Seismotectonics

Seismic moment and magnitude

- Fault scarps
- Elastic rebound
- Richter scale
- Energy of earthquakes
- Seismic moment
- Fault area, horizontal slip

Fault plane solutions

- Fault displacement and double couple
- Source radiation pattern
- Beach balls
- Fault plane solutions

Fault scarps

California

Fault scarps

Grand Canyon

Fault scarps

California

Fault scarps

California

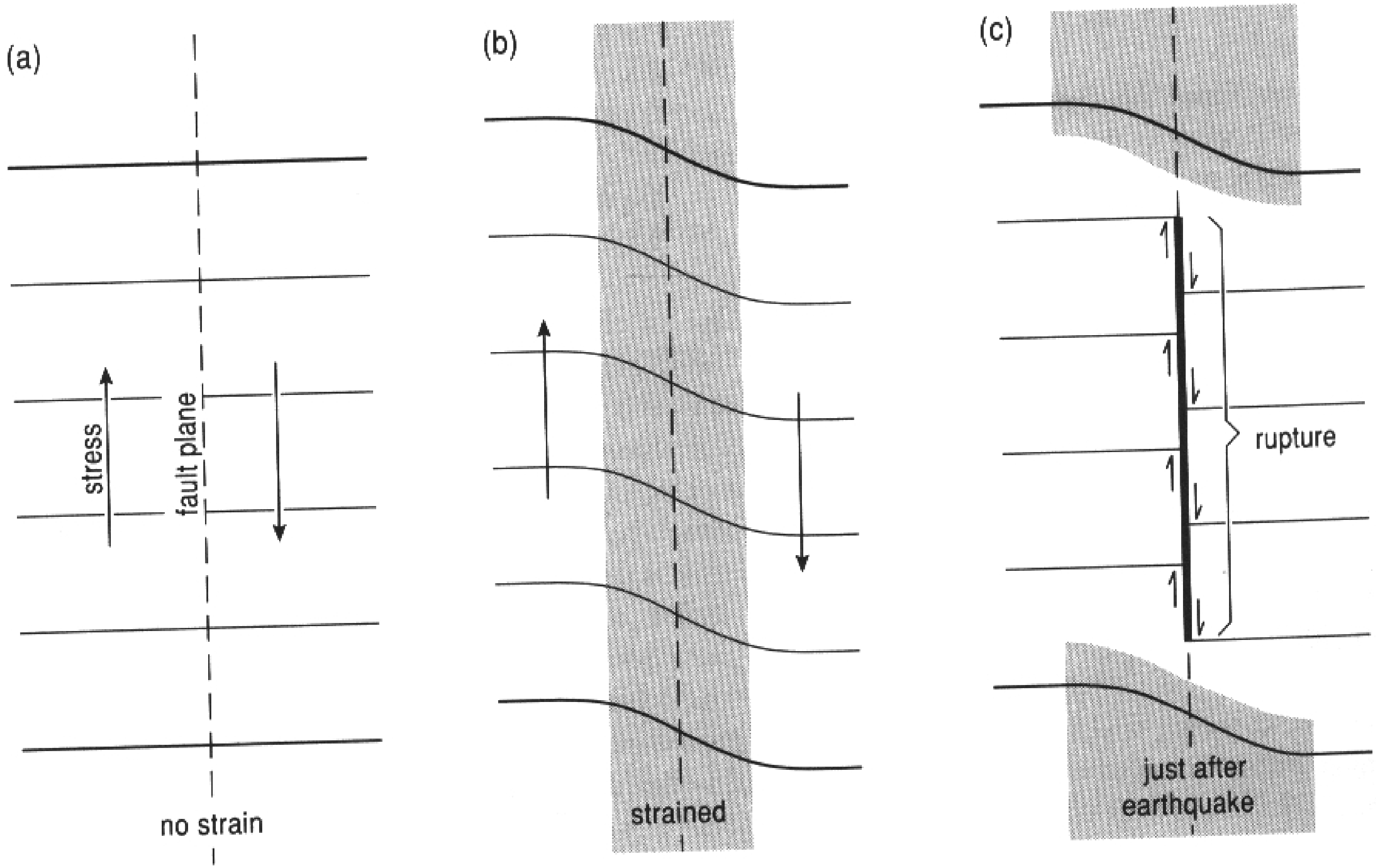
Fault scarps

Taiwan

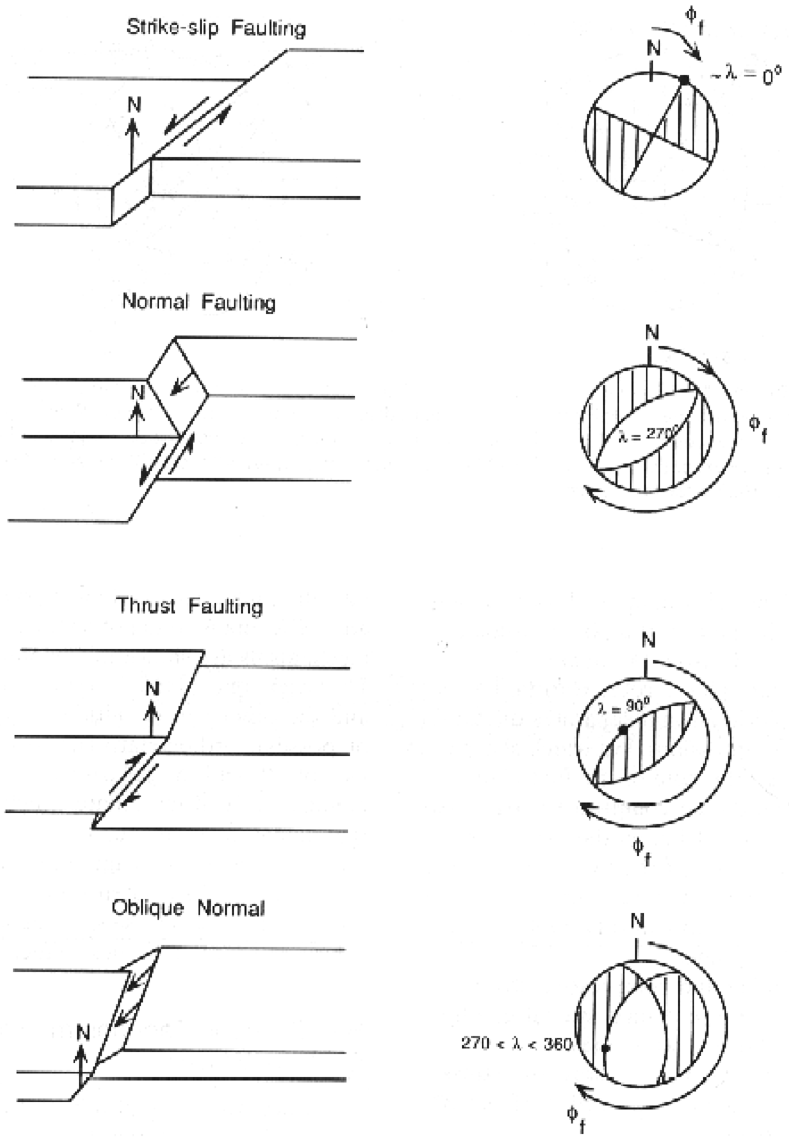
Fault scarps

Taiwan

Elastic rebound

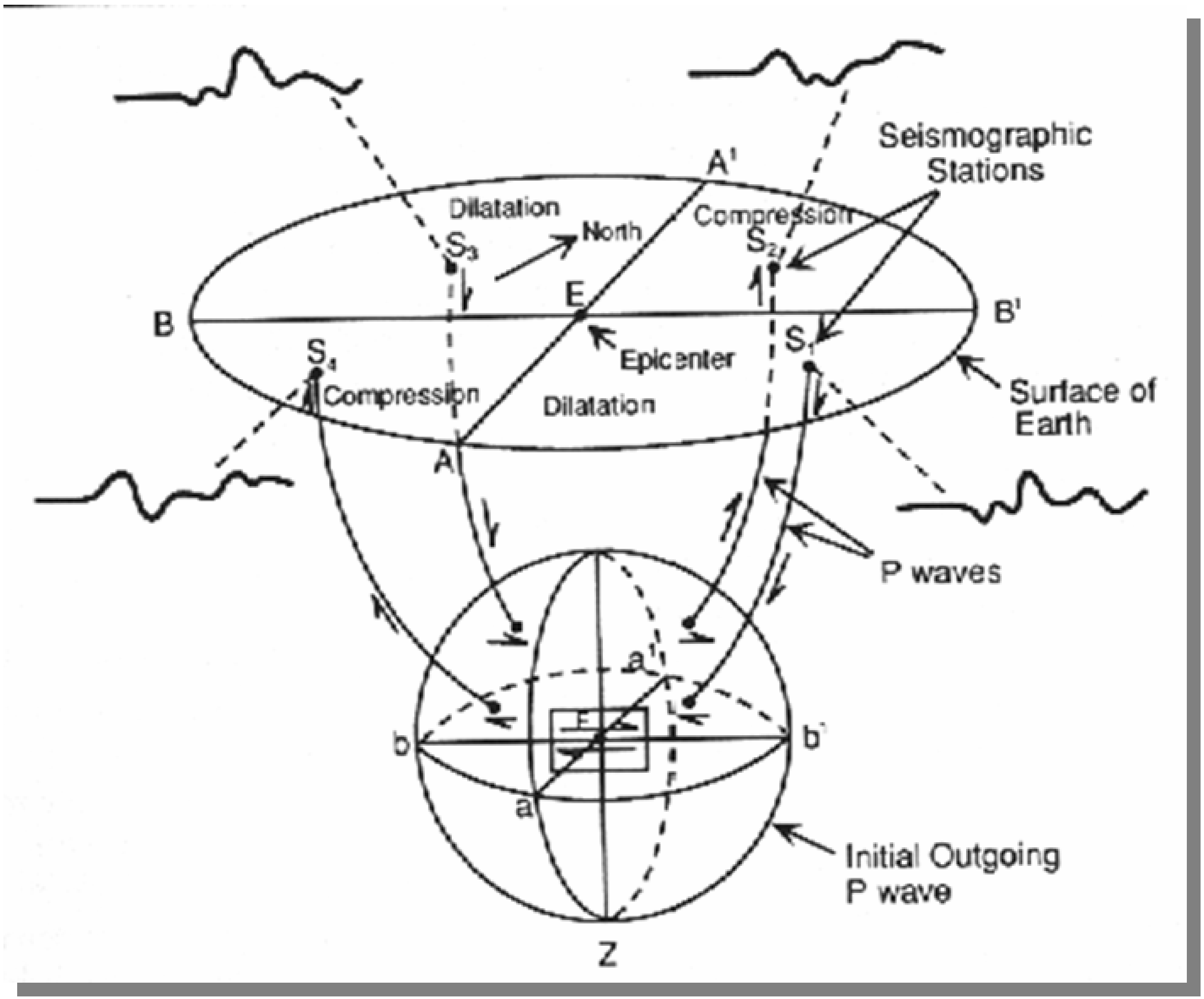


Fault types



Basis fault types and their appearance in the focal mechanisms. Dark regions indicate compressional P-wave motion.

Radiation from shear dislocation

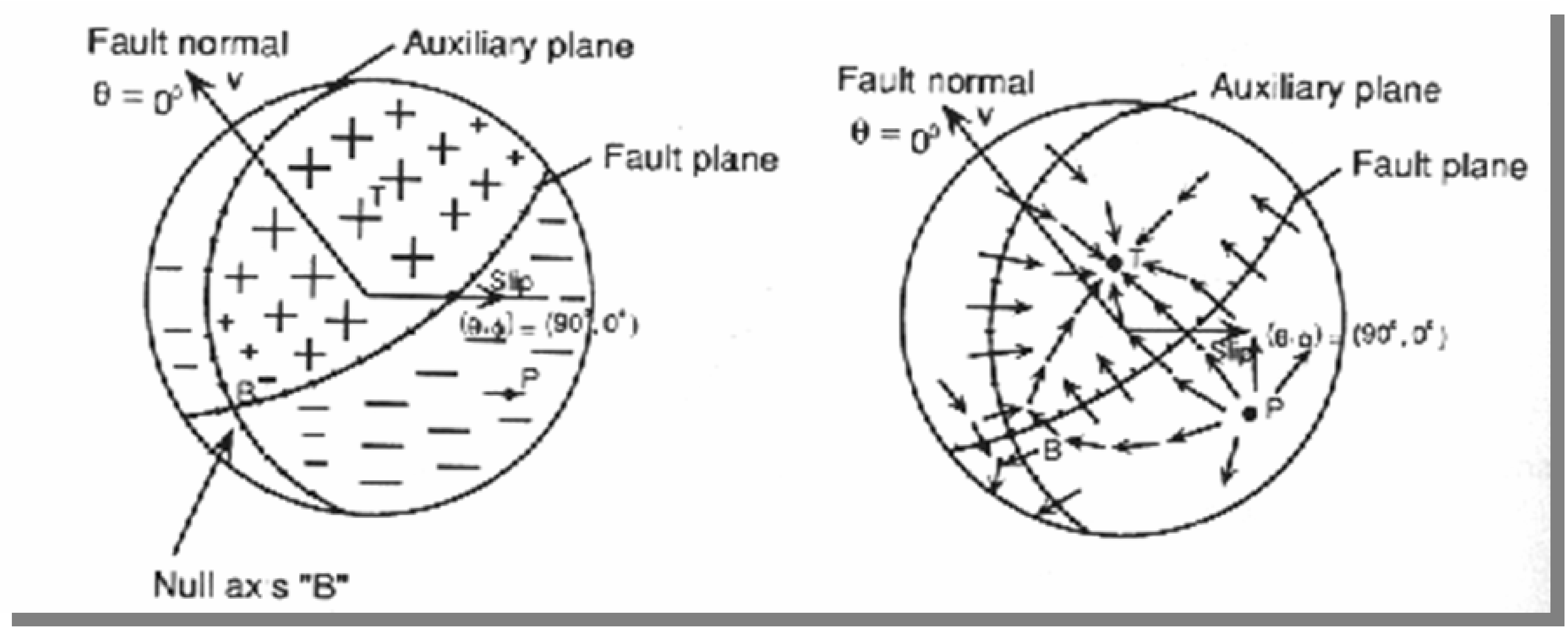


First motion of P waves at seismometers in various directions.

The polarities of the observed motion is used to determine the point source characteristics.

