Earthquakes and Tsunamis

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Part I

2011 Tohoku earthquake and tsunami

Fukushima Dai-ichi NPP accident

Earthquake ground motion
- Reactors automatically shutodwn
- Cooling using Diesel Generators

Tsunami arrived
- DG was flooded, failed to cooldown
- Core Damage
- Hydrogen Explosion
- Release of radioactive materials

TEPCO

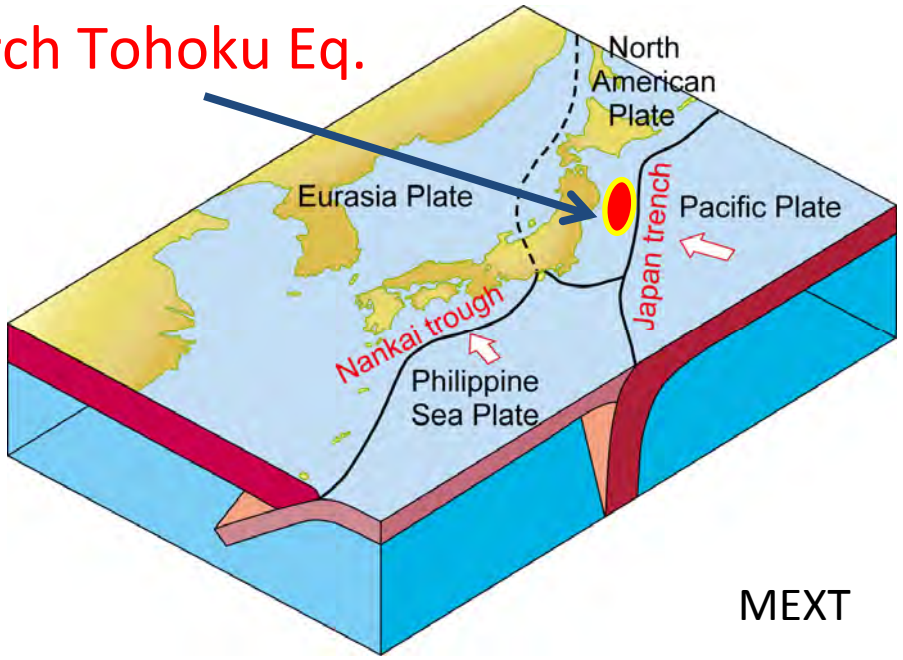
Outline

1. March 11 earthquake and tsunami
2. Tsunami warning system in Japan
3. Long-term forecast of earthquakes
4. Past tsunamis on Sanriku coast and Sendai plain
5. Source model inferred from tsunami waveforms
6. Giant earthquakes in the world

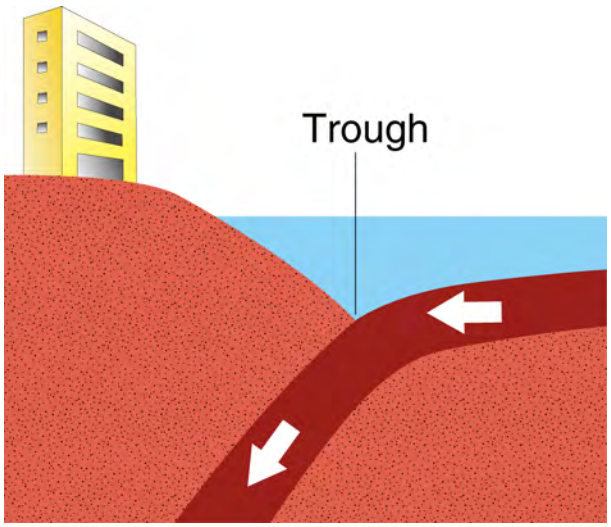
The 2011 Tohoku Earthquake

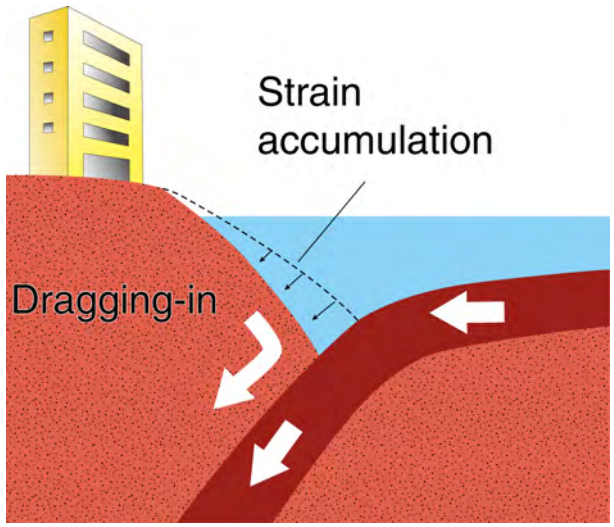
- Interplate earthquake due to subduction of Pacific plate at 8 cm /year or 8 m / century

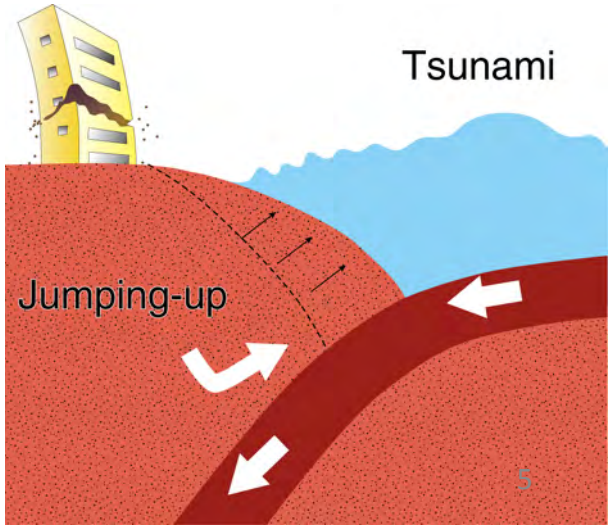
- Largest size (M=9.0) in Japan's history



MEXT



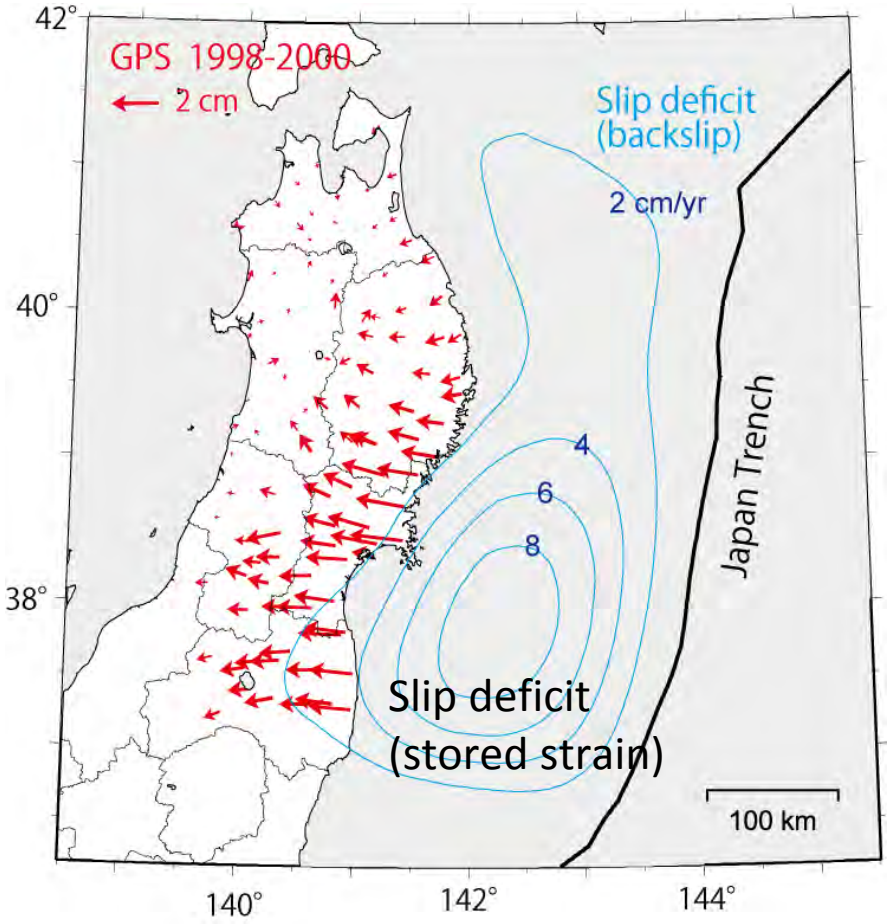




GPS data and slip distribution

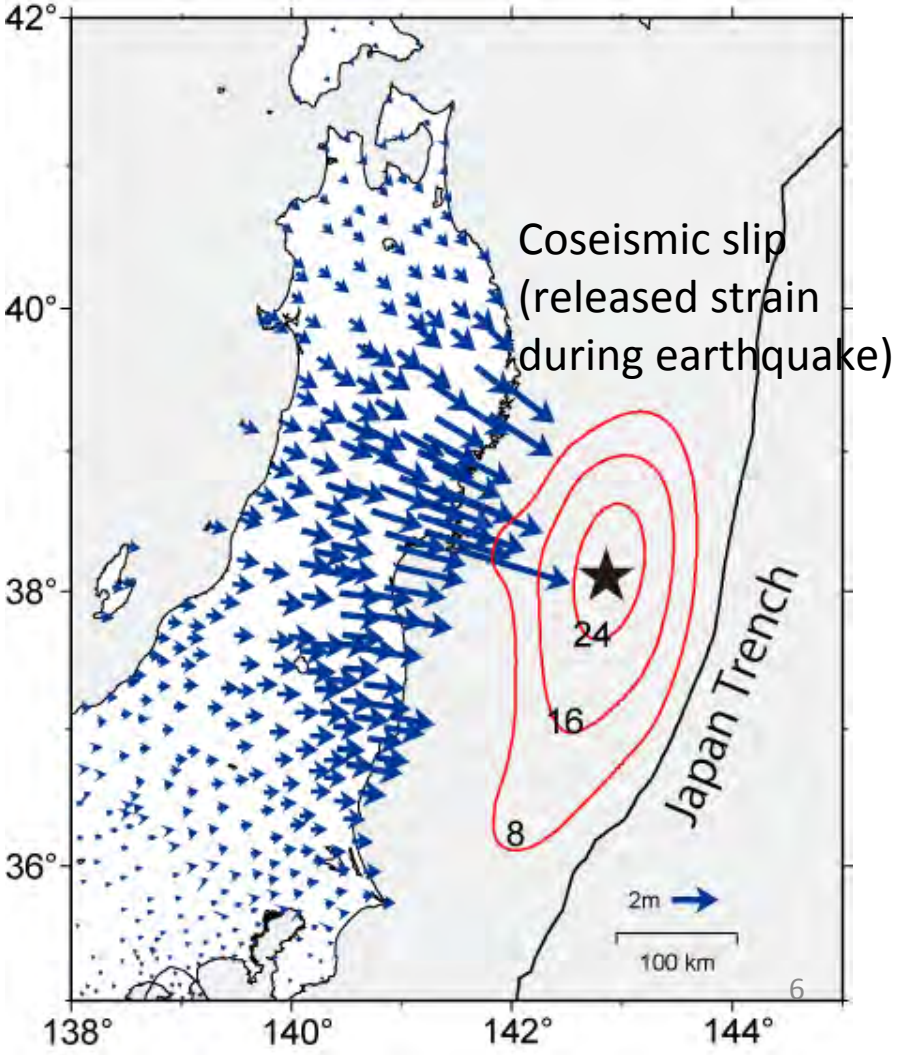
About 1,300 GPS stations monitor the movement of Japan

Westward motion in 1998-2000



GSI (2010, 2011)

Eastward rebound on March 11

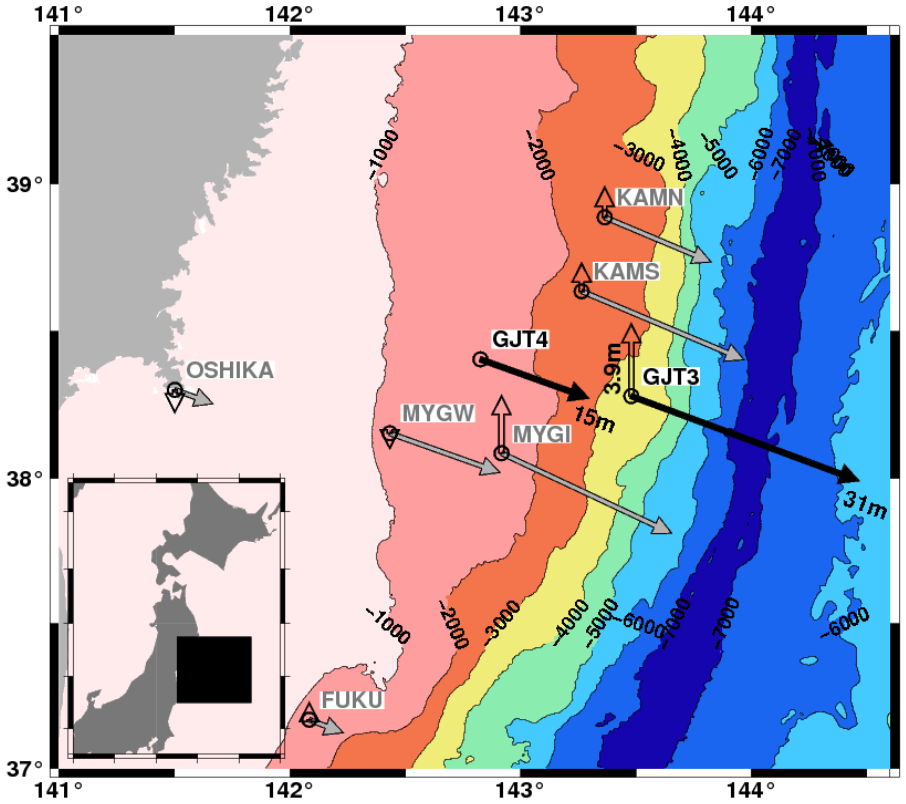


Seafloor displacement

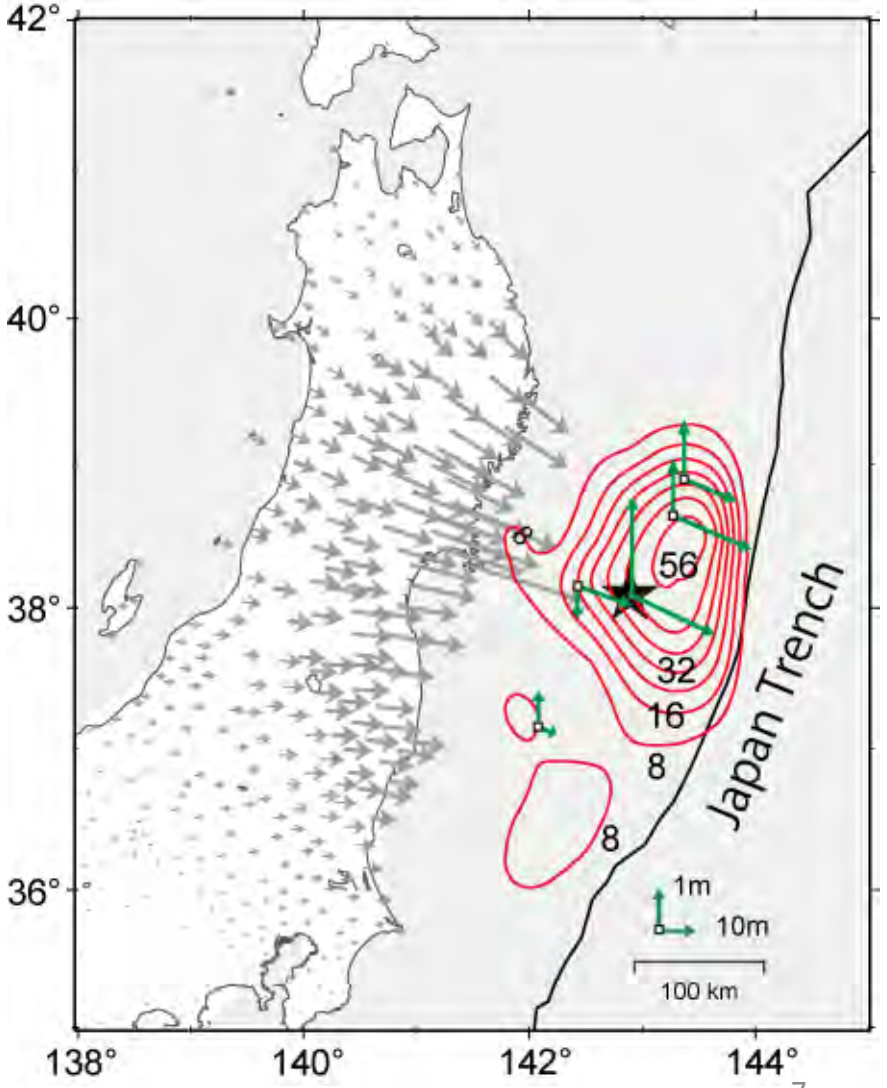
Max slip on fault (estimated): > 50 m

Ocean bottom GPS/A

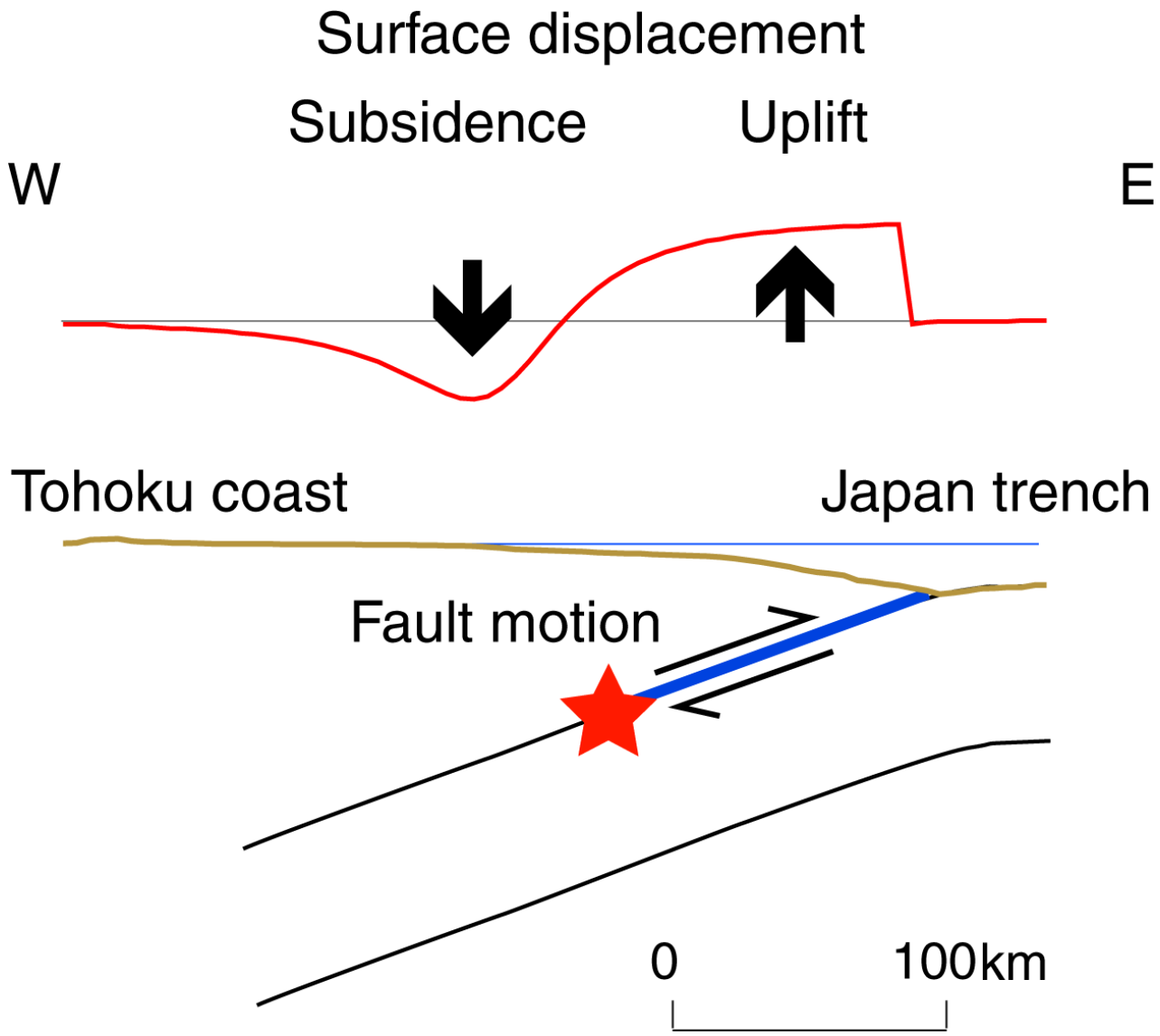
Kido et al. (2011, GRL)



