The Great Off Tohoku Earthquake of 11 March 2011

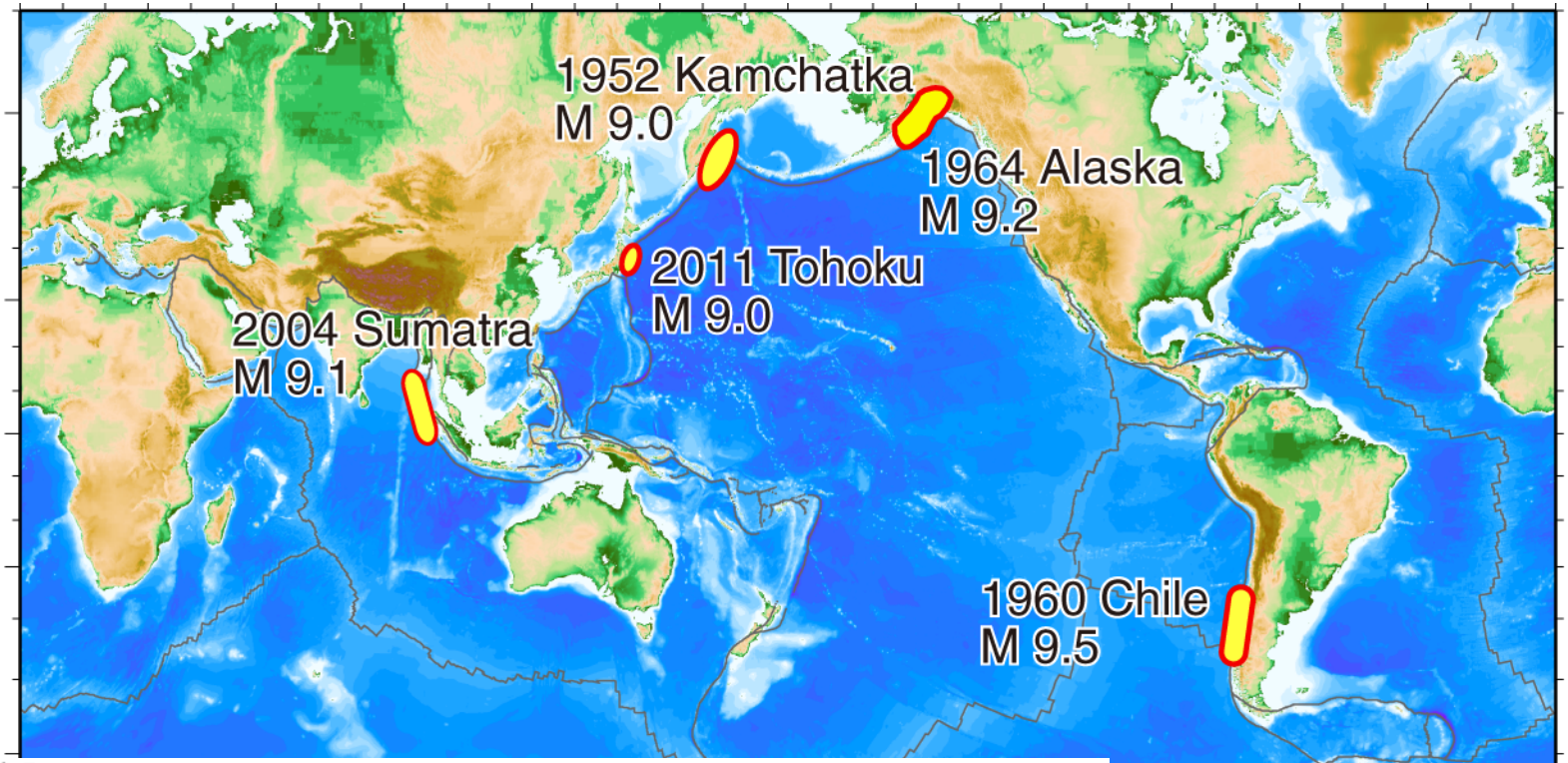
Kenji Satake

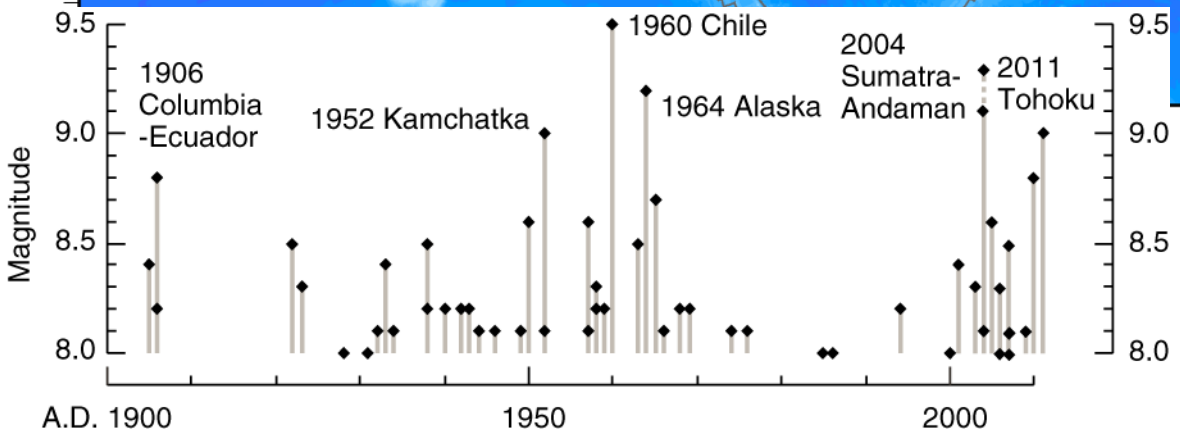
Earthquake Res. Inst. Univ. Tokyo

Outline

1. 2011 Tohoku earthquake was the largest (M~9) in Japan's history
2. Tsunami warning saved many lives yet caused significant (~23,000) fatalities
3. Long-term forecast estimated 99 % probability but M=7.5 in Miygai-oki.
4. Sanriku coast and Sendai plain experienced similar tsunamis in the past
5. The 2011 earthquake may be a combination of 1896-type and 869-type earthquakes

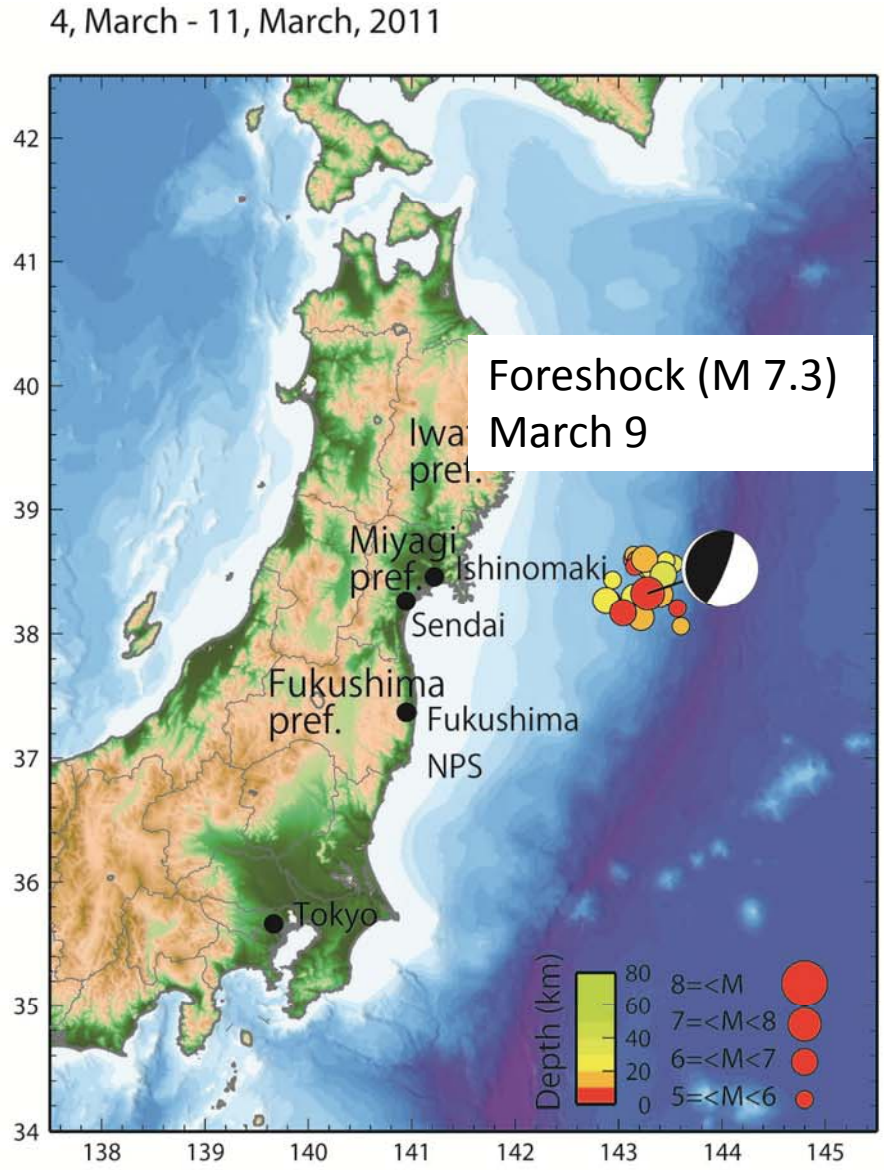
Only five M9 earthquakes since 20th century

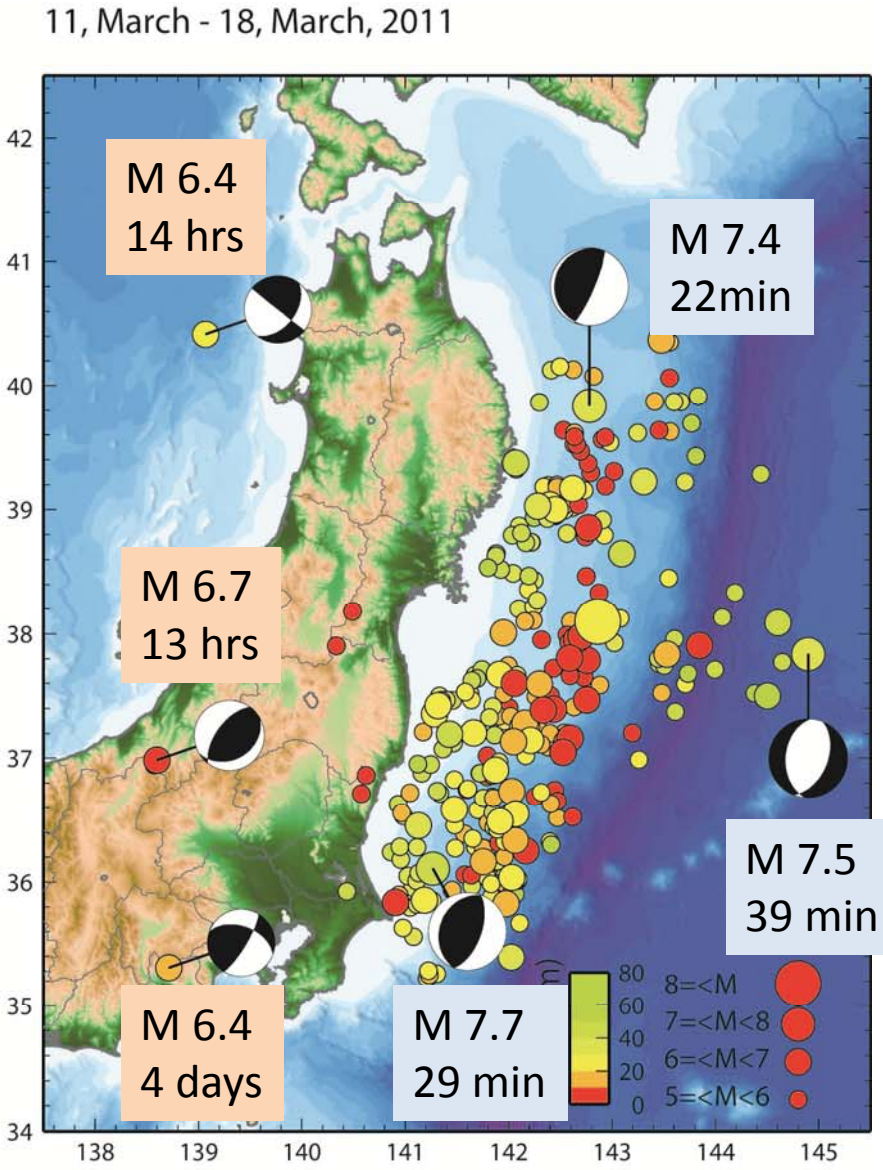




Updated
Satake and Atwater (2007, Ann. Rev. Earth Planet. Sci.)

