***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, r 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.

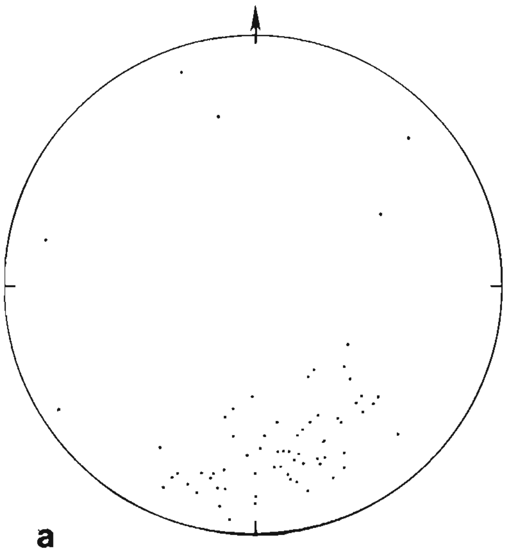
***Step 3:*** Follow the same method as in Schmidt contouring to obtain concentrations at the grid points (Fig. 8-12b).

***Step 4:*** Using Equation 8-6, calculate a value for $\sigma$ (1.57). Contour the concentrations at $2\sigma$, $4\sigma$, $6\sigma$, and $8\sigma$ (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 Vistelius (1966).

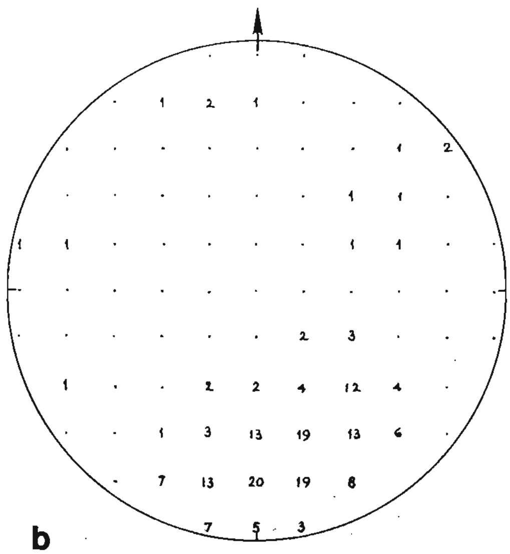
## 8-4 PATTERNS OF POINT DATA ON EQUAL-AREA PROJECTIONS

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

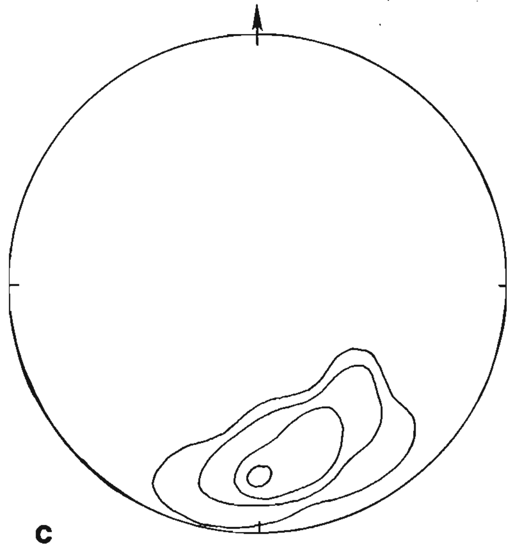


a

72 poles to foliation



b



c

Contours at $2\sigma$, $4\sigma$, $6\sigma$ and $8\sigma$

**Figure 8-12.** The Kamb method of contouring described in Problem 8-4, for the same data as Problem 8-1. Contours drawn at $2\sigma$, $4\sigma$, $6\sigma$, and $8\sigma$.

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 poles to planar elements indicates that the planes could all intersect along the same line. For example, a girdle pattern is obtained by plotting poles 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

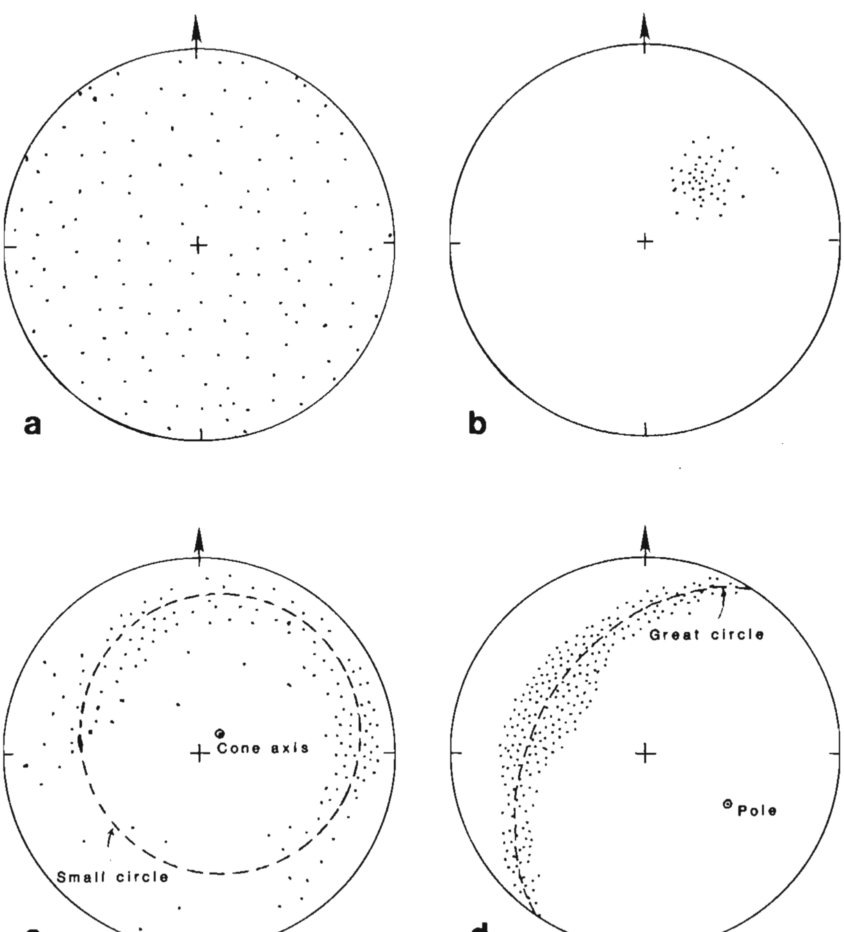



**Figure 8-13.** Patterns of point data on an equal-area projection. (a) Uniform distribution; (b) point maximum; (c) great-circle girdle; (d) small-circle girdle.

described as orthorhombic or monoclinic, depending on the pattern of clusters 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) *Cylindrical folds* 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) *Noncylindrical folds* 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 nonsystematic, 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 ß-diagrams or π-diagrams on an equal-area projection.

### ß-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 ß-axis. For n plotted planar attitudes (Fig. 8-14), the number of intersections (x) is given by the arithmetic progression

$$x = 0 + 1 + 2 + \ldots + (n - 1) = n(n - 1)/2 \quad \text{(Eq. 8-9)}.$$

Thus, if there are 200 plotted planes, the number of intersections is 19,900. Contouring of the intersection

