Intergovernmental Oceanographic Commission

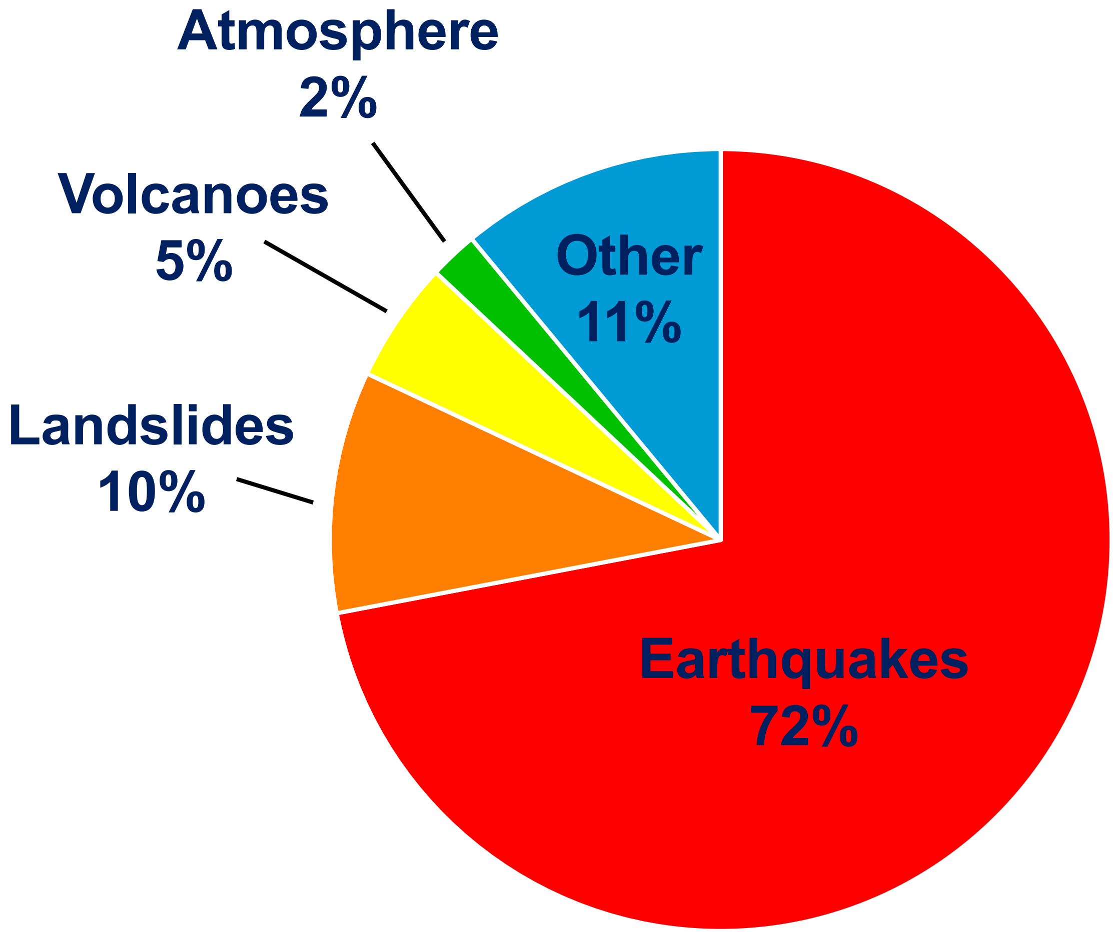
UNESCO/IOC – NOAA ITIC Training Program in Hawaii (ITP-TEWS Chile)
TSUNAMI EARLY WARNING SYSTEMS
AND THE PACIFIC TSUNAMI WARNING CENTER (PTWC) ENHANCED PRODUCTS
TSUNAMI EVACUATION PLANNING AND UNESCO IOC TSUNAMI READY PROGRAMME
19-30 August 2024, Valparaiso, Chile

Earthquake Science for Tsunamis

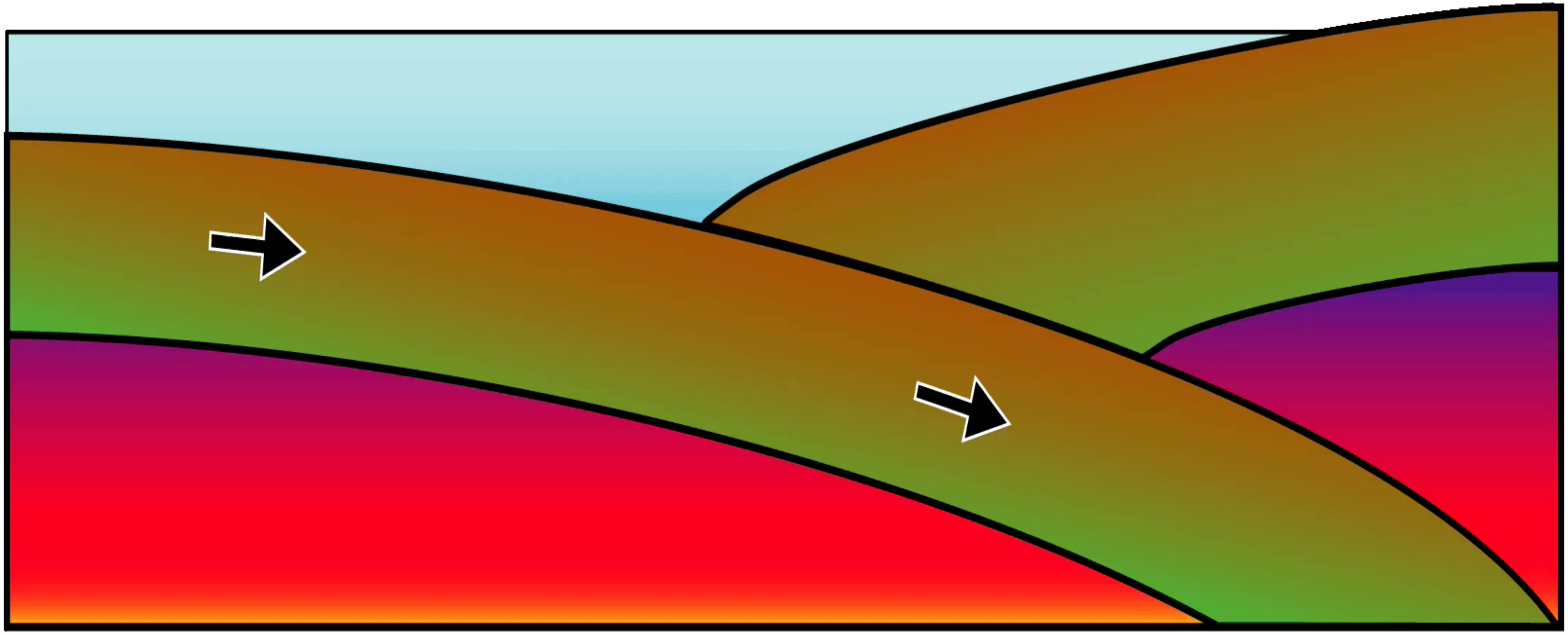
Kenji Satake
University of Tokyo

Causes of tsunamis

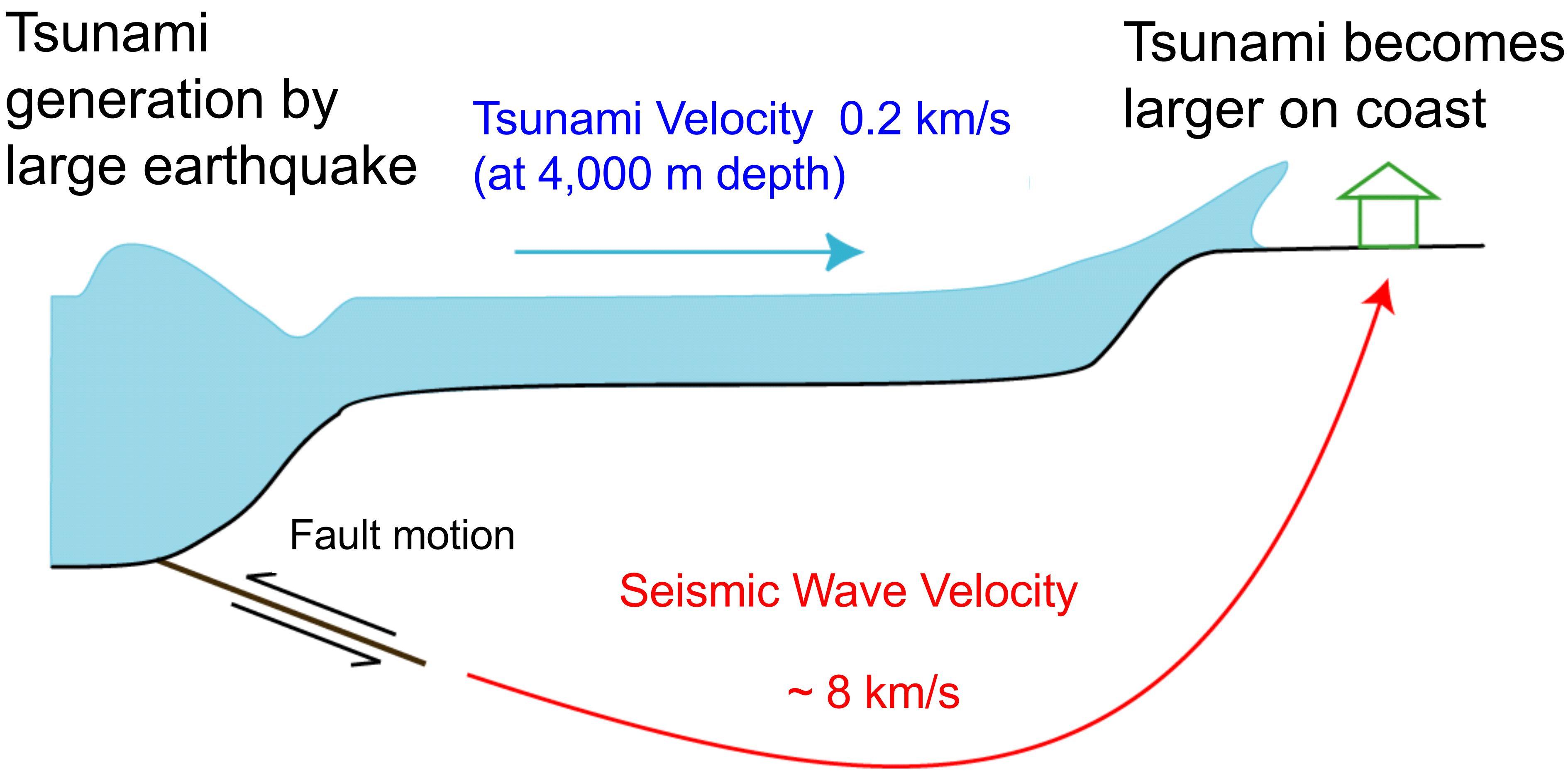
A tsunami is a series of long-period waves created by an abrupt, large-scale displacement of the ocean.



Most Tsunamis are caused by Shallow, Large Earthquakes at Subduction Zones

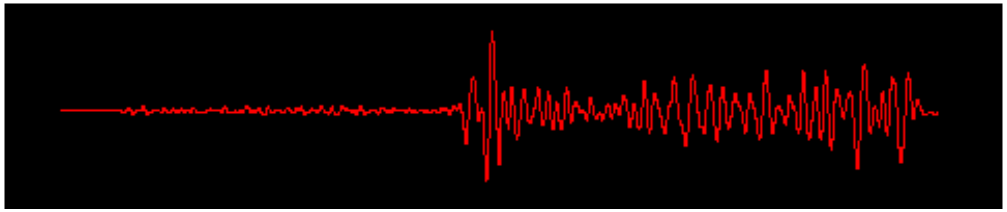


Earthquake and tsunami source

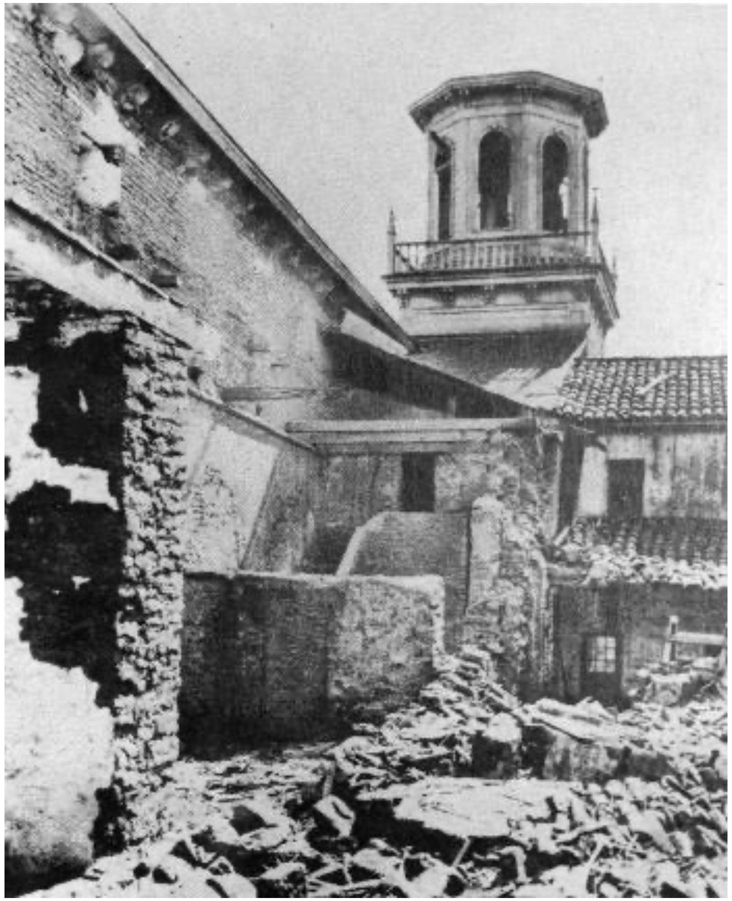


What is an Earthquake?

