Earthquake Sources

Based on a lecture by James Mori of the Earthquake Hazards Division, Disaster Prevention Research Institute, Kyoto University

U.S. Department of the Interior
U.S. Geological Survey

Theoretical Seismology 1: Sources

- What is the Earthquake Source?
  Elastic Rebound
  Fault Slip ⇔ Double-couple Force

- Seismic Moment Tensor

- Models of Earthquake Faults

- Earthquake Size
  Magnitudes
  Seismic Moment
  Energy

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What is an Earthquake ?

The Source

Fault mechanisms

The Shaking

Wave propagation

Structures

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What is the cause of Earthquakes ?

- Associated with faults (source or cause?)
- Associated with magma?

(Most) Earthquakes are fault movements

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Comparing an earthquake to the breaking of a chopstick

- Failure
- Build-up of stress (strain energy)
- Difficult to predict time and place
- Breaks at weakest point
- Hear precursors
- Sound of breaking same as seismic waves

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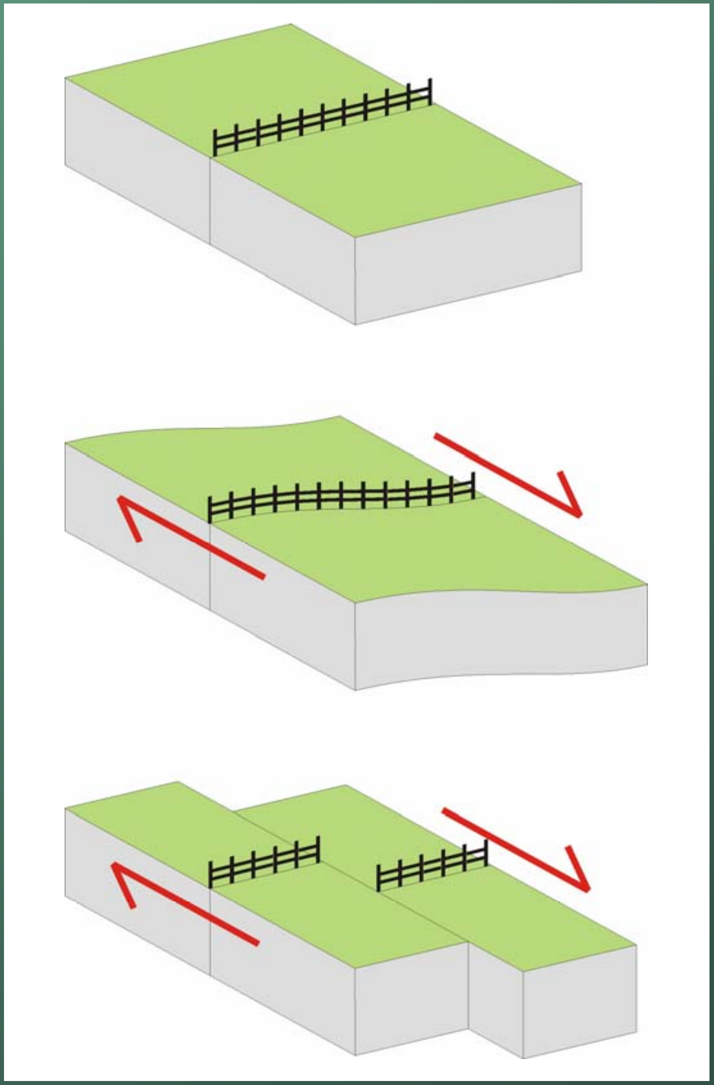
Elastic Rebound Theory

Reid (1910)

8.5 feet offset in San Andreas fault from 1906 earthquake. Marin County



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San Francisco Earthquake
April 18, 1906

Mw 7.7-7.9
470 km rupture of
San Andreas fault

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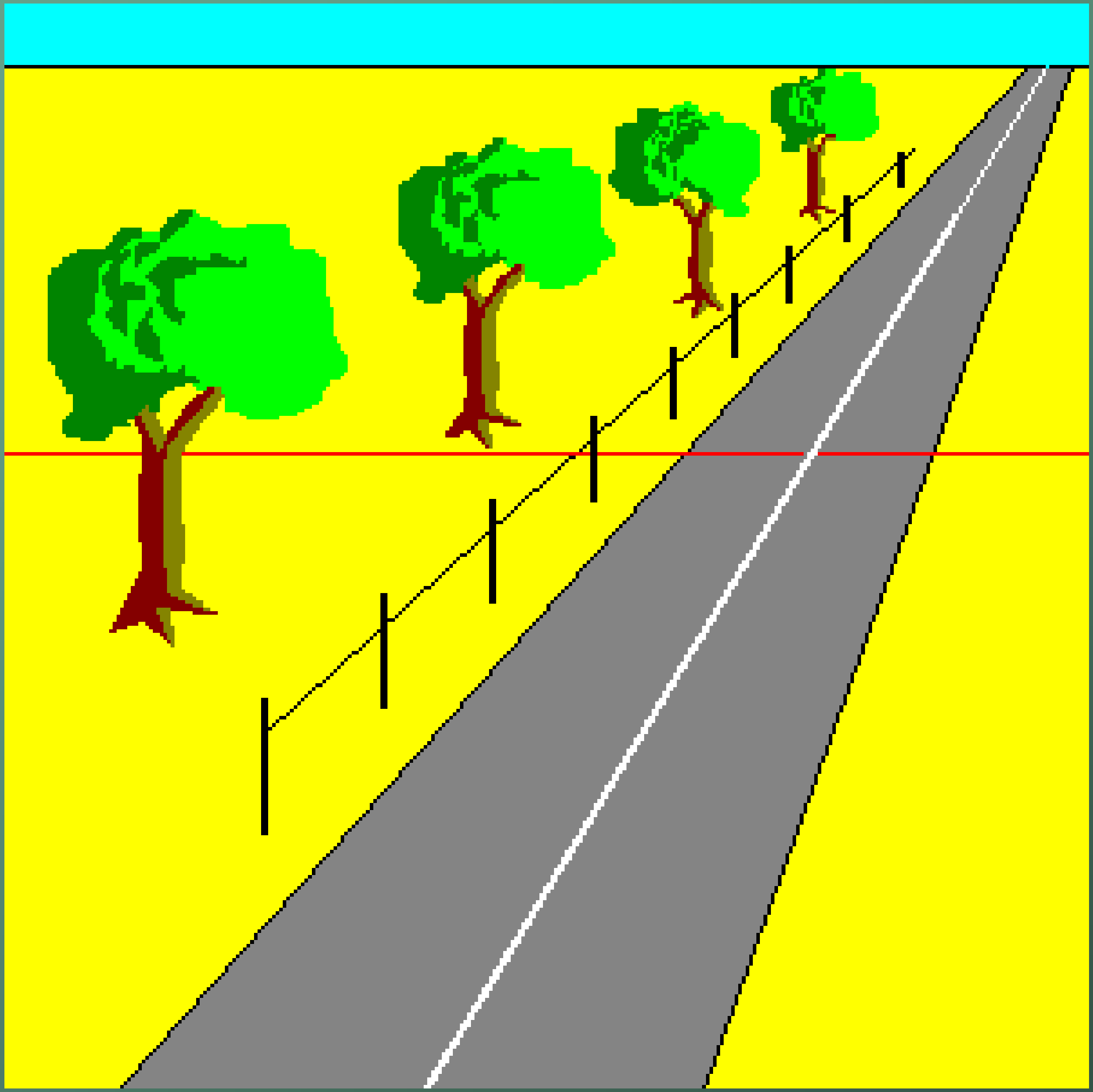
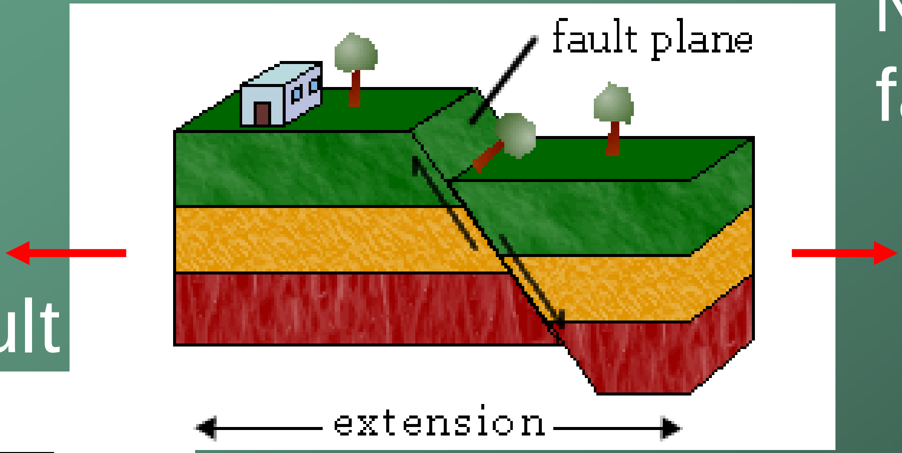


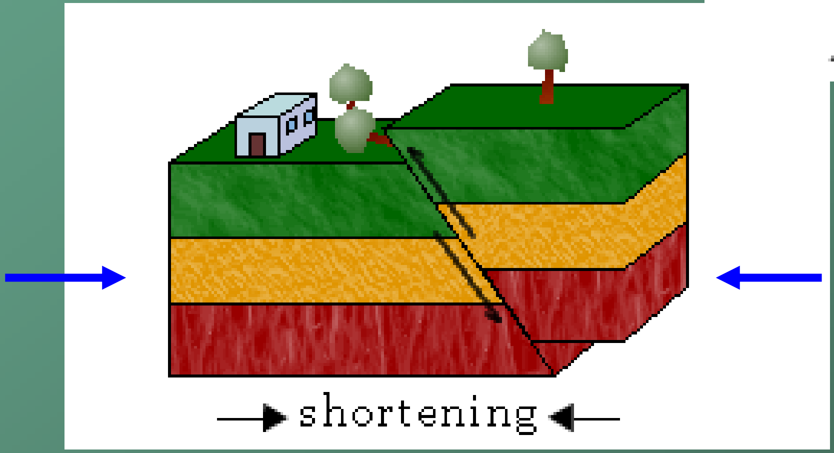
www.uwgb.edu/DutchS/EarthSC202Notes/quakes.htm