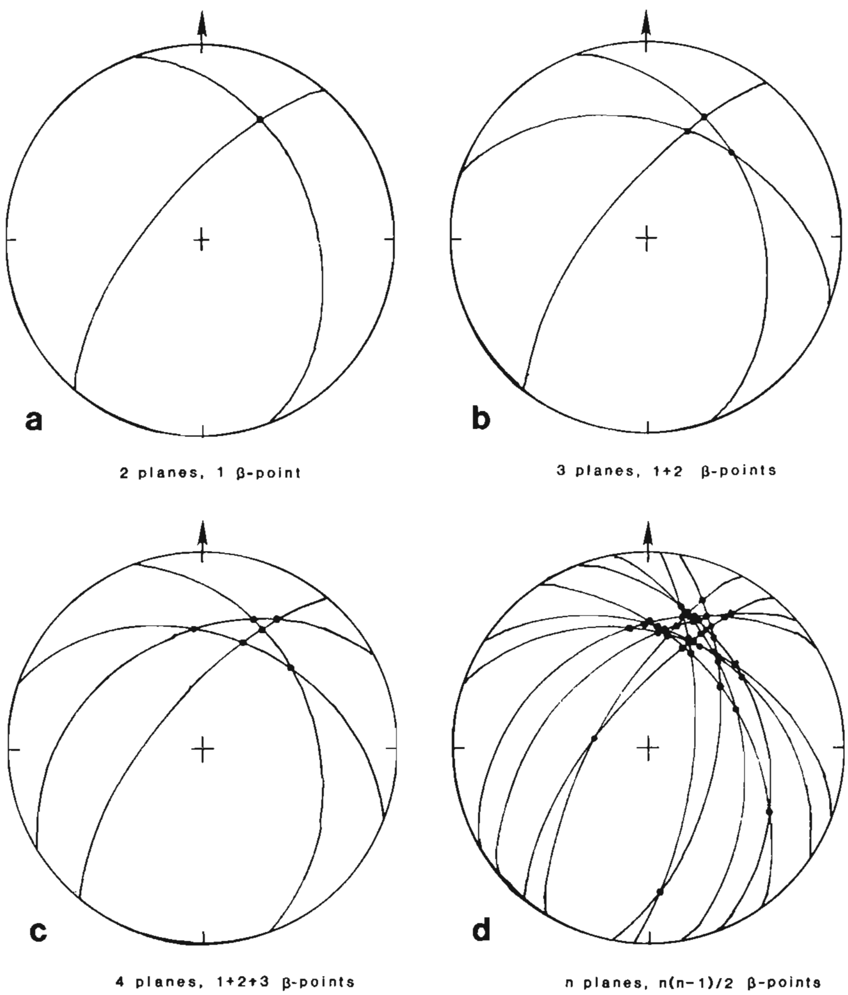



**Figure 8-14.** β-diagram of cylindrical fold. The number of intersections of great circles increases rapidly as the number of plotted planes increases. (Adapted from Ramsay, 1967.)

points will emphasize the maximum concentration of intersections.

A plot of ß-axes is *not* generally the best way to represent attitude measurements on a fold, for several reasons. First, the number of points on a ß-axis plot is far greater than the actual number of measurements; thus, such a plot may make you think you have more data than you actually have. Second, if there is any scatter in the original data, there can be concentrations of ß-axes away from the main concentration, leading to an erroneous interpretation. Such errors become unacceptably large if the interlimb angle is very small (<40°), as in tight folds, or very large (>140°), as in open folds. Finally, construction of a ß-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.

## π-Diagrams of Cylindrical Folds

Because of the disadvantages of the ß-axis diagram, a *π-diagram* is the preferred method for representing measurements from a folded surface. A π-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 *π-circle* (Fig. 8-15). The pole to the π-circle is the π-axis (Fig. 8-15), and it represents the fold axis. The π-axis should coincide with the ß-axis on a plot. For a very open fold, with a very large interlimb angle, the π-diagram will

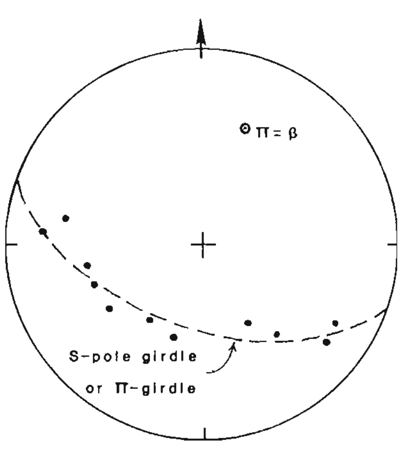



**Figure 8-15.** π–diagram of cylindrical fold. Poles to planes lie on a great circle girdle whose pole gives the fold axis (π = ß).

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-cricle girdle (Fig. 8-16; e.g., Ragan, 1985).

A π-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 points will be uniform within the π-circle girdle, and the two extreme points on the girdle will define the interlimb angle (Fig. 8-17a). The π-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 π-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 π-diagram, because factors other than dips in the two limbs of the folds determine fold symmetry (Hobbs, Means, and Williams, 1976; Ramsay, 1967). A concentration of points along a girdle may also be a consequence of sampling bias. However, if the spatial distribution of measurements 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 π-diagram (Fig. 8-17d). 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 π-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 π-circle girdle) is the same. The great circle passing through the bisector and π-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 π-circle girdle on an equal-area projection. For example, if the fold axis is horizontal, then the π-axis lies on the primitive and the girdle passes through the center of the net, but if the fold axis is plunging, then the π-axis lies inside the primitive, and the girdle follows a curve that does not pass through

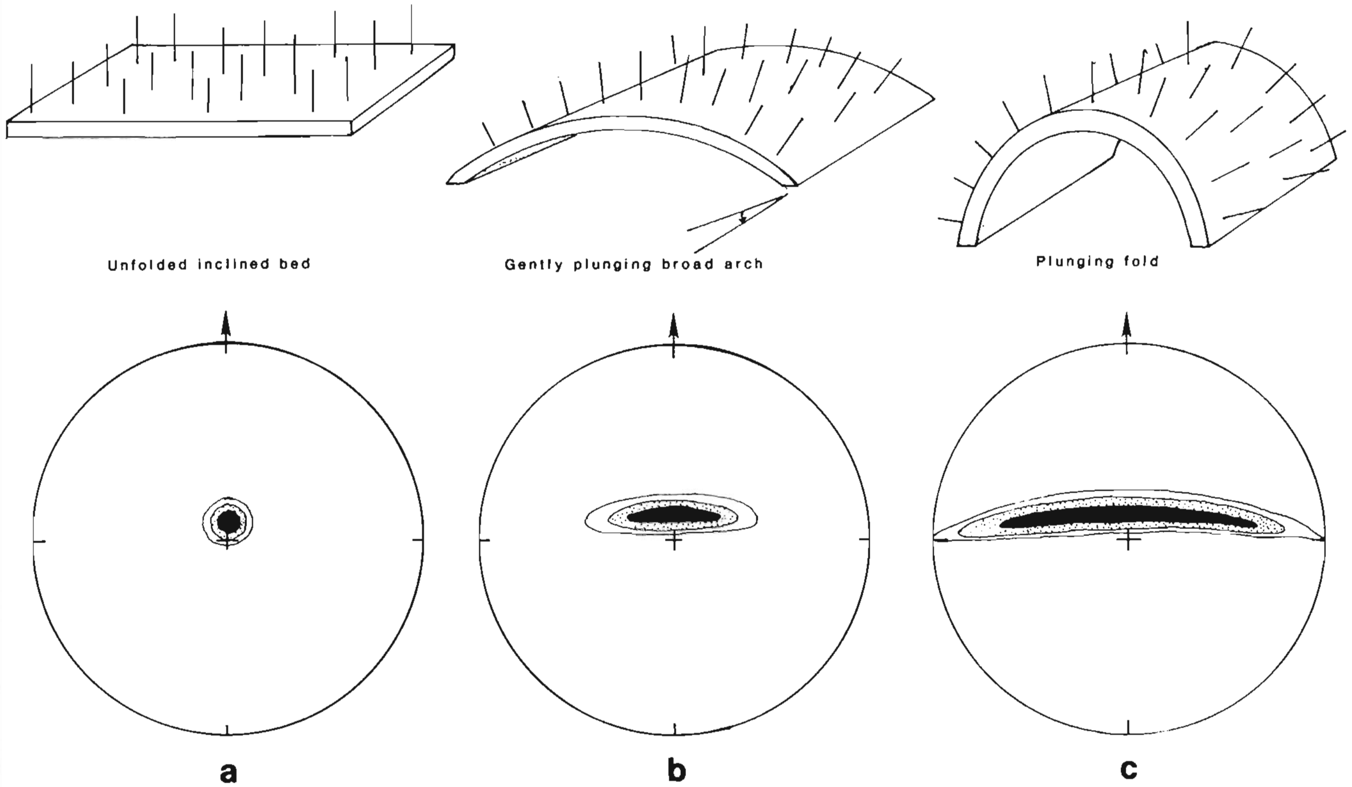



**Figure 8-16.** Change in pole pattern on the π-diagram with decrease in fold interlimb angle. (Adapted from Ragan, 1985.)