- Instrumentally recorded (or felt) ground shaking, normally a result of underground movement on a fault

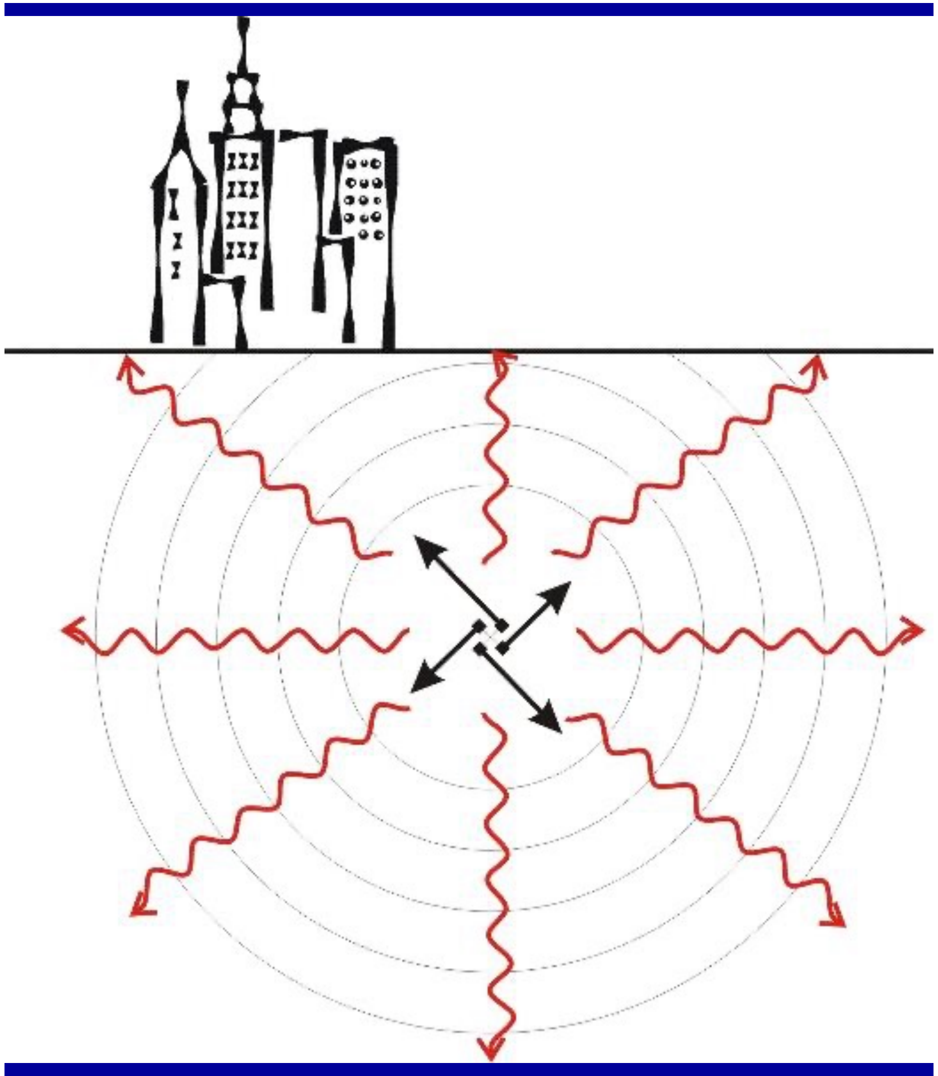


Seismogram of the 1906 earthquake recorded in Germany



San Francisco 1906 (USGS)

What is an Earthquake?



Broadband seismometer

Faulting

Seismic waves

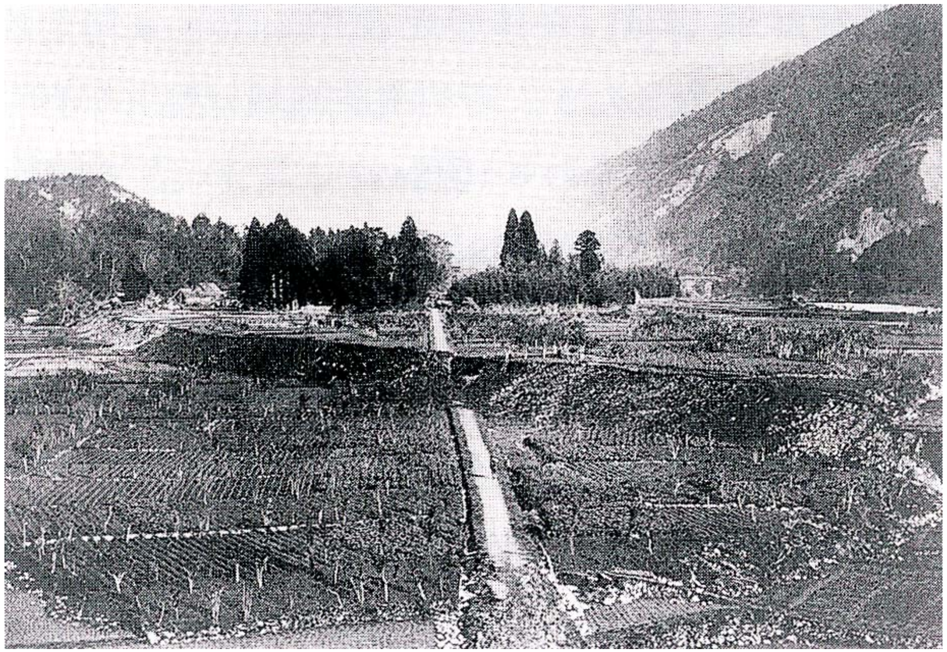
USGS

USGS
science for a changing world

Types of fault motions

1995 Kobe earthquake
(Nojima fault)

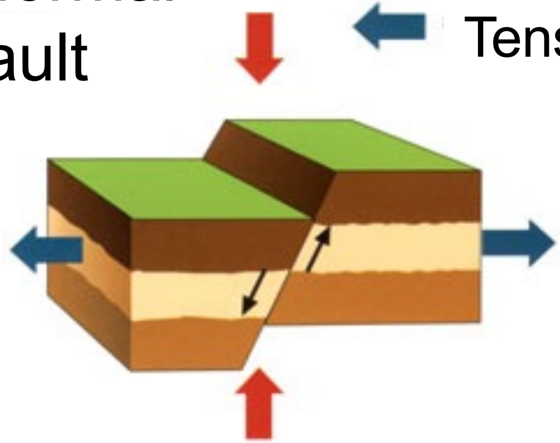
1891 Nobi earthquake
(Midori fault)



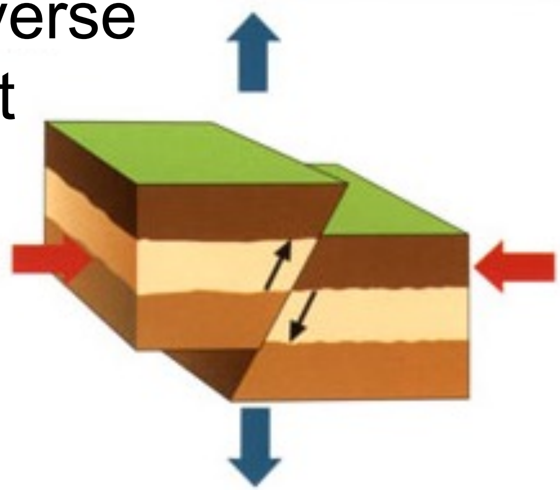
Types of fault motions

Normal fault

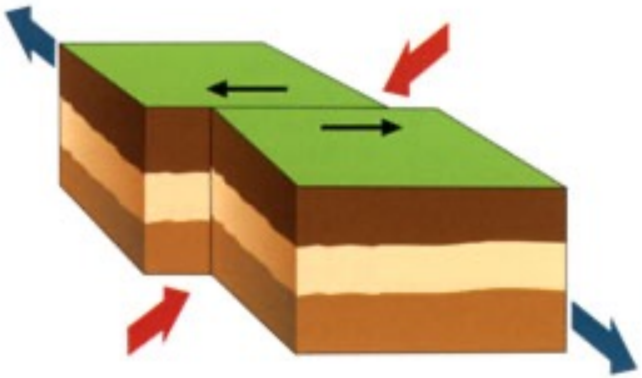
Compression
Tension



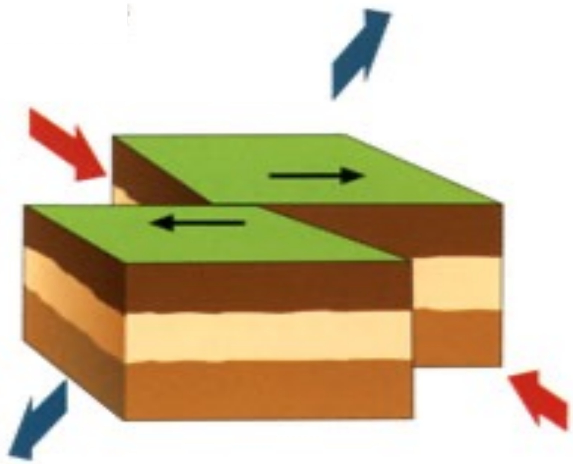
Reverse fault



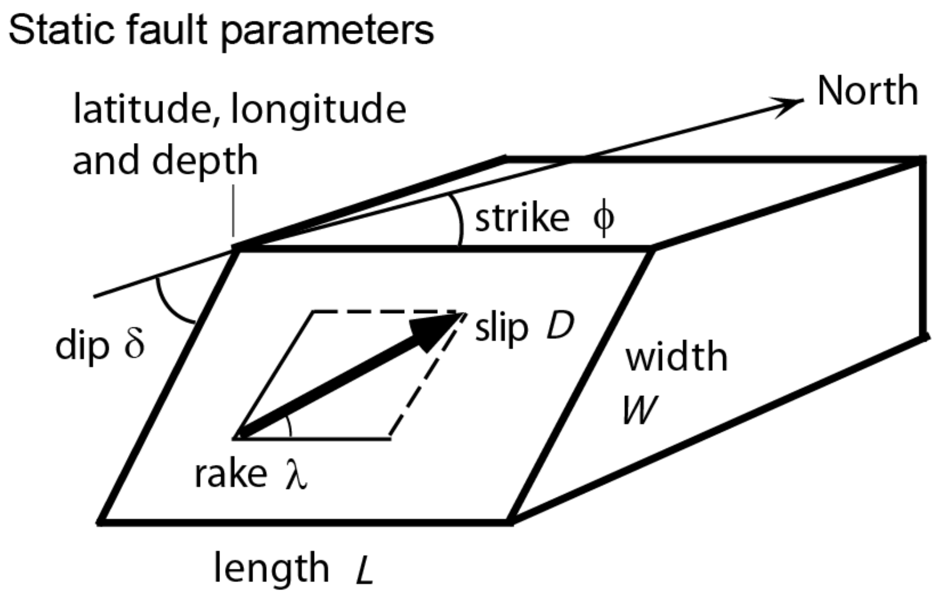
Left-lateral, Sinistral, fault



Right-lateral, Dextral, fault



Simple Fault Model



Static parameters:

- Location of reference point (latitude and longitude)
- Fault length L
- Fault width W
- Slip amount D
- Depth of upper edge d
- Strike direction θ
- Dip angle δ
- Slip (or rake) angle λ

Strike ϕ clockwise from north $0^\circ \leq \phi < 360^\circ$

Dip angle δ downward from horizontal $0^\circ \leq \delta \leq 90^\circ$

Rake angle λ counterclockwise from horizontal $-180^\circ \leq \lambda \leq 180^\circ$

$\lambda > 0^\circ$ reverse fault ; $\lambda < 0^\circ$ normal fault

$|\lambda| < 90^\circ$ left-lateral ; $|\lambda| > 90^\circ$ right-lateral

Vertical Deformation due to Reverse Fault

dip-slip fault

$\delta = 30^{o}$

Large uplift above fault plane
Small subsidence in left
(hanging wall) side

$\delta = 60^{o}$

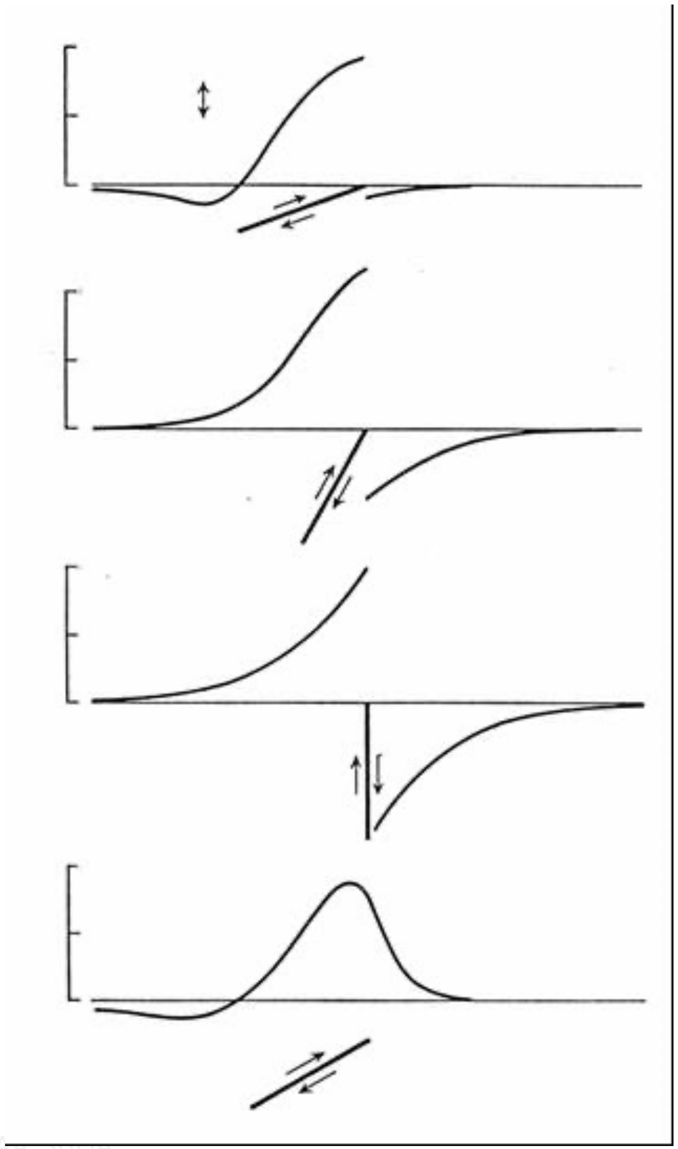
Large uplift above fault plane
Small subsidence in right
(foot wall) side

