Giant Earthquakes and Tsunamis

-When and Where

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Tsunami Warning

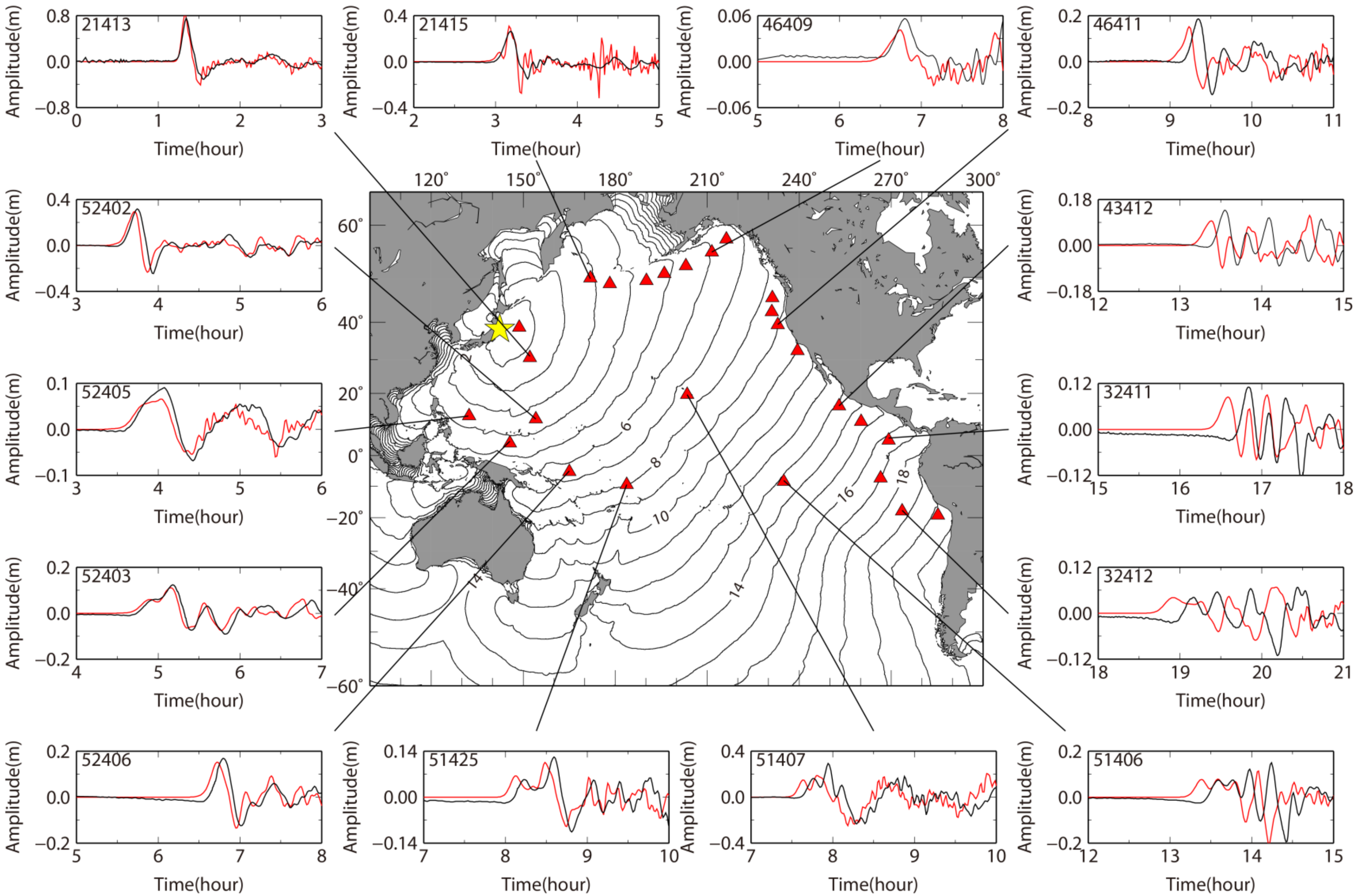
Far-field tsunamis (several hours or more)

- Seismic wave analysis
- Tsunami monitoring
- Accurate estimation of arrival time and heights
- Technical improvement of tsunami travel times

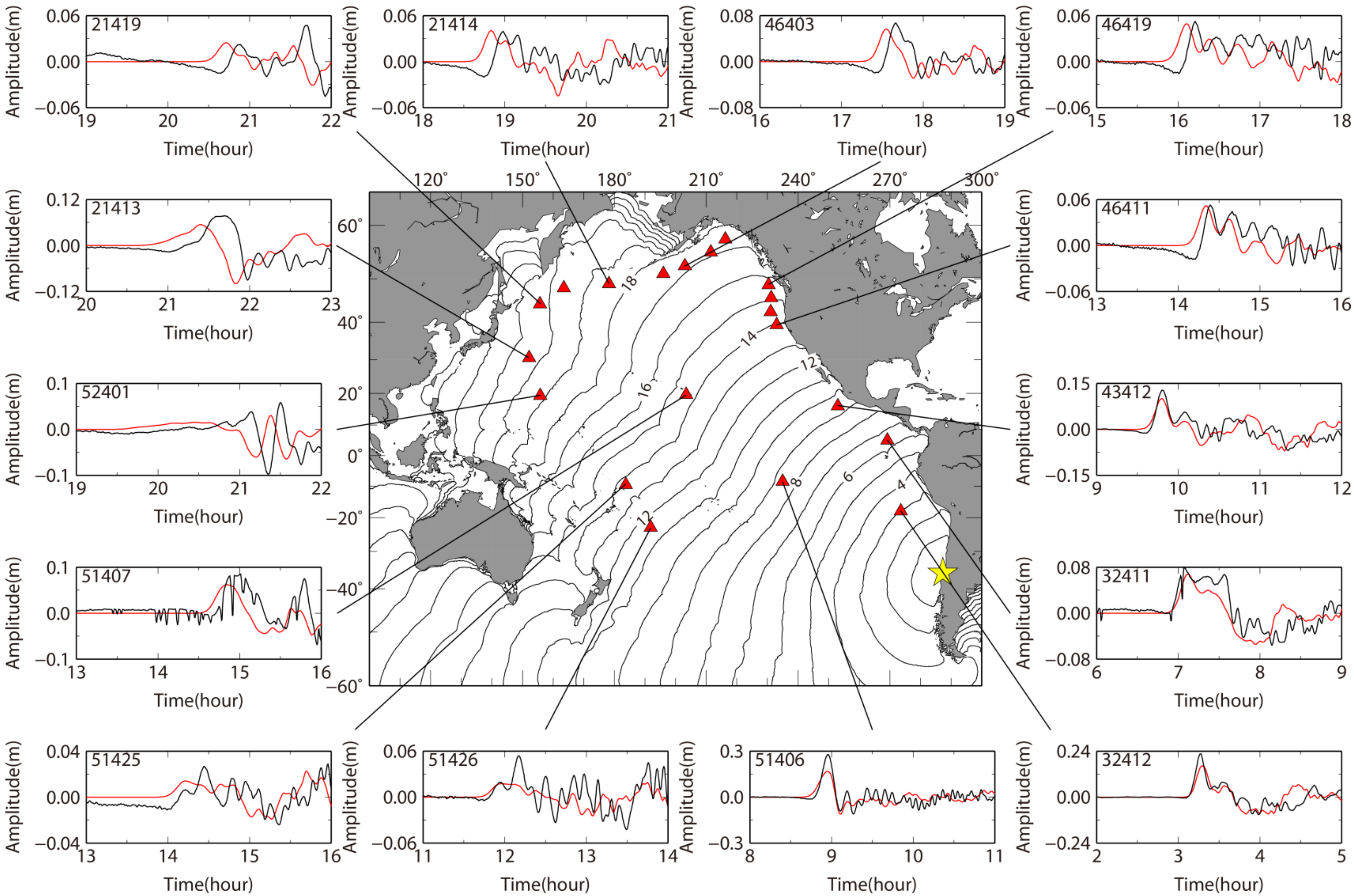
Near-field tsunamis (less than an hour)

