CHAPTER 8
EQUAL-AREA PROJECTIONS AND STRUCTURAL ANALYSIS

8-1 INTRODUCTION

In previous chapters we used a specific type of azimuthal projection, called the stereographic projection, to solve a range of geometric problems in structural geology. The stereographic projection has two important properties: (1) The projection preserves angular relationships and is therefore, often called an equal-angle projection. This means that the angle between the tangents to two intersecting great-circle traces at their point of intersection is the same as the angle between the two real planes that the great-circle traces represent (Fig. 8-1a). (2) The stereographic projection does not conserve area. This means that projections of identical circles inscribed on different parts of a projection sphere appear as circles of different sizes on the stereogram (Fig. 8-1b). In fact, the stereographic projection of a circle may vary in area by up to a factor of two, depending on where it is projected; a circle of a given area will appear to be much larger if plotted near the primitive than if it is plotted at the center of the net (Fig. 8-1b). Likewise, a $10^6$ X $10^6$ area at the edge of a Wulff net is much larger than a $10^6$ X $10^6$ area at the center of the net (Fig. 8-1c).

The latter property makes the stereographic projection useless for applications in which the statistical treatment of orientation data is of interest. Such applications are common in structural analysis. For example, information on the preferred orientation (most common orientation) of joints in an area may provide information on paleo-stress fields. The orientation of the joints can be represented on a rose diagram or a histogram (see Chapter 12), but these graphs represent orientation only in two dimensions (i.e., they can represent strike or dip, but not both). An appropriate azimuthal projection can represent a preferred orientation in three dimensions as a cluster of poles, if the concentration of poles per unit area of the projection is proportional to the real concentration of planes of a specific orientation. A stereographic projection, because it distorts area, cannot be used for such representations; equal concentrations of poles at different localities on the surface of a projection sphere appear as unequal concentrations of poles on the plane of a stereographic projection.

In problems for which the statistical distribution of points is important, an alternative form of azimuthal projection called the Lambert or equal-area projection is used. A grid constructed on an equal-area projection is called a Schmidt net, named after a German petrologist (Fig. 8-2). Such a projection does not cause the area of a projected circle to vary with its position, although its shape does change (Fig. 8-3a); thus, the concentration of a cluster of points does not vary with position on the projection. Likewise, on a Schmidt net the size of a $10^6$ X $10^6$ area near the primitive is the same as that at the center (Fig. 8-3b). The purpose of this chapter is to introduce the equal-area projection, show how data distributions on such projections can be represented by contours, and illustrate some applications of the equal-area projection to structural analysis.
8-2 EQUAL-AREA PROJECTIONS
AND THE SCHMIDT NET

Construction of an Equal-Area Net

The equal-area projection is simply another form of
azimuthal projection that can be used to project a
lower-hemisphere spherical projection onto a horizontal
plane. The geometric basis for construction of the
equal-area projection is shown in Figure 8-4. This figure
draws a vertical cross section through the center of a
projection sphere; Z is the zenith of the sphere, C is the
center of the sphere, and C' is the base of the sphere.
The projection plane is tangent to the sphere at C', which is
the center of the azimuthal projection. Any inclined line
(AD) that passes through the center of the projection sphere
intersects the surface of the sphere at a point P. Point P is
the spherical projection of line CP. A circular arc, whose
center is at C and which passes through point P,
intersects the projection plane at P'. P' is the projection of
P on the azimuthal projection plane. The distance of point
P' from the center of the azimuthal projection (C) can be
calculated as follows:

\[ \angle (CPP') = \theta = 90^\circ - \phi \]

where \( \phi \) is the inclination of line CP, so

\[ \angle (CPP') = \theta / 2 \]

Triangle CPP' is a right triangle, so

\[ PC' = 2r \sin(\phi/2) \]  \hspace{1cm} (Eq. 8-1)

\[ PC' = PC = 2r \sin(\phi/2) \]  \hspace{1cm} (Eq. 8-2)

where \( r \) is the radius of the projection sphere. Using
a similar method, we can calculate the radius (R = C'T) of
the primitive on the projection plane:

\[ TC' = TC = 2r \sin(\phi/2) \]  \hspace{1cm} (Eq. 8-3)

Remember that in the case of the equal-angle projection, it
was easier to visualize the projection by passing the
projection plane through the center of the projection
sphere, so that the radius of the primitive equals the radius
of the projection sphere. It is similarly convenient to scale
an equal-area projection to be the same radius as the
projection sphere. In order to change the scale of the
primitive so that it has the same radius as the projection
sphere, we make \( TC' = r \) by dividing Equation 8-3 by \( v_2 \), and
so determine the position of any point within the
scaled projection circle by dividing Equation 8-2 by \( v_2 \):

\[ PC' = 2r \sin(\phi/2) \]  \hspace{1cm} (Eq. 8-4)

Note that in the projection technique described above, a
2º-wide segment of the surface of the projection sphere
will correspond to the same line length on the azimuthal
projection, regardless of whether the segment is near the
equator or near the pole. Therefore, an azimuthal
projection constructed according to the preceding method
is an equal-area projection.

Using this projection procedure, it is possible to construct
an equal-area net (Fig. 8-2). The net is merely a
grid of curves. The suite of curves on this grid that run
from the north to south poles represent the equal-area
projections of a suite of planes of different dips passing
through the north-south horizontal axis of the projection
sphere. The second suite of curves represents the equal-area
projections of right-circular cones whose vertices are at
the center of the projection sphere and whose axes are
coaxial with the north-south axis of the projection sphere.
Thus, the equal-area grid is analogous to the grid on a
Wulff net, and it is used in exactly the same way for plotting lines,
planes, and poles. The curves on an equal-area net, in
to contrast to those on an equal-angle net, however, are
elliptic arcs, not segments of circular arcs. Nevertheless,
the north-south trending grid lines are usually referred to as
great circles, and the other set of grid lines are referred to as
small circles. The trace of a plane on an equal-area net is
called a great-circle trace.

Which Net Is Which?

There is sometimes confusion about the names assigned to
different types of azimuthal projections. A stereographic
projection is one type of azimuthal projection. The terms
Wulff net or stereonet refer only to grids drawn on a
stereographic projection, and a stereonet refers only to a
plot of points or curves on a stereographic projection. An
equal-area projection is a second type of azimuthal
projection. An equal-area projection is a not a stereographic
projection. The term Schmidt net refers to a grid drawn on
an equal-area projection, and it is not the same as a
stereonet; formally, the term stereonet should be used only
with respect to a grid on a stereographic projection, and
the term equal-area plot should be used only for points or curves
drawn on an equal-area projection. In practice, however,
geologists tend to use the term stereonet loosely, to refer to
either a Wulff net or a Schmidt net (see Chapter 15).

