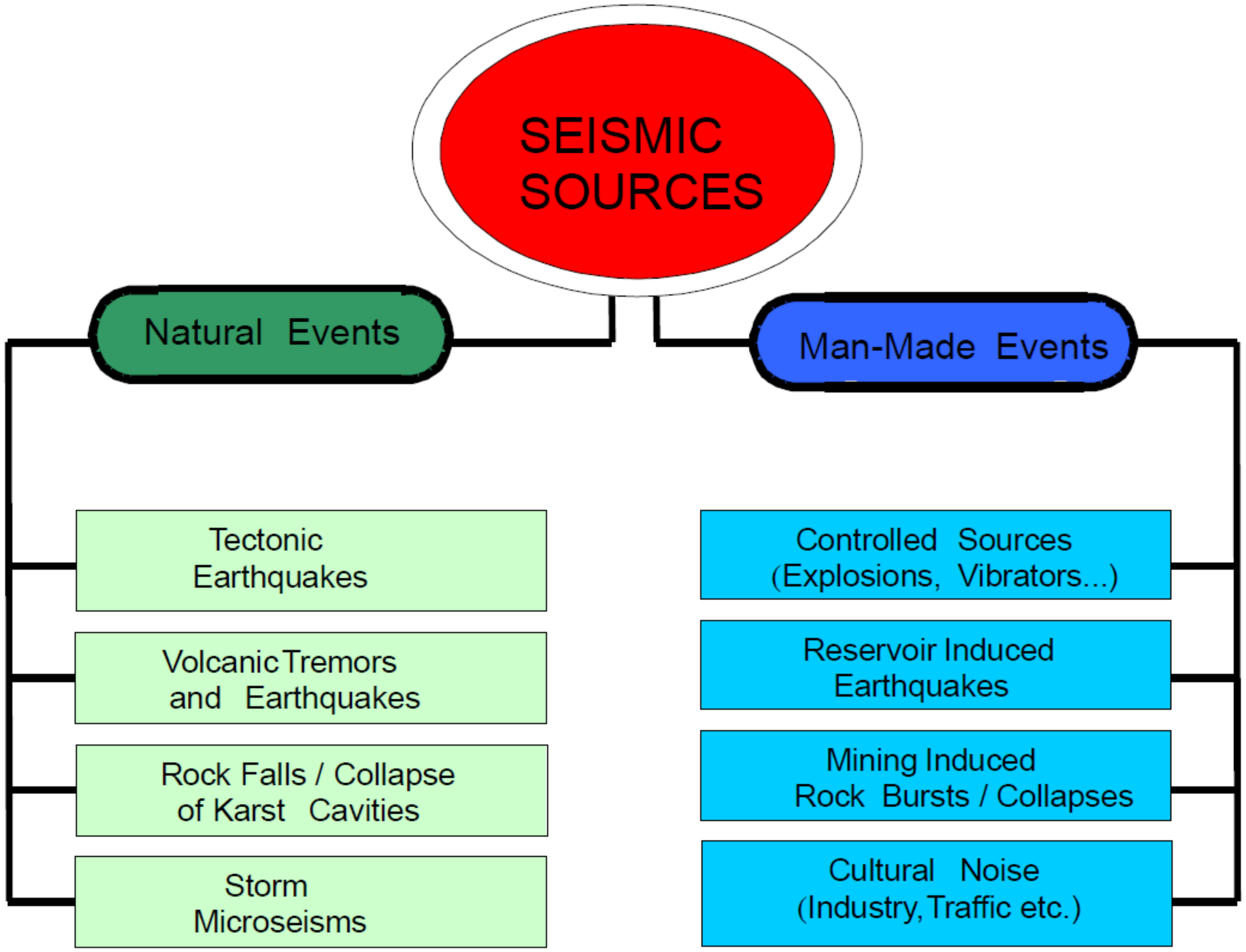
UNIVERSITÀ DEGLI STUDI DI TRIESTE

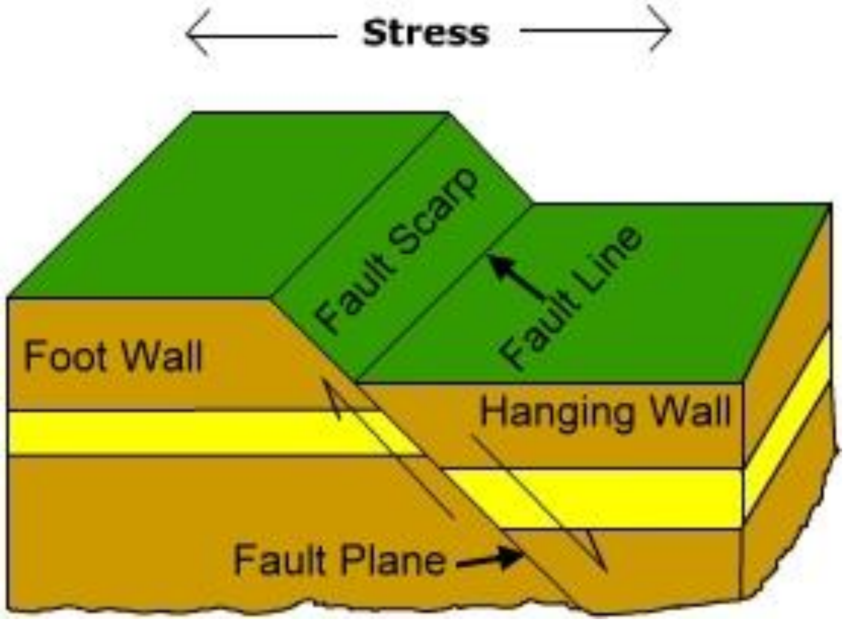
Applied seismology

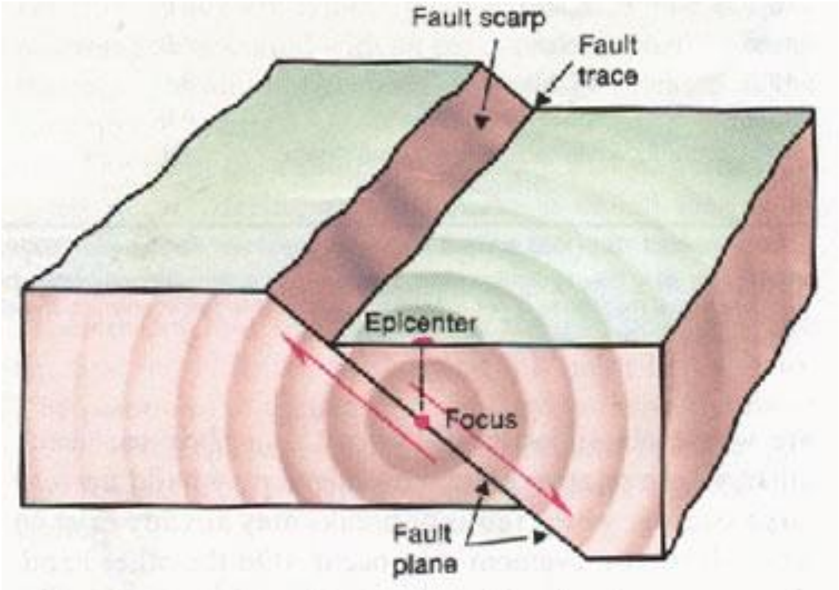
Seismic source

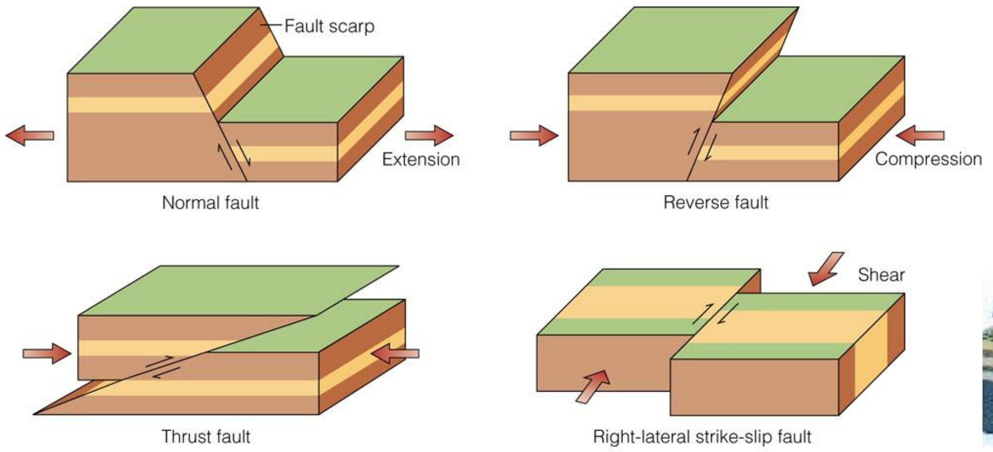
Giovanni Costa - costa@units.it

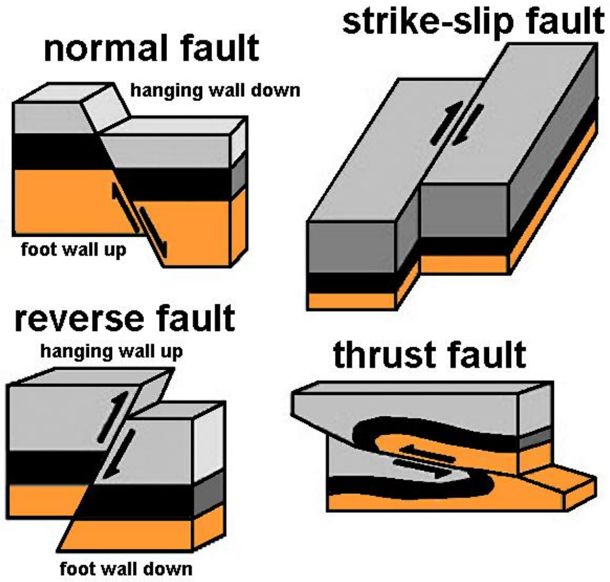


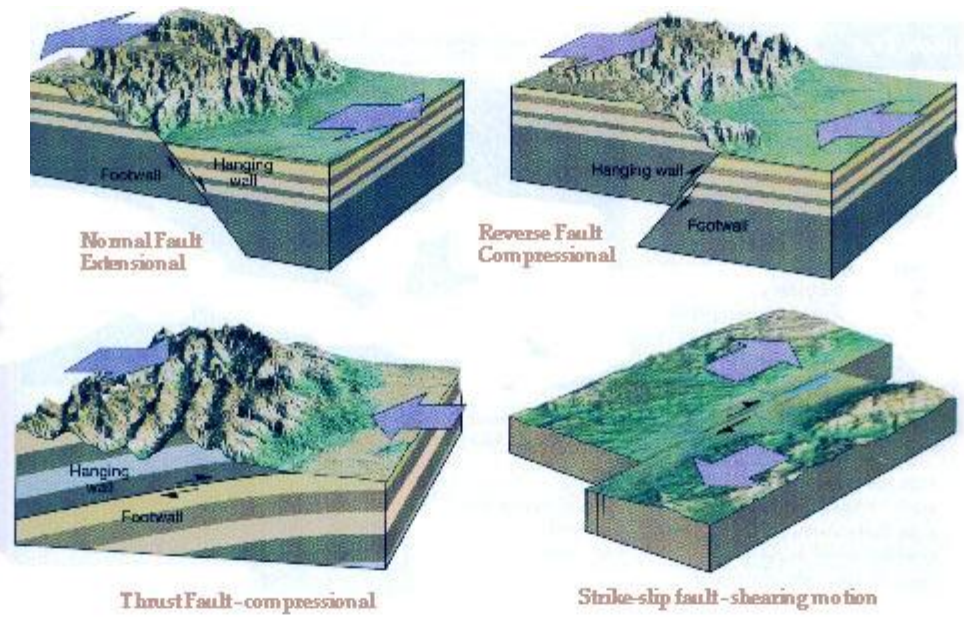
Schematic classification of various types of events that generate seismic waves.


Stress
Fault Scarp
Fault Line
Foot Wall
Hanging Wall
Fault Plane

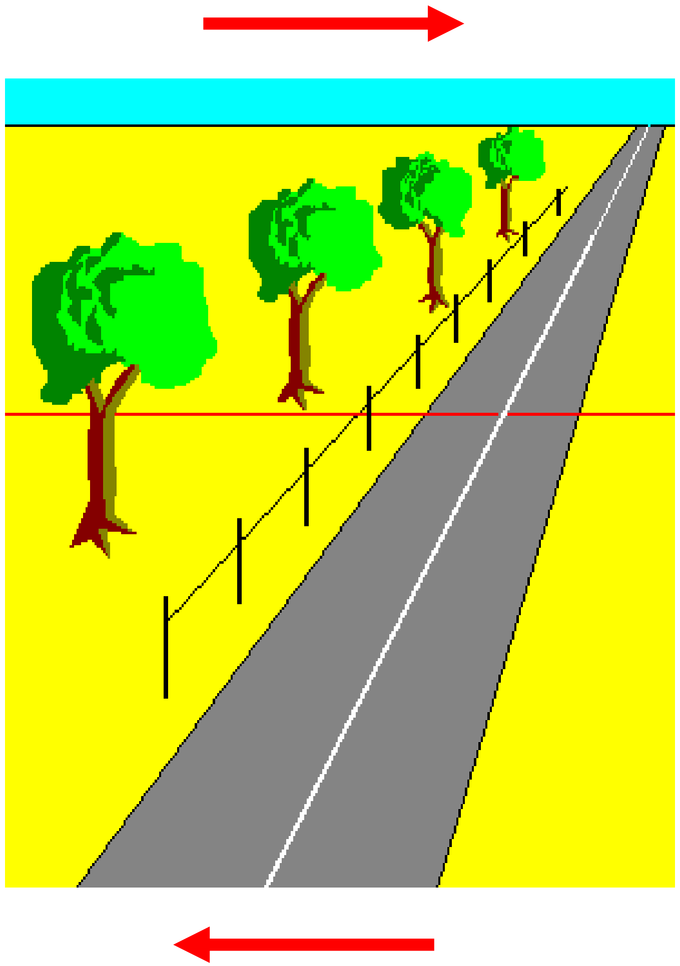

Fault scarp
Fault trace
Epicenter
Focus
Fault plane

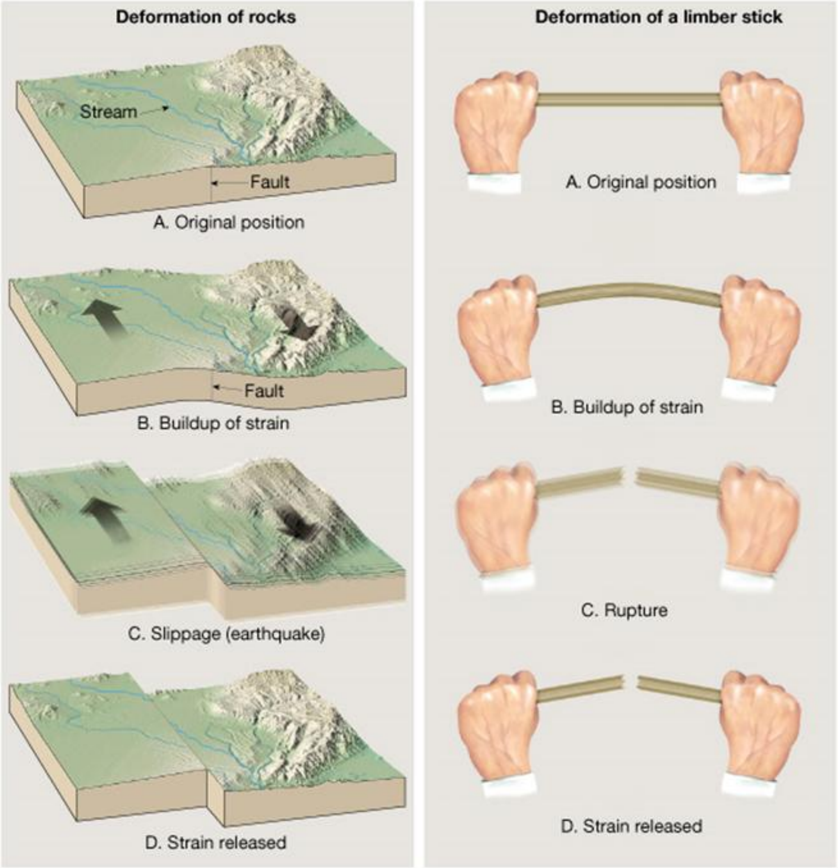

Fault scarp
Extension
Normal fault
Compression
Reverse fault
Thrust fault
Shear
Right-lateral strike-slip fault

