Challenges for Forecasting Size and Time for Future Great Earthquakes in Subduction Zone

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Outline

1. The 2011 Tohoku Earthquake

2. Long-term forecast in Japan before 2011

3. Long-term forecast in Japan after 2011

4. Great earthquakes in the world

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1. The 2011 Tohoku Earthquake
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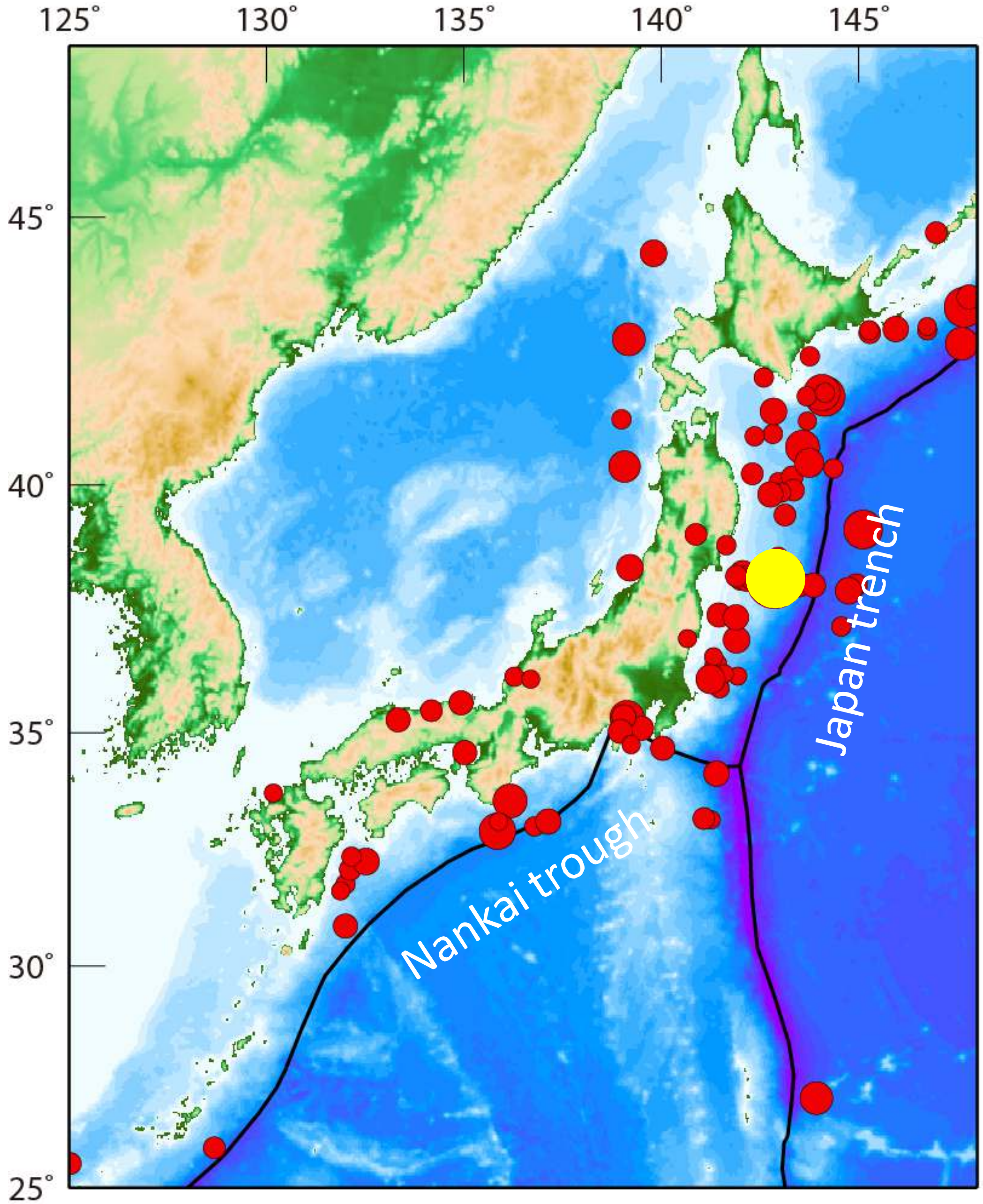
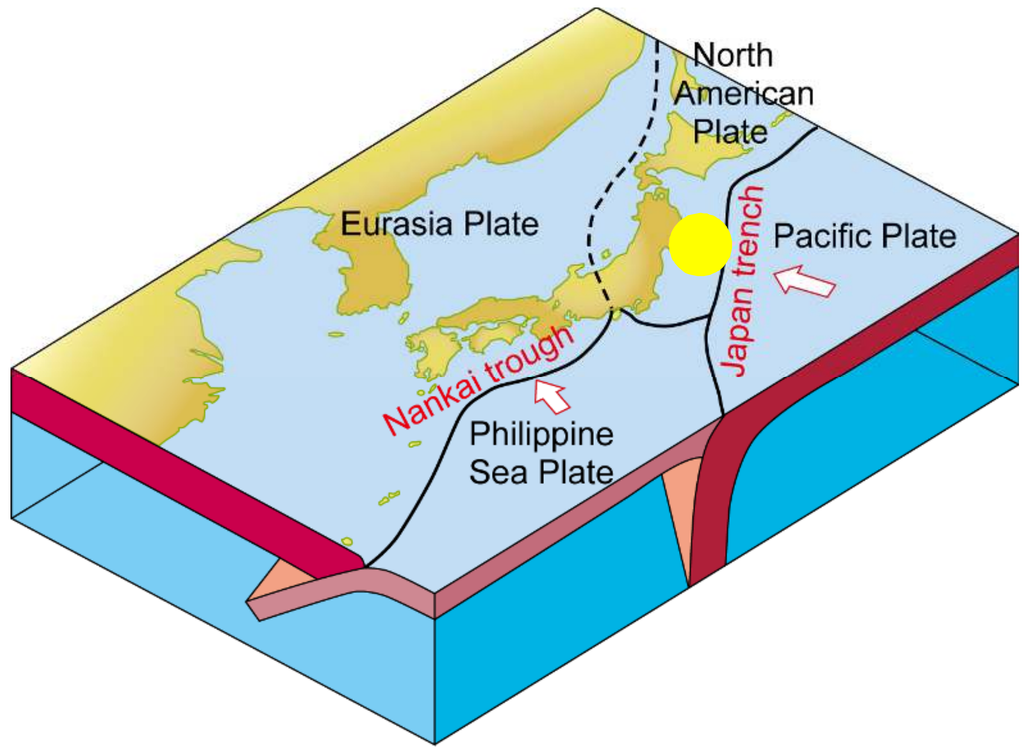
Large earthquakes around Japan

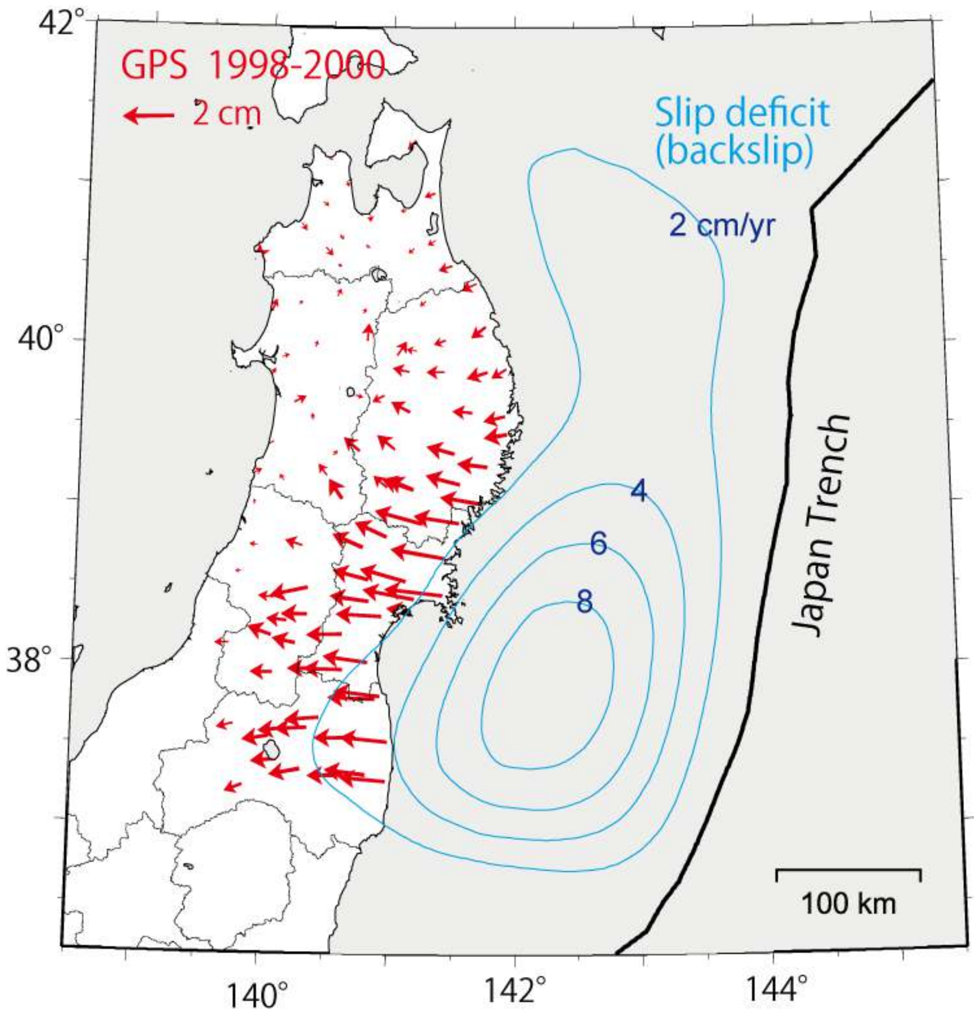


Large (M>7) Shallow (H<100 km) 1923-2013



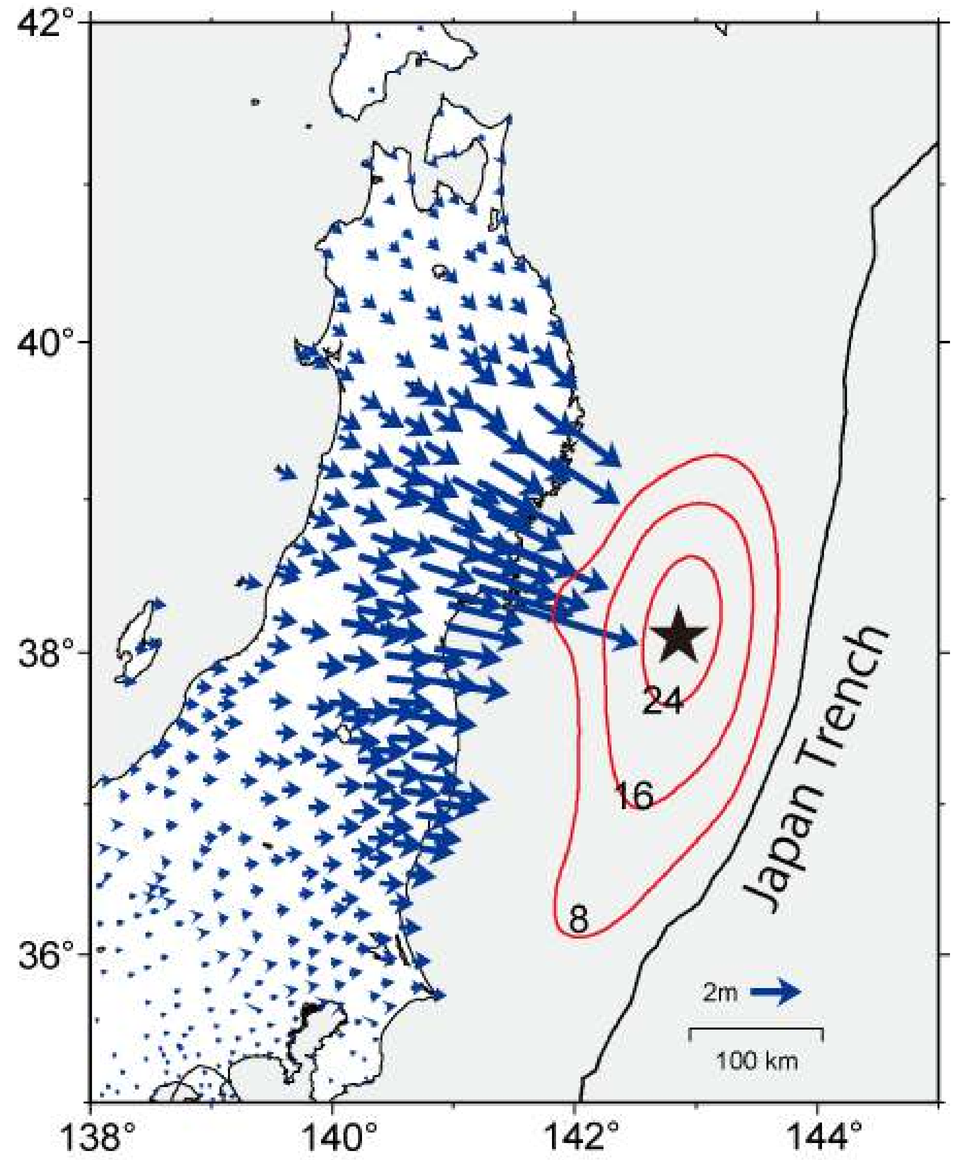
GPS data and slip distribution

1998-2000

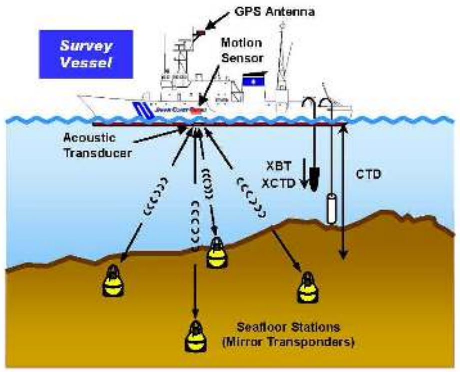


GSI (2010, 2011)

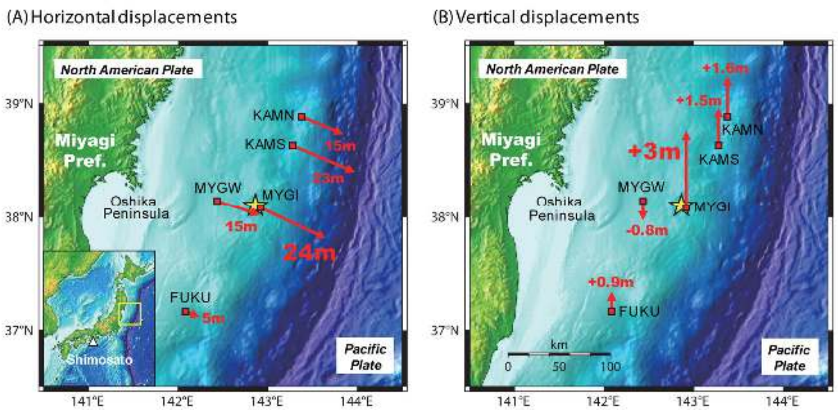
March 11, 2011



Large slip revealed by seafloor observations

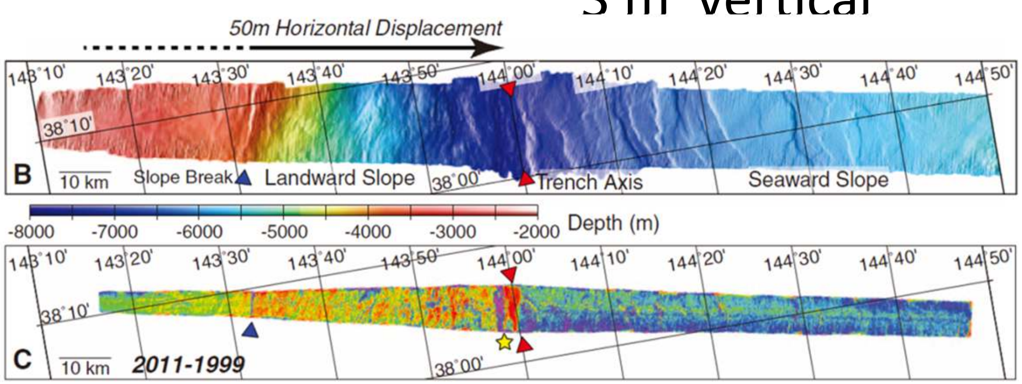


Sato et al.
(Science 2011)



Max observed slip: 24 m horizontal

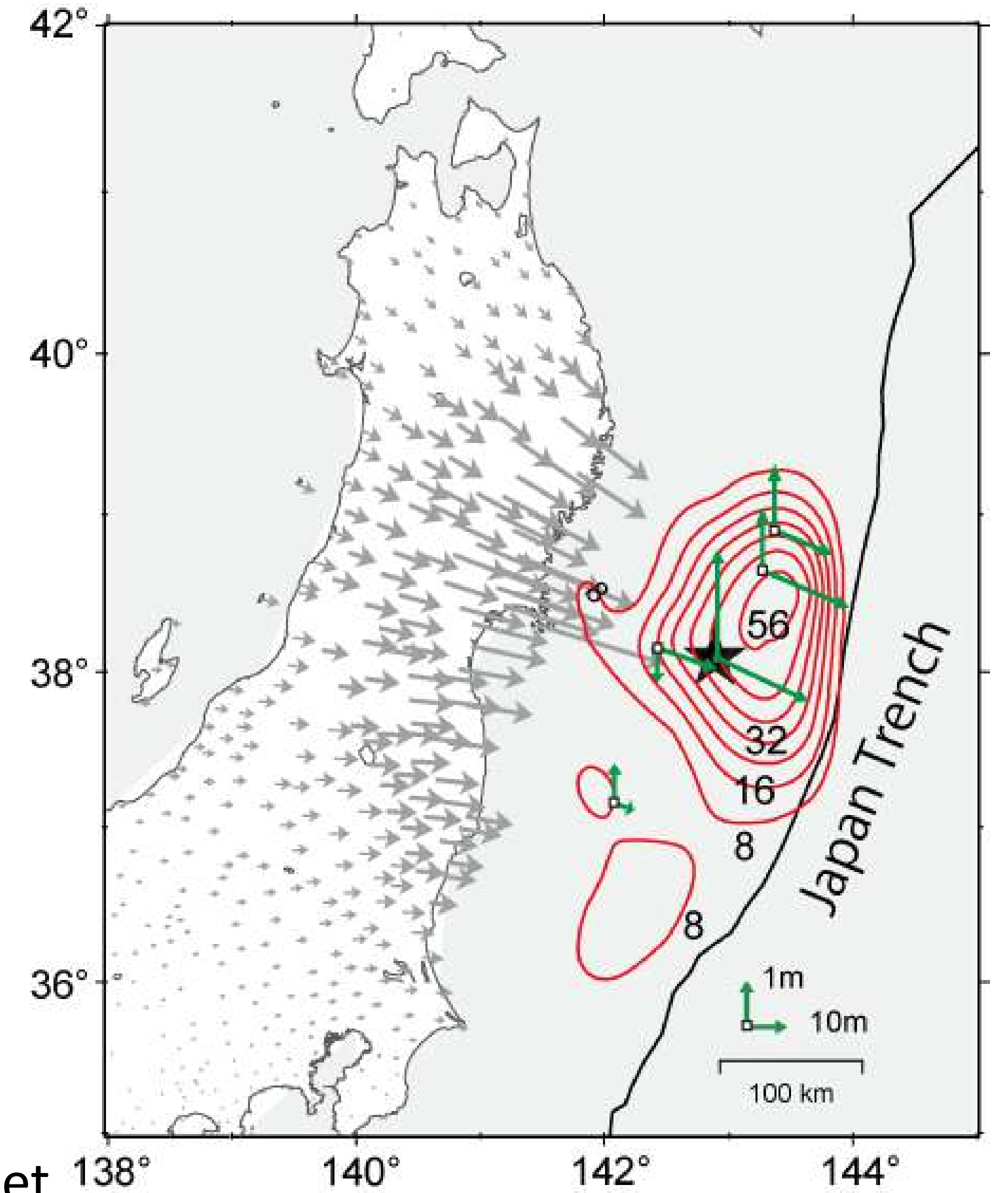
3 m vertical



Repeated bathymetry sounding: ~ 50 m offset

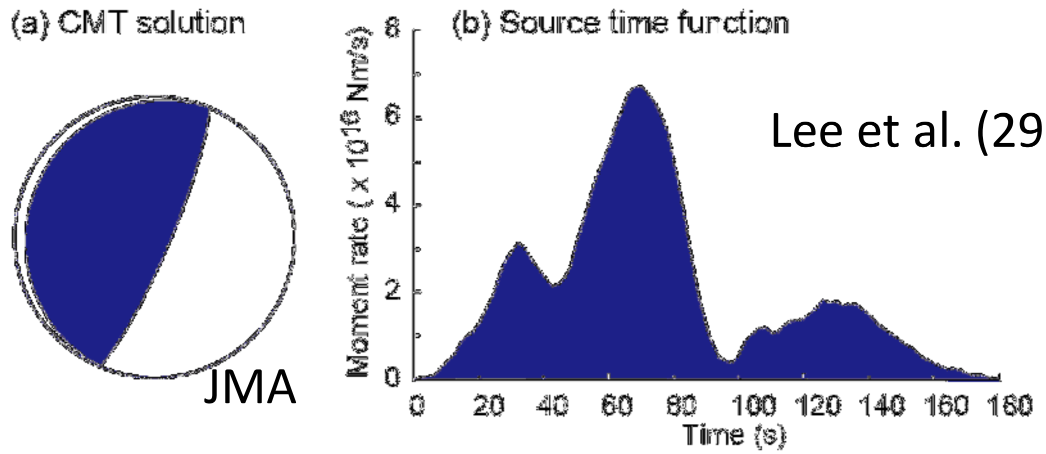
Fujiwara et al. (Science 2011)