A question often arises as to when it is appropriate to use
a Schmidt net instead of a Wulff net, and vice versa, for
plotting data. The Schmidt net must be used in all
applications where the concentration of points on the plot
is significant; thus, it is particularly applicable for analysis
of a large number of measurements. A Wulff net must be
used where angles between structures on the net will be
measured with a protractor (e.g., Chapter 7). In applications where lines, planes, and poles are to be plotted for geometric calculations without a protractor (i.e., all problems in Chapters 5 and 6), either net can be used; thus, all figures in Chapters 5 and 6 could have been drawn on a Schmidt net. The Schmidt net, therefore, has the most common application for problems in structural geology and is usually the net that geologists carry with them to the field.

We will see that measurements made at many localities around certain structures yield characteristic distribution patterns of poles on a Schmidt net. The distributions of poles shown in Figure 8.5 represent more-or-less ideal patterns. In actual geologic examples the distribution patterns are never quite perfect, and patterns may be difficult to recognize. If the scatter from an ideal pattern is large, the pattern may be unrecognizable unless more data are obtained.

### 8.3 CONTOURING OF EQUAL-AREA PLOTS

From the experience gained in the exercises of the previous three chapters, you should now be adept at visualizing the orientation of a structure represented on an azimuthal projection. In the process of collecting data on a structure in the field, you will have occasion to make numerous measurements of either planar or linear attitudes. A plot of such data may show clusters of points (poles or lineations) on either a stereonet or an equal-area plot. A projection that shows only points is called a scatter diagram or a point diagram. From clusters on a scatter diagram it is often possible to estimate the dominant orientation of a structural element in your study area. But in order to obtain a more precise representation of variations in orientation, you must quantify the number of points per unit area of the projection. Such quantification can be done on an equal-area net and may allow you to recognize subtle variations in the preferred orientations of a structural element as measured in different localities. The most efficient way of representing variations in the concentration of points on an equal-area plot is by contouring of point data.

A contour line on an equal-area plot separates zones of the plot in which the densities of point data are different. Densities of point data are usually measured as a percentage of the total number of points per 1% area of the stereogram. If the total area of the plot is 100 cm², 1% of the plot is 1 cm²; if there are 100 points plotted on the equal-area net, and 10 points lie in a specific 1 cm² area, then the density of points in that area is 10% of total points per 1% area. Contour lines are drawn on an equal-area plot to separate zones in which the percentage of total points per 1% area falls within a specified range. For example, if the contour interval is 2, then the lowest contour line is drawn separating the zone in which there are fewer than 2% of total points per 1% area from the zone in which there are more than 2% of total points per 1% area. The next contour line is drawn to separate the zone in which there are 2 to 4% of total points per 1% area from the zone in which these are more than 4% of total points per 1% area, and so forth. Admittedly, describing the contour interval on a contoured equal-area plot is a bit of a tongue twister.

Certain general rules can be followed when contouring an equal-area plot.

1. On the basis of the minimum and maximum concentrations, contour intervals should be chosen such that there are no more than 6 contours on the final plot. Then should be a constant contour interval.

2. The lowest contour is usually drawn at 1 point per 1% area. The highest contour should be chosen to emphasize and differentiate maxima that are large enough to stand out clearly on the projection.

3. A contour that crosses the primitive has to reappear at the diametrically opposite end of the stereogram.

4. It is easiest to start drawing the contours at the area of greatest concentration and work outward.

5. After preliminary contouring, it may be useful to go back to the counting net to determine the true maximum. This is done by moving the 1% counting circle (described below) around the net until the largest number of points lie within the counting circle. The center of the counting circle then locates the true maximum.

6. It is also useful to smooth out some contours, after preliminary contouring, or to eliminate contours if the lines are too close to one another.

7. The values of the contours should be indicated in the legend in the form 1-5-9-13% per 1% area, maximum 14%, for example. On the finished plot the area of highest concentration should be blackened. Progressively decreasing densities of stippling are used for areas of lesser concentration. The lowest concentration is left blank. On many plots only the areas within the contours of highest concentration are shown.

8. It is very useful to present the contoured diagram side by side with the scatter diagram (showing points on the stereogram) in order to convey as much objective data as possible.

Once the diagram has been contoured, the mean or dominant orientation of principal structures can readily be determined from the positions on the net where the greatest number of points occur. It is common practice to abstract these data by plotting, on a separate equal-area (or equal-angle) net, the orientations of the principal structural elements within a region. A diagram on which a single great circle or point is used to represent the mean or dominant orientation of several structural elements is called a normative diagram.

Increasingly, computers are being used to construct concurved equal-area plots, but it still is important to understand contouring principles using graphical methods. There are a number of graphical methods that are used for contouring point data, some of which are very precise and can easily be used in the field. For most graphical methods it is convenient to use a 50 cm diameter stereonet (Appendix 4 provides a net with this diameter). The method described here refers to a 15 cm diameter stereonet (Fig. 8.8a) provides a net with this diameter). The method described here refers to a 15 cm diameter stereonet (Appendix 4 provides a net with this diameter).

### Method 8.1 (Schmidt method)

Step 1: Construct a square grid with grid points 0.75 cm apart. The dimensions of the grid must exceed that of your equal-area plot.

Step 2: A Schmidt counter contains two circular holes at opposite ends of a cardboard strip. Each hole has an area equal to 1% of the total area of your equal-area projection. You will see that two dimensionally opposite holes are needed to...
count points along the edges of the equal-area plot, while only one circle is needed for counting points in the interior of the plot. The holes to be used with our 15-cm-diameter net should be 1.5 cm in diameter. The counter can be constructed from a strip of poster board that is 18 cm long and 3.5 cm wide (Fig. 8-6). Draw two 1.5-cm-diameter circular holes in the strip, one at each end, such that the centers of the holes are 15 cm apart. In ink, draw a circular arc of 15 cm diameter that passes through the centers of the counting holes, and draw lines through the centers of the holes perpendicular to the line that joins the two centers; these ink marks should be visible on the cardboard borders of the counting holes and will serve as guides during counting (Fig. 8-7). Now, cut out the counting holes, and cut a 2-cm-long thin slot in the middle of the strip, halfway along the inscribed line joining the two centers of the holes. Draw a centerline to mark the center of the slot.

