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

TWC operations: Real-time Earthquake Detection and Fast Source Characterization, Methods and Limitations

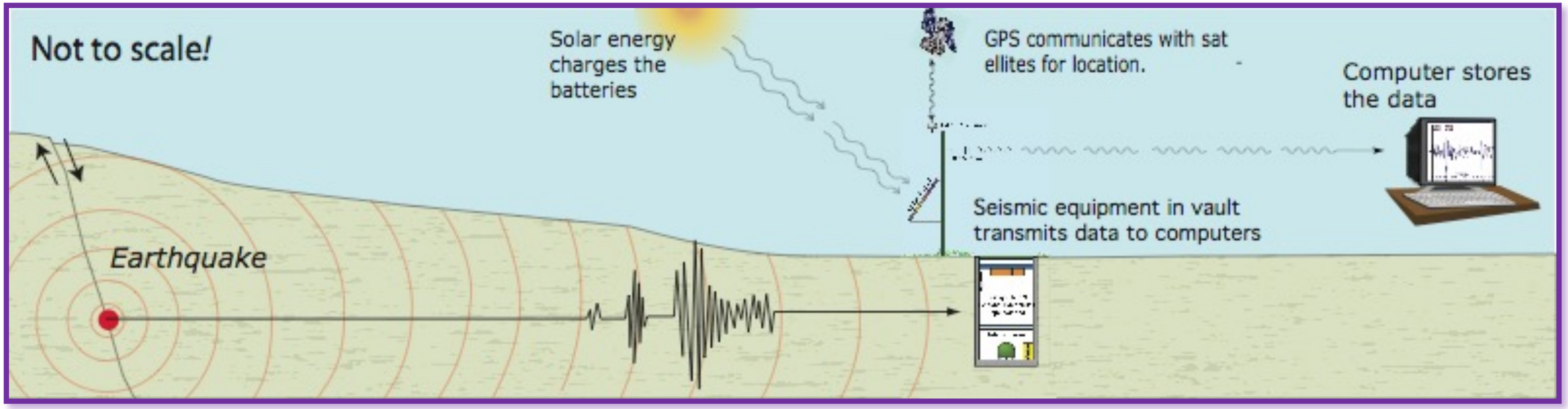
Kenji Satake
University of Tokyo

TWC operations

- Locating earthquakes
- Estimating Magnitudes
- Seismic moment and magnitude
- Moment tensor solutions
- Centroid Moment Tensor inversion
- W phase CMT inversion
- Summary of magnitudes

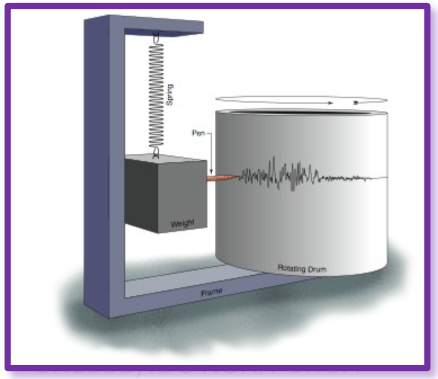
Locating Earthquakes

How do we measure earthquakes?

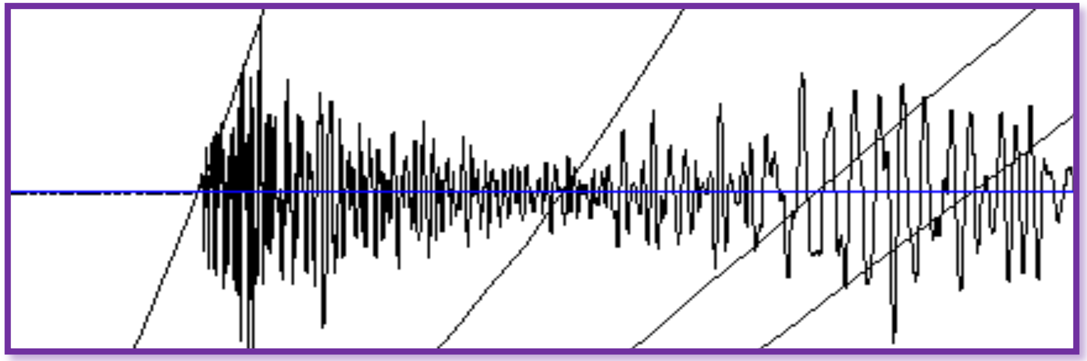


When an earthquake occurs, the seismic waves travel through the Earth to the seismic station where the information is transmitted to distant computers.

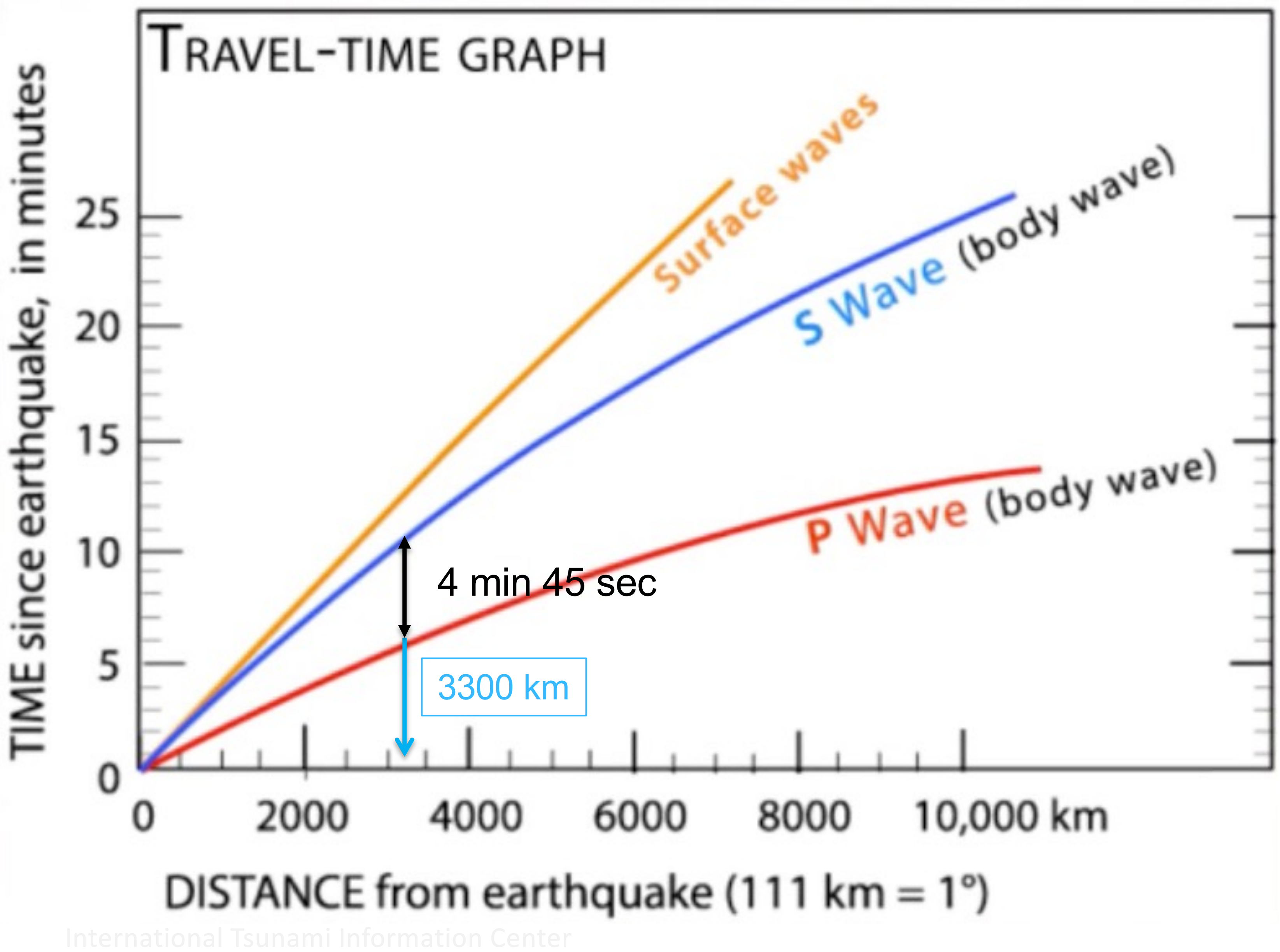
A seismograph detects and records earthquakes