Max slip on fault (estimated): > 50 m



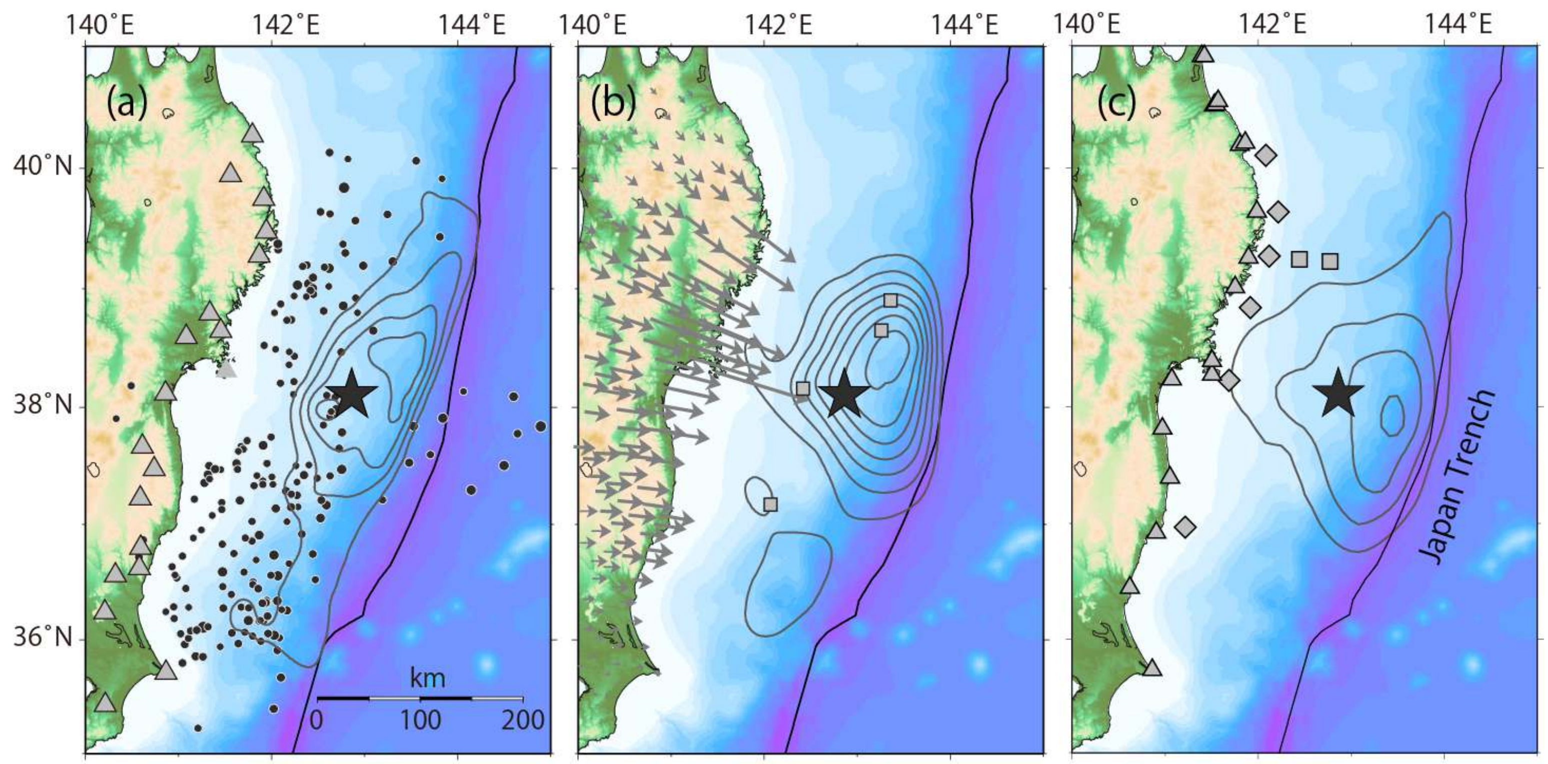
The 2011 Tohoku earthquake

Seismological Analysis



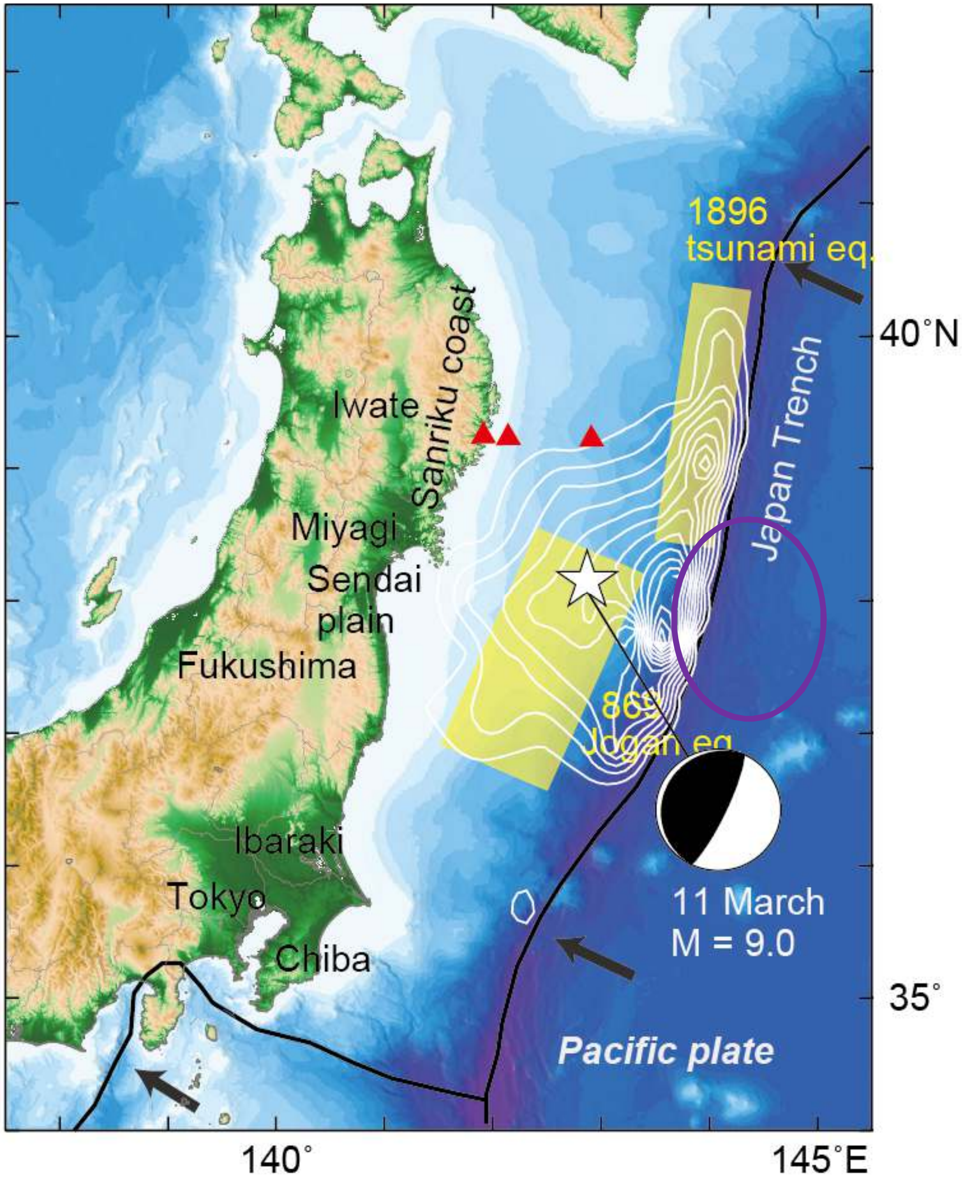
Lee et al. (2911)

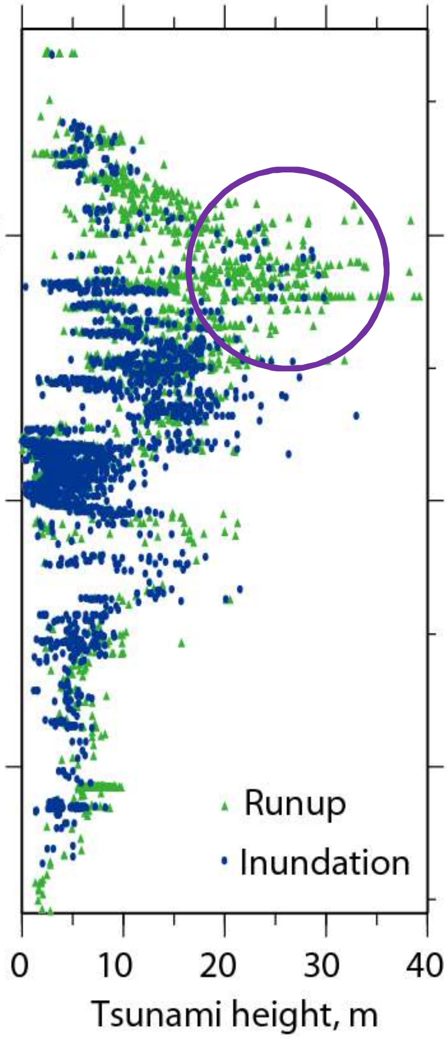
Slip Distribution from Seismological, Geodetic and Tsunami Data

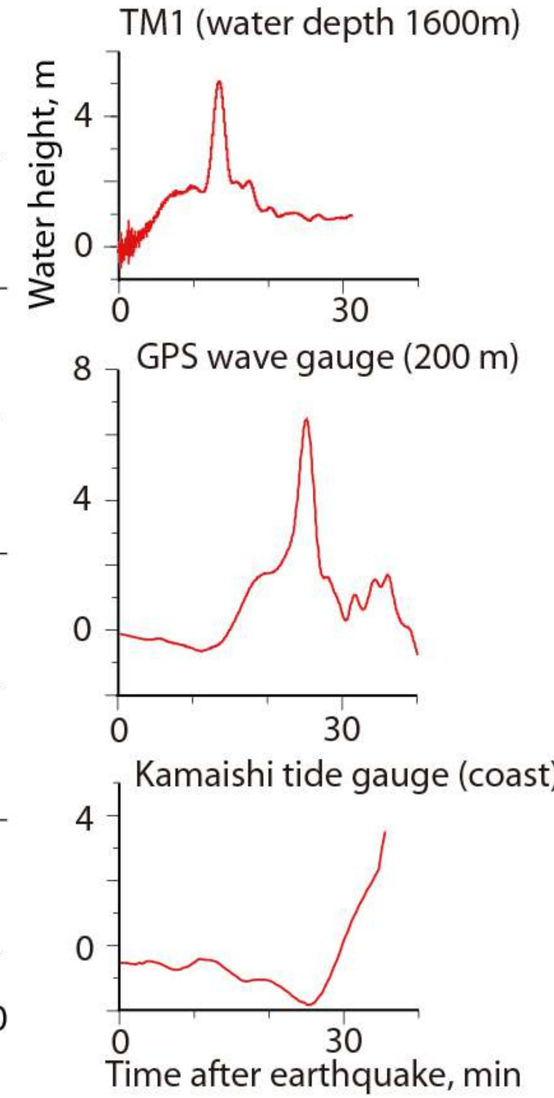


Yoshida et al. (2011) GSI (2011) Satake et al. (2013)

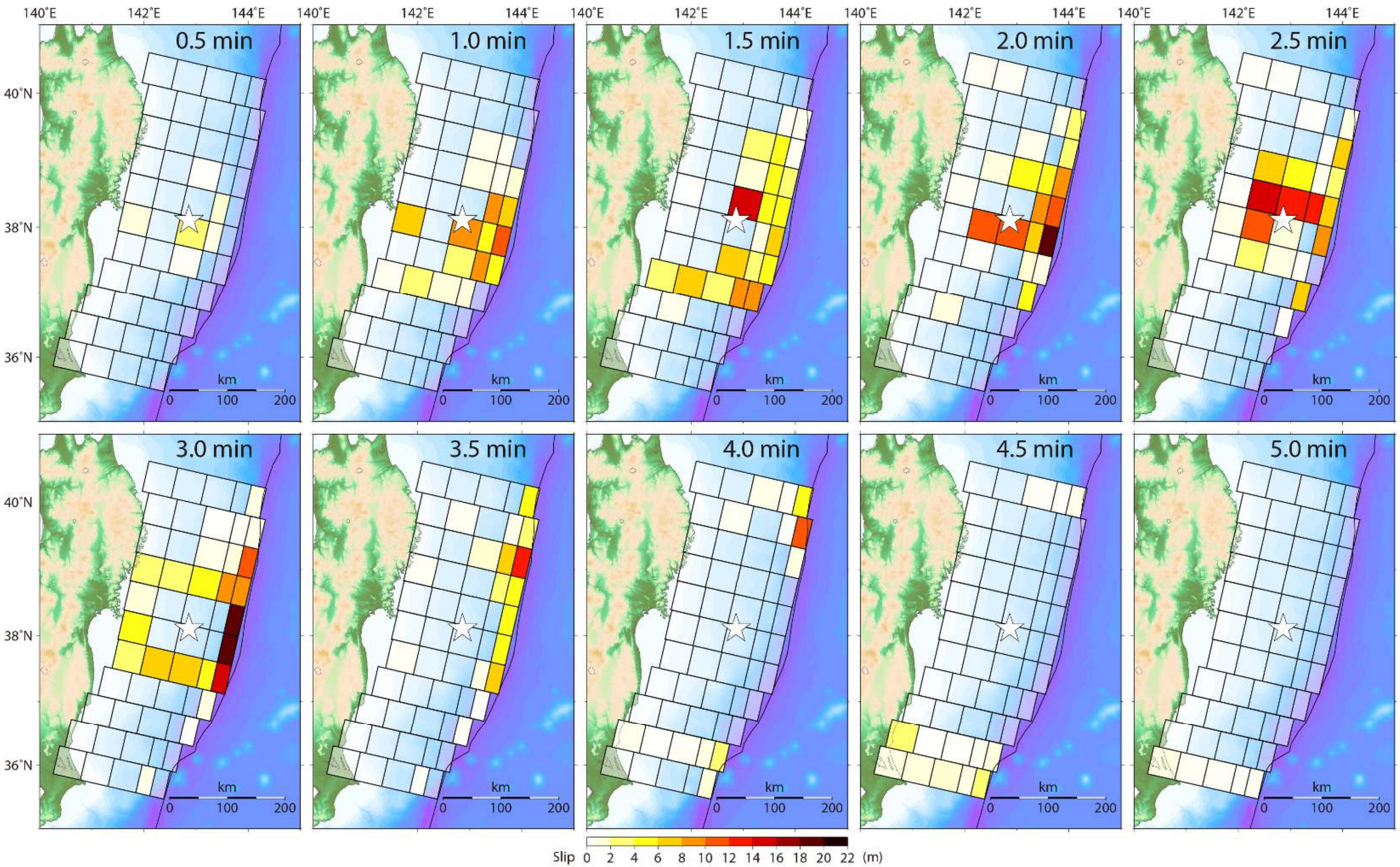
The 2011 Tohoku Earthquake Tsunami







The 2011 Tohoku Earthquake Tsunami



Satake et al. (2013: BSSA)

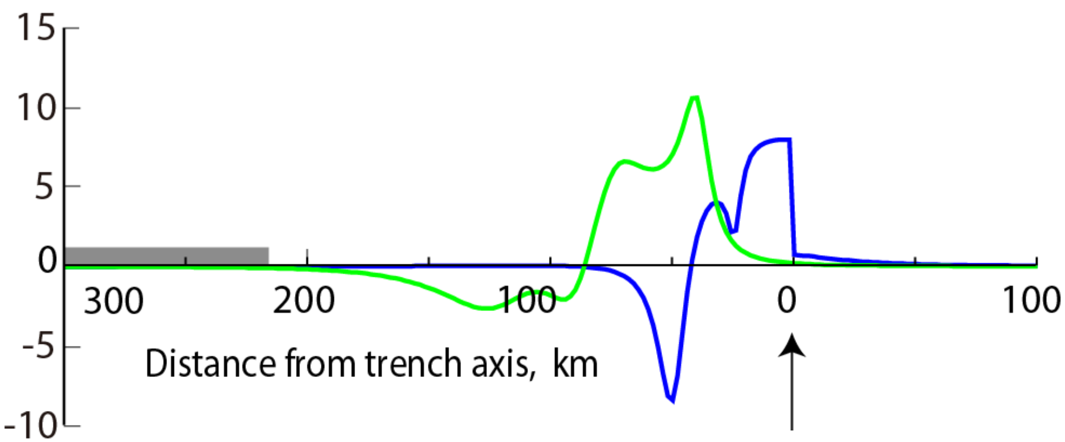
Deep and Shallow Subfaults

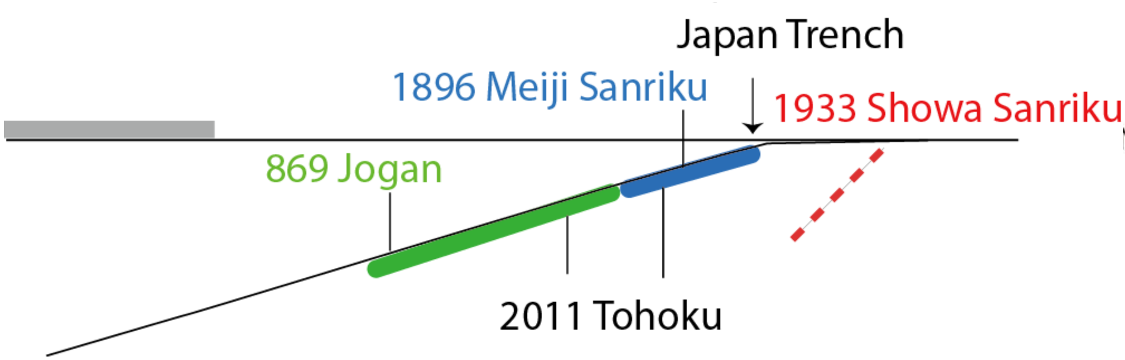
Long wavelength

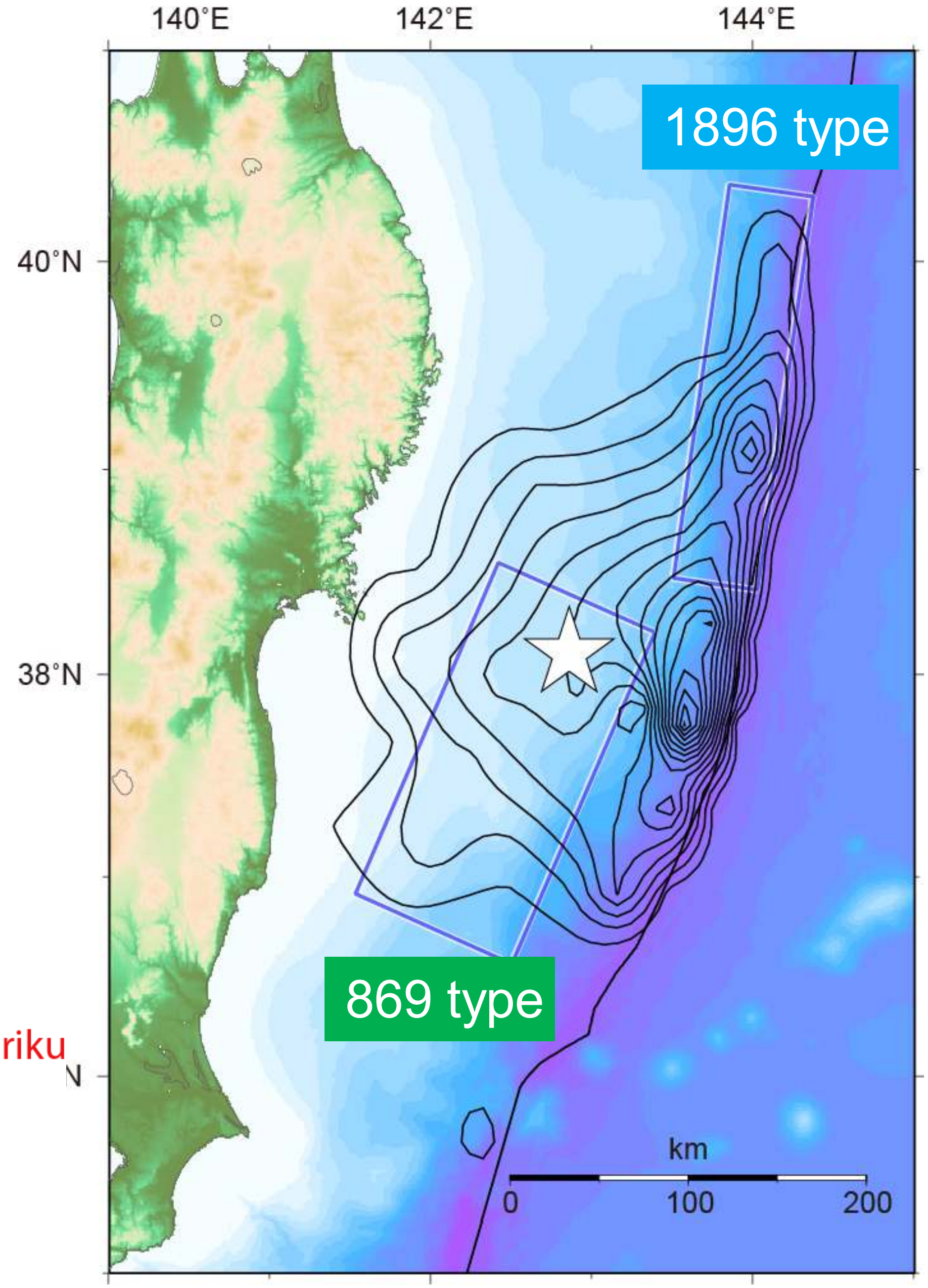
Large inundation in Sendai plain

Short wavelength and large peak

High tsunami on Sanriku coast



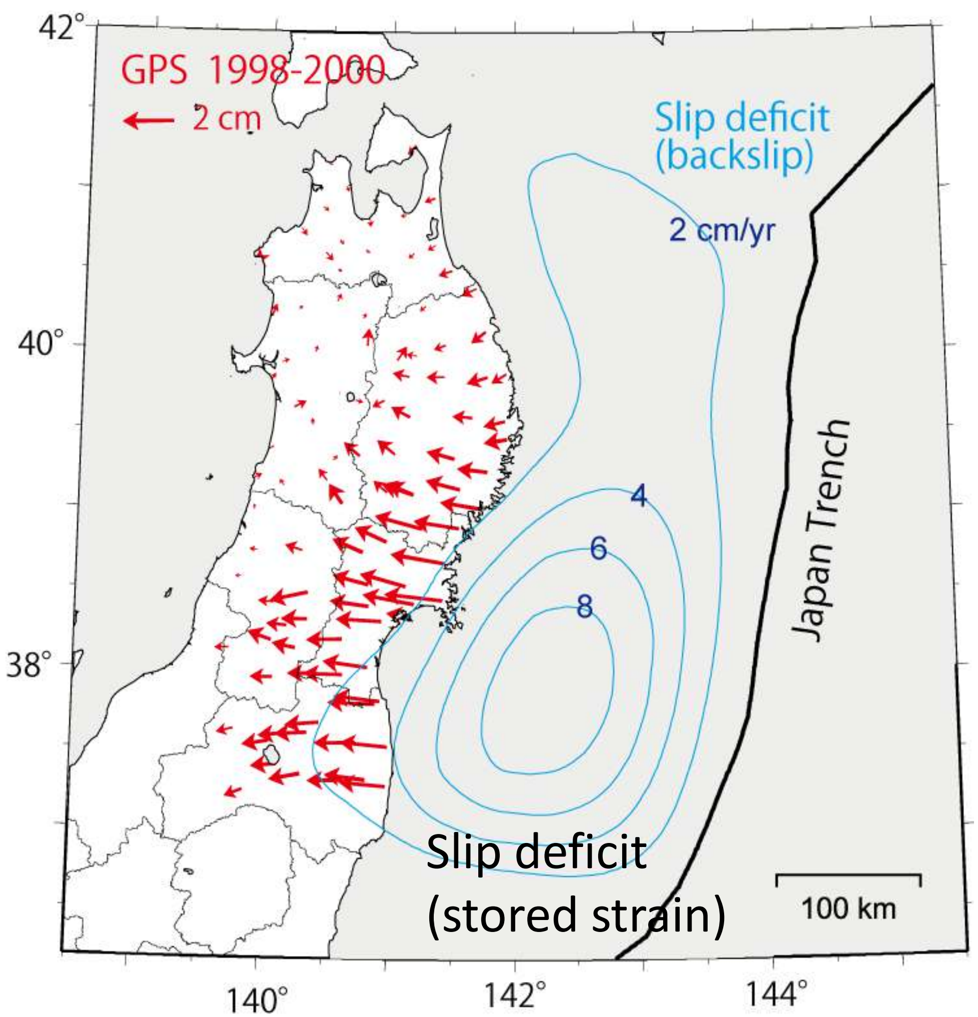




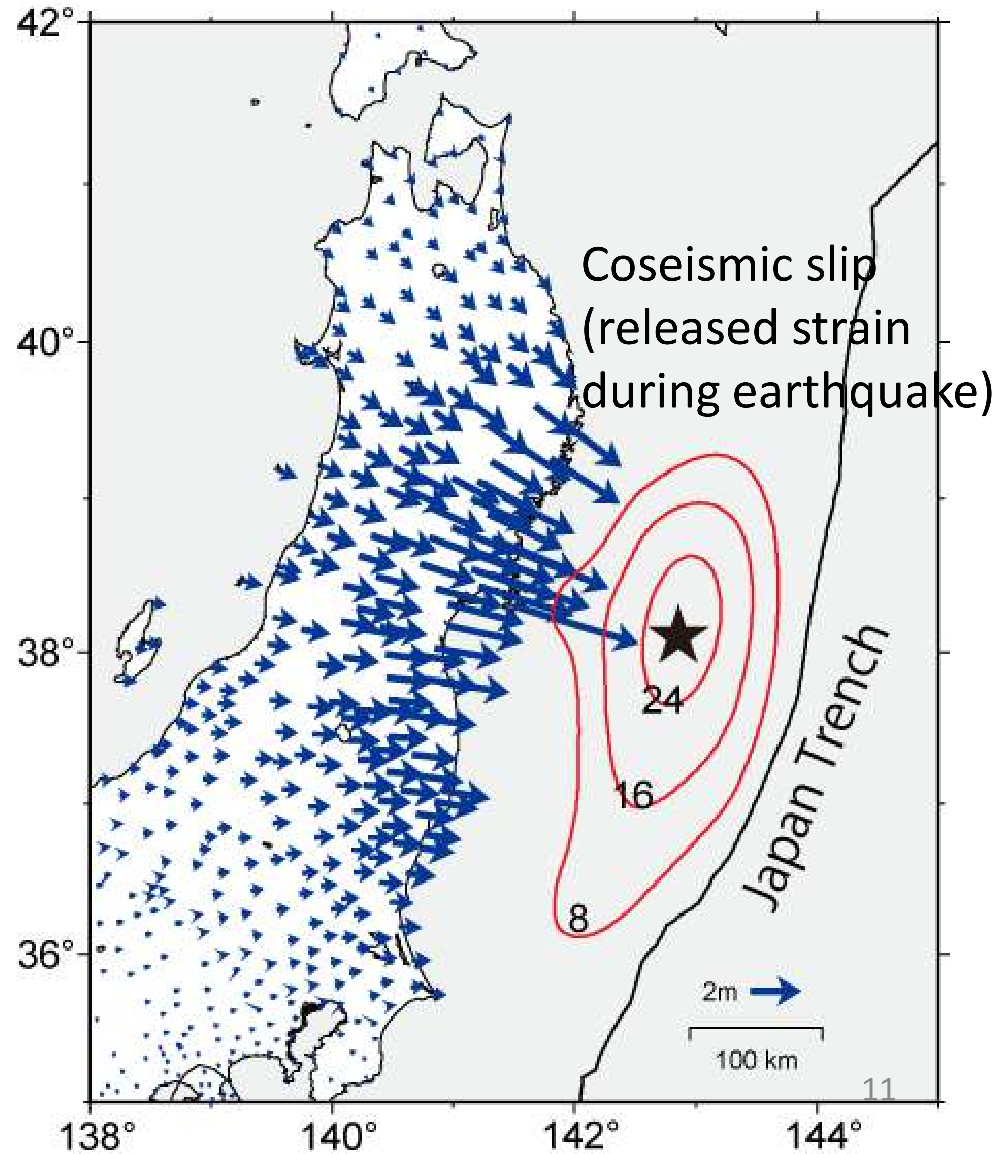
Satake et al. (2013: BSSA)

Why wasn't it forecasted?