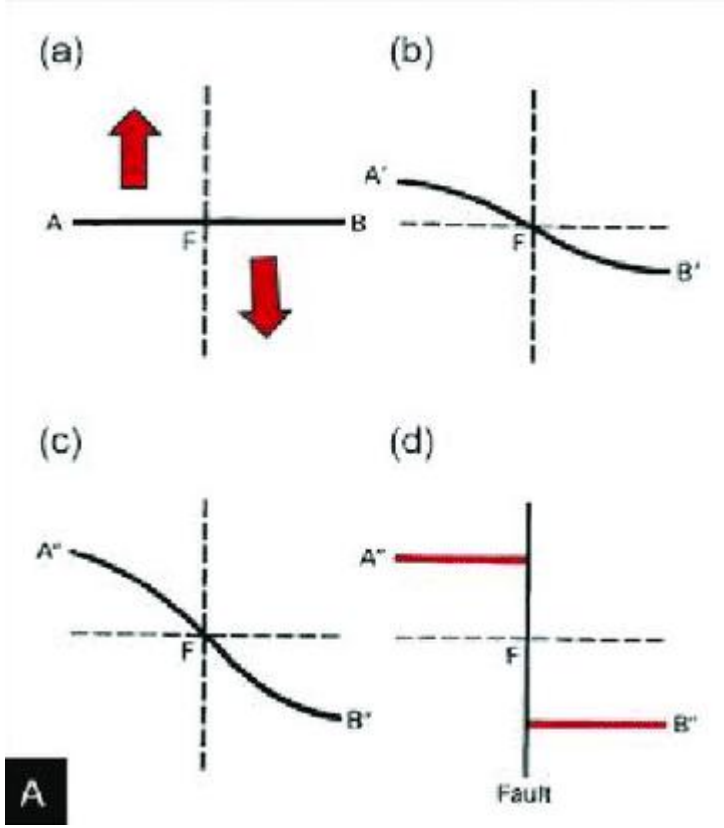

normal fault
hanging wall down
foot wall up
strike-slip fault
reverse fault
hanging wall up
foot wall down
thrust fault


Footwall
Hanging wall
Normal Fault
Extensional
Hanging wall
Footwall
Reverse Fault
Compressional
Hanging wall
Footwall
Thrust Fault - compressional
Strike-slip fault - shearing motion

Theory of elastic rebound

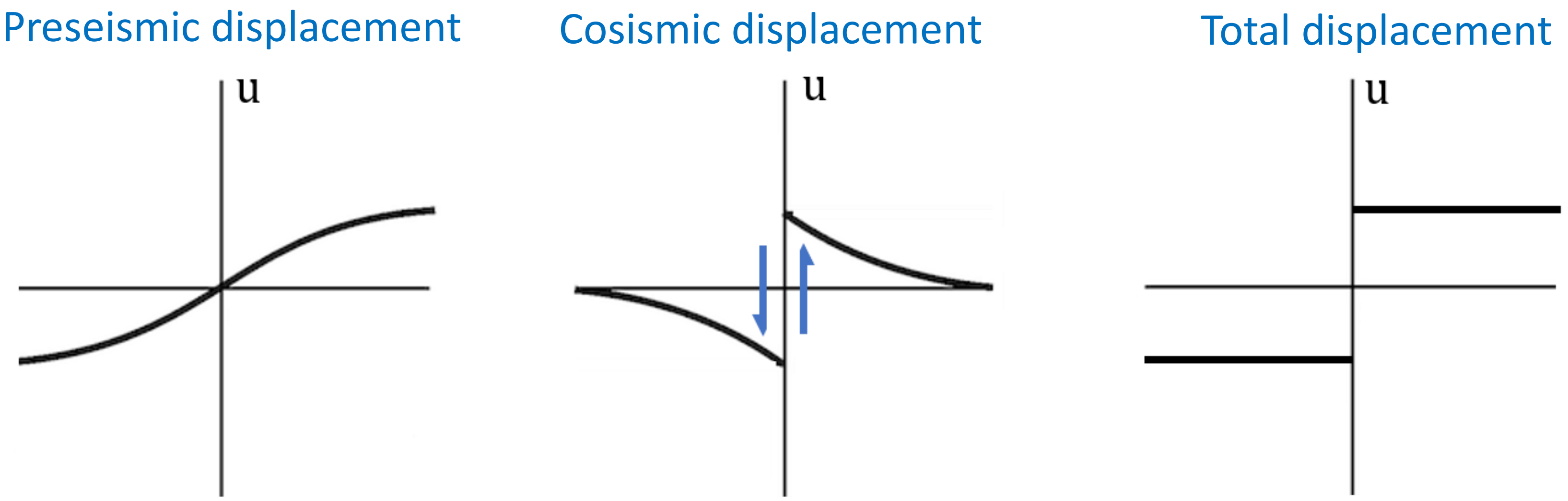




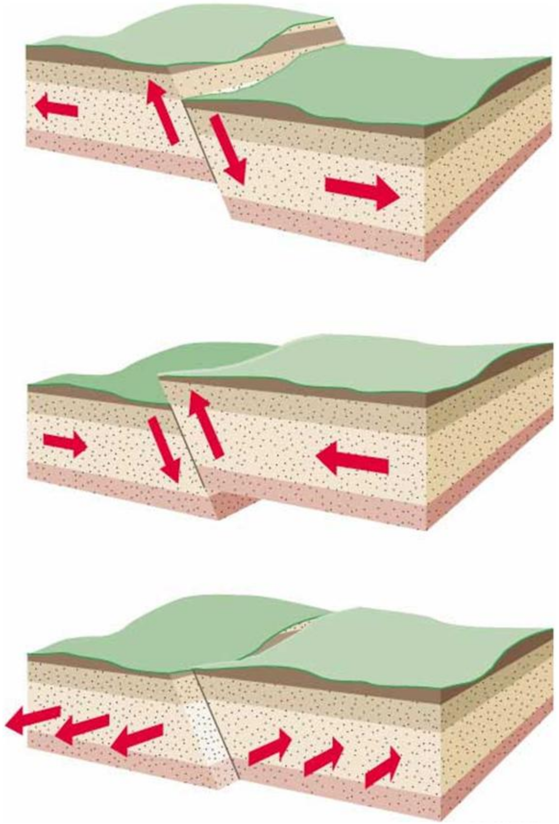


The elastic rebound theory is one explanation of how energy is released during earthquakes. When rocks on opposite sides of a fault are subjected to forces and displacements, they accumulate energy and slowly deform until they overcome their internal force. At that time, sudden movement occurs along the fault, releasing the accumulated energy, and the rocks return to their original undeformed shape.

THEORY OF ELASTIC REBOUND



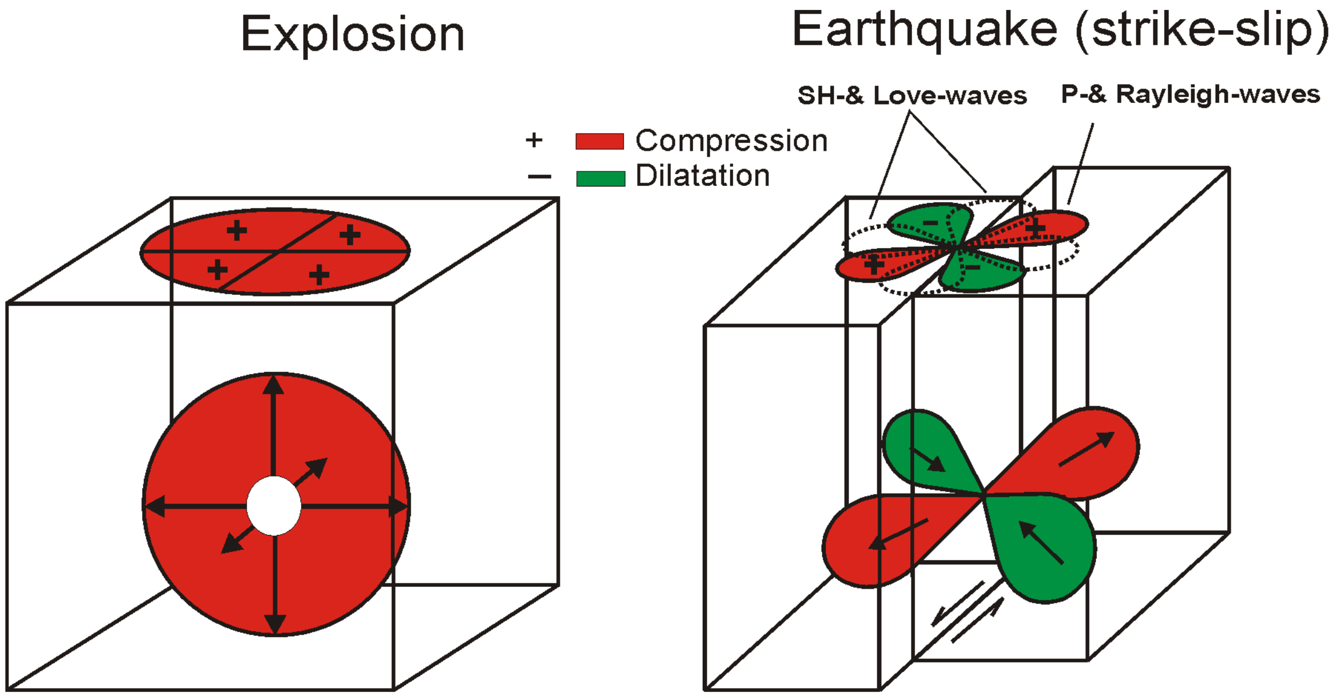
Faults



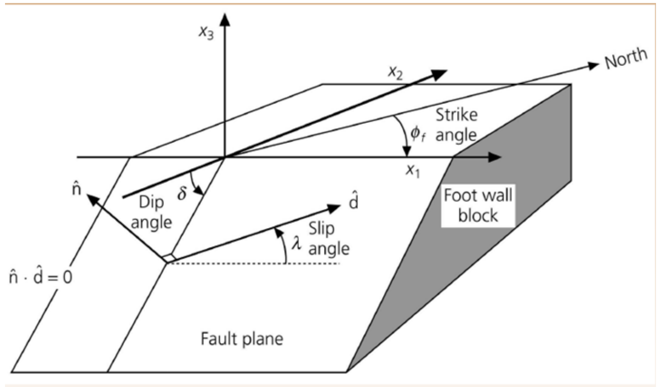
Direct

Reverse

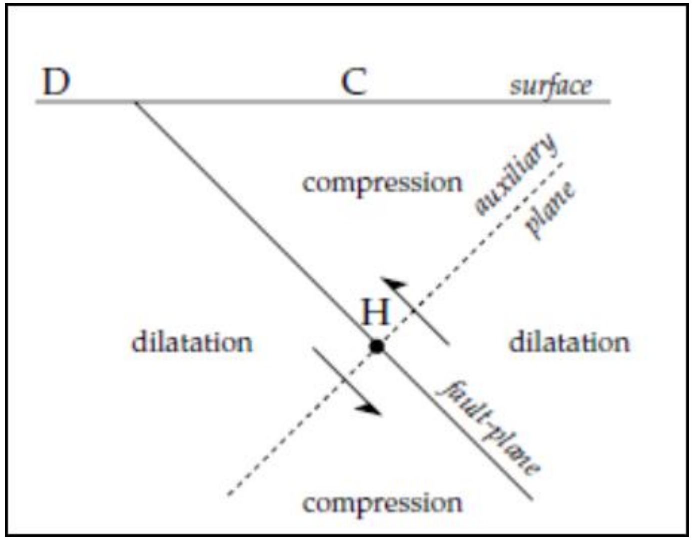
Strike Slip



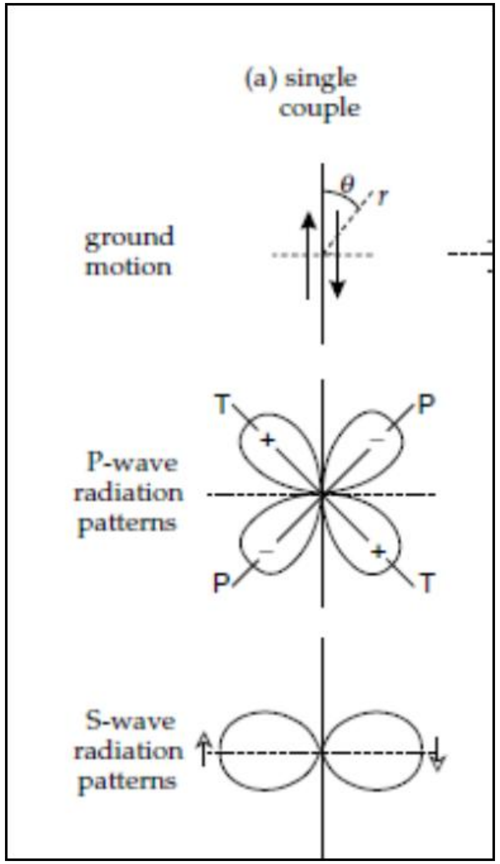
Schematic sketches of an idealized underground explosion and strike-slip earthquake along a vertical fault. The motion of the fault is "left lateral," i.e., counterclockwise. Arrows show directions of compressional (outward, + polarity, shaded red) and dilational (inward, polarity, shaded green) motions. The trends shown on the surface indicate the azimuthal variation of the observed amplitudes or direction of the first motions in the seismic recordings, respectively.