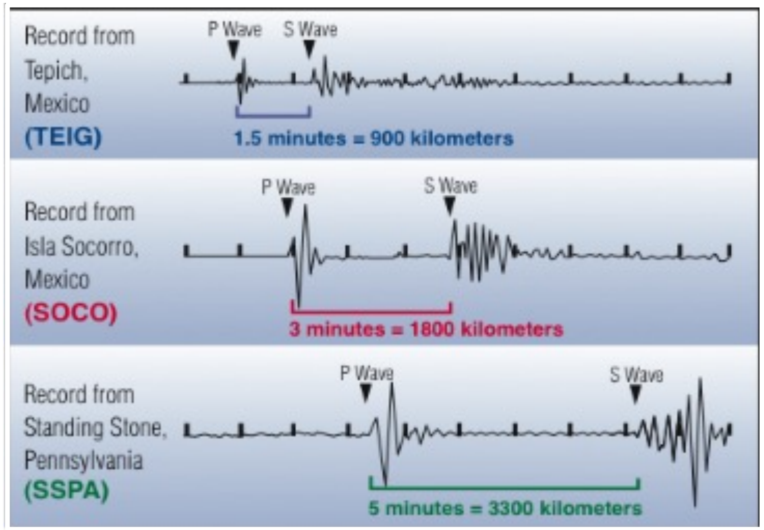
A seismogram is the earthquake record

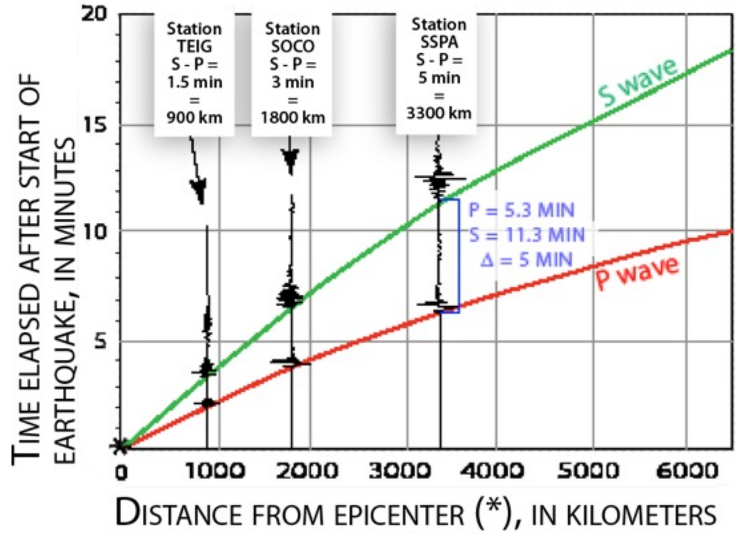


Distance of earthquake from seismometer



Locating an earthquake...the basics

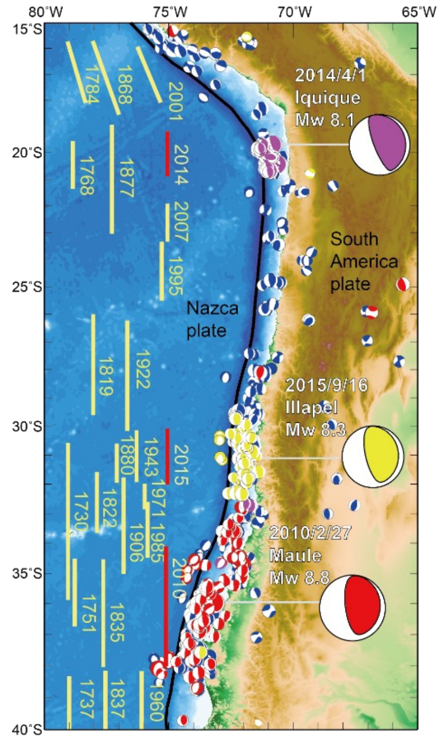


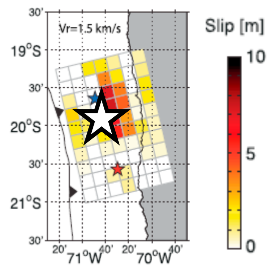


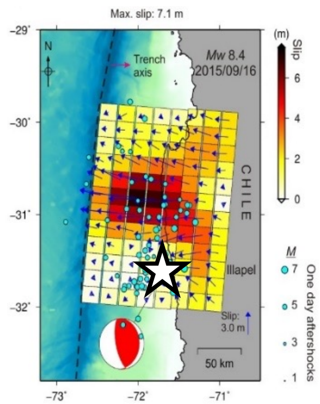
1. Determine distance of EQ from three seismic stations by calculating the S minus P arrival times.
2. Plot on the travel-time graph.
3. Intersection of the circles gives the location.

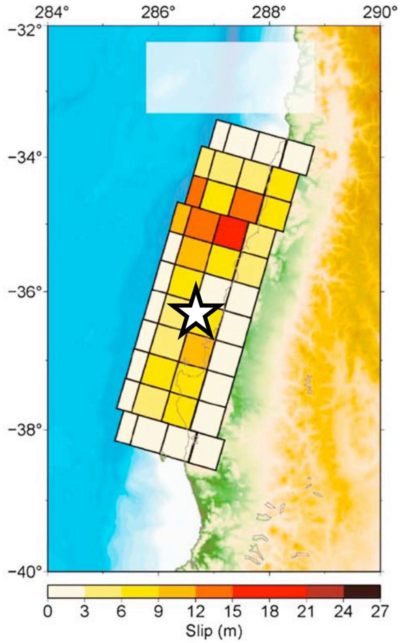
Slip distributions of Chilean earthquakes

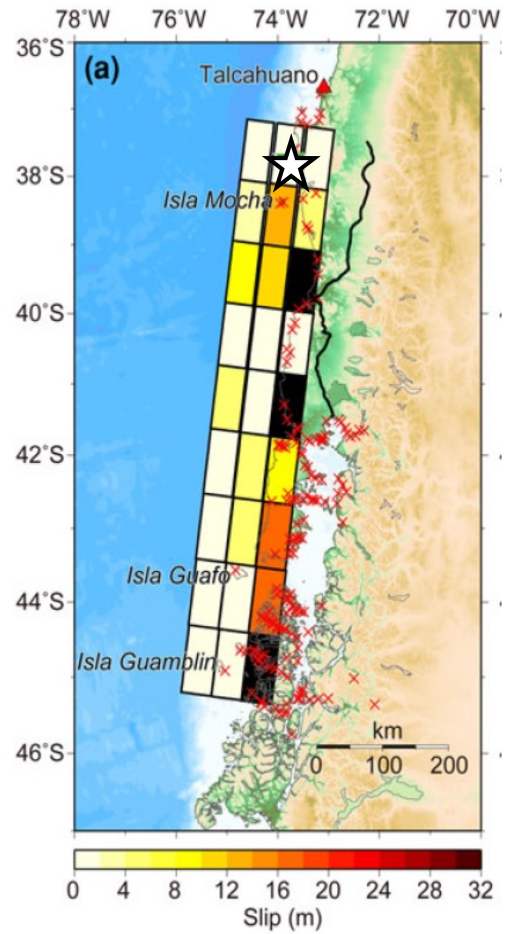
	2014 Iquique	2015 Illapel	2010 Maule	1960Valdivia
	Mw 8.0	Mw 8.3	Mw 8.8	Mw 9.2











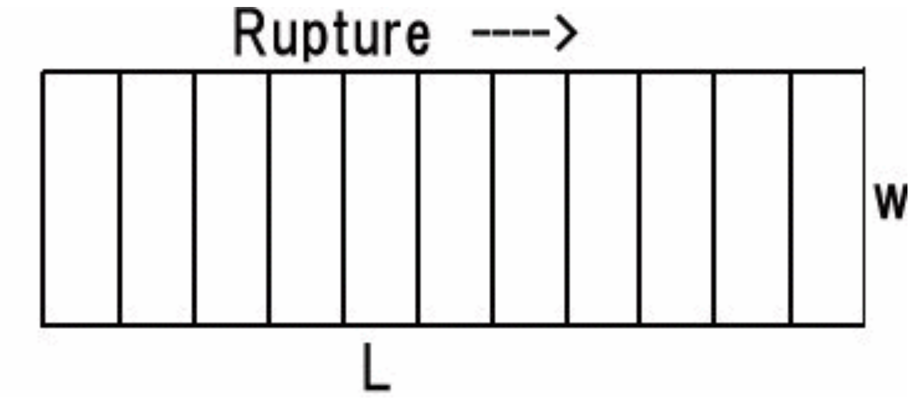
Earthquake Rupture Complexity

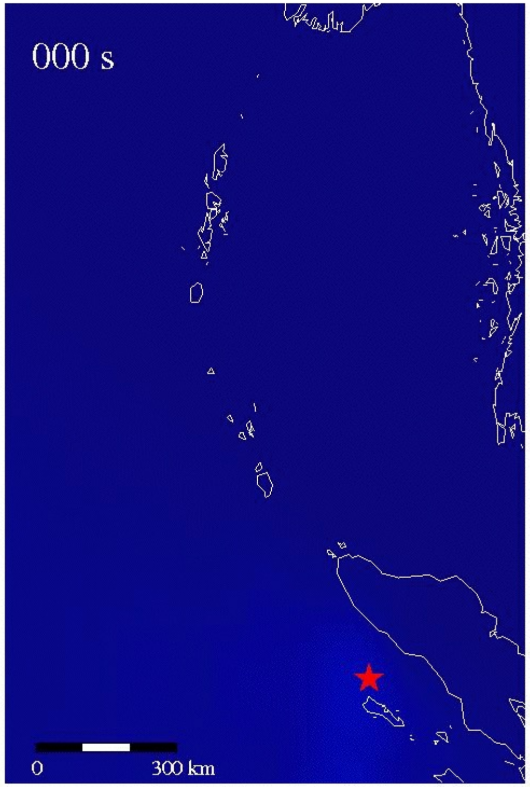
Great Earthquakes (M ≥ 8)

- **Shake for a long time (10s sec to 2-3 minutes)**
- **Rupture for 100s miles**