$\delta = 90^{o}$

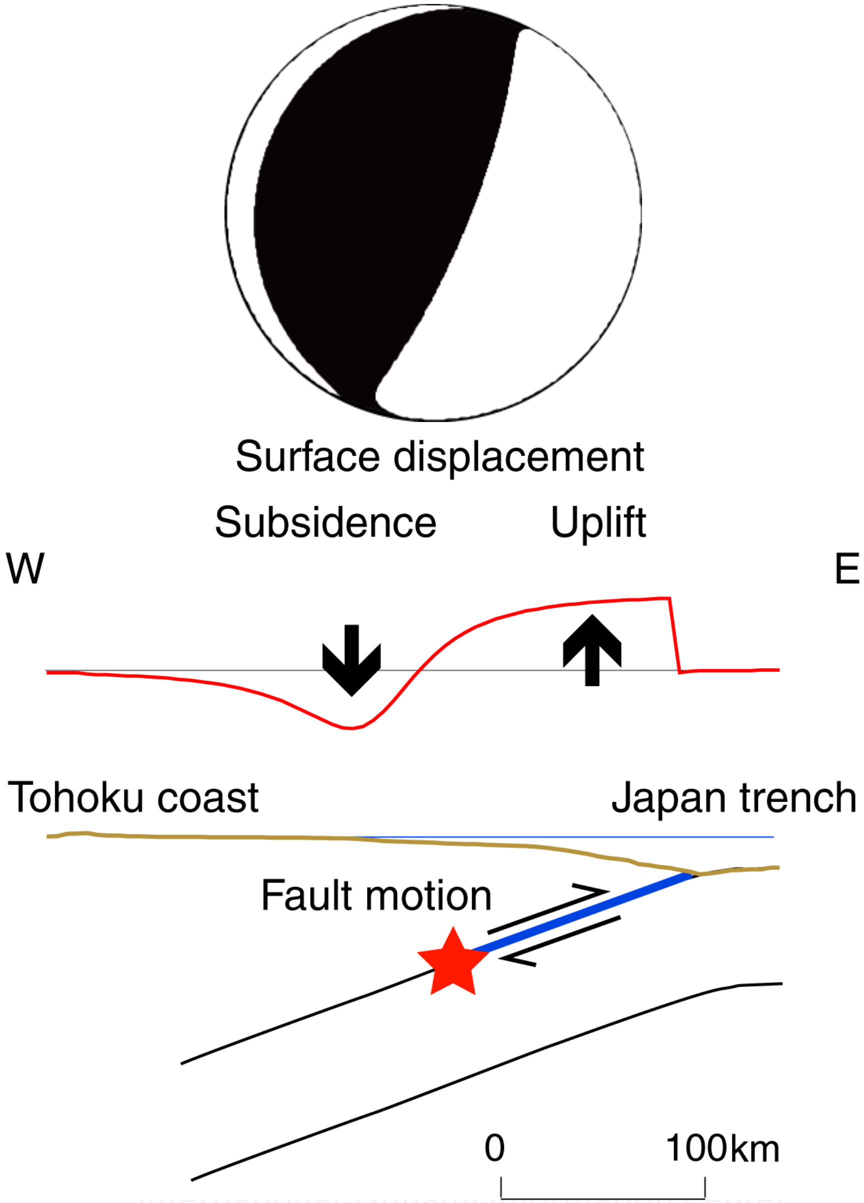
Uplift = Subsidence

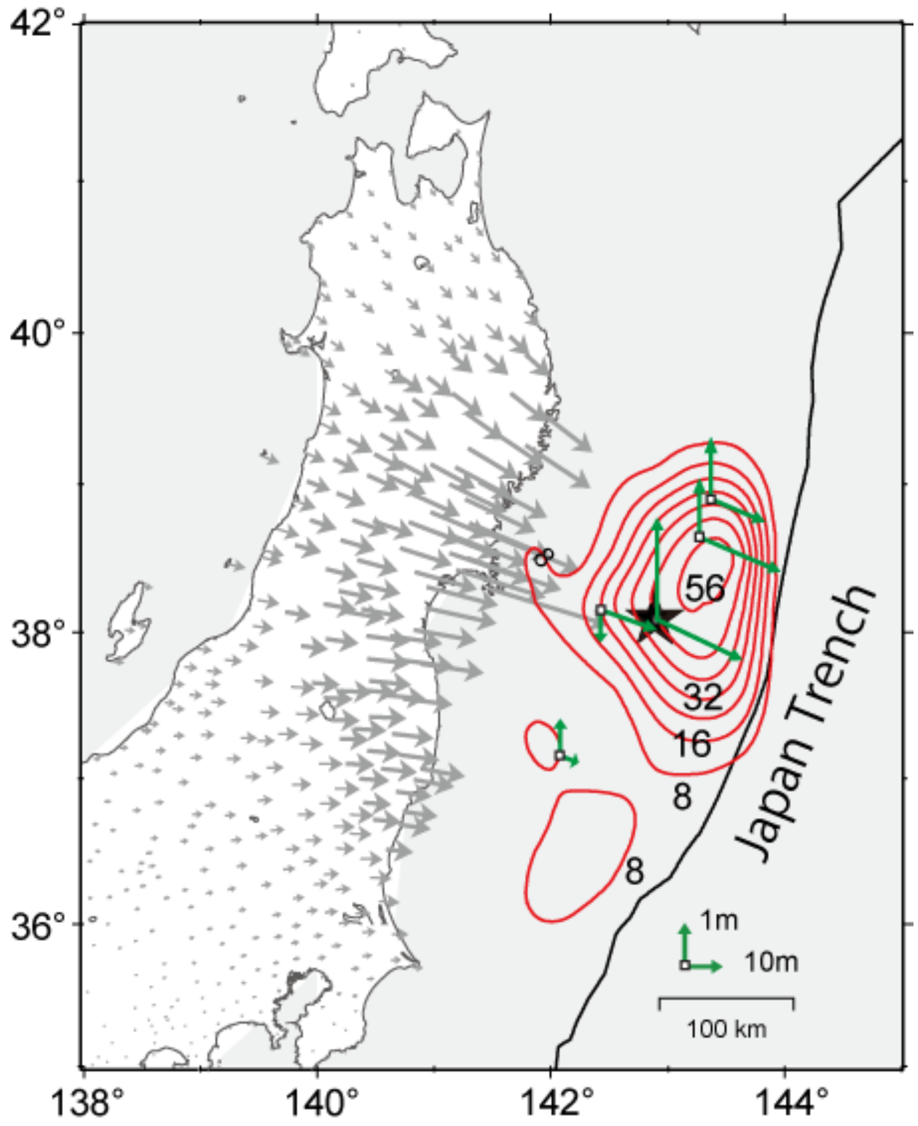
buried fault
$\delta = 30^{o}$

No discontinuity

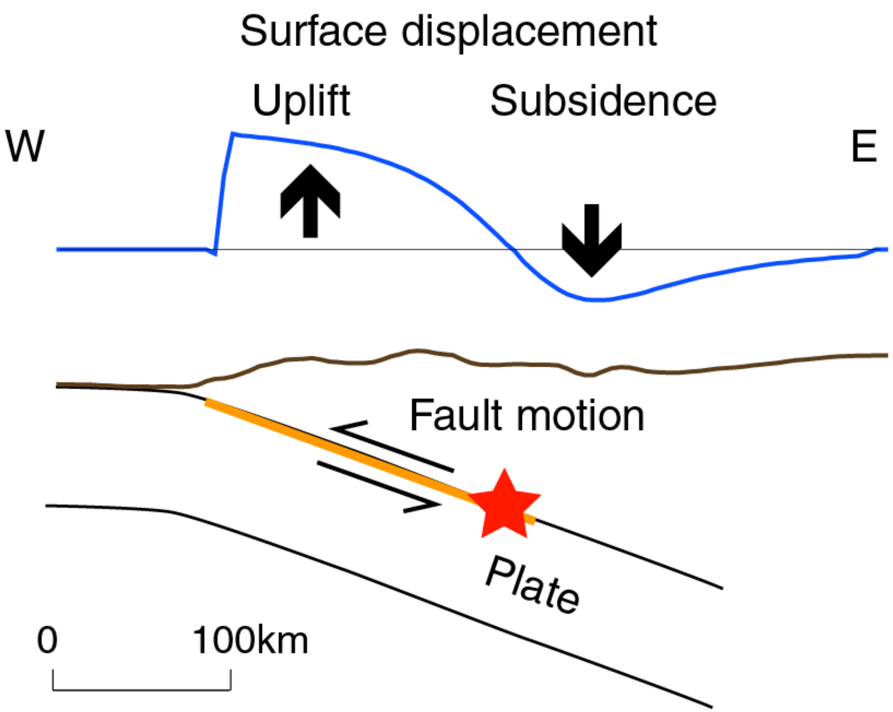


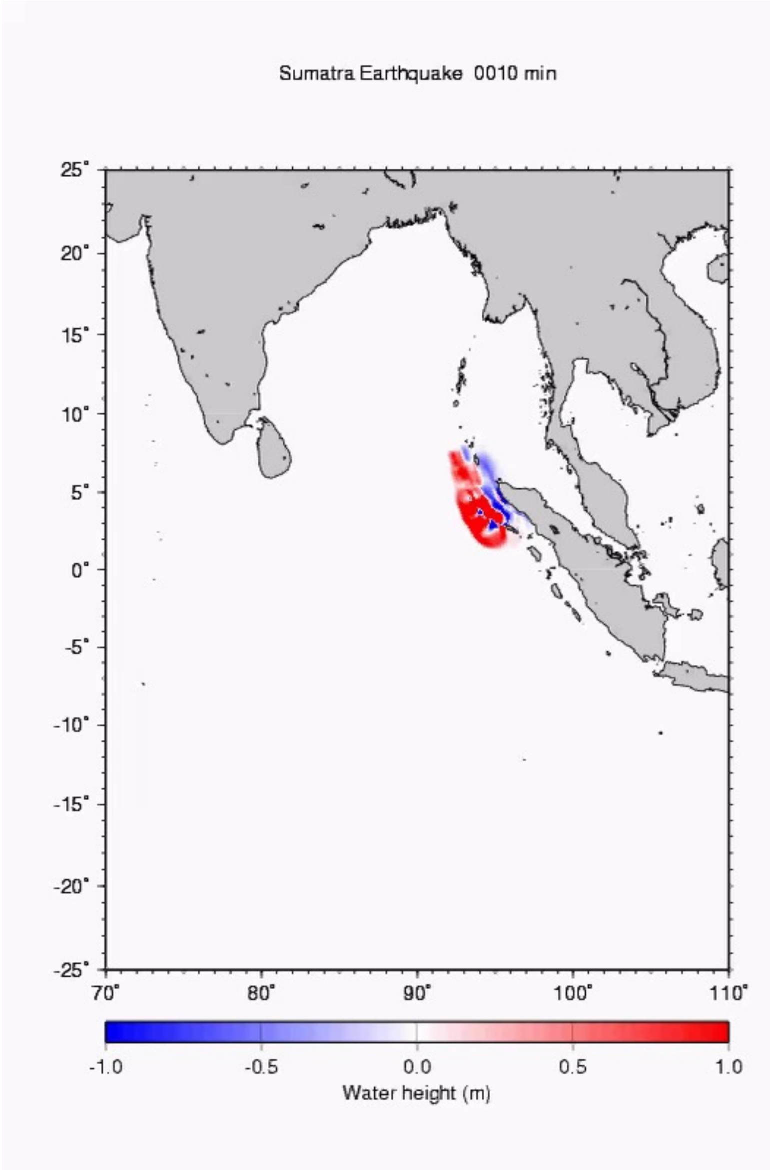
The 2011 Tohoku earthquake



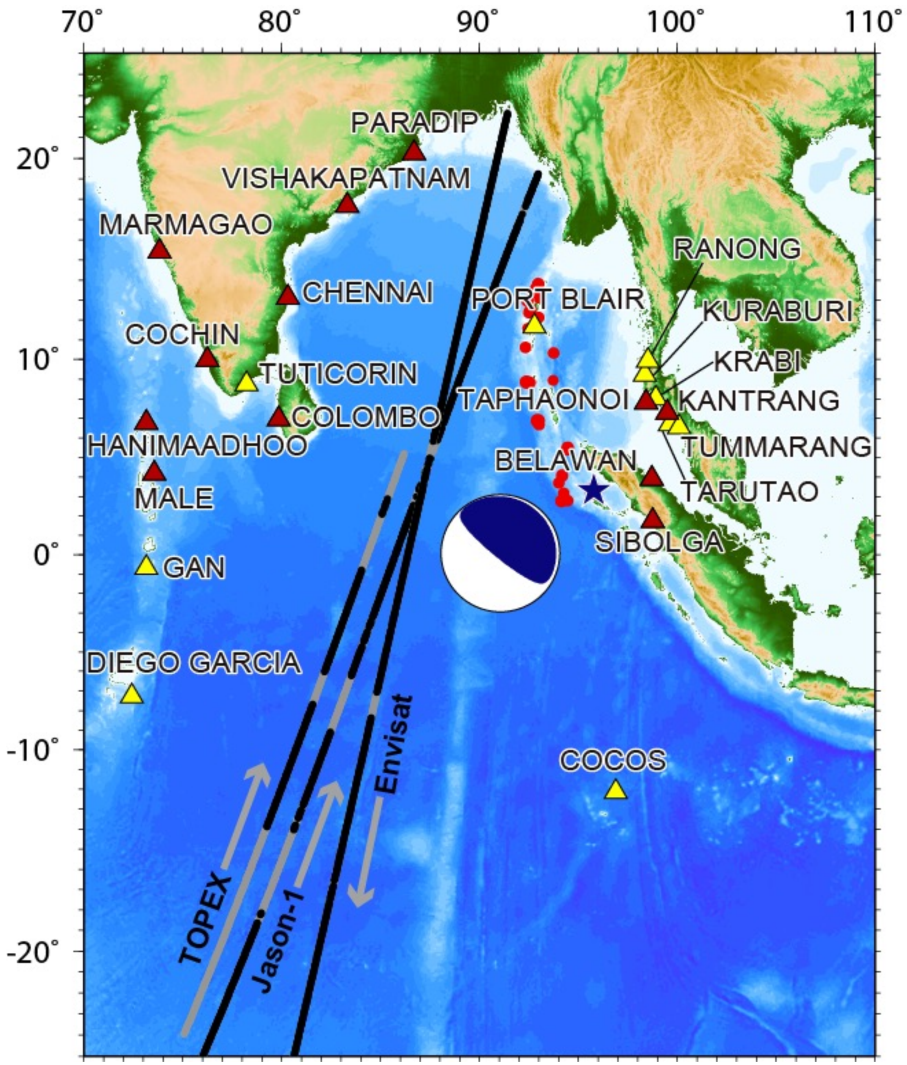


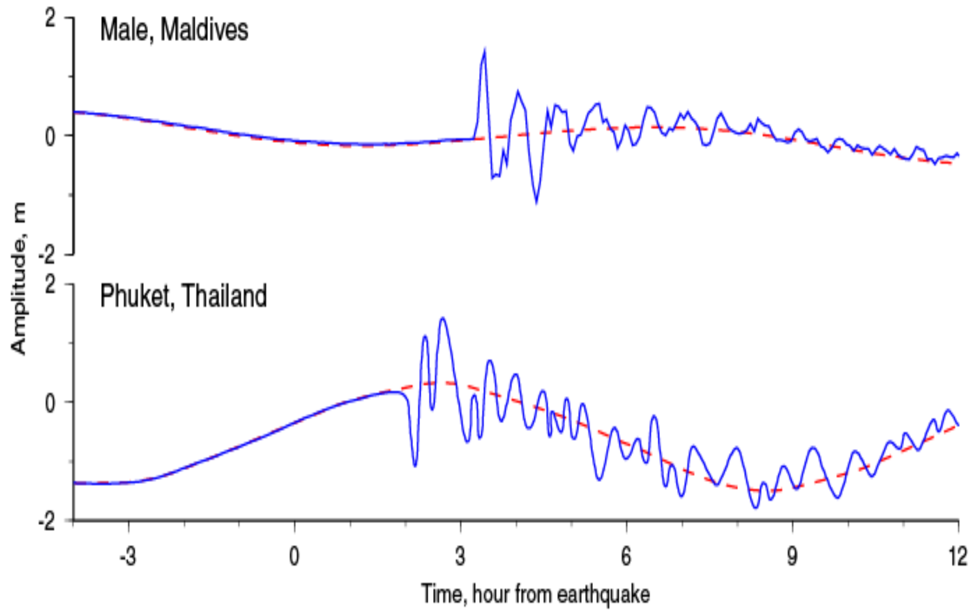
2004 Indian Ocean Tsunami





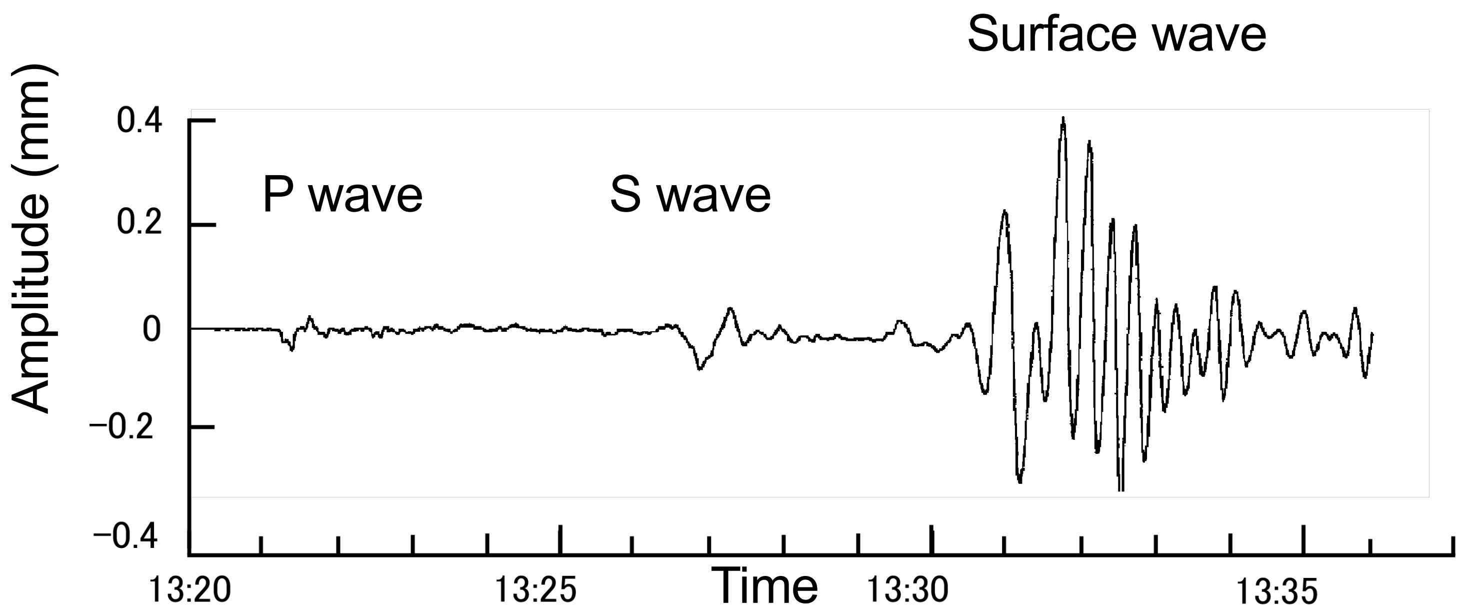
2004 Indian Ocean Tsunami





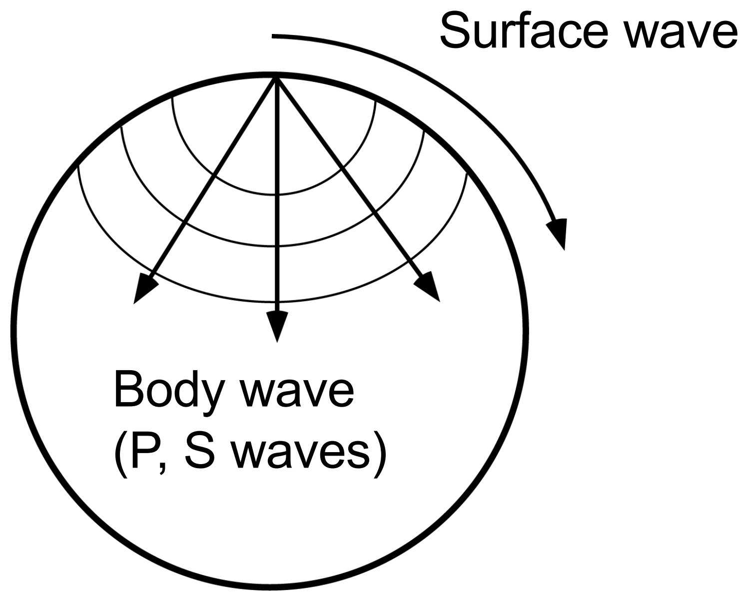
Univ. Hawaii Sea Level Center
Hydrographic Dept. Royal Thai Navy

Seismic waves