Westward motion in 1998-2000

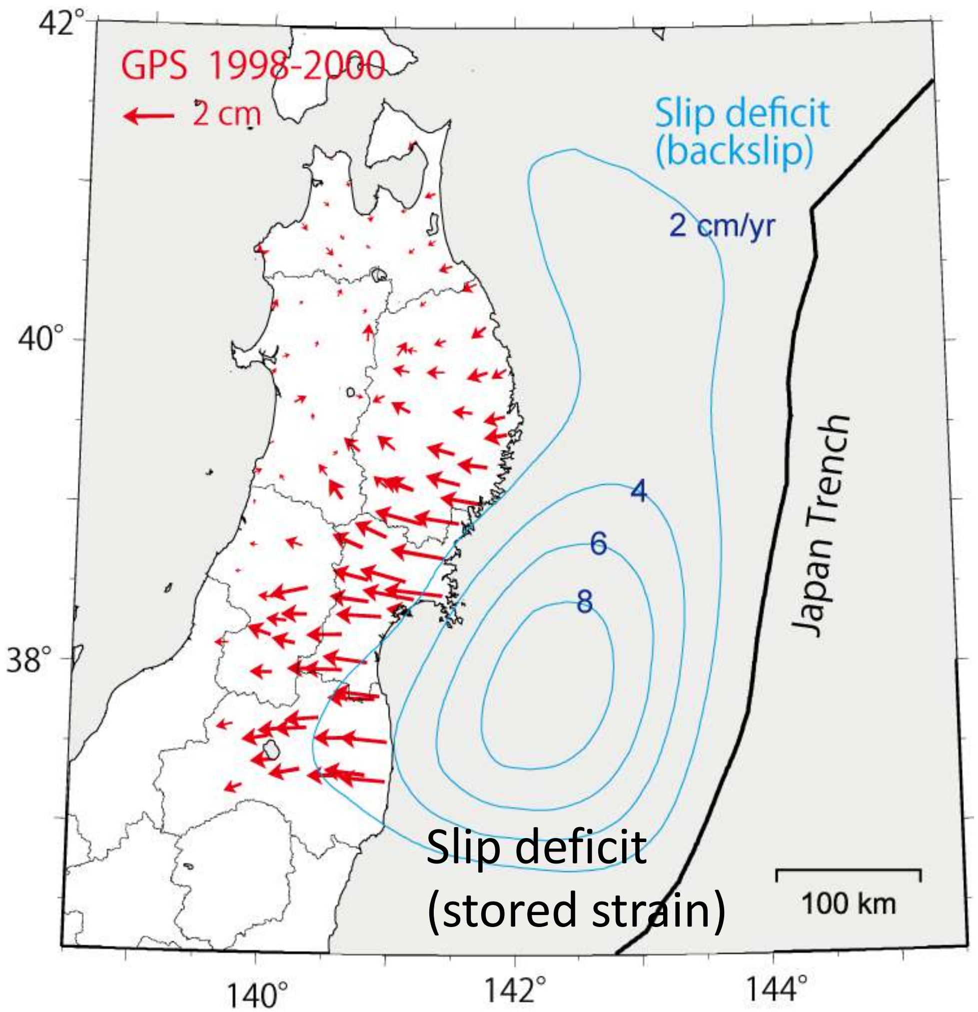


Eastward rebound on March 11

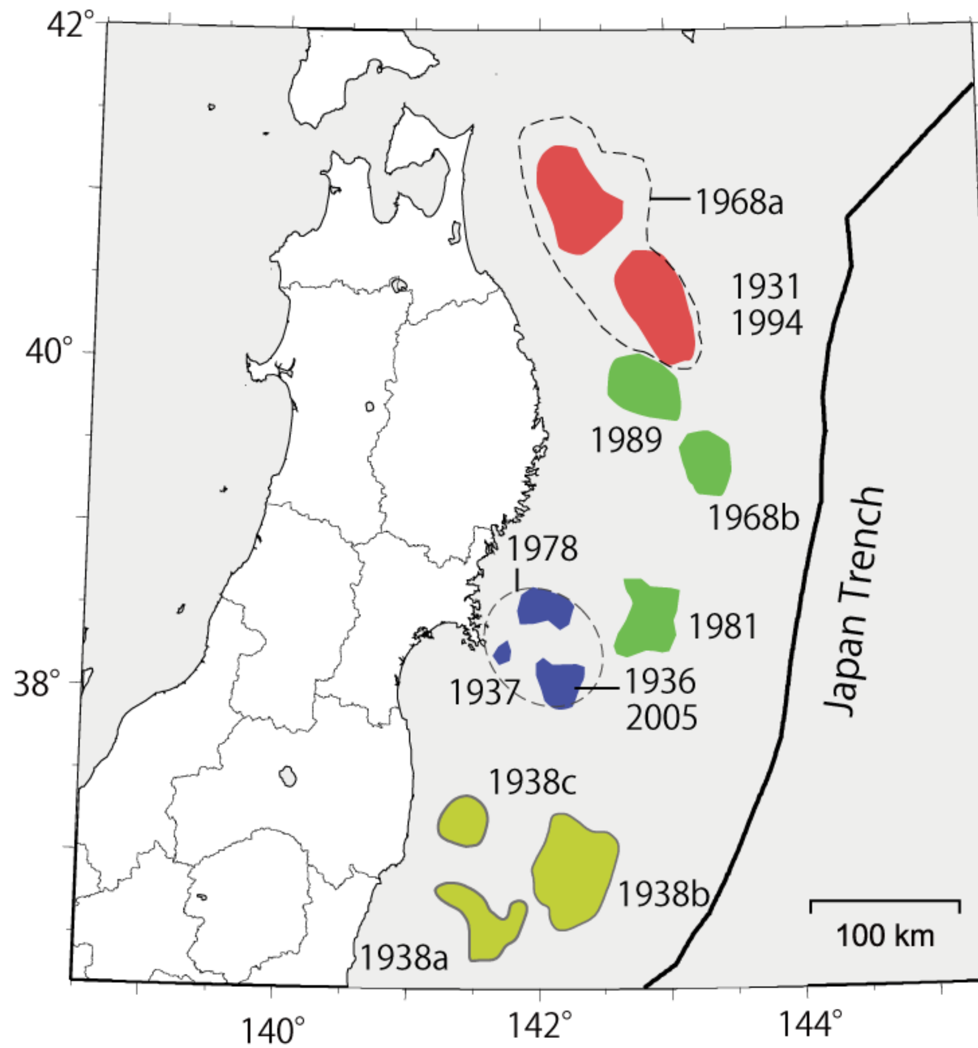


Why wasn't it forecasted?

Westward motion in 1998-2000



Large (M>7) earthquakes
in 20th century



Yamanaka and Kikuchi (2004)

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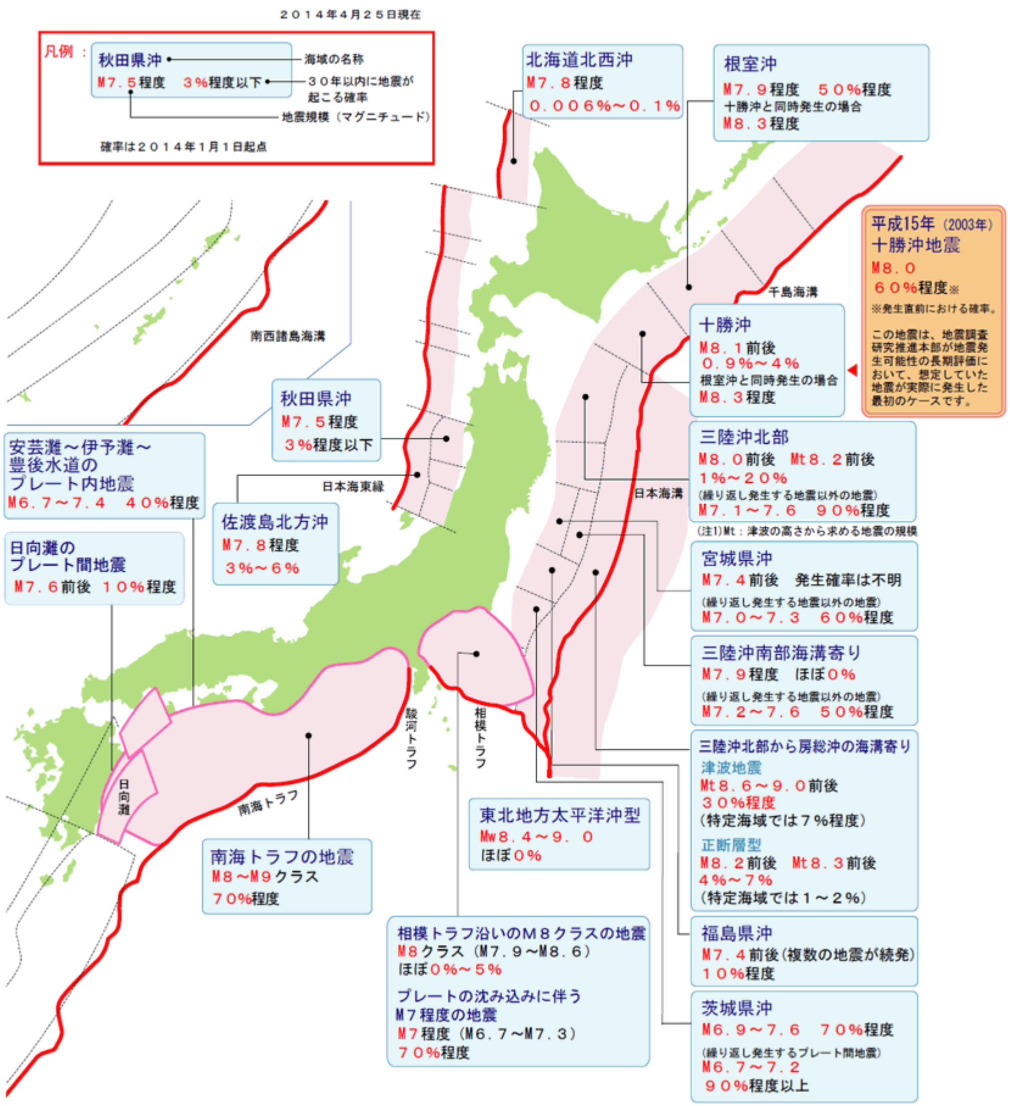
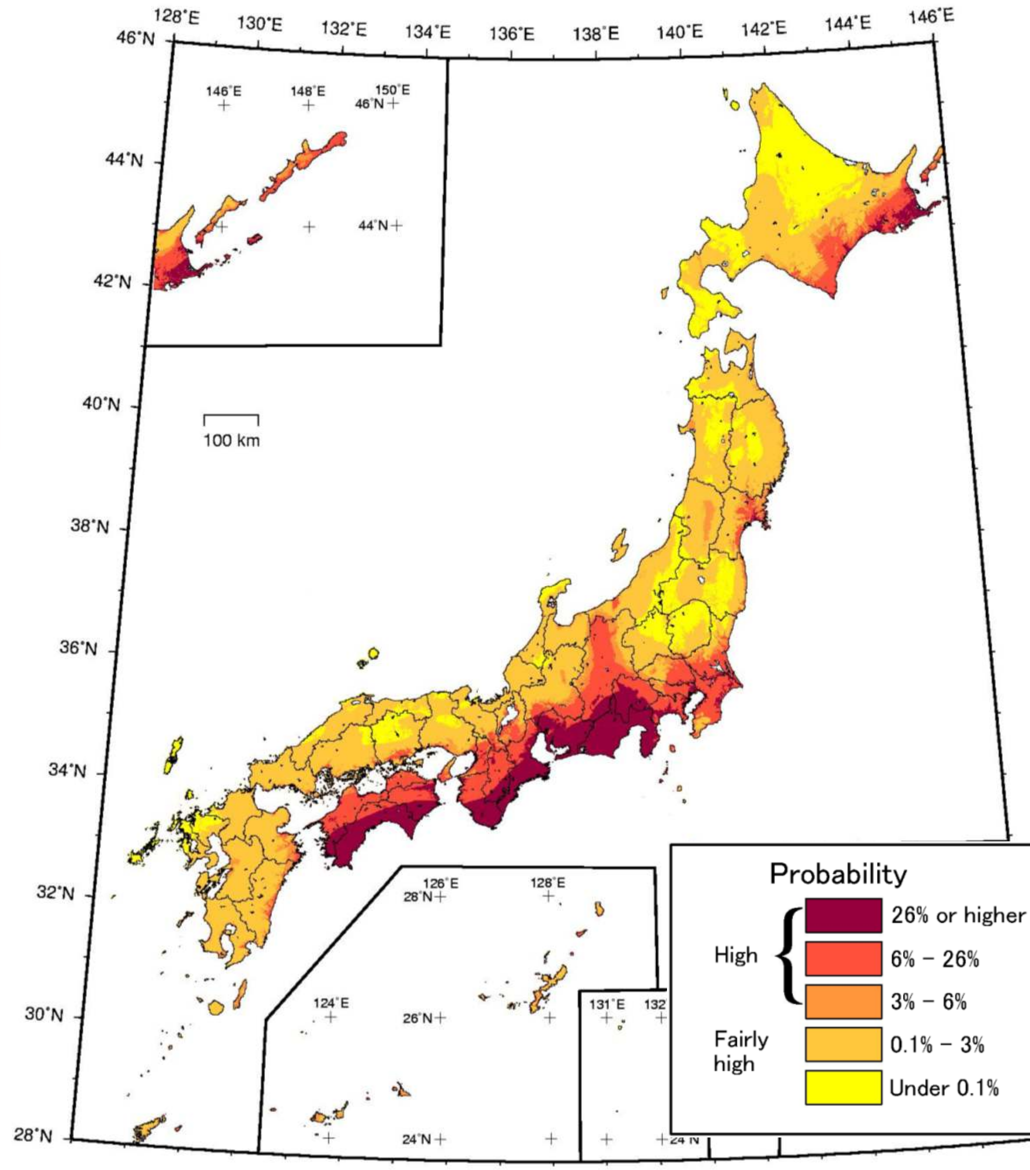
Earthquake Research Committee

Long-term forecast

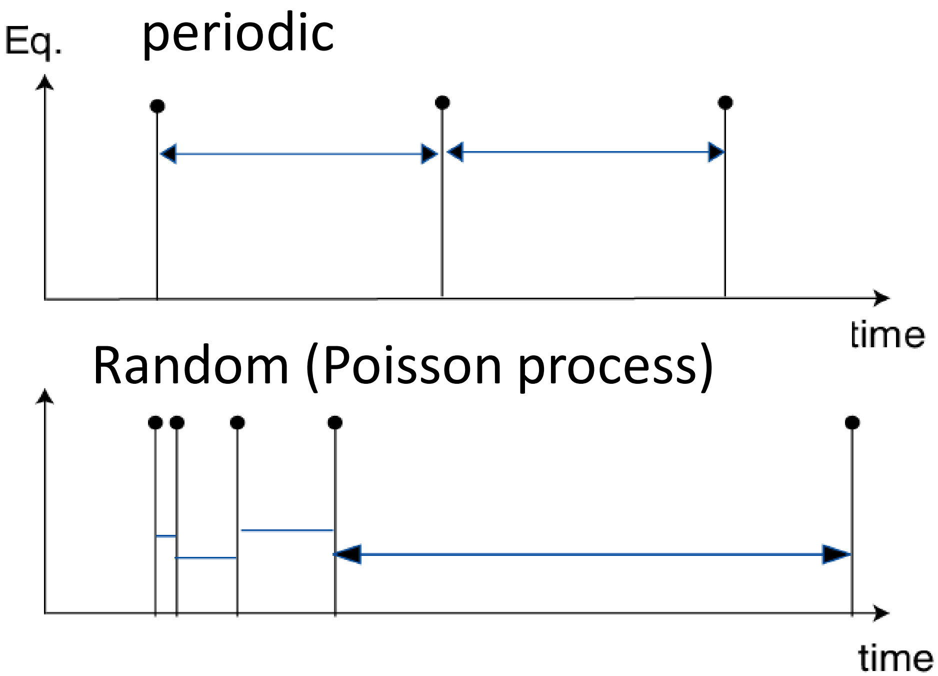


National Seismic Hazard Map

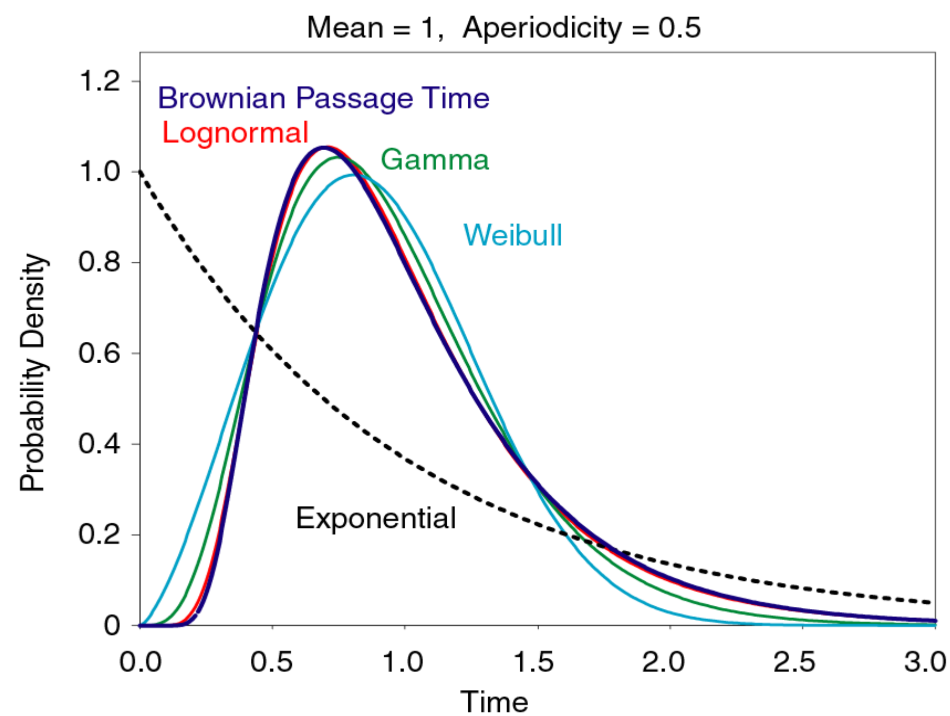


Earthquake Recurrence and Hazard Rate

Earthquake Occurrence

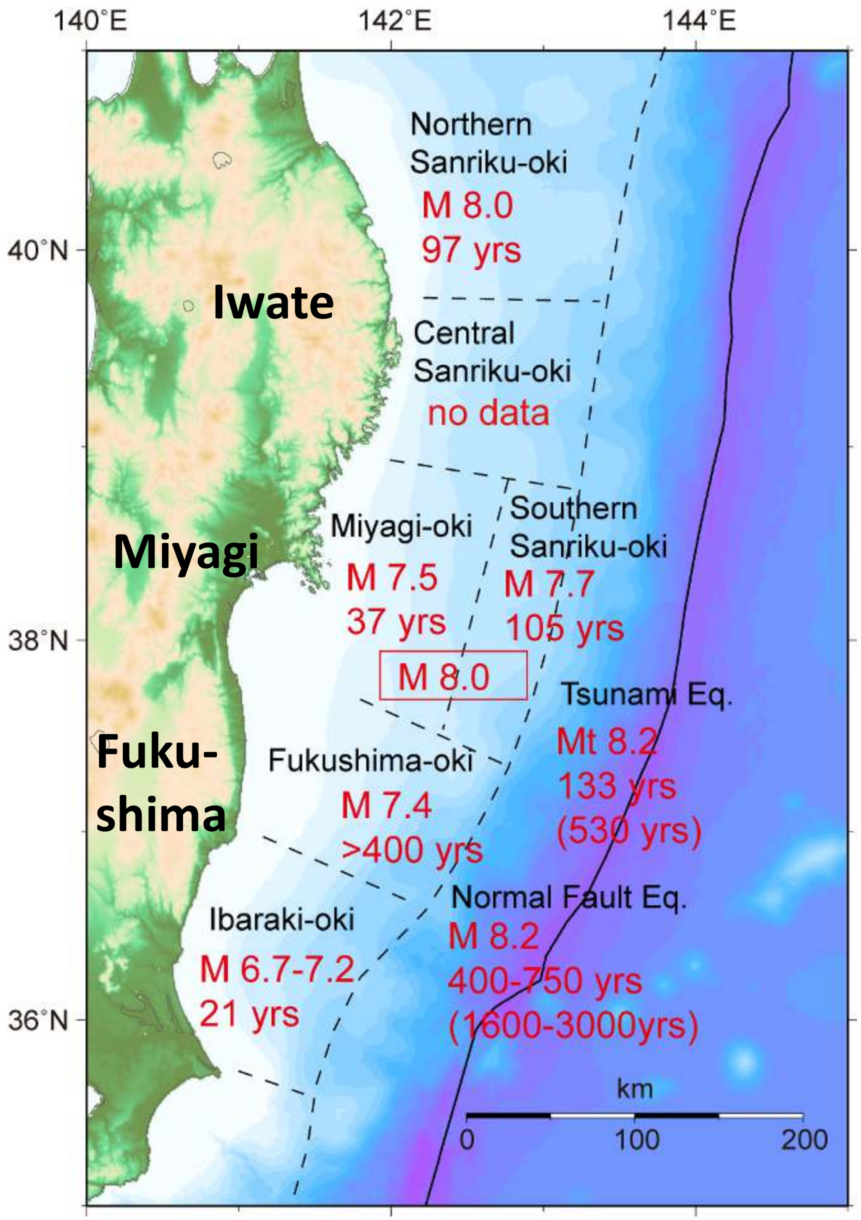


Interval between eq.

