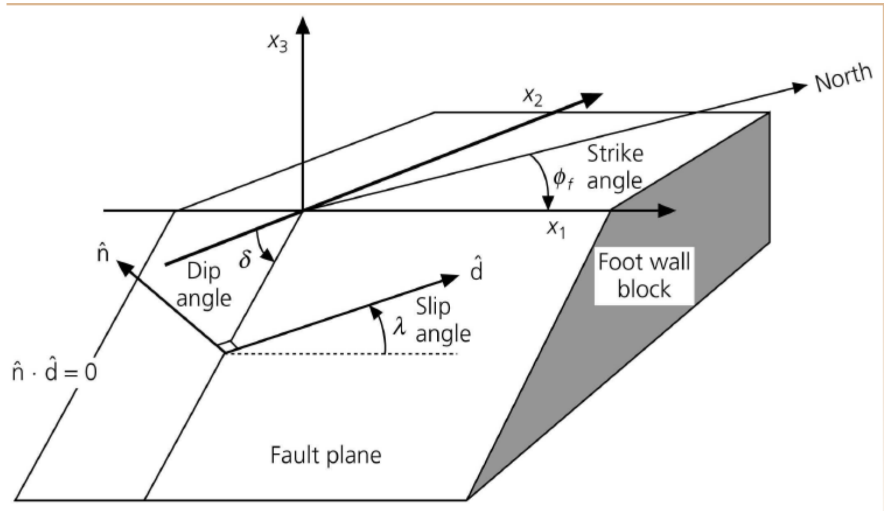
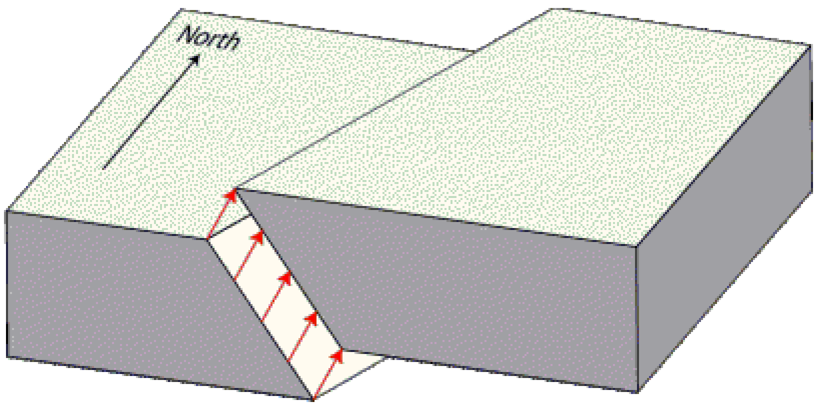
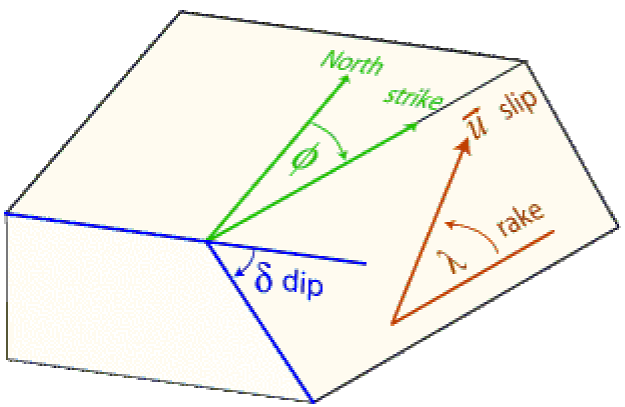
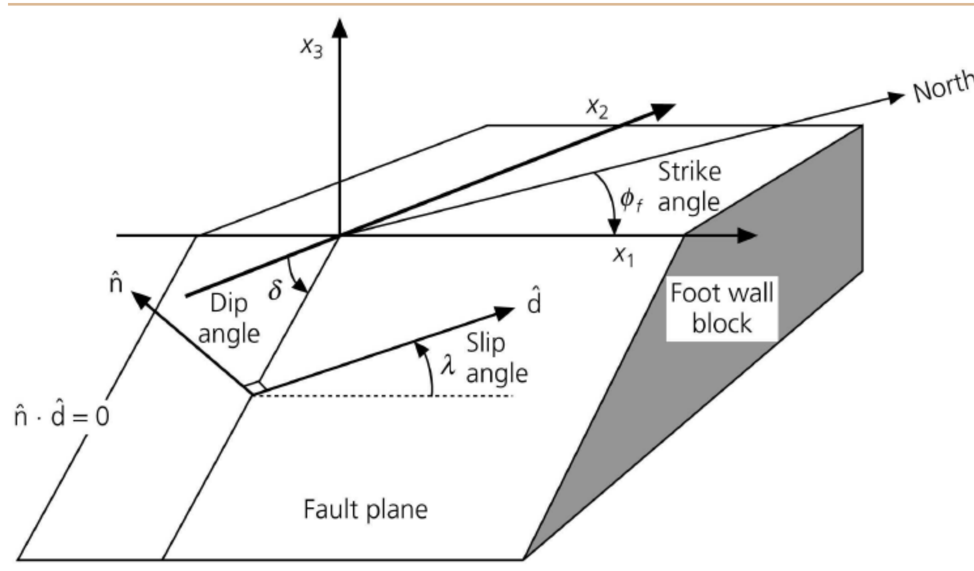
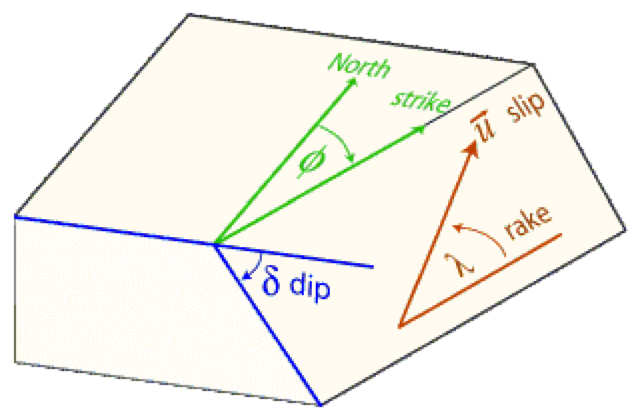


To determine the focal mechanism we need three parameters:
Two for the fault plane and one for the slip direction:
Φ → the strike of the fault: Fault strike is the direction of a line created by the intersection of a fault plane and a horizontal surface, 0° to 360°, relative to North. Strike is always defined such that a fault dips to the right side of the trace when moving along the trace in the strike direction. The hanging-wall block of a fault is therefore always to the right, and the footwall block on the left. This is important because rake (which gives the slip direction) is defined as the movement of the hanging wall relative to the footwall block
δ→ dip angle: Fault dip is the angle between the fault and a horizontal plane, 0° to 90°
λ → Rake is the direction a hanging wall block moves during rupture, as measured on the plane of the fault. It is measured relative to fault strike, ±180°. For an observer standing on a fault and looking in the strike direction, a rake of 0° means the hanging wall, or the right side of a vertical fault, moved away from the observer in the strike direction (left lateral motion). A rake of ±180° means the hanging wall moved toward the observer (right lateral motion). For any rake>0, the hanging wall moved up, indicating thrust or reverse motion on the fault; for any rake<0° the hanging wall moved down, indicating normal motion on the fault.


North


North
strike
slip
ϕ
$\vec{u}$
rake
λ
δ dip


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


North
strike
slip
ϕ
$\vec{u}$
rake
λ
δ dip

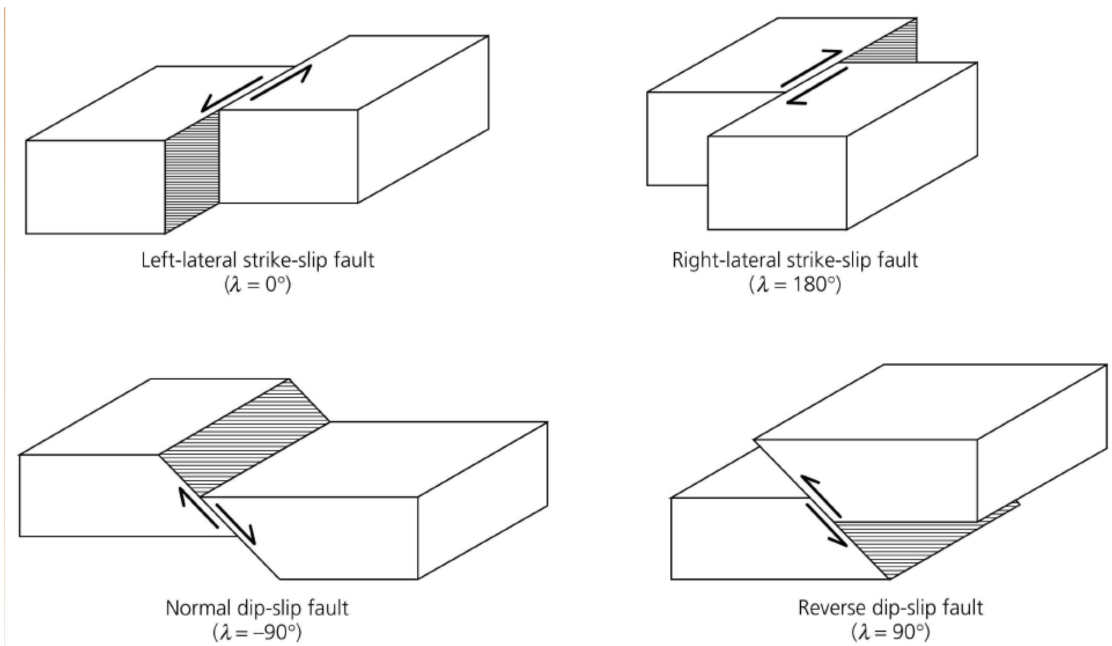
For rake there usually are used two conventions:

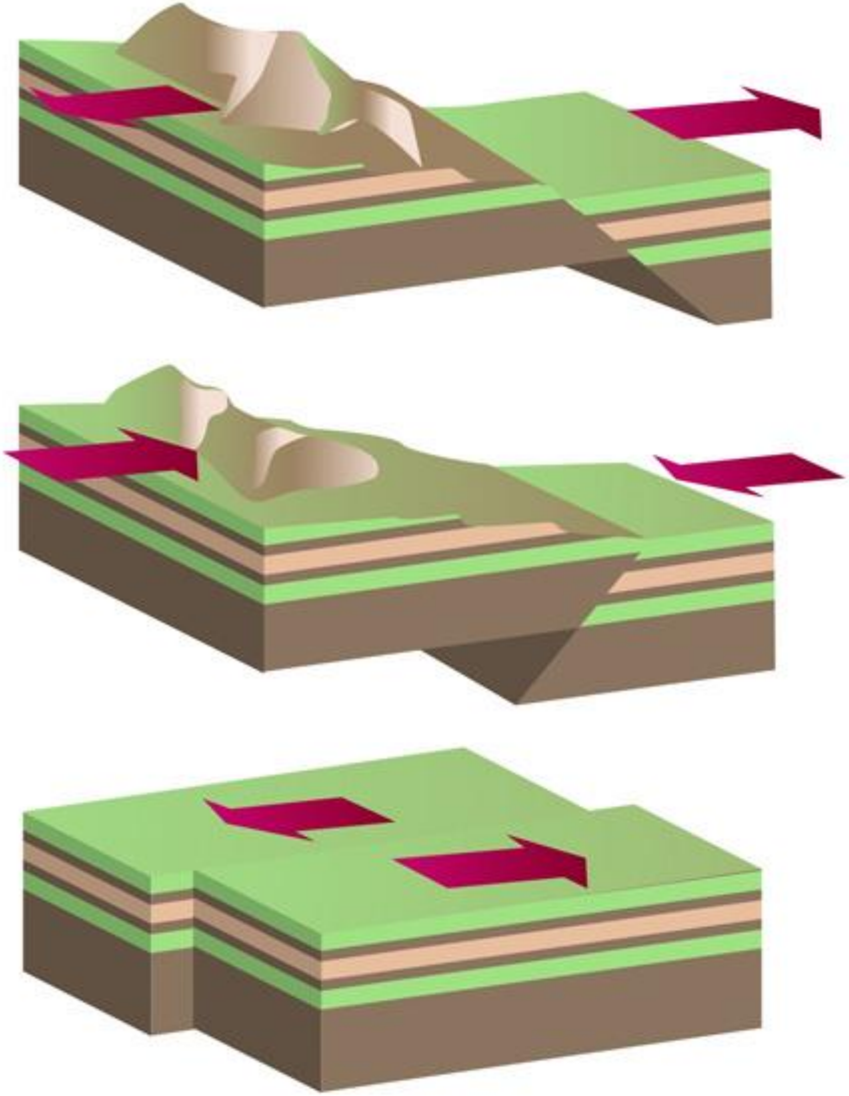
1) $-180° < \lambda \leq 180°$ by Aki & Richards, 1980
2) $0 \leq \lambda < 360°$ by Panza et al, 1973

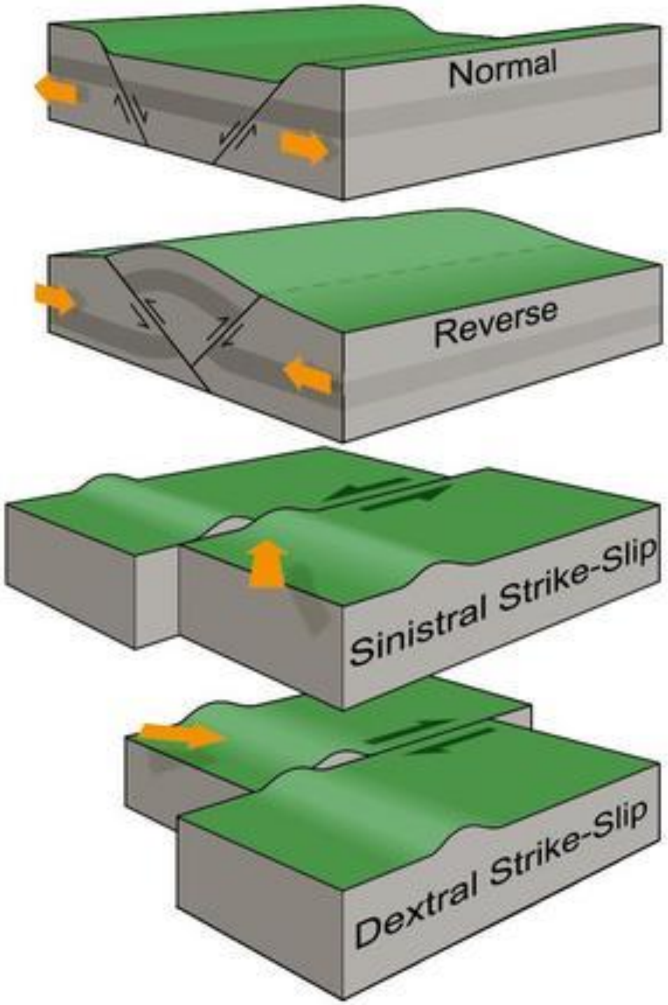
Reverse fault: 1) $0° < \lambda < 180°$
2) $0° < \lambda < 180°$

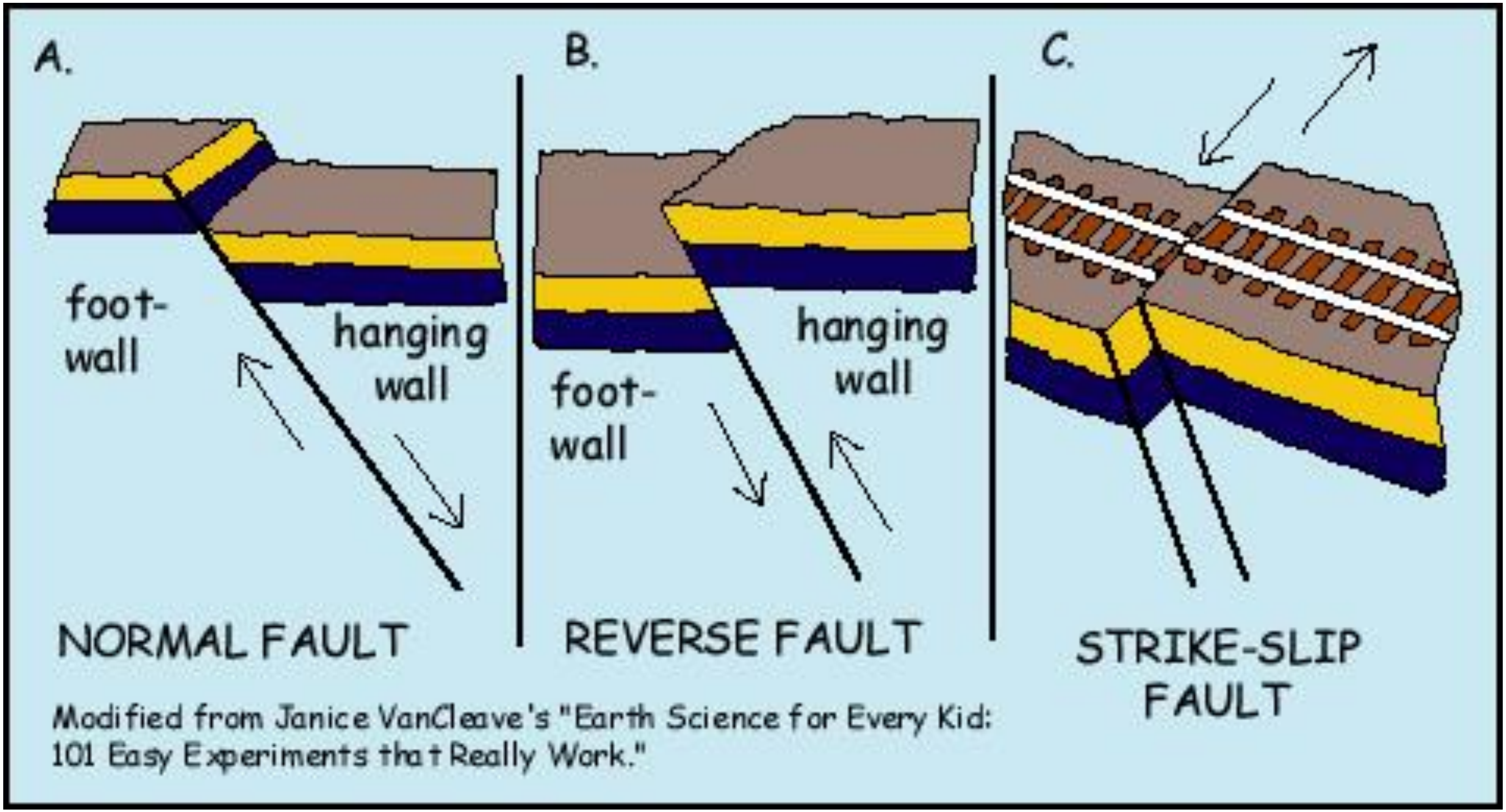
Normal fault: 1) $-180° < \lambda < 0°$
2) $180° < \lambda < 360°$

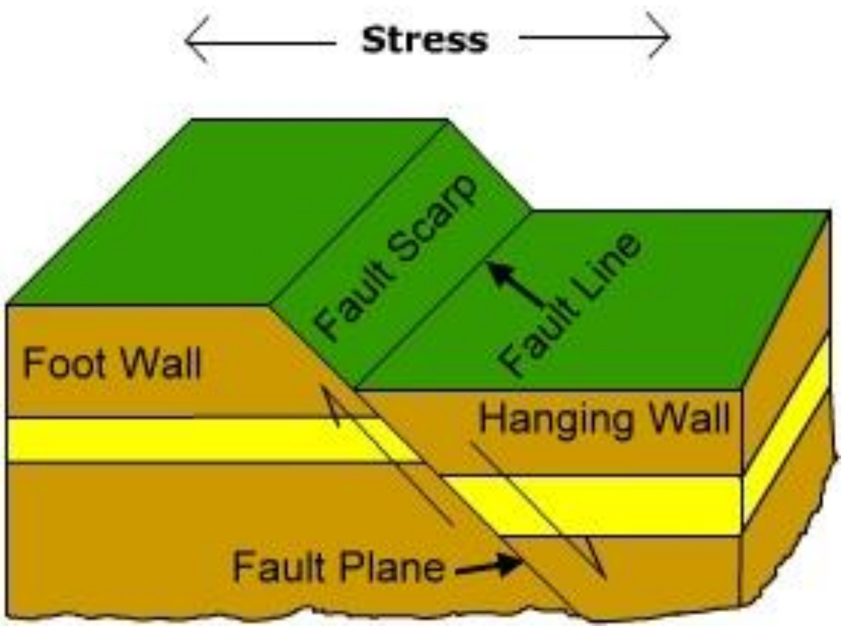
Strike-slip fault: 1) $\lambda = 0°$ left - lateral
2) $\lambda = 180°$ right - lateral