- Quick estimation of earthquake size and tsunami potential
- Possibilities of giant earthquake or “tsunami earthquake”

The 2011 Tohoku earthquake tsunami

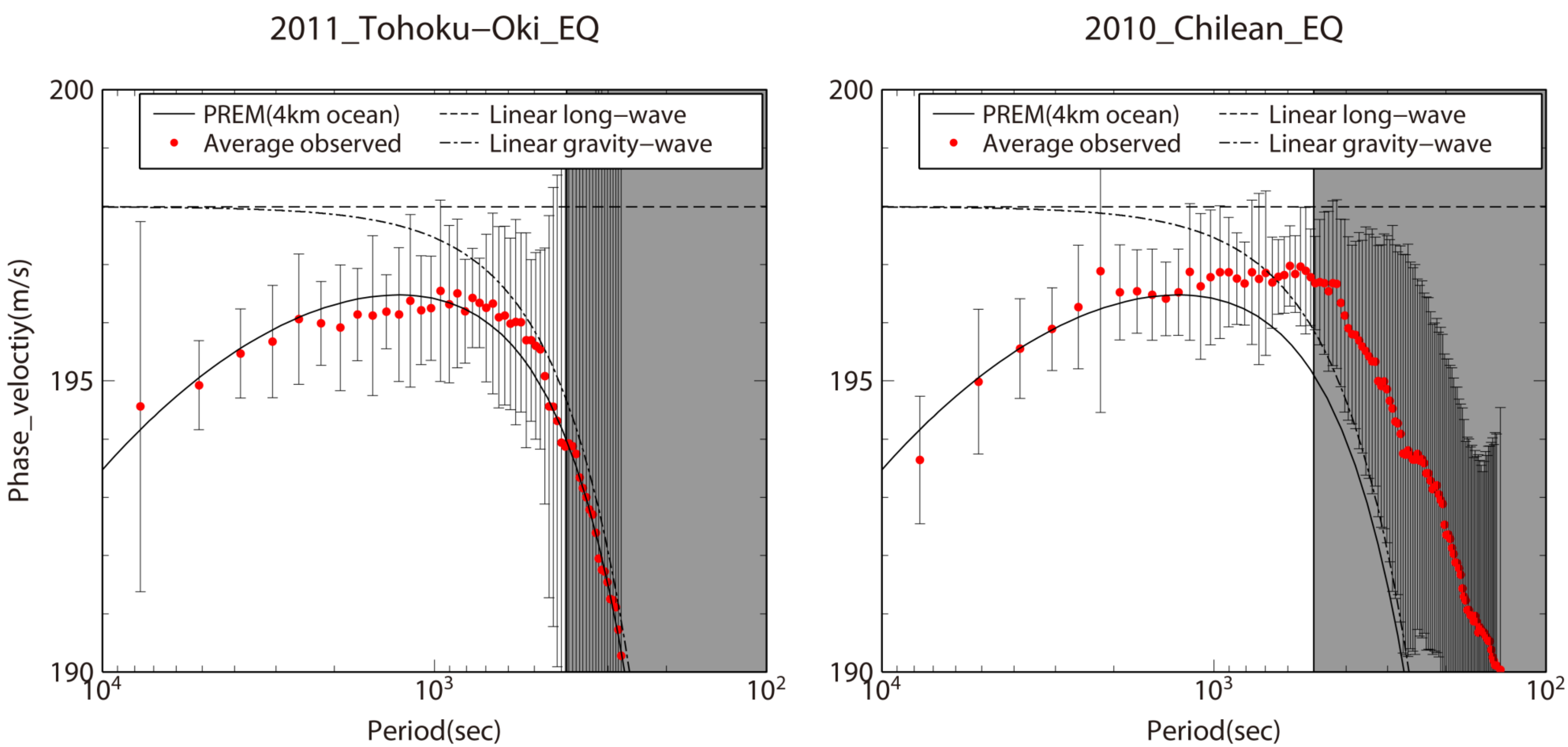


The 2010 Chile earthquake tsunami



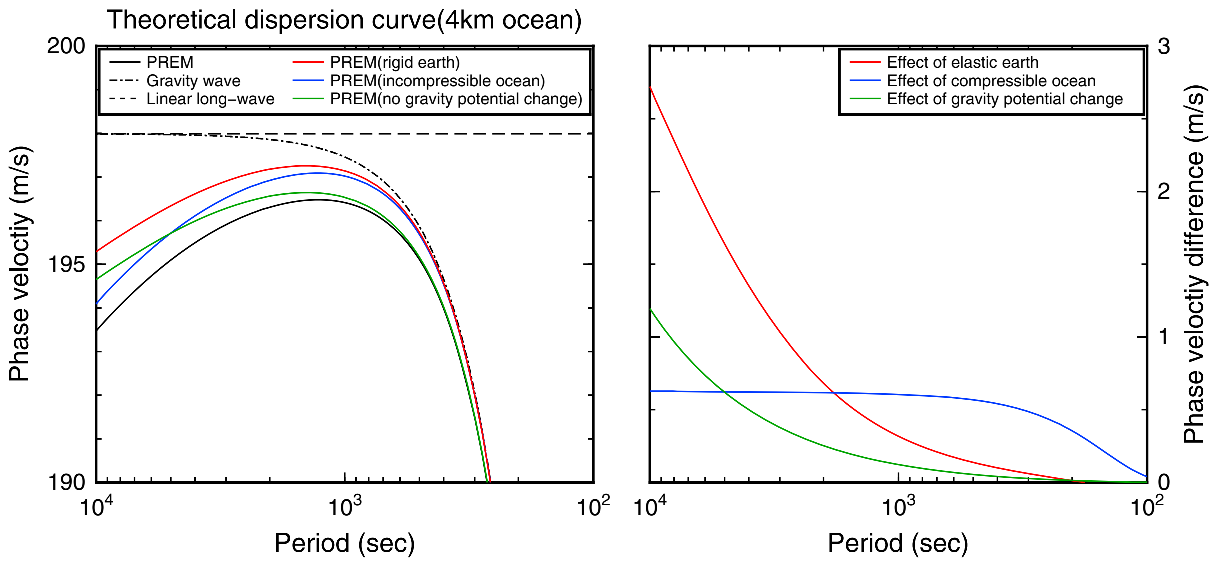
Trans-oceanic Tsunami Waveforms

Phase velocity measurements

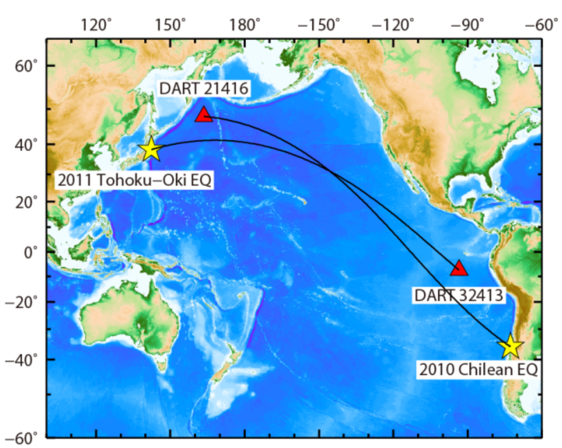


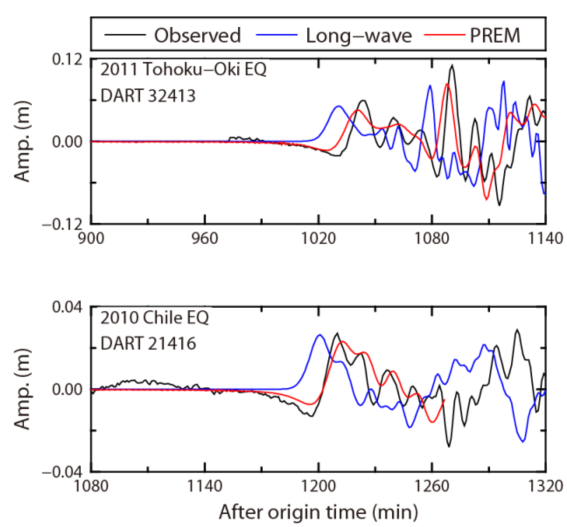
Normalized at 4 km depth ocean
Average of 26 stations for 2011 Tohoku and
20 stations for 1010 Chile tsunami

Trans-oceanic Tsunami Waveforms



Effects of
elasticity of the earth
compressibility of sea water
gravitational potential





