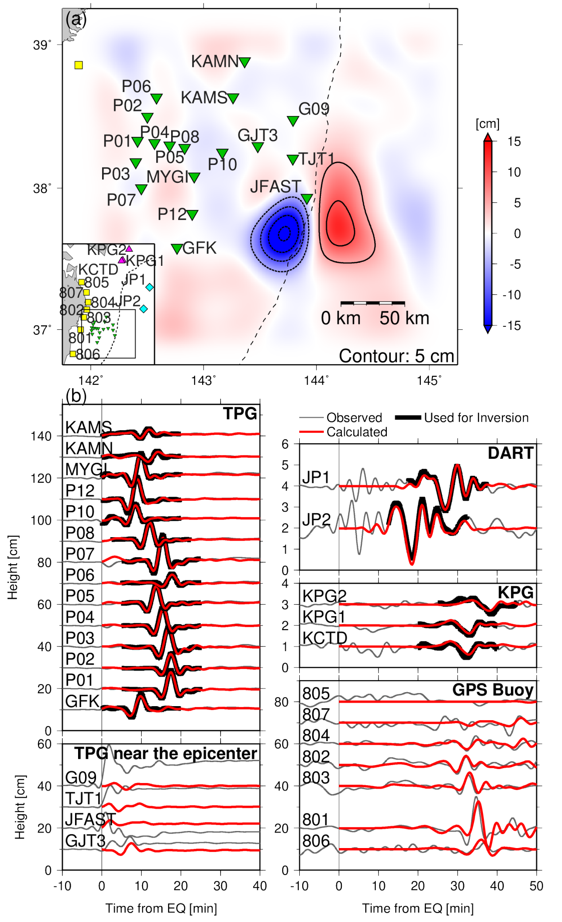


Satake et al. (2013BSSA)

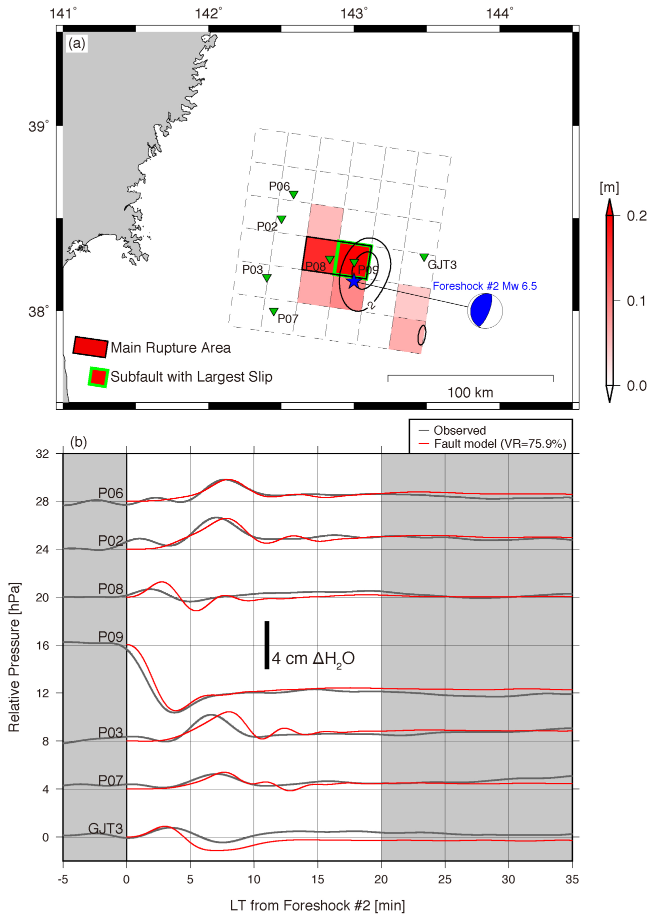
Mw 9.0 ~10^2 cm



Maeda et al. (2011EPS)



Kubota et al. (2019PEPS)



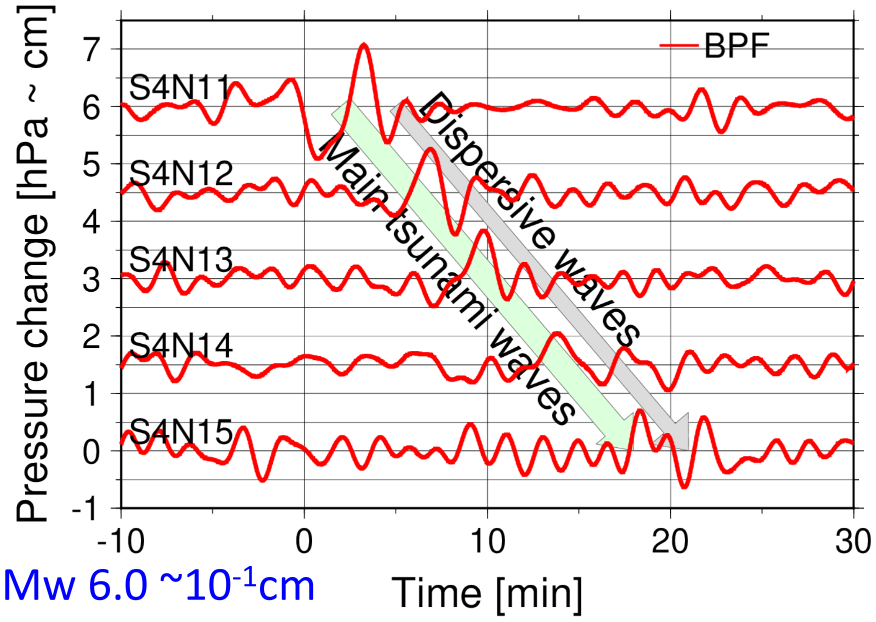
Kubota et al. (2017EPSL)

Millimeter-scale tsunami in the 2016 Off-Sanriku EQ (Mw 6.0)