Focal Mechanisms

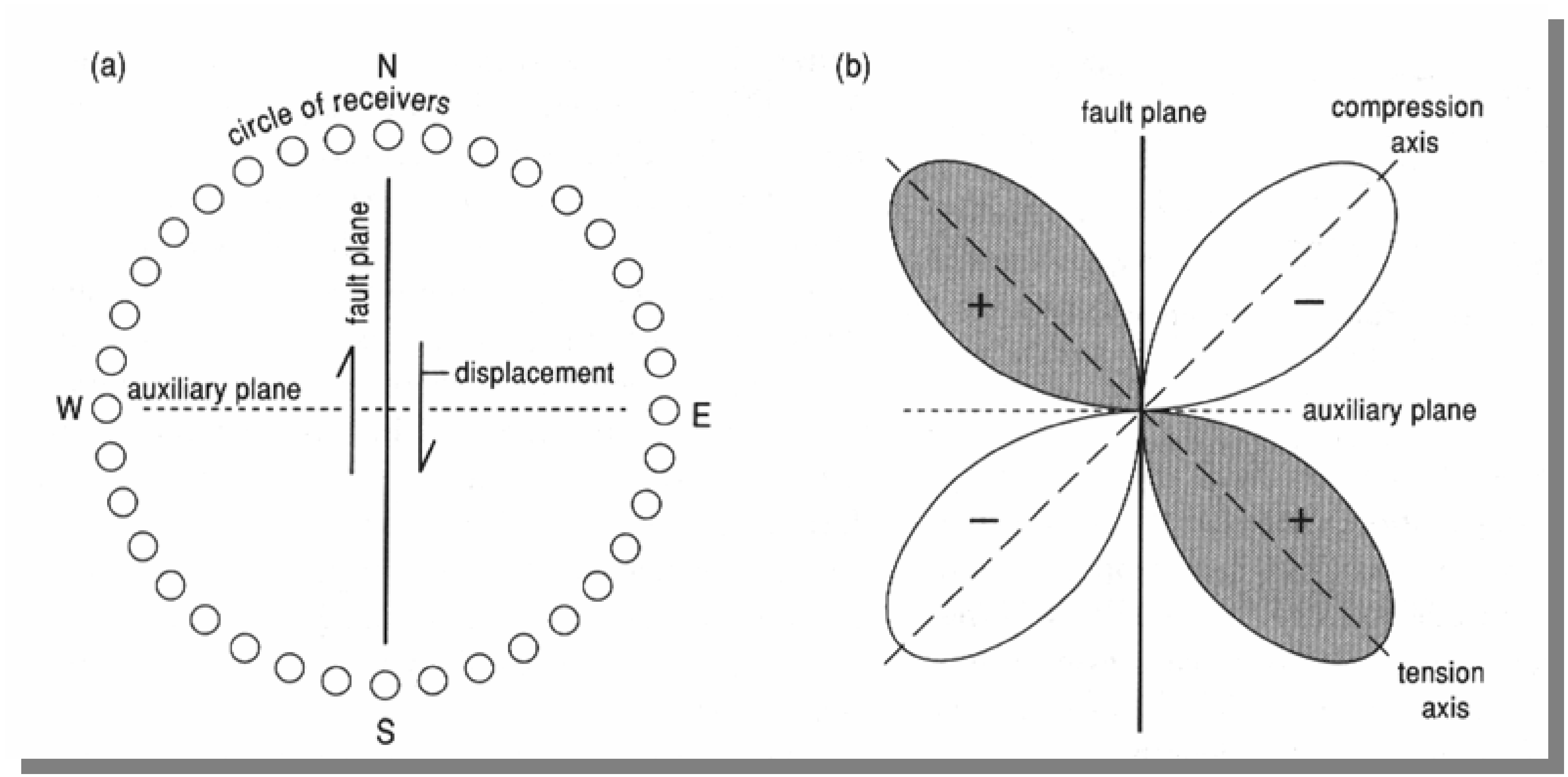
Focal mechanism for an oblique-slip event.



P-wave polarities and relative amplitudes

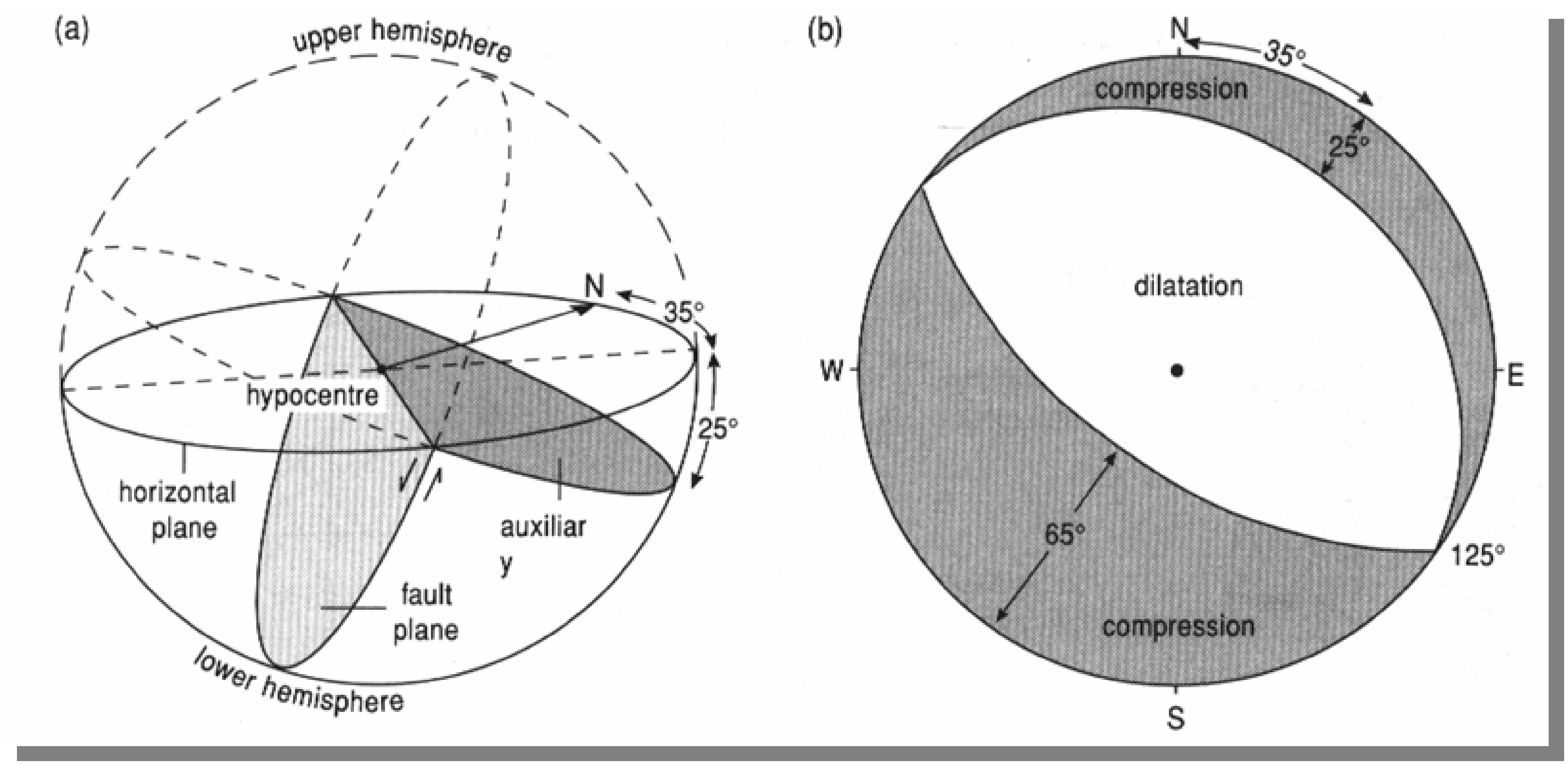
S-wave polarizations and amplitudes

Seismic sources



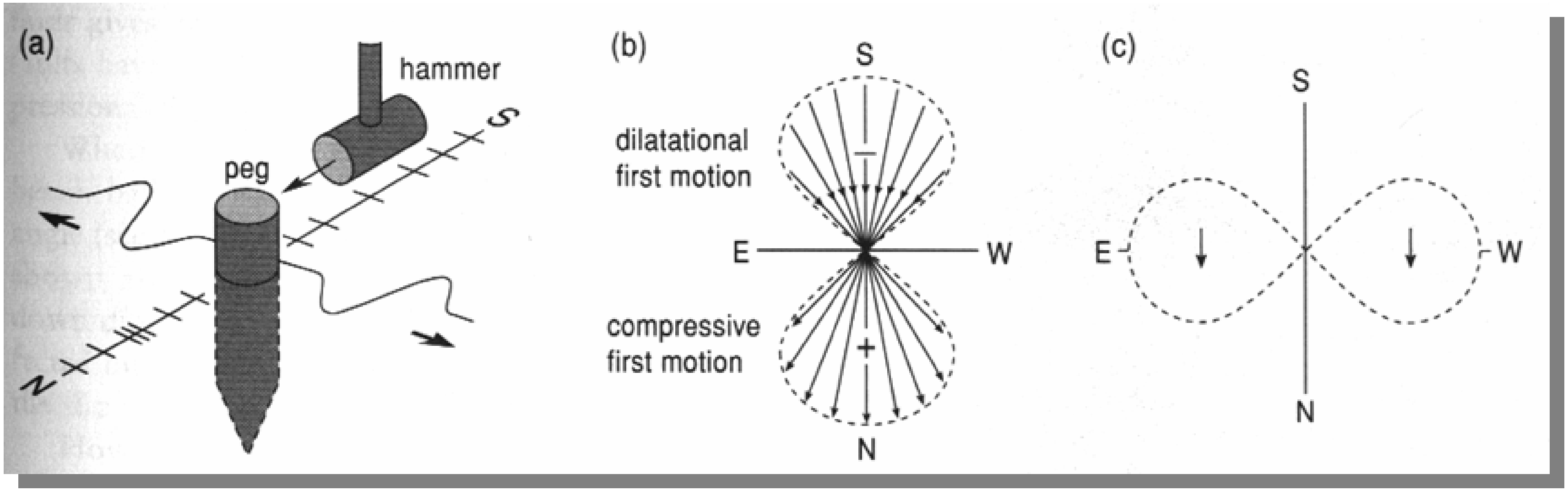
The basic physical model for a source is two fault planes slipping in opposite directions

Seismic sources



Our goal: find the **fault plane** and the **slip direction**

Seismic sources



The radiation from seismic sources is in general strongly direction-dependent

Radiation from a point source

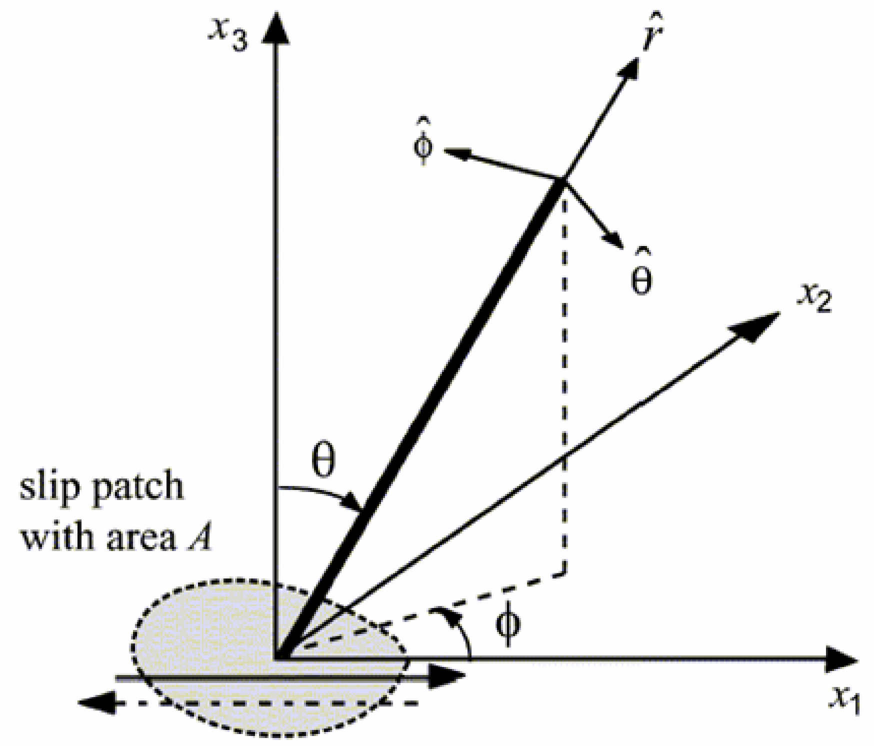


FIGURE 5 Cartesian and polar coordinate systems for analysis of radiation by a slip patch with area A and average slip $\langle \Delta u(t) \rangle$.

Geometry we use to express the seismic wavefield radiated by point double-couple source with area A and slip Δu

Here the fault plane is the x_1x_2-plane and the slip is in x_1-direction. Which stress components are affected?

Radiation from a point source

$$u(x,t) = \frac{1}{4\pi\rho} A^N \frac{1}{r^4} \int_{r/v_P}^{r/v_S} \tau M_0(t-\tau)\, d\tau$$
$$+ \frac{1}{4\pi\rho v_P^2} A^{IP} \frac{1}{r^2} M_0(t - r/v_P)$$
$$+ \frac{1}{4\pi\rho v_S^2} A^{IS} \frac{1}{r^2} M_0(t - r/v_S)$$
$$+ \frac{1}{4\pi\rho v_P^3} A^{FP} \frac{1}{r} \dot{M}_0(t - r/v_P)$$
$$+ \frac{1}{4\pi\rho v_S^3} A^{FS} \frac{1}{r} \dot{M}_0(t - r/v_S).$$

… one of the most important results of seismology!
… Let's have a closer look …

u ground displacement as a function of space and time
ρ density
r distance from source
V_s shear velocity
V_p P-velocity
N near field
IP/S intermediate field
FP/S far field
M_0 seismic moment

$$A^N = 9\sin 2\theta \cos\phi \hat{r} - 6(\cos 2\theta \cos\phi \hat{\theta} - \cos\theta \sin\phi \hat{\phi}),$$
$$A^{IP} = 4\sin 2\theta \cos\phi \hat{r} - 2(\cos 2\theta \cos\phi \hat{\theta} - \cos\theta \sin\phi \hat{\phi}),$$
$$A^{IS} = -3\sin 2\theta \cos\phi \hat{r} + 3(\cos 2\theta \cos\phi \hat{\theta} - \cos\theta \sin\phi \hat{\phi}),$$
$$A^{FP} = \sin 2\theta \cos\phi \hat{r},$$
$$A^{FS} = \cos 2\theta \cos\phi \hat{\theta} - \cos\theta \sin\phi \hat{\phi},$$

Radiation from a point source

$$
\begin{aligned}
u(x, t) &= \frac{1}{4\pi\rho} A^{N} \frac{1}{r^4} \int_{r/v_P}^{r/v_S} \tau M_0(t-\tau)\, d\tau \\
&+ \frac{1}{4\pi\rho v_P^2} A^{IP} \frac{1}{r^2} M_0(t - r/v_P) \\
&+ \frac{1}{4\pi\rho v_S^2} A^{IS} \frac{1}{r^2} M_0(t - r/v_S) \\
&+ \frac{1}{4\pi\rho v_P^3} A^{FP} \frac{1}{r} \dot{M}_0(t - r/v_P) \\
&+ \frac{1}{4\pi\rho v_S^3} A^{FS} \frac{1}{r} \dot{M}_0(t - r/v_S).
\end{aligned}
$$

Near field term contains the static deformation

Intermediate terms

Far field terms: the main ingredient for source inversion, ray theory, etc.