Phase corrections to simulated waveforms (Watada et al., 2014 JGR)

Tsunami Warning

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Near-field tsunamis (less than an hour)

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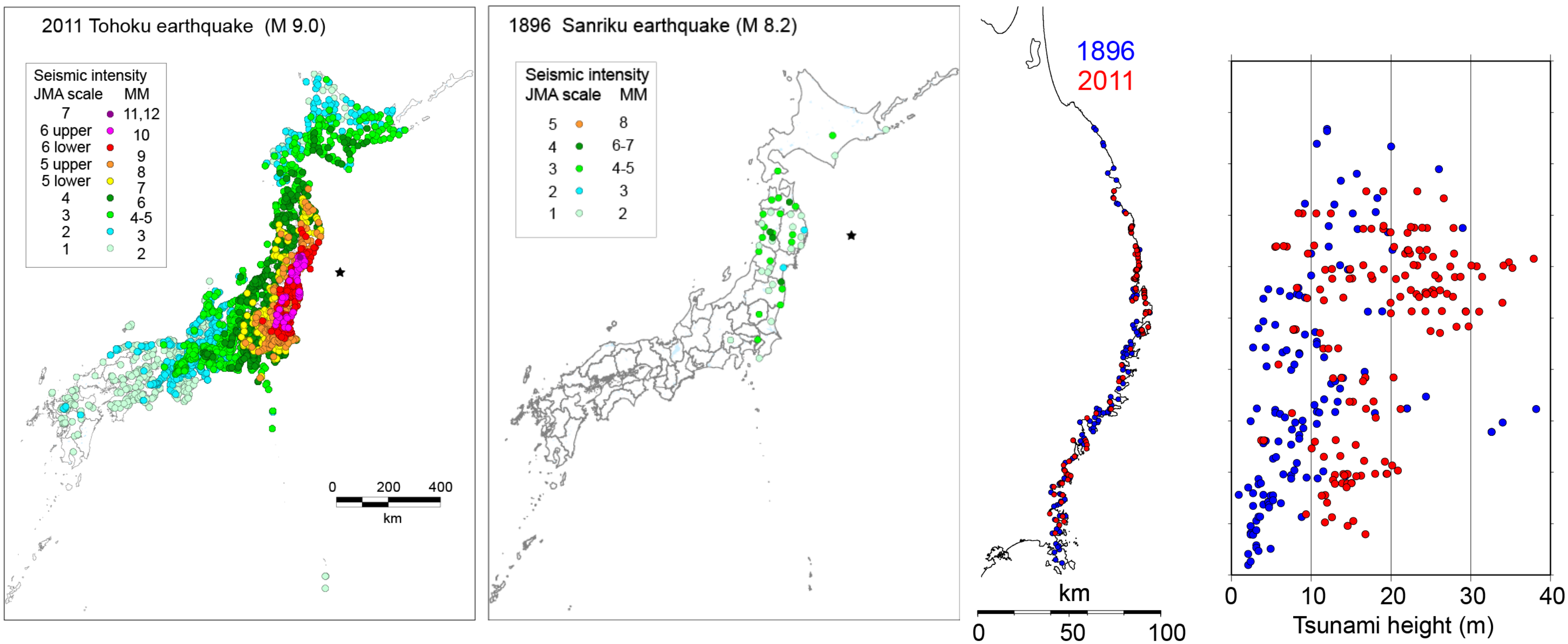
TOWS-WG Inter ICG Task Team on Hazard Assessment Related to Highest Potential Tsunami Source Areas

Our tasks are:

- Summarize current knowledge on “tsunami earthquakes”
- Present selected studies on tsunami hazard assessment and review how maximum credible earthquake size and likelihood have been incorporated.
- Discuss how different approaches can be harmonized.
- Work towards a consensus on best practices for tsunami hazard assessments.

