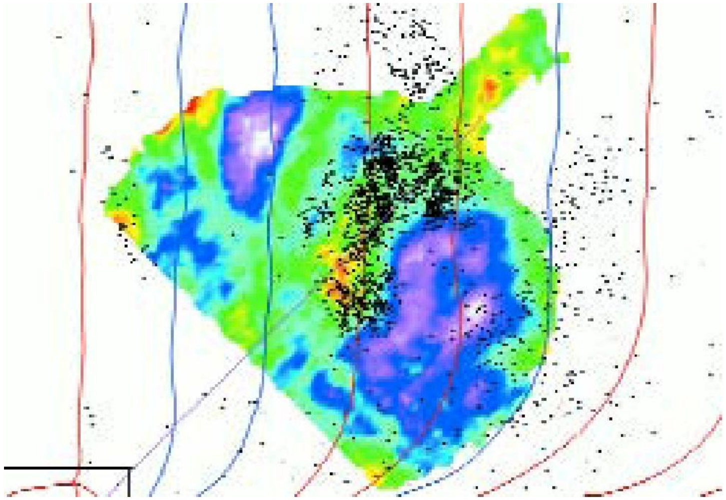
Microseismic focal mechanisms: A tutorial

…beyond dots in a box



McGillivray, 2005

David W. Eaton
Department of Geoscience
University of Calgary

Outline

- Magnitude scales
- Earthquake spectra
- Demystifying beach balls
- Moment tensors
- Stress transfer

Earthquake magnitude

General form:

