Tsunami simulation of the 2011 Tohoku-oki earthquake at Fukushima Nuclear Power Plant

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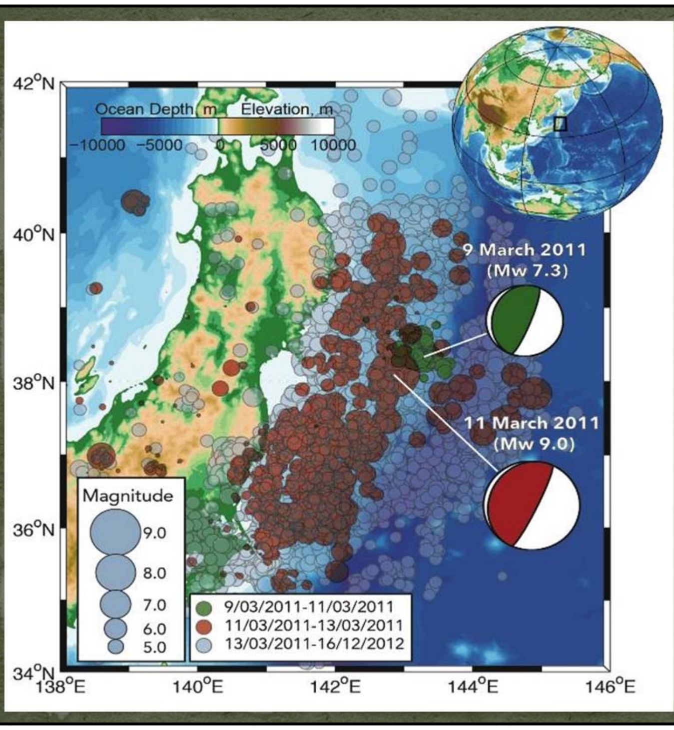
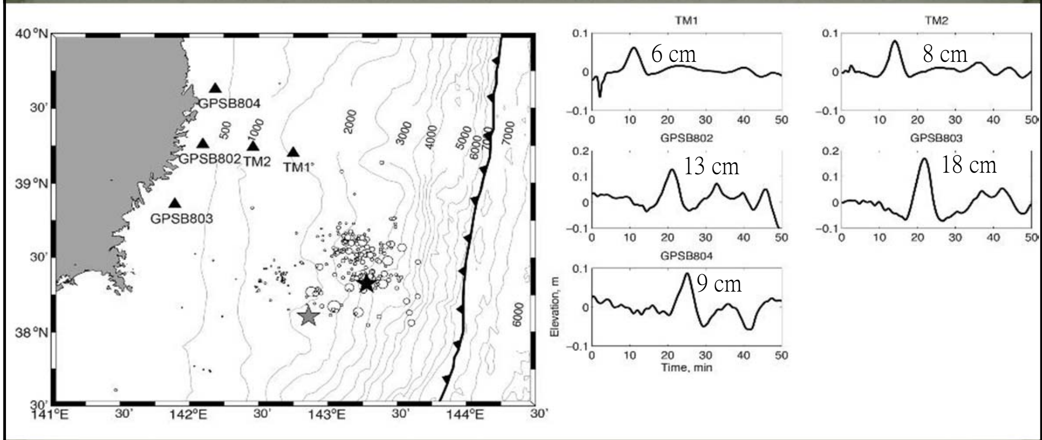


The 2011 Tohoku Great Earthquake Sequence

1) Tsunami Inversion for the Largest foreshock (Mw 7.3) of the 2011 Tohoku earthquake [Gusman et al., GRL, 2013].

2) Joint Inversion using tsunami waveforms and crustal deformation for the mainshock of the 2011 Tohoku earthquake (Mw 9.0) [Gusman et al., EPSL, 2012].

Tsunami Waveform Data

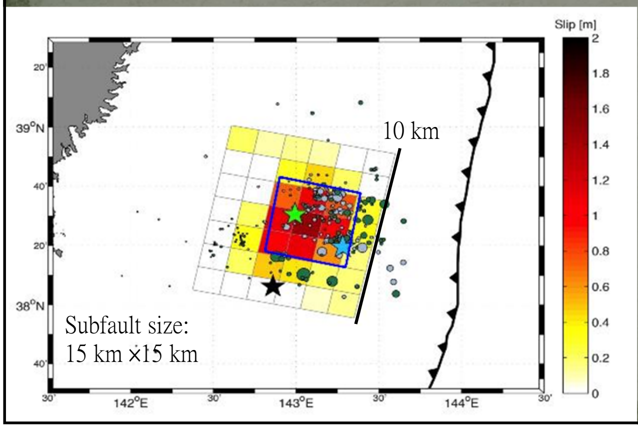


To obtained the tsunami waveforms, the tides and high frequency waves are removed from the records.
The TM1 and TM2 sampling rate is 10 Hz
The GPS buoys (802, 803, and 804) sampling rate is 1 Hz

Tsunami Waveform Inversion Result: Slip Distribution

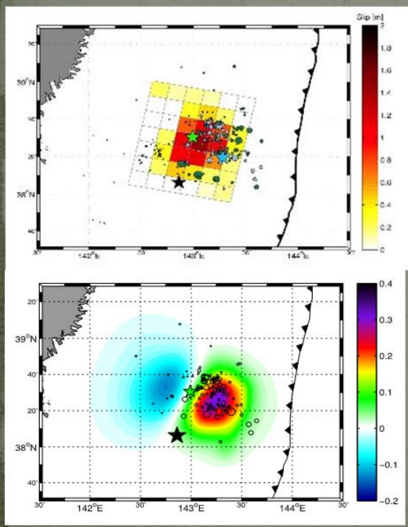
USGS CMT Solution
Strike/dip/rake
192°/14°/81°

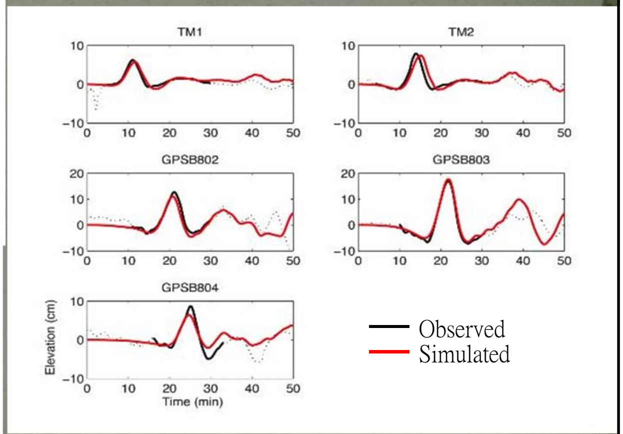
- Major slip region 45 km × 45 km with slip amounts ranged from 0.6 to 1.5 m
- The major slip region is located on the down-dip side of the hypocenter.
- The major slip region is centered at a depth of ~20 km



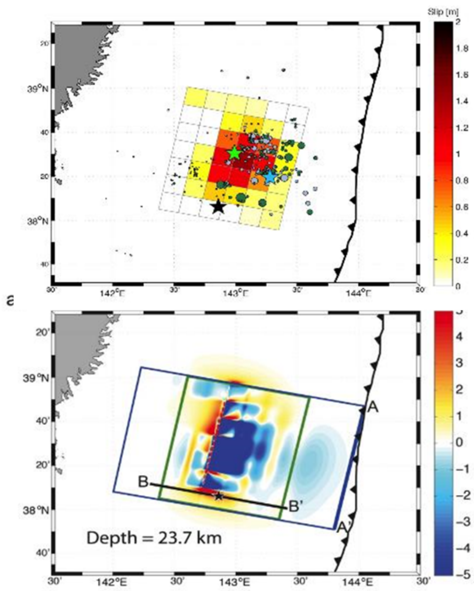
- The center of the major slip region is located near the centroid (USGS)
- The seismic moment calculated from the slip distribution is 1.2×10^{20} N m which is equivalent to Mw 7.3

Tsunami Waveform Comparisons

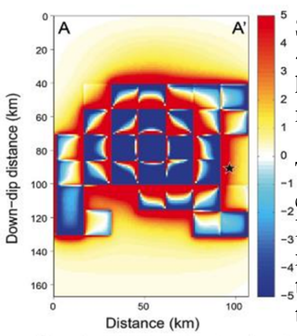




Coulomb Stress Change

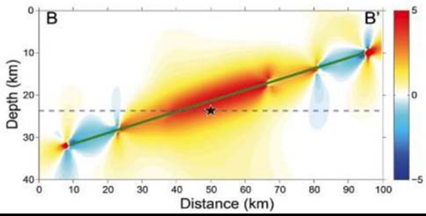


Cross-sectional view of the stress change

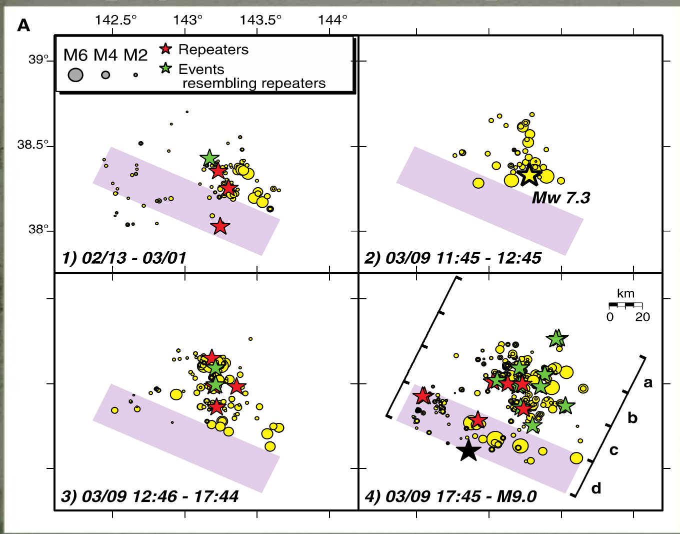


Stress increased by ~3.5 bars at the hypocenter of the mainshock

The static stress change from the largest foreshock might have brought the mainshock closer to failure.