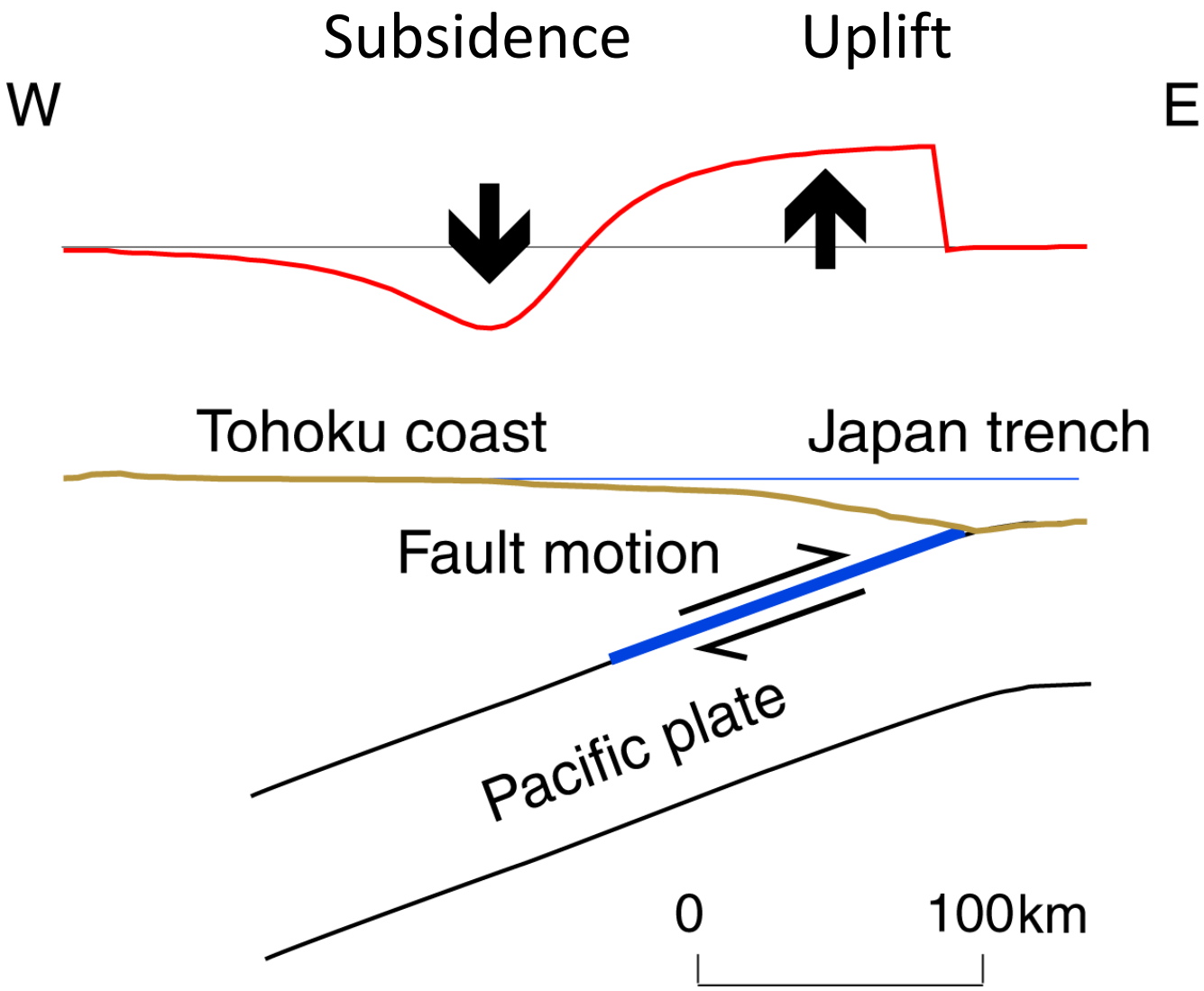
Seismicity before and after March 11





Japan Meteorological Agency

Seafloor displacement (cross-section)

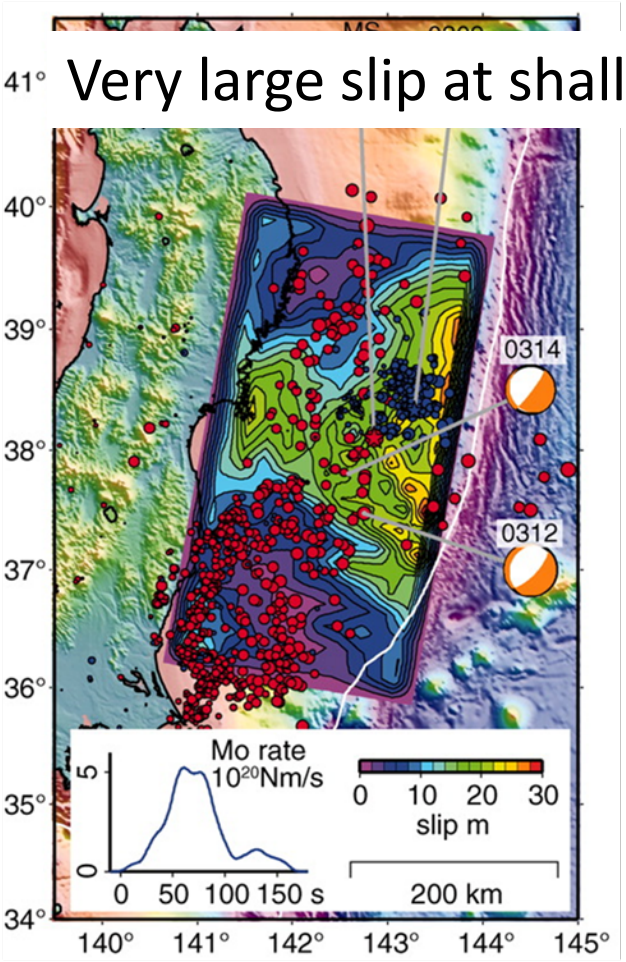


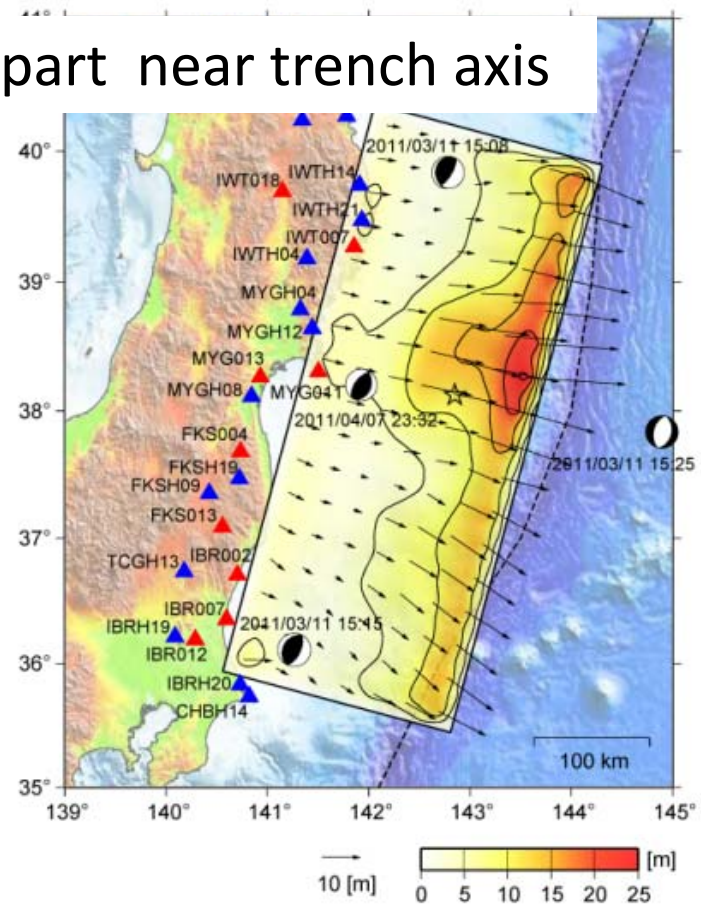
Slip distribution from seismic wave analysis

Teleseismic waves

Near-field strong-motion data

Very large slip at shallow part near trench axis



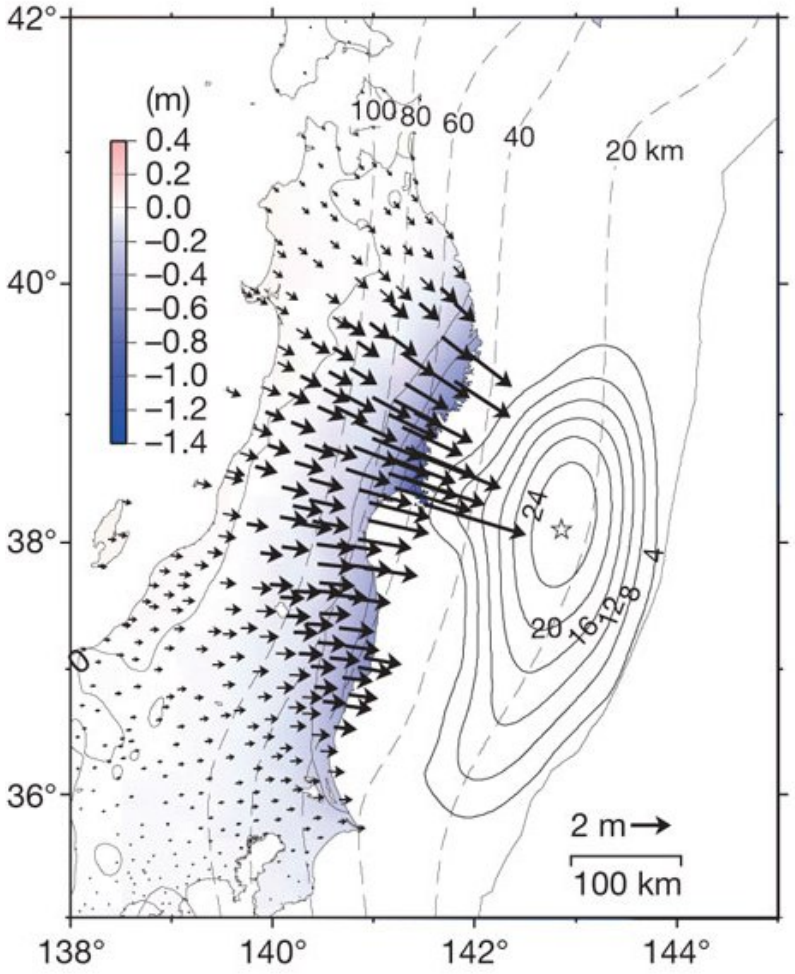


Ide et al. (2011, Science)