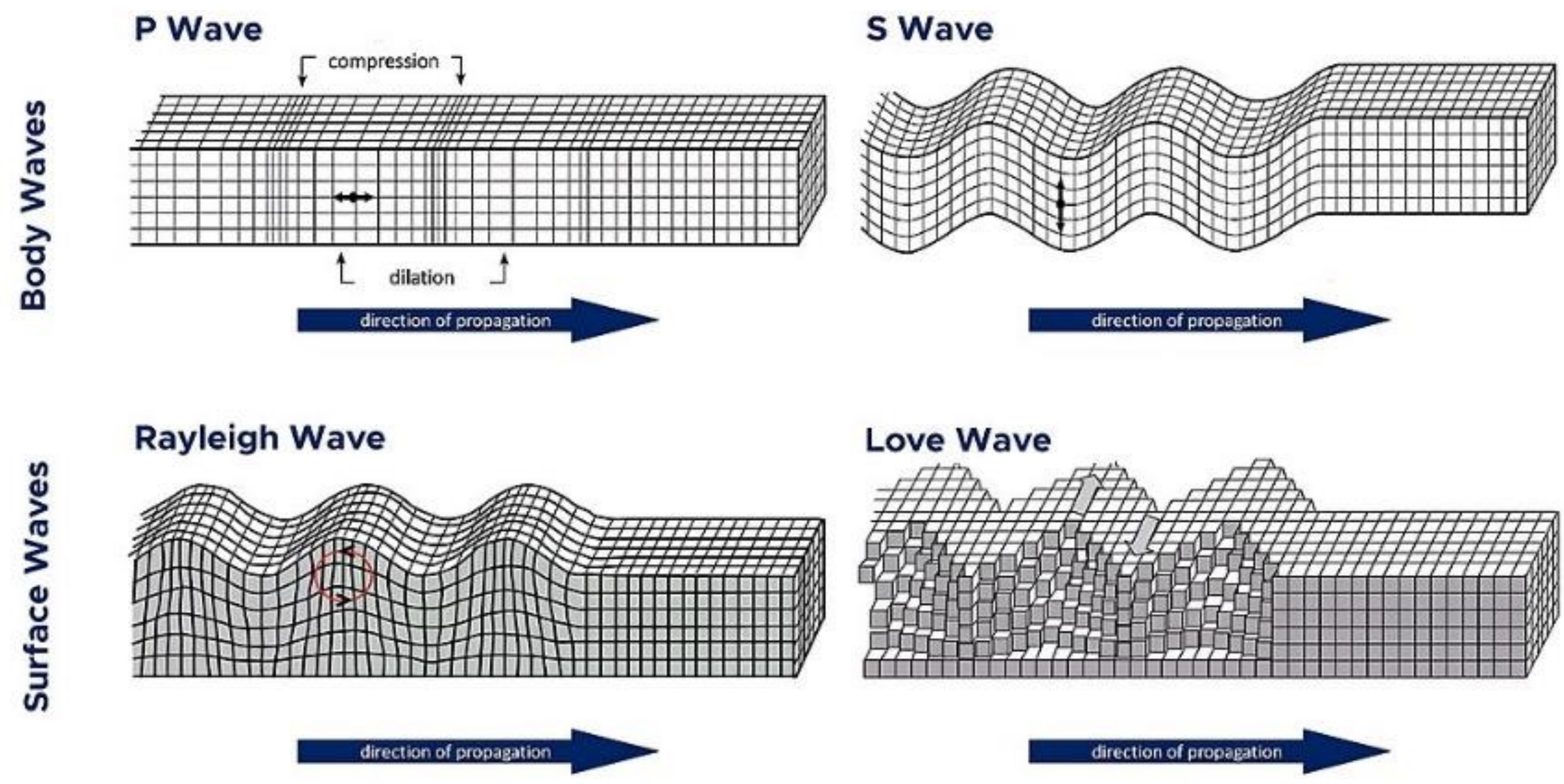


Body waves travel through the Earth
P wave   longitudinal motion
S wave   transverse motion

Surface waves
Rayleigh wave
Love Wave



Types of Seismic Waves



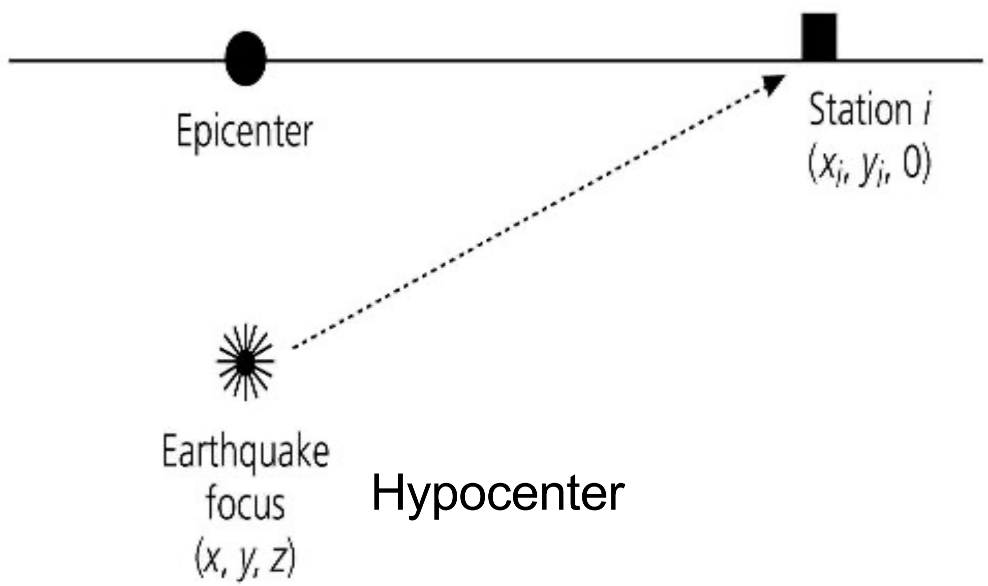
Earthquake Nomenclature

Described by Time (t) and Location (x,y,z)

Hypocenter (Focus):
Origin Time,
Latitude, Longitude,
Depth
Location in Earth where energy in the rock being strained is released

Epicenter:
Latitude, Longitude
Point on Earth's surface directly above Hypocenter

Figure 7.2-1: Geometry for earthquake location in a homogeneous halfspace.