Propagation of Slow Slip



Kato et al. [2012]

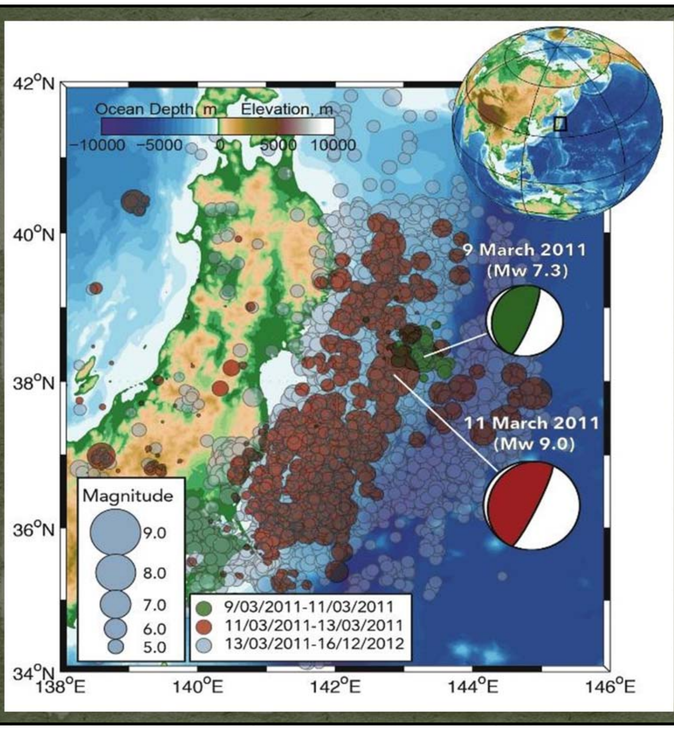
Foreshocks occurred near and migrating toward the mainshock.

This foreshock migration interpreted as a propagation of slow-slip [Kato et al., 2012]

The slow-slip also increased the static stress on the plate interface in addition to that by the largest foreshock.

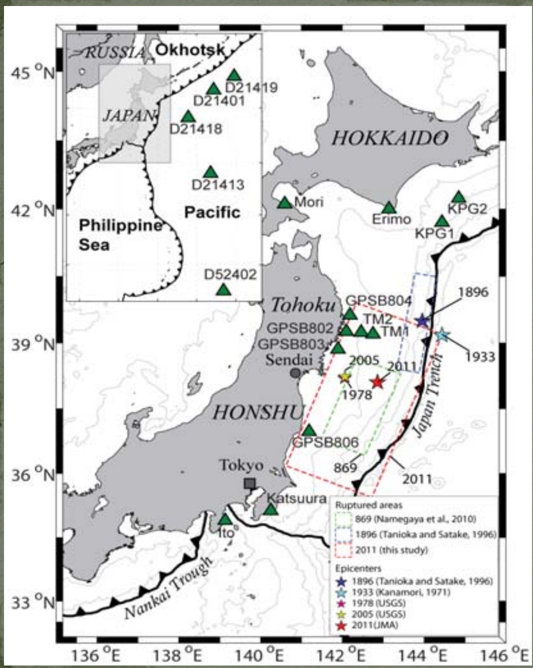
These static stress increases might have finally brought the 2011 Tohoku earthquake to failure.

The 2011 Tohoku Great Earthquake Sequence



1) Tsunami Inversion for the Largest foreshock (Mw 7.3) of the 2011 Tohoku earthquake

2) Joint Inversion using tsunami waveforms and crustal deformation for The mainshock of the 2011 Tohoku earthquake



Sea Level Observation Stations

To estimate slip distribution of the 2011 Tohoku earthquake we used tsunami waveforms at 17 stations.

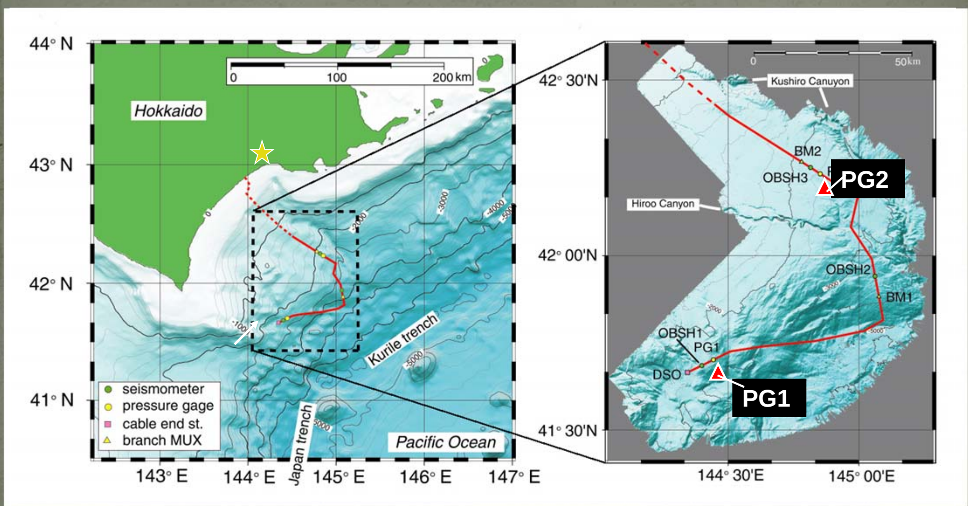
5 NOAA's DART buoys (DART21401, DART21413, DART21418, DART21419 and DART52402)

4 tide gauges in Hokkaido, Chiba, and Shizuoka Prefectures.

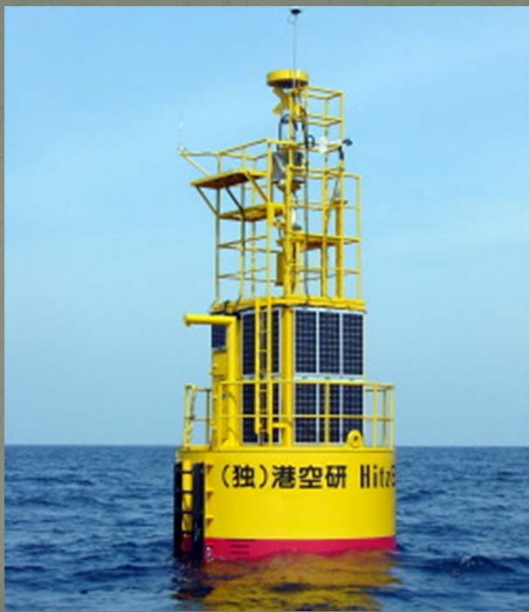
4 bottom-pressure gauges (KPG1, KPG2, TM1 and TM2)

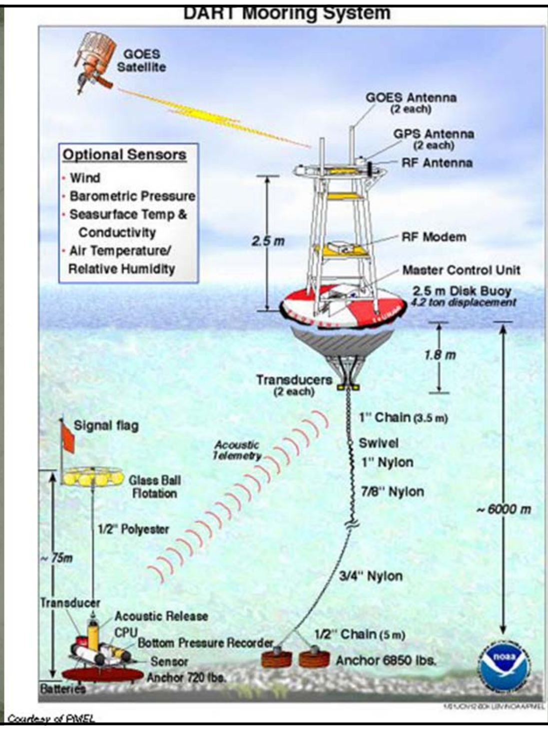
4 GPS buoys (GPSB802, GPSB803, GPSB804 and GPSB806).

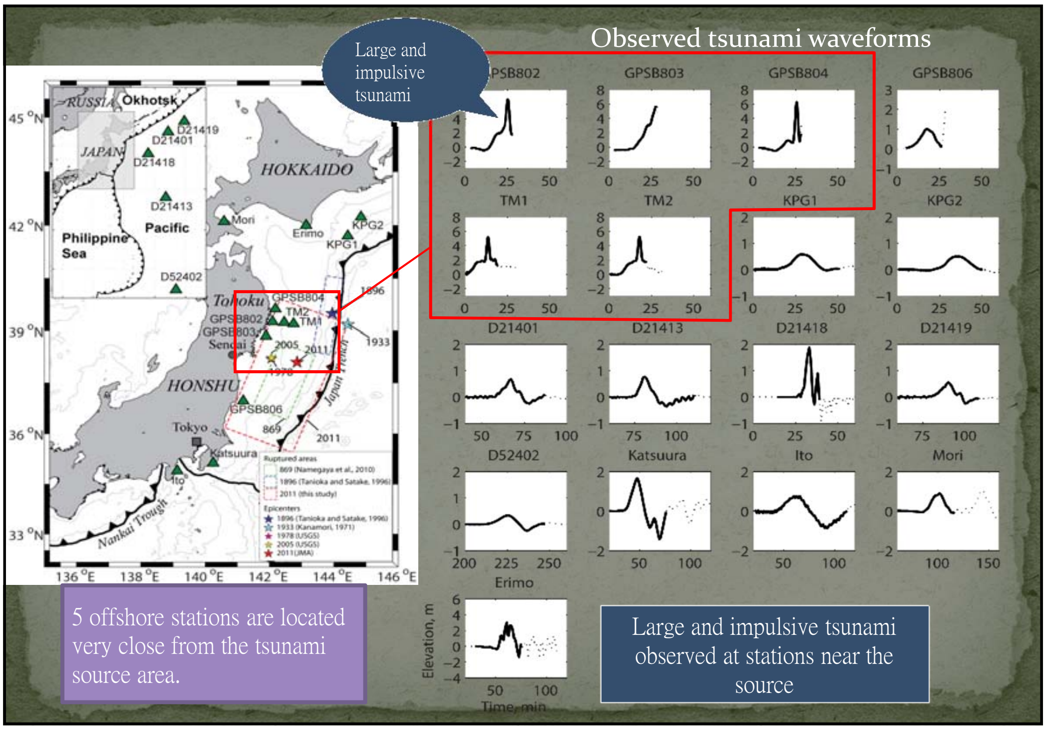
Ocean bottom pressure gauges off Kushiro (JAMSTEC)