$$M = \log (A/T^n) + Q(h,\Delta)$$

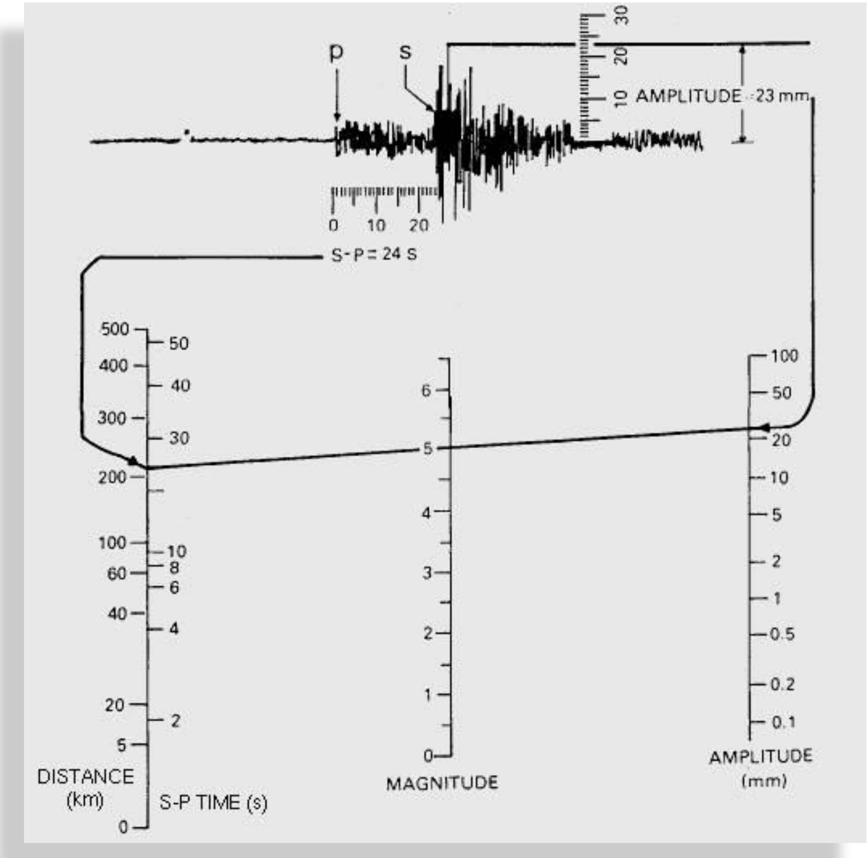
where

A is signal amplitude

T is dominant period

h is focal depth

Δ is distance



Bolt, 1993

Richter magnitude

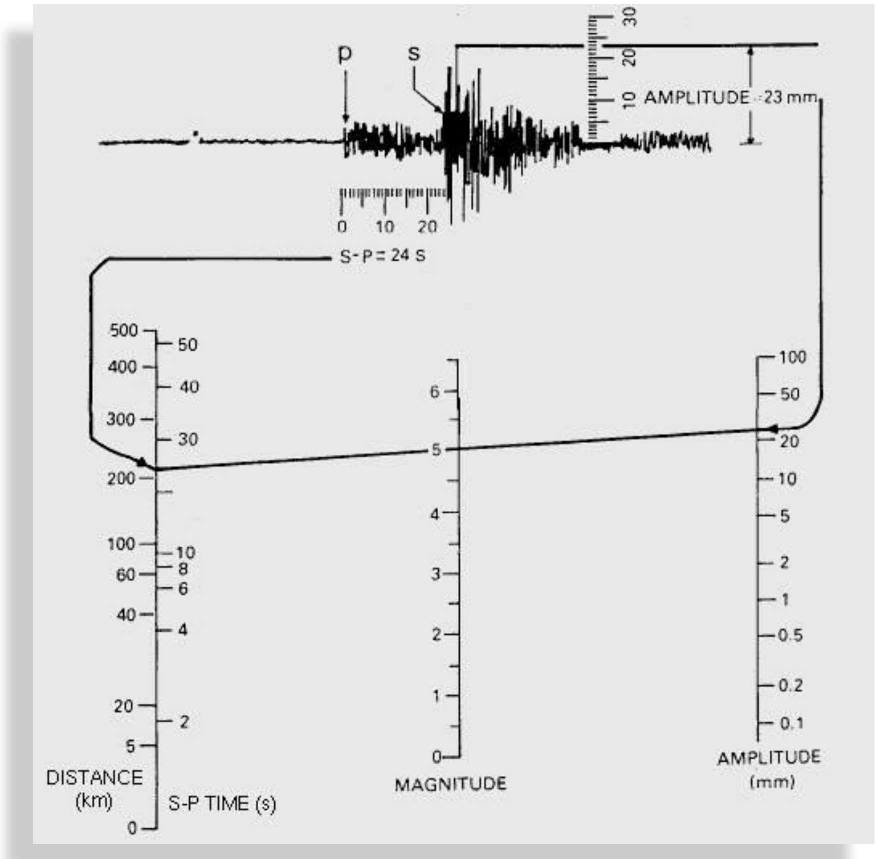
Richter scale (California):

$M_L = \log A + 2.56 \log \Delta - 1.67$

where

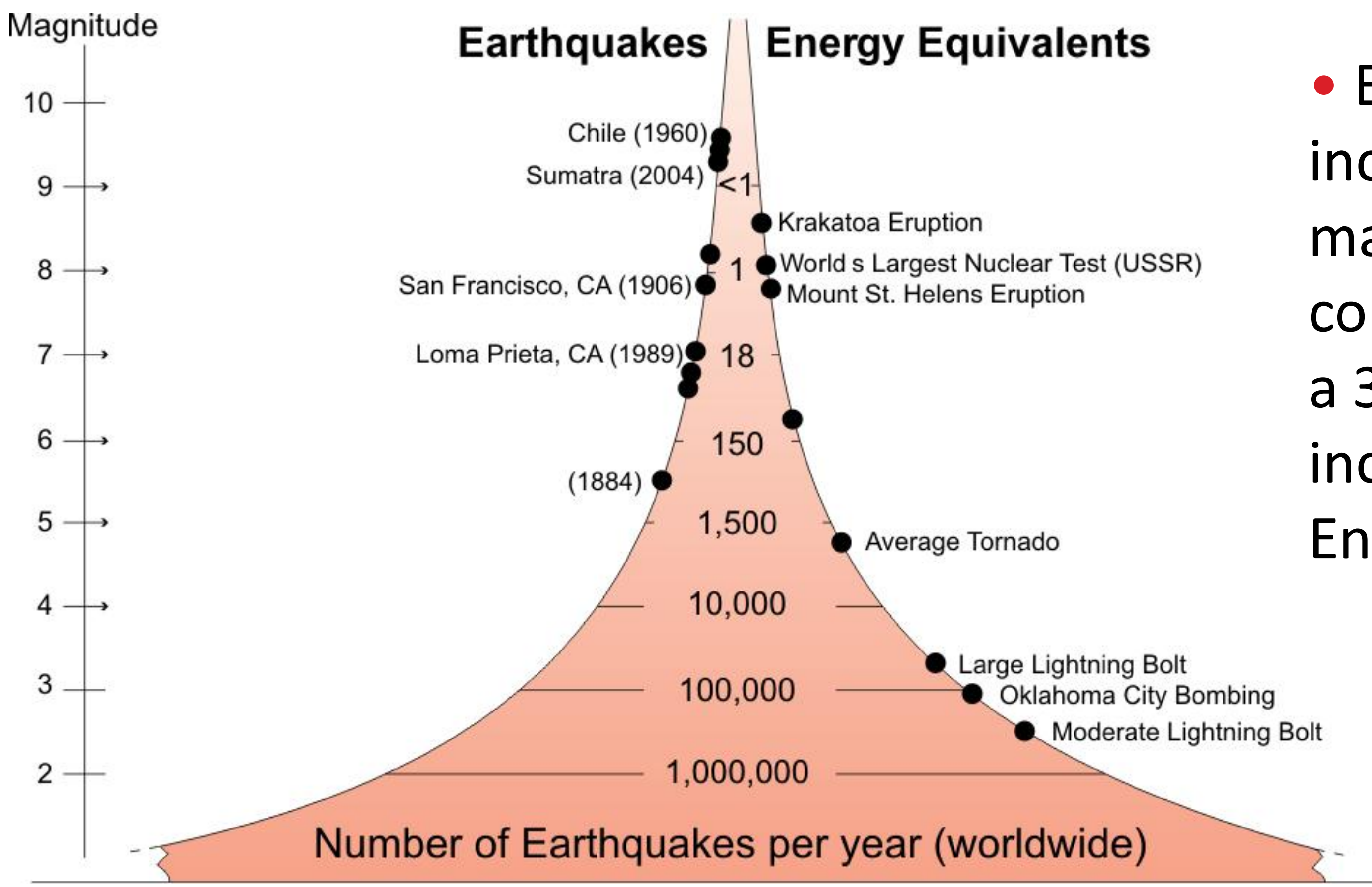
A is maximum amplitude in mm measured on a Wood-Anderson seismograph

