A Draft Primer on Focal Mechanism Solutions for Geologists

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Preface

In recent years, I have devoted an increasing amount of my (seemingly decreasing) research time to the study of active faulting -- a topic that is unambiguously useful to society and nicely combines my interests in remote sensing, tectonics, structural geology, engineering geology and field geology. Versions of this primer have have been used in undergraduate as well as graduate courses in structural geology. When used in the introductory structural geology course, it is the focus of a laboratory session after students have gained a working knowledge of plotting data on stereonets.

The goal is for students to be able to recognize and interpret the "beachball" diagram that graphically represents the geometry of a moment tensor derived by seismologists using sophisticated wave-form analysis. I leave most of the quantitative details of the process of obtaining the moment tensor to courses in seismology or to the literature; however, I find that some knowledge of how focal mechanism solutions (FMS) have been obtained manually is useful to students, so that the entire process is not so much of a black-box dark art. An partially annotated bibliography is included near the end of this document for the benefit of those who would like to delve more deeply into the theory and methodology used in computing FMSs.

What is a focal-mechanism solution and why should structural geologists know about them?

A focal mechanism solution (FMS) is the result of an analysis of wave forms generated by an earthquake and recorded by a number of seismographs. It usually takes at least 10 records to produce a reasonable FMS, and then only if the seismograph stations are well distributed geographically around the epicenter. The complete characterization of an earthquake's focal mechanism provides important information, including the origin time, epicenter location, focal depth, seismic moment (a direct measure of the energy radiated by an earthquake), and the magnitude and spatial orientation of the 9 components of the moment tensor. And from the moment tensor, we can ultimately resolve the orientation and sense of slip of the fault. This wealth of information about an earthquake is plainly of interest to a structural geologist working on active structures.

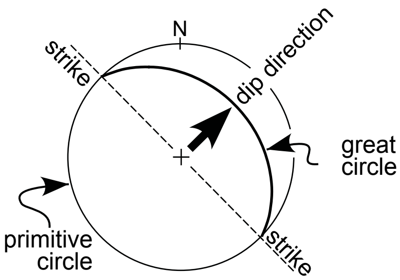
Detailed modeling of the generation of an earthquake by frictional slip or non-linear flow along a fault surface is, to say the least, a non-trivial matter. The fault itself is part of the problem, because it constitutes a significant discontinuity within the system. (It is much easier to develop mechanical models of continuous media that have relatively simple rheologies than to work with discontinuous media.)

As luck would have it, the radiation pattern of energy emitted by a crustal earthquake can be modeled to the first order using a simpler process that does not explicitly involve a fault discontinuity: the double force couple or simply the *double couple*. The double couple is mathematically described in 3 dimensions by a symmetrical tensor with 9 components, known as the *moment tensor*. Like the stress and strain tensors, the moment tensor can be described in terms of three orthogonal axes: P (for pressure; a compressive axis), T (for tension) and N (for null). The orientation and magnitude of these axes for a given earthquake can be resolved using data recorded by several seismographs that are distributed around the epicenter. The orientation of the axes of a moment tensor is of interest to a structural geologist because the fault surface along which the earthquake was generated is 45° from the P and T axes, and contains the N axis.

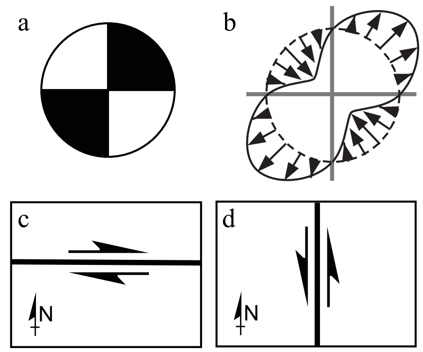
That's the good news. The bad news is that for any moment tensor, there are two possible planes that meet those criteria. The two planes are called the *nodal planes*, and they are at right angles to one another and intersect along the N axis. One of the planes is the fault surface, and the other is called the *auxiliary plane* and has no structural significance. All a seismologist can say with reference to the moment tensor alone is that the earthquake was generated on one or the other of the nodal planes. It takes geological input to differentiate between the two possible fault-plane solutions.

Assuming that the fault plane can be differentiated from the auxiliary plane, the FMS provides the structural geologist with the orientation of the fault plane, the direction of hanging-wall slip, and hence the type of fault involved in the earthquake: strike-slip, reverse, normal, oblique. And all of this information can be obtained within seconds by a structural geologist who knows how to interpret a graphic depiction of the FMS, known as a "beachball" diagram. Analysis of several FMS in a main shock-aftershock sequence allows us to map the patch along the fault that slipped, and evaluate whether more than one fault generated earthquakes during the sequence. More sophisticated quantitative analysis of the earthquake source mechanics can sometimes identify the direction of fault propagation.

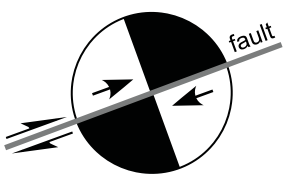
Quick-and-dirty eyeball interpretation of FMS beachball diagrams



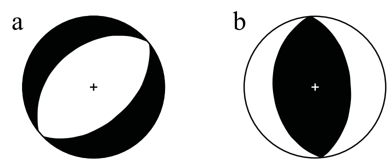
FMS beachball diagrams are lower-hemisphere stereographic projections that show two black quadrants and two white quadrants separated by great-circle arcs oriented 90° from each other. The great-circle arcs are the nodal planes, one of which coincides with the fault surface that generated the earthquake. The strike of the fault is indicated by a line connecting the two points at which the great circle corresponding to the fault intersects the outer edge of the beachball diagram (*i.e.*, where the fault great circle intersects the primitive circle -- the dashed line in the illustration at left). The dip direction is 90° from strike, in the direction indicated by the bold arrow from the center of the plot to the middle of the great circle arc.