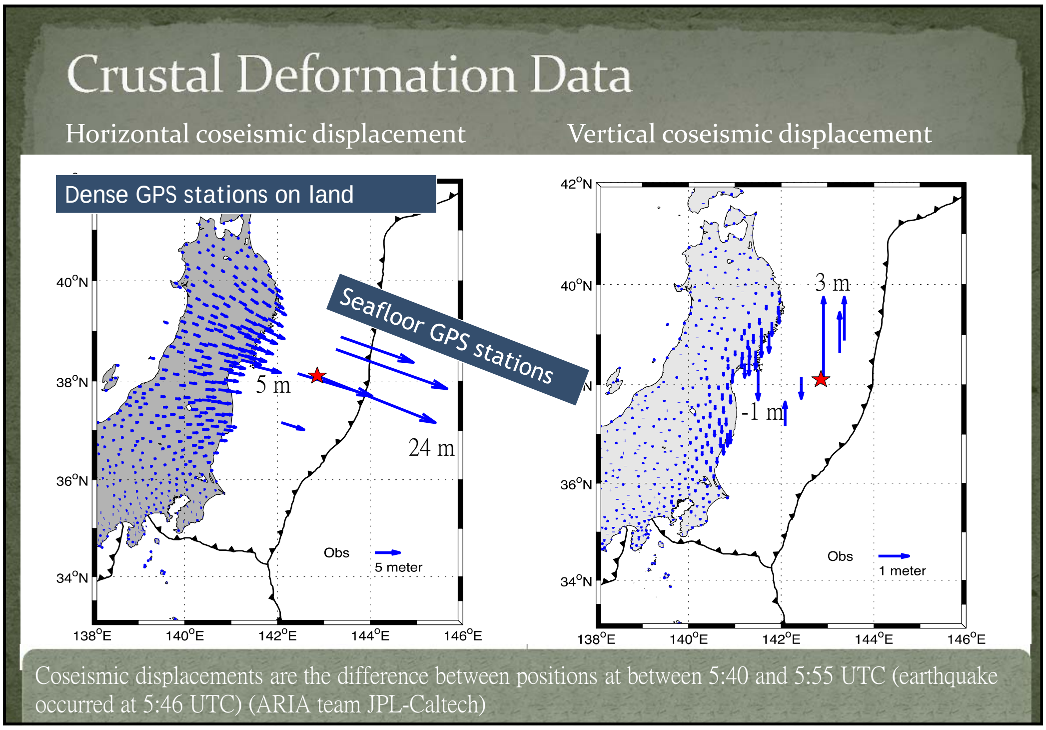


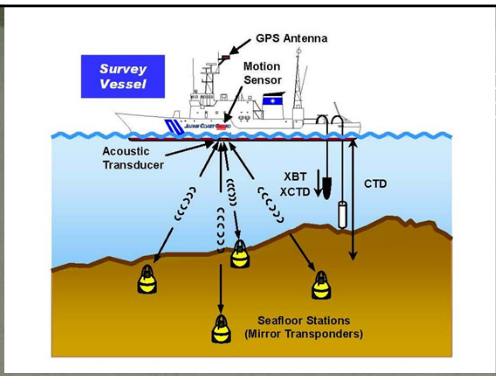
GPS Tsunami meter （Port and Airport Research Institute)





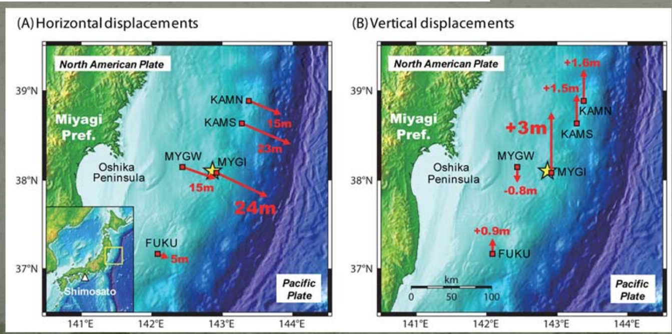

Observed tsunami waveforms
Large and impulsive tsunami
GPSB802
GPSB803
GPSB804
GPSB806
TM1
TM2
KPG1
KPG2
D21401
D21413
D21418
D21419
D52402
Katsuura
Ito
Mori
Erimo
Elevation, m
Time, min
RUSSIA
Okhotsk
JAPAN
HOKKAIDO
Philippine Sea
Pacific
Tohoku
Sendai
HONSHU
Tokyo
Nankai Trough
Japan Trench
5 offshore stations are located very close from the tsunami source area.
Large and impulsive tsunami observed at stations near the source


Crustal Deformation Data
Horizontal coseismic displacement
Vertical coseismic displacement
Dense GPS stations on land
Seafloor GPS stations
5 m
24 m
3 m
-1 m
Obs
5 meter
1 meter
Coseismic displacements are the difference between positions at between 5:40 and 5:55 UTC (earthquake occurred at 5:46 UTC) (ARIA team JPL-Caltech)



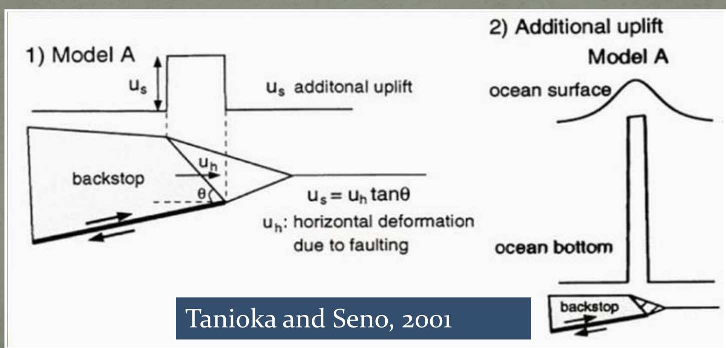
Ocean Bottom Crustal Deformation Observation

Sato et al. (Science 2011)



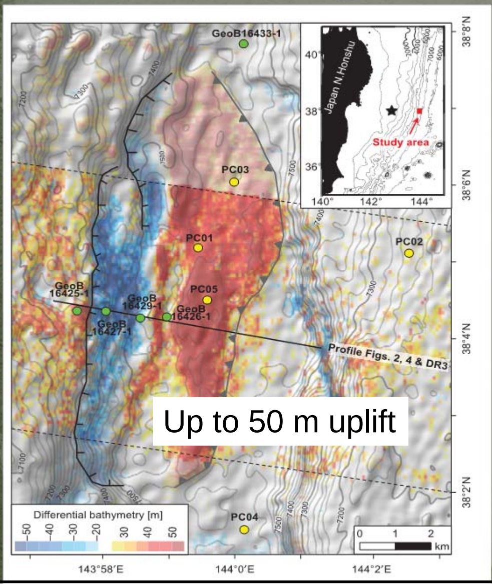
Sediment Uplift Near Trench

Previous studies indicated that large slip beneath a sedimentary wedge near the trench caused large horizontal movement of backstop and then generated large additional uplift of the sediment (Seno, 2000; Tanioka and Seno, 2001; Seno and Hirata, 2007).

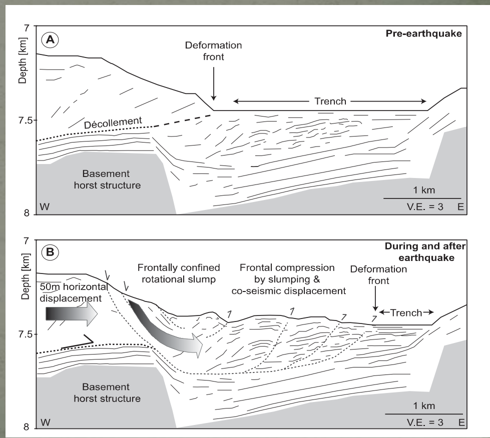


Tanioka and Seno, 2001

Rotational slumping induced by co-seismic displacement of the sedimentary block above the horst structure over the graben

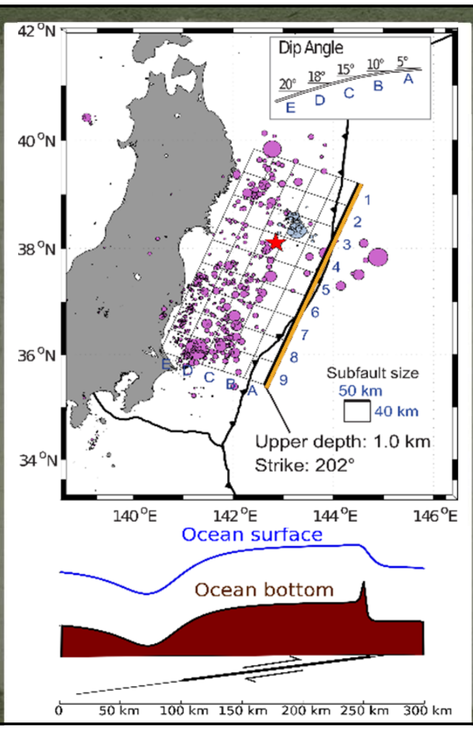


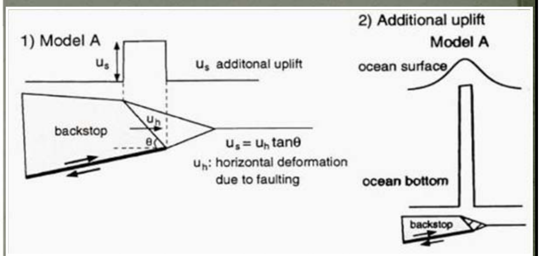
Conceptual sketch of slumping near the trench from seismic interpretation, new bathymetric and core data.