Δ is epicentral distance in km



Bolt, 1993

Magnitude versus Energy



- Each unit increase in magnitude corresponds to a 30-fold increase in Energy

Typical range for micro-seismic events

Seismic Moment

$$M_0 = \mu D A$$

where

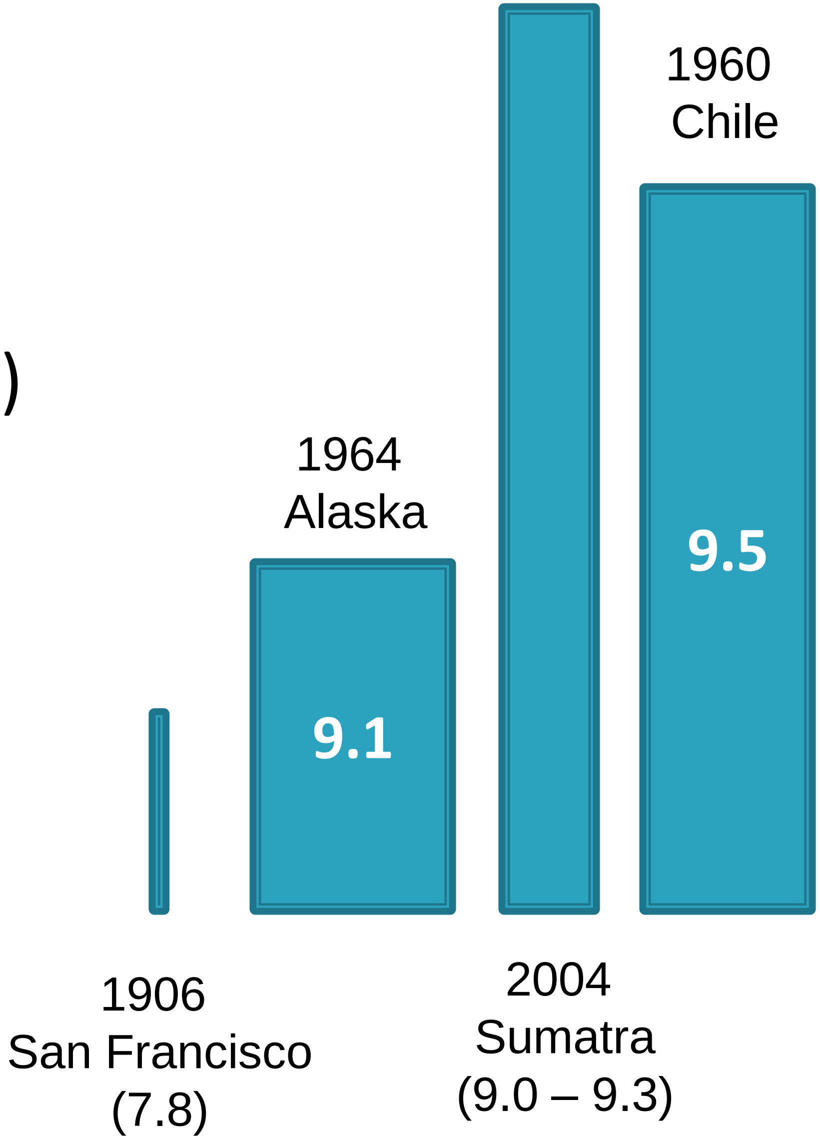
μ is shear modulus (rigidity)

D is average slip

A is rupture area

Moment magnitude:

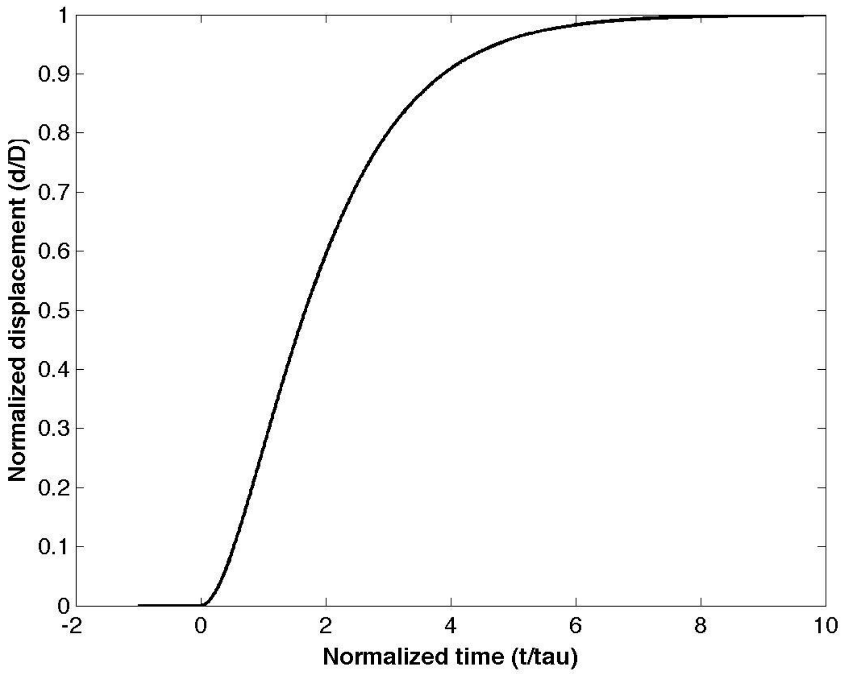
$M_w = \log M_0/1.5 - 10.73$



Spectral Characteristics

Dislocation on a small circular crack

(Brune source model)



$$d(t) = D\left[1 - (1 + t/\tau)e^{-t/\tau}\right]$$

Far-field spectra

$$\tilde{a}(\omega) = \frac{M_0 \omega^2}{1 + \left(\frac{\omega}{\omega_c}\right)^2}$$

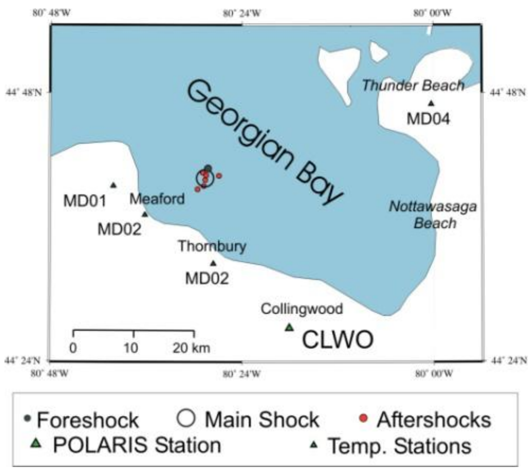
$$\tilde{d}(\omega) = \frac{M_0}{1 + \left(\frac{\omega}{\omega_c}\right)^2}$$

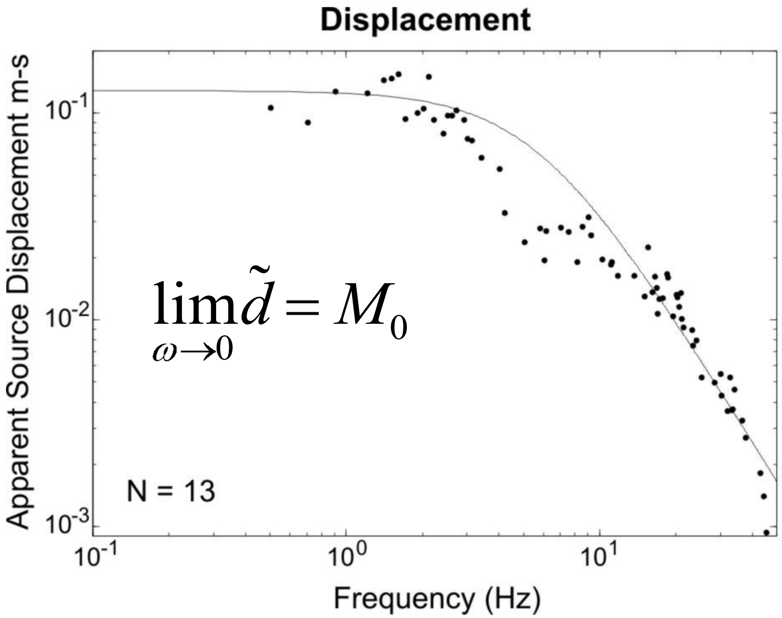
$\omega_c = 1/\tau$ is the corner frequency