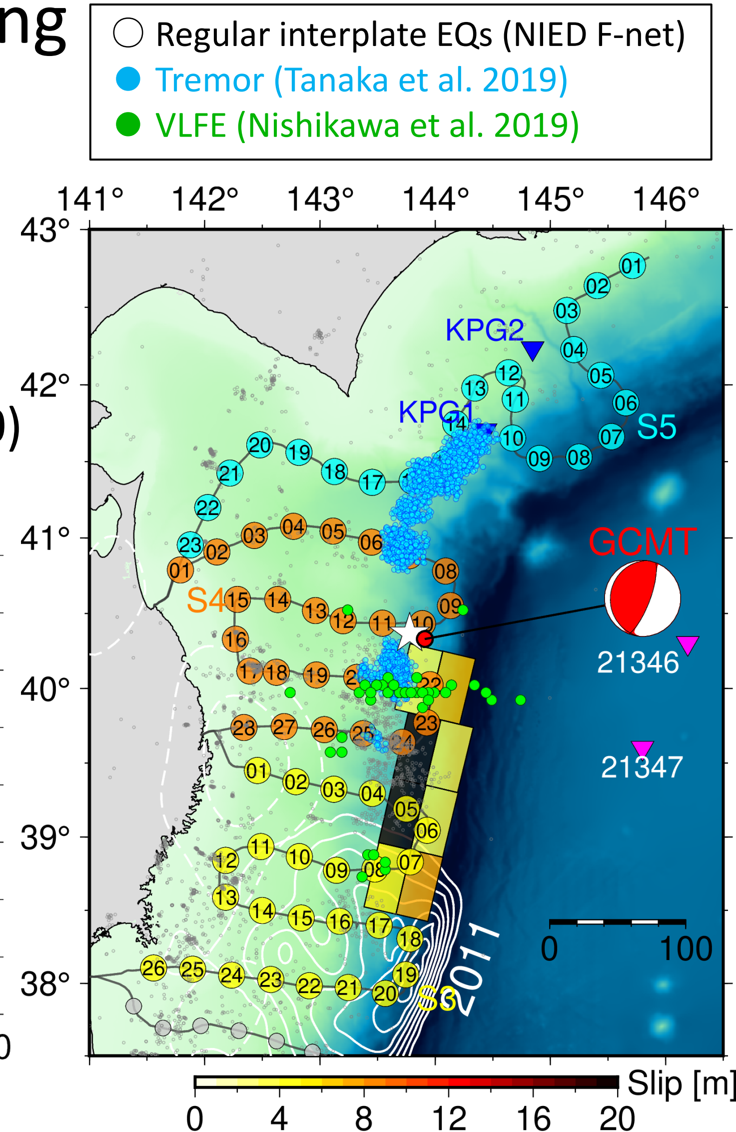
- ✓ Recently a new dense and wide observation network (S-net) is constructed.
- ✓ Millimeter-scale tsunami was observed by the S-net during an Mw 6.0 EQ off Sanriku on 20 Aug 2016.
  - at northern edge of the 1896 Sanriku EQ.
  - near the active regions of the low-frequency tremors and very-low frequency EQs (VLFEs)

(e.g., Tanaka et al. 2019; Nishikawa et al. 2019; Baba et al. 2020)

➢ Purpose
- estimate fault model using the S-net millimeter-scale tsunami data
- examine its relationship with other interplate phenomena

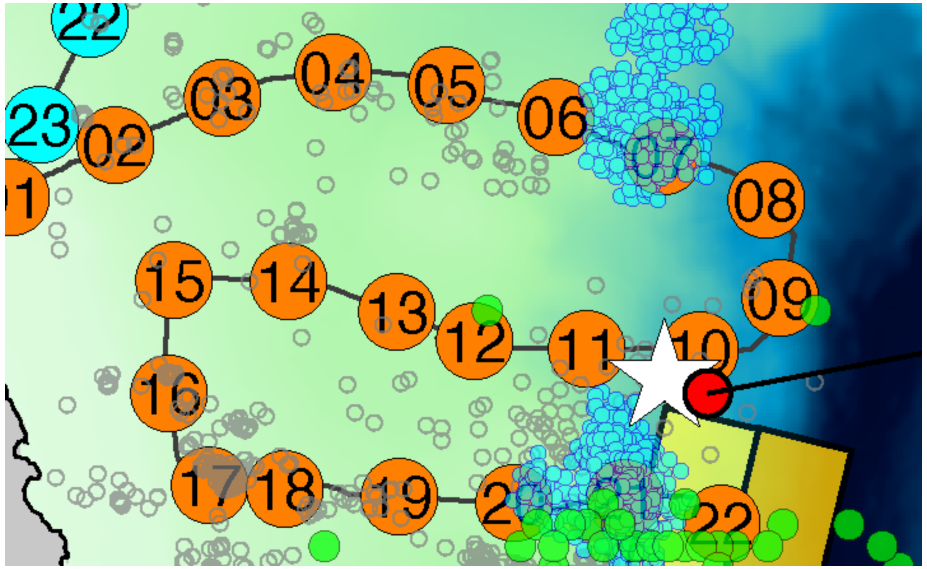


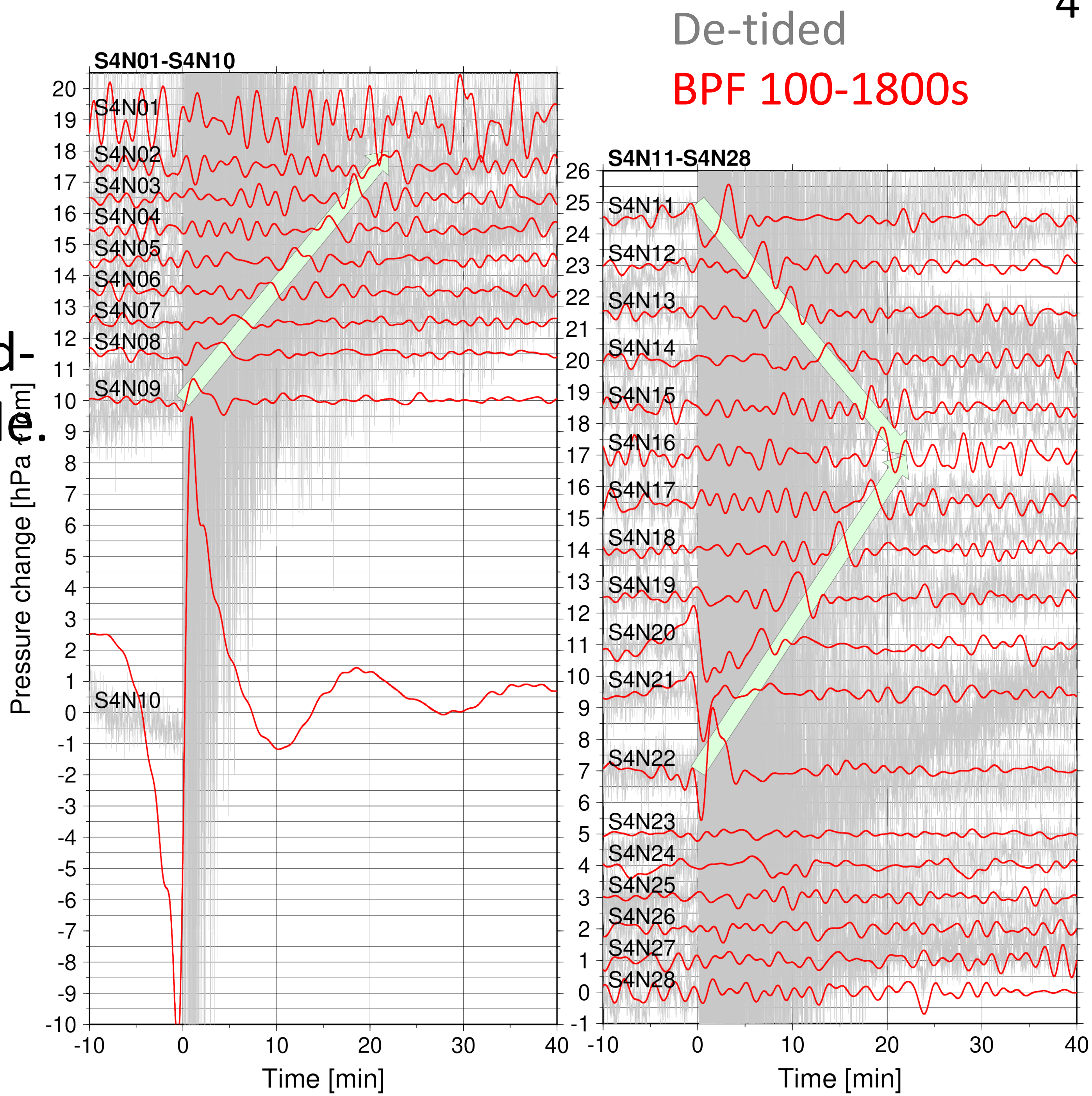
Mw 6.0 ~10^{-1}cm



Data processing

- ✓ If only from each single trace, it is difficult to recognize tsunami due to noise.
- ✓ When traces are aligned, westward-propagating tsunami is recognizable.
- ✓ Large step-like signal is observed at S4N10.

