UNESCO/IOC – NOAA ITIC Training Program in Hawaii (ITP-Hawaii)
TSUNAMI EARLY WARNING SYSTEMS
AND THE PACIFIC TSUNAMI WARNING CENTER (PTWC) ENHANCED PRODUCTS
TSUNAMI EVACUATION PLANNING AND UNESCO IOC TSUNAMI READY PROGRAMME
7-18 August 2023, Honolulu, Hawaii USA

Tsunami Warning Center Operations:

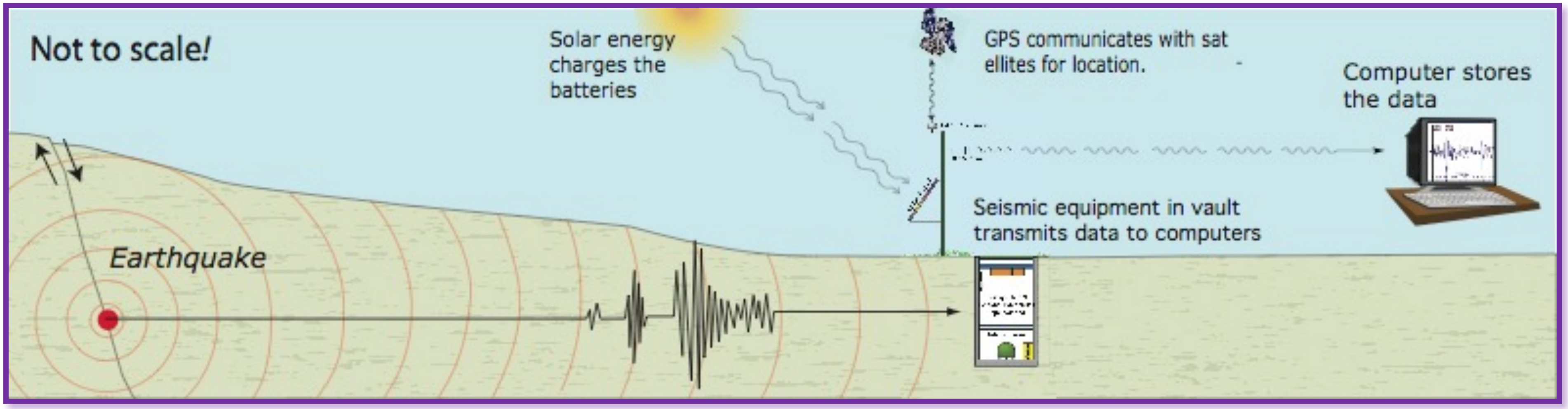
Real-Time Earthquake Detection and Fast Source Characterization – Methods to Determine Magnitude and Fault Mechanism

Kanoa Koyanagi, Jonathan Weiss, Stuart Weinstein, Nathan Becker and colleagues
NOAA Pacific Tsunami Warning Center

Laura Kong
UNESCO/IOC – NOAA International Tsunami Information Center

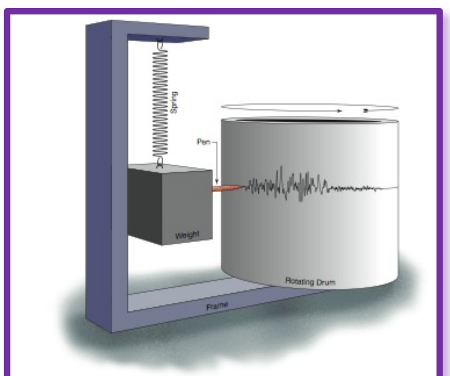
Locating Earthquakes

How do we measure earthquakes?

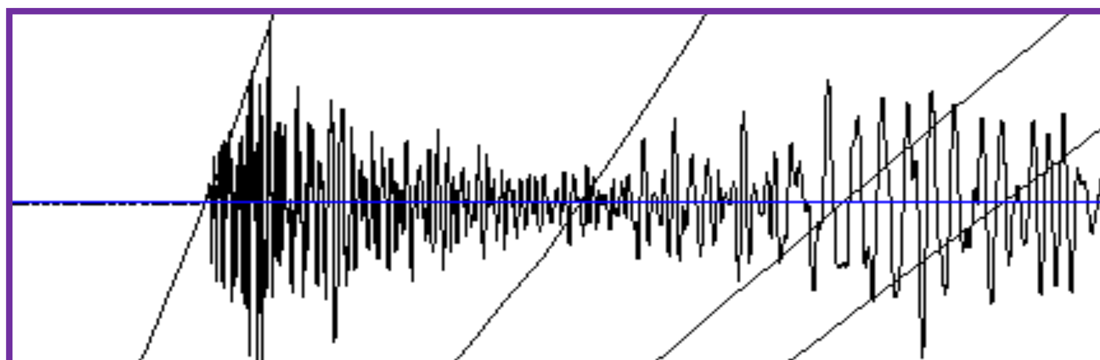


When an earthquake occurs, the seismic waves travel through the Earth to the seismic station where the information is transmitted to distant computers.

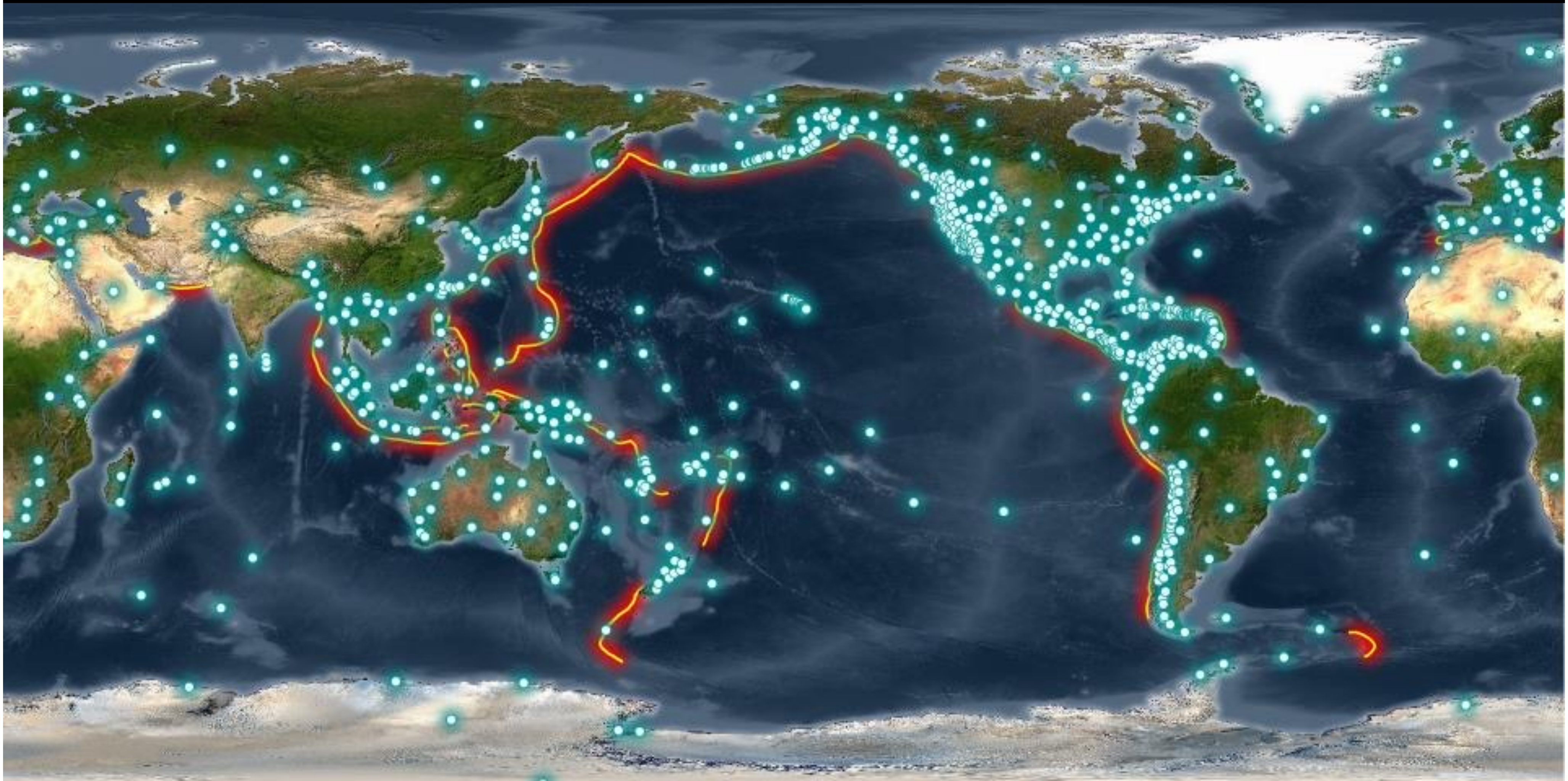
A **seismograph** detects and records earthquakes



A **seismogram** is the earthquake record

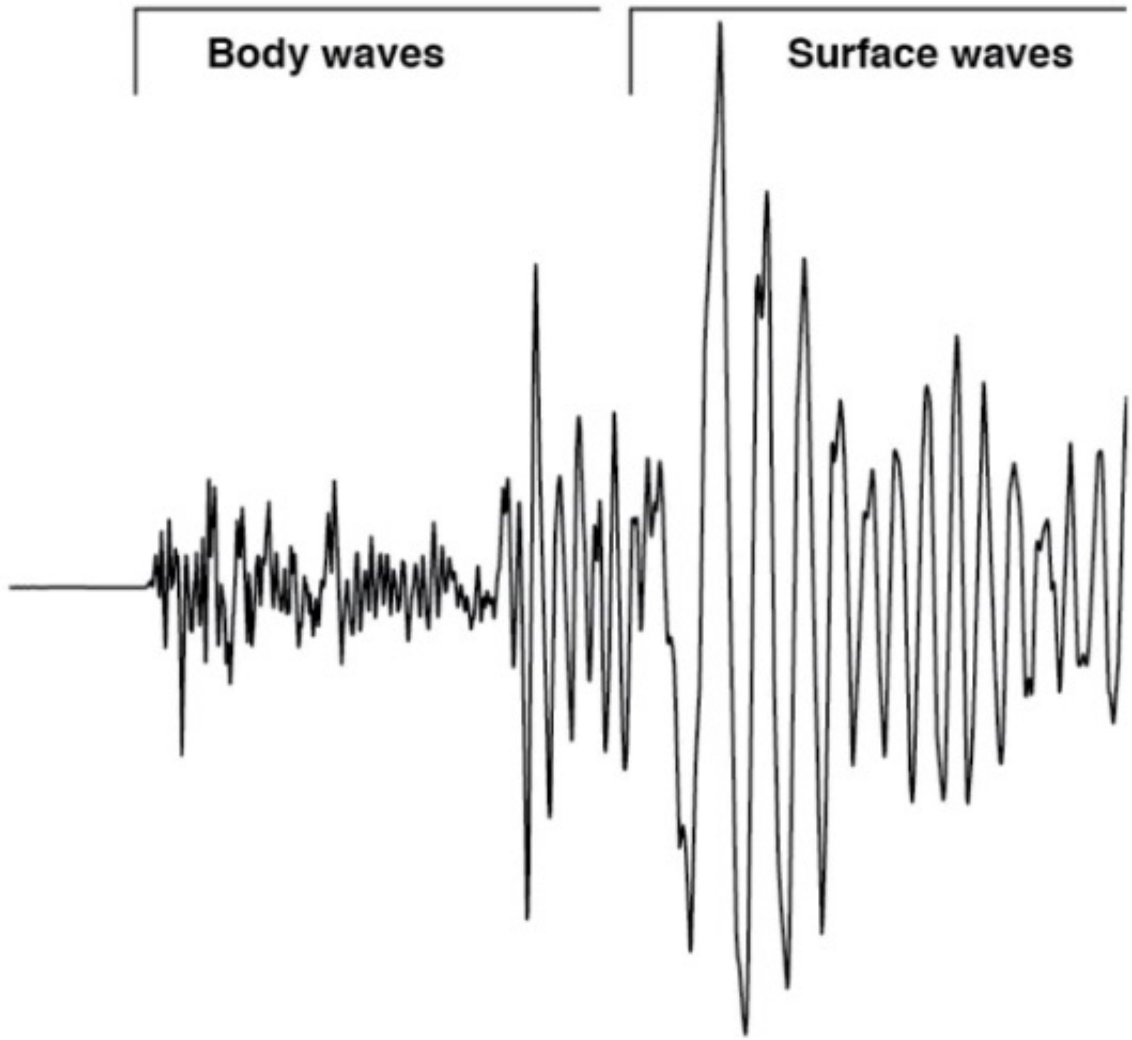


Global Seismic Network



PTWC monitors >800 seismic stations worldwide

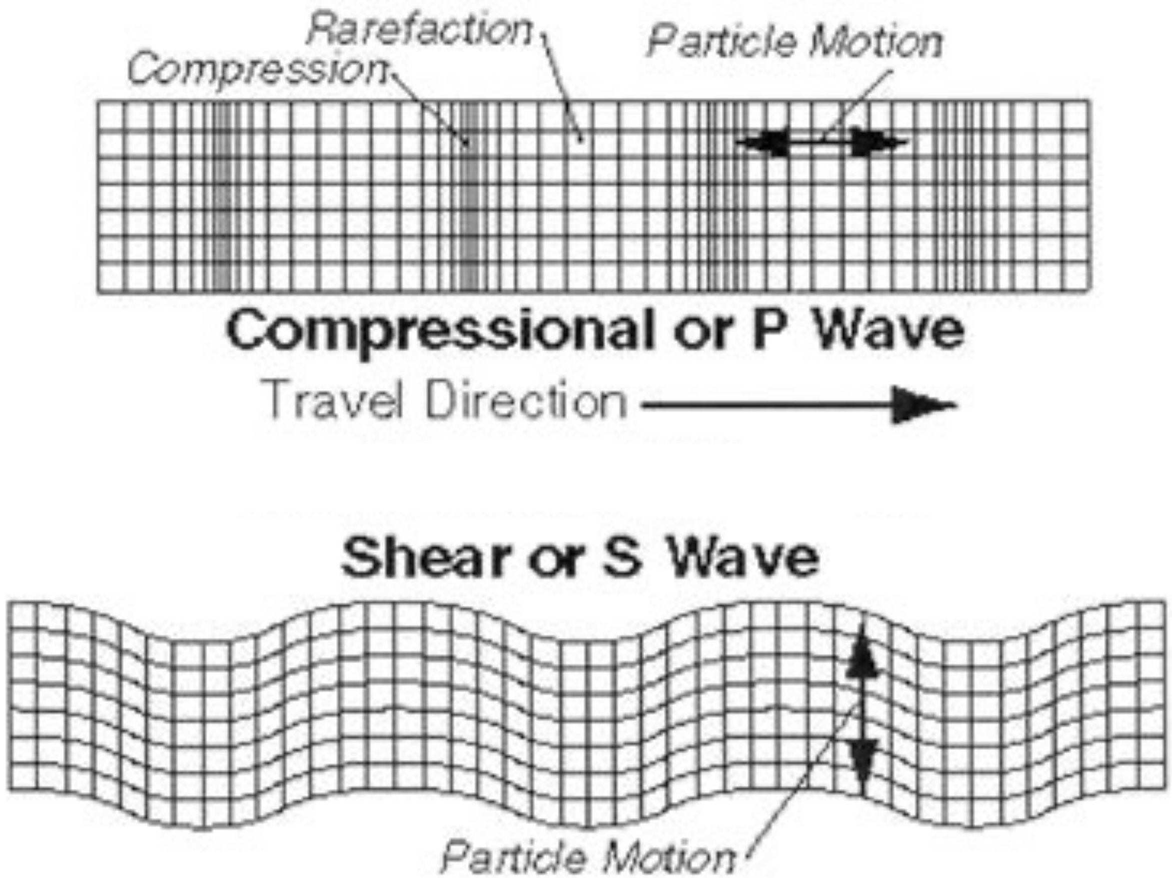
Basic Types of Seismic Waves



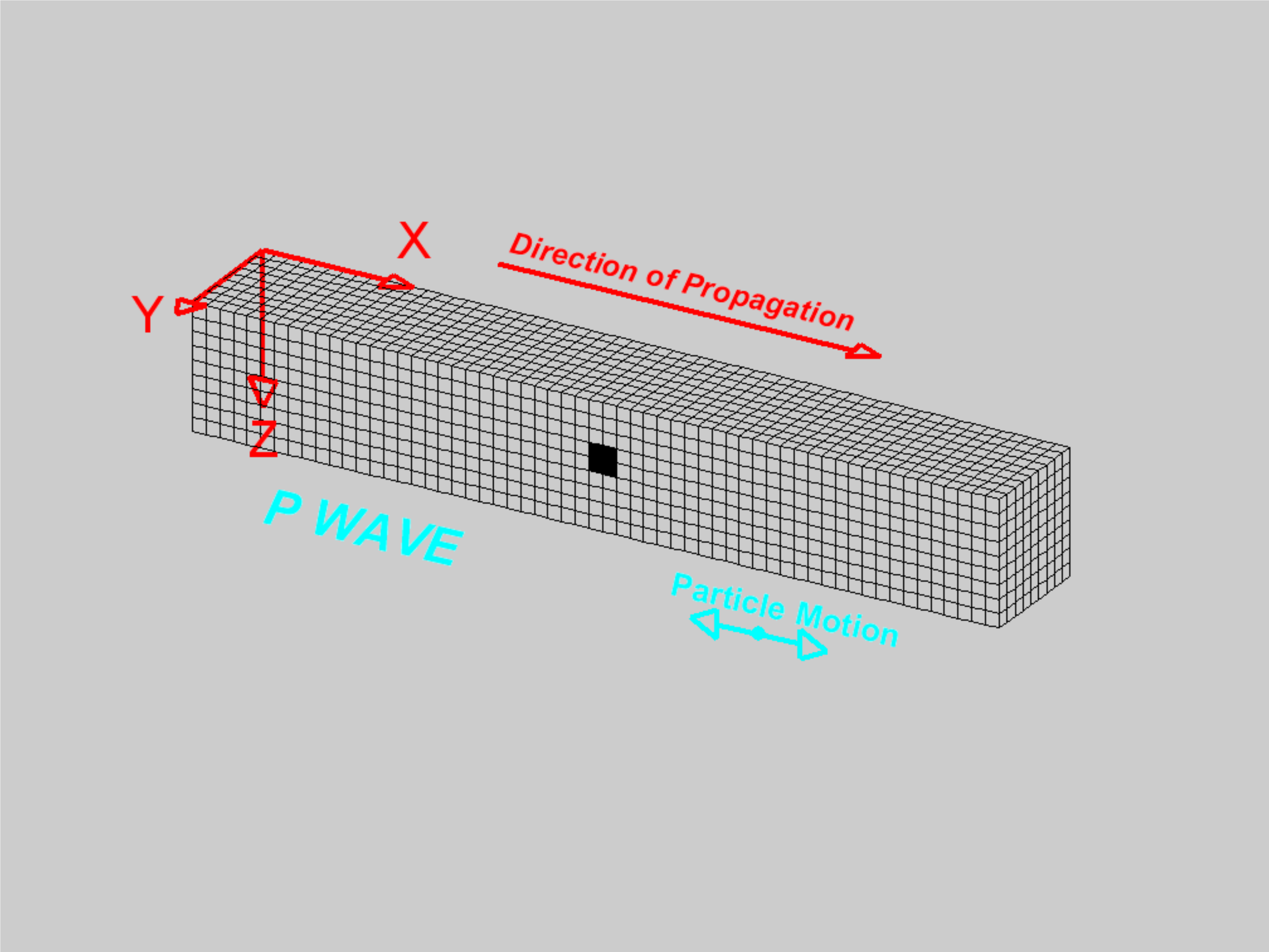
Surface waves arrive after the body waves. They have lower frequency and larger amplitude than body waves.