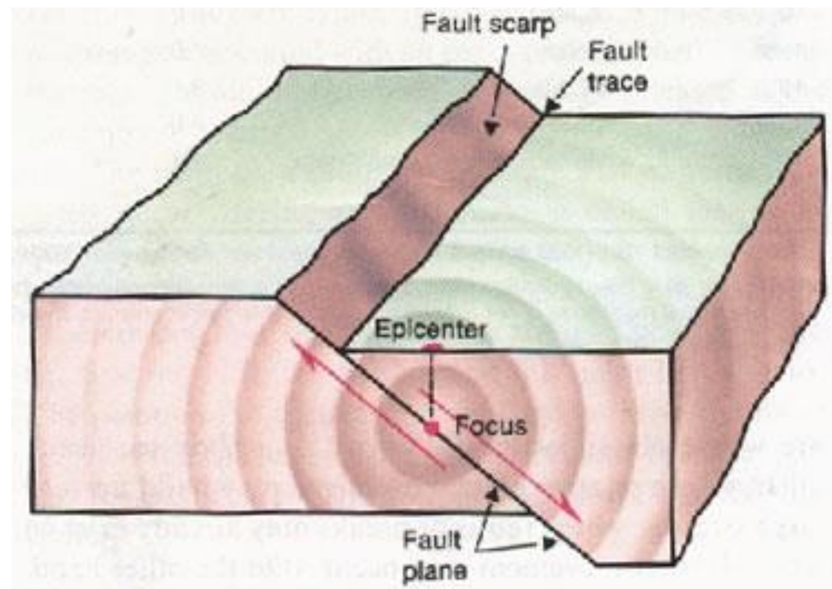


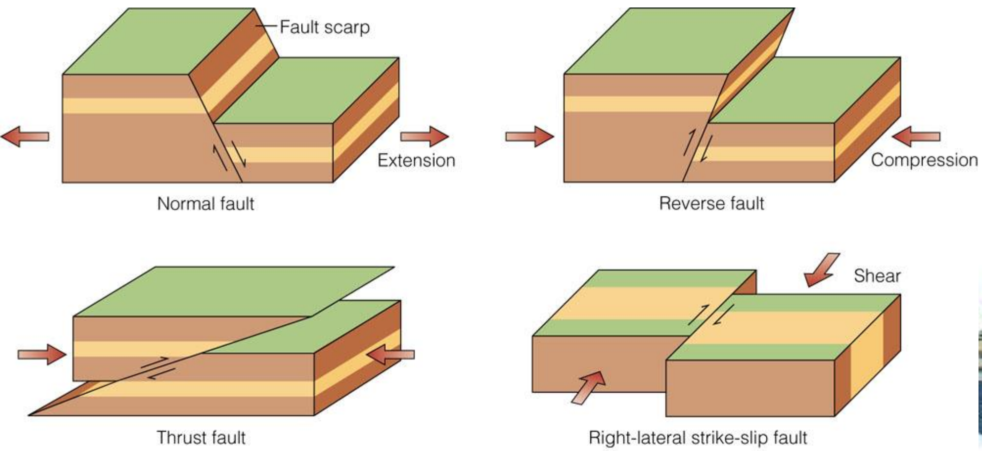


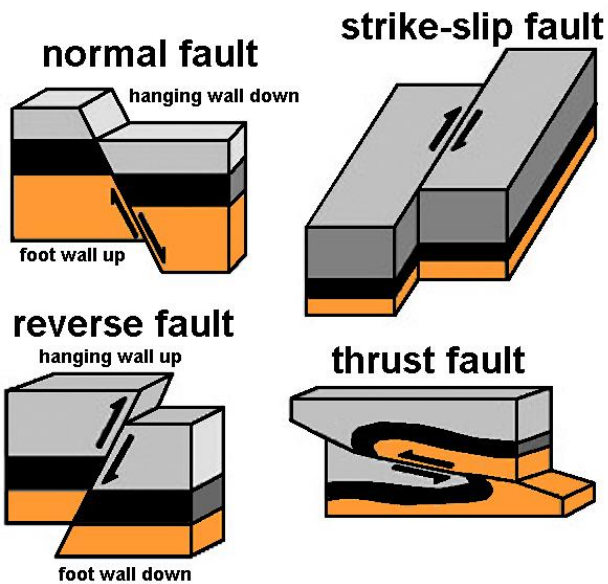

Normal
Reverse
Sinistral Strike-Slip
Dextral Strike-Slip

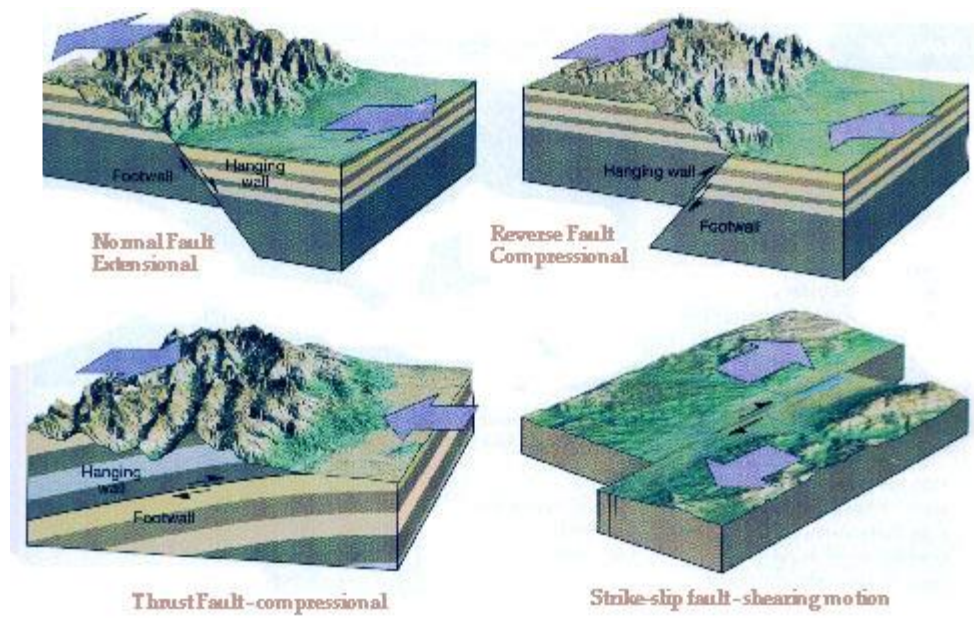

A.
B.
C.
foot-wall
hanging wall
foot-wall
hanging wall
NORMAL FAULT
REVERSE FAULT
STRIKE-SLIP FAULT
Modified from Janice VanCleave's "Earth Science for Every Kid: 101 Easy Experiments that Really Work."


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
Shear
Thrust fault
Right-lateral strike-slip fault

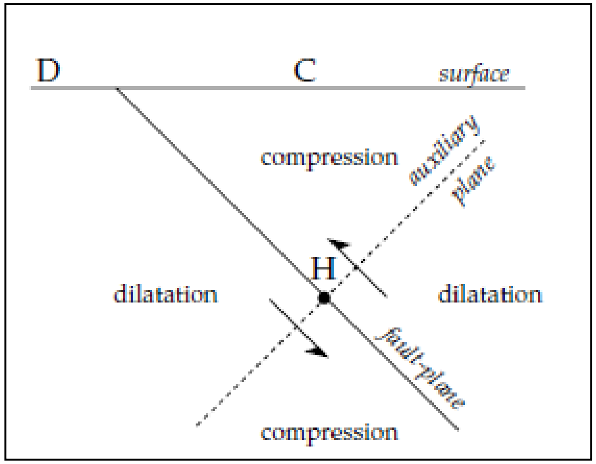

normal fault
hanging wall down
foot wall up
strike-slip fault
reverse fault
hanging wall up
foot wall down
thrust fault


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

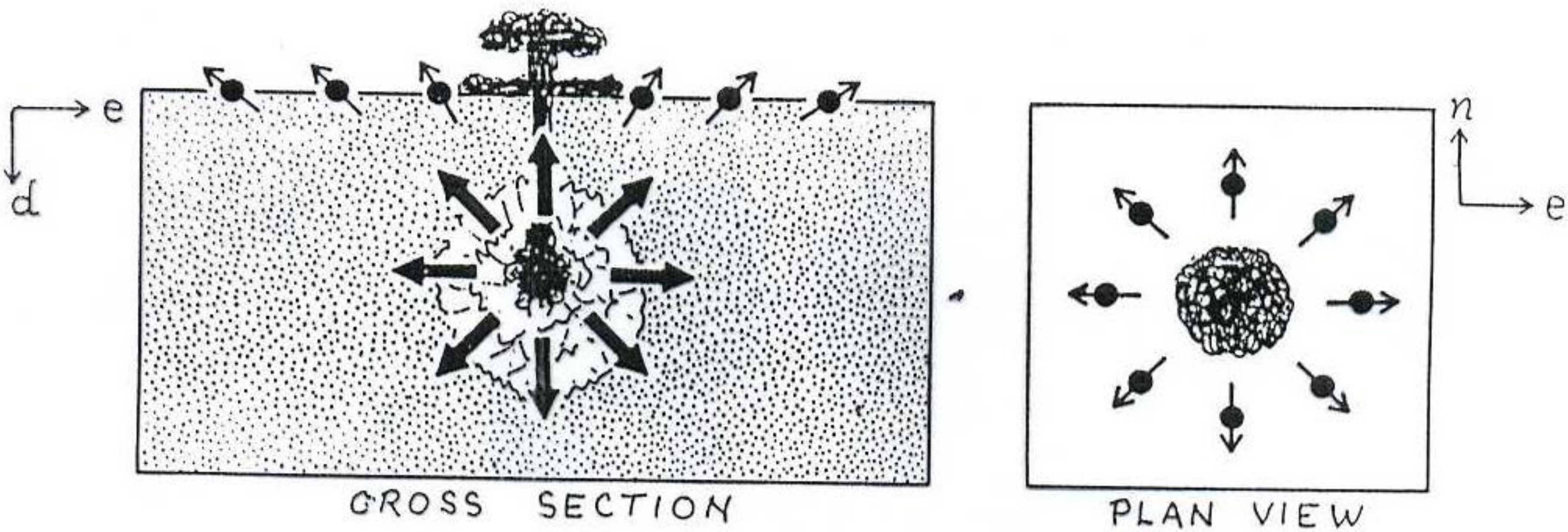
Focal mechanism

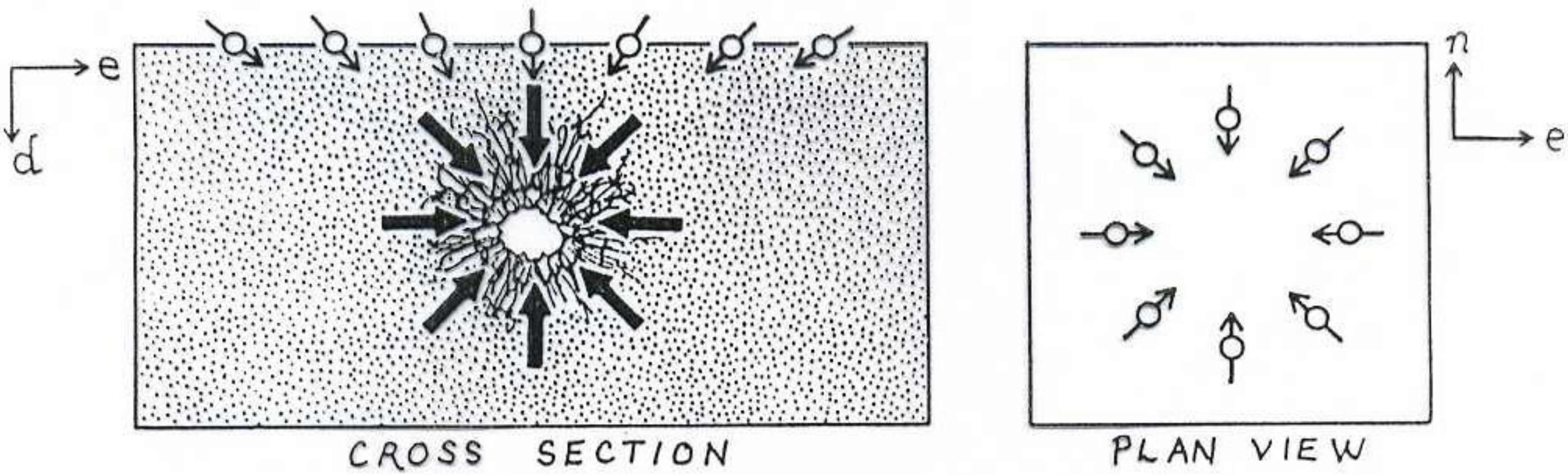
• During an earthquake the accumulated elastic energy is released suddenly by physical displacement of the ground, as heat and as seismic waves that travel outwards from the focus. By studying the first motions recorded by seismograph at distant seismic stations, the focal mechanism of the earthquake can be inferred and the motion on the fault-plane interpreted.

Consider a vertical section perpendicular to the plane of a normal fault on which the hypocenter of an earthquake is located at the point H. When the region above the fault moves up-slope, it produces a region of compression ahead of it and a region of dilatation.
In conjunction with the compensatory down-slope motion of the lower block, the earthquake produces two regions of compression and two regions of dilatation surrounding the hypocenter.

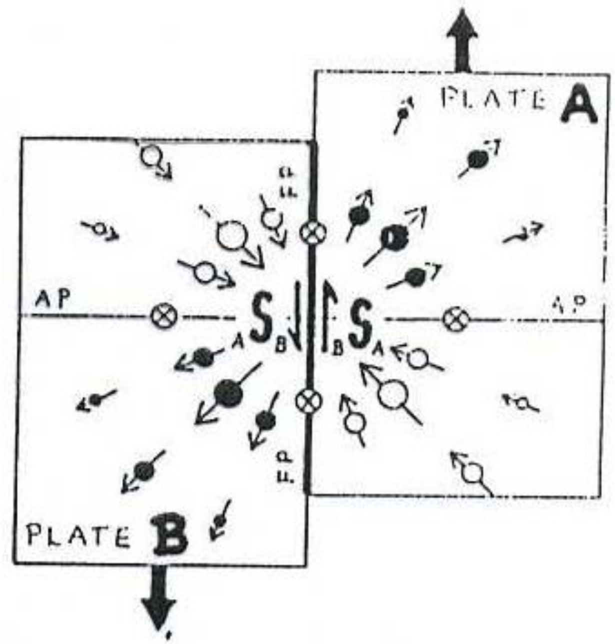


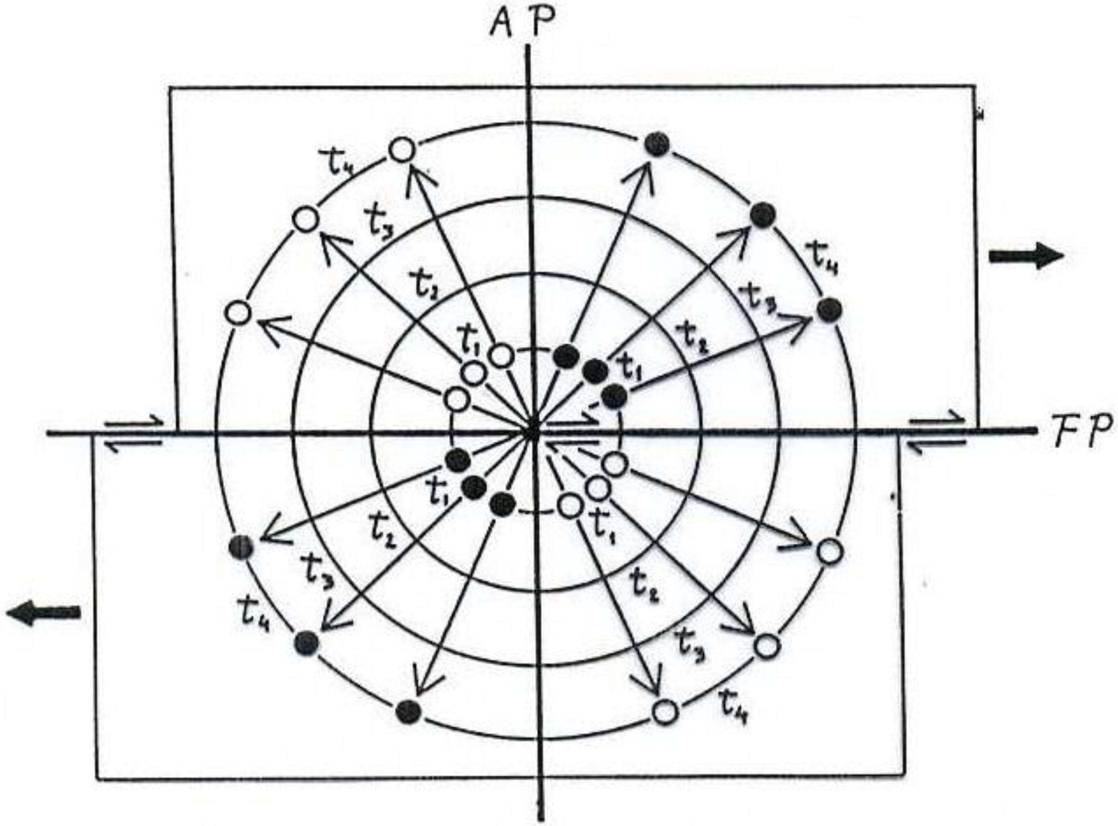
• These are separated by the fault-plane itself, and by an auxiliary plane through the focus and normal to the fault plane.
• When a seismic P-wave travelling out from a region of compression reaches an observer at C, its first effect is to push the Earth's surface upwards; the initial effect of a P-wave that travels out from a region of dilatation to an observer at D is to tug the surface downwards.
• The P wave is the earliest seismic wave to reach a seismograph at C or D and therefore the initial motion recorded by the instrument allows us to distinguish whether the first arrival was compressional or dilatational.