Radiation pattern

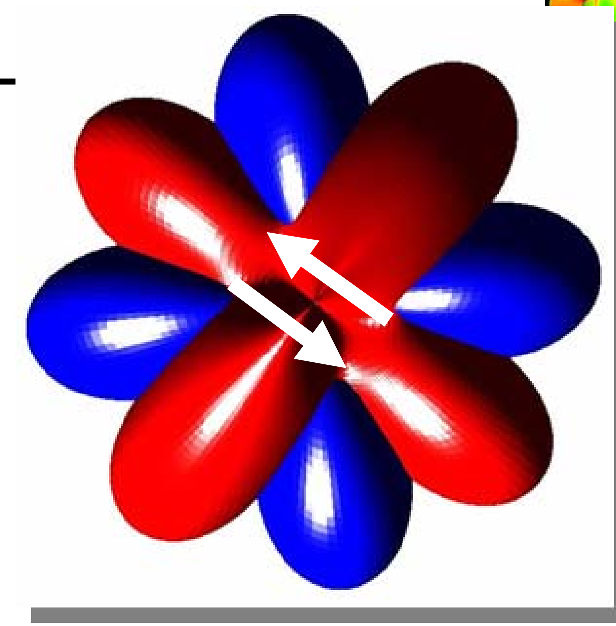
$$\mathbf{A}^{N} = 9\sin 2\theta \cos\phi \hat{\mathbf{r}} - 6(\cos 2\theta \cos\phi \hat{\boldsymbol{\theta}} - \cos\theta \sin\phi \hat{\boldsymbol{\phi}}),$$

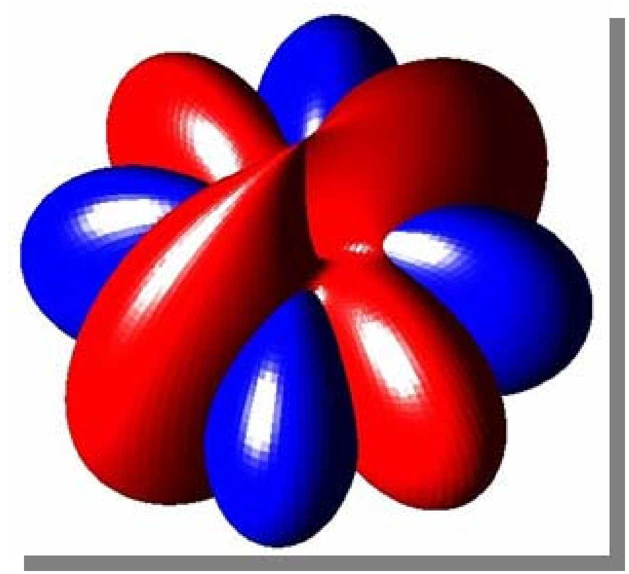
$$\mathbf{A}^{IP} = 4\sin 2\theta \cos\phi \hat{\mathbf{r}} - 2(\cos 2\theta \cos\phi \hat{\boldsymbol{\theta}} - \cos\theta \sin\phi \hat{\boldsymbol{\phi}}),$$

$$\mathbf{A}^{IS} = -3\sin 2\theta \cos\phi \hat{\mathbf{r}} + 3(\cos 2\theta \cos\phi \hat{\boldsymbol{\theta}} - \cos\theta \sin\phi \hat{\boldsymbol{\phi}}),$$

$$\mathbf{A}^{FP} = \sin 2\theta \cos\phi \hat{\mathbf{r}},$$

$$\mathbf{A}^{FS} = \cos 2\theta \cos\phi \hat{\boldsymbol{\theta}} - \cos\theta \sin\phi \hat{\boldsymbol{\phi}},$$





Far field P – blue
Far field S - red

Seismic moment M_0

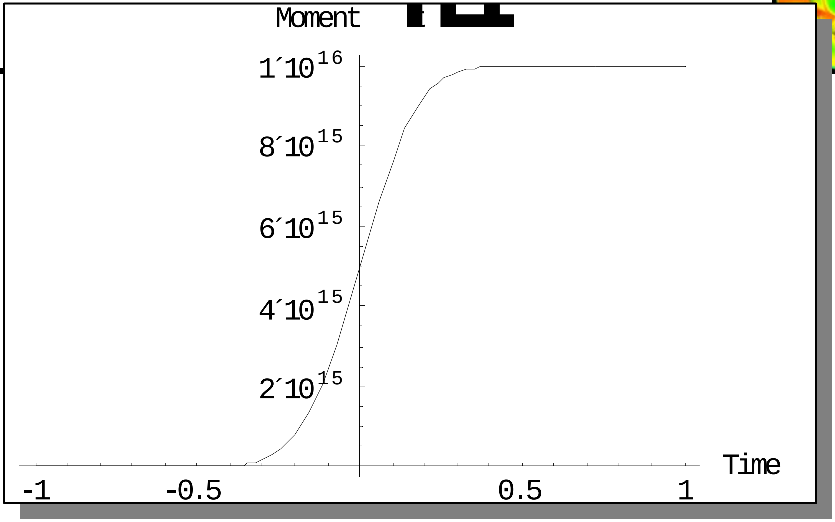
$$u(x,t) = \frac{1}{4\pi\rho} A^N \frac{1}{r^4} \int_{r/v_P}^{r/v_S} \tau M_0(t-\tau)\, d\tau + \frac{1}{4\pi\rho v_P^2} A^{IP} \frac{1}{r^2} M_0(t - r/v_P) + \frac{1}{4\pi\rho v_S^2} A^{IS} \frac{1}{r^2} M_0(t - r/v_S) + \frac{1}{4\pi\rho v_P^3} A^{FP} \frac{1}{r} \dot{M}_0(t - r/v_P) + \frac{1}{4\pi\rho v_S^3} A^{FS} \frac{1}{r} \dot{M}_0(t - r/v_S).$$

$$\boxed{M_0 = \mu \langle \Delta u(t) \rangle A}$$

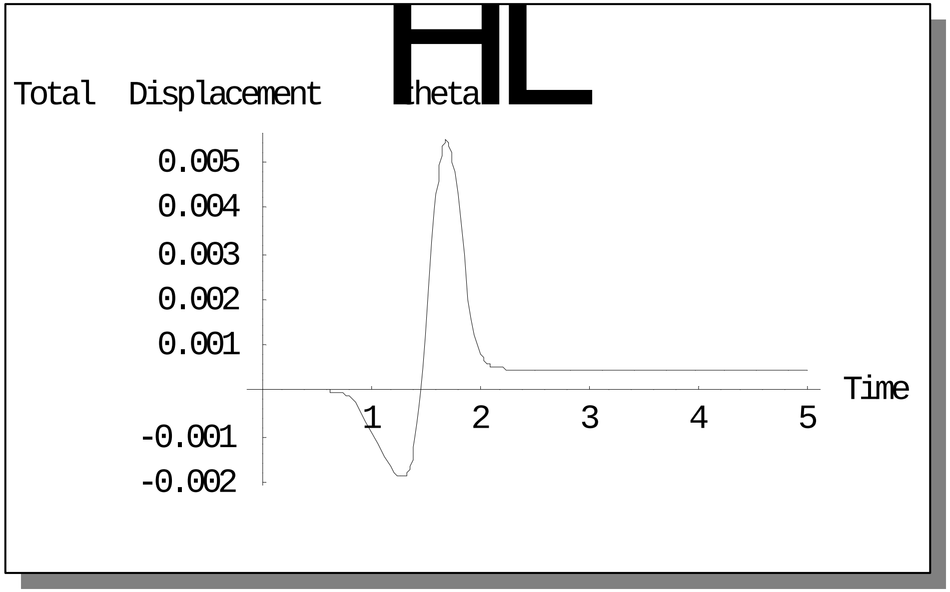
M_0	seismic moment
μ	rigidity
$\langle\Delta u(t)\rangle$	average slip
A	fault area

Note that the far-field displacement is proportional to the moment rate!

Seismograms

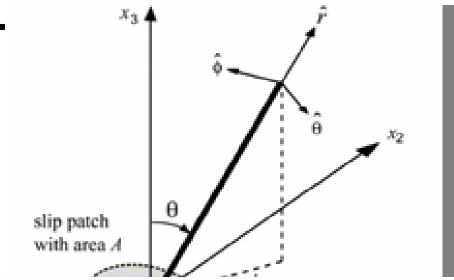


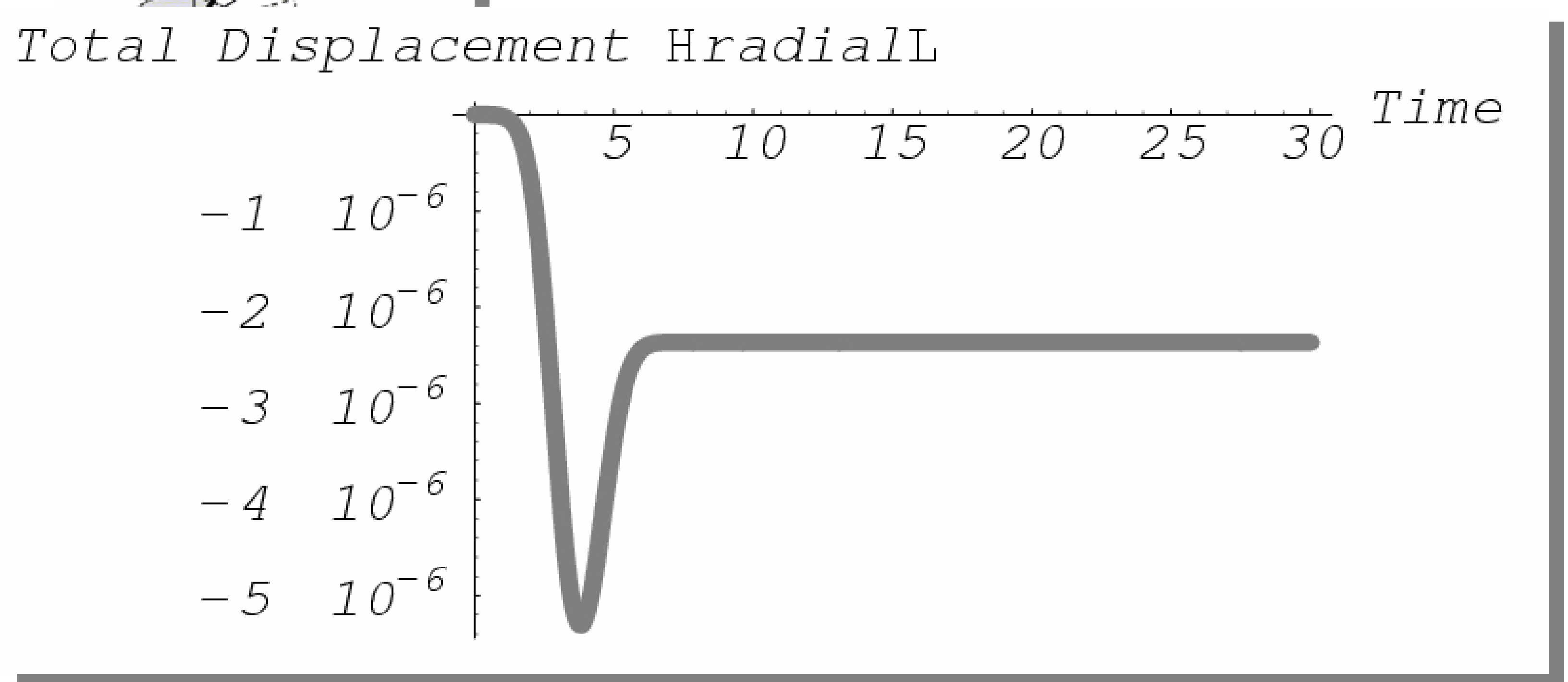
Typical moment M(t)