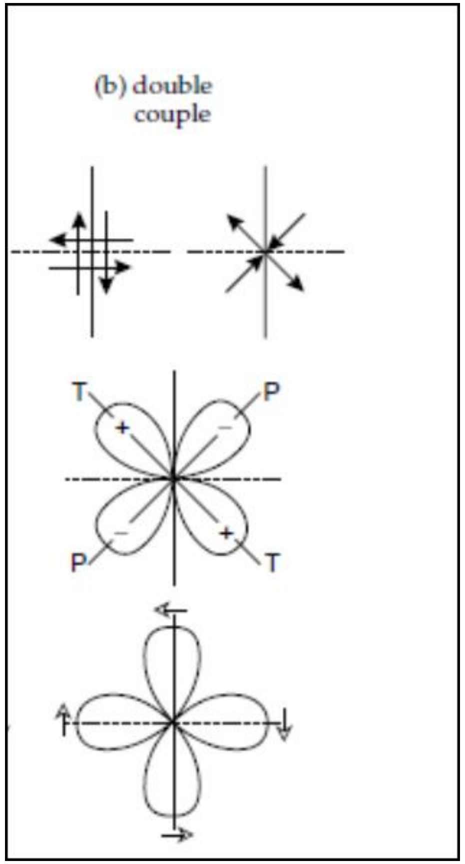
x_3
x_2
North
Strike angle
ϕ_f
x_1
$\hat{n}$
Dip angle
δ
$\hat{d}$
Slip angle
λ
Foot wall block
$\hat{n} \cdot \hat{d} = 0$
Fault plane



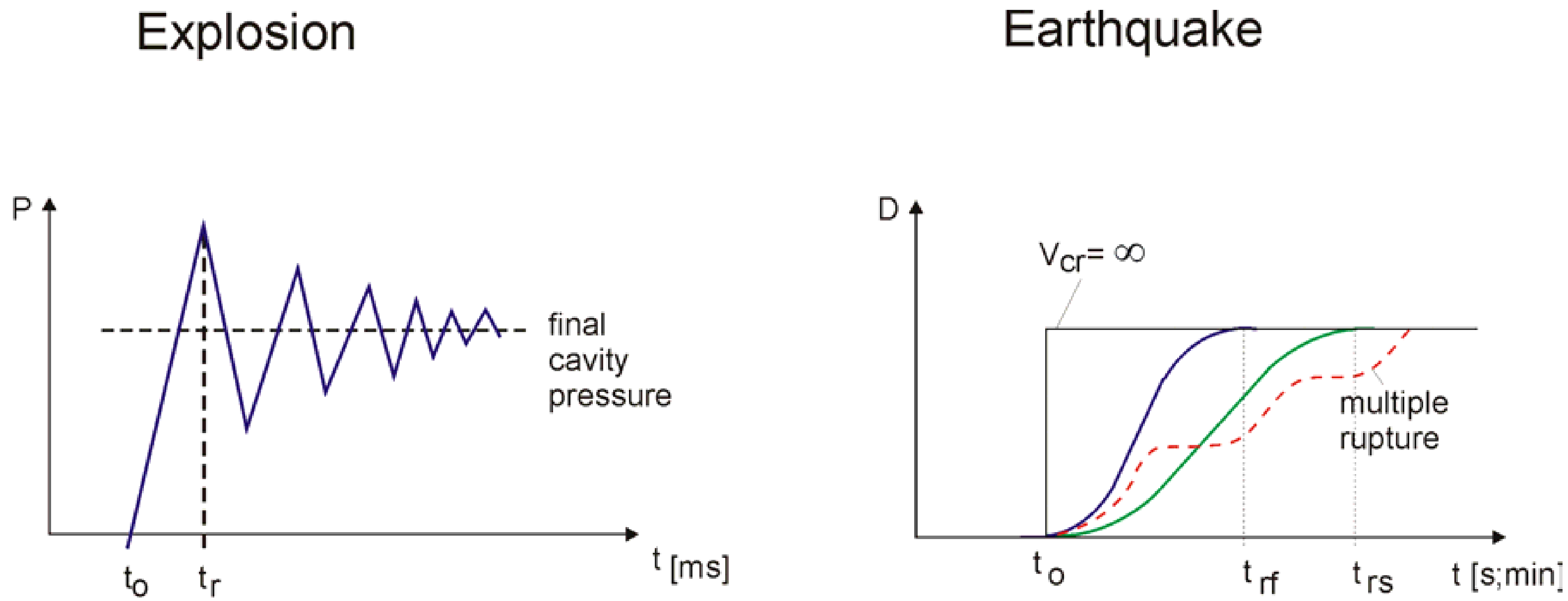
D
C
surface
compression
auxiliary plane
H
dilatation
dilatation
fault-plane
compression



(a) single couple
ground motion
θ
r
P-wave radiation patterns
T
P
+
–
S-wave radiation patterns



(b) double couple
T
P
+
–



Schematic diagrams of the different source functions of explosions (left) and earthquakes (right). P - pressure in the explosion cavity, D - fault displacement, t - time, t_0 - time of origin of the event, rise time of P or D to its maximum values, rise time of fast rupture, t_{rs} - rise time of slow rupture; the step function in the diagram on the right would correspond to an earthquake with infinite crack propagation velocity v_{cr}. Current rupture models assume that vcr is about 0.6 to 0.9 times the shear wave propagation speed.

SEISMIC MOMENT

$$M_0 = \mu\ \bar{D}\ A$$

With μ stiffness or shear modulus of the medium, **D** mean ultimate displacement after rupture, **A** - the surface area of rupture.

In a homogeneous half-space M_0 can be determined from the spectra of seismic waves observed at the earth's surface using the relation:

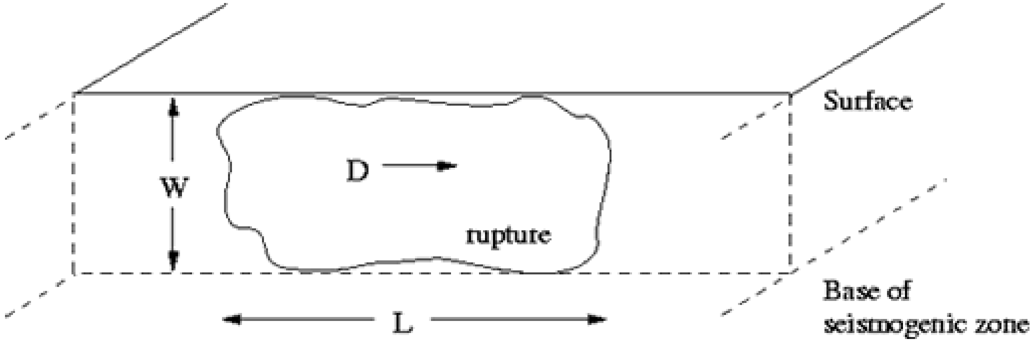
$$M_0 = 4\pi d\rho v_{p,s}^3 u_0 / R_{\theta,\varphi}^{p,s}$$

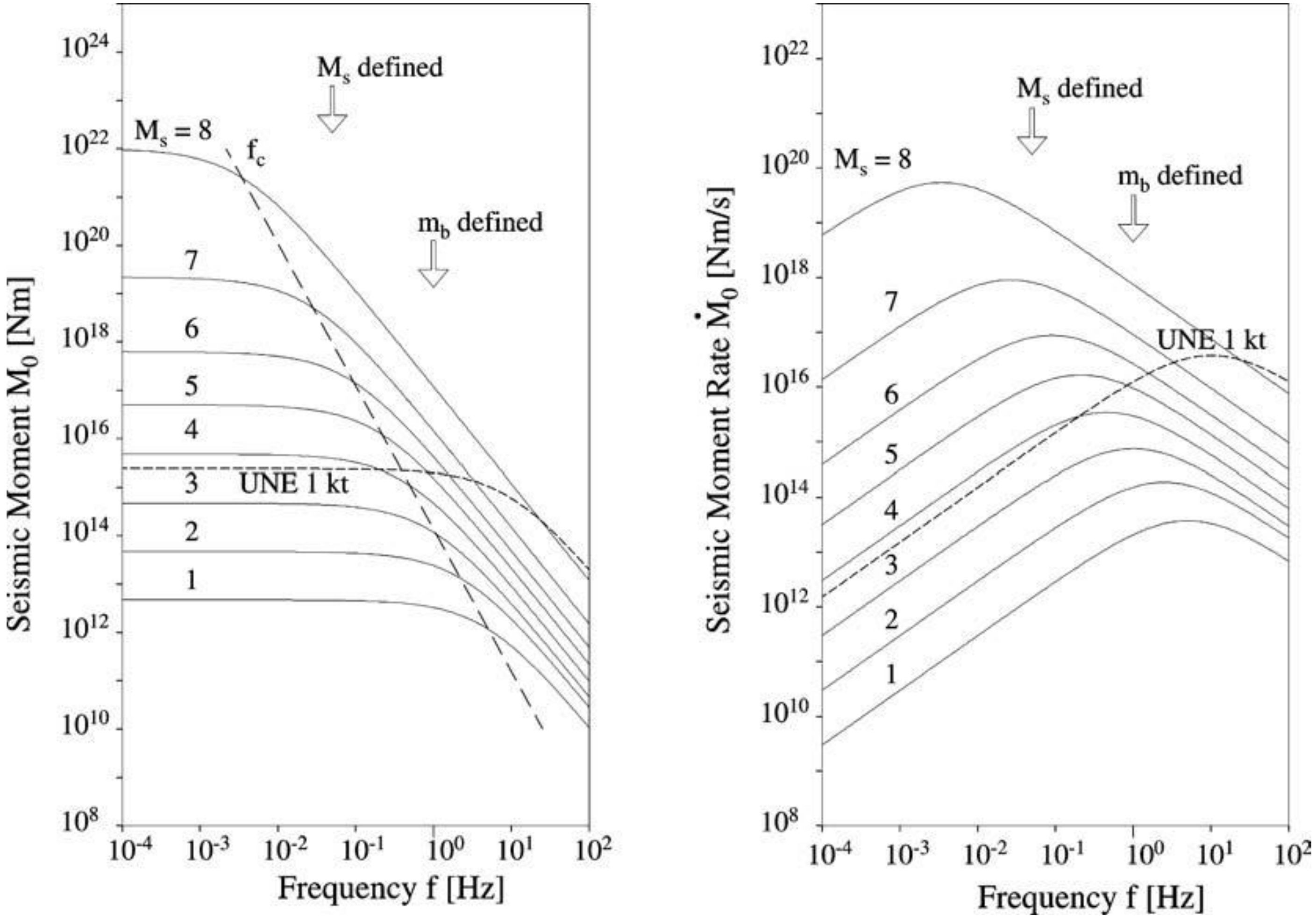
with: **d** - hypocentral distance between the event and the seismic station; **ρ** - average rock density; and $v_{p,s}$ - velocity of **P** or **S** waves around the source; $R_{\theta,\varphi}^{p,s}$ - correction factor of the observed amplitudes for the influence of the radiation pattern of the seismic source, which is different for **P**- and **S**- waves; u_0 - amplitude at the low frequency derived from the seismic spectrum of **P**- or **S**- waves, corrected for instrumental response, wave attenuation, and surface amplification.

$$Sforzo = \mu \times deformazione \rightarrow F/S = \mu\bar{u}/L \rightarrow FL = \mu\bar{u}S$$

$$\boxed{M_0 = \mu\bar{u}S}$$

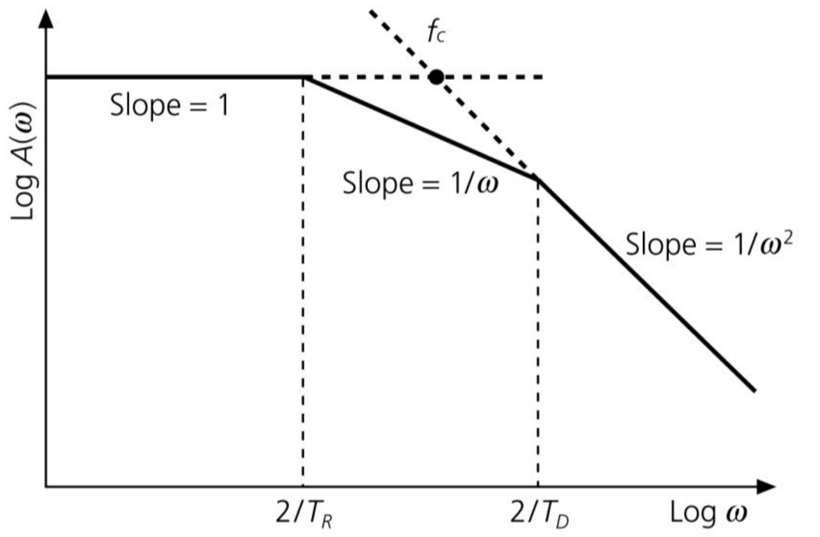
The seismic moment is the product of the area of fault surface that ruptures, the average displacement along that surface, and a constant -- a measure of the elastic property of rock (i.e. how easily it can be stretched) called the **modulus of rigidity**.





"Source spectra" of ground displacement (left) and velocity (right) for a seismic source. "Source spectrum" here means the attenuation-corrected ground displacement. The broken line (long dashes) shows the increase in corner frequency fc with decreasing seismic moment of the event; the short dashed line gives the approximate "source spectrum" for an underground nuclear explosion.

Seismic moment is a measure of the size of an earthquake based on the area of fault rupture, the average amount of slip, and the force required to overcome the friction joining the rocks that have been offset by the fault.
Seismic moment can also be calculated from the amplitude spectra of seismic waves.



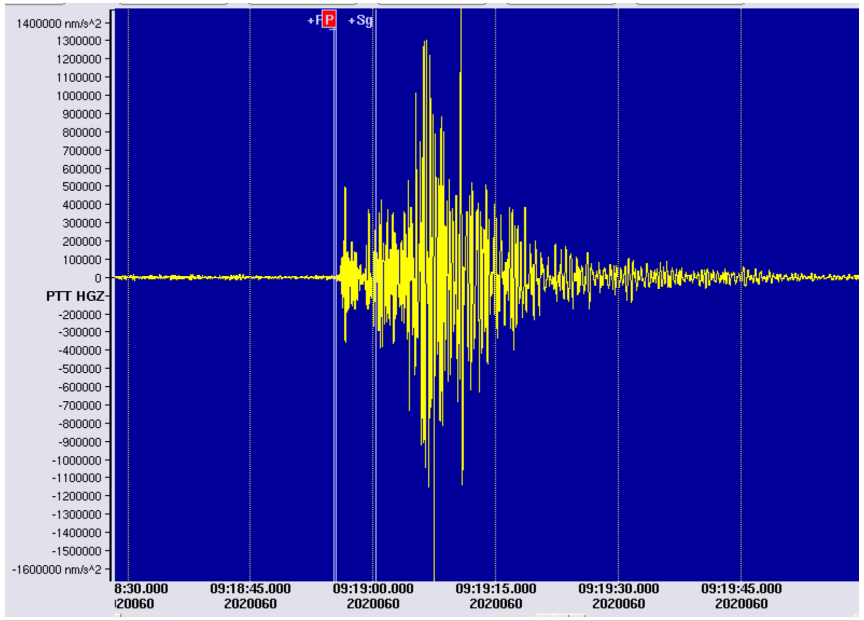
Amplitude spectrum approximation of a trapezoidal box car function

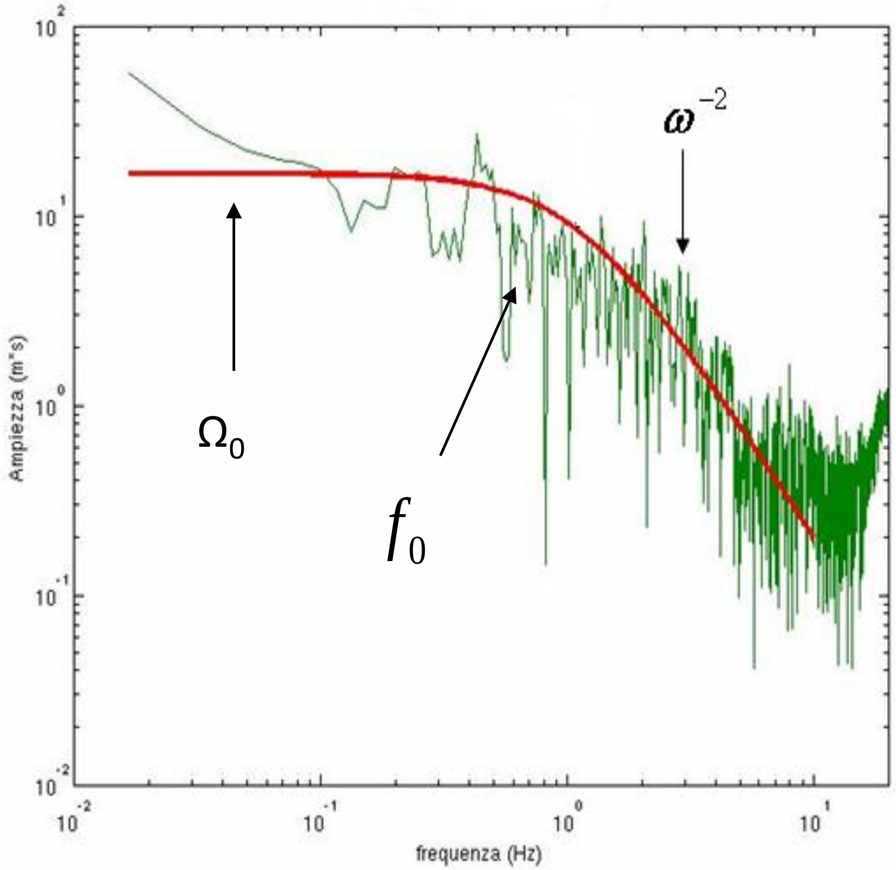
$$\log|A(\omega)| =$$

$$= \begin{Bmatrix} \log M_0 & \omega < 2/T_R \\ \log M_0 - \log(T_R/2) - \log\omega & 2/T_R < \omega < 2/T_D \\ \log M_0 - \log(T_R T_D/4) - 2\log\omega & 2/T_D < \omega \end{Bmatrix}$$

the spectrum is often defined in terms of the corner frequency

- The SOURCE SPECTRUM is flat and equal to the seismic moment at periods longer than the corner frequency 2 / TR
- They decay below the frequency of the angle
- Angular frequency shifts to the left (lower frequency) for larger earthquakes with larger faults





On the left seismogram (time series), on the right recorded source spectrum (green line) with corresponding synthetic spectrum (red line).