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 several examples of π-diagrams and the folds that they represent.

## π-Diagrams of Noncylindrical Folds

If the folded surface is conical, with the cone having an apical angle μ, each pole makes an angle of ($90^o$ - μ/2) with respect to the cone axis. In other words, the poles to bedding generate a coaxial cone with an apical angle of (180 - μ). 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 replot 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 π-diagram will generally give several possible orientations for the π-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 π-axis orientation. In *plane* noncylindrical folds the axial surface is planar and has a constant orientation, althought the orientation of the fold axis (π-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

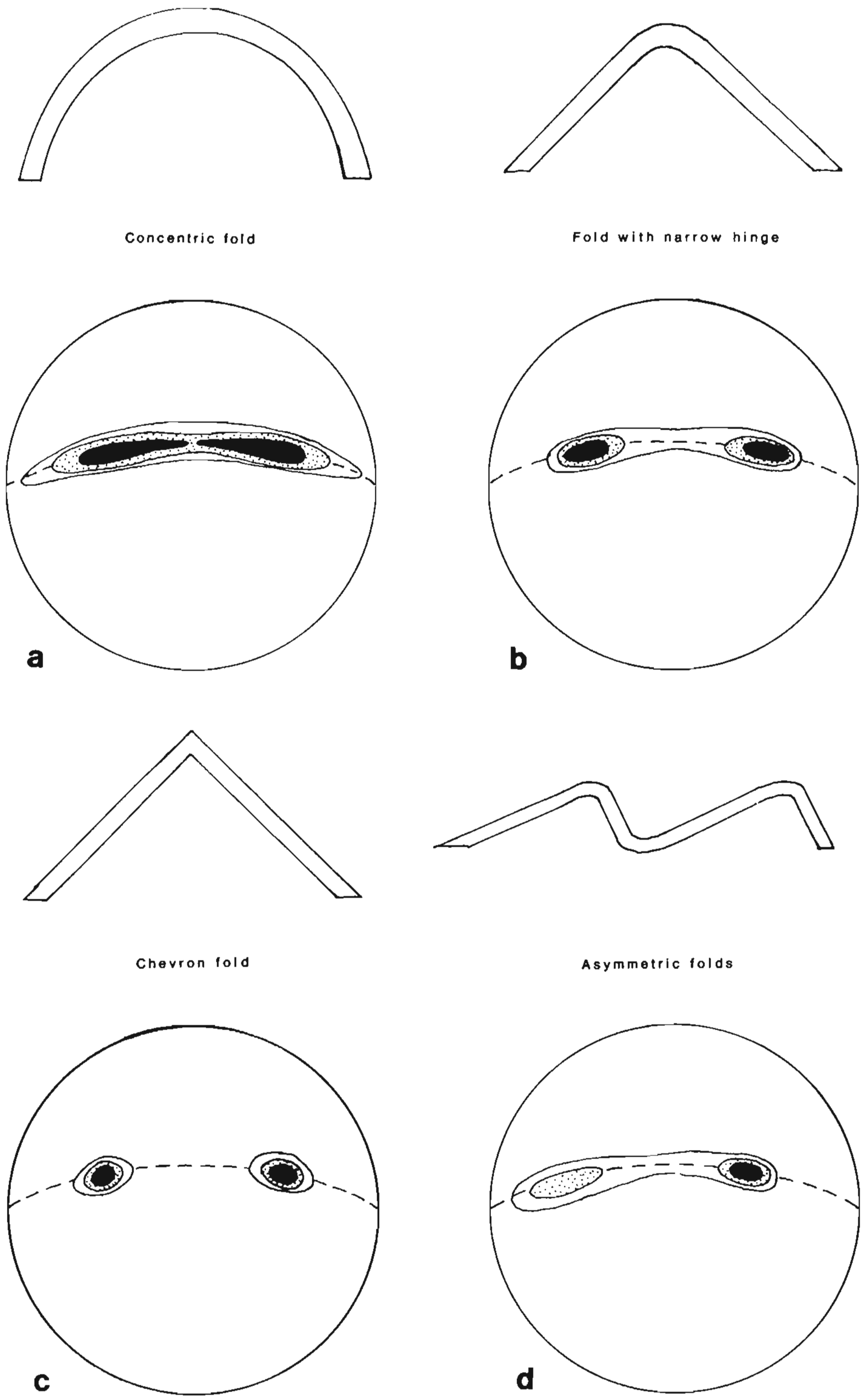



**Figure 8-17.** Variation in $\pi$–diagrams with change in fold form. (a) Fold with broad, rounded hinge; (b) fold with narrow hinge; (c) chevron fold; (d) asymmetric folds.

resulting from deformation are referred to as *tectonites*. Three major classes of tectonites are recognized, based on whether the fabric can be described as a foliation, a lineation, or both. (1) *S-tectonites* 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, 1963). (2) *L-tectonites* have a well-developed lineation but no foliation (Fig. 8-22b). The lineation in an L-tectonite is defined by alignment of prismatic minerals or uniaxially elongated grains parallel to