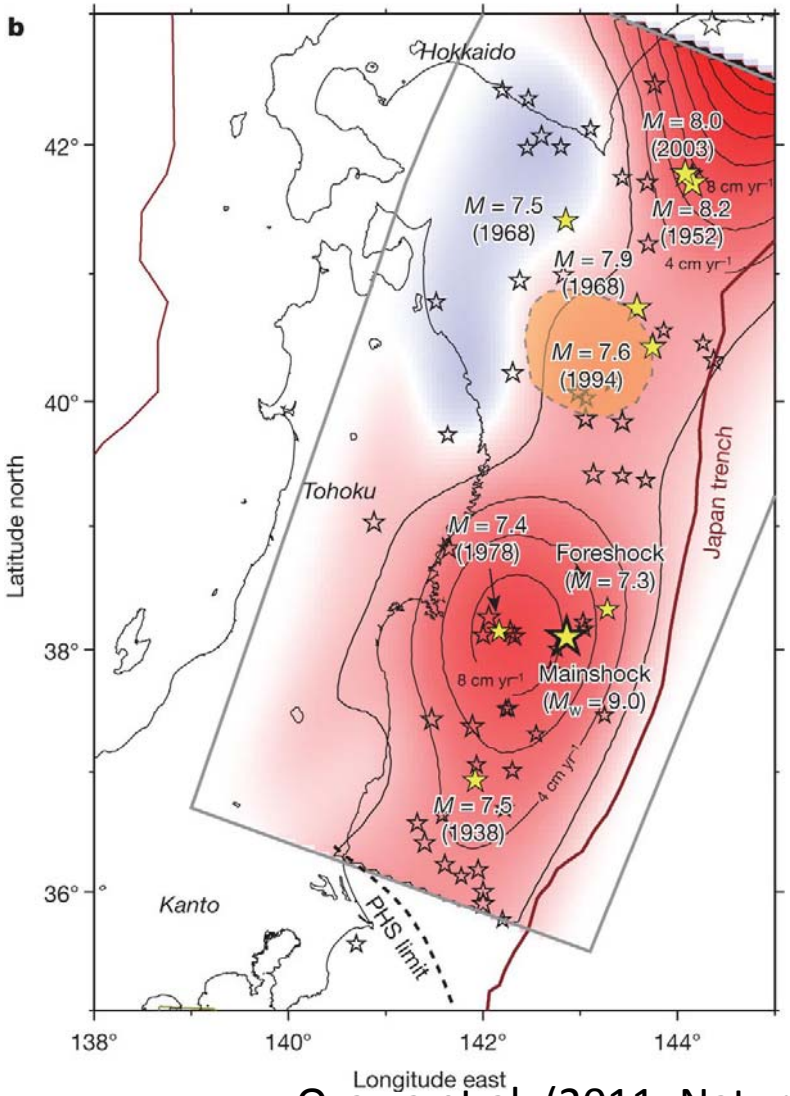
NIED

Coseismic slip and slip deficit

Max disp (obs) : 5 m horizontal)
1 m vertical
Max slip on fault (estimated): 24m



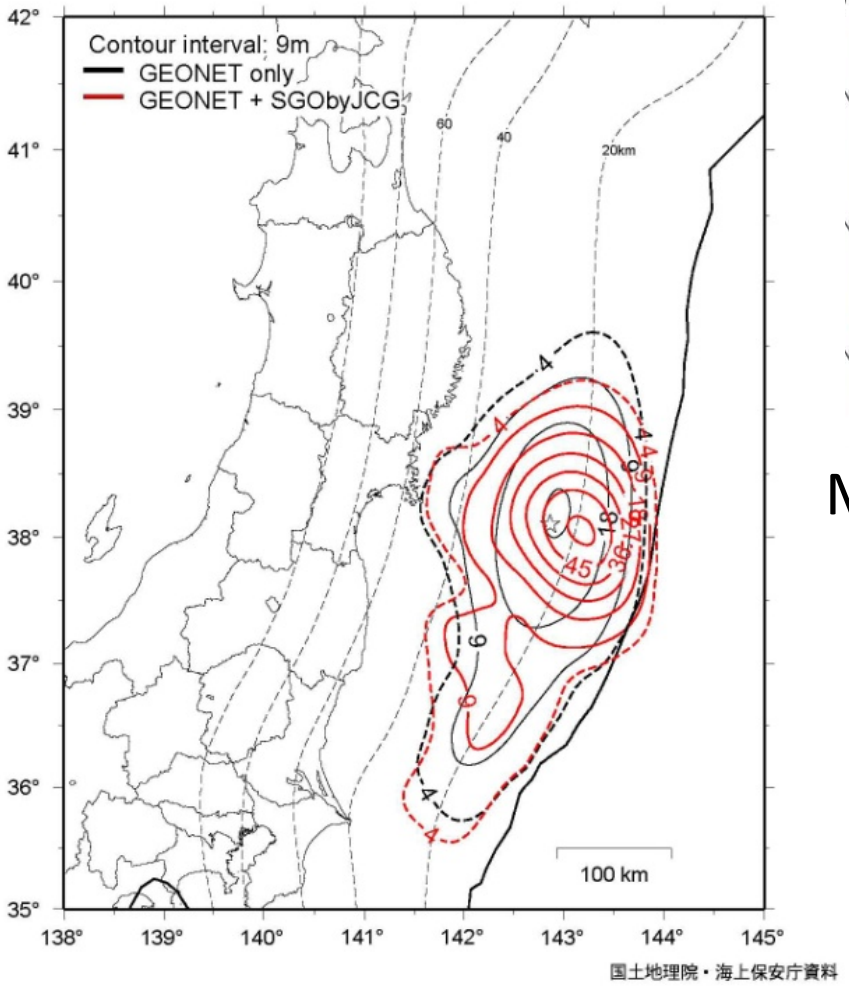
Slip deficit from cont. GPS

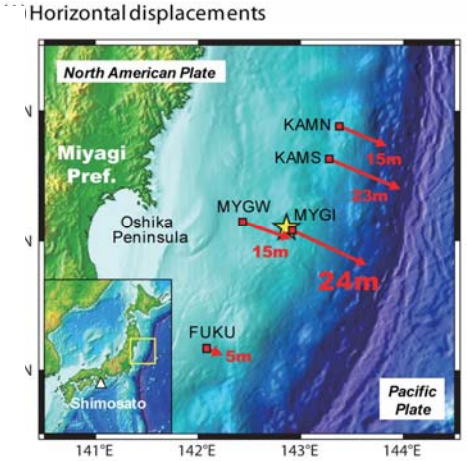


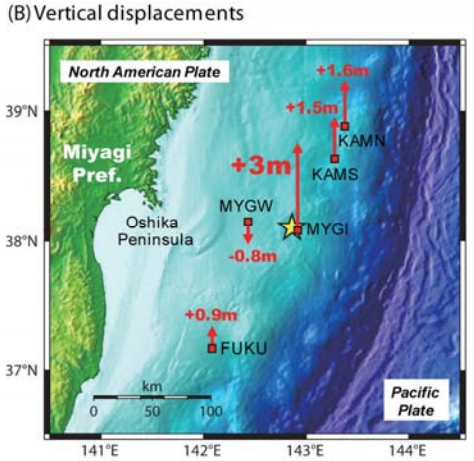
Ozawa et al. (2011, Nature)

Seafloor displacement

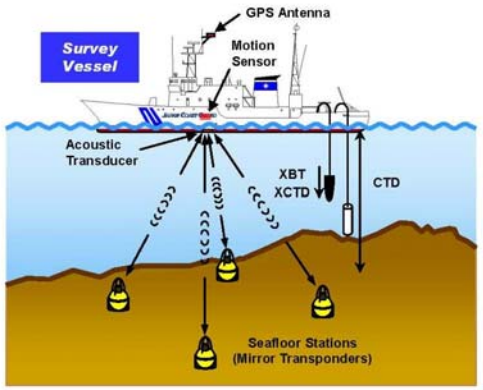
Max slip on fault (estimated): > 50 m







Max observed slip: 24 m horizontal
3 m vertical



GSI and JCG

Sato et al. (Science 2011)

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2. Tsunami warning saved many lives yet caused significant (~23,000) fatalities
3. Long-term forecast estimated 99 % probability but M=7.5 in Miygai-oki.
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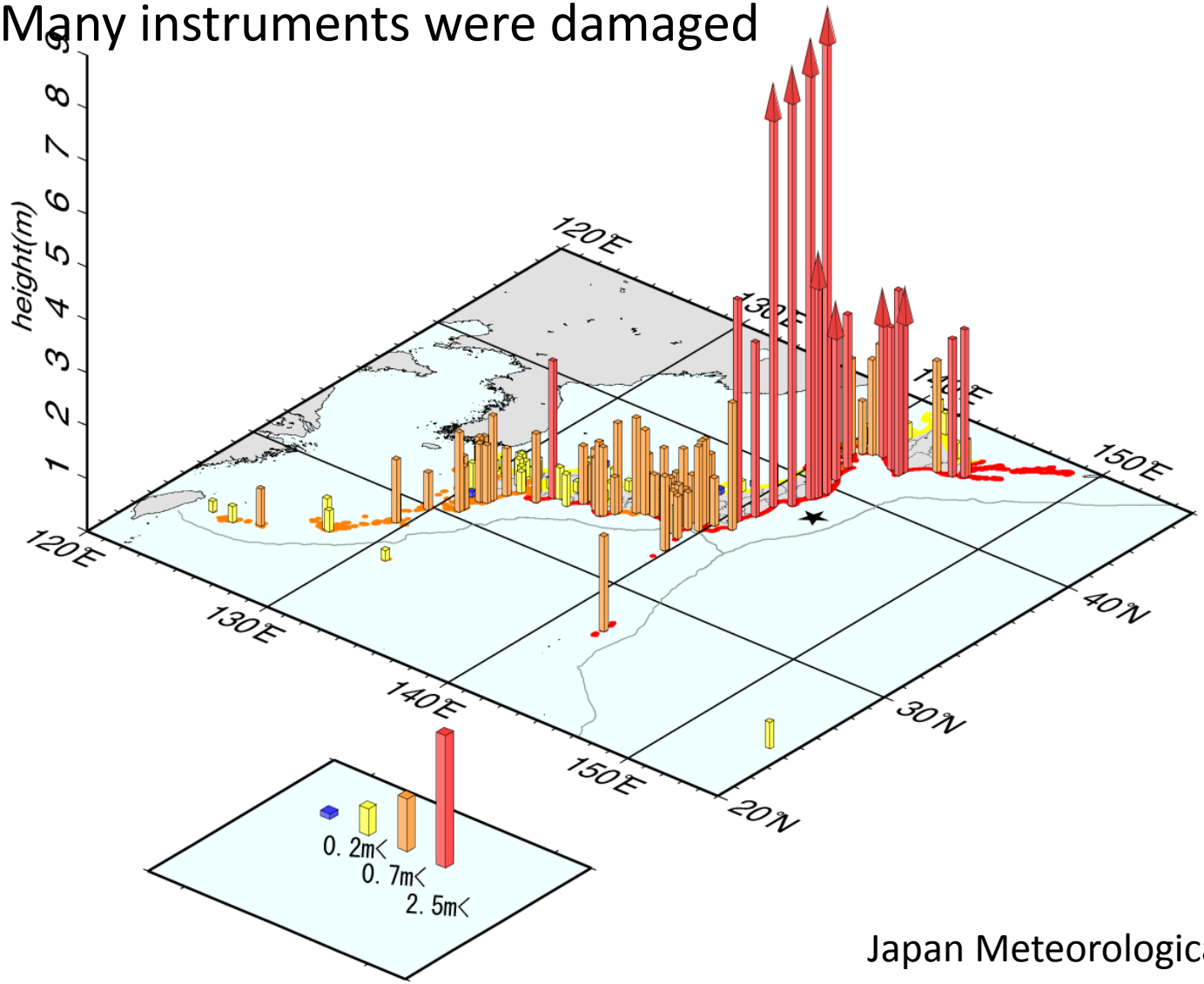
Tsunami observation

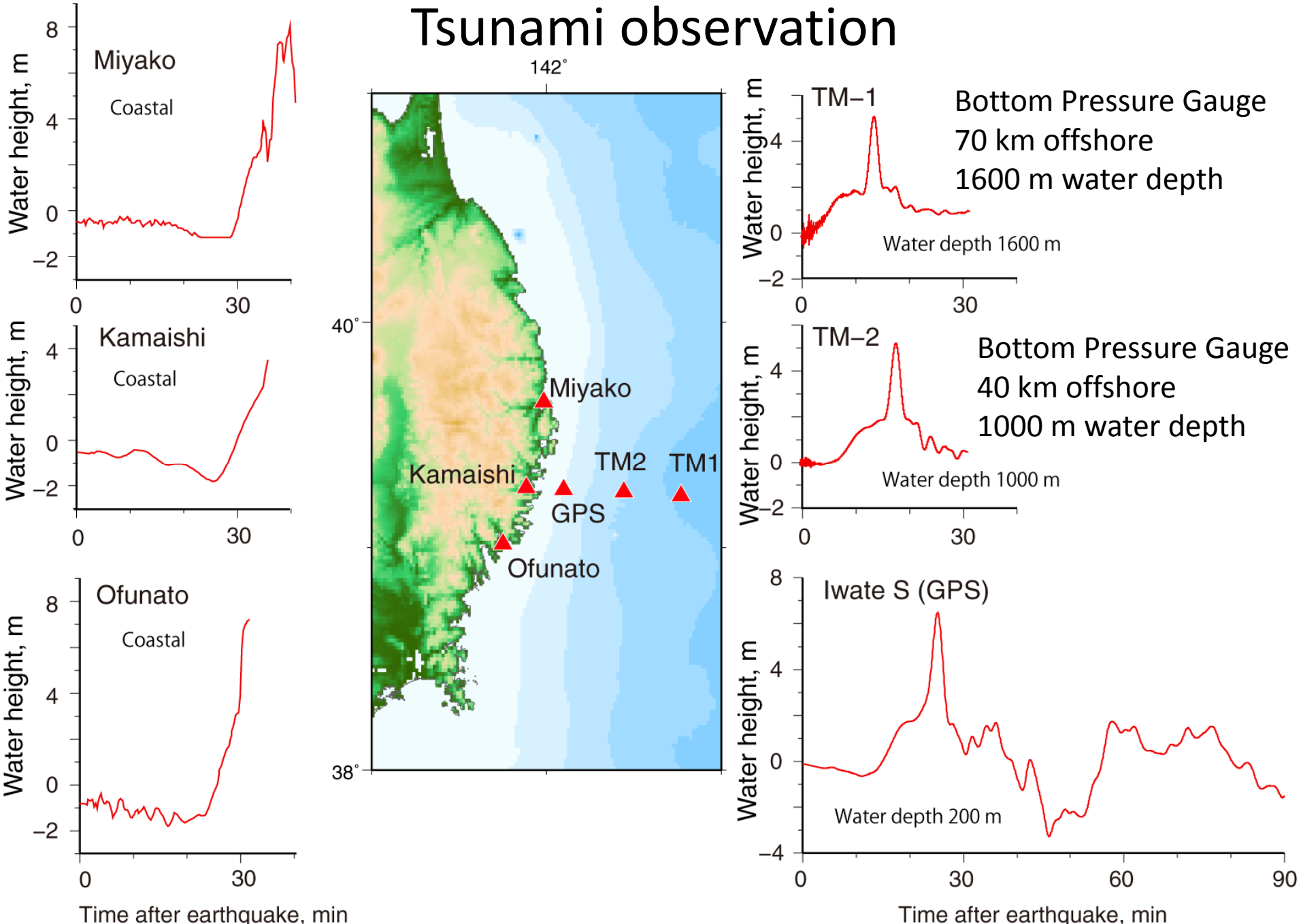
Max height > 9m (instrumental)