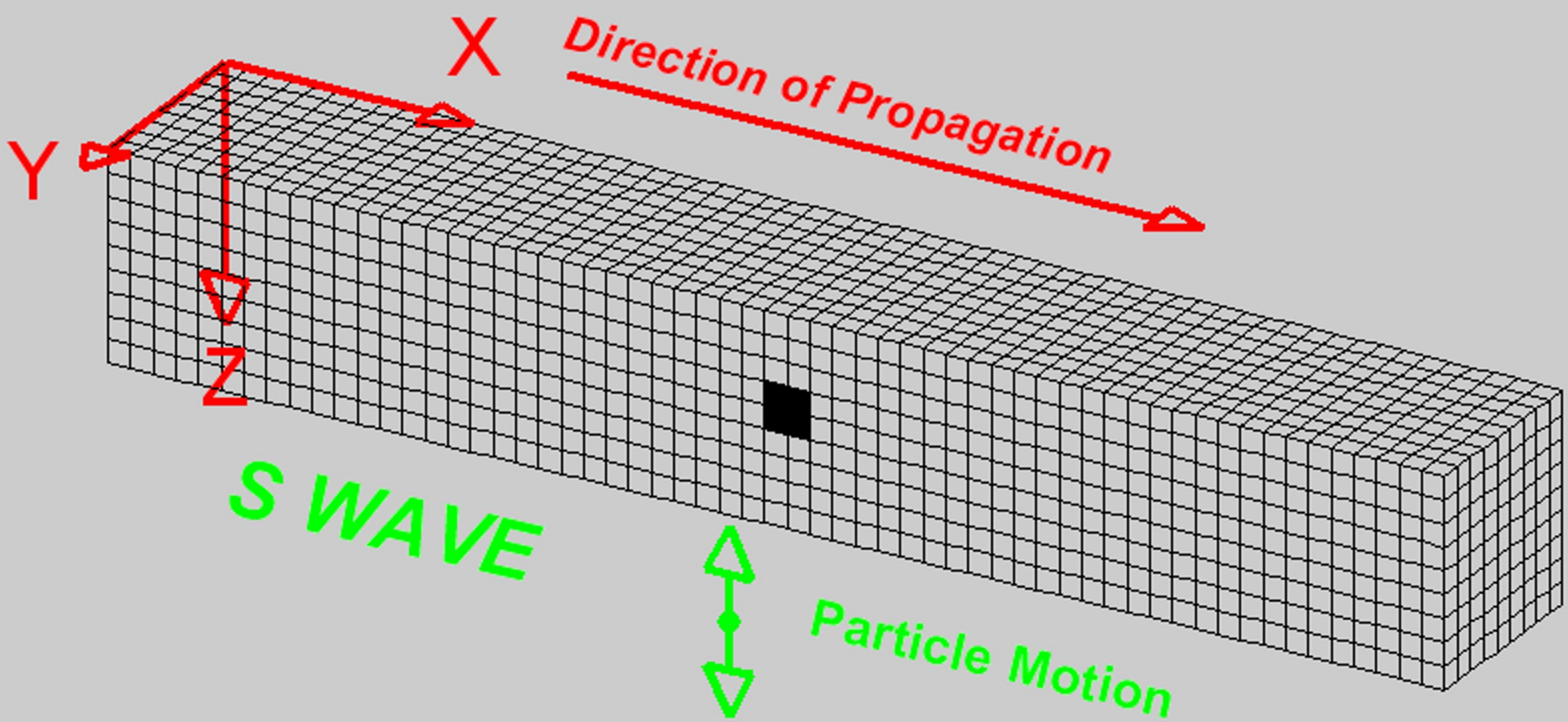
Basic Types of Seismic Waves

P and S Waves (also called body waves)



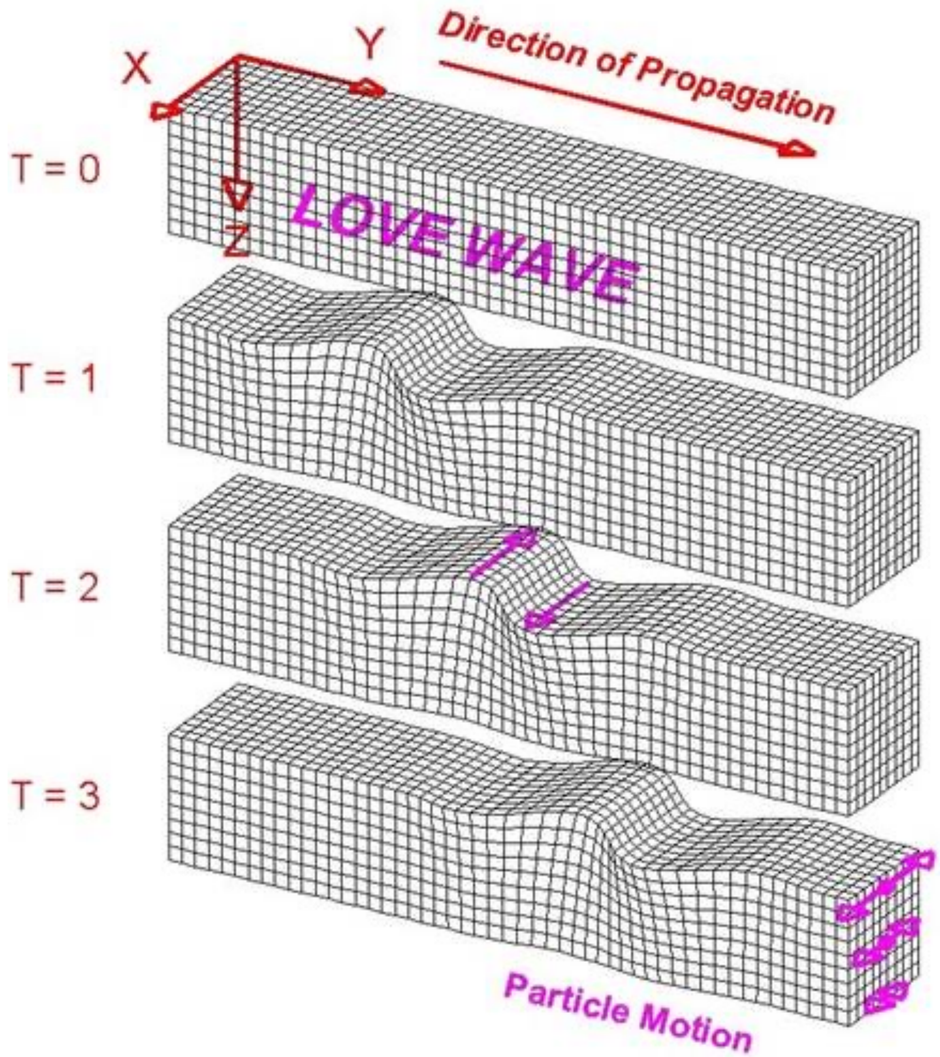
P waves are faster and travel at speeds of **6-14 km/s**


X
Y
Z
Direction of Propagation
P WAVE
Particle Motion

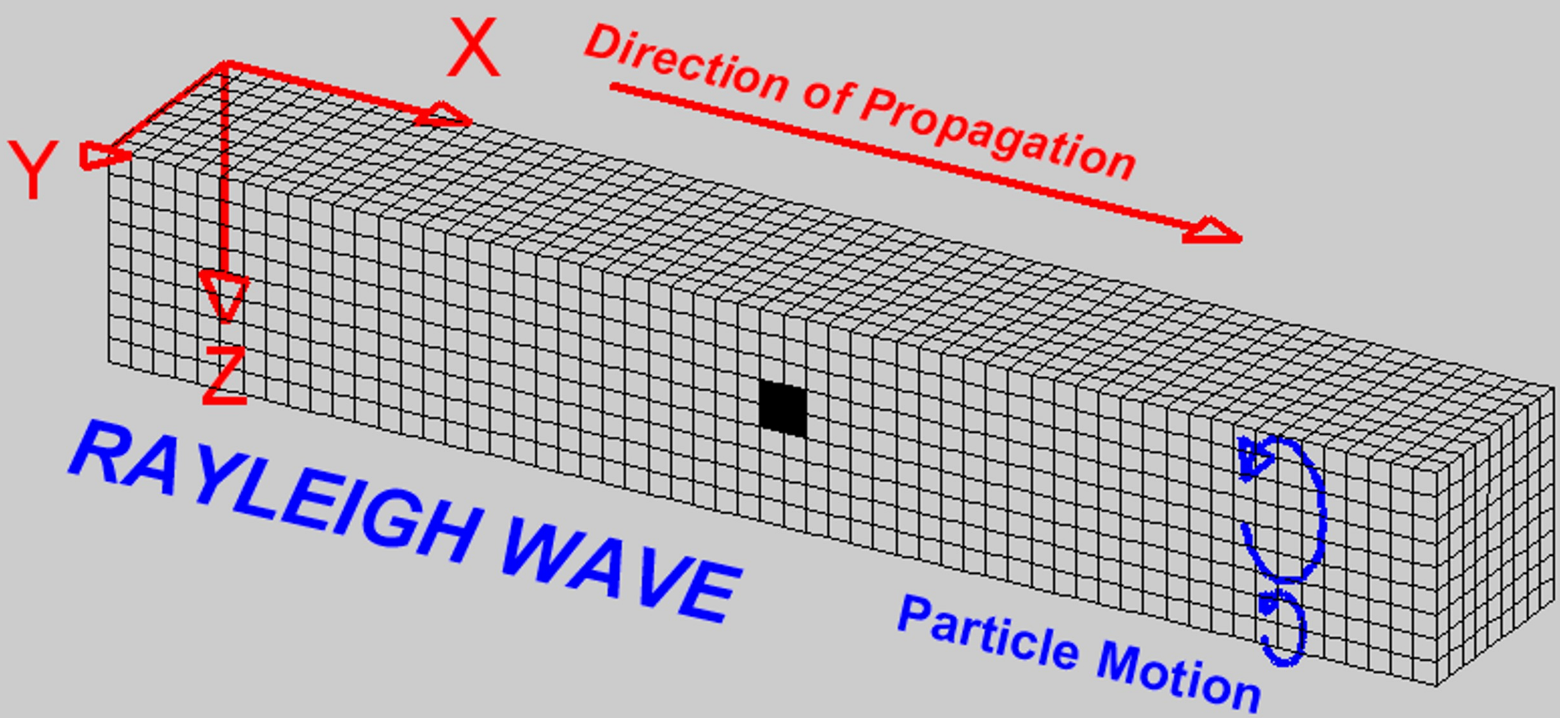

X
Direction of Propagation
Y
Z
S WAVE
Particle Motion

Basic Types of Seismic Waves

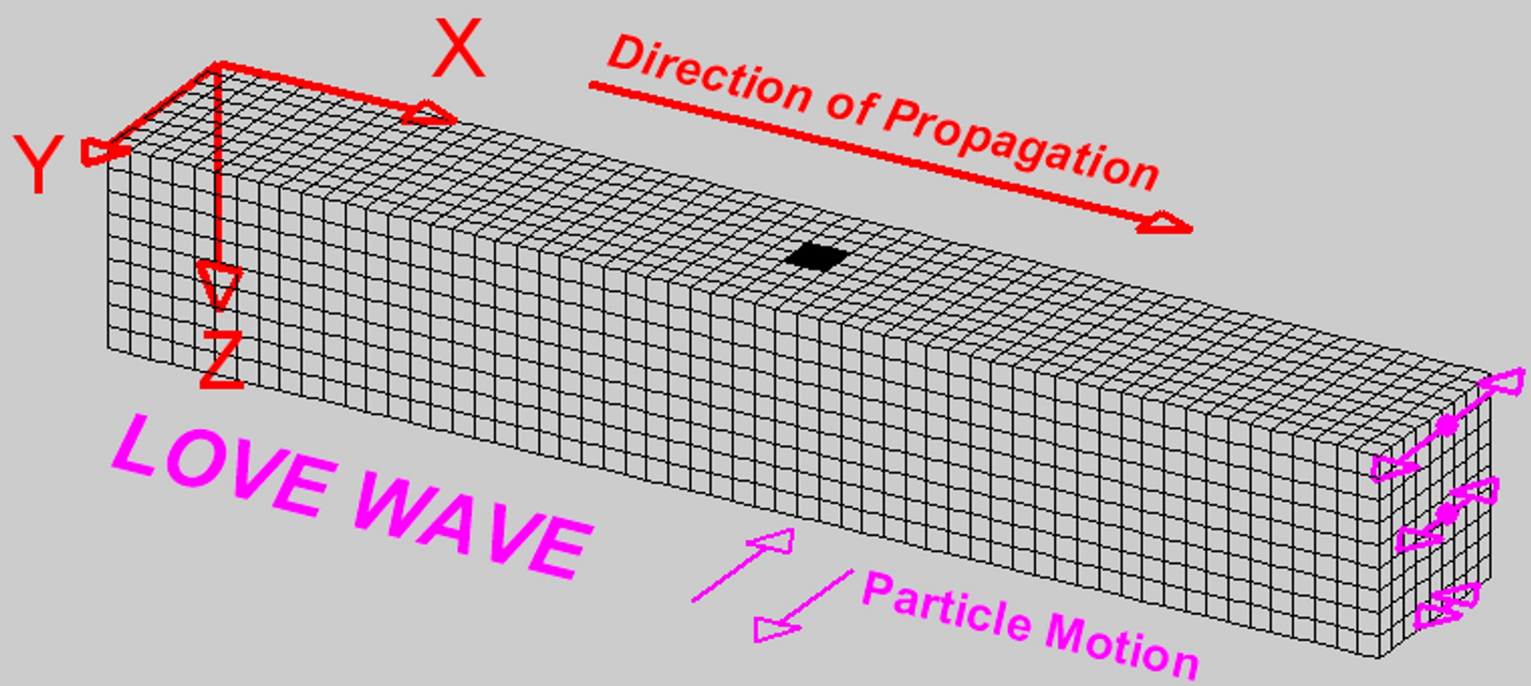
Surface Waves
(do not travel through the earth)

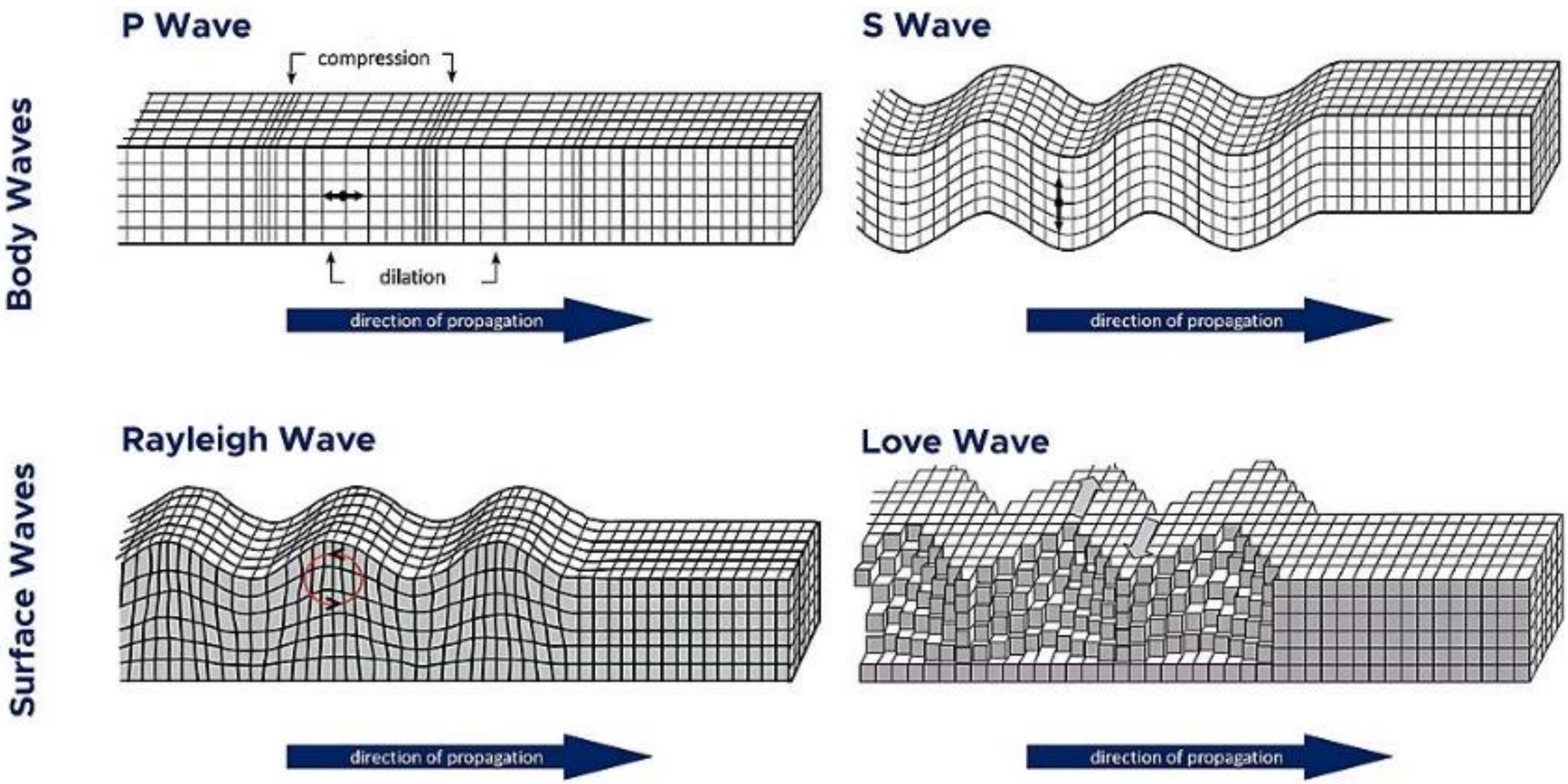


Surface waves travel along the Earth's surface at speeds of **~3/km/sec**, much slower than the body waves.