Tsunami earthquakes

Tsunami earthquake: the 1896 Sanriku tsunami

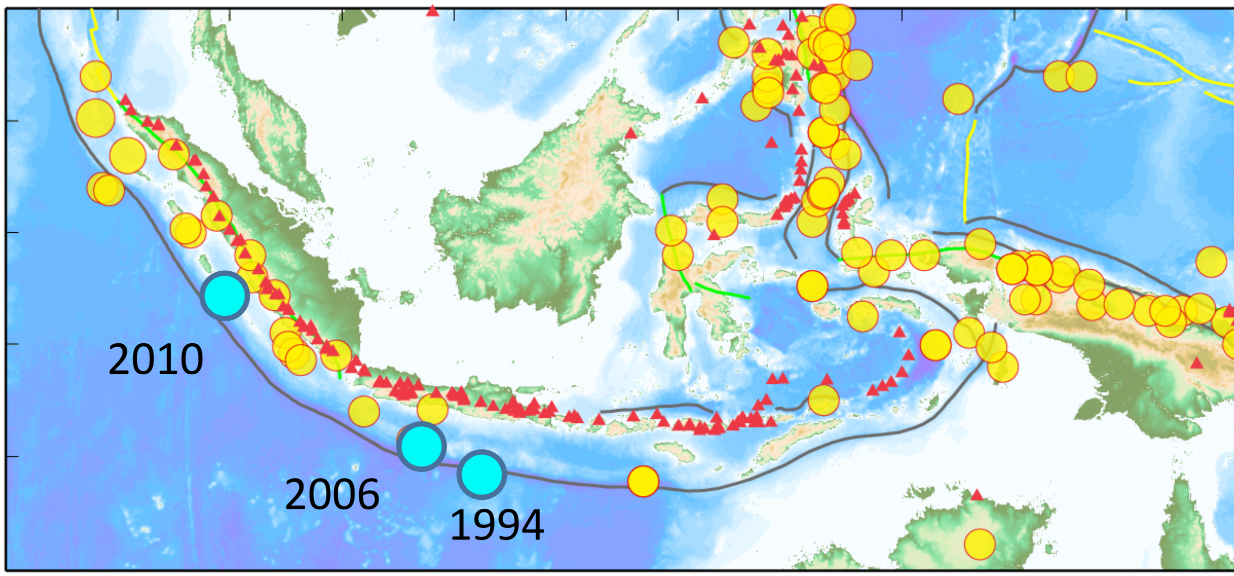


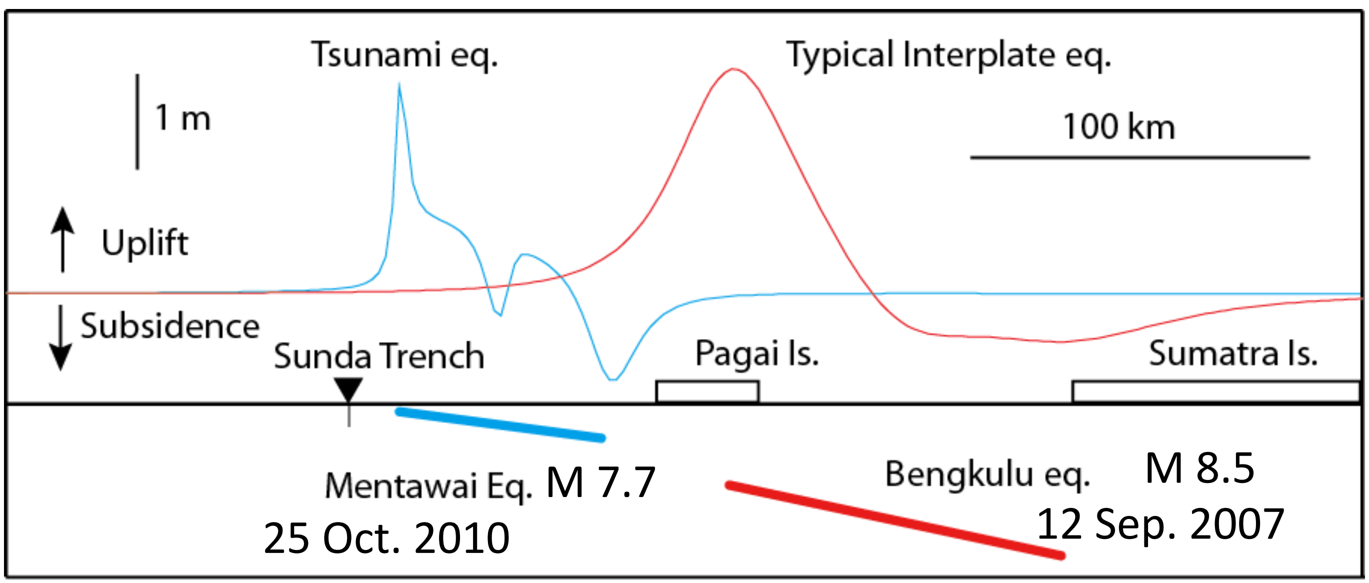
Weaker ground shaking than the 2011 Tohoku earthquake

Tsunami heights were similar

More casualties (~ 22,000)

Tsunami earthquake: the 2010 Mentawai Eq.





Fujii and Satake (2008, EPS)
Satake et al. (2013, Pageoph)

Tsunami earthquakes

Can "tsunami earthquake" happen any subduction zones ?
How can we identify "tsunami earthquakes" in real-time ?

Slowness Parameter $$\Theta = \log_{10} \frac{E^E}{M_0}$$

Newman and Okal (1998)