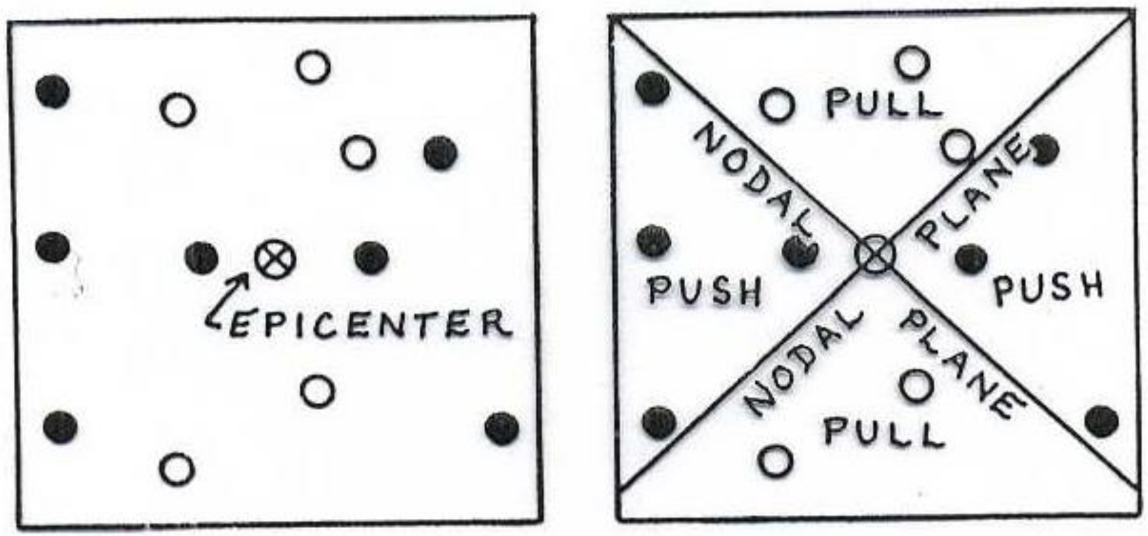

e
d
CROSS SECTION
n
e
PLAN VIEW

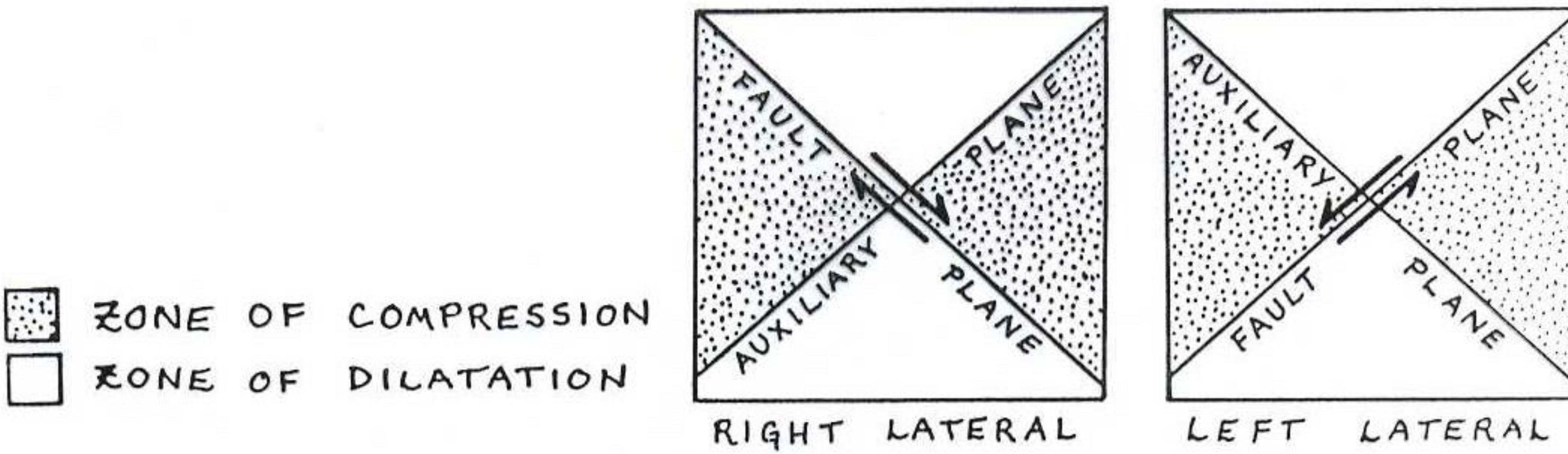

e
d
CROSS SECTION
n
e
PLAN VIEW

→ DIRECTION OF FIRST MOTION
● FIRST MOTION IS PUSH (COMPRESSION)
○ FIRST MOTION IS PULL (DILATATION)
⊗ NO FIRST MOTION (UNDEFINED)
$_A S_B$ ↓ SLIP VECTOR SHOWING MOTION OF PLATE B RELATIVE TO PLATE A



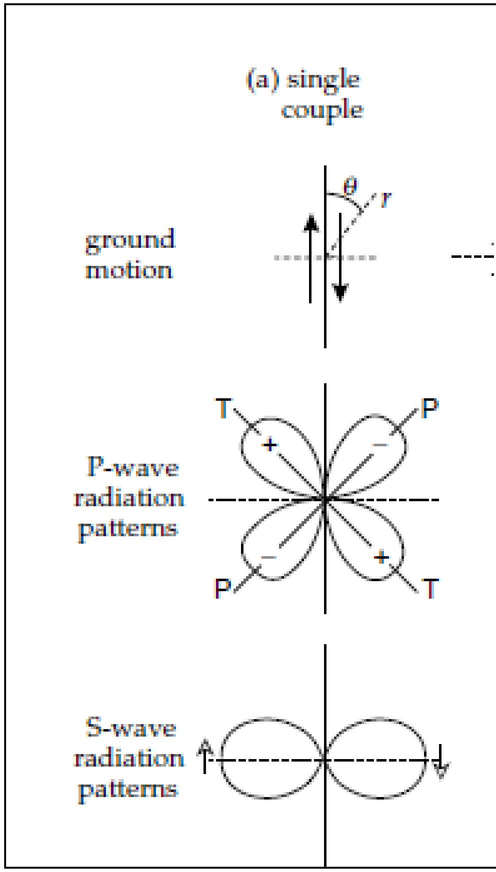

A P
F P
t1
t2
t3
t4


EPICENTER
NODAL PLANE
NODAL PLANE
PULL
PUSH
PUSH
PULL


ZONE OF COMPRESSION
ZONE OF DILATATION
FAULT
PLANE
AUXILIARY
PLANE
RIGHT LATERAL
AUXILIARY
PLANE
FAULT
PLANE
LEFT LATERAL

- The amplitudes of P-waves and S-waves vary with distance from their source because of the effects of physical damping and geometric dispersion.
- The amplitudes also depend geometrically on the angle at which the seismic ray leaves the source. This geometric factor can be calculated mathematically, assuming a model for the source mechanism.
- The simplest is to represent the source by a single pair of antiparallel motions. Analysis of the amplitude of the P-wave as a function of the angle θ between a ray and the plane of the fault gives an equation of the form:

$$A(r,t,\alpha,\theta) = A_0(r,t,\alpha)\sin 2\theta \qquad [Eq\ 2]$$

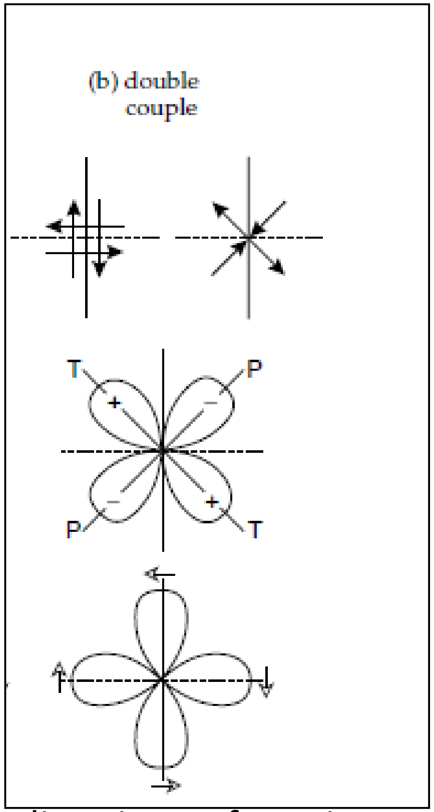


in which $A_0(r, t, \alpha)$ describes the decrease in amplitude with distance r, time t, and seismic P-wave velocity a. A plot of the amplitude variation with u is called the radiation pattern of the P-wave amplitude, which for the single-couple model has a quadrupolar character. It consists of four lobes, two corresponding to the angular variation of amplitude where the first motion is compressional and two where the first motion is dilatational. The lobes are separated by the fault-plane and the auxiliary plane.

• An alternative model of the earthquake source is to represent it by a pair of orthogonal couples.

•The double-couple source gives the same form of radiation pattern for P-waves as the single-couple source, but the radiation pattern for S-waves is quadrupolar instead of dipolar.

• This difference in the S-wave characteristics enables the seismologist to determine which of the two earthquake source models is applicable. S-waves arrive later than P-waves, so their first motions must be resolved from the background noise of earlier arrivals. They can be observed and are consistent with the double-couple model .



Note that the maximum P-wave amplitudes occur at 45° to the fault plane. The directions of maximum amplitude in the compressional and dilatational fields define the T-axis and P-axis, respectively. Here T and P imply “tension” and “compression,” respectively, the stress conditions before faulting. Geometrically the P- and T-axes are the bisectors of the angles between the fault-plane and auxiliary plane. The orientations of these axes and of the fault-plane and auxiliary plane can be obtained even for distant earthquakes by analyzing the directions of first motions recorded in seismograms of the events. The analysis is called a fault-plane solution, or focal mechanism solution.

The maximum compressive (P) and the minimum compressive (T) axes can be found by bisecting the dilatational and compressional qudrants respectively. To bisect the angle between two nodal planes on the stereonet, we find the poles for the two planes, draw the great circle connecting them, and mark the point on it half way between the poles.

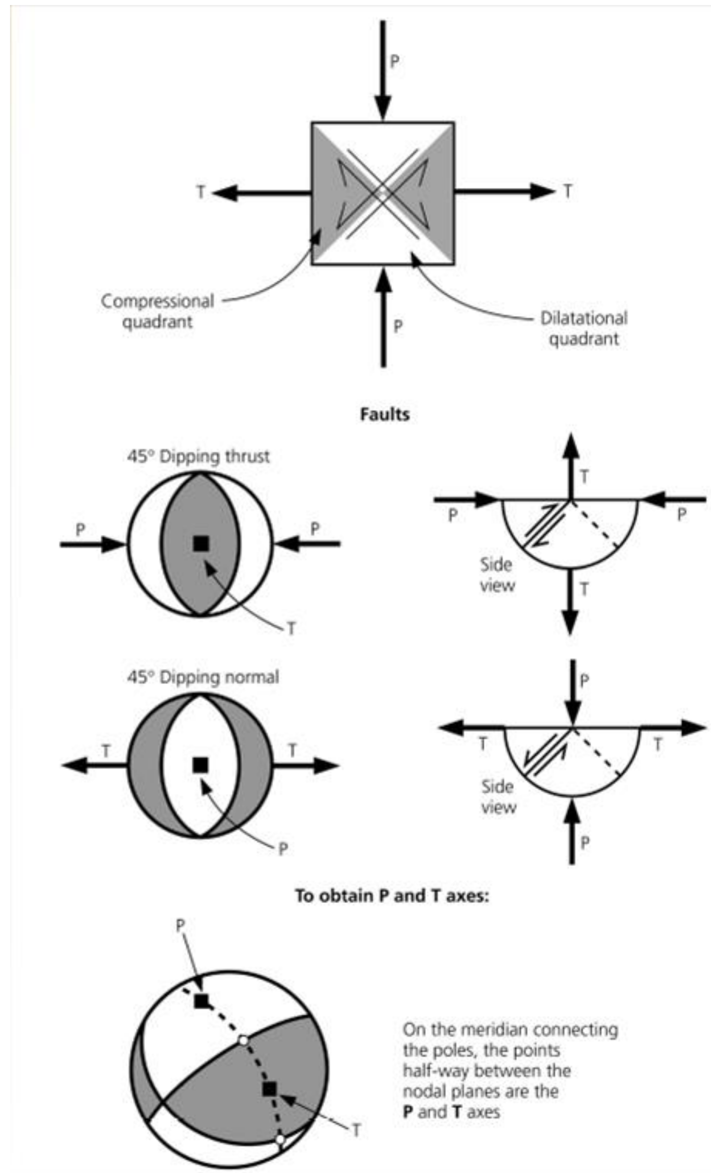
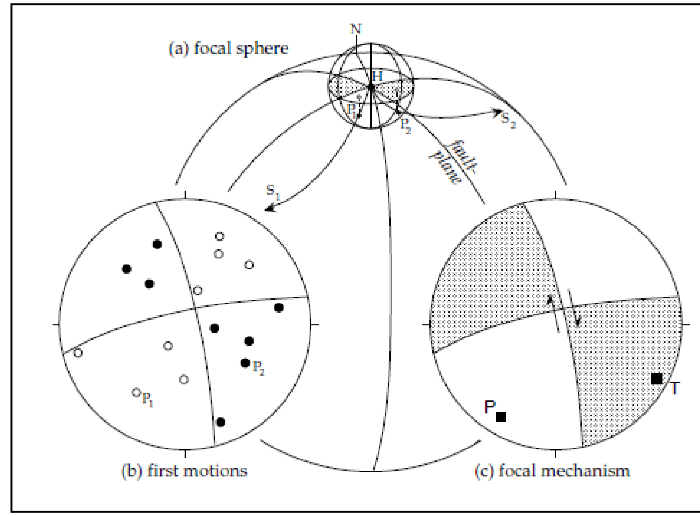


Illustration of the relationship between fault planes and the maximum (P) and minimum (T) compressive stresses. Using first motion studies, it can be difficult to accurately constrain nodal planes due to uneven sampling of the wavefield

• The ray path along which a P-wave travels from an earthquake to the seismogram is curved because of the variation of seismic velocity with depth. The first step in the fault plane solution is to trace the ray back to its source. A fictitious small sphere is imagined to surround the focus and the point at which the ray intersects its surface is computed with the aid of standardized tables of seismic P wave velocity within the Earth.

• The azimuth and dip of the angle of departure of the ray from the earthquake focus are calculated and plotted as a point on 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 with a solid point if the first motion was a push away from the focus (i.e., the station lies in the field of compression). An open point indicates that the first motion was a tug towards the focus (i.e., the station lies in the field of dilatation). First-motion data of any event are usually available from several seismic stations that lie in different directions from the focus. The solid and open points on the stereogram usually fall in distinct fields of compression and dilatation.

• Two mutually orthogonal planes are now drawn so as to delineate these fields as well as possible. The fit is best made mathematically by a least square technique, but often a visual fit is obvious 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. The regions of the stereogram corresponding to compressional first motions are usually shaded to distinguish them from the regions of dilatational first motions. The P- and T-axes are the lines that bisect the angles between the fault-plane and auxiliary plane in the fields of dilatation and compression, respectively

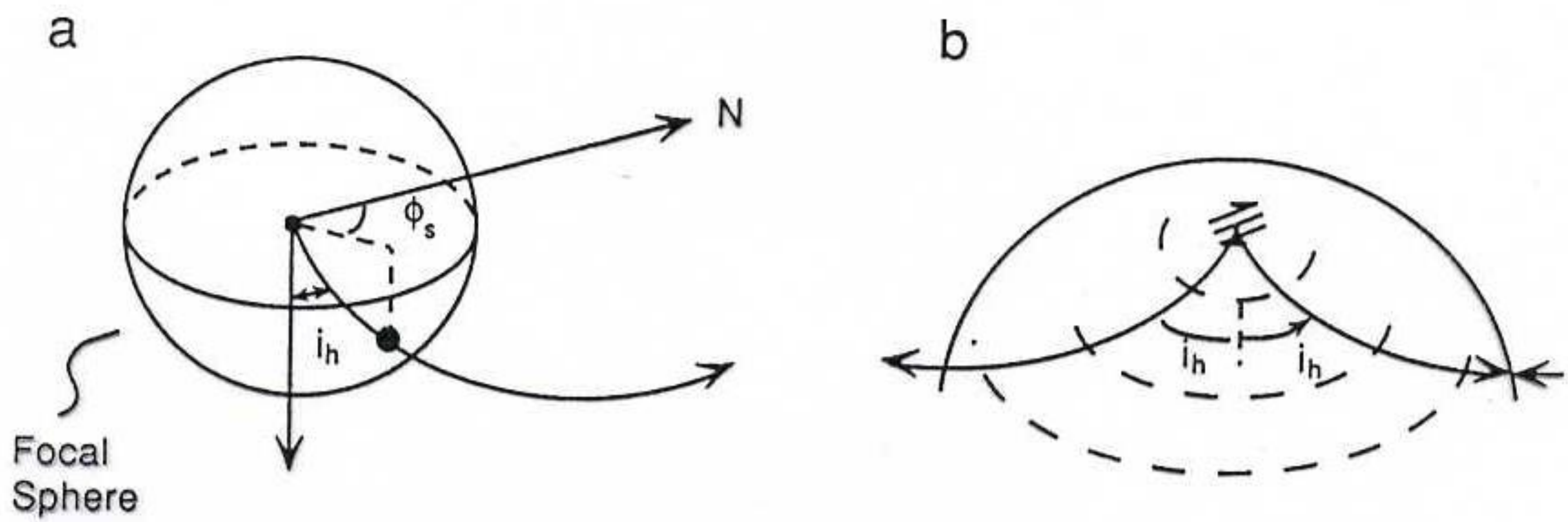
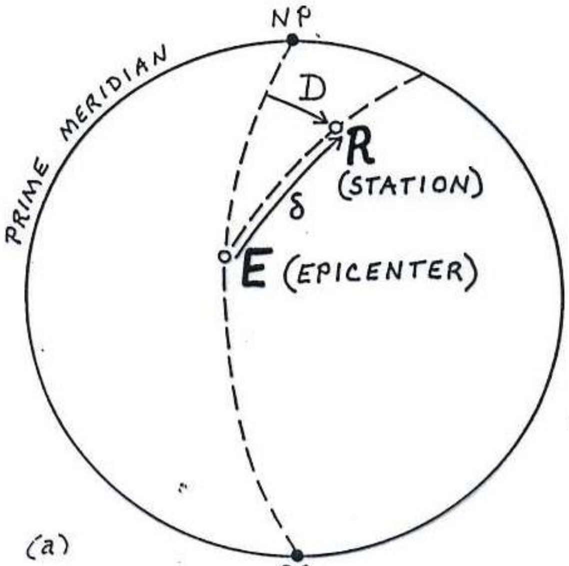
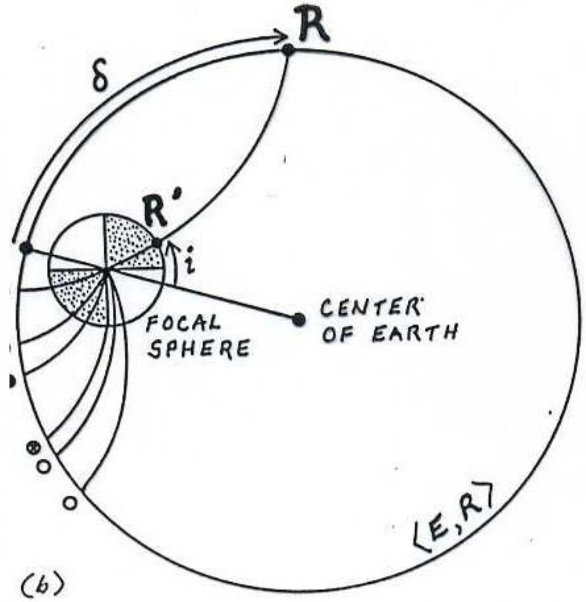


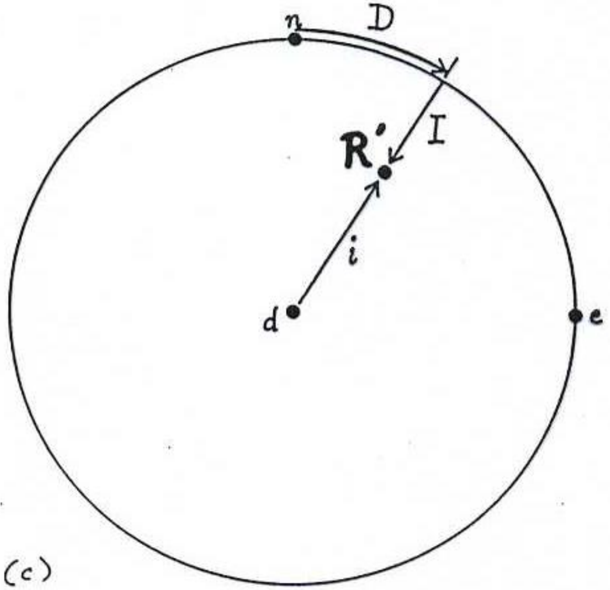
FIGURE 8.23 (a) The small focal sphere near the source, which can be thought of as the initial outgoing *P* (or *S*) wavefront. The raypath to a point on the Earth's surface (b) will have an associated takeoff angle and azimuth.