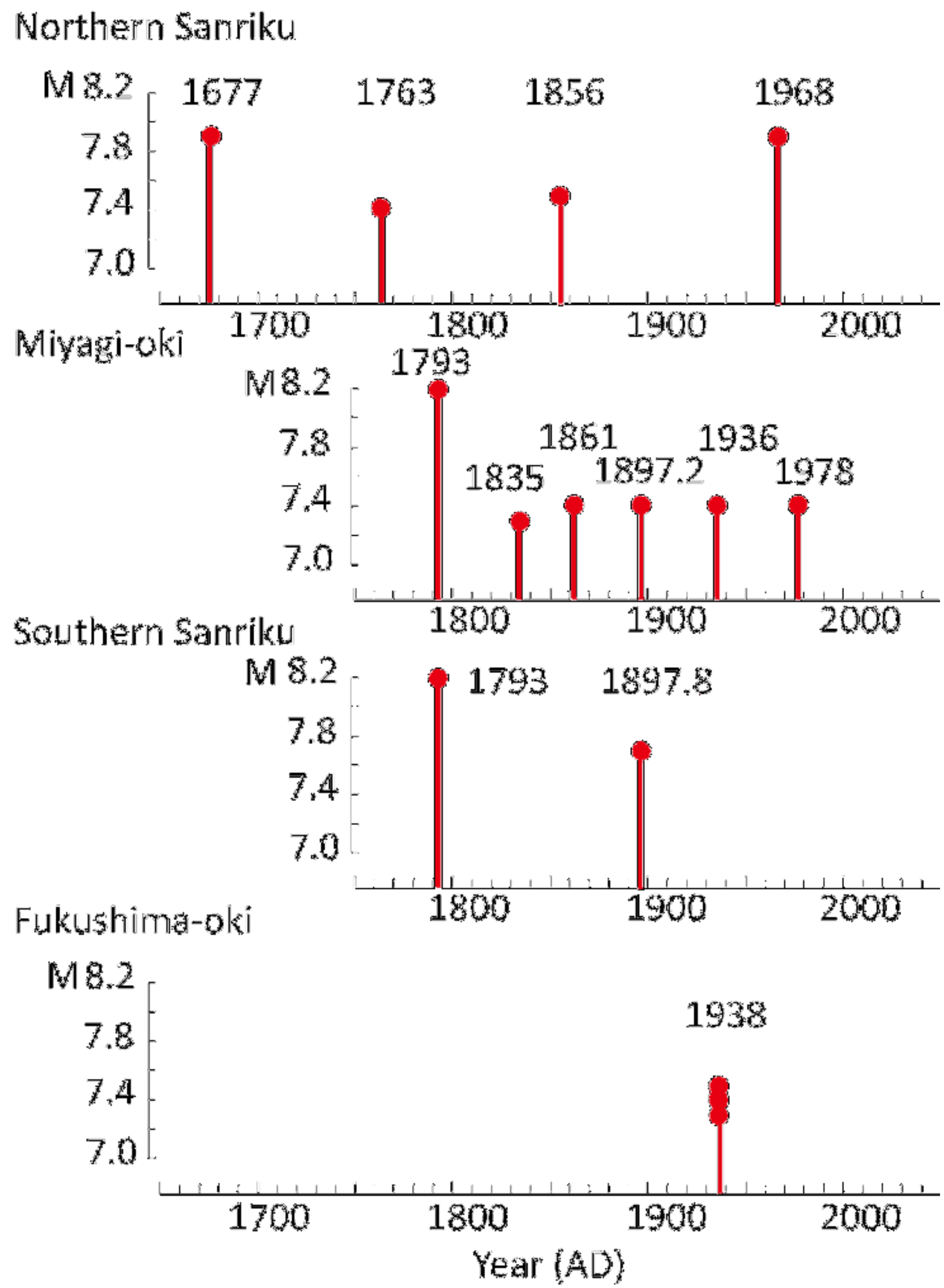


Future (e.g., in next 30 years) probability can be computed from past recurrence data

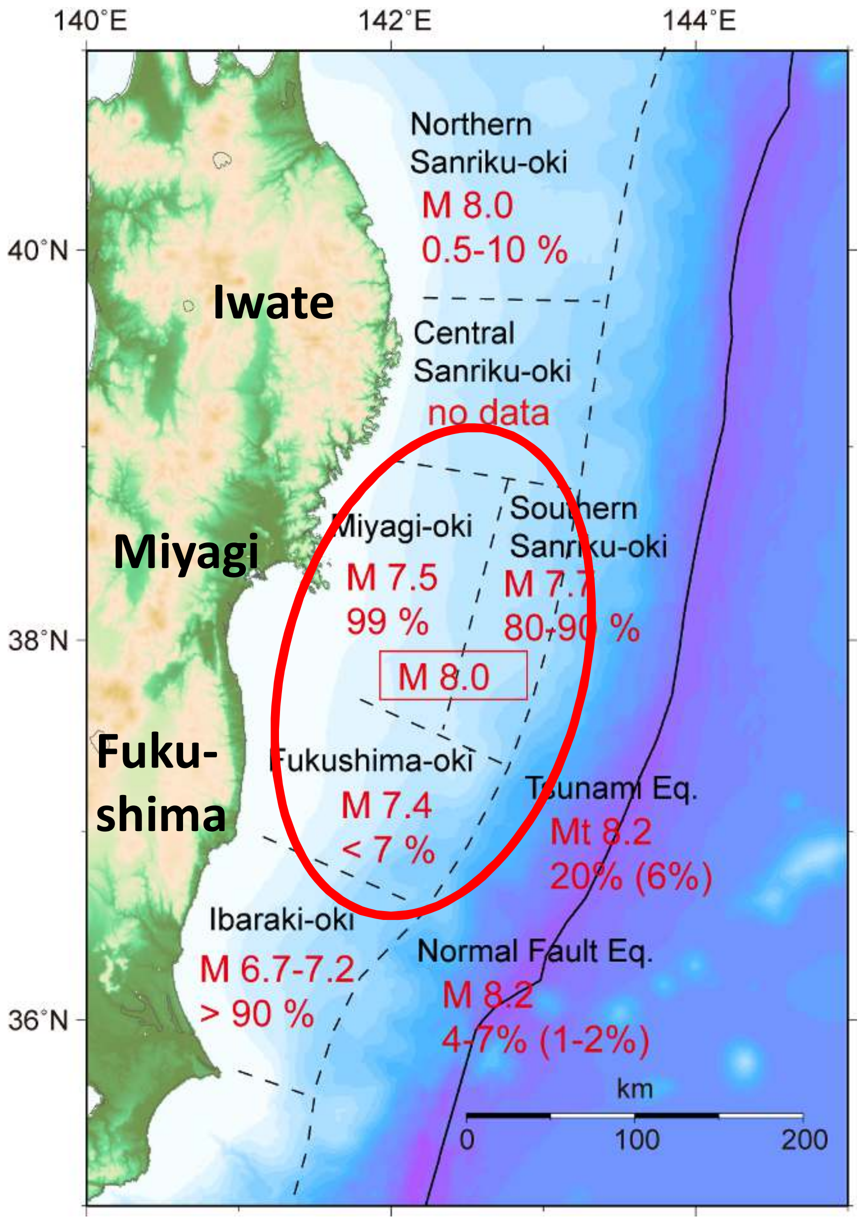
Long-term forecast of earthquakes



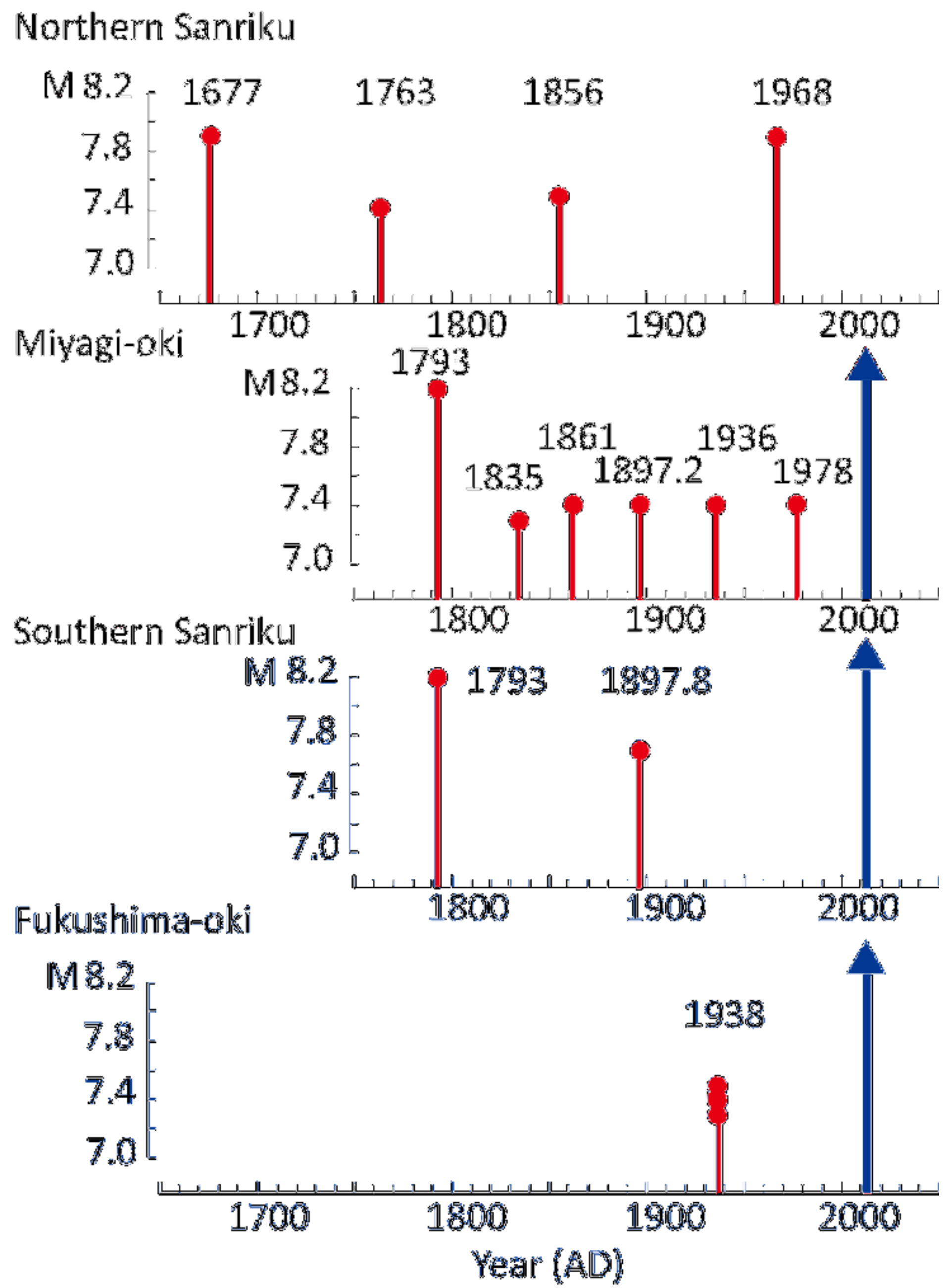
Long term forecast by ERC



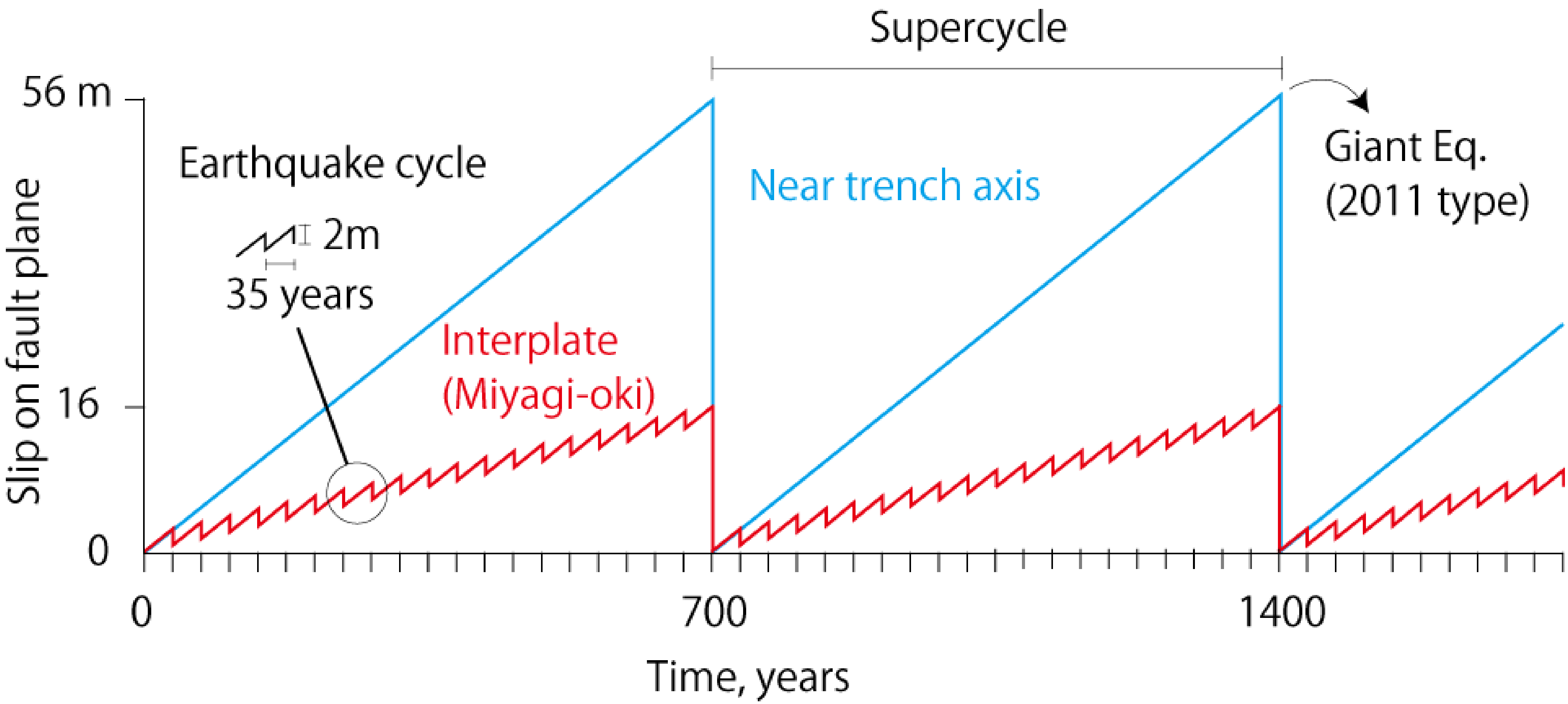
Long-term forecast of earthquakes



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 recurrence in the 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
- March 9 earthquake was a foreshock
- Earthquake supercycle may exist

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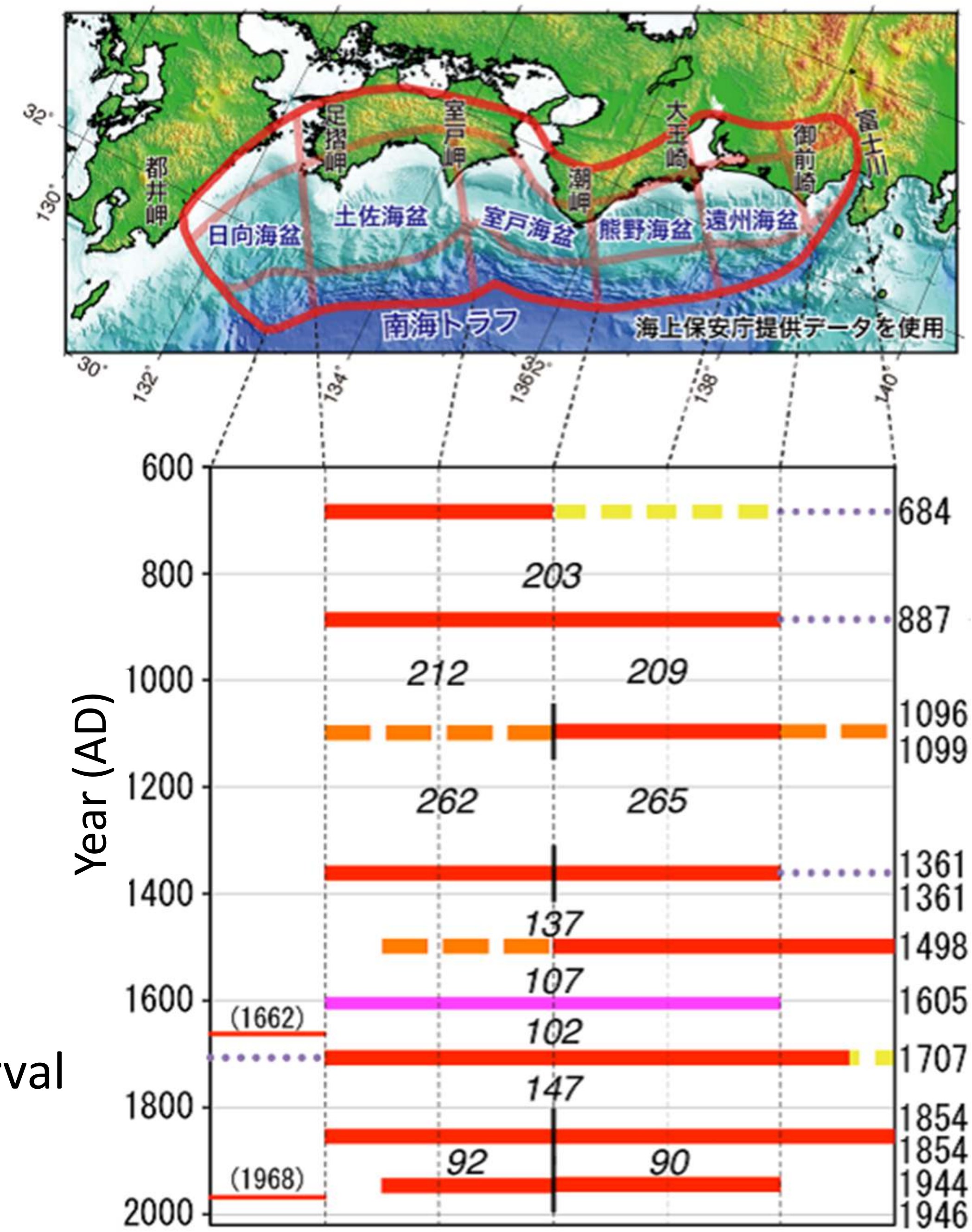
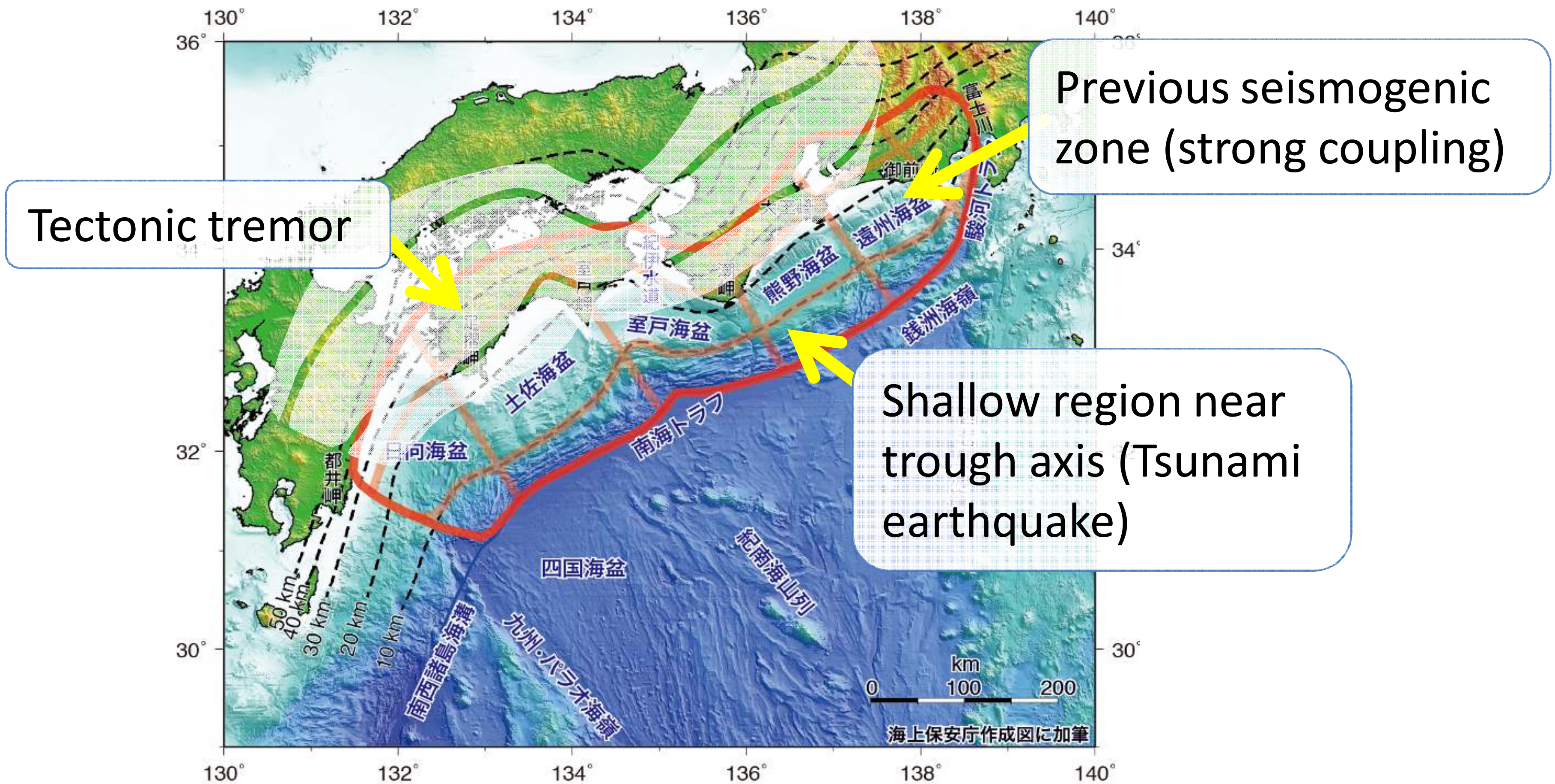
Past Nankai Earthquakes (Historical Data)



M~8 earthquakes
Have repeated
At 90-150 yrs interval

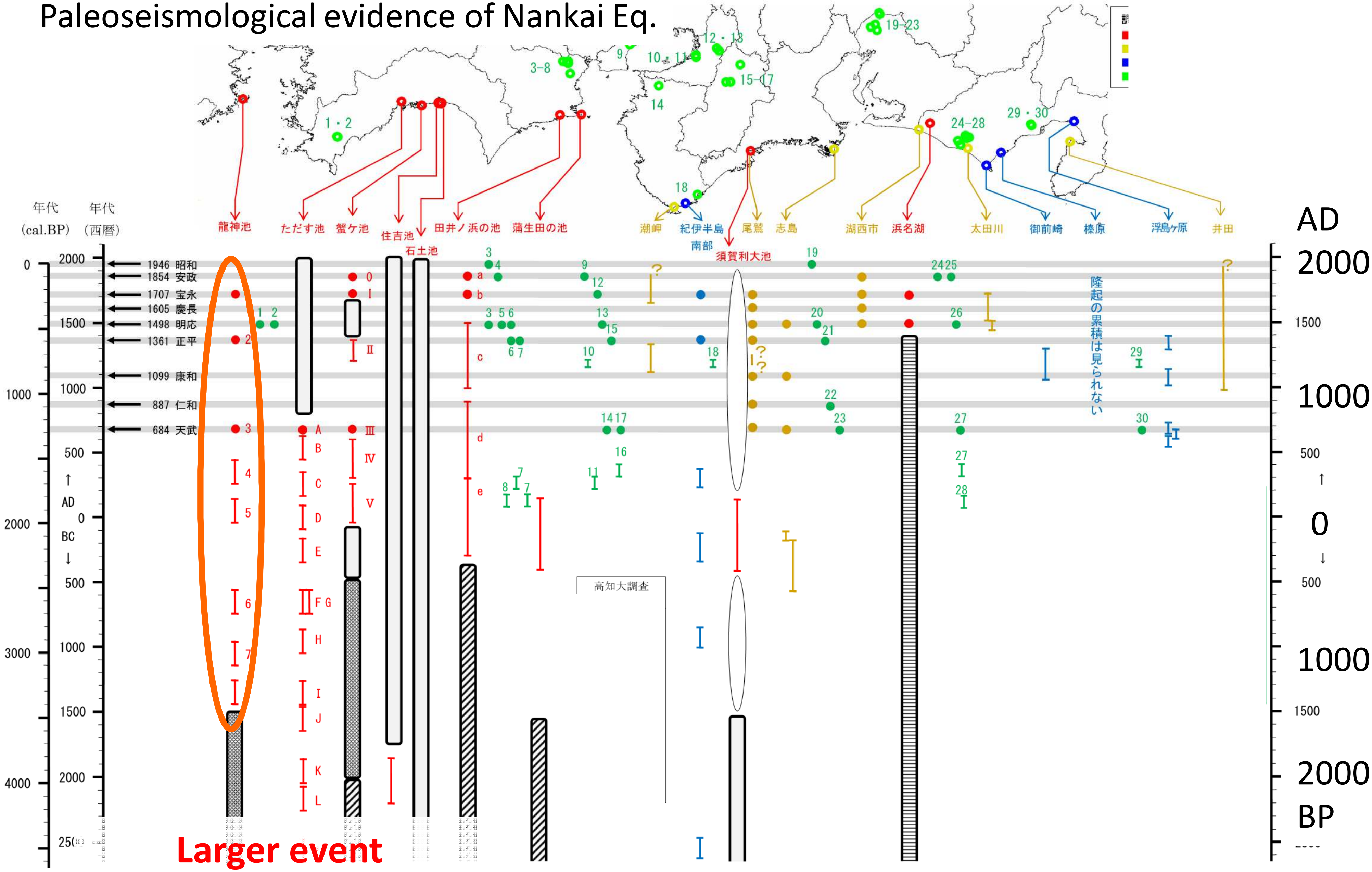
Nankai Trough (Maximum Earthquake Size)



Earthquake	Area (10^3 km^2)	Mw
Nankai (new estimate)	140	9.1
Nankai (old estimate)	60	8.7
2011 Tohoku	100	9.0

Past Nankai Earthquakes (Geological Data)

Paleoseismological evidence of Nankai Eq.

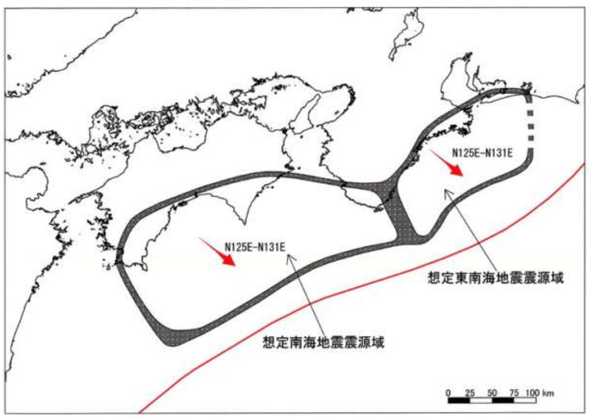


Larger event

At 300-700 yr interval?