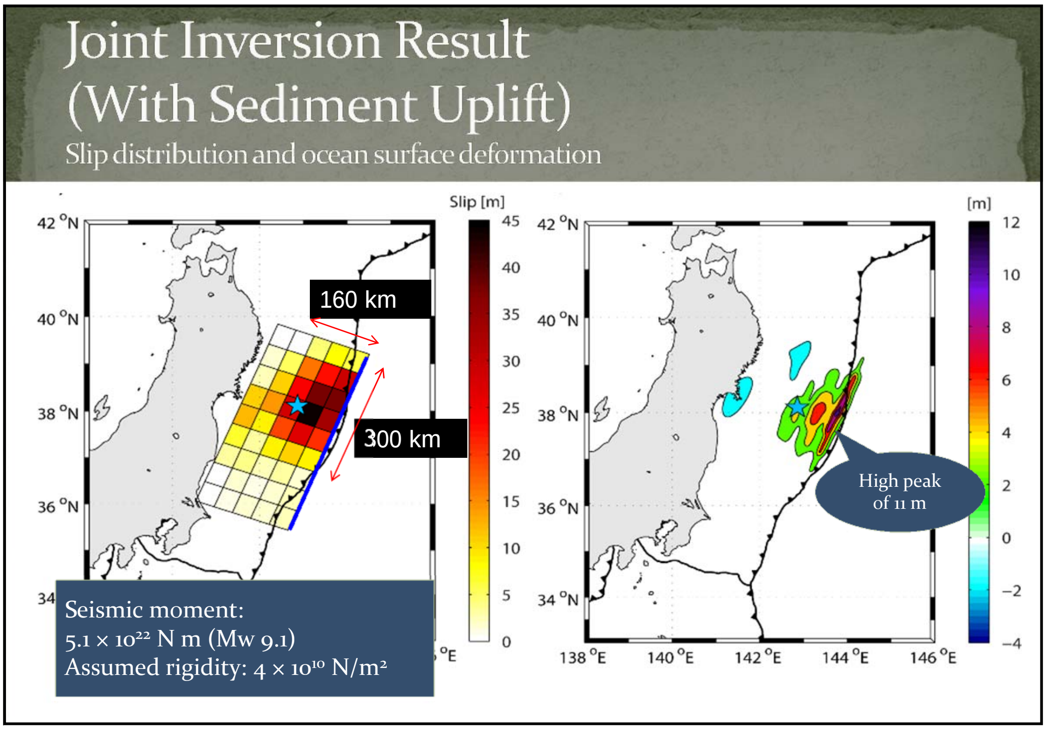
Strasser et al., Geology (2013)

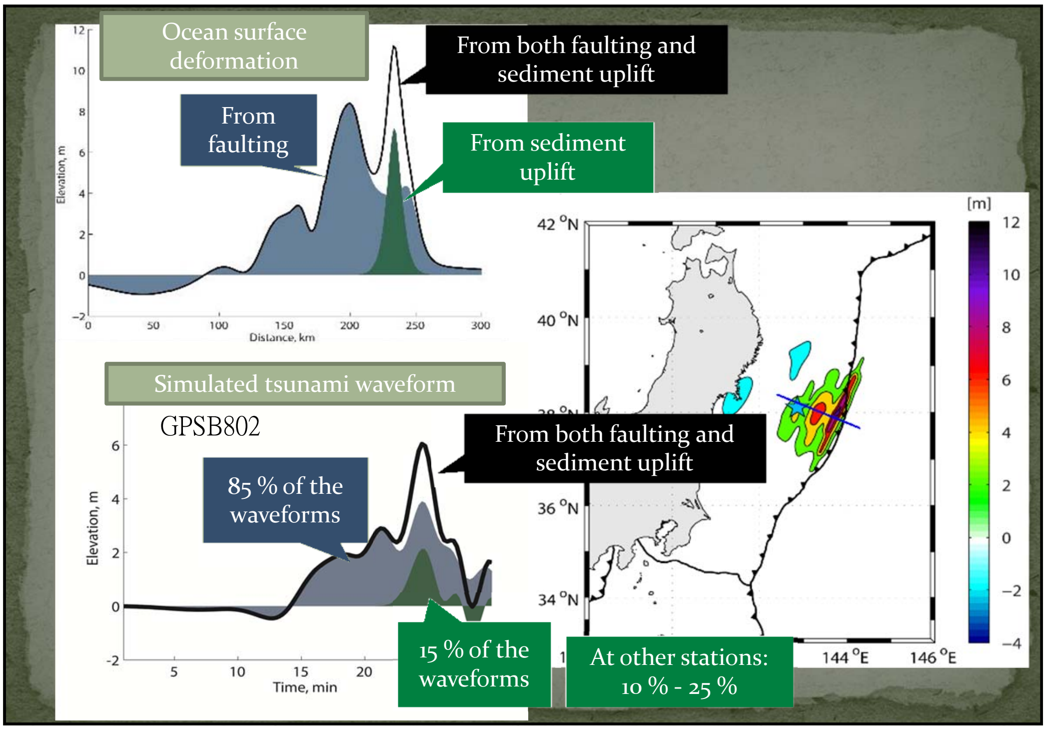
Inversion Settings





- Synthetic tsunami waveforms and coseismic displacements at the stations are computed from each subfault and sediment uplift.
- Ocean bottom deformation is calculated by Okada (1985) equations
- Ocean surface deformation is calculated by Kajiura (1963) equations from ocean bottom deformation

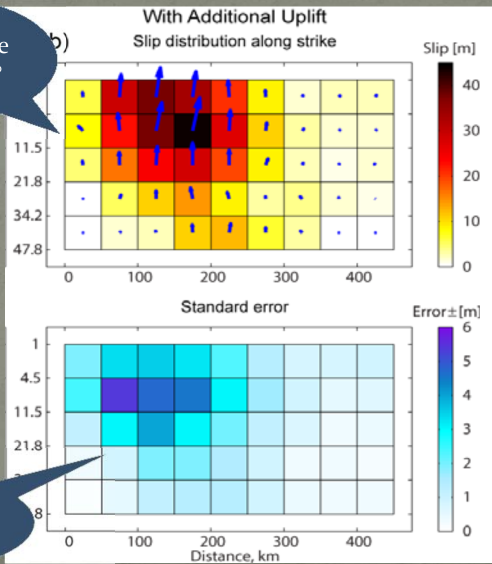

Joint Inversion Result
(With Sediment Uplift)
Slip distribution and ocean surface deformation
Slip [m]
160 km
300 km
Seismic moment:
5.1 × 10²² N m (Mw 9.1)
Assumed rigidity: 4 × 10¹⁰ N/m²
[m]
High peak
of 11 m
42 °N
40 °N
38 °N
36 °N
34 °N
138 °E
140 °E
142 °E
144 °E
146 °E


Ocean surface
deformation
From both faulting and
sediment uplift
From
faulting
From sediment
uplift
Elevation, m
Distance, km
Simulated tsunami waveform
GPSB802
85 % of the
waveforms
From both faulting and
sediment uplift
15 % of the
waveforms
At other stations:
10 % - 25 %
Elevation, m
Time, min
[m]

Joint Inversion Result:
Slip and rake angle distribution

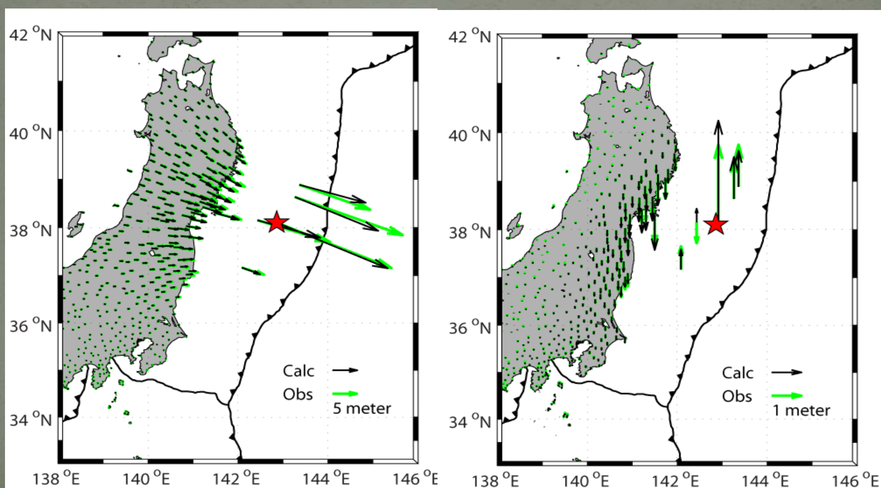
Average rake angle is 87°

Rake angle at the Centroid is 88° (GCMT)