According to Kostrov (1974), the radiated seismic strain energy is proportional to the stress drop $\Delta\sigma$, i.e. $\mathbf{E_S \approx \Delta\sigma\ \bar{D}\ A/2}$. With Eq.

$$M_0 = 4\pi d\rho v_{p,s}^3 u_0 / R_{\theta,\varphi}^{p,s}$$

it can be written $\mathbf{E_S \approx (\Delta\sigma/2\mu)\ M_0}$. (*ex: 3.4*). Assuming a reasonable value for the shear modulus μ in the crust and upper mantle (about $3\text{-}6 \times 10_4\ MP_a$) and assuming that, according to, the stress drop of large earthquakes is constant (ranging from about 2 to 6 MPa), we obtain as an average $\mathbf{E_S \approx M_0/2x10_4}$ (see Fig. 3.38). Plugging this into the relationship proposed by Gutenberg and Richter (1956c) between the seismic strain energy released E_s and Ms, namely:

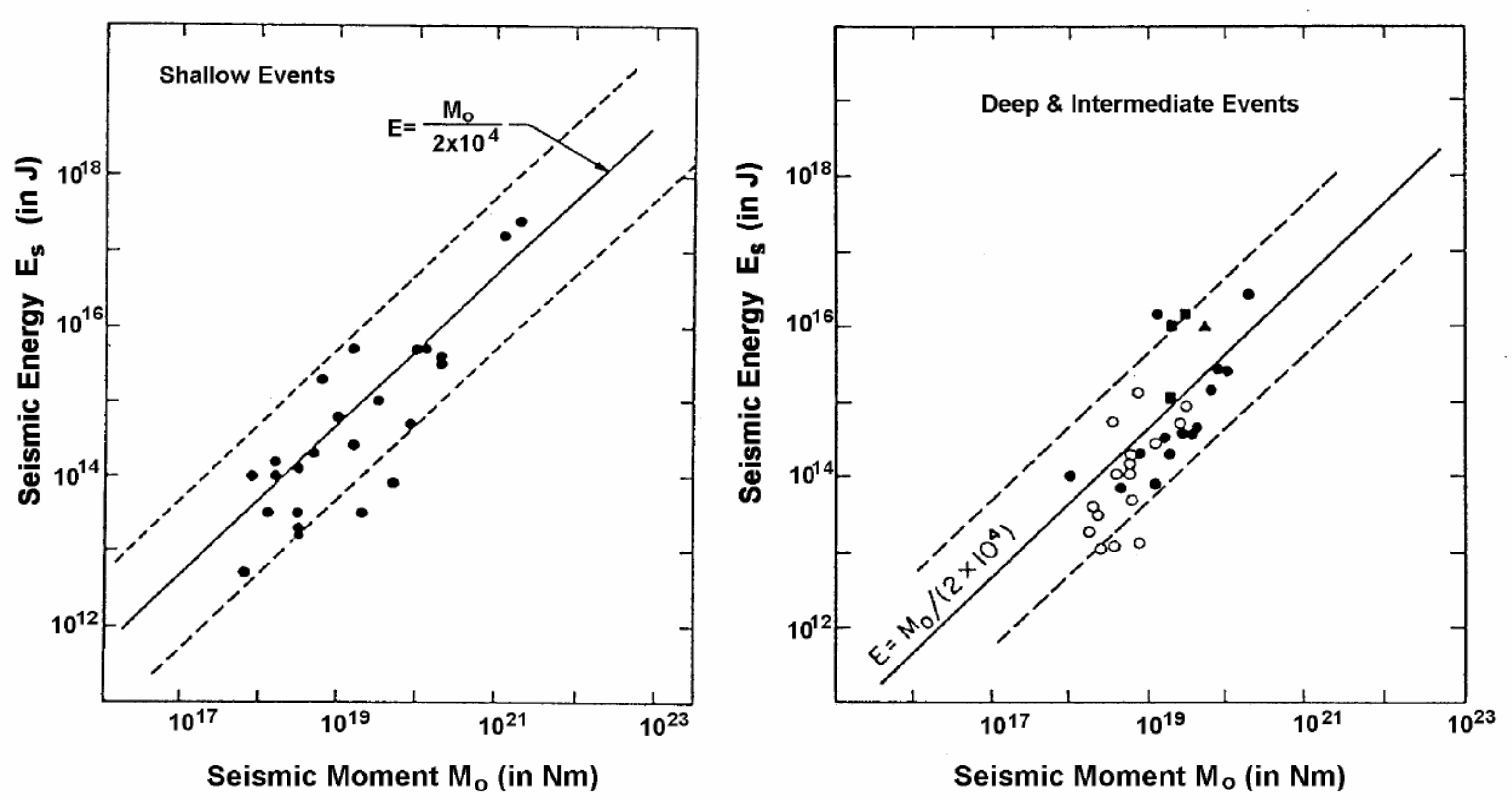
$$\mathbf{\log E_S = 4.8 + 1.5\ Ms\ (in\ SI\ units\ Joule\ J = Newton\ meter\ Nm)}$$

it follows

$$\mathbf{\log M_0 = 1.5\ M_s + 9.1}$$

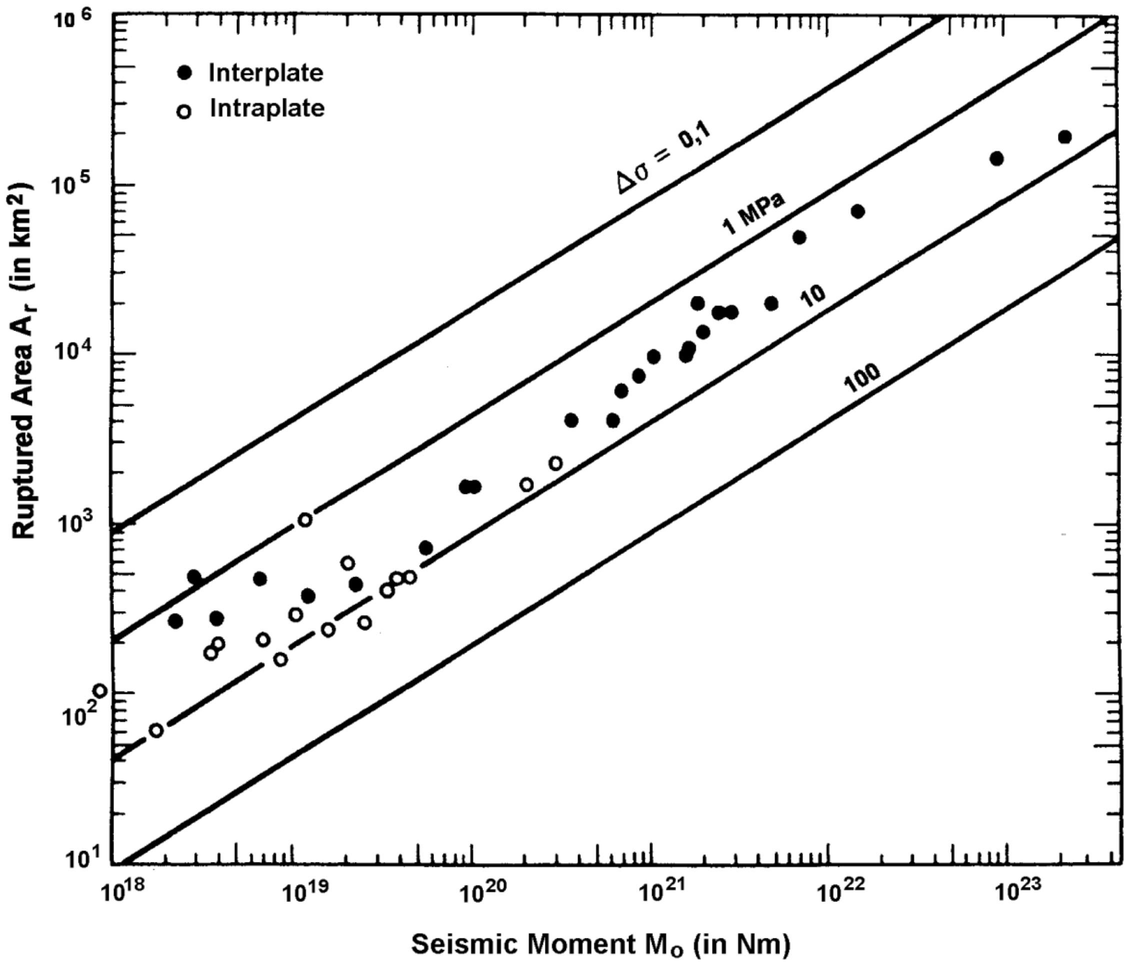
Solving for the magnitude and replacing M_s with M_w gives:

$$\mathbf{Mw = 2/3\ (\log M_0 - 9.1)}$$

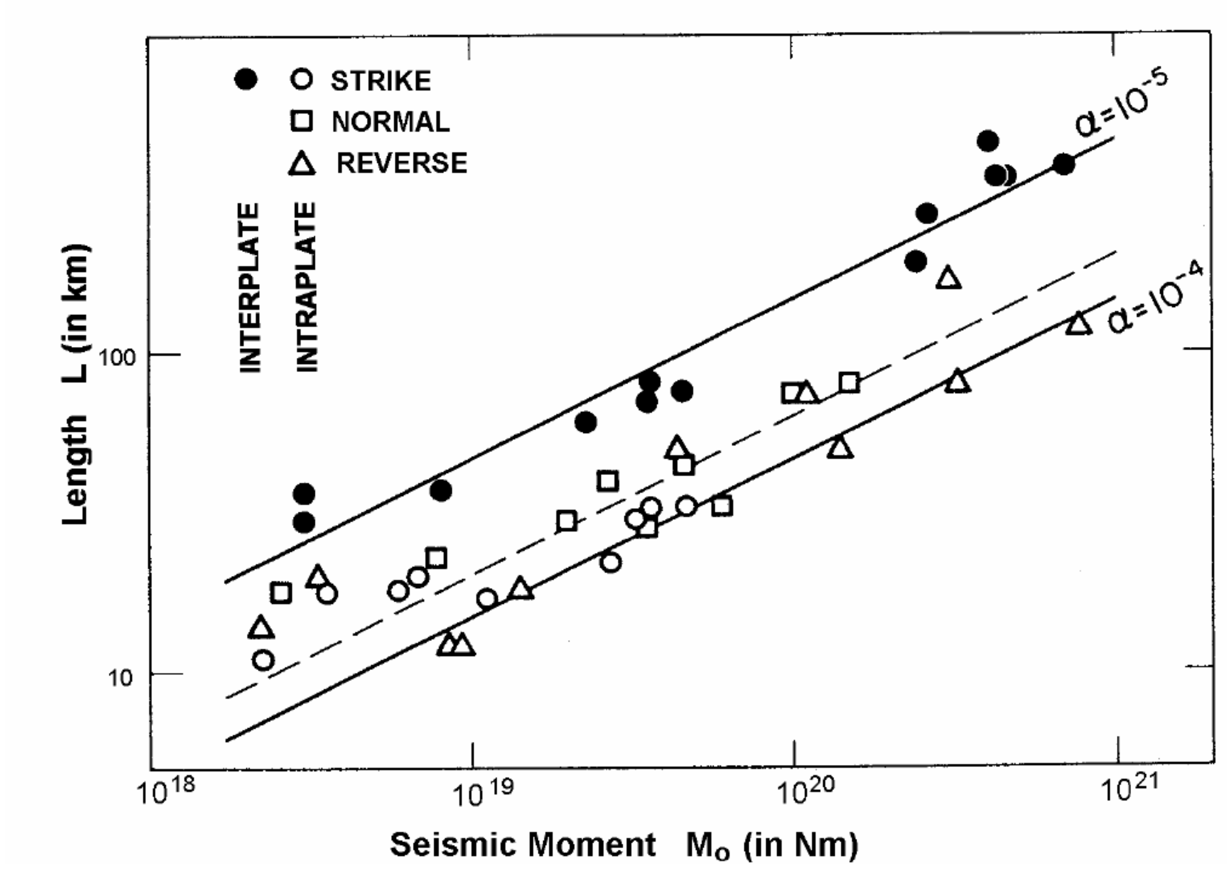


Relationships between seismic moment M_0 and energy E_S for surface events (left) and intermediate or deep events (right) according to Vassiliou and Kanamori (1982). The solidola row indicates the $E_S = M_0 /(2\times10^4)$ relationship suggested by Kanamori (1977).

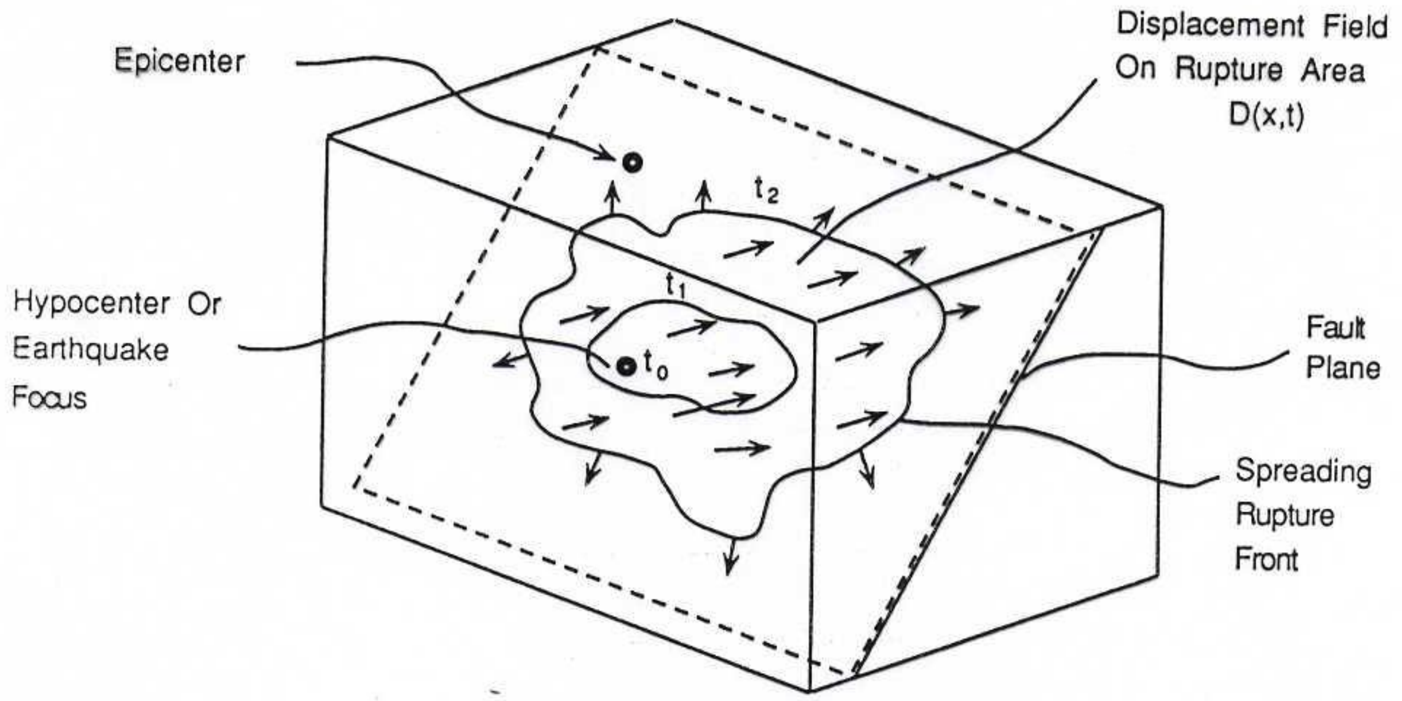
Da: New Manual of Seismological Observatory Practice – NMSOP
CHAPTER 2: Seismic Sources and Source Parameters (Peter Bormann, Michael Baumbach, Günther Bock, Helmut Grosser, George L. Choy and John Boatwright)



Relationship between fault rupture area A_r and seismic moment M_0 for inter- and intraplate. The solid lines give the respective relationships for different stress drop $\Delta\sigma$ (in MPa; $1\ Pa = 10^{-5}$ bars).



