7

Stereographic Analysis of Folded Rocks

OBJECTIVES

Construct beta diagrams and pi diagrams of folds

Construct and interpret a contoured equal-area diagram of structural data

In situations where the structures are very large-scale or are not well exposed, it may be impossible to analyze folds using the techniques discussed in Chapter 6. By stereographic projection, data from isolated outcrops may be combined to characterize the fold geometry. Stereographic analysis of the folded Paleogene rocks of the Bree Creek Quadrangle will serve as the major exercise in this chapter.

While the techniques described in this chapter will be applied specifically to the analysis of folds, stereographic analysis is also commonly used to study structures such as joints, faults, and cleavages at many scales.

Beta diagrams

A simple method for determining the orientation of the axis of a cylindrical fold is to construct a beta diagram (or β-diagram). Any two planes tangent to a folded surface intersect in a line that is parallel to the fold axis (Fig. 7.1). Such a line is called a β-axis. A β-axis is found by plotting attitudes of foliations (such as bedding or cleavage) on an equal-area net; the β-axis is the intersection point of the planes.

Suppose, for example, that the following four foliation attitudes are measured at different places on a folded surface: N82W, 40S; N10E, 70E; N34W, 60SW; N50E, 44SE. These attitudes are shown plotted on an equal-area net in Fig. 7.2. The β-axis, and therefore the fold axis, plunges 39, S7E.

Few folds are perfectly cylindrical, and usually the great circles will not intersect perfectly. If data from areas with different folding histories are plotted together, different β-axes will appear.

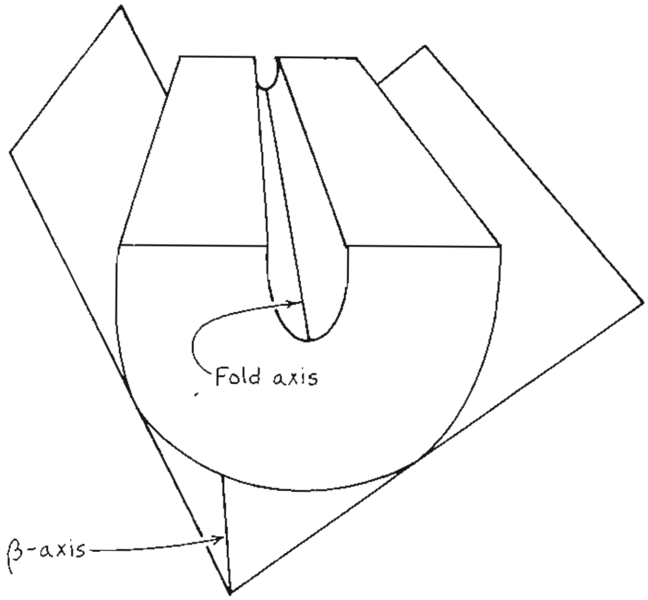

Fig. 7.1 Beta axis is the intersection of planes tangent to a folded surface.

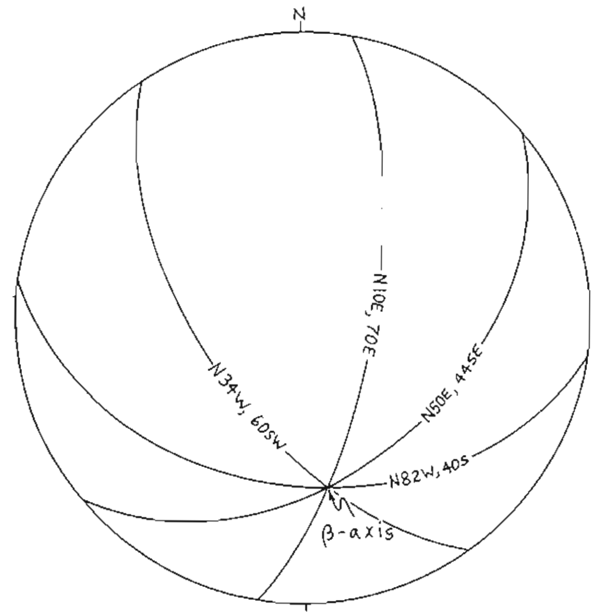

Fig. 7.2 Beta diagram. Great circles representing four foliation attitudes of a cylindrical fold intersect at the β-axis.

Pi (π) diagrams

A less tedious method of plotting large numbers of attitudes is to plot the poles (called s-poles) of a folded surface (s-surface) on an equal-area net. In a cylindrical fold these s-poles will lie on one great circle, called the pi circle (π-circle). The pole to the π-circle is the π-axis, which like the β-axis is parallel to the fold axis. Figure 7.3 shows the same four attitudes that were plotted on the β-diagram in Fig. 7.2, and the corresponding π-circle and π-axis. In most cases π-diagrams are more revealing, as well as more quickly constructed, than β-diagrams.