**Step 3**: Place an overlay containing the point data of an equal-area plot (Fig. 8-8a), a tracing of the primitive, and a north reference mark, over the square grid. The center of the overlay must coincide with the intersection of two grid lines. Fix the overlay with tape.

**Step 4**: Place a second overlay, showing only the trace of a 15-cm-diameter circle and a north mark, on top of the first. The circles on the two overlays should be concentric, and the north marks should coincide.

**Step 5**: Place one end of the counter over the two overlays, such that the center of the circular hole coincides with a grid point; you may use the ink line that passes through the center of the hole as a guide (Fig. 8-7b). The number of points that are visible within the hole represent the number of points per 1% area. Make a dot at the grid point on the second overlay, count the number of points on the first overlay that are visible within the hole, and write it next to the dot on the second overlay. Reposition the counter so that its center is over the adjacent grid point, and repeat the procedure for all the grid points. Leave blank the areas in which there are no points (Fig. 8-8b).

**Step 6**: In the peripheral zone near the primitive, one counting circle will not fall entirely within the primitive, and you will need to use both circles of the counter. Pierce the center of the grid and the two overlays with a thumbtack, and put the point of the tack through the central slot of the counter. Points within both counting circles at diametrically opposite ends of the projection must be counted together (Fig. 8-7a). Intersections of the grid lines with the primitive are used to center the counting circle where necessary.

**Step 7**: Once numbers have been written in at each grid point on the second overlay (Fig. 8-8b), convert the number of points (N) next to each dot to a percentage by the equation

$$n(100)/N = \%,$$

where N is the total number of points on the plot. Draw contours at intervals corresponding to the appropriate point densities (Fig. 8-8c).

**Figure 8-7. Method for counting points for contouring.** (a) For points that lie close to the primitive; (b) for points inside the primitive. (Adapted from Turner and Weiss, 1963.)

**Figure 8-8. Procedure for contouring described in Problem 8-1.** (a) Equal-area projection of poles to 72 foliation measurements; (b) point count using grid and Schmidt counter; (c) the final contoured diagram with contours at 1, 3, 7, 11, and 15%. A Schmidt counting grid is available in Appendix 4.

**Method of Contouring**

This method is convenient for a small number of points (<100) and for populations of points that do not show local high concentrations. It is particularly useful for determining the contour of minimum density (i.e., usually the one-point contour).

**Problem 8-2**

Contour the data in Figure 8-9a using the Mellis method.

**Method 8-2 (Mellis contouring)**

**Step 1**: Construct an overlay on which only the primitive and the north mark are shown. Construct a counting circle that is 1.5 cm in diameter (i.e., 1% of the total area of your equal-area projection). Place the overlay over your equal-area plot so that it is concentric and aligned with the north arrow. Tape it down.

**Step 2**: Draw a 1.5-cm-diameter circle around each point in the population (Fig. 8-9a). The overlapping areas of two circles have a 2X concentration of a single circle, overlapping areas of three circles have a 3X concentration of a single circle, and so on. The percentage of the total number of points that is represented by one point can be calculated. The 2X and 3X areas are merely double and triple that percentage respectively.

**Step 3**: Place a third overlay over the second, and outline the areas of different point concentrations. It is best not to smooth the contour lines in this type of plot (Fig. 8-9b).

The Mellis method is the least subjective and most accurate method for contouring. The results are completely
reproducible, and for the same population of points the results will be identical for any two workers using the method. Its use, however, is limited to small populations and low concentrations; the method would obviously be cumbersome and difficult to use if four or more circles overlapped in a certain area.

Kalsbeek Method of Contouring

The Kalsbeek method (Kalsbeek, 1953) of contouring is quick and easy and thus is particularly appropriate in the field. It can be used with any population of point data on an equal-area plot.

Problem 8-3

The equal-area plot in Figure 8-11a is the same as that used for Problem 8-1. Contour the data using the Kalsbeek method.

Method 8-3 (Kalsbeek contouring)

Step 1: Obtain a Kalsbeek counting net (one is provided in the back of this book). This net is subdivided into small triangles (Fig. 8-10). Each set of six triangles forms a hexagonal area that covers 1% of the total area of the net. The triangles are arranged so that the net has six radial rays. The counting areas at the ends of these rays are semicircles, rather than hexagons.

Figure 8-10. Counting net. (From Kalsbeek, 1953.)

Step 2: Place an overlay containing your equal-area scatter plot over the counting net, with the sixth mark of your plot at the tip of one of the radial rays. Place a second overlay, with only the primitive and the north mark, over the first.

Step 3: Count the number of points that fall within each hexagon, and write the number of points next to a dot at the center of the hexagon on the second overlay (Fig. 8-11b). Since the hexagons overlap, each point is counted on three occasions. Along the primitive combine the points within each half-hexagon with points from the half-hexagon at the diametrically opposite end of the stereogram. Count the points at the ends of the six radial rays of the net by using the two complementary semicircles at opposite ends of the diameters. As with the Schmidt method, leave areas with no points blank.

Step 4: When you have finished counting, translate the numbers into percentages of the total number of points, and contour the results (Fig. 8-11c) in the same way as you did for the Schmidt method. Note that the contoured plot looks similar to that obtained in Problem 8-1 (Fig. 8-8c), but it is not exactly the same.

Kamb Method

Kamb (1959) proposed a contouring method that permits graphic analysis of the statistical significance of point concentrations on an equal-area plot. In the Schmidt or Mellis methods just described, the area (A) of the counting circle was 1% of the total area of the equal-area projection. We could, alternatively, choose A to be any fraction (of the total area) from 0 to 1.

Consider an equal-area plot on which there are N points. If the distribution of points is statistically uniform, there are (N X A) points within a counting circle of area A and [N X (1 - A)] points outside the counting circle. Call (N X A) the expected number of points. If the actual number of points (n) that falls within the counting circle is significantly greater than the expected number, then we have a significant cluster. The distribution of n values is a binomial distribution (see a statistics book for the definition of a binomial distribution), and the mean (µ) and standard deviation (σ) of such a distribution are given by

\[ \mu = NA \]  
\[ \sigma = \sqrt{N(A(1-A))} = NA[(1-A)/NA]^{1/2} \]

or

\[ \sigma = \sqrt{(1-A)/NA} \]  

To smooth out wild fluctuations from expected densities, A is chosen such that if the population has no preferred orientation, the number of points (NA) expected to fall within the counting circle is 5% of the number of points (n) that actually fall within the counting circle under random sampling of the population. Thus, by setting \( \sigma(NA) = 1/3 \), we can calculate from Equation 8-2 the appropriate area (A) of the counting circle for a given fabric represented by N points.
Chapter 8 Equal-Area Projections and Structural Analysis

Problem 8-4
The equal-area plot of Figure 8-12a shows the same data as that used in Problem 8-1. Determine the appropriate diameter for the counting circle, for the Kamb method of contouring, and contour the data using this method.