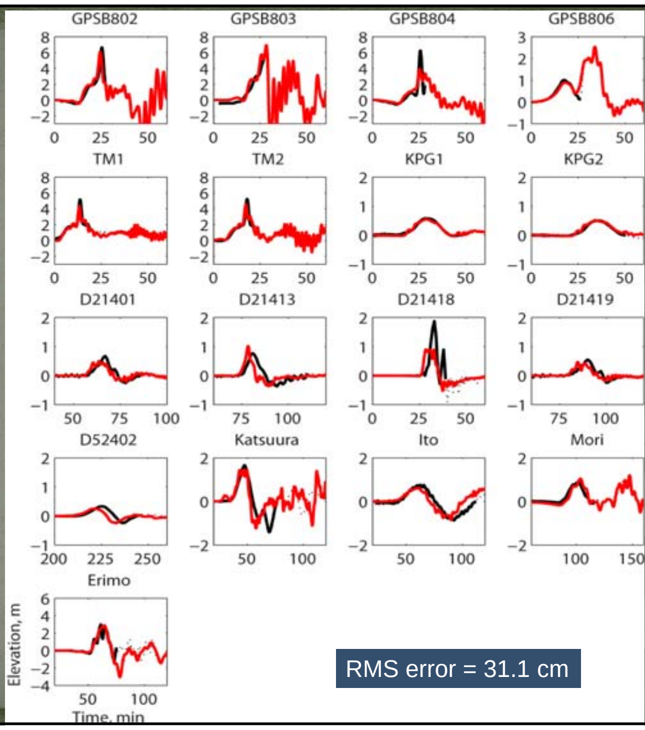


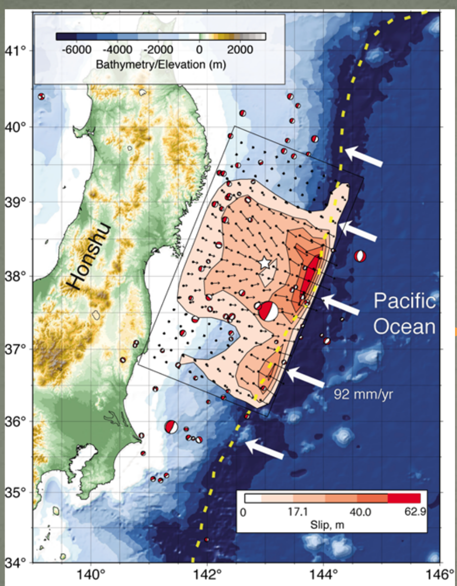
Maximum error is ± 6 m

Comparison of Horizontal and Vertical Coseismic Displacements

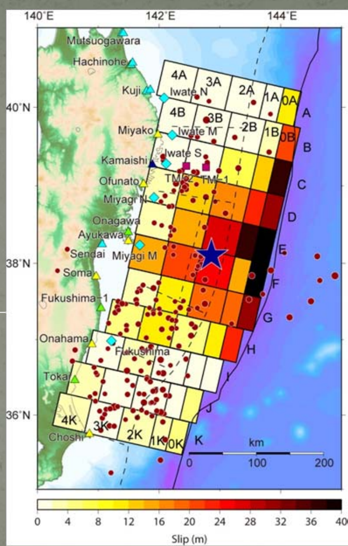


Comparisons of Tsunami Waveforms

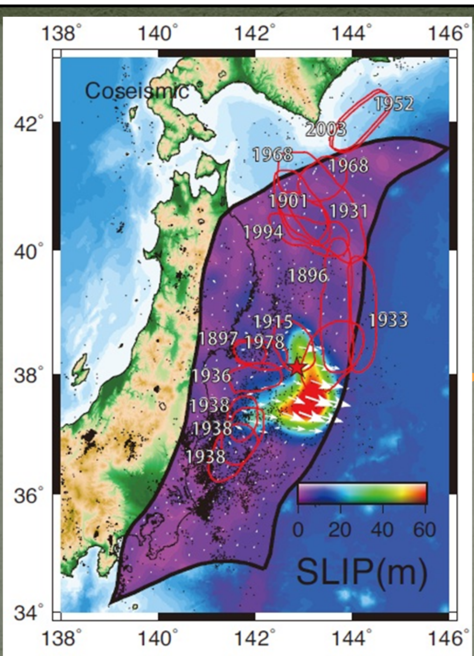




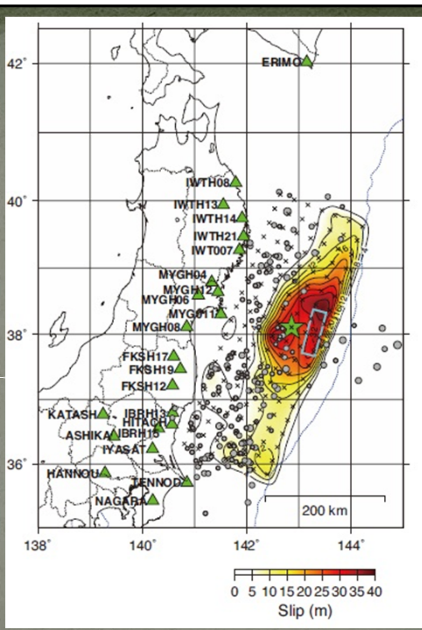
Telesismic waveform analysis
Lay et al. (2011)



Tsunami waveform
Satake et al. (2013)



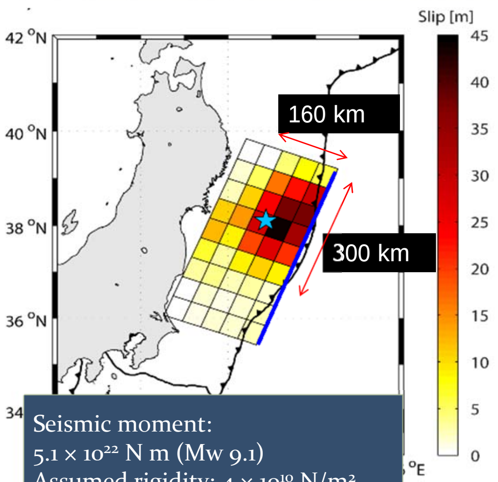
GPS data and seafloor deformaion data
Ito et al. (2011)



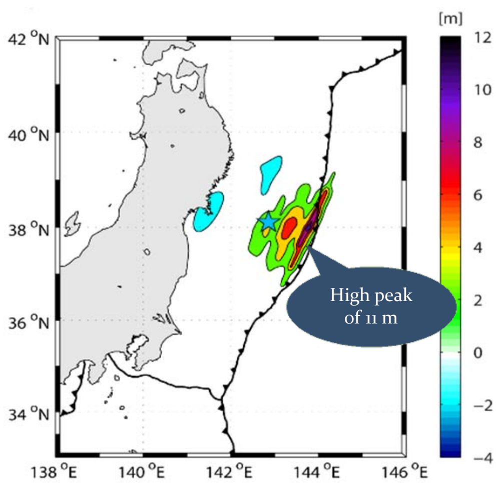
Strong motion waveforms
Yoshida et al. (2011)

Joint Inversion Result (With Sediment Uplift)

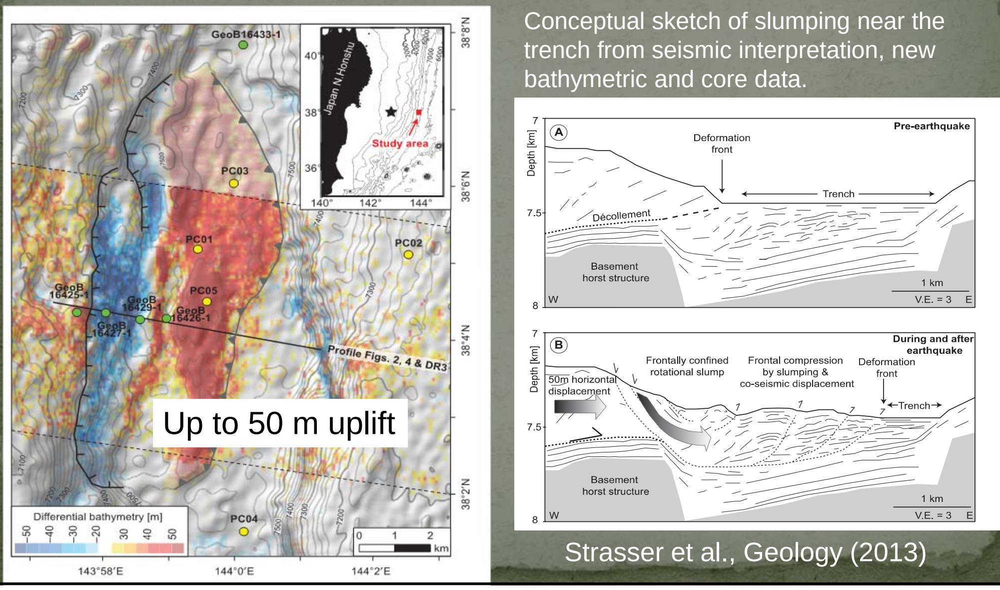
Slip distribution and ocean surface deformation