Gray arrows: Sato et al. (2011, Science)
Black arrows: Kido et al. (2011, GRL)



Seafloor displacement (cross-section)



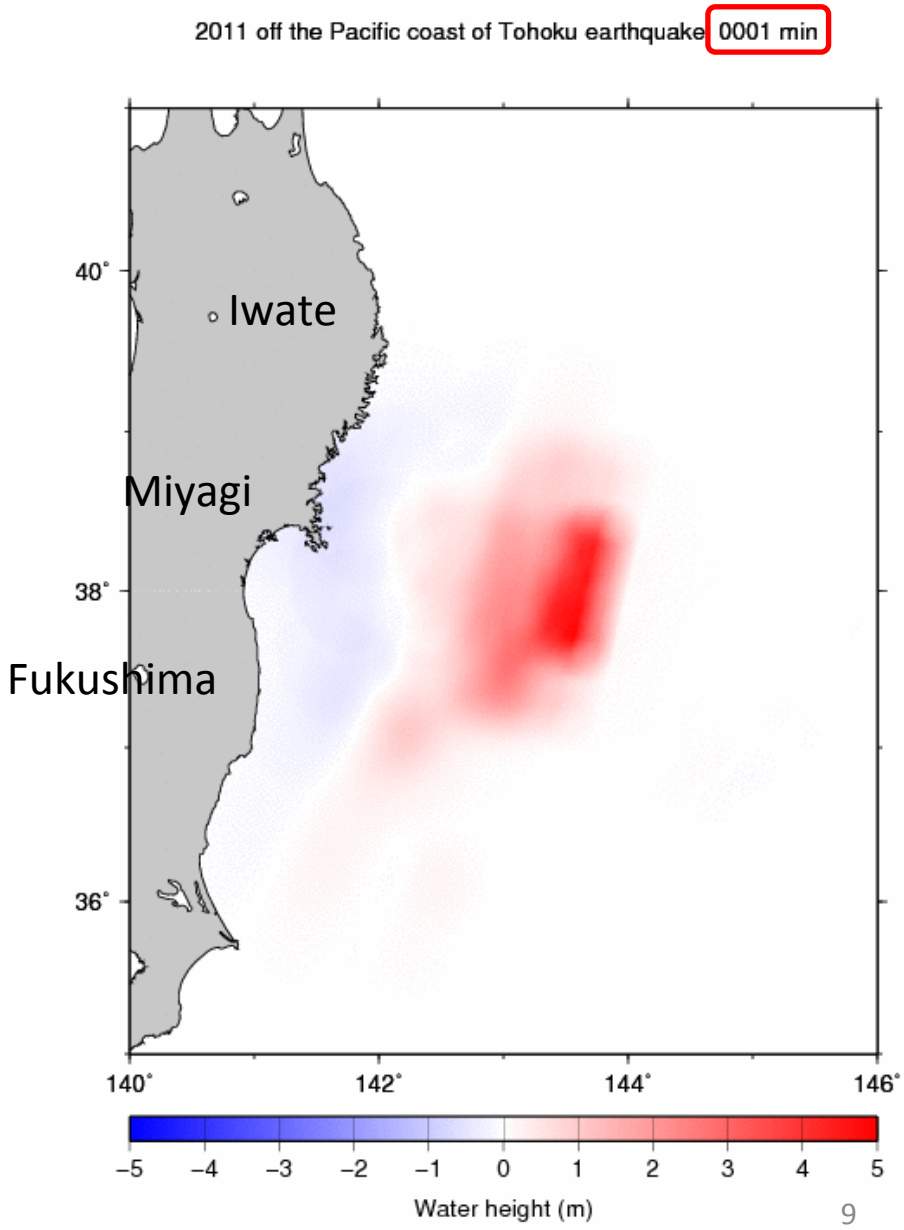
March 11, 2011 tsunami

Sanriku coast

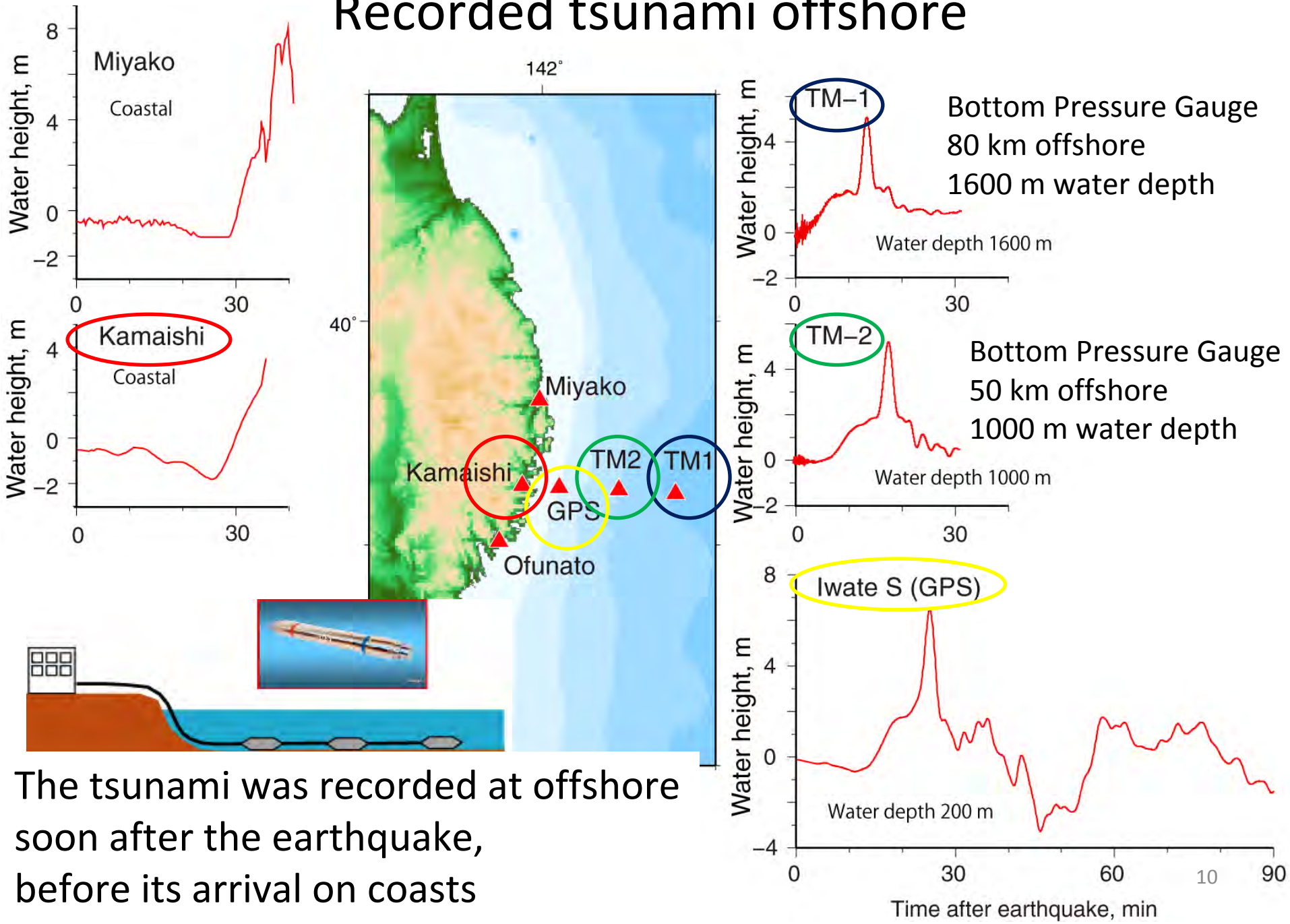
High tsunami
about 30 minutes
after the earthquake

Sendai plain

Large inundation
about 1 hour after eq.

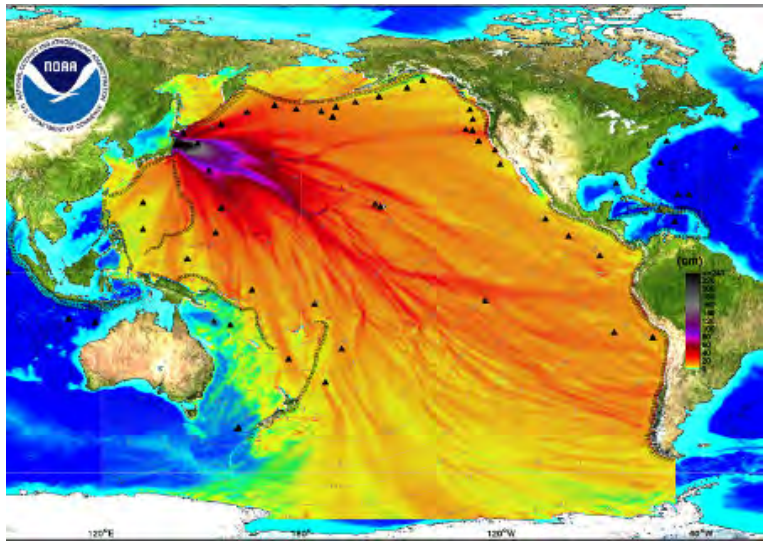


Recorded tsunami offshore

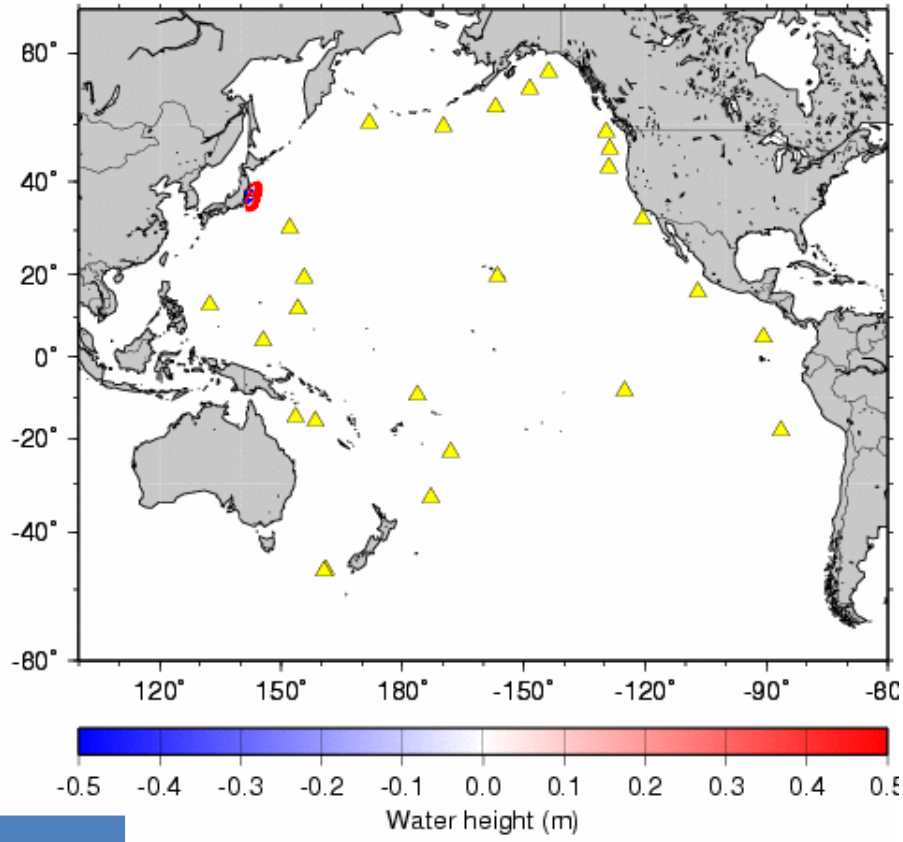


The tsunami was recorded at offshore soon after the earthquake, before its arrival on coasts

Effects to other countries

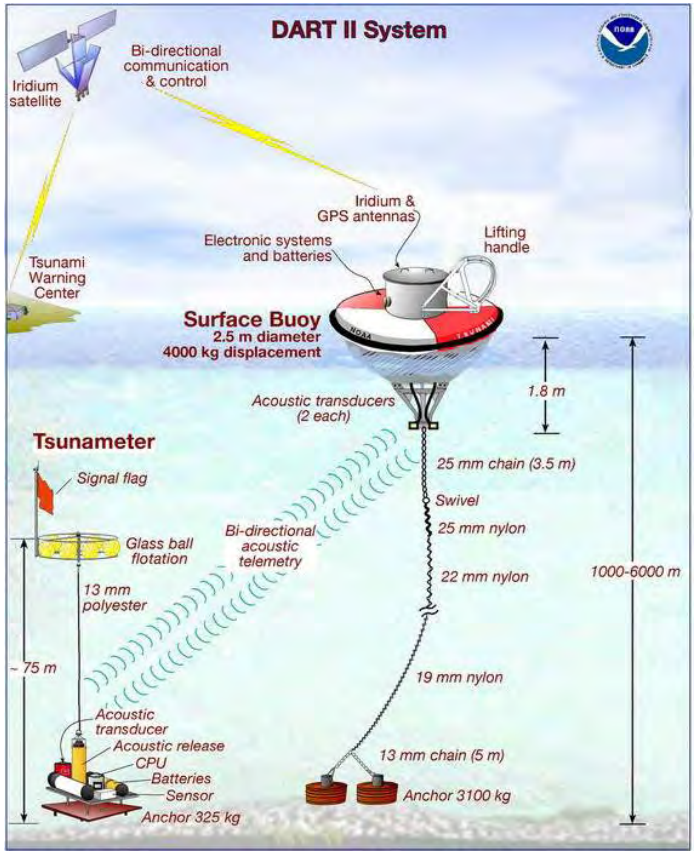


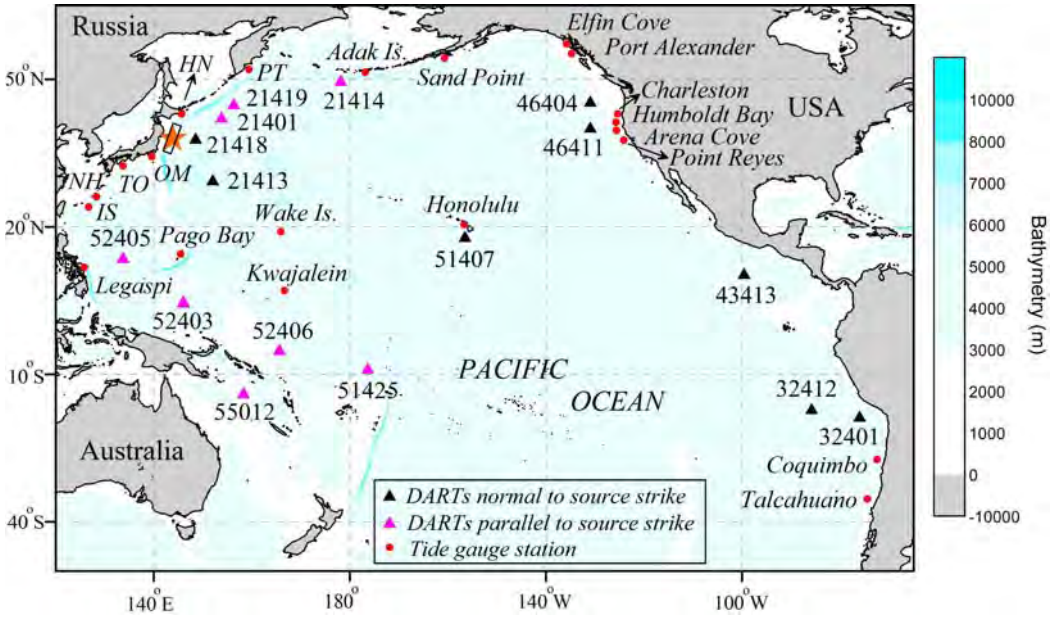
NOAA



Area	time	heights	damage
Hawaii	7 hrs	5 m	$ 8 million
California	12 hrs	3 m	1 death, $20 million
Chile	22 hrs	3 m	$ 4 million
Indonesia	6 hrs		1 death