Spectral Characteristics

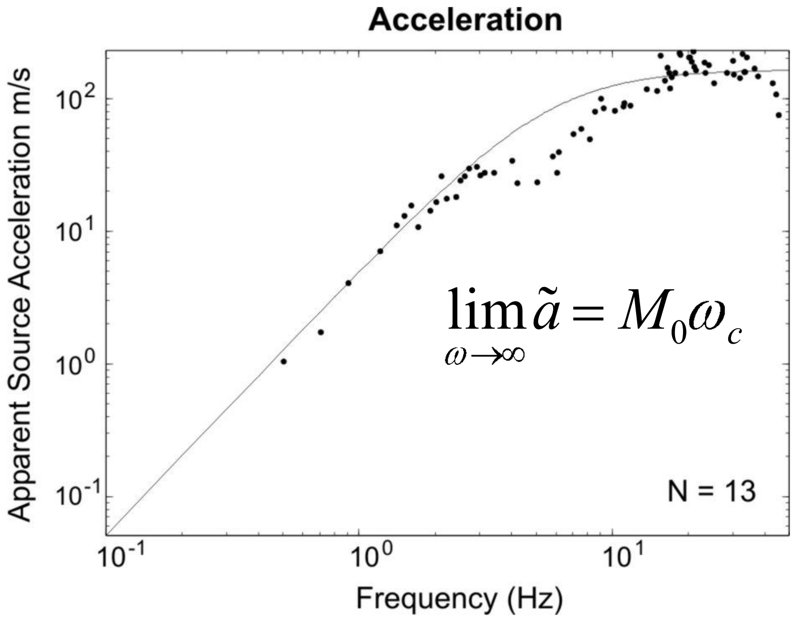
Example: small earthquake in Georgian Bay, Ontario

$\omega_c \sim 25\ s^{-1}$





$$\lim_{\omega \to 0} \tilde{d} = M_0$$



$$\lim_{\omega \to \infty} \tilde{a} = M_0 \omega_c$$

Dineva et al., 2006

Spectral Characteristics

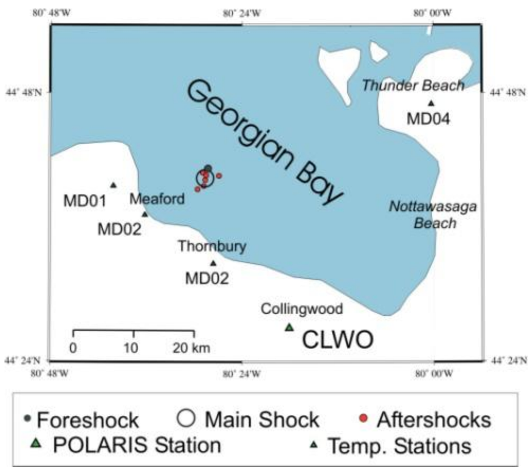
Source radius

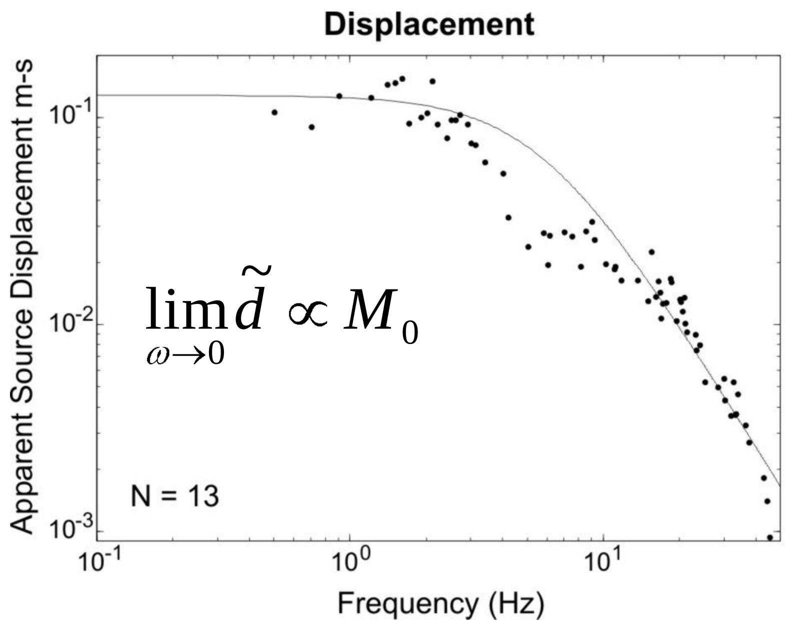
$$R \approx 2.34 \frac{V_s}{\omega_c} = 280m$$

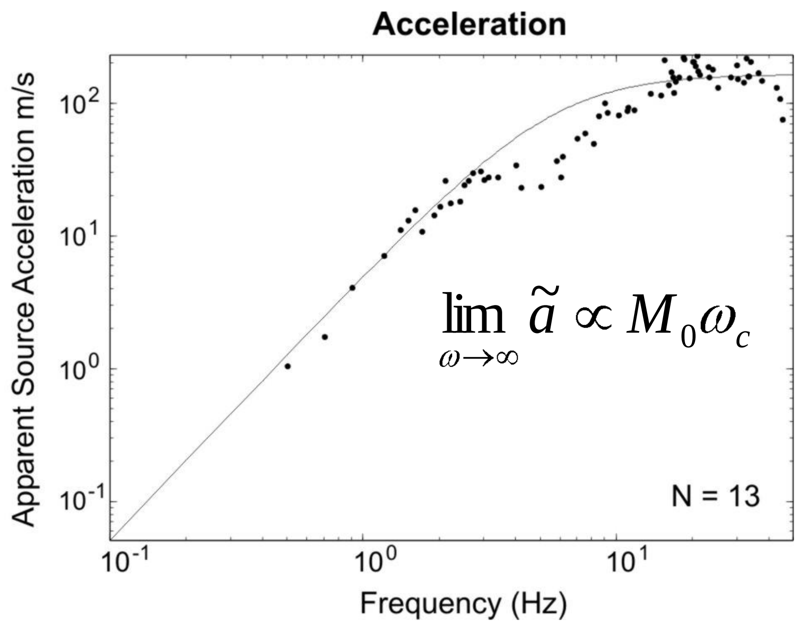
Stress drop

$$\omega_c \approx 2.34 \times 2V_s \left(\frac{\Delta\sigma}{M_0} \right)^{1/3}$$