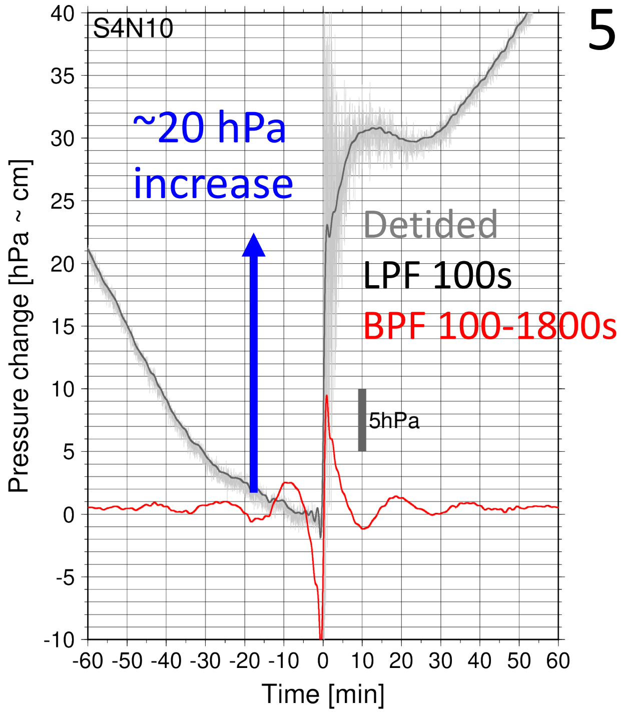


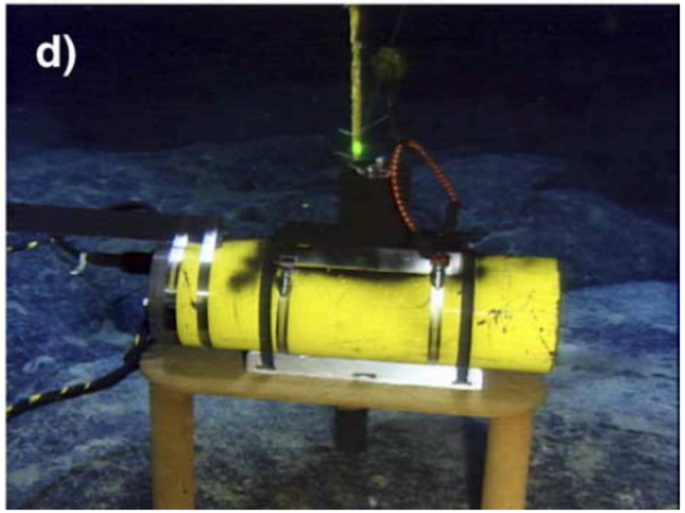


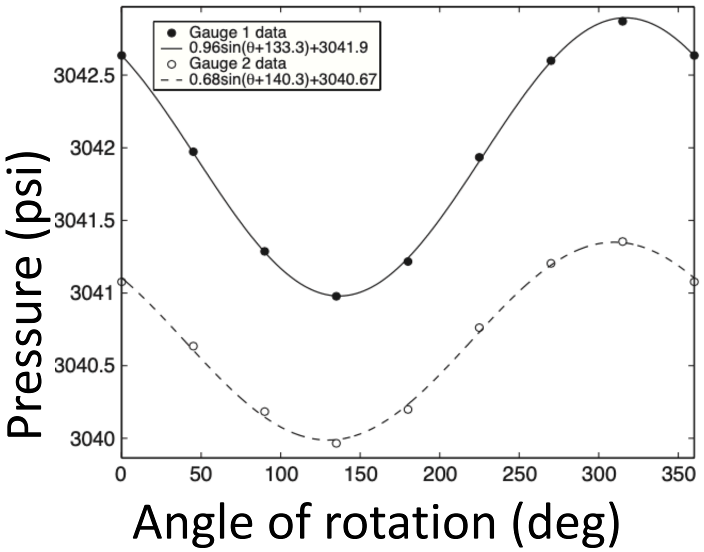
Note: abrupt pressure increase at S4N10

- ✓ Rotation of 5.7° was observed based on co-located accelerometer (Takagi et al. 2019)
- ✓ PG sensor is sensitive to its rotation (Chadwick et al. 2006)

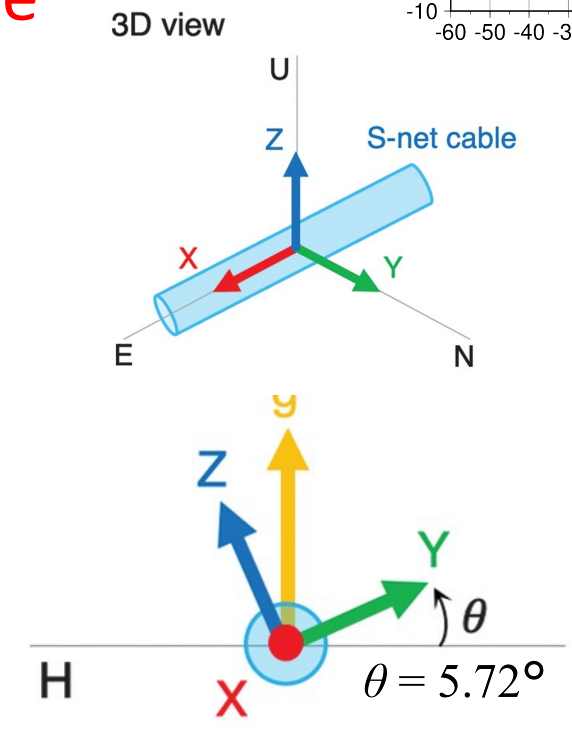
- ➢ The step-like signals are likely due to the sensor rotation associated with the seafloor seismic motion.
- ➢ Careful analysis is required to use the near-source S-net PG data.