Long-term forecast of Nankai Earthquakes

Ver. 1 (September 2001)



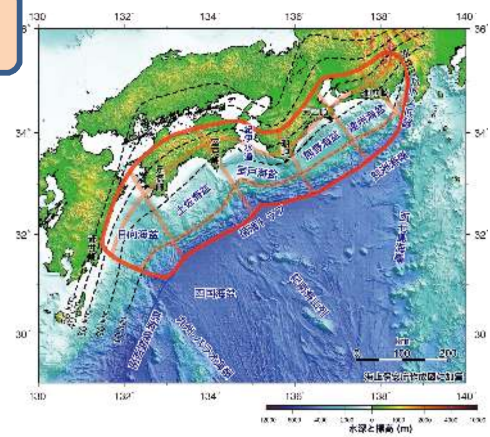
- Based on recent events with enough geophysical data
- Characteristic earthquake model (Similar size events repeat with similar interval)

Source Area

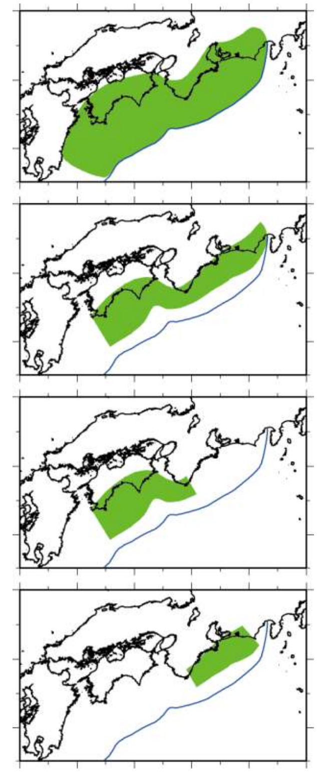
Next Event

	Size	30 yr prob
Tonankai	M~8.1	~ 50% (70-80% in 2013)
Nankai	M~8.4	~40% (60% in 2013)

Ver. 2 (May 2013)



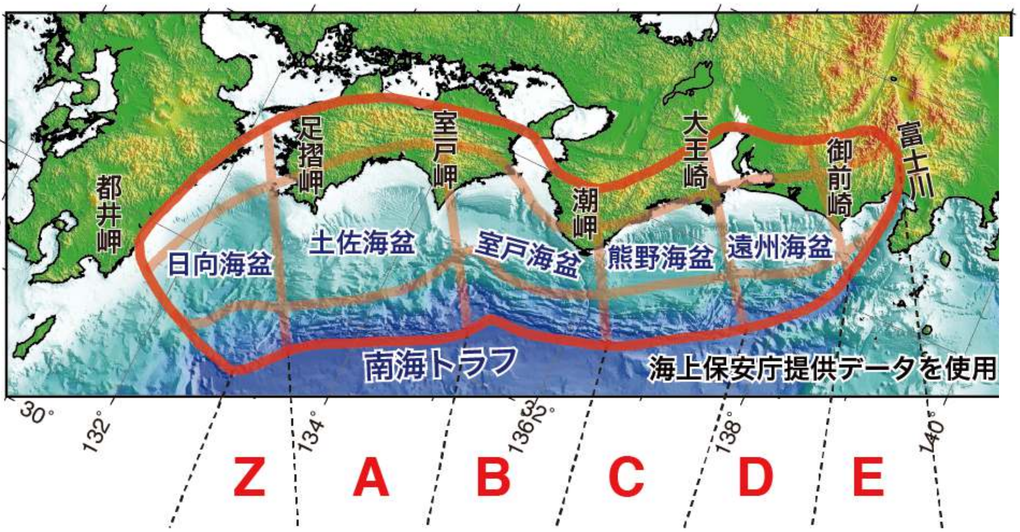
Maximum source based on geo-morphology, historical data, seismicity



Variability

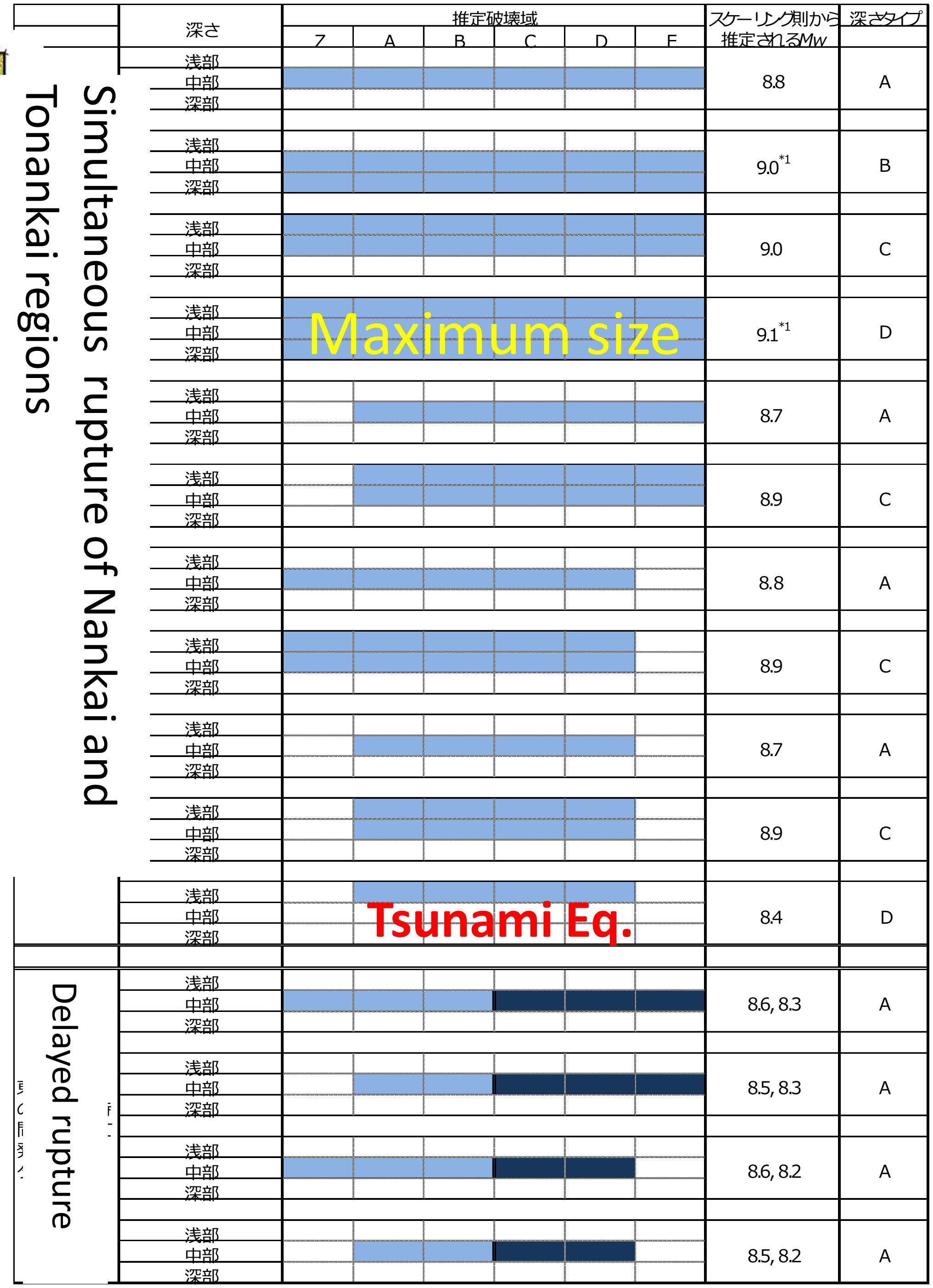
	Size	30 yr prob
Nankai Trough	M8～M9	60 - 70%

Long-term forecast of Nankai Earthquakes



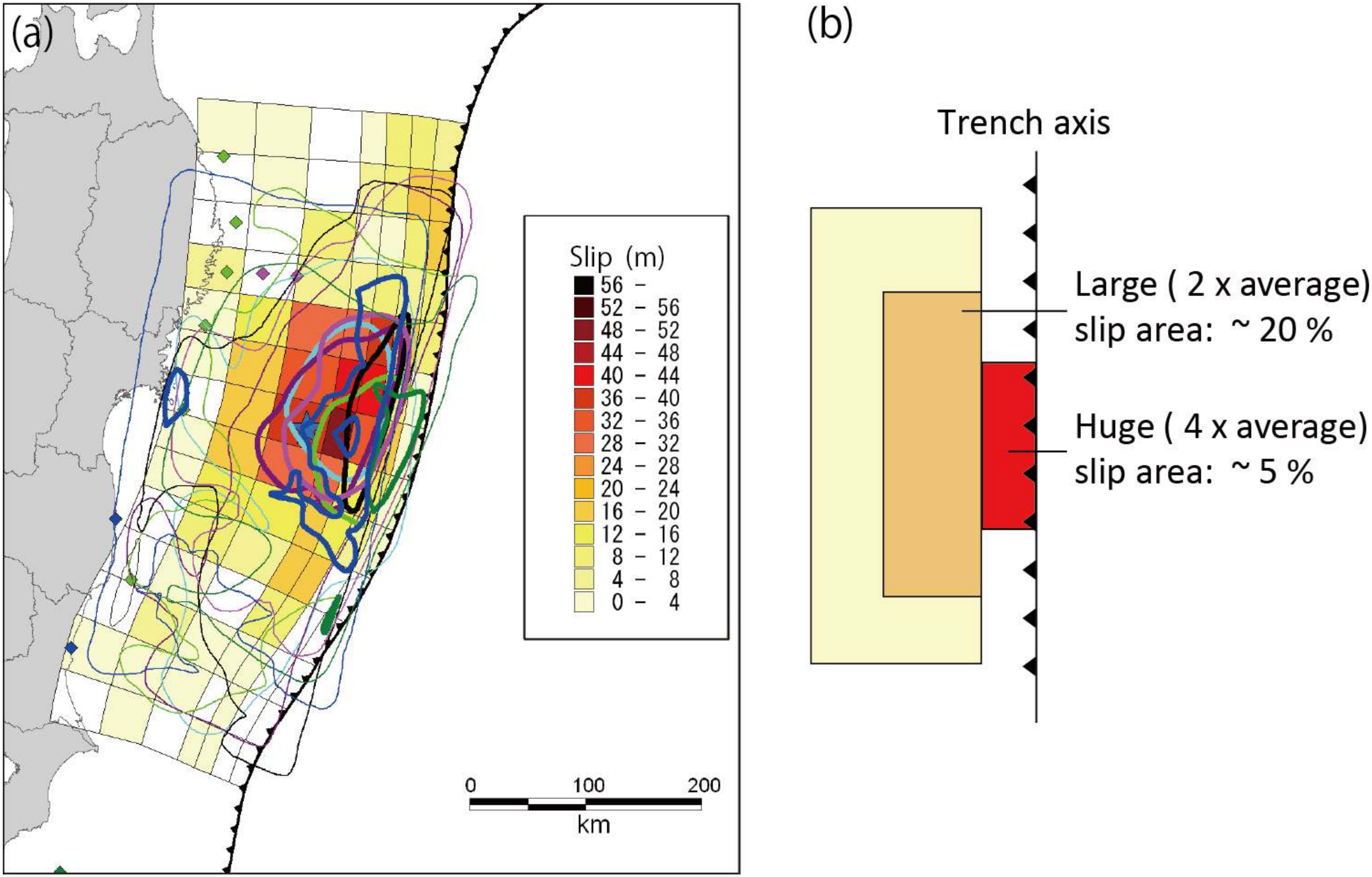
Historical data and tsunami deposits indicate variability of past earthquakes along Nankai trough

Various patterns such the entire part or a portion of seismogenic zone, or shallow part near trough axis are assumed



*1 内閣府（2011）強震動計算モデル
*2 内閣府（2011）津波計算モデル

The 2011 Tohoku earthquake

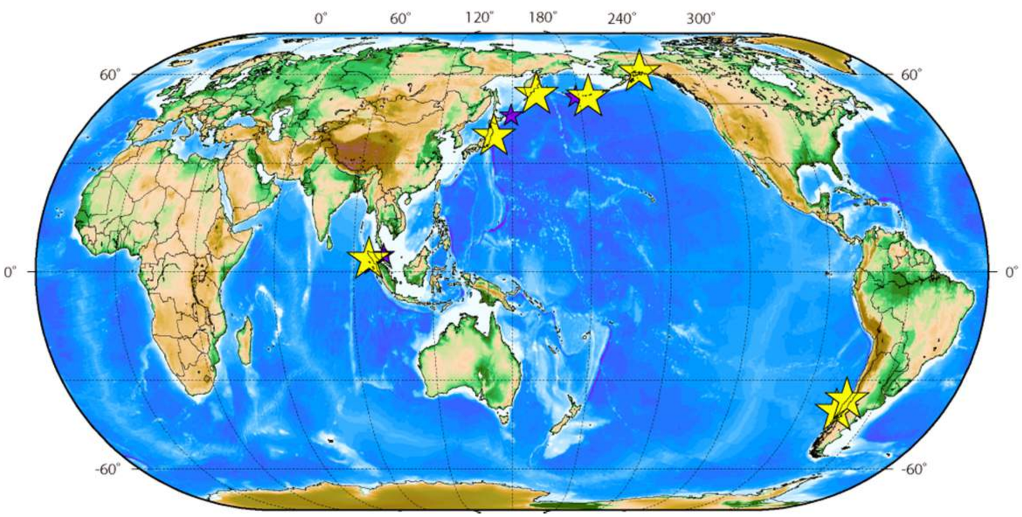


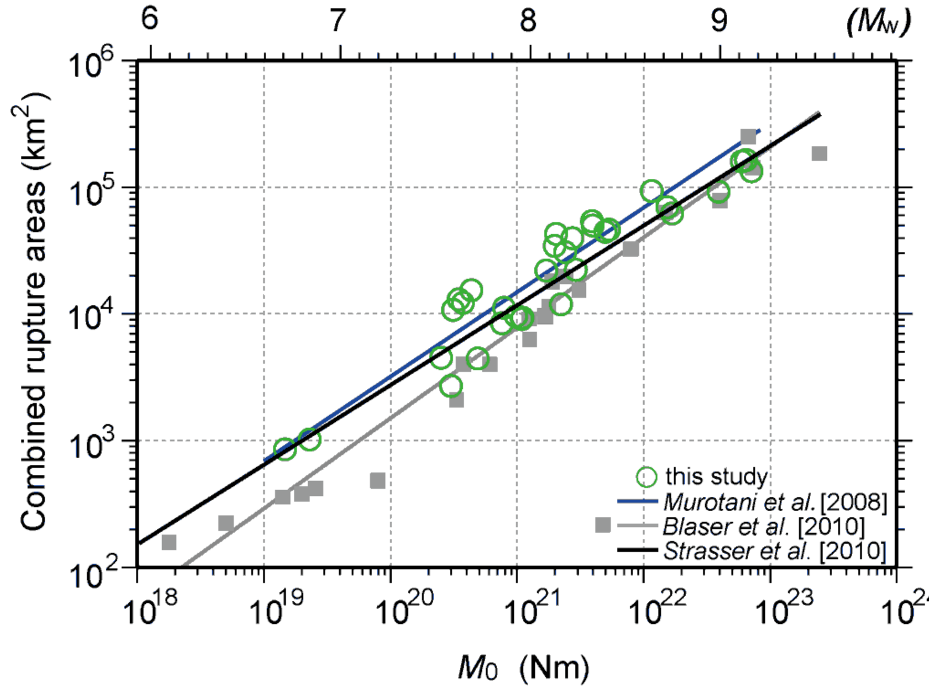
Central Disaster Management Council (2011)

Scaling Relations for Giant Plate-boundary Eqs

Murotani et al., 2013; GRL

- Data□7 giant eq. in the world and 25 models of 10 eqs. in and around Japan.
- Scaling relations for seismic moment, rupture are, average slip, and asperity area.





- Mw and average slip from total area
- Asperity size from Mw

  Asperity: large and huge slip areas
- Variable location of asperities

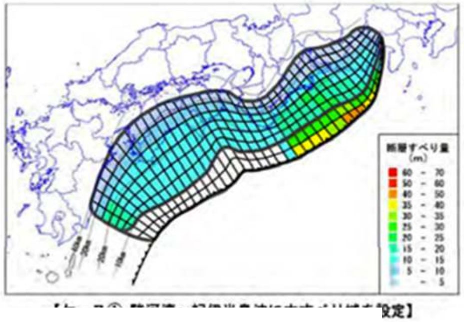
$S=1.34\times10^{-11}M_0^{2/3}$ (M_0:N□m)

$D=1.66\times10^{-7}M_0^{1/3}$ (D:m)

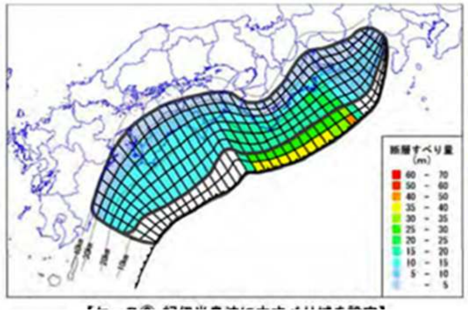
$Sa=2.81\times10^{-11}M_0^{2/3}$ (M_0:N・m)

$Sa/S=0.2$

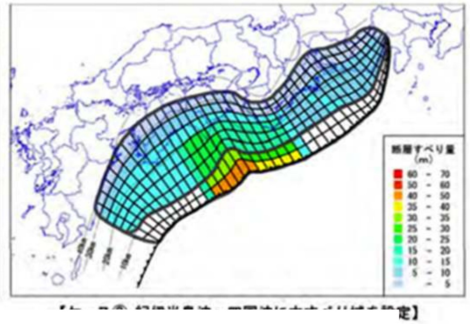
Various Slip Distributions for Nankai Earthquake