Method 8-4
Step 1: Determine the appropriate diameter of the counting circle. Using Equation 8-8 for \( N = 72 \), it is found to be 0.188 of the radius of the equal-area projection. For a 15 cm diameter net, the counting area is a circle of diameter 2.82 cm.

Step 2: Construct a counting grid with a spacing equal to the radius of the counting circle, i.e., 1.41 cm.

Step 3: Follow the same method as in Schmidt contouring to obtain concentrations at the grid points (Fig. 8-12b).

Step 4: Using Equation 8-4, calculate a value for \( r \) (1.57). Contour the concentrations at 2\( r \), 4\( r \), 6\( r \), and 8\( r \) (Fig. 8-12c). Notice that the contoured diagram is significantly different from those obtained by the Schmidt and Kalsbeek methods.

Additional methods of contouring equal-area plots and of statistical analysis of equal-area plots are described by Vistelas (1966).

8-4 PATTERNS OF POINT DATA ON EQUAL-AREA PROJECTIONS

The distribution of points on an equal-area projection graphically expresses the degree of preferred orientation (or lack thereof) of a particular structural element (such as foliation or lineation). The key to interpreting the
projection lies in recognizing the pattern defined by the distribution of points (where "points" refers to either the projection of a line representing a linear structure or the projection of a pole representing a planar structure). Recognition of patterns is often easier to do with a contoured diagram. There are four main patterns that can be recognized:

Uniform Distribution: A statistically random distribution in the orientation of structural elements is expressed by a scatter of points on an equal-area plot in which there are no obvious local concentrations. The lack of any concentration on a plot is called a uniform distribution (Fig. 8-13a).

Point Maximum: A preferred orientation of structural elements is represented by a high concentration (significant cluster) of points symmetrically distributed around a single mean orientation (Fig. 8-13b). The center of the cluster is the point maximum. A single data set can show more than one point maximum.

Great-Circle Girdle: A concentration of points along an arc approximating a great circle is called a great-circle girdle (Fig. 8-13c). The pole of the great-circle girdle is called the girdle axis. A girdle may contain one or more distinct maxima. In some cases, two girdles may intersect, forming a crossed girdle pattern. A girdle pattern for linear elements indicates that the lineations all lie in a single plane but are not parallel to one another. In such a case the girdle approximates the attitude of the plane containing the lineations, and the girdle axis is the pole to that plane. A girdle pattern for points or planar elements indicates that the planes could all intersect along the same line. For example, a girdle pattern is obtained by plotting points to bedding taken around a cylindrical fold (see below).

Small-Circle Girdle: A small-circle girdle is a concentration of points along an arc that approximates a small circle (Fig. 8-13d). Such a girdle may contain one or more distinct maxima. For both linear and planar elements such a girdle indicates a preferred orientation in a cone about a single axis (the girdle axis).

We can describe the point-distribution pattern on an equal-area plot in terms of the type of symmetry displayed (e.g., the number of mirror planes that can be drawn on the plot, across which the point clusters are mirror images of one another) by analogy with the description of point groups in crystallography. For example, a fold may be described as orthorhombic or monoclinic, depending on the pattern of lineations displayed on a plot of poles to bedding. For further discussion of this terminology see Turner and Weiss (1963).

8.5 ANALYSIS OF FOLDING WITH AN EQUAL-AREA NET

Geometrically, a fold is merely a curved surface. There are two basic types of folds: (1) Cylindrically folded are generated by moving an imaginary straight line parallel to itself in space. The line that generates the fold is called the fold axis. (2) Noncylindrically folded are generated by a line that moves in a nonparallel manner through space. If one end of the generating line is fixed, the resulting fold form is called a conical fold. If the movement of the generating line is noncylindrical, a complex fold results. Sometimes complex folds can be subdivided into parts that are approximately cylindrical. The geometry of cylindrical or conical surfaces can be analyzed with either 8 diagrams or π-diagrams on an equal-area projection.

9-DIAGRAMS OF CYLINDRICAL FOLDS

Every segment of a cylindrically folded surface contains a line segment that is parallel to the fold axis. Any two tangential planes to the folded surface will intersect along a line that is parallel to the fold axis. On an equal-area projection, therefore, the great circles representing the attitudes of the folded surface at different points on the fold should all intersect at a common point representing the fold axis. This point is called the β-axis. In practice, however, real folds do not have a perfectly cylindrical form, so strike and dip measurements around the fold produce great circles that do not all intersect at a common point, although the points of intersection do show a point maximum that gives an average orientation for the β-axis. For n plotted planar attitudes (Fig. 8-14), the number of intersections (k) is given by the arithmetic progression

\[ x = 0 + 1 + 2 + \ldots + (n - 1) = \frac{(n - 1)n}{2} \]  
(Eq. 8-9).

Thus, if there are 200 plotted planes, the number of intersections is 19,900. Contouring of the intersection...
points will emphasize the maximum concentration of intersections.

A plot of B-axes is not generally the best way to represent attitude measurements on a fold, for several reasons. First, the number of points on a B-axis plot is far greater than the actual number of measurements; thus, such a plot may make you think that you have more data than you actually have. Second, if there is any scatter in the original data, there can be concentrations of B-axes away from the main concentration, leading to an erroneous interpretation. Such errors become unacceptable large if the interlimb angle is very small (<90°), as in tight folds, or very large (>140°), as in open folds. Finally, construction of a B-diagram is time consuming, because a large number of great circles must be plotted, and the number of intersections can become unmanageably large for even a small data set.

\(n\)-Diagrams of Cylindrical Folds

Because of the disadvantages of the B-axis diagram, a \(n\)-diagram is the preferred method for representing measurements from a folded surface. A \(n\)-diagram is an equal-area plot of the poles to planes that are tangential to the folded surface. Practically, this means that if we have strike and dip measurements from many locations on a fold, we plot the pole for each plane rather than the great-circle trace. On a cylindrical fold, each of the poles is perpendicular to the fold axis; thus, the poles are parallel to a plane perpendicular to the fold axis. On an equal-area plot, the poles approximate a great-circle girdle, which is variously called the S-pole circle, the pole circle, or the \(n\)-circle (Fig. 8-15). The pole to the \(n\)-circle is the \(n\)-axis (Fig. 8-15), and it represents the fold axis. The \(n\)-axis should coincide with the B-axis on a plot. For a very open fold, with a very large interlimb angle, the \(n\)-diagram will show an elliptical point maximum. With progressive decrease in the interlimb angle, the pole pattern changes from a point maximum, to an incomplete great-circle girdle, and finally, to a complete great-circle girdle (Fig. 8-16; e.g., Ragan, 1985).