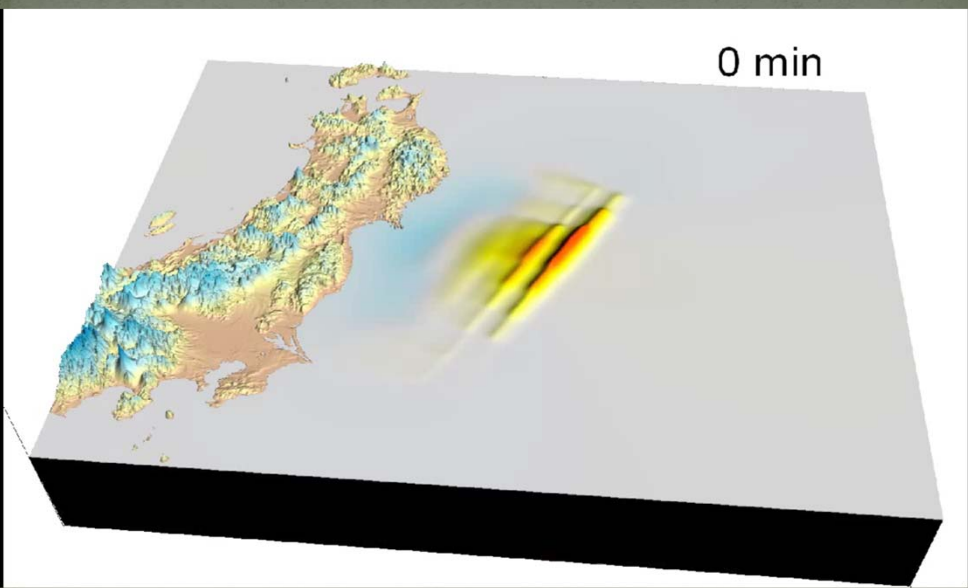


Seismic moment:
5.1 × 10²² N m (Mw 9.1)
Assumed rigidity: 4 × 10¹⁰ N/m²

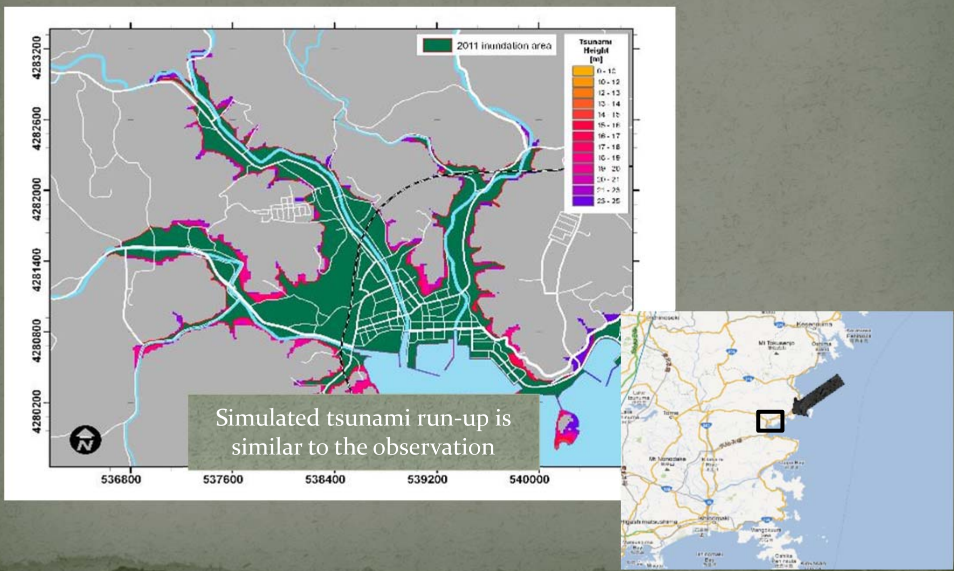


Rotational slumping induced by co-seismic displacement of the sedimentary block above the horst structure over the graben

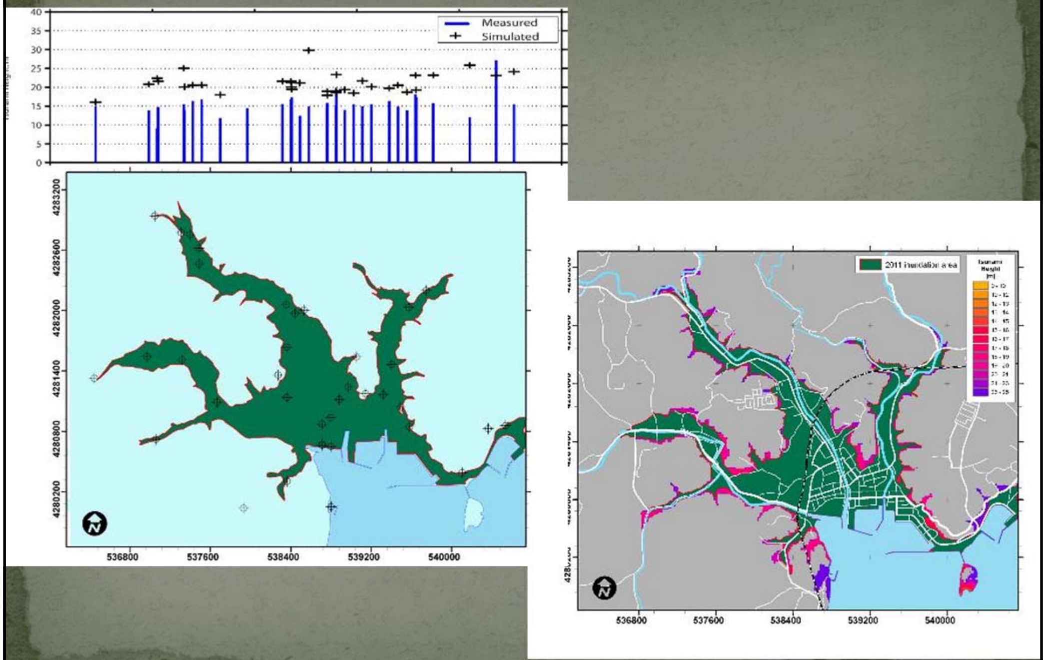




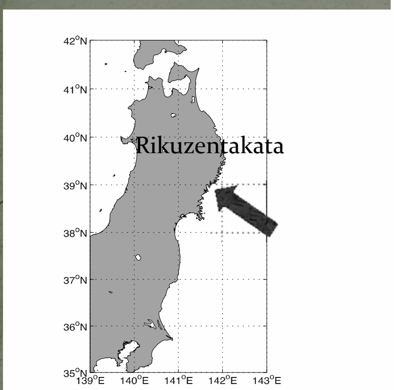
Tsunami Inundation: Minamisanriku

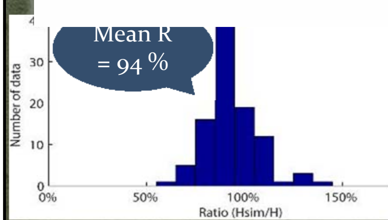


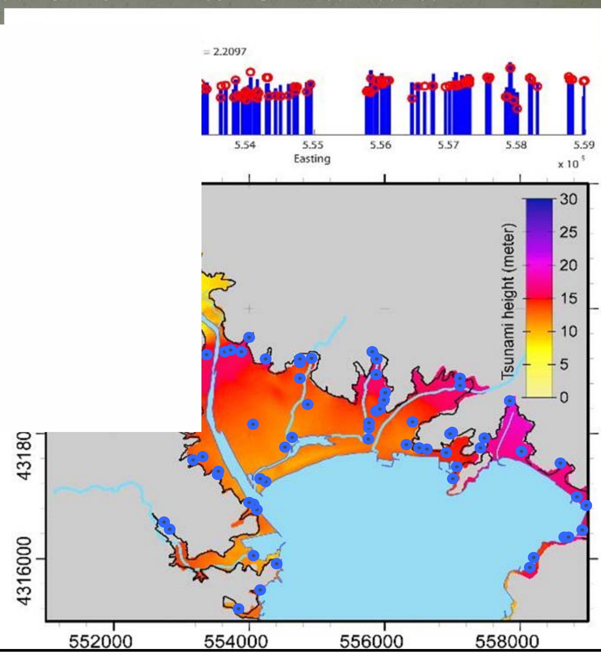
Simulated tsunami run-up is similar to the observation