Length of fault L versus seismic moment M_0 for large inter- and intraplate earthquakes. The solid lines give the respective relationship for the ratio $\alpha = \bar{D}/L$



Schematic diagram of rupture on a fault that expands from the hypocenter on the fault plane. The motion starts at the focus and expands according to a front break on the fault plane function of space and time, separating regions that are in motion by those who still are not. All regions continuously radiate energy waves P and S. The displacement field varies over the surface of the fault. Note that the direction of propagation of the rupture is generally not parallel to the direction of sliding. (Modif. da Bolt, 1988)

Seismic source parameters

It is seen that the earthquake causes a discontinuity (jump) along a fault. We then describe the seismic source by a discontinuity of displacements. The mathematical treatment of the discontinuity, however, is rather complicated.

One may ask what system of forces in a continuous medium (= without faults, discontinuities) gives rise to the same displacements and forces generated by a discontinuity of displacement along a fault.

As the Earth before and after the earthquake is in a state of equilibrium, the system of forces can not be a single force - a singlet - which would result in a shift of the entire medium. The Earth must be in balance for rotations and then a couple of forces - single couple - is not acceptable. Therefore, the system forces it easier for an internal source to the Earth for which the sum of forces and moments is zero and that (proof omitted!) Is equivalent to a discontinuity of displacement along the fault, appears to be the TWO PAIR.

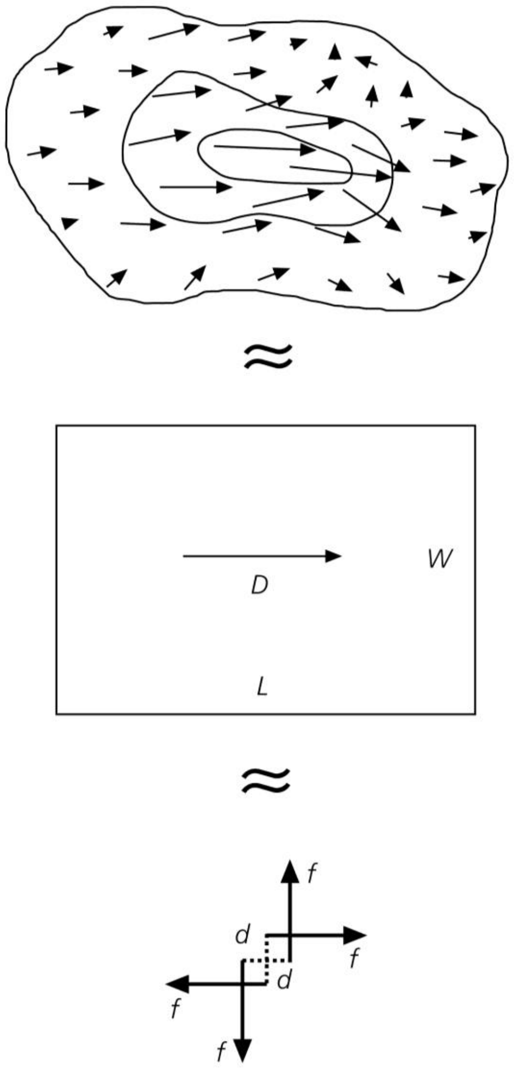
For a description of a discontinuity of displacements oriented arbitrarily, we need a combination of nine pairs, called the seismic moment tensor.

Simple representation yields seismic waves produced by a complex rupture involving displacements varying in space and time on irregular fault

First, approximate rupture with a constant average displacement D over a rectangular fault

Approximate further as a set of force couples.

Approximations are surprisingly successful at matching observed seismograms.



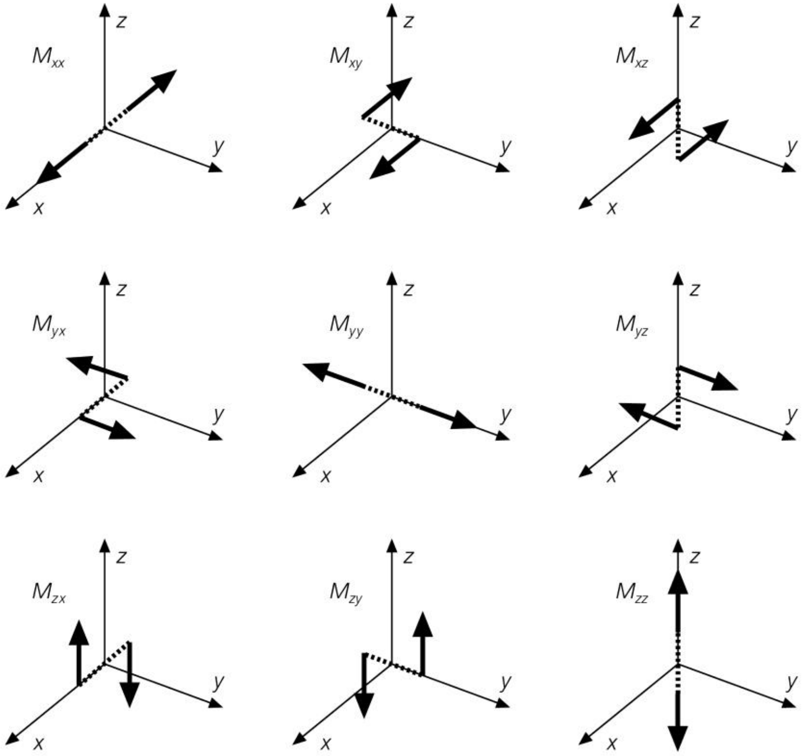
$$M = \int_A \mu D(A)\,dA$$

$$M = \mu DLW$$

$$M = fd$$

A seismic source oriented arbitrarily in space, can be described with the help of the seismic moment tensor, whose elements are the individual pairs oriented along the spatial axes. With the moment tensor, you can describe also sources not two pair type, i.e., sources that have an isotropic component (explosion or implosion).

Figure 4.4-4: Nine force couples which compose the seismic moment tensor.



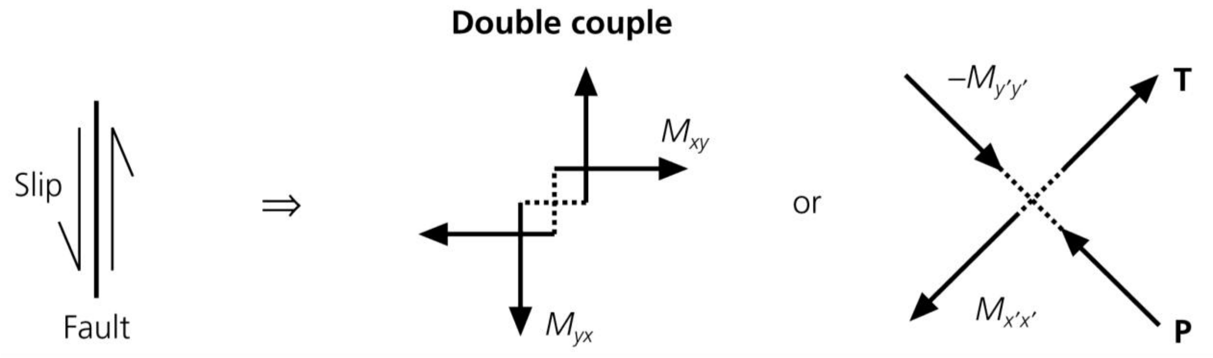
The general form of seismic moment tensor is:

$$M = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix}$$

A double couple acting in the plane of the x and y axes (or axis 1 and axis 2) respectively along the axes x and y, which will be represented by tensor elements with the two pairs (1,2) and (2,1):

$$M = M_0 \begin{bmatrix} 0 & M_{12} & 0 \\ M_{12} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$ Mo is scalar moment

FOR FAULT ORIENTED NORMAL TO COORDINATE AXIS, MOMENT TENSOR IS



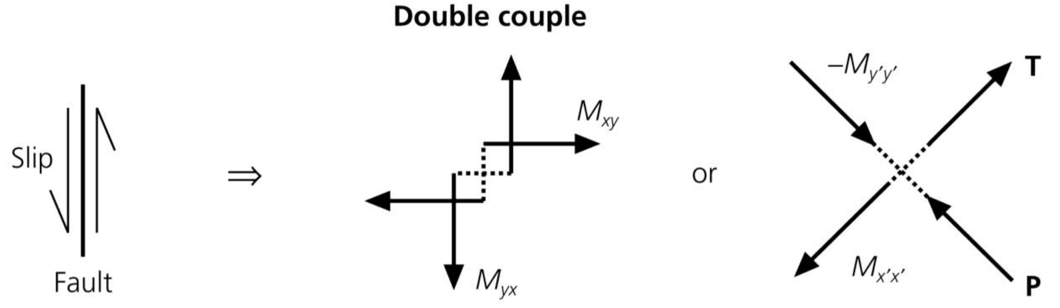
$$\mathbf{M} = \begin{pmatrix} 0 & M_0 & 0 \\ M_0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} = M_0 \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

A double couple acting in the plane of the x and y axes (or axis 1 and axis 2) respectively along the axes x and y, which will be represented by tensor elements with the two pairs (1,2) and (2,1):

$$M = M_0 \begin{bmatrix} 0 & M_{12} & 0 \\ M_{12} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

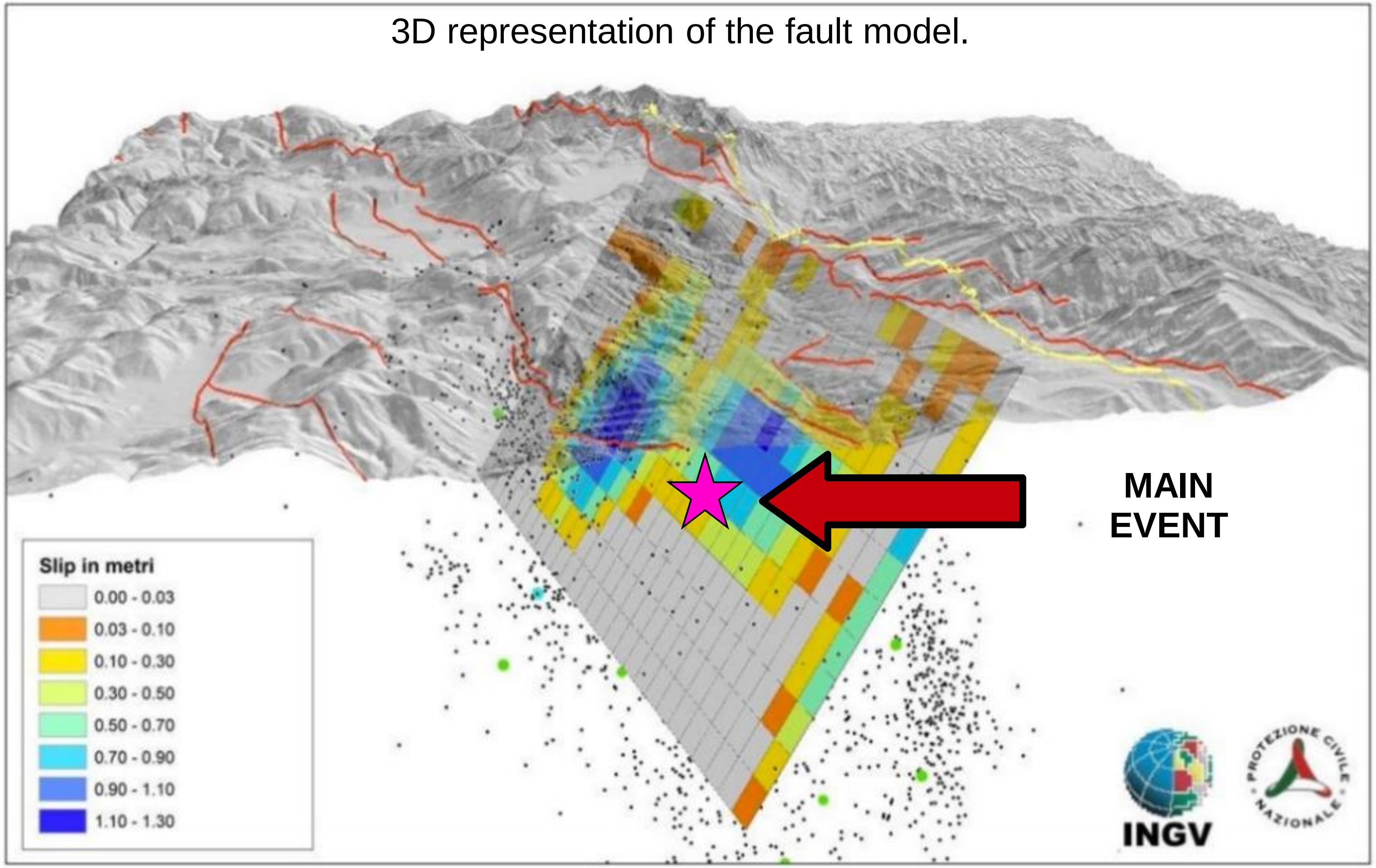
Mo is scalar moment

FOR FAULT ORIENTED NORMAL TO COORDINATE AXIS, MOMENT TENSOR IS



$$\mathbf{M} = \begin{pmatrix} 0 & M_0 & 0 \\ M_0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} = M_0 \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

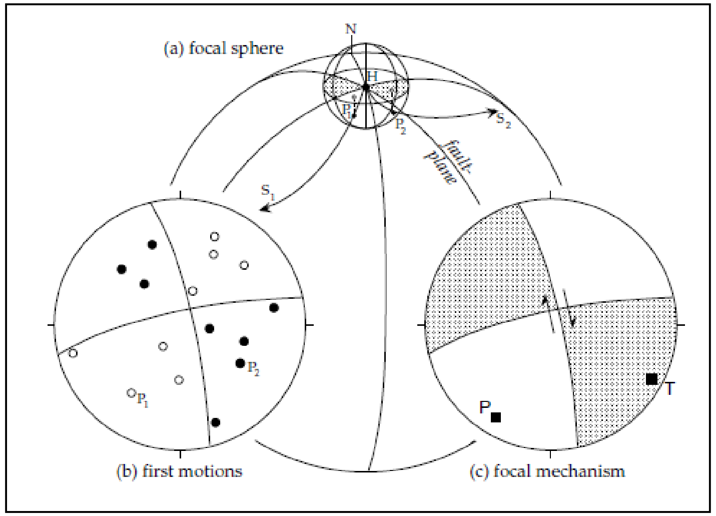
Amatrice earthquake 24 agosto 2016



Determinazione delle soluzioni del piano di faglia

•The path of the ray along which a P wave travels from an earthquake to the seismogram is curved due to the variation of seismic velocity with depth. The first step in solving the fault plane is to trace the ray to its source. A small fictitious sphere surrounding the fault is imagined; the point where the radius intersects its surface is calculated with the help of tables

• The azimuth and dip of the ray departure angle from the earthquake focus are calculated and plotted as a point in the lower hemisphere of the small sphere. This direction is then projected onto the horizontal plane through the epicenter.