A \(n\)-diagram not only gives information on the orientation of a fold axis but also contains clues to the form of the fold. For example, if a fold has a broad, rounded hinge, the density of poles will be uniform within the n-circle girdle, and the two extreme points on the girdle will define the interlimb angle (Fig. 8-17a). The \(n\)-circle girdle for a fold with planar limbs and a narrow hinge zone will contain maxima on the girdle corresponding to the two limbs, and these maxima can be used to determine the interlimb angle (Fig. 8-17b). For a chevron fold there is no well-defined girdle, and the \(n\)-circle on the projection is defined by two point maxima corresponding to the two limbs (Fig. 8-17c). Most natural folds show patterns that are intermediate between the broad-hinge girdle and the two-maxima (limbs) girdle.

It is generally not possible to say anything conclusive about the symmetry of folds from just a \(n\)-diagram, because factors other than dips in the two limbs of the folds determine fold symmetry (Hobbs, McNeill, and Williams, 1976; Ramsey, 1967). A concentration of points along a girdle may also be a consequence of sampling bias. However, if the spatial distribution of measurements is in a train of folds is uniform, there will be fewer readings from the short limbs of asymmetric folds, resulting in an asymmetry in the pole pattern on the \(n\)-diagram (Fig. 8-17b). Generally, in order to determine asymmetry of folds, we need additional information such as variation in thickness from limb to limb, orientation of the enveloping surface, and orientation of the axial surface (see Chapter 11).

The orientation of the axial surface (or the axial plane) can be determined if the \(n\)-axis is known and if the orientation of the axial trace at a locality can be determined; the great circle passing through these two points gives the orientation of the axial plane (Fig. 8-18a). In the case of chevron folds and kink folds, the axial plane may be defined as a plane containing the bisector of the interlimb angle. The bisector is represented by the point whose angular distance from the two point maxima (measured along the \(n\)-circle girdle) is the same. The great circle passing through the bisector and \(n\)-axis represents the axial plane (Fig. 8-18b).

The attitudes of the fold axis and the axial plane are, of course, reflected in the position of the \(n\)-circle on an equal-area projection. For example, if the fold axis is horizontal, then the \(n\)-axis lies on the primitive and the girdle passes through the center of the net, but if the fold axis is plunging, then the \(n\)-axis lies inside the primitive, and the girdle follows a curve that does not pass through the center of the net. If the axial plane of the fold is vertical, it is represented by a diameter of the equal-angle plot; if it is horizontal, it is represented by the primitive; and if it is inclined, it is represented by some intermediate great circle. A fold with a plunging axis and an inclined axial plane may display a complex pattern on an equal-area net. Figure 8-19 shows a few examples of \(n\)-diagrams and the axes that they represent.

\(n\)-Diagrams of Noncylindrical Folds

If the folded surface is conical, with the cone having an apical angle \(\mu\), each pole makes an angle of \(90° - \mu\) with respect to the cone axis. In other words, the poles to bedding generate a coaxial cone with an apical angle of \(180° - \mu\). Thus, the poles define a small circle, with its center representing the cone axis (Fig. 8-20). If an approximate small-circle pattern is recognized, it may be worthwhile to plot the poles on a Wulff net, since a small circle projects as a circle on the stereographic projection. A small circle can then be fitted to the plotted points, and the center of the circle (representing the cone axis) can be located. The cone axis can be rotated to the primitive, and the small circles of the net can be used to analyze the angular relationships within the fold.

In nonconical noncylindrical folds, both the axial surface and the fold axis vary in attitude, and construction of a \(n\)-diagram will generally give several possible orientations for the \(n\)-axis. Commonly, areas of superposed folding exhibit this kind of geometry. To analyze such folds, they must be subdivided, by trial and error if necessary, into domains of plane cylindrical folding (see Problem 8-7). Each domain should have its own constant \(n\)-axis orientation. In plane noncylindrical folds the axial surface is planar and has a constant orientation, although the orientation of the fold axis (\(n\)-axis) may vary. The mean orientation of the axial plane is defined as the great circle passing through the axes of the different cylindrical domains (Fig. 8-21).

8-6 ANALYSIS OF FABRICS WITH AN EQUAL-AREA NET

Types of Fabrics

The internal geometric and spatial configurations of the components of a rock constitute its fabric. If a fabric is visible in a rock regardless of the scale of observation, it is said to be penetrative. Rocks that have penetrative fabric
resulting from deformation are referred to as sectonites. Three major classes of sectonites are recognized, based on whether the fabric can be described as a foliation, a lineation, or both. (1) S-sectonites have a strong foliation but no lineation (Fig. 8-22a). The foliation is defined by parallel alignment of platy minerals, lenticular mineral aggregates, or flattened grains. The letter S is used because of the longstanding convention of referring to foliations as S-surfaces (Turner & Weiss, 1962). (2) L-sectonites have a well-developed lineation but no foliation (Fig. 8-22b). The lineation in an L-sectonite is defined by alignment of prismatic minerals or uniaxially elongated grains parallel to

Figure 8-17. Variation in n-diagrams with change in fold form. (a) Fold with broad, rounded hinge; (b) fold with narrow hinge; (c) chevron foliation; (d) asymmetric folds.

Figure 8-18. Determining attitude of fold axial surface from an n-diagram.

Figure 8-19. Variations in position of n-circle girdle with changes in attitude of the fold axis and axial plane. (a) Nonplunging upright (normal) fold; (b) plunging normal fold; (c) plunging inclined fold; (d) plunging overturned fold (note the presence of vertical beds indicated by the plotting of some bedding poles on the primitive); (e) recumbent fold; (f) recumbent fold; axial plane coincides with the primitive. (See Fig. 11-17.)
one another. (3) L-S-recticitons have both a foliation and a lineation (Fig. 8-20c). In an L-S-recticton either the lineation or the foliation may be more pronounced. The L-S fabric may be defined by the alignment of elongated platy minerals or of ellipsoidal grains. It may also be the result of crenulation of a foliation or the intersection of two foliations.