Δσ ~ 20 bars





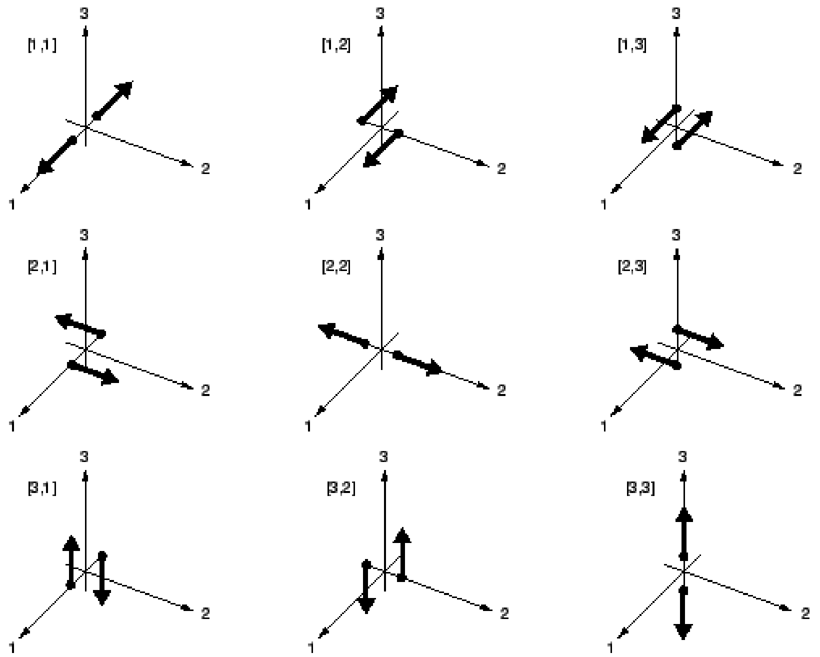


Dineva et al., 2006

Seismic Moment Tensor

$$\mathbf{M} = M_0 \begin{bmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{bmatrix}$$

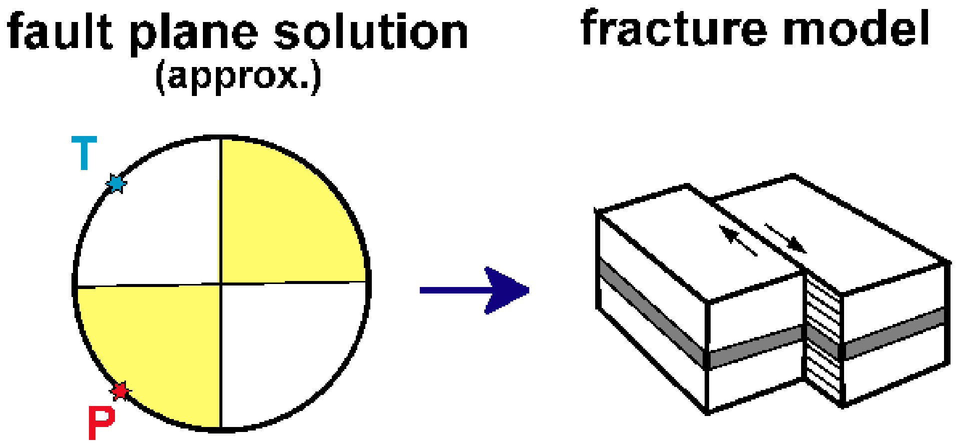
- A more general representation of an earthquake source
- Each tensor component represents a force couple
- Since **M** is symmetric (zero net torque), 6 are independent



Aki and Richards, 1980

Seismic Moment Tensor

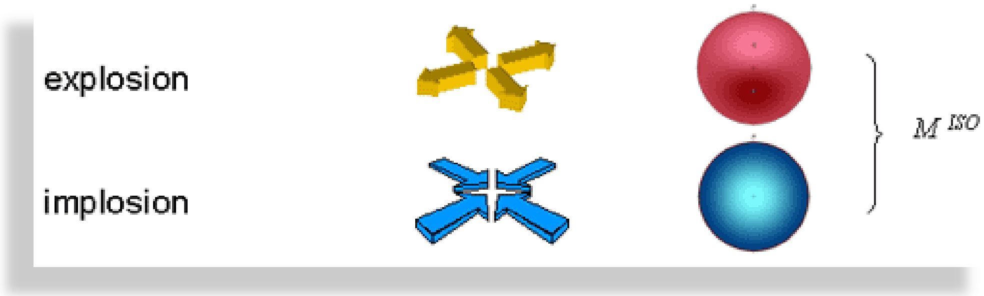
- Most earthquakes can be approximated by a double-couple
- As with other forms, eigenvectors of **M** yield principal stress axes (P, T)



$$\begin{bmatrix} 0 & M_0 & 0 \\ M_0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Seismic Moment Tensor