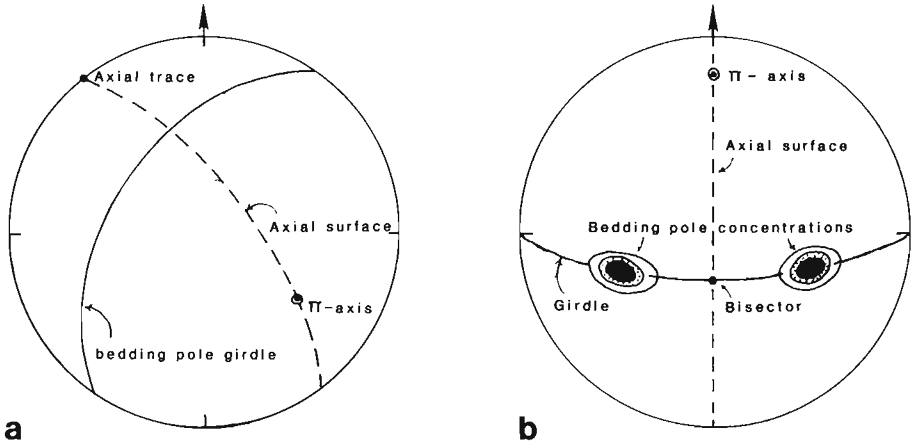



**Figure 8-18.** Determining attitude of fold-axial surface from a π-diagram.

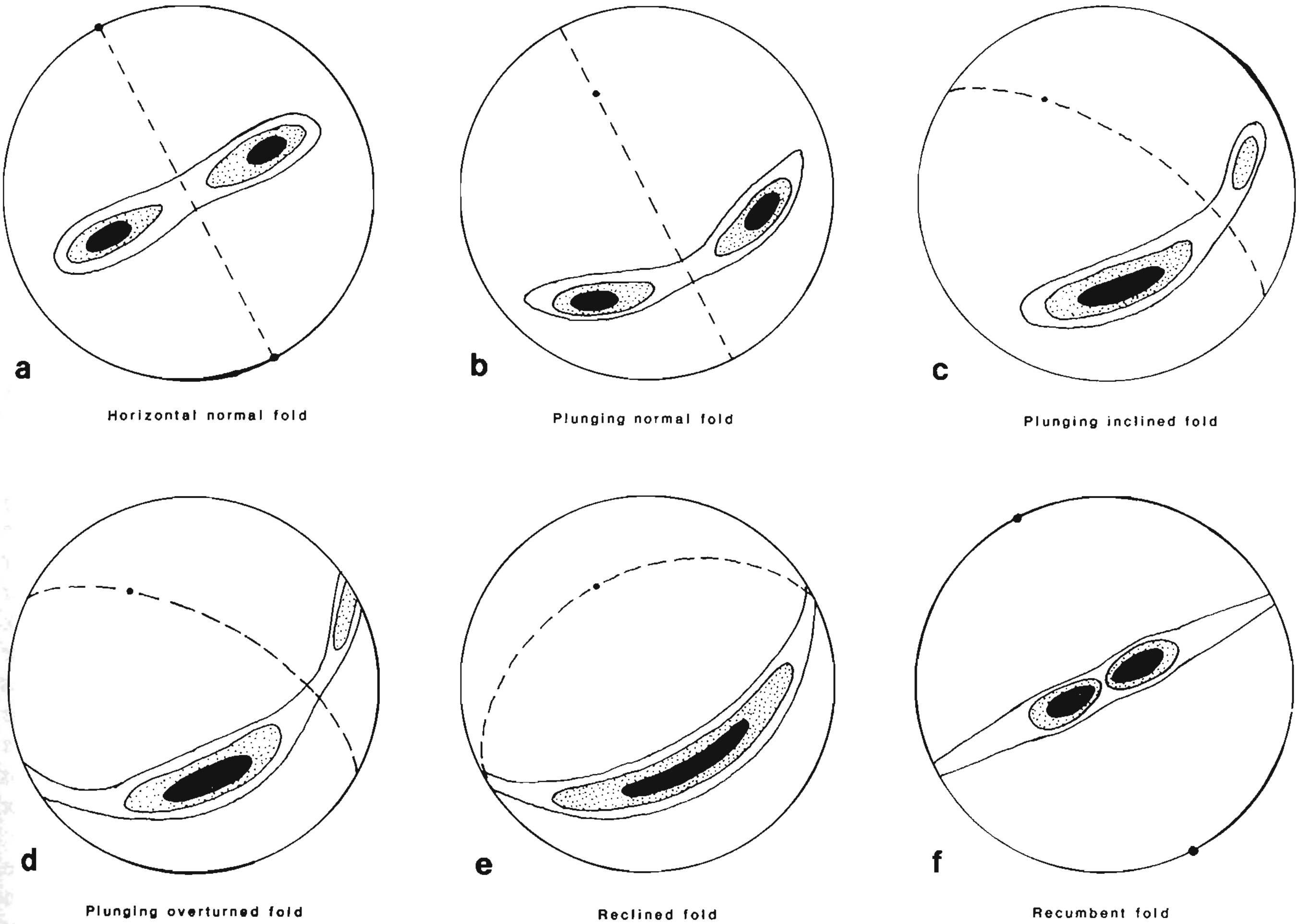



**Figure 8-19.** Variations in position of π-circle girdle with changes in attitude of the fold axis and axial plane. (a) Nonplunging upright (normal) fold; (b) plunging normal fold; (c) plunging inclined fold; (d) plunging overturned fold (note the presence of vertical beds indicated by the plotting of some bedding poles on the primitive); (e) reclined fold; (f) recumbent fold; axial plane coincides with the primitive. (See Fig. 11-17.)

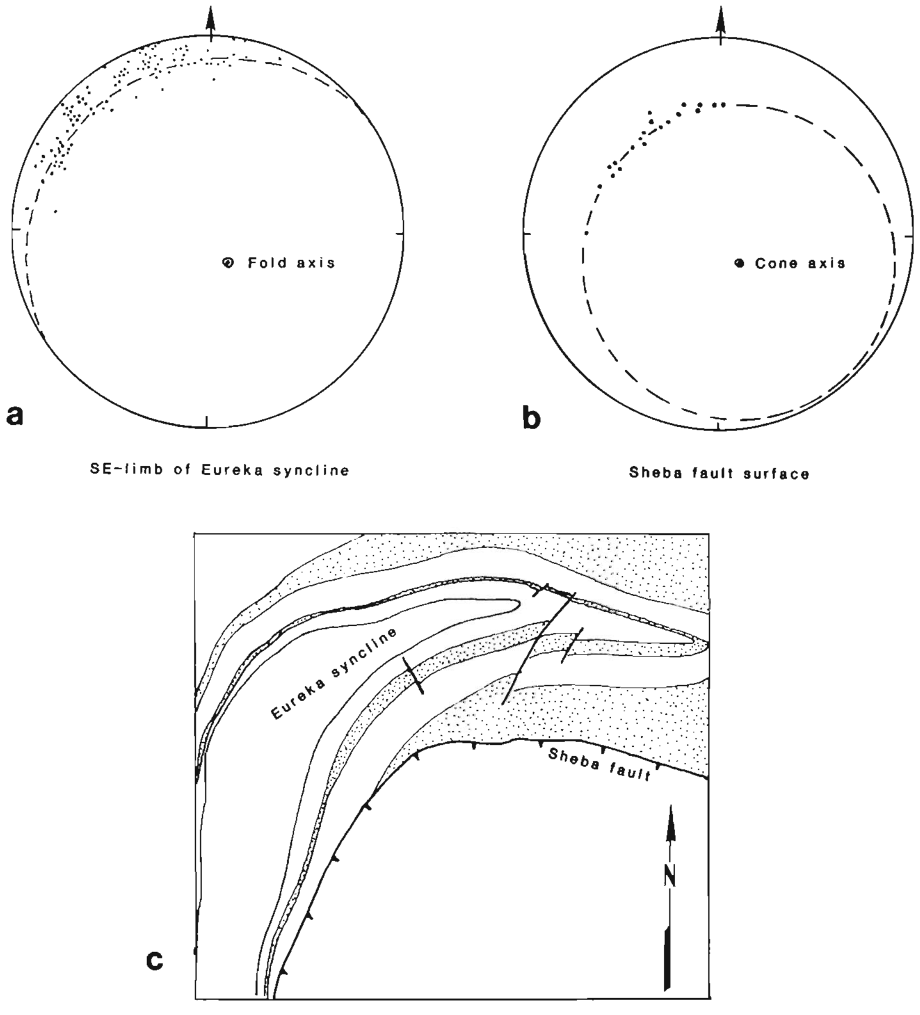



**Figure 8-20.** Flexural-slip folding of sedimentary rocks and a fault (at low angles to bedding). The southeast limb of the Eureka syncline shows cylindrical folding. The Sheba fault surface is conically folded. (Adapted from Ramsay, 1967.)

one another. (3) *L-S-tectonites* have both a foliation and a lineation (Fig. 8-22c). In an L-S-tectonite 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-tectonite 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 *homogeneous*, 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 homogeneous*, 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 *inhomogeneous*. 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 homogeneous 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 *isotropic*. 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-tectonites. 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