Tsunami Inundation: Rikuzentakata

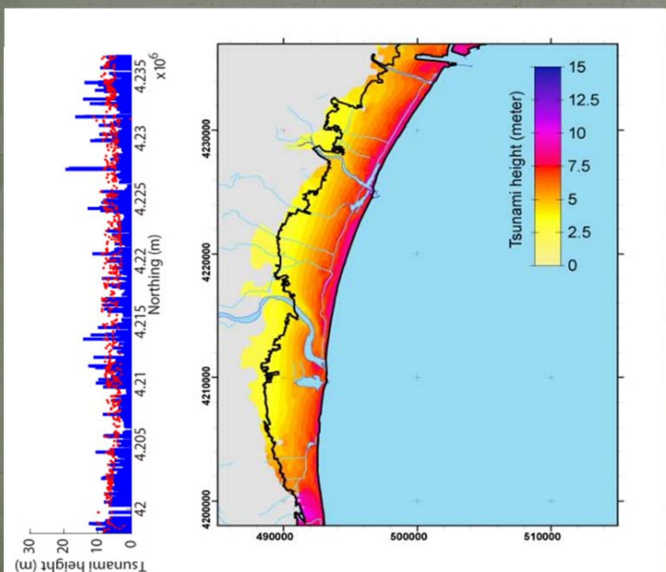


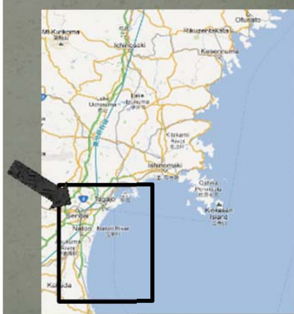




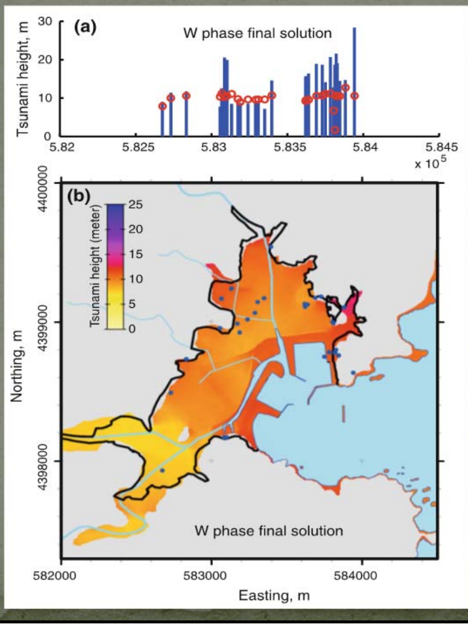
Rikuzentakada

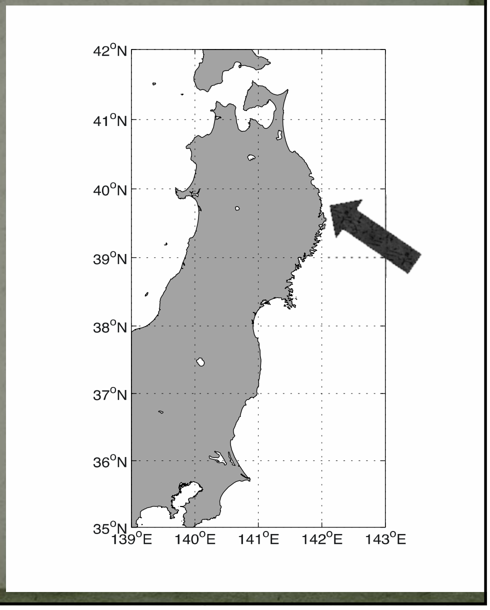
Tsunami Inundation: Sendai Plain





Tsunami Inundation: Taro





Past Tsunami in Taro, Miyako city

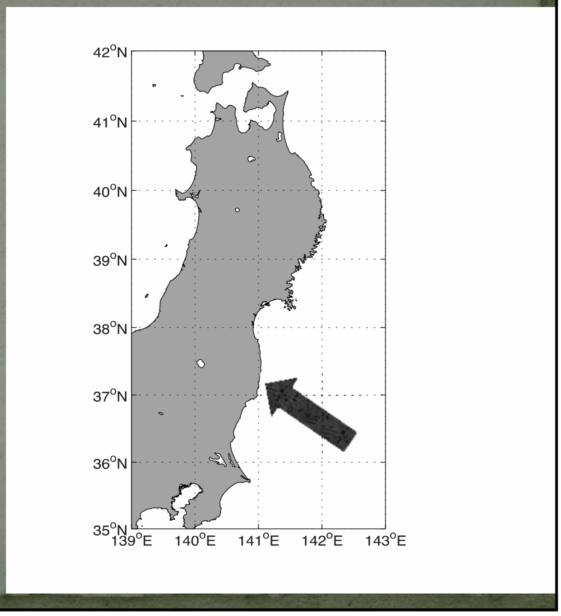
1896 Meiji tsunami: 1867 deaths (out of 2248 residents, or 83%)

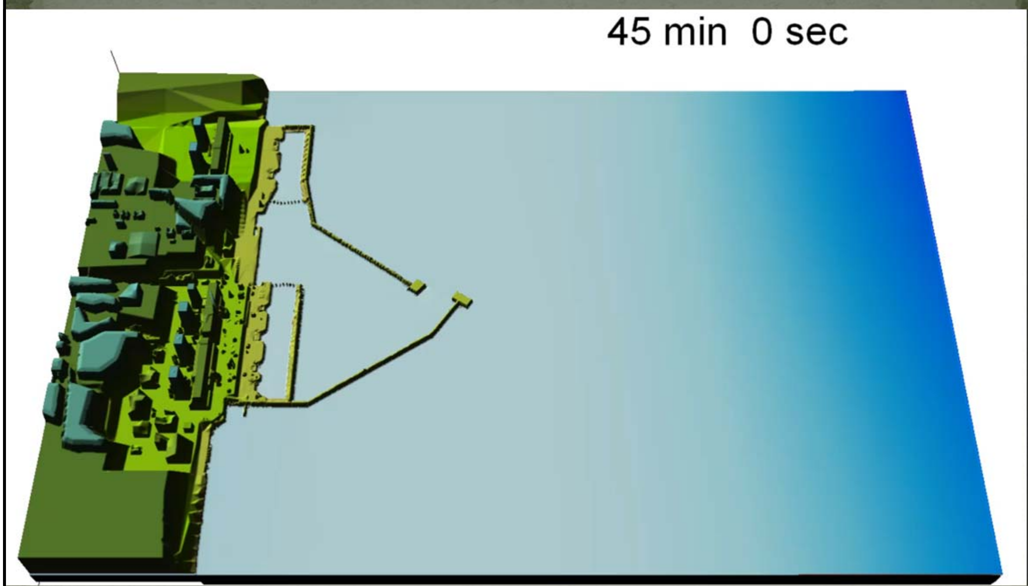
1933 Showa tsunami: 972 deaths (out of 4945, or 20%)

2011 Tohoku-oki tsunami: 230 casualties (out of 4000, or 6%)

10m high 2.5 km long breakwater around Town

Tsunamai simulation at Fukushima





Nuclear Regulation Authority

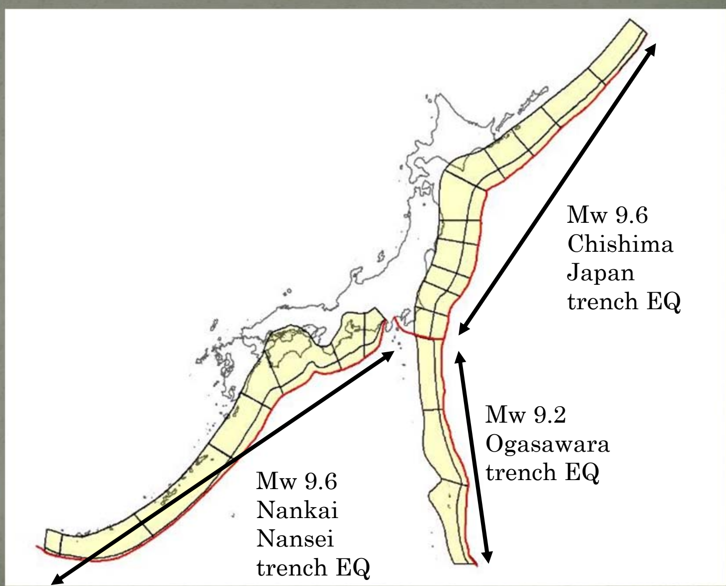
was established after the 2011 Tohoku-oki earthquake

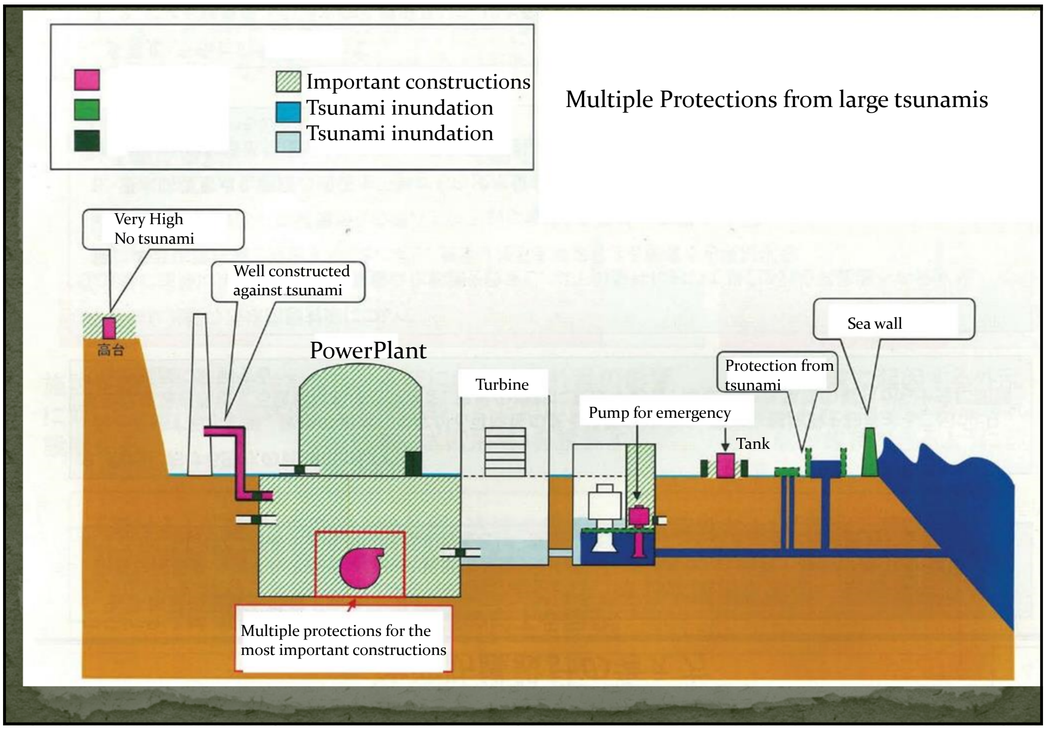
A new regulation agency totally independent from the other governmental agencies

- The special team for the earthquake and tsunami regulation has been established in the Authority