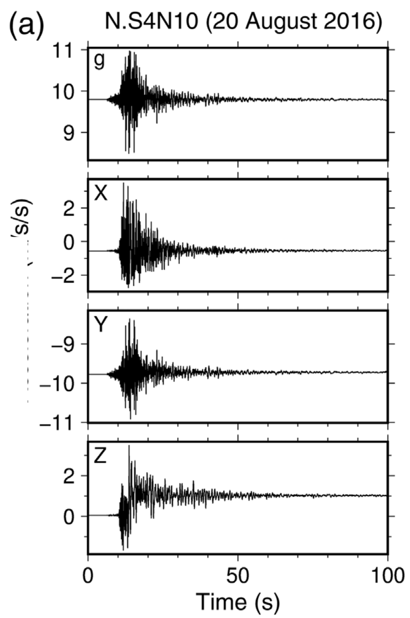






Chadwick et al. (2006)

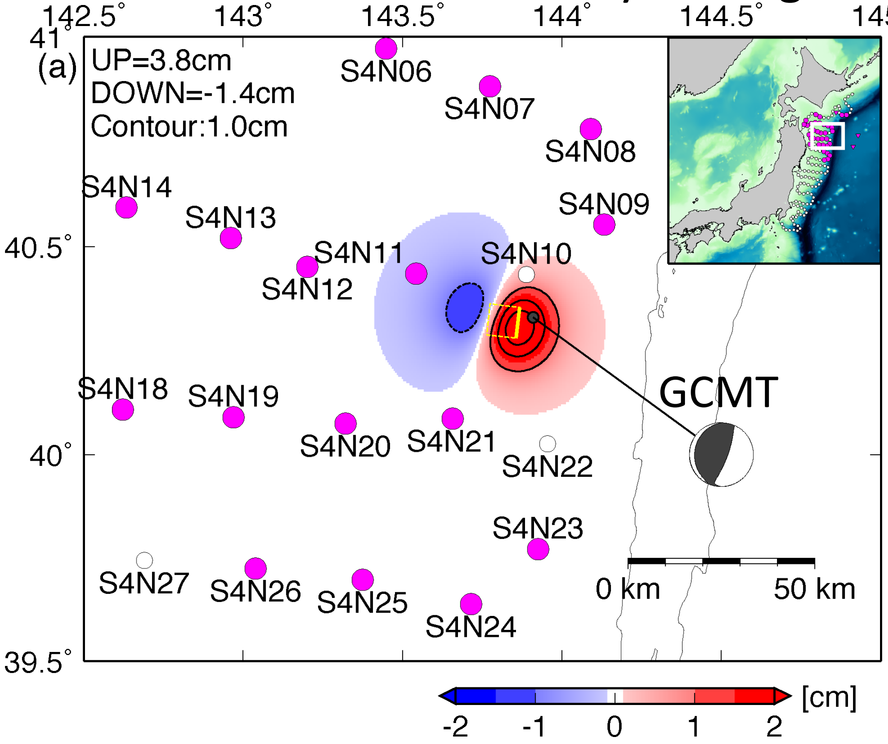




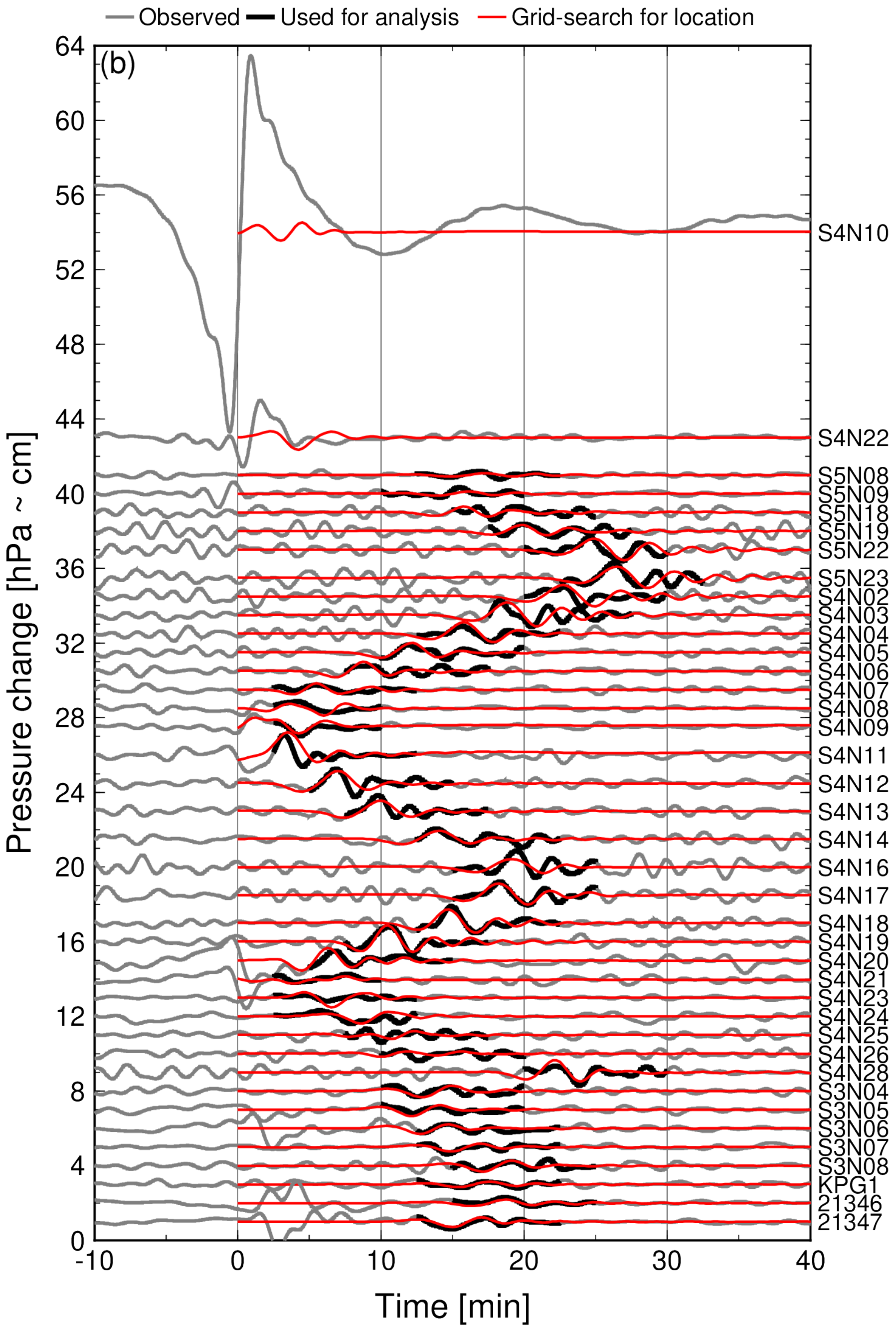
Takagi et al. (2019)

Analysis (1): Estimation of fault horizontal location

- ✓ <u>Horizontal location of the fault was estimated via the grid-search analysis</u>
  - Scaling law of Blaser et al. (2010) is used for assuming the rectangular fault dimension (*L* and *W*).
  - GCMT seismic moment is used to determine slip amount *D*.
  - Depth is fixed to coincide with the plate boundary model of Iwasaki et al. (2015).
  - Tsunami is calculated by solving linear-dispersive equation.