- An explosive source is represented by an isotropic moment tensor

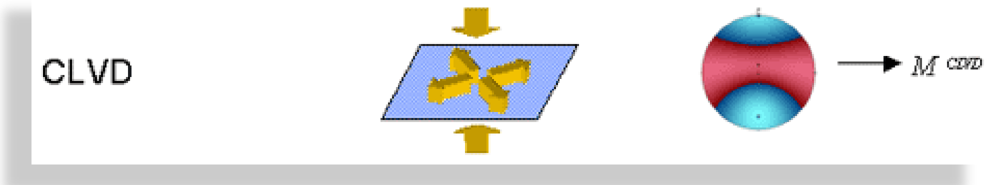


http://www.iwb.uni-stuttgart.de/grosse/aet/mti.htm

$$\begin{bmatrix} M_0 & 0 & 0 \\ 0 & M_0 & 0 \\ 0 & 0 & M_0 \end{bmatrix}$$

Seismic Moment Tensor

- A crack opening under tension (fluid injection) can be represented by the sum of an isotropic moment tensor and a compensated linear vector dipole (CVLD)



http://www.iwb.uni-stuttgart.de/grosse/aet/mti.htm

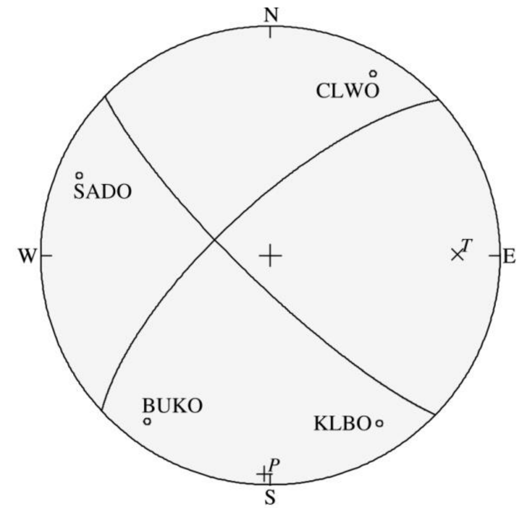
$$\begin{bmatrix} M_0 & 0 & 0 \\ 0 & -2M_0 & 0 \\ 0 & 0 & M_0 \end{bmatrix}$$

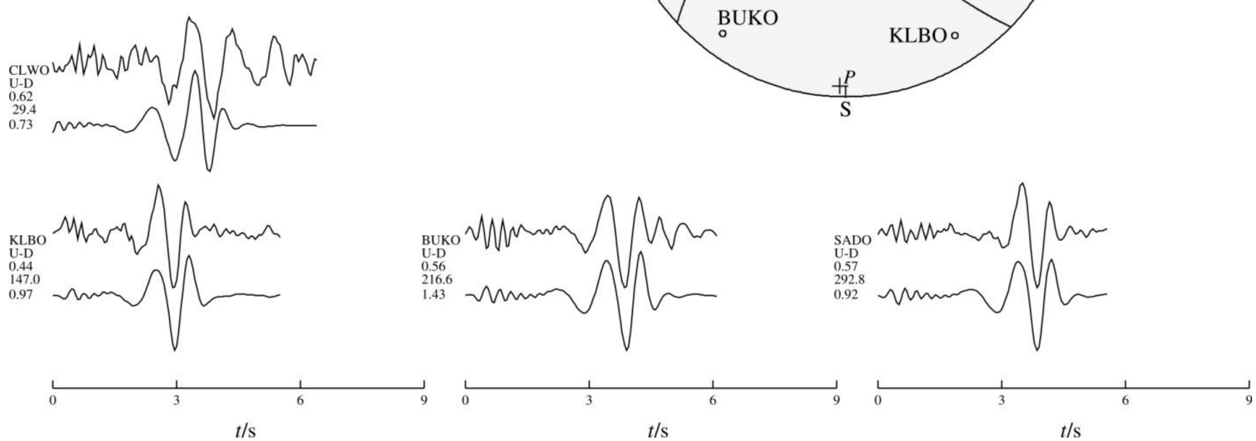
Moment Tensor Inversion

- Waveform inversion for source mechanism
- Requires good velocity model

	strike (°)	dip (°)	rake (°)
Plane1	134	80	162
Plane2	227	72	11

	azimuth (°)	plunge (°)
P	182	5
T	90	20





Ma and Eaton, 2008

Coulomb Failure Function

Stress transfer due to an earthquake can be modelled using the so-called Coulomb failure function (Stein, 1999)