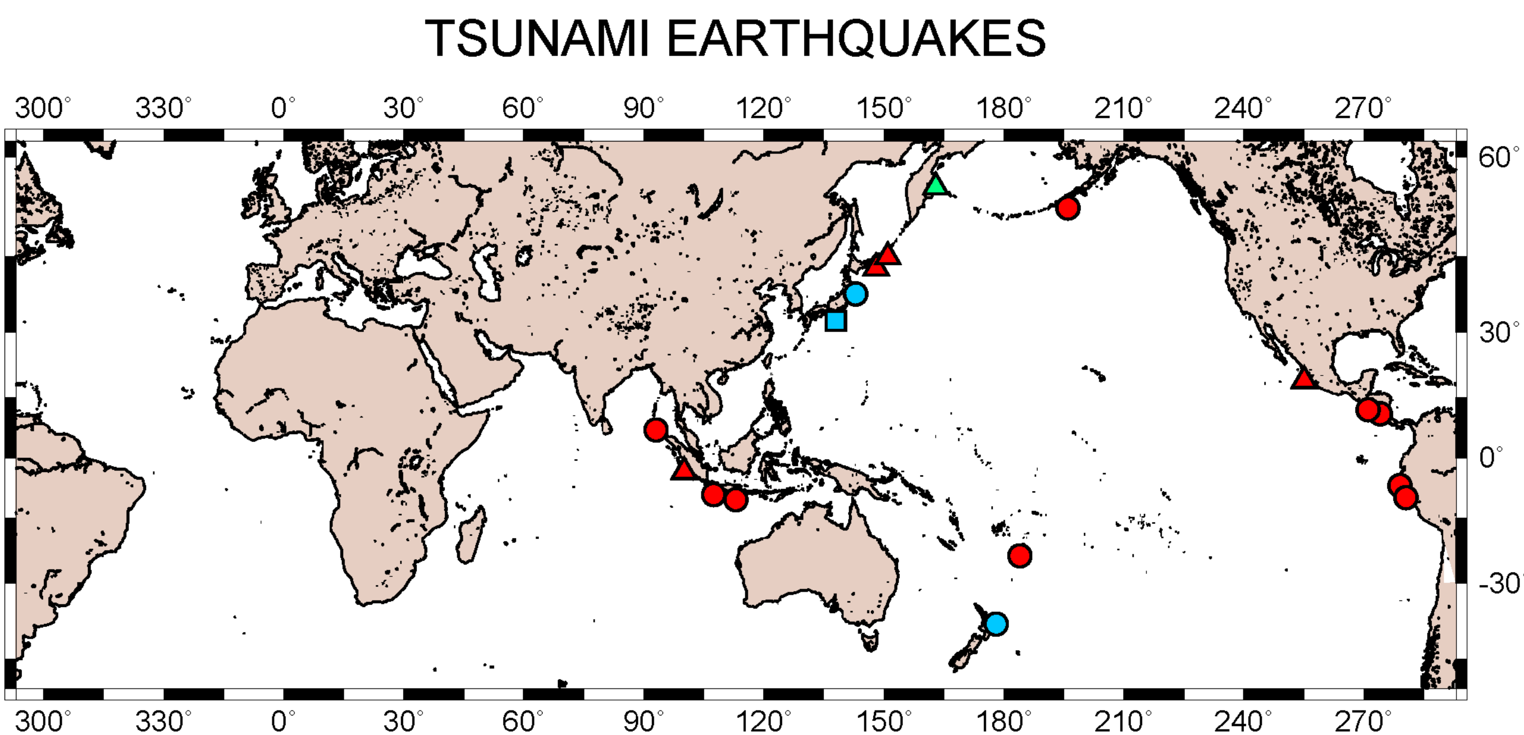
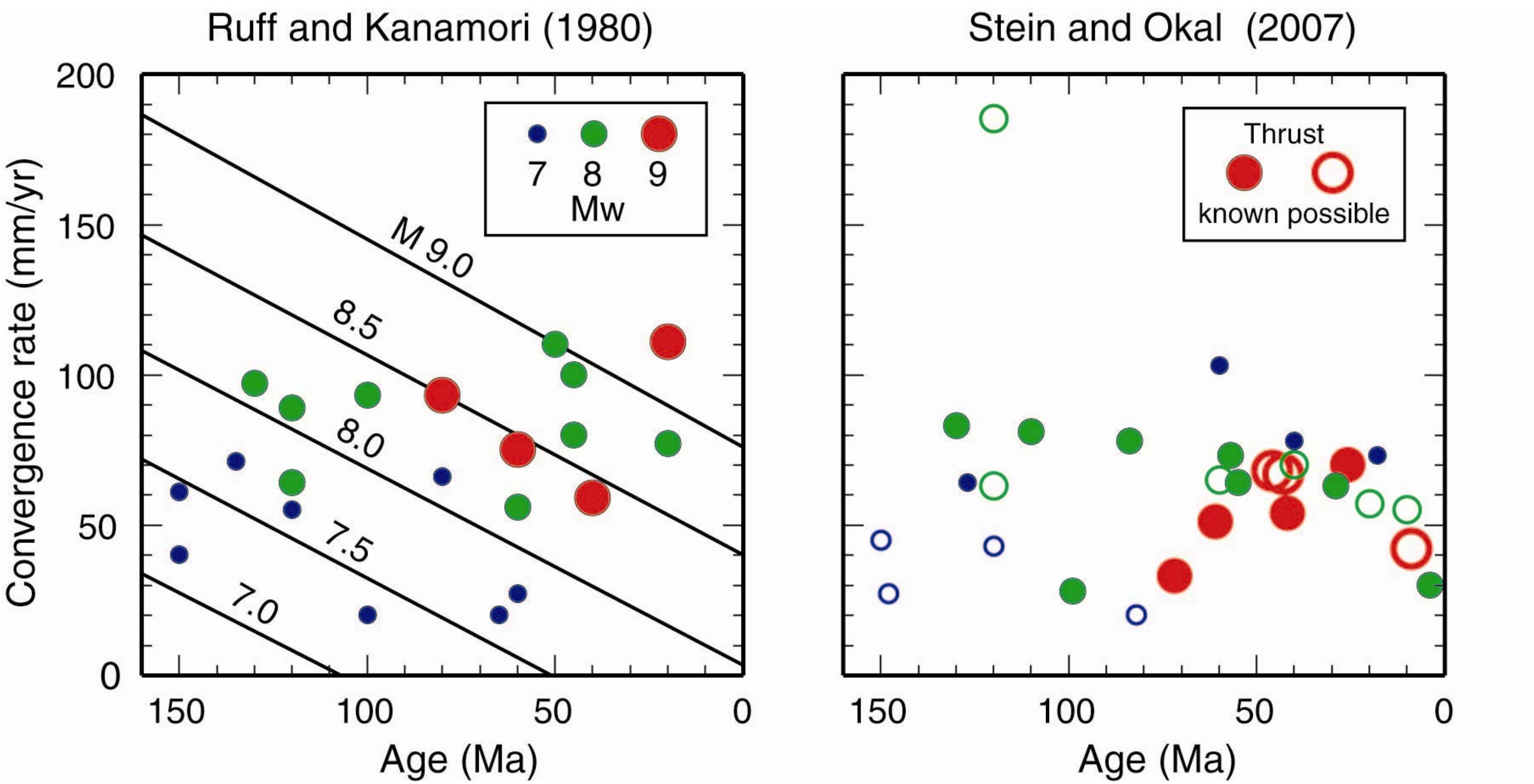


Figure made by Emile Okal (2015)

Maximum earthquake size

in the world's subduction zones

What controls the maximum earthquake size ?



Age and convergence rate of subducting plate now seem to have weak control

Can any subduction zone host M~9 earthquake?

Faster subduction ➡ shorter recurrence interval ➡ more chance to be observed
Slower subduction ➡ longer recurrence interval ➡ less chance to be observed