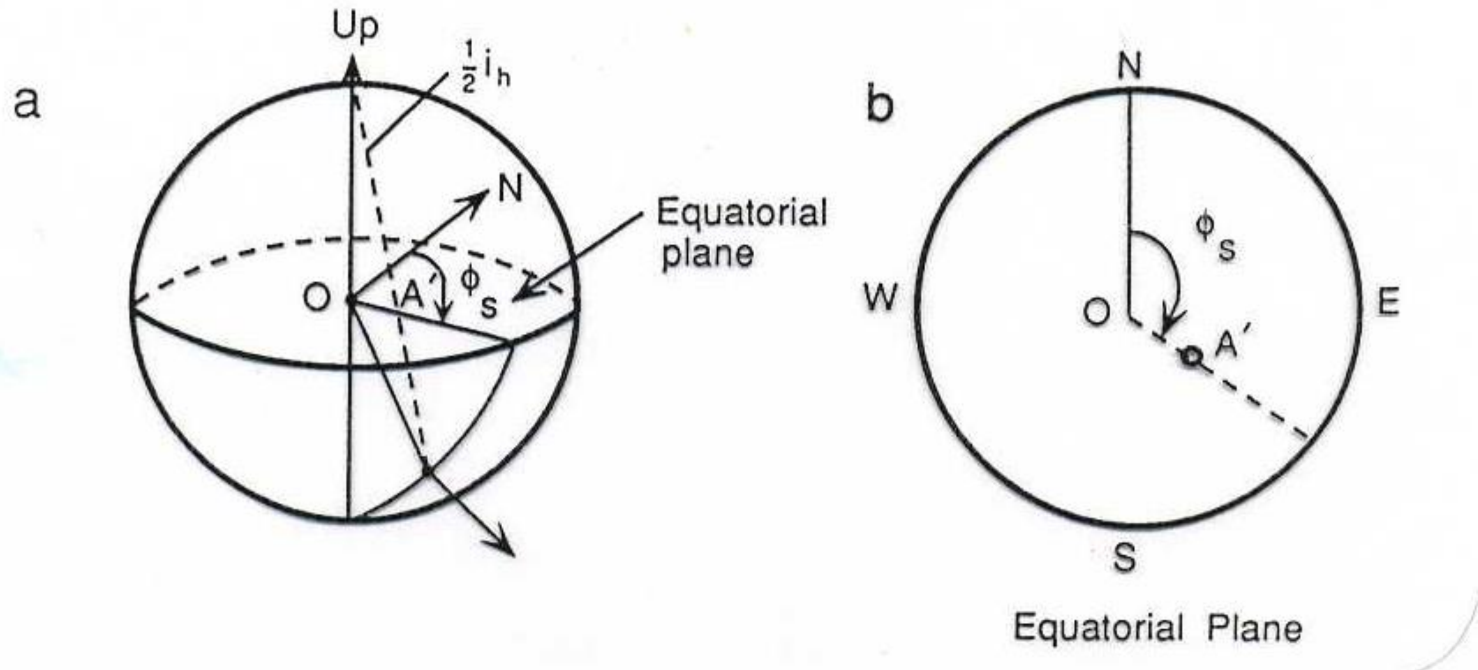
(a)
UPPER HEMISPHERE PROJECTION OF EARTH



(b)
CROSS-SECTION OF GLOBE THROUGH GREAT CIRCLE ⟨E,R⟩



(c)
LOWER HEMISPHERE PROJECTION OF FOCAL SPHERE

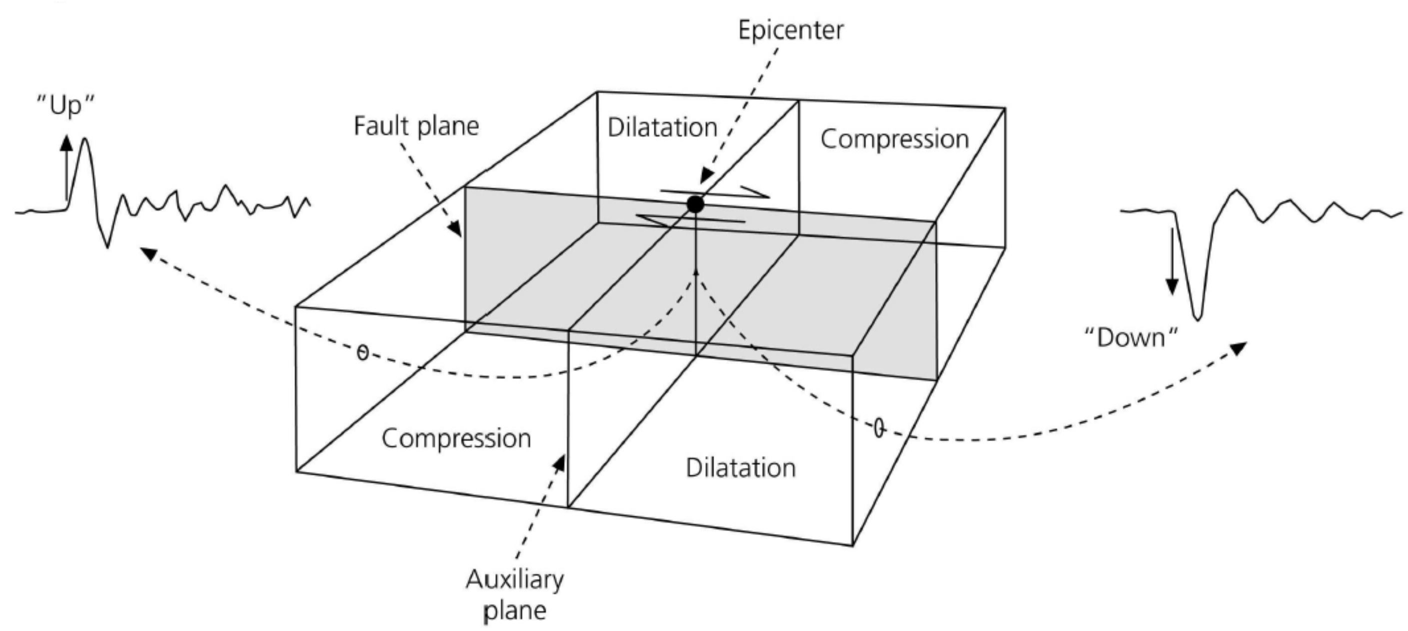


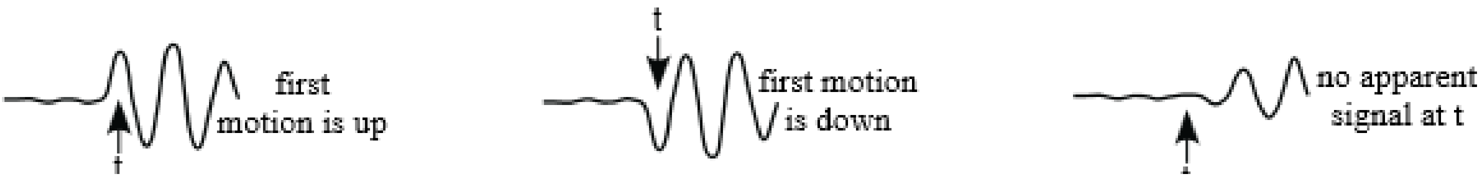
Stereographic $OA' = \tan(\frac{1}{2} i_h)$

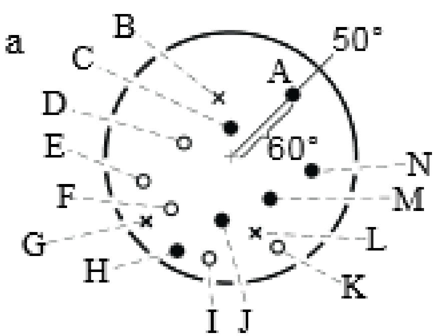
Equal area $OA' = \sqrt{2} \sin(\frac{1}{2} i_h)$

FIGURE 8.24 Projections for mapping spherical surfaces onto a plane. Both stereographic and equal-area projections are used, with the difference being the radial point *A′* used to represent the chord from the top of the focal sphere to the point intersected by the outgoing raypath. A ray going straight down intersects the center of the equatorial plane. Azimuth is preserved in the projection.

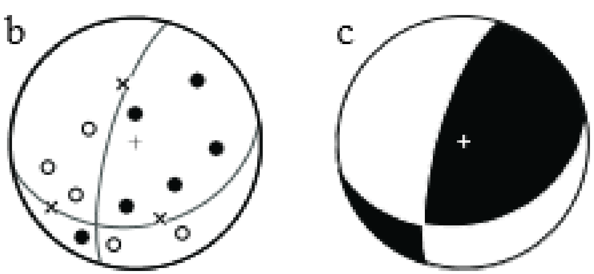
Example of first motions from a pure strike-slip earthquake. The P-waves impinge on a station from below







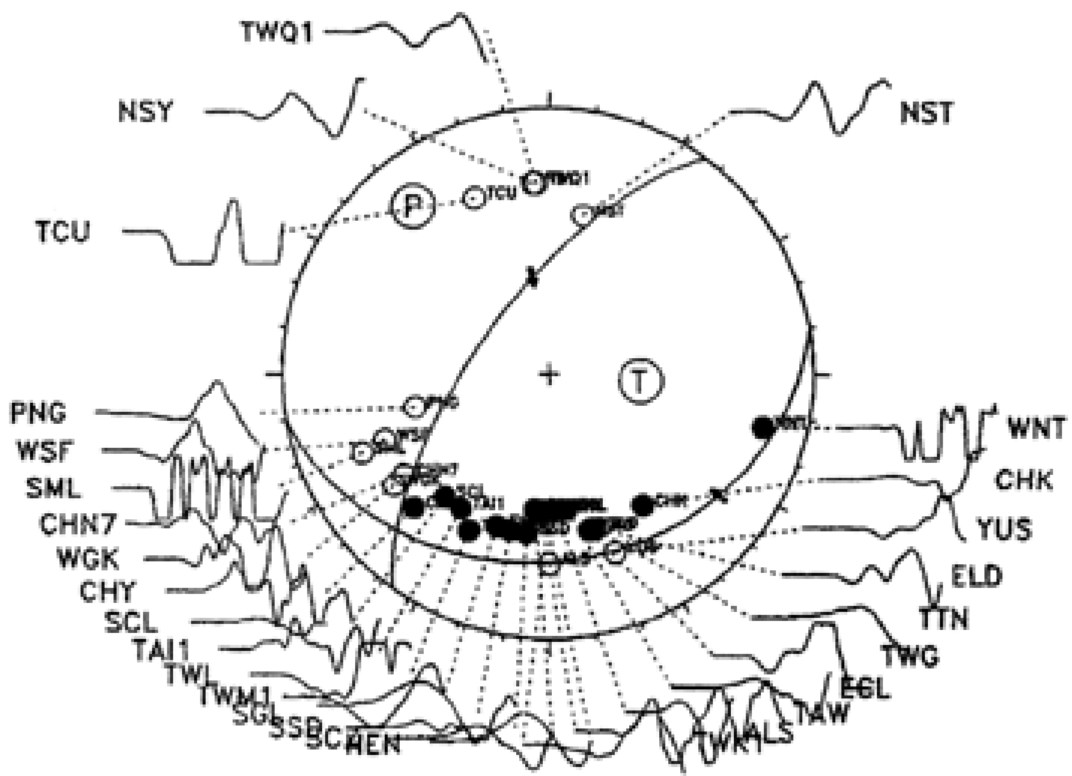
Stn	P wave	symbol	Stn	P wave	symbol	Stn	P wave	symbol
A		●	F		○	K		○
B		×	G		×	L		×
C		●	H		●	M		●
D		○	I		○	N		●
E		○	J		●			



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.

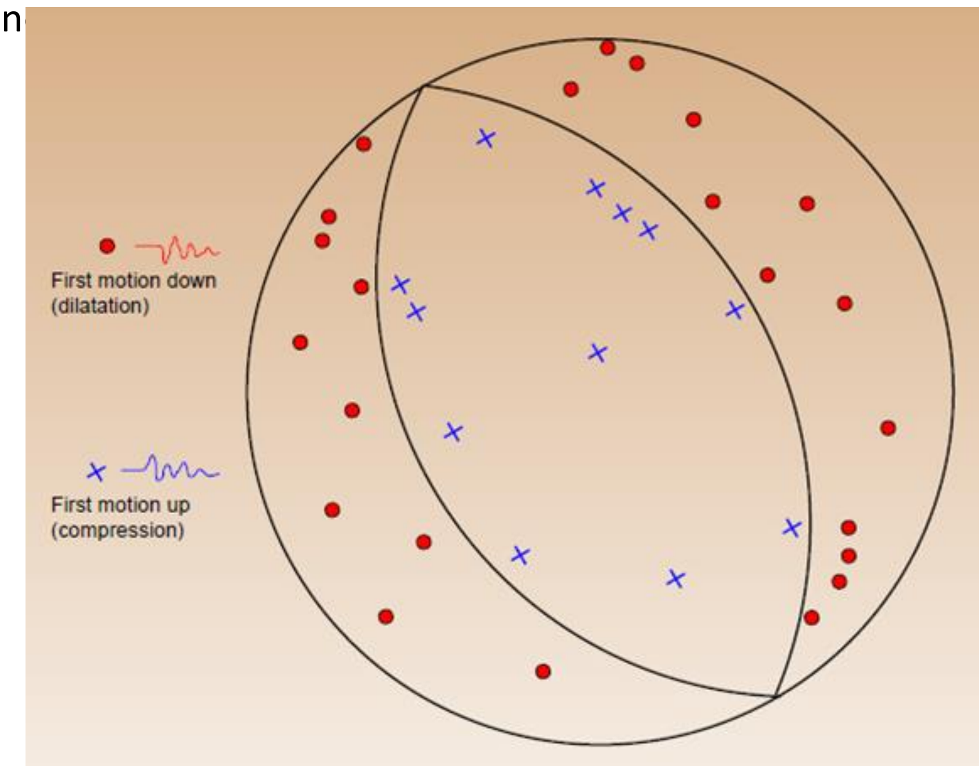
Data from CWB, Taipei

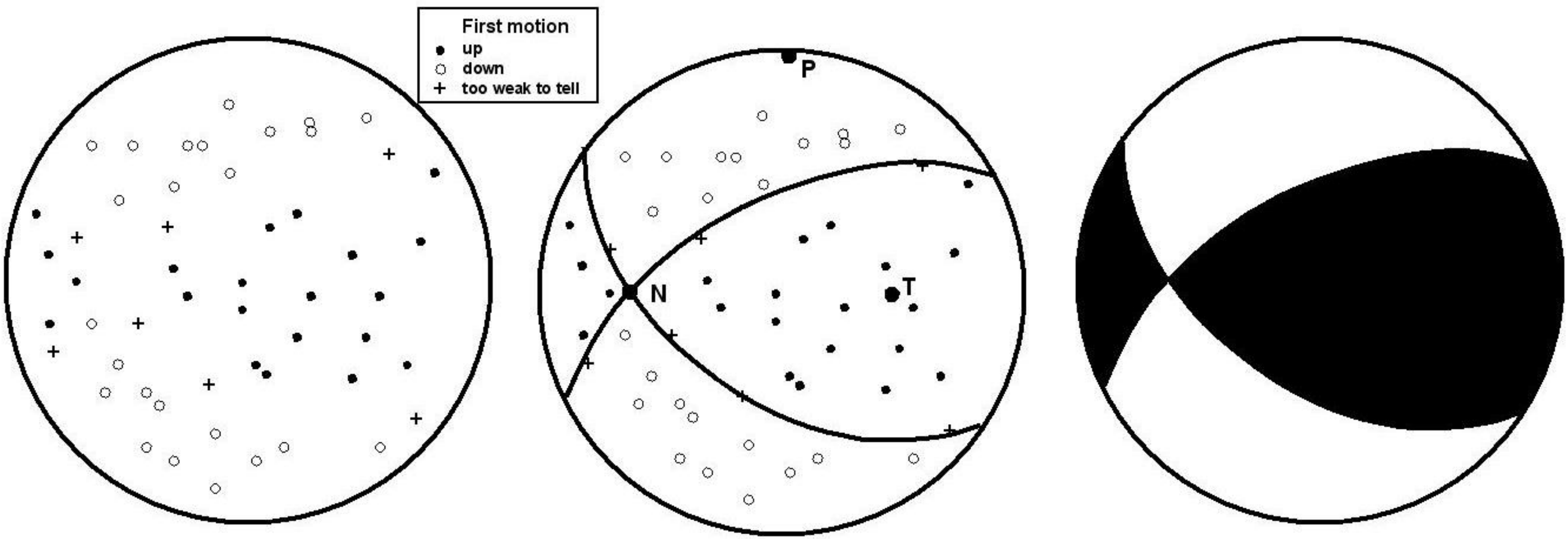
```
UT   : 09/20/99  17:47  ML:7.3
HYPO: 23.85N  120.81E  Z:   7KM
Strike  Dip  Rake:   80  30   130
Strike  Dip  Rake:  216  67    70
```



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 plan

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.



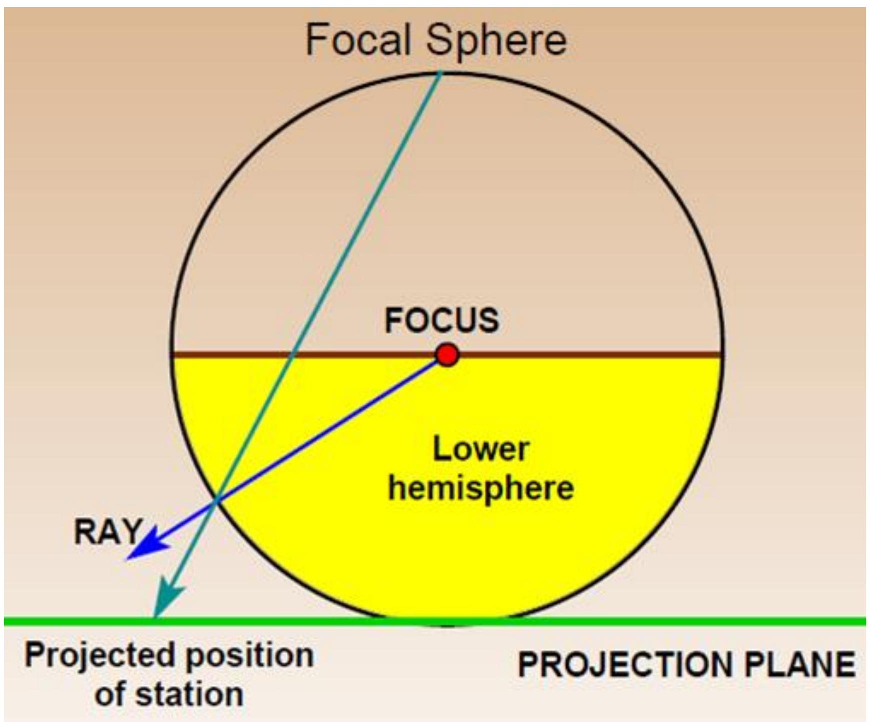


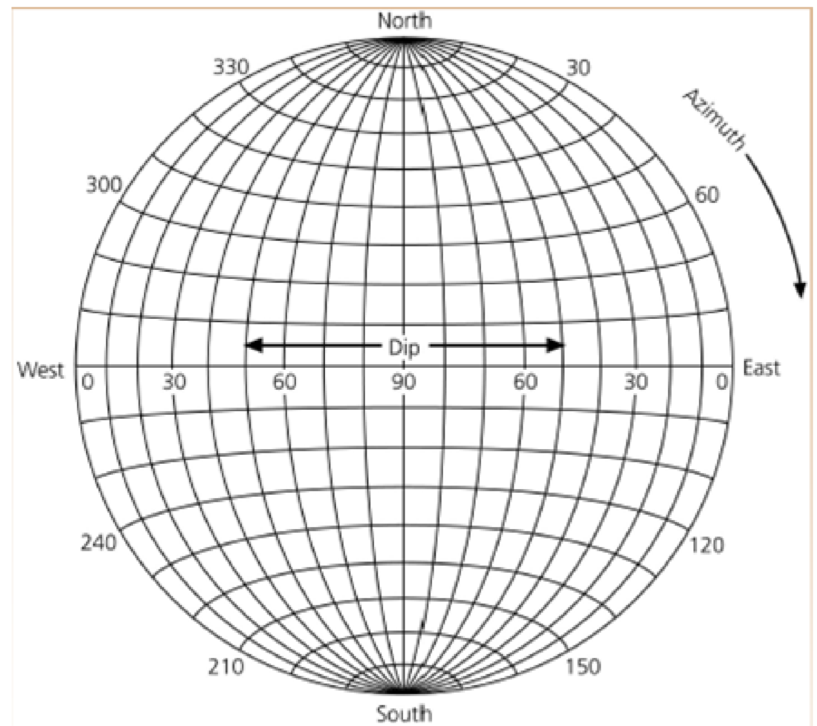
First motion data for a hypothetical earthquake from various seismograph stations

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

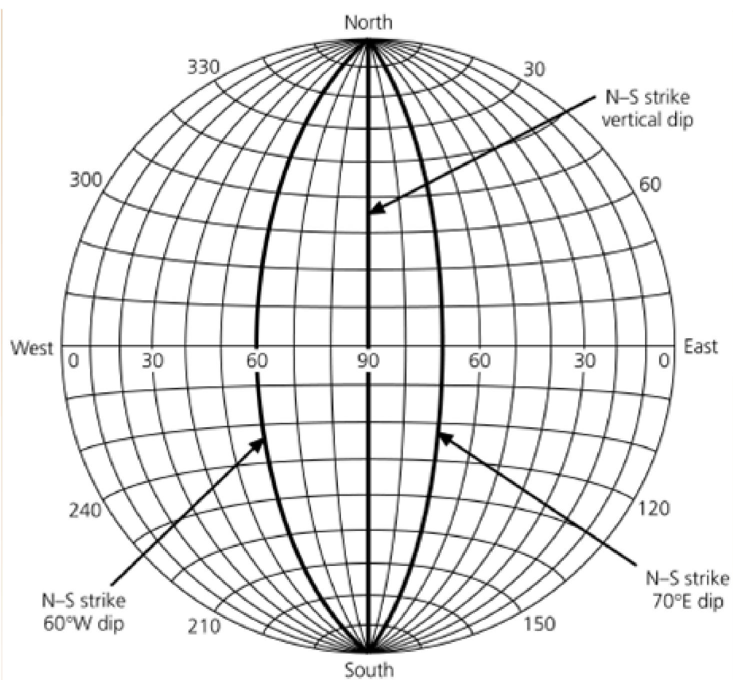
Resultant 'beachball' plot showing that the earthquake resulted from reverse oblique movement on a fault of one of two possible orientations

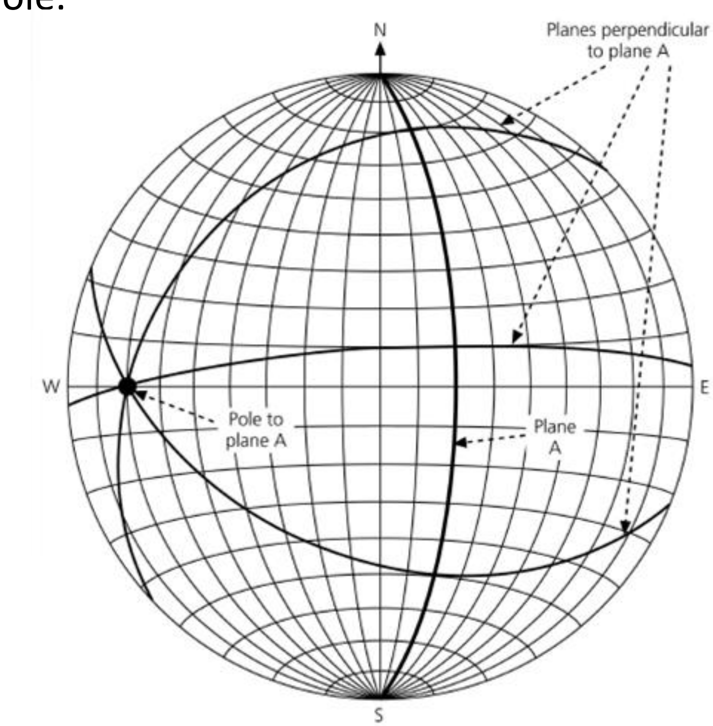
The lower hemisphere of the focal sphere can be plotted into a plane via a stereographic projection referred to as a stereonet. On a stereonet, lines and planes which pass through the centre of the focal sphere plot as points and lines respectively.