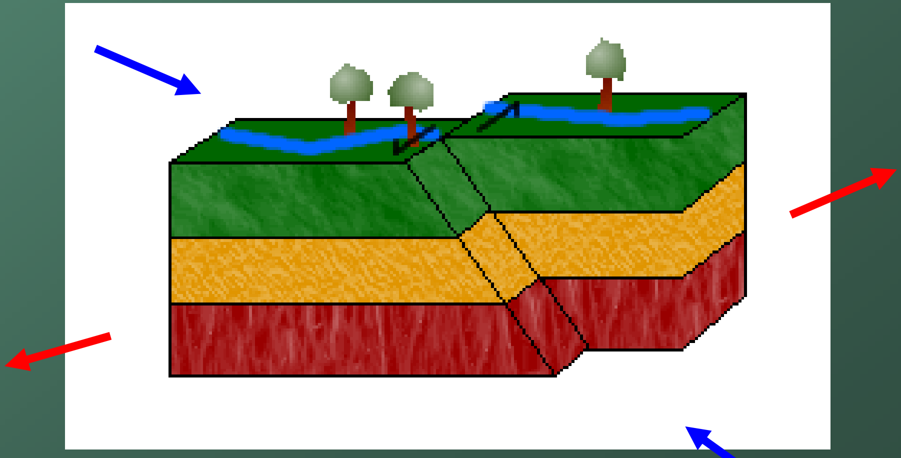
Types of faults

Normal fault



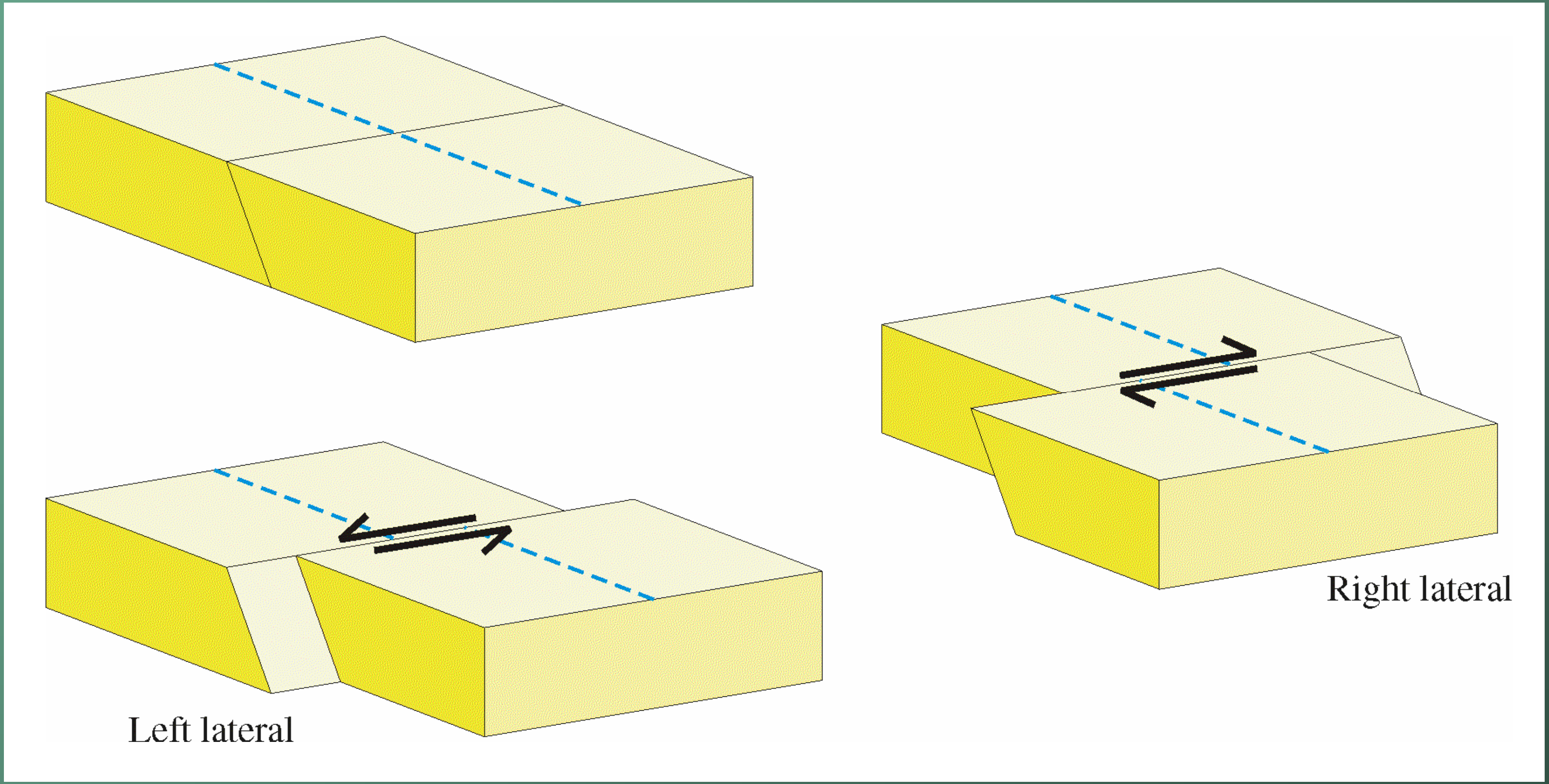
Thrust (Reverse) fault



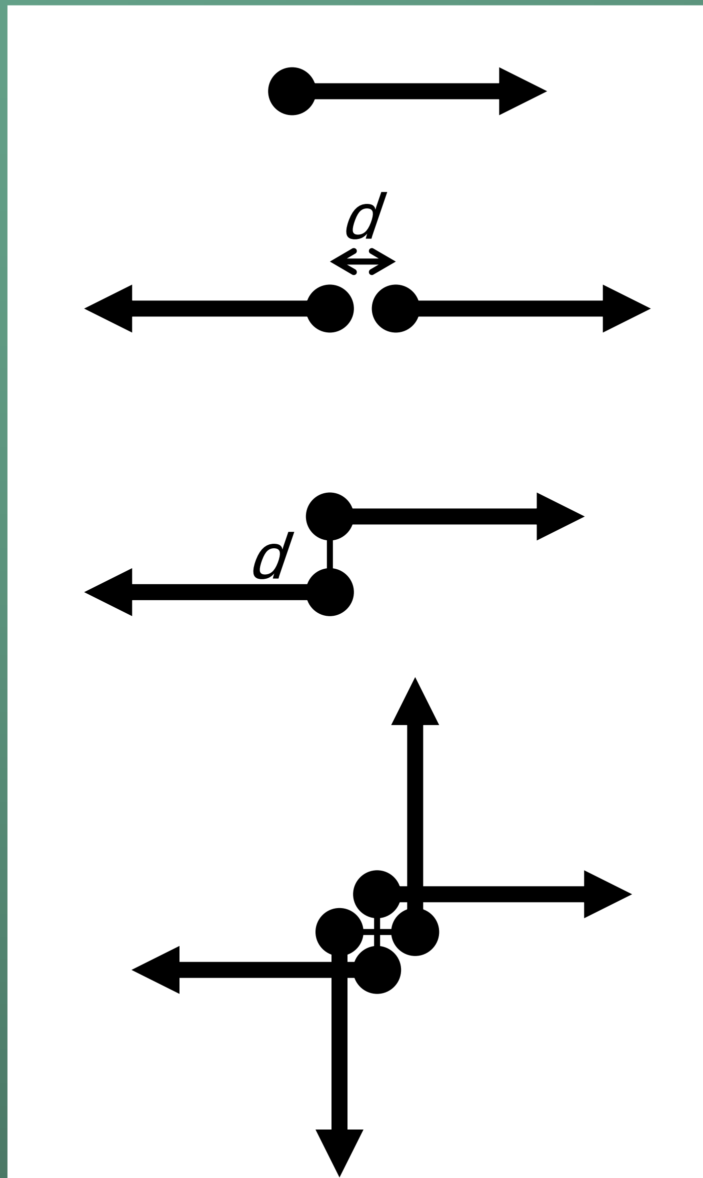


Strike-slip fault

Images courtesy of IRIS


Left lateral
Right lateral

Equivalent Body Forces



Single Force

Dipole

Couple
(Single Couple)

Double Couple

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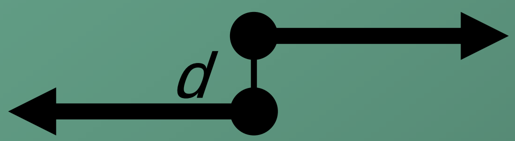
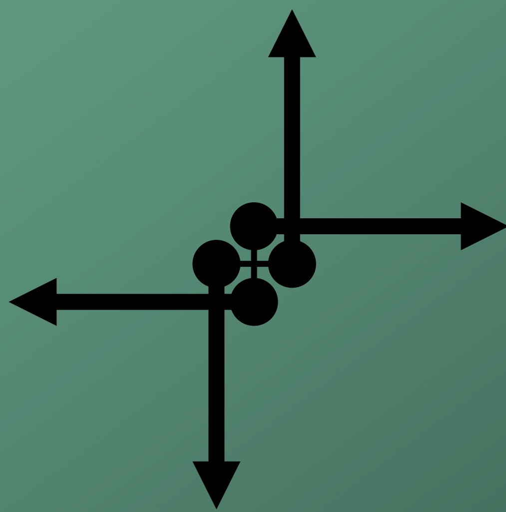
Single Couple versus Double Couple