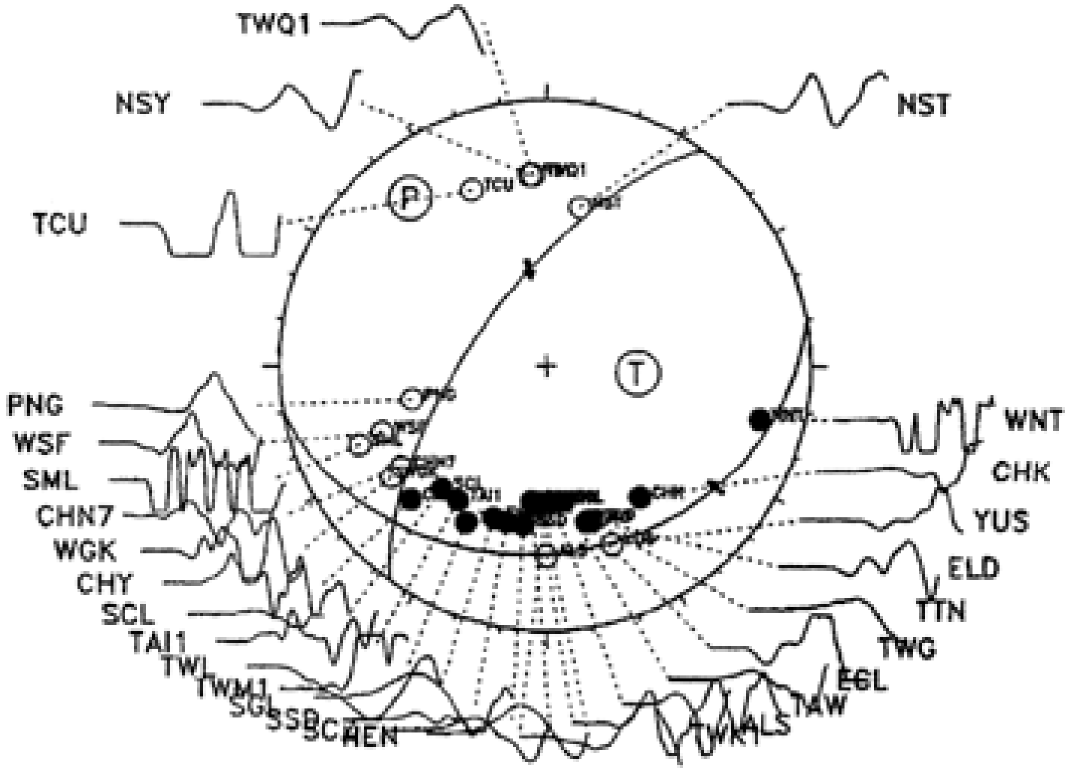


• The projection of the entire lower hemisphere is called a stereogram. The direction of the ray is marked by a solid dot if the first recorded motion was a tension with respect to the fault (i.e., the station is in the compression field). A blank dot indicates that the first motion was a pressure to the fault (i.e., the station is in the dilation field). First-motion data from any event are usually available from several seismic stations that are located in different directions from the epicenter. Solid and hollow points on the stereogram fall in distinct compression and dilation fields.

•Two mutually orthogonal planes are then drawn so as to delineate these fields as best as possible. This is best accomplished mathematically with a least square technique, but often a visual fit is clear and sufficient. The two mutually orthogonal planes correspond to the fault plane and the auxiliary plane, although it is not possible to decide which is the active fault plane from the seismic data alone. Regions of the stereogram corresponding to early compressional motions are usually shaded to distinguish them from regions of early dilational motions. The P and T axes are the lines that bisect the angles between the fault plane and the auxiliary plane in the dilatational and compressive fields, respectively

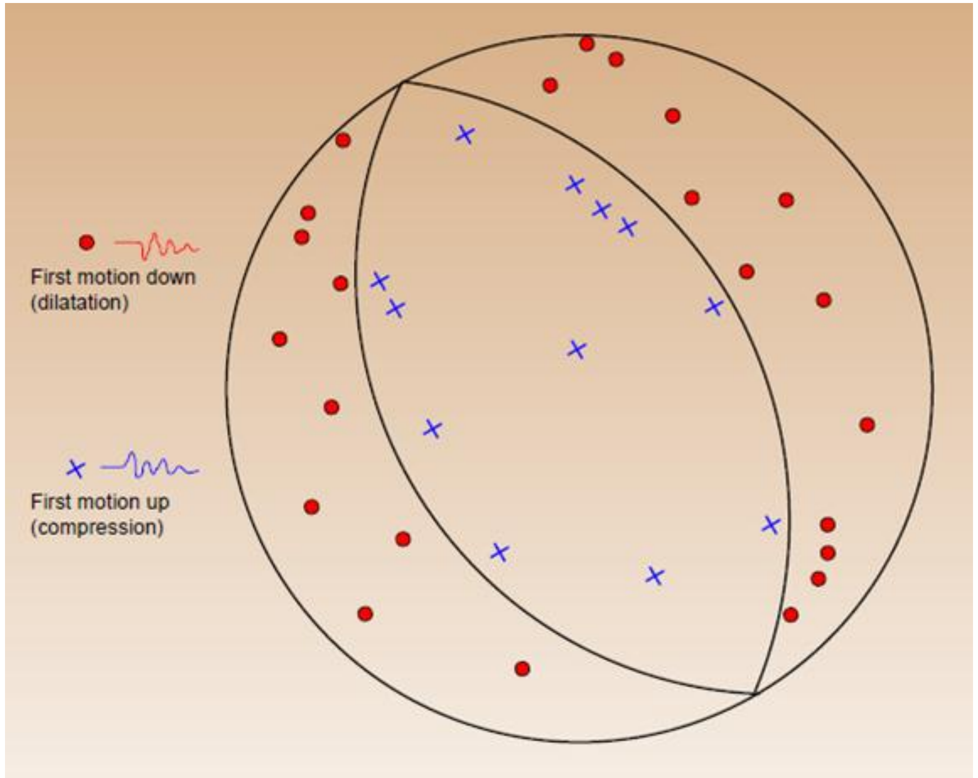
Data from CWB, Taipei

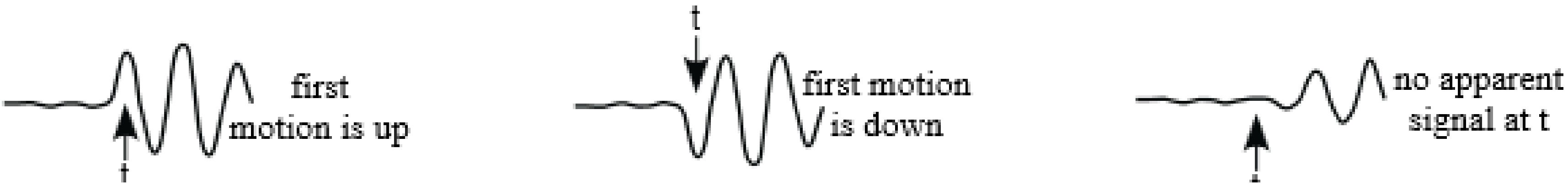
UT : 09/20/99 17:47 ML:7.3
HYPO: 23.85N 120.81E Z: 7KM
Strike Dip Rake: 80 30 130
Strike Dip Rake: 216 67 70

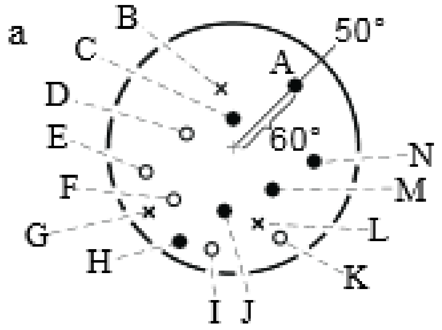


The first motion define four quadrants, two compressional and two dilatational. The division between quadrants occurs along the fault palne and a plane perpendicular to it.
Seismograms ehibit small or zero first motions in these directions, because the first motion changes from
dilatational to compressional. The perpendicular planes are called nodal planes, and if their orientations can be found, then the faul geometry is known. However, first motions alone cannot distinguish between the fault plane and the perpendicular auxiliary plane.

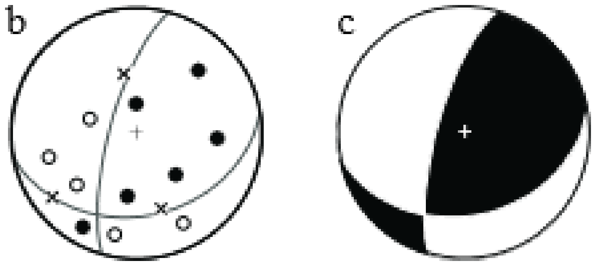
The focal sphere, used for the fault plane solutions, represents an imaginary sphere surrounding the earthquake location. The pattern of compressions and dilatations can be mapped into this sphere according to where source-receiver paths intersect the lower hemisphere.



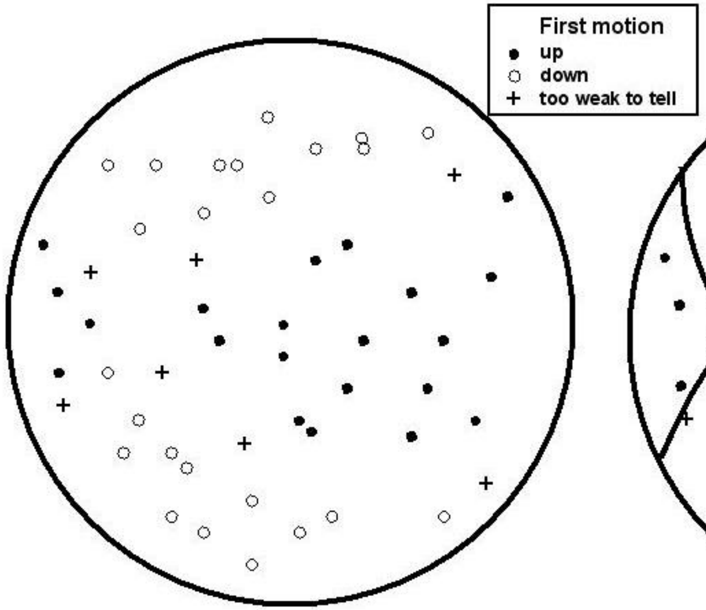




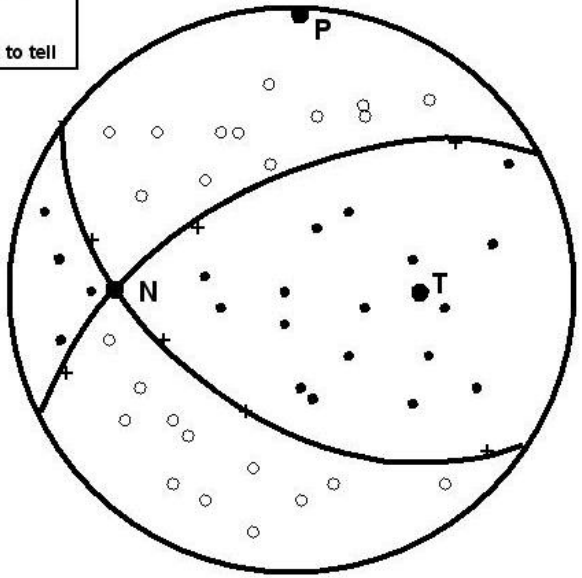
Stn	P wave	symbol
A		●
B		×
C		●
D		○
E		○
F		○
G		×
H		●
I		○
J		●
K		○
L		×
M		●
N		●



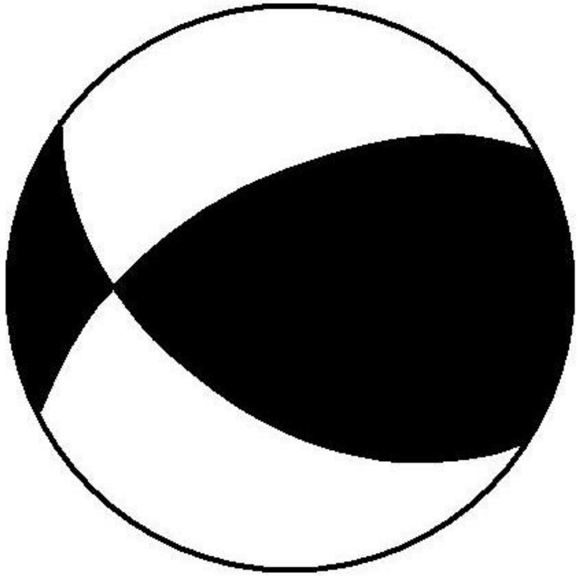
After all of the first-motion data are plotted (illustration "a"), we identify two great-circle arcs on the stereonet representing two planes that are at right angles to one another, that separate the circles from the black dots, and that pass near or through the x symbols (b). These are the nodal planes, one of which is coincident with the fault that produced the earthquake. Finally, we fill-in the quadrants according to convention (c). Clearly, the solution is non-unique, but it is still useful in providing information about the type and orientation of the fault that produced the earthquake.



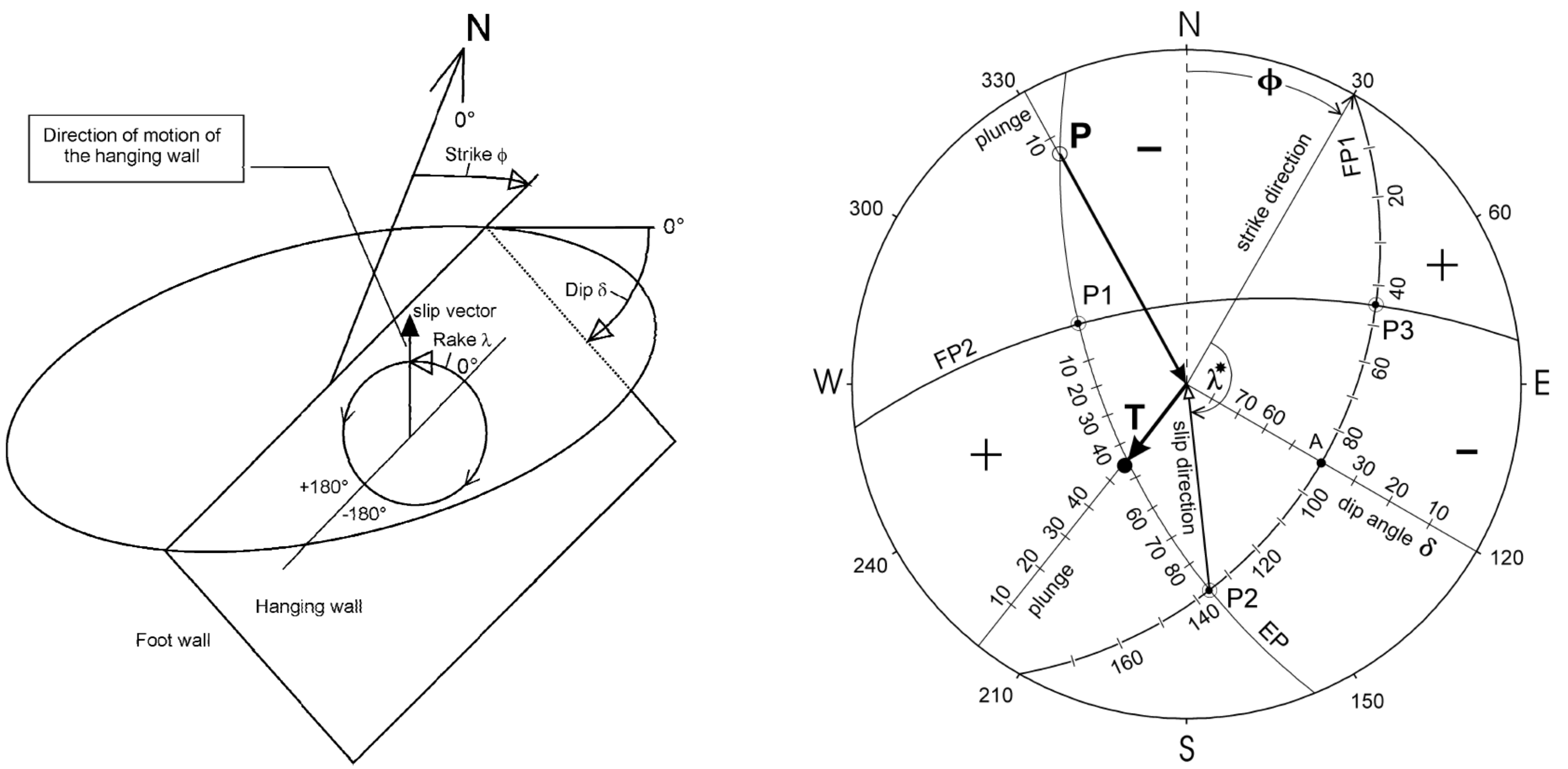
First motion data for a hypothetical earthquake from various seismograph stations