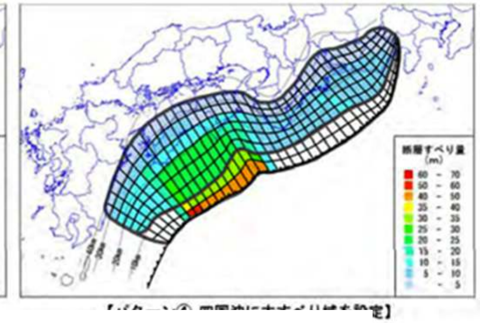
Case 1



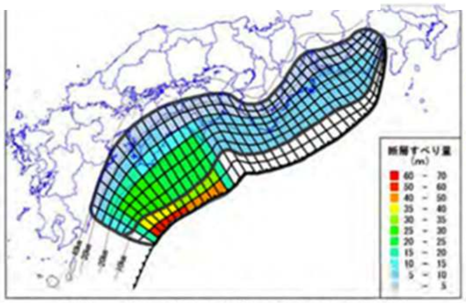
Case 2



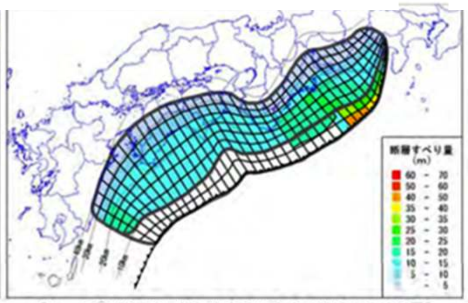
Case 3



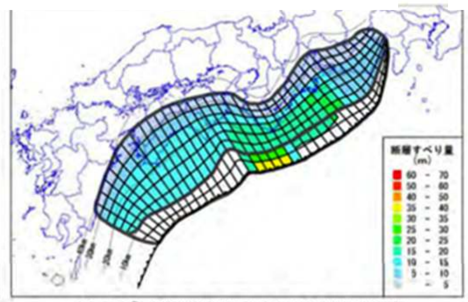
Case 4



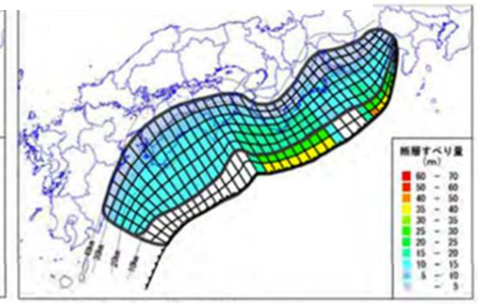
Case 5



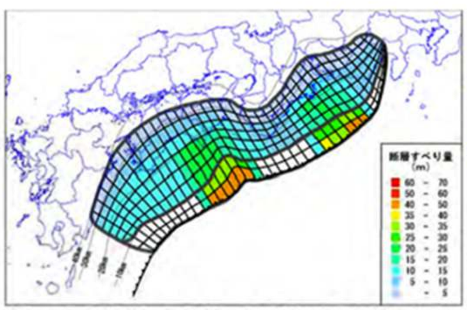
Case 6



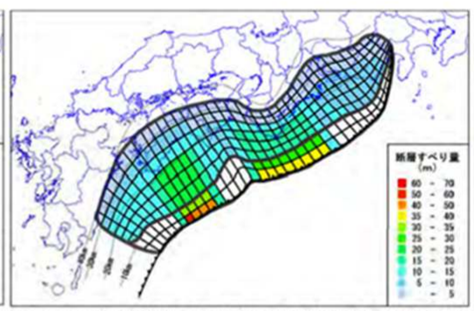
Case 7



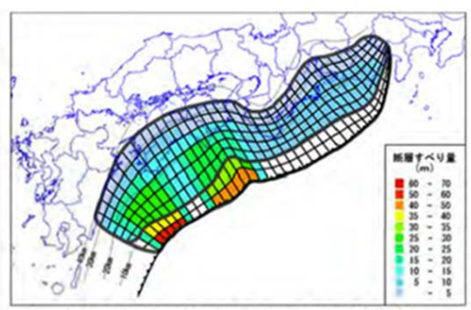
Case 8



Case 9



Case 10



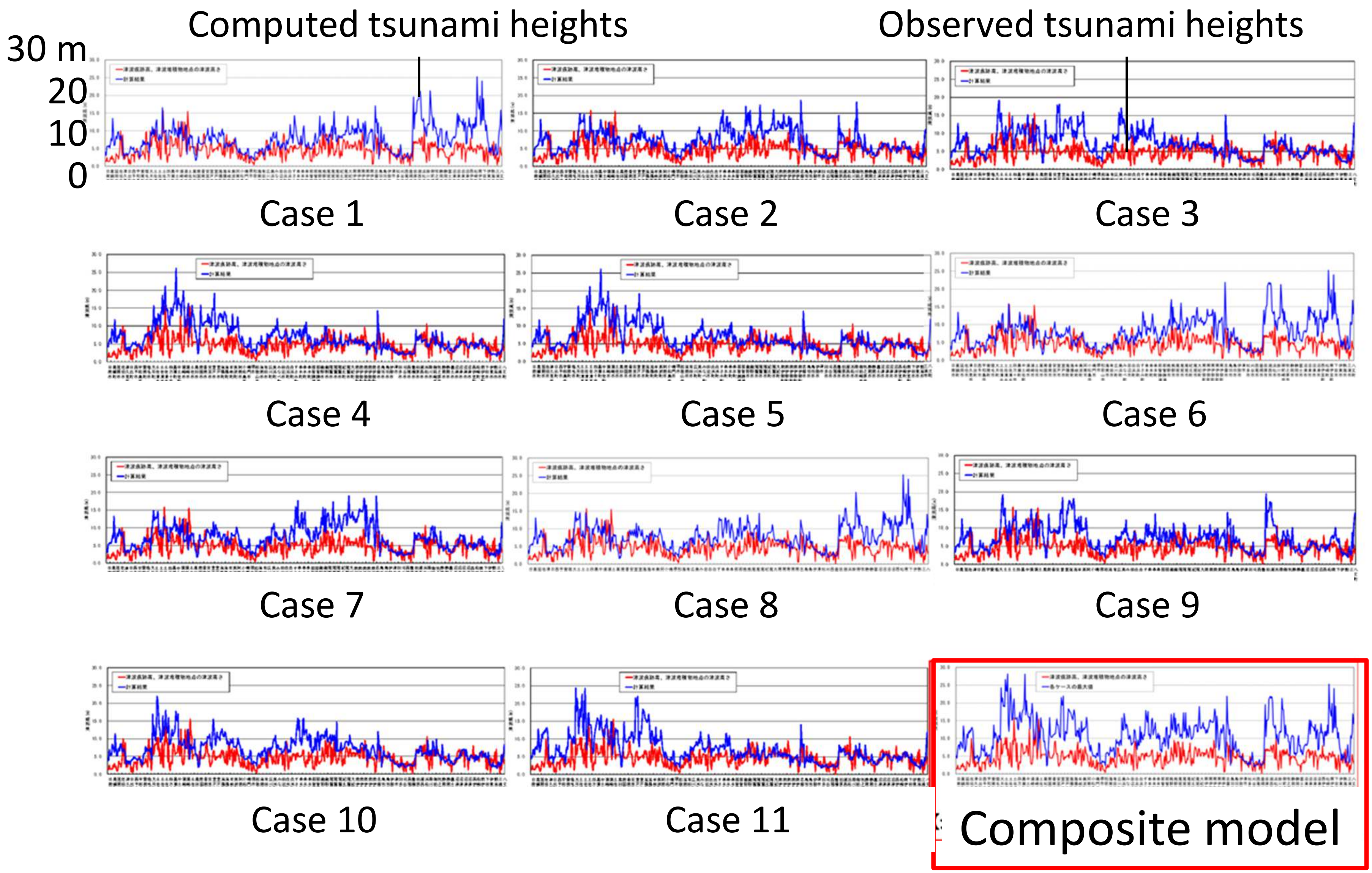
Case 11

Huge (4 x average) slip area: 0 - 10 %

Large (2 x average) slip area: 20 %

Cabinet Office, 2012

Tsunami Heights from Various Nankai Earthquakes



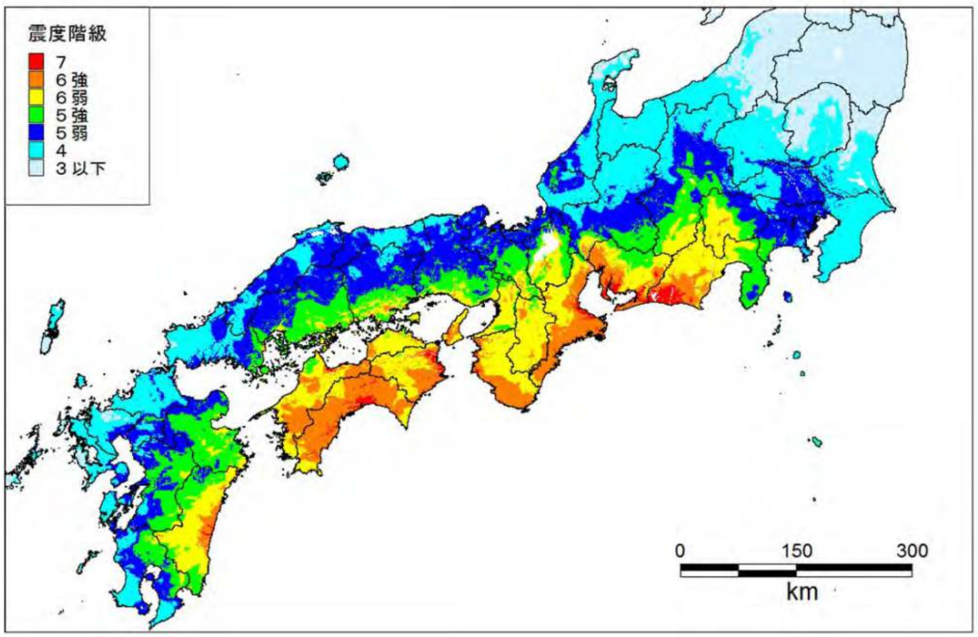
Huge (4 x average) slip area: 0 - 10 %

Large (2 x average) slip area: 20 %

Cabinet Office, 2012

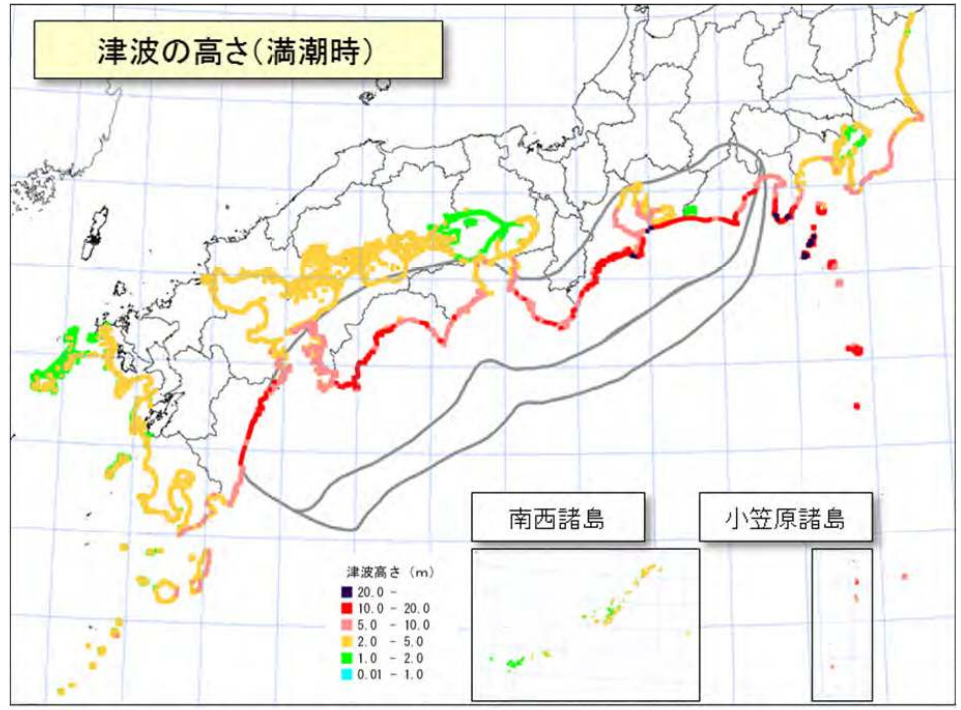
Damage (Loss) Estimate

Strong motion (seismic intensity)



陸側ケースの震度分布

Tsunami heights



【ケース①「駿河湾～紀伊半島沖」に大すべり域を設定】

Damage estimation
- economic damage 2.2 x 10^{14} yen (~2 trillion dollars)
- approximately 10 times 2011 damage, 40 % of GDP
- maximum casualties: 320,000

Cabinet Office, 2012

Nuclear Regulation Authority

Modeling interplate earthquakes need to consider

(1)Maximum width

(2)Land displacements at site

(3)Combination of segments

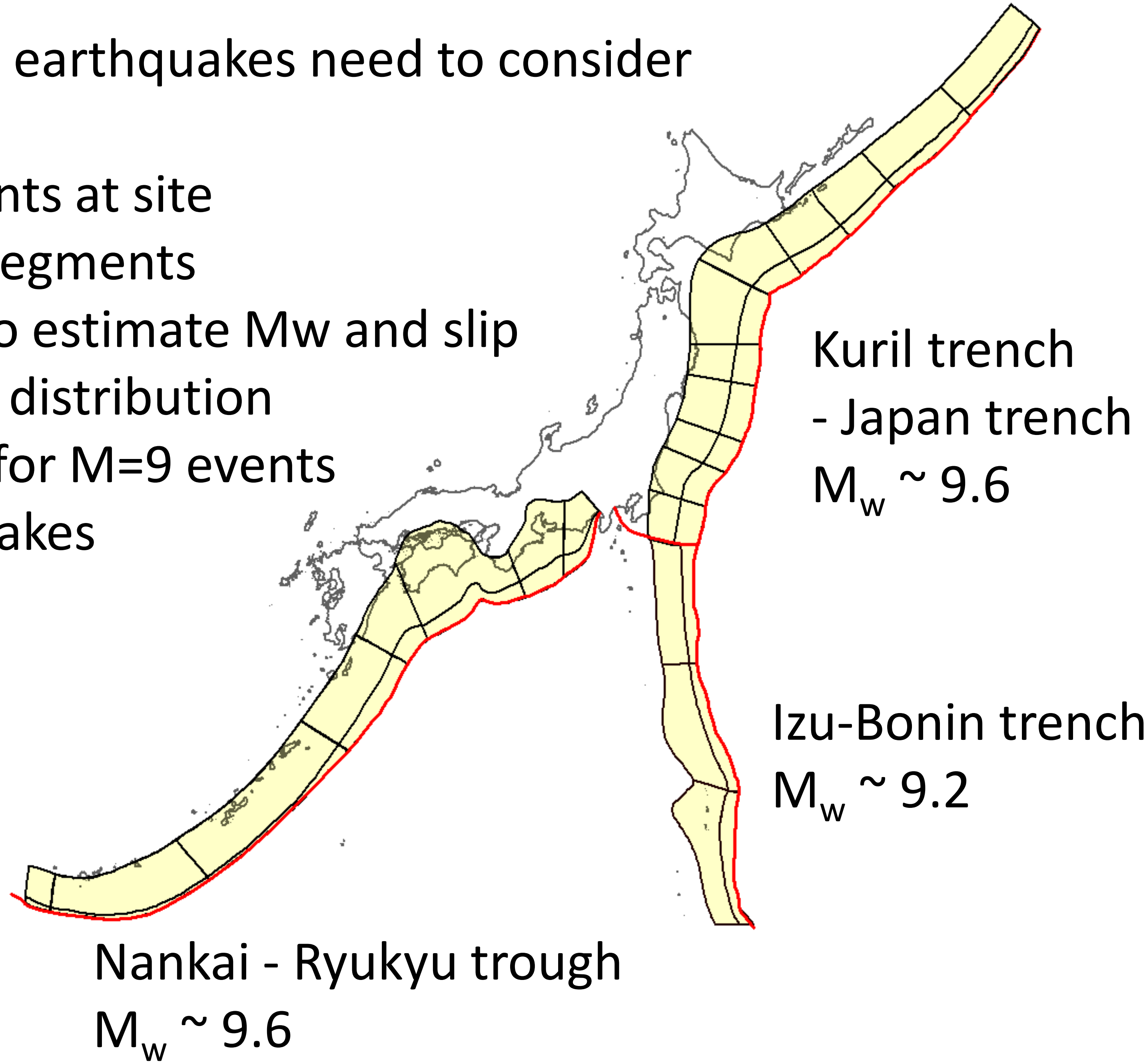
(4)Scaling relation to estimate Mw and slip

(5)Non-uniform slip distribution

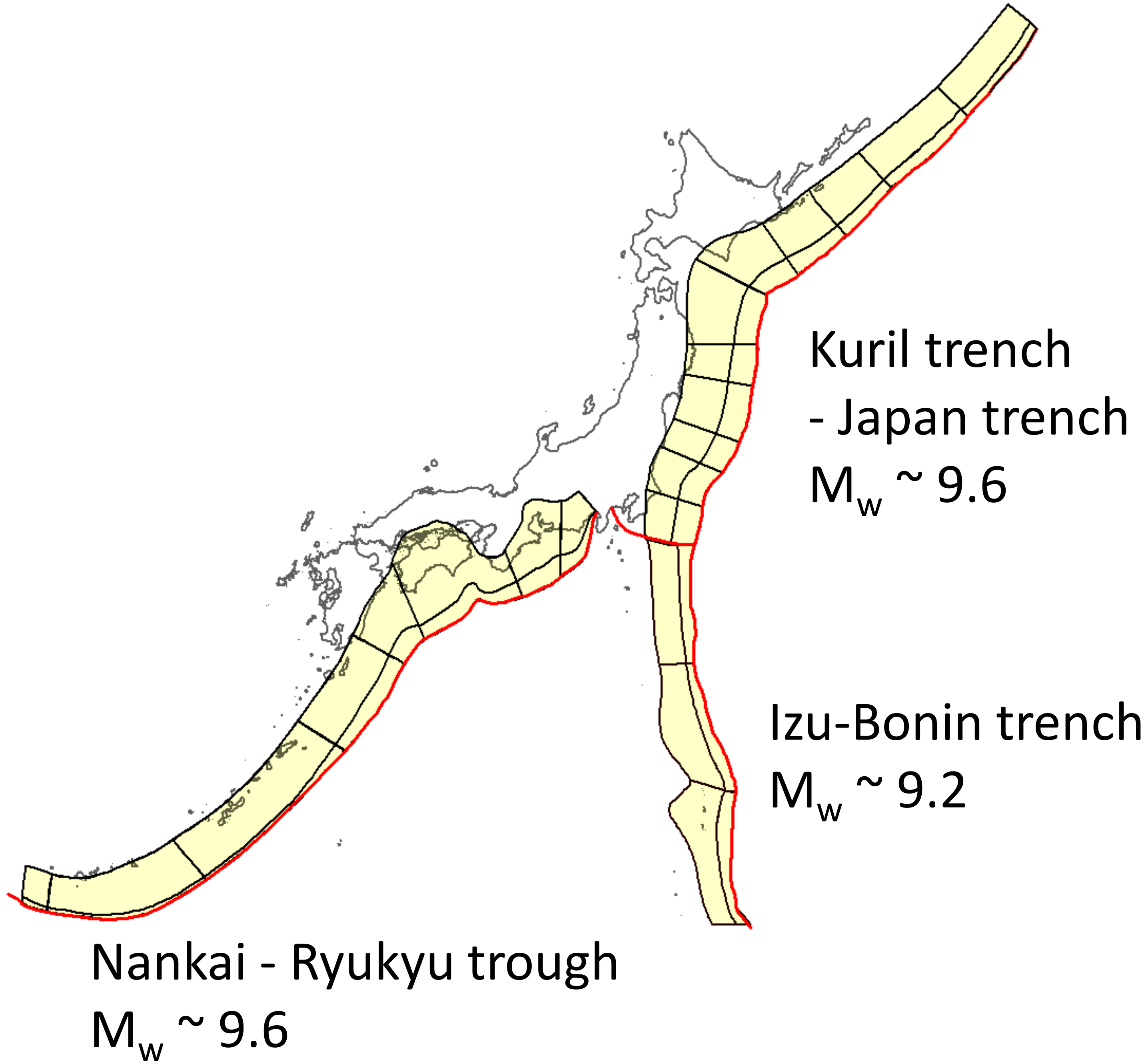
(6)Rupture pattern for M=9 events

(7)Tsunami earthquakes

(8)Splay faults

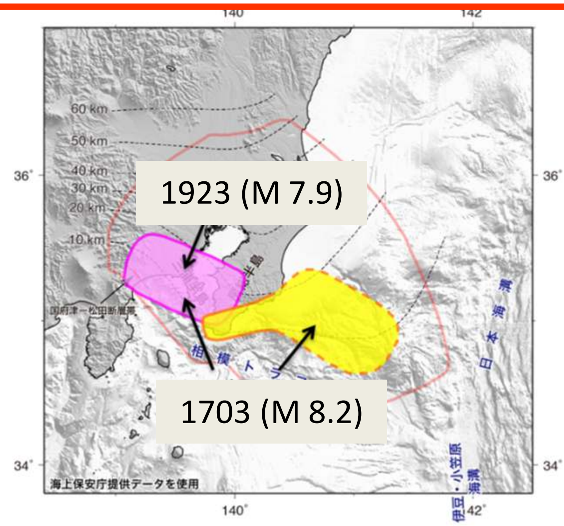


Nuclear Regulation Authority



ERC forecast of large earthquakes in Sagami Trough

Previous (2004)



- Two types of characteristic eqs.

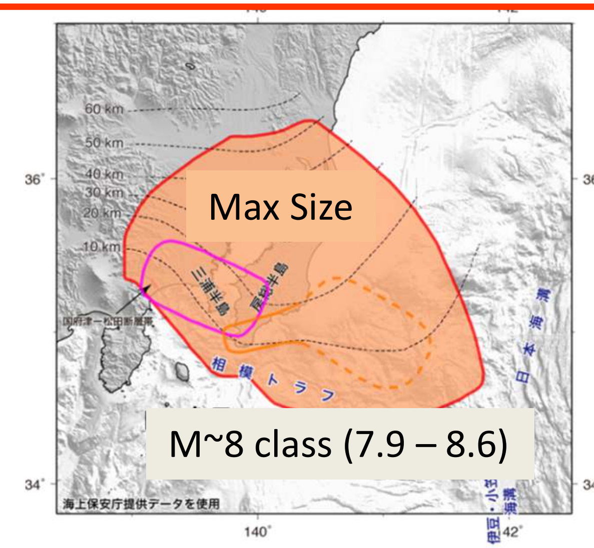
	Size	30-yr prob
1703 type	M ~ 8.1	~ 0 % (~ 0%)
1923 type	M~ 7.9	0 - 0.8% (0 – 2 %)

1703 (Genroku) and 1923 (Taisho) types
Probability in () is as of 2014

Source Area

Next Event

Recent (2014)



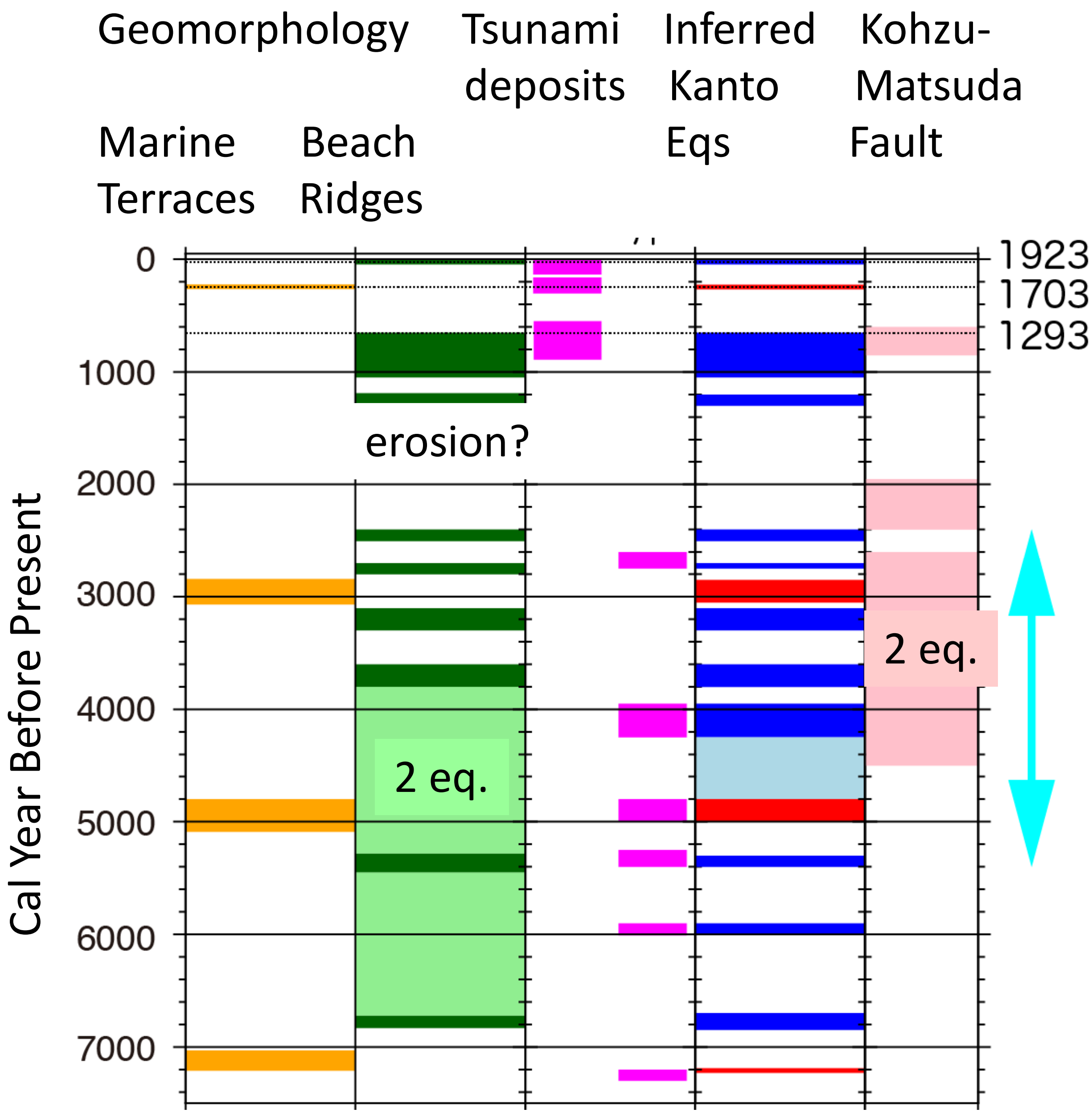
- Maximum source area
- Variable size of earthquakes

	Size	30-yr prob
M~8 interplate earthquake	Entire region (M7.9 - 8.6)	0 - 5%(※)
	1703 (M 8.2) or larger	~ 0%

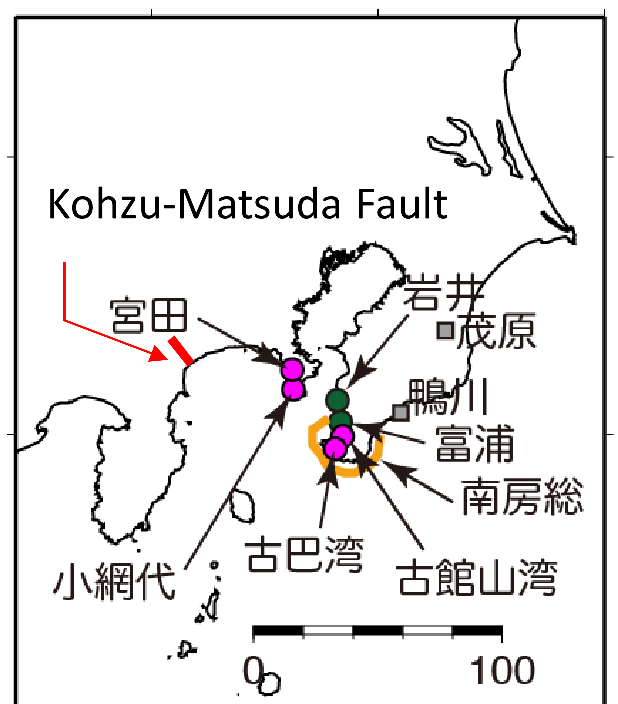
Size and probability have uncertainties

※ Range based on statistical analysis

Earthquake Res. Comm. (Government of Japan) Long-term forecast of Large Eq. along Sagami Trough



Paleoseismological Evidence
● : Beach ridges
● : Tsunami Deposits
◯ : Marine terrace

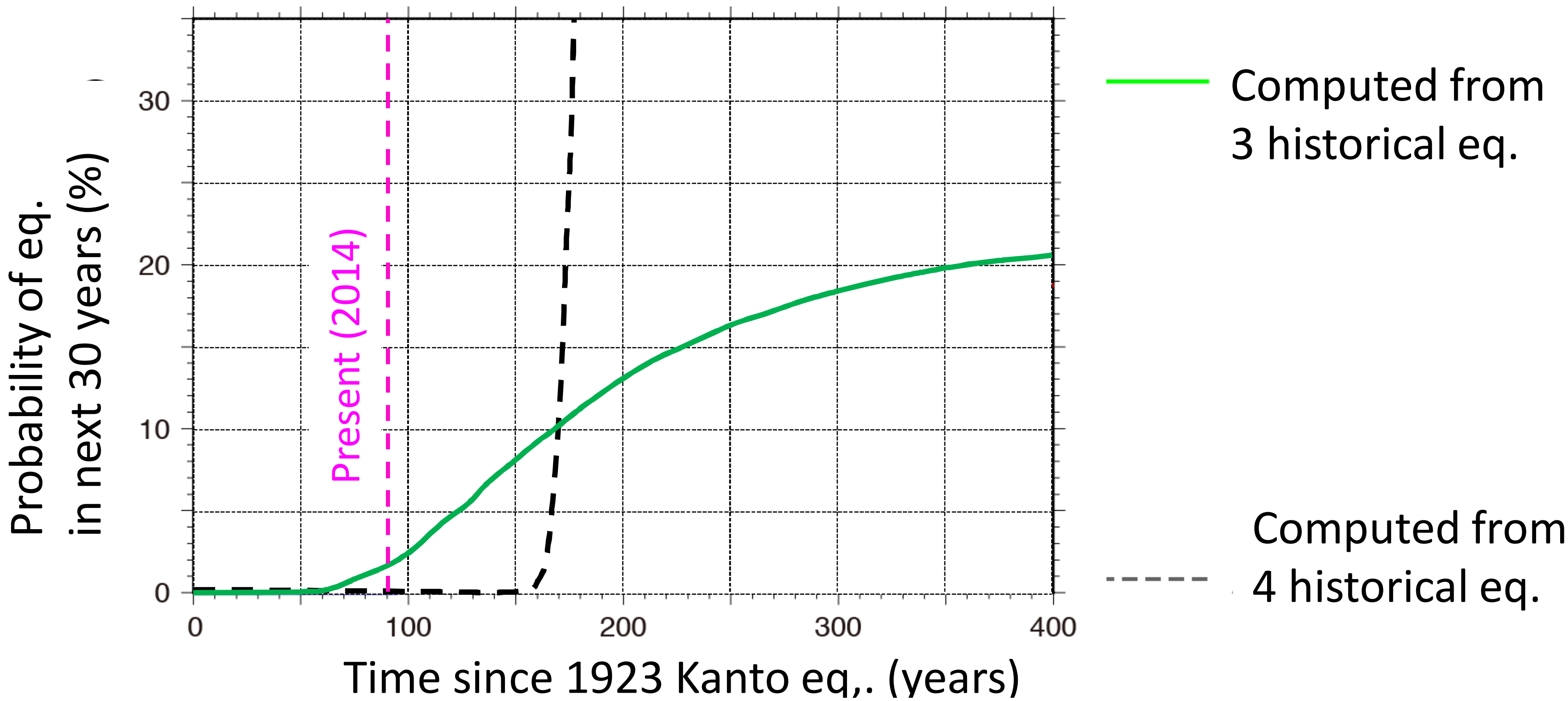


If the 1495 event was Kanto earthquake

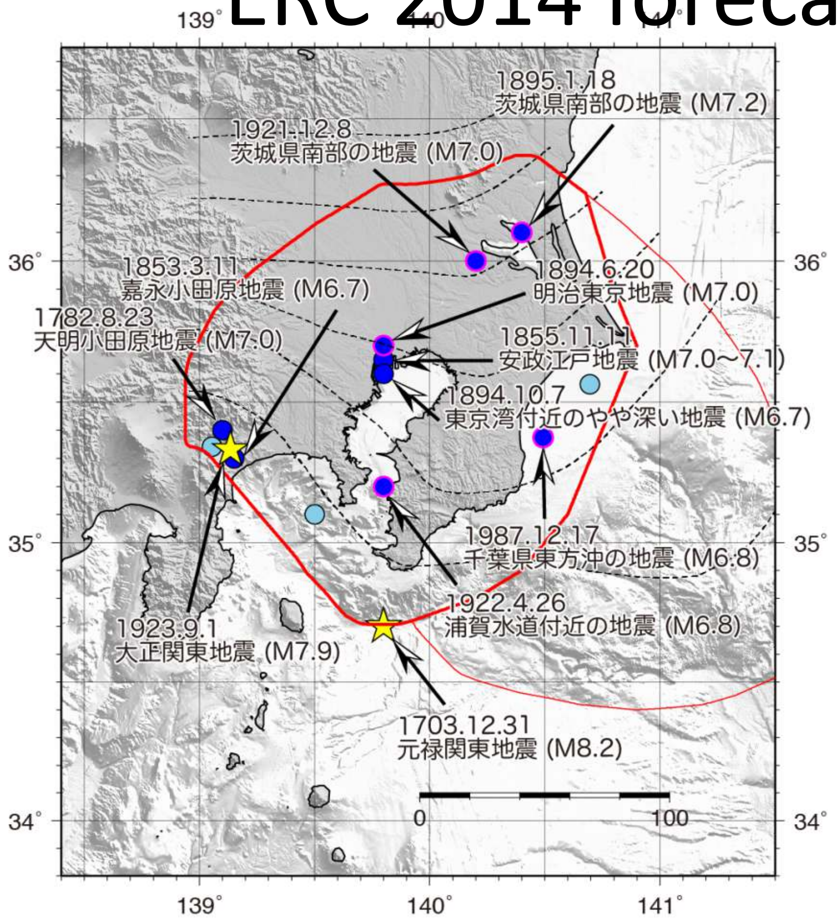
1293	–	1495	–	1703	–	1923
	202yrs		208 yrs		220yrs	