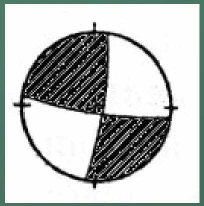


Single Couple



Double Couple

- P polarity pattern same
- S polarity pattern different
- Single Couple ‘resembles’ fault slip



Controversy settled by Maruyama (1963)

Showed that Double Couple was equivalent to fault slip

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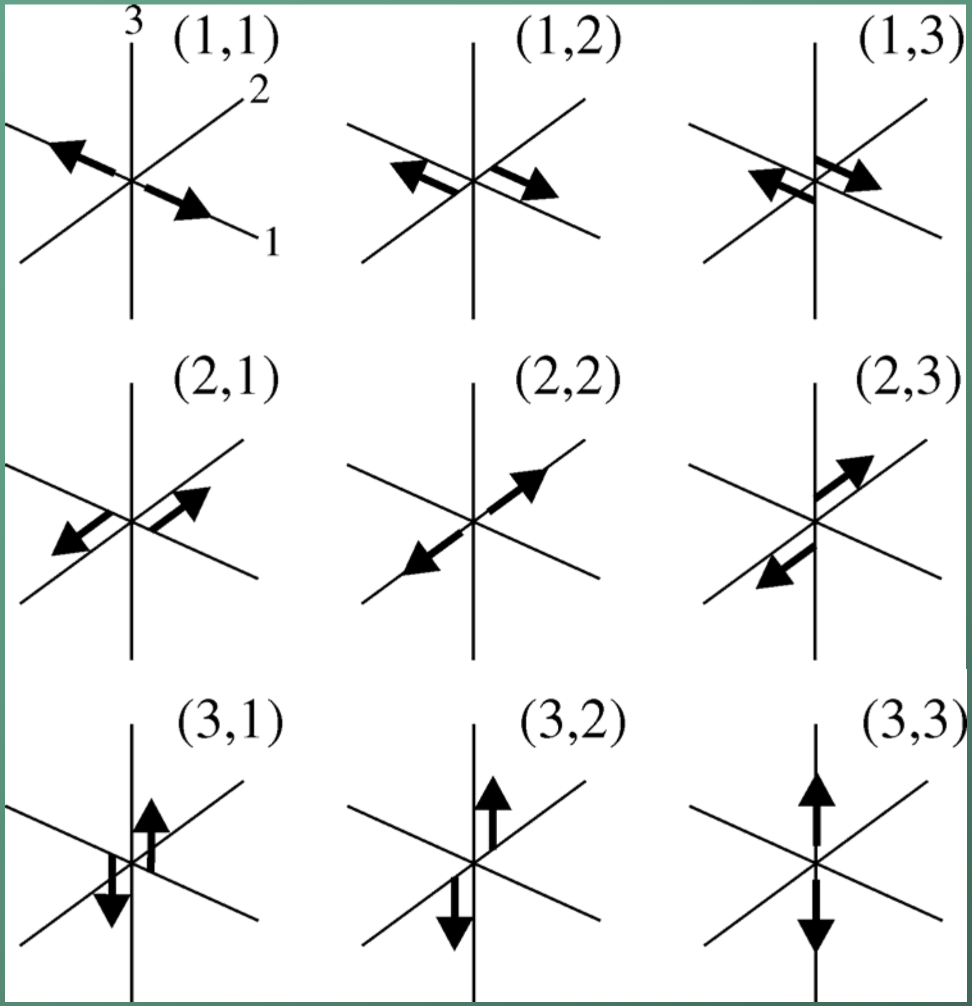
Moment tensor: dipoles and couples



$$M_{pq}(t) = \int_V \eta_q f_p(\boldsymbol{\eta}, t)\, dV(\boldsymbol{\eta})$$

9 components, but symmetric matrix so 6 are independent

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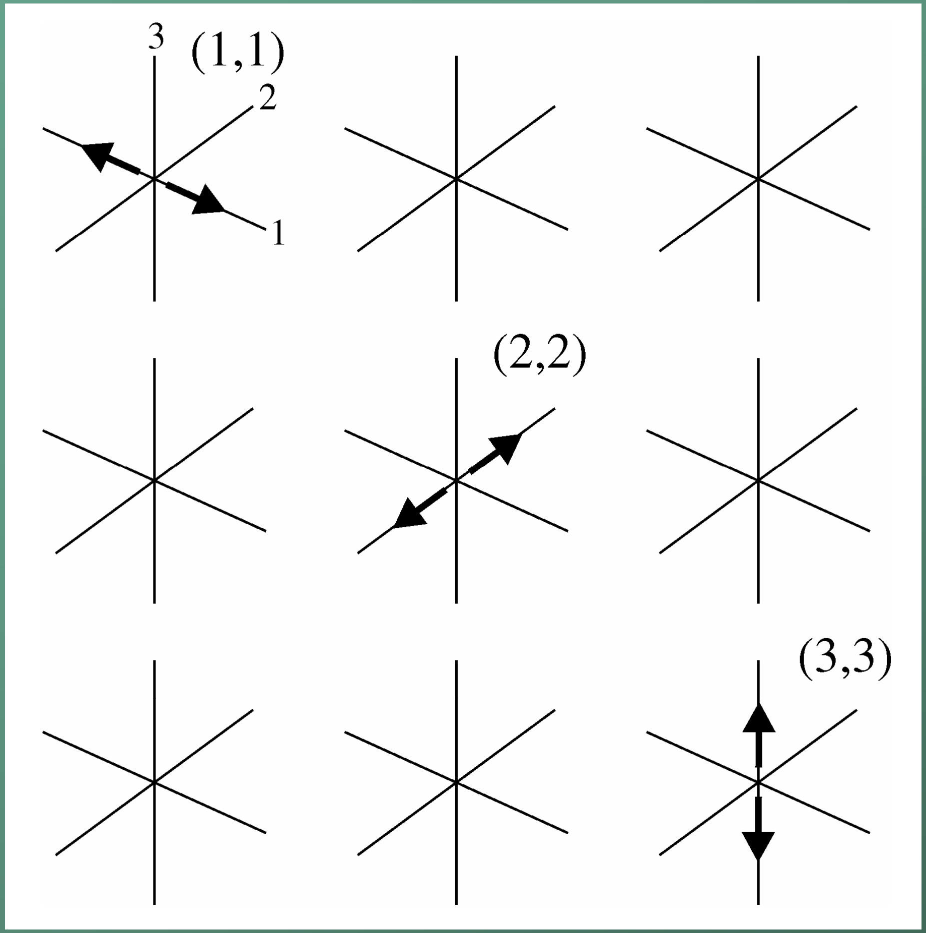
Moment Tensor for an Explosion



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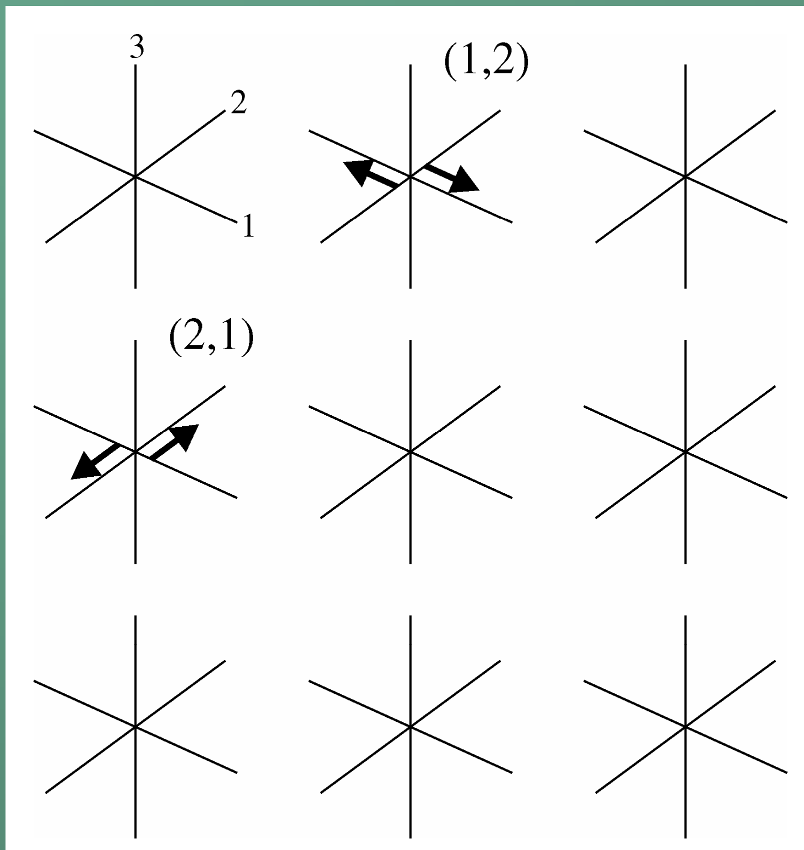
$$M_{11} = M_{22} = M_{33}$$

$$M_{12} = M_{21} = M_{13} = M_{31} = M_{23} = M_{32} = 0$$

Moment Tensor for Fault Slip



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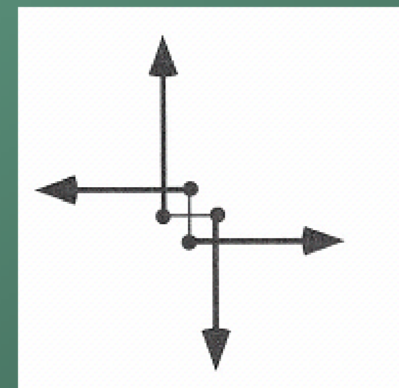