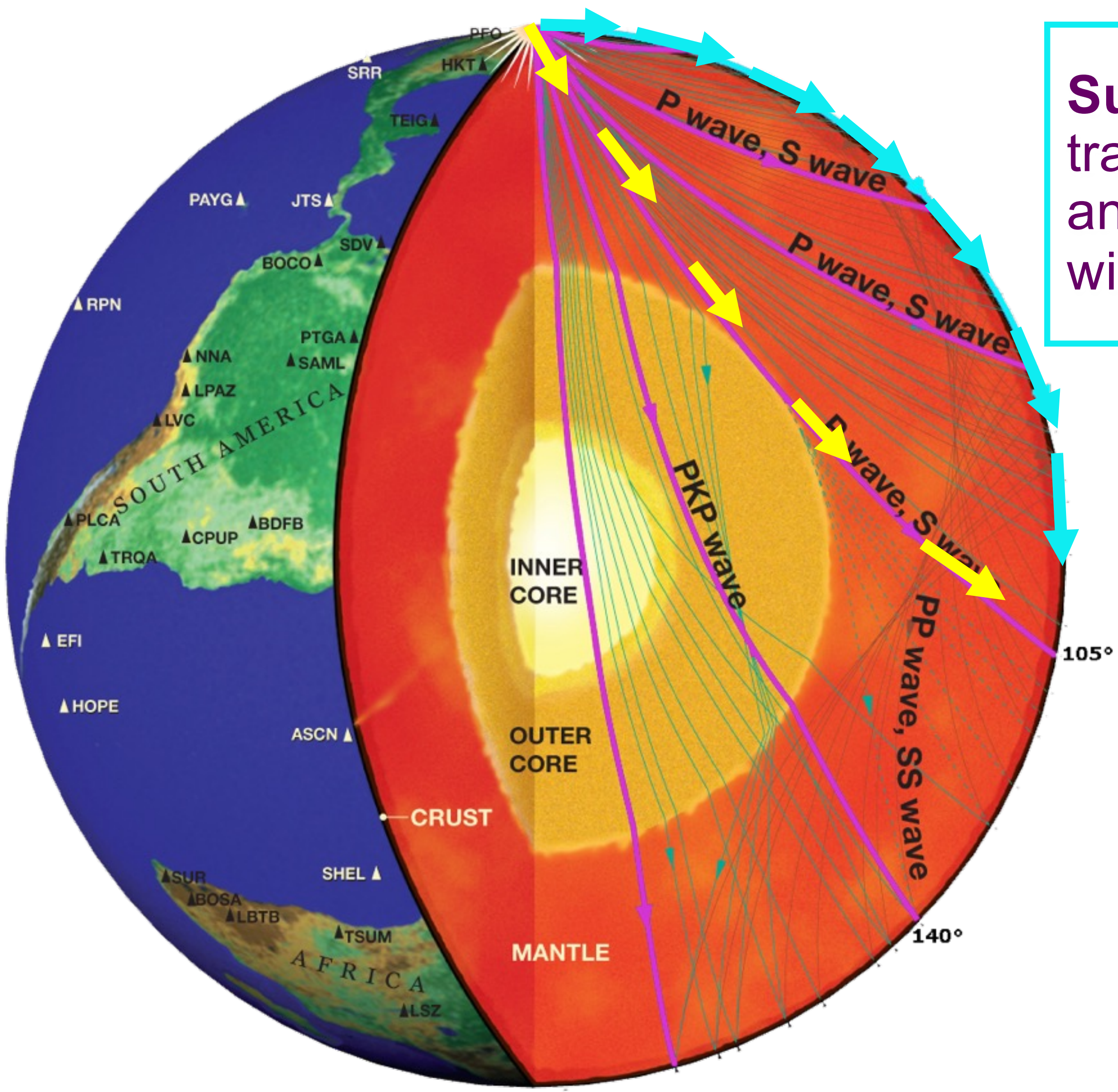


X
Y
Z
Direction of Propagation
RAYLEIGH WAVE
Particle Motion


X
Y
Z
Direction of Propagation
LOVE WAVE
Particle Motion


Body Waves
P Wave
compression
dilation
direction of propagation
S Wave
direction of propagation
Surface Waves
Rayleigh Wave
direction of propagation
Love Wave
direction of propagation

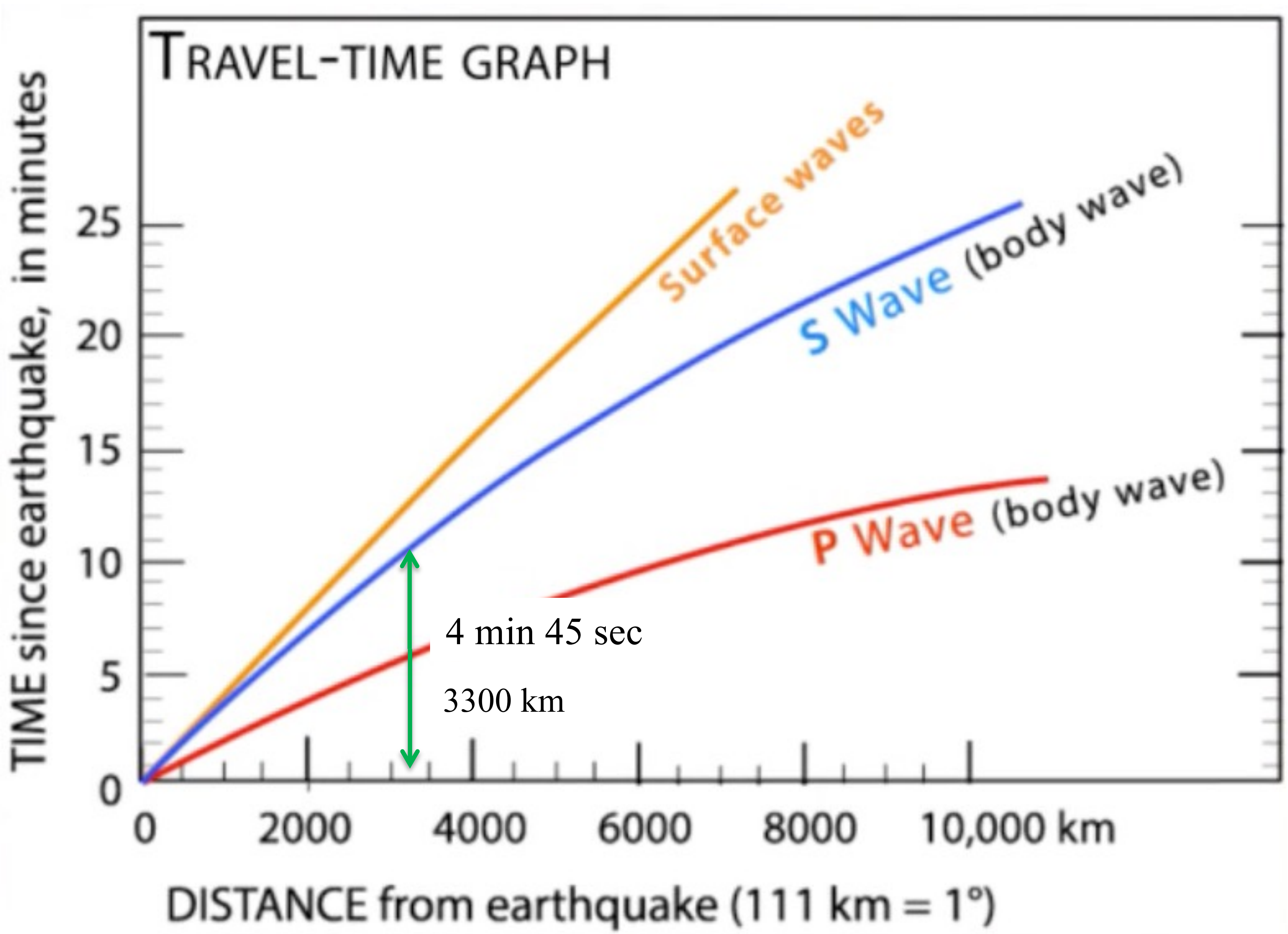
Body Waves and Surface Waves



Surface waves
travel along Earths surface, and decrease in amplitude with depth

Body waves
(P and S) radiate in all directions and travel inside Earth

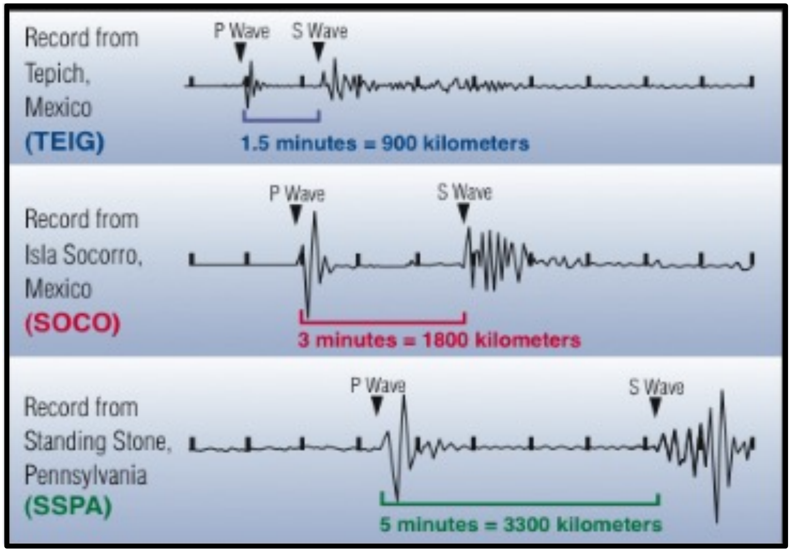
Distance of earthquake from seismometer



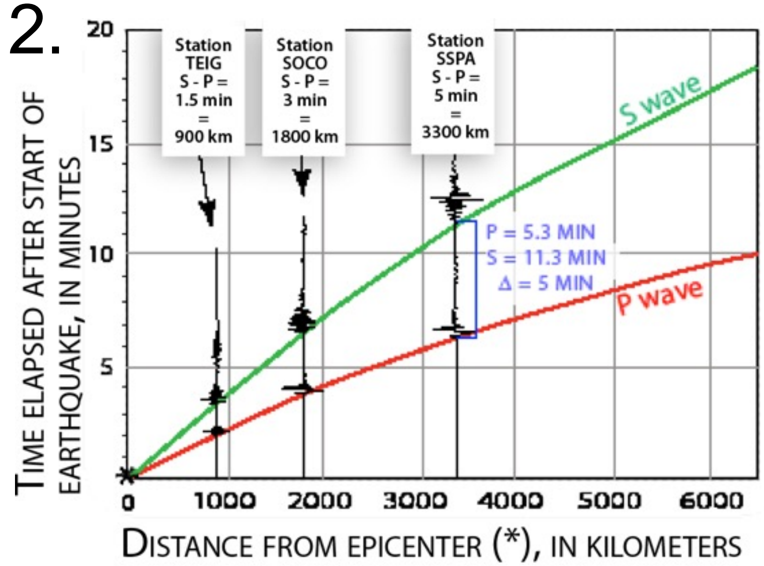
determined from S arrival time - P arrival time

Locating an earthquake...the basics

1.



2.

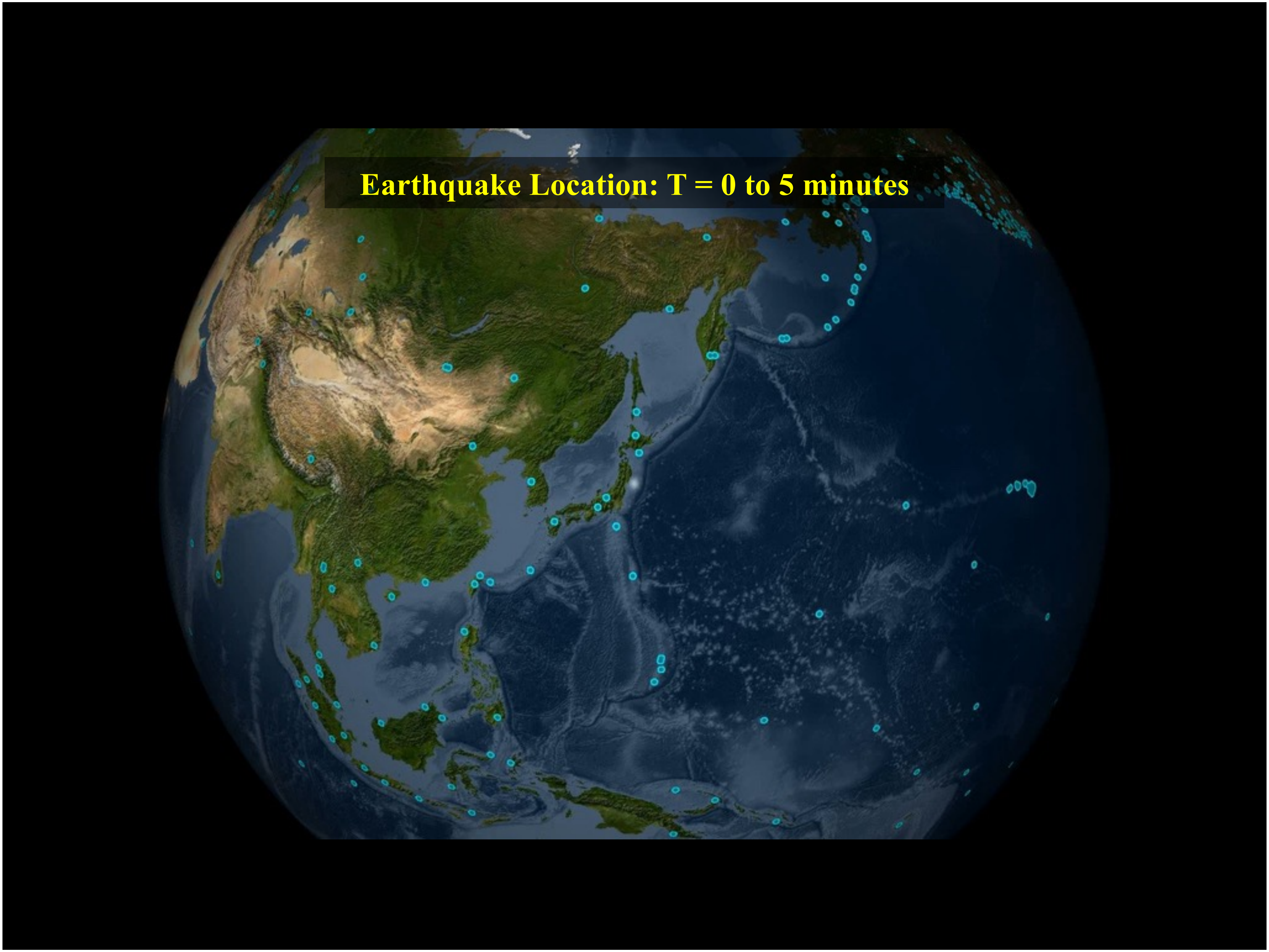


1. Determine distance of EQ from three seismic stations by calculating the S minus P arrival times.

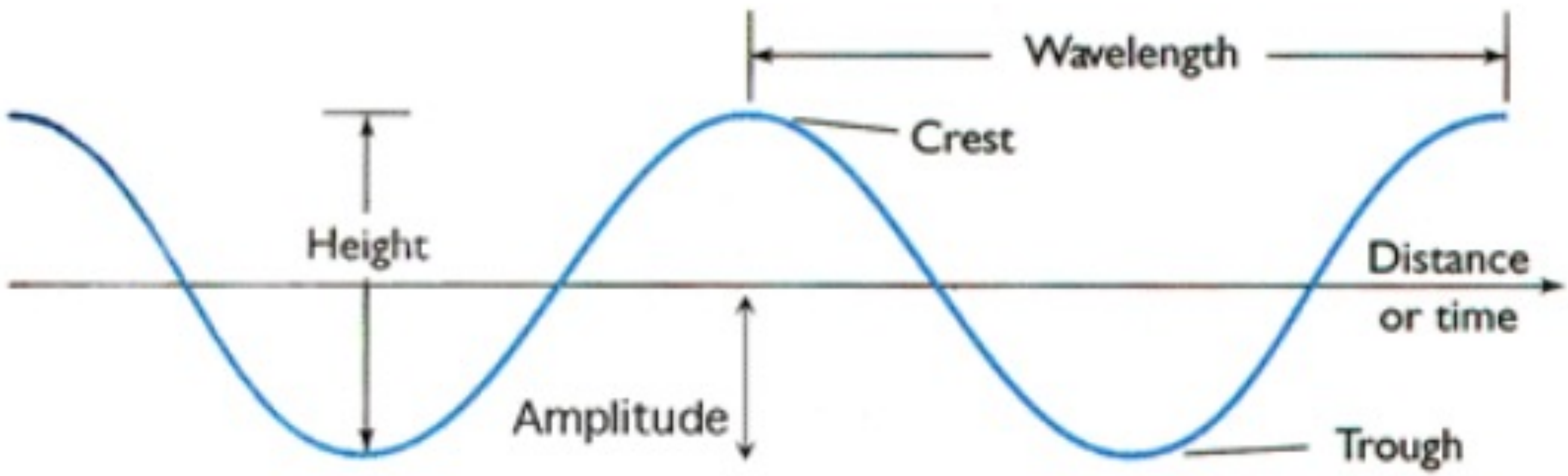
2. Plot on the travel-time graph.