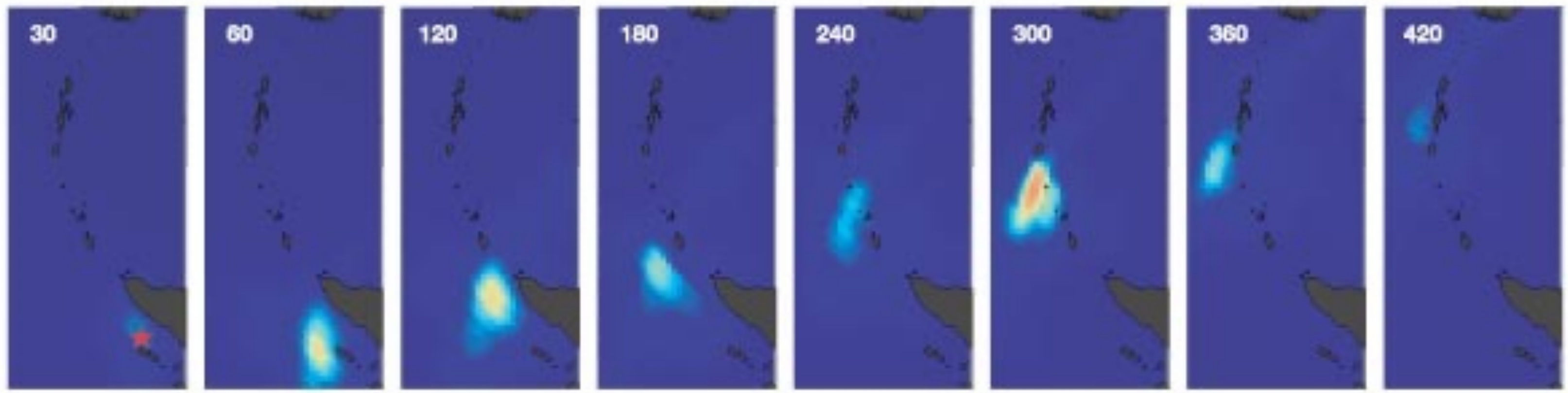
2004 Sumatra earthquake

Haskell Line Source
Dislocation Source





Energy Release imaged by Japan HINET Array



Ishii et al., 2005

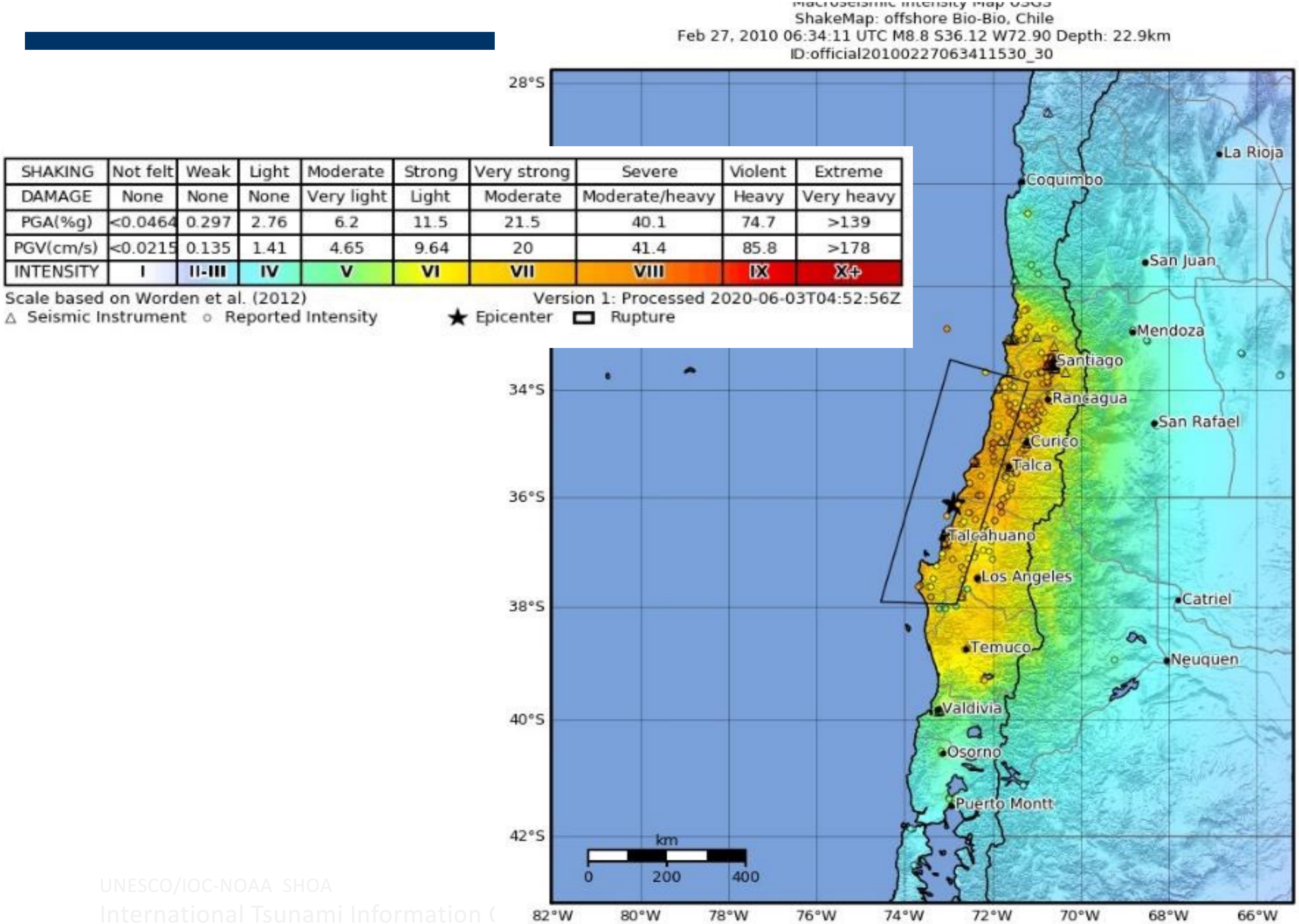
Measuring Earthquake size

- **Historical – Used macroseismic information**
  - Fatalities
  - Maximum shaking
  - Area of intense shaking
- **Did not correlate well from one quake to the next because damage depended on**
  - ”True” size (i.e., magnitude)
  - Distance from the epicenter
  - Building design
  - Surface material (rock or dirt) beneath buildings
  - Proximity to populated regions

Modified Mercalli Intensity Scale

CIIM Intensity	People's Reaction	Furnishings	Built Environment	Natural Environment
I	Not felt			Changes in level and clarity of well water are occasionally associated with great earthquakes at distances beyond which the earthquakes felt by people.
II	Felt by a few.	Delicately suspended objects may swing.		
III	Felt by several; vibration like passing of truck.	Hanging objects may swing appreciably.		
IV	Felt by many; sensation like heavy body striking building.	Dishes rattle.	Walls creak; window rattle.	
V	Felt by nearly all; frightens a few.	Pictures swing out of place; small objects move; a few objects fall from shelves within the community.	A few instances of cracked plaster and cracked windows with the community.	Trees and bushes shaken noticeably.
VI	Frightens many; people move unsteadily.	Many objects fall from shelves.	A few instances of fallen plaster, broken windows, and damaged chimneys within the community.	Some fall of tree limbs and tops, isolated rockfalls and landslides, and isolated liquefaction.
VII	Frightens most; some lose balance.	Heavy furniture overturned.	Damage negligible in buildings of good design and construction, but considerable in some poorly built or badly designed structures; weak chimneys broken at roof line, fall of unbraced parapets.	Tree damage, rockfalls, landslides, and liquefaction are more severe and widespread wiht increasing intensity.
VIII	Many find it difficult to stand.	Very heavy furniture moves conspicuously.	Damage slight in buildings designed to be earthquake resistant, but severe in some poorly built structures. Widespread fall of chimneys and monuments.	
IX	Some forcibly thrown to the ground.		Damage considerable in some buildings designed to be earthquake resistant; buildings shift off foundations if not bolted to them.	
X			Most ordinary masonry structures collapse; damage moderate to severe in many buildings designed to be earthquake resistant.	

USGS ShakeMap 2010 M_w 8.8 Maule, Chile



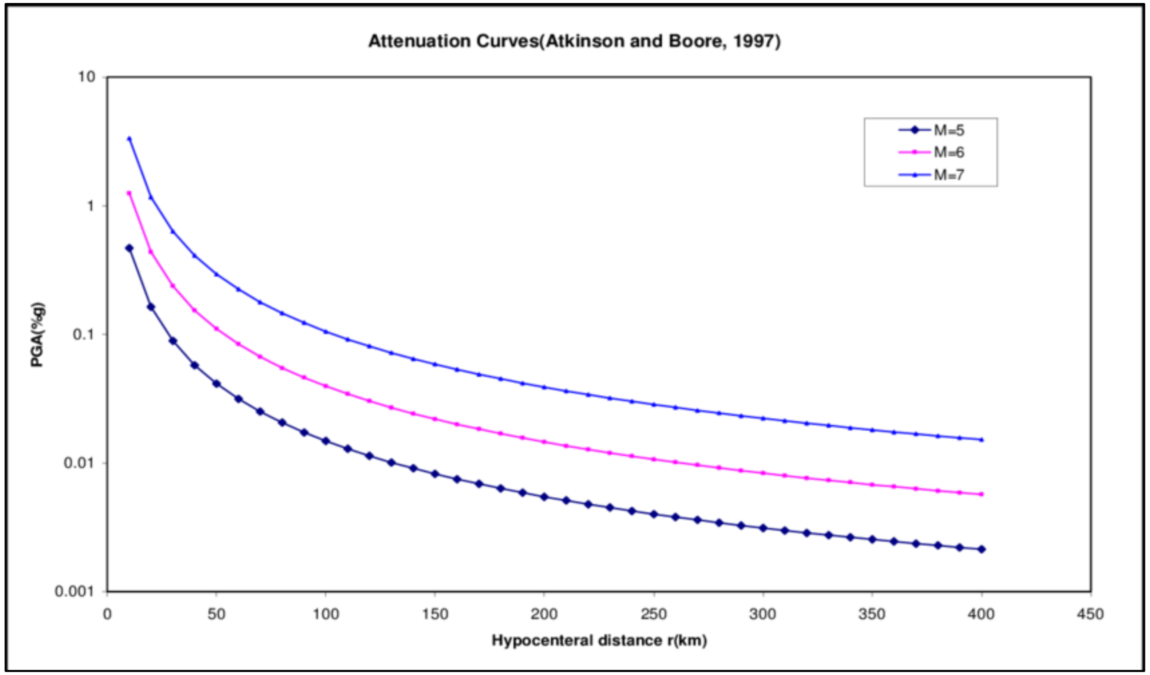
SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.0464	0.297	2.76	6.2	11.5	21.5	40.1	74.7	>139
PGV(cm/s)	<0.0215	0.135	1.41	4.65	9.64	20	41.4	85.8	>178
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Earthquake Magnitude

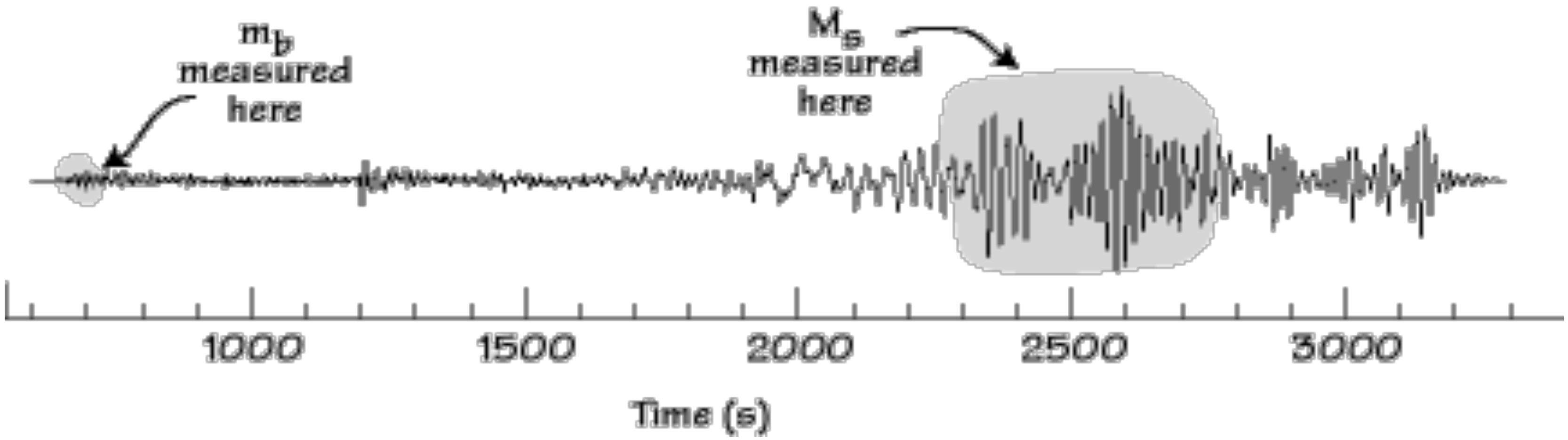
General form:

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

Amplitude — Period — Correction for depth and distance — Regional scaling factor



Richter and Gutenberg's Teleseismic magnitudes Body wave Magnitude mb and Surface wave and M_S



mb = log (A/T) +Q(D,h)

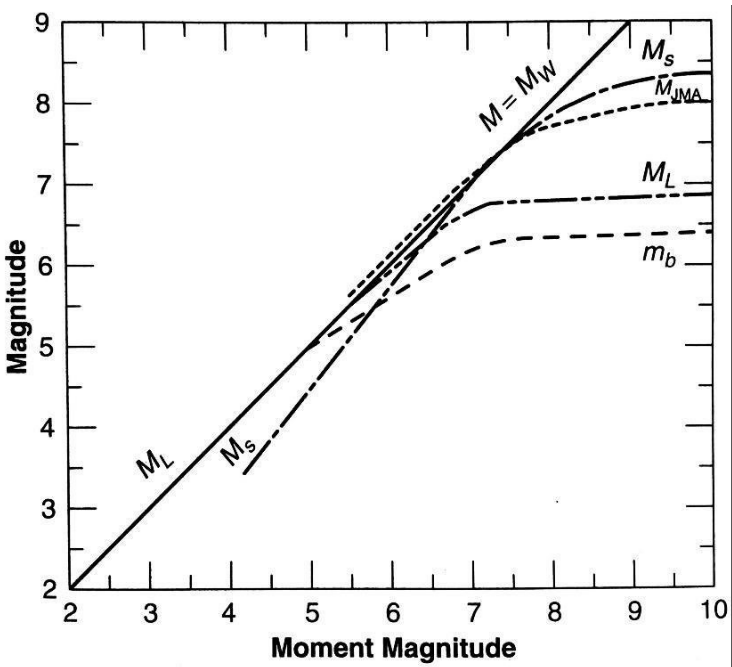
T: period (secs), 0.1 ≤ T ≤ 3.0
A: P wave amplitude (microns) (not necessarily the maximum)
Q: scale factor (D ≥ 5°)