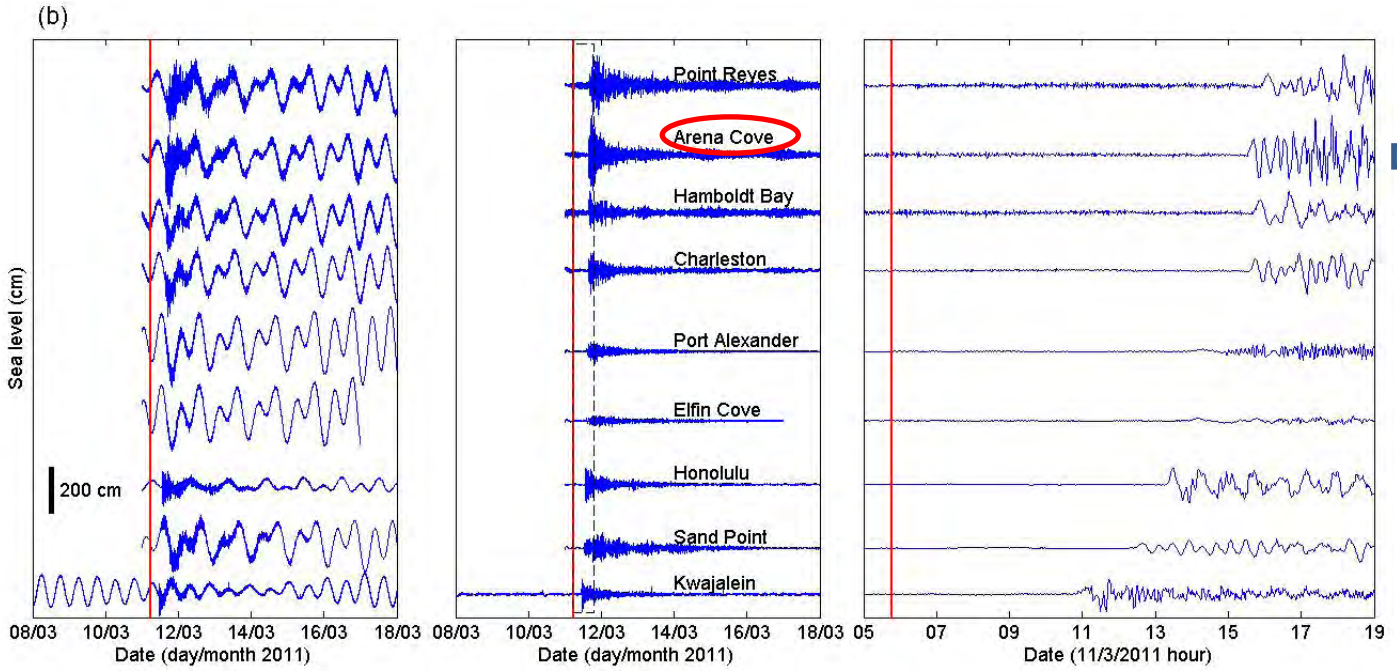
Tsunami Record across Pacific Ocean





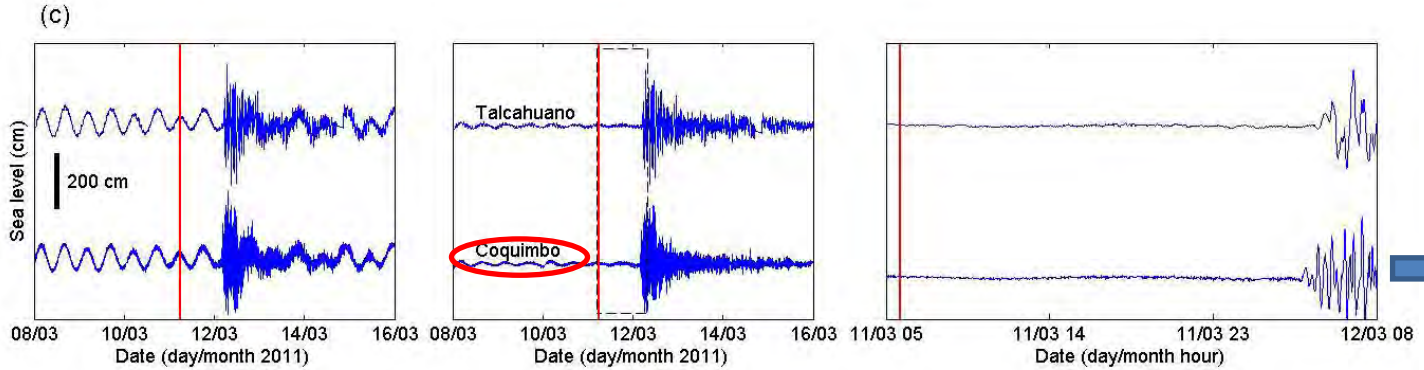
NOAA

Tsunami Record across Pacific Ocean



Arena Cove
(CA)
p-p 303 cm

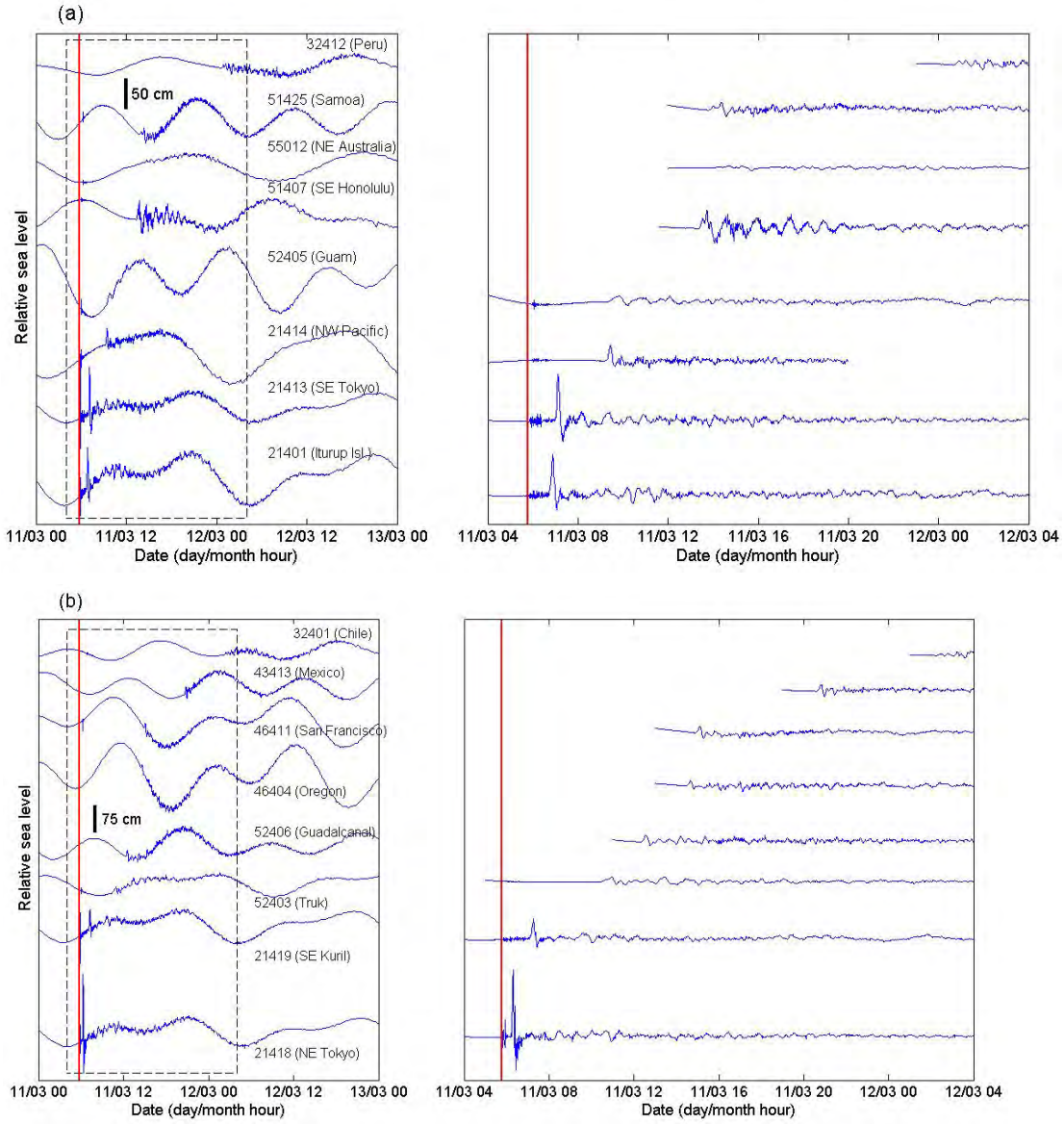
One casualty
in California



Coquimbo
(Chile)
p-p 394 cm

Heidarzadeh and Satake (2012, Pageoph)

Tsunami Record across Pacific Ocean



DART data

- first wave was the largest
- smaller amplitude than coastal tide gauges
- duration ~ 2 days
  (< 4 days on tide gauges)

Heidarzadeh and Satake (2012, Pageoph)

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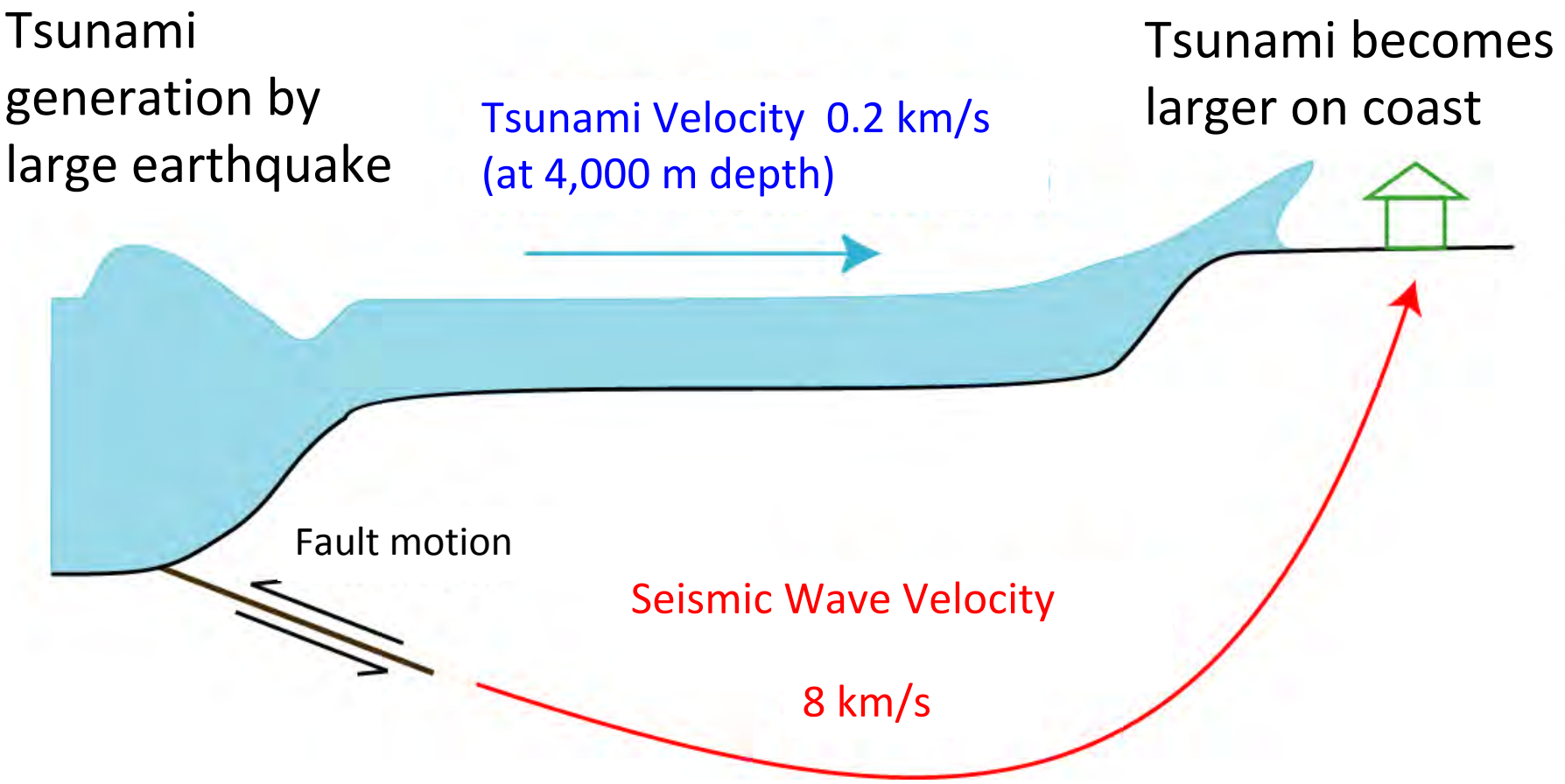
Principle of Tsunami Warning

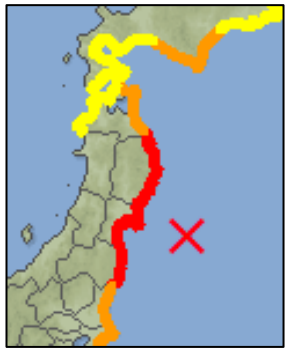


Tsunami Warning System (JMA)

Seismic Obs.

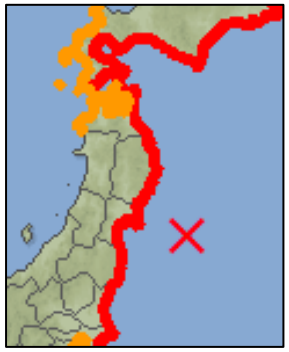
Epicenter and M

Quantitative Modeling

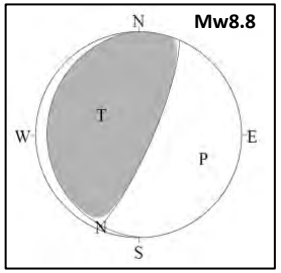


Tsunami Warning

Update warning

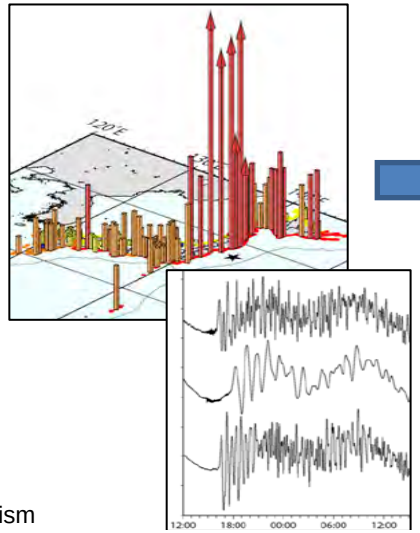


CMT solution



Sea Level Measurements

Evaluation based on Obs.



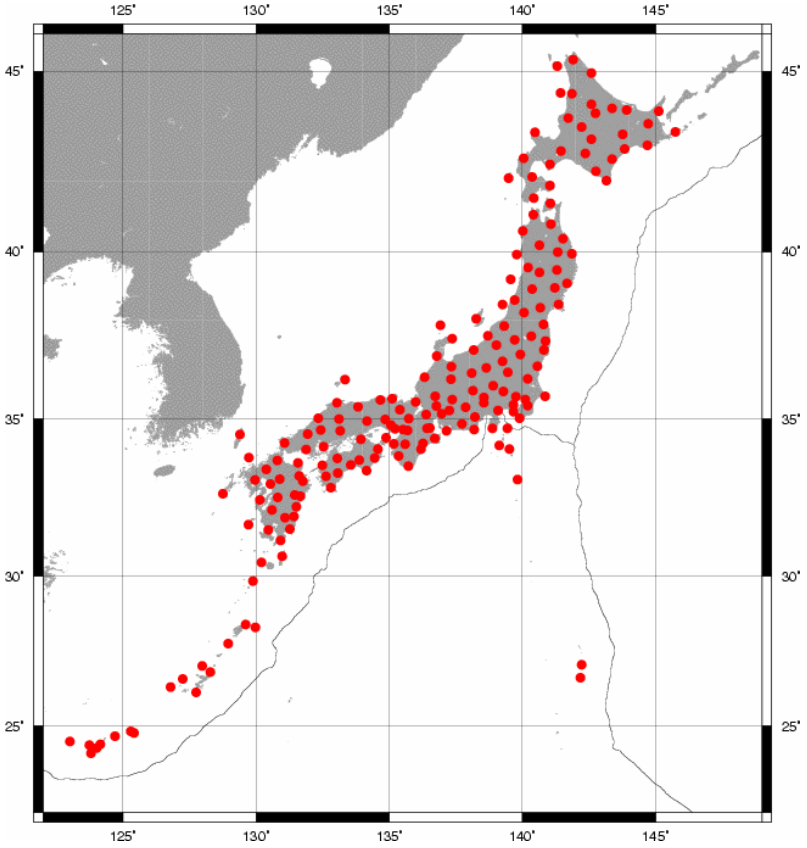
Ministry of Land, Infrastructure, Transport and Tourism

Tsunami Warning System (JMA)