3. Intersection of the circles gives the location.

3.


Earthquake Location: T = 0 to 5 minutes

Basic (Seismic) Wave Properties

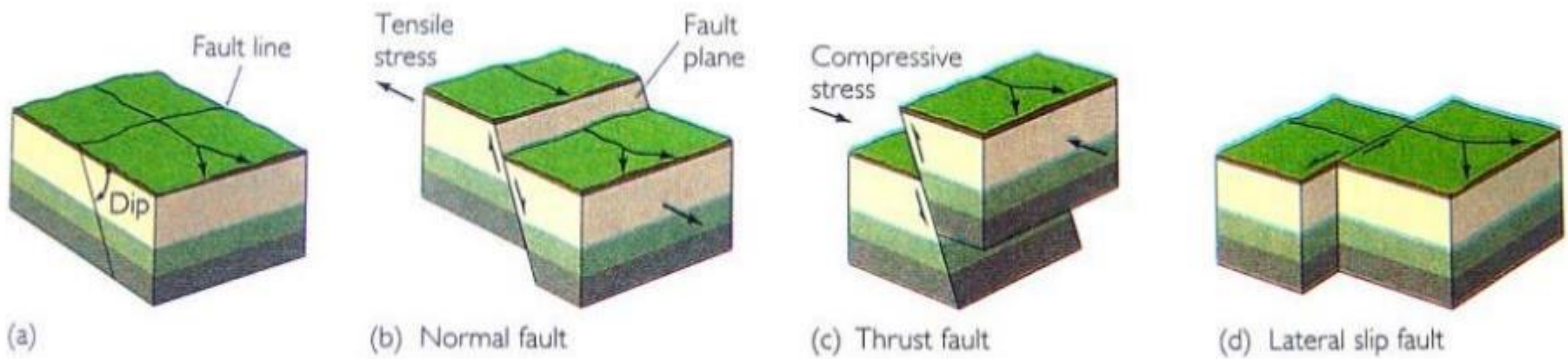


- Wavelength - distance between successive crests of the wave
- Wave period - time it takes for the wave to travel one wavelength

Faulting

Types of Earthquake Faulting

- ***Normal fault***
- ***Thrust or reverse fault***
- ***Lateral slip or strike-slip fault***



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

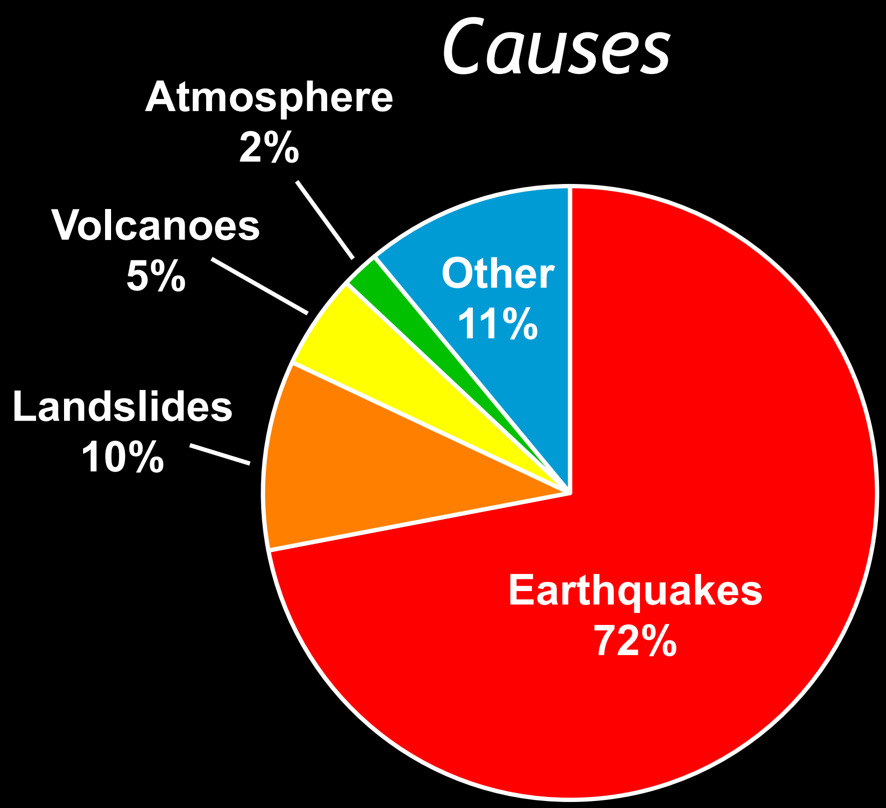
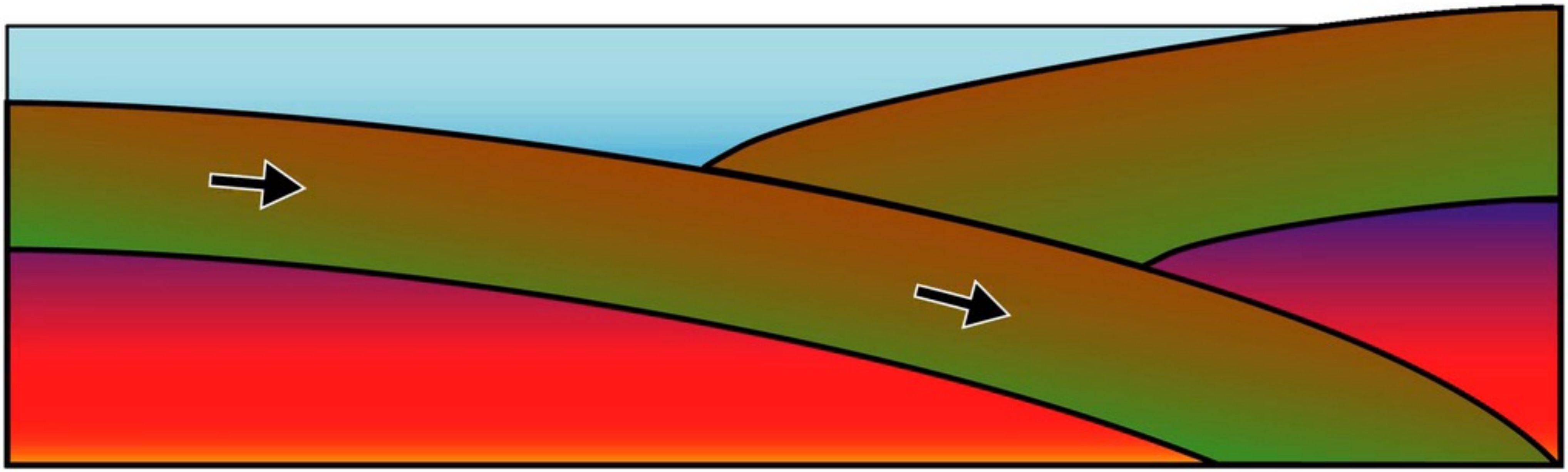


Plate motion builds up strain for hundreds of years



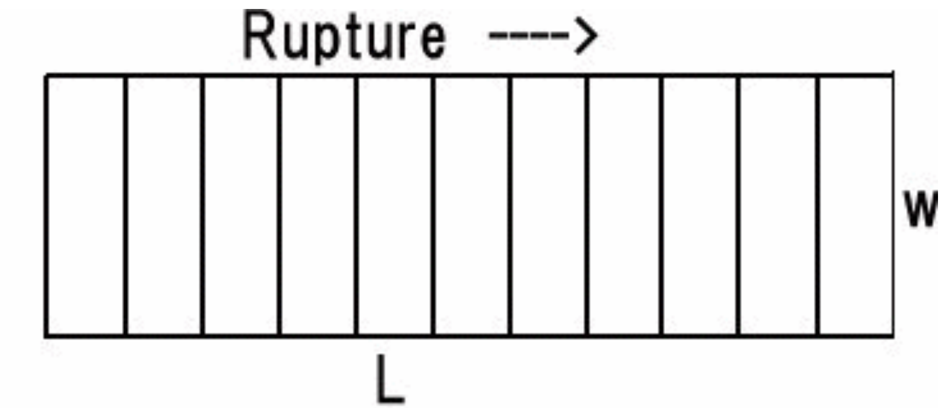
Earthquake Rupture Complexity

Great Earthquakes (M ≥ 8)

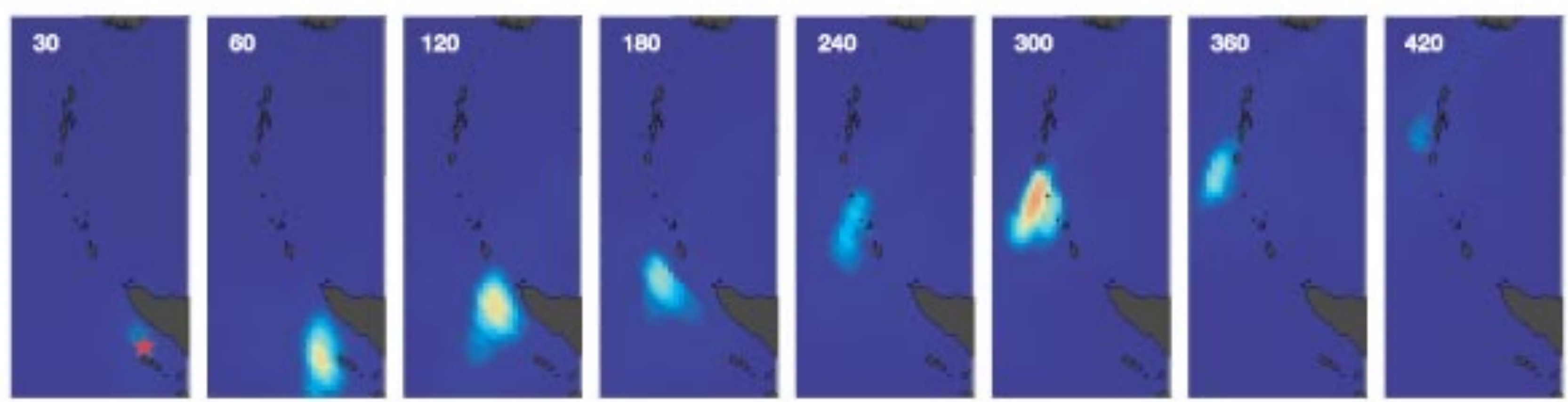
- Shake for a long time (10s sec to 2-3 minutes)
- Rupture for 100s miles

2004 Sumatra earthquake

Haskell Line Source
Dislocation Source



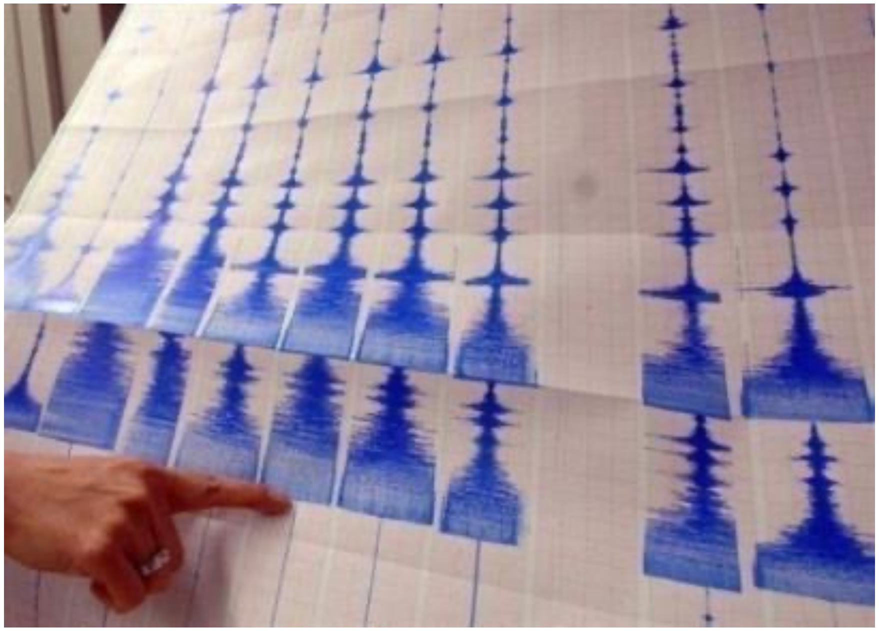
Energy Release imaged by Japan HINET Array