Many instruments were damaged



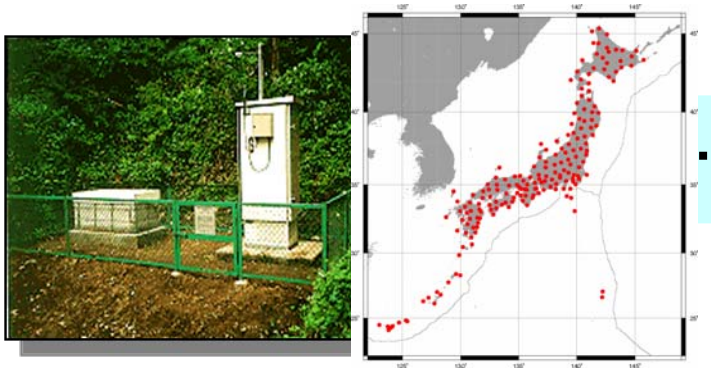
Japan Meteorological Agency

Tsunami observation

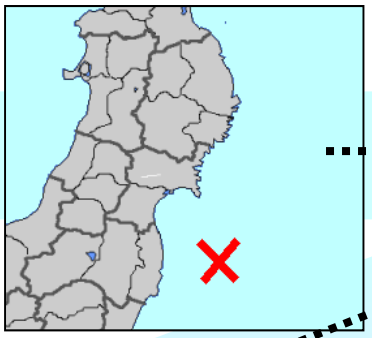


Tsunami Warning System (JMA)

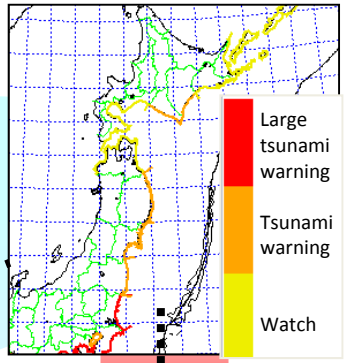
Seismic Obs.



Epicenter and M



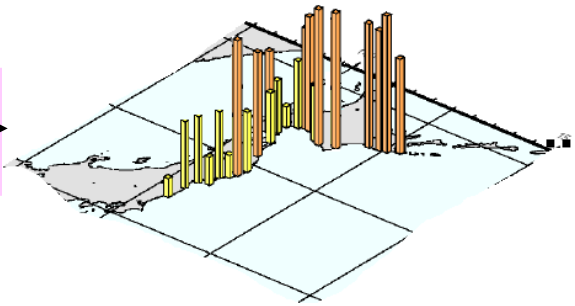
Quantitative Modeling



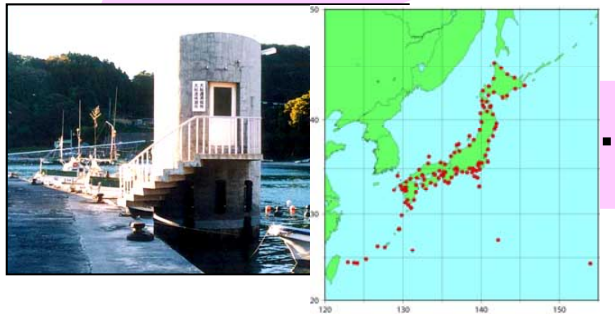
Tsunami Warning

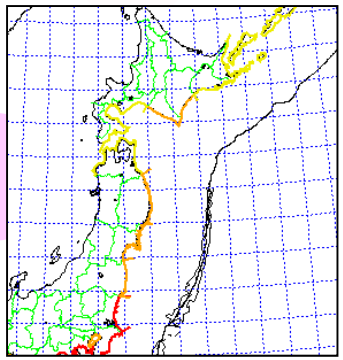
Update warning

Evaluation based on Obs.



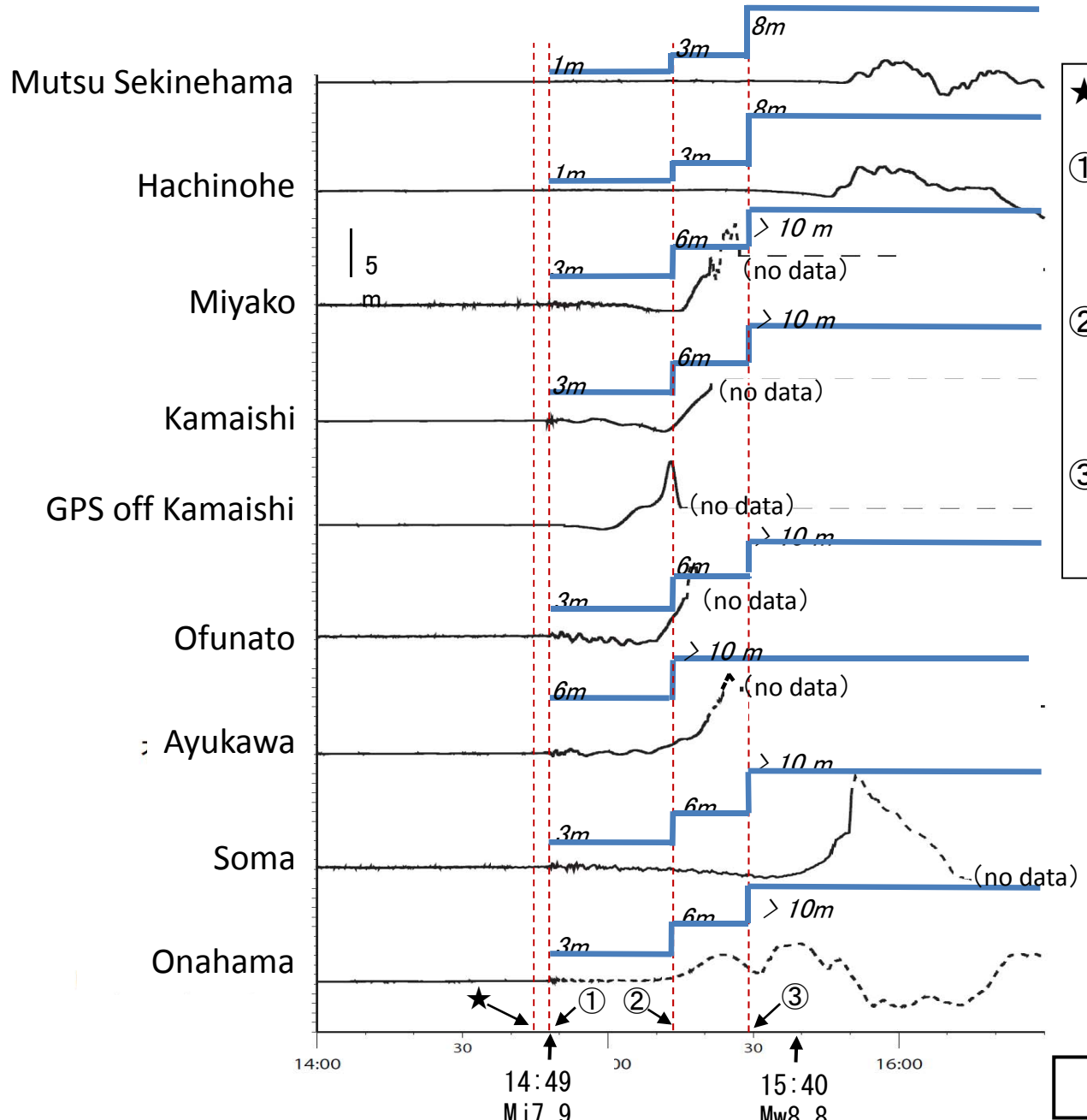
Sea Level Measurements





Japan Meteorological Agency

Tsunami Warning from JMA



★3/11 14:46 Earthquake

①3/11 14:49 Initial tsunami warning
14:50 Iwate 3m, Miyagi 6m,
Fukushima 3m, Aomori 1m

②3/11 15:14 Update of tsunami warning
Iwate 6m, Miyagi > 10m,
Fukushima 6m, Aomori 3m

③3/11 15:30 Update of tsunami warning
15:31 > 10 m for the Pacific coast

Tsunami warning was updated
Based on GPS wave gauge data

Water level data (monitored)

Water level (recovered later)

Tsunami warning level

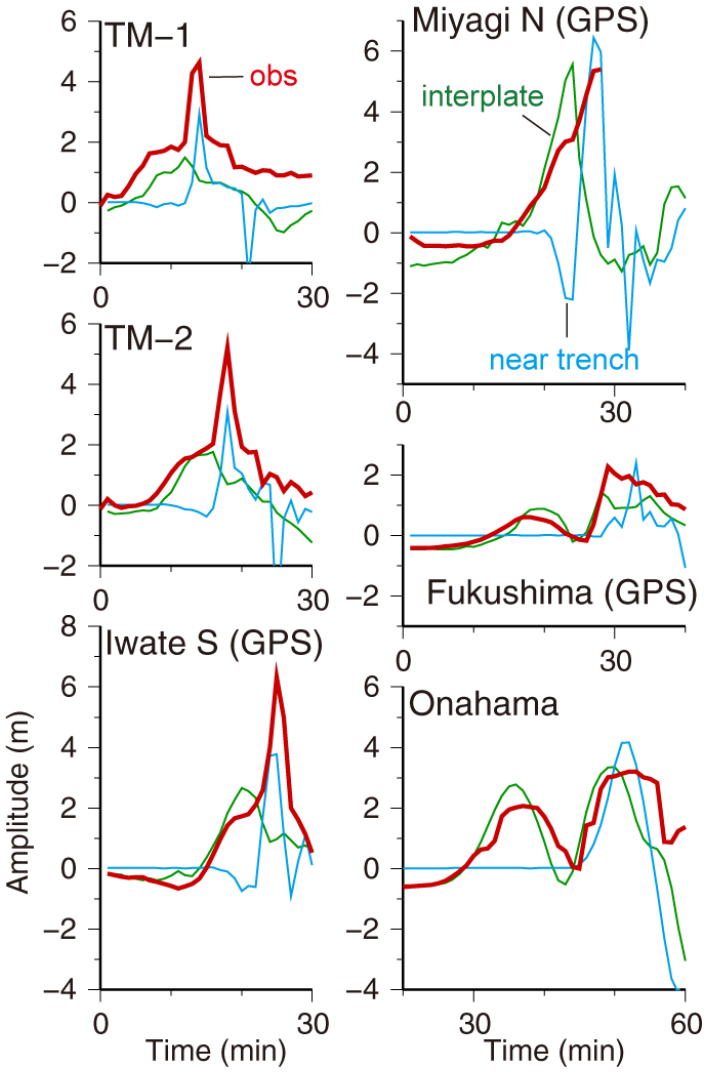
Press Release MJma 8.4 16:00
Mw 8.8 17:30

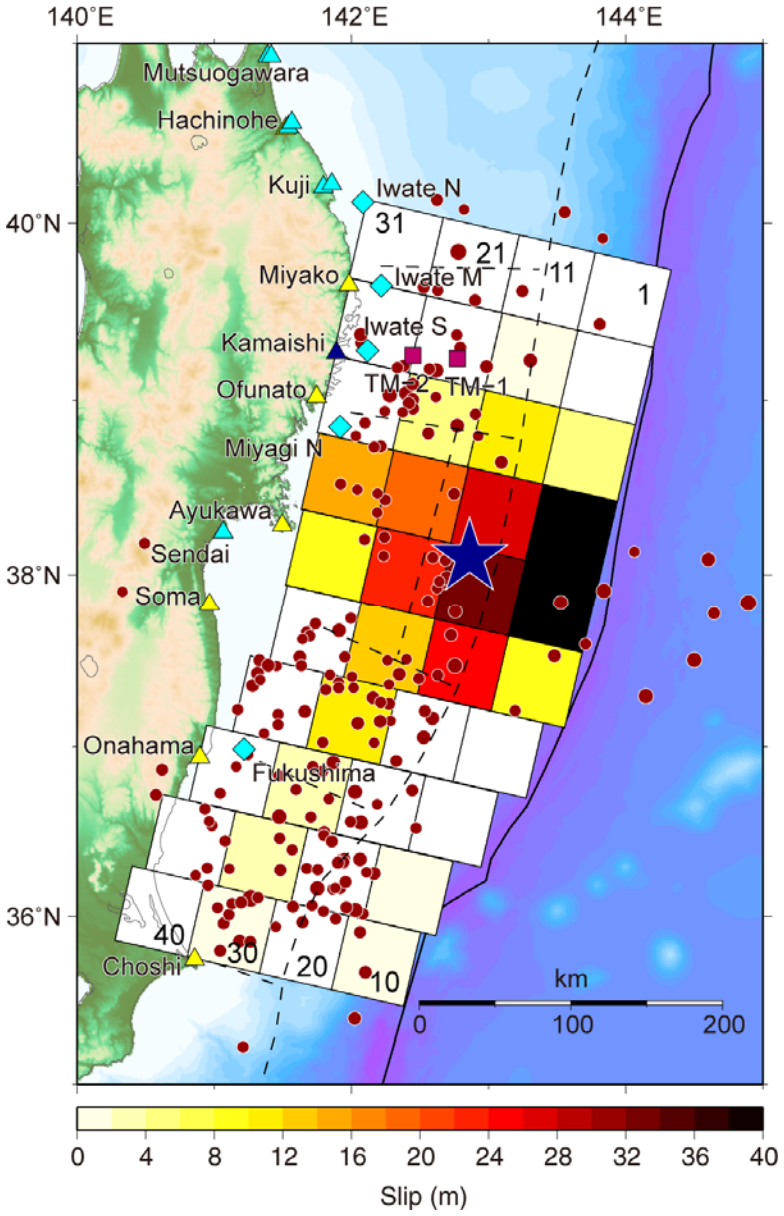
Japan Meteorological Agency

Tsunami Warning from JMA

Time	Time after Eq.	M	Seismic Intensity and Tsunami Warning
14 : 46	0	M 7.2	4th report of EEW Intensity 4 to 5- in central Miyagi
14 : 47	1 min	M 7.7	10th report of EEW Intensity 5- in central Miyagi
14 : 49	3 min	M 7.9	Tsunami Warning: 6 m Miyagi, 3 m Iwate and Fukushima
15 : 14	28 min	M 7.9	Tsunami Warning: > 10 m Miyagi, 6 m Iwate, Fukushima
15 : 30	44 min	M 7.9	Tsunami Warning: > 10 m Iwate, Fukushima, Ibaraki, Chiba
15 : 30	1 hour	M 8.4	Revision of M
17 : 30	3 hours	M 8.8	Revision of M
12th 03 : 20	13 hours	M 8.8	Tsunami warning or advisory for the entire coast of Japan
13th 07 : 30	1.5 days	M 8.8	Tsunami warning partially cleared
13th 12 : 55	2 days	M 9.0	Revision of M
13th 17 : 58	2 days	M 9.0	Tsunami advisory all cleared