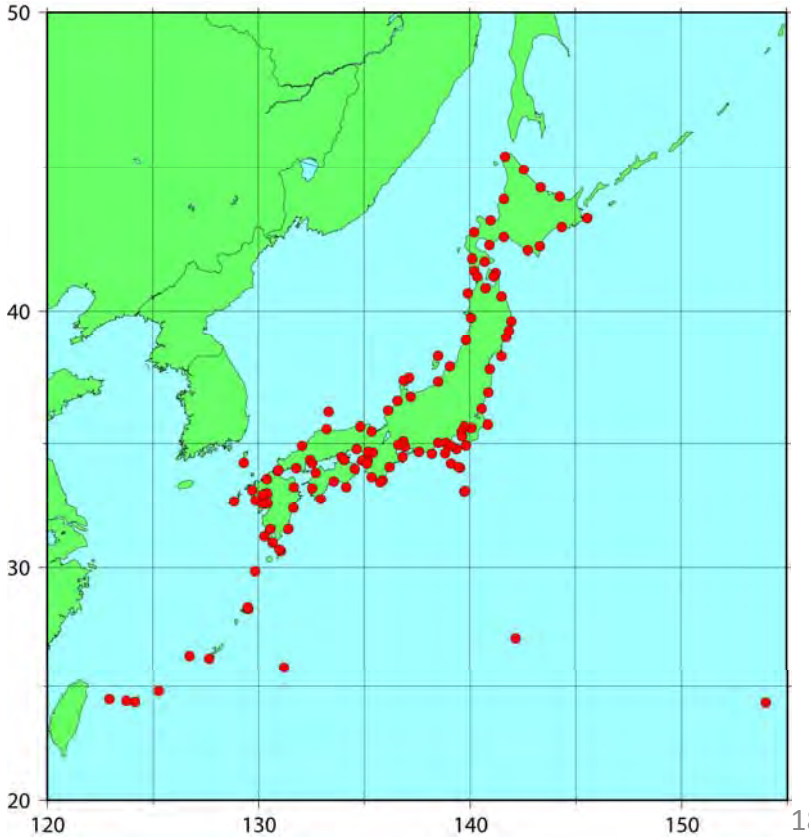
Local / Regional tsunamis

tsunami arrival within minutes of earthquakes

Seismic Network



Sea Level Network



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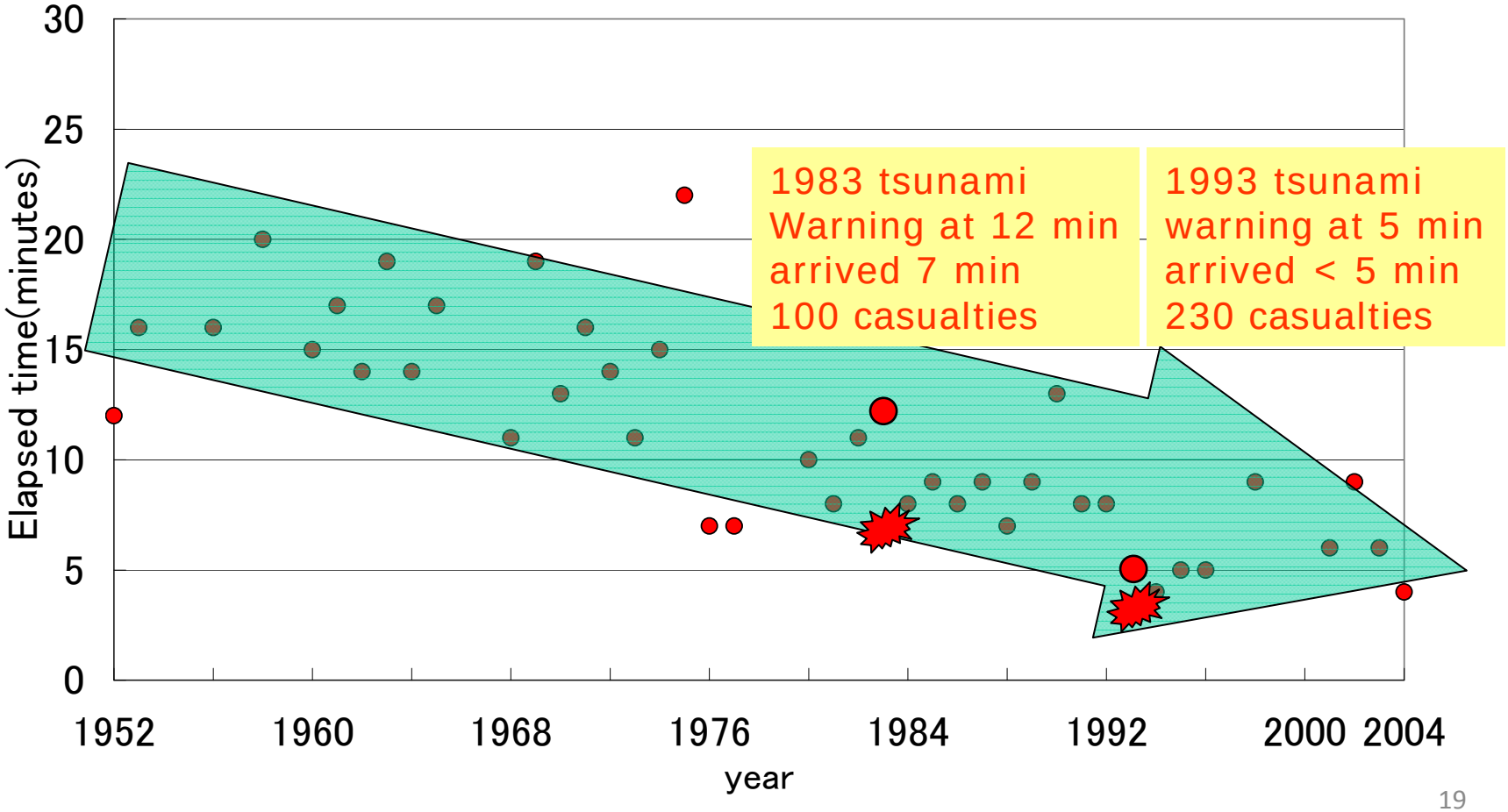
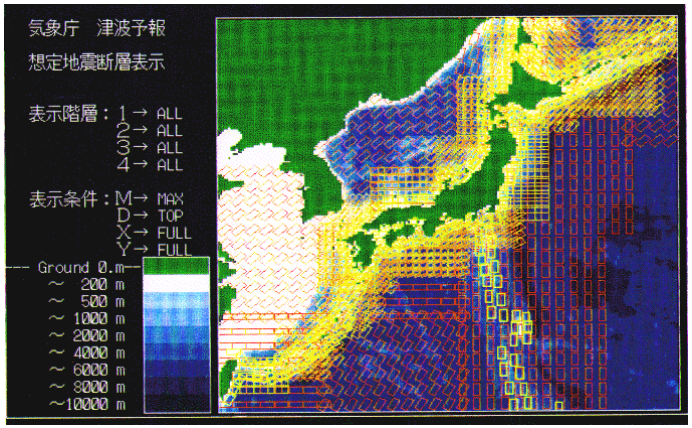
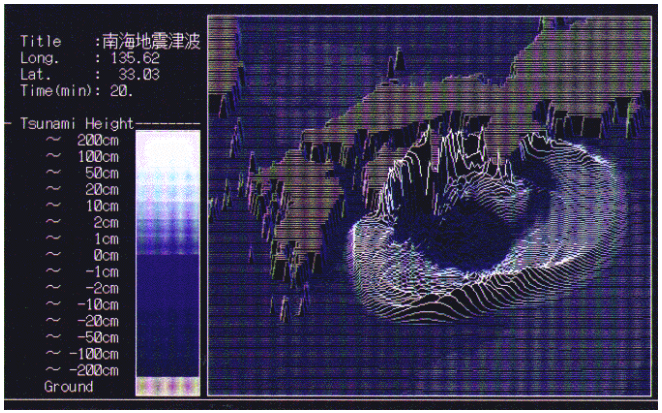


Quantitative Warning based on Database (JMA)

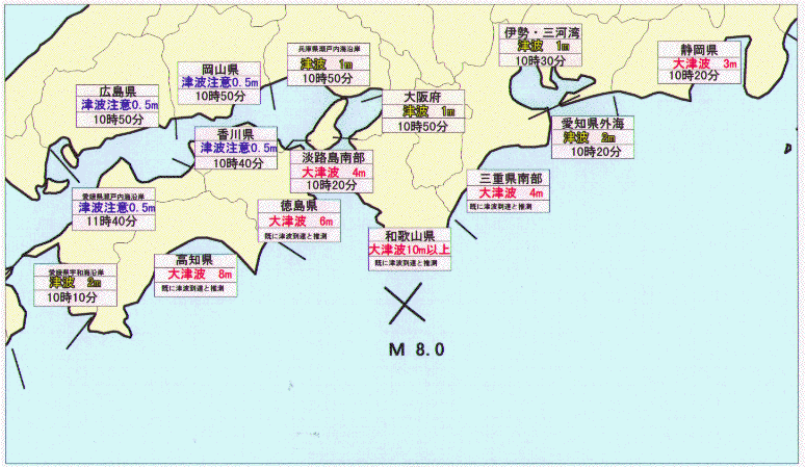


Assumed faults around Japan (100,000 cases)



Numerical simulation results stored in database

Arrival times and Estimated Heights (66 coastal regions)



Tsunami Warning System (JMA)

Japanese coast is divided into 66 regions

Tsunami warning and watch			
Message		Maximum height	Predicted height
Warning	Large tsunami	Maximum height > 3 m	3 m, 4 m, 6 m, 8 m, >10 m
	Tsunami	Maximum height > 2m	1 m, 2 m
Advisory		Maximum height > 0.5 m	0.5 m

Tsunami Warning from JMA

Time	after Eq.	M	Seismic Intensity and Tsunami Warning
14 : 46	0		Earthquake
14 : 49	3 min	7.9	Tsunami Warning: 6 m Miyagi, 3 m Iwate and Fukushima
15 : 14	28 min	7.9	Tsunami Warning: > 10 m Miyagi, 6 m Iwate, Fukushima
15 : 30	44 min	7.9	Tsunami Warning: > 10 m Iwate, Fukushima, Ibaraki, Chiba
12th 03 : 20	13 hrs	8.8	Tsunami warning or advisory for the entire coast of Japan
13th 07 : 30	1.5 days	8.8	Tsunami warning partially cleared
13th 17 : 58	2 days	9.0	Tsunami advisory all cleared

Tsunami Warning from JMA

Success

- JMA issued tsunami warning in 3 min after the earthquake
- Many people evacuated to high ground and survived

Failure

- The earthquake size and tsunami heights were initially underestimated
- Upgrade information did not reach affected coasts

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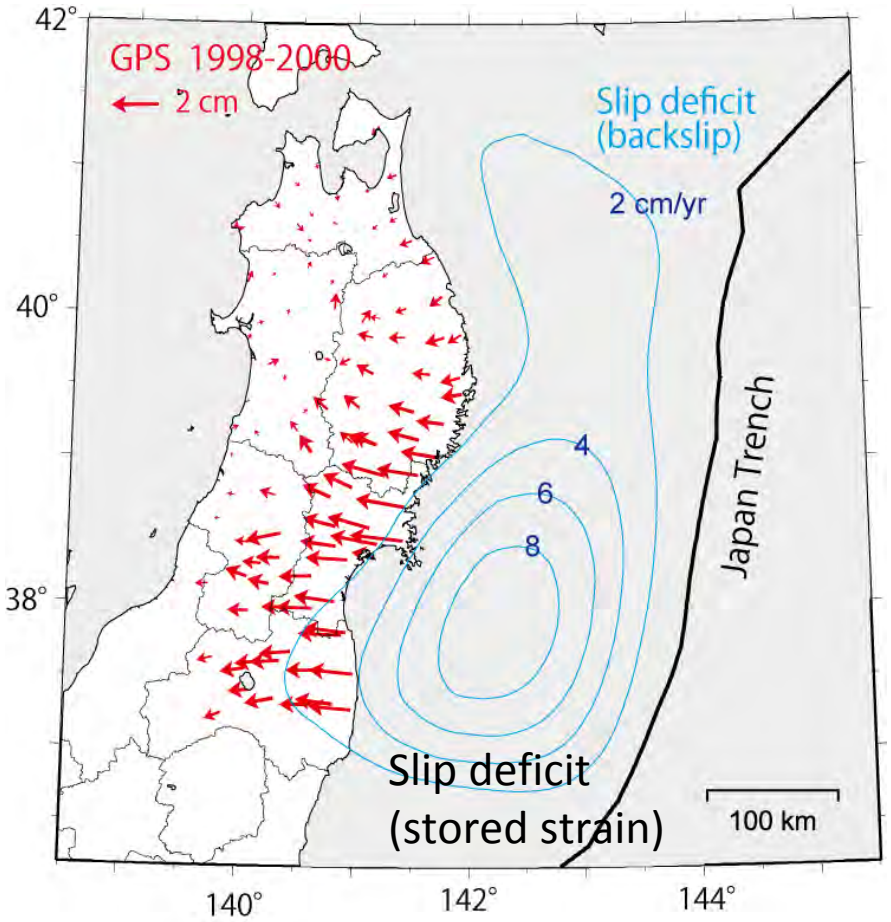
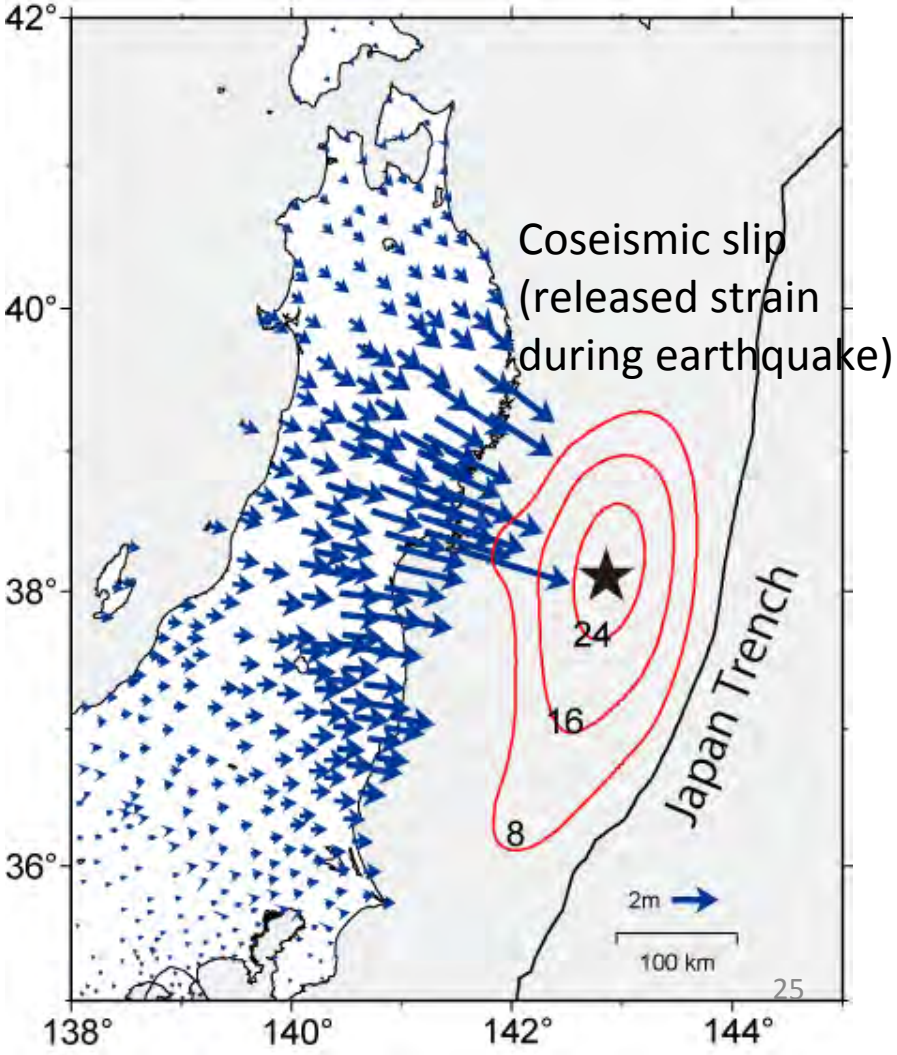
Why wasn't it forecasted?

Westward motion in 1998-2000



GSI

Eastward rebound on March 11



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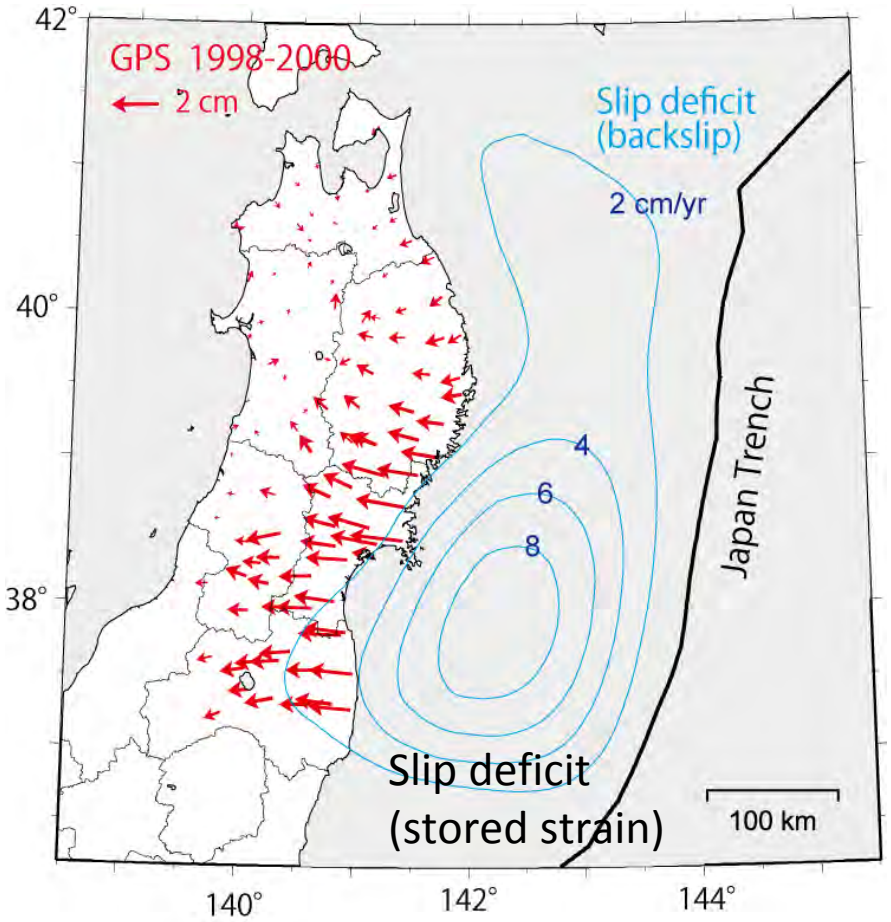
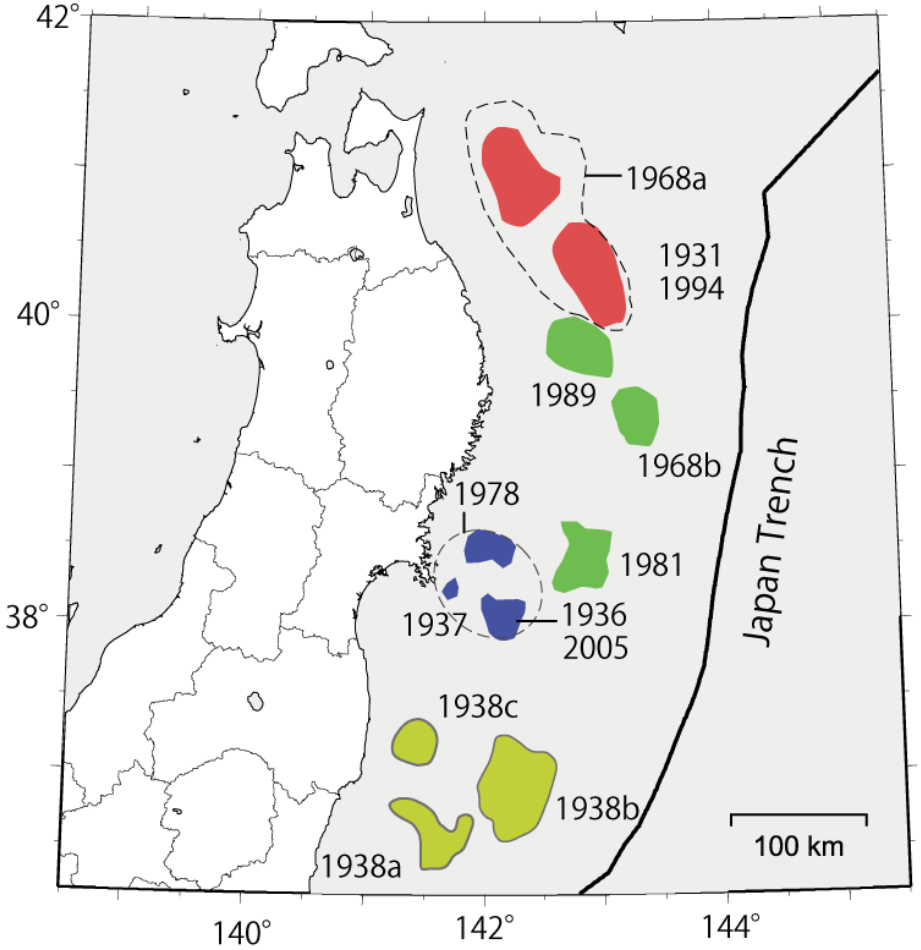