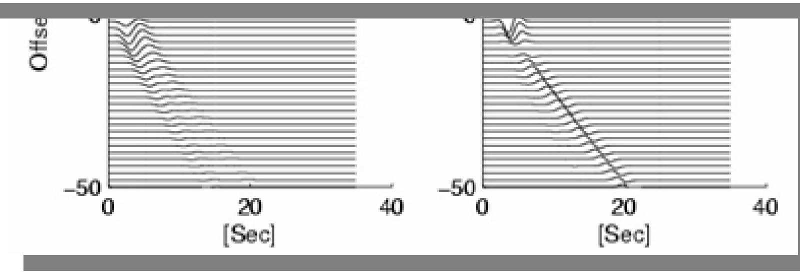


Horizontal displacement 5km away from the source

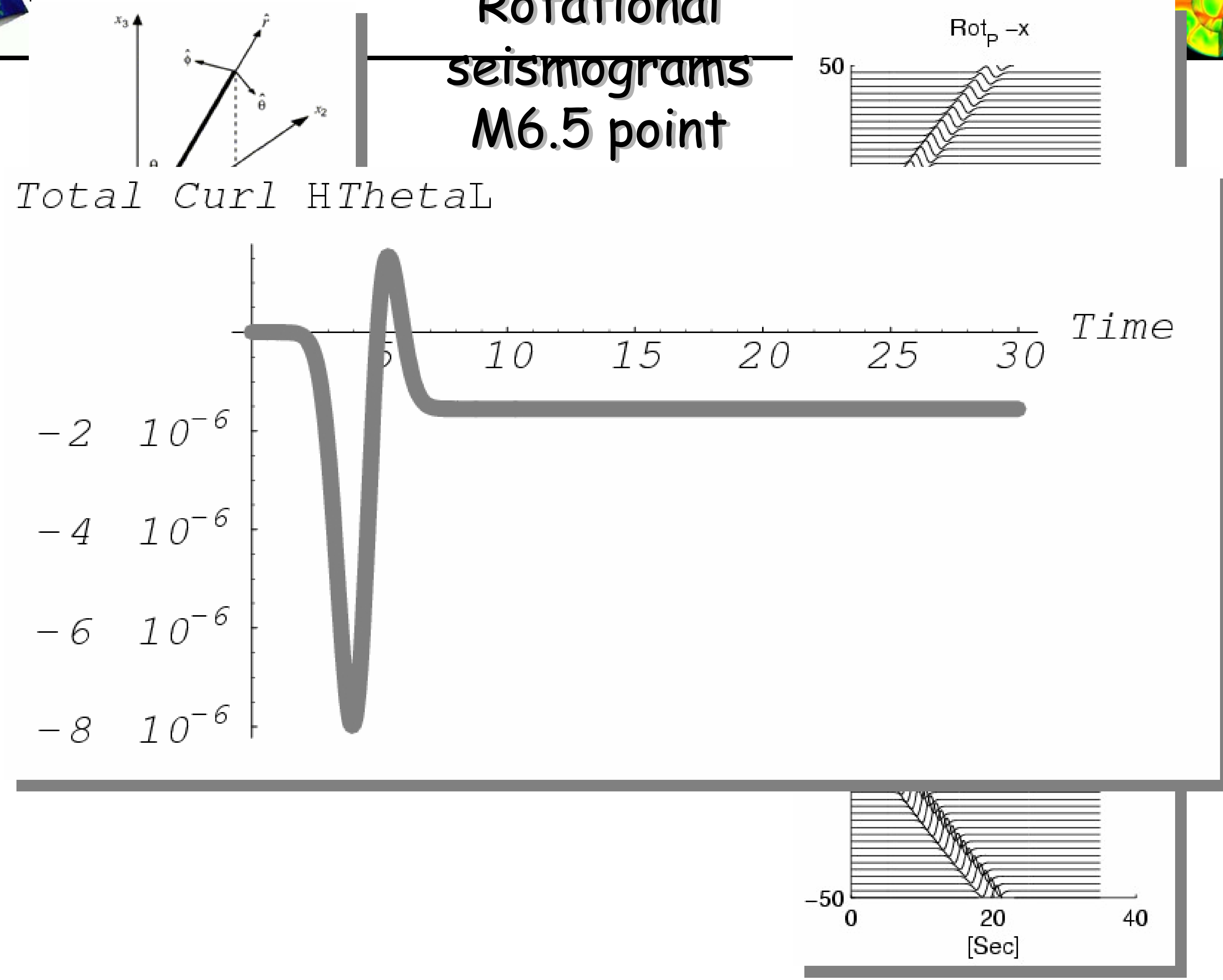
Velocity seismograms
M6.5 point source



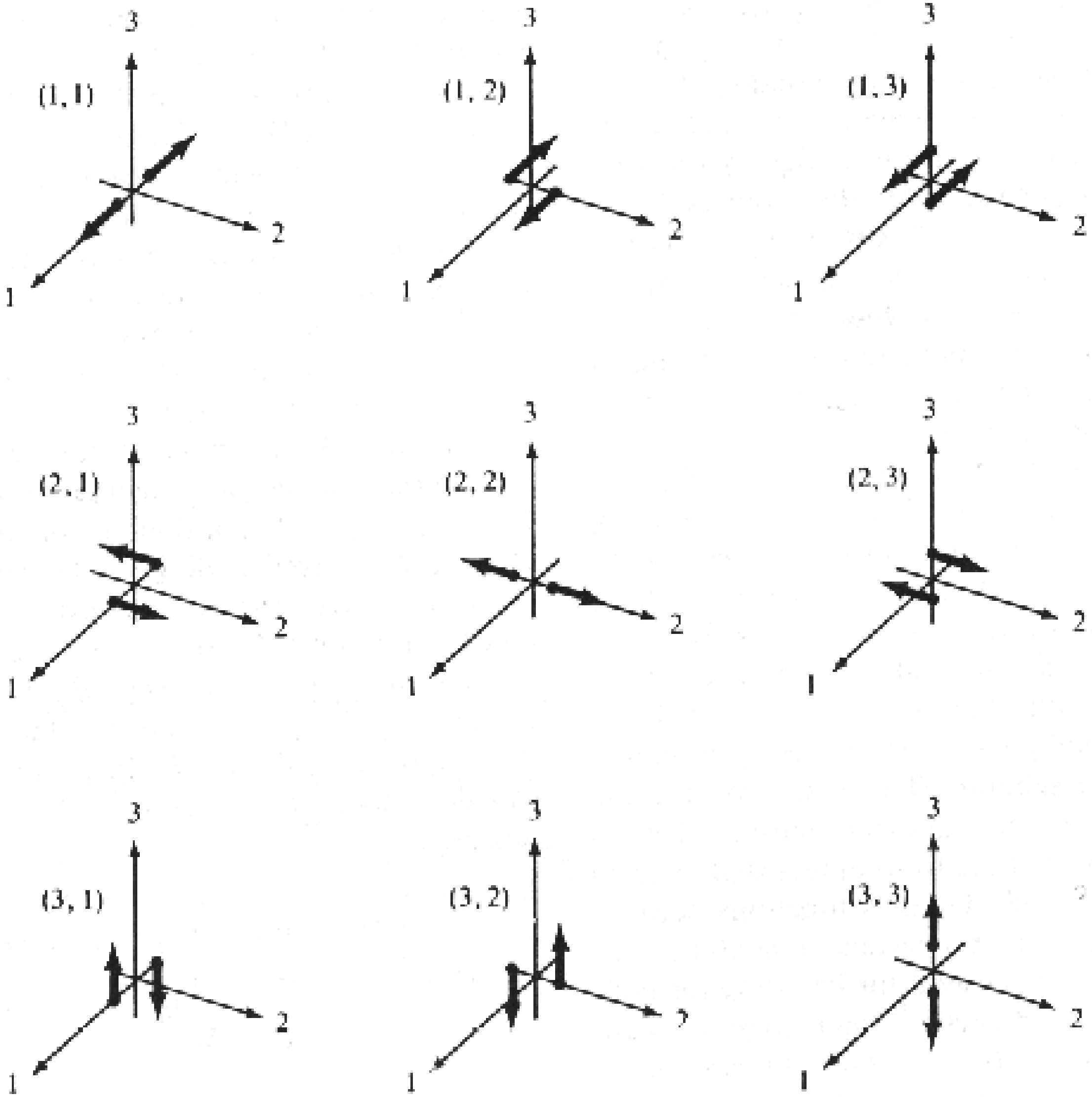




Rotational seismograms M6.5 point

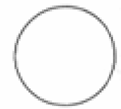
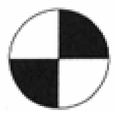
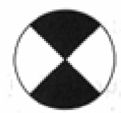
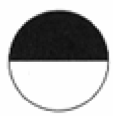
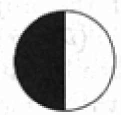
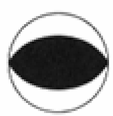
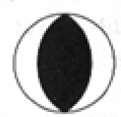
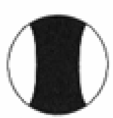
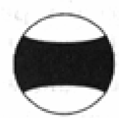
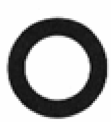
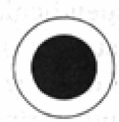


Moment tensor components

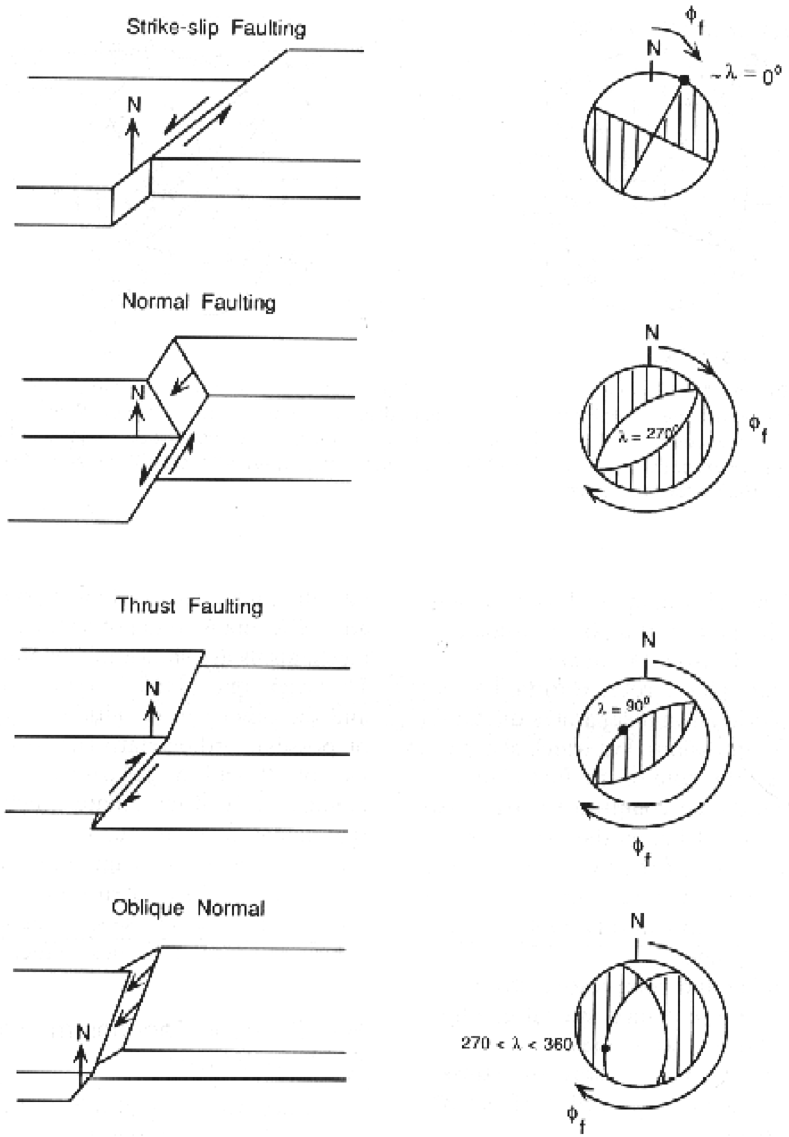


Point sources can be described by the seismic moment tensor M. The elements of M have clear physical meaning as forces acting on particular planes.

Beachballs and moment tensor

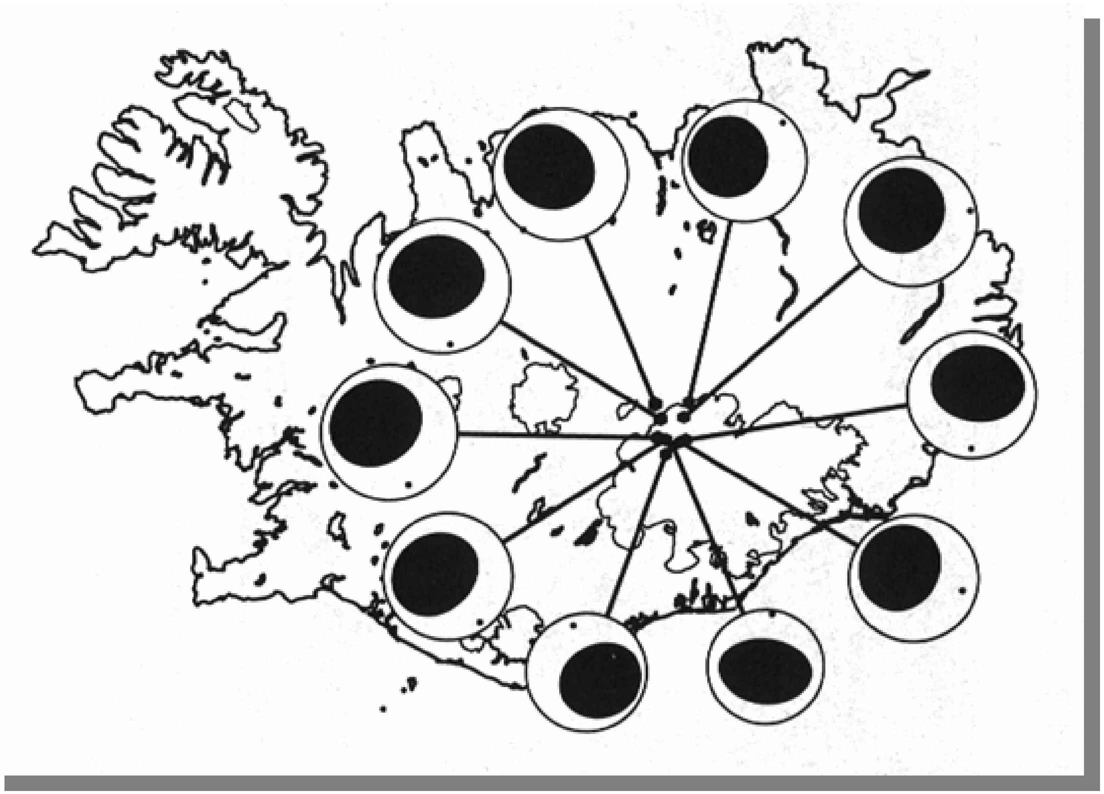
Moment Tensor	Beachball	Moment Tensor	Beachball	
$\frac{1}{\sqrt{3}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}$		$-\frac{1}{\sqrt{3}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}$		explosion - implosion
$-\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&0\\0&0&1\\0&1&0\end{pmatrix}$		$\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&0\\0&1&0\\0&0&-1\end{pmatrix}$		vertical strike slip fault
$\frac{1}{\sqrt{2}}\begin{pmatrix}0&1&0\\1&0&0\\0&0&0\end{pmatrix}$		$\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&1\\0&0&0\\1&0&0\end{pmatrix}$		vertical dip slip fault
$\frac{1}{\sqrt{2}}\begin{pmatrix}1&0&0\\0&-1&0\\0&0&0\end{pmatrix}$		$\frac{1}{\sqrt{2}}\begin{pmatrix}1&0&0\\0&0&0\\0&0&-1\end{pmatrix}$		45° dip thrust fault
$\frac{1}{\sqrt{6}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&-2\end{pmatrix}$		$\frac{1}{\sqrt{6}}\begin{pmatrix}1&0&0\\0&-2&0\\0&0&1\end{pmatrix}$		compensated linear vector dipoles
$\frac{1}{\sqrt{6}}\begin{pmatrix}-2&0&0\\0&1&0\\0&0&1\end{pmatrix}$		$-\frac{1}{\sqrt{6}}\begin{pmatrix}-2&0&0\\0&1&0\\0&0&1\end{pmatrix}$		

Fault types



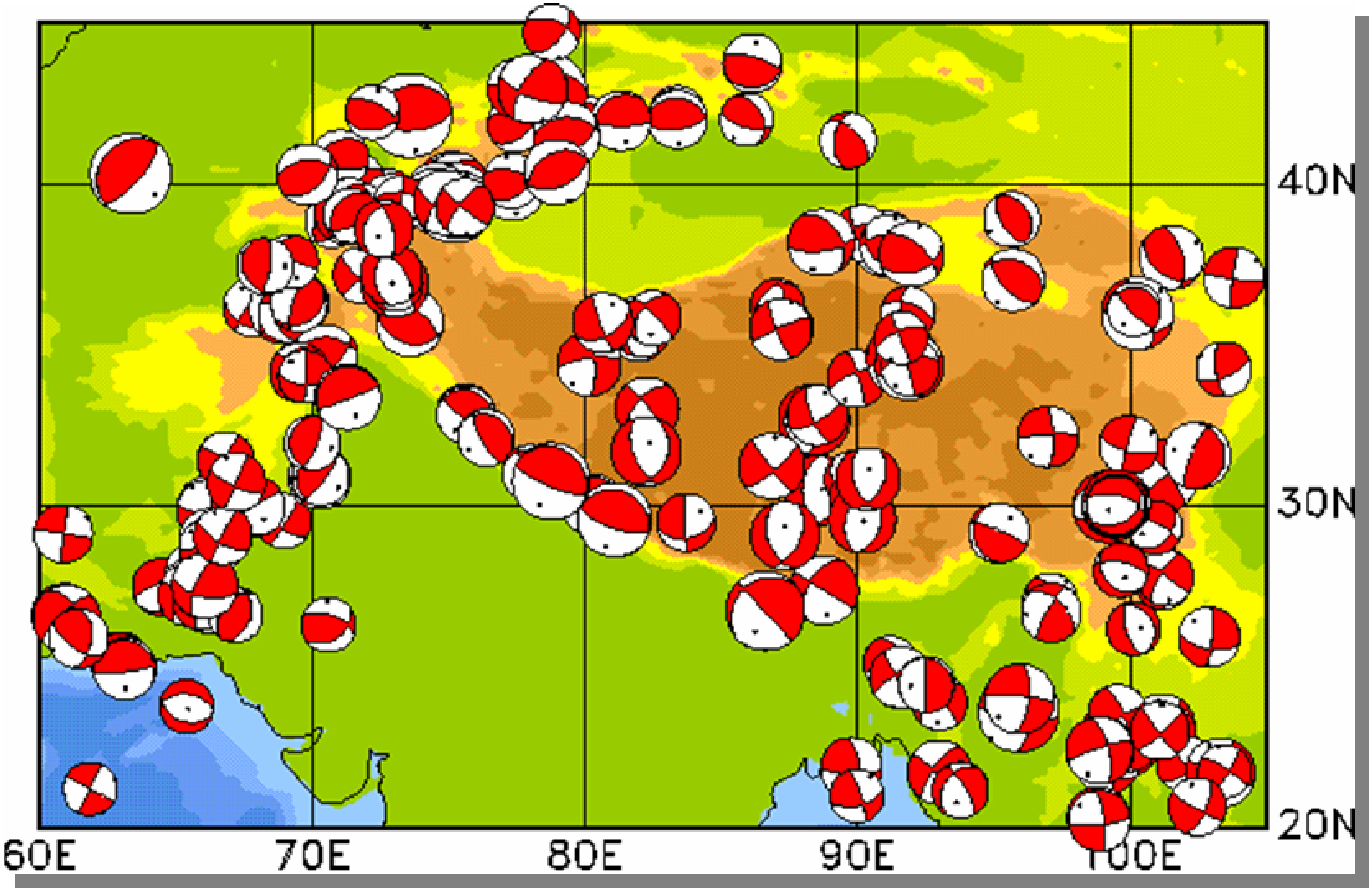
Basis fault types and their appearance in the focal mechanisms. Dark regions indicate compressional P-wave motion.