Slip distribution from tsunami waveforms





Fujii et al. (EPS in press)

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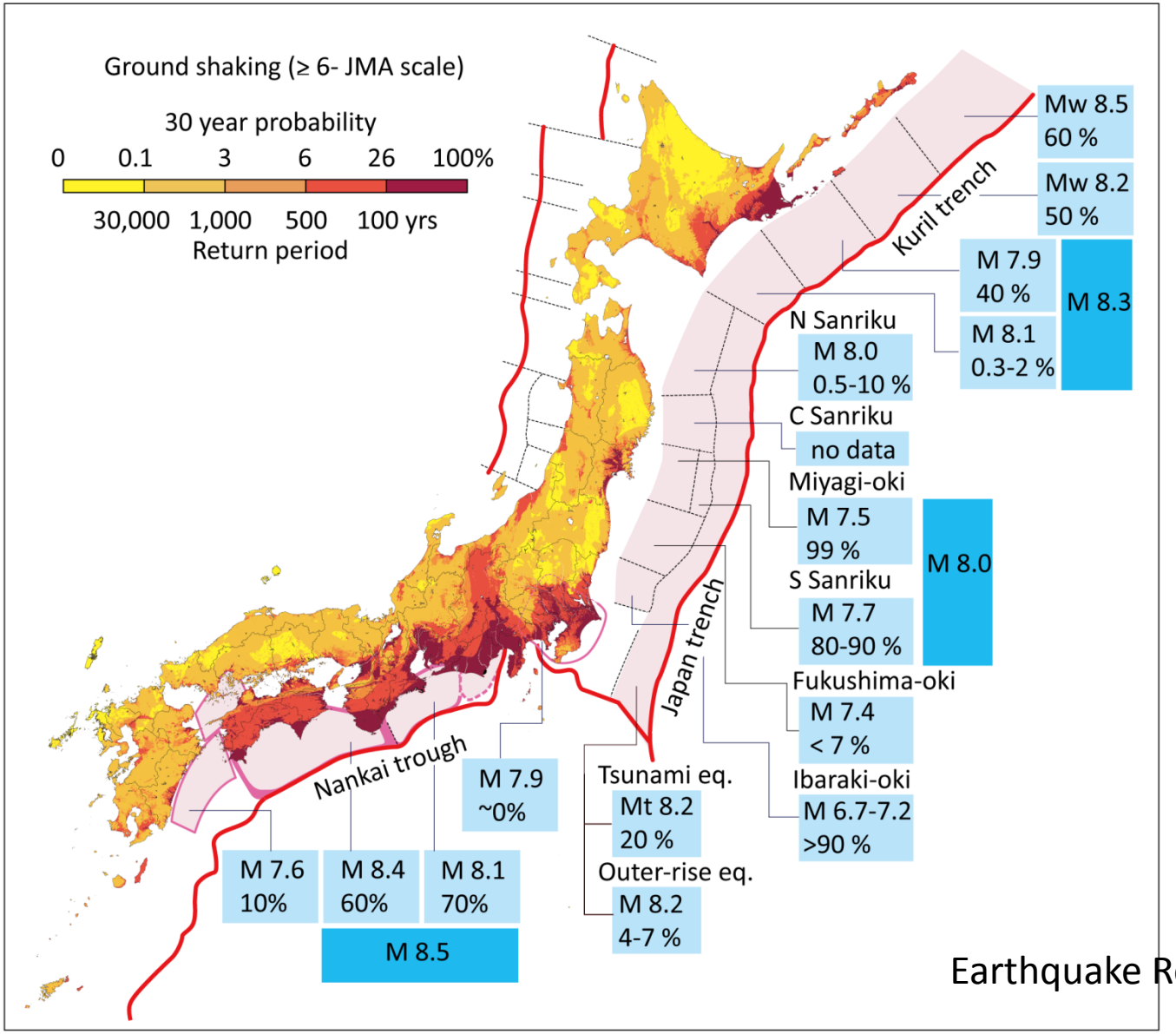
Long-term forecast for subduction zone earthquakes around Japan



Earthquake Res. Com.

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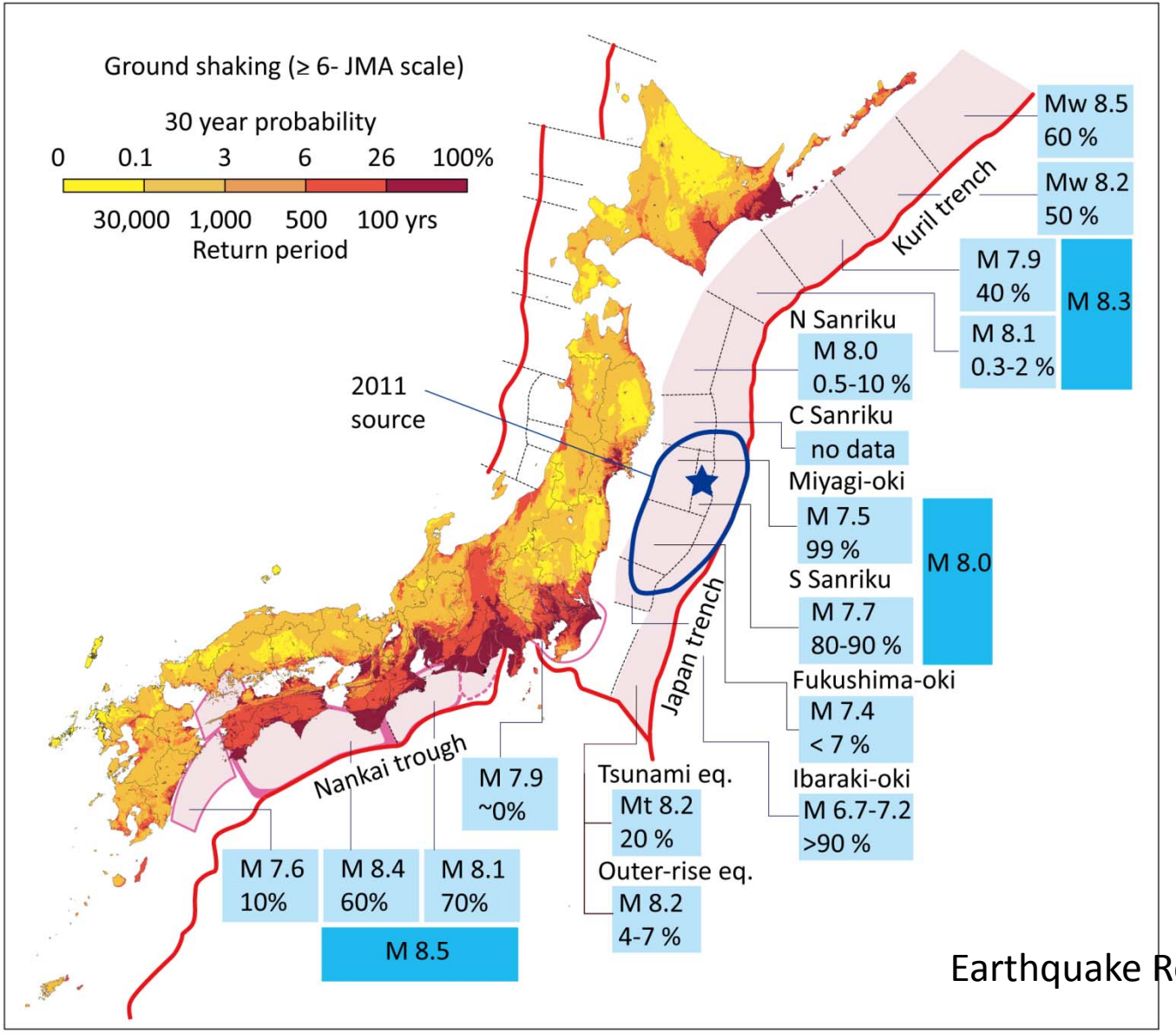
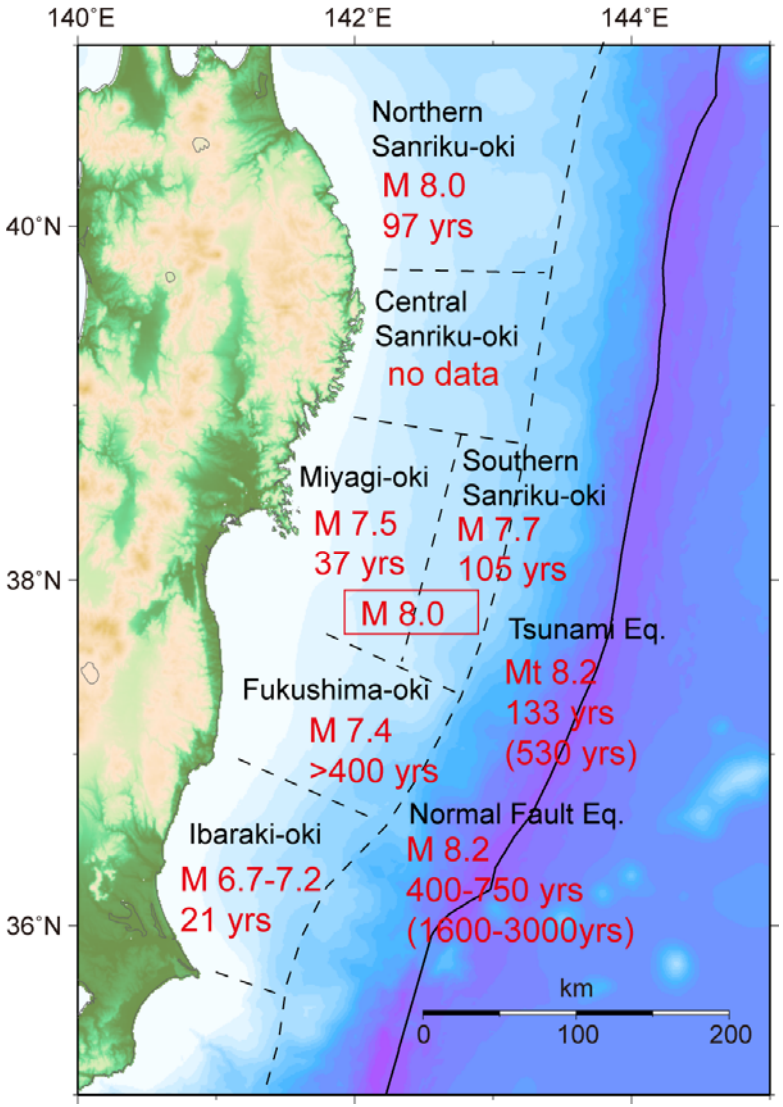
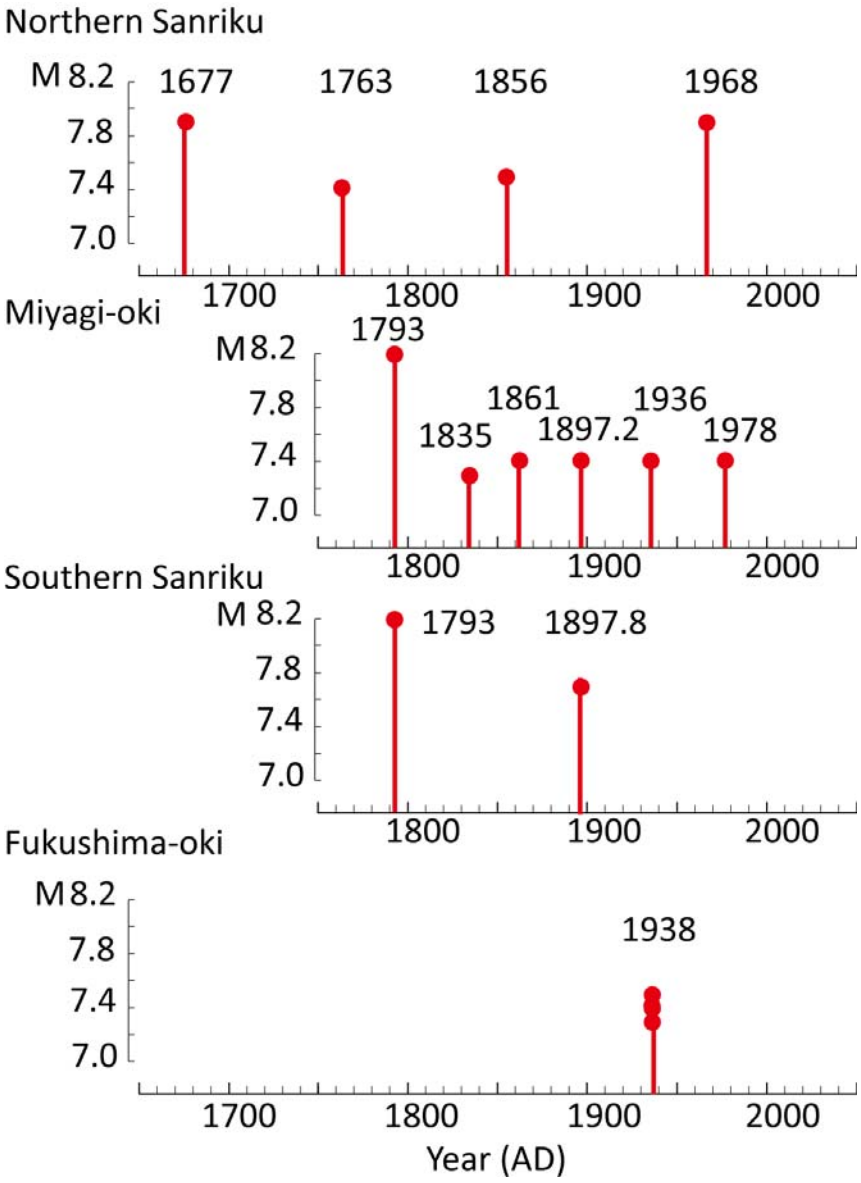