Traces on outcrop faces in a tectonite may represent either the lineation or the foliation or both. Planes perpendicular to, or at high angles to, the foliation will show traces of the foliation. The best-developed traces in an L-S tectonite will be on a plane parallel to the lineation and perpendicular to the foliation. Lineation traces alone will appear best developed on all planes parallel to, or at acute angles to, the lineation and are absent or, at most, poorly developed on planes perpendicular to, or at high angles to, the lineation. In an L-S-recticton an outcrop face parallel to the foliation itself shows the true attitude of the lineation.

In order to apply the methods of structural analysis, the fabric in a rock body must be homogeneic, meaning that equal volumes of rock from different localities in the body are structurally identical. True fabric homogeneity never really occurs, but it is common to find rocks that are statistically homogeneic, meaning that the sample over which the homogeneity is to be assessed is much larger than the scale over which inhomogeneity occurs. A rock in which the degree of development (intensity) or the orientation of a fabric differs as a function of location is inhomogeneic. An inhomogeneous rock can usually be subdivided into homogeneous parts. Each of these parts is a three-dimensional portion of a rock body that is statistically homogeneic and is called a fabric domain or simply a domain.

If the fabric within a single domain has the same properties in all directions, then it is called isotopic. In most deformed rocks, however, the structural elements within any domain show some degree of preferred orientation, and the fabric is, therefore, said to be anisotropic. Rocks with anisotropic fabrics may be S-, L-, or L-S-recticitons. Equal-area nets are useful in analyzing fabric in two ways. First, they may be used to calculate the true orientation of fabrics, given partial measurements on different planes; second, they may be used to describe

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**Figure 8-20.** Fluidal-slip folding of sedimentary rocks and a fault (at low angles to bedding). The southeast limb of the Eureka syncline shows cylindrical folding. The Shale fault surface is concavely folded. (Adapted from Ramsay, 1967.)

**Figure 8-21.** Plane noncylindrical folding. The area is subdivided into domains of cylindrical folding, each with its own fold axis, but all fold axes lie on a common axial plane (as shown on the synoptic equal-area plot). (Adapted from Turner and Weiss, 1965.)

**Figure 8-22.** The penetrative fabric of a rock defined by overall grain shape, elongated or platy minerals, and ellipsoidal markers. Three different classes are defined. (a) S-recticton; (b) L-recticton; (c) L-S-recticton.
variations in the geometry of fabrics that occur between different domains. Finally, in rocks with multiple fabrics, an equal-area projection may be the only way of distinguishing various fabric elements.

**Calculation of Planar and Linear Attitudes**

The trace of a planar structure on any surface is its apparent dip in that plane. If two or more such apparent dips can be measured, the orientation of the planar structure can be determined on an equal-area projection (Method 5-8). With more than two traces, the plane is defined by the best fitting great circle that passes through the data points.

**Problem 8-5**

The trace of a foliation (S) is seen on three nonparallel faces. The attitudes of the faces were measured, and the rake of the foliation trace on each face was measured, with the following results:

<table>
<thead>
<tr>
<th>Attitude</th>
<th>Rake</th>
</tr>
</thead>
<tbody>
<tr>
<td>N44°E, 60°NW</td>
<td>24°PSW</td>
</tr>
<tr>
<td>S60°E, 30°PSW</td>
<td>49°NWW</td>
</tr>
<tr>
<td>S11°E, 70°NE</td>
<td>25°NWW</td>
</tr>
</tbody>
</table>

**Determine the orientation of the foliation (S).**

**Method 8-5**

**Step 1:** On an equal-area projection, plot the great circle trace of each face (Fig. 8-23a, b, c). Measure the rake of the lineation on each face, and plot the point representing the trace of the foliation for each face.

**Step 2:** Find the best fitting great circle that passes through the three points representing the foliation traces (Fig. 8-23d). The great circle represents the plane of the foliation, which has an attitude of N30°E, 60°NW.

Often, lineations (such as minor fold axes or mineral lineations) can be directly measured on an exposed surface. At some localities, however, linear structures do not lie on a plane of easy breakage and thus cannot be measured directly. The orientation or poorly exposed lineations can be determined by measuring the apparent lineation on two or more differently oriented faces and plotting the data on an equal-area projection. Imagine a rod-shaped fabric element (e.g., a dowel with a circular cross section). Any section of the rod oblique to its axis will be elliptical (Fig. 8-24). The long axis of the ellipse is an apparent lineation on the plane of exposure; the true linear structure is contained in a plane perpendicular to the exposure plane and passing through the long axis of the ellipse. The orientation of the apparent lineation can be measured either by its rake on the plane of exposure or by its plunge and bearing. The measurements are plotted on a stereogram to obtain the true attitude of the lineation. The following problem illustrates the method.

**Problem 8-6**

Traces of a lineation were measured on three nonparallel faces. The orientations of the three faces and the rake of the apparent lineation in each face are as follows:

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Rake</th>
</tr>
</thead>
<tbody>
<tr>
<td>S50°E, 5°NW</td>
<td>15°NW</td>
</tr>
<tr>
<td>N32°E, 30°S</td>
<td>84°W</td>
</tr>
<tr>
<td>N80°E, 7°S</td>
<td>22°S</td>
</tr>
</tbody>
</table>

Determine the true attitude of the lineation.

**Method 8-6**

**Step 1:** On an equal-area projection, plot each face, its pole, and the trace of the lineation on the face (Fig. 8-25a, b, c).
Step 2: For each face draw the great circle passing through the pole and the lineation trace (Fig. 8-25a, b, c). The three great circles intersect (ideally) in one point defining the attitude of the lineation (Fig. 8-25c) as 249°, 85°W. This is referred to as Lowe's method (Lowe, 1946).

Step 3: Alternatively, after step 1, find the poles (\(G_1, G_2, G_3\)) to the great circles that pass through the pole to the face and the lineation trace. All these "new" poles lie on a great circle that represents the plane perpendicular to the lineation (Fig. 8-25b). Thus, the poles to this great circle give the attitude of the lineation (Fig. 8-25c). This method, which was devised by Cruden (1971), avoids the problem of trying to find a single point of intersection to define the attitude of the lineation by allowing a best-fit great circle to be drawn.

Analysis of Fabric Geometry

Patterns of variation in the attitude of fabrics around folds may help determine the chronology of fabric development with respect to folding. A number of patterns are possible, depending on the nature of the fabric, the timing of fabric development with respect to folding, and the mechanism of folding. The patterns are discussed next individually. A complete discussion of fabric types is beyond the scope of this book; our goal here is solely to show how fabric geometry can be practically analyzed with the equal-area net.