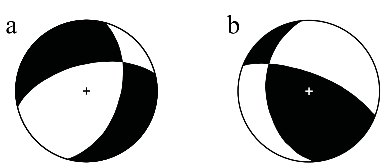
Strike-slip faulting results in FMS beachballs with a distinctive cross pattern. The beachball at right (a) has vertical auxiliary planes that strike north-south and east-west. At the instant the earthquake occurred, motion of the P wave through the material around the focus caused particles in the black quadrants to move away from the focus, while particles in the white quadrants were drawn toward the focus (b). This could have resulted either from right-lateral slip along an east-west fault (c), or it could have resulted from left-lateral slip along a north-south fault (d). Field data is needed to differentiate between these two options.



So how can a mere mortal remember how to interpret the sense of slip along a particular fault surface represented in a beachball diagram? Using the strike-slip mechanism at left, assume that we know that the active fault strikes toward the east-northeast (along the gray line). In my mind's eye, I place myself on one of the white quadrants, and look parallel to the fault at the dark quadrant that becons just beyond the auxiliary plane. And I hear the immortal words of Darth Vader, "Come to the dark side." The direction I would move if I heeded his nefarious call indicates the sense of slip along the fault, from white quadrant to black quadrant.



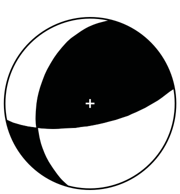
Pure dip-slip faults include normal faults and thrust faults. Only three of the four quadrants are observable in the beachball diagram for pure dip-slip faults, as shown at right. The center of the beachball plot is white for normal-fault mechanisms (a), and the center is black for reverse-fault mechanisms (b). Reverse-fault FMS diagrams look like my cat's eyes.



Oblique-slip faults have both strike-slip and dip-slip components. All four quadrants of a FMS beachball diagram are included for oblique slip earthquakes, as shown at left. If the center of the beachball plot is in a white quadrant (a), the fault has a normal component of slip, regardless of which of the two nodal planes is the fault; if the center is in a black quadrant (b), the fault has a reverse component of slip.

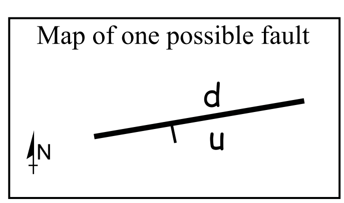
Practice with basic interpretation

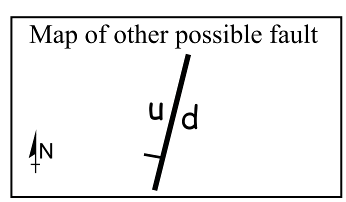
Some FMS beachball diagrams are presented below. For each one, identify the general type of faults depicted (strike-slip, reverse, normal, oblique normal, oblique reverse) and sketch a map of each of the two possible faults, representing their proper strike and indicating their dip direction if any and sense of displacement. The first one is done for you as an example.

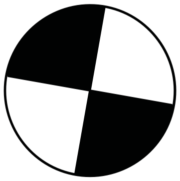


Type of faults:

reverse oblique



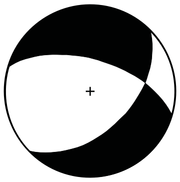




Type of faults:

Map of one possible fault

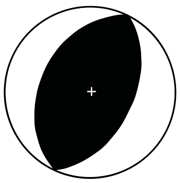
Map of other possible fault



Type of faults:

Map of one possible fault

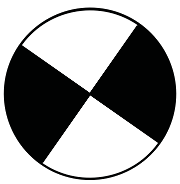
Map of other possible fault



Type of faults:

Map of one possible fault

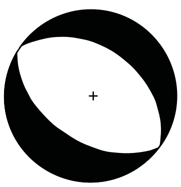
Map of other possible fault



Type of faults:

Map of one possible fault

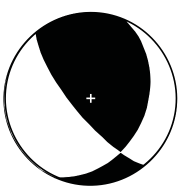
Map of other possible fault



Type of faults:

Map of one possible fault

Map of other possible fault



Type of faults:

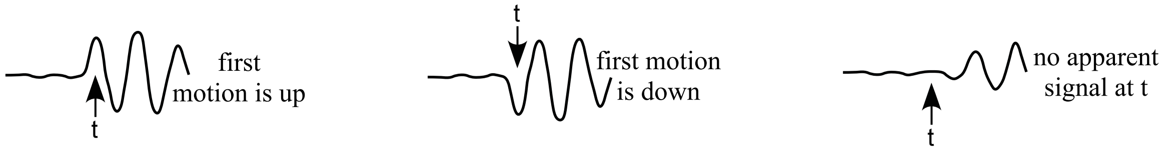
Map of one possible fault

Map of other possible fault

How is a focal mechanism solution derived?

In current practice, a FMS is based on the derivation of a moment tensor from analysis of sets of waveform data. There are several methods for finding the components of the moment tensor that best fits the available data for a given earthquake. The fault-plane solution or beachball diagram is a product of the moment tensor inversion. The beachball diagram can also be obtained by graphic techniques from a study of P-wave first motions, as described below; however, the graphic technique does not provide enough information to define the moment tensor for the earthquake.

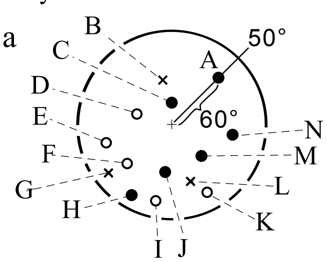
The basic techniques for using P-wave first motions recorded by an array of seismographs to define a FMS beachball diagram were developed before the advent of the microcomputer, and it is still useful to have at least a crude understanding of how to make the diagram manually (description after Kasahara, 1981, p. 38-44). From the preliminary determination of the epicenter, we know the location and origin time of the earthquake. Let us say that 14 geographically separate seismograph stations recorded the event. From the well-known locations of those stations, we compute the distance between each station and the epicenter. Then we use a standard seismic-velocity model of Earth to define the exact time (t) that the P-wave of the earthquake should have arrived at each station. Consulting the seismogram recording the vertical component at each station, we evaluate whether the first motion detected at that station was an "up" motion, a "down" motion, or no apparent signal at the expected time.