Beachballs - Iceland

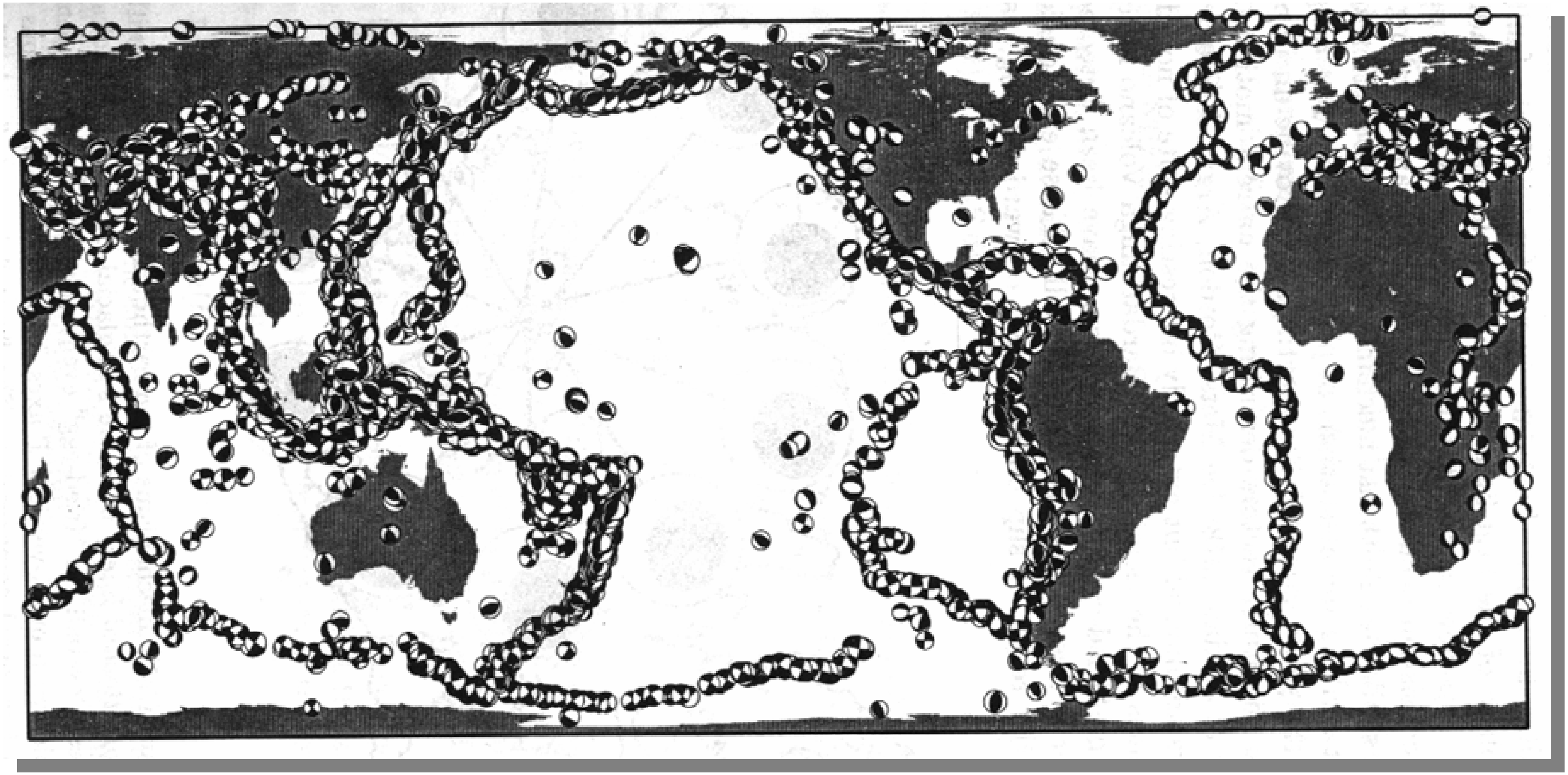


Fried eggs: simultaneous vertical extension and horizontal compression

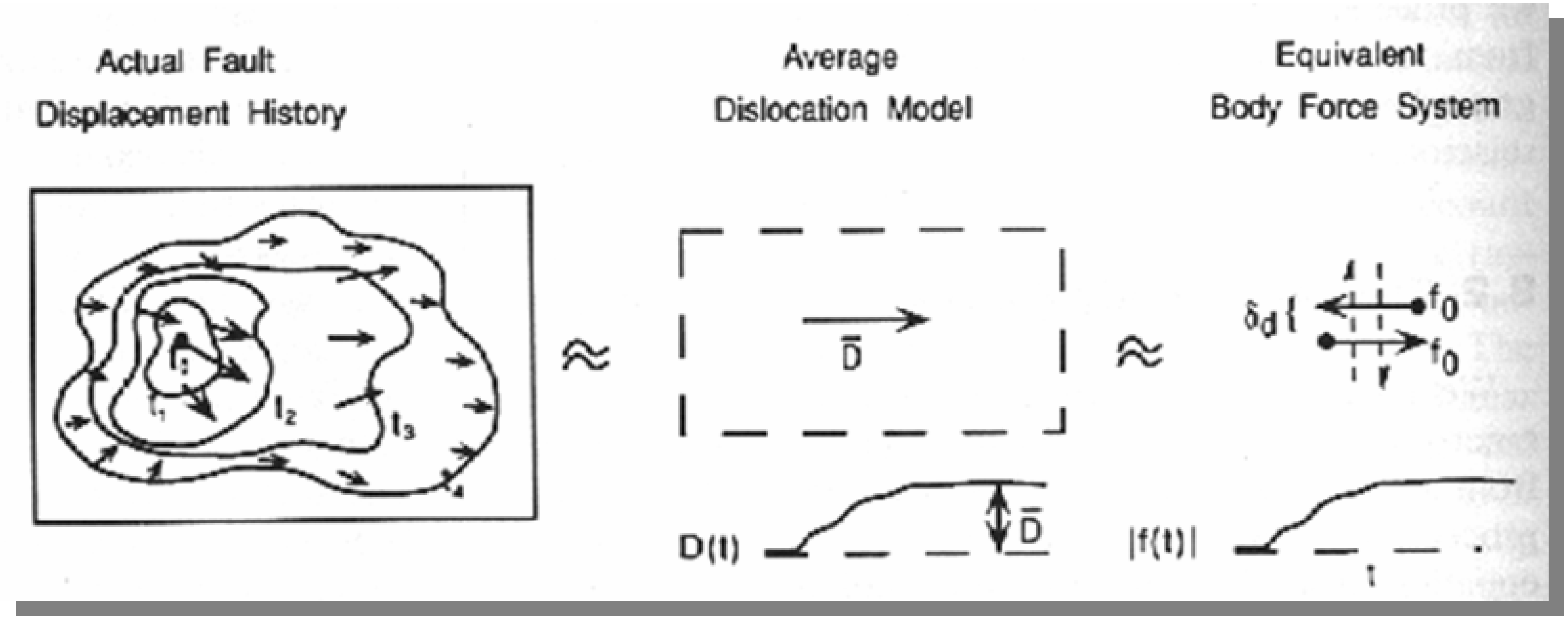
Beachballs - Himalaya



Beachballs - global

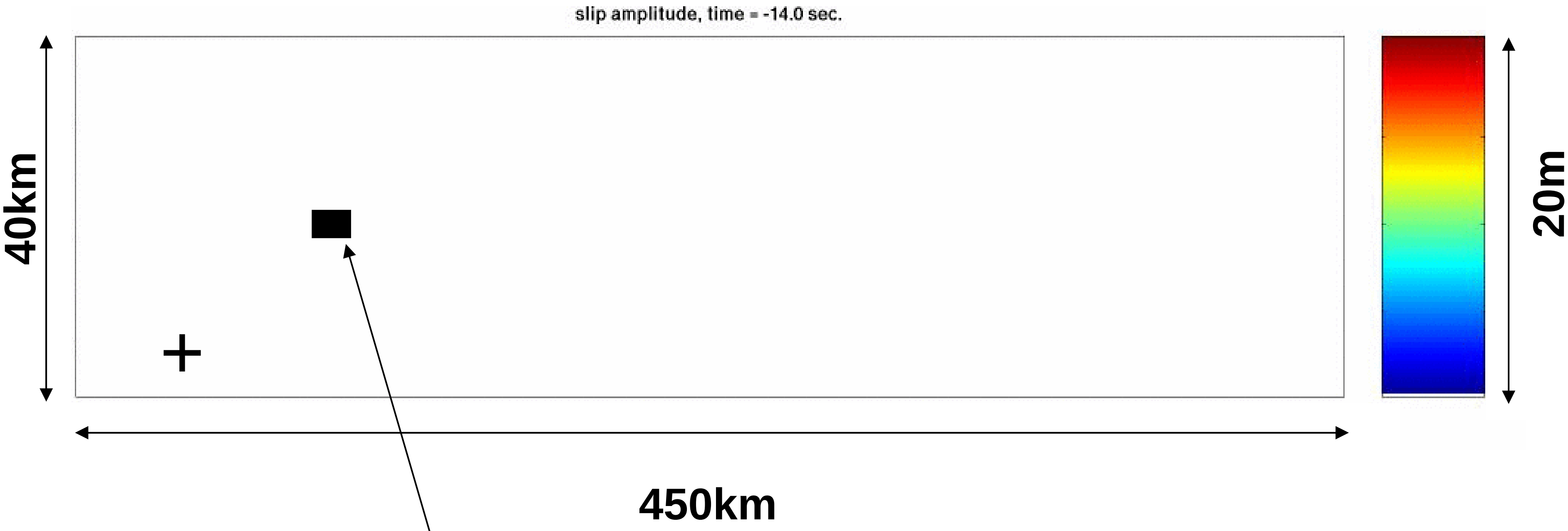


Equivalent Forces: concepts



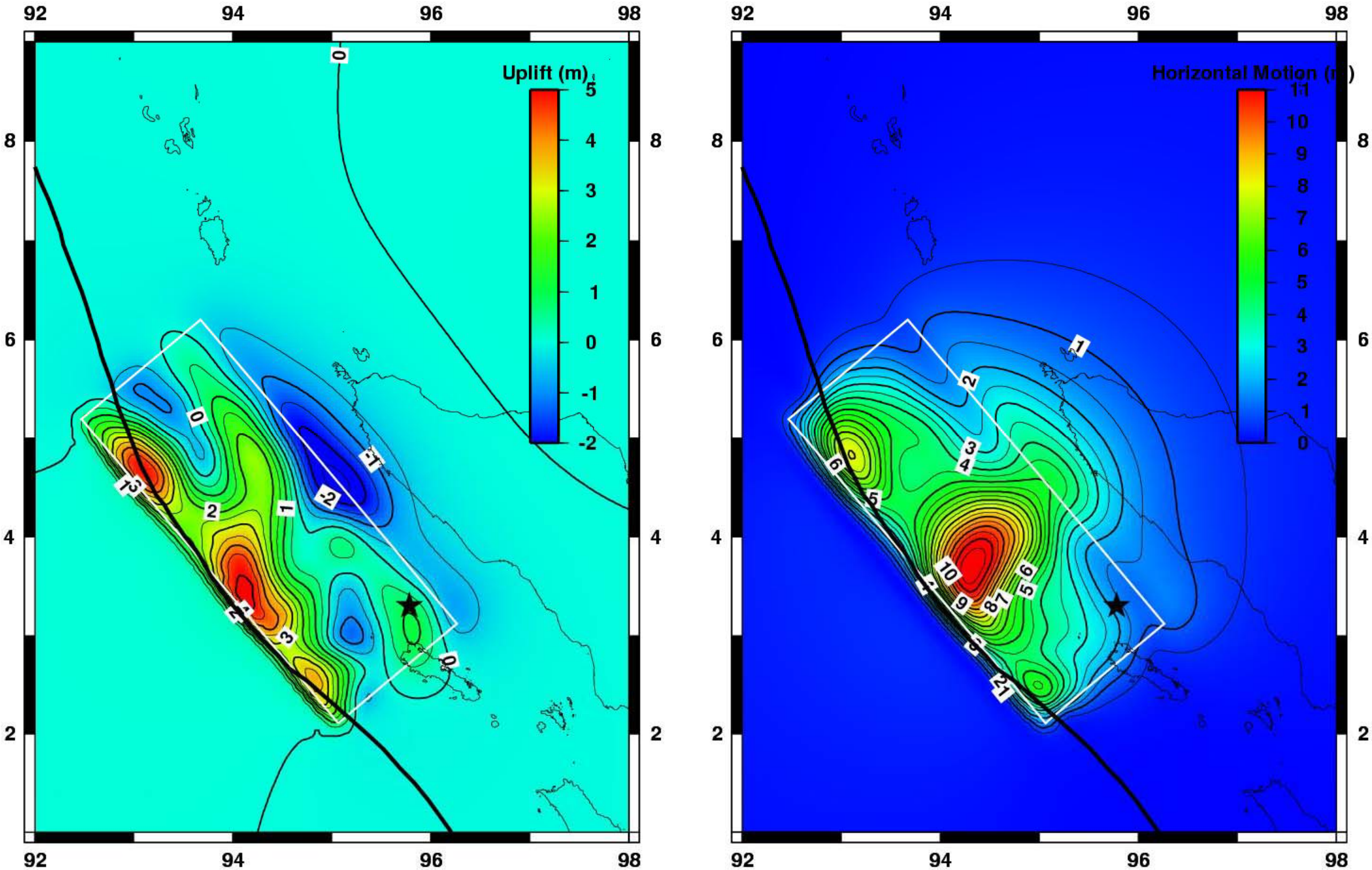
The actual slip process is described by superposition of equivalent forces acting in space and time.