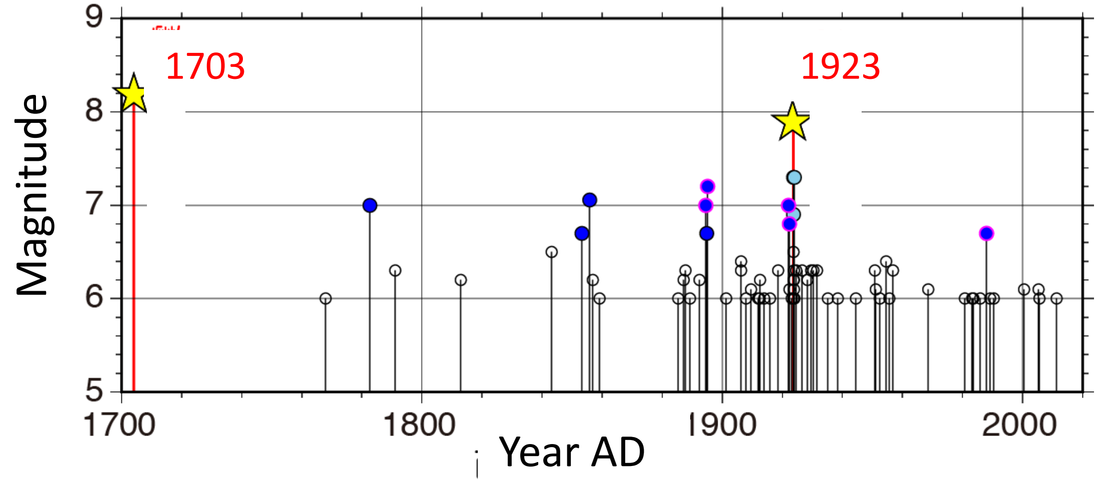
Long-term forecast by Earthquake Research Committee (2014)

	Ave Interval	α	30-yr prob BPT with α	30-yr prob Poisson
3 eqs.	315 yrs	0.45	2 %	9 %
4 eqs.	210 yrs	0.04	0 %	10 %



ERC 2014 forecast for M~7 earthquakes





●	: Earthquakes counted in 2014 forecast
●	: Aftershocks of 1923 Kanto eq.
○	: Earthquakes counted in 2004 forecast
☆	: Interplate eqs. Of M ~ 8

※ Shallow crustal earthquakes are not included

Next earthquake

Previous (2004)

	Size	30-yr prob
Other eqs in southern Kanto	M6.7～7.2	70 %

1885 to 2004 5 events

Average interval 23.8 yrs

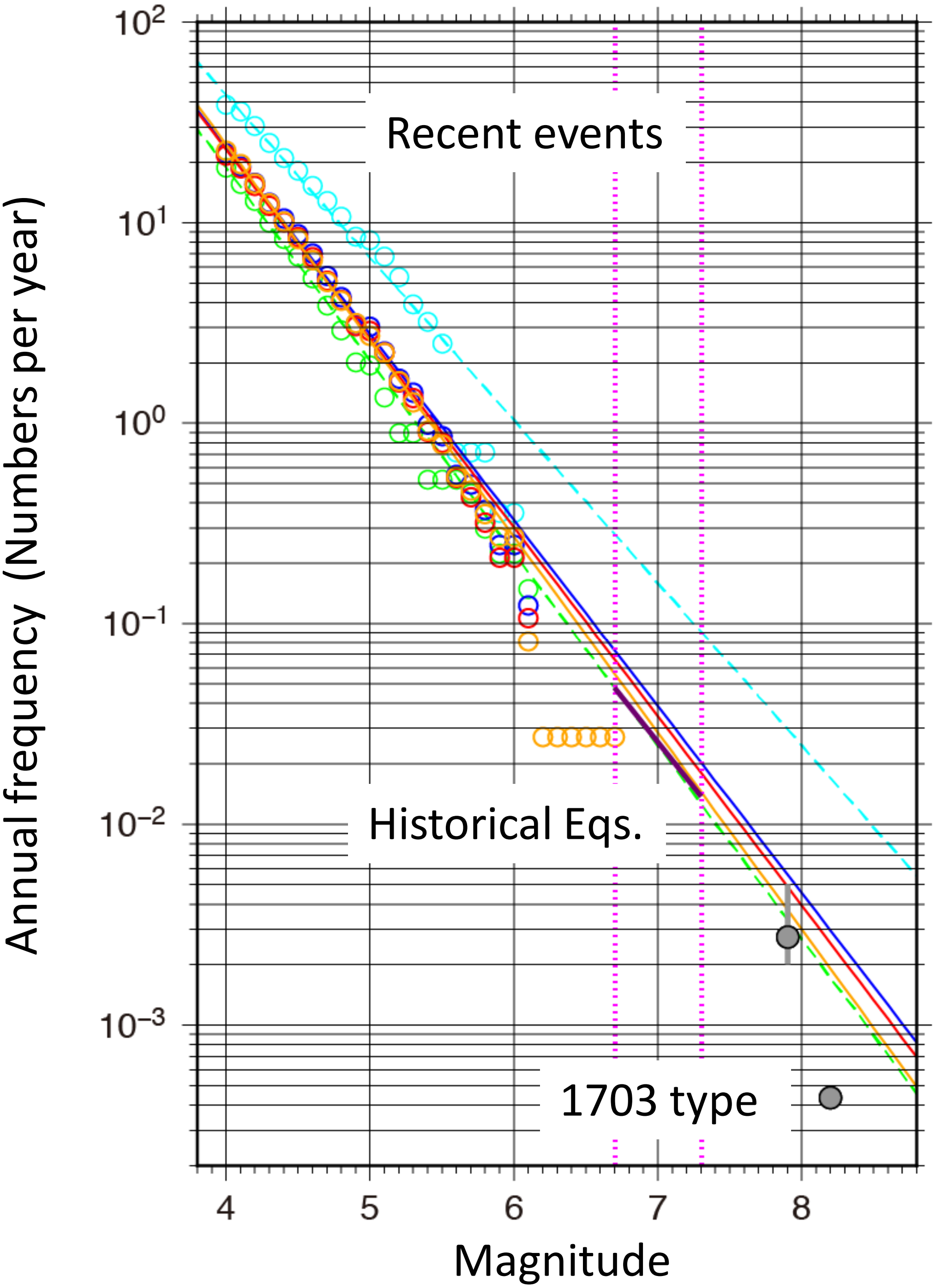
Recent (2014)

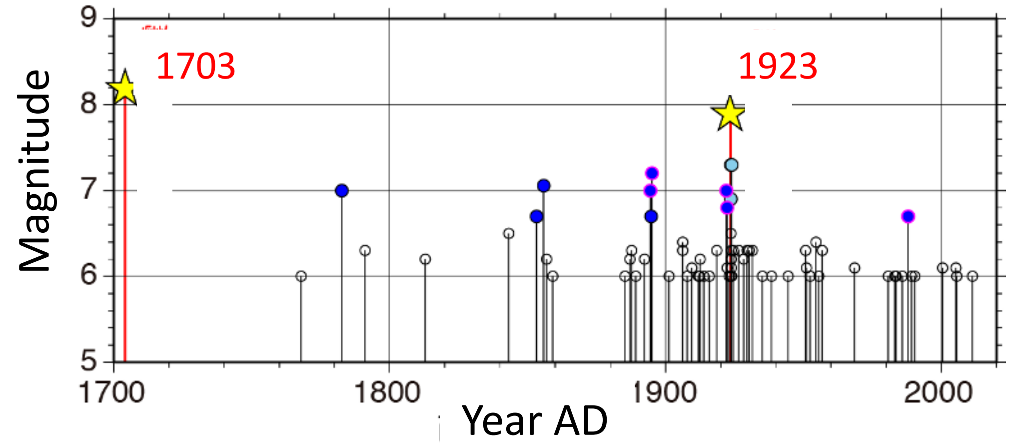
	Size	30-yr prob
M~7 eq. related to subduction	M7 (M6.7～7.3)	70 %

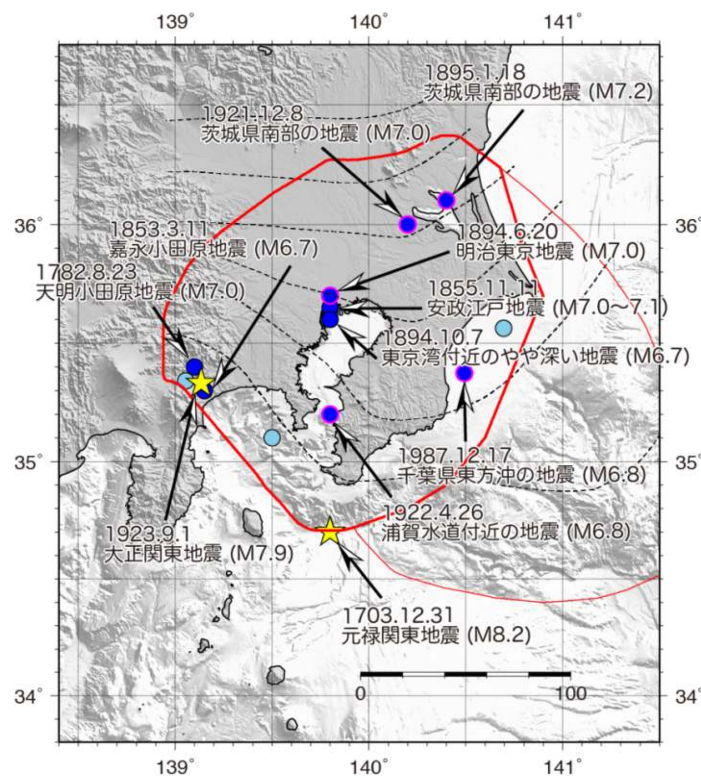
1703 to 2014: 9 events
1703 to 1923: 8 events

Average interval 27.5 yrs

ERC 2014 forecast for M~7 earthquakes



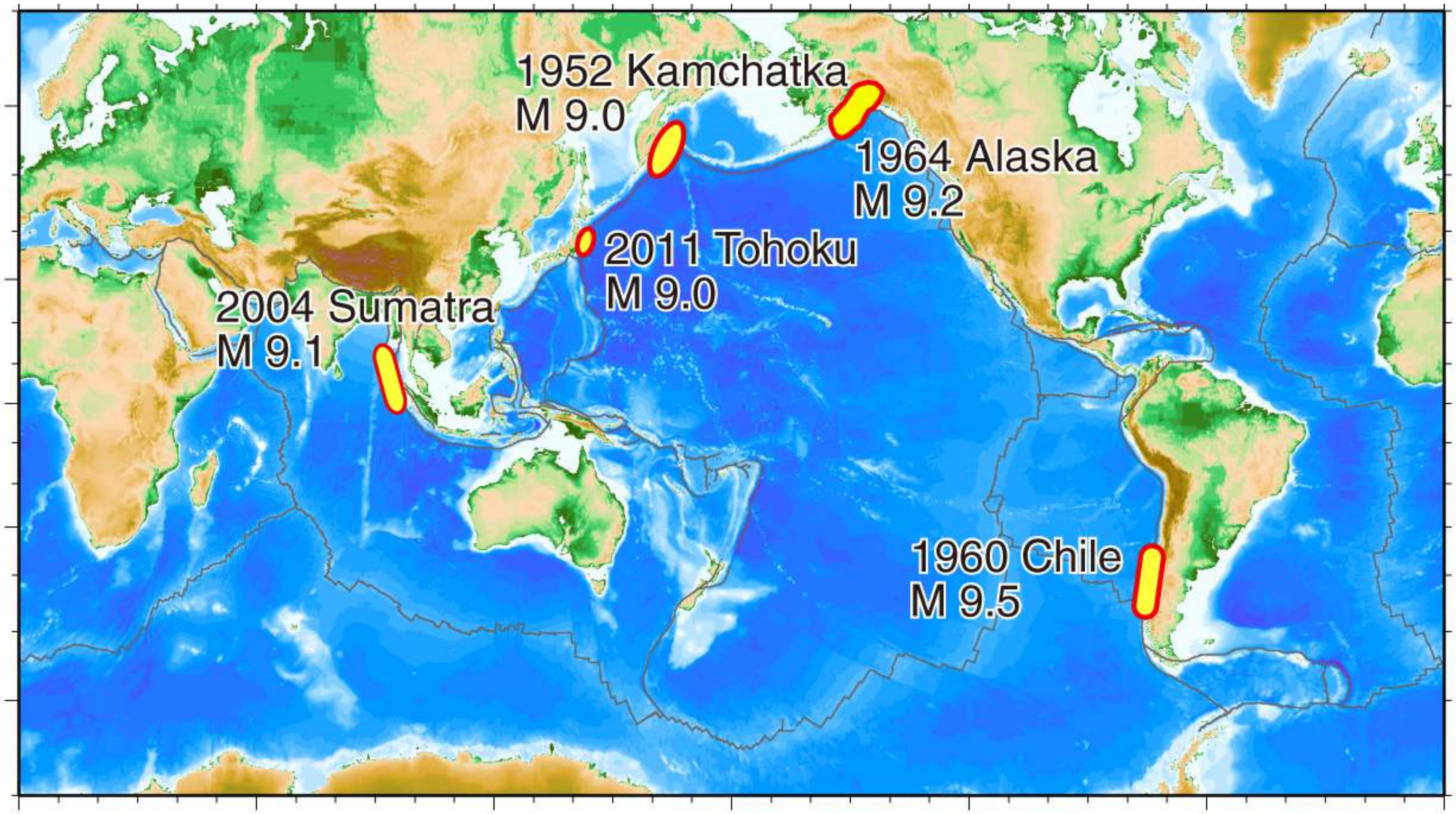


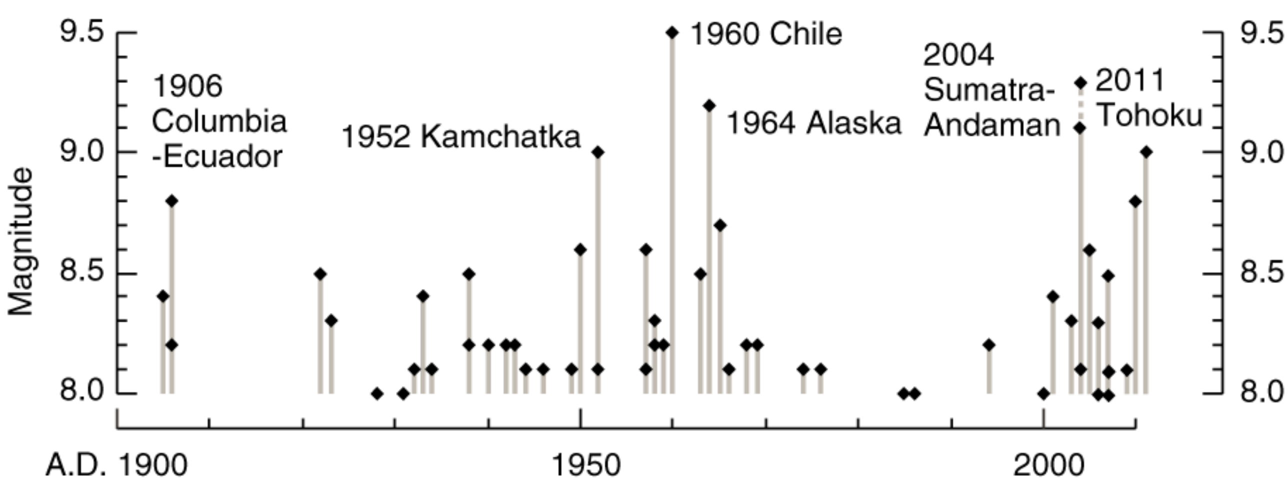


Outline

1. The 2011 Tohoku Earthquake
2. Long-term forecast in Japan before 2011
3. Long-term forecast in Japan after 2011
4. Great earthquakes in the world