The portion of the energy received by each seismograph, that left the earthquake focus in the form of a compressional P-wave, can be thought of as having traveled along a *ray path* from the focus to the seismograph. We need to learn two things about that ray for each station: the *azimuth* along which it traveled from the earthquake focus to the station, and its *take-off angle* (also known as angle of emergence). The take-off angle is the angle between the ray *as it just emerges from the focus* and an imaginary vertical line extending through the focus. In routine work, the take-off angle is interpreted from a table that relates take-off angle to distance between the focus and the station (*e.g.*, Hodgson and Storey, 1953; Hodgson and Allen, 1954).

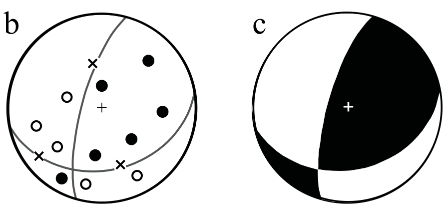
We are now ready to plot the data on a lower-hemisphere stereographic projection -- we choose to use an equal-area stereonet (after Sykes, 1967; a stereonet is reproduced at the end of this document). We will represent the data from each seismograph station with one of three symbols: a circle (○) if the P-wave first motion was down, a black dot (●) if the first motion was up, or an x (×) if the first motion was too weak to differentiate. For each station, the symbol is placed along a line extending from the center of the plot toward the azimuth of the station relative to the earthquake focus, and the take-off angle defines the angular distance from the center of the plot to the symbol. In the example below, the symbol associated with station A is 60° from the center of the plot along a line directed toward azimuth 50°.

a



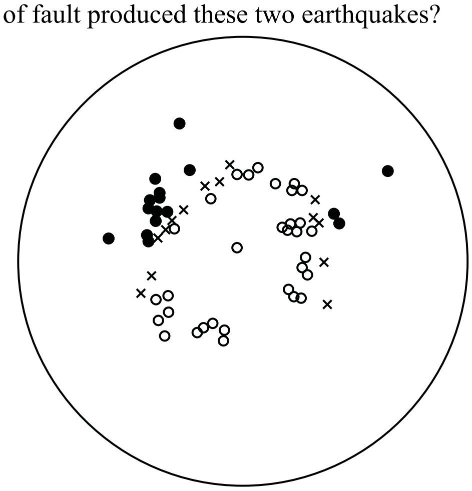
Stn	P wave	symbol	Stn	P wave	symbol	Stn	P wave	symbol
A		●	F		○	K		○
B		×	G		×	L		×
C		●	H		●	M		●
D		○	I		○	N		●
E		○	J		●			

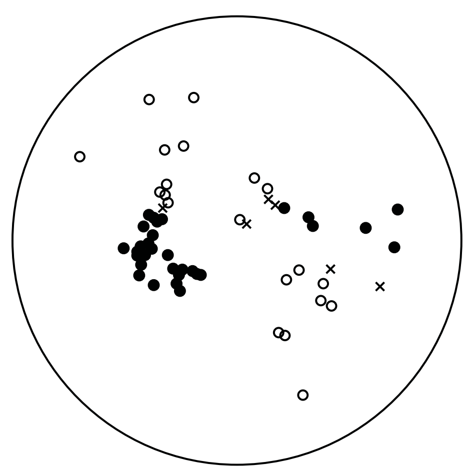
b c



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.

The following data are adapted from two of the focal mechanism solutions published by Lynn Sykes in his classic paper on the mechanisms of earthquakes along transform faults (Sykes, 1967, Figs. 11 and 14). The symbols used are the same as in the previous example. Sketch two admissible nodal planes, and shade the appropriate quadrants black. What kind of fault produced these two earthquakes?





USGS seismologists routinely generate focal mechansm solutions using a semiautomated method developed by Stuart Sipkin, which he has described in detail in the literature (Sipkin, 1982, 1984, 1994). A similar (but not identical) semiautomated method for computing FMSs has been developed and used by Dziewonski and others (1981) at Harvard, providing very useful alternative interpretations. Solutions are checked or even manually produced using a wider array of methods for earthquakes in which there is a particular research interest, including large earthquakes that cause damage or casualties. As an example of how the USGS routinely computes solutions, the NEIC and the IRIS Data Management Center (IRIS DMC) have developed a program…

> "…to produce rapid estimates of the seismic moment tensor for most earthquakes with a body-wave magnitude or surface-wave magnitude of 5.5 or greater. …In many cases an estimate of the moment tensor can be produced within 20 minutes of the arrival of the 'gophered' broadband P-waveform data from the IRIS DMC. The resulting determination of earthquake depth, geometry, and size can be very useful in the planning of post-earthquake studies, such as damage surveys and the deployment of temporary seismic arrays. In some cases such information can be crucial in the decision whether or not to issue a tsunami warning. Because of the manner in which the data and the synthetic seismograms are aligned, the method is insensitive to the effects of timing errors, epicentral mislocation, and lateral heterogeneity.
>
> "The flow of data is as follows. An automatic process at the NEIC, using real-time data from the U.S. National Seismograph Network (USNSN), identifies phase arrivals, associates the data, and computes an origin time and hypocenter. This information is sent by e-mail to the IRIS DMC where it triggers the Gopher system. Four minutes of broadband data containing the P-arrival are retrieved from the ring buffers of the "open" IRIS stations and transmitted to the NEIC by Internet. These data are merged with the USNSN dataset and used to refine the location and compute a body-wave moment tensor using a technique based on the theory of optimal filter design. This solution is then broadcast by e-mail to a list of subscribers. Because of the growing number of broadband seismic stations with either real-time or dial-up capability, these preliminary solutions are usually very similar to those produced later, using data from the entire network" (neic.usgs.gov/neis/FM/fast_moment.html).

Where can FMSs be obtained?