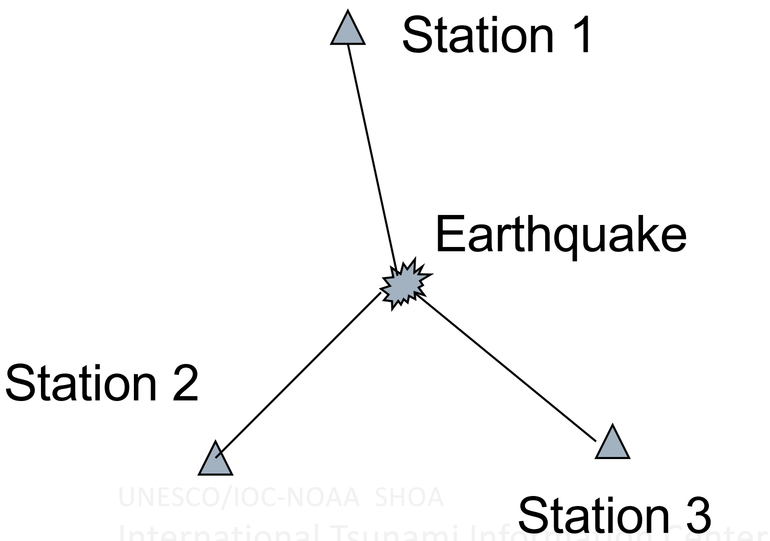


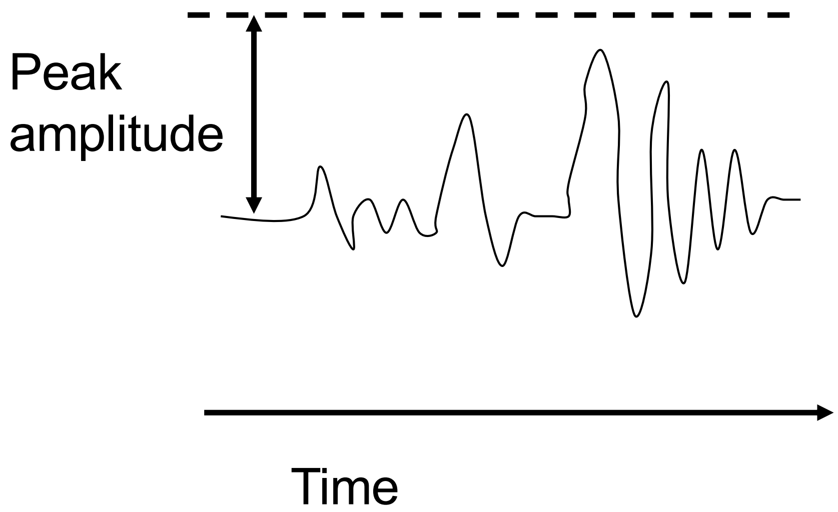
Magnitude scale

- **Originally derived as size based on seismograms, e.g., maximum or "peak" ground motion measured**
- Measure of amount of energy released by earthquake
- **Base-10 logarithmic scale**

$$M = \log(A/T) + F(h, \Delta) + C$$

- 1st magnitude scale by Charles Richter (1935) to measure California earthquakes.
- Now, many scales for various observational conditions.





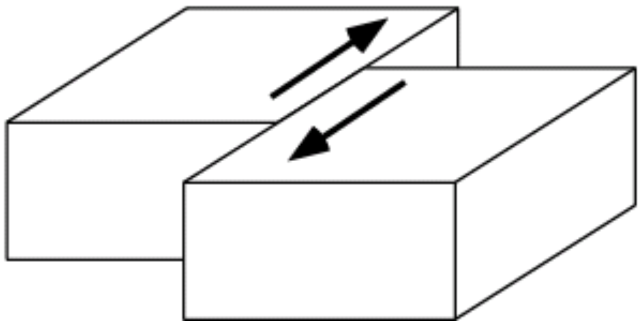
Magnitude Scales – wave type, period

			Period Range
M_L	Local magnitude (California)	regional S & surface waves	0.1-1 sec
M_j	JMA (Japan Meteorol. Agency)	regional S & surface waves	5-10 sec
m_b	Body wave magnitude	teleseismic P waves	1-5 sec
M_s	Surface wave magnitude	teleseismic surface waves	20 sec
M_w	Moment magnitude	teleseismic surface waves	> 200 sec
M_{wp}	P-wave moment magnitude	teleseismic P waves	10-60 sec
M_m	Mantle magnitude	teleseismic surface waves	> 200 sec

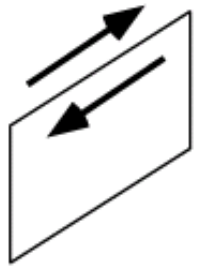
Ref: USGS Seismology and Tsunami Warnings, 2006 (Earthquake Source)

Fault motion and equivalent force

Fault motion



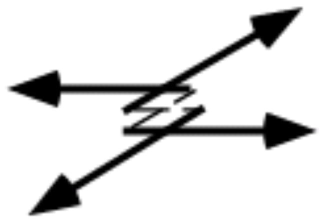
Dislocation



Equivalent Body Force

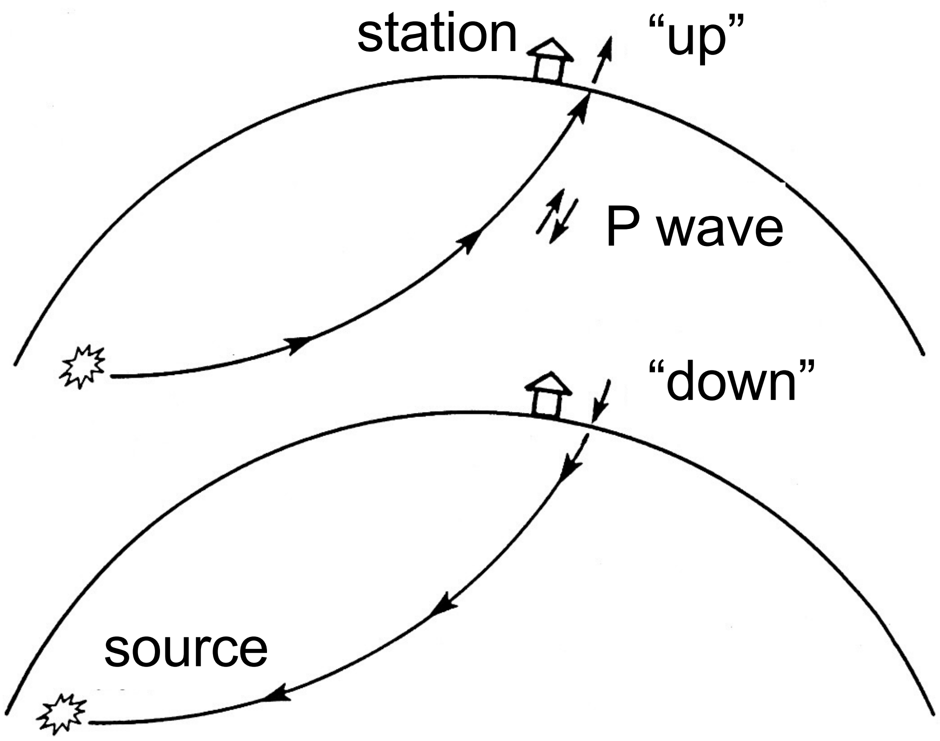
single force

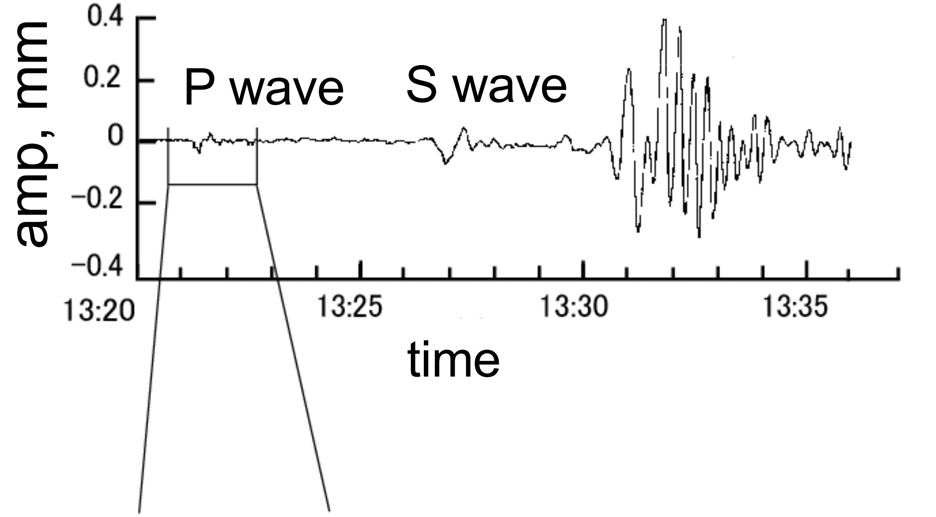
single couple



double couple

Estimation of fault motion from initial motion

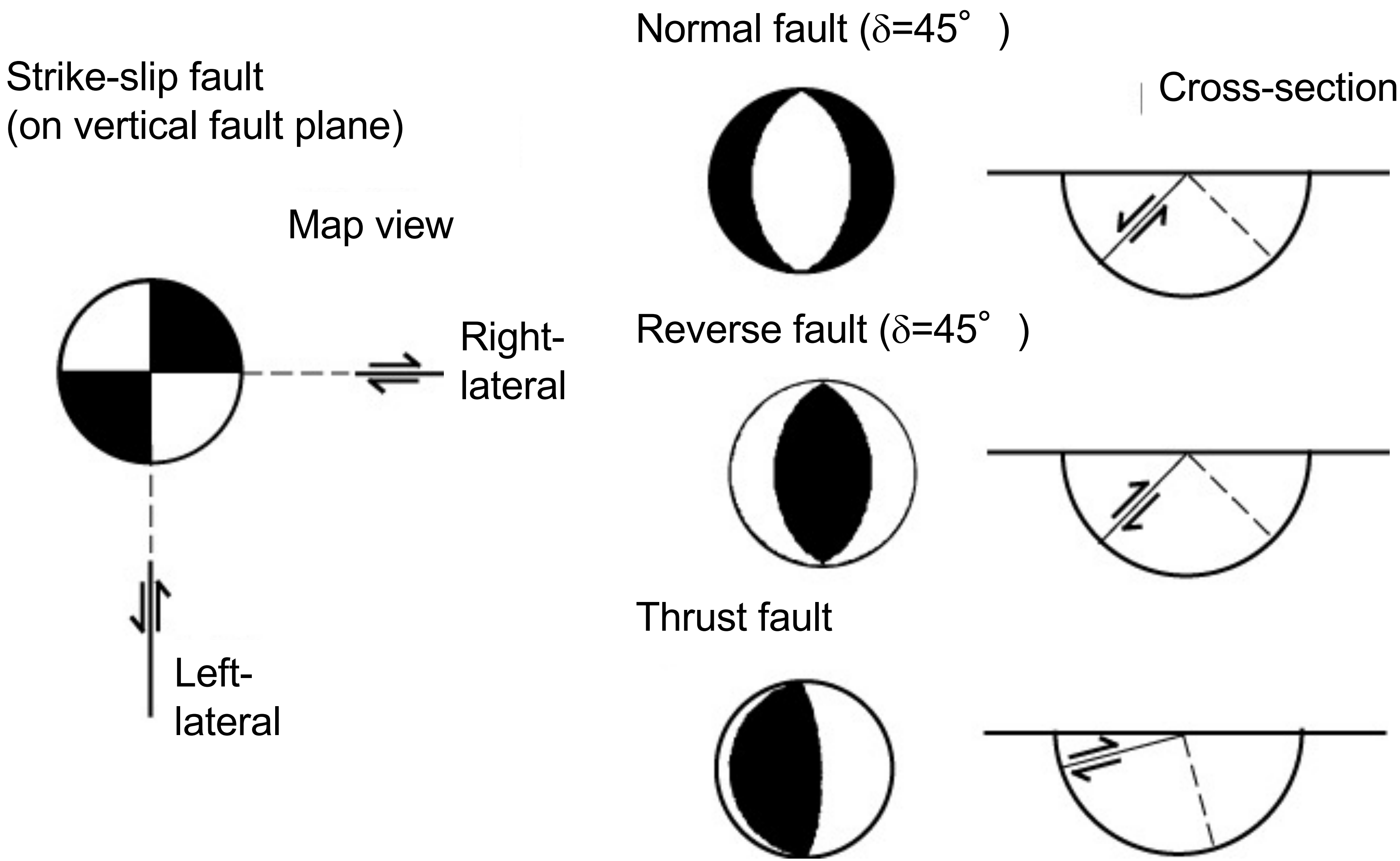




First motion is "up", away from the source

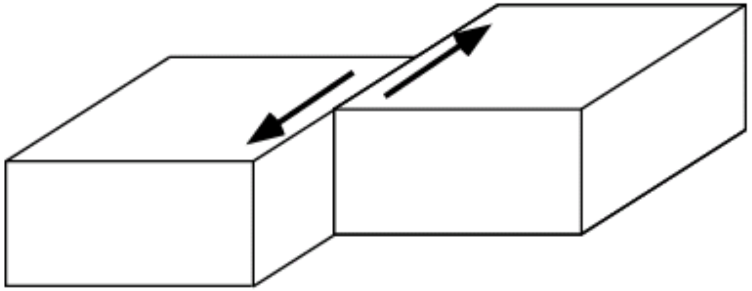
First motion is "down", toward the source