Double Couple
Fault - Slip

$$M_{12} = M_{21}$$

$$M_{11} = M_{22} = M_{33} = M_{23} = M_{23} = M_{13} = M_{31} = 0$$

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1979 Imperial Valley, California (M=6.5)

Photo by D. Cavit, USGS

Harvard/NEIC Moment Tensor Solutions

```
This is a REVISED solution for today's earthquake near Sumatra.
The solution includes approximately the first 9 hours of data
recorded after the earthquake. Owing to the large size of the
earthquake, the short-period cutoff for the analysis was set
to 300 s.

December 26, 2004, OFF W COAST OF NORTHERN SUMATRA, MW=9.0

Meredith Nettles
Goran Ekstrom

CENTROID, MOMENT TENSOR SOLUTION
HARVARD EVENT-FILE NAME M122604A
DATA USED: GSN
MANTLE WAVES:    73S,202C, T=300
CENTROID LOCATION:
ORIGIN TIME       01:01: 9.0 0.3
LAT  3.09N 0.04;LON  94.26E 0.03
DEP  28.6 1.3;HALF-DURATION 95.0
MOMENT TENSOR; SCALE 10**29 D-CM
  MRR= 1.04 0.01; MTT=-0.43 0.01
  MPP=-0.61 0.01; MRT= 2.98 0.16
  MRP=-2.40 0.16; MTP= 0.43 0.00
 PRINCIPAL AXES:
 1.(T) VAL=  4.01;PLG=52;AZM= 36
 2.(N)      -0.12;     3;    130
 3.(P)      -3.89;    38;    222
BEST DOUBLE COUPLE:M0=4.0*10**29
 NP1:STRIKE=329;DIP= 8;SLIP= 110
 NP2:STRIKE=129;DIP=83;SLIP=  87
```

```
           -#######---
       #################--
     #####################--
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  ----#############   #######--
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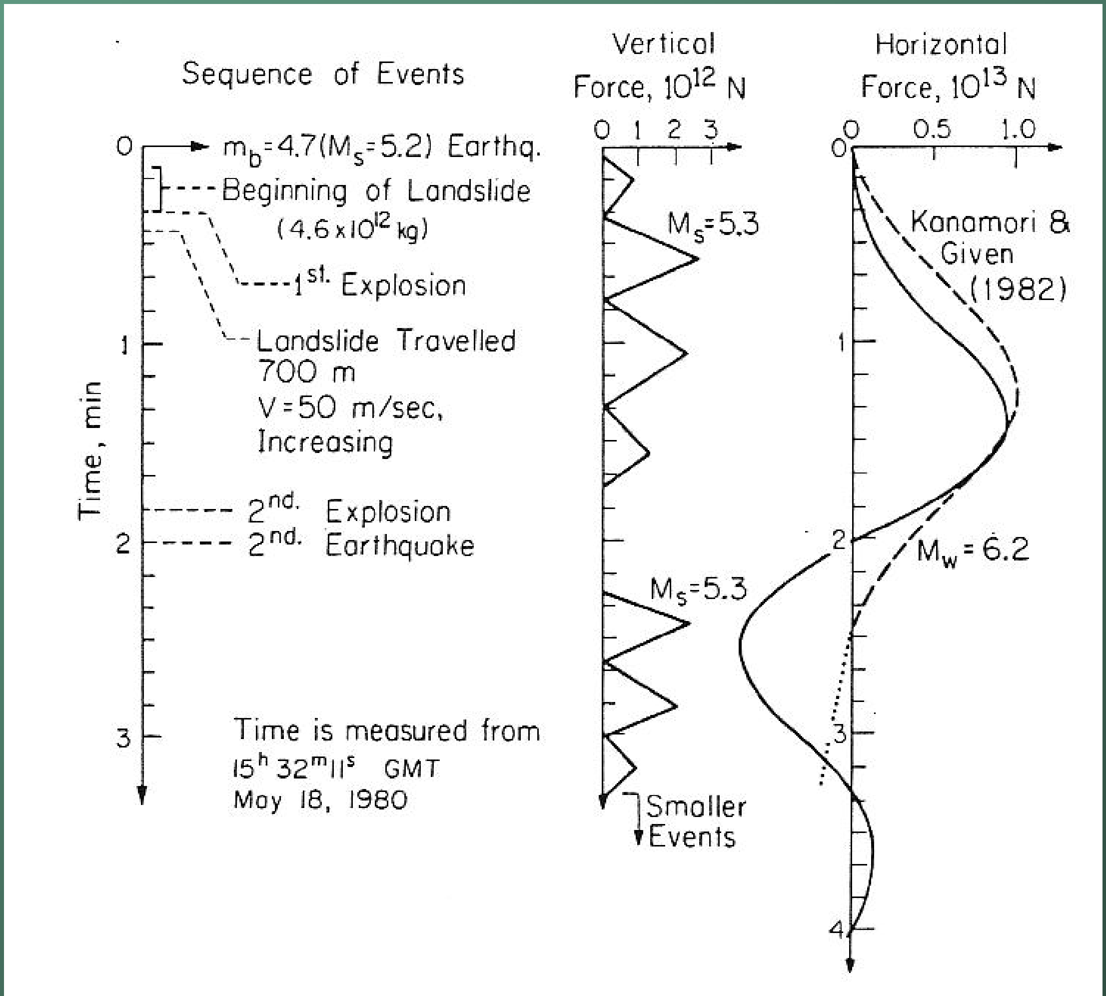