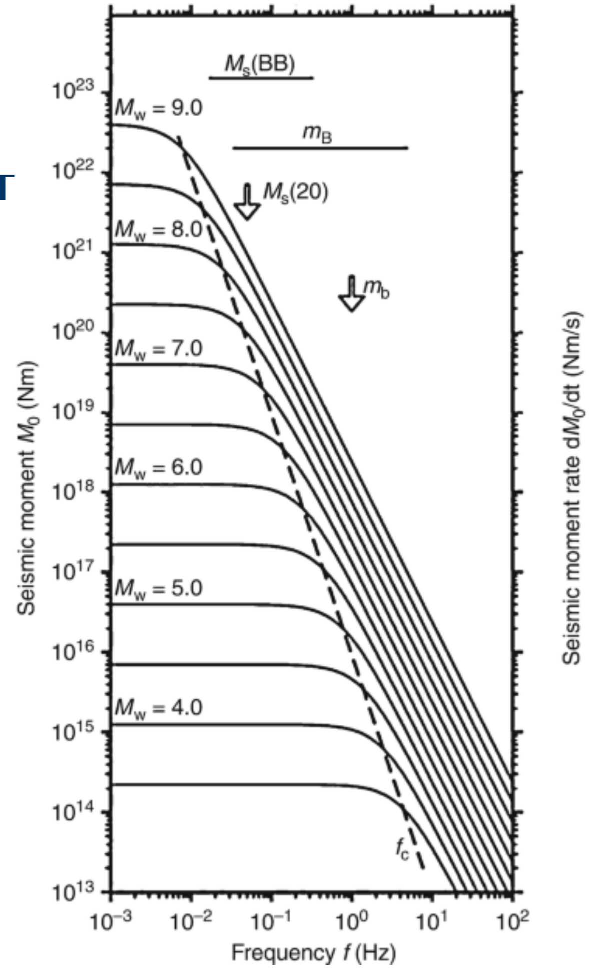
Ms = log (A/T) + 1.66 log D + 3.3

A: maximum amplitude (microns) vertical component of the surface wave within the period range 18 <= **T** <= 22.
D: 20° ≤ D ≤ 160°.

No depth corrections!

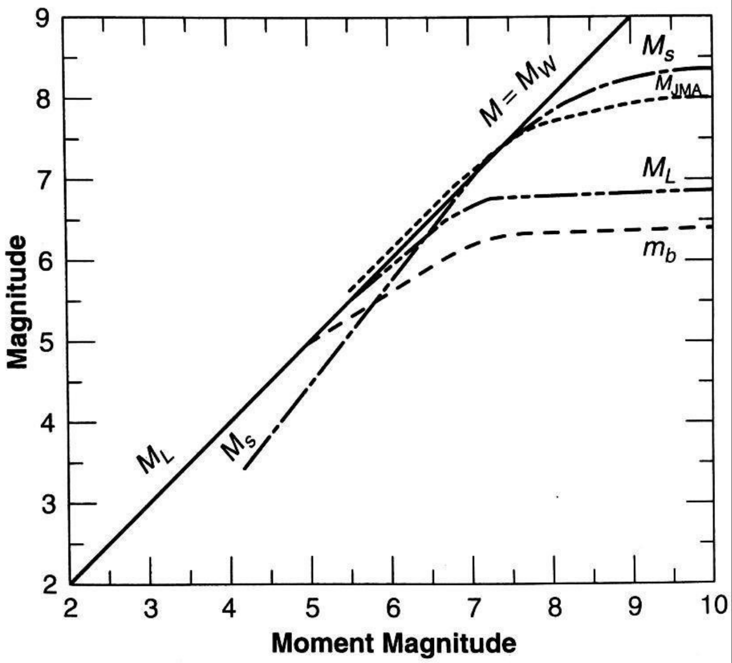
Magnitude saturation

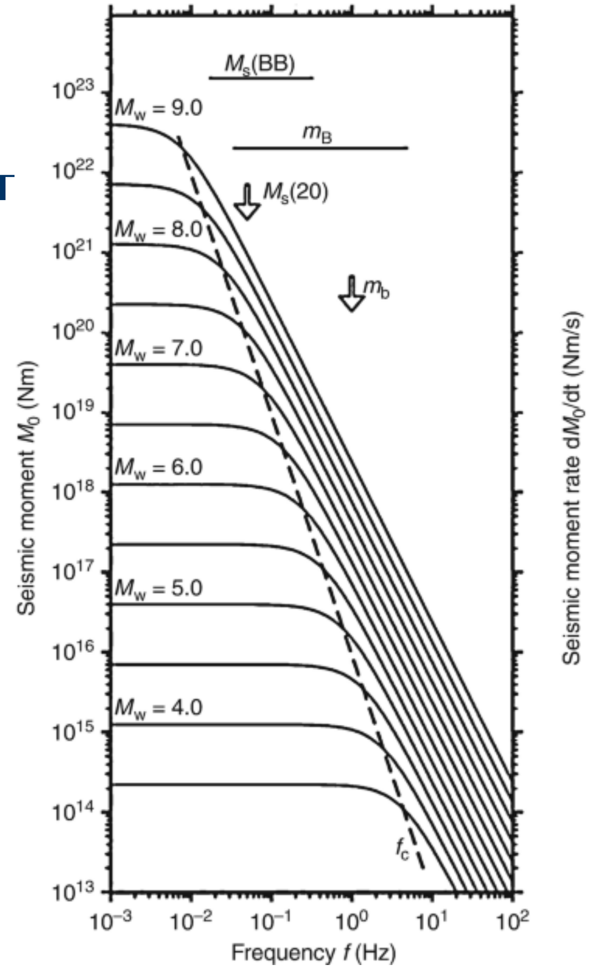




1) Time window saturation - time window that is less than duration of rupture (particularly affects mb)
2) Spectral saturation – Wavelength too short to see entire rupture (affects mb, M_L, and M_s)

Magnitude saturation





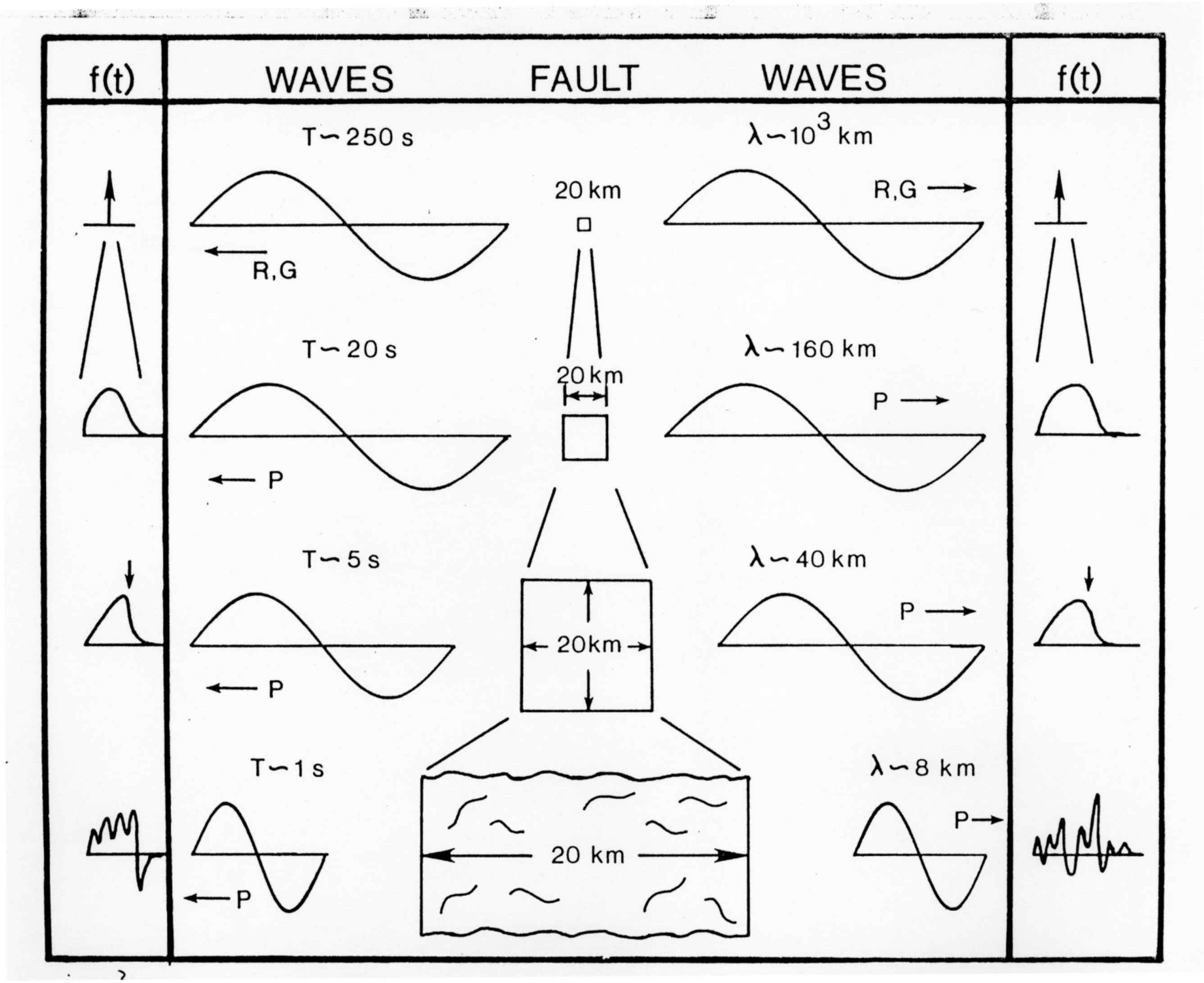
How do we overcome this problem?