How to read beach balls

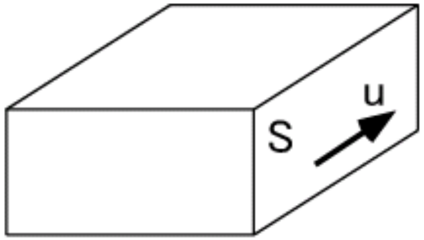


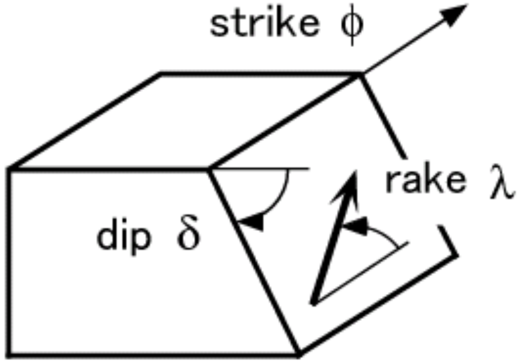
Fault Motion and Double Couple

Fault motion



Dislocation

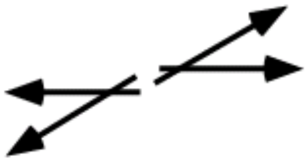


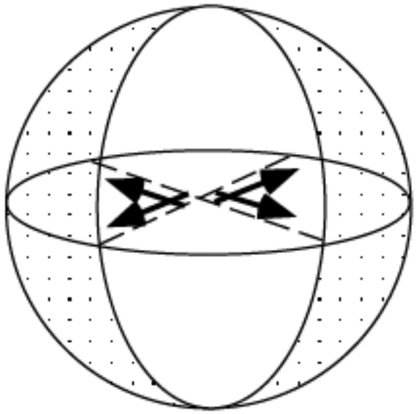


Seismic moment

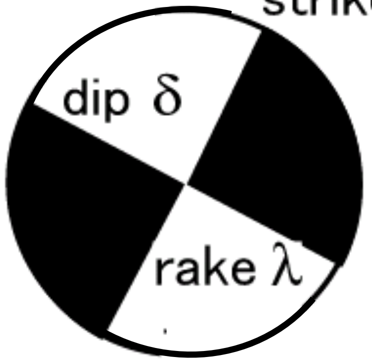
$M_o = \mu u S$

Double couple





moment M_o



Seismic moment

Physical property to represent the source size

Mo = μ *u L W*

Mo: Seismic moment （N m）

μ: rigidity (N/m^2)

u: slip amount (m)

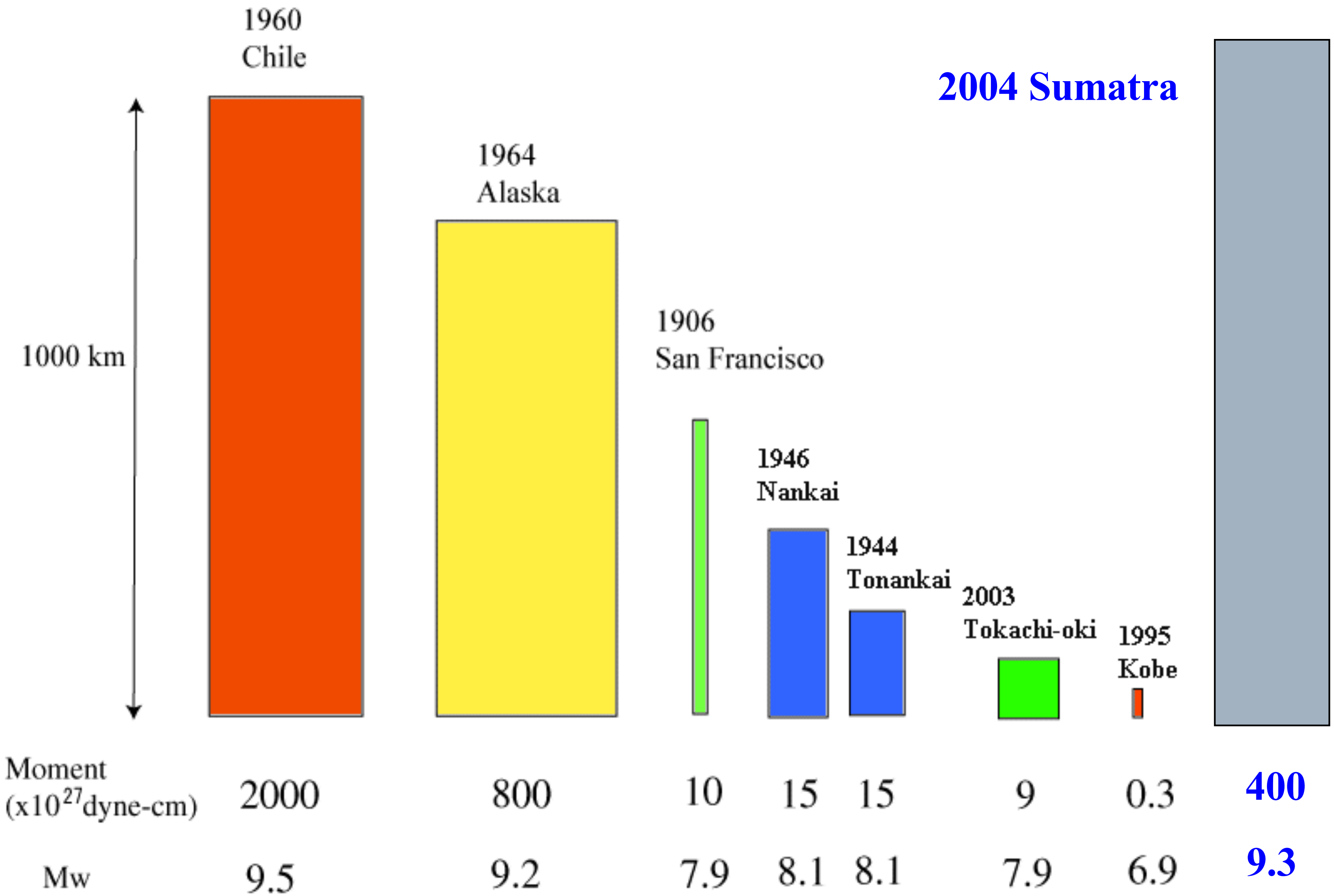
L: fault length (m)

W: fault width (m)

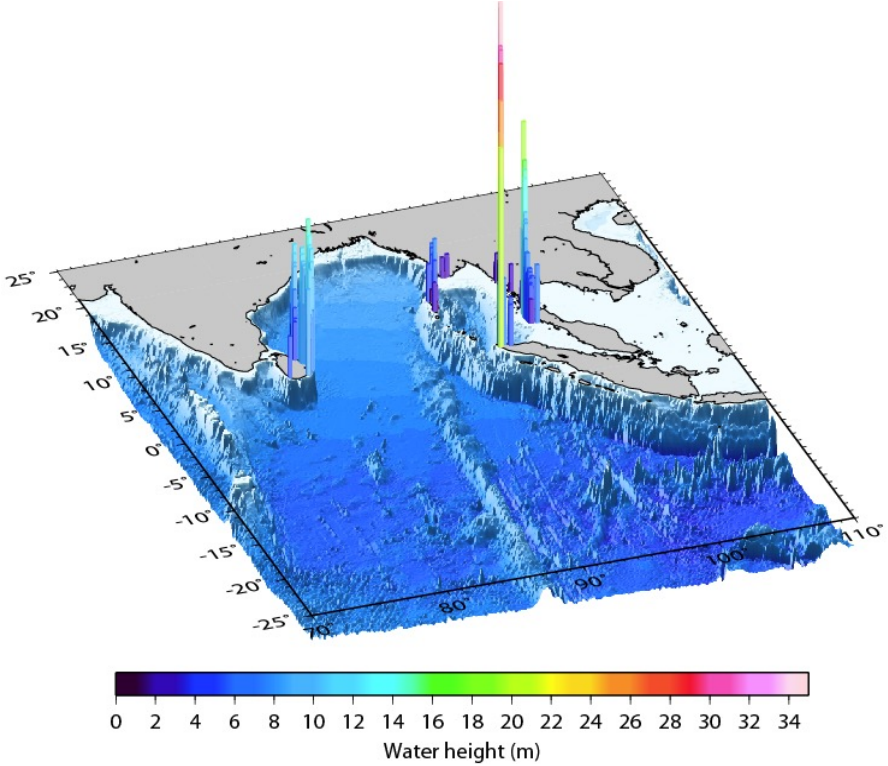
Moment magnitude Mw

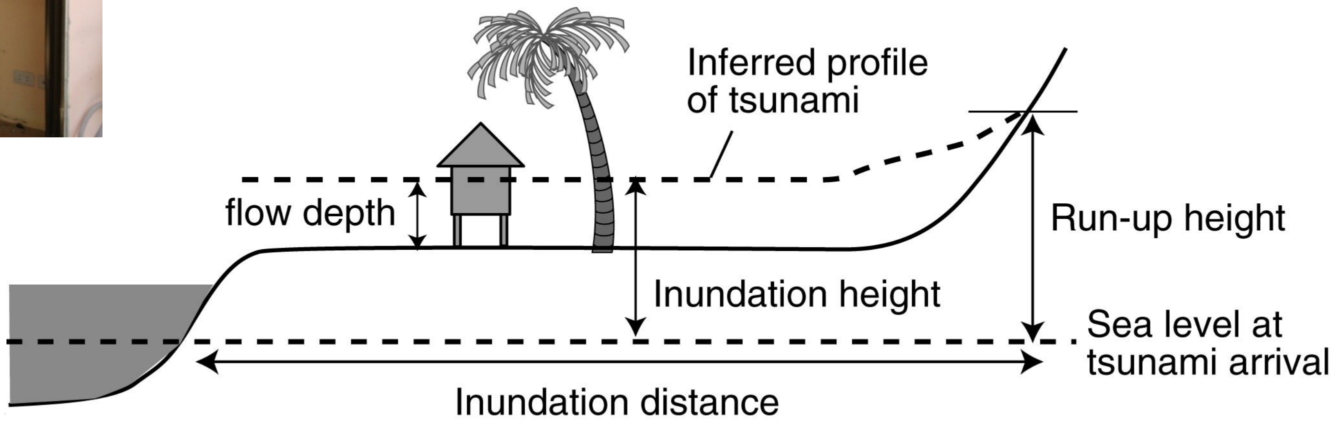
Mw = (log Mo - 9.1) / 1.5

Seismic moments and fault areas of some famous earthquakes

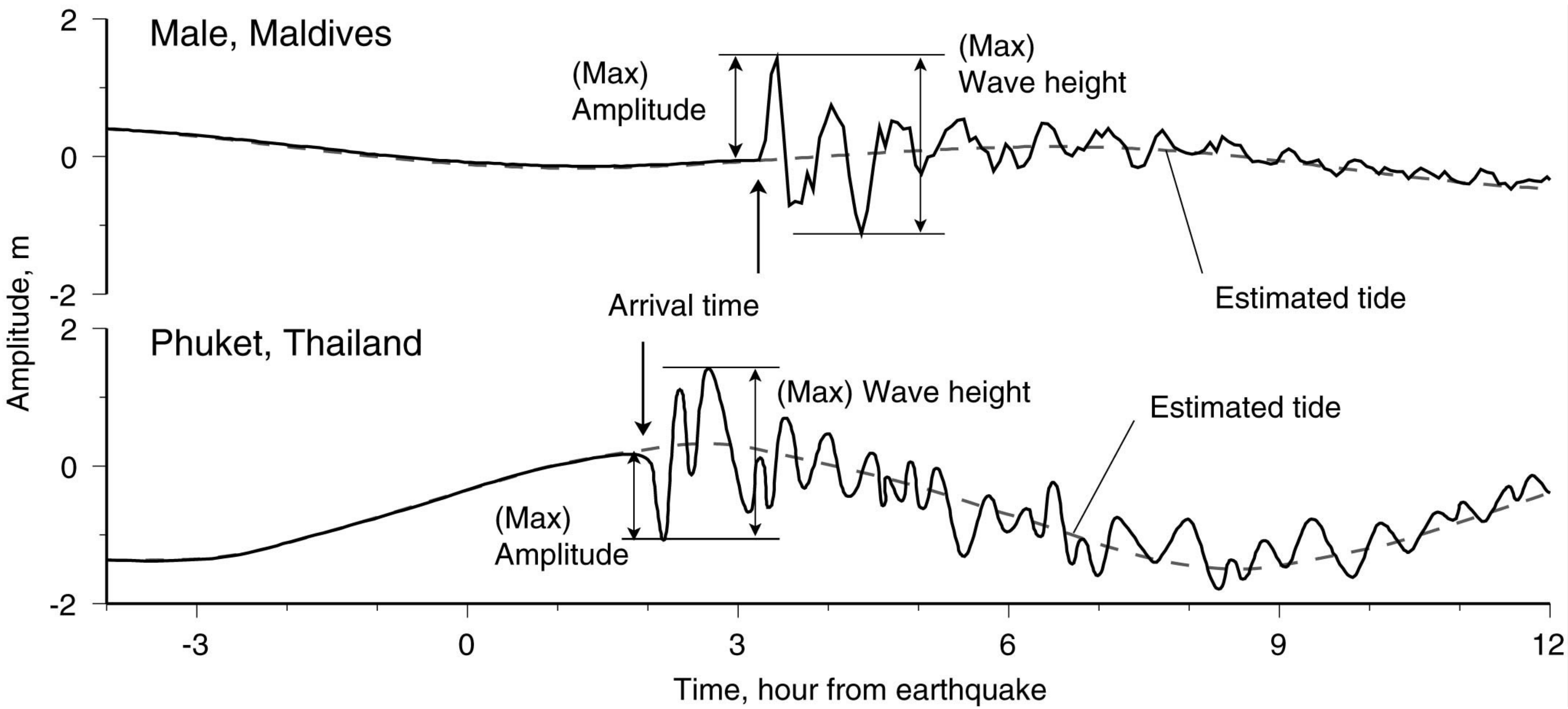


Survey of Tsunami Heights





Amplitude and Wave Heights



Tsunami Magnitude Scale: M_t

Developed by K. Abe

H_t: amplitude on tide gauges (m)

calibrated with Mw (moment magnitude)

H_t can be estimated from M of eq.