Single-force earthquakes
volcanic eruptions and landslides

Mount St. Helens, USA
Before and after eruption
Photos by Harry Glicken, USGS



Kanamori et al. *Journal of Geophysical Research, v. 89,* p. 1856-1866 1984

Circular Crack – Sato and Hirasawa, 1973

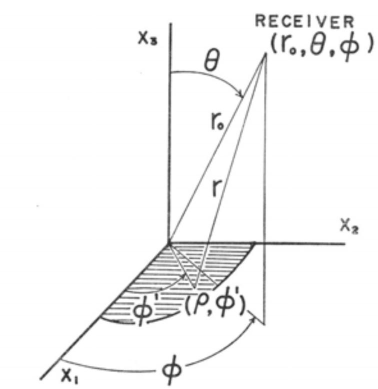
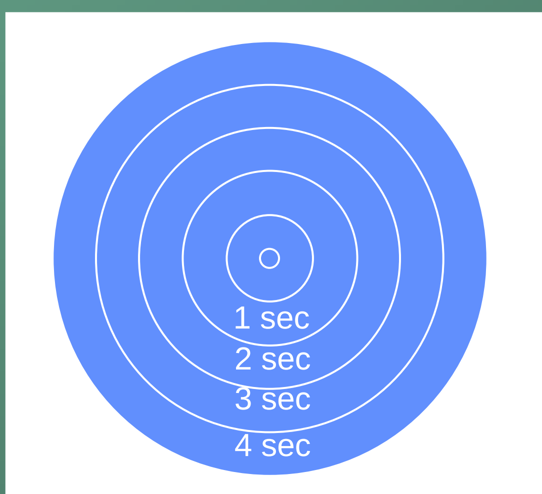


Fig. 2. Coordinate system used. Shaded area in the x_1-x_2 plane represents fault surface.



T. SATO and T. HIRASAWA

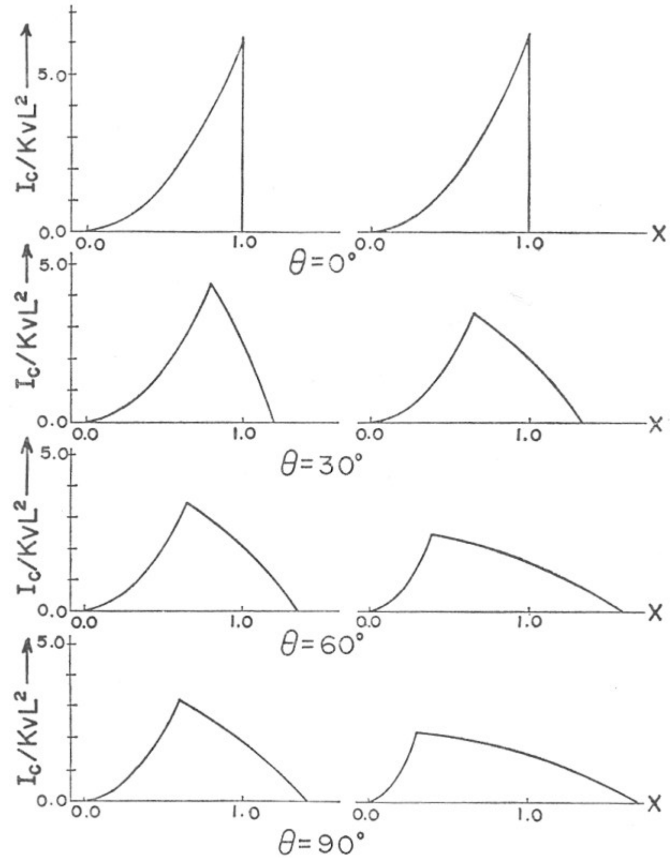
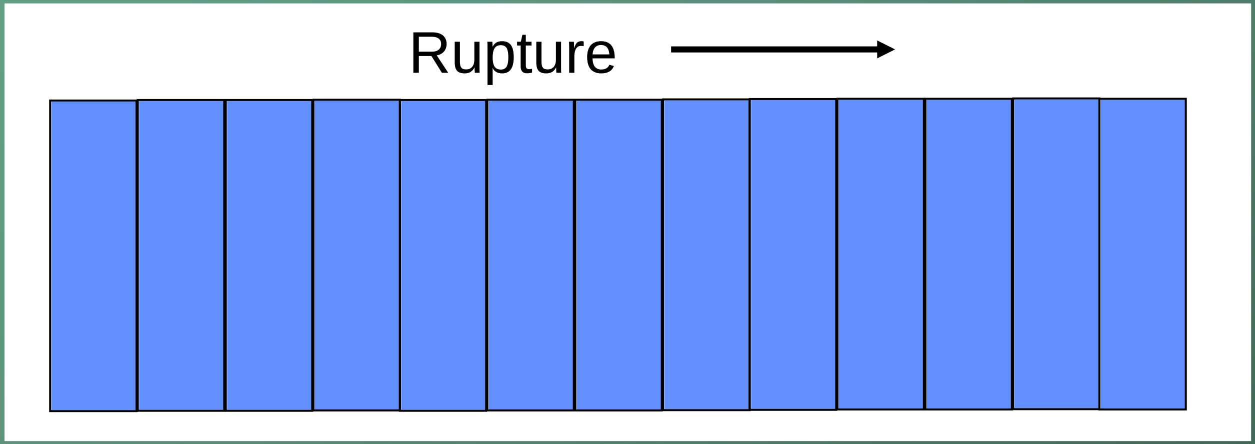


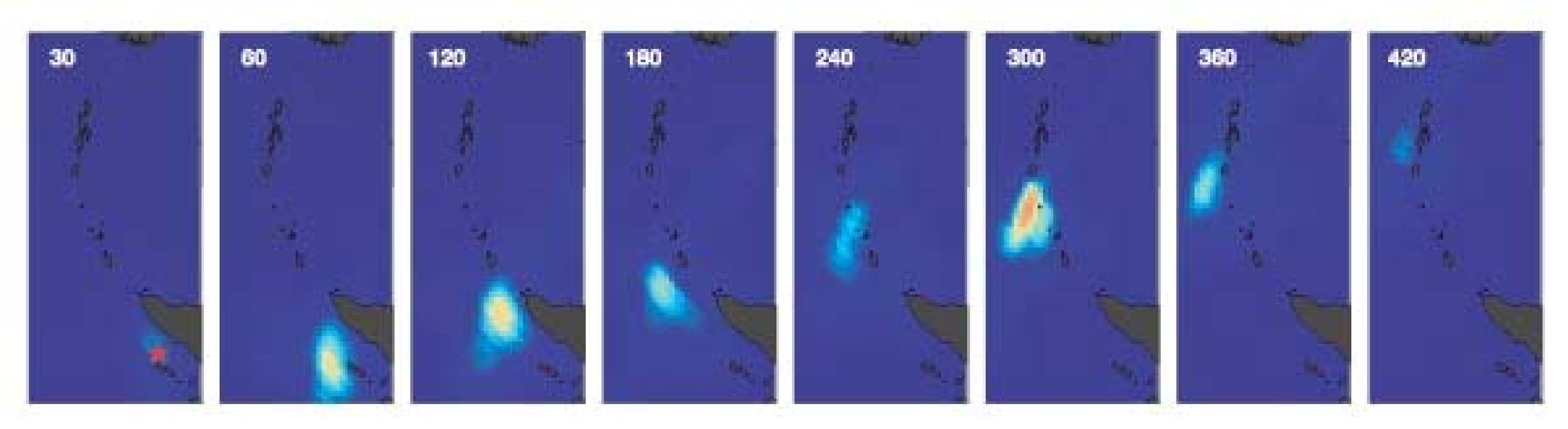
Fig. 3. The far-field displacement as a function of time radiated from the present model. The figures in the left column represent the P waves and those in the right column the S waves. The time, L/v, required for rupture to travel from the center to the edge of the fault surface is chosen as a unit of time. This is for the case $v/\beta=0.7$.

Sato, Y., and Y. Hirasawa (1973). Body wave spectra from propagating shear cracks, *J. Phys. Earth* **21,** 415–431

Haskell Line Source
Dislocation Source



Sumatra earthquake, Dec 28, 2004



Ishii et al., Nature 2005 doi:10.1038/nature03675

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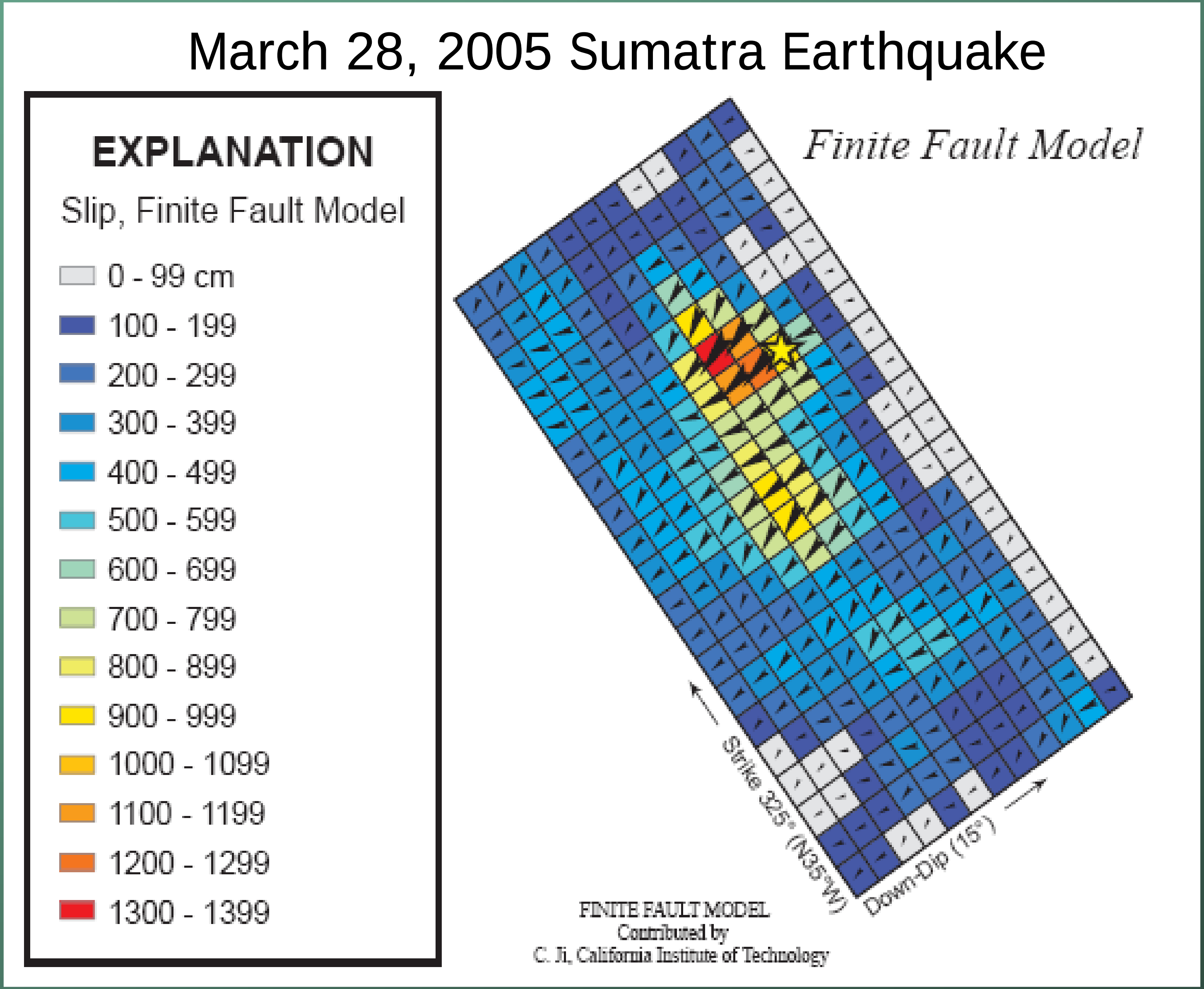
Complicated Slip Distributions



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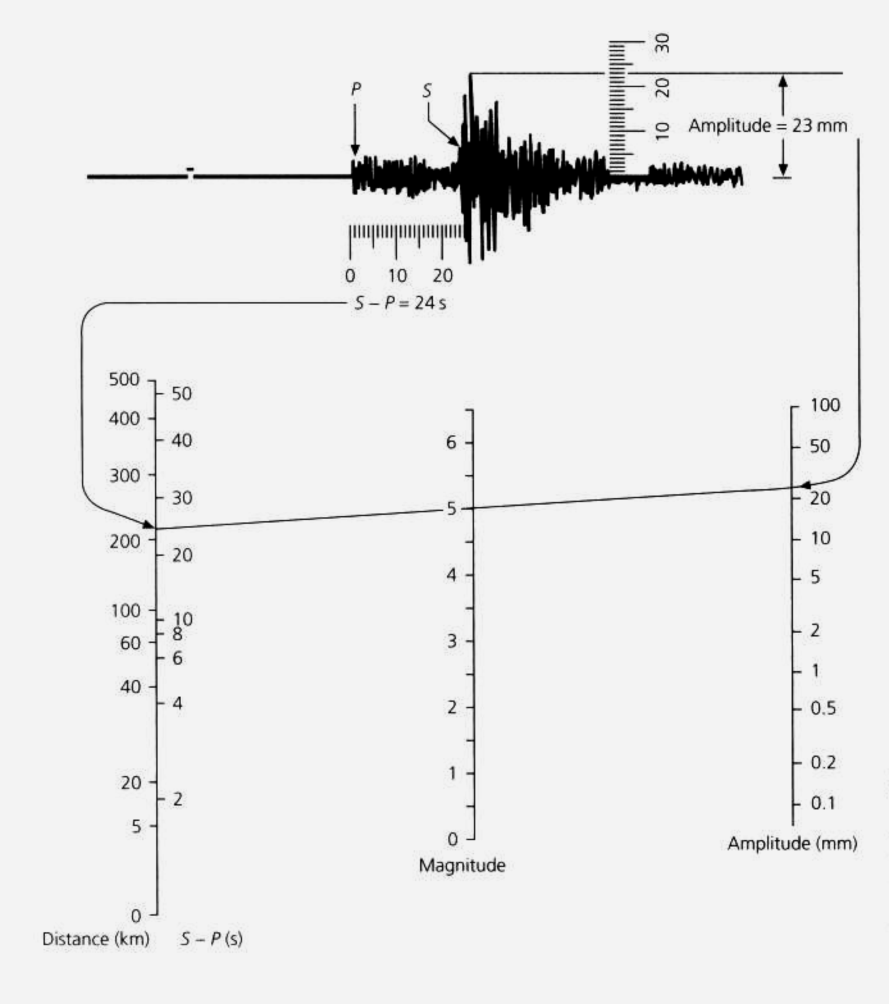
Earthquake Size – Magnitude

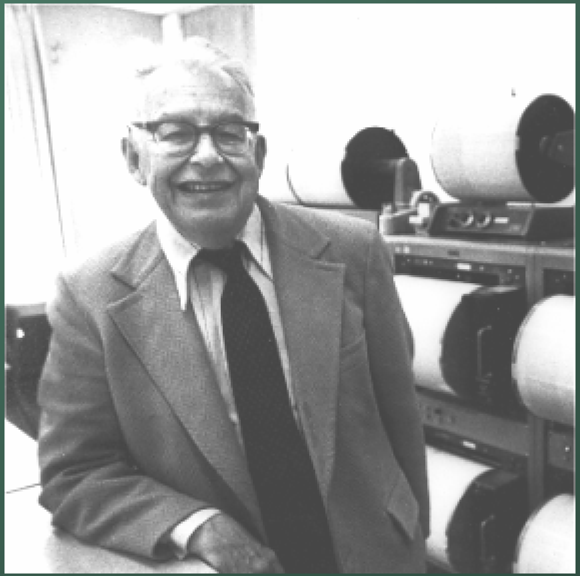