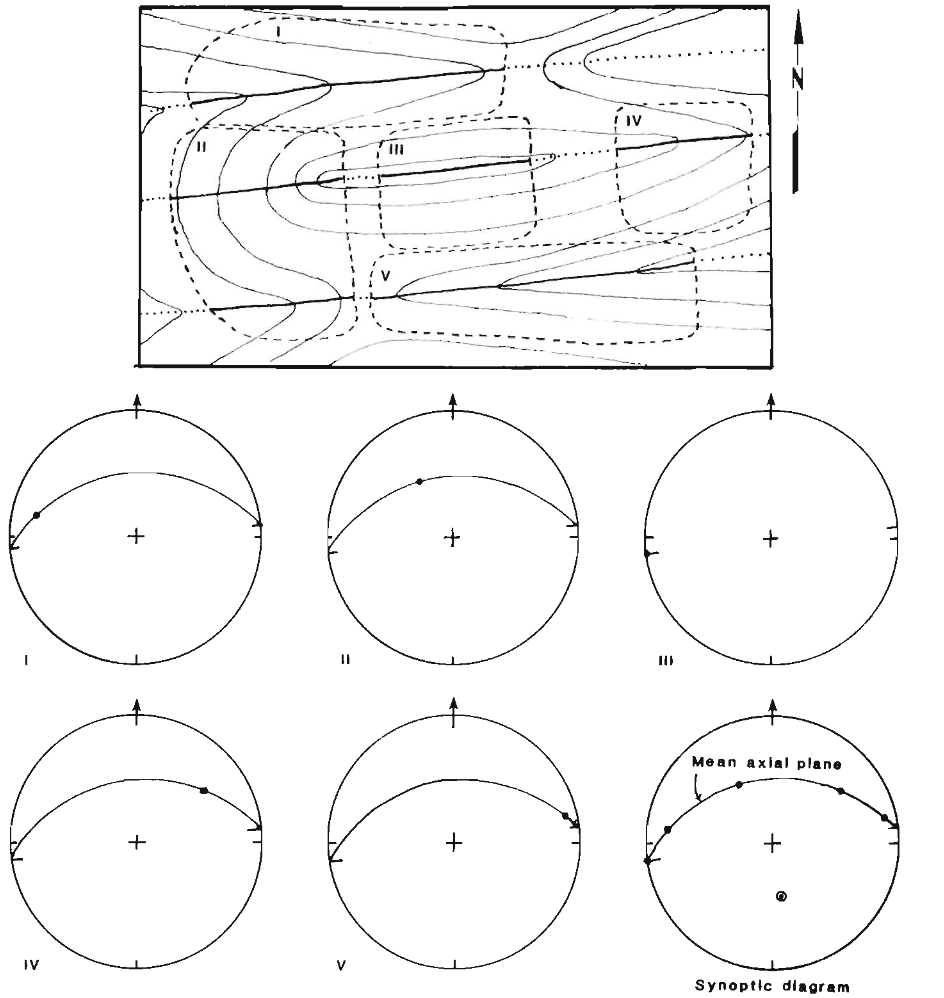



**Figure 8-21.** Plane noncylindrical folding. The area is subdivided into domains of cylindrical folding, each with its own fold axis, but all the fold axes lie on a common axial plane (as shown on the synoptic equal-area plot). (Adapted from Turner and Weiss, 1963.)

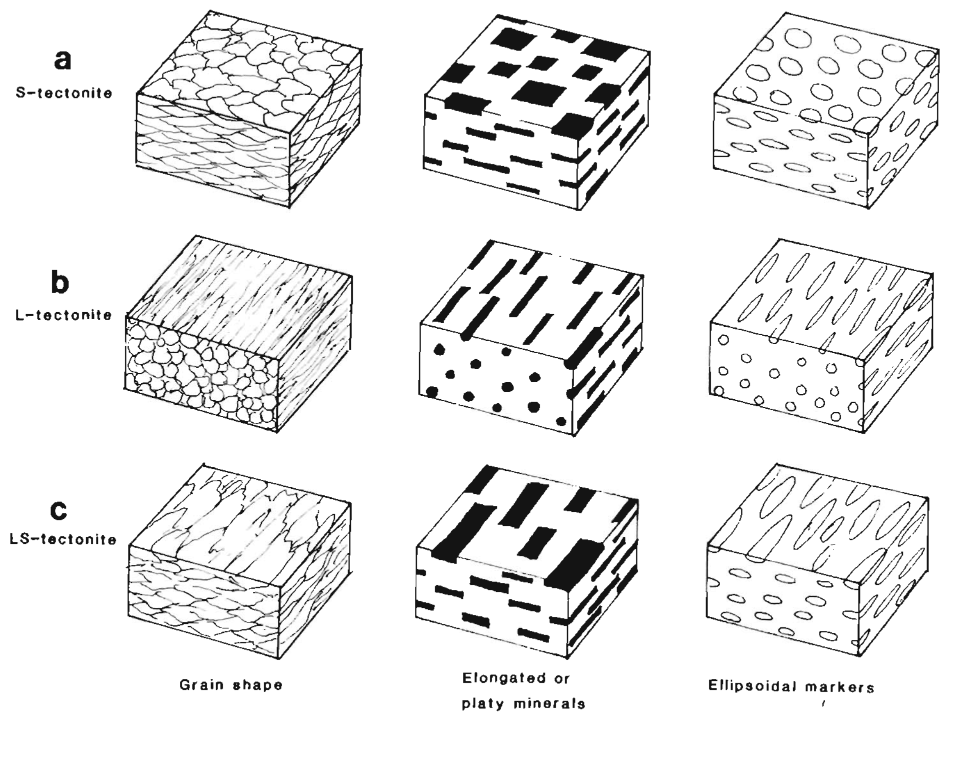



**Figure 8-22.** The penetrative fabric of a rock defined by overall grain shape, elongated or platy minerals, and ellipsoidal markers. Three different classes are defined. (a) S-tectonite; (b) L-tectonite; (c) LS-tectonite.

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:

| Attitude | Rake |
|---|---|
| N44°E,60°NW | 24°SW |
| S66°E,80°SW | 40°NW |
| S11°E,70°NE | 28°NW |

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,40°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

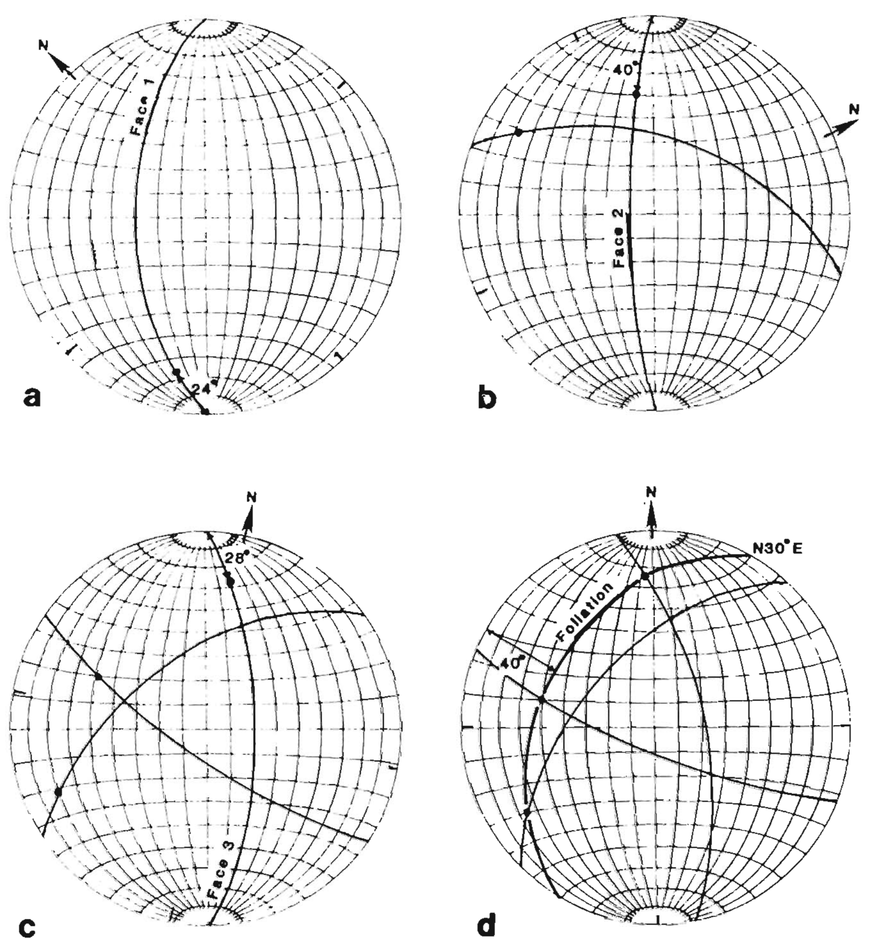



**Figure 8-23.** Procedure for determining orientation of a foliation described in Problem 8-6.

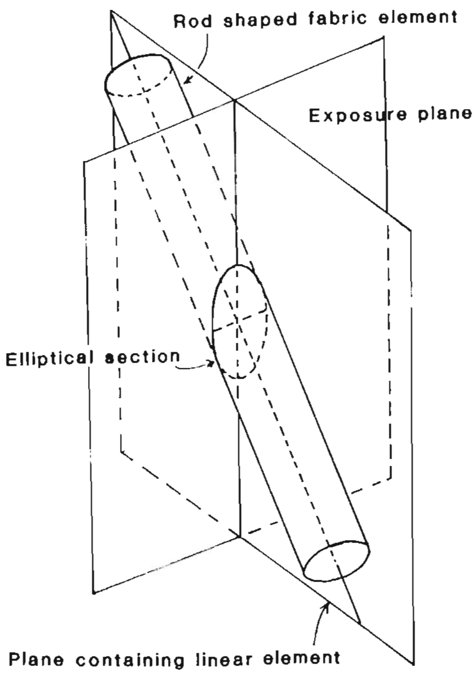



**Figure 8-24.** Apparent lineation on a planar surface obliquely intersecting a rod-shaped linear structure.

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:

| Orientation | Rake |
|---|---|
| S56°E,52°NW | 15°NW |
| N82°E,30°S | 84°W |
| N09°E,70°W | 22°S |

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).