Der Bruchvorgang



Größte zu erwartende Bruchfläche in Deutschland

Verschiebung am Meeresboden



Simulation of rotational motions in 3D (heterogeneous) media: finite faults

Mw: 6.5

L: 23 km

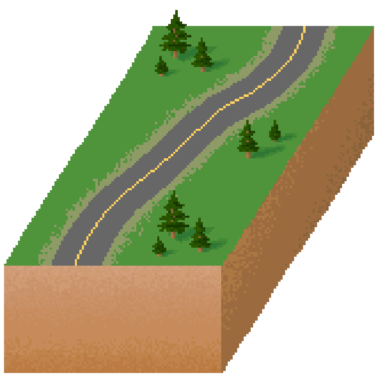
W: 14 km

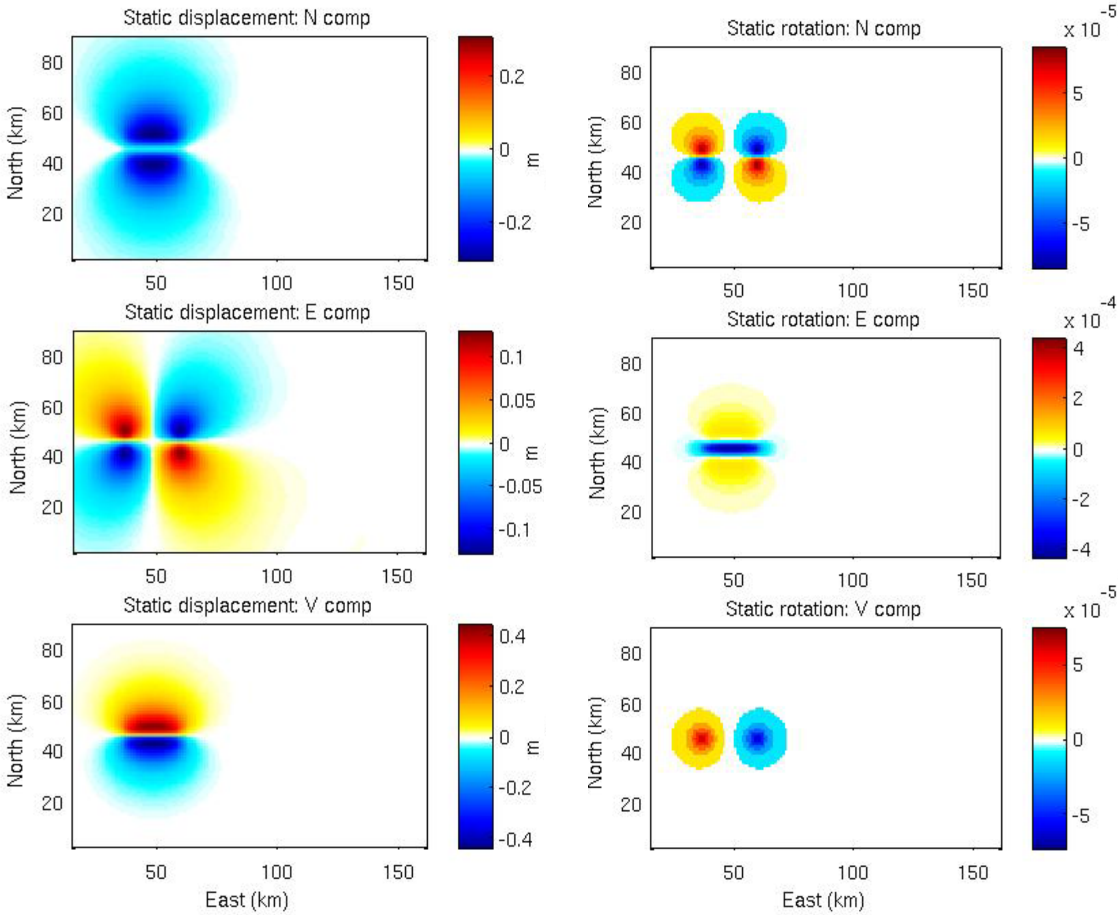
L_e: 1x1 km

N: 22x14

Haskell rupture model

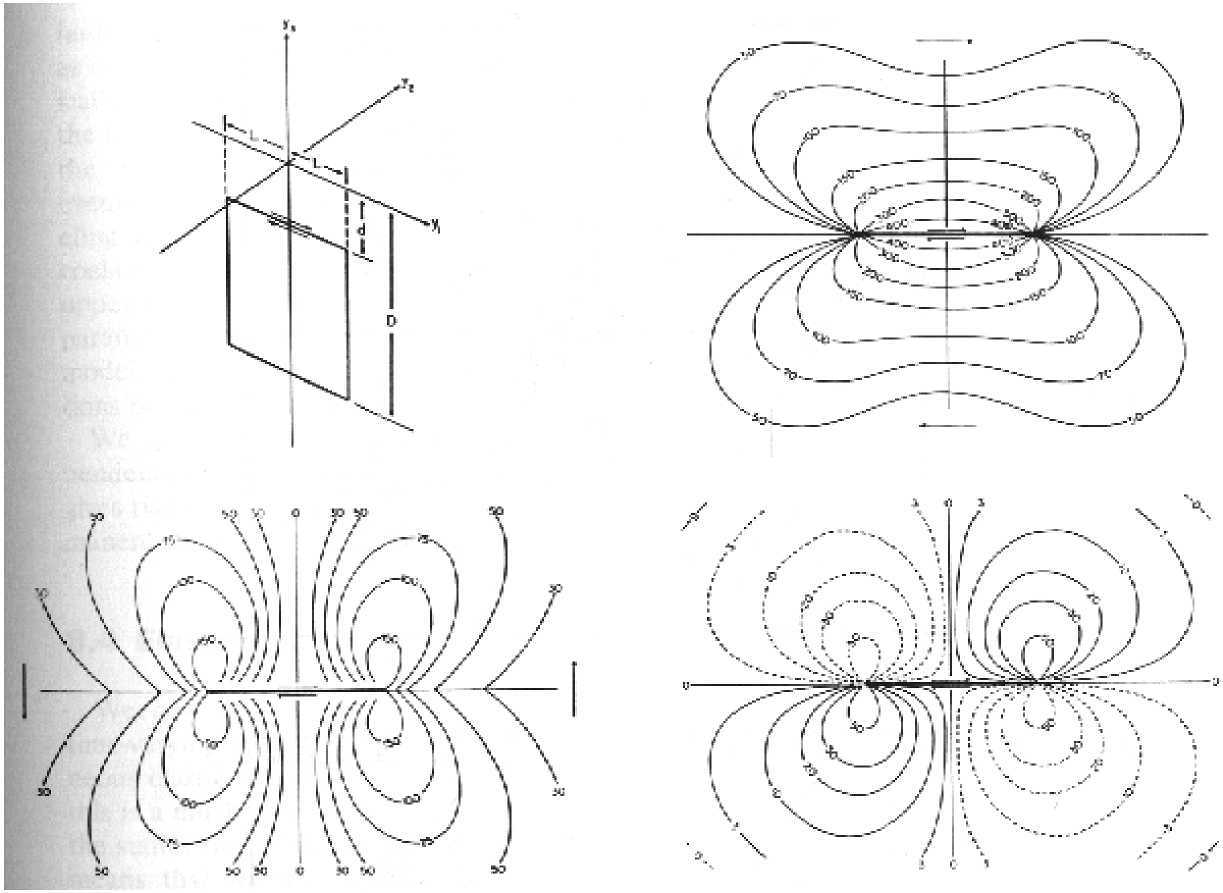
Strike slip





(Results shown for homogeneous model)

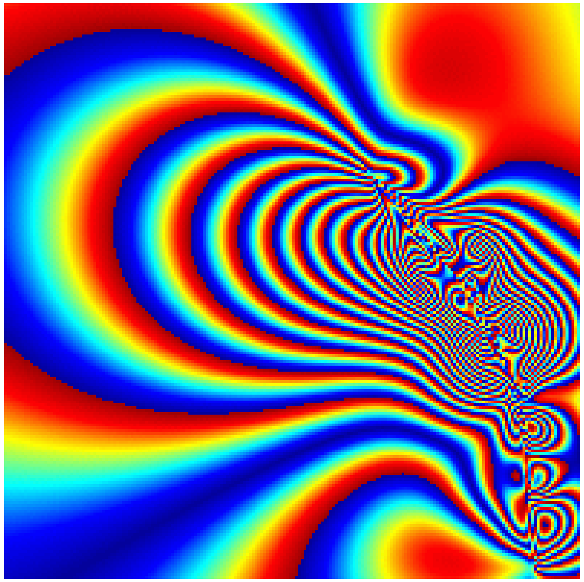
Static Displacements



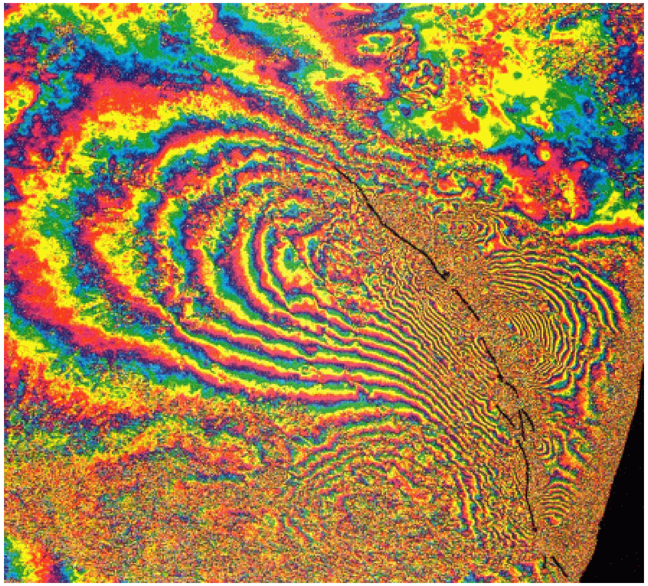
Ground displacement at the surface of a vertical strike slip.

Top right: fault parallel motion
Lower left: fault perpendicular motion
Lower right: vertical motion