Foliation Postdating Folding: If a plane cylindrical fold that folds \(S_1\) and forms coevally with \(S_2\) is cut by a later planar (solution) \(S_3\), the intersection between \(S_2\) and \(S_3\) will vary around the fold (Fig. 8-26a). However, all the attitudes of the lineation lie on a single plane \((S_3)\) and fall along a great-circle girdle (Fig. 8-26b). Also, the angle between the lineation and the \(S_2\) fold axis varies as a function of \(S_3\) attitude (Fig. 8-26b).

Flexural-Slip Folding of a Lineation: Development of flexural-slip folds is accommodated by layer-parallel slip with minimal internal distortion of layers. Thus, to a first approximation, the movement of a layer during folding can be described as a rotation, and the angle \(\phi\) between the fold axis and the pre-existing lineation remains constant everywhere on the folded surface (Ramsey, 1967; Fig. 8-27a). On an equal-area projection, the points representing the lineation, therefore, lie on a small circle centered on the fold axis (6) (Fig. 8-27b). If the original lineation is perpendicular to the fold axis, the circle is great (Fig. 8-27c). Remember that the rotation of a line around an axis inscribes a small circle (see Chap. 7).

In reality, the discontinuity of material distortion of layers is not correct. Because individual layers in a flexural-slip fold are backfolded, each folded layer has a neutral surface that shows ideal concentric geometry, but the outer arc is extended and the inner arc is shortened (Fig. 8-28a). Therefore, on the outer arc, the angle between the lineation and the fold axis is slightly increased \((\phi > \phi)\), and the lineation points lie on an arc that is broader than the small-circle arc but is still centered on the fold axis (Fig. 8-28b). Similarly, the angle between the fold axis and the lineation is slightly decreased \((\phi < \phi)\) on the inner arc, and the lineation points lie on an arc that is narrower than the small-circle arc (Fig. 8-28c).

Passive Folding of a Lineation: Development of a passive fold is geometrically analogous to the passive reorientation of a marker layer by shearing on a set of close-spaced planes that are oblique to the foliation. In reality, discrete slip planes need not exist. The axial plane of the fold is parallel to the hypothetical shear planes, and the fold axis is parallel to the shear plane-marker layer intersection lineation. Points along an original linear feature on the marker layer are transposed variable distances along parallel lines (at the slip direction) and are positioned on the surface of the folded layer so that the folded lineation is contained in a plane defined by the original lineation and the slip direction (Fig. 8-29a). Thus, on an equal-area projection the points representing the folded lineation lie on a great circle that is oblique to the fold axis (Fig. 8-29b). This geometry is the same as that for an intersection lineation due to a foliation superposed on a preexisting fold, except that in this case, there may be no foliation developed parallel to the plane containing the lineation.

Complex Refolding of Lineations: Many natural folds show complex patterns for refolded lineation; the lineations often lie in arcs intermediate between a small circle and a great circle. Such modifications may result from layer-parallel shortening prior to folding, homogeneous flattening after folding, or some form of...
longitudinal layer-parallel strain accompanying folding. Details of these various possibilities are discussed in Turner and Weiss (1962) and Ramsay (1967).

**Flexural-Slip Folding of Obliquely Inclined Surfaces:** Folding of rocks containing two preexisting foliations ($S_1$ and $S_2$) that are oblique to one another results in simultaneous folding of both foliations (Ramsay, 1967). The foliations could, for example, be bedding and cleavage, or two preexisting cleavages, or even cross bedding and its enclosing matrix bedding. The geometric patterns resulting from such folding are readily analyzed on an equal-area net. During flexural-slip folding, if the $S_1/S_2$ intersection lineation is parallel to the fold axis, then both surfaces are folded into cylindrical folds that are coaxial (Fig. 8-30a). If, on the other hand, the $S_1/S_2$ intersection lineation is perpendicular to the fold axis, and one surface ($S_2$) is folded into a cylindrical fold, the other surface ($S_1$) maintains its dihedral angle with respect to $S_1$ and is folded in conical form, with the cone axis parallel to the fold axis for $S_1$ (Fig. 8-30b). Oblique intersections between $S_1$ and $S_2$ give rise to more complex patterns, with the $S_1/S_2$ intersection lineation falling on a small-circle arc centered on the fold axis for $S_1$, and the dihedral angle between $S_1$ and $S_2$ varying continuously around the fold (Ramsay, 1967) (Fig. 8-30c).

**Passive Folding of Obliquely Inclined Surfaces:** During passive folding the $S_1/S_2$ intersection lineation is folded (Fig. 8-31a) but still lies in a plane defined by its original orientation and the slip direction on the hypothetical shear planes. Thus, after folding, the intersection lineations lie on a great circle (Fig. 8-31b). Both $S_1$ and $S_2$ are folded into cylindrical folds with a common axis plane ($S_3$) parallel to the shear planes. The two folded surfaces have different fold axes ($S_1$ and $S_2$) determined by their lines of intersection with the shear planes (Fig. 8-31b, c). The dihedral angle between $S_1$ and $S_2$ generally varies across the fold (Ramsay, 1967) (Fig. 8-31c).

**$\alpha$-Diagram Analysis of Superposed Folds**

Supersposed folding refers to the overprint of a later generation of folds over an earlier one. Depending on their orientation, the later generation of folding can cause reorientation of the earlier folds. Typically, in areas of supersposed folding there are multiple generations of folds and multiple sets of foliations. Sometimes, each foliation set can be shown to be in an axial-planar orientation with respect to a particular generation of folds. In analyzing an area of supersposed folding, the first step is to recognize and define domains of plane cylindrical folding of any foliation. The foliation that is analyzed may be different in different domains. The earliest foliation possible is bedding and is usually labeled $S_0$. Successive later foliations are labeled $S_1$, $S_2$, $S_3$, etc. Next, we illustrate how an area of supersposed folding can be analyzed with the aid of an equal-area net. Additional examples are provided in Chapter 15.

**Problem 8.7**

The example shown in Figure 8.32 is taken from Turner and Weiss (1963). The map shows folded foliation ($S_1$). There are two kinds of axial traces: first, broken lines ($P_2$), which are folded; and second, solid lines ($P_3$), which do not show any constant folding. With the aid of an equal-area net, identify structural domains, and determine the generation of fold responsible for the orientation of foliation in each domain.