Preliminary FMSs are routinely computed for earthquakes with reported magnitudes of 5.5 or greater, and for smaller earthquakes with a large number of reported arrivals. Subscribers to the USGS National Earthquake Information Center (NEIC) earthquake notification services (earthquake.usgs.gov/products/neic_data_services.html) receive "fast moment tensor solutions" via email within a few hours after an earthquake of M≥5.5. NEIC also maintains a web-based searchable database of "NEIC first-motion, NEIC moment tensor, NEIC radiated energy, Harvard centroid moment tensor, scalar moment from the University of California at Berkeley for regional earthquakes, and teleseismic moment from the Laboratoire de Geophysique, Papeete (PPT)" at neic.usgs.gov/neis/sopar/.

Email notifications of FMSs are also produced by participants in Harvard's Centroid-Moment Tensor (CMT) Project, whose work is described at www.seismology.harvard.edu/projects/CMT/. The CMT catalog can be searched online via www.seismology.harvard.edu/CMTsearch.html.

Many more FMS are embedded in research papers and not contained within searchable earthquake catalogs.

Geometric regularity of an ideal FMS "beachball" diagram

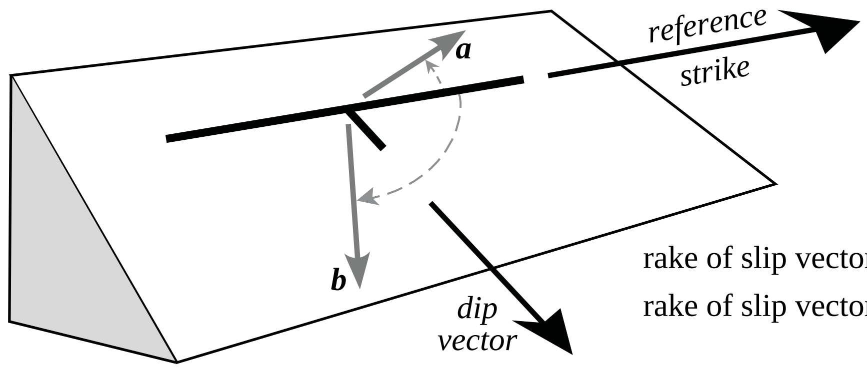
Because of the symmetry of the force double couple and moment tensor on which it is based, the FMS beachball diagram has a crystal-like regularity to it.

- The two nodal planes are perpendicular to each other.
- The pole of the auxiliary plane is colinear with the slip vector on the fault plane.
- The N axis is coincident with the intersection of the two nodal planes, and so is contained within both of the nodal planes.
- The N, T and P axes have an orthogonal relationship to one another: each is 90° from the other.
- The T and P axes bisect the dihedral angles between the nodal planes; that is, the T and P axes are 45° from the nodal planes.
- The plane defined by the T and P axes also contains the vectors normal to the nodal planes, one of which is the slip vector.
- The P axis is in the middle of the white quadrant, and the T axis is in the middle of the black quadrant.

Minimum data to specify a focal mechanism solution's geometry

Just three data elements are needed to completely specify the orientation of a FMS beachball diagram (e.g., two elements to specify the orientation of the fault plane and one element to specify the orientation of the slip vector on that plane). Seismologists commonly report the dip azimuth and dip angle of the inferred fault plane, and the rake of the hanging-wall slip vector in that plane. Cronin and Sverdrup (1998) reported the dip azimuth and dip angle of the inferred fault plane and the azimuth of the hanging-wall slip vector, cognizant of the fact that geologists commonly use the word "rake" in a far less precise manner than seismologists use the same term.

The rake of the hanging-wall slip vector is measured in the plane of the fault, relative to the reference strike of the fault plane. The reference strike is defined using the right-hand method. An angle measured through an anticlockwise rotation from the reference strike is considered a positive angle; an angle measured clockwise from the reference strike is a negative angle. A slip vector that is directed up relative to strike has a positive rake, and a slip vector that is directed down the plane is negative. The range of permissible rake values is +180° to –180°.



Hanging-wall slip vectors that have a positive rake have at least some component of reverse slip. A rake of 90° indicates slip that is entirely reverse with no strike-slip component. Similarly, hanging-wall slip vectors with a negative rake have at least some component of normal slip, with a rake of –90° indicating slip that is entirely normal with no strike-slip component. Hauksson (1990) defined normal-slip vectors as having rakes of –45° to –135° and reverse-slip vectors having rakes of 45° to 135°, with strike-slip vectors having rakes of 44° to –44° or 136° to 224° (–136°). A geologist might be more confortable with a differentiation of fault types along the lines outlined in the following table:

rake of slip	fault type
0° or 180°	pure strike-slip
90°	pure dip-slip reverse
–90°	pure dip-slip normal
–20° to 20°	left-lateral strike-slip
20° to 70°	reverse left-lateral oblique
70° to 110°	reverse
110° to 160°	reverse right-lateral oblique
–160° to 160°	right-lateral strike-slip
–110° to -160°	normal right-lateral oblique
–70° to –110°	normal
–20° to –70°	normal left-lateral oblique

Constructing a FMS beachball from 3 input data

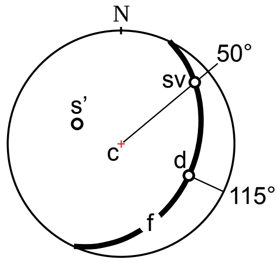
Tables of earthquake focal mechanism data do not do us much good if we are not able to reconstruct an accurate FMS beachball diagram from them. Such tables usually (but not always) list the orientation of the inferred fault and its corresponding slip vector. Otherwise if the fault has not been interpreted, the table might simply list orientation data for one of the two nodal planes and the corresponding potential slip vector.

An example

Problem: Given a table of FMS data listing a fault with dip azimuth = 115°, dip angle = 35°, and azimuth of hanging-wall slip vector = 50°, reconstruct the corresponding focal mechanism solution "beachball" diagram and determine the approximate azimuth and plunge angle of the N, P and T axes. Describe the type of fault that produced the earthquake. Based on the focal mechanism solution, construct a map of what the fault might look like.