log of amplitude

Distance correction

$$M = \log A - \log A_0$$

Charles Richter
1900-1985



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Bruce Bolt. Earthquakes.
WH Freeman and Company

Types of Magnitude Scales

			Period Range
M_L	Local magnitude (California)	regional S and surface waves	0.1-1 sec
M_j	JMA (Japan Meteorol. Agency)	regional S and 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

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Relationship between different types of magnitudes

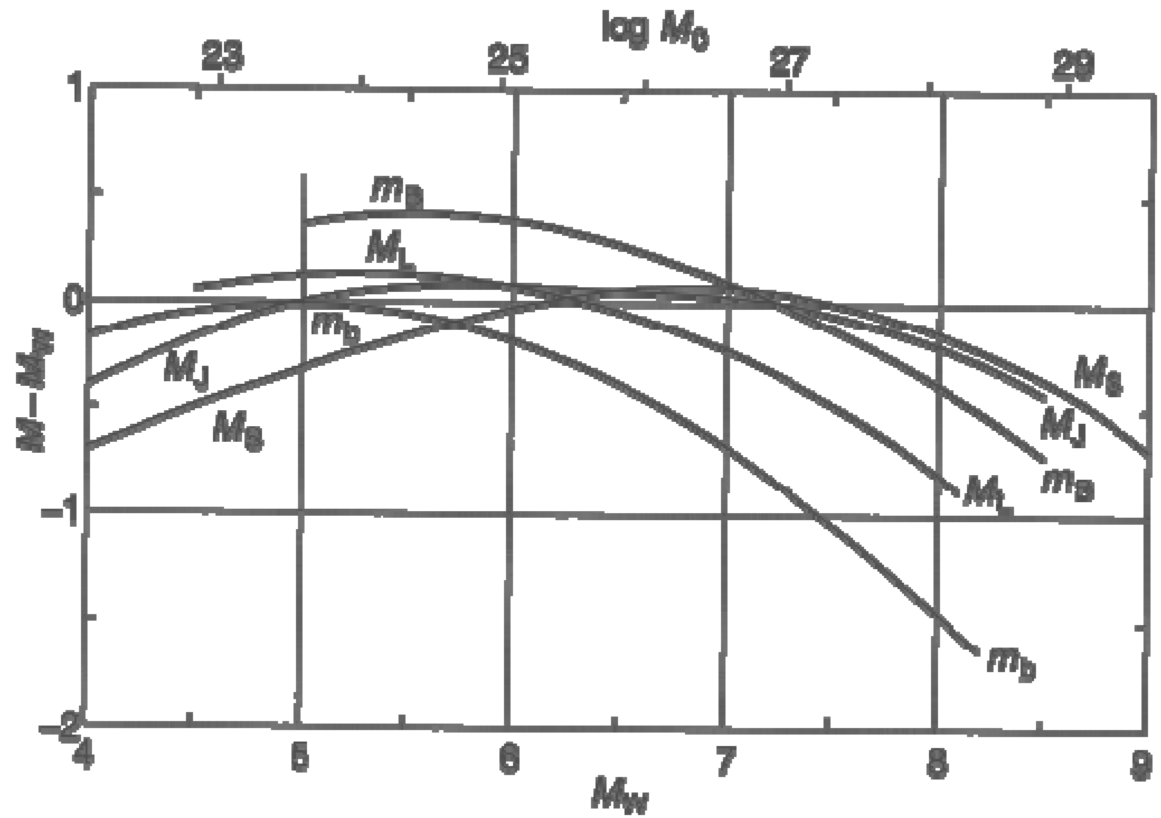

FIGURE 1 Curves for the average magnitude differences. Variations of M_S–M_W, m_B–M_W, m_b–M_W, M_L–M_W, and M_J–M_W with M_W (or log M_0) are shown.

From Chapter 44, International Handbook of Earthquake & Engineering Geoscience

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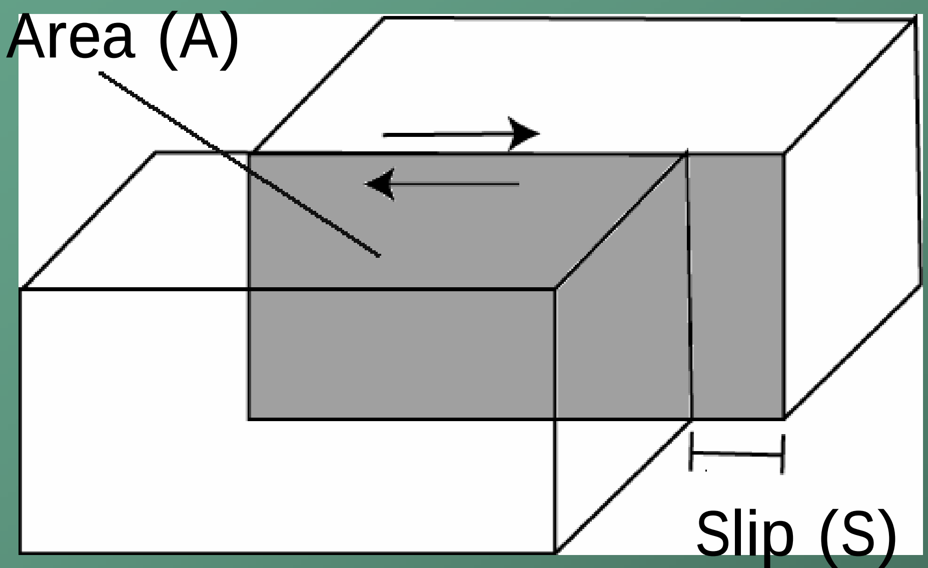
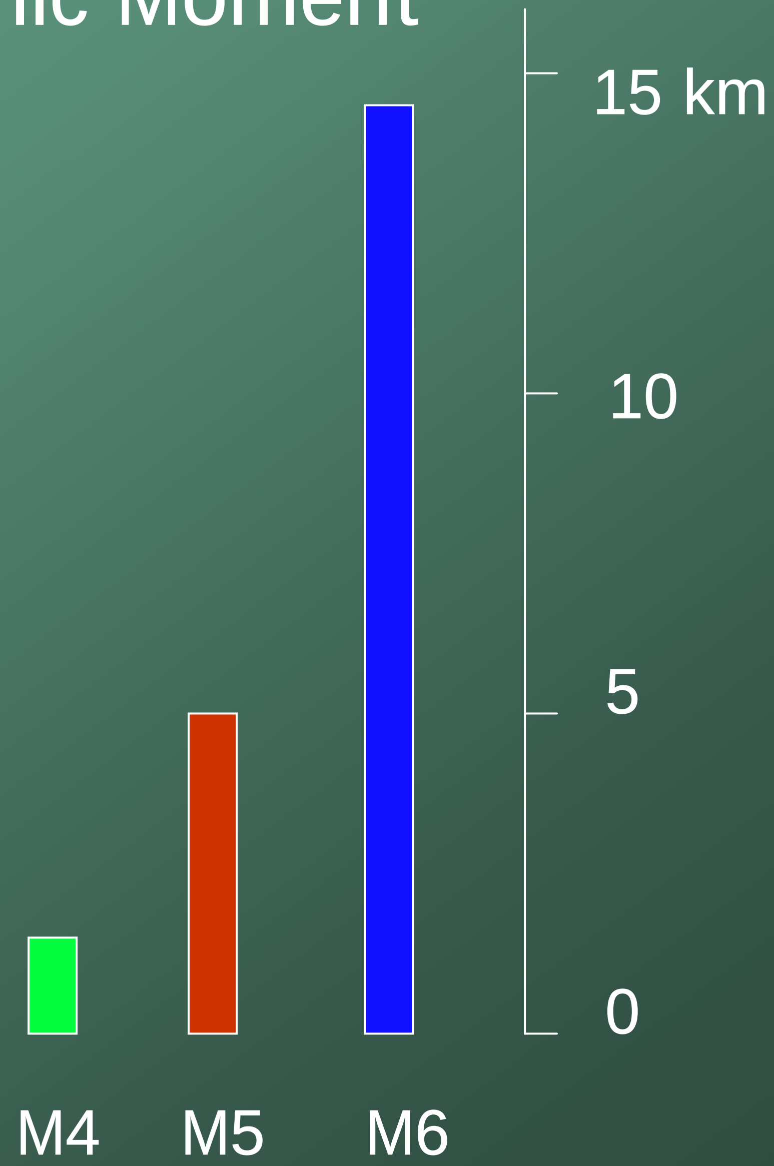
Earthquake size - Seismic Moment



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

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



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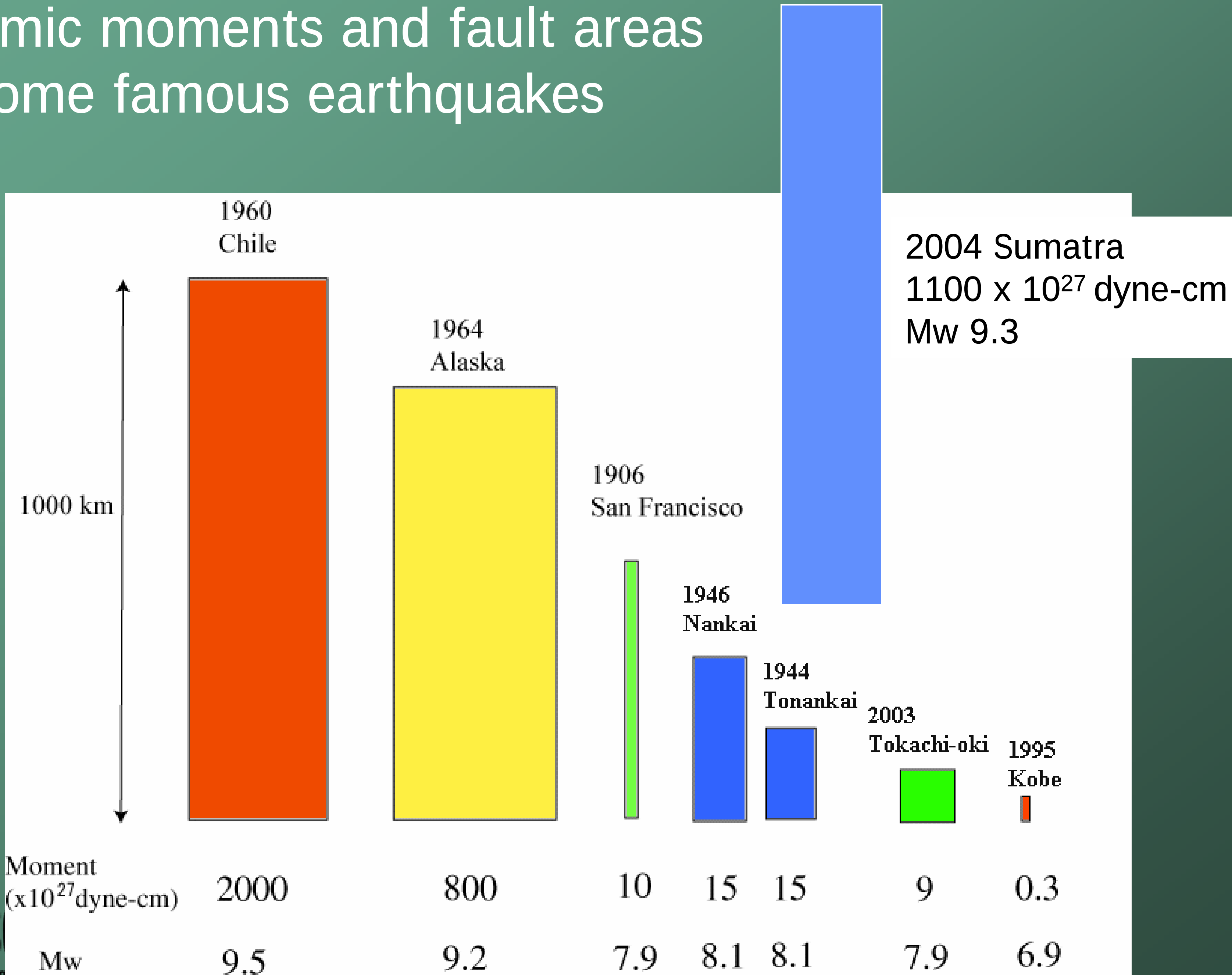
Seismic moments and fault areas of some famous earthquakes



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Magnitudes for Tsunami Warnings

- Want to know the moment (fault area and size) but takes a long time (hours) to collect surface wave or free oscillation data