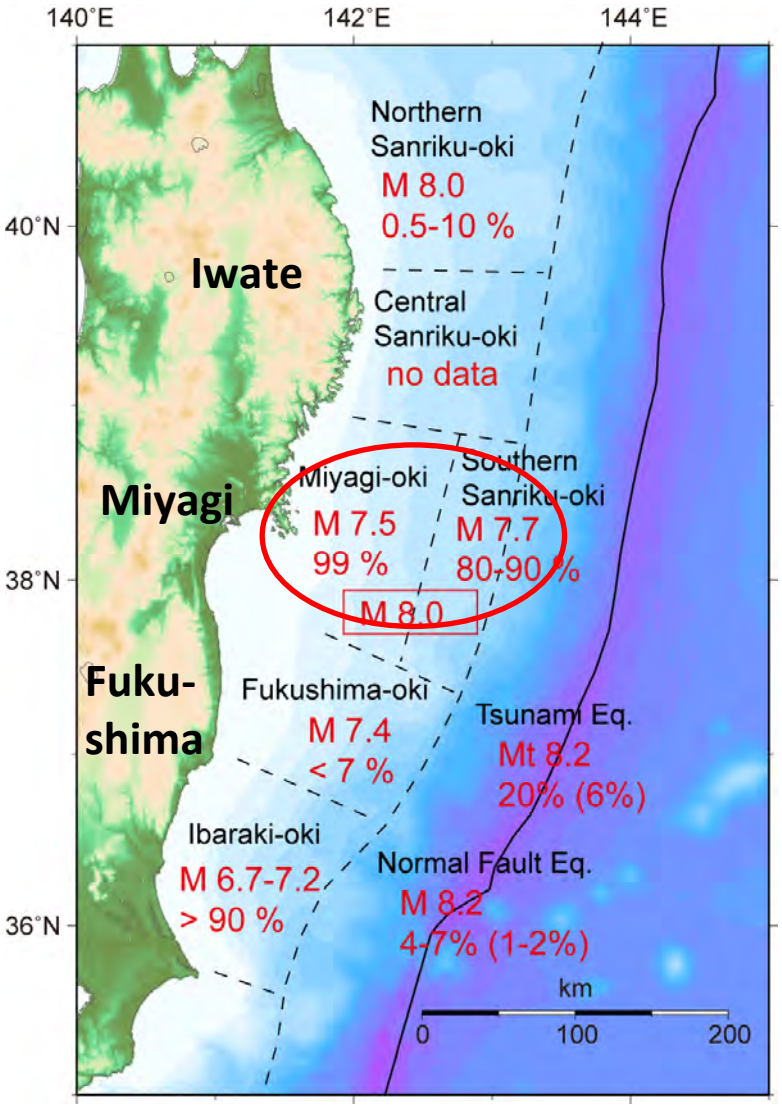
GSI

Large (M>7) earthquakes
in 20th century

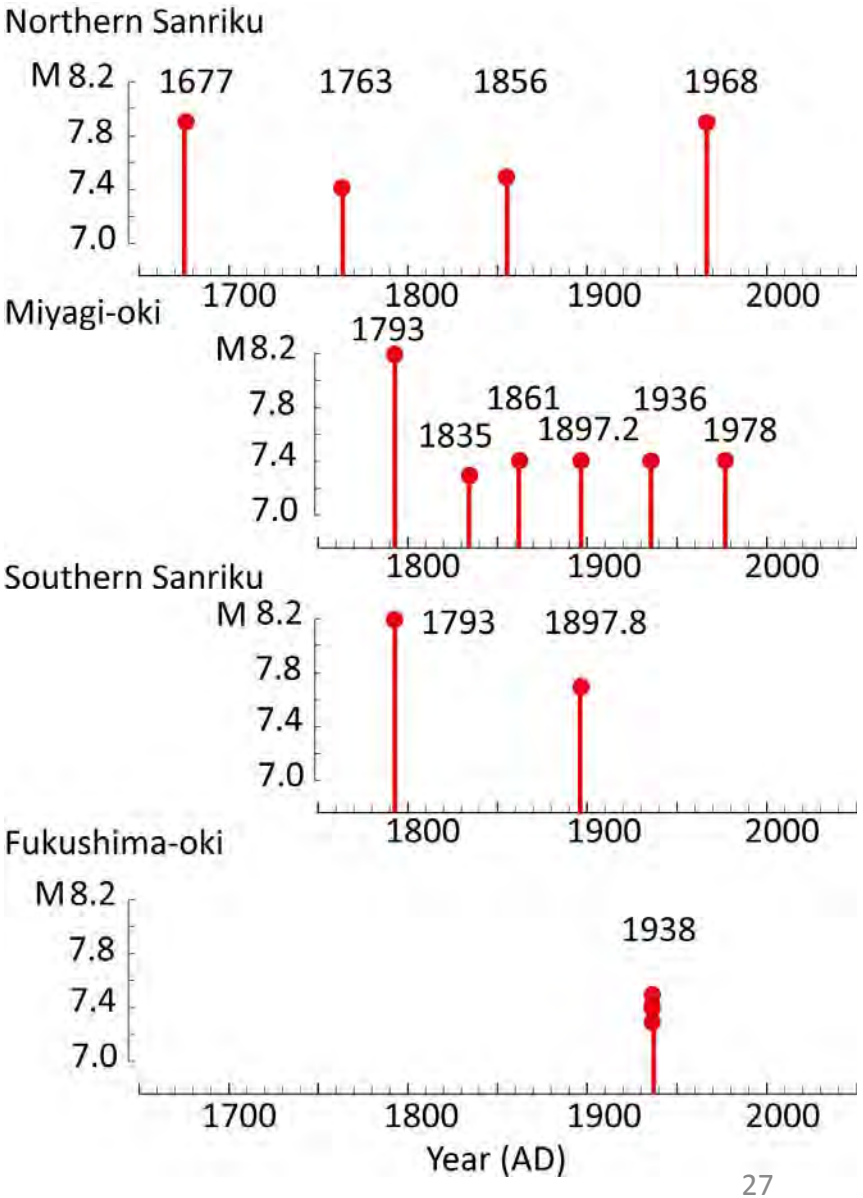


Yamanaka and Kikuchi (2004, JGR)

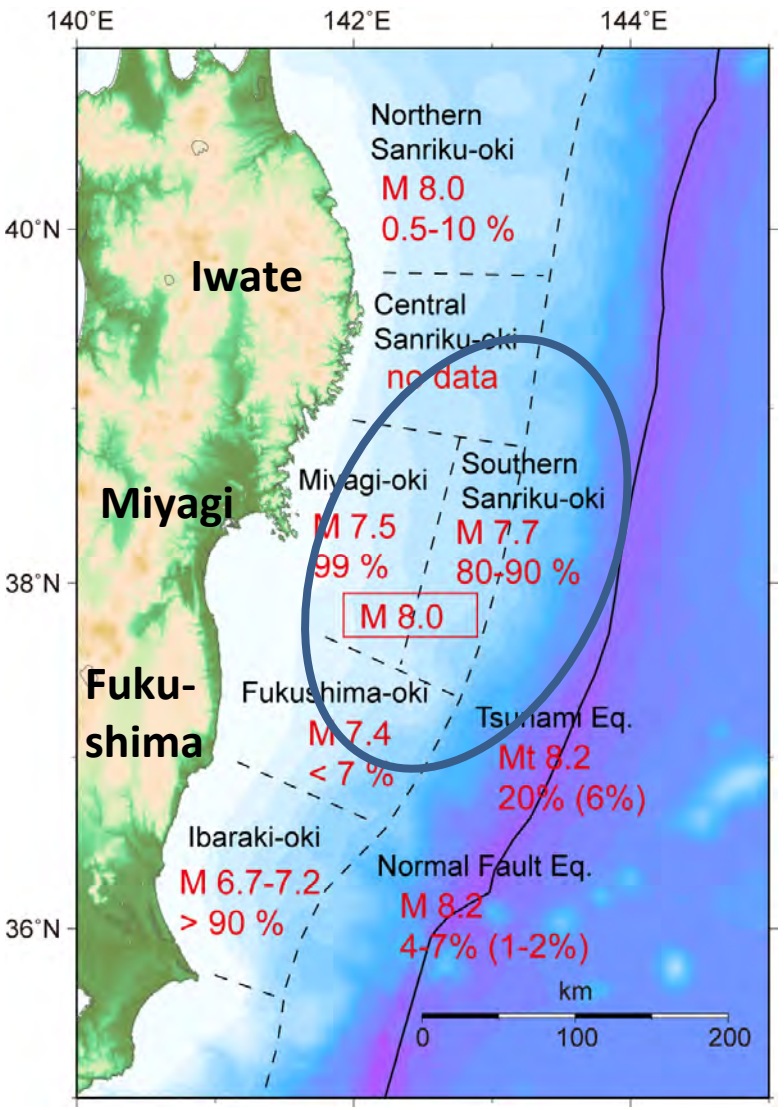
Earthquake history and long-term forecast



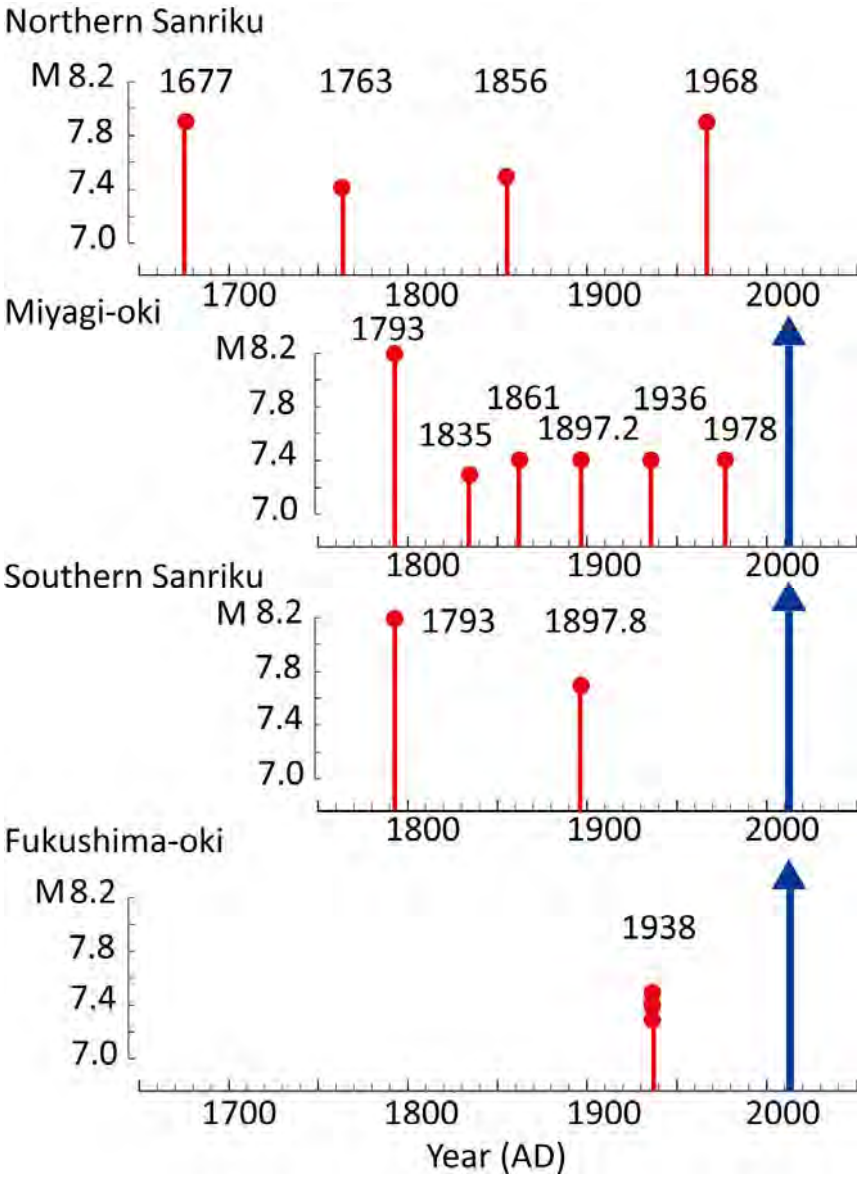
Long term forecast by ERC



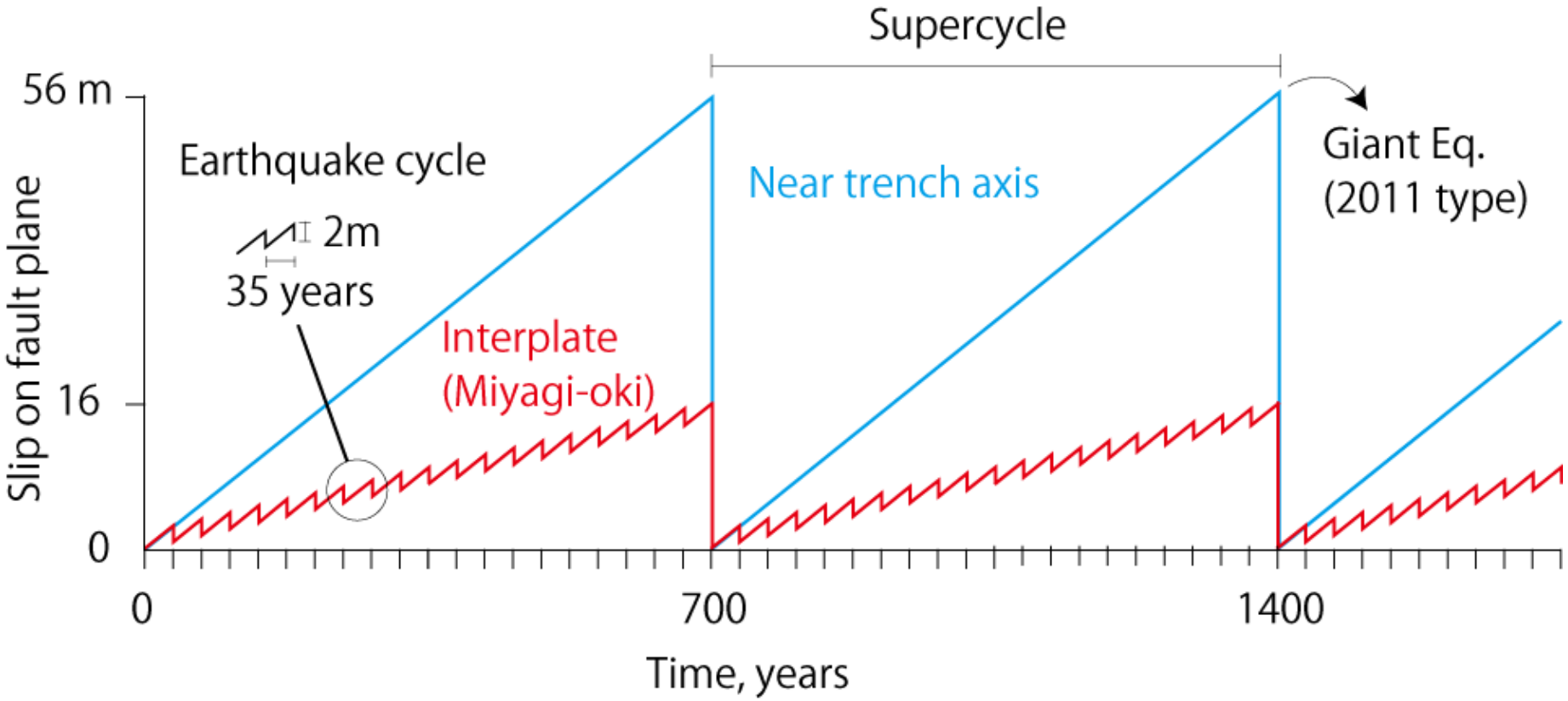
Earthquake history and long-term forecast



Long term forecast by ERC



Supercycle of earthquakes



Seismologists assumed earthquake cycle (~35 years) from past records of two centuries and made forecast (99% in 30 years), but there seems to be a supercycle (~700 years) on top of it.

Long-term forecast of earthquakes

Long-term forecast

- based on earthquake history in last few centuries
- 99 % probability in next 30 years but smaller size (M~8)

March 11 earthquake was much larger (M=9.0)

- GPS data suggested such slip deficit
- Earthquake supercycle may exist

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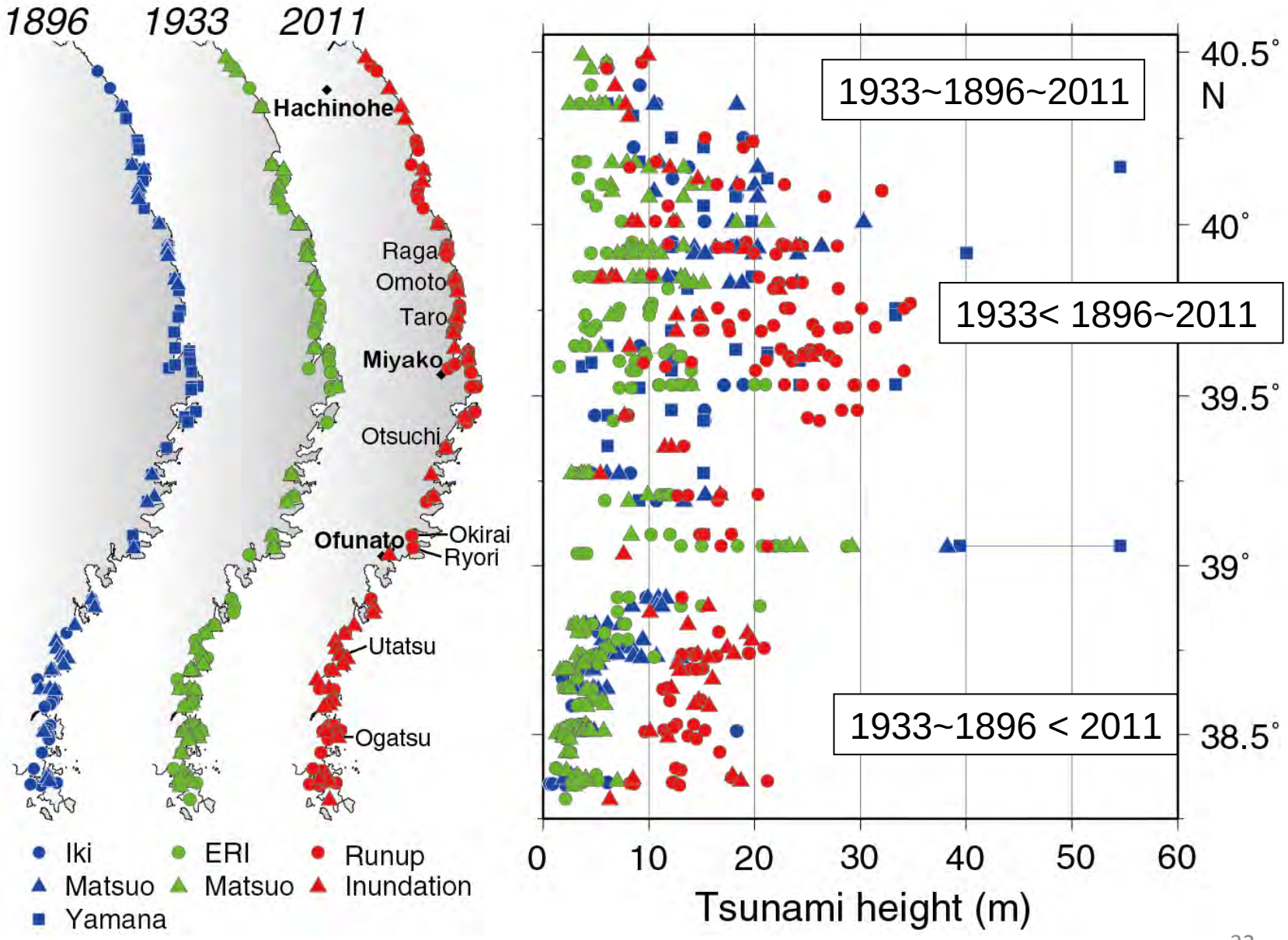
Past Tsunami Heights