Nodal planes and N, P & T axes fitted to the data



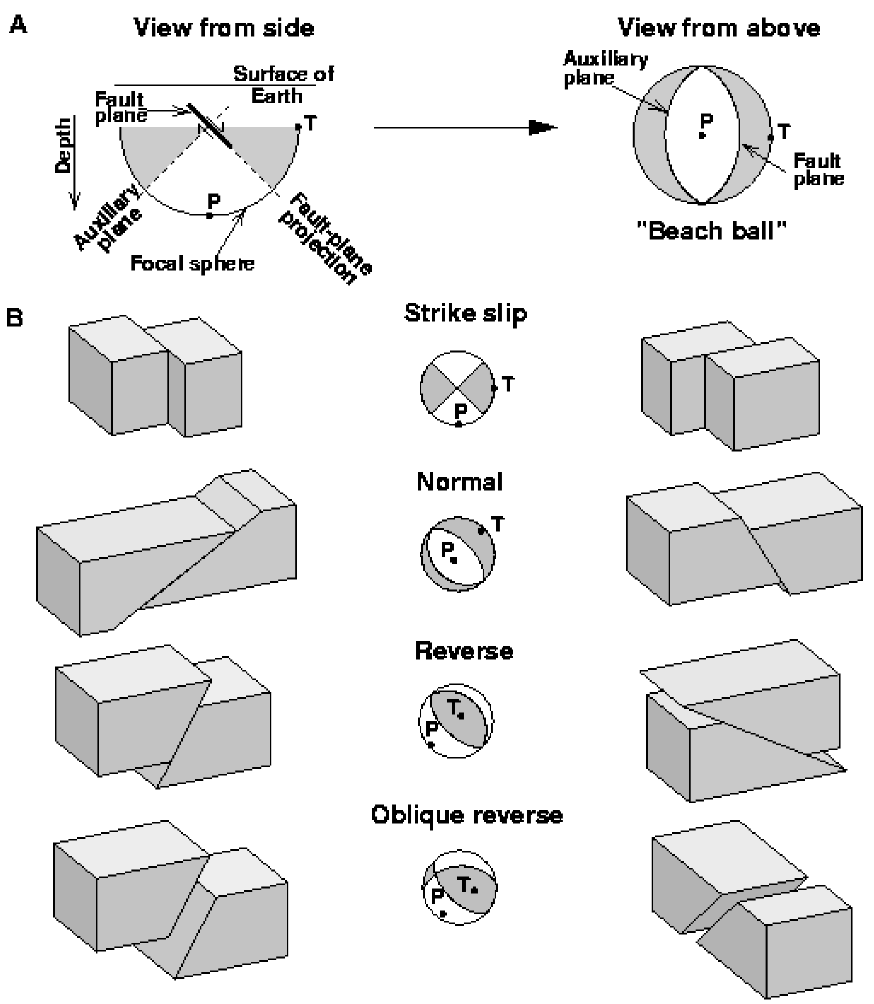
Resultant 'beachball' plot showing that the earthquake resulted from reverse oblique movement on a fault of one of two possible orientations



Determination of fault plane parameters ϕ, δ and λ in the diagrams. The polarity distribution, slip direction and fault plane projection shown correspond to the fault shown in the figure above. P1, P2 and P3 are the poles (i.e., 90° off) of FP1, FP2 and EP, respectively. P and T are the poles of the pressure and voltage axes, respectively. The + and - signs mark the quadrants with compression and first dilational motions of the P wave.

Da: New Manual of Seismological Observatory Practice – NMSOP
CHAPTER 2: Seismic Sources and Source Parameters (Peter Bormann, Michael Baumbach, Günther Bock, Helmut Grosser, George L. Choy and John Boatwright)

Schematic diagram of a focal mechanism



USGS, 1996

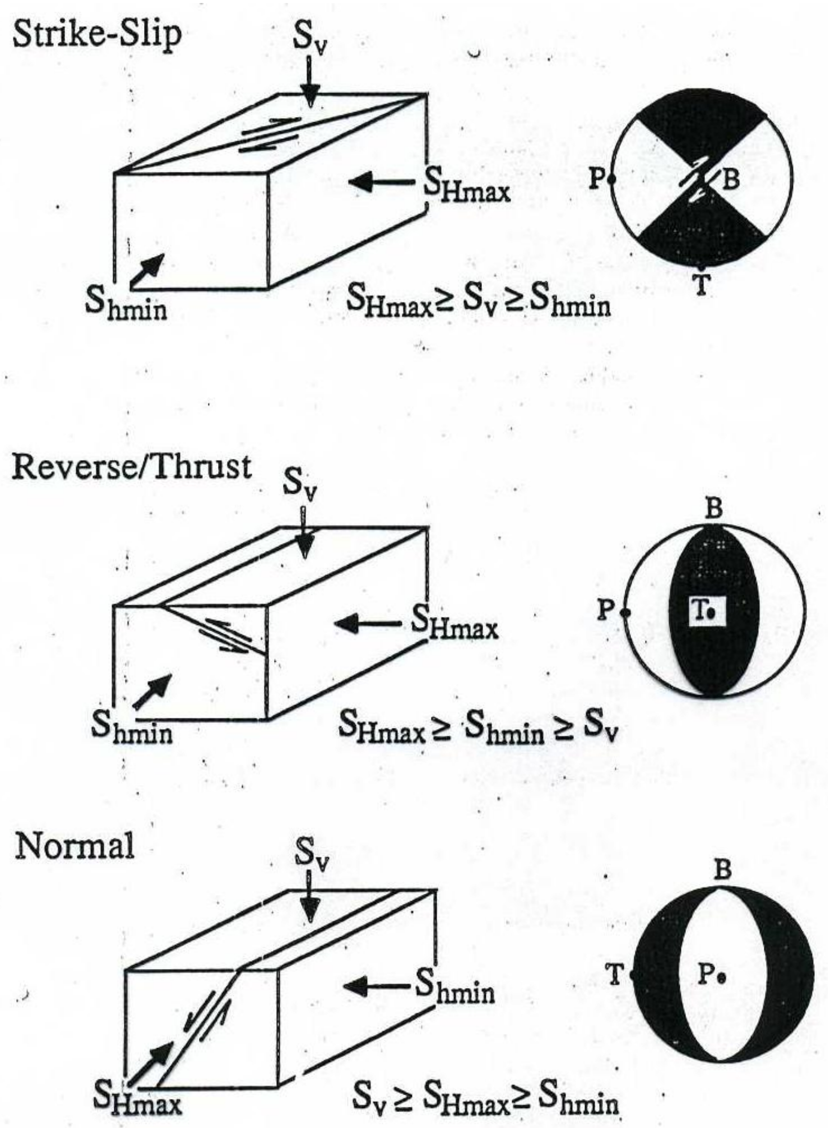


FIGURE 2. Simplified illustration of the variot s types of faulting, the relative magnitudes of the . .incipal stresses and lower-hemisphere projection earthquake focal plane mechanisms.

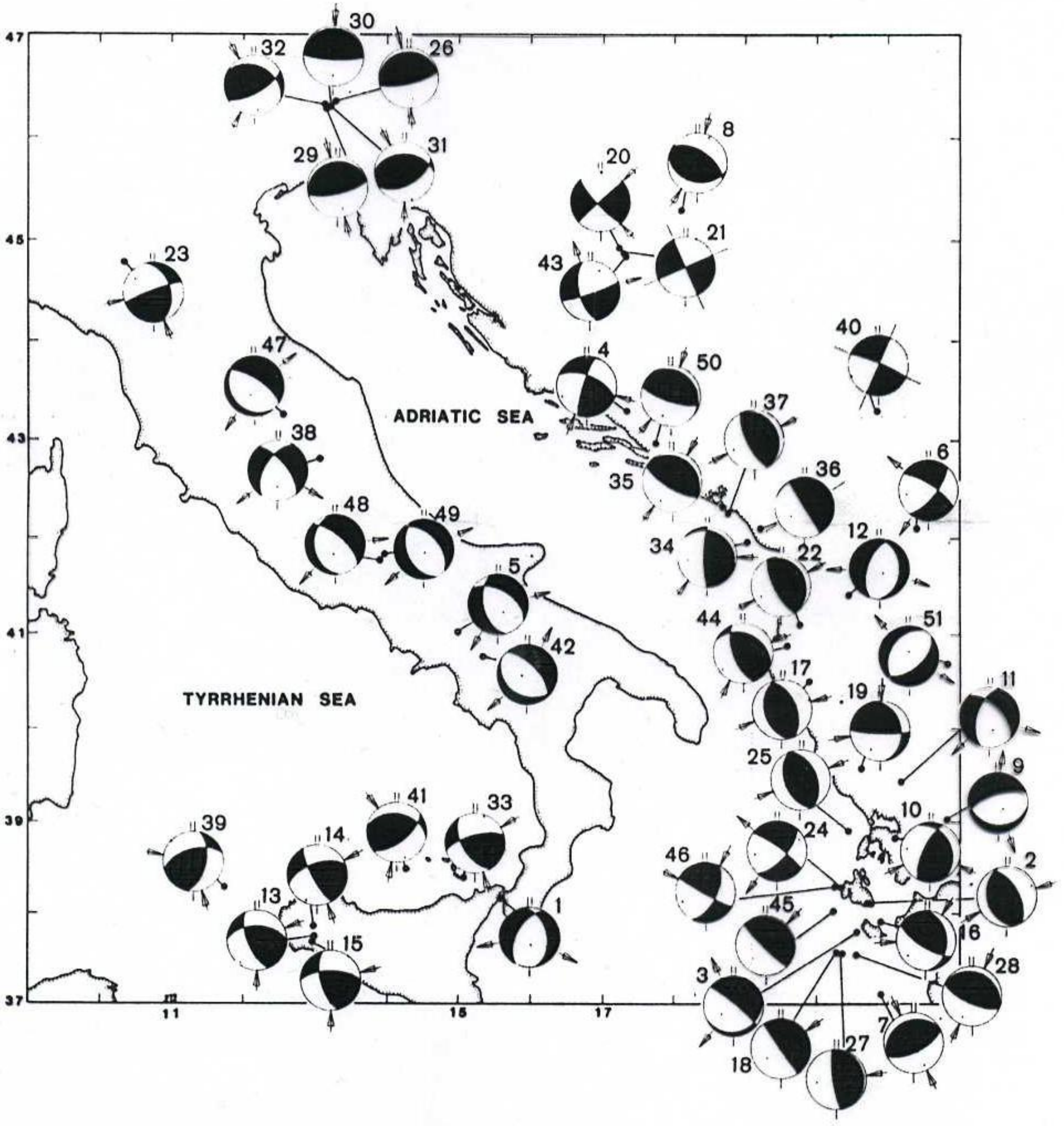
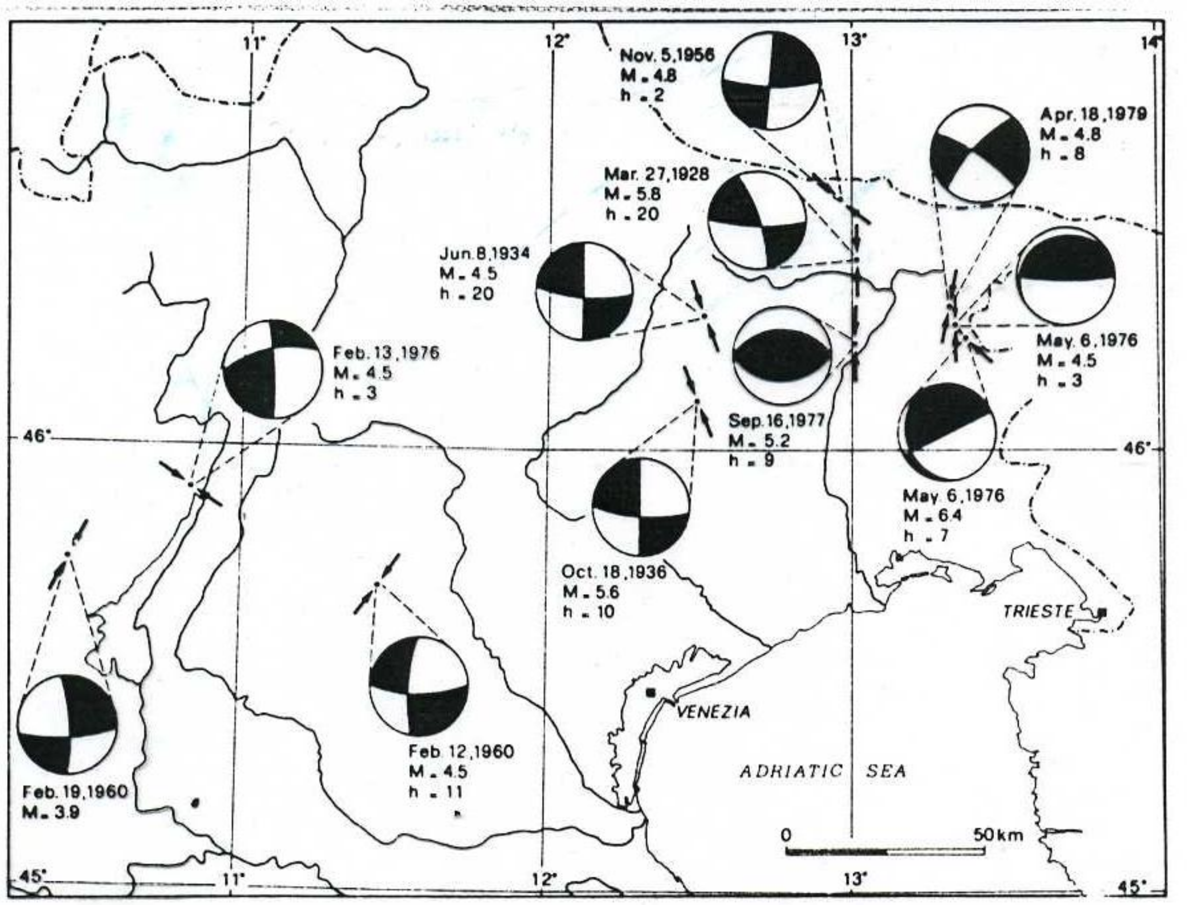
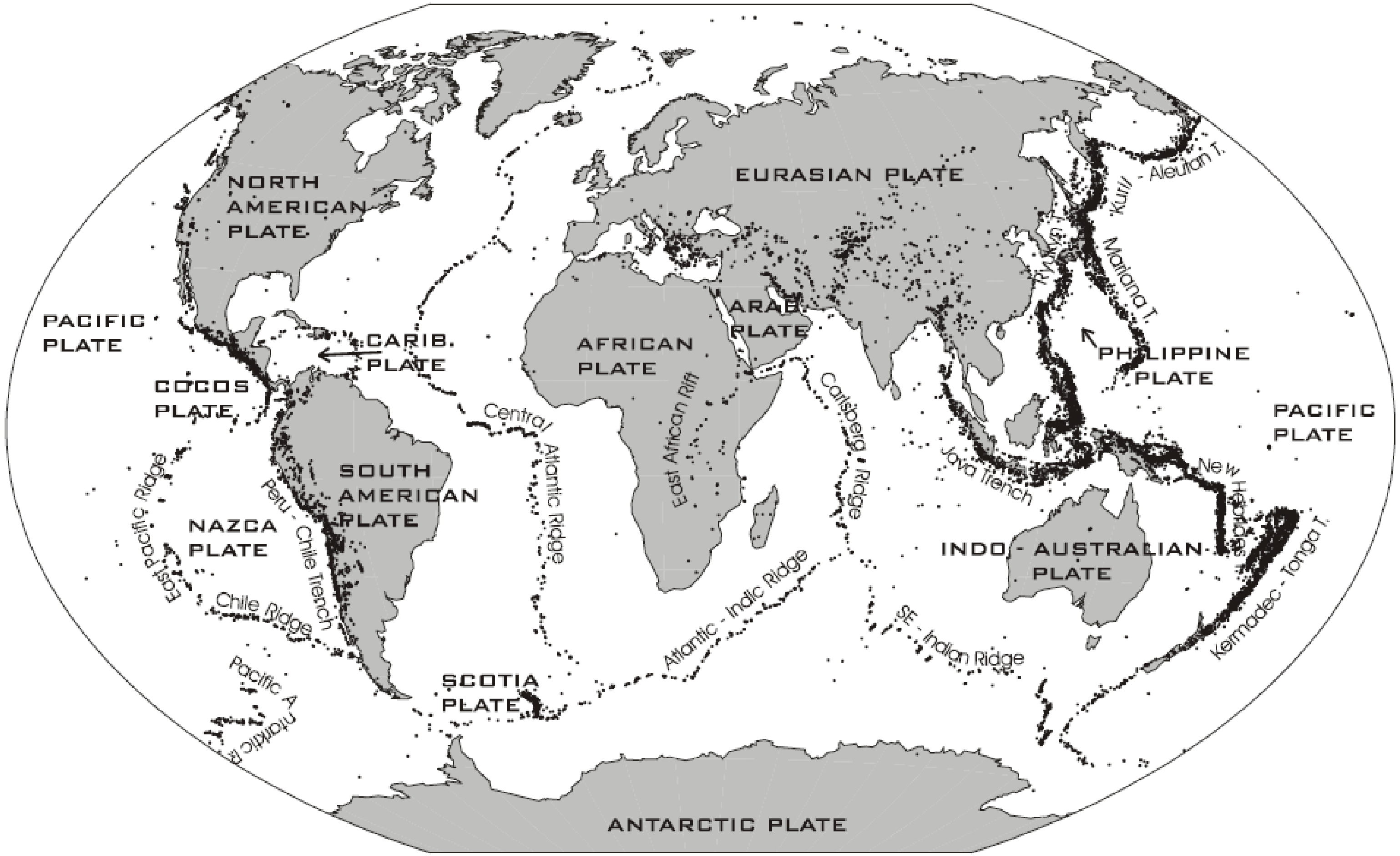