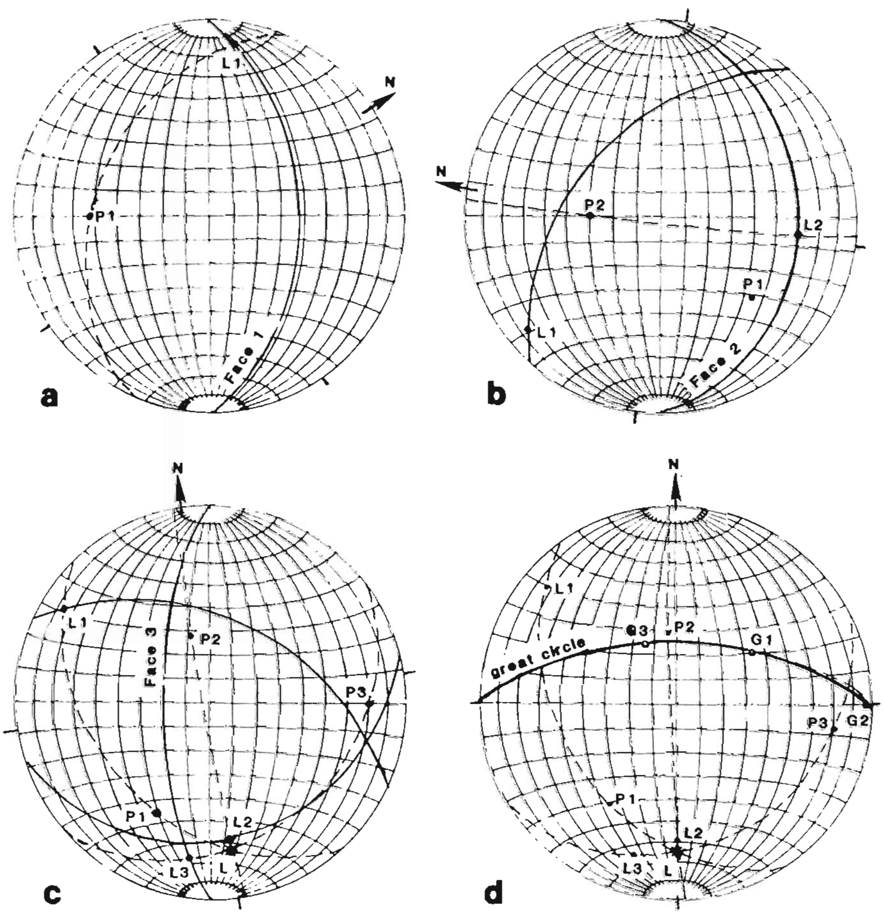



**Figure 8-25.** Procedure for determining orientation of a lineation described in Problem 8-7.

***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 24°,S2°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. 8-25d). Thus, the pole to this great circle gives the attitude of the lineation (Fig. 8-25d). 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 the fold. 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 formed coevally with $S_2$ is cut by a later planar foliation ($S_3$), the intersection lineation between $S_3$ and $S_1$ 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 $F_2$ fold axis varies as a function of $S_1$ 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 ($\mu$) between the fold axis and the preexisting lineation remains constant everywhere on the folded surface (Ramsay, 1967; Fig. 8-27a). On an equal-area projection, the points representing the lineation, therefore, lie on a

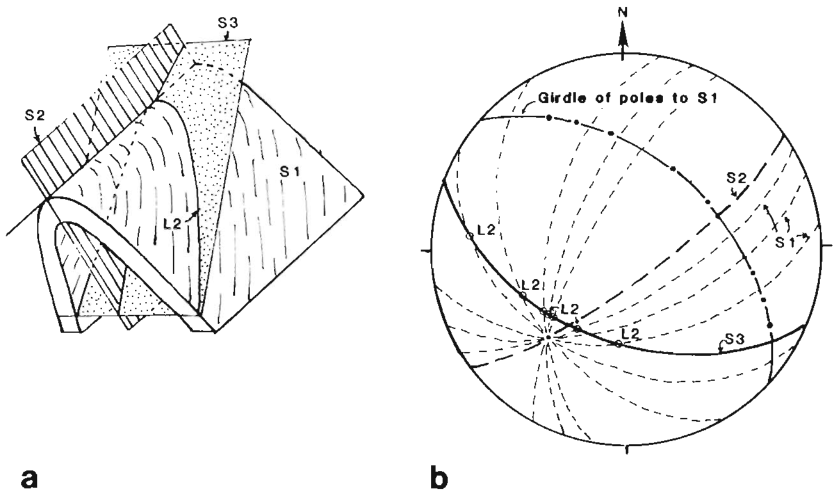



**Figure 8-26.** Intersection lineation produced by a later planar foliation ($S_3$) cutting an earlier folded foliation ($S_1$). (Adapted from Turner and Weiss, 1963.)

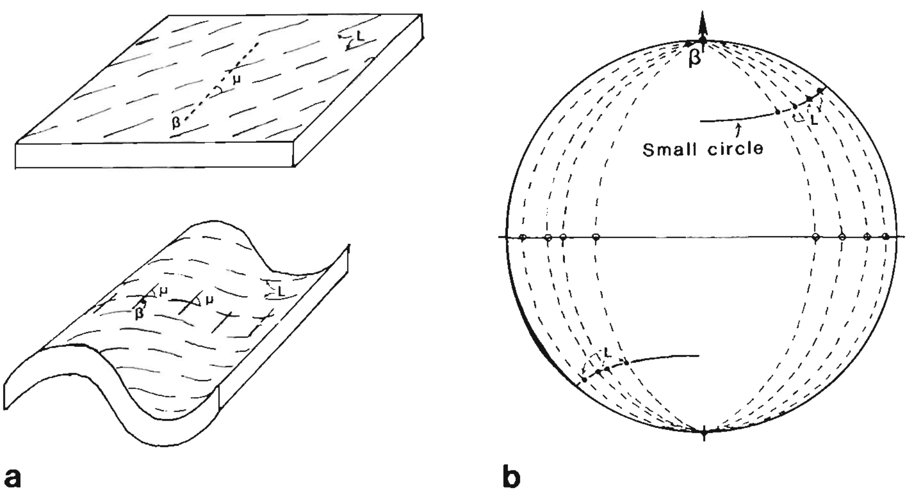



**Figure 8-27.** Flexural-slip folding of a preexisting lineation. Lineation points lie on a small circle centered on the fold axis. Lineation that was perpendicular to the fold axis (open circles on equal-area plot) lies on a great circle after folding. (Adapted from Ramsay, 1967.)

small circle centered on the fold axis (β) (Fig. 8-27b), unless the original lineation is perpendicular to the fold axis in which case the folded lineation lies on a great circle (Fig. 8-27b). Remember that the rotation of a line around an axis inscribes a small circle (see Chapter 7).