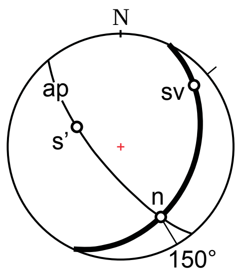
Solution:

a



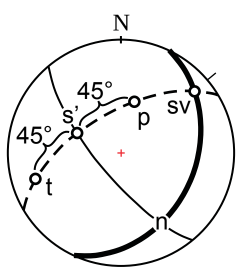
1) Use the azimuth (115°) and the plunge (35°) of the dip vector (d) to plot the trace of the fault plane (f). The fault has a strike of 115° – 90° = 25°, and a dip of 35° (same as the plunge of the dip vector).
2) Plot the pole of the fault plane (s').
3) Given that the azimuth of the slip vector is 50°, construct a line from the center of the plot (c) toward azimuth 50°, and locate the slip vector (sv) where that line intersects the trace of the fault (f). In the final presentation of the beachball diagram, we are going to leave a small portion of that line extending out from the circumference of the diagram to indicate the direction of hanging wall slip.
4) Determine the plunge of the slip vector (sv): it plunges ~27°.

b



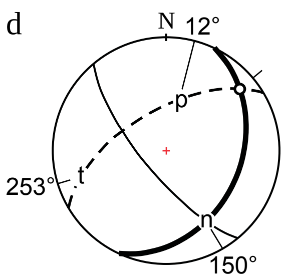
5) Plot the trace of the auxiliary plane (ap) by using the slip vector (sv) as the pole to that plane. Note that s' is located on the auxiliary plane.
6) The N axis (n) is located at the intersection of the fault plane and the auxiliary plane. Determine the trend and plunge of the N axis: it trends 150° and plunges ~30°.

c



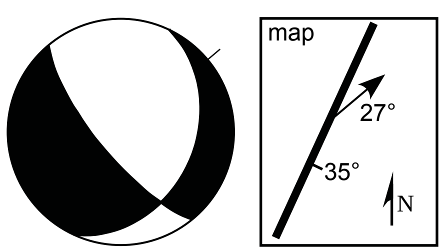
7) Plot the trace of the plane whose pole is the N axis (dashed great circle).
8) Plot the P axis (p) 45° from s' toward the slip vector along the dashed great circle (*i.e.*, half way between s' and sv).
9) Plot the T axis (t) 45° from s' and 135° from the slip vector along the dashed great circle.

d



10) Determine the trend and plunge of the P axis (p): it trends ~12° and plunges ~52°.
11) Determine the trend and plunge of the T axis (t): it trends ~253° and plunges ~23°

e



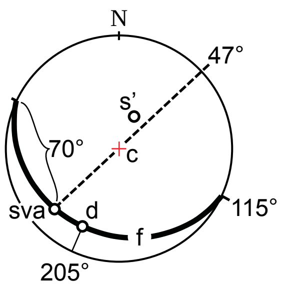
12) Fill the quadrants through which the T axis passes with black, and the quadrants through which the P axis passes with white. Leave the short line indicating the direction of slip on the outside of the beachball diagram.
13) The map is a depiction of the corresponding fault as it exists near the focus of this earthquake. It is an oblique fault with components of normal and left-lateral slip.

Another example

Problem: Given a table of FMS data listing a fault with dip azimuth = 205°, dip angle = 25°, and rake of hanging-wall slip vector = +70°, reconstruct the corresponding focal mechanism solution "beachball" diagram and determine the approximate azimuth and plunge angle of the N, P and T axes. Describe the type of fault that produced the earthquake. Based on the focal mechanism solution, construct a map of what the fault might look like.

Solution:

a



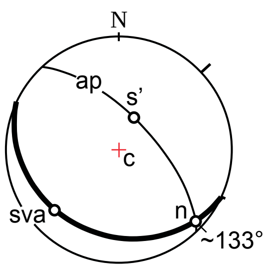
1) Use the azimuth (205°) and the plunge (25°) of the dip vector (d) to plot the trace of the fault plane (f). The fault has a strike of 205° – 90° = 115°, and a dip of 25° (same as the plunge of the dip vector).

2) Plot the pole of the fault plane (s').

3) The reference strike is toward azimuth 115°. Given that the rake of the slip vector is +70°, it will not plot on a lower-hemisphere stereonet; however, the antipode of the slip vector (sva) does plot on the stereonet -- the antipode is 180° from the slip vector. The antipode is along the trace of the fault, 70° from the primitive circle as illustrated at left. Project a line from the slip vector antipode (sva) through the center of the plot (c) to just beyond the circumference of the stereo plot (*i.e.*, beyond the primitive circle). That line, trending 47°, defines the trend of the slip vector. In the final presentation of the beachball diagram, we are going to leave a small portion of that line extending from the edge of the diagram to indicate the direction of hanging-wall slip.

4) Determine the plunge of the slip vector, which is identical in magnitude to the plunge of the slip vector antipode (sva): the slip vector plunges ~23° upward, with a trend of 47°.

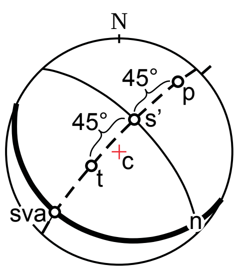
b



5) Plot the trace of the auxiliary plane (ap) by using the slip vector antipode (sva) as the pole to that plane. Note that s' is on the auxiliary plane.

6) The N axis (n) is located at the intersection of the fault plane and the auxiliary plane. Determine the trend and plunge of the N axis: it trends 133° and plunges ~8°.

c

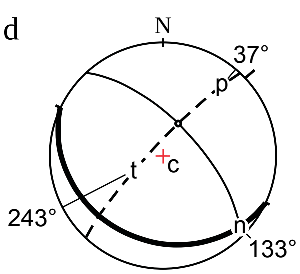


7) Plot the trace of the plane whose pole is the N axis (dashed great circle).

8) Plot the P axis (p) 45° from s' and 135° from the slip vector antipode (sva) along the dashed great circle.

9) Plot the T axis (t) 45° from s' toward the slip vector antipode (sva) along the dashed great circle.