2004 Sumatra earthquake & tsunami

Earthquake Magnitude & Energy

M7, Papua New Guinea earthquake



TAKE 2

Myth-conceptions

Dispelling myths, misconceptions, & misunderstandings about Earth science

Earthquake Magnitude vs. Earthquake Intensity

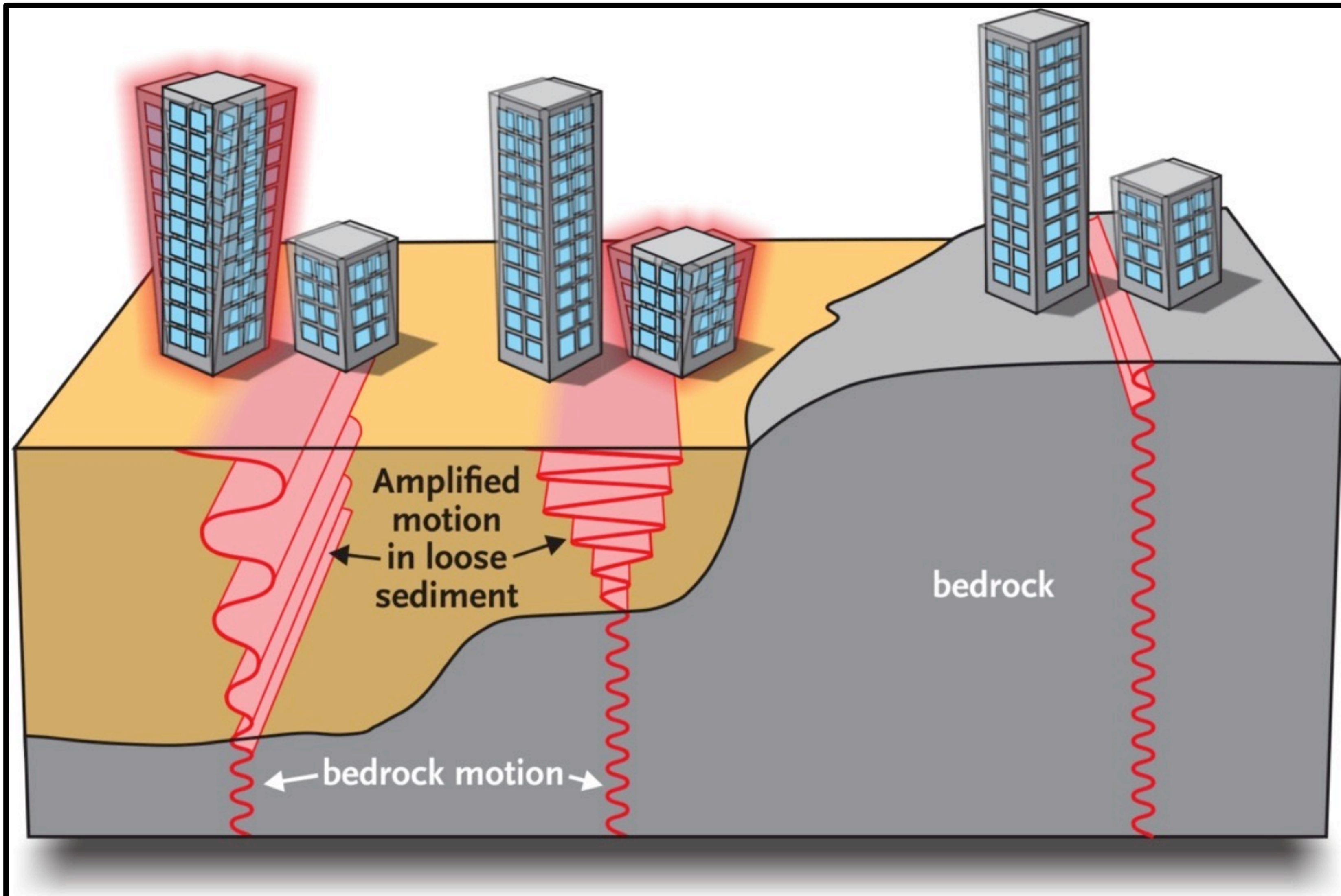
Fixed value vs. variable

IRIS

www.iris.edu/earthquake

INCORPORATED RESEARCH INSTITUTIONS FOR SEISMOLOGY

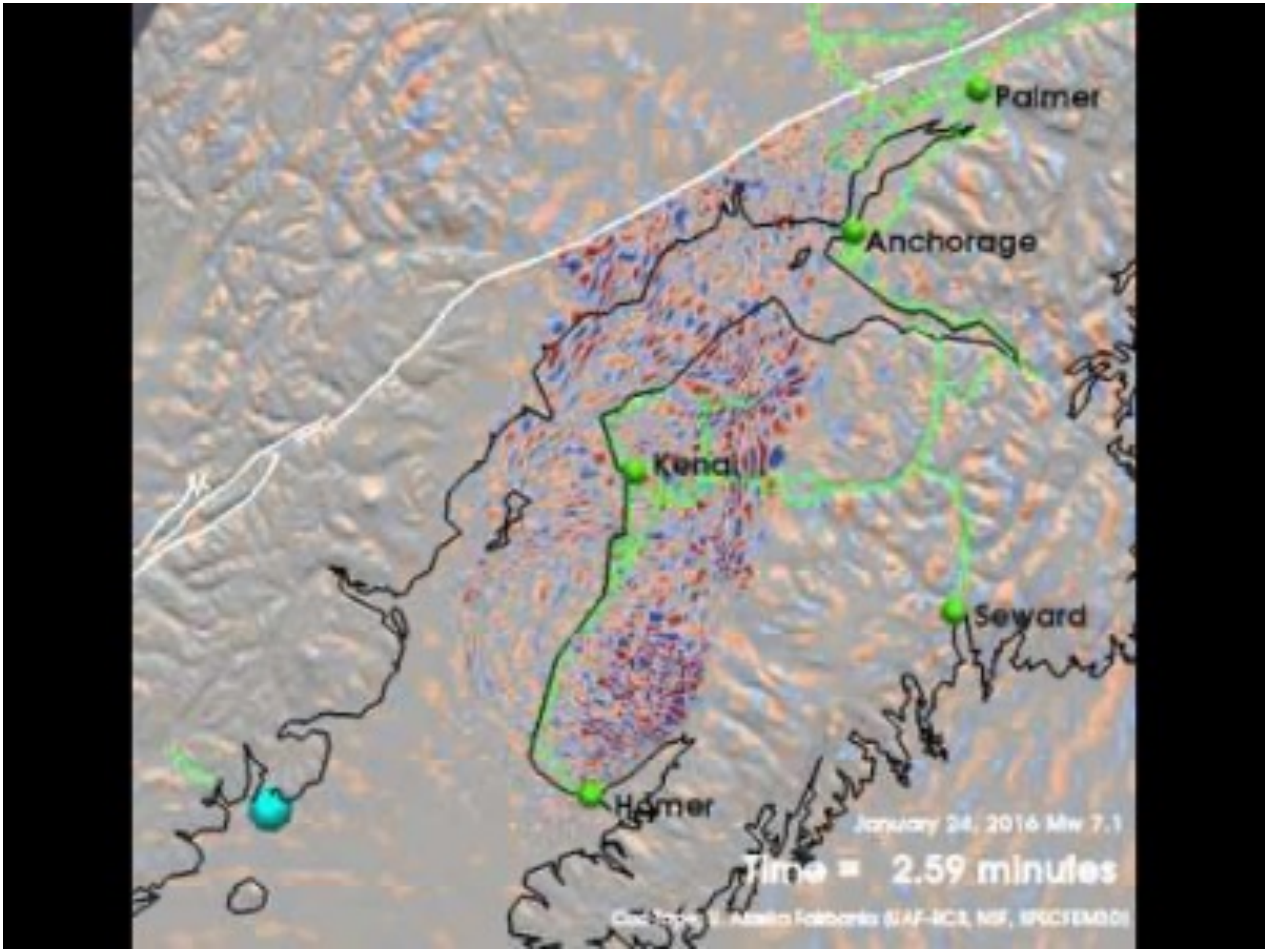
Ground-Shaking Amplification



Seismic waves are amplified as they pass from bedrock into basins filled with sedimentary rock.

Site Effects Related to soils and topography

M7.1 Pedro Bay Earthquake (animation by Carl Tape)



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

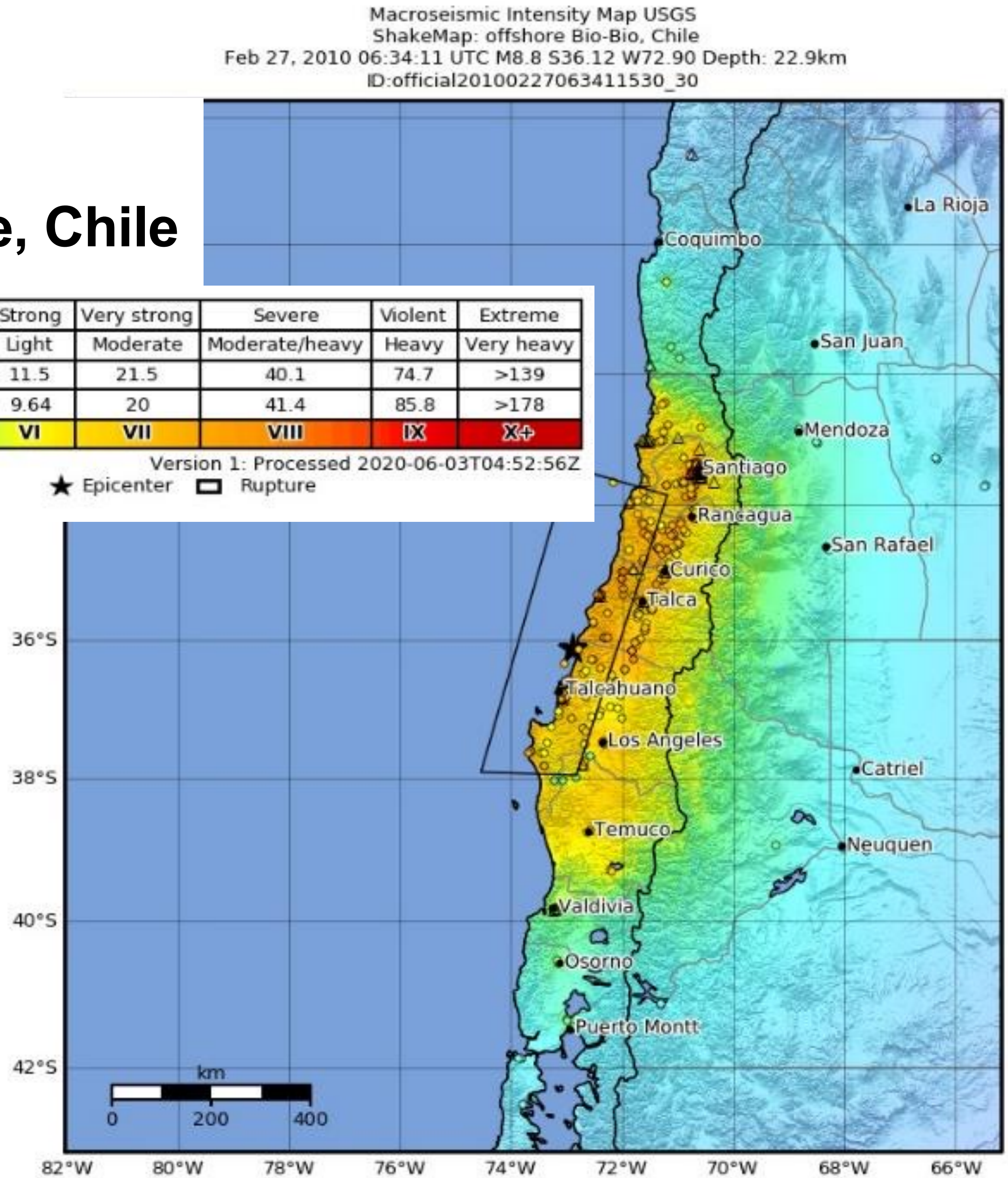
Modified Mercalli Intensity Scale

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.	

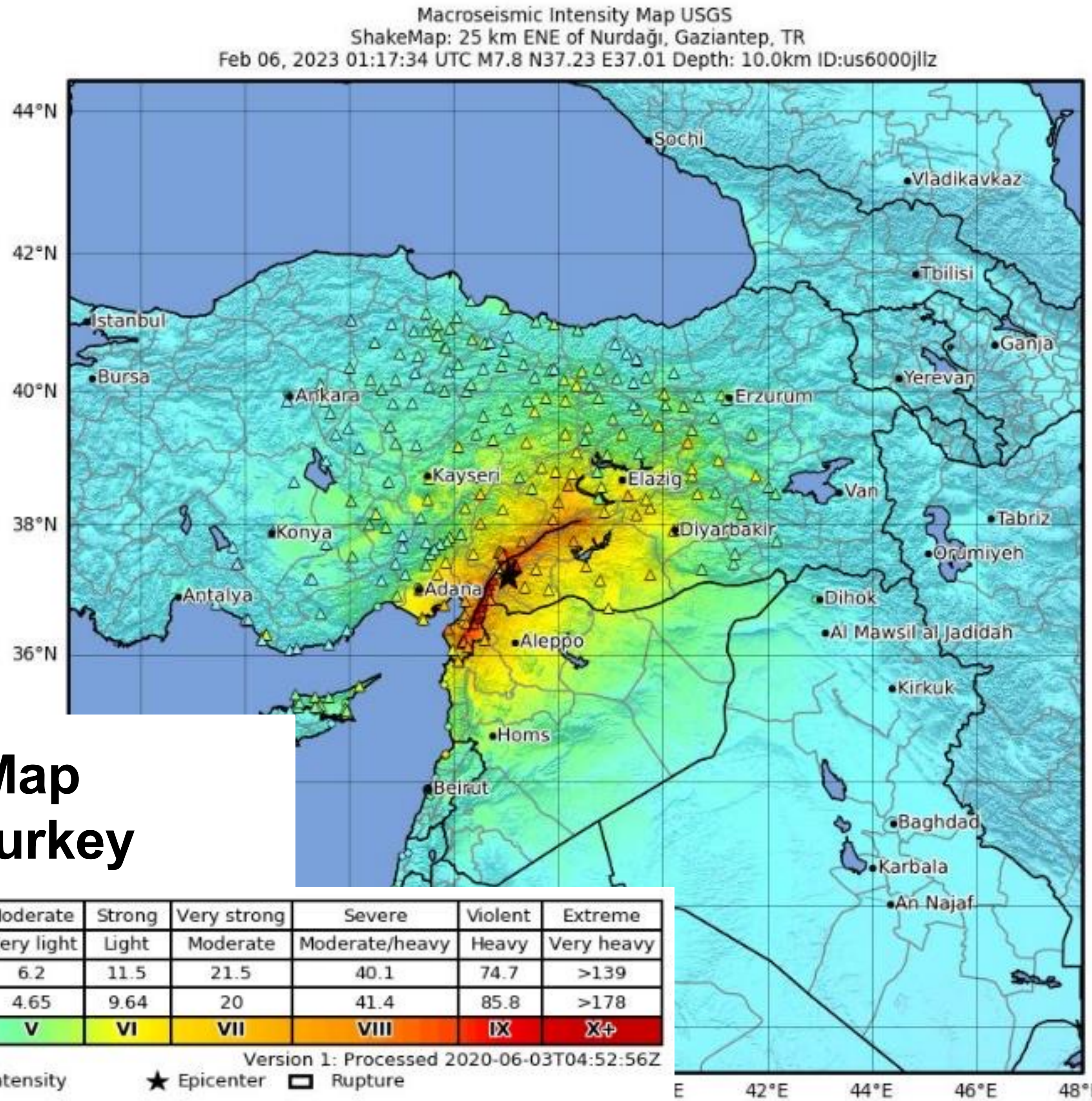
USGS ShakeMap
2010 M_w 8.8 Maule, Chile

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+

Scale based on Worden et al. (2012)
Version 1: Processed 2020-06-03T04:52:56Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter ▭ Rupture



USGS ShakeMap
2023 M_w 7.8 Turkey



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Scale based on Worden et al. (2012) Version 1: Processed 2020-06-03T04:52:56Z

△ Seismic Instrument ○ Reported Intensity ★ Epicenter ▭ Rupture

Earthquake Magnitude

General form:

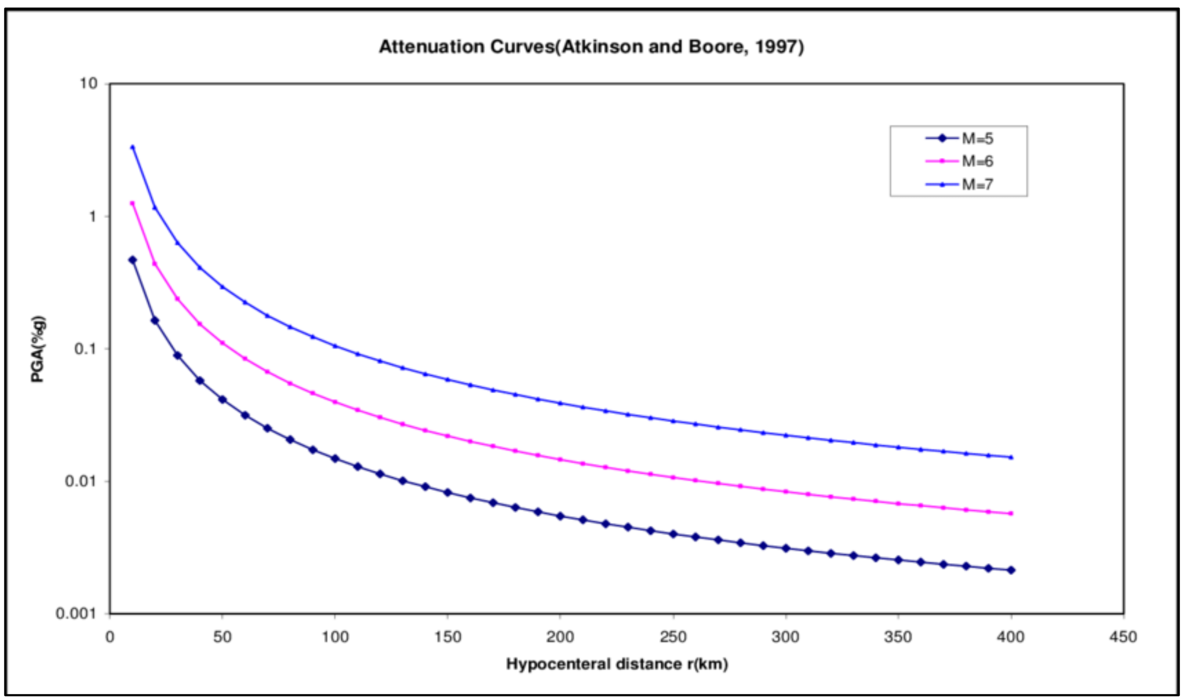
$$M = log(A/T) + F(h,\Delta) + C$$

Amplitude

Period

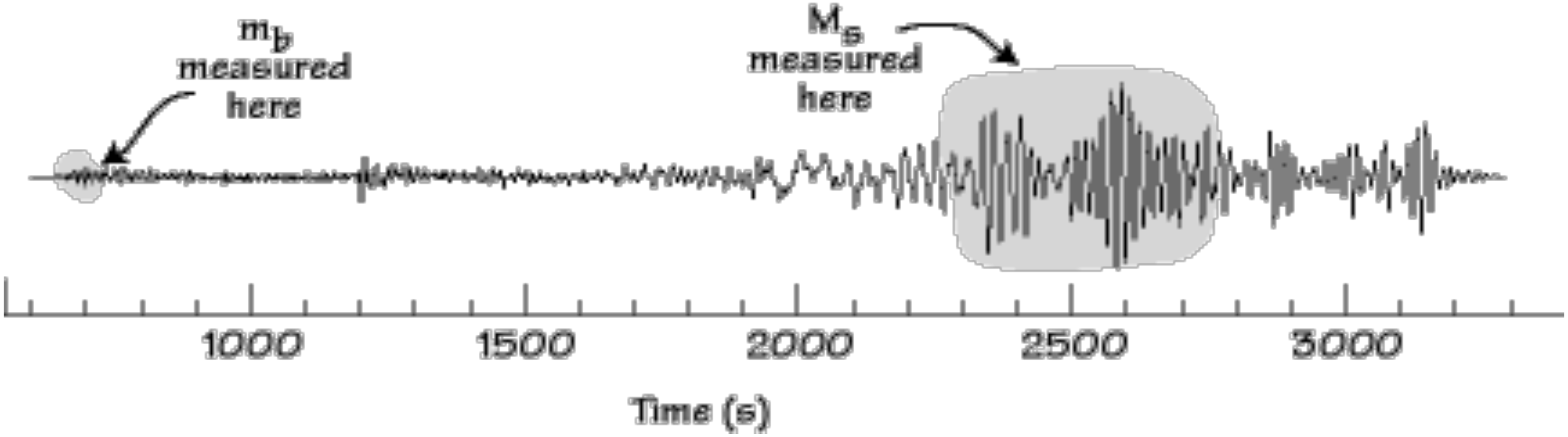
Correction for depth and distance

Regional scaling factor



Richter and Gutenberg's Teleseismic (distant) magnitudes

Body wave Magnitude mb and Surface wave and M_S



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

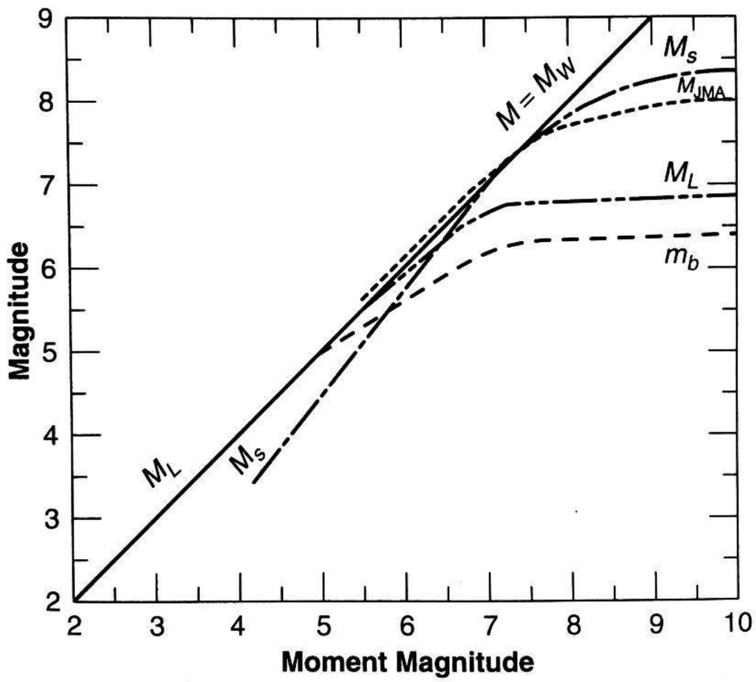
T: period (secs), $0.1 \leq T \leq 3.0$
A: P wave amplitude (microns)
(not necessarily the maximum)
Q: scale factor ($D \geq 5°$)