Co-seismic deformation



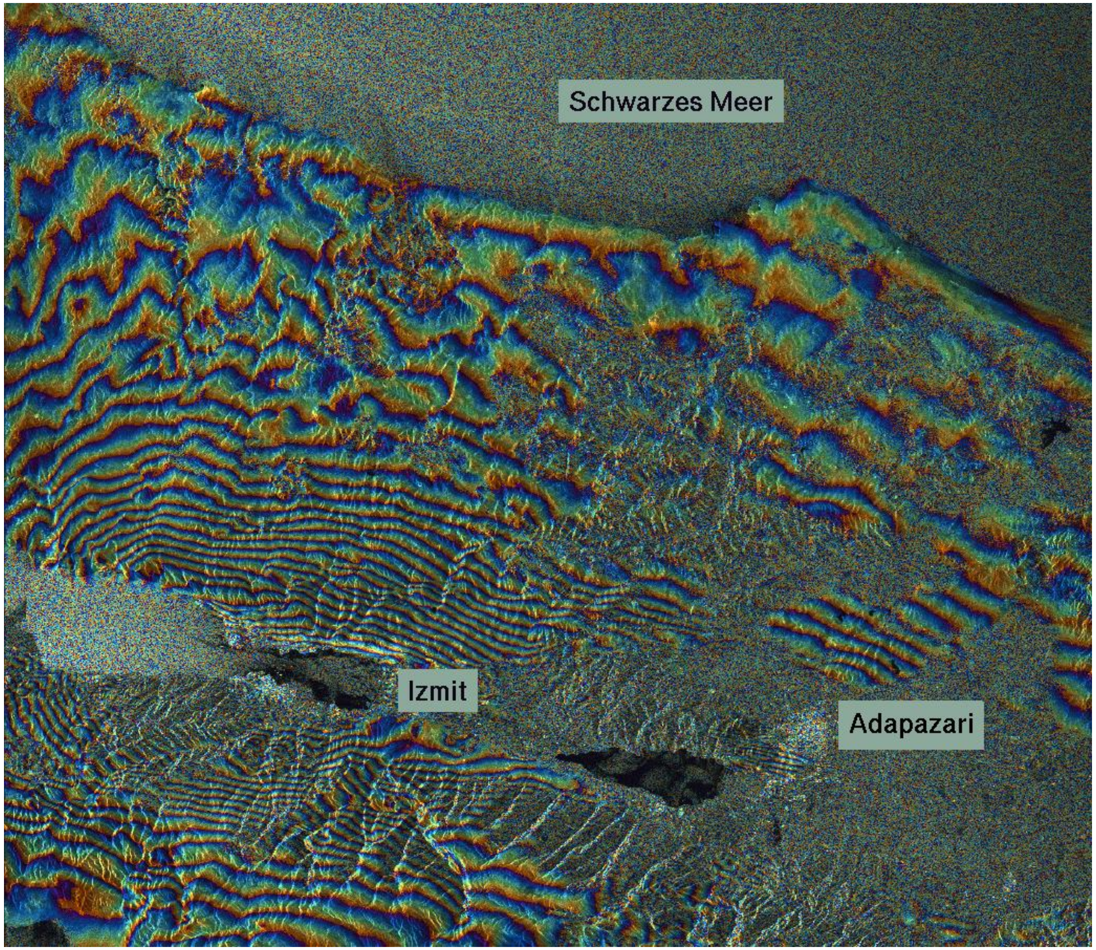
Simulated deformation



Observed deformation

Source Kim Olsen, UCSB

Static Displacements

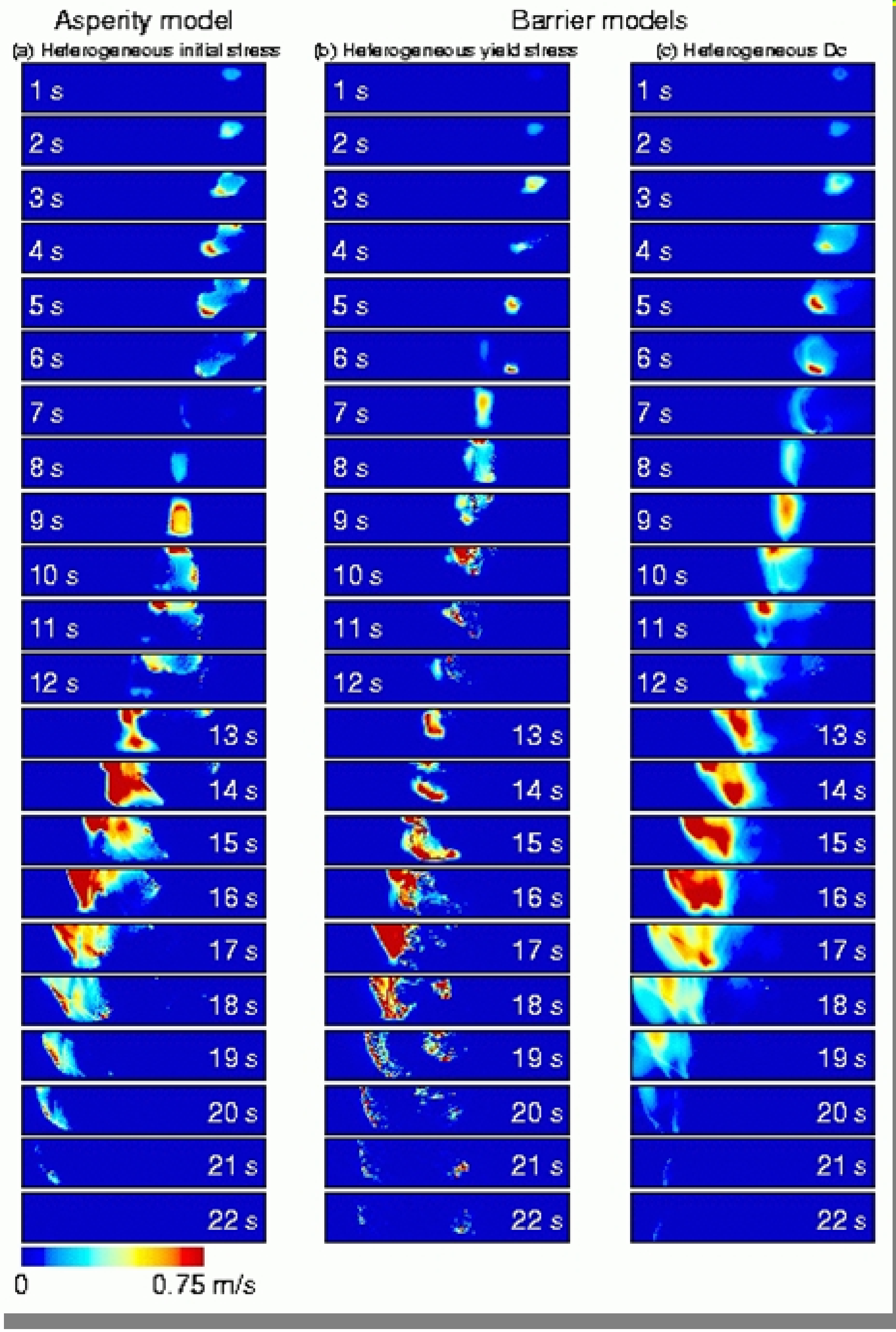


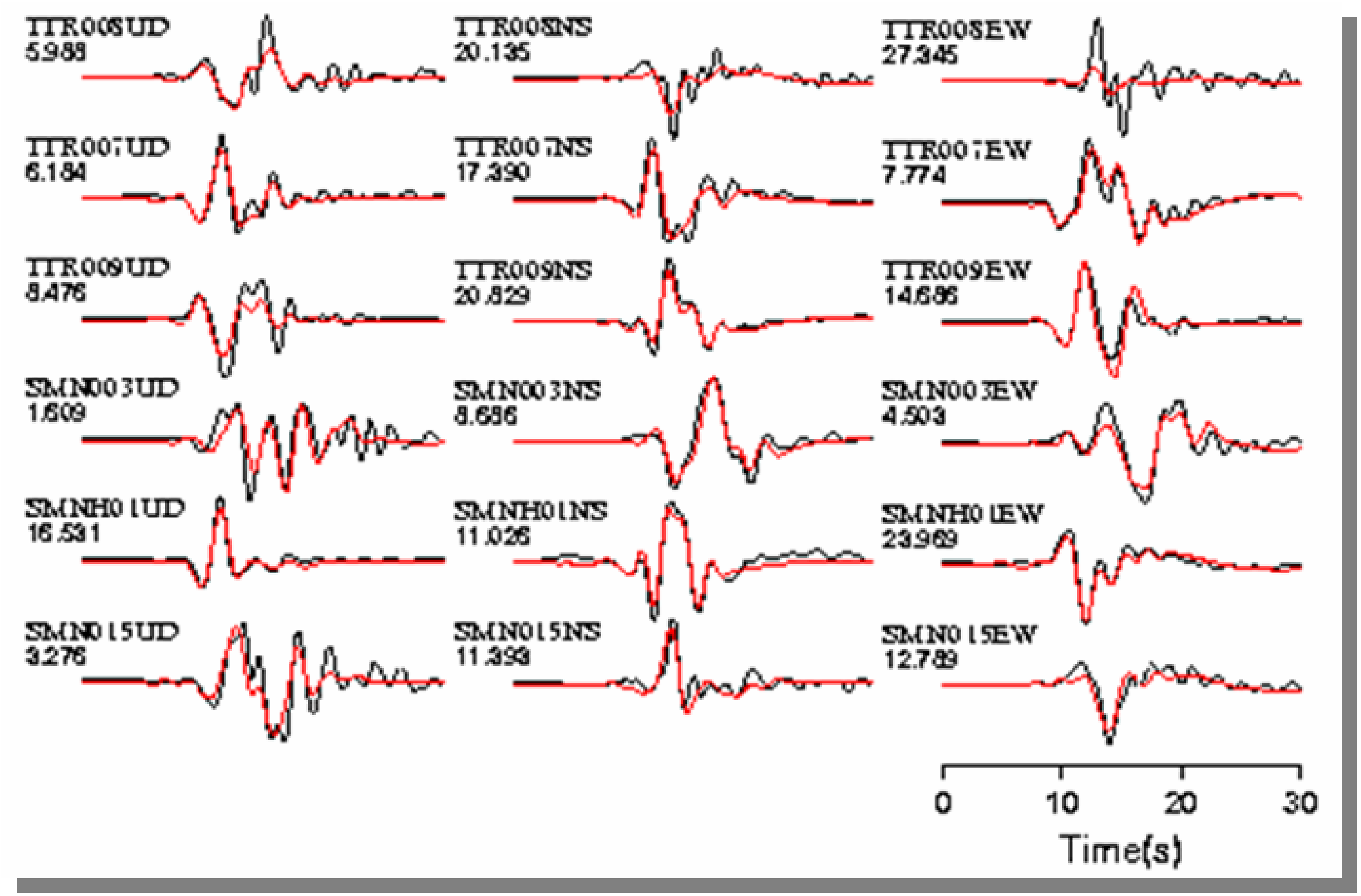
Displacements after Turkey earthquake 1999.

Source kinematics

Slip rate as a function of various fault conditions (Landers earthquake)

Source: K Olsen, UCSB



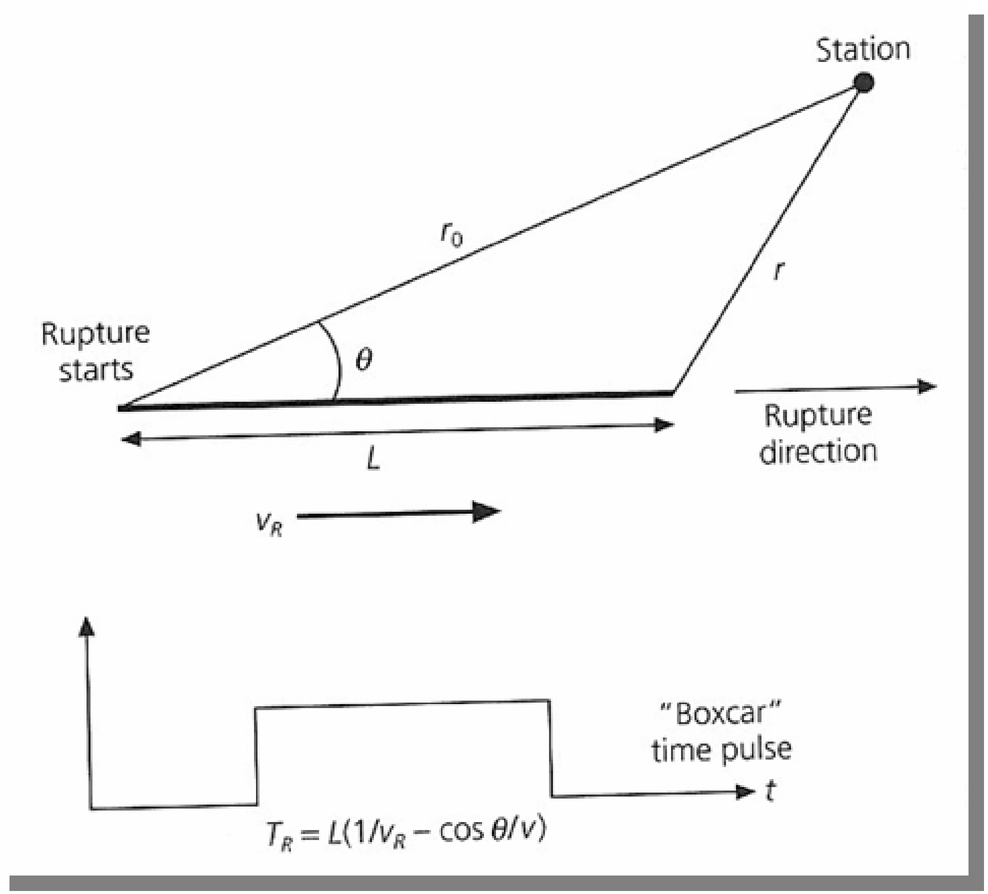


TTR008UD
5.988
TTR008NS
20.135
TTR008EW
27.345
TTR007UD
6.184
TTR007NS
17.390
TTR007EW
7.774
TTR009UD
8.476
TTR009NS
20.829
TTR009EW
14.686
SMN003UD
1.609
SMN003NS
8.686
SMN003EW
4.503
SMNH01UD
16.531
SMNH01NS
11.026
SMNH01EW
23.969
SMN015UD
3.276
SMN015NS
11.393
SMN015EW
12.789
0
10
20
30
Time(s)

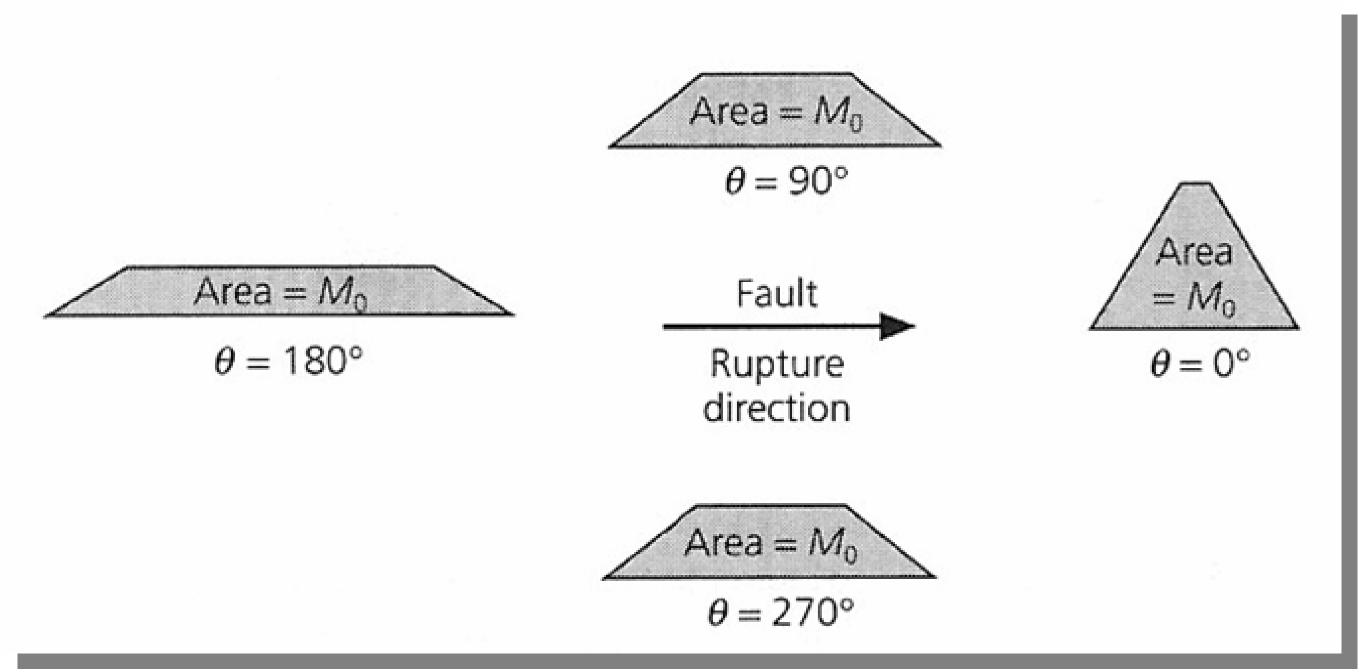
Source directivity

When a finite fault ruptures with velocity v_r, the time pulse is a boxcar with duration

$T_R = L(1/v_r - \cos(\theta/v))$



Source directivity



The energy radiation becomes strongly anisotropy (Dopple effect). In the direction of rupture propagation the energy arrives within a short time window.

Source kinematics

Point source characteristics (source moment tensor, rise time, source moment, rupture dimensions) give us some estimate on what happened at the fault. However we need to take a closer look. We are interested in the space-time evolution of the rupture.

Here is the fundamental concept:

The recorded seismic waves are a superpositions of many individual double-couple point sources.

This leads to the problem of estimating this space-time behavior from observed (near fault) seismograms. The result is a kinematic description of the source.

Seismic moment

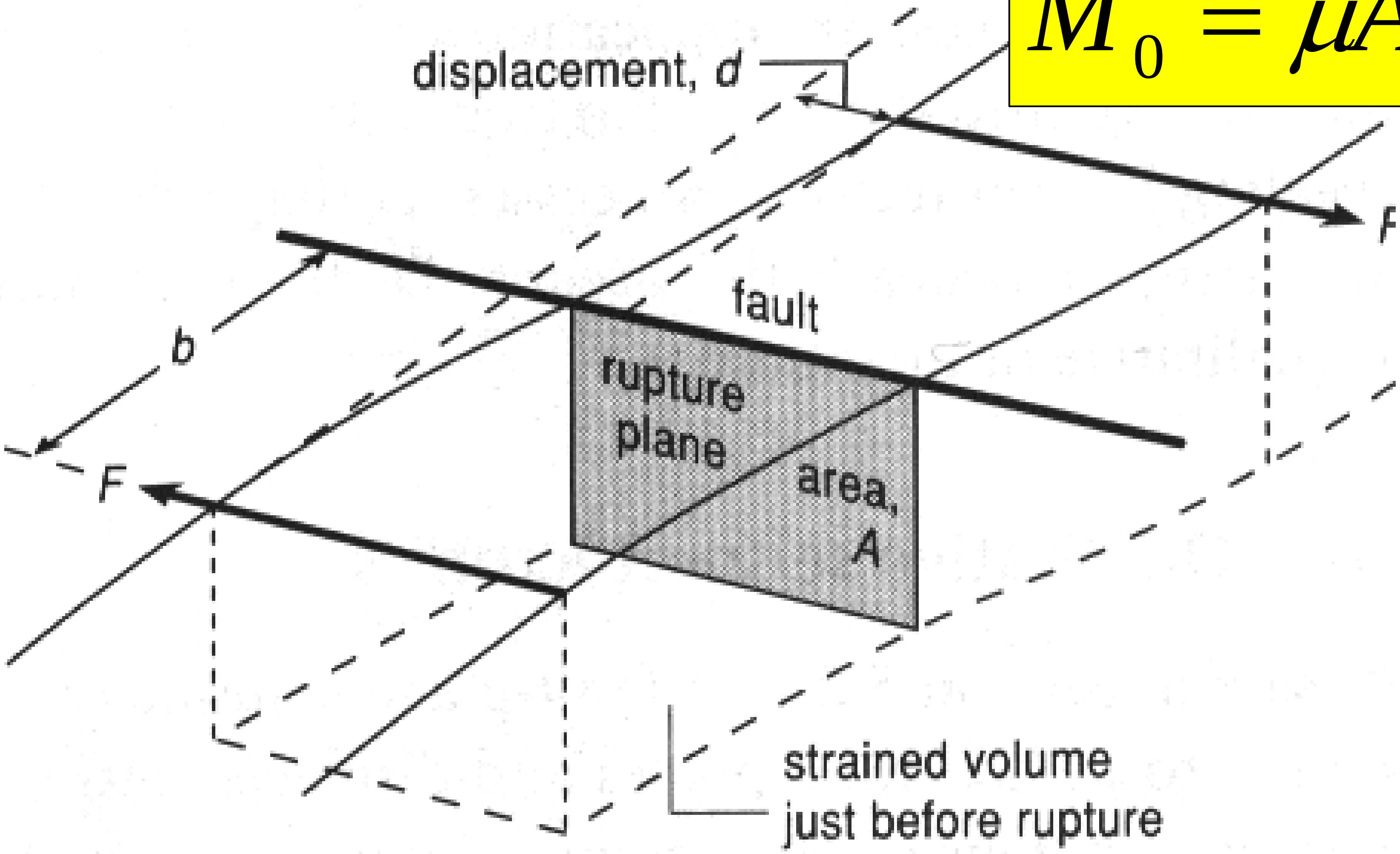
Seismologists measure the size of an earthquake using the concept of seismic moment. It is defined as the force times the distance from the center of rotation (torque). The moment can be expressed suprisingly simple as:

$$M_0 = \mu A d$$

M_0 seismic moment
μ Rigidity
A fault area
d slip/displacement

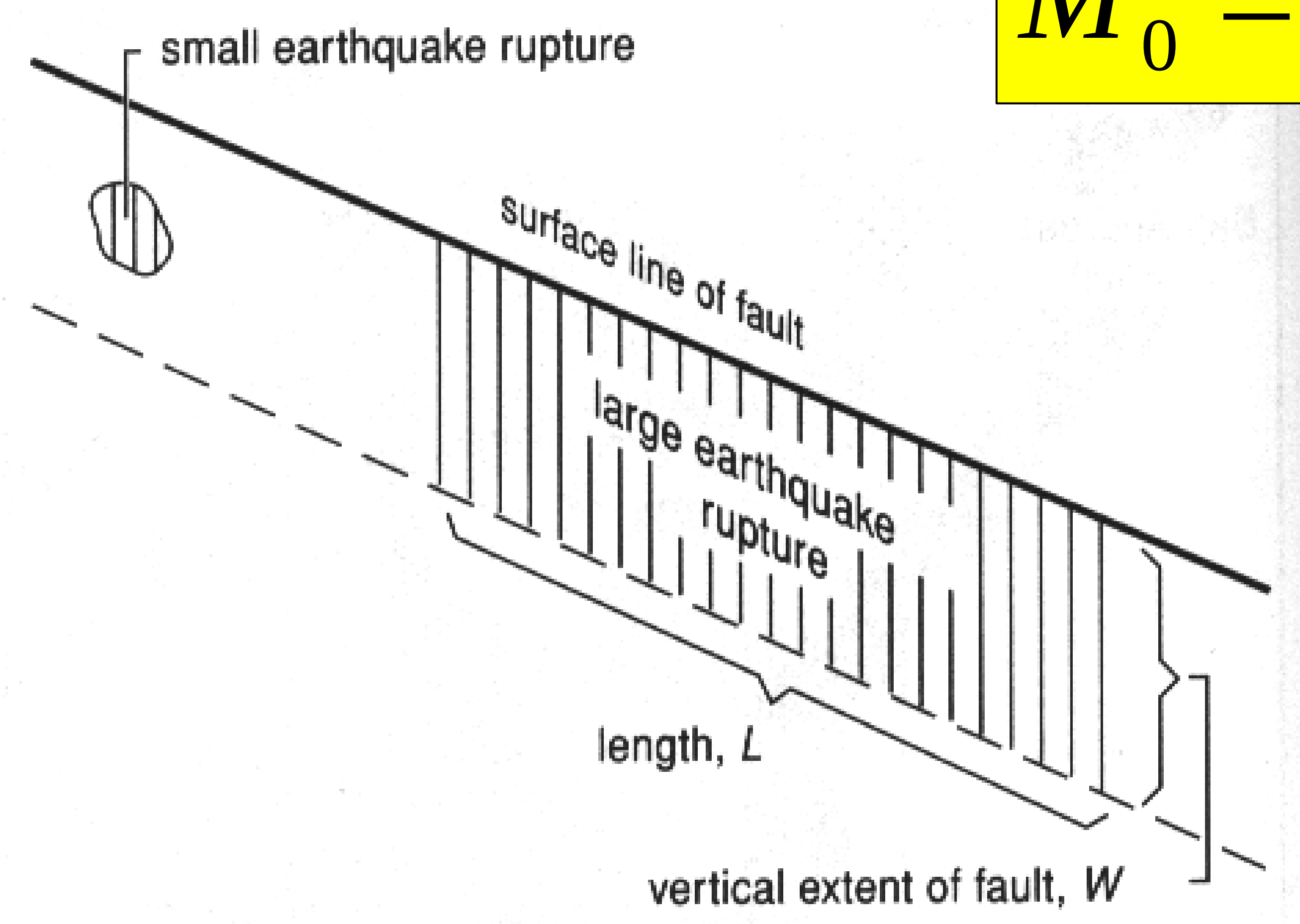
Seismic moment

$$M_0 = \mu A d$$

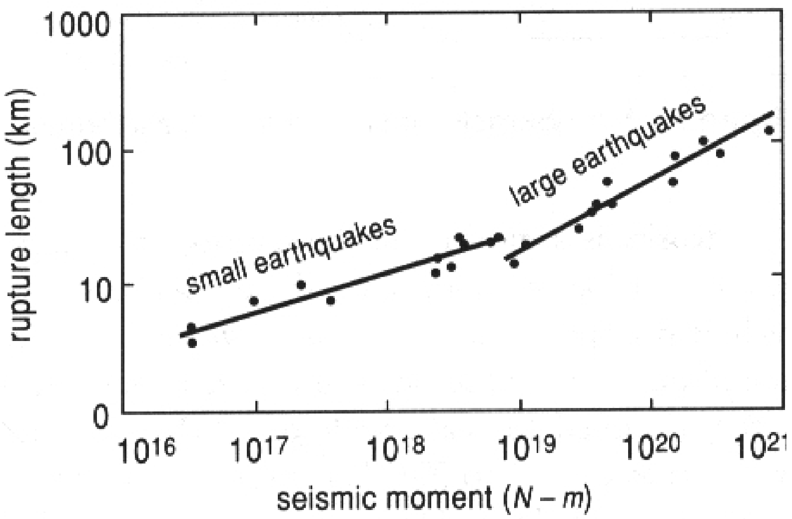


Seismic moment

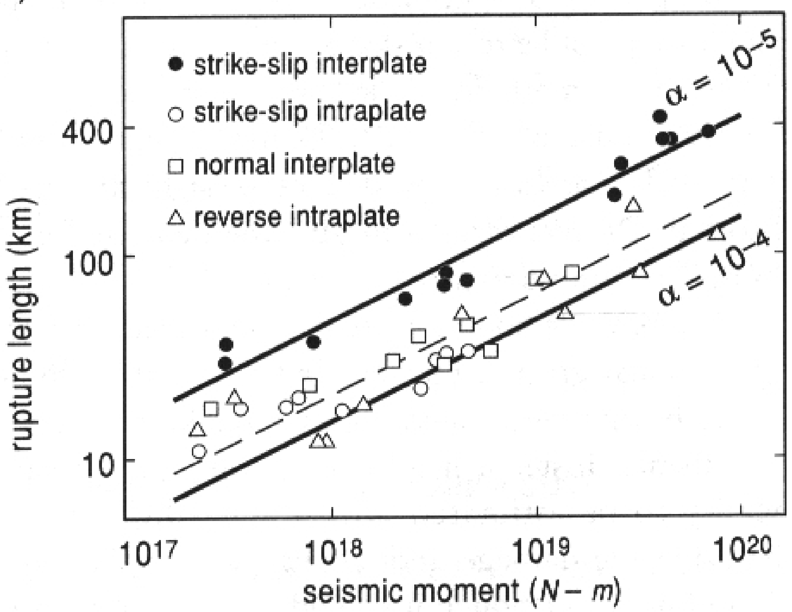
$$M_0 = \mu A d$$



Seismic moment



(c)



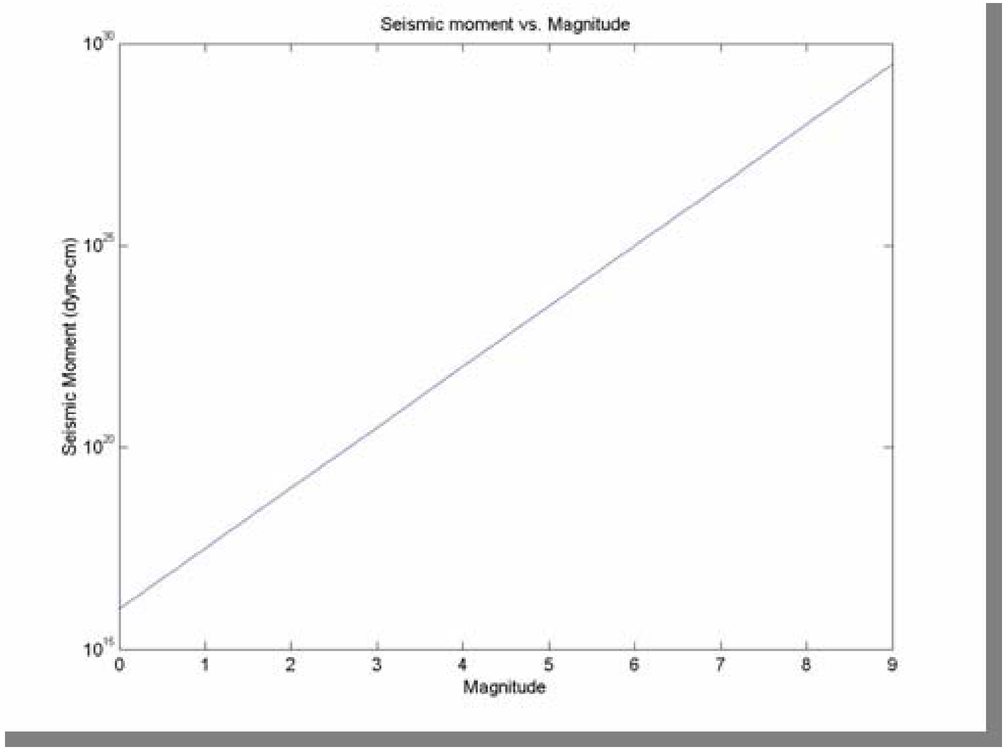
$$M_0 = \mu A d$$

There are differences in the scaling of large and small earthquakes

Seismic moment - magnitude

There is a standard way of converting the seismic moment to magnitude M_w:

$$M_w = \frac{2}{3}\left[\log_{10} M_0(dyne-cm) - 16.0\right]$$



Seismic energy

Richter developed a relationship between magnitude and energy (in ergs)

$$\log E_S = 11.8 + 1.5M$$

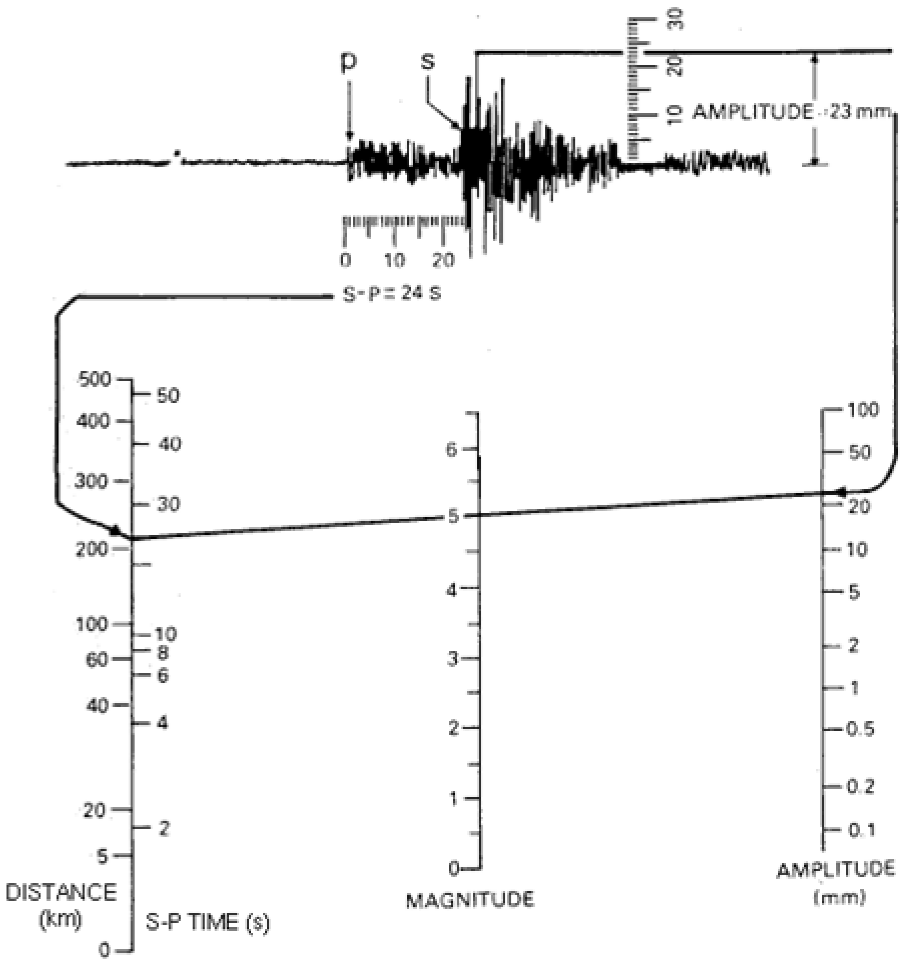
... The more recent connection to the seismic moment (dyne-cm) (Kanamori) is

$$Energy = Moment / 20000$$

Seismic energy (Examples)

Richter Magnitude	TNT for Seismic Energy Yield	Example (approximate)
-1.5	6 ounces	Breaking a rock on a lab table
1.0	30 pounds	Large Blast at a Construction Site
1.5	320 pounds	
2.0	1 ton	Large Quarry or Mine Blast
2.5	4.6 tons	
3.0	29 tons	
3.5	73 tons	
4.0	1,000 tons	Small Nuclear Weapon
4.5	5,100 tons	Average Tornado (total energy)
5.0	32,000 tons	
5.5	80,000 tons	Little Skull Mtn., NV Quake, 1992
6.0	1 million tons	Double Spring Flat, NV Quake, 1994
6.5	5 million tons	Northridge, CA Quake, 1994
7.0	32 million tons	Hyogo-Ken Nanbu, Japan Quake, 1995; Largest Thermonuclear Weapon
7.5	160 million tons	Landers, CA Quake, 1992
8.0	1 billion tons	San Francisco, CA Quake, 1906
8.5	5 billion tons	Anchorage, AK Quake, 1964
9.0	32 billion tons	Chilean Quake, 1960
10.0	1 trillion tons	(San-Andreas type fault circling Earth)
12.0	160 trillion tons	(Fault Earth in half through center, OR Earth's daily receipt of solar energy)

Richter Scale



Determination of the magnitude of an earthquake graphically.

$$M_L = \log_{10} A(mm) + (\text{Distance correction factor})$$

Seismic sources

Far away from the source (far-field) seismic sources are best described as point-like double couple forces. The orientation of the inital displacement of P or S waves allows estimation of the orientation of the slip at depth.

The determination of this focal mechanism (in addition to the determination of earthquake location) is one of the routine task in observational seismology. The quality of the solutions depends on the density and geometry of the seismic station network.

The size of earthquakes is described by magnitude and the seismic moment. The seismic moment depends on the rigidity, the fault area and fault slip in a linear way. Fault scarps at the surface allow us to estimate the size of earthquakes in historic times.