- Magnitude from P waves (mb) is fast but underestimates moment

  ⇒ If have time (hours), determine M_m from mantle waves

⇒ For quick magnitude (seconds to minutes), determine M_{wp} from P waves

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M_m Mantle Magnitude

Source Correction

$$M_m = \log_{10}(X(\omega)) + Cd + Cs - 3.9$$

Distance Correction

Spectral Amplitude

- amplitude measured in frequency domain
- surface waves with periods > 200 sec

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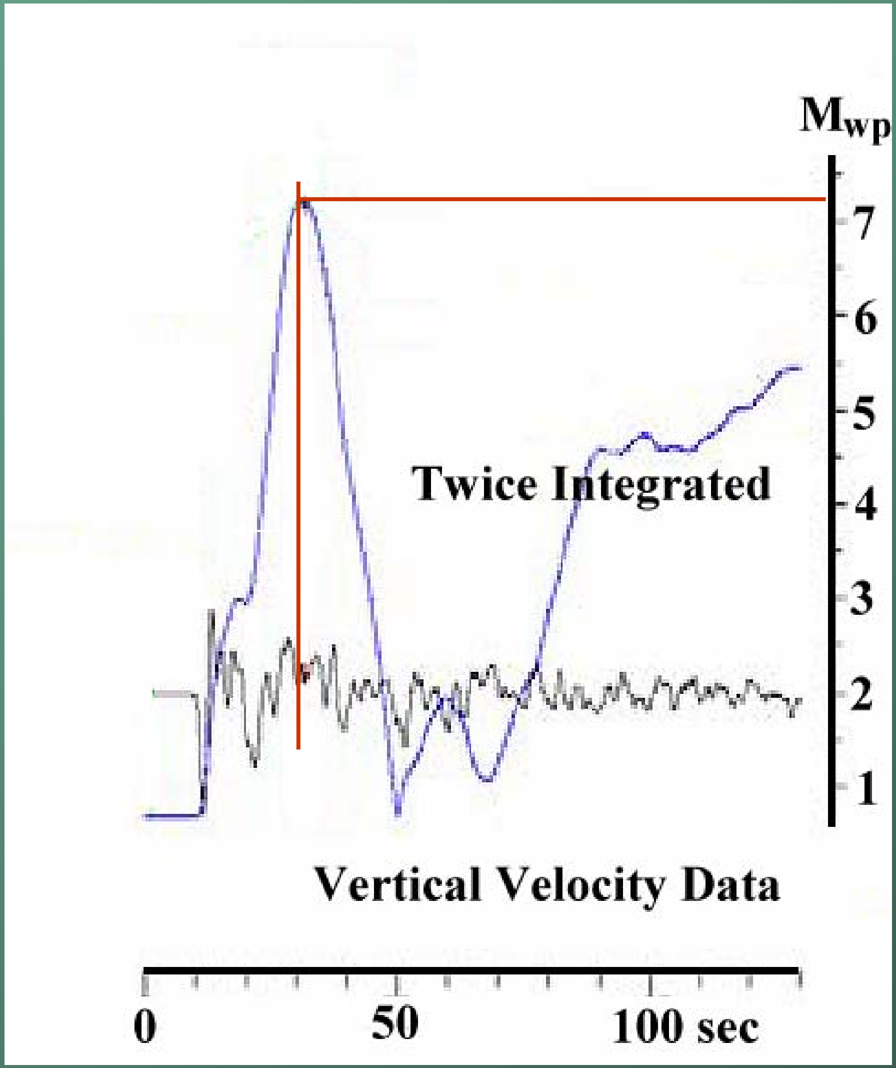
M_{wp} P-wave moment magnitude



$$\int u_z(t)dt \propto M_o$$

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M_{wp} P-wave moment magnitude

$$M_o = \text{Max}\ \left|\int u_z(t)dt\right|\ 4\pi\rho\alpha^3 r/F^p$$

$$M_w = (\log_{10} M_o)/1.5 - 10.73$$

- Quick magnitude from P wave
- Uses relatively long-period body waves (10-60 sec)
- Some problems for M>8.0

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Magnitudes for the Sumatra Earthquake

m_b	7.0	1 sec P wave	131 stations
m_{blg}	6.7	1 sec Lg waves	6 stations
M_{wp}	8.0 – 8.5	60 sec P waves	
M_s	8.5 - 8.8	20 sec surface waves	118 stations
M_w	8.9 - 9.0	300 sec surface waves	
M_w	9.1 - 9.3	3000 sec free oscillations	

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Number of Earthquakes Worldwide for 2000 - 2006 Located by the US Geological Survey National Earthquake Information Center							
Magnitude	2000	2001	2002	2003	2004	2005	2006