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

***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 transported variable distances along parallel lines (in 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

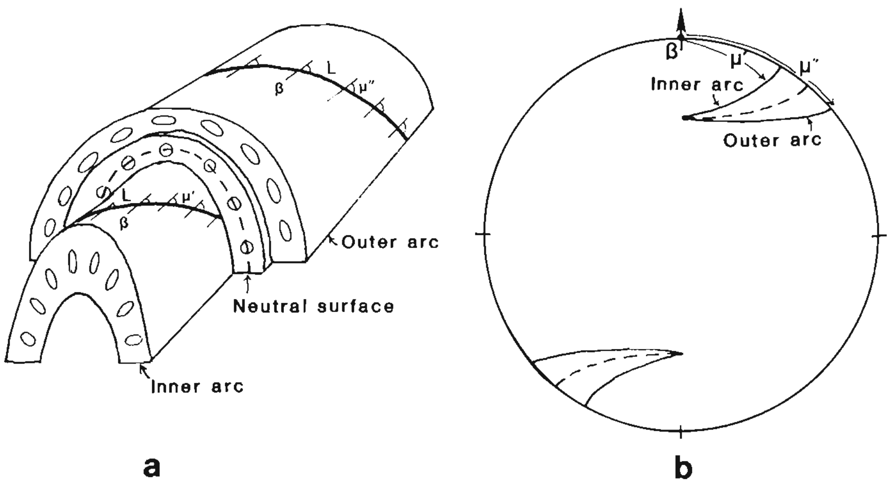



**Figure 8-28.** Effect of buckling of individual layers during flexural-slip folding. The small-circle arc pattern of lineations is modified in the outer and inner arcs of the fold. (Adapted from Ramsay, 1967.)

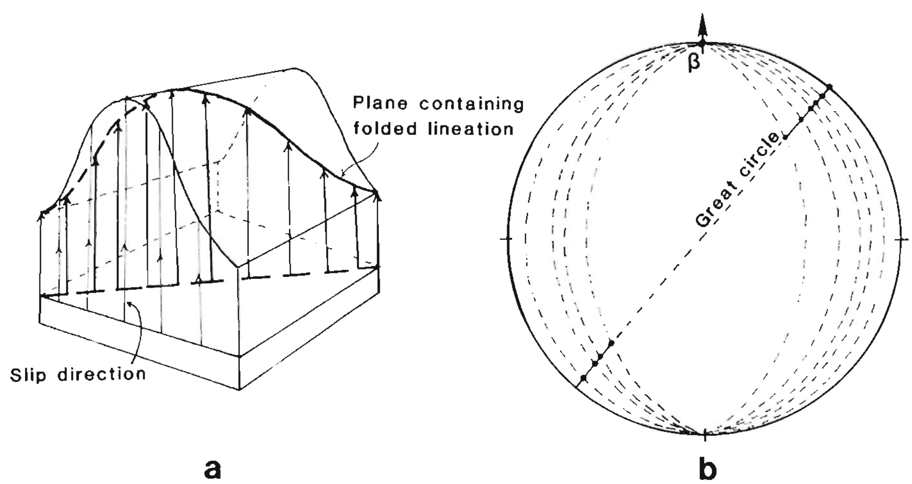



**Figure 8-29.** Passive folding of a lineation. Lineation points lie on a great circle oblique to the fold axis. (Adapted from Ramsay, 1967.)

longitudinal layer-parallel strain accompanying folding. Details of these various possibilities are discussed in Turner and Weiss (1963) 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 master 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 ($S_2$) 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 axial plane ($S_3$) parallel to the shear planes. The two folded surfaces have different fold axes (ß1 and ß2) 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).

## π-Diagram Analysis of Superposed Folds

*Superposed 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

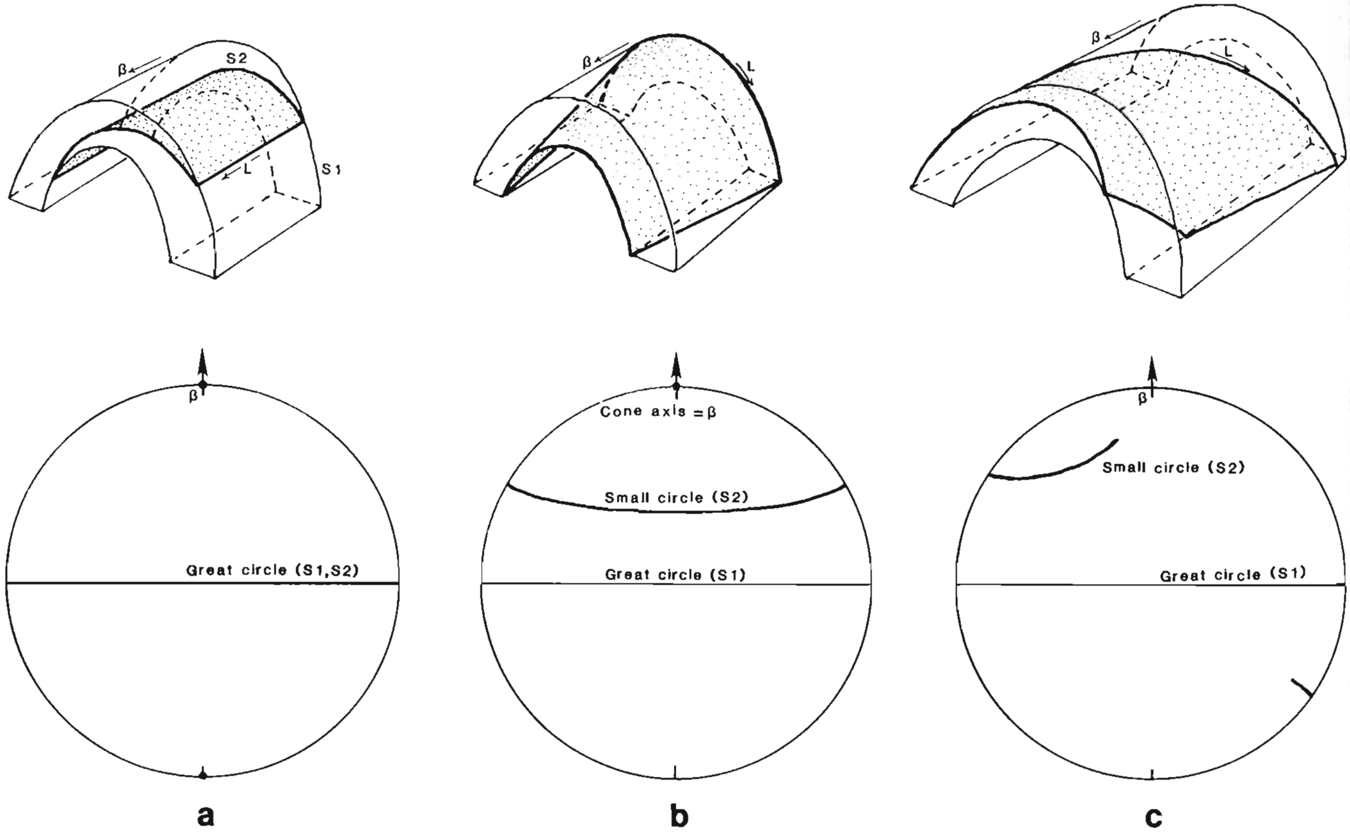



**Figure 8-30.** Flexural-slip folding of obliquely inclined surfaces. (a) $S_1/S_2$ intersection lineation parallel to the fold axis; (b) $S_1/S_2$ intersection lineation perpendicular to the fold axis; (c) $S_1/S_2$ intersection lineation oblique to the fold axis. (Adapted from Ramsay, 1967.)