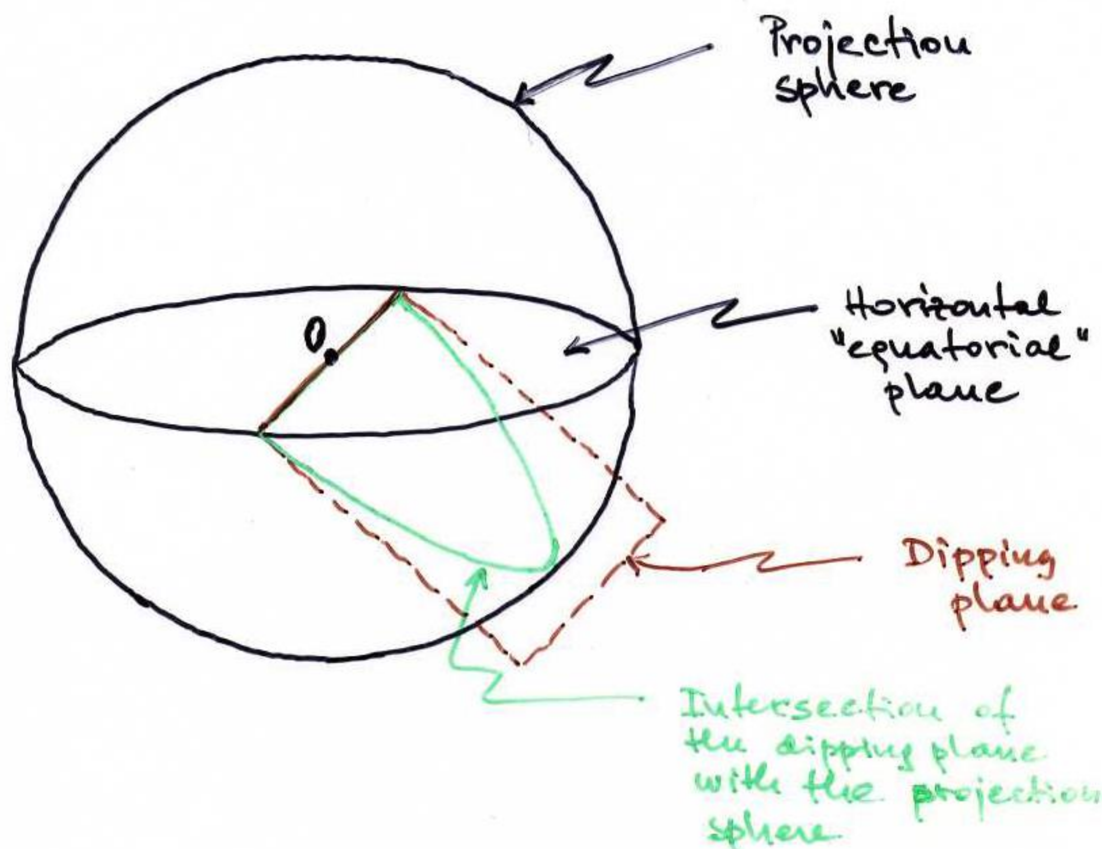


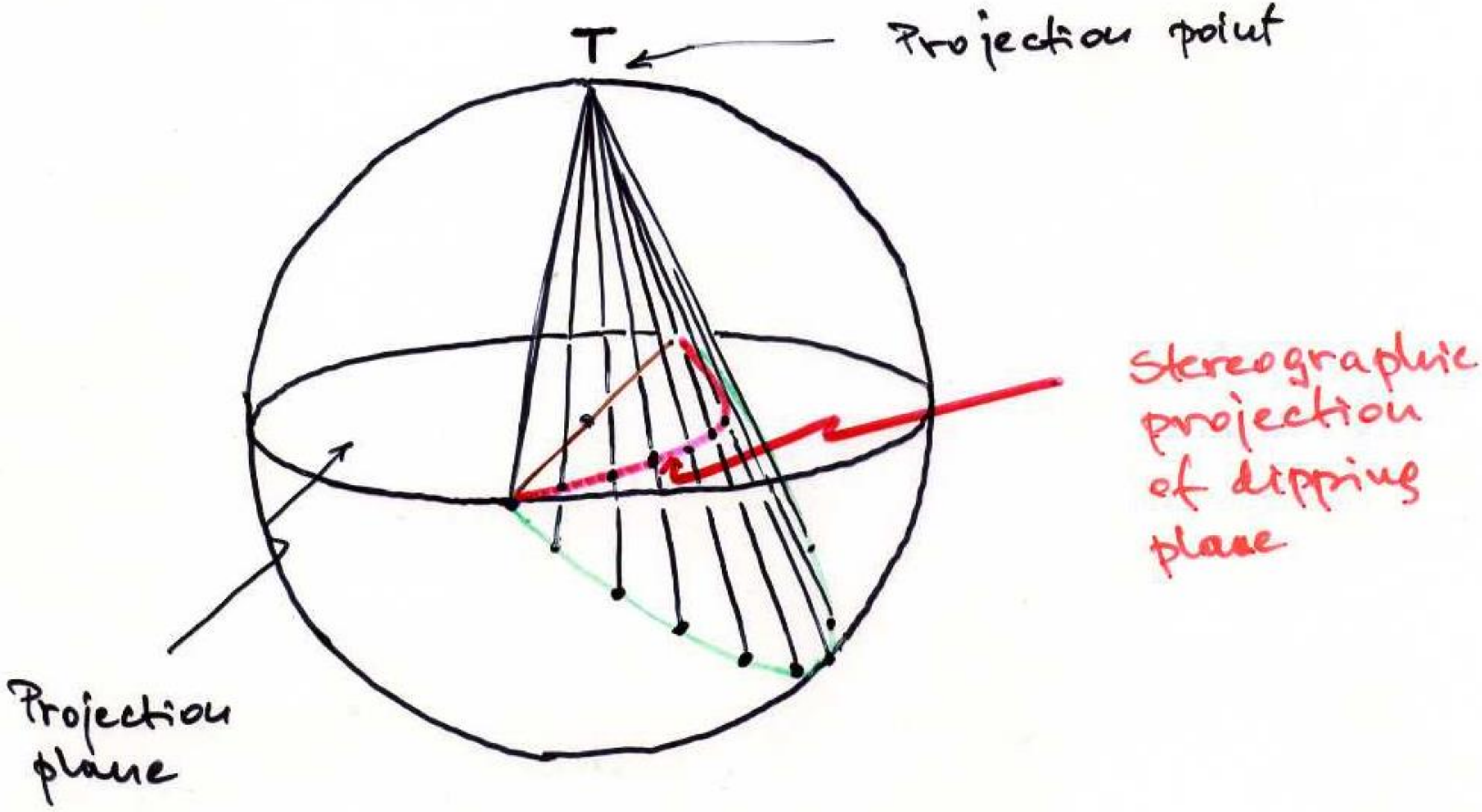
Note that it is only intersections between lines or planes and the focal sphere that are projected. For example a vertically dipping N-S plane plots as a straight line through the centre. If the plane dips at an angle, then it will plot along one of the meridians of the stereonet. Planes striking at different azimuths can be plotted in a similar way by rotating the stereonet. It is also straight forward to plot planes perpendicular to a given plane; simply rotate the stereoner so that the plane lies on a meridian, and find the point on the equator 90° from the intersection of the plane with equator. This point is the pole of the plane. The pole to a plane represents where the normal to the plane intersects the sphere. Any plane perpendicular to the original plane must contain the pole.



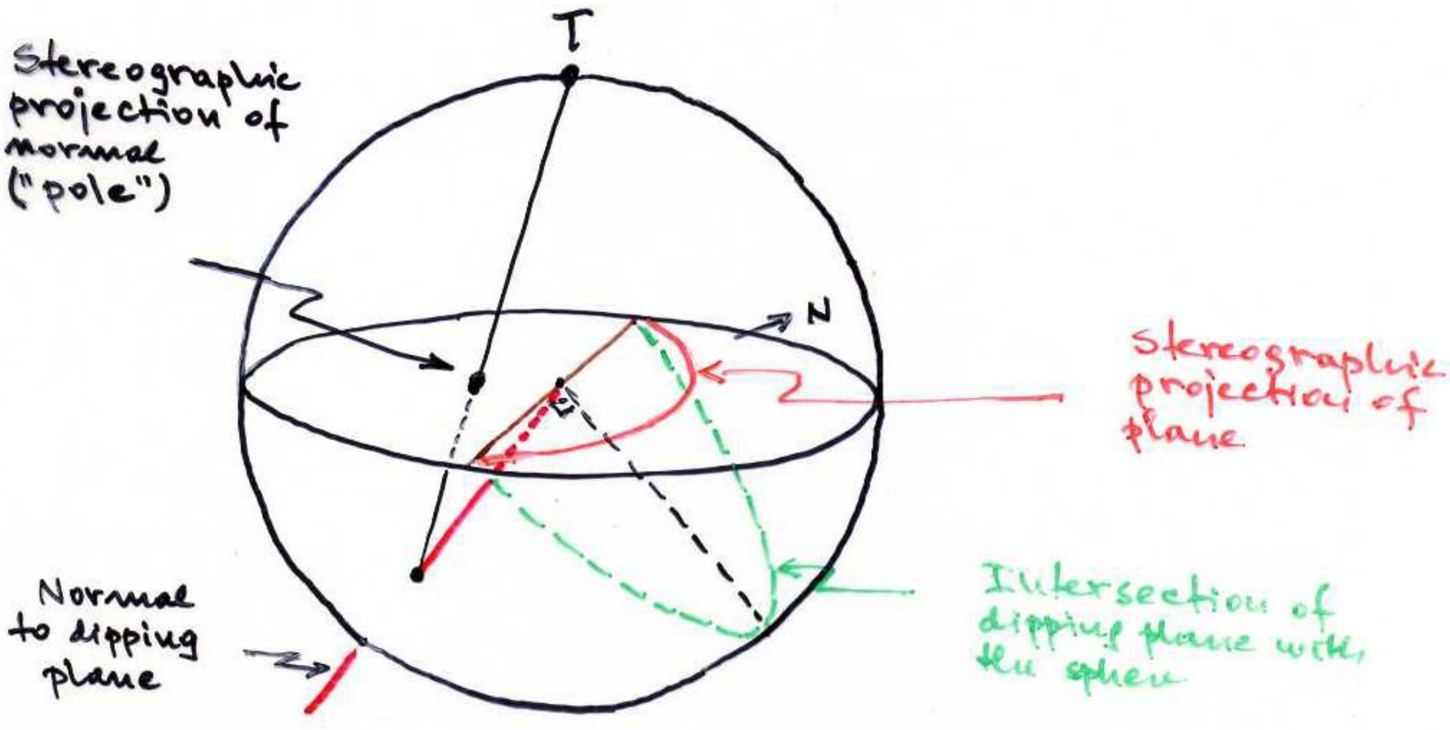


STEREOGRAPHIC PROJECTION OF PLANES




T
Projection point
Stereographic projection of dipping plane
Projection plane

STEREOGRAPHIC PROJECTION OF NORMAL

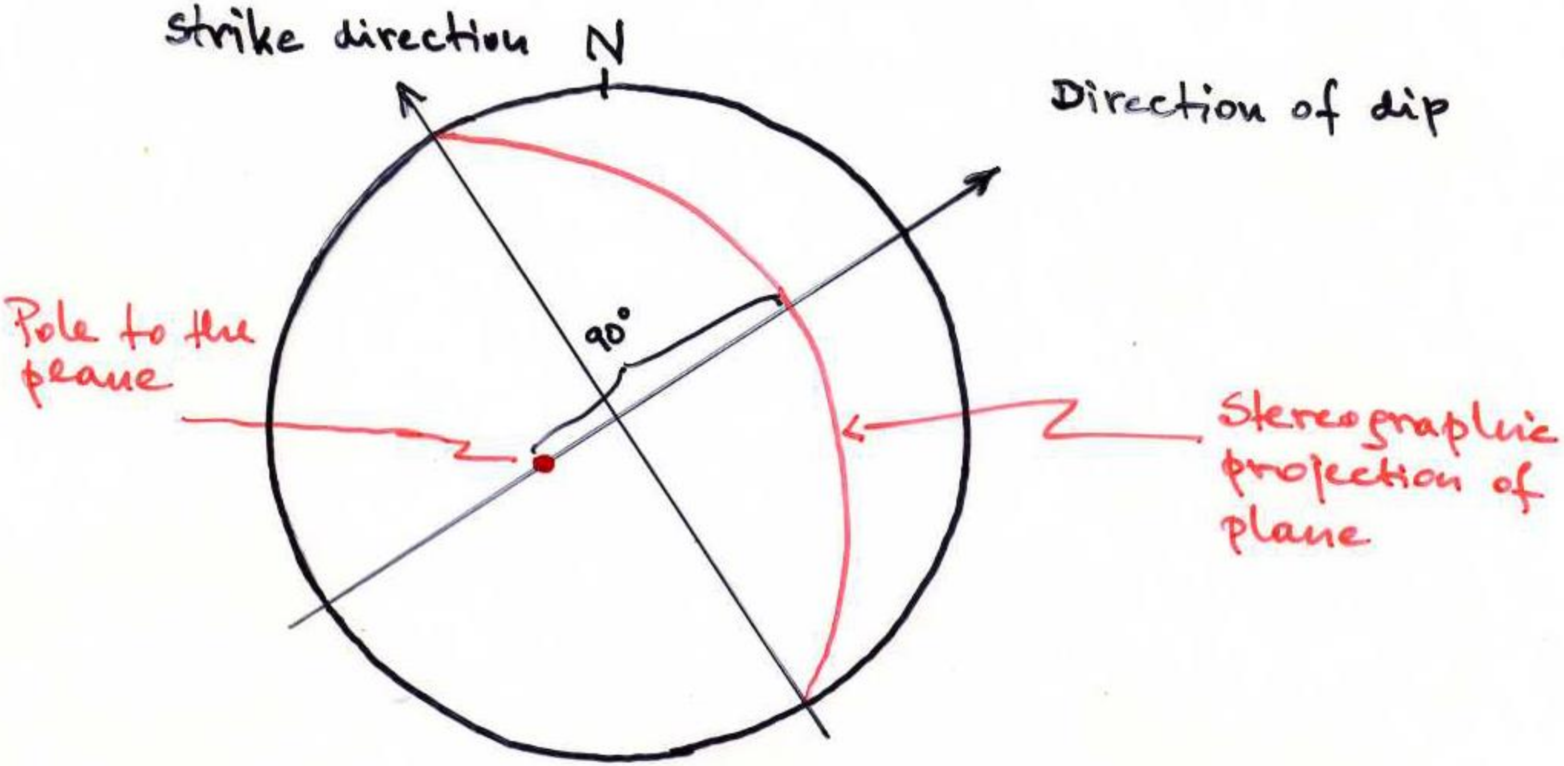


La proiezione della normale di un piano viene detta polo del piano.

Ogni polo viene parametrizzato da due quantità:

- direzione (trend) cioè l'angolo tra la direzione della normale nel piano orizzontale ed il nord.
- inclinazione (plunge), angolo tra il piano orizzontale e la direzione della normale

La stessa parametrizzazione vale per gli assi di compressione, tensione e l'asse nullo.



Plane view of equatorial plane

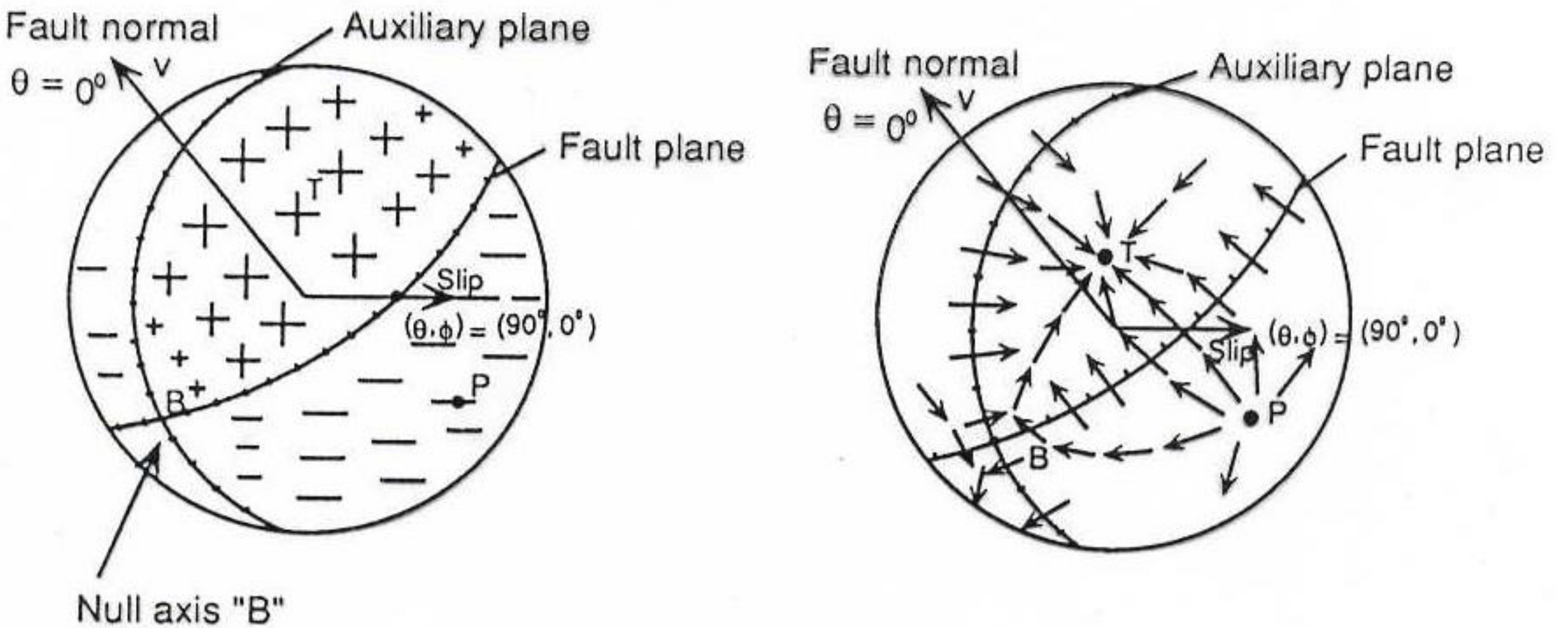


FIGURE 8.27 Focal mechanisms for an oblique-slip event showing *P*-wave polarities and relative amplitudes (left) and *S*-wave polarizations and amplitudes (right). Plus signs (+) indicate compressions. The fault and auxiliary planes are shown as well as projections of the *P*, *T*, and *B* axes. (Modified from Aki and Richards, 1980. Copyright ©1980 by W. H. Freeman and Co. Reprinted with permission.)