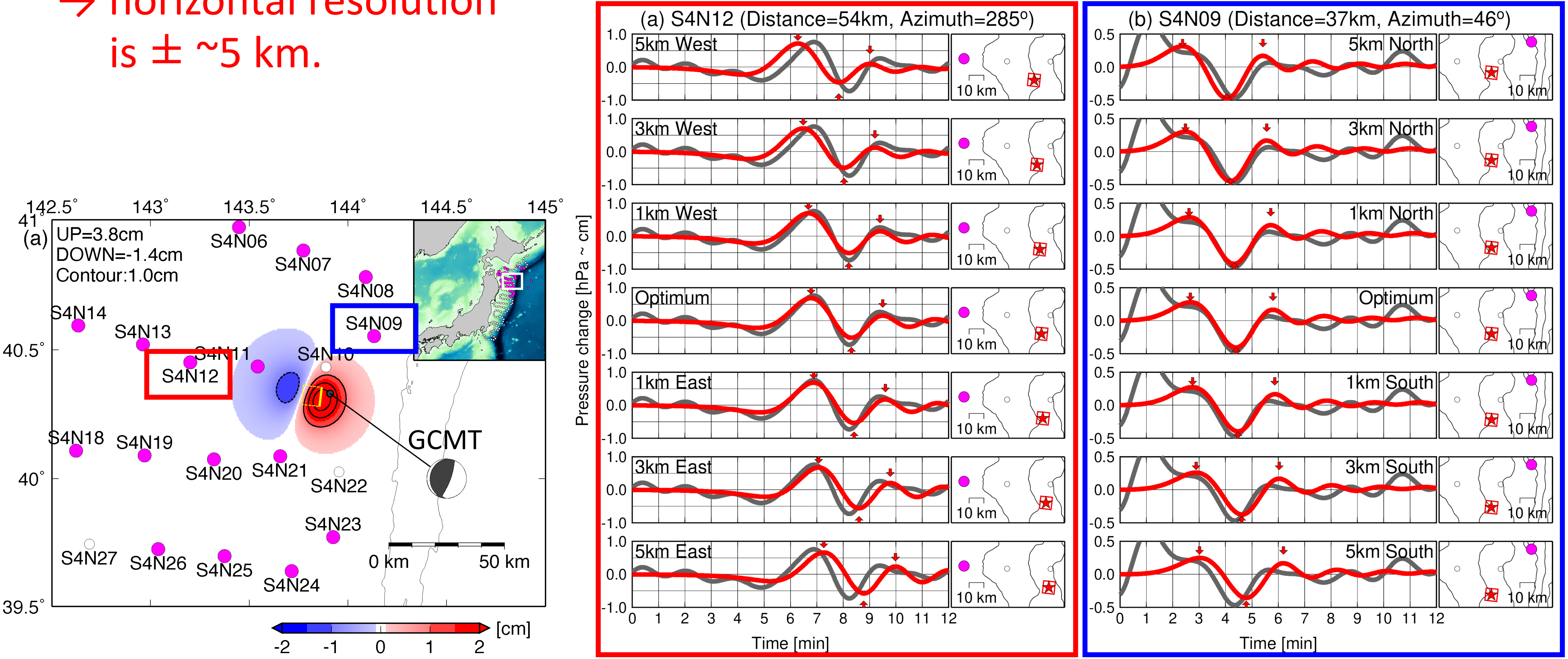
$$D = \frac{M_0}{\mu L W} \quad (\mu = 40\text{GPa})$$



Analysis (1): Estimation of fault horizontal location

- ✓ Optimum fault was estimated at ~10 km west of the GCMT centroid.
- ➢ When shifting the location by ~ 5km, the arrival time cannot be explained.

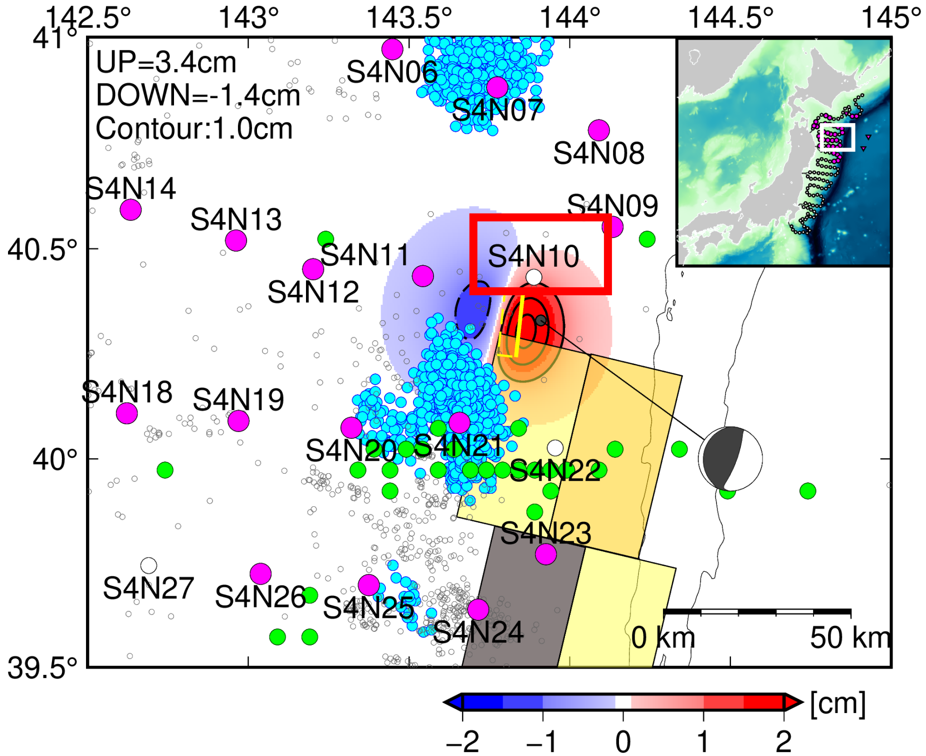
  → horizontal resolution is ± ~5 km.