Earthquake Res. Com.

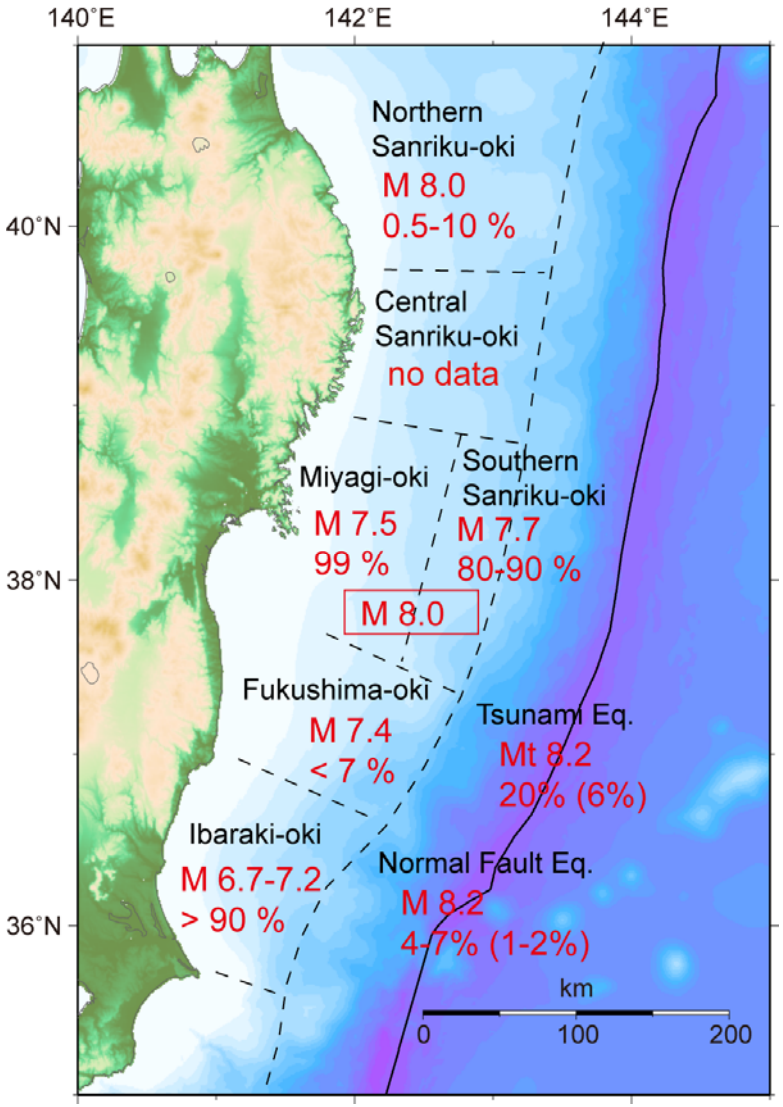
Sanriku long-term forecast

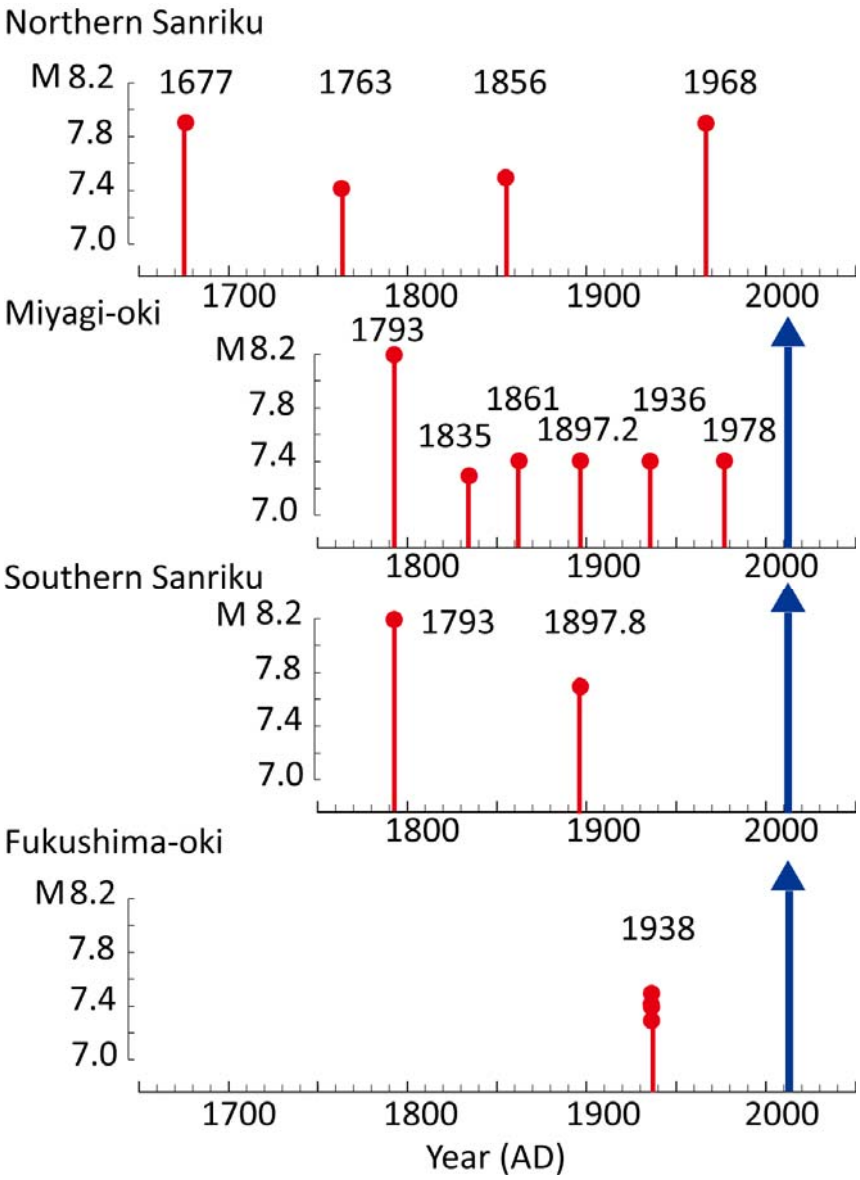


Long term forecast by ERC



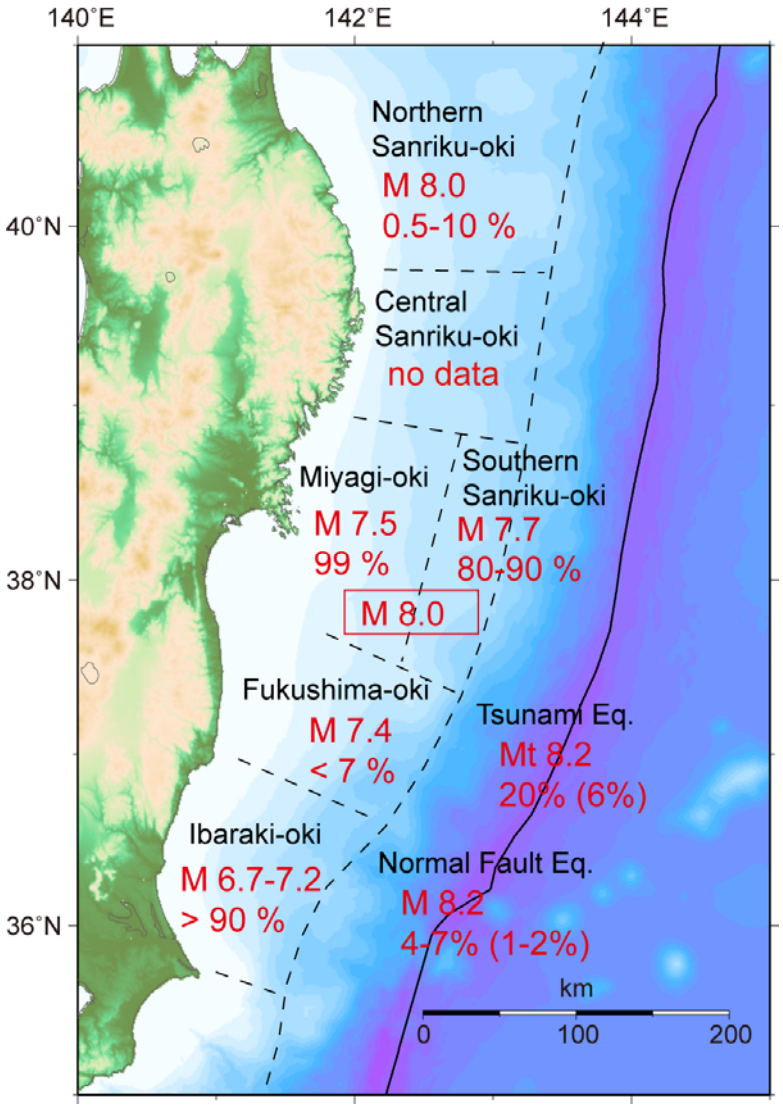
Sanriku long-term forecast





Long term forecast by ERC

2011 Tohoku earthquake



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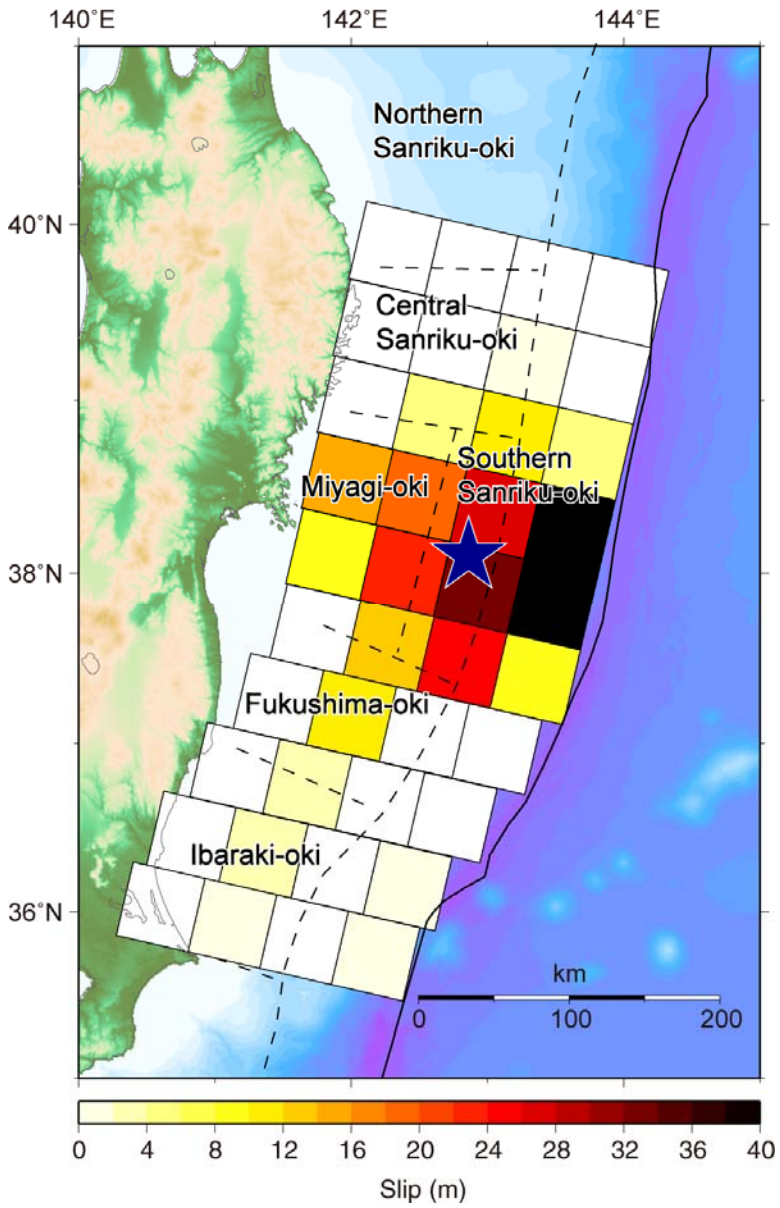