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

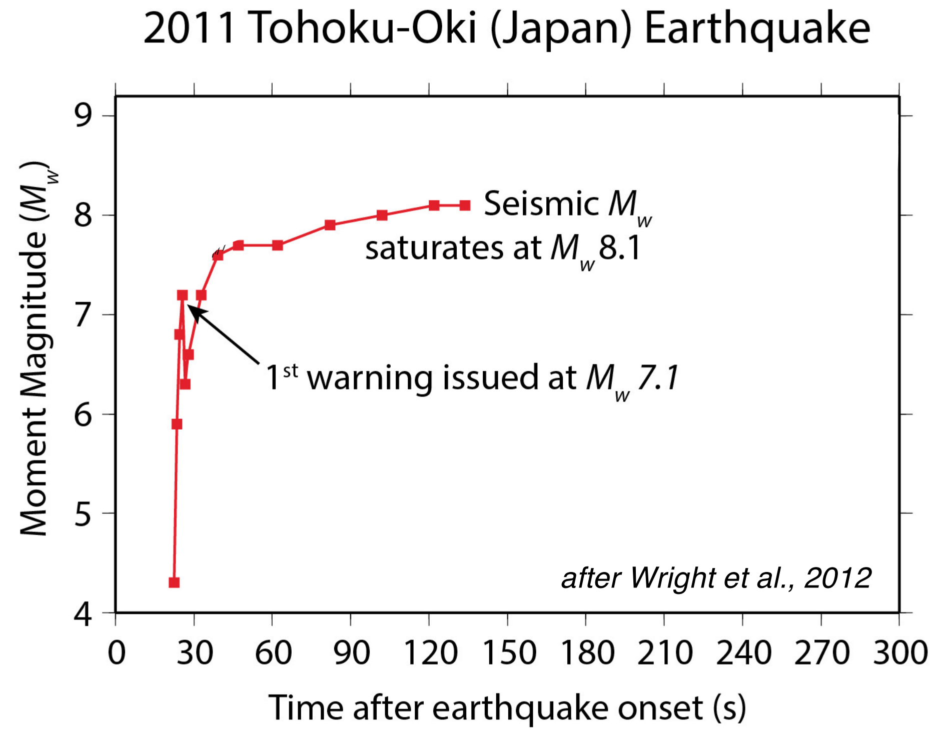
A: maximum amplitude (microns) vertical component of the surface wave within the period range 18 <= **T** <= 22.
D: $20° \leq D \leq 160°$.

No depth corrections!

Saturation!



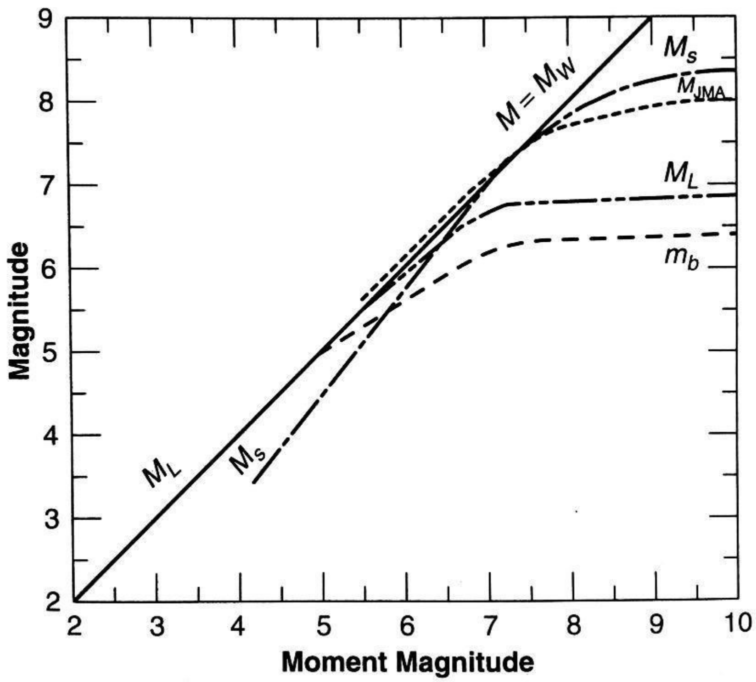
Idriss, 1985



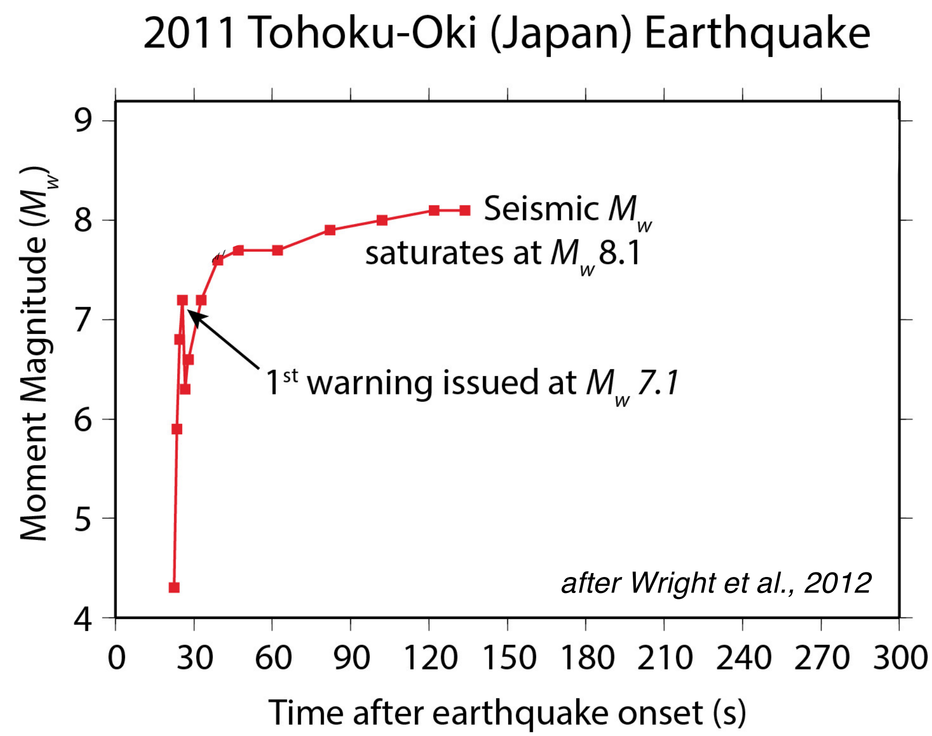
1) Time window saturation - time window that is less than duration of rupture (particularly affects mb)

2) Spectral saturation – Wavelength too short to see entire rupture (affects mb, M_L, and M_s)

Saturation!



Idriss, 1985



How do we overcome this problem?

→ Examine longer period waves

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

→ GNSS/GPS data (later in the talk)

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

Moment Magnitude

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:

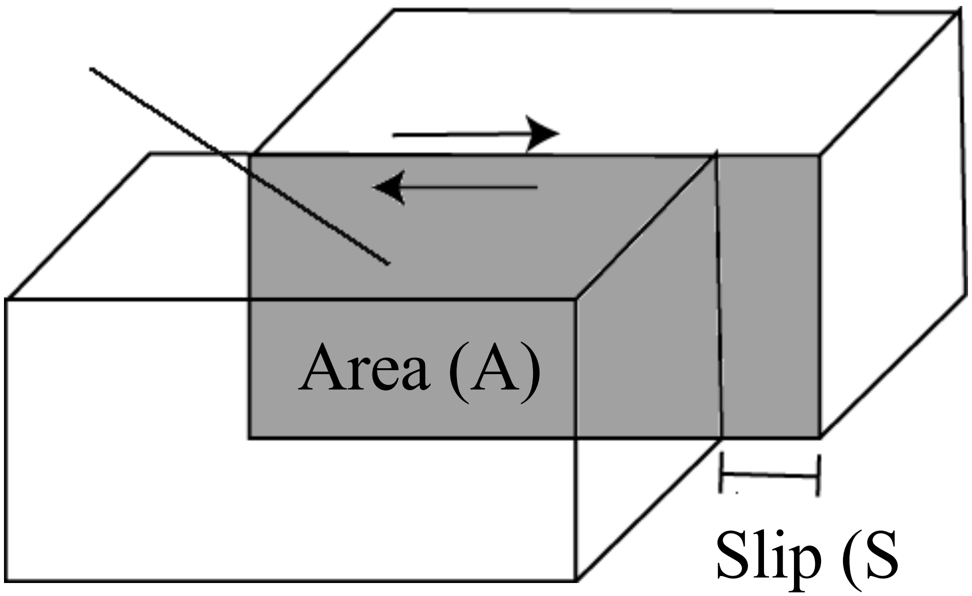
Mwp	P-wave moment magnitude	teleseismic P waves	10-60 sec
M_w	Moment magnitude	teleseismic surface waves	> 200 sec
M_m	Mantle magnitude	teleseismic surface waves	> 200 sec

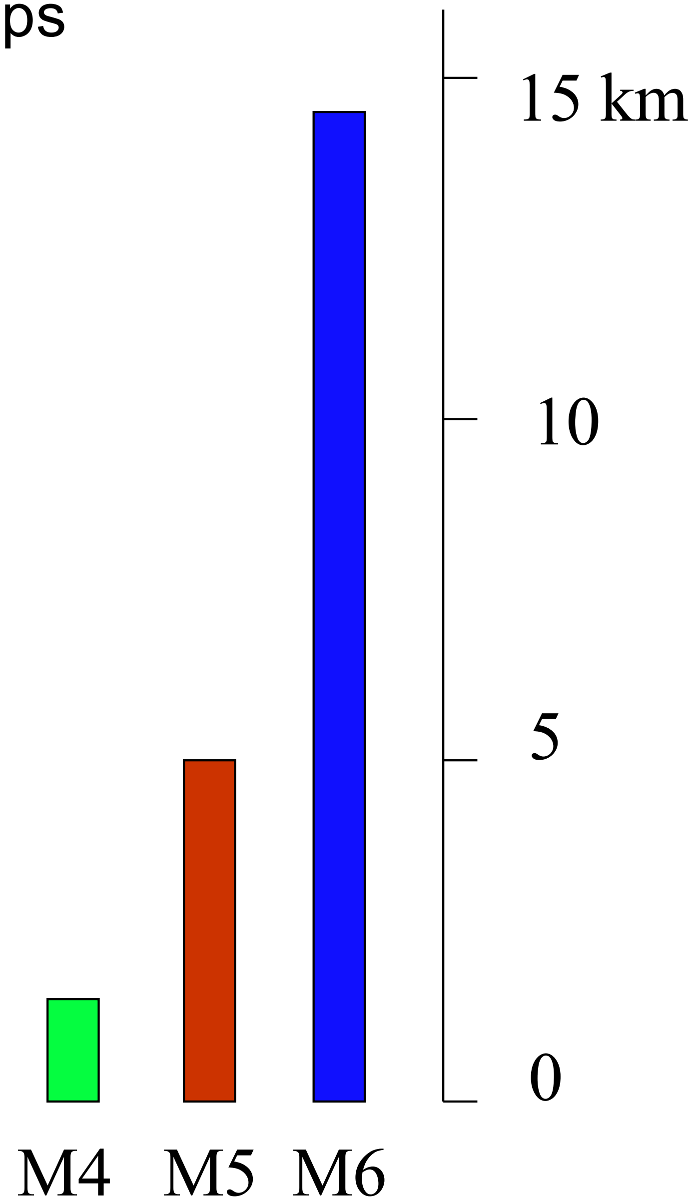
Ref: USGS Seismology and Tsunami Warnings, 2006 (Earthquake Source)

Earthquake size - Seismic Moment (M_0)