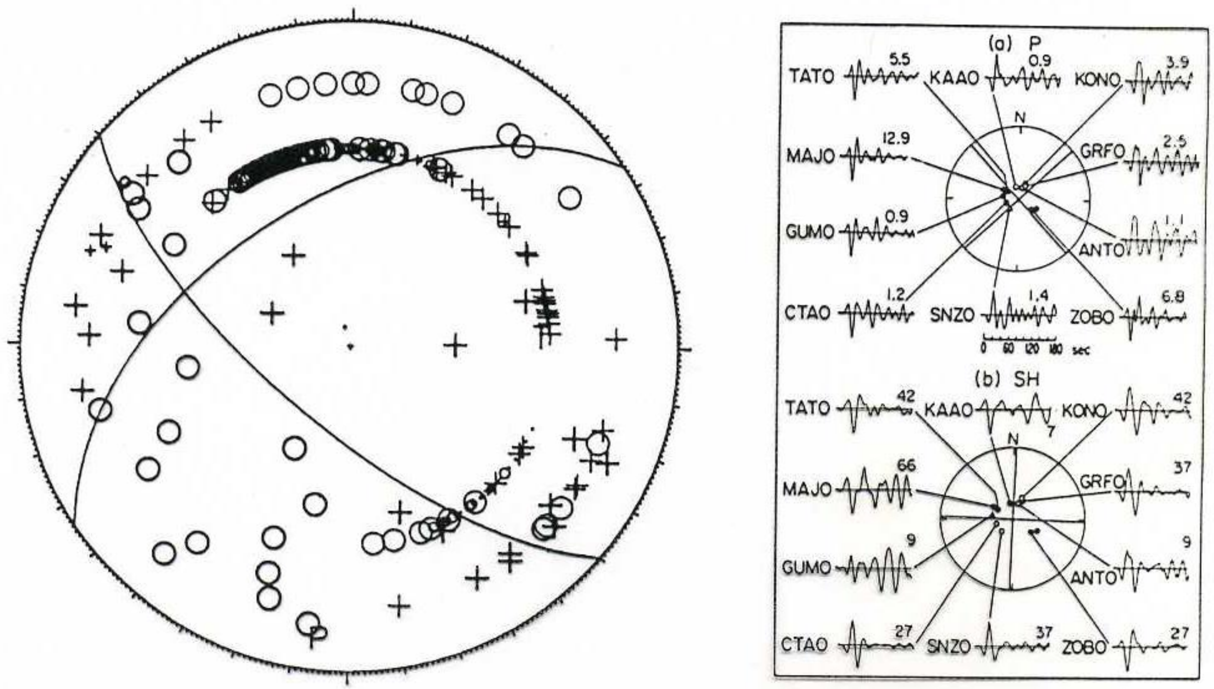
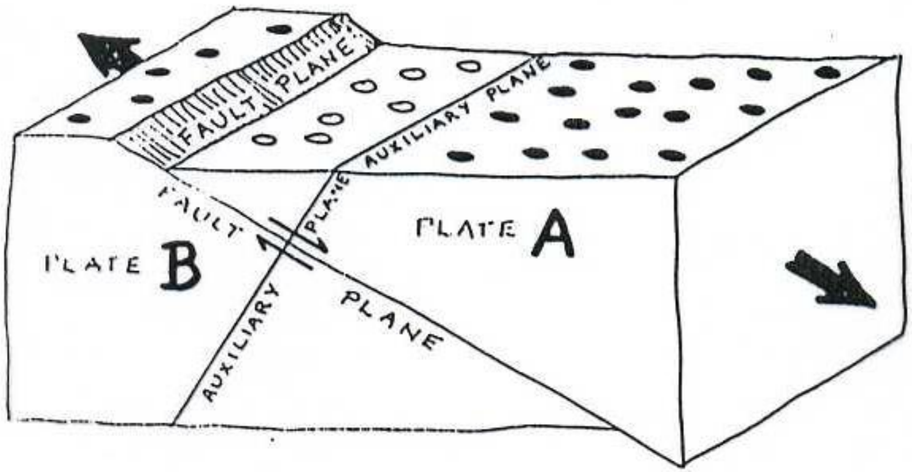
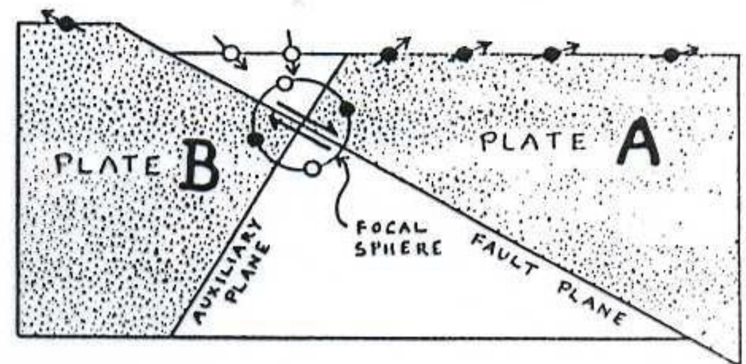
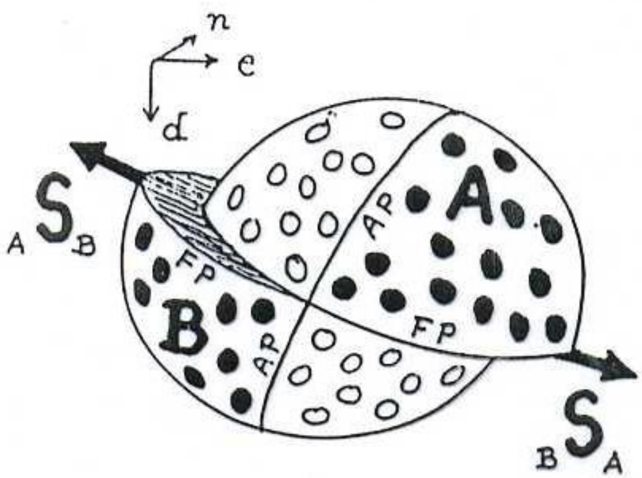
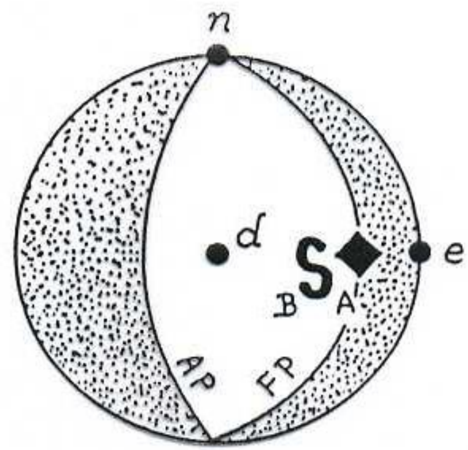


FIGURE 8.28 Examples of well-constrained focal mechanisms. On the left, *P*-wave first motions for the 1989 Loma Prieta earthquake from regional-distance stations are shown in an equal-area lower-hemisphere projection. Compressional motions are indicated by (+) and dilatations by (O). In this case $\phi_f = 130°$, $\delta = 70°$, and $\lambda = 140°$. On the right, teleseismic *P*-wave and *SH*-wave first motions are shown with *P*- and *SH*-radiation nodal planes for the November 8, 1980 Eureka, California earthquake. This left-lateral strike–slip event has $\phi_f = 48°$, $\delta = 90°$, and $\lambda = 0°$. Upward motions of *P* waves correspond to compressions (solid dots), while upward motion of *SH* corresponds to counterclockwise motion at the source. First-arrival amplitudes are shown for an equalized instrument gain. (Left from Oppenheimer, *Geophys. Res. Lett.* **17**, 1199–1202, 1990; © Copyright by the American Geophysical Union. Right from Lay *et al.*, 1982.)

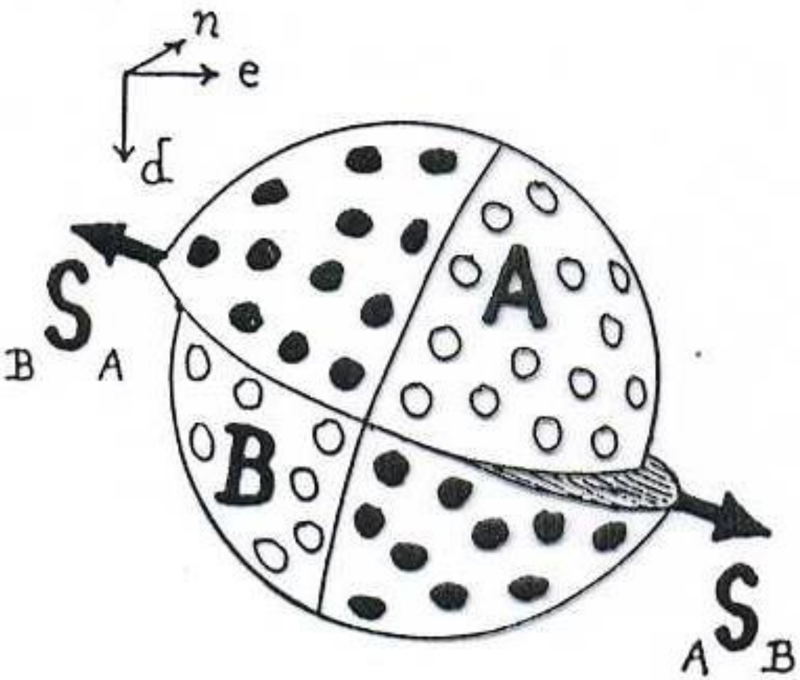


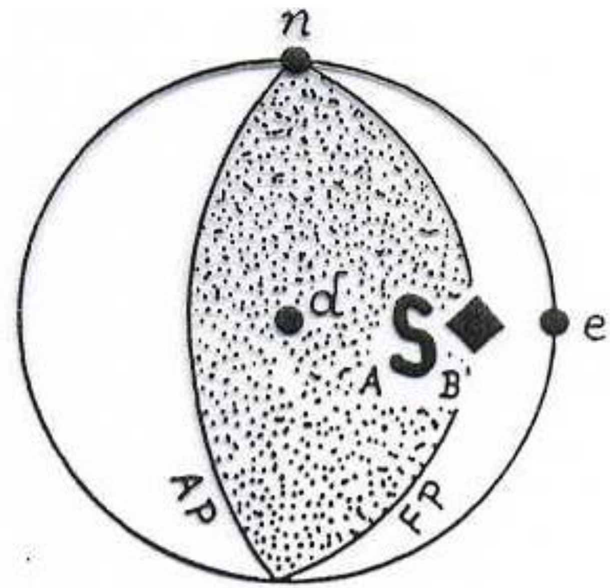




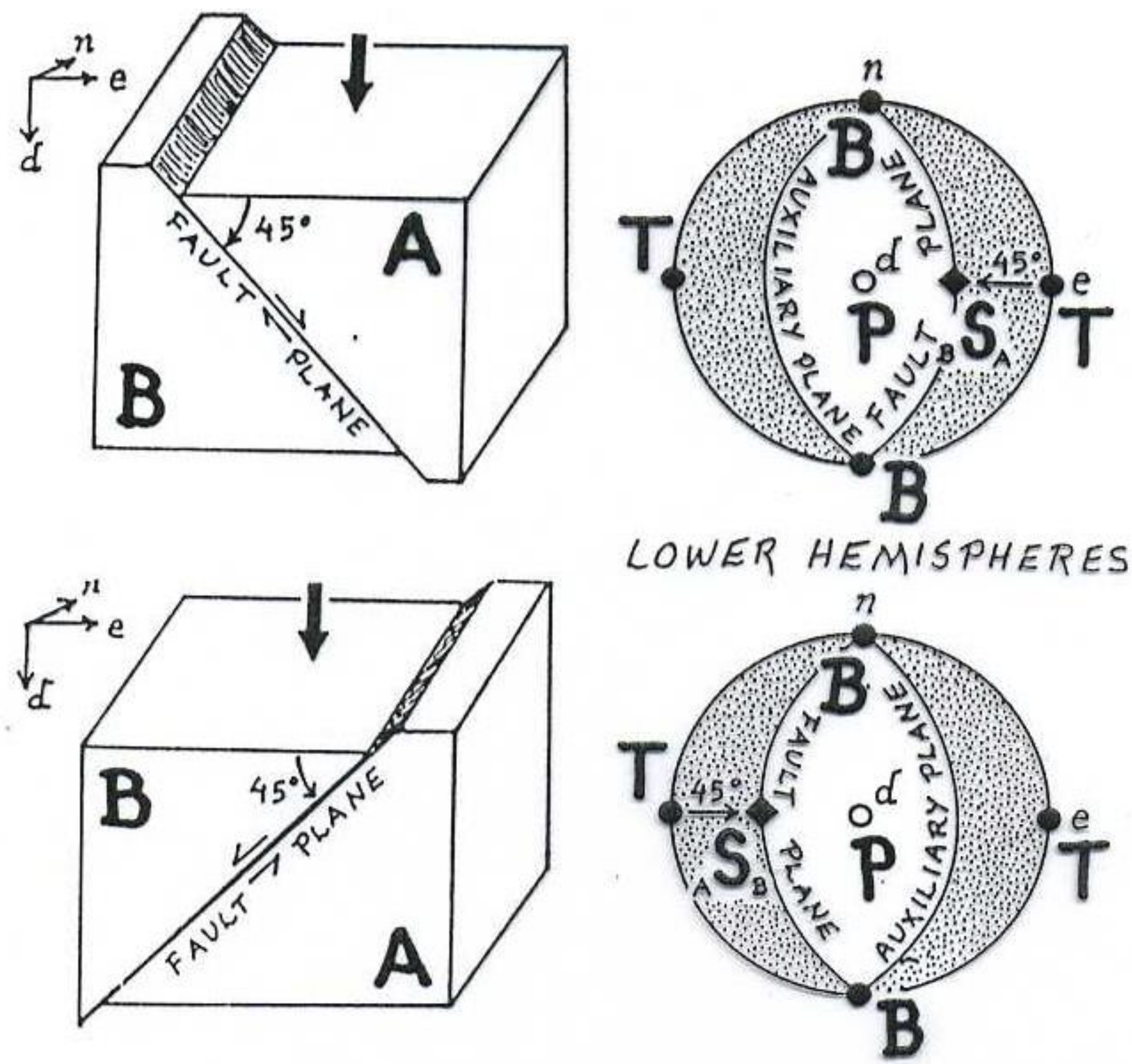


NORMAL FAULT





THRUST FAULT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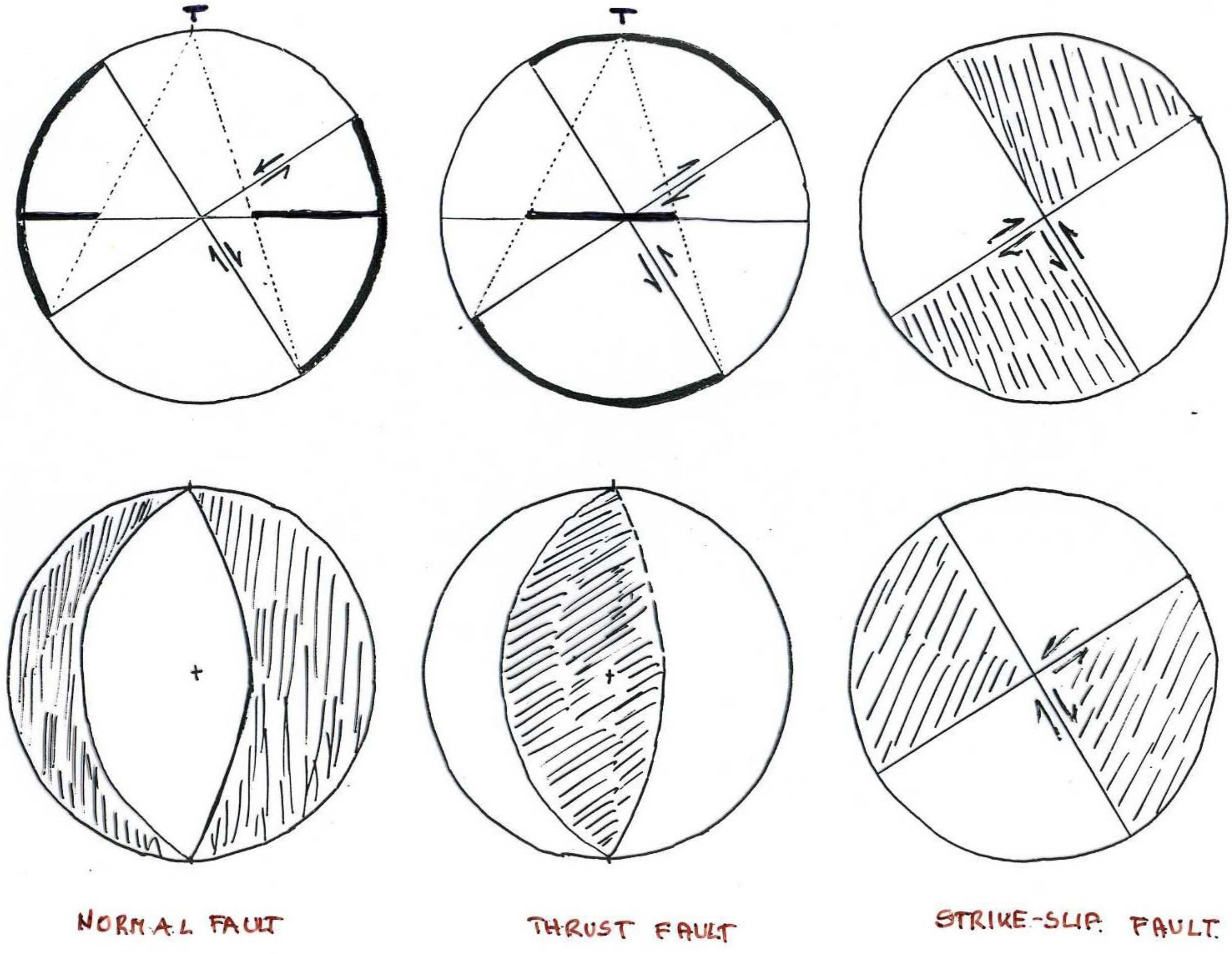
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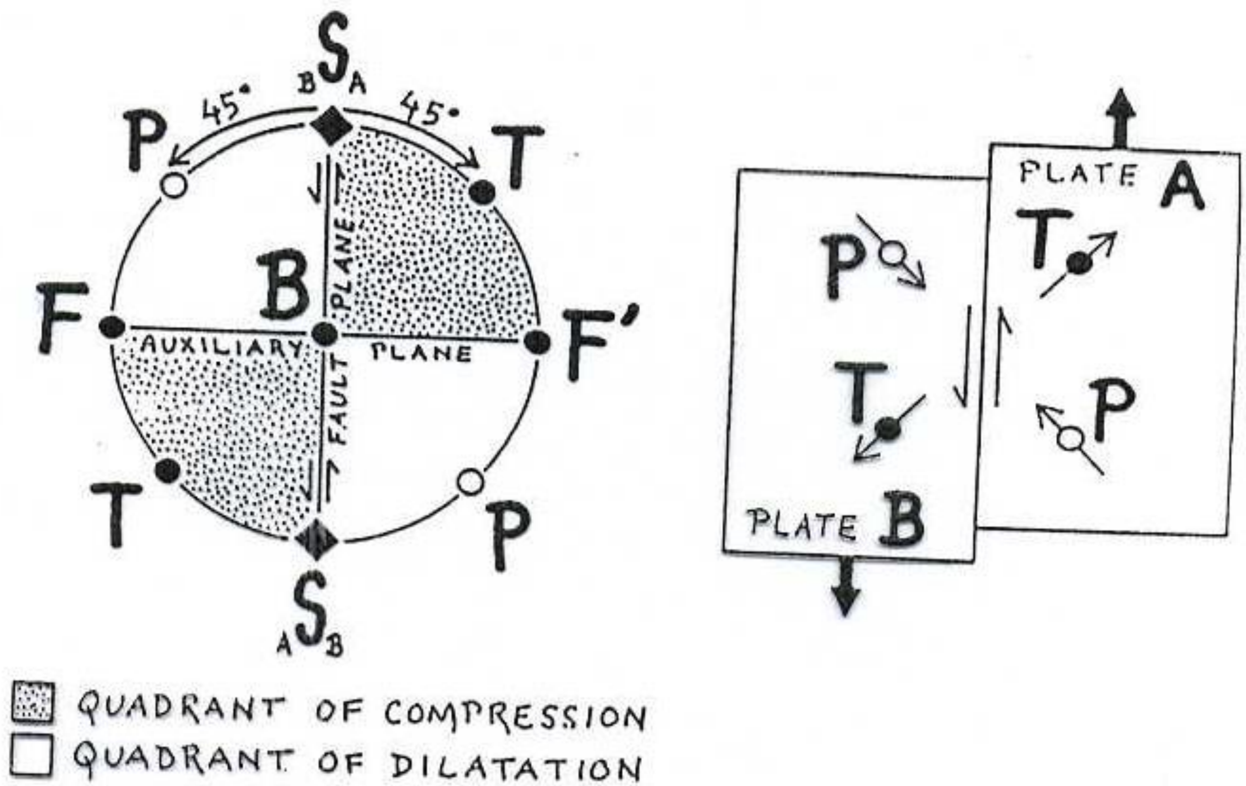
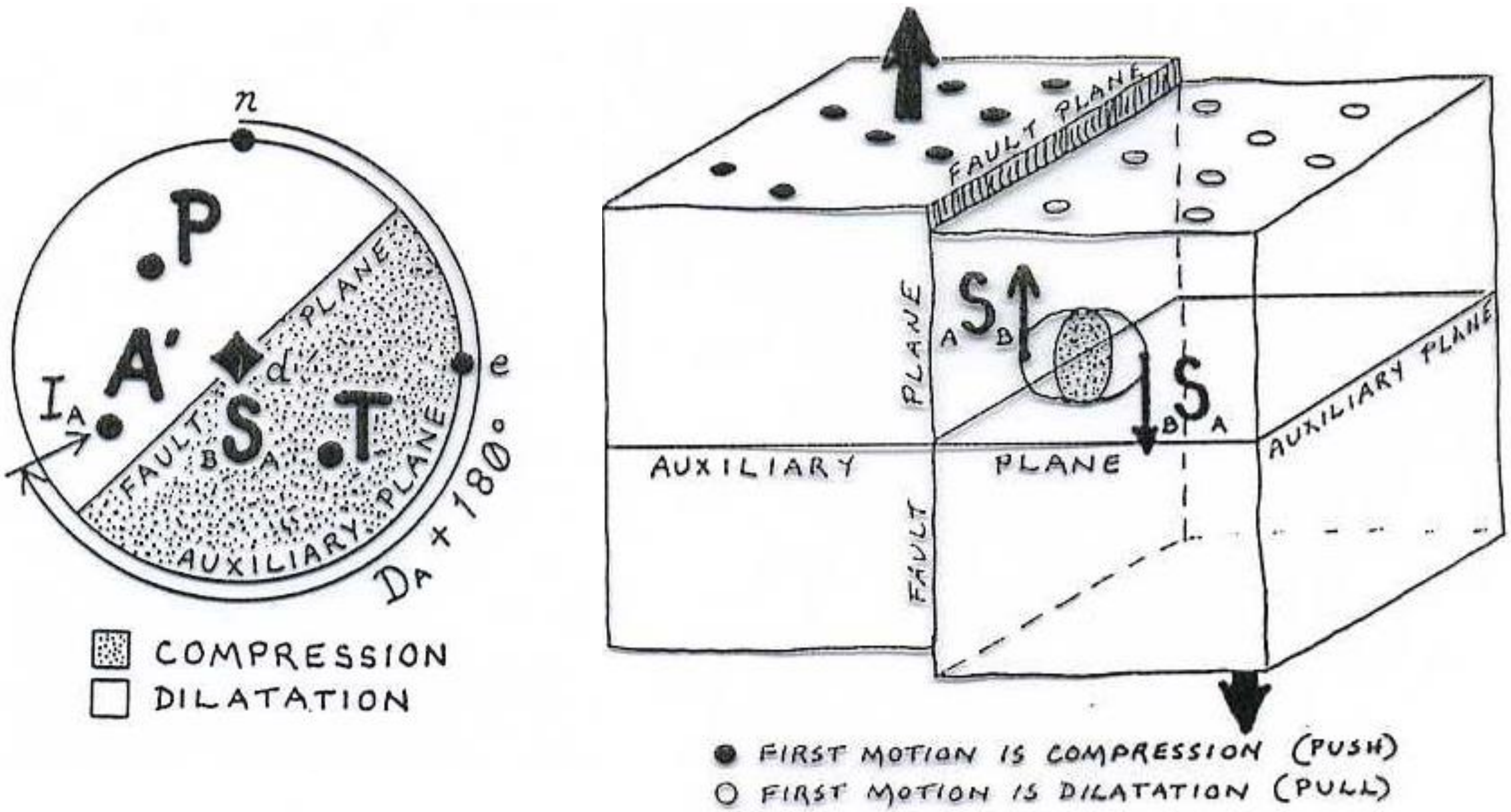
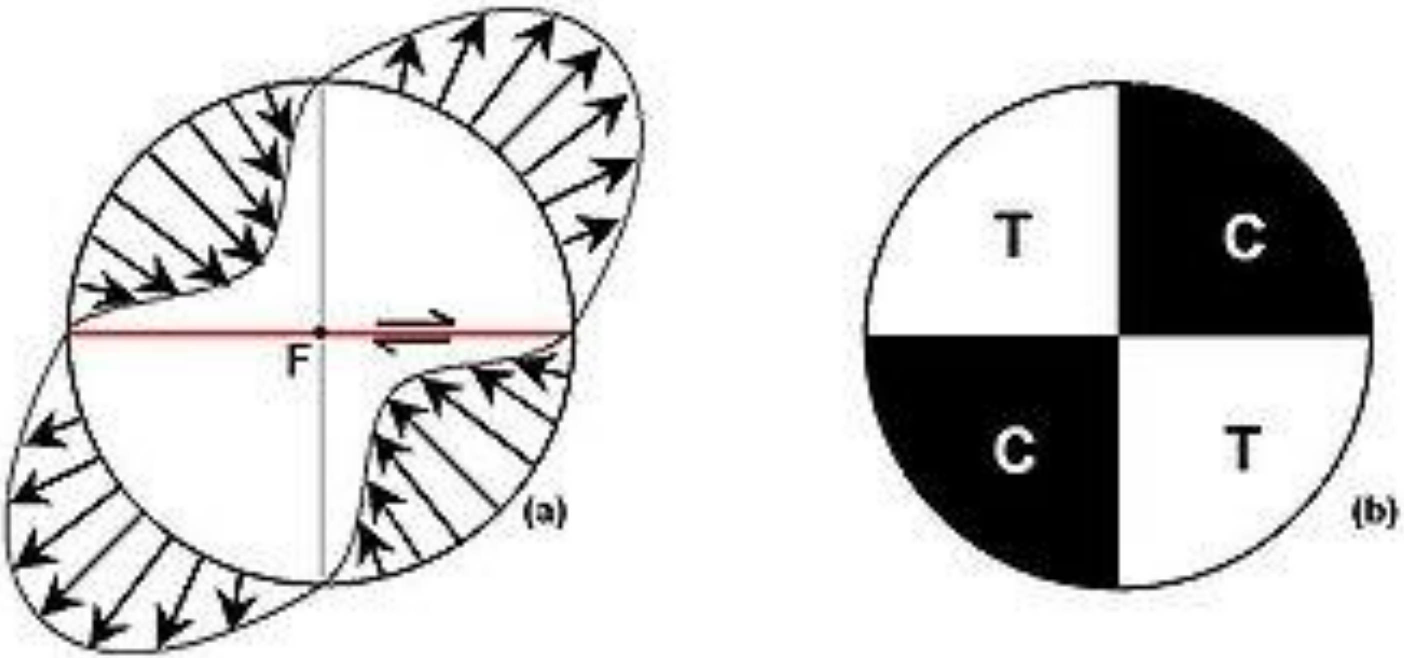
NORMAL FAULT
THRUST FAULT
STRIKE-SLIP FAULT