1. far-field tsunami

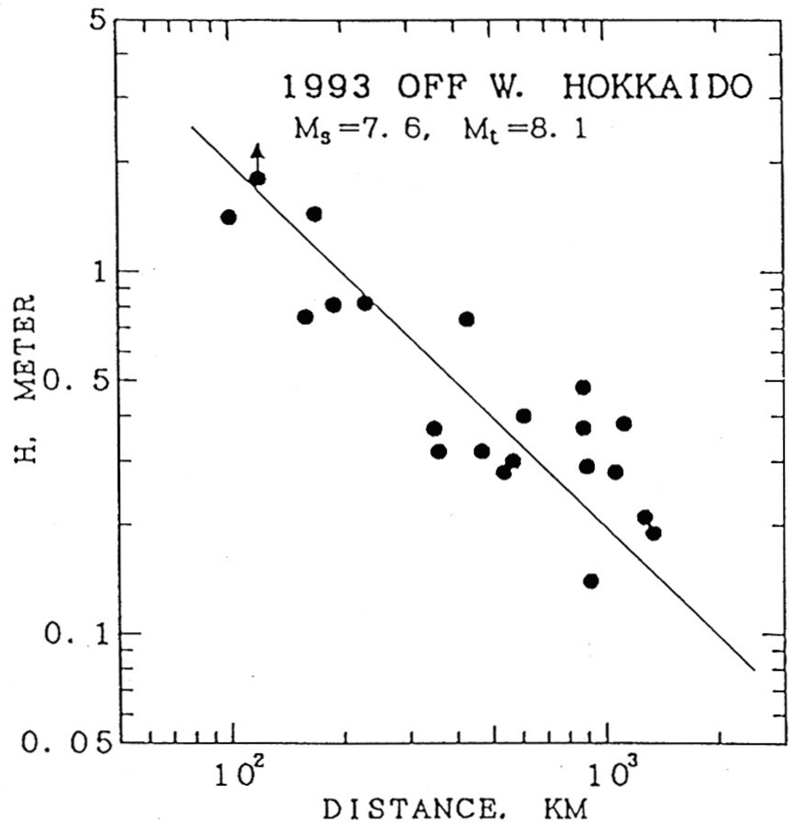
$$M_t = \log H_t + 9.1 + C$$

C: constant for source & stations

2. near-field tsunamis

$$M_t = \log H_t + \log D + 5.8$$

D: distance (km)



Tsunami Magnitude Scale: M_t

For trans-Pacific tsunami

$$M_t = \log H_t + 9.1 + C$$

C: constant for source & stations

H_t: amplitude on tide gauges (m)

calibrated with Mw (moment magnitude)

H_t can be estimated from M of eq.

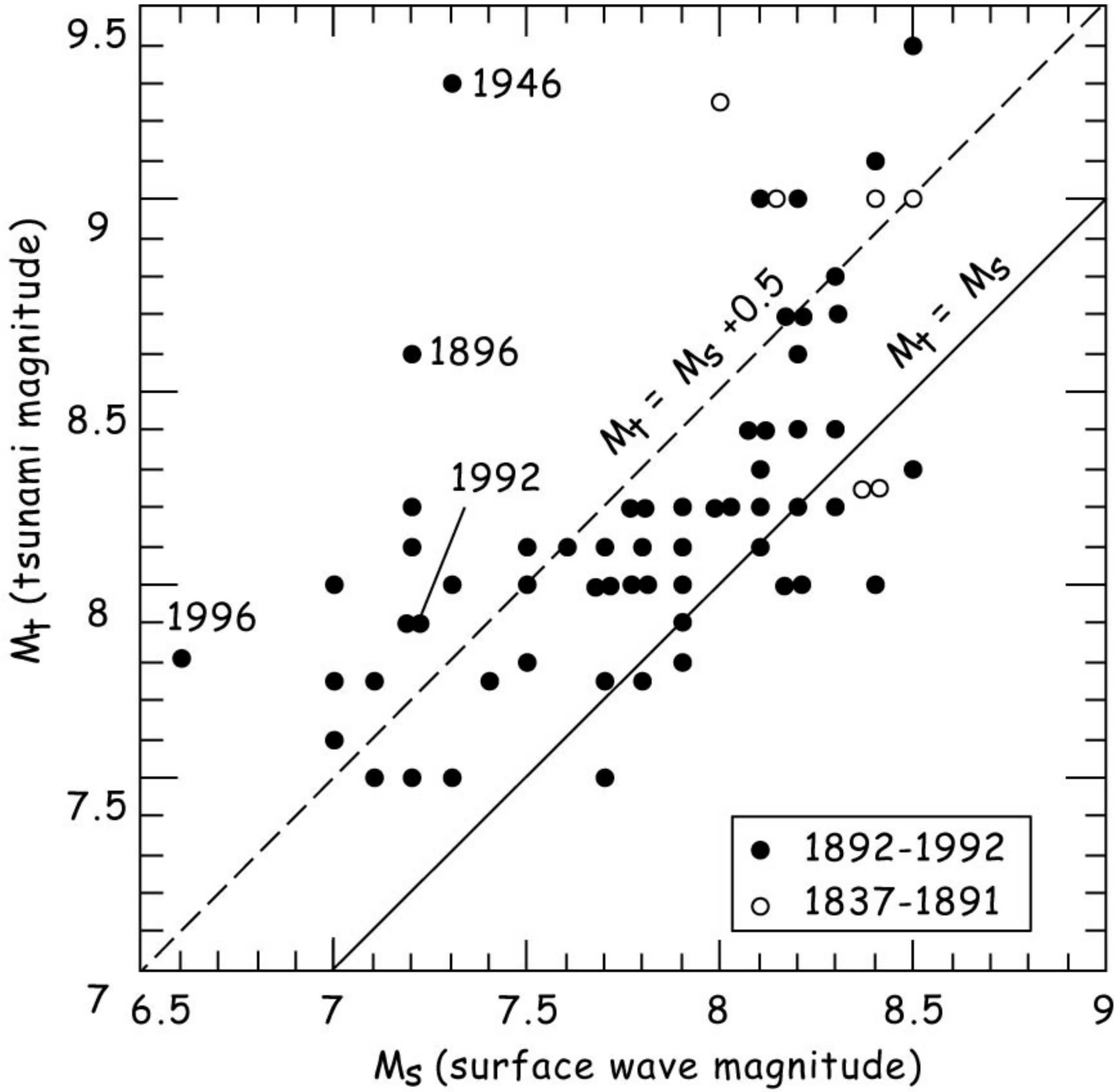
Abe (1979)

Mw 9.1 Ht = 1 m

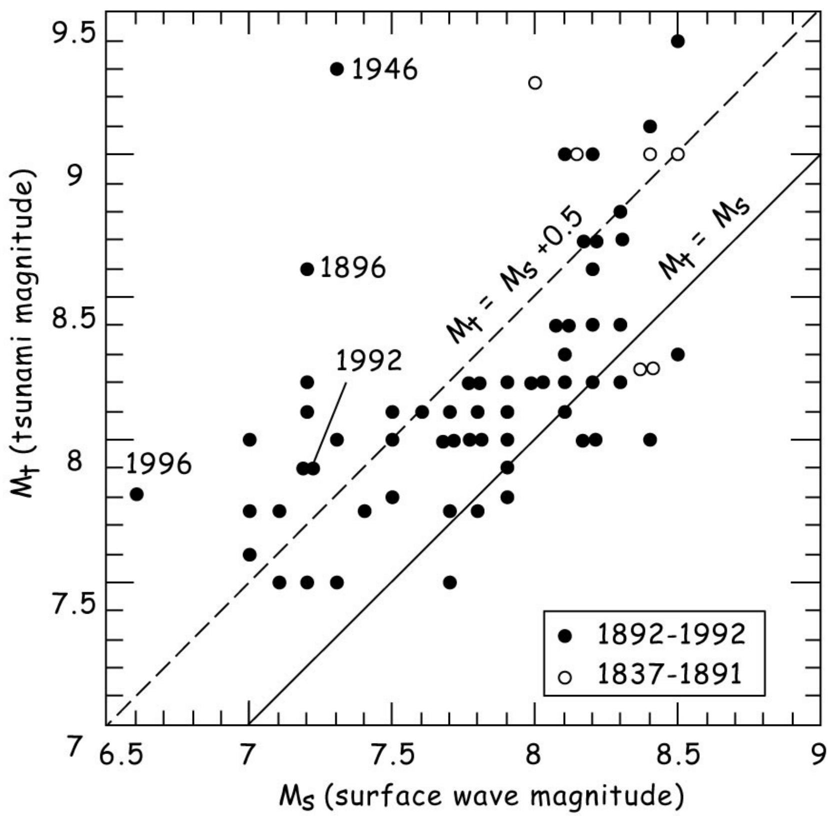
Mw 9.5 Ht = 2.5 m

Source region	C				
	Honolulu	Hilo	California	Japan	Aleutian
Peru, Chile	+ 0.2	- 0.6	+ 0.2	0.0	+ 0.2
Alaska, Aleutian	+ 0.1	0.0	+ 0.2	+ 0.3	--
Kamchatka, Kuril, Japan	0.0	- 0.4	+ 0.1	- 0.2	- 0.2
Whole region	+ 0.1	- 0.3	+ 0.2	0.0	0.0

M_t-M_s for Tsunami Earthquakes



Tsunami Earthquakes

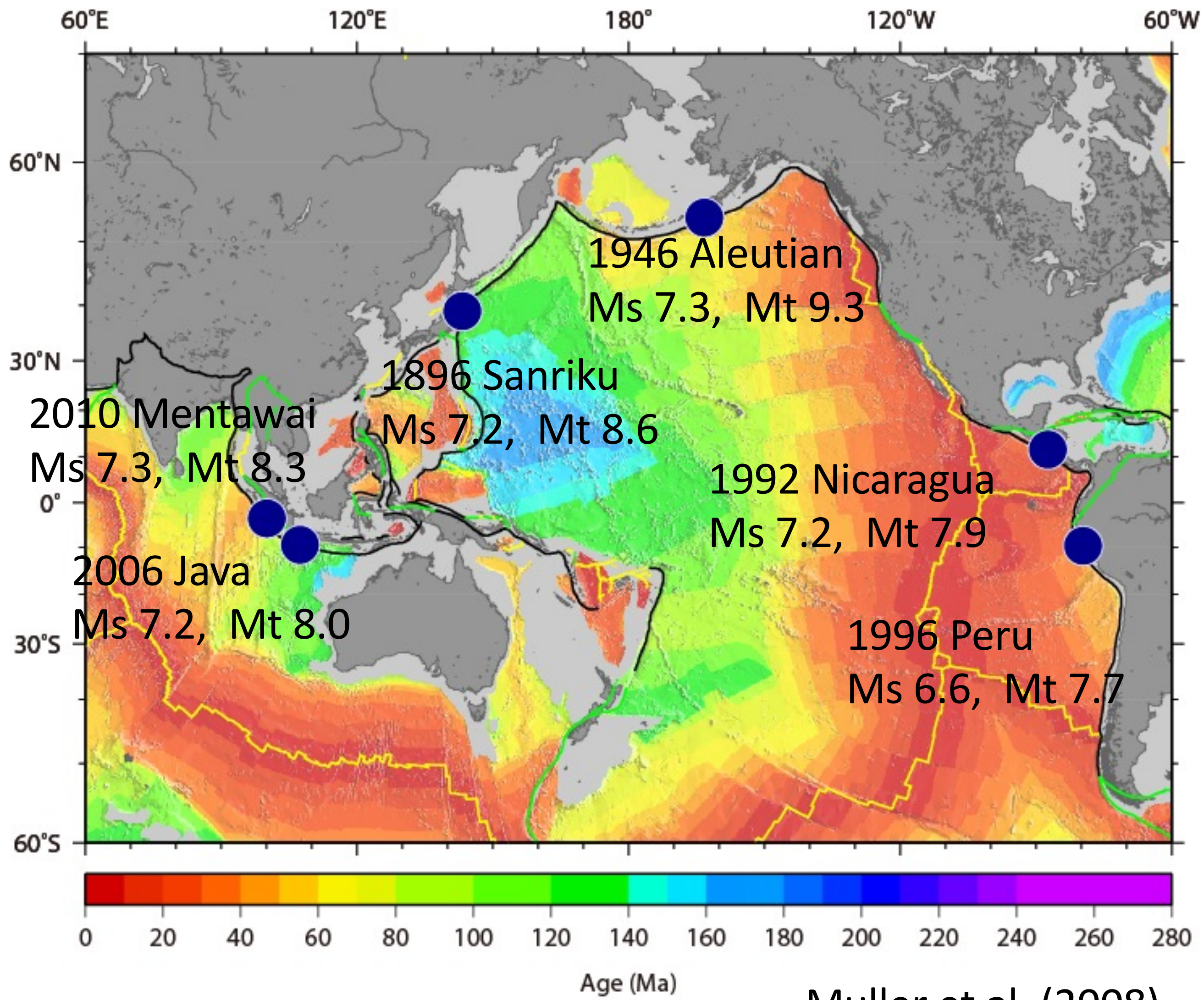


An earthquake that generates abnormally large tsunami despite its weak seismic shaking