Mechanical measure of EQ size

How large an area and how much the fault slips

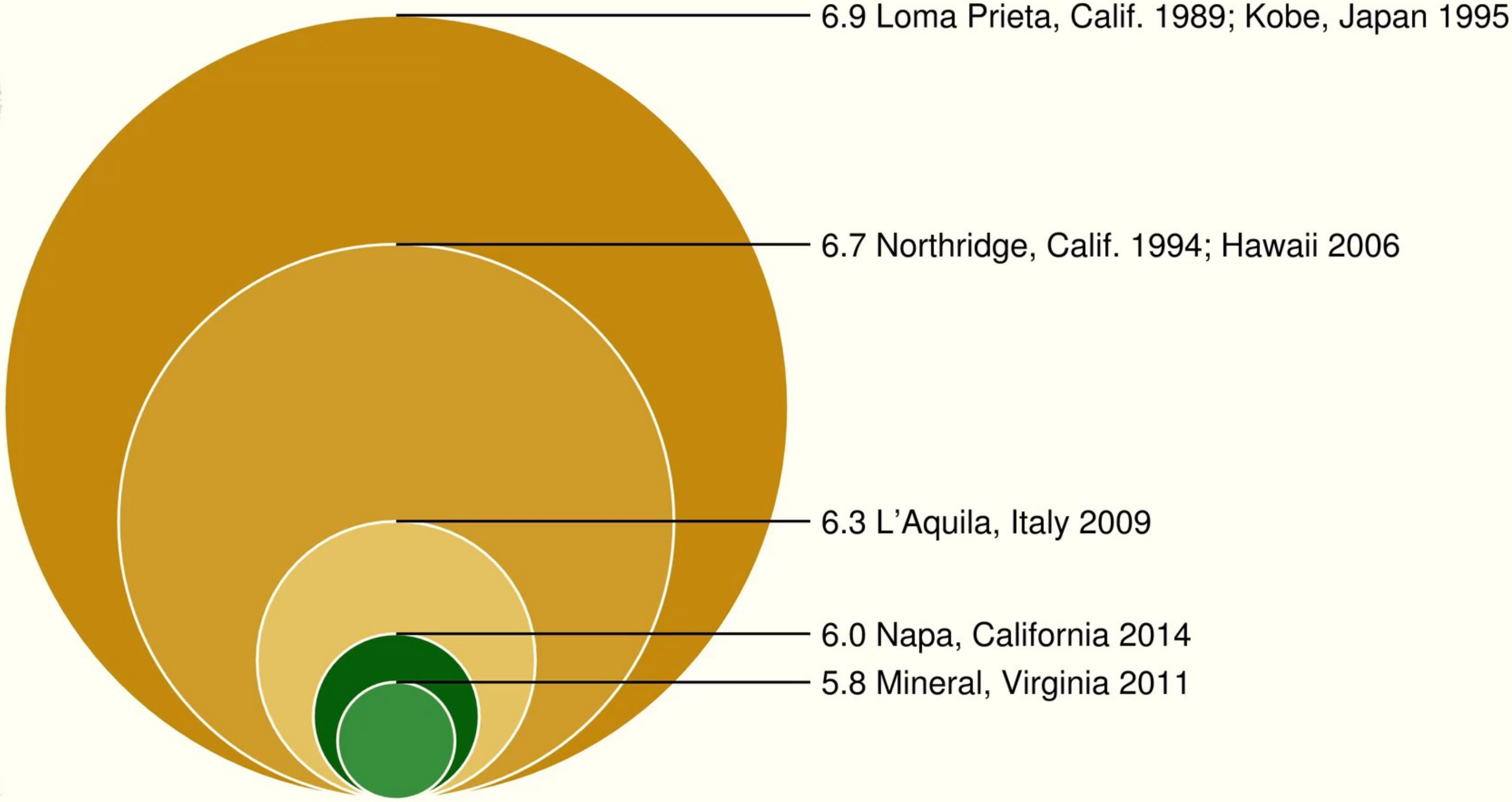


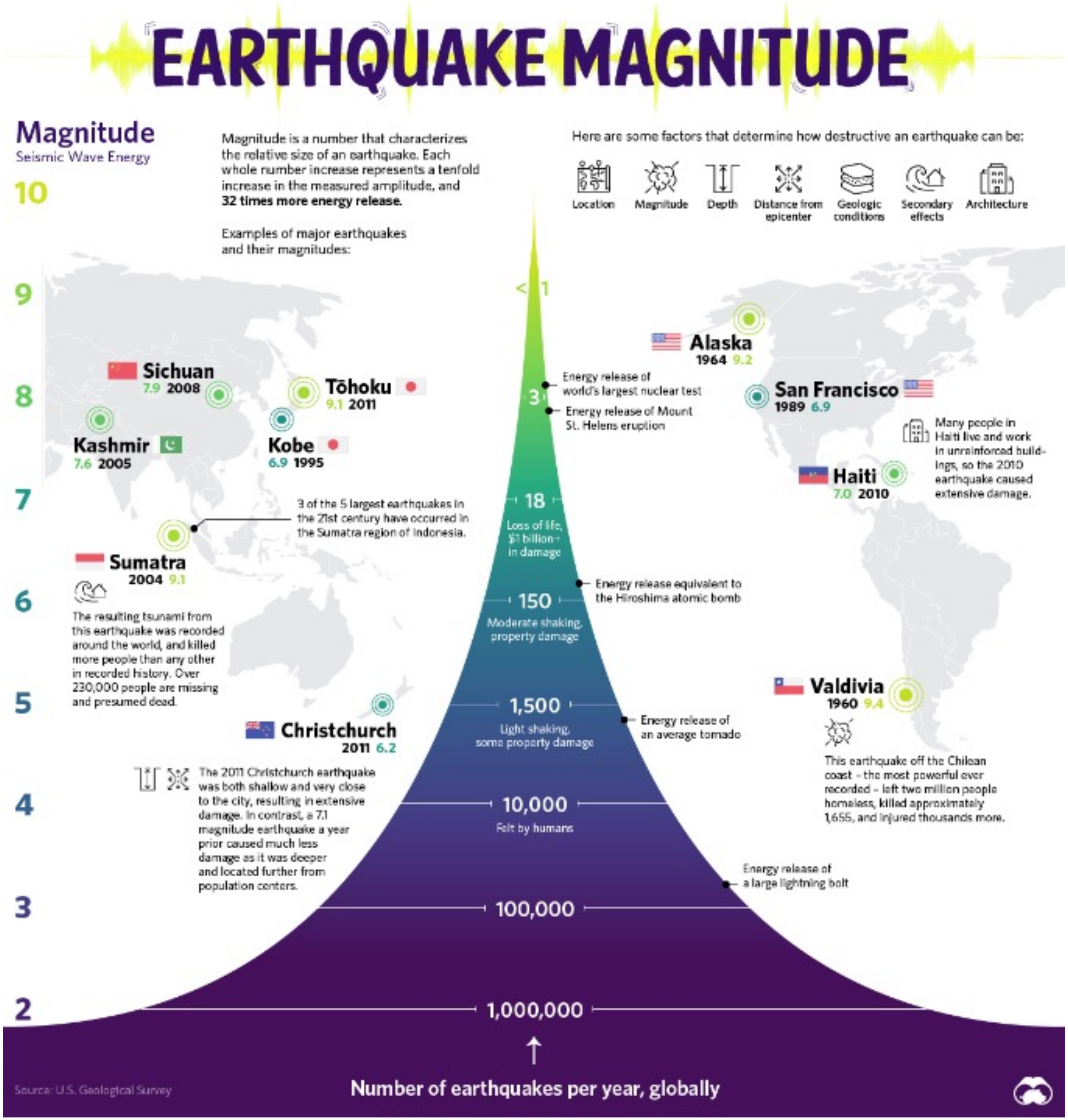


Seismic Moment = (Rigidity)(Area)(Slip)

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

Comparison of Recent and Historic Earthquakes by Energy Release



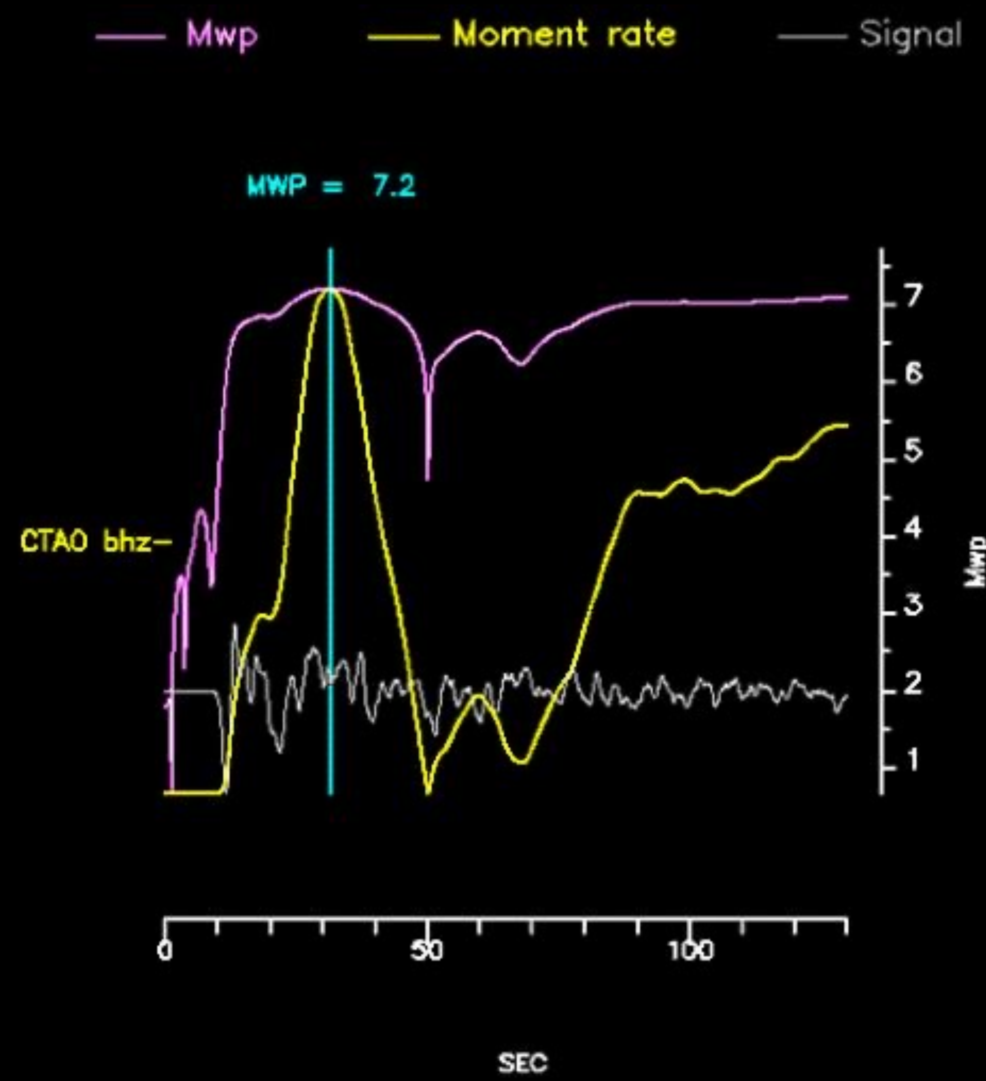

EARTHQUAKE MAGNITUDE
Magnitude
Seismic Wave Energy
Magnitude is a number that characterizes the relative size of an earthquake. Each whole number increase represents a tenfold increase in the measured amplitude, and **32 times more energy release.**
Examples of major earthquakes and their magnitudes:
Here are some factors that determine how destructive an earthquake can be:
Location
Magnitude
Depth
Distance from epicenter
Geologic conditions
Secondary effects
Architecture
10
9
8
7
6
5
4
3
2
<1
3
18
Loss of life, $1 billion+ in damage
150
Moderate shaking, property damage
1,500
Light shaking, some property damage
10,000
Felt by humans
100,000
1,000,000
Number of earthquakes per year, globally
Energy release of world's largest nuclear test
Energy release of Mount St. Helens eruption
Energy release equivalent to the Hiroshima atomic bomb
Energy release of an average tornado
Energy release of a large lightning bolt
Sichuan
7.9 2008
Tōhoku
9.1 2011
Kashmir
7.6 2005
Kobe
6.9 1995
3 of the 5 largest earthquakes in the 21st century have occurred in the Sumatra region of Indonesia.
Sumatra
2004 9.1
The resulting tsunami from this earthquake was recorded around the world, and killed more people than any other in recorded history. Over 230,000 people are missing and presumed dead.
Christchurch
2011 6.2
The 2011 Christchurch earthquake was both shallow and very close to the city, resulting in extensive damage. In contrast, a 7.1 magnitude earthquake a year prior caused much less damage as it was deeper and located further from population centers.
Alaska
1964 9.2
San Francisco
1989 6.9
Many people in Haiti live and work in unreinforced buildings, so the 2010 earthquake caused extensive damage.
Haiti
7.0 2010
Valdivia
1960 9.4
This earthquake off the Chilean coast – the most powerful ever recorded – left two million people homeless, killed approximately 1,655, and injured thousands more.
Source: U.S. Geological Survey

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

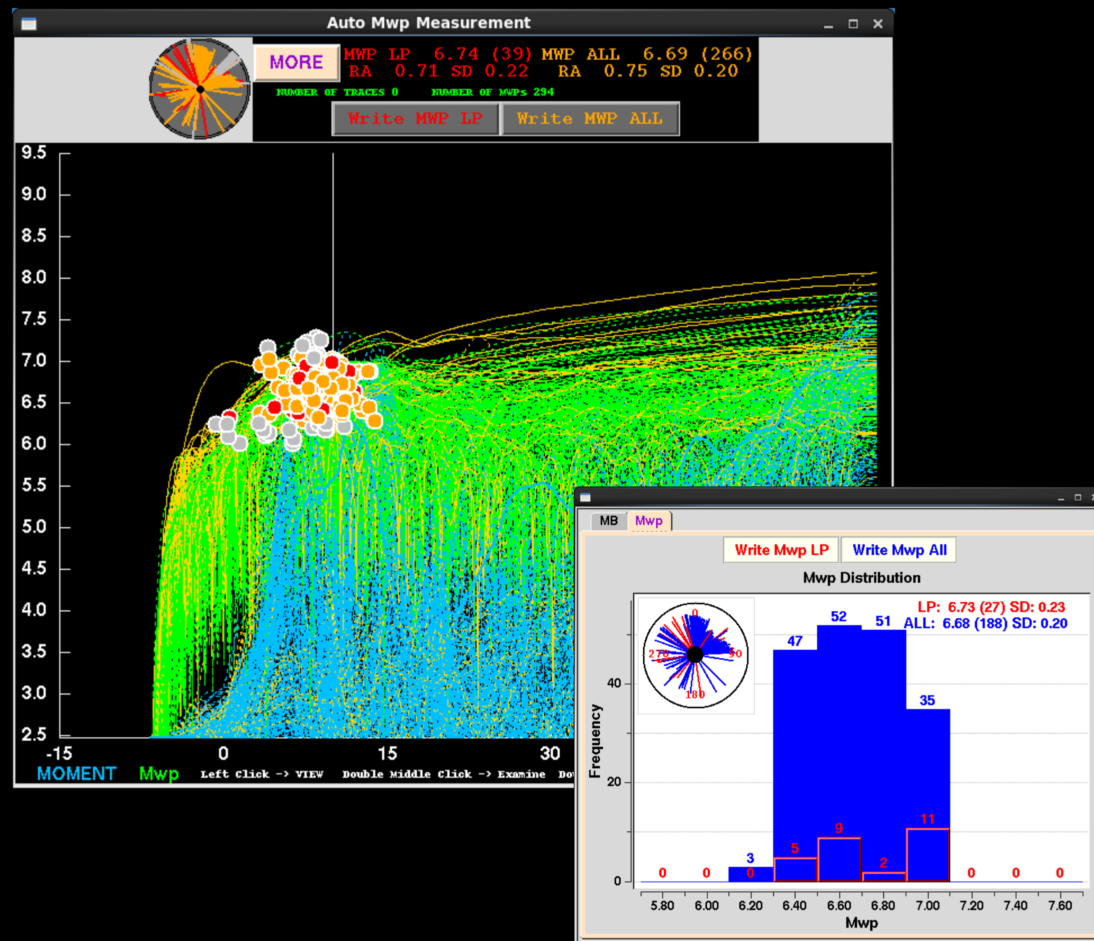
M_{wp} [Tsuboi et al.,1995;1999]

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



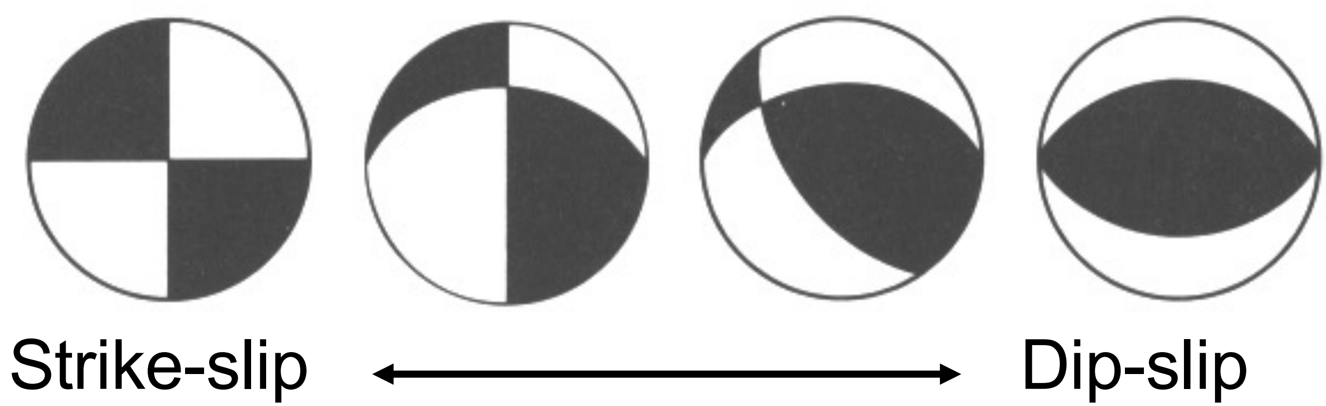
M_{wp} [Tsuboi et al.,1995;1999]

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



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



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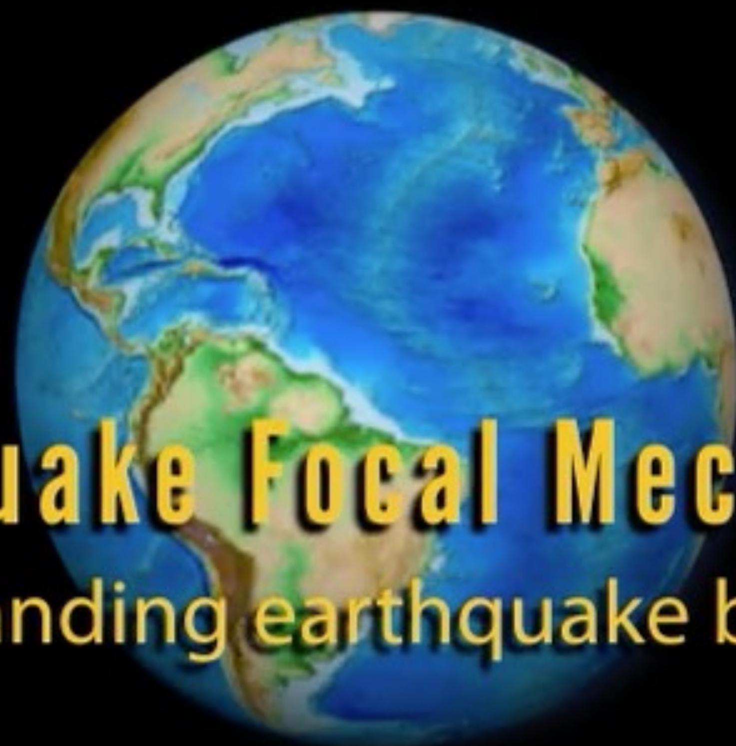

Earthquake Focal Mechanisms

Understanding earthquake beachballs

www.iris.edu/earthquake

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.