Box 6-5. Focal Sphere for a Vertical Normal Fault.



Box 6-6. Plotting First Motions for a Normal Fault on a Projection.



Schematic diagram showing the direction of initial movement of particles around the focus (F) of an earthquake on a W-E dextral strike-slip fault, viewed from above (a) and the equivalent zones of compressional (C) and tensional (T) sense first motion in the seismic waves radiating outward (b).

Note that due to the symmetry, an identical pattern would result from movement on an N-S sinistral strike-slip fault passing through the focus

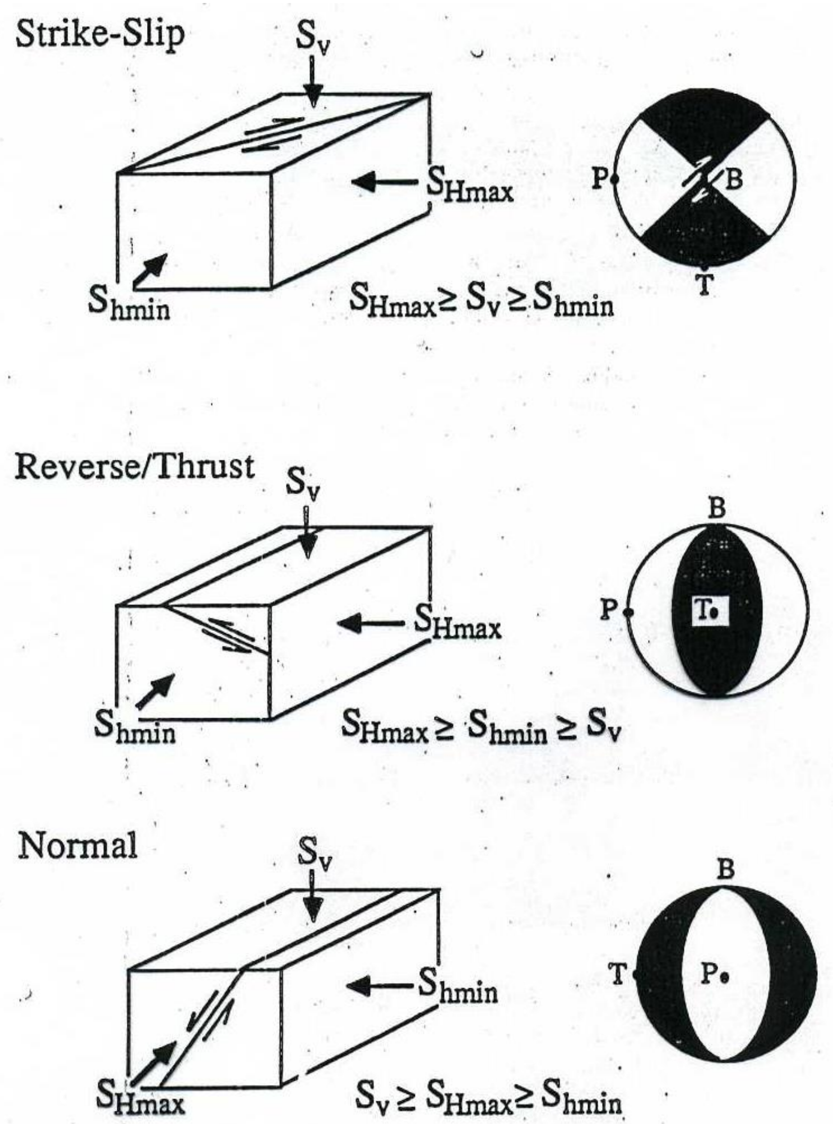
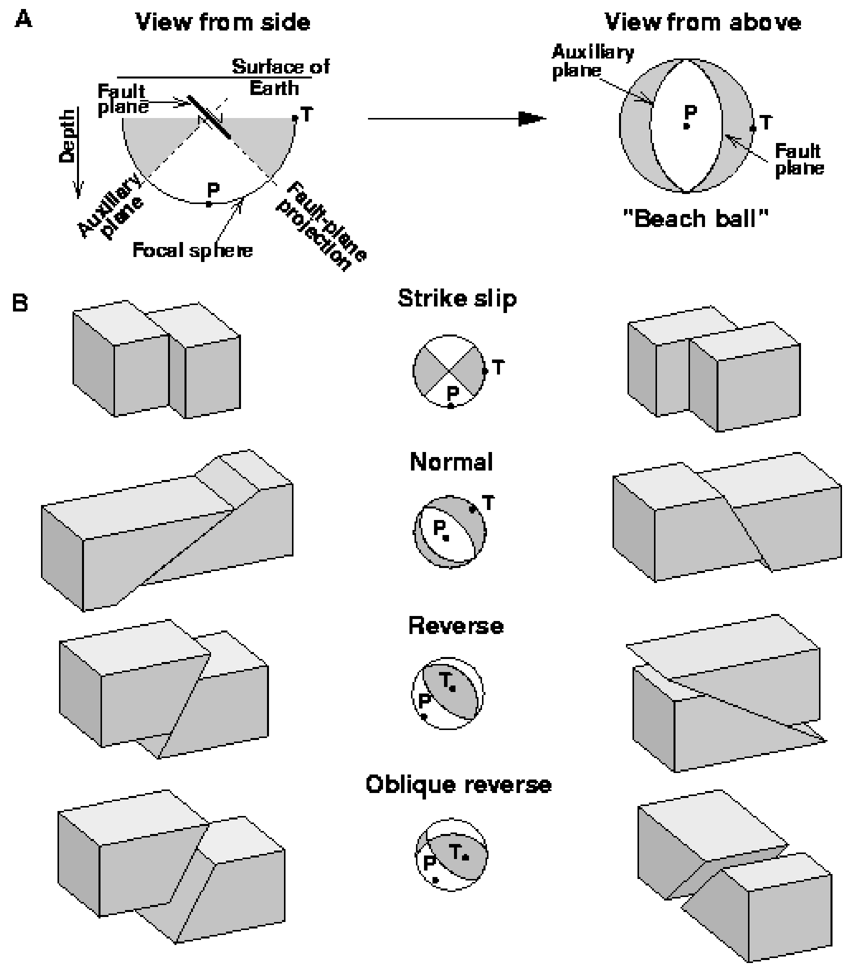


FIGURE 2. Simplified illustration of the variot s types of faulting, the relative magnitudes of thc . incipal stresses and lower-hemisphere projection earthquake focal plane mechanisms.

Schematic diagram of a focal mechanism



USGS, 1996

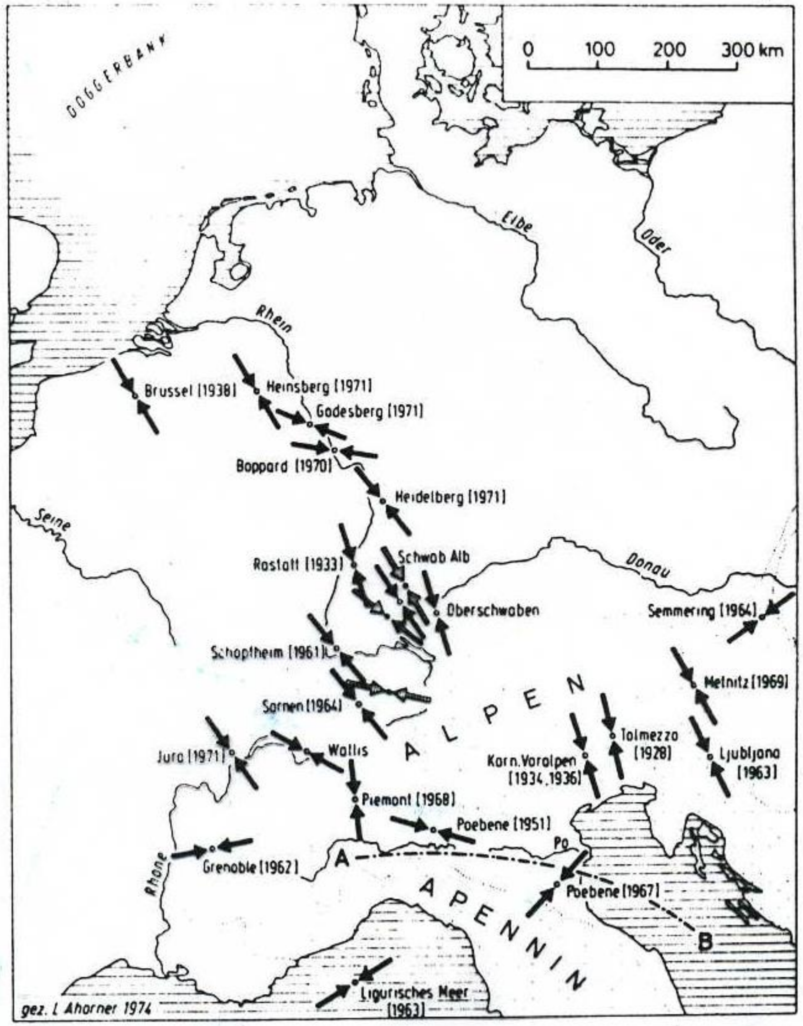


Fig. 10 — Horizontal compressive stresses in Central Europe. Strike of horizontal component of maximum compressive stress is shown at each locality by a pair of arrows. Solid arrows denote pressure axis of earthquakes focal mechanism. (From Ahorner, 1975).

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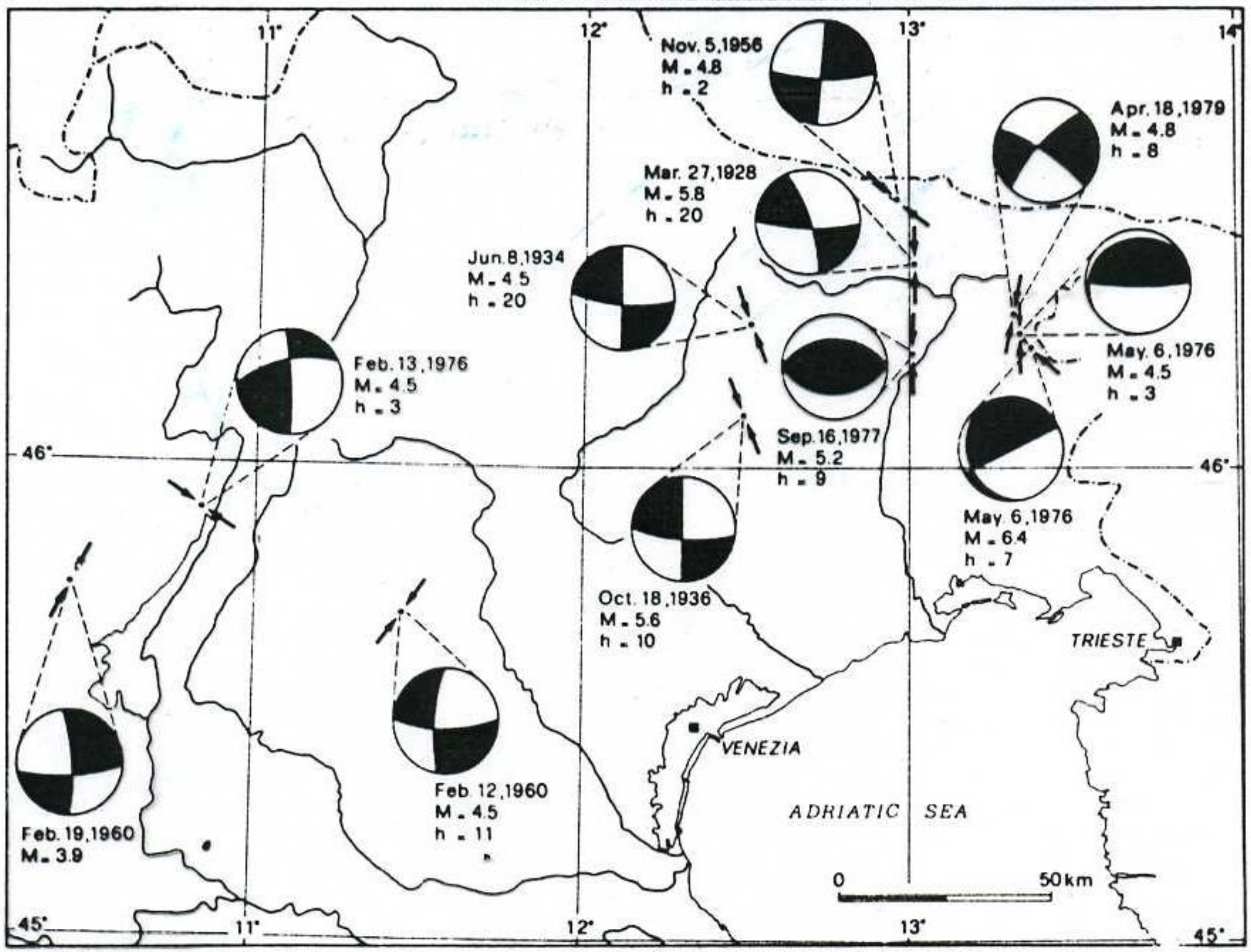


Fig. 9 — Fault plane solutions of earthquakes in the studied area. The solutions are shown as stereographic projection of the lower hemisphere of the first-motion radiation field. Black quadrants denote compressions. (M = local corrected magnitude, h = focal depth). Solid arrows denote axis of