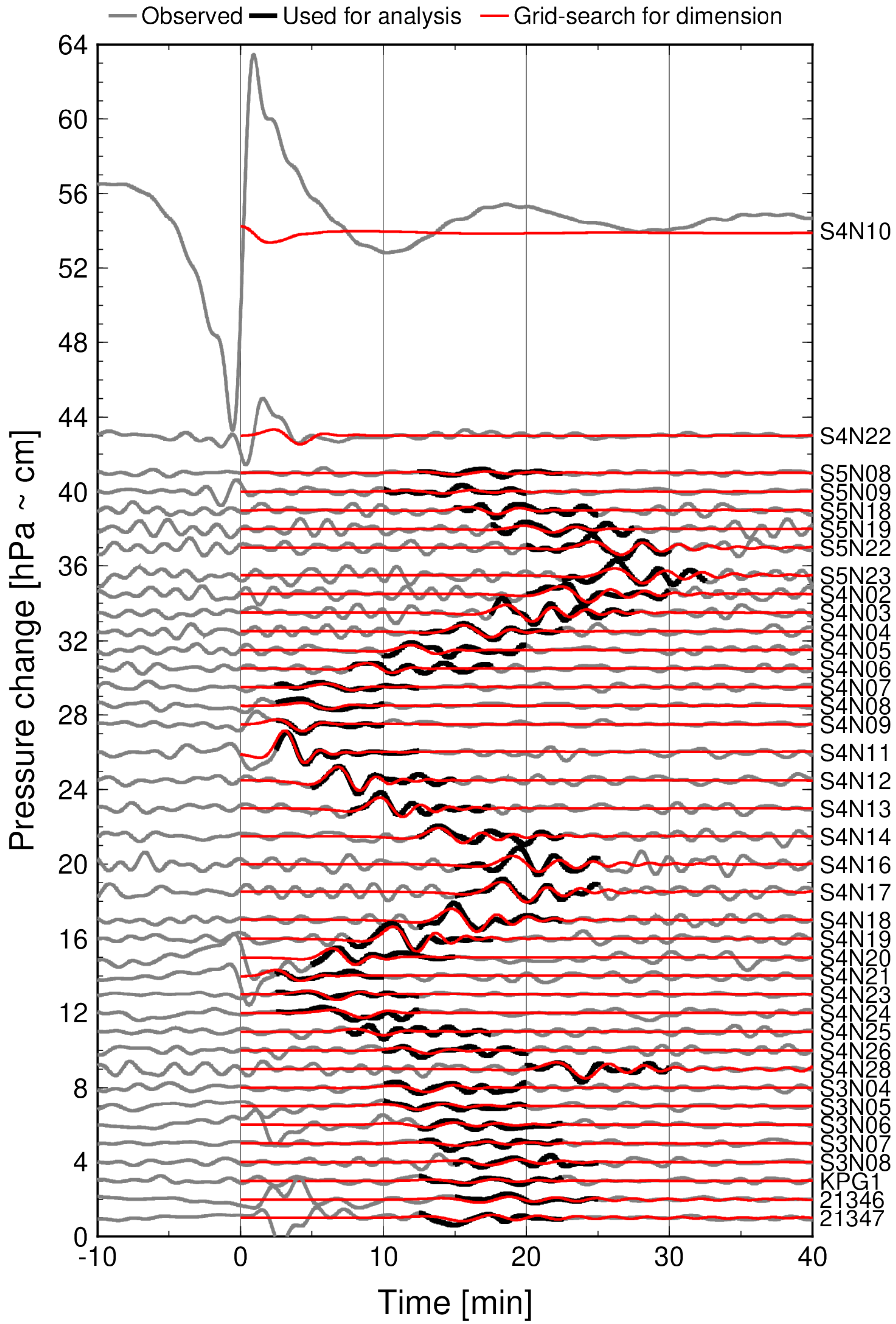
Analysis (2): Fault dimension modeling

- ✓ Optimum model had L=17 km, W=5 km, and D=40.5 cm (Mw 6.0, μ=40GPa)
- ✓ Static stress drop of Δσ ~ 1.5 MPa

➢ Waveforms were reproduced well except for S4N10

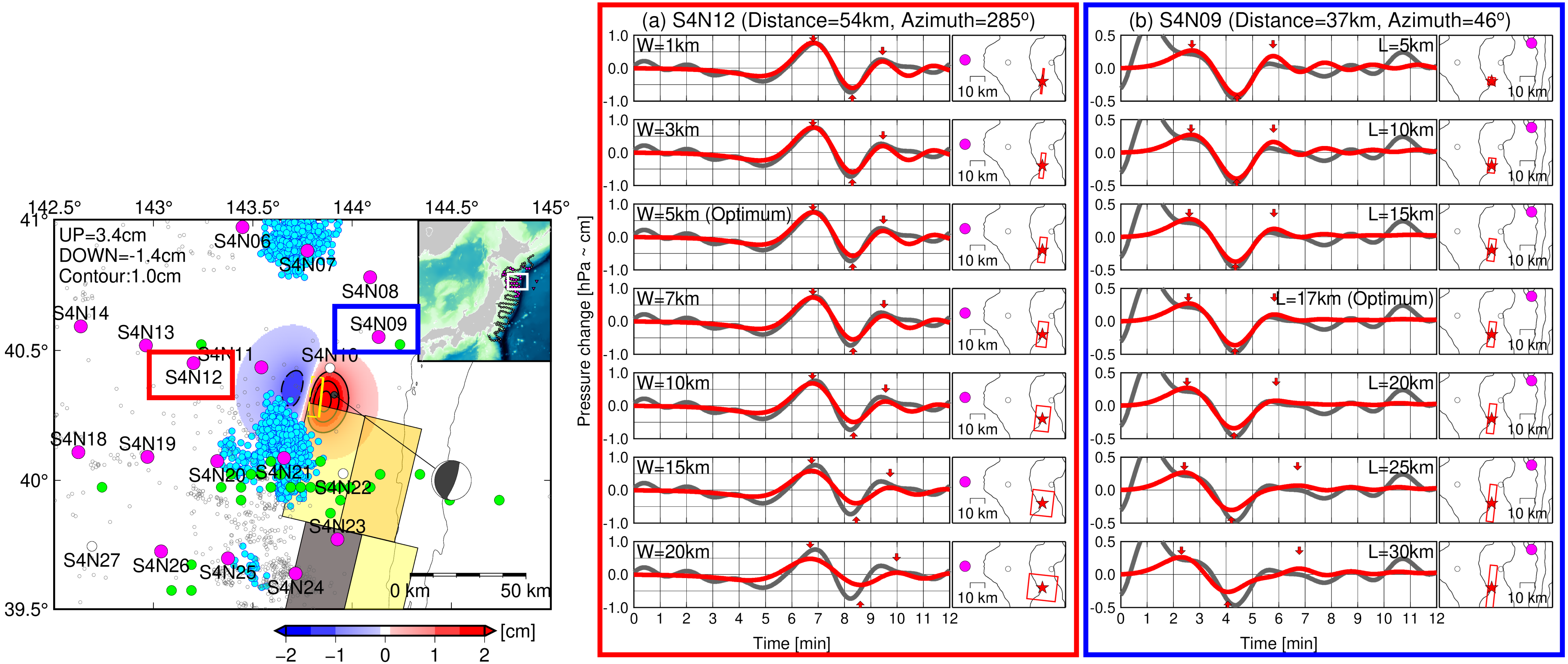


$$\Delta\sigma = \frac{8\mu}{3\pi}\frac{M_0}{(LW)^{3/2}}$$



Analysis (2): Fault dimension modeling

- Fault dimensions of *L* > 20 km or W > *7* km cannot explain the observation.
  → Uncertainty of fault dimension is *L* ≤ 20 km and *W* ≤ 7 km