⟶ Examine longer period waves

→ M_w, Mwp, Mantle magnitude (Mm), Centroid Moment Tensor (CMT)

→ GNSS/GPS data

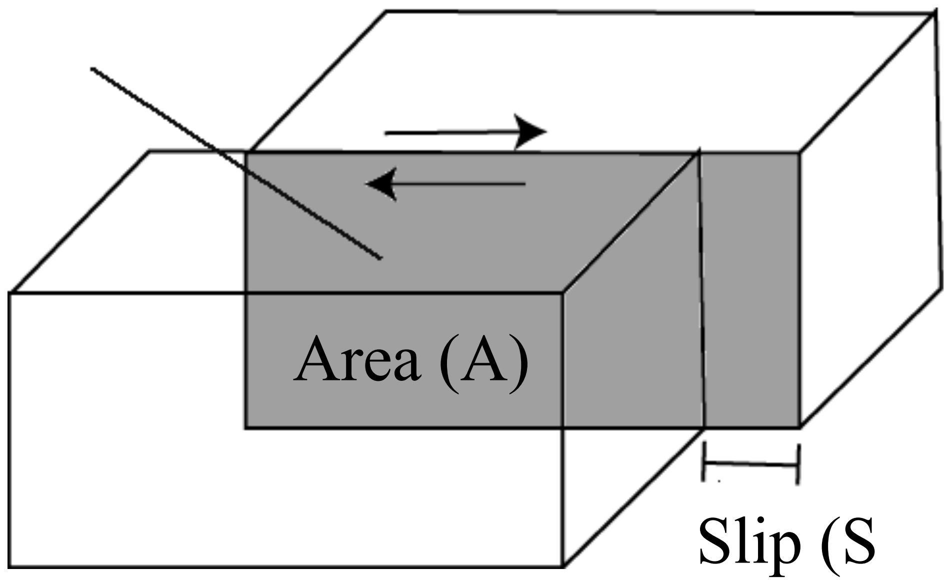
Wavelength and Period of seismic waves



Ruff (1989)

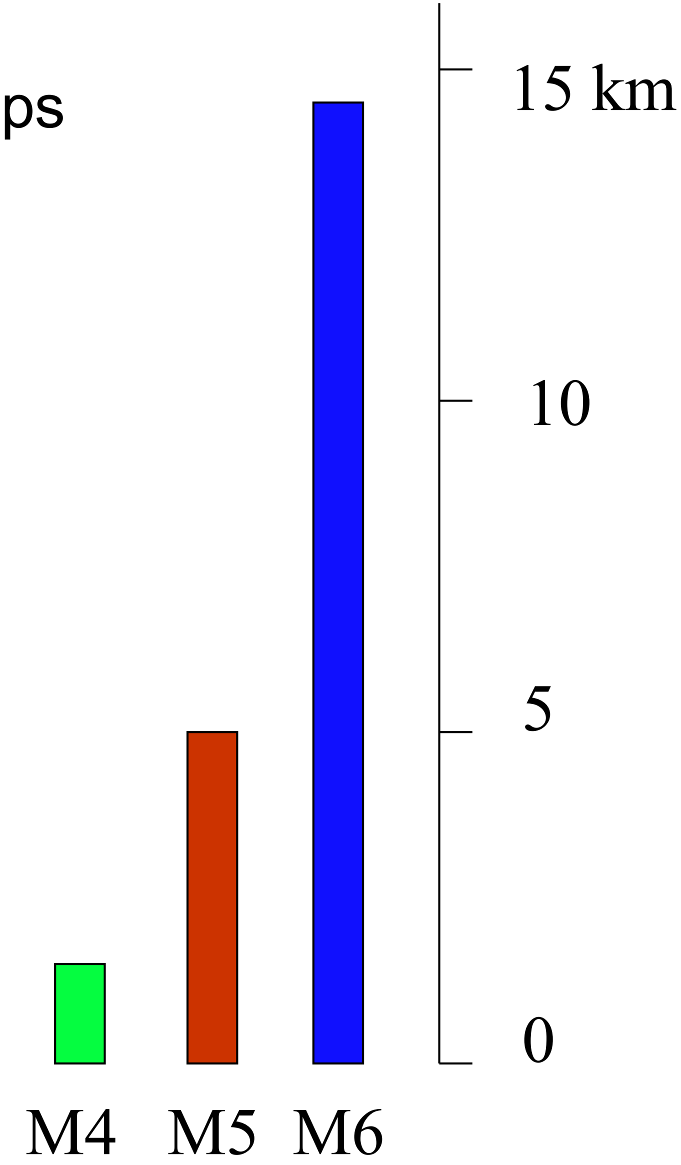
Earthquake size - Seismic Moment (M_0)

Mechanical measure of EQ size
How large an area and how much the fault slips



Seismic Moment = (Rigidity)(Area)(Slip)

$$M_0(t) = \mu \cdot S \cdot \Delta u(t)$$



Moment magnitude (Mw)

$$Mw = (2/3) \log_{10} (Mo) - 16.1$$

- Introduced in 1979 by Hanks and Kanamori
- Based on source parameter Mo and is not frequency dependent, does NOT saturate
- Based on earthquake energy release
- Related to fault slip and not ground shaking
- Used to estimate the magnitude of large earthquakes
- Very useful for tsunami modeling

Types of Magnitude Scales

			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

The methods below overcome the effects of saturation:

Mwp	P-wave moment magnitude	teleseismic P waves	10-60 sec
M_w	Moment magnitude	teleseismic surface waves	> 200 sec
M_m	Mantle magnitude	teleseismic surface waves	> 200 sec

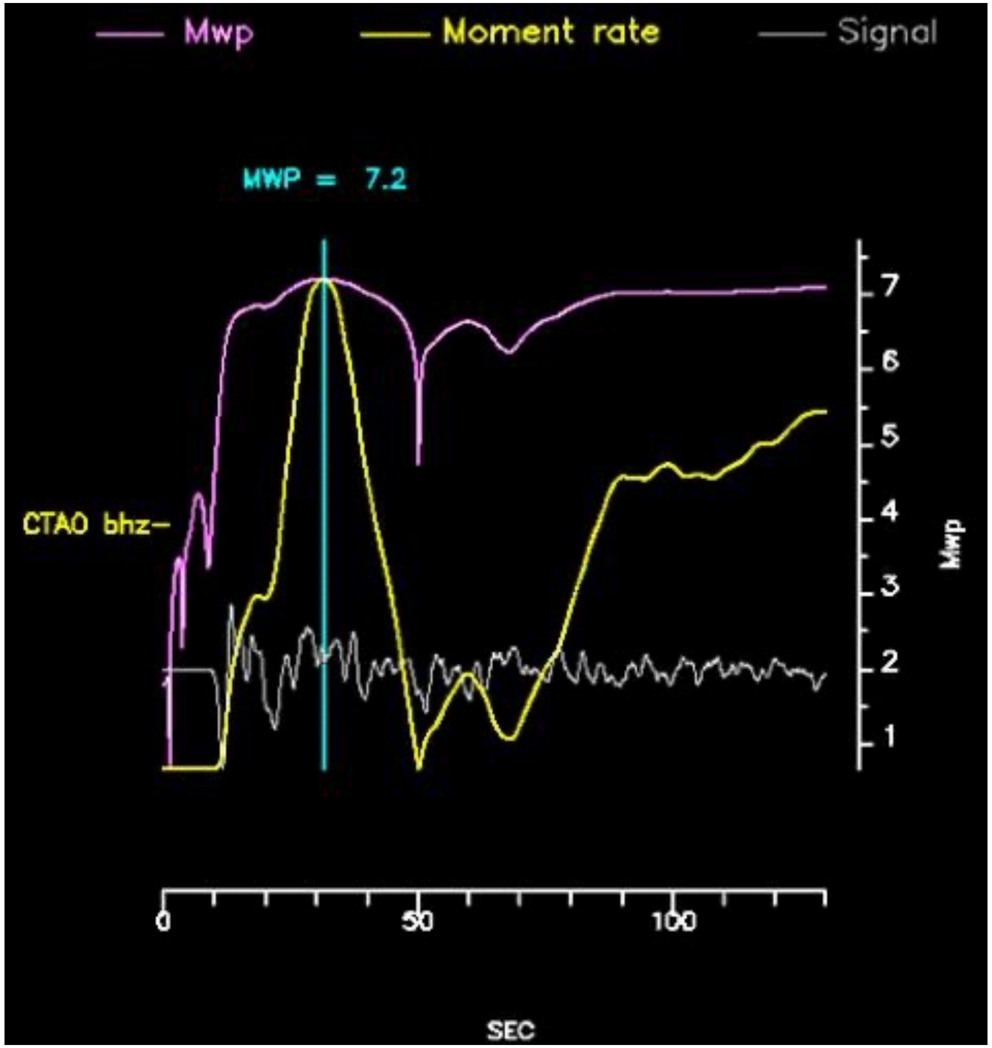
Ref: USGS Seismology and Tsunami Warnings, 2006 (Earthquake Source)

Mwp Magnitude

- Moment magnitude based on initial long-period P-waves
- Developed by S. Tsuboi and others (1995)
- Empirical estimate of the moment magnitude
  - integrate the vertical velocity from a seismogram
- Accurate results within **3-4 minutes** of OT (P, pP arrivals)
- Primary initial magnitude estimate at PTWC for M>6 (replaced Ms)
- Subject to site and path effects, source complexity, contamination from other large earthquakes

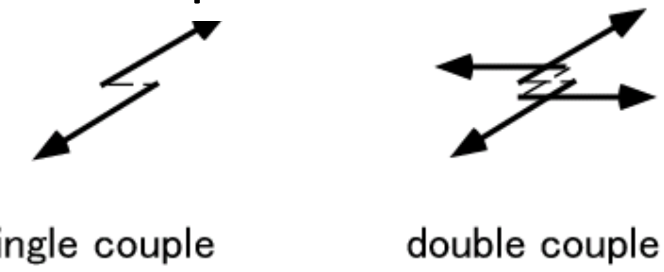
Mwp Magnitude

- Double integration of *v(t)* *v(t)* → *Mo(t)* → *Mw(t)*
- Peak *Mw(t)* → *Mwp*
- Fast; less prone to saturation