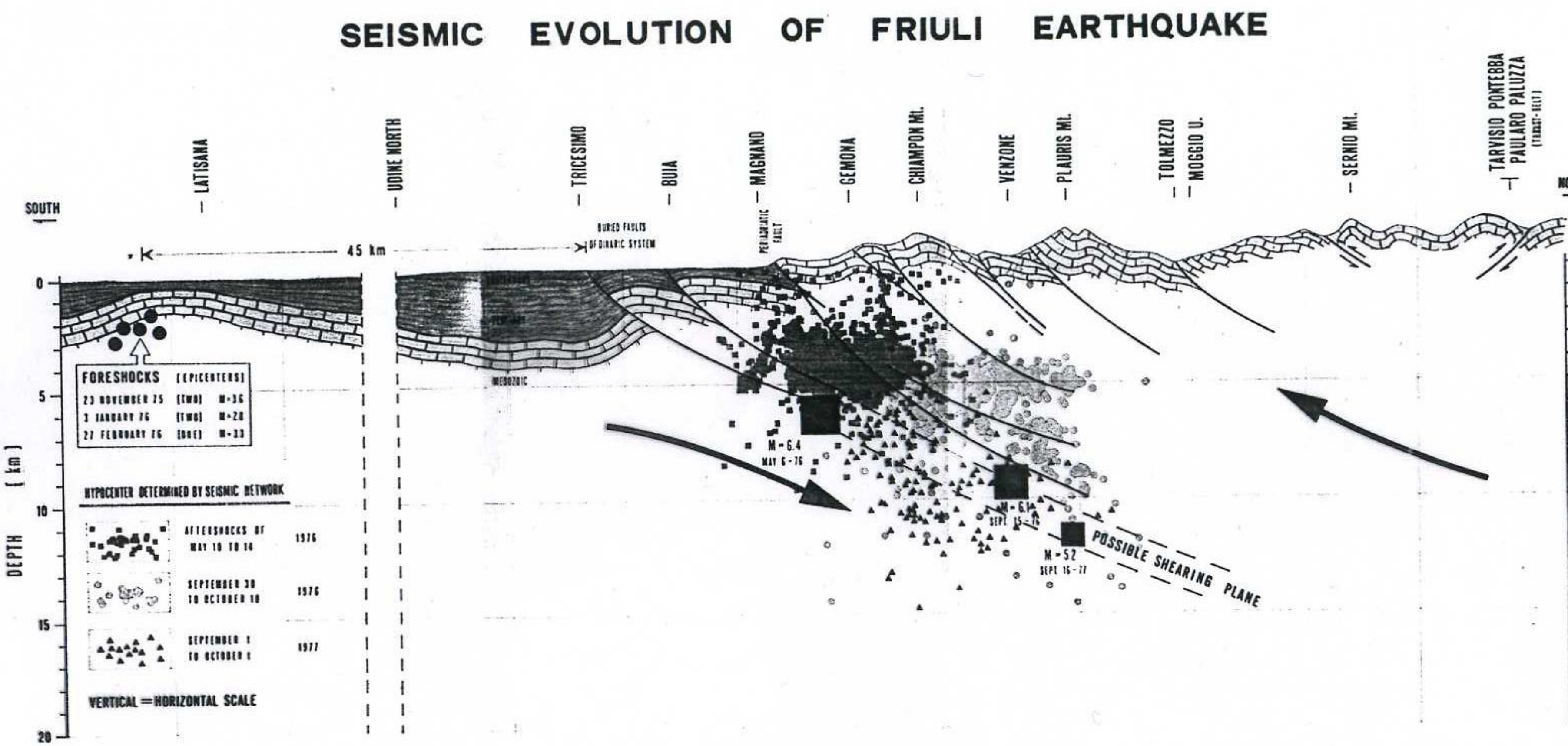


Fig. 2 - SCHEMA DELLA POSIZIONE DEGLI IPOCENTRI DELLE SCOSSE SUCCEDUTESI DAL 6 MAGGIO '76 AL SETTEMBRE '77. I quadrati in nero rappresentano la posizione ipocentrale indicativa delle principali scosse. In verde sono riportati gli ipocentri dell'attività sismica delle scosse di assestamento succedutesi subito dopo il 6 maggio; in arancione quelli dopo il 15 settembre '76; in nero (triangoli) quelli del settembre '77. Si nota un progressivo approfondimento degli ipocentri da S a N che potrebbe essere collegato ad un piano di scollamento degli strati soprastanti che sono imbricati gli uni sugli altri. Le scosse avvenute alcuni mesi prima del maggio '76 nell'area di Latisana sono interpretate come le scosse premonitrici (Foreshocks) del sistema in sovracompressione.

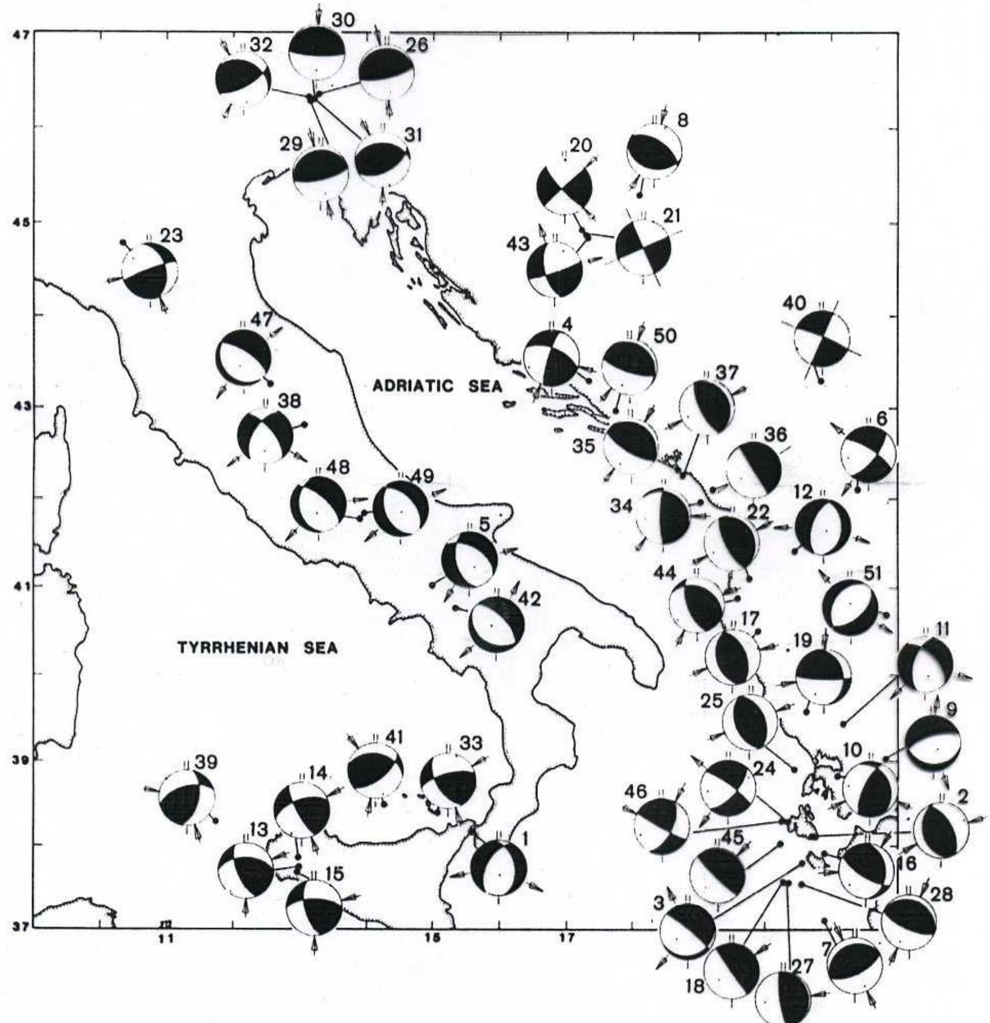


Figure 5. Fault-plane solutions for shallow earthquakes of the peri-Adriatic. Compressional quadrants are shaded and each event is numbered as in Table 1. *P*-axes are shown as a dot in the dilatational quadrant and the horizontal projections of slip vectors are shown as arrows. Location and nodal plane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

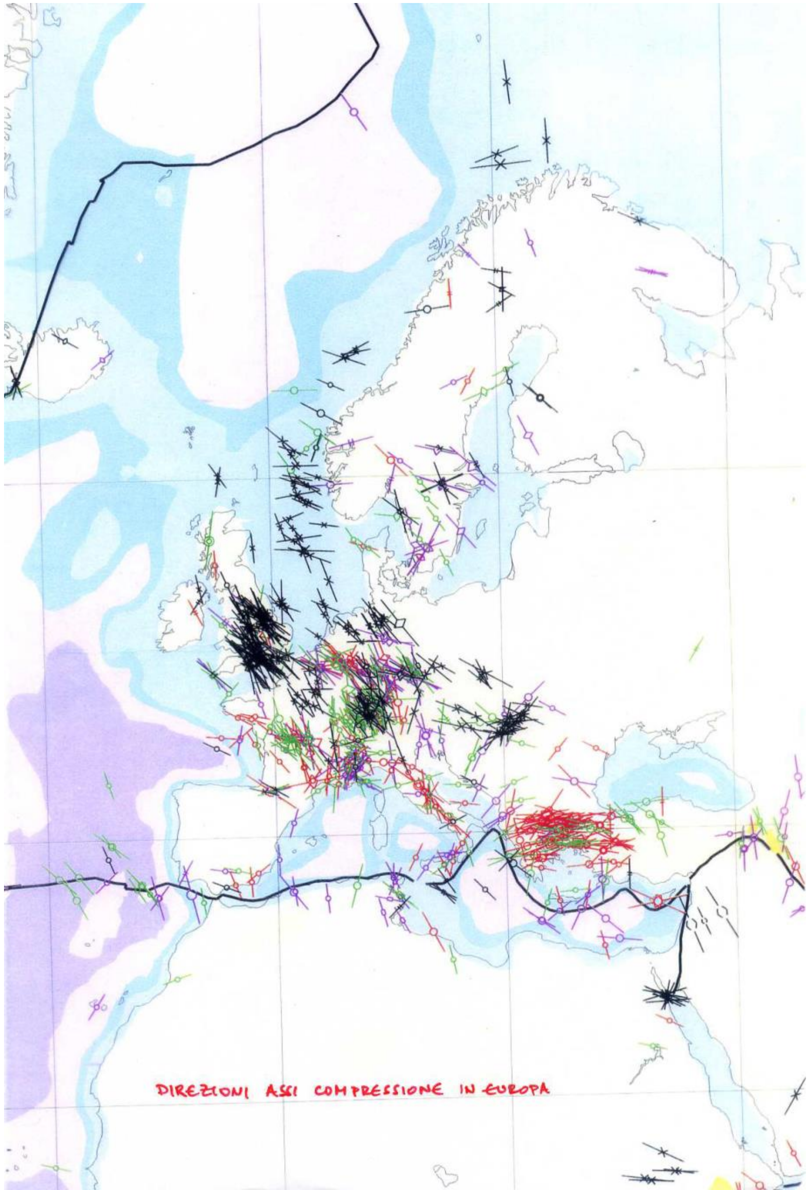
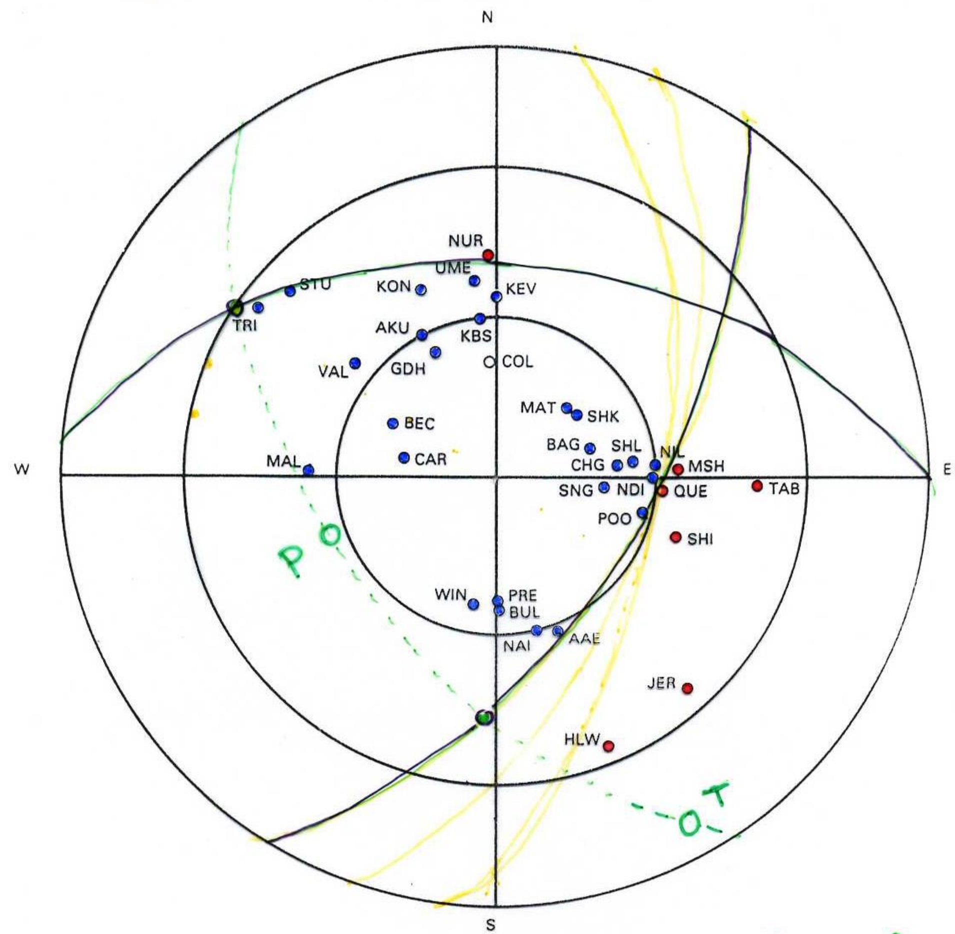

DIREZIONI ASSI COMPRESSIONE IN EUROPA

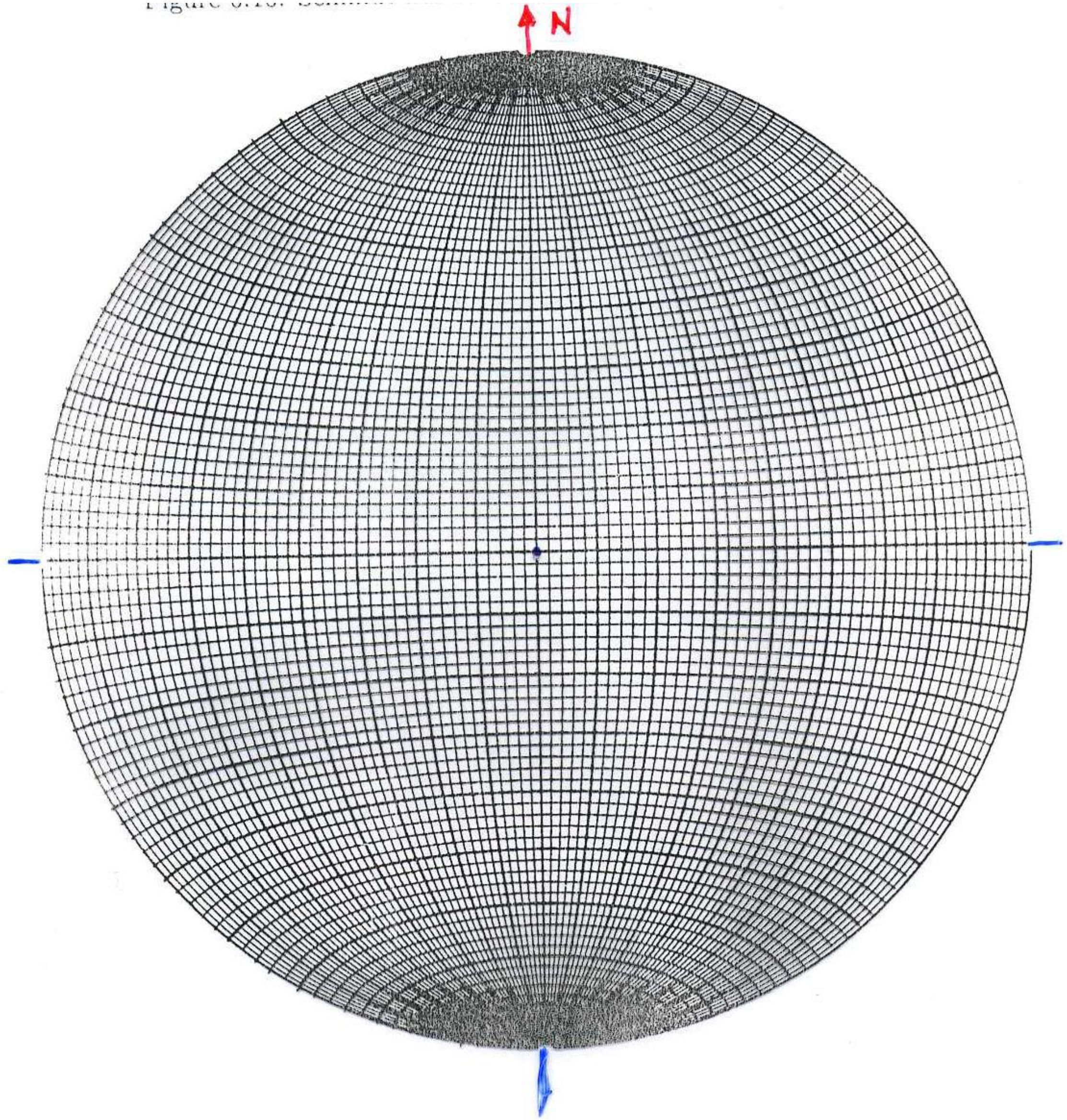
Figure 6.9: Focal sphere for Practical 4

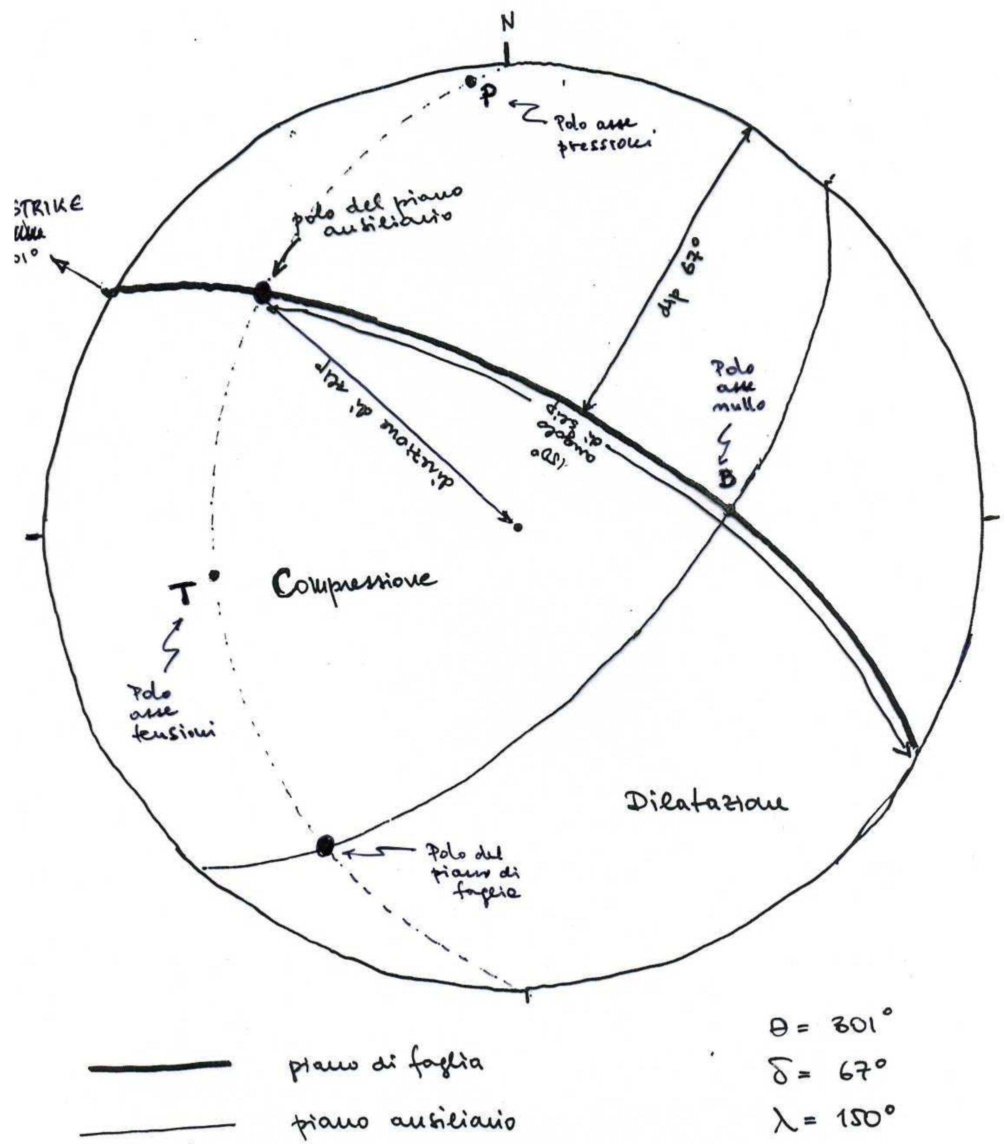


$\theta = 35°$

$\delta = 62°$

$\lambda = 232°$


N



N
P
Polo asse pressioni
polo del piano ausiliario
dip 67°
Polo asse nullo
B
Compressione
T
Polo asse tensioni
Dilatazione
Polo del piano di faglia
piano di faglia
piano ausiliario
θ = 301°
δ = 67°
λ = 150°