$$\Delta\sigma_f = \Delta\tau + \mu(\Delta\sigma_n + \Delta P)$$

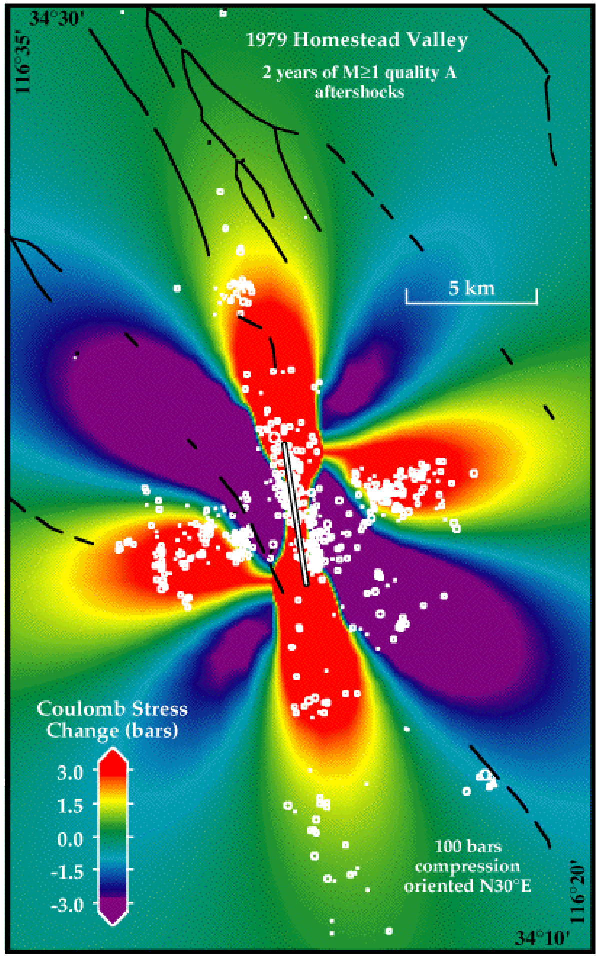
Where

$\Delta\tau$ is the change in shear stress

μ is the coefficient of friction

$\Delta\sigma_n$ is the normal stress

ΔP is change in pore pressure

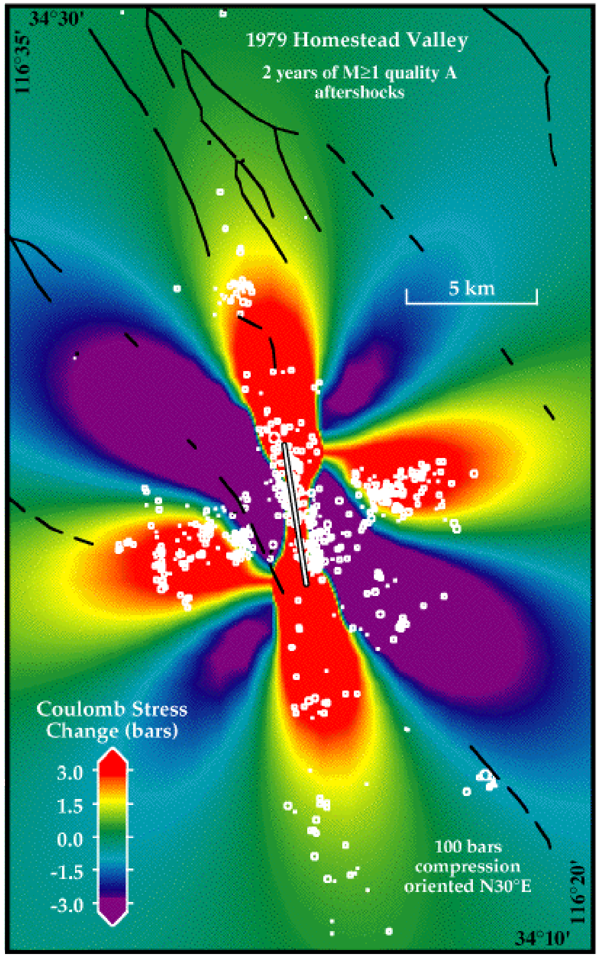


King et al., 1994

Coulomb Failure Function

Although far-field stress changes are small (a few bars or less), earthquake aftershocks are more probable in regions of increased $\Delta\sigma_f$ and less probable in regions of decreased $\Delta\sigma_f$ (Stein, 1999)

→ Potential application to induced microseismicity from hydraulic fracturing?



King et al., 1994

Key points

CREWES

- Various methods are used to describe earthquakes (magnitude, seismic moment, focal mechanism) and are applicable, in principle, to microseismic monitoring studies
- Application of these methods may yield useful information about stress state and failure mechanisms
- Recent models for stress transfer may also have applicability to modelling and understanding induced seismicity

UNIVERSITY OF CALGARY

MO SHÙILE TOGAM SUAS

GeoScience