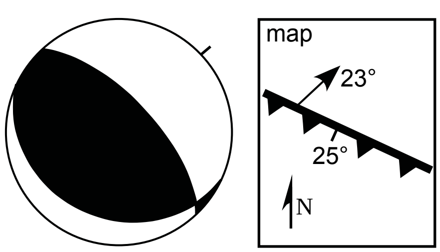
d



10) Determine the trend and plunge of the P axis (p): it trends ~37° and plunges ~21°.

11) Determine the trend and plunge of the T axis (t): it trends ~243° and plunges ~78°

e



12) Fill the quadrants through which the T axis passes with black, and the quadrants through which the P axis passes with white. Leave the short line indicating the direction of hanging-wall slip on the outside of the beachball diagram.

13) The map is a depiction of the corresponding fault as it exists near the focus of this earthquake. It is a reverse or reverse-oblique fault with a comonent of right-lateral slip.

Practice with constructing a beachball diagram

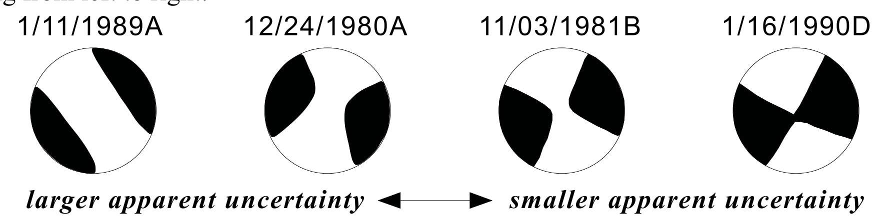
Problem: Given a table of FMS data listing a fault with dip azimuth = 130°, dip angle = 60°, and rake of hanging-wall slip vector = –125°, reconstruct the corresponding focal mechanism solution "beachball" diagram and determine the approximate azimuth and plunge angle of the N, P and T axes. Describe the type of fault that produced the earthquake. Based on the focal mechanism solution, construct a map of what the fault might look like.

Representing uncertainty in FMS

Earthquakes with smaller magnitudes tend to be recorded by fewer seismographs, and so their focal locations are more poorly known. The parameter that is most poorly known for many earthquakes is the focal depth. For earthquakes detected by seismographs that are not well distributed in azimuth around the focus, even the location of the epicenter may be poorly constrained. For example, earthquakes along the Blanco transform fault zone are routinely mislocated to the northeast of their actual foci due largely to the uneven distribution of seismographs available to record the moderate-to-small earthquakes along the Blanco (e.g., Cronin and Sverdrup, 2003a, 2003b).

The uncertainty associated with published focal mechanism solutions is generally unstated. Because the construction of FMSs involves defining a best-fit of interpreted first-motion or wave-form data, the uncertainties in a FMS tend to increase as the number of different seismograph stations whose data reports were used to compute the FMS decreases. Fewer reported arrivals, more uncertain FMS.

One graphical approach to this problem has been taken by Harvard's CMT Project. In their beachball diagrams, the quality of the CMT solution is suggested by the degree to which the four quadrants are sharply defined as quadrants. (Numerical error estimates are available through their web-searchable database.) A set of examples drawn from CMT solutions for earthquakes recorded along the Blanco transform fault are shown below, with the apparent resolution of the CMT improving from left to right:



Some problems

1. A published focal mechanism solution for a magntude (mb) 6.5 earthquake below northern Peru on October 28, 1997, lists the azimuth (trend) and plunge of the three principal axes as follows: T 247, 8; N 337, 0; P 69, 82. What is the strike and dip of the two nodal planes, one of which is parallel to the fault that generated the earthquake? What are the orientations (trend and plunge, or rake) of the two possible hanging-wall slip vectors?

2. In a published datafile listing the fault strike azimuth (right-hand rule), dip angle, and rake of hanging-wall slip vector, the data for a given earthquake are 135, 60, 120. Make a FMS beachball diagram (lower-hemisphere stereographic plot) for this earthquake.

3. In a published datafile listing the fault dip direction, dip angle, and rake of hanging-wall slip vector, the data for a given earthquake are 216, 65, -100. Make a FMS beachball diagram (lower-hemisphere stereographic plot) for this earthquake.

4. A field geologist measures the orientation of a fault surface and the direction of hanging-wall slip indicated by grooves and striations on that surface. The fault's strike-and-dip in the azimuth method is 35, 63SE, and the rake of the hanging-wall slip vector is 75° (as rake is defined by seismologists). For no particularly good reason other than a persistent case of seismologist envy, he wants to represent these data on his map as a pseudo-focal-mechanism solution beachball (which, by the way, is not a good idea). For the sake of humoring this poor sod, make a FMS beachball diagram from the field data.

5. You will be provided with a topographic map on which the surface trace of some faults are indicated. Two earthquake occur in the area. Given the location of the focus of each earthquake and their respective focal mechanism solutions, project likely fault planes to the surface to assess if any of the currently-mapped faults are active, or if there might be a previously unmapped fault in the area.

Some definitions

auxiliary plane The N axis is along the auxillary plane, and the fault is perpendicular to the auxillary plane. The auxillary plane is orthogonal to the two force couples (*i.e.*, either perpendicular or parallel to the force couples).

beachball diagram Lower-hemisphere equal-area stereographic projection of a focal-mechanism solution, including the two nodal planes separating opposite quadrants that are generally filled either with black (compressional quadrants in which p-wave first motion is up) or white (dilatational quadrants in which p-wave first motion is down).

force couple A non-zero component of a force field containing the derivative of a Dirac delta function, which can be visualized as two parallel vectors of equal magnitude but different directions acting at a short distance from one another.

double couple This is the simplest force condition that explains or reproduces the observed energy radiation pattern observed in earthquakes generated by fault slip. A double couple includes two force couples at right angles (90°) to each other acting at a short distance from one another.

hanging wall The block that is above an inclined fault surface, as contrasted with the foot wall that exists below the fault surface. The hanging wall "rests" on the foot wall. By convention, slip vectors in focal mechanism solutions reflect the motion of the hanging wall relative to the footwall.

epicenter The location of the point on Earth's surface that is directly (*i.e.,* vertically) above the focus of an earthquake.

fault plane Surface or zone across which there is shear displacement; in this application, the fault is an assumed-planar surface containing the earthquake focus. The fault plane is a nodal plane. The N axis is in/along the fault plane. The slip vector is in the fault plane, perpendicular to the N axis.

focal sphere Imaginary small projection sphere that is centered on the earthquake focus.

focus The best mean solution for the point of origin of an earthquake, and includes the earthquake depth and the longitude and latitude of the point vertically above the focus (*i.e.*, the location of the epicenter)..