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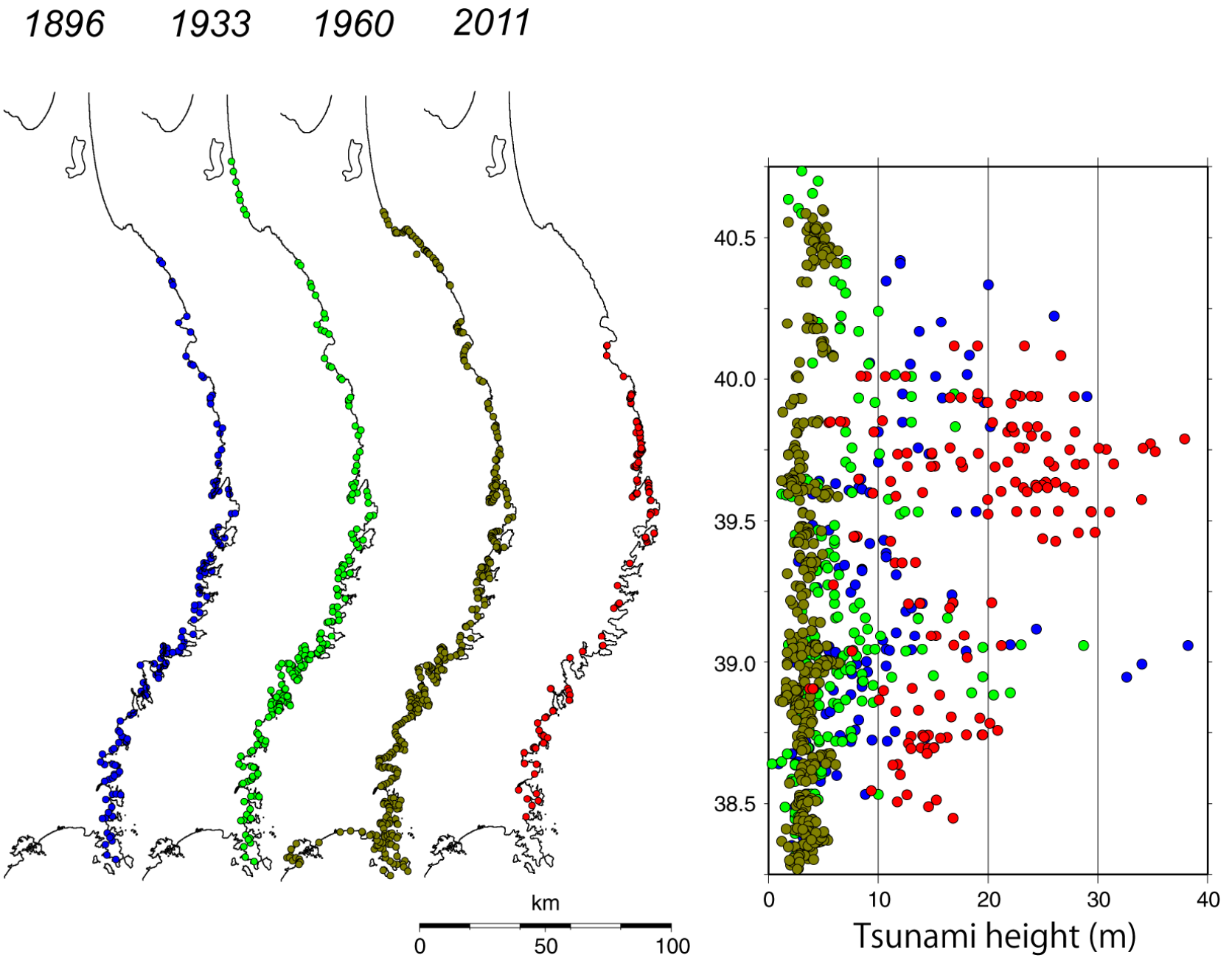
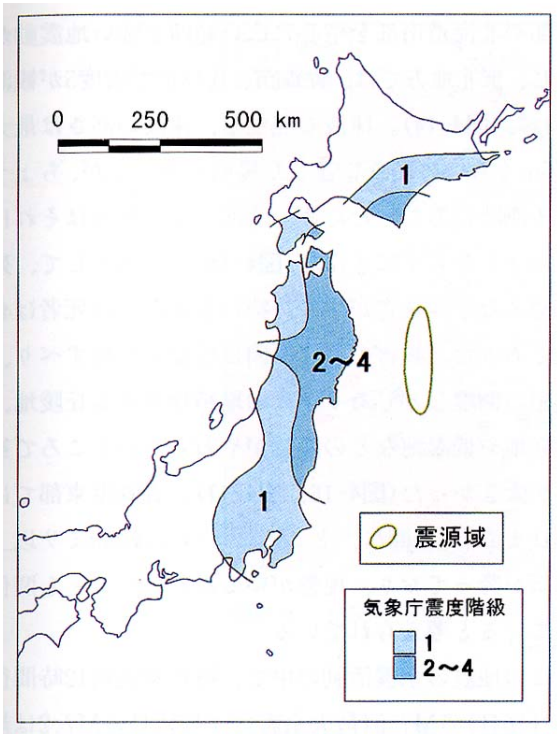
Past tsunamis



Past Tsunami in Taro, Miyako city

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



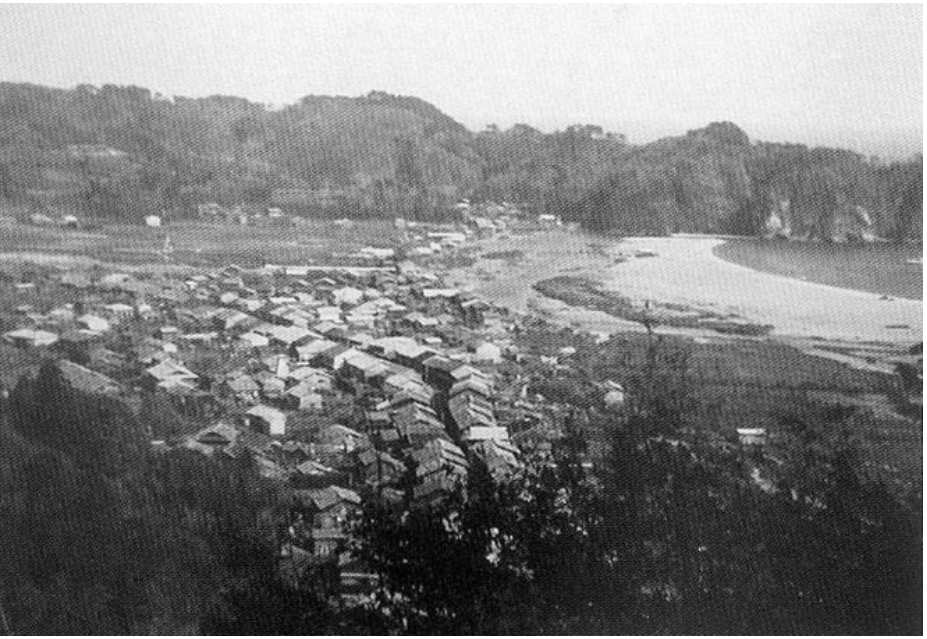
Weak shaking but large tsunami
“Tsunami earthquake”

Seismic intensity <4 (JMA)
Largest tsunami 38 m

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%)



Before and after the 1933 tsunami

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%)

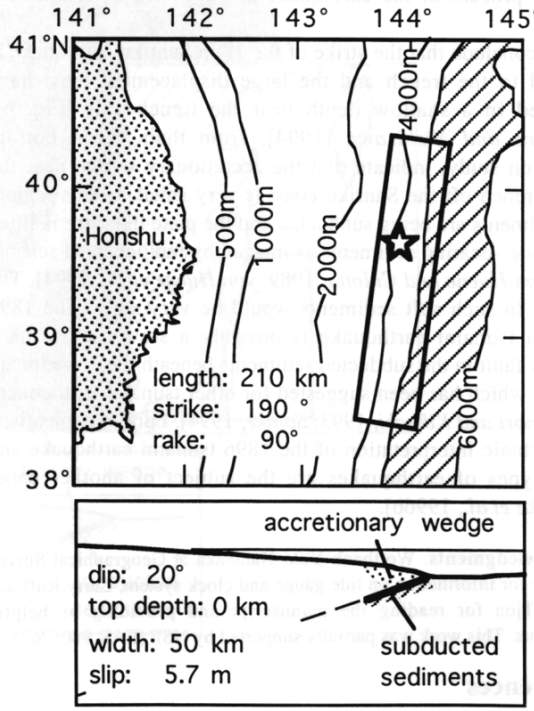
2011 Tohoku-oki tsunami: 230 casualties (out of 4000, or 6%)

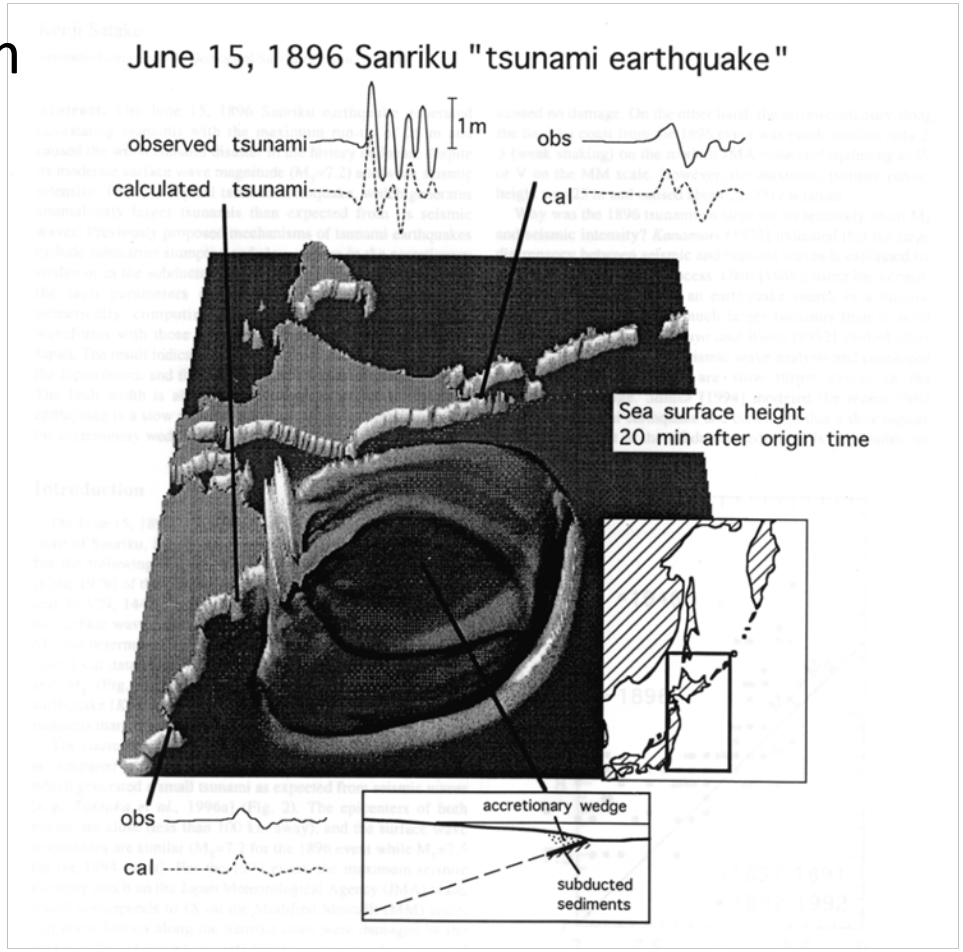
10m high 2.5 km long breakwater around Town