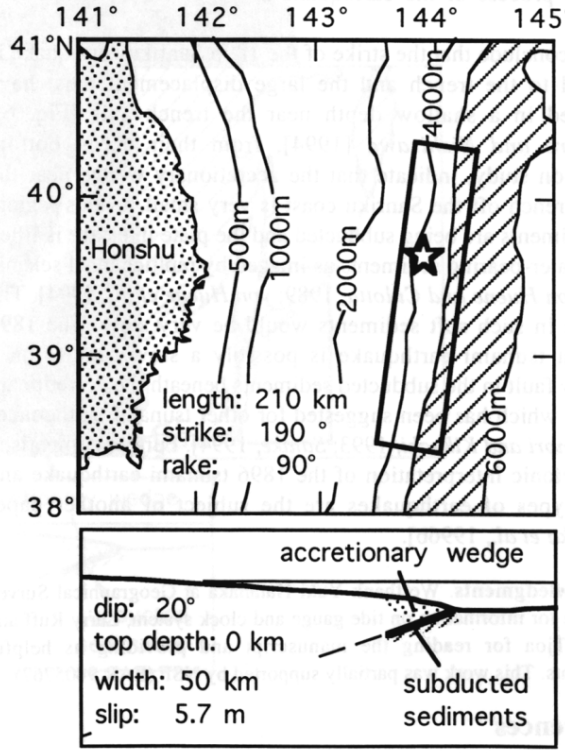


The 1896 Meiji Sanriku tsunami

1896 Meiji tsunami: 22,000 casualties (more than 2011 tsunami)

M 7.2, Max tsunami height 38 m
Weak shaking but large tsunami
“Tsunami earthquake”

ERI



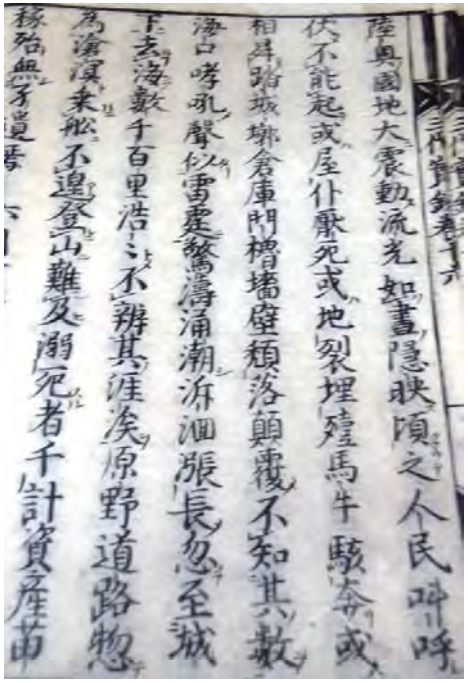
Width: 50 km, slip: 10 m
Near trench axis

Tanioka and Satake (1996,GRL)

The 869 Jogan earthquake

Nihon Sandai Jitsuroku (Chronicle of Japan)

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



Tsunami deposit studies

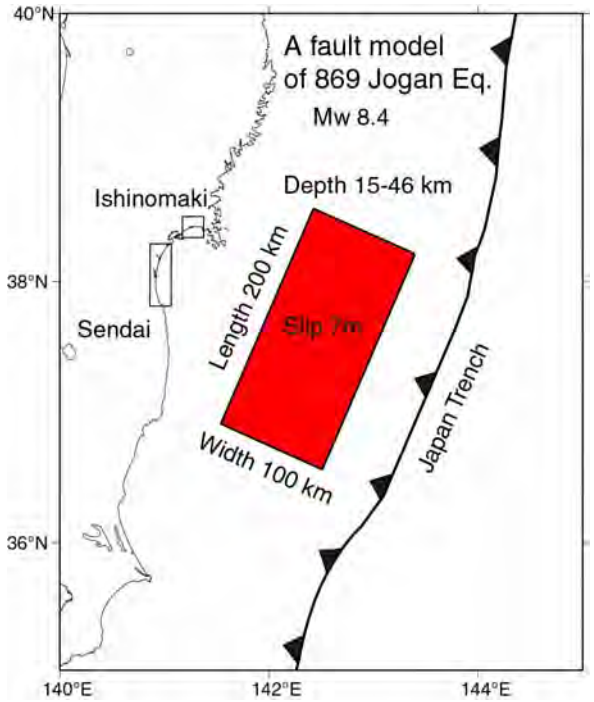
Sand layer brought by tsunami
below volcanic ash (AD915)

distributed ~ 5 km
from the coast

AIST

The 869 Jogan Earthquake

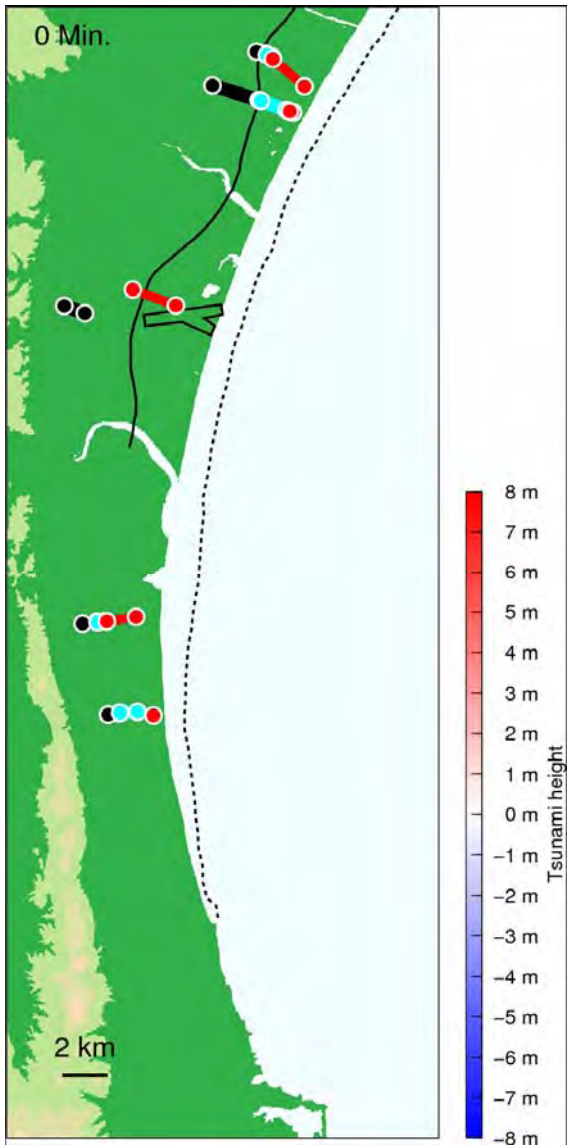
A fault model



Satake et al. (2008)
Namegaya et al. (2010)

- The 869 deposits
- Possible 869 deposits
- No deposits

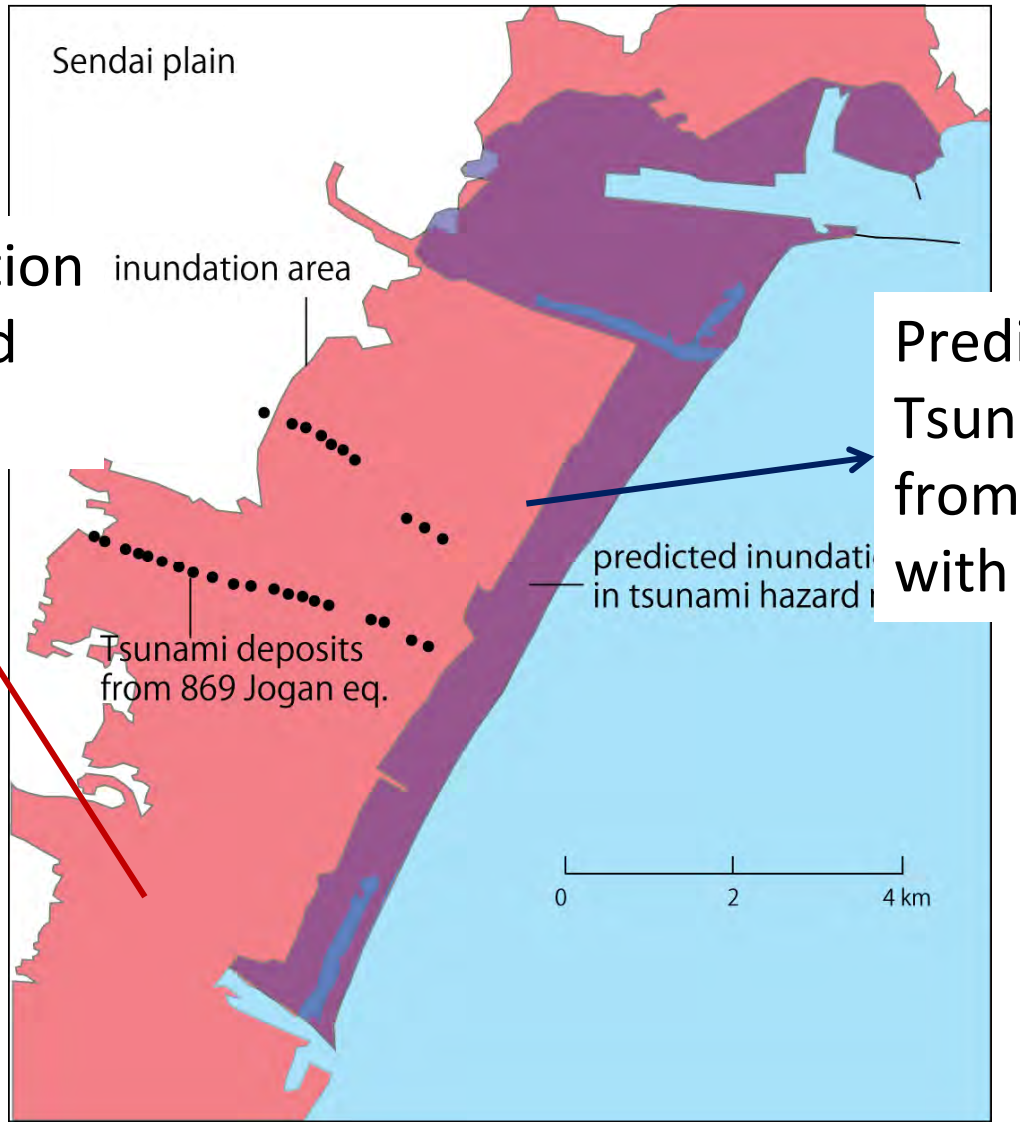
869 Simulation



2011 inundation

The 869 Jogan earthquake

Tsunami inundation
From AD 869 and
AD 2011



Predicted
Tsunami inundation
from earthquakes
with 99% probability

Past tsunamis

Sanriku coast

- Attacked by tsunamis in 1896 (22,000 casualties) , 1933 (3,000 casualties), and 1960 (Chilean eq., 142 casualties)
- The 2011 tsunami was similar heights with 1896

Sendai Plain

- Historical and geological data recorded AD 869 tsunami
- The AD 869 tsunami was very similar to 2011
- Tsunami hazard maps or break waters were prepared for a more frequent (99%, M~8) tsunami

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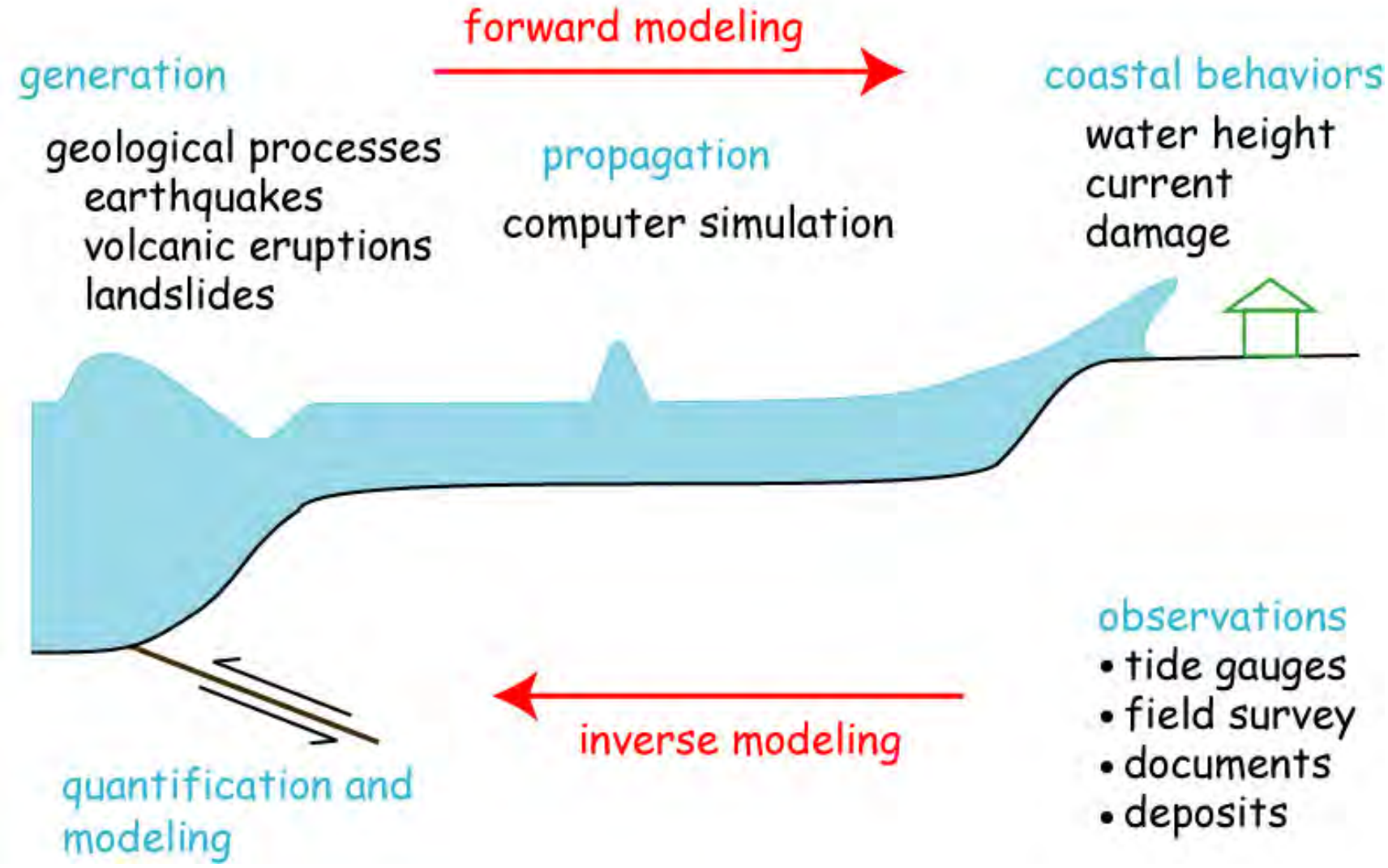
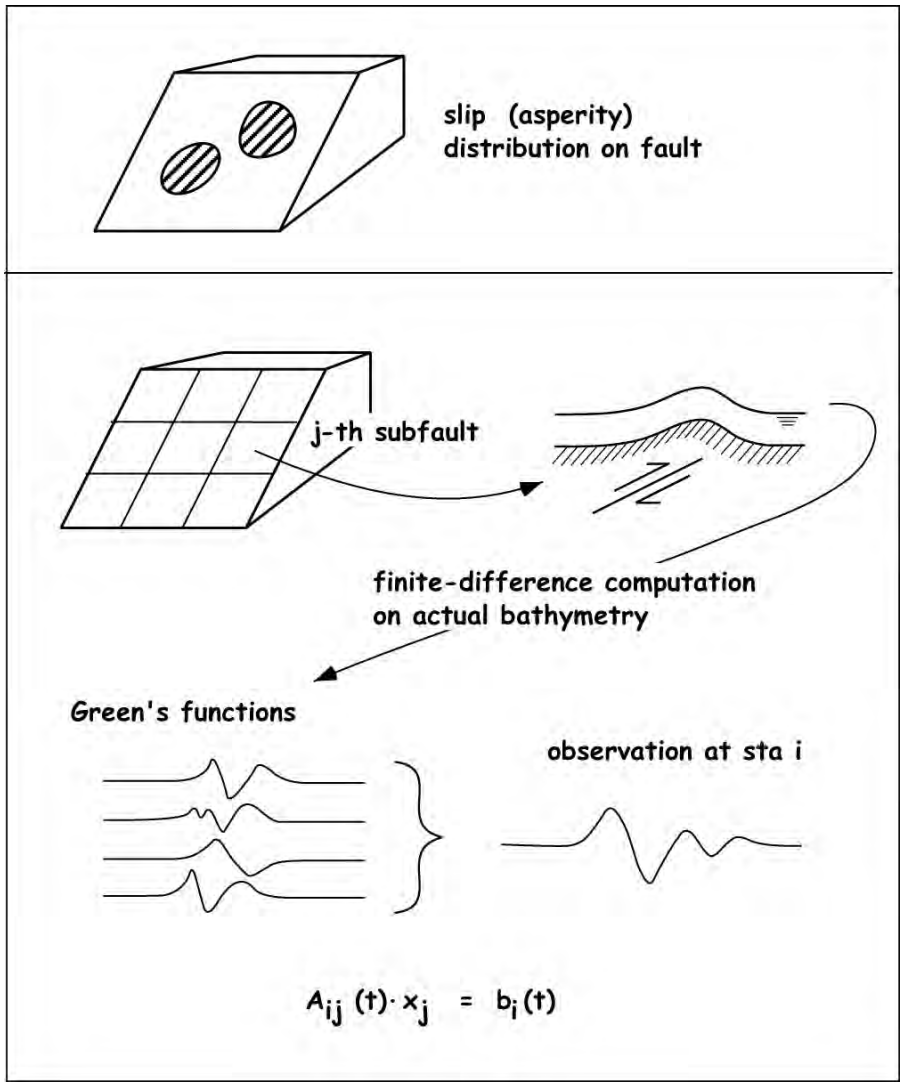
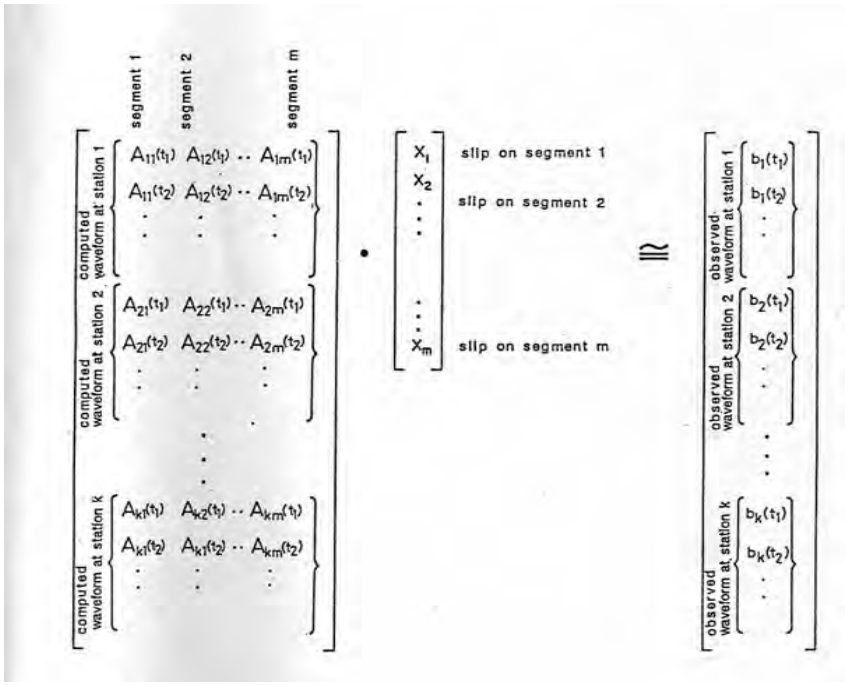
Forward and Inverse Problems