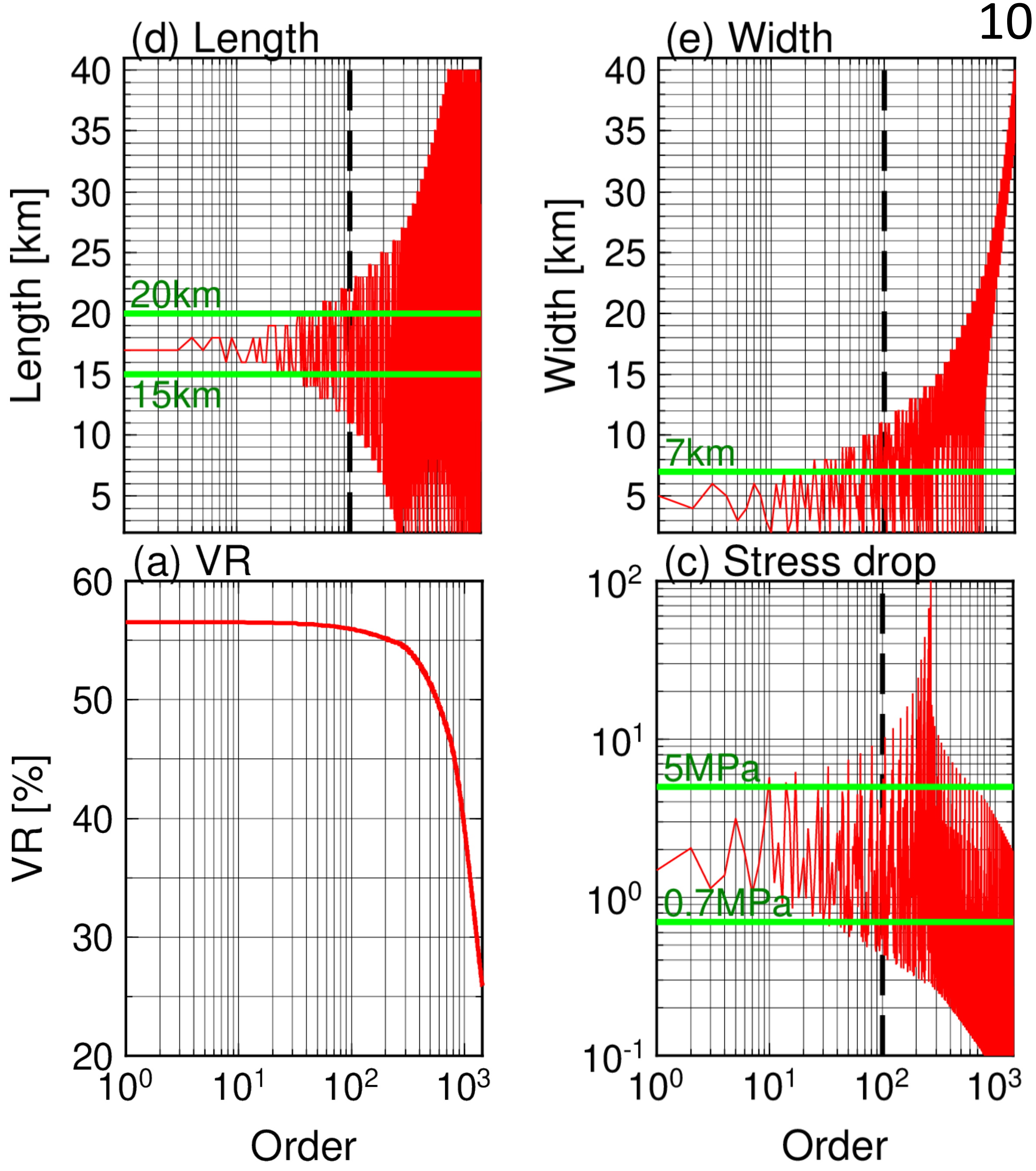
Stress drop uncertainty

<u>We evaluate plausible range of fault parameters by changing *L* or *W*</u>

✓ Models with relatively high variance reduction (VR) had ranges of $15 \leq L \leq 20$km, $W \leq 7$ km, and $0.7 \leq \Delta\sigma \leq 5$ MPa

➢ Δσ seems not so small as expected in "tsunami earthquake" like the 1896 Sanriku earthquake, characterized by extremely small Δσ (<< 1 MPa)

$$\Delta\sigma = \frac{8\mu}{3\pi}\frac{M_0}{(LW)^{3/2}} \qquad VR = \left[1 - \frac{\sum_i \left(x_i^{cal} - x_i^{obs}\right)^2}{\sum_i \left(x_i^{obs}\right)^2}\right] \times 100[\%]$$

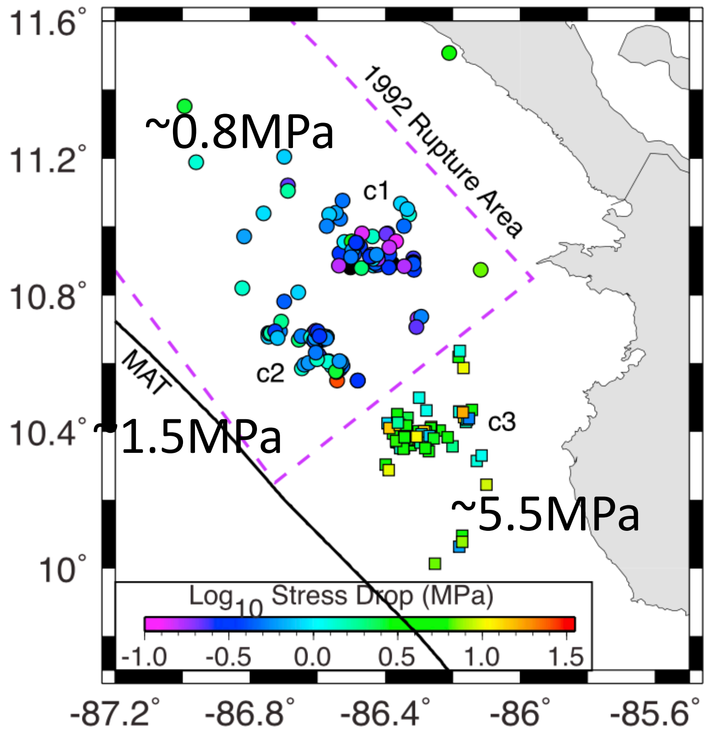


*Mo was fixed to that of the optimum model.