1896 Sanriku “tsunami earthquake”

M 7.2

Max. tsunami height: 38 m





Width: 50 km, slip: 6m

Near trench axis

Tanioka and Satake (1996)

AD 869 Jogan Earthquake

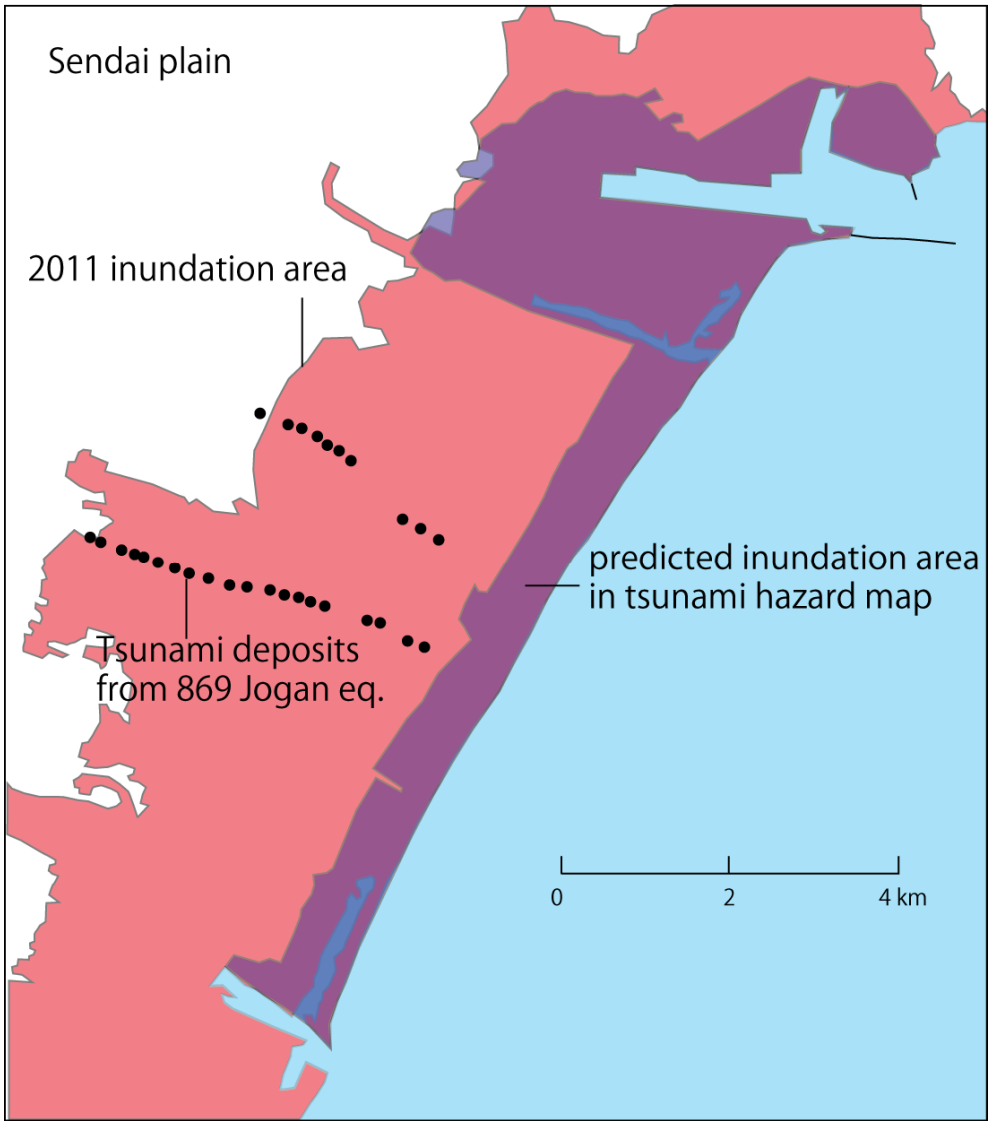
Nihon Sandai Jitsuroku (Chronicle of Japan)

A large earthquake in Mutsu
People, panic stricken by violent tremblings, lying on the ground
Fallen houses, wide-opened ground fissured
Roaring like thunder heard from the sea
The sea rushed into the castle, a few hundred miles
About 1,000 people were killed

Tsunami deposits

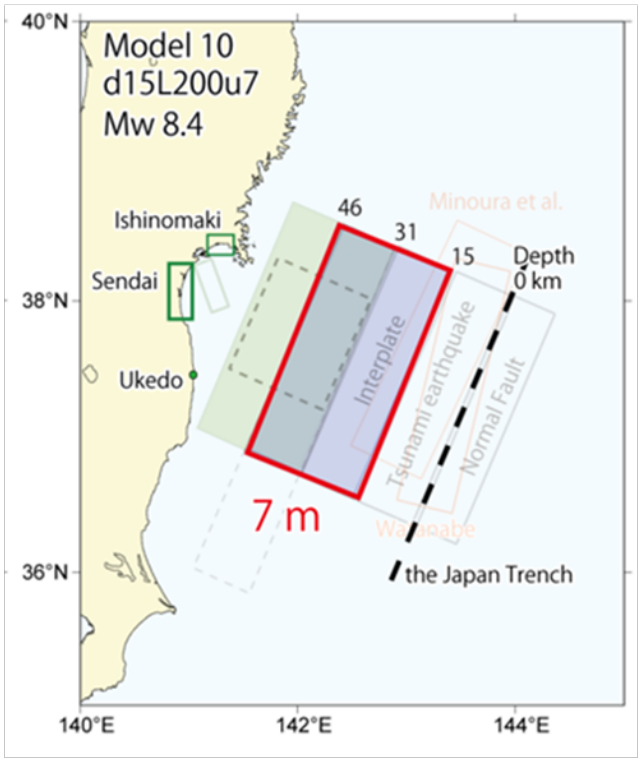
Abe et al. (1990)
Minoura and Nakaya (1990), Minoura et al. (2001)
Sawai et al. (2008)
Shishikura et al. (2009), Sawai et al. (2009)

AD 869 Jogan Earthquake



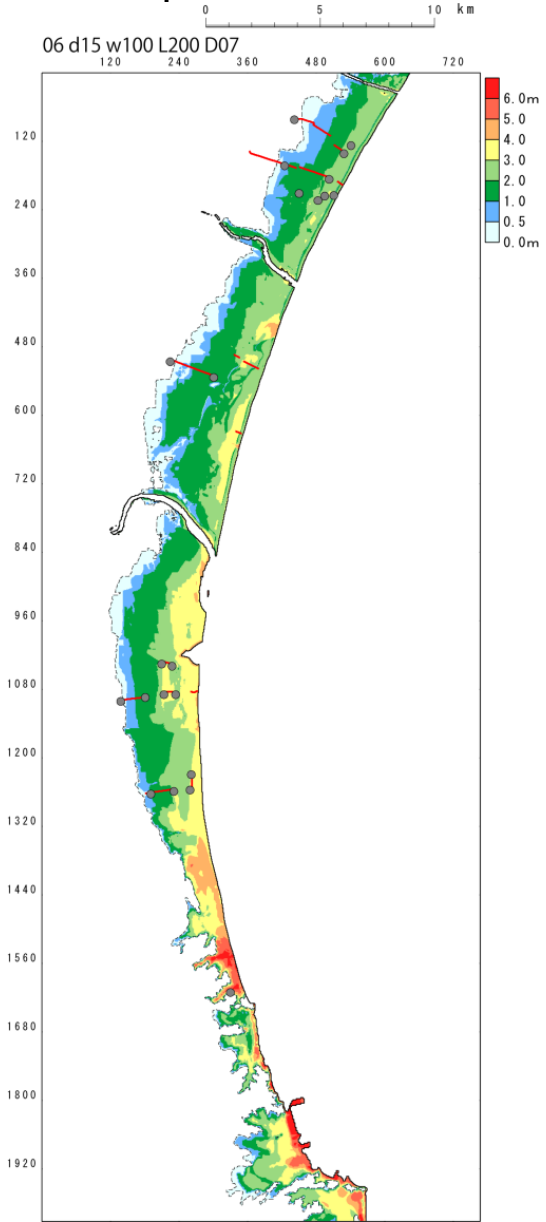
AD 869 Jogan Earthquake

A fault model



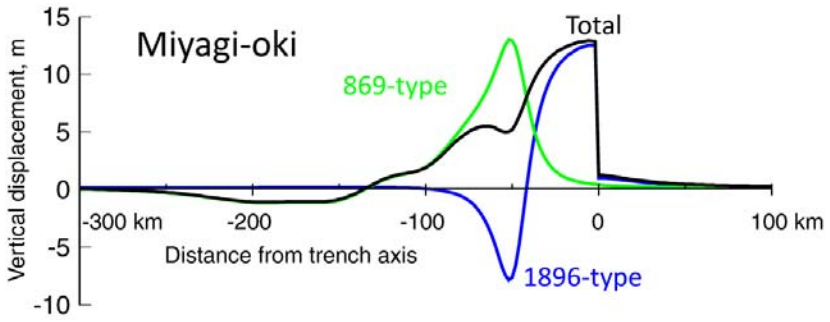
Namegaya et al. (2010)
AIST

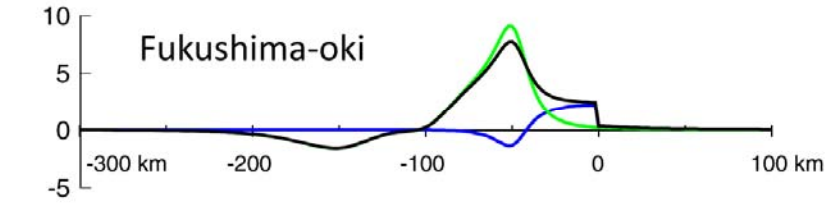
Computed inundation

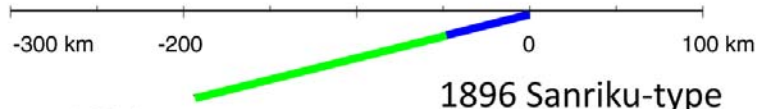


2011 Inundation

2011 earthquake: 1896 and 869 types

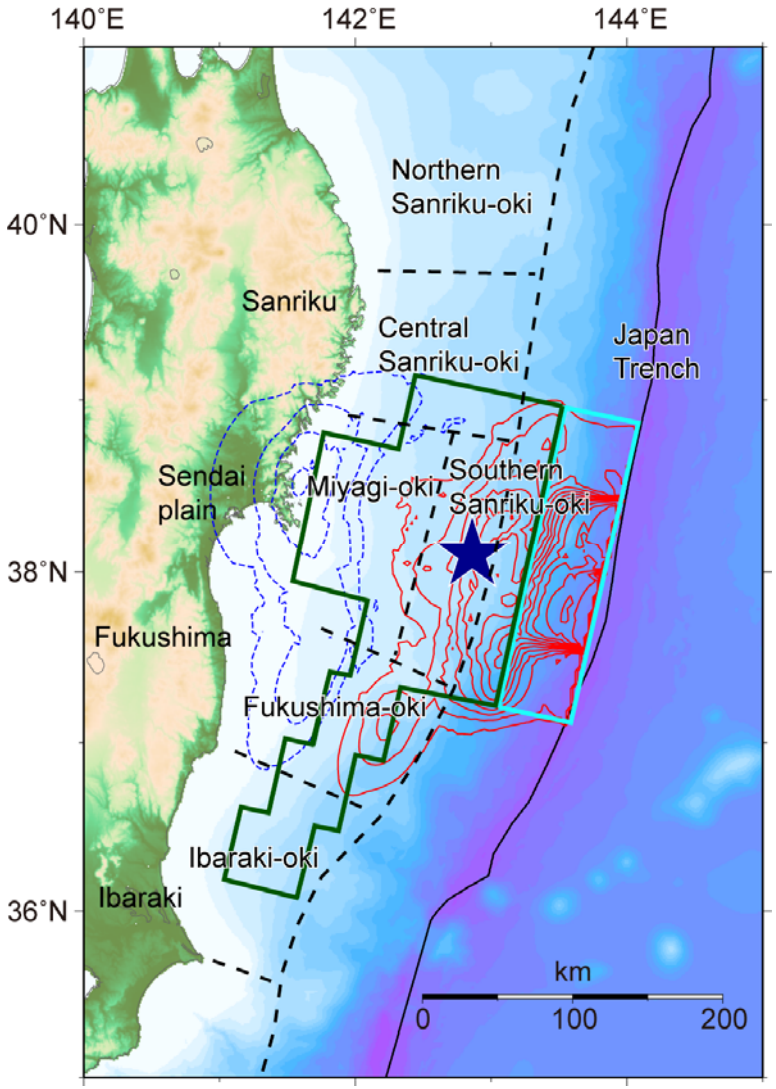






869 Jogan-type
15-20 m slip Miyagi-oki
<10 m slip Fukushima-oki

1896 Sanriku-type
>40m slip off Miyagi-oki



Fujii et al. (EPS in press)

Conclusions

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