**Method 8.7**

**Step 1:** Divide the map into domains of plane cylindrical folding by choosing areas with straight axial traces. Plot poles to $S_1$ foliation within each domain on a separate equal-area plot. By trial and error, adjust domain boundaries so that the plot from each domain displays a single $\alpha$-axis; $\alpha$-axes for different domains will be different. The axial trace, determined from the map, and $\alpha$-axis permit calculation of the orientation of the axial plane for each domain.

**Step 2:** Group the domains based on orientation of the axial plane defined by $S_1$ foliation attitudes within the domain. In this example, we can do this by inspection: Domains I to VII have $S_3$ as the axial plane, while domains VIII to XIV have $S_2$ as the axial plane.

**Step 3:** Draw synoptic diagrams for each group of domains:

(a) For domains I to VII the fold axes (determined from $S_1$ poles) lie on a great circle and are almost coplanar to $S_1$ planes; (b) for domains VIII to XIV the axes (from $S_1$ poles) also lie on a great circle. The $S_2$ planes intersect to define an axis that lies on the same great circle as the axes from domains I to VII. Generally, in natural examples the older folds do not show such a regular pattern because of inhomogeneities that develop during refolding.
Chapter 8  Equal-Area Projections and Structural Analysis

Step 4: If \( S_2 \) and \( S_3 \) cannot be distinguished by inspection, then we can attempt to group the domains either by trial and error or by using minor structures (foliations, axial-plane lineations) to establish age relationships among structures. The latter is usually more fruitful, especially any macroscopic analysis of complex folding is unsatisfactory without the information provided by relationships among various minor structures, and among minor and major structures.

EXERCISES

1. The following series of attitude measurements were obtained from the limbs of a fold:
   
   \[
   \begin{align*}
   &106^\circ, 36^\circ, 56^\circ, 216^\circ, 60^\circ, 90^\circ, 126^\circ, 210^\circ, 15^\circ \\
   &150^\circ, 45^\circ, 50^\circ, 210^\circ, 60^\circ, 90^\circ, 126^\circ, 210^\circ, 15^\circ \\
   &070^\circ, 40^\circ, 50^\circ, 210^\circ, 60^\circ, 90^\circ, 126^\circ, 210^\circ, 15^\circ
   \end{align*}
   \]

   (a) Plot a \( \beta \)-diagram using these data.
   (b) Plot a \( \alpha \)-diagram using these data.
   (c) Describe the structural significance of the \( \beta \)-axis, the \( \alpha \)-axis, and the circle girdle. Give the orientation of each. Which diagram (\( \alpha \) or \( \beta \)) is easier for you to interpret?

2. A geologist measured a prominent mineral lineation on foliation surfaces of the Highwater Gneiss exposed on a horizontal pediment near Tarantula Gulch, Arizona. A simplified version of the map of this area is presented as Figure 8-M1. The geologist measured the pitch of the lineations. This problem emphasizes the fact that geometric calculations can readily be done with an equal-area net.

   (a) Complete the following table.

<table>
<thead>
<tr>
<th>Attitude of Foliation</th>
<th>Rate of Lineation</th>
<th>Plunge and bearing of lineation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A N35ºE,30ºSE</td>
<td>42ºSW</td>
<td></td>
</tr>
<tr>
<td>B N55ºE,40ºE</td>
<td>11ºN</td>
<td></td>
</tr>
<tr>
<td>C N25ºW,60ºNE</td>
<td>08ºNW</td>
<td></td>
</tr>
<tr>
<td>D N55ºW,70ºSW</td>
<td>27ºNE</td>
<td></td>
</tr>
<tr>
<td>E N85ºW,40ºE</td>
<td>75ºE</td>
<td></td>
</tr>
</tbody>
</table>

   Figure 8-M1. Map of the Tarantula Gulch area for exercise 2.
(b) Using appropriate structural symbols, complete Figure 8-M1 by plotting the foliation and lineation attitudes at the appropriate stations. Indicate the axial trace of the fold.
(c) Calculate the attitude of the fold axis, and using your mapped axial trace, calculate the attitude of the fold-axis plane.
(d) Calculate the angle between lineation and the fold axis at each station.
Based on the results of this calculation, do you think the fold at Taramula Gully formed by a flexural-slip mechanism or a passive mechanism?

3. Below are attitudes of poles to bedding planes measured around a fold. From these measurements determine whether the fold is cylindrical or conical.

<table>
<thead>
<tr>
<th>Pole Attitude</th>
<th>Fold Attitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°N110°E</td>
<td>38°N025°W</td>
</tr>
<tr>
<td>47°N165°W</td>
<td>50°N45°W</td>
</tr>
<tr>
<td>37°N75°W</td>
<td>24°N525°W</td>
</tr>
</tbody>
</table>

\[ \text{Figure 8-M2. Equal-area plots of structural data from a fold-thrust belt for exercise 4. (a) Poles to bedding; (b) poles to cleavage; (c) poles to small strike-slip faults.} \]

4. Figure 8-M2 provides several equal-area plots of structural data collected in a fold-thrust belt. If you wish, you may reduce a Schmidt net to the appropriate size to determine carefully the attitudes of the structures shown, but you should be able to estimate the attitudes of structures from the equal-area plots.
(a) Estimate the attitudes of the structures shown in each plot.
(b) Describe the contour pattern (e.g., a girdle, a point concentration).
(c) With the results of part a, construct a synoptic diagram of the data.
(d) Write a brief interpretation of the structures in the area.

5. The scatter plots of Figure 8-M3 show the attitudes of two types of cleavage that were measured on an upright syncline with a horizontal hinge. Cleavage A is a siltly cleavage found in beds of fine-grained slate. Cleavage B is a spaced cleavage found in beds of slightly micaceous quartzite.
(a) Describe the differences between the two plots.
(b) Which cleavage is more likely to represent the axial-plane attitude of the fold?
(c) If you are familiar with the process of cleavage formation, explain why the two plots are so different from one another.

\[ \text{Figure 8-M3. Equal-area plots of structural data from a syncline. (a) Poles to silt cleavage set A; (b) poles to spaced cleavage set B.} \]

6. Figure 8-M4a shows a contoured equal-area plot of poles to foliation in a Precambrian augen gneiss that occurs in the Buckskin Mountains "metamorphic core complex" of Arizona. The plot was contoured by the Schmidt method, and the contours are at 2%-4%-6%-8% per 1% area. The area within the 8% contour is blackened. Figure 8-M4b shows a contoured equal-area plot of lineations in shear zones that cut the foliation of the mylonites. Interpret these plots by answering the following questions.
(a) Is the augen-gneiss foliation folded, and if so what is the approximate attitude of the axes associated with the folds?