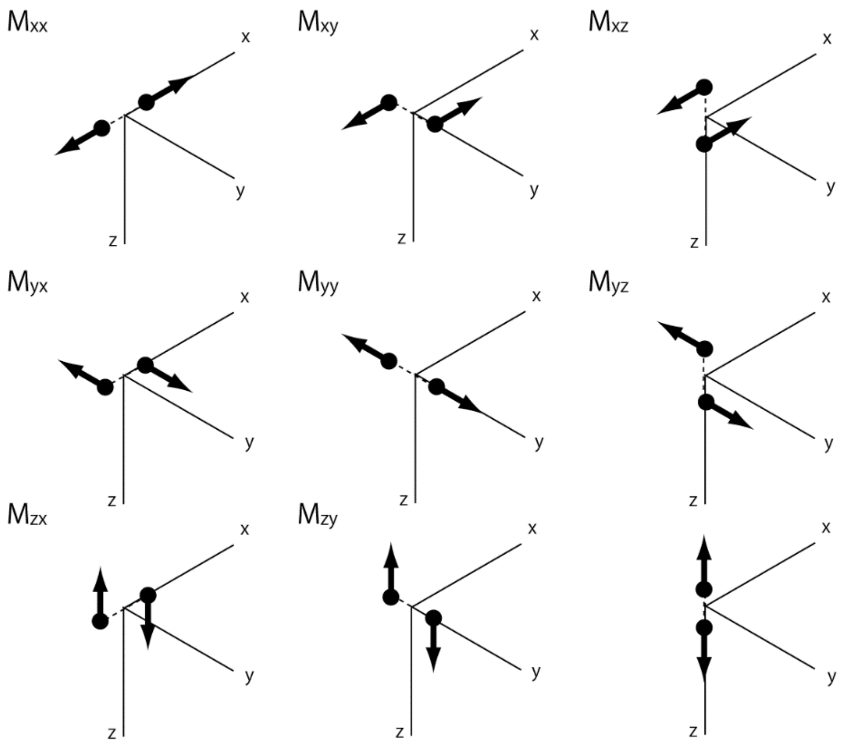


Force couples and moment tensor

Force couples



Moment tensor



$$\begin{bmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{bmatrix}$$

$M_{xy}=M_{yx}$

$M_{xz}=M_{zx}$

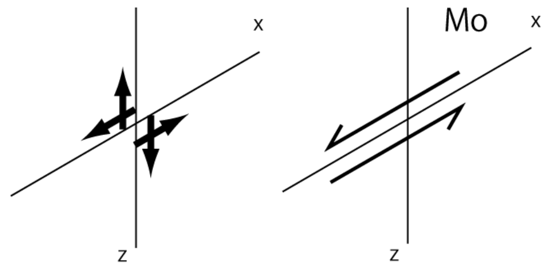
$M_{yz}=M_{zy}$

If no volume change, then

$M_{xx}+M_{yy}+M_{zz}=0$

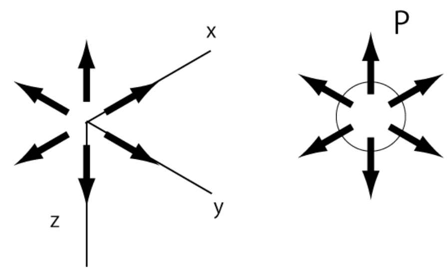
Moment Tensor Elements

Shear dislocation
(x direction on z plane)



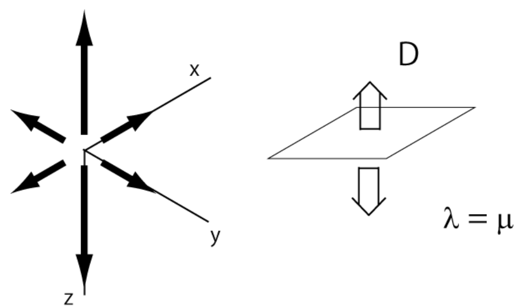
$$\begin{bmatrix} 0 & 0 & Mo \\ 0 & 0 & 0 \\ Mo & 0 & 0 \end{bmatrix}$$

explosion



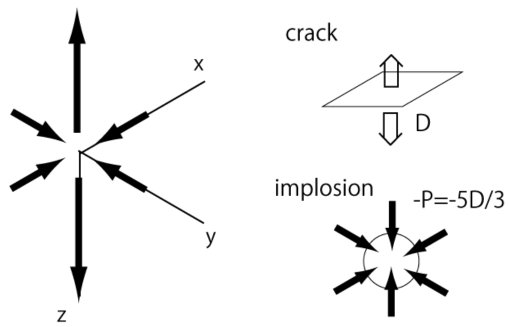
$$\begin{bmatrix} P & 0 & 0 \\ 0 & P & 0 \\ 0 & 0 & P \end{bmatrix}$$

tensile crack
(z plane)



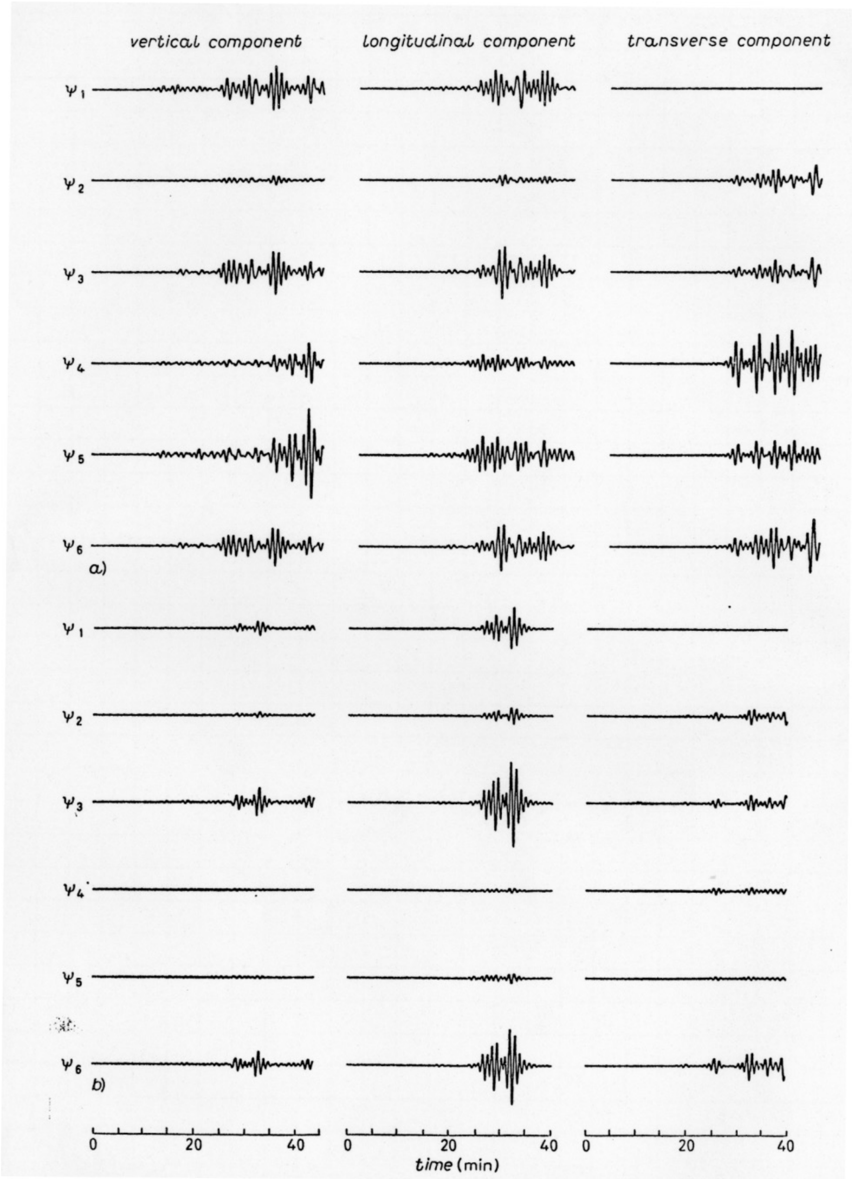
$$\begin{bmatrix} D & 0 & 0 \\ 0 & D & 0 \\ 0 & 0 & 3D \end{bmatrix}$$