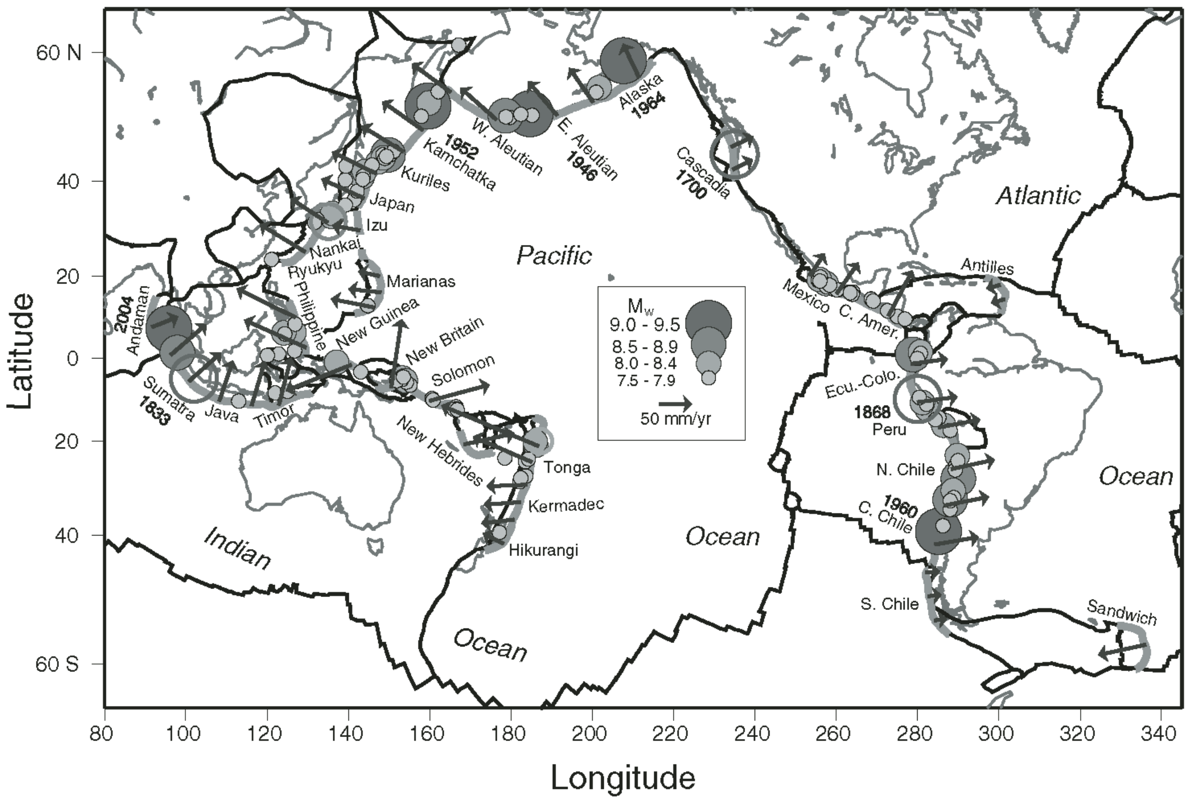
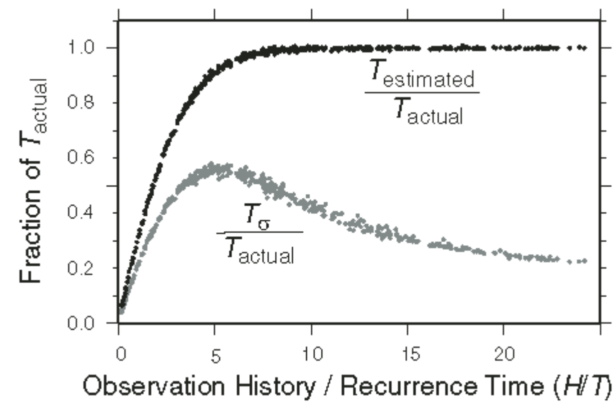
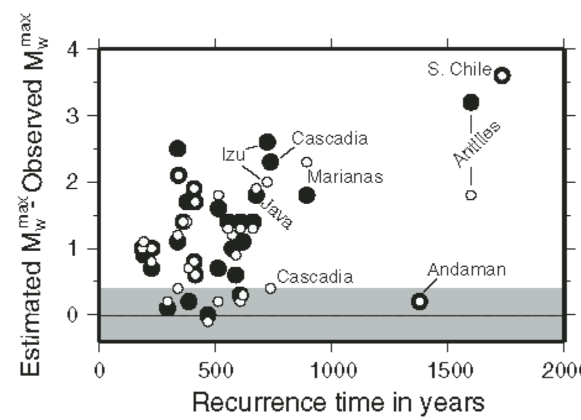


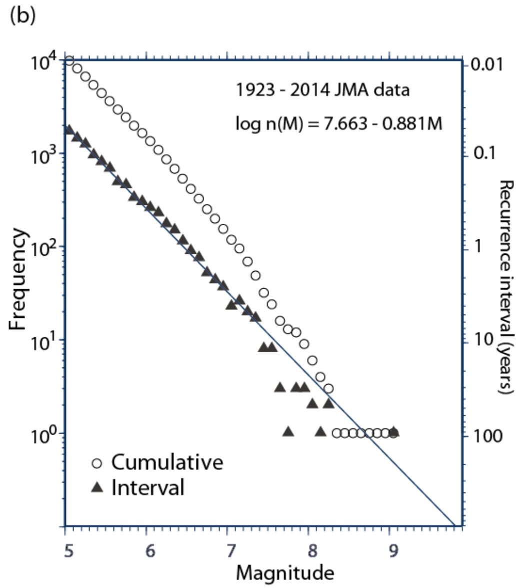
Figure 1. Map of world's major subduction zones (thick gray lines) and tectonic plate boundaries (Bird, 2003). Filled circles show locations of known earthquakes of $M_w \geq 7.5$ or greater since 1900 (circle radius and grayscaled by magnitude). Open circles are largest known earthquakes from A.D. 1700 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.





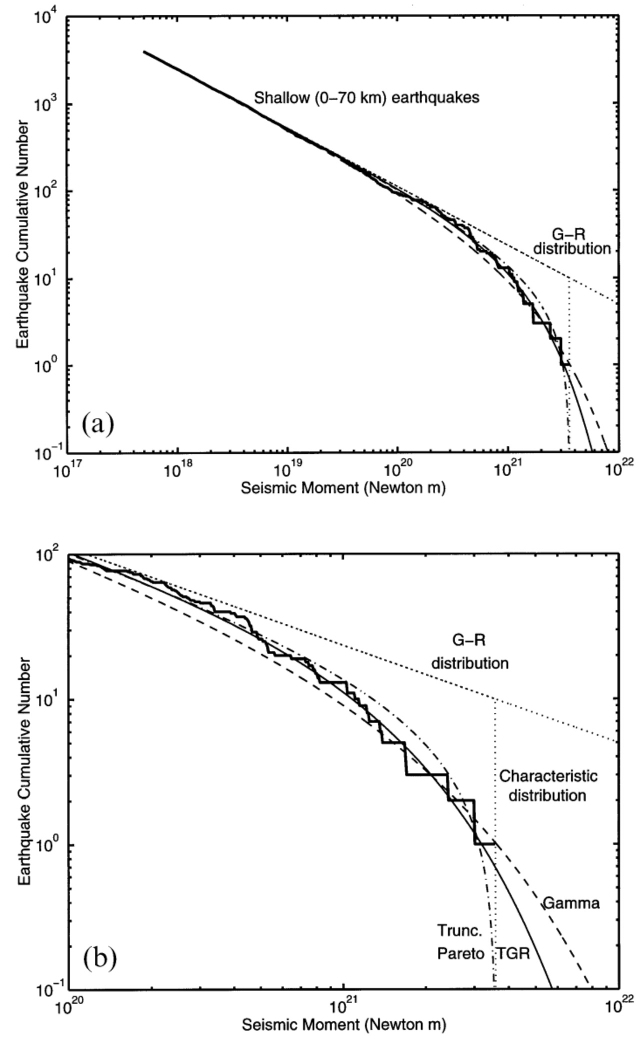
McCaffrey (2008 Geology)
"Global frequency of M 9 earthquakes"

Estimation of Mmax from seismicity data



Gutenberg-Richter relation for magnitude

log N = a – b m



GR for moment M M_0 : threshold moment, β = b / 1.5

$$\Phi(M)=(M_0/M)^{\beta} \quad \text{for } M_0 \le M \le \infty$$

Truncated GR M_t : truncated moment

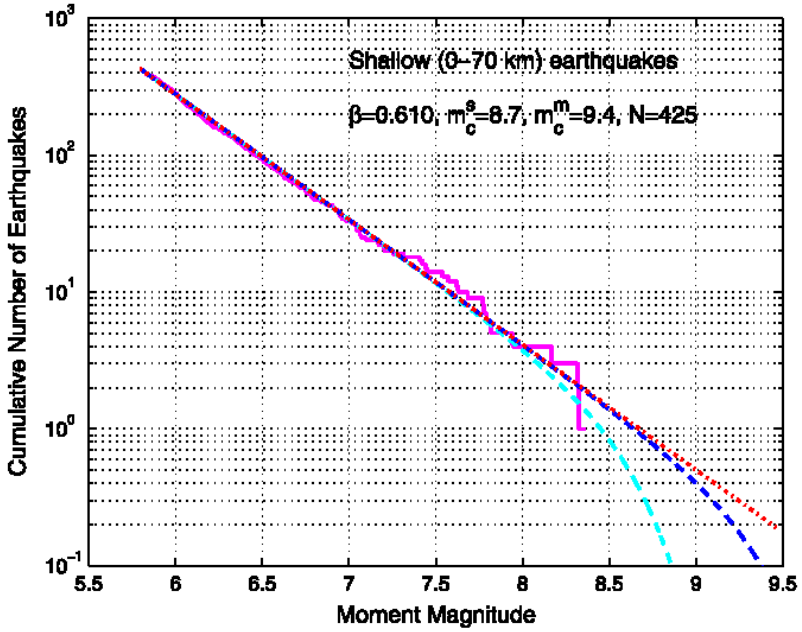
$$\Phi(M)=\frac{(M_0/M)^{\beta}-(M_0/M_t)^{\beta}}{1-(M_0/M_t)^{\beta}} \quad \text{for } M_0 \le M \le M_t$$