N-axis The so-called "null" axis, the N-axis is one of the principal axes of the moment tensor. The orientation of the N-axis coincides with the orientation of one of the eigenvectors of the moment tensor – the eigenvector with the intermediate eigenvalue between that of the P and T axes. A seismograph that lies along a ray path through the N axis will not record a discernable signal from the earthquake at the expected arrival time. The N axis is along the intersection of the two nodal planes, and is orthogonal to (*i.e.,* 90° from) both the P and T axes.

nodal plane Each nodal plane is parallel to one of the two force couples centered on the earthquake focus, and perpendicular to the other force couple. One of the nodal planes is coincident with the fault surface, and the other is coincident with the auxiliary plane. A seismograph that lies along a ray path along one of the nodal planes will not record a discernable signal from the earthquake at the expected arrival time.

P-axis The so-called "pressure" or compressional axis, the P-axis is one of the principal axes of the moment tensor. The orientation of the P-axis coincides with the orientation of one of the eigenvectors of the moment tensor – the eigenvector with the smallest eigenvalue (*i.e.,* a negative value). A P-wave traveling along a ray path through the P axis will produce the largest amplitude negative (down) first motion as recorded on a distant seismograph, normalized for travel distance. The P axis bisects the dihedral angle between the two nodal planes, and is orthogonal to (*i.e.,* 90° from) both the N and T axes.

rake Angle measured *in the plane of the fault* between the reference strike (right-hand rule) and the slip vector. Vectors with a positive rake point above the strike line; vectors with a negative rake are directed downward, below the strike line.

reference strike The strike of a given inclined plane is the azimuth of a horizontal line contained within that plane. But since a horizontal line may be characterized by either of two azimuths, each 180° from the other, it is necessary to differentiate between these two azimuths to define one of the two directions as the reference strike. Hence, the reference strike is identified through a 90° anti-clockwise (right-handed) rotation from the dip vector. For example, the reference strike for an east-dipping plane is toward the north; for a northwest-dipping plane, the reference strike is toward the southwest. Put another way, if the trend of the dip vector is θ°, the azimuth of the reference strike is θ°–90°.

slip vector By convention among those who use focal mechanism solutions, the slip vector represents the direction of motion of the hanging wall relative to the foot wall. The slip vector is always contained within the fault plane (*i.e.,* the point that represents the slip vector lies along the trace of the fault plane on a stereographic plot or beachball diagram).

T-axis The so-called "tension" axis, the T-axis is one of the principal axes of the moment tensor. The orientation of the T-axis coincides with the orientation of one of the eigenvectors of the moment tensor – the eigenvector with the largest eigenvalue. A P-wave traveling along a ray path through the T axis will produce the largest amplitude positive (up) first motion as recorded on a distant seismograph, normalized for travel distance. The T axis bisects the dihedral angle between the two nodal planes, and is orthogonal to (*i.e.,* 90° from) both the N and P axes.

take-off angle The angle, measured from a vertical line extending down from an earthquake focus, that a particular ray path takes as it leaves the focus.