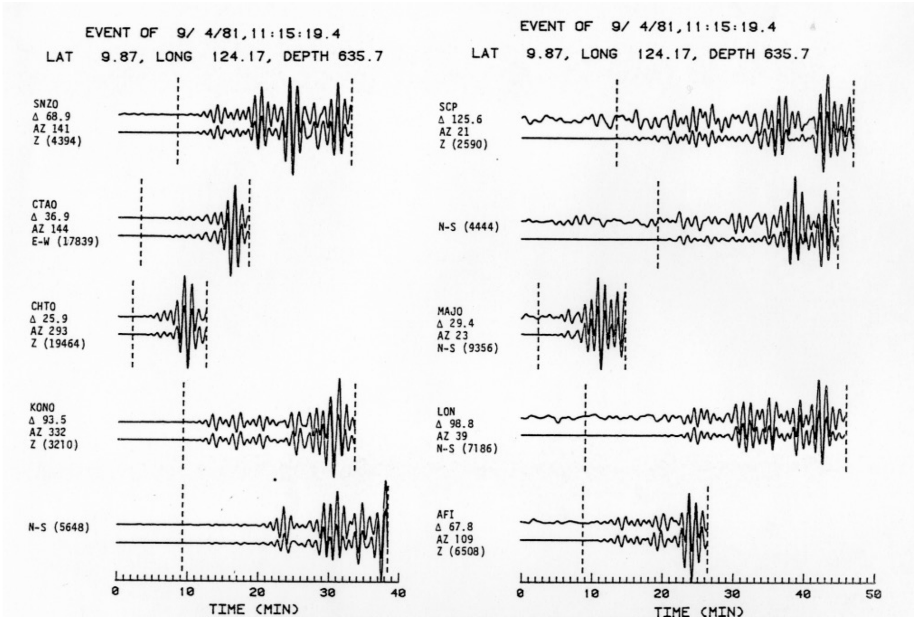
CLVD
Compensated Linear Vector Dipole



$$\begin{bmatrix} -Q & 0 & 0 \\ 0 & -Q & 0 \\ 0 & 0 & 2Q \end{bmatrix}$$

Centroid Moment Tensor Inversion

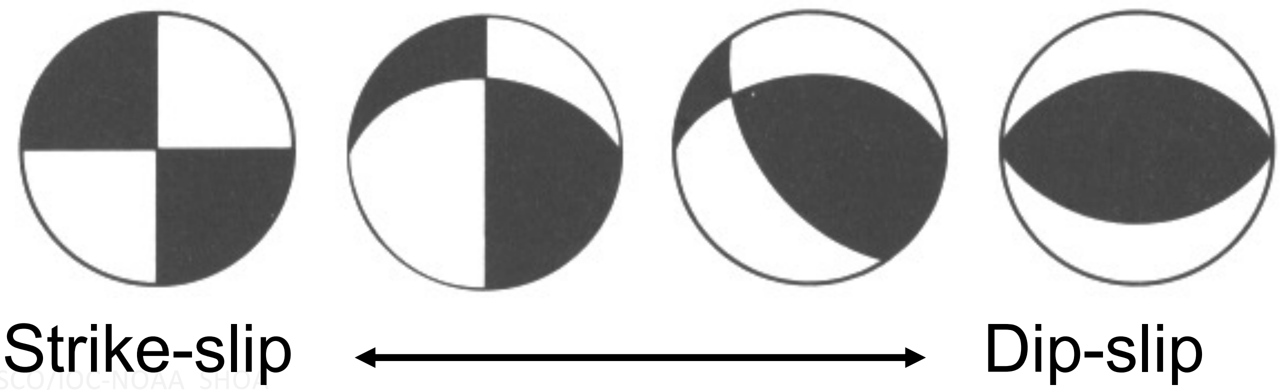




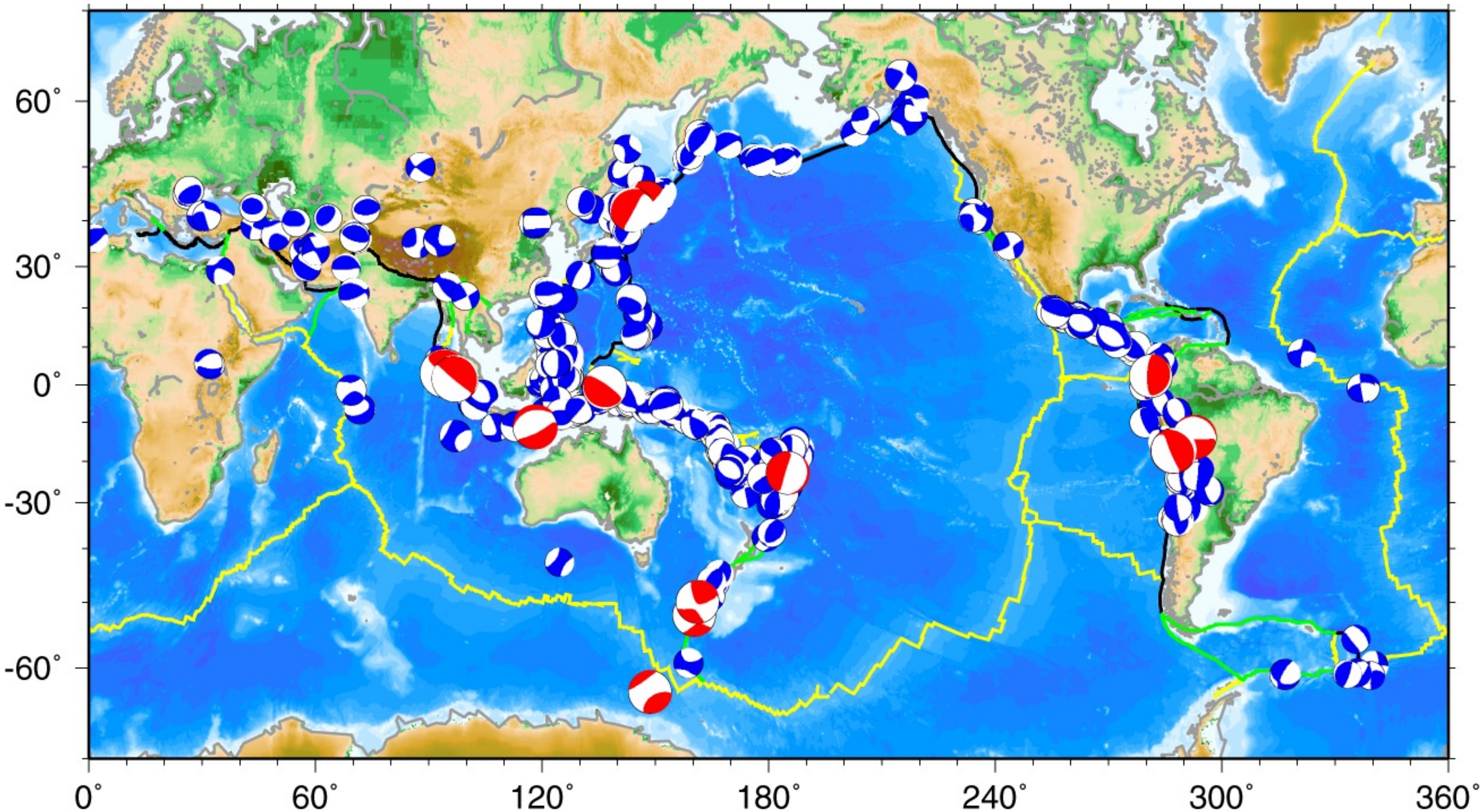
Dziewonski and Woodhouse (1981)

Centroid Moment Tensor (CMT)

- Characterizes the geometry of the earthquake
- Can be used to compute surface deformation
- Fits shape/amplitude of waves to synthetic seismograms
- Usually based on longer period and very slow surface waves, so often requires around 90 minutes to compute

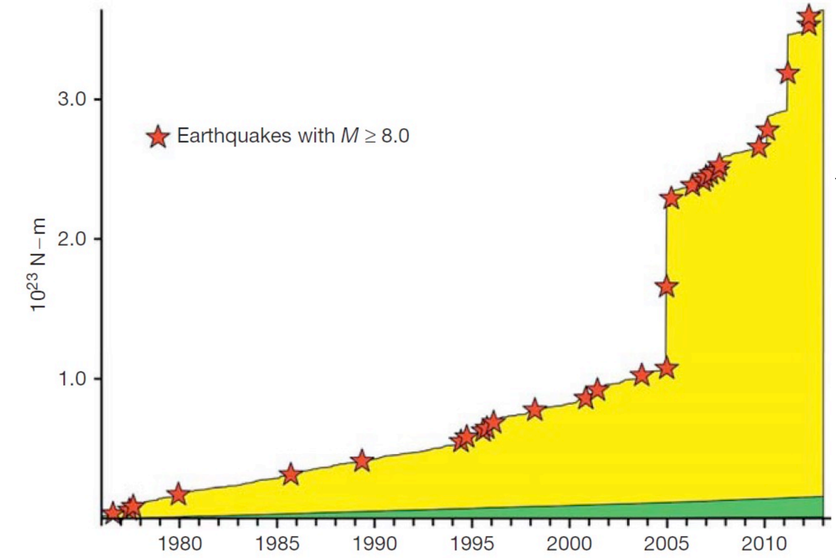


Global CMT (former Harvard CMT)



Global CMT (former Harvard CMT)

Seismic moment

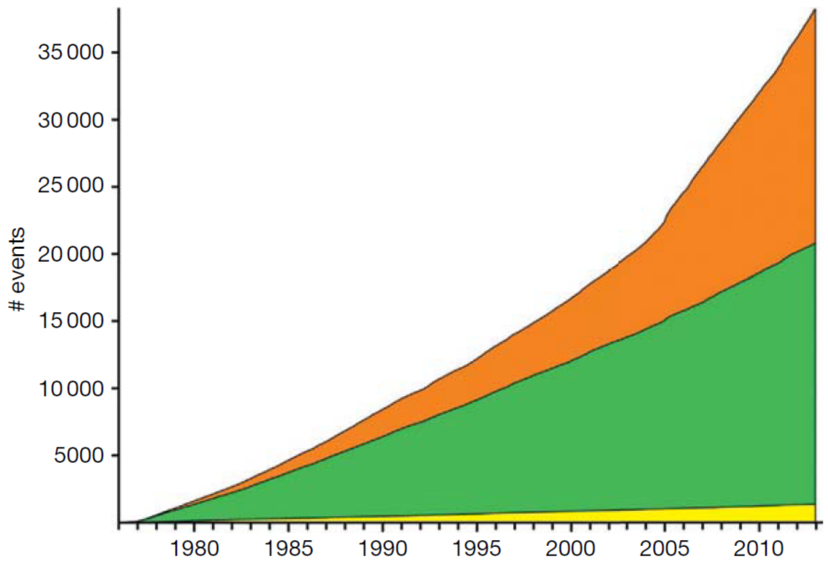


Yellow: M ≥ 6.5

Green: 5.3 ≤ M ≤ 6.5

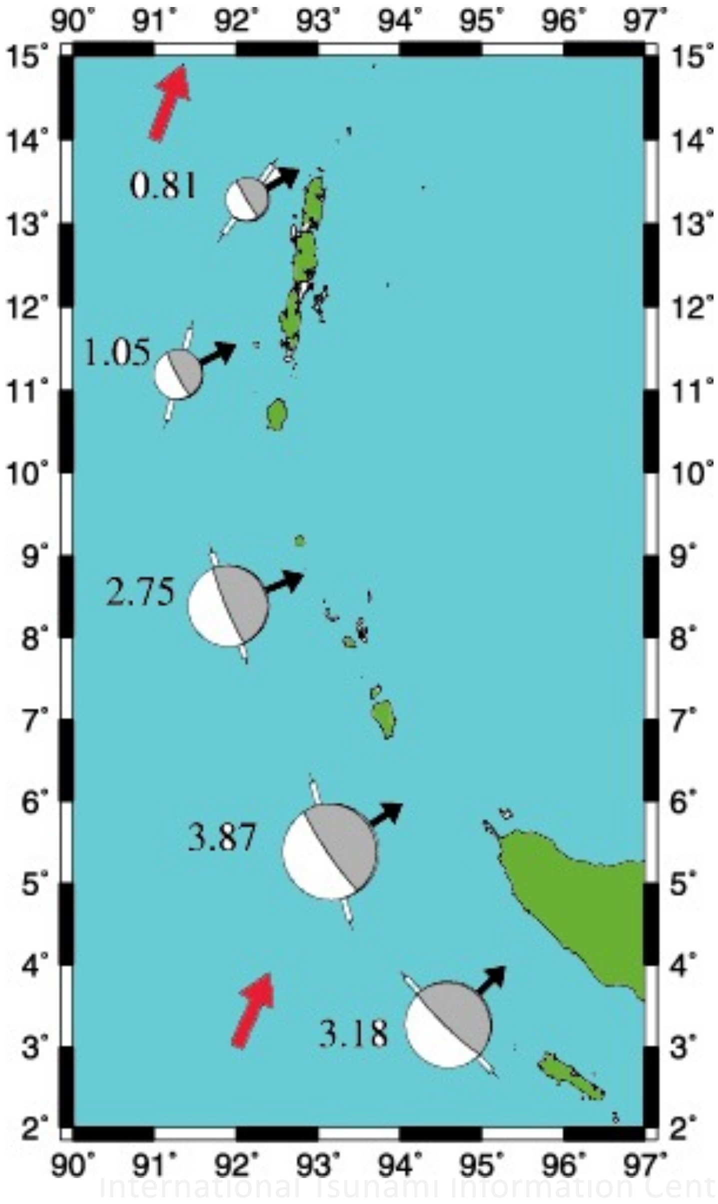
Number of events

Orange: M ≤ 5.3 (not visible in cumulative moment)