8.0 to 9.9	1	1	0	1	2	1	0
7.0 to 7.9	14	15	13	14	14	10	4
6.0 to 6.9	158	126	130	140	141	150	21
5.0 to 5.9	1345	1243	1218	1203	1515	1720	239
4.0 to 4.9	8045	8084	8584	8462	10888	13897	1834
3.0 to 3.9	4784	6151	7005	7624	7932	9151	1202
2.0 to 2.9	3758	4162	6419	7727	6316	4639	502
1.0 to 1.9	1026	944	1137	2506	1344	26	4
0.1 to 0.9	5	1	10	134	103	0	1
No Magnitude	3120	2938	2937	3608	2939	866	120
Total	22256	23534	27454	31419	31194	* 30460	* 3927
Estimated Deaths	231	21357	1685	33819	284010	89354	12

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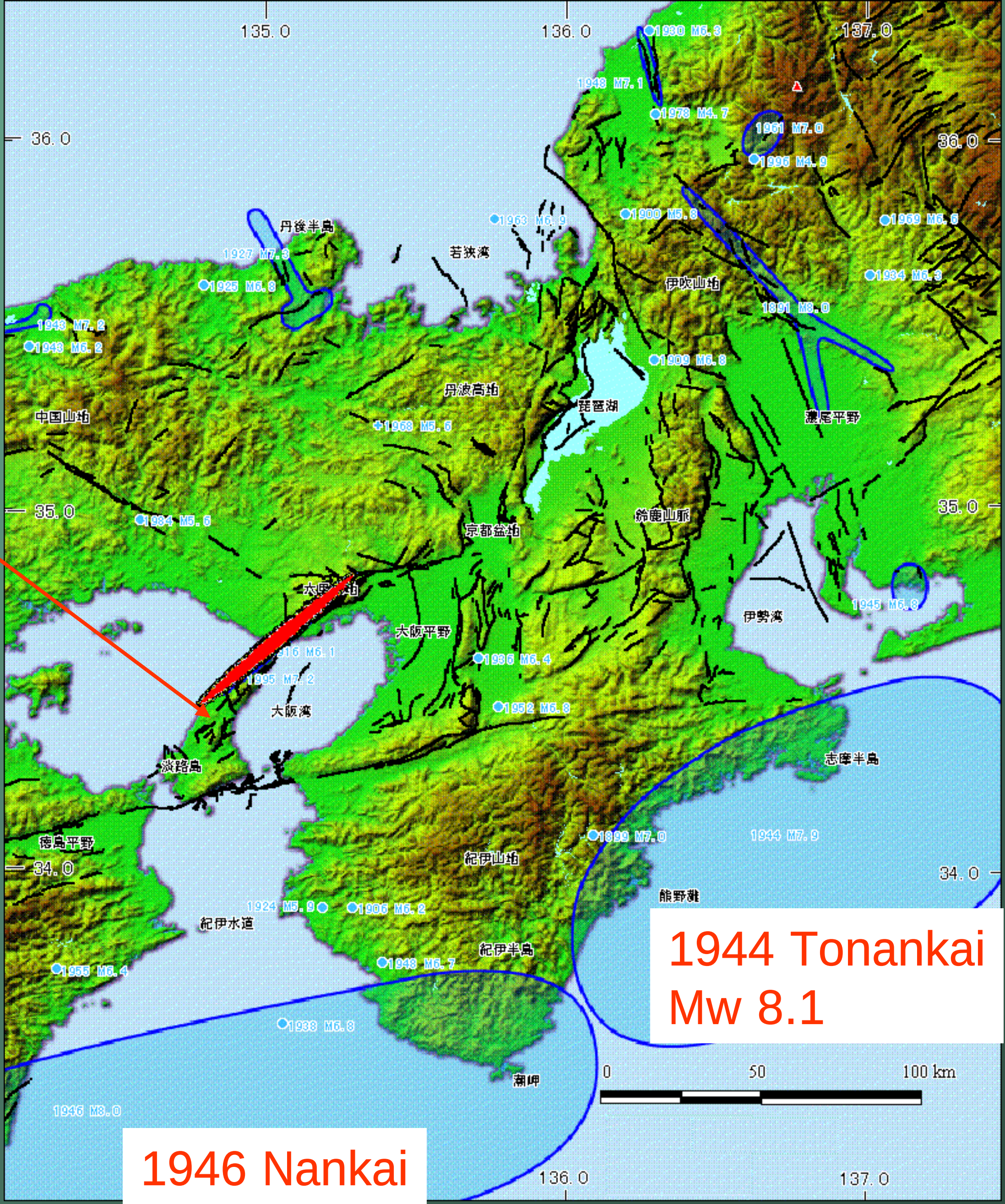
Fault Areas of Damaging Earthquakes

1995 Kobe
Mw 6.9



1944 Tonankai
Mw 8.1

1946 Nankai
Mw 8.1

Deaths	
1944	1000
1946	1330
1995	5502

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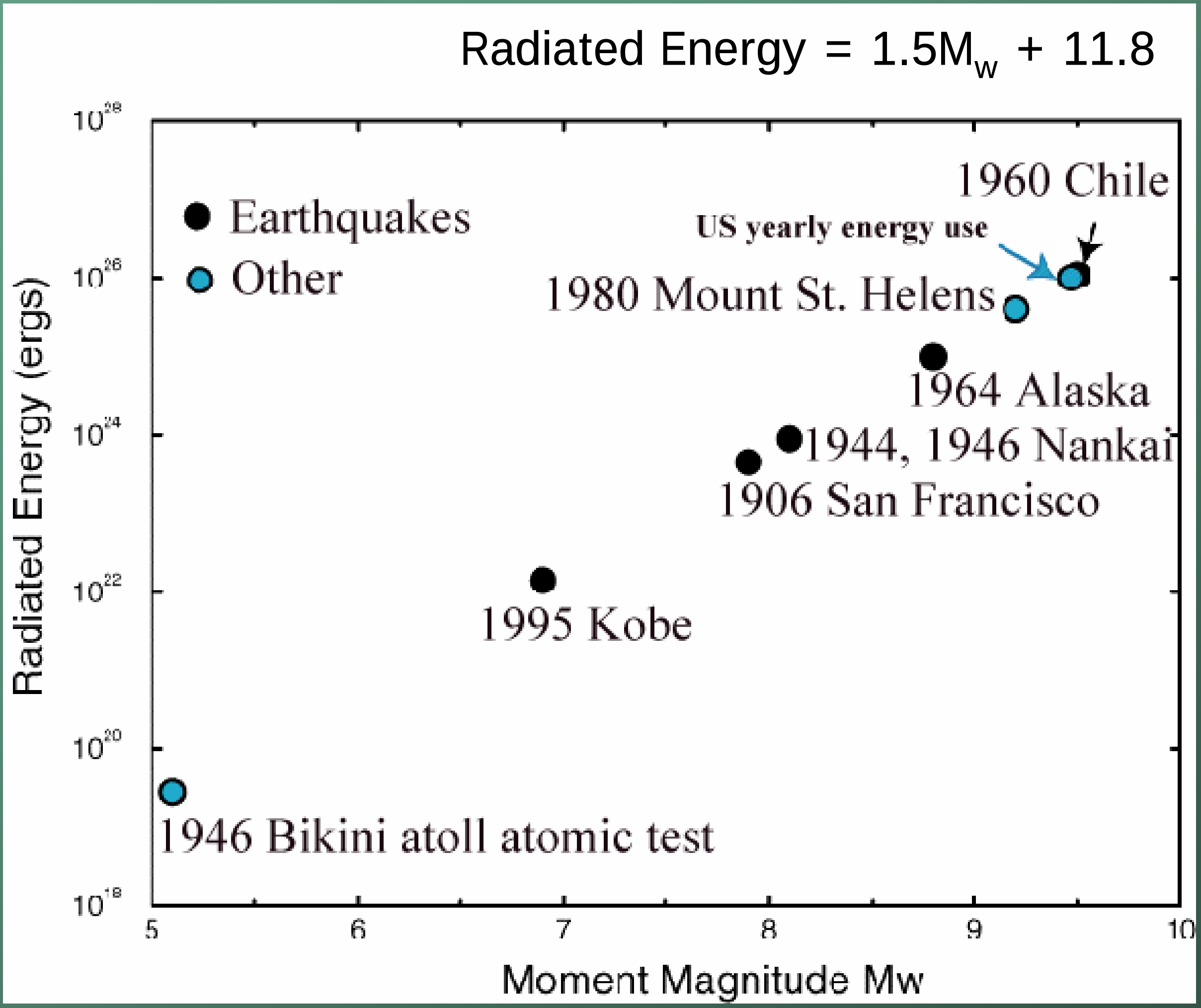
Seismic Radiated Energy



Kanamori, 1977

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Things to Remember

1. Earthquake sources are a double couple force system which is equivalent to Fault Slip

2. The moment tensor describes the Force System for earthquakes and can be used to determine the geometry of the faulting

3. Earthquake ruptures begin from a point (hypocenter) and spread out over the fault plane

4. The size of an earthquakes can be described by magnitudes, moment, and energy. M_m and M_{wp} are types of magnitudes used for tsunami warning systems

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