CMT via Wphase Inversion
Japan 2011, M_w 9.1

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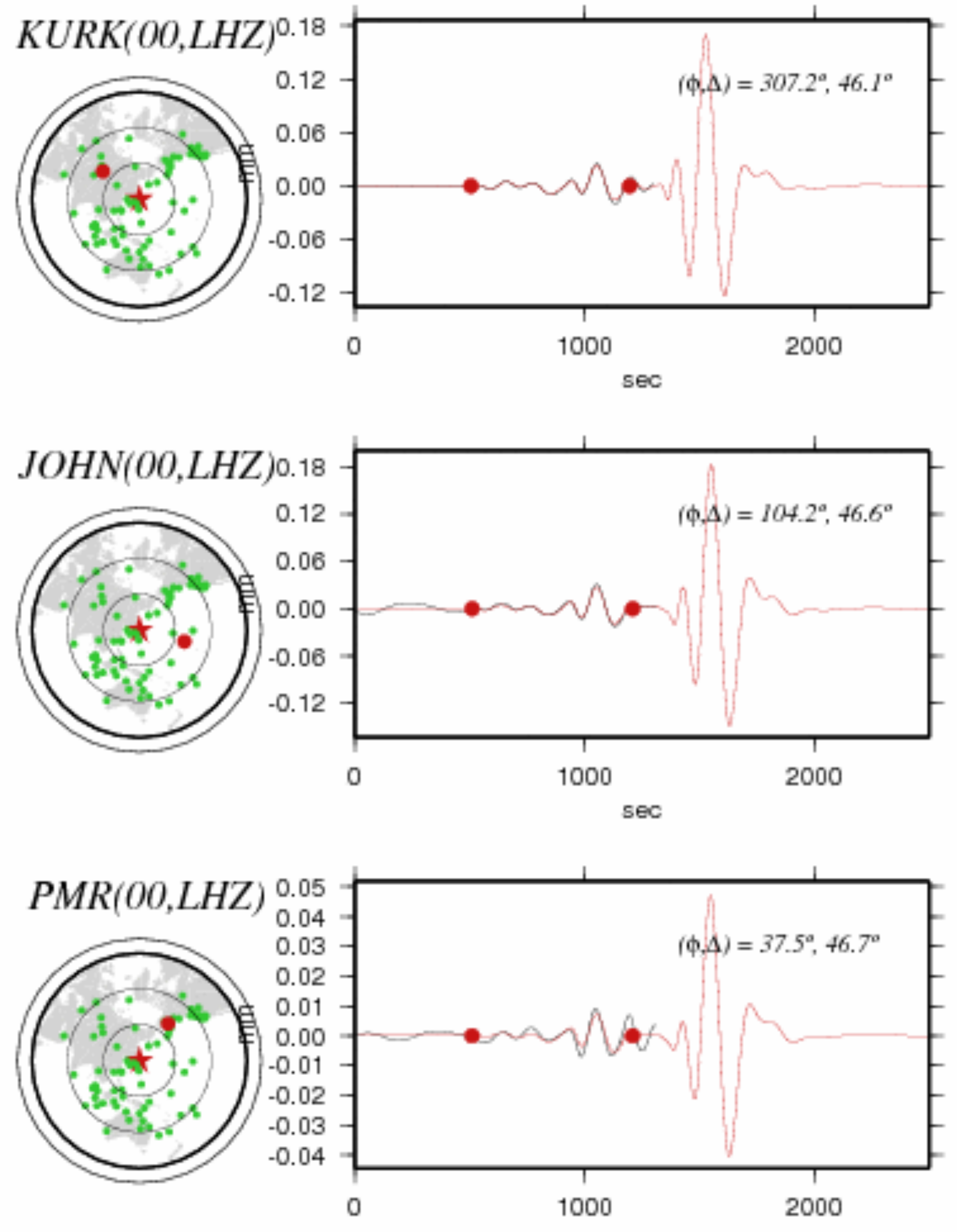


TWC magnitude determination

PTWC uses 5 primary methods:

ML - local magnitude, HI/PR/USVI (2<M<6)

mb - body wave magnitude, largest P-waves (4<M<6.5)

Mm - mantle wave magnitude, 50-400s surface waves (M>6)

Mwp – estimate of the moment magnitude from integrated P-waves (5<M<8)

W-phase - long-period phase, gives stable results, does not saturate, but takes ~20-25 minutes (M>5)

TWC magnitude determination

- Measurements are not precise, different magnitudes result from using different scales/methods and datasets.

- Many methods saturate for large earthquakes

- Mo → EQ energy → ”true” EQ size but takes time

- TWC’s rely on Mwp for preliminary message products, method can still underestimate great earthquake sizes.

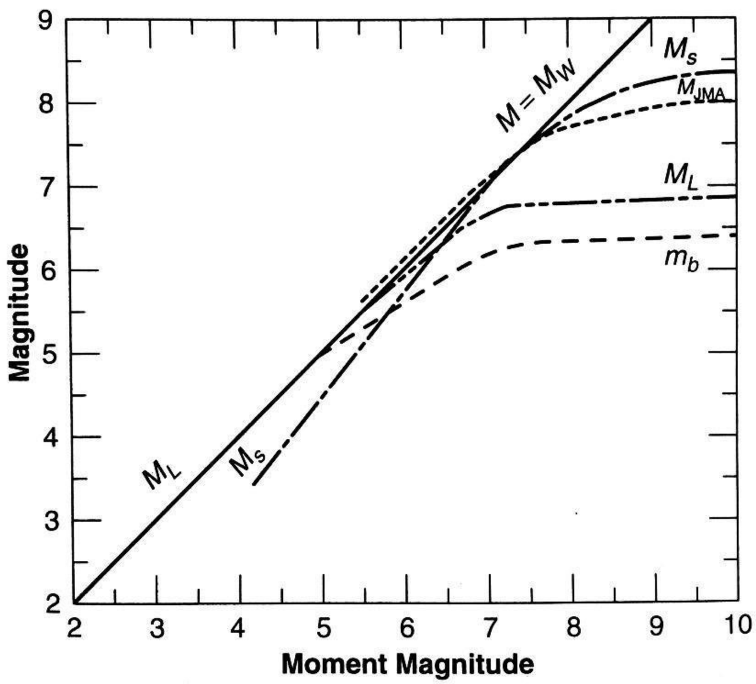
- WCMT provides fault geometry and authoritative estimate of Mw but takes time (~15-25 minutes)

Magnitude Types (NEIC)

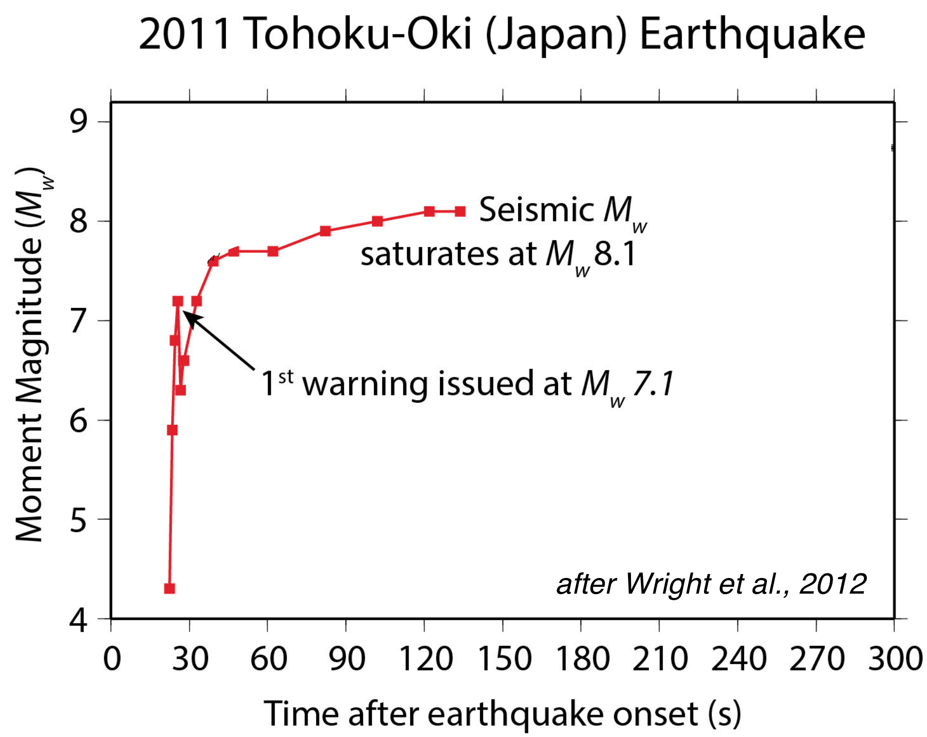
Magnitude Type	Magnitude Range	Distance Range
Mww W-phase moment	~5.0 and larger	1-90 degrees
Mwc Centroid moment tensor	~5.5 and larger	20-180 degrees
Mwb Body wave moment tensor	~5.5 to ~7.0	30-90 degrees
Mwr Regional moment tensor	~4.0 to ~6.5	0-10 degrees
Ms_20 or Ms Surface wave	~5.0 to ~8.5	20-160 degrees
Mb Short-period body wave	~4.0 to ~6.5	15-100 degrees
ML, Ml or ml Local magnitude	~2.0 to ~6.5	0-600 km (5.4˚)
mbLg, mblg or MLg Short-period surface wave	~3.5 to ~7.0	150-1110 km (10˚)
MD Duration	~4.0 and smaller	0-400 km
Mi or Mwp Integrated P-wave	~5.0 to ~8.0	all
Me Energy	~3.5 and larger	all
Finite Fault	~7.0 and larger	30-90 degrees

Highlighted magnitude types are currently used in near-real time operations at the PTWC because they can be computed from seconds to ~20 minutes after origin time.

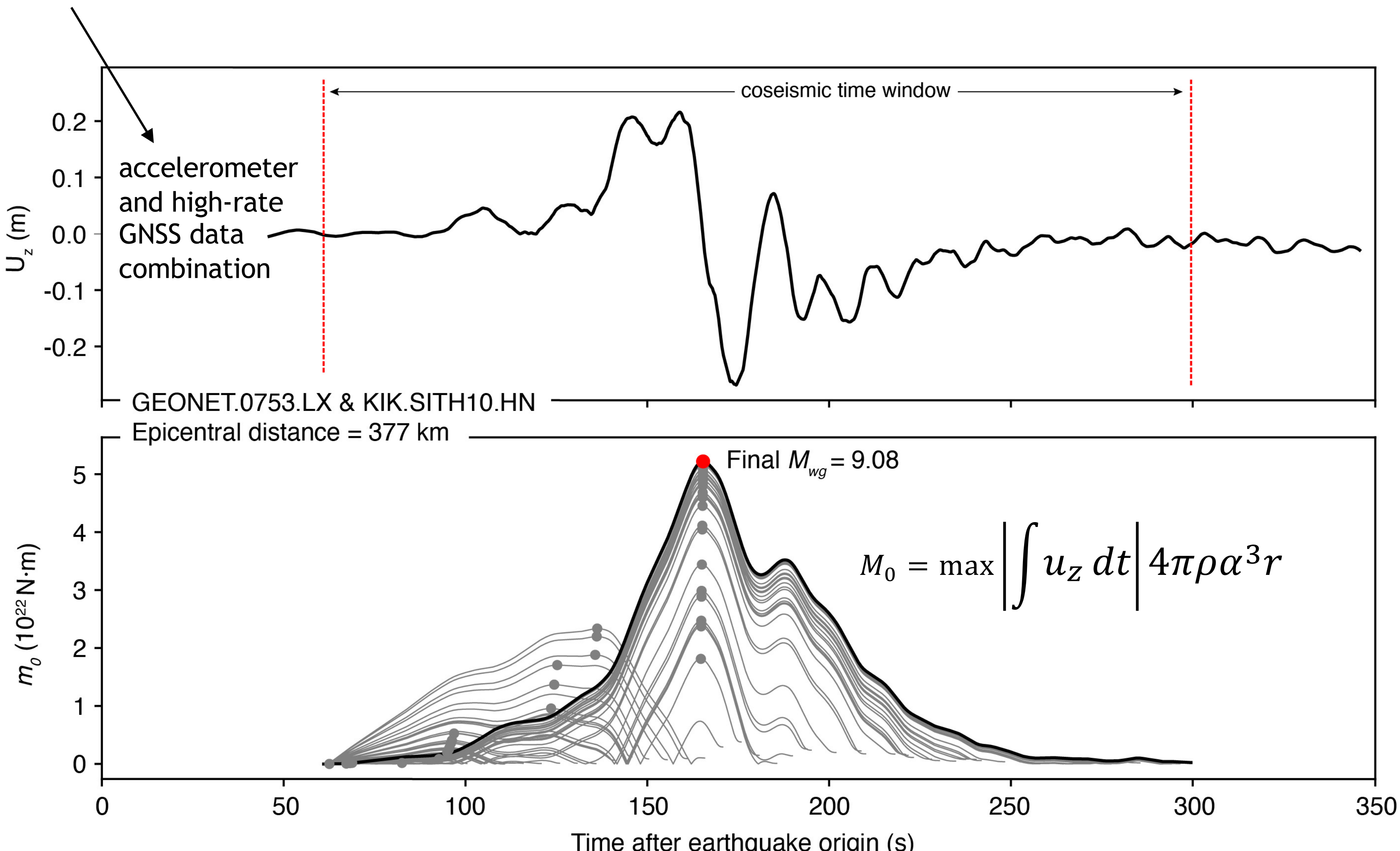
The future of rapid and accurate earthquake magnitude estimation and tsunami warning **will** include high-rate GNSS/GPS data



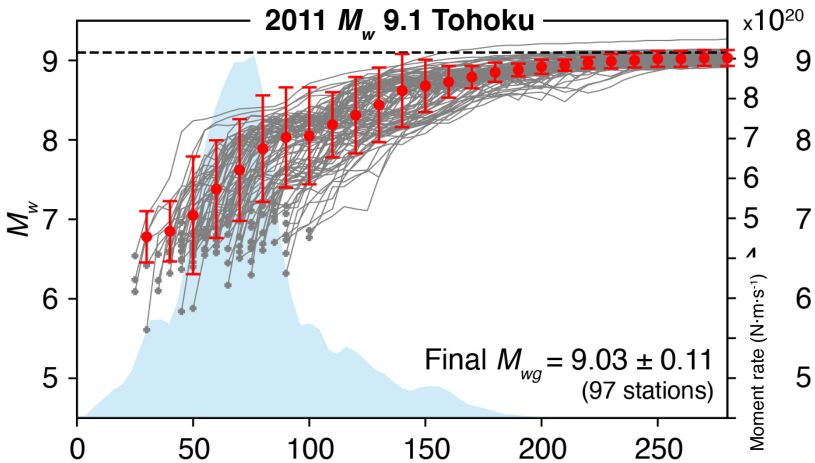
Idriss, 1985



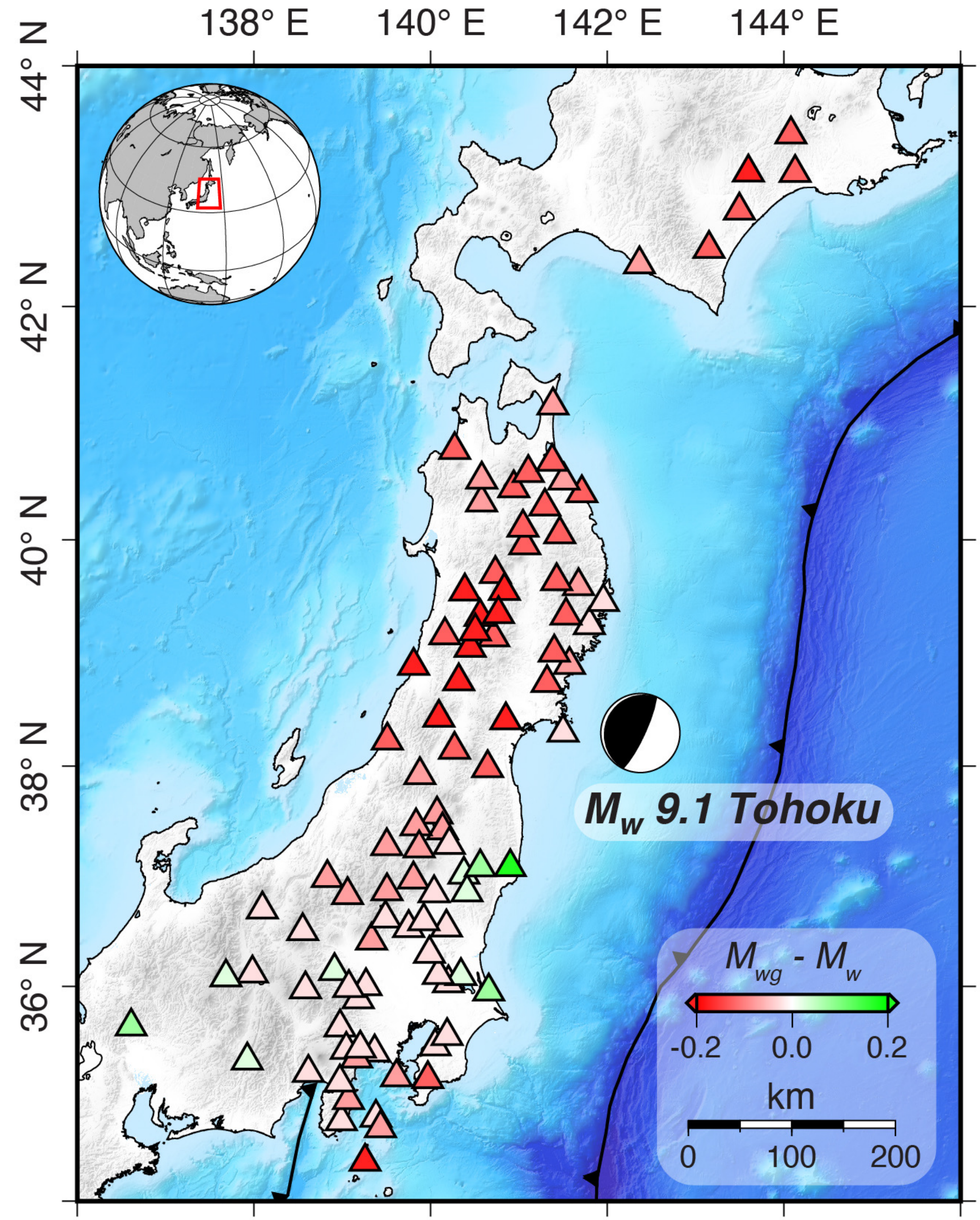
Seismogeodetic displacements & derived moment function during the 2011 M_w 9.1 Tohoku earthquake



Golriz et al., 2023



- GNSS/GPS data provide direct measurements of surface displacement
- Fast & accurate, M_w 1-3 mins. after rupture initiation
- No saturation, can handle earthquakes with complex source time functions
- Working to incorporate in TWC operations…stay tuned



Golriz et al., 2023

Thank You

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