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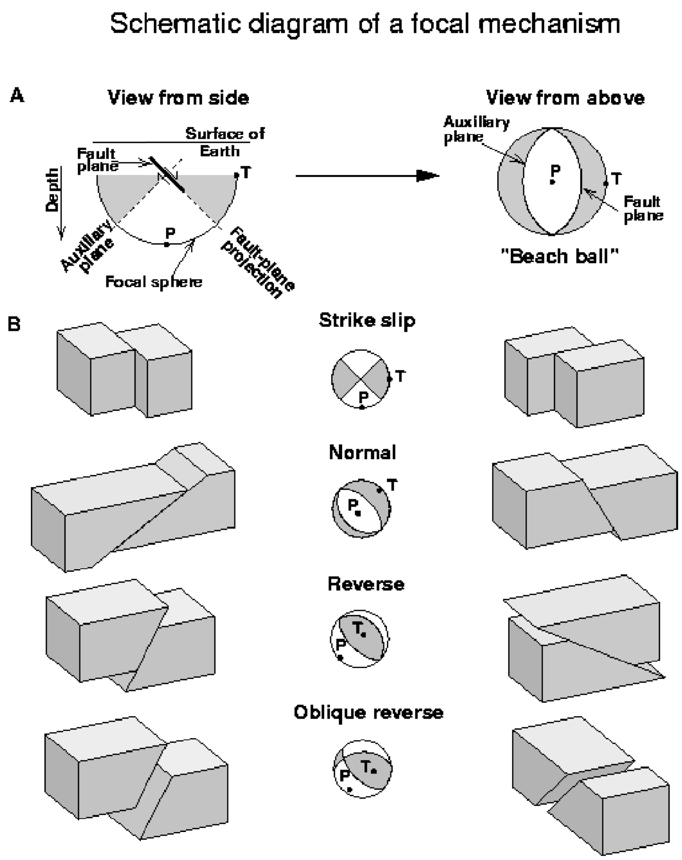
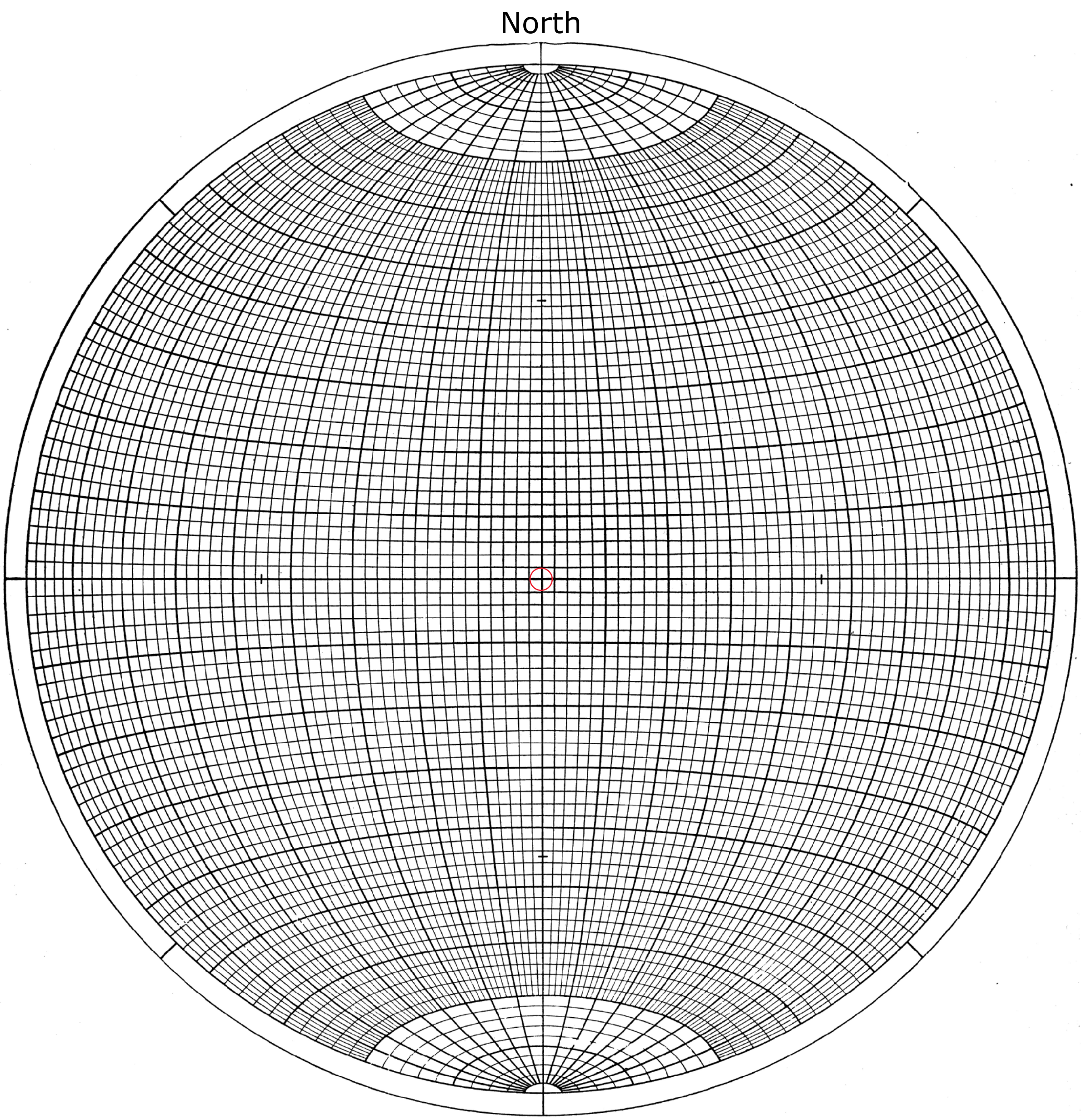
A brief description of focal mechanism solutions by Dave Oppenheimer of the USGS

"Seismologists refer to the direction of slip in an earthquake and the orientation of the fault on which it occurs as the focal mechanism. They use information from seismograms to calculate the focal mechanism and typically display it on maps as a "beach ball" symbol. This symbol is the projection on a horizontal plane of the lower half of an imaginary, spherical shell (focal sphere) surrounding the earthquake source (A). A line is scribed where the fault plane intersects the shell. The stress-field orientation at the time of rupture governs the direction of slip on the fault plane, and the beach ball also depicts this stress orientation. In this schematic, the gray quadrants contain the tension axis (T), which reflects the minimum compressive stress direction, and the white quadrants contain the pressure axis (P), which reflects the maximum compressive stress direction. The computed focal mechanisms show only the P and T axes and do not use shading.



"These focal mechanisms are computed using a method that attempts to find the best fit to the direction of P-first motions observed at each station. For a double-couple source mechanism (or only shear motion on the fault plane), the compression first-motions should lie only in the quadrant containing the tension axis, and the dilatation first-motions should lie only in the quadrant containing the pressure axis. However, first-motion observations will frequently be in the wrong quadrant. This occurs because a) the algorithm assigned an incorrect first-motion direction because the signal was not impulsive, b) the earthquake velocity model, and hence, the earthquake location is incorrect, so that the computed position of the first-motion observation on the focal sphere (or ray azimuth and angle of incidence with respect to vertical) is incorrect, or c) the seismometer is mis-wired, so that "up" is "down". The latter explanation is not a common occurrence. For mechanisms computed using only first-motion directions, these incorrect first-motion observations may greatly affect the computed focal mechanism parameters. Depending on the distribution and quality of first-motion data, more than one focal mechanism solution may fit the data equally well.

"For mechanisms calculated from first-motion directions as well as some methods that model waveforms, there is an ambiguity in identifying the fault plane on which slip occurred from the orthogonal, mathematically equivalent, auxiliary plane. We illustrate this ambiguity with four examples (B). The block diagrams adjacent to each focal mechanism illustrate the two possible types of fault motion that the focal mechanism could represent. Note that the view angle is 30-degrees to the left of and above each diagram. The ambiguity may sometimes be resolved by comparing the two fault-plane orientations to the alignment of small earthquakes and aftershocks. The first three examples describe fault motion that is purely horizontal (strike slip) or vertical (normal or reverse). The oblique-reverse mechanism illustrates that slip may also have components of horizontal and vertical motion" (quake.wr.usgs.gov/recenteqs/beachball.html).



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