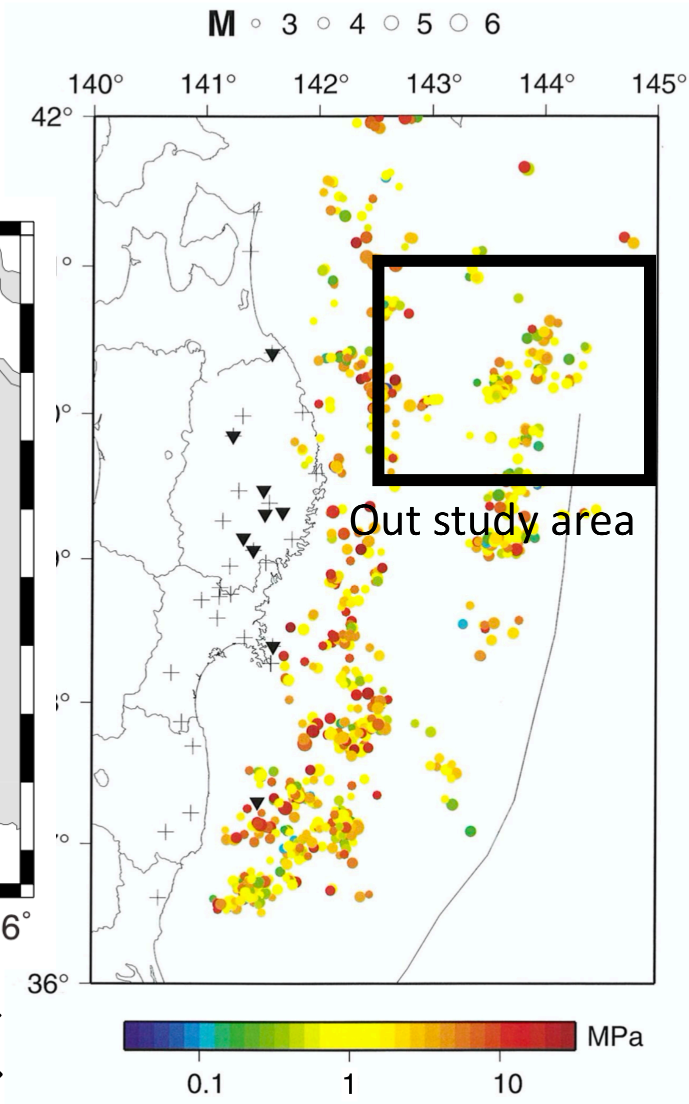
Discussion (1): spatial heterogeneity of stress drop

- ✓ Δσ inside the rupture area of the 1992 Nicaragua tsunami EQ was significantly smaller than outside (Bilek et al. 2016)
  - – However:
    no systematic spatial difference of Δσ was seen off-Sanriku (e.g., Yamashita et al. 2004).

- ➢ To discuss in more detail, we need to:
  - – compare Δσ deduced from the S-net seismometers.
  - – examine more examples of nearby moderate EQs.



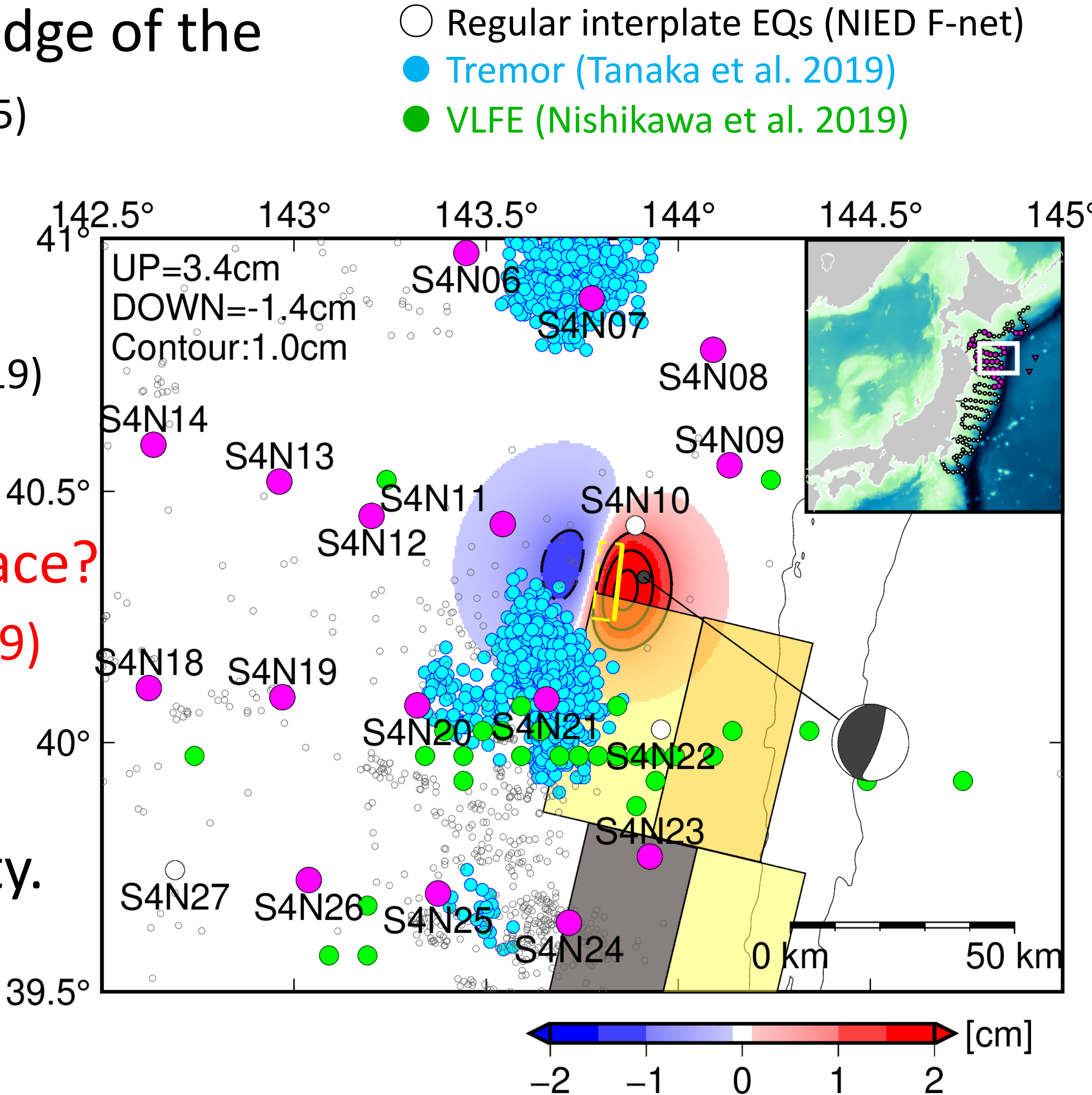
Bilek et al. (2016)↑



Yamashita et al. (2004 M thesis, Tohoku Univ.) →

Discussion (2): relationship with other interplate phenomena

- ✓ The 2016 fault is located at northern edge of the 1896 Sanriku tsunami EQ (Satake et al. 2015)
- ✓ The 2016 event is isolated from the low-frequency tremors and VLFEs (Tanaka et al. 2019; Nishikawa et al. 2019)
- ➢ These may reflect spatial difference in frictional properties along plate interface? (e.g., Nishikawa et al. 2019)
  - – further investigation of regular EQs will be important to discuss the heterogeneous frictional property.



Summary

We investigated the S-net millimeter-scale tsunami records during the 2016 Off-Sanriku EQ, recorded by the S-net, new seafloor pressure gauge network.

- ✓ The fault was located ~10 km to the west of the GCMT centroid and was unlikely to overlap with regions where slow earthquakes phenomena occur such as the tremors and VLFEs.
- ✓ Stress drop seemed not so small as expected in tsunami EQ like the 1896 Sanriku EQ, which may reflect the spatial heterogeneity of frictional property along the plate interface.

- Take-home massage!
  - S-net array dramatically increases the detectability of a millimeter-scale tsunami and the constraints on earthquake source parameters of moderate EQs off eastern Japan.
  - More tsunami examples due to minor-to-moderate EQs by this S-net dense and wide array will reveal the spatial variation of the stress drops or heterogeneity of mechanical properties along the plate interface, with much higher resolution than previously possible.