Inversion of Tsunami Waveforms

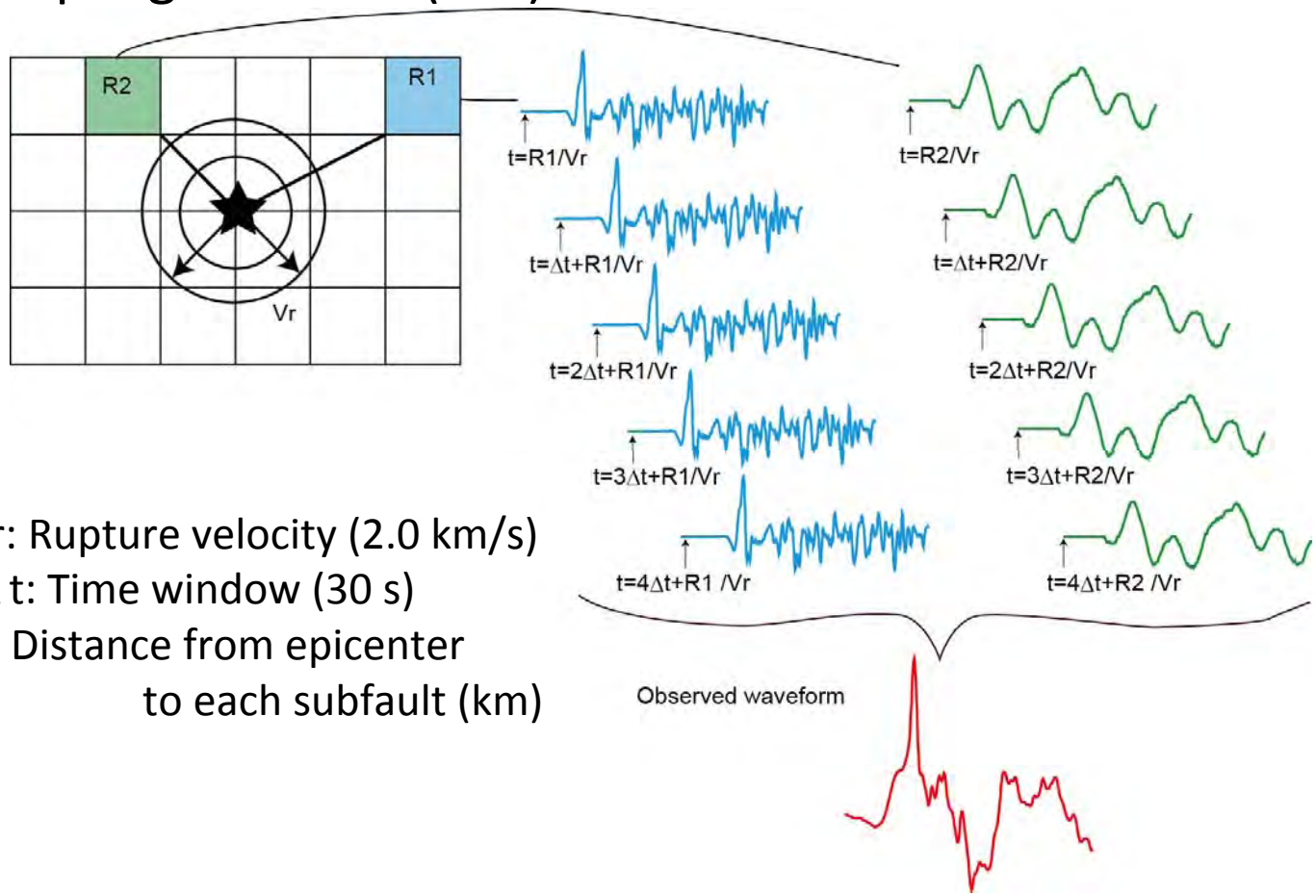




Satake (1987, JPE)

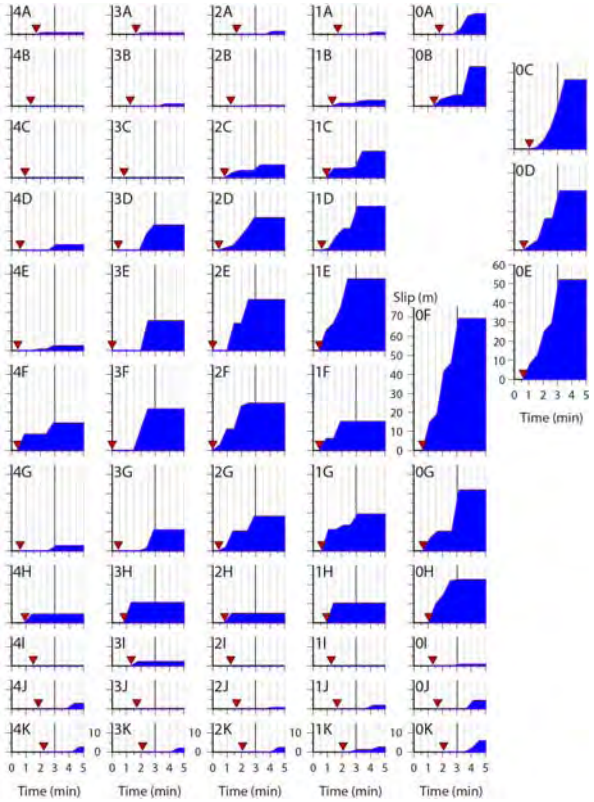
Multiple Time Window Analysis

- Rupture propagation is considered
- Constant rupture velocity (1.5, 2.0, 2.5 km/s, infinite)
- Space-time distribution of fault slip
- Data sampling: 0.2 min (12s)

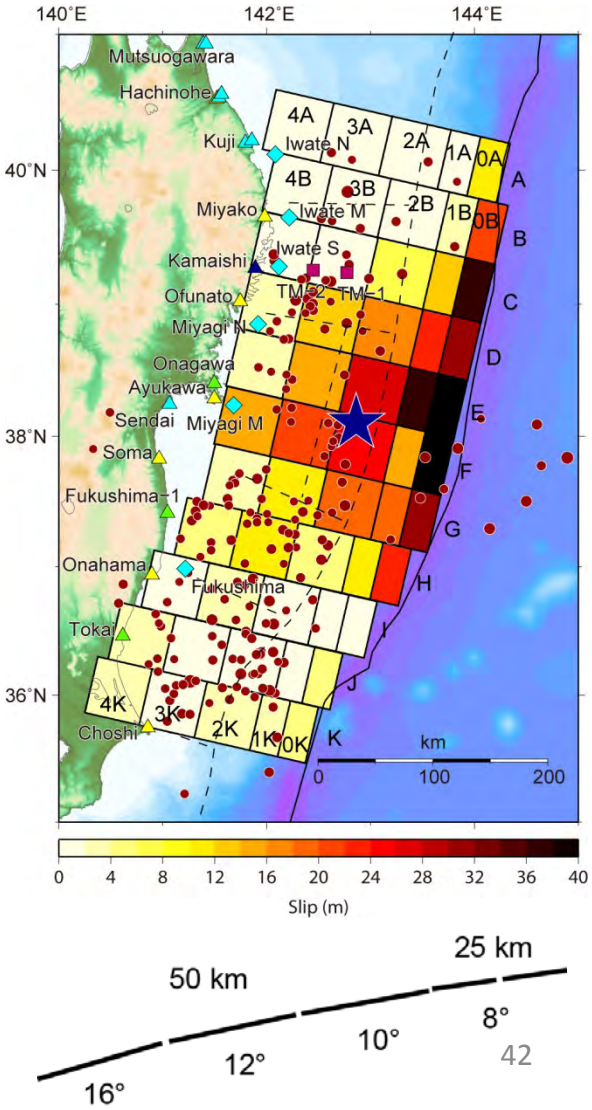


Vr: Rupture velocity (2.0 km/s)
Δ t: Time window (30 s)
R: Distance from epicenter
to each subfault (km)

Temporal and Spatial Slip Distribution

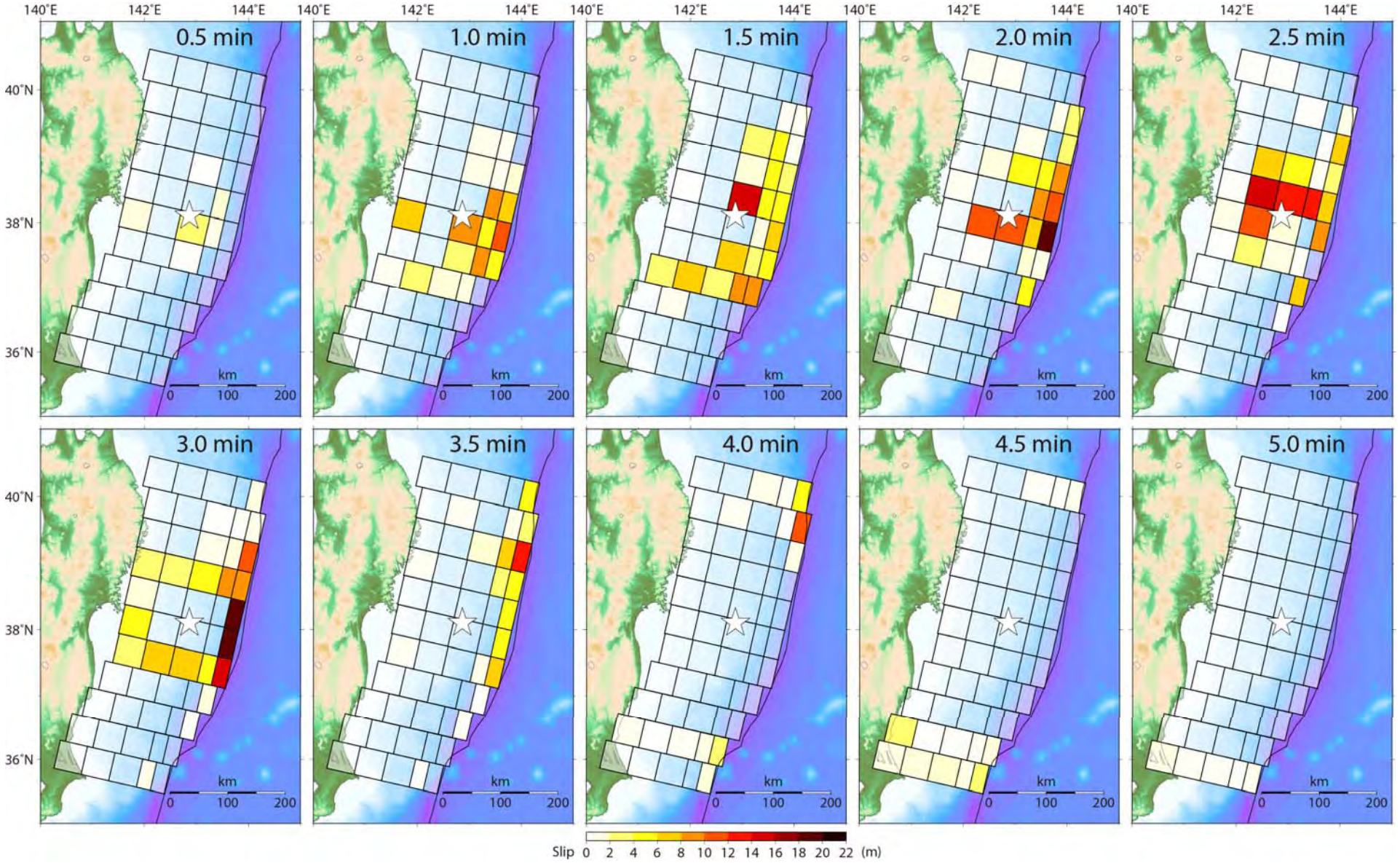


Ver 8.0 (55 subfaults)



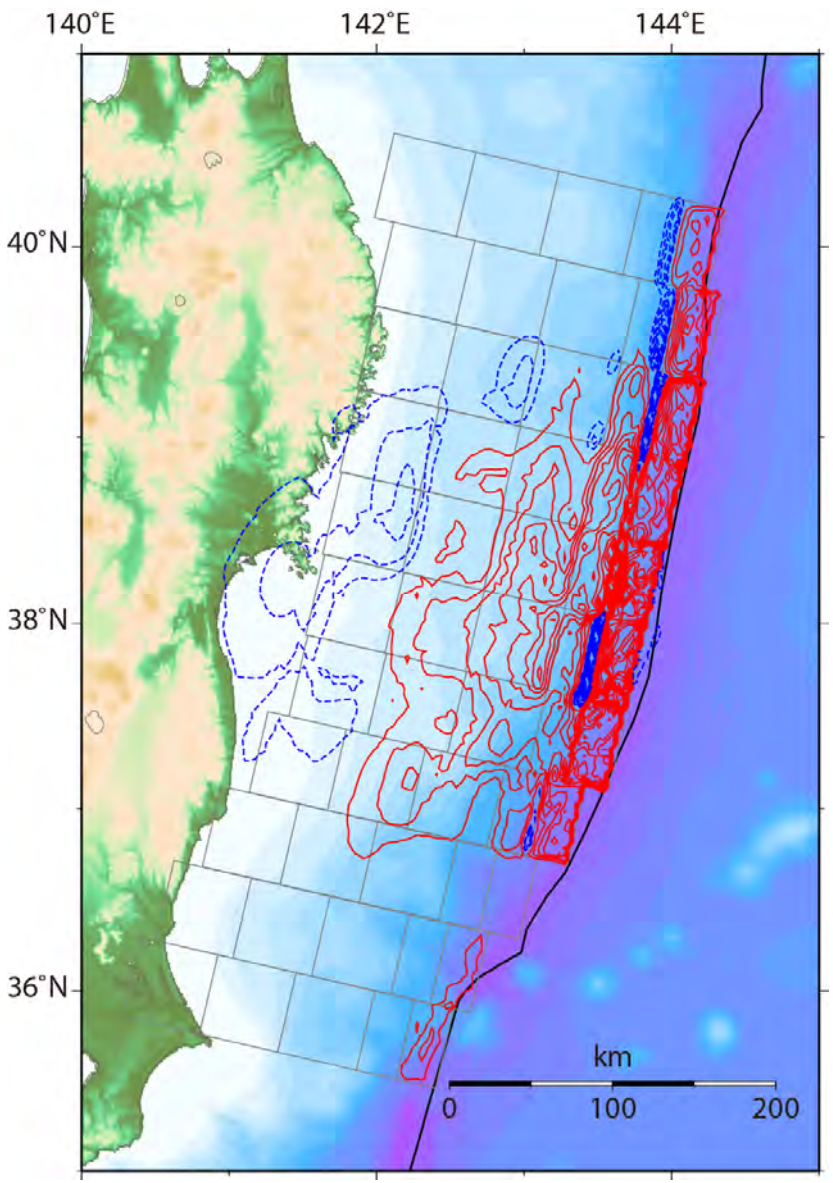
1. The final slip at > 2.5 min
2. Max slip at shallowest fault > 69m
3. Deep slip near epicenter: ~ 25 m
4. Northern shallow slip: at 3 - 4 min
5. Shallow faults (> 10 m) : 400 km

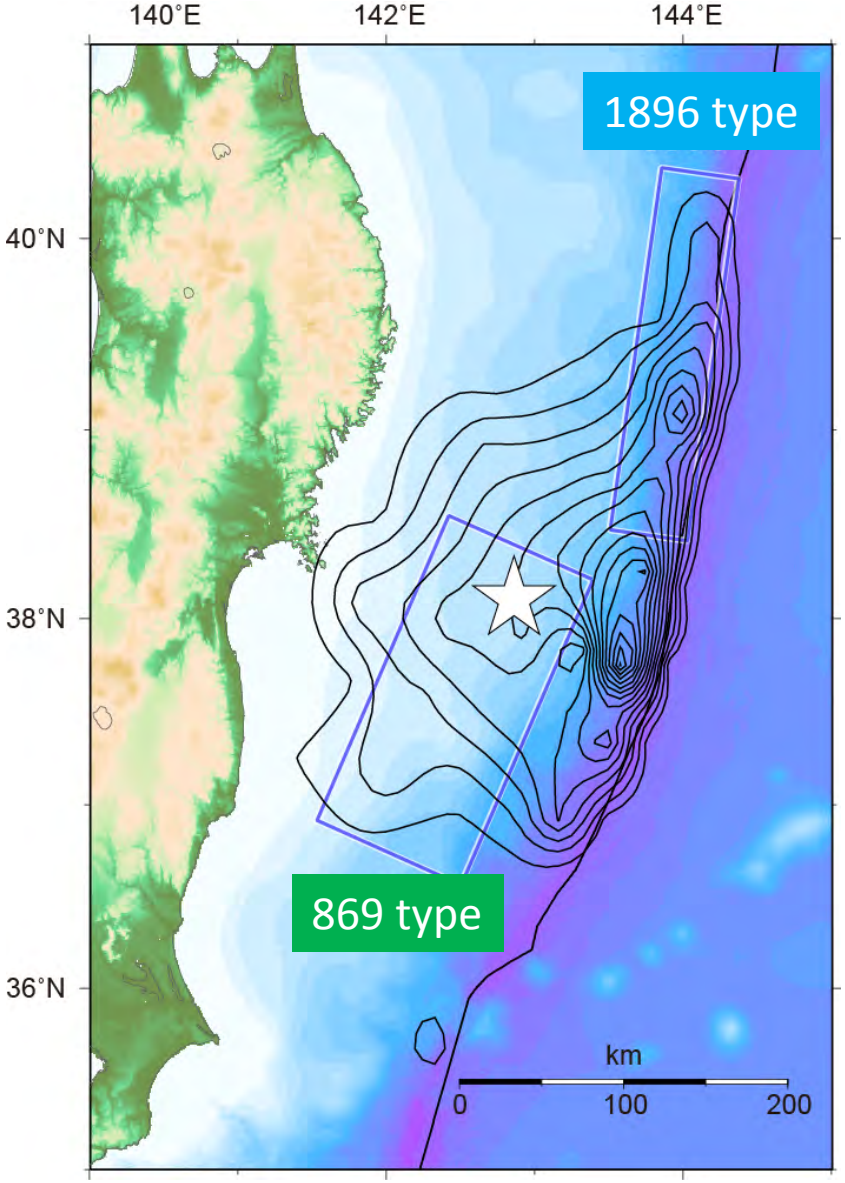
Temporal and spatial distribution of slips