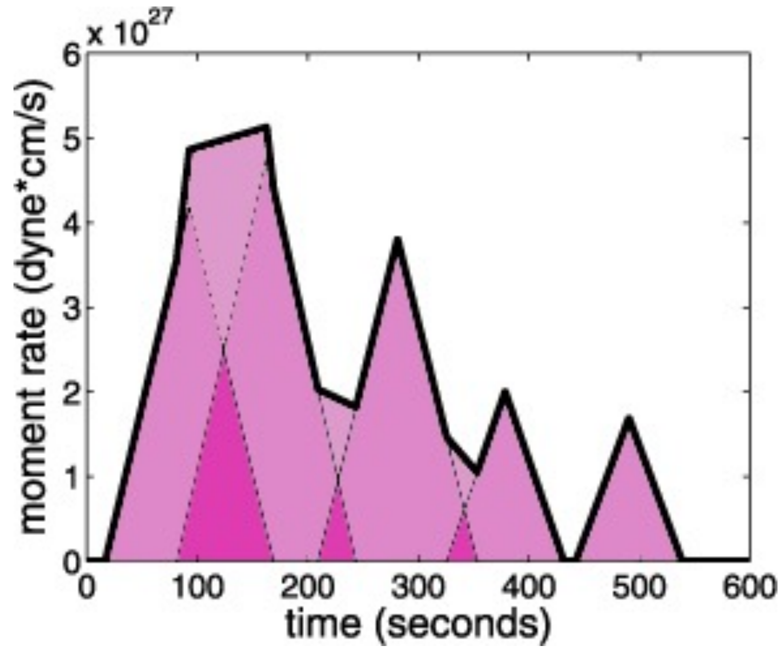


Ekstrom (2015) Treatise of Geophysics

2004 Sumatra-Andaman Eq



Single source
4×10^{22} Nm Mw 9.0
Five sources
12×10^{22} Nm Mw 9.3

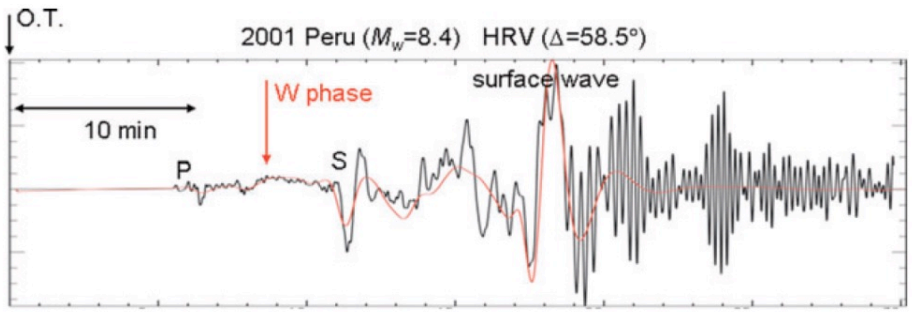


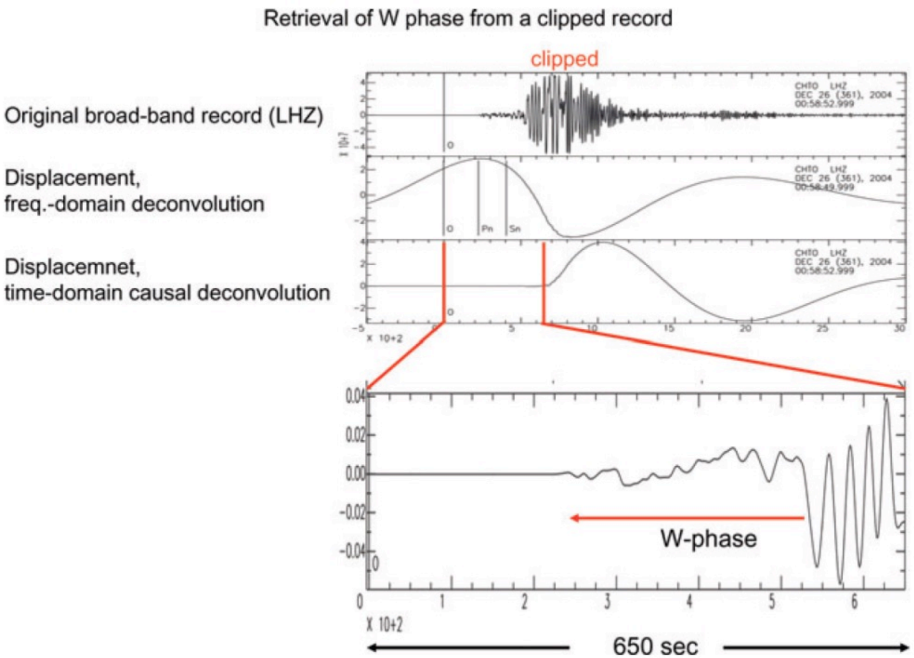
Tsai et al. (2005, GRL)

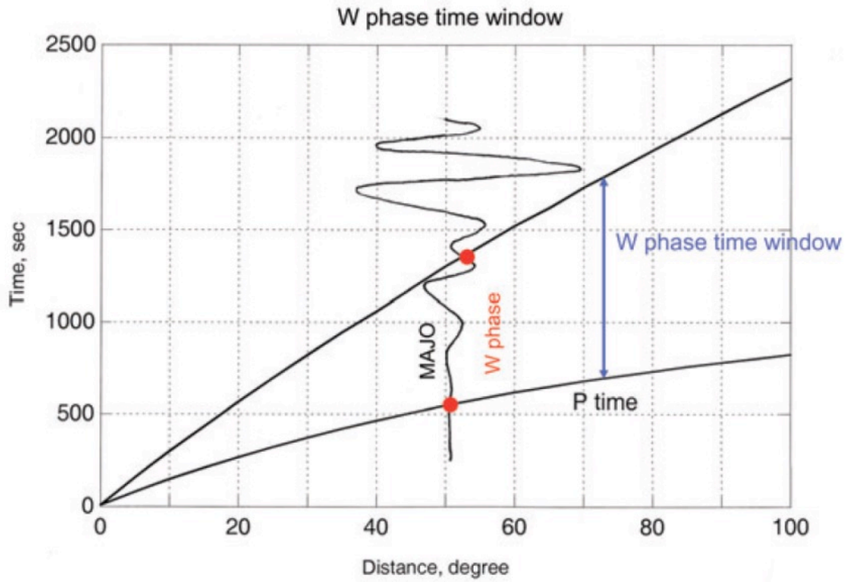
W-phase CMT

- Introduced by Kanamori and Rivera (2008)
- The W-phase travels several times faster than surface waves
- Gives fault geometry and authoritative magnitude 20-25 minutes after the earthquake. Now the primary method the NEIC uses to obtain initial magnitudes for strong – major earthquakes.
- Primary reason why PTWC can now quickly issue a reliable (tsunami) forecast within the first hour after an event.

W-phase CMT





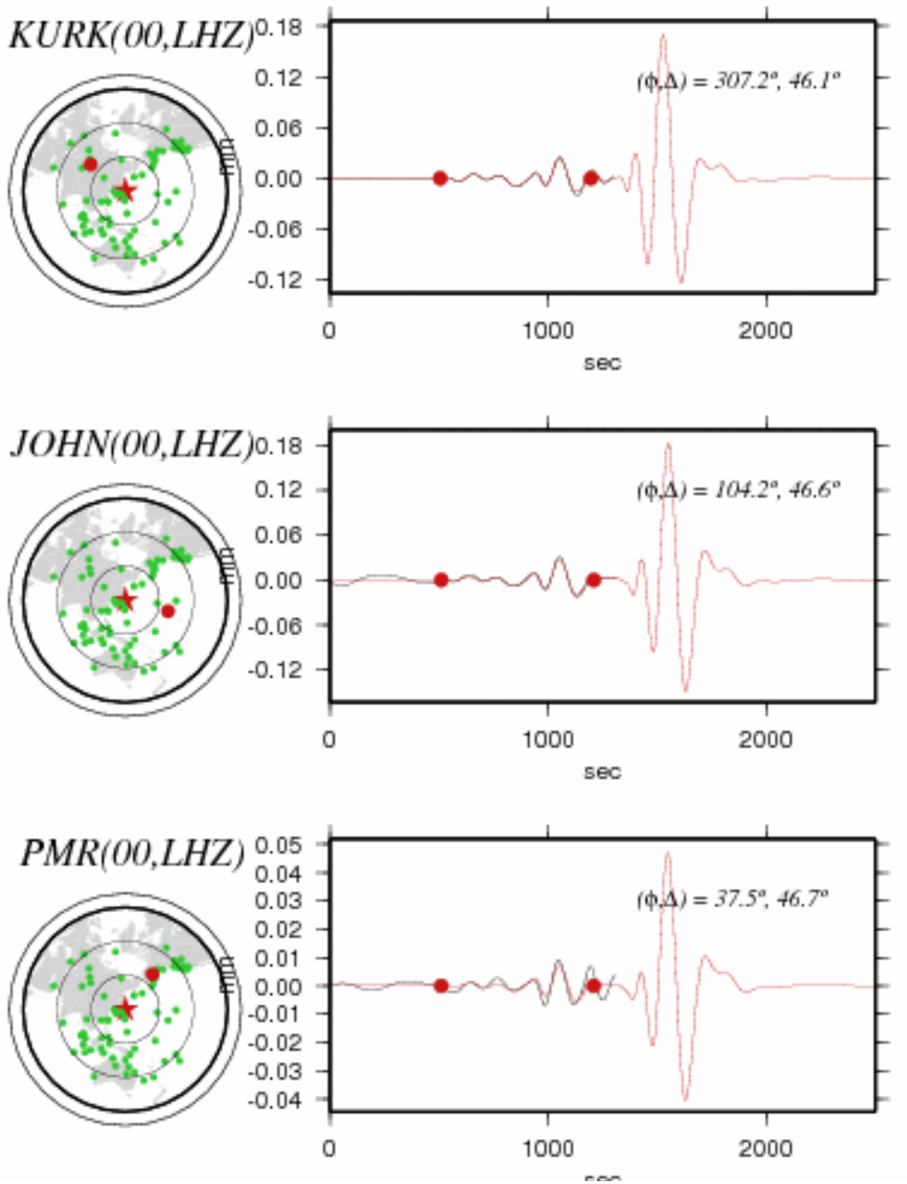


Kanamori and Rivera (2008)

W-phase CMT

2011 Tohoku, Japan, earthquake

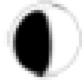
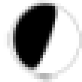
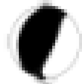
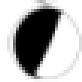
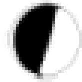
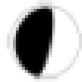
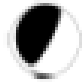
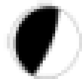
```
              ----#####
         -----############
      -----##################
    -----#################-----
   -----#################-------
  -----##################--------
 -----##################----------
-----#######   #########-----------
-----####### T ########------------
----########   #######-------------
----#################--------------
----#################-------   ----
 ---################-------- P ---
  ---##############---------   --
   --#############--------------
    --###########--------------
      ##########-------------
         #######----------
           #####----
```



W-phase CMT

2011 Tohoku, Japan, earthquake

Table 1. Real-Time W phase solutions obtained for the 2011 Tohoku Earthquake. The real-time instances of the W phase algorithm are running with a fixed depth, specified for each solution in the table.

Delay	Origin	M_w	Strike/Dip/Rake, deg	Depth, km	# chan.	Mech.
20 min	USGS automatic trigger (internal)	9.0	222.7/16.8/134.6	24.4	6	
22 min	PTWC automatic trigger 1	8.8	165.4/10.3/55.3	83.5	29	
30 min	PTWC automatic trigger 2	8.8	194.3/22.8/81.3	83.5	74	
40 min	PTWC manual trigger	9.0	190.6/11.1/76.7	24.4	105	
45 min	IPGS automatic trigger 1	9.0	199.6/10.8/93.5	24.4	31	
48 min	USGS automatic trigger (internal)	8.9	204.4/14.8/104.3	24.4	74	
1 h 02 min	USGS Published	8.9	162.0/16.9/45.1	24.4	89	
1 h 30 min	IPGS automatic trigger 2	9.0	196.3/14.4/85.1	24.4	146	

Duputel et al. (2011)

Thank You

Kenji Satake
University of Tokyo
satake@eri.u-tokyo.ac.jp