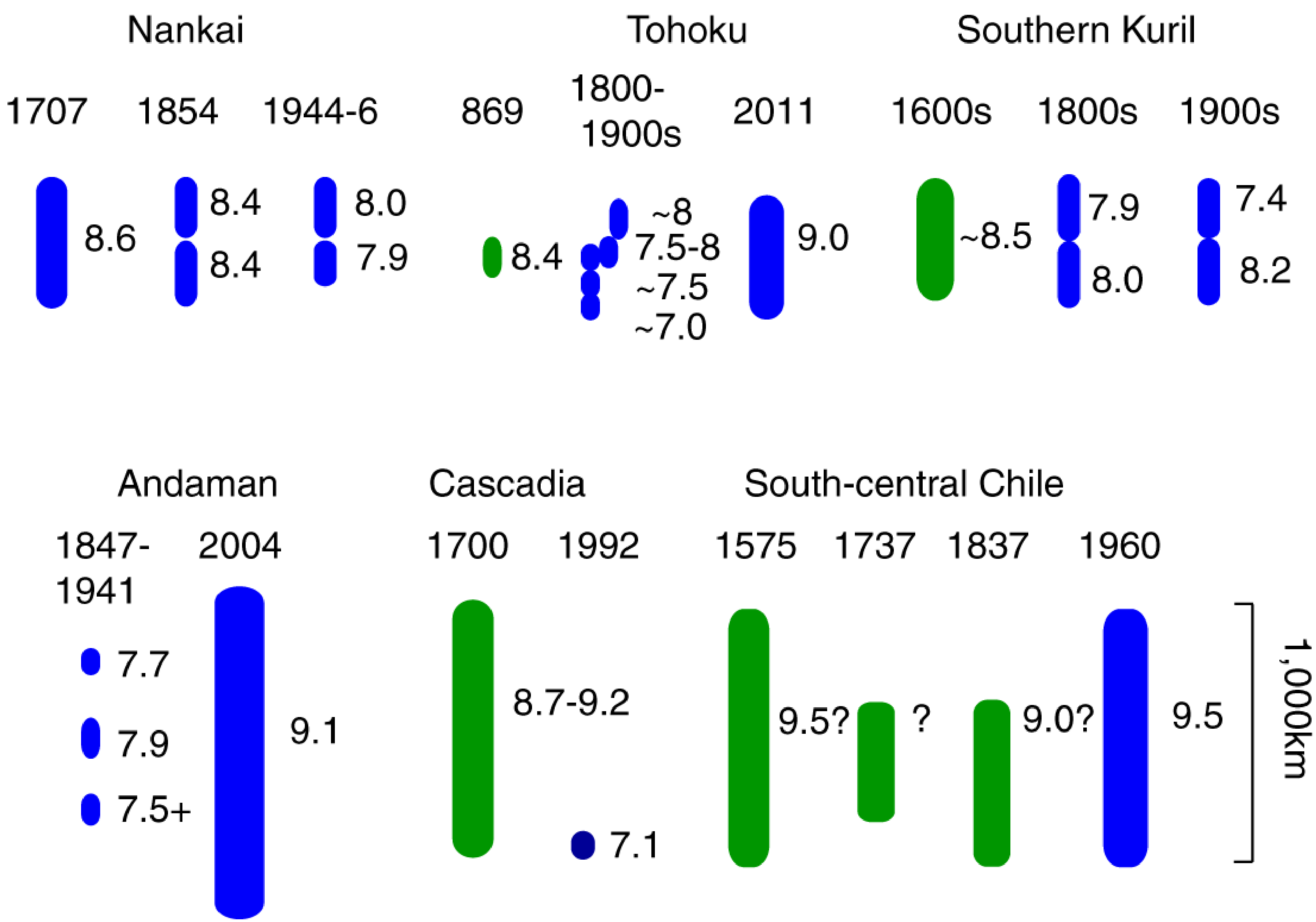
Giant earthquakes in the world





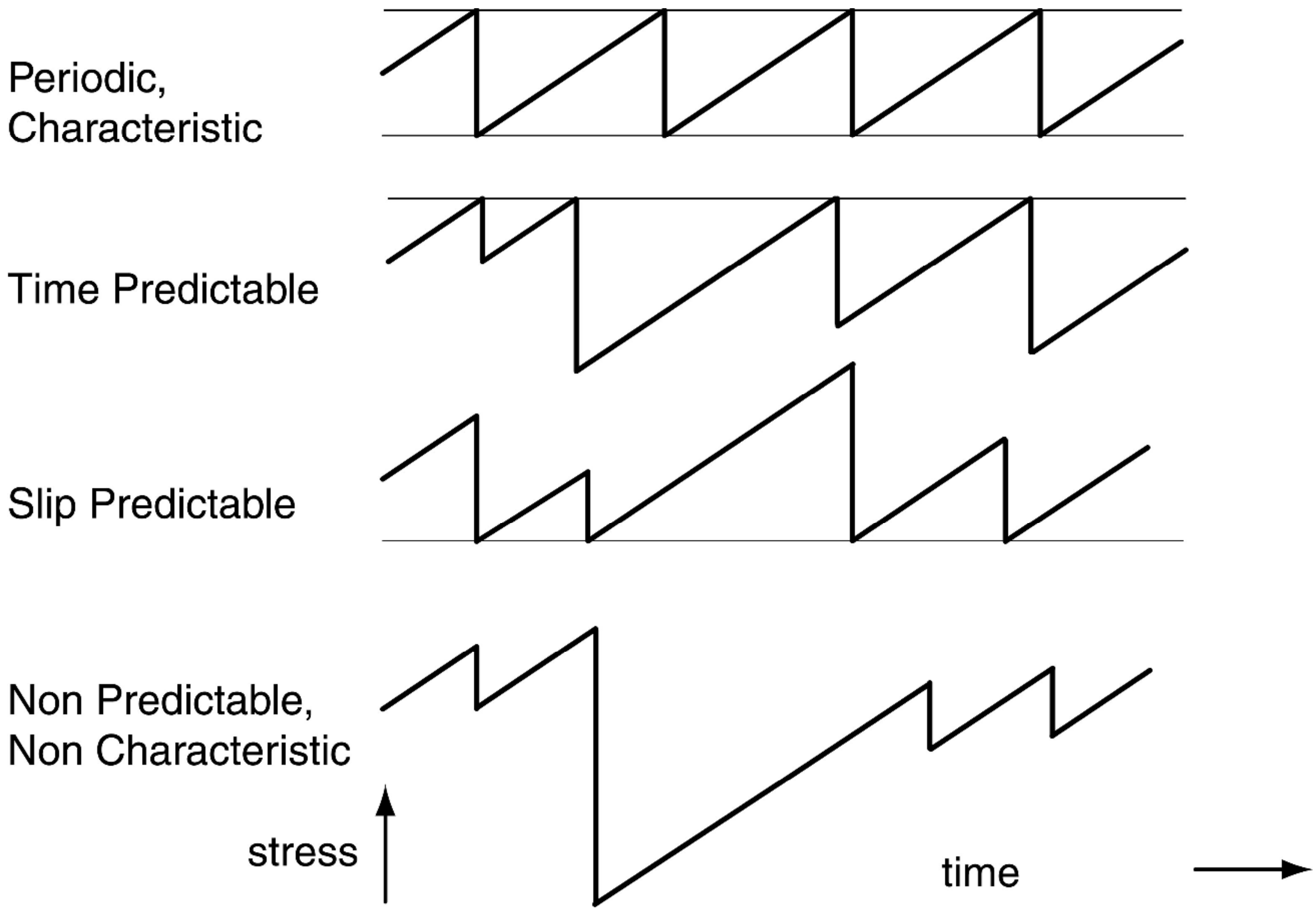
Satake and Atwater (2007) updated

Giant earthquakes in the world



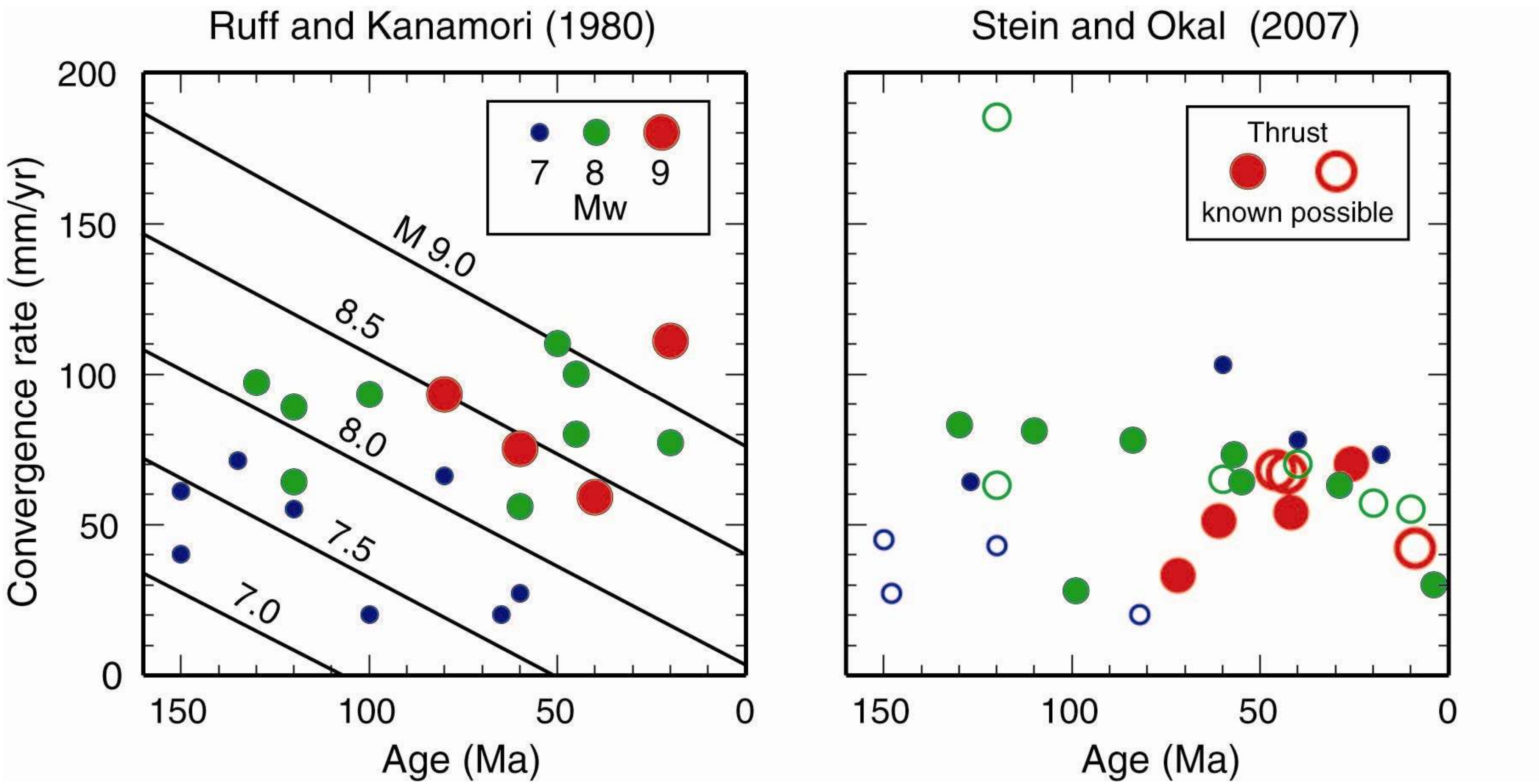
Satake and Atwater (2007 Ann. Rev. Earth Planet .Sci.) updated

Time and slip predictable models



Modified from Shimazaki and Nakata (1980)

Maximum earthquake size



McCaffrey (2008)
Global frequency of M 9 earthquakes

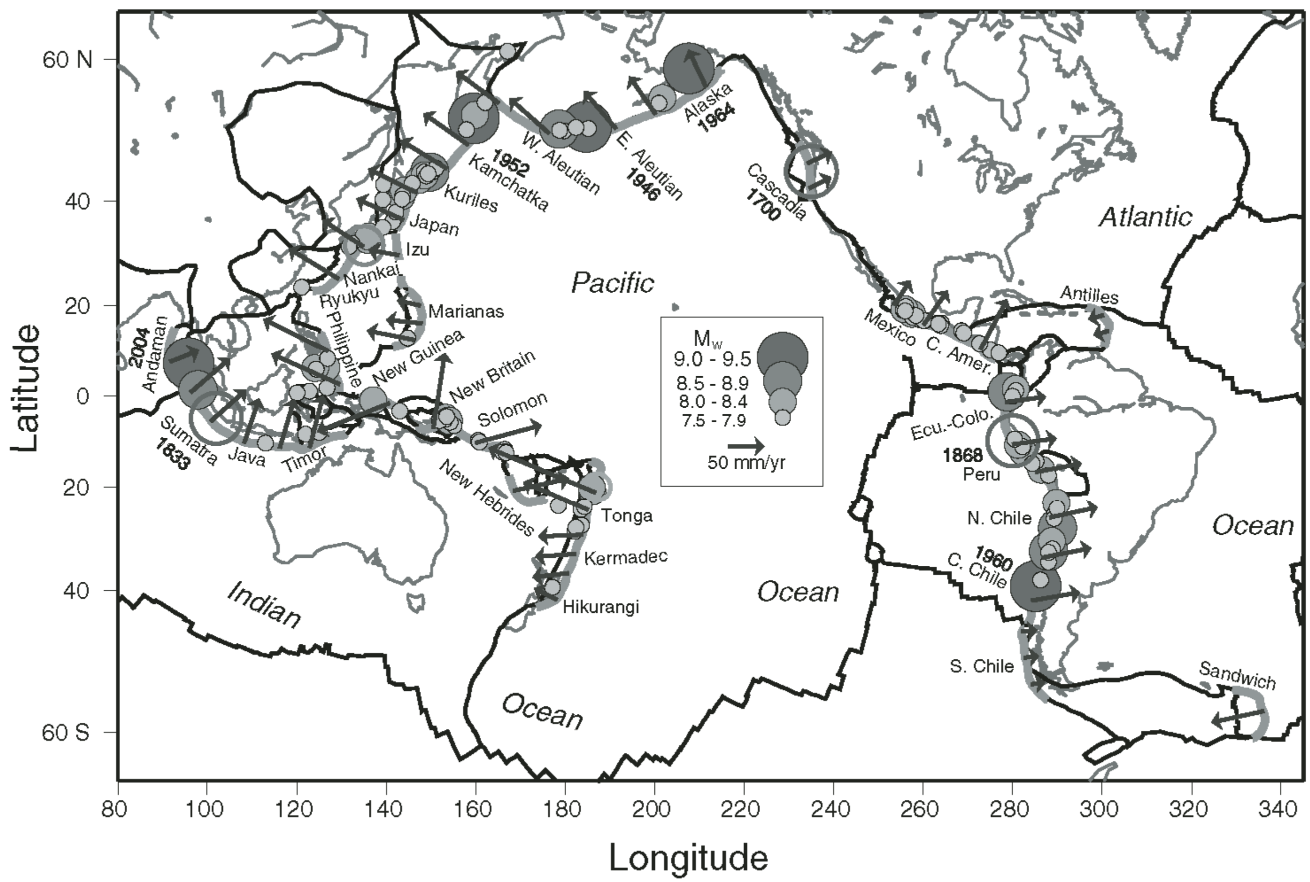
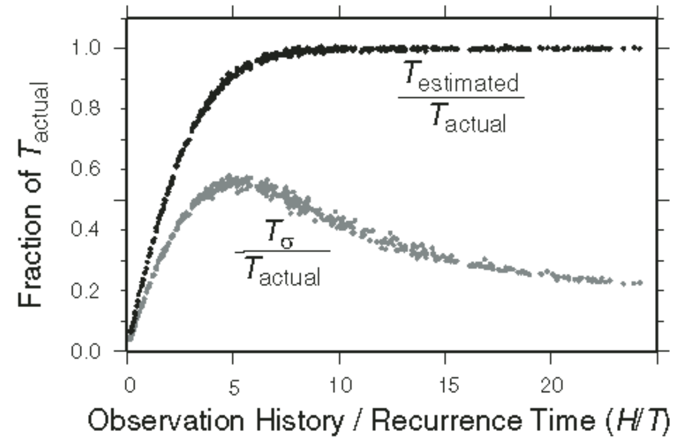
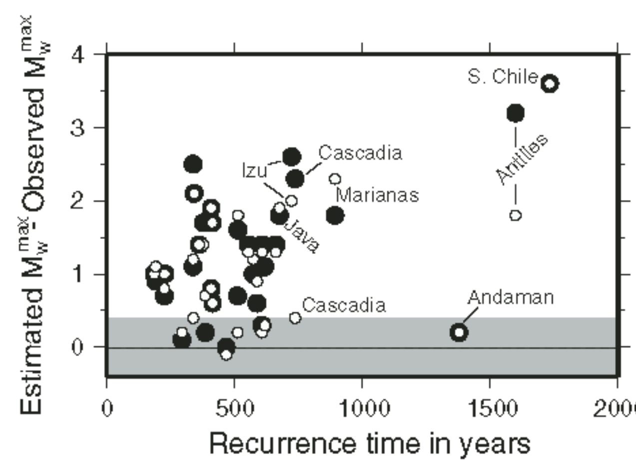


Figure 1. Map of world's major subduction zones (thick gray lines) and tectonic plate boundaries (Bird, 2003). Filled circles show locations of known earthquakes of $M_w \geq 7.5$ or greater since 1900 (circle radius and grayscaled by magnitude). Open circles are largest known earthquakes from A.D. 1700 to 1900 (compiled by Stein and Okal, 2007). Arrows show horizontal velocity of subducting plate relative to overriding plate. Dates are given for all M9 quakes.

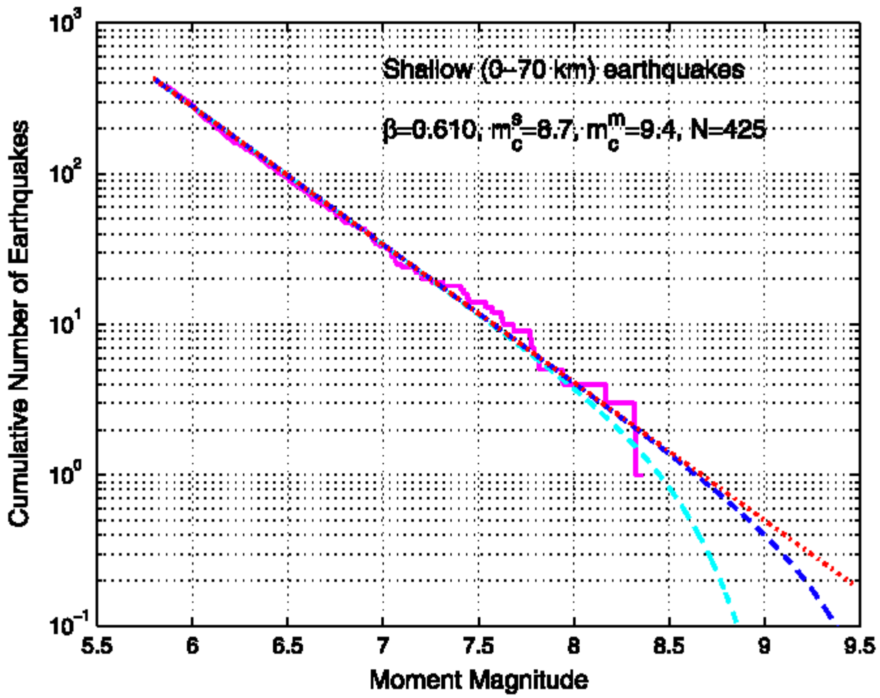


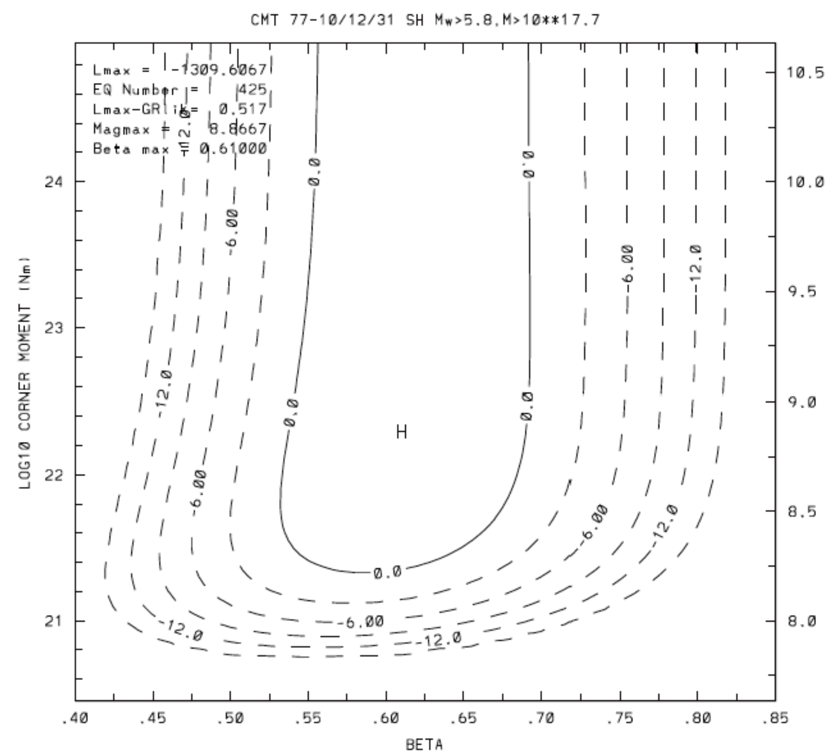


Faster subduction ➡ shorter recurrence interval ➡ more chance to be observed

Slower subduction ➡ longer recurrence interval ➡ less chance to be observed

Kagan and Jackson (2013)
Tohoku earthquake: A surprise ?





Observed (Global CMT catalog)

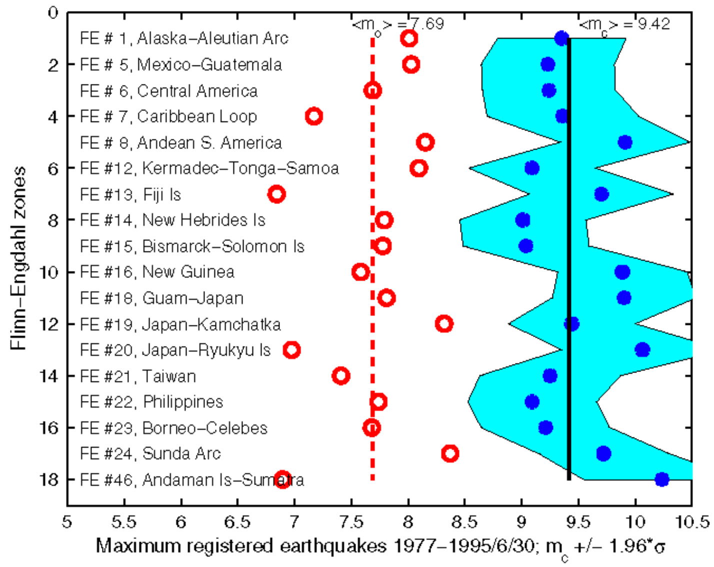
Gutenberg-Richter

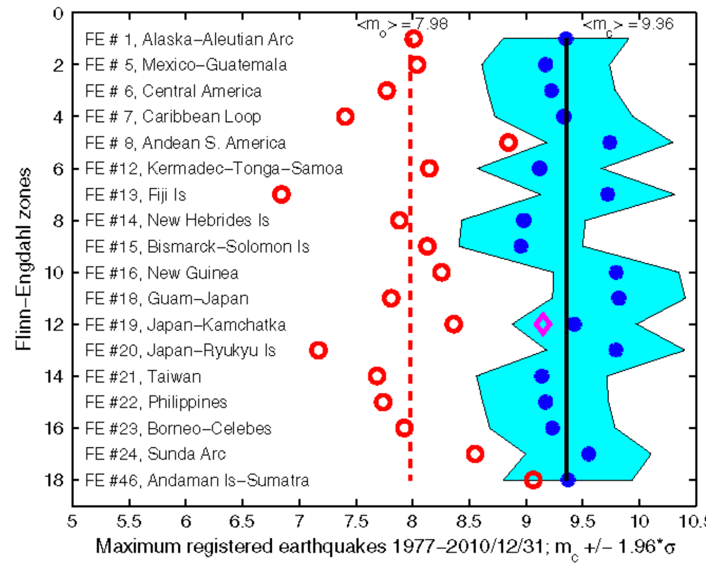
Tapered GR $m_c^s = 9.4$

Tapered GR $m_c^s = 8.7$

Maximum likelihood estimate of parameters β and m_c

Kagan and Jackson (2013)
Tohoku earthquake: A surprise ?





Global catalogs for different period

(A) 1977-1995

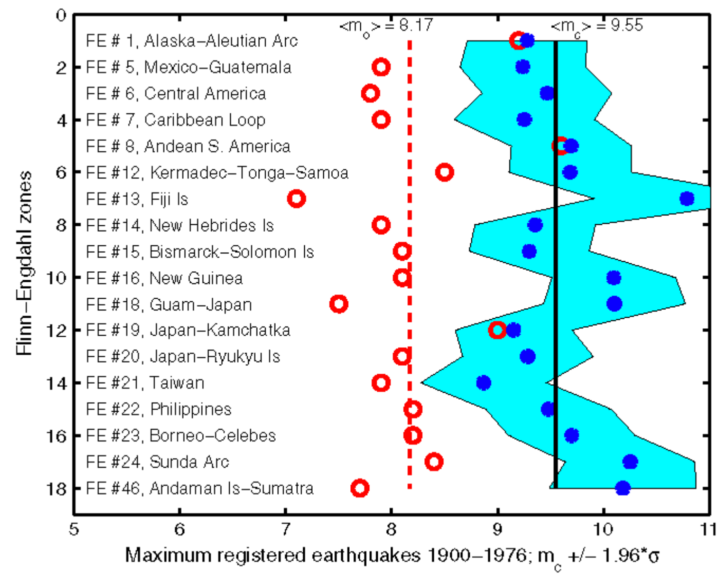
(B) 1977-2010

(C) 1900-1976

Longer period give larger m_o and m_c

m_o: observed magnitude

m_c: corner magnitude



Summary

- The 2011 Tohoku earthquake was the largest (M~9) in Japan’s written history. It was a combination of the 869 Jogan-type source and the 1896 “tsunami earthquake” type events.
- Long-term forecast, based on characteristic earthquake mode, estimated 99 % probability but M~8 in Miygai-oki.
- Variability in earthquake recurrence, including the estimate of probable maximum size, need to considered in long-term forecast.

Methods of M_{max} Estimation East of the Rocky Mountains

R.L. Wheeler

USGS Open File Report 2009-1018

1. Mmax equals Largest Observed M in a Source Zone (Mobs)
2. Mmax equals Mobs plus an Increment
3. Mmax from Seismicity Rate
4. Mmax from Magnitude-Frequency Extrapolation of Historical Record
5. Mmax from the Saturation Magnitude of Mb, approximately 7.5
6. Mmax from Local Geologic Features
7. Mmax from North American Tectonic Analogs
8. Mmax from Global Tectonics Analogs
9. Mmax from Baysian Method
10. Mmax from Physical Principles
11. Mmax from Statistical Approaches
12. Mmax from Pattern Recognition
13. Mmax from Crustal Lg Coda Q at 1Hz (Qo)

Pros and Cons: past events

Method	Pros	Cons
1. Mmax = Mobs	The Mobs method is simple. It can be applied anywhere. It provides an unarguable lower bound for Mmax.	(1) Short historical records produce samples of seismicity that are too small to constrain Mmax. (2) Results of the Mobs method are inconsistent with paleoseismic findings, which show Mmax exceeding Mobs by as much as approximately 2.1- to 3.2-M units.
2. Mmax = Mobs + an increment	The increment method is simple. It can be applied anywhere.	(1) Short historical records produce samples of seismicity that are too small to constrain Mmax. (2) Results of the increment method are inconsistent with paleoseismic findings, which imply increments that range from approximately zero to 3.2.

Pros and Cons: Seismicity

Method	Pros	Cons
3. Seismicity rates	A high moment-release rate may smooth and link faults faster, and allow larger rupture zones and slips than in less seismically active areas.	(1) The argument from fault smoothing and linking may apply to plate boundaries, but it is unclear whether it applies to stable continental regions (SCRs). (2) Even if the seismicity-rate method is valid in SCR, it does not appear to apply below Mmax of approximately 7.0. (3) Above Mmax 7.0, paleoseismic studies can provide support for Mmax estimates.
4. Extrapolation of the historical record by a magnitude-frequency graph	The extrapolation method calculates the M that would recur at whatever recurrence interval is specified, such as 1,000 years. The method is simple and it can be applied anywhere	(1) The extrapolation method gives results that vary with the size of the study area and the specified recurrence interval. (2) Results of the method are inconsistent with paleoseismically determined recurrence intervals of large earthquakes.
5. Saturation value of mb	This is approximately 7.5 globally.	Moment magnitude does not saturate and is preferred for moderate and large earthquakes.

Pros and Cons: Tectonics

Method	Pros	Cons
6. Local geologic features	An area with distinctive geology, faults, or geophysical anomalies might have distinctive fault properties that could control rupture-zone size, such as fault lengths, widths, strengths, or orientations.	(1) Short historical records of small source zones produce small samples of seismicity, which can be too sparse to clearly show long-term spatial associations between seismicity and geologic features. (2) Few CEUSAC earthquakes have been linked to specific faults or systems of faults. (3) The geologic controls on SCR rupture propagation are enigmatic
7. North American tectonic analogs	(1) The arguments in favor of the method of North American tectonic analogs include those favoring the local-geology method. (2) Including all North American tectonic analogs of a CEUSAC source zone could capture larger earthquakes, providing a higher lower bound to	(1) The arguments against the method of North American tectonic analogs are the same as those against the local-geology method. However, the arguments are weaker because the seismicity sample of the combined analog areas is larger. (2) The meaning of “analog” is unclear.

Pros and Cons: Tectonics

Method	Pros	Cons
8. Global tectonic analogs	(1) The arguments in favor of the methods of local geologic features and of North American tectonic analogs apply here as well. (2) Including all global tectonic analogs of a CEUSAC source zone produces the largest possible sample of historical seismicity and makes capture of some true Mmax values more likely than with any smaller sample.	The meaning of “analog” is unclear.
9. Bayesian method	(1) The arguments in favor of the methods of global tectonic analogs apply here as well. (2) Including all global tectonic analogs of a CEUSAC source zone produces the largest possible sample of historical seismicity and makes capture of some true Mmax values more likely than with any smaller sample. (3) Separation of the analysis into specification of a prior distribution and a likelihood function can simplify explanation and justification	(1) The meaning of “analog” is unclear. (2) The prior distribution is partly subjective, which can hinder its explanation and justification.

Pros and Cons: Others

Method	Pros	Cons
10. Arguments from physical principles	The arguments support the existence of an Mmax that could vary locally or regionally.	(1) Short historical records produce samples of seismicity that are too small to constrain Mmax. (2) The physics of rupture propagation in SCR crust may be poorly understood. (3) Few SCR areas have had earthquakes large enough to be recognized as Mmax. All three factors impede testing of physical theories.
11. Statistical methods	The methods do not require understanding of the physics or geologic controls on SCR rupture propagation.	(1) Short historical records produce small samples of seismicity. (2) Few SCR areas have had earthquakes large enough to be taken as Mmax. Both factors impede testing of statistical models.
12. Pattern recognition	The method does not require understanding of the physics or geologic controls on SCR rupture propagation.	Few SCR areas have had earthquakes large enough to be taken as Mmax. This impedes testing results of pattern recognition.
13. Q0	Q0 varies inversely with	(1) Results of the Q0 method are