55-subfault model: Ver. 8.0

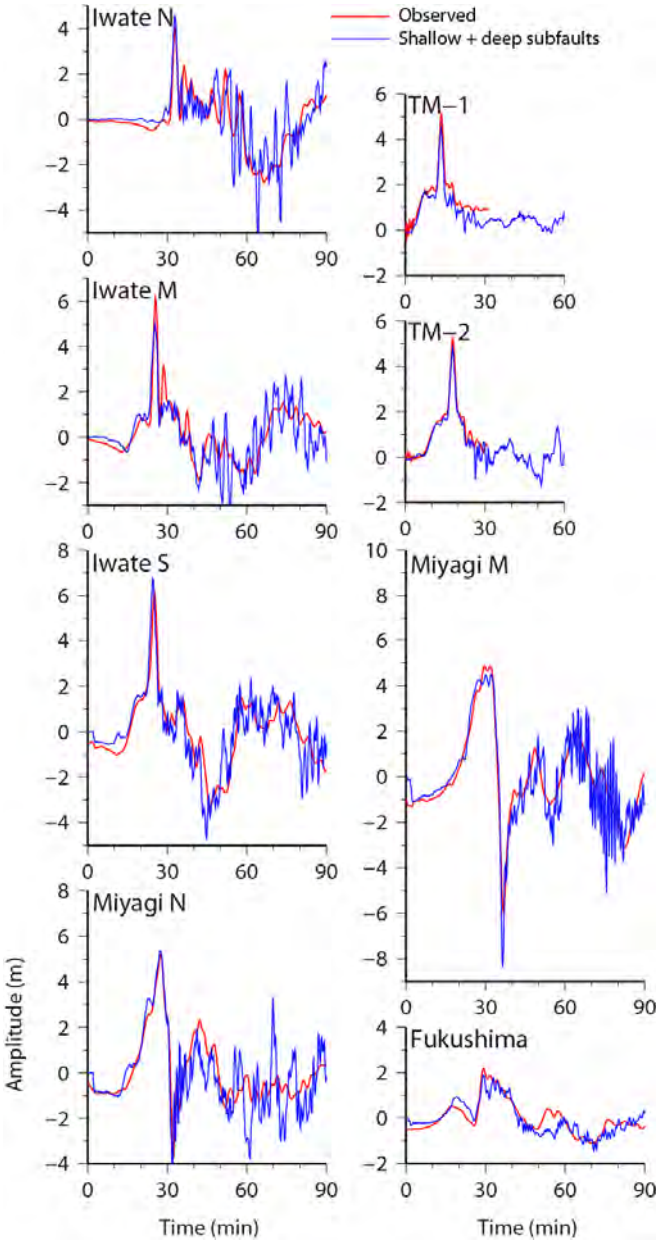
Seafloor displacement and slip distribution



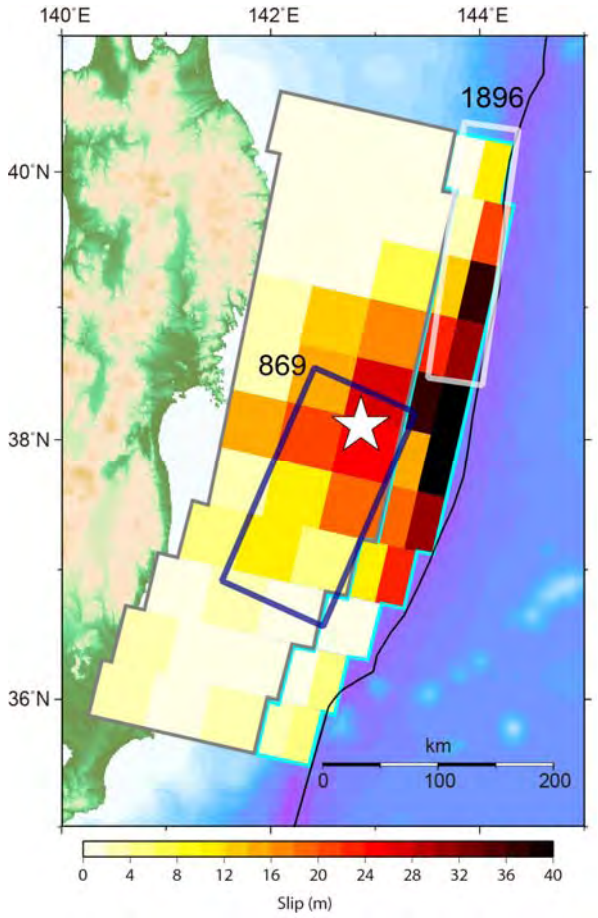


Ver. 8.0

Deep and Shallow Subfaults

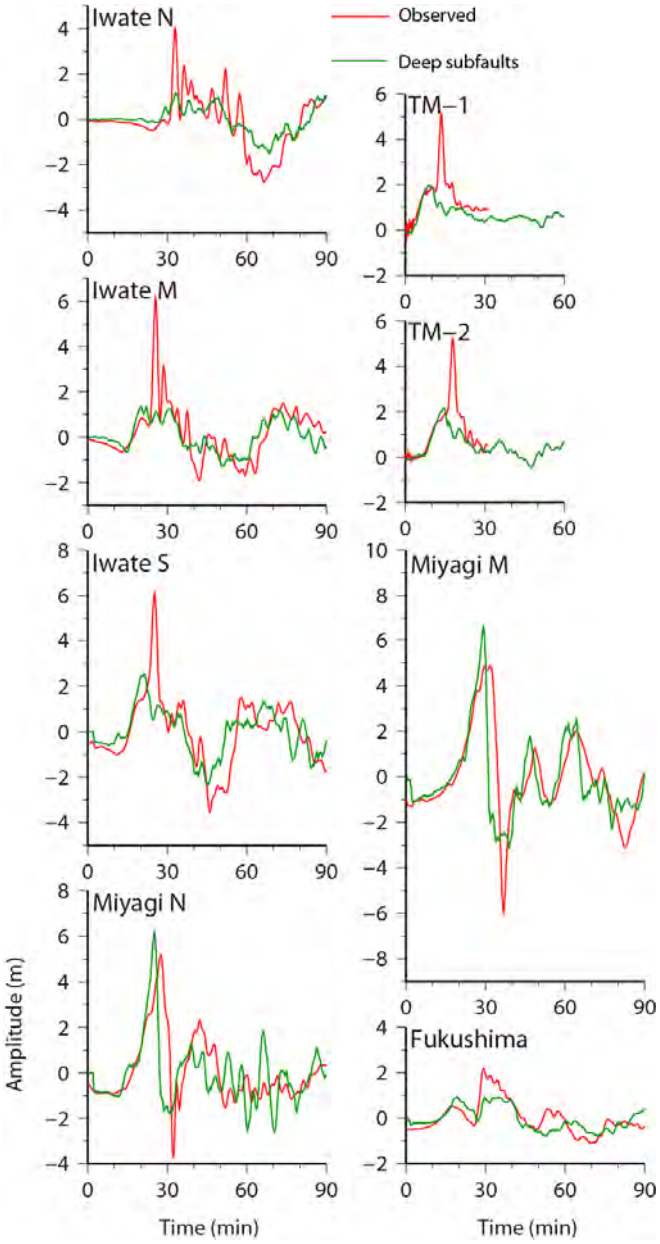


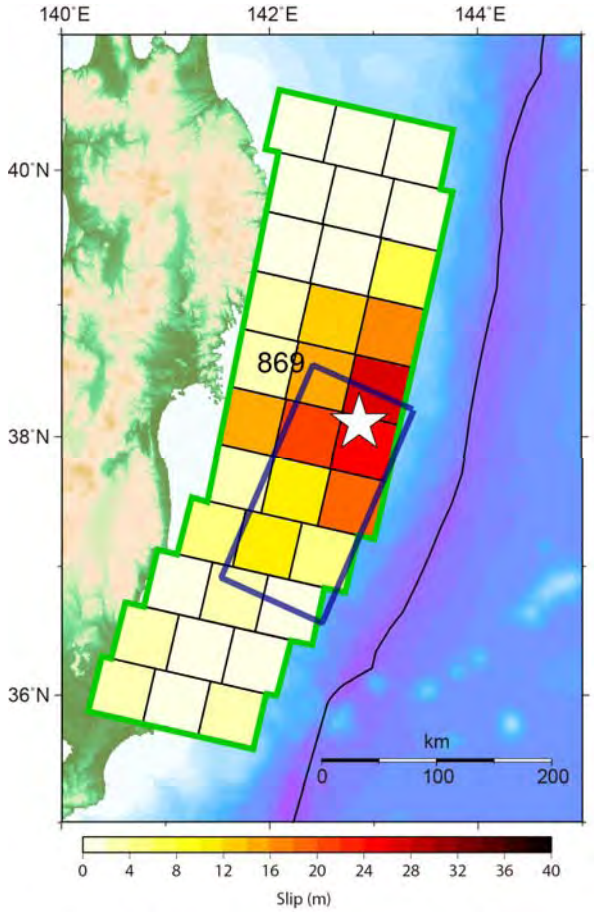
Ver 8.0 (55 subfaults)



Total
Average slip 9.5 m
Moment 4.21 x 10^{22} Nm (Mw = 9.0)

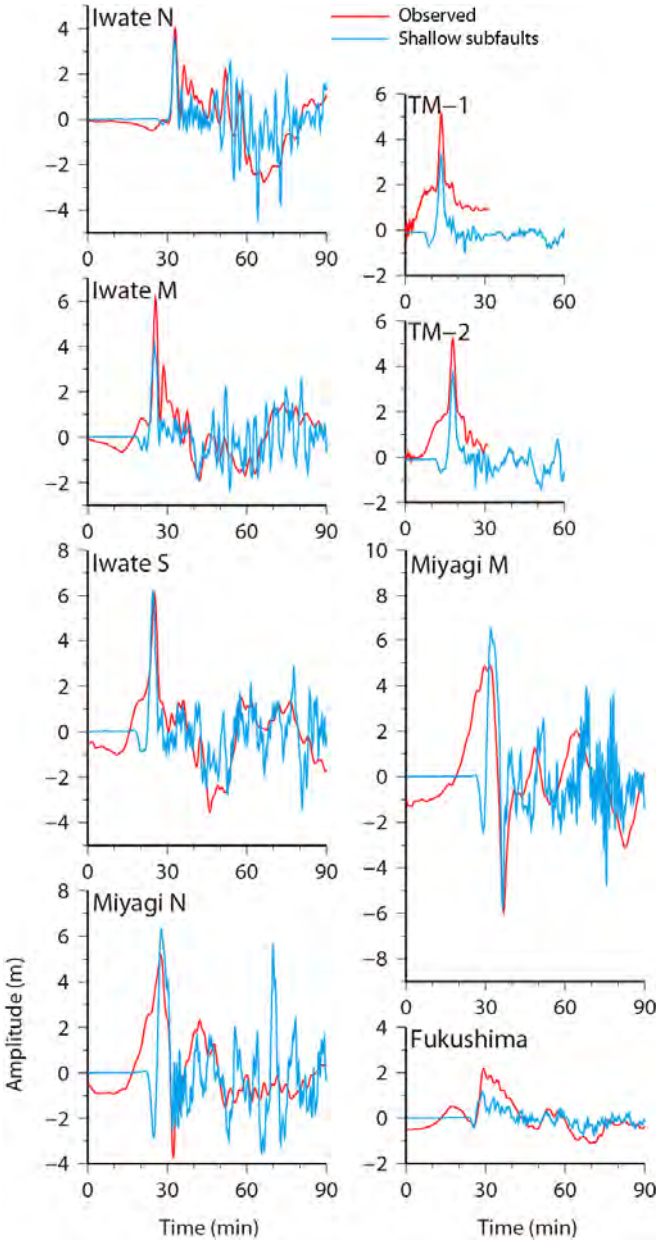
Deep Subfaults (Jogan model type)

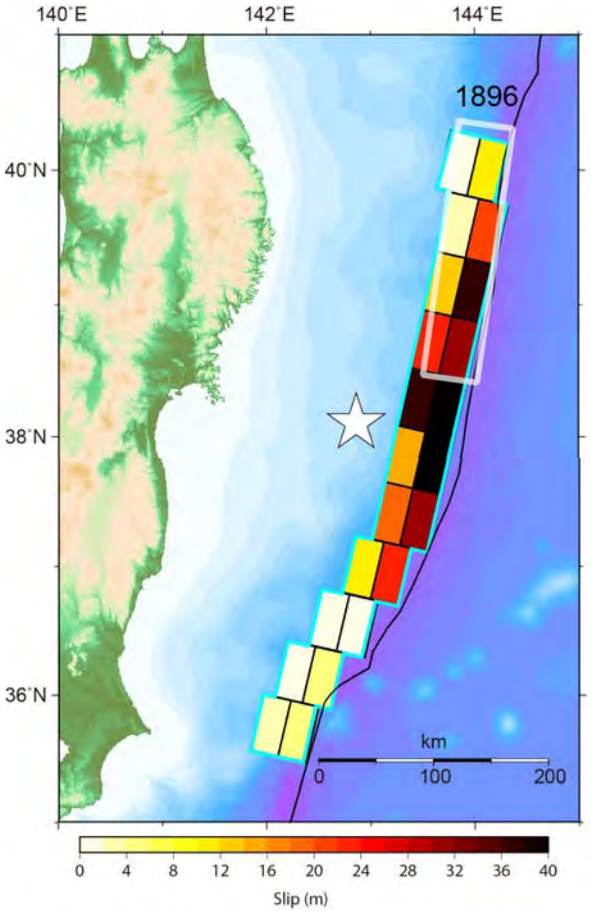




"Jogan" type
Average slip 6.4 m
Moment 2.1 x 10^{22} Nm (Mw = 8.8)

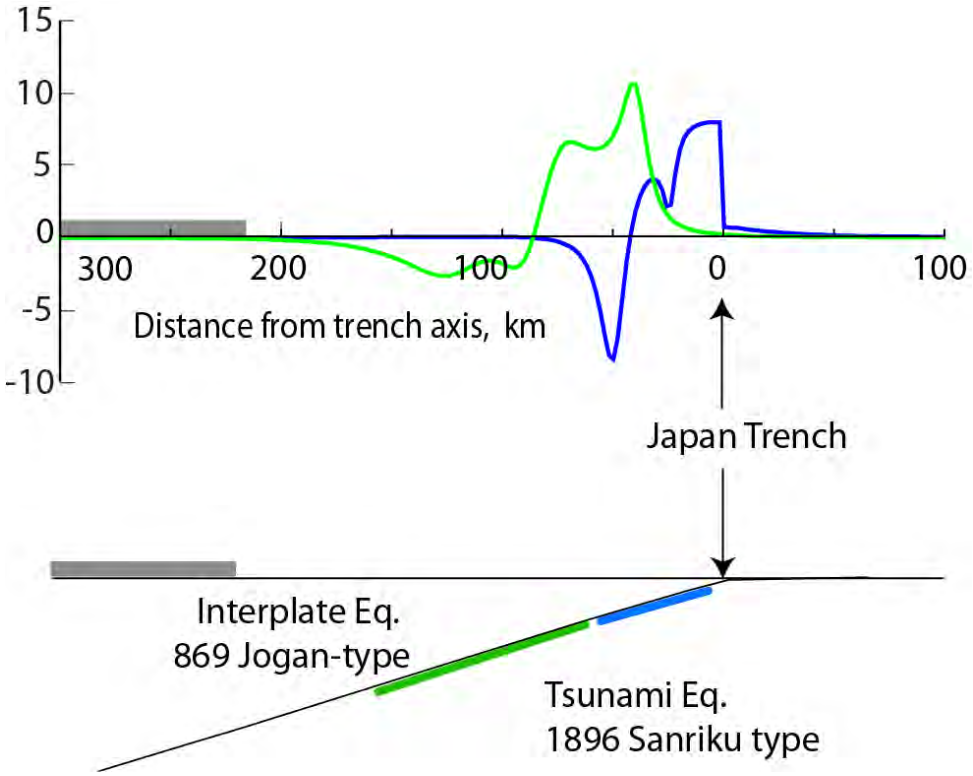
Shallow Subfaults (Tsunami Earthquake type)

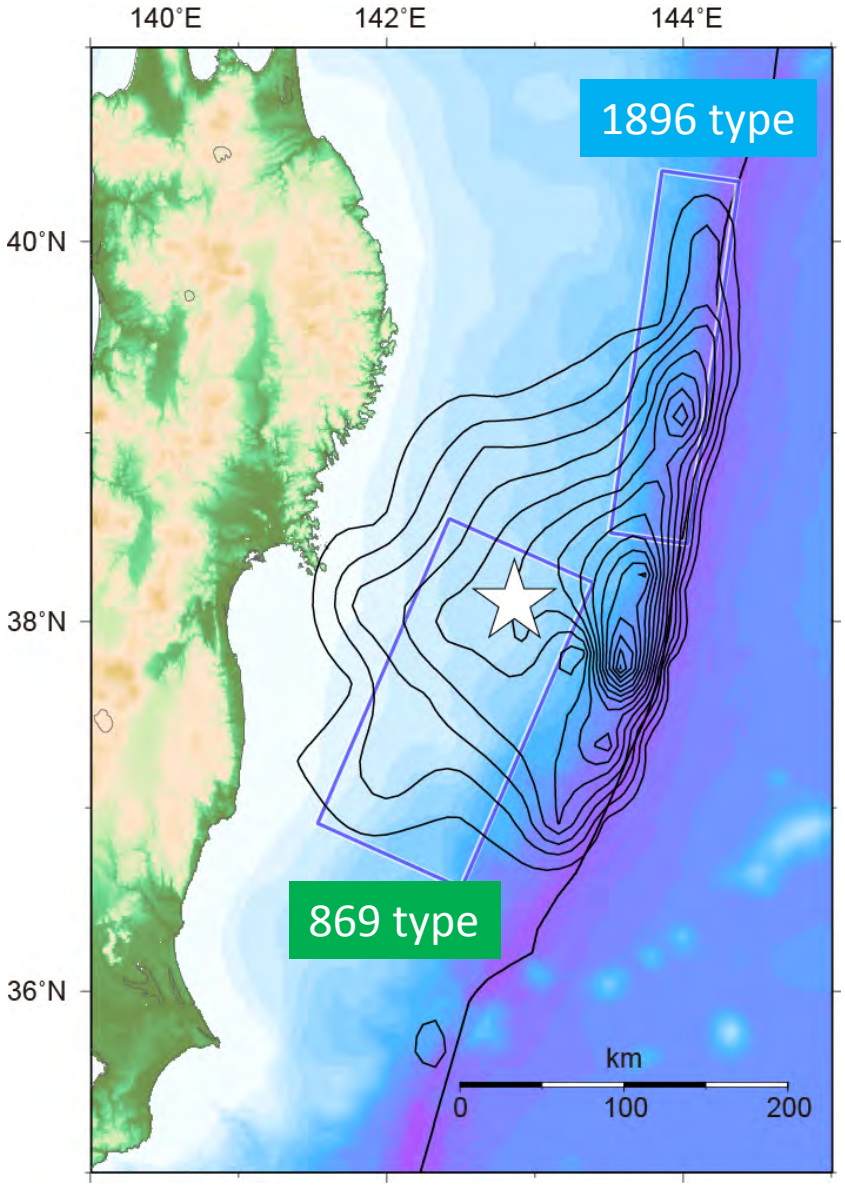




Tsunami earthquake type
Average slip 18.6 m
Moment 2.1 x 10^{22} Nm (Mw = 8.8)

Deep and Shallow Subfaults





Ver. 8.0