  The regulation for earthquake and tsunami was made In July 2013

Examples of the tsunami sources needed to be tested

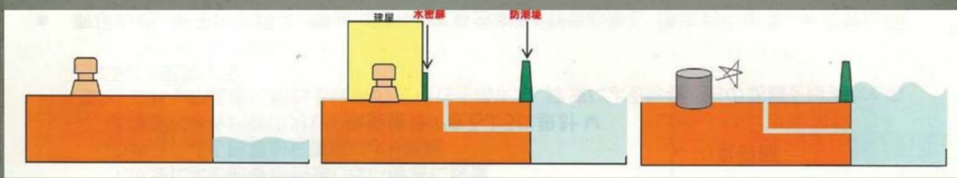




Avoid

Protect

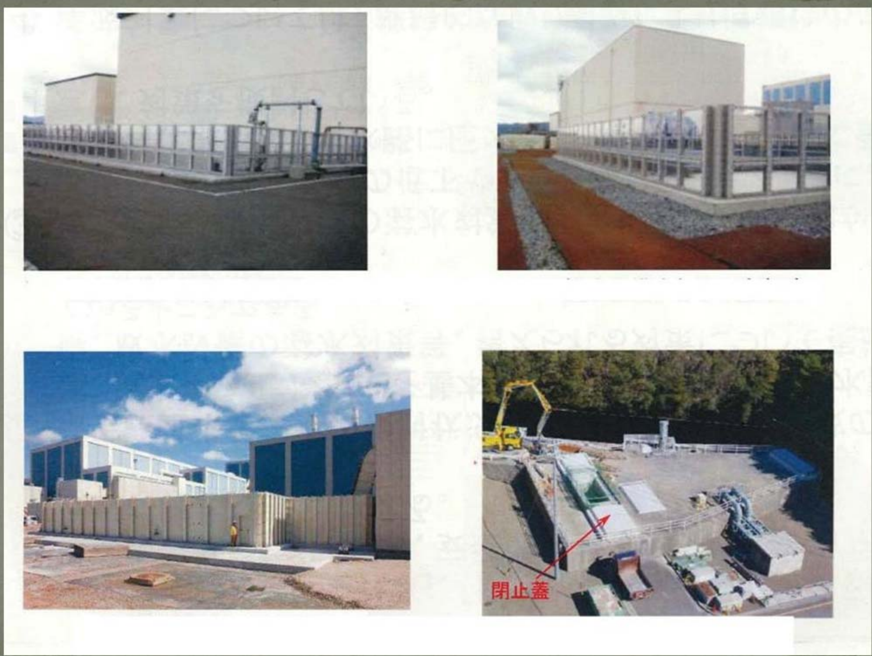
Stand

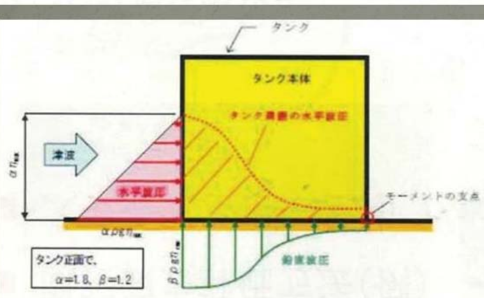


Structures
in high enough place

Structures
protected from tsunami

Structures strong eougnh
to stand agenst tsunami



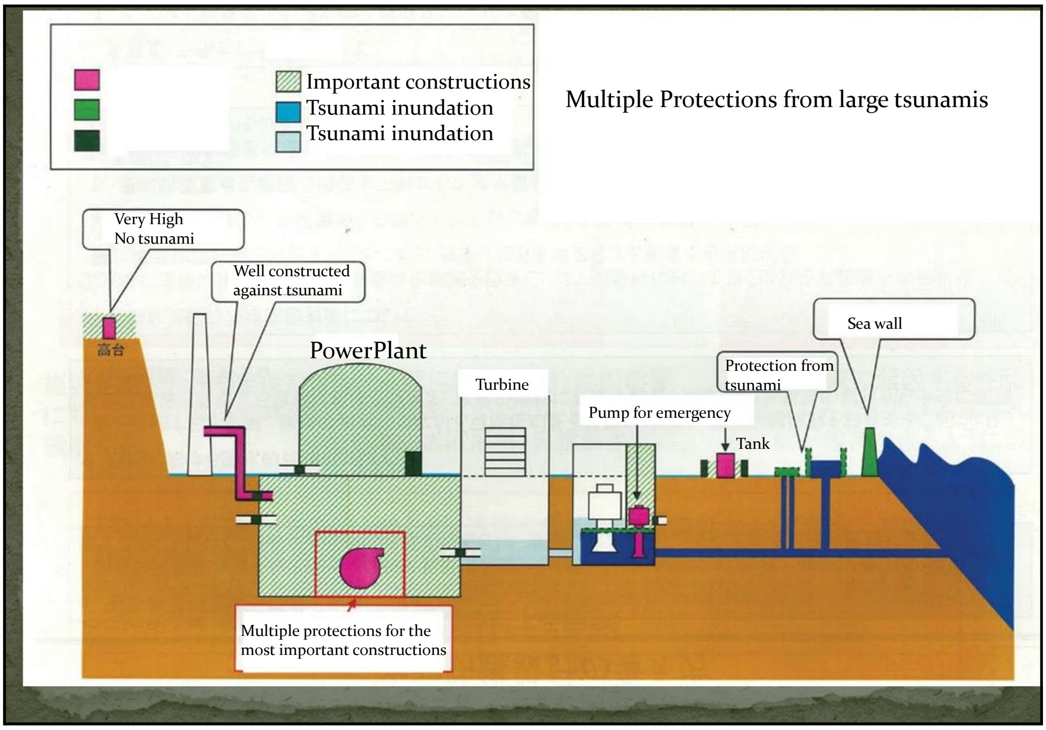


$$F_{tH} = \frac{1}{2}\int_{-\pi}^{\pi} \rho g \left[h_x^{max}(\theta)\right]^2 R \cos\theta d\theta$$

$$h_x^{max}(\theta) = \alpha \eta_{max} \sum_{m=0}^{3} p_m \cos m\theta$$

η_{max}：最大浸水深	F_{tV}：鉛直波力
V_{max}：最大流速	h_c^{max}：タンク周囲の水位（鉛直波力評価時）
F_{tH}：水平波力	M_{tV}：鉛直モーメント
h_x^{max}：タンク周囲の水位（水平波力評価時）	R：タンク半径
M_{tH}：水平モーメント	θ：周方向角度（前面でθ=0）

$F_r = V_{max}/\sqrt{g\eta_{max}}$：フルード数



Conclusions

The Largest Foreshock (Mw 7.3) of the 2011 Tohoku Earthquake

- We estimated the slip distribution of the largest foreshock of the 2011 Tohoku earthquake by using tsunami waveforms at near-field stations.
- The slip amounts on the major slip region (45 km × 45 km) range from 0.6 to 1.5 m.
- By assuming the rigidity of 4×10^{10} N m^{-2}, the seismic moment calculated from the slip distribution is 1.2×10^{20} N m which is equivalent to Mw 7.3.
- The inferred slip distribution shows that the largest foreshock did not rupture the plate interface where the dynamic rupture of the mainshock was initiated.
- The largest foreshock increased the Coulomb stress by 3.5 bars on the plate interface at the hypocenter of the mainshock.
- The static stress changes from the largest foreshock might have brought the great 2011 Tohoku earthquake closer to failure.

Conclusions

The Mainshock of the 2011 Tohoku earthquake

- Slip distribution of the great 2011 Tohoku earthquake is estimated from tsunami waveforms and crustal deformation data data by a joint inversion.
- The maximum slip amount is estimated to be 44 m and the major slip region is located up-dip of the hypocenter with dimensions of roughly 300 km long and 160 km wide.
- Calculated seismic moment from the slip distributions are 5.1 and 5.5 × 10^{22} N m (Mw 9.1), which are consistent to that estimated by GCMT (5.3 × 10^{22} N m).
- Additional uplift of the sediment near the trench have significant effect on tsunami generation of the 2011 Earthquake.
- Seafloor monitoring and offshore sea level observation are important to accurately estimate the slip distribution near the trench of interplate earthquakes in the subduction zone.

Inversion Method

- The following objective function is minimized in the inversion [Gusman et al., JGR, 2010]

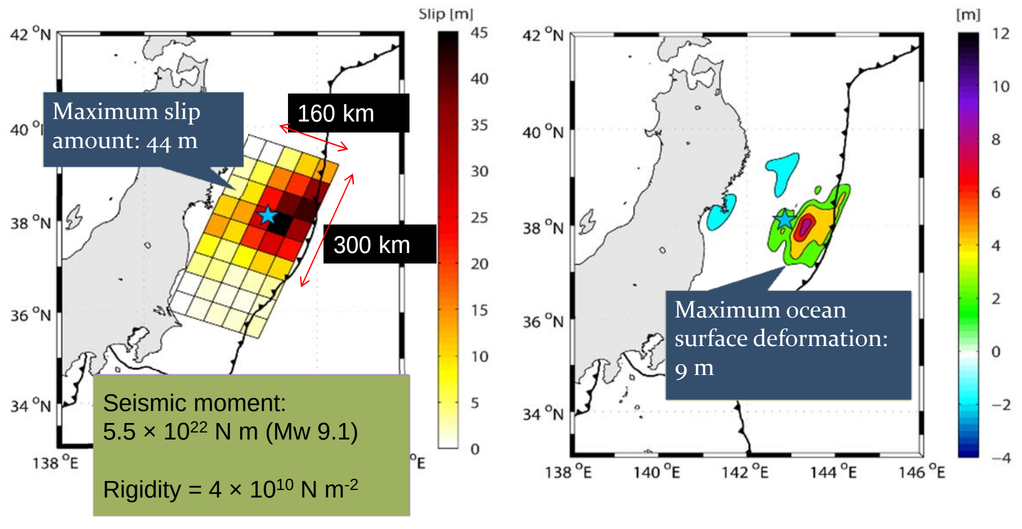
$$s(\mathbf{m}) = \boldsymbol{\lambda}^2(\mathbf{d}-\mathbf{Gm})^T\mathbf{E}^{-1}(\mathbf{d}-\mathbf{Gm}) + \alpha^2\mathbf{m}^T\mathbf{Hm}$$

- A spatial smoothness constraint on the slip distribution is included into the inversion procedure.
- To determine the optimal value of smoothing factor we used ABIC [Akaike, 1980]

$$ABIC(\alpha^2) = (N+P-M)\log s(\mathbf{m}) - P\log\alpha^2 + \log\|\mathbf{G}^T\mathbf{E}^{-1}\mathbf{G}+\alpha^2\mathbf{H}\| + C$$

Joint Inversion Result

Slip distribution and ocean surface deformation



Slip distributions of the largest aftershock and mainshock of the 2011 Tohoku sequence