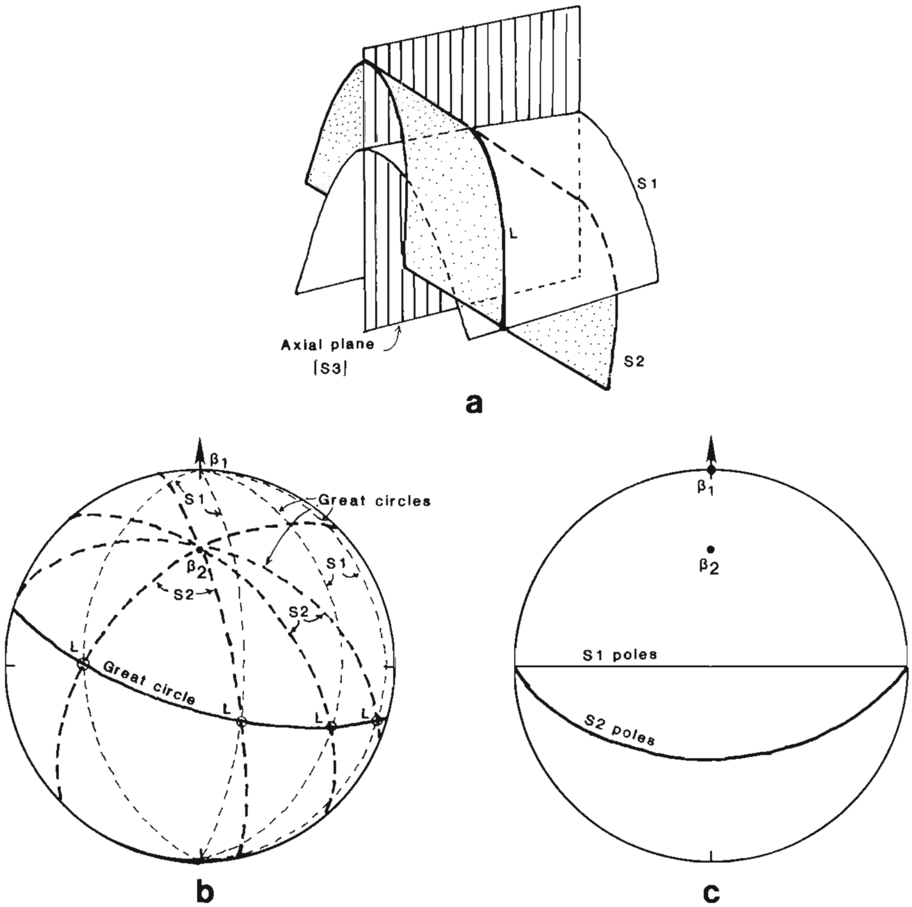



**Figure 8-31.** Passive folding of obliquely inclined surfaces. $S_1/S_2$ intersection lineation is folded but lies on a plane (great circle) after folding.

reorientation of the earlier folds. Typically, in areas of superposed 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 superposed 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 $S_1, S_2, \ldots$, etc. Next, we illustrate how an area of superposed 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 ($F_2$), which are folded; and second, solid lines ($F_3$), which do not show any consistent folding. With the aid of an equal-area net, analyze the structures shown in the map of Figure 8-32. 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 $\pi$-axis; $\pi$-axes for different domains will be different. The axial trace, determined from the map, and $\pi$-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 $S_3$ 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.

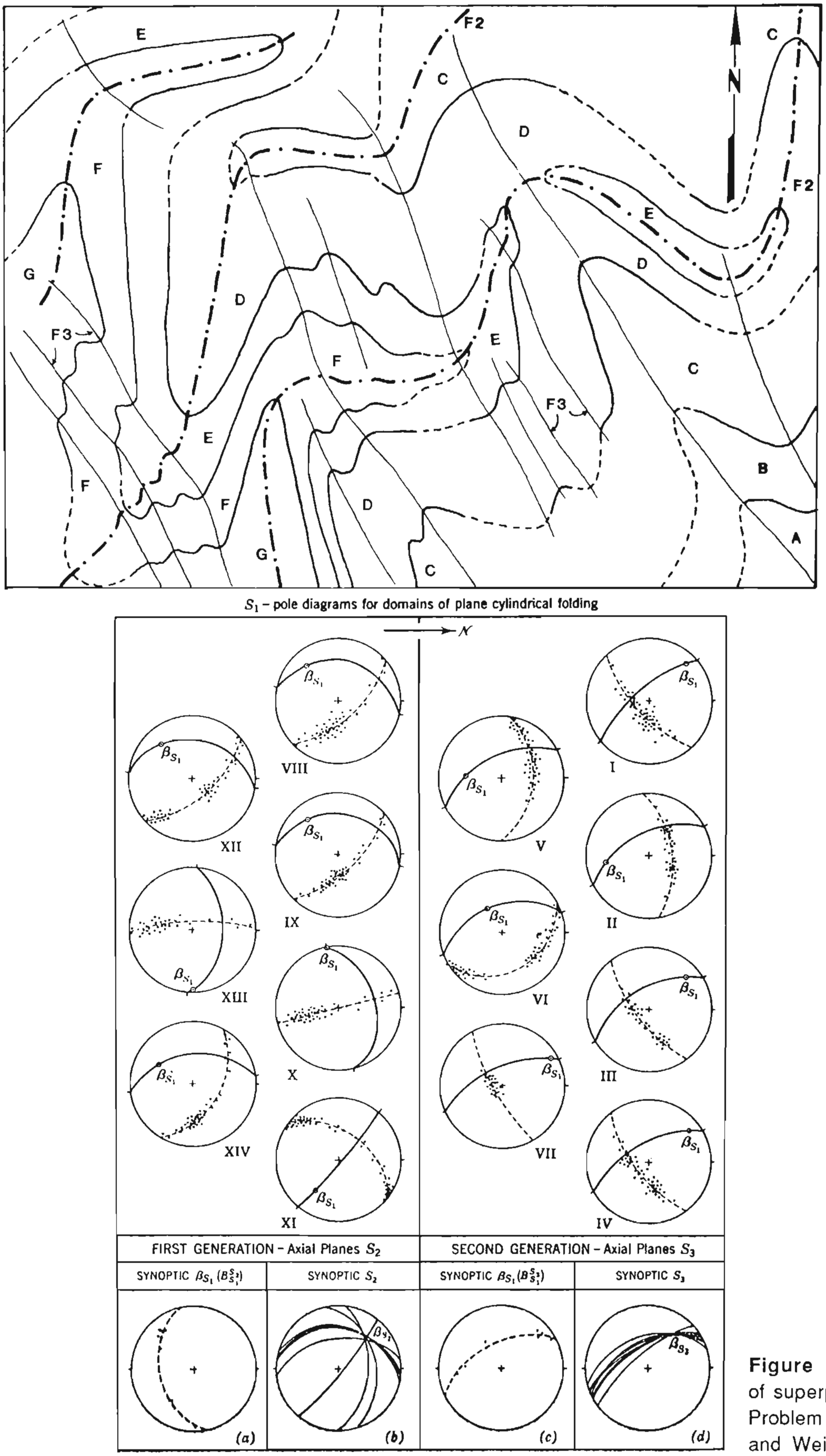



**Figure 8-32.** $\pi$-diagram analysis of superposed folding described in Problem 8-5. (Adapted from Turner and Weiss, 1963.)

***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 (folds, axial-plane foliations, intersection lineations) to establish age relationships among structures. The latter is usually the more fruitful approach, since 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:

| | |
|---|---|
| 106°,36°SW | N40°E,60°SE |
| 150°,45°SW | S03°E,65°SW |
| 079°,40°SE | N53°E,50°SE |

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

2. A geologist measured a prominent mineral lineation on foliation surfaces of the Hightower 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.

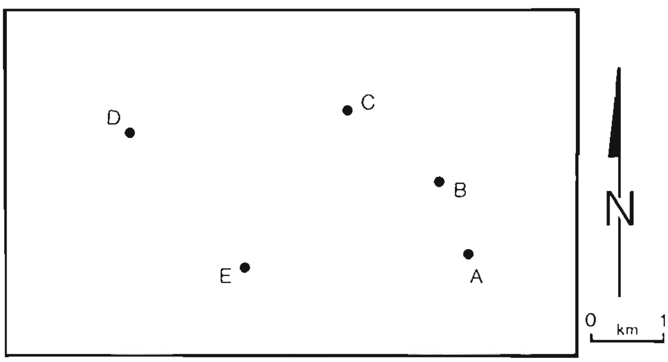



**Figure 8-M1.** Map of the Tarantula Gulch area for exercise 2.

(a) Complete the following table.

| Attitude of foliation | Rake of lineation | Plunge and bearing of lineation |
|---|---|---|
| A N37°E,30°SE | 42°SW | |
| B N-S,40°E | 11°S | |
| C N23°W,60°NE | 04°NW | |
| D N55°W,70°SW | 27°SE | |
| E N85°W,40°S | 75°E | |