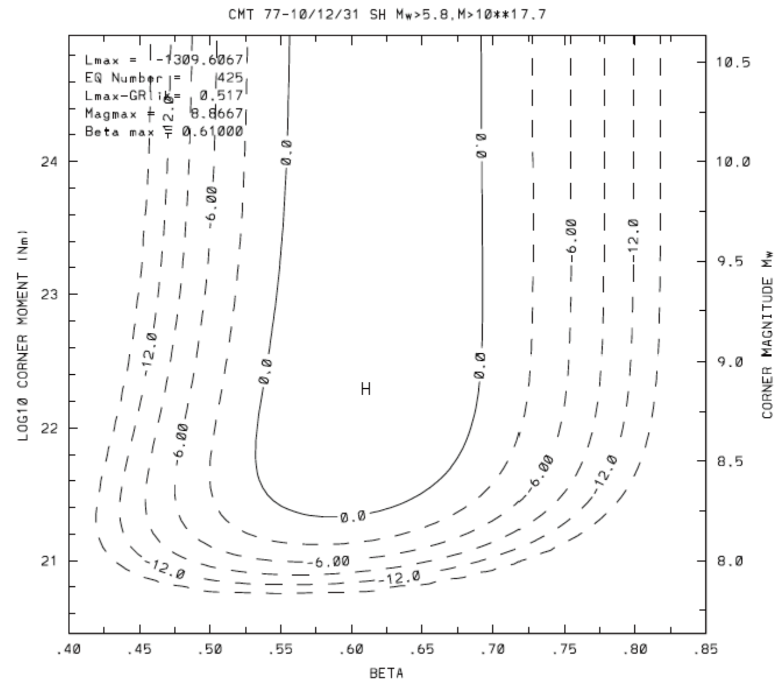
Tapered GR M_c : corner moment

$$\Phi(M)=(M_0/M)^{\beta} \exp\left((M_0-M)/M_c\right) \quad \text{for } M_0 \le M \le \infty$$

Kagan (2002)

Estimation of Mmax from seismicity data





- Observed (Global CMT catalog)
- Gutenberg-Richter
- Tapered GR M_c = 9.4
- Tapered GR M_c = 8.7

Maximum likelihood estimate of parameters β and M_c

Slope β is well constrained, but M_c is not

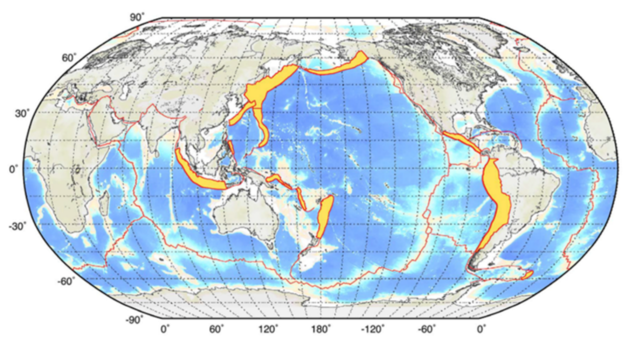
Kagan and Jackson (2013 BSSA) "Tohoku earthquake: A surprise ?"

GEM report: an attempt to estimate Mmax

GLOBAL EARTHQUAKE MODEL
working together to assess risk

The GEM Faulted Earth Subduction Characterisation Project

Report produced in the context of the GEM Faulted Earth Global Component



Version 1.0 – June 2013

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Table 3.1 Subduction Zone Parameters.

*Note all subduction zones divided into segments (Alaska, Central America, much of the South American margin) are divided into segments to preserve the trench geometry and kinematics for these very long subduction zones. However, they will be treated as a single, long segment in the seismic hazard models.

Subduction Zone	Segment	Plate pairs	Left_E_LONG	Left_N_LAT	Left_REL_VEL	Left_REL_AZI	Right_E_LONG	Right_N_LAT	Right_REL_VEL	Right_REL_AZI	Length (km)
Alaska	Komandorski	PA\NA	164.066	55.209	74.6	311	170.700	52.498	74.3	313	531
Alaska	Western Aleutians	PA\NA	170.700	52.498	74.3	313	-162.413	53.367	64.0	329	1963
Alaska	Shumagin	PA\NA	-162.413	53.367	64.0	329	-157.986	54.101	61.0	332	302
Alaska	Semidi	PA\NA	-157.986	54.101	61.0	332	-154.160	55.239	58.4	336	279
Alaska	Kodiak	PA\NA	-154.160	55.239	58.4	336	-149.220	56.925	55.0	340	361
Alaska	Prince William Sound	PA\NA	-149.220	56.925	55.0	340	-144.316	59.918	51.4	347	444
Alaska	Yakataga	PA\NA	-144.316	59.918	51.4	347	-140.128	60.381	49.0	350	250
Cascadia		JF\NA	-130.850	51.612	47.8	58	-124.742	40.313	32.7	58	1415
Japan		PA\OK	141.992	34.666	93.0	294	144.454	40.847	91.1	295	742
Kanto		PS\OK	138.674	35.034	36.0	317	141.883	34.213	34.1	312	312
Nankai		PS\AM	132.824	30.754	55.7	310	138.674	35.034	44.4	310	762

Table 3.1 Continued.

Subduction Zone	Segment	Dip - pref	Trench depth	Updip _pref	Updip _min	Updip _max	Down-dip depth - pref	Down-dip depth - min	Down-dip depth - max	Width - pref	Width - min	Width - max	Coupling coefficient - pref
Alaska	Komandorski	15	5.5	10.5	5.5	24	35	25	45	95	4	153	0.5
Alaska	Western Aleutians	18	7	12	7	27	50	30	55	123	10	155	0.5
Alaska	Shumagin	14	6	11	6	16	26	20	32	62	17	107	0.16
Alaska	Semidi	14	6	11	6	24	30	25	50	79	4	182	0.7
Alaska	Kodiak	8	4.5	9.5	4.5	24.5	28	25	50	133	4	327	0.8
Alaska	Prince William Sound	6	4.5	14.5	4.5	24.5	42	25	50	263	5	435	0.8
Alaska	Yakataga	15	4	9	4	9	15	10	20	23	4	62	0.5
Cascadia		15	2.5	7.5	2.5	12.5	25	20	30	68	29	106	0.8
Japan		15	7	7	7	7	50	40	65	166	128	224	0.7
Kanto		15	1	6	1	9	25	20	30	73	43	112	0.9
Nankai		15	3.5	8.5	3.5	11.5	25	20	30	64	33	102	0.9
Kurile-Kamchatka		16	8	13	8	16	50	40	60	134	87	189	0.8
Ryukyu		15	6	11	6	14	20	15	25	35	4	73	0.2

Table 3.1 Continued.