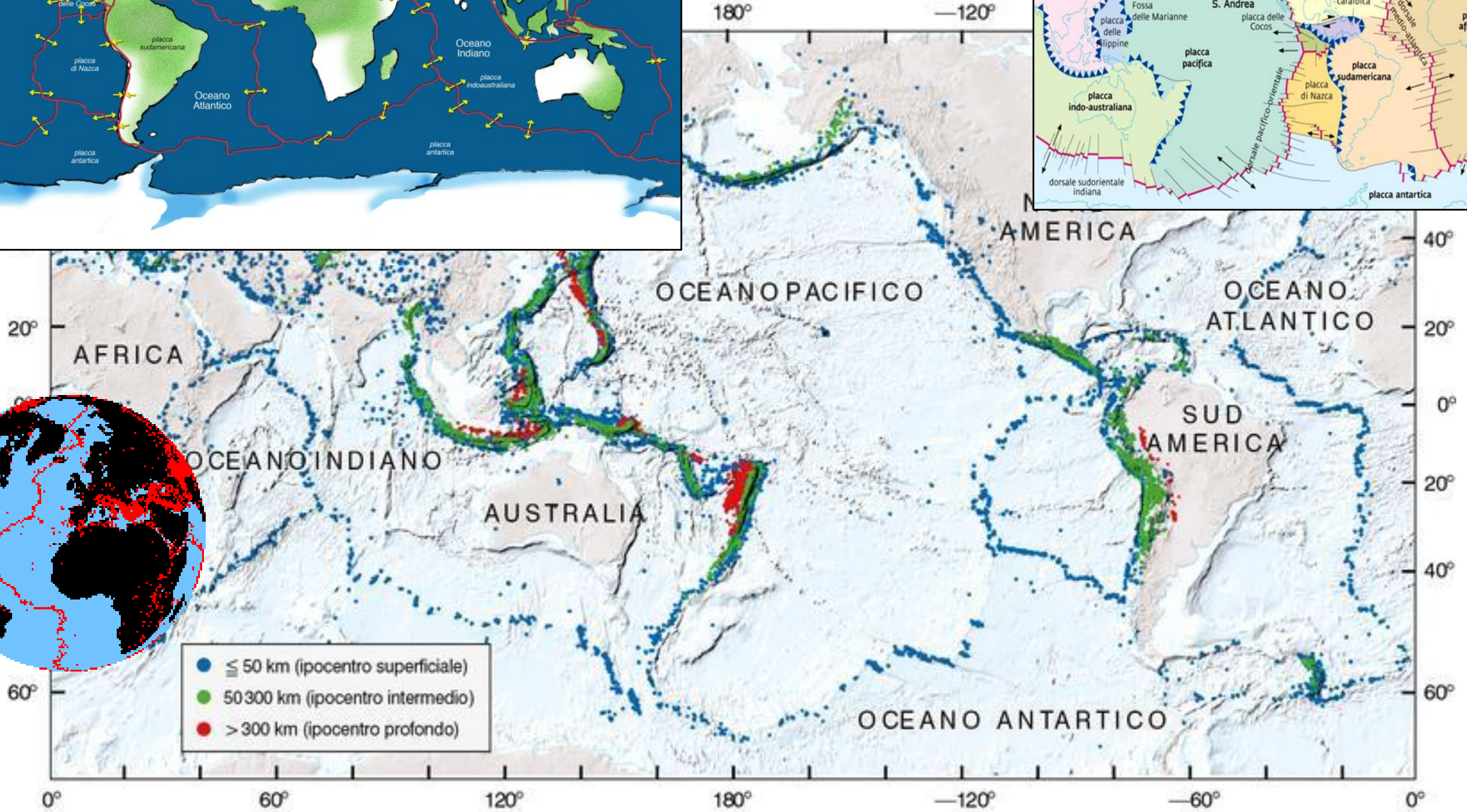
Figure 5. Fault-plane solutions for shallow earthquakes of the peri-Adriatic. Compressional quadrants are shaded and each event is numbered as in Table 1. *P*-axes are shown as a dot in the dilatational quadrant and the horizontal projections of slip vectors are shown as arrows. Location and nodal plane information is given in Appendices 1 and 2.



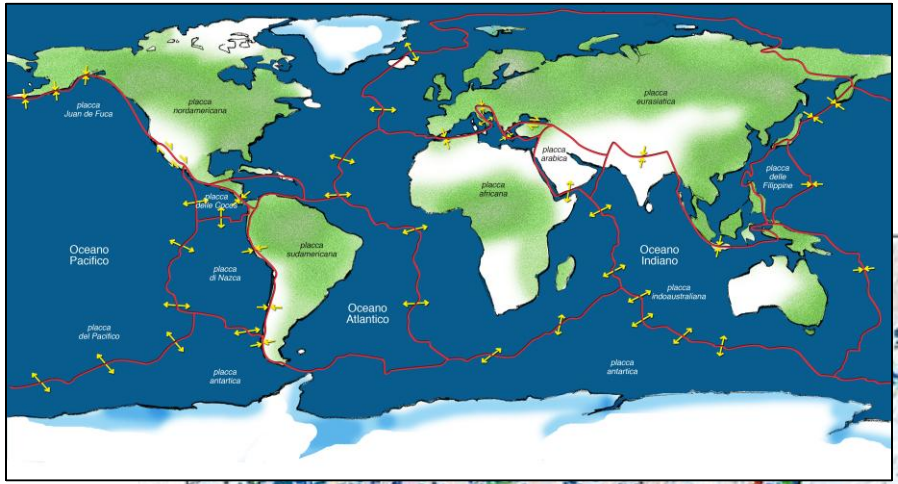
ig. 9 — Fault plane solutions of earthquakes in the studied area. The solutions are shown as stereographic projection of the lower hemisphere of the first-motion radiation field. Black quadrants denote compressions. (M = local corrected magnitude, h = focal depth). Solid arrows denote axis of



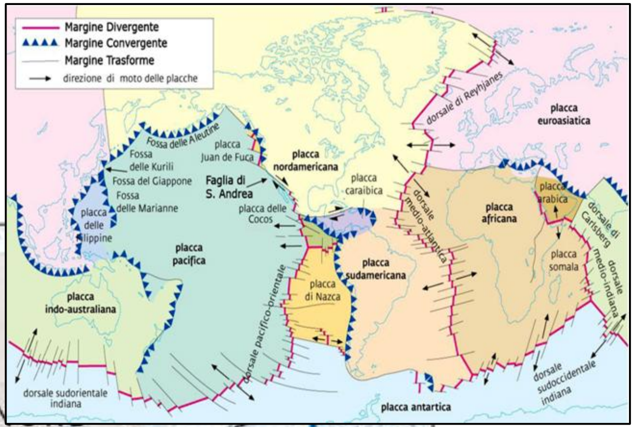
Global distribution of earthquake epicenters according to the U.S. National Earthquake Information Center (NEIC) data catalog, January 1977 to July 1997, and related major lithospheric plates



180°
—120°
NORD AMERICA
OCEANO PACIFICO
OCEANO ATLANTICO
AFRICA
OCEANO INDIANO
AUSTRALIA
SUD AMERICA
OCEANO ANTARTICO
20°
60°
40°
0°
0°
60°
120°
180°
—120°
—60°
0°
≤ 50 km (ipocentro superficiale)
50 300 km (ipocentro intermedio)
> 300 km (ipocentro profondo)

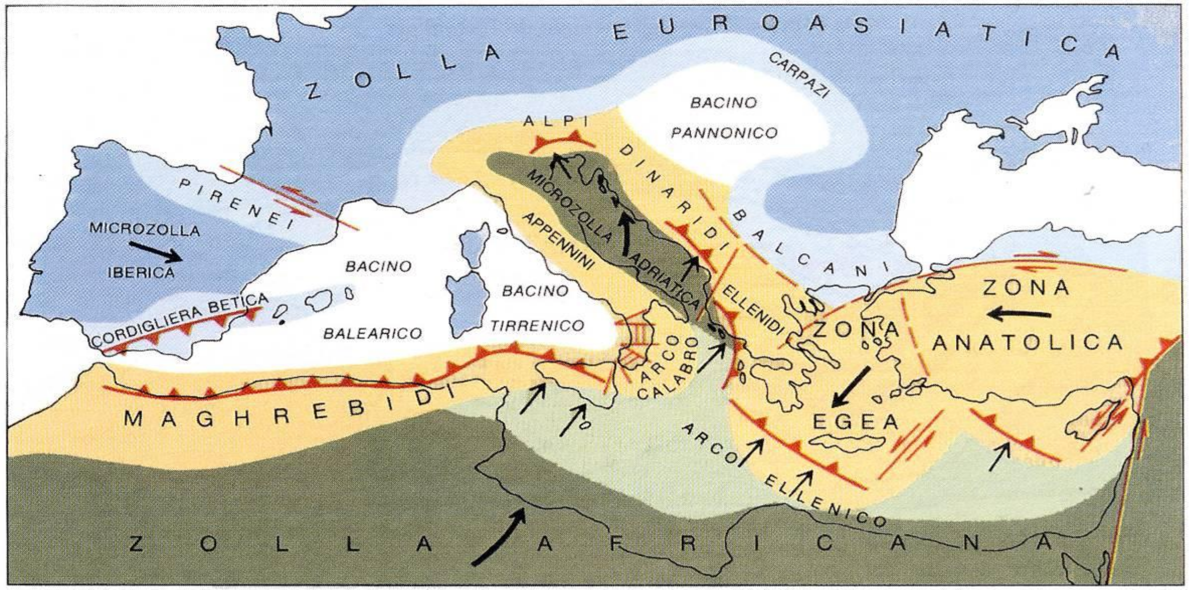


placca Juan de Fuca
placca nordamericana
placca eurasiatica
placca arabica
placca africana
placca delle Filippine
placca delle Cocos
placca sudamericana
Oceano Pacifico
placca di Nazca
Oceano Atlantico
Oceano Indiano
placca indoaustraliana
placca del Pacifico
placca antartica

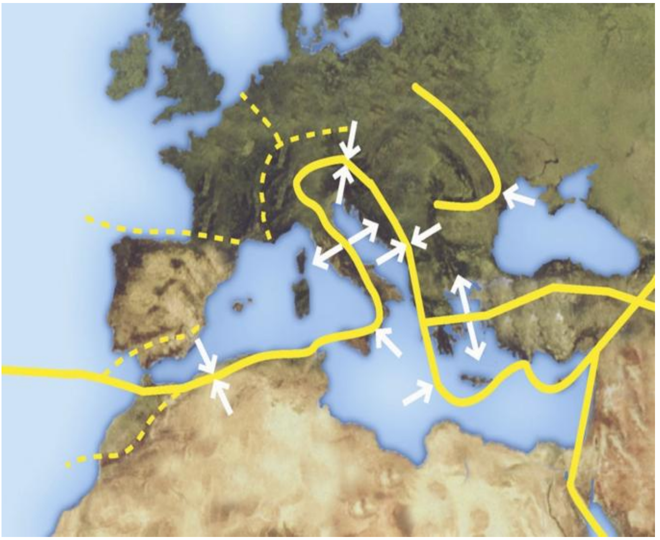


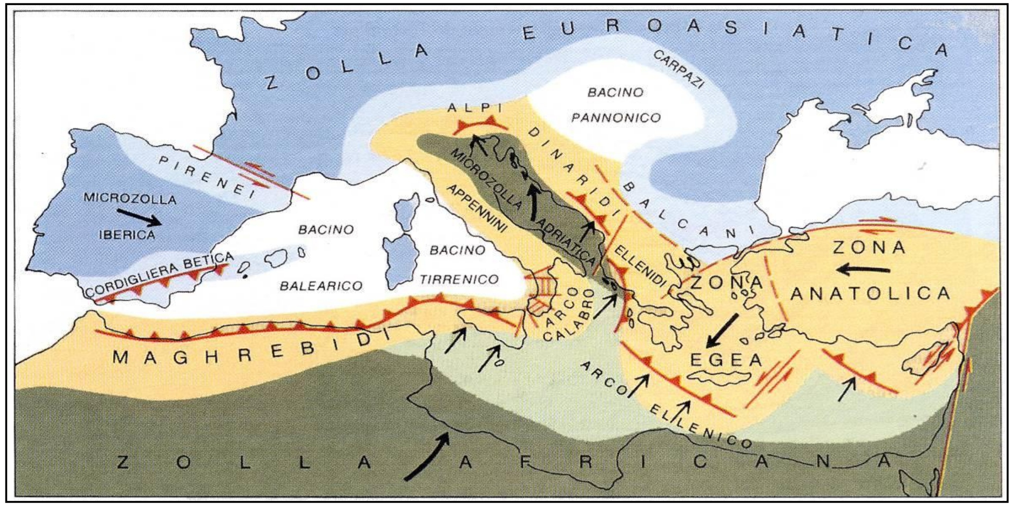
Margine Divergente
Margine Convergente
Margine Trasforme
direzione di moto delle placche
placca euroasiatica
placca nordamericana
placca caraibica
placca africana
placca arabica
placca pacifica
placca indo-australiana
placca sudamericana
placca di Nazca
placca antartica
Faglia di S. Andrea

Italy is located at the convergence margin between two major plates, the African and Eurasian plates. The relative movement between these two plates causes the accumulation of energy and deformation that are occasionally released in the form of earthquakes of varying magnitude.



The African and Eurasian clusters, which have convergent motion (continent-continent collision), have a margin characterized by portions with different behavior: in some areas, there is subduction with deep earthquakes (Calabrian and Hellenic arc)in others, compression without subduction with reverse fault mechanisms (Maghrebids, Eastern Alps and Dinarids)





Two structures play a key role in the tectonic situation: the Adriatic microsphere and the Tyrrhenian basin. The closely interconnected dynamics of these structures are responsible for the most important earthquakes that have occurred in Italy (Friuli, 1976-77, Southern Apennine earthquakes)