Tsunami is nor abnormally large, but short period seismic waves are abnormally small, hence tsunami becomes relatively larger

Tsunami size can be estimated by analyzing very long period seismic waves

Tsunami Earthquakes



Muller et al. (2008)

1896 Sanriku
Tanioka and Satake (1996)
Tanioka and Seno (2001)

1946 Aleutian
Johnson and Satake (1997)
Tanioka and Seno (2001)

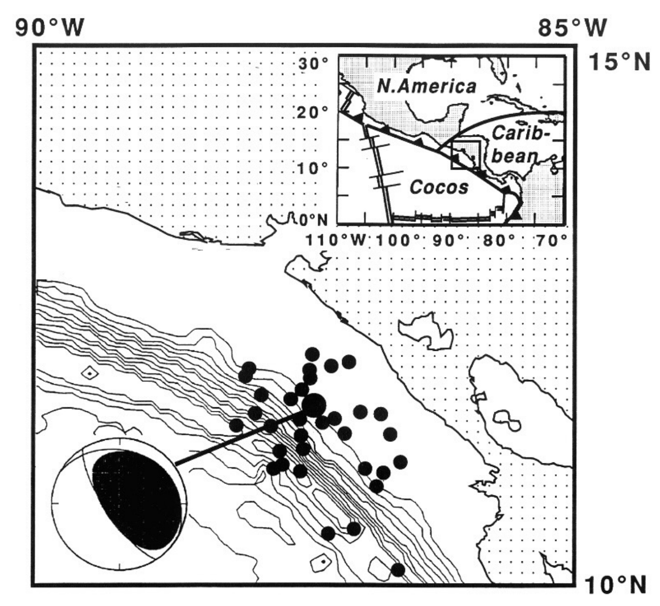
1992 Nicaragua
Satake (1994)

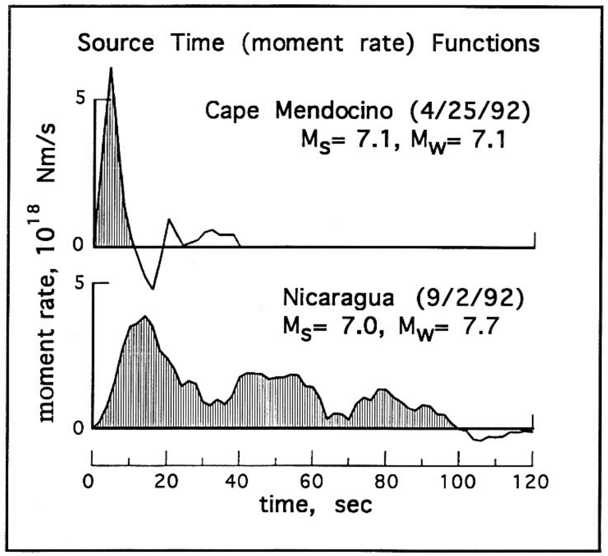
1996 Peru
Satake and Tanioka (1999)

2006 Java
Fujii and Satake (2006)

2010 Mentawai
Stake et al. (2012)

1992 Nicaragua Earthquake





Typical "tsunami earthquake"

-Weak intensity (M~6)

-Moderate surface wave magnitude (Ms 7.2)

-Large tsunamis (M~8)

→ Slow rupture: duration ~ 100 s

Seismic Moment Estimates

-Seismic analyses: 3-4 x 10^{20} Nm

(w/ long duration)

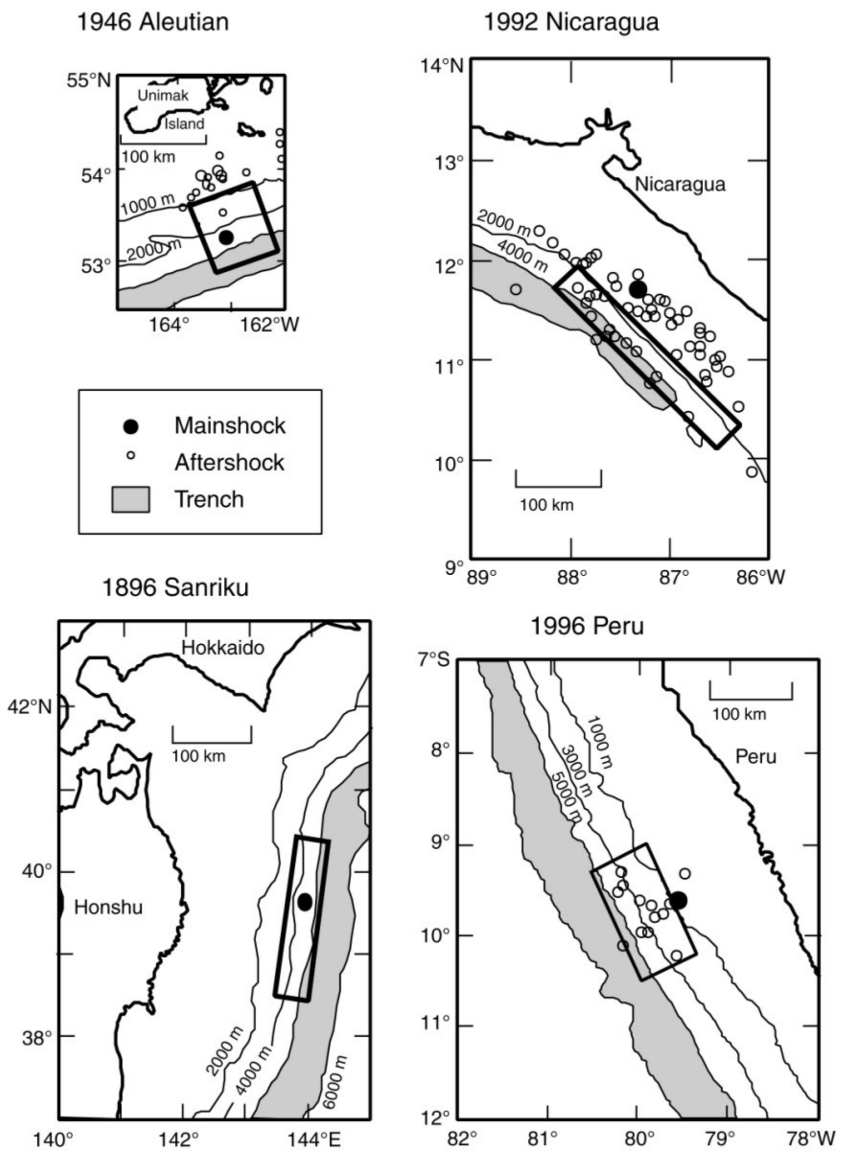
-Tsunami modeling: 3 x 10^{21} Nm

→ Shallow faulting

(within subducted sediments)

Satake et al. (1993)

Tsunami Earthquakes



1896 Sanriku

Ms =7.2, Mt =8.6

1992 Nicaragua

Ms = 7.2, Mt = 7.9

1946 Aleutian

Ms = 7.3, Mt = 9.3

1996 Peru

Ms = 6.6, Mt = 7.8

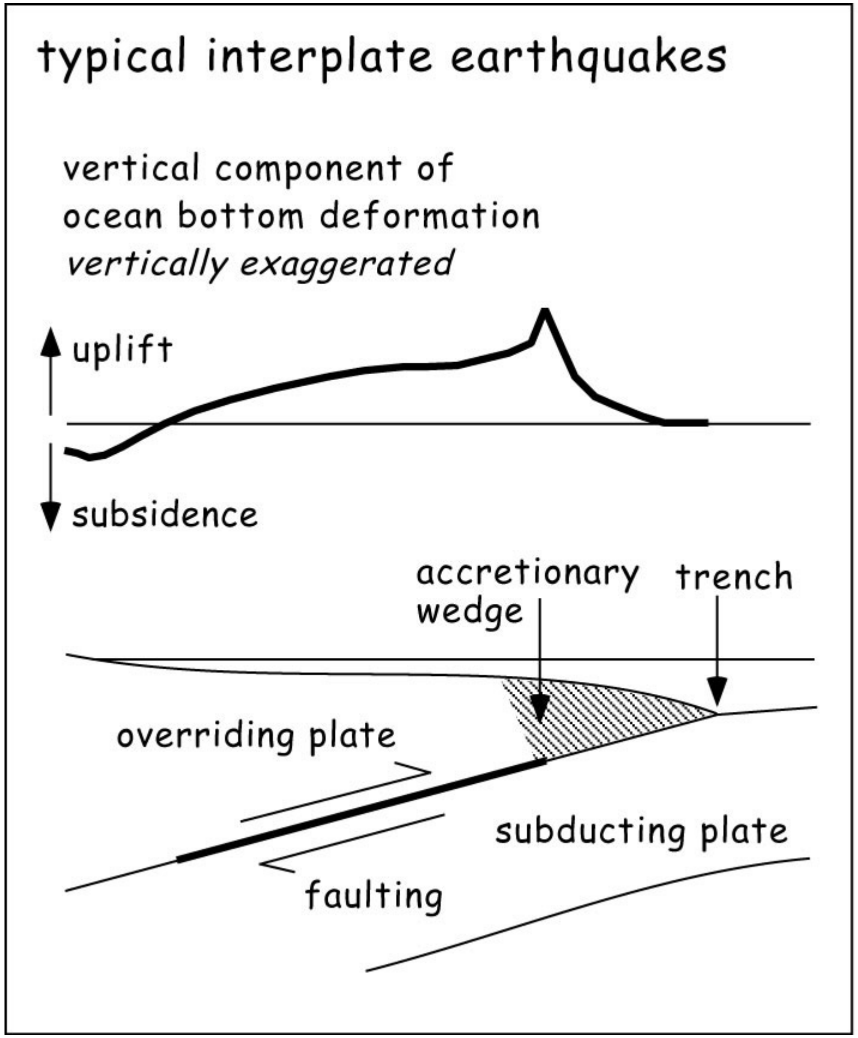
2006 Java

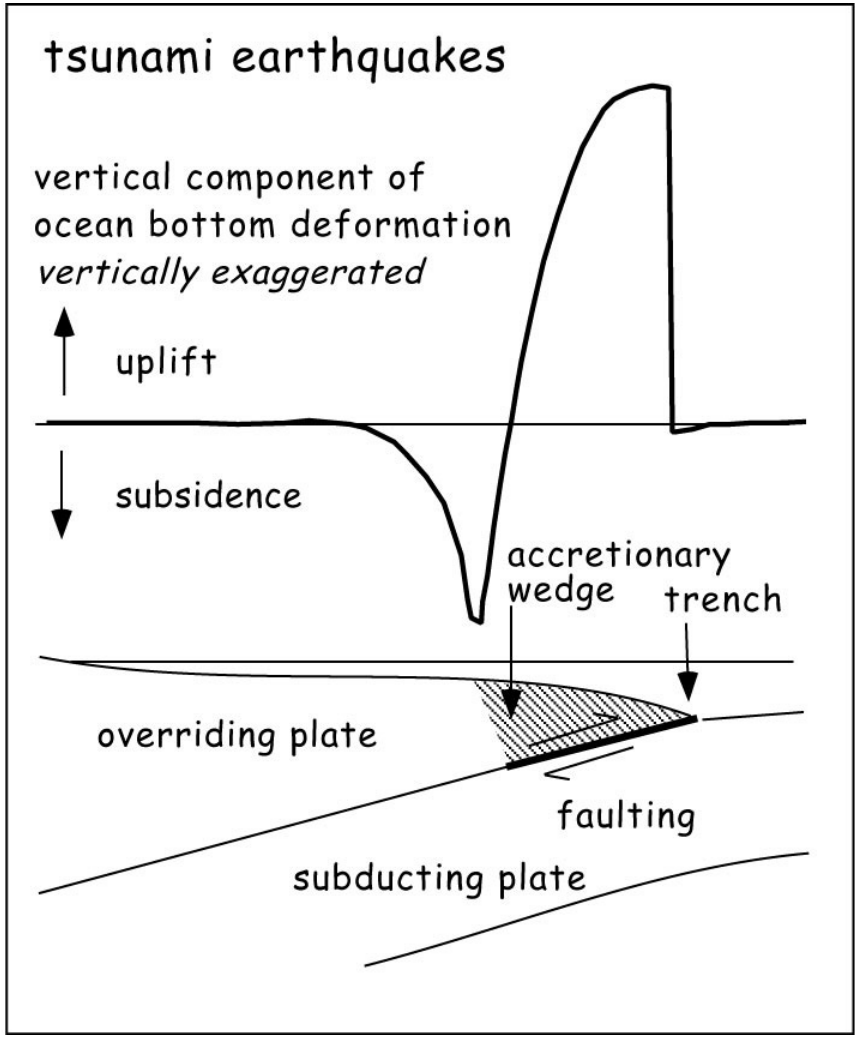
Ms = 7.2, Mt = 8.0

2010 Mentawai

Ms = 7.3, Mt = 8.3

Tsunamigenic and Tsunami Earthquakes





Satake and Tanioka (1999, Pageoph)

Thank You

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