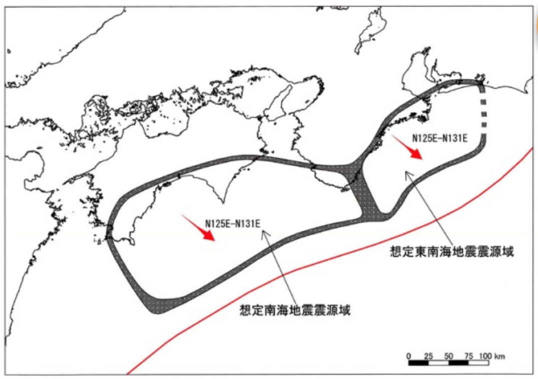
Subduction Zone	Segment	Coupling coefficient - min	Coupling coefficient - max	Mmax - pref	Mmax - min	Mmax - max	B-value - pref	B-value - min	B-value - max
Alaska	Komandorski	0.3	0.7	8.40	8.00	8.80	0.54	0.4	0.8
Alaska	Western Aleutians	0.3	0.7	9.42	9.20	9.63	0.8	0.7	1
Alaska	Shumagin	0.02	0.7	7.93	7.50	8.35	0.54	0.4	0.8
Alaska	Semidi	0.6	0.9	8.50	8.34	8.50	0.8	0.7	1
Alaska	Kodiak	0.9	1	9.20	8.63	9.20	0.8	0.7	1
Alaska	Prince William Sound	0.9	1	9.20	9.00	9.20	0.54	0.4	0.8
Alaska	Yakataga	0.3	0.7	8.10	8.00	8.10	0.54	0.4	0.8
Cascadia		0.7	0.9	9.00	8.80	9.20	0.54	0.4	0.8
Japan		0.6	0.9	9.08	9.00	9.16	1	0.8	1.2
Kanto		0.8	1	8.21	8.00	8.42	1	0.8	1.2
Nankai		0.8	1	8.70	8.50	8.90	0.54	0.4	0.8
Kurile-Kamchatka		0.7	0.9	9.37	9.00	9.73	1	0.8	1.2
Ryukyu		0.1	0.7	8.54	8.00	9.09	0.8	0.7	1
Izu-Bonin		0.1	0.7	8.21	7.20	9.21	0.8	0.7	1
Marianas		0.1	0.7	8.34	7.20	9.48	0.8	0.7	1

Maximum earthquake size

around Japan

ERC's long-term forecast of Nankai Earthquakes

Ver. 1 (September 2001)



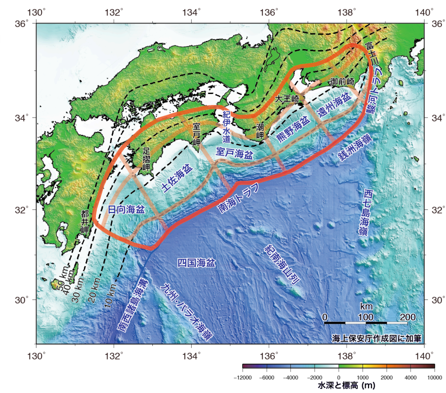
Source Area

Next Event

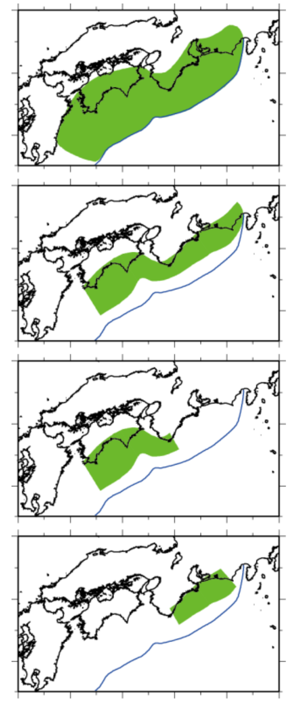
- Based on recent events with enough geophysical data
- Characteristic earthquake model (Similar size events repeat with similar interval)

	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



M9.1 Max

M8.7

M8.6

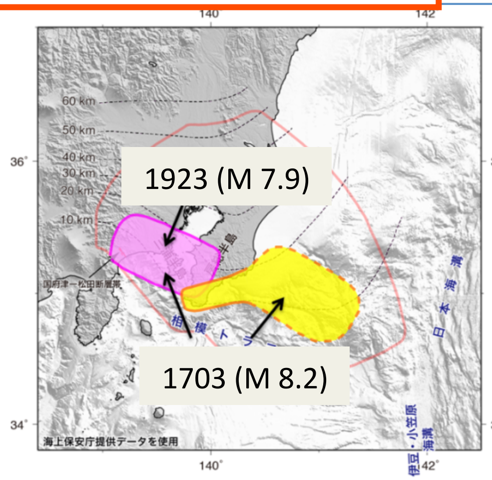
M8.4

Variability

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

ERC's forecast in Sagami Trough

Previous (2004)



- Two types of characteristic eqs.

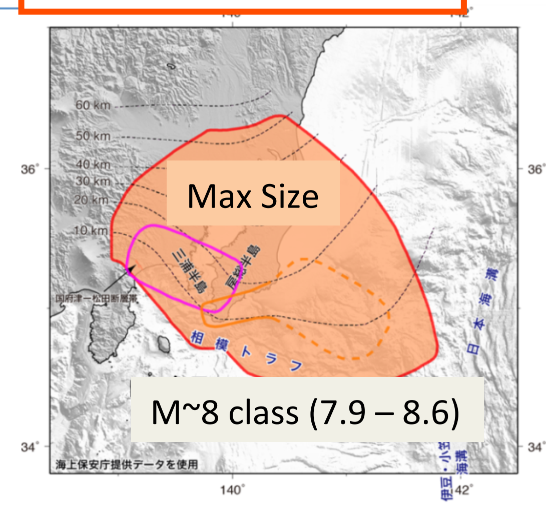
	Size	30-yr prob
1703 type	M ~ 8.1	~ 0 % (~ 0%)
1923 type	M~ 7.9	0 - 0.8% (0 – 2 %)

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

Summary

1. Far-field tsunamis (arrival times, waveforms) can be accurately forecasted within a few hours of great eq.
2. For near-field tsunami warning, possibility of "tsunami earthquakes" and possible maximum earthquakes size would be useful information.
3. "Tsunami earthquake" may occur any subduction zones.
4. Maximum earthquake size in the world's subduction zones are being estimated by various methods, such as paleoseismological data, plate convergence rate/coupling ratio, or seismicity.
5. TOWS-WG Inter ICG Task Team is summarizing the current status of the above research for tsunami warning operations.
6. Attempts to estimate Mmax have been done in Japan.