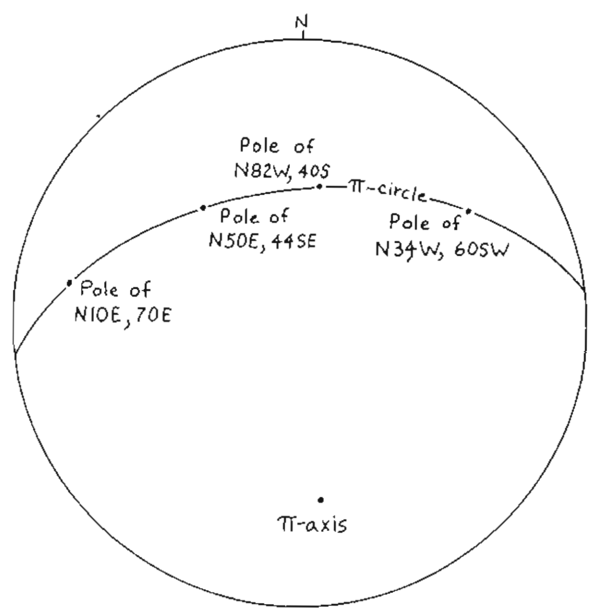

Fig. 7.3 Pi diagram. Pi circle is the great circle common to four poles of foliations of a cylindrical fold.

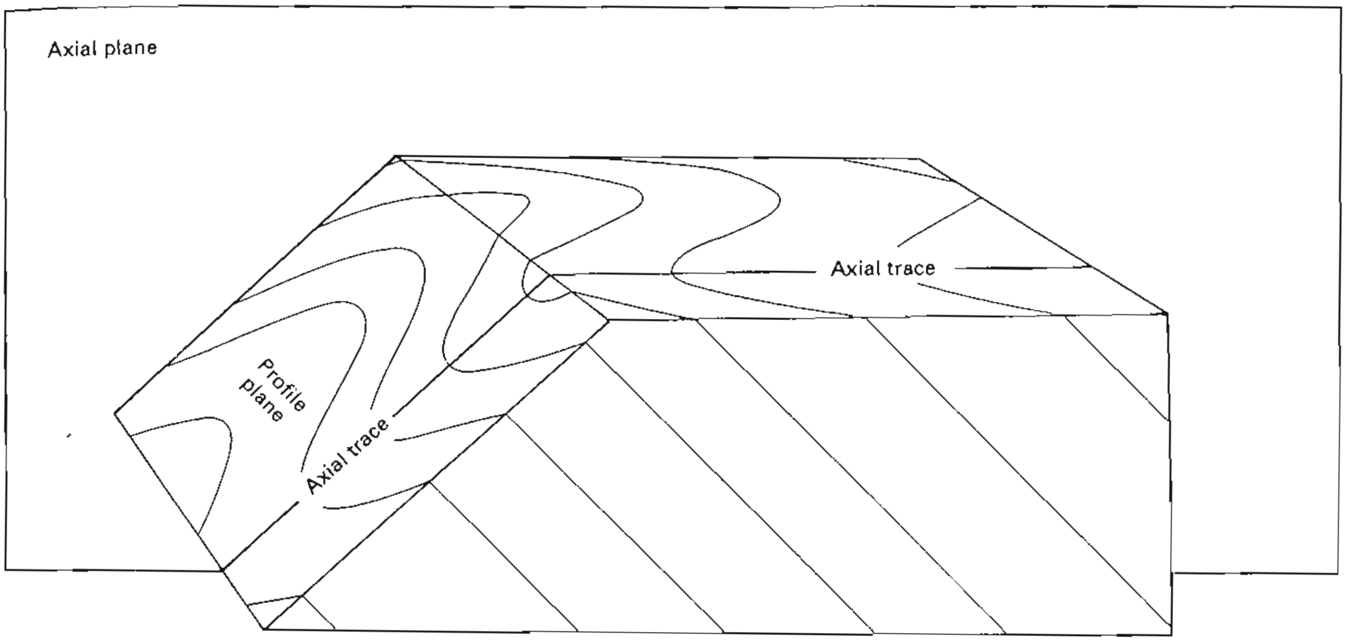

Fig. 7.4 Block diagram of folds showing profile plane and axial plane.

Determining the orientation of the axial plane

The orientation of a fold is defined not only by the trend and plunge of the fold axis, but also by the attitude of the axial plane. The axial plane can be thought of as a set of coplanar lines, one of which is the hinge line and another the surface axial trace (Fig. 7.4). If the axial trace can be located on a geologic map, and if the trend and plunge of the hinge line can be determined, then the orientation of the axial plane can easily be determined stereographically: it is the great circle that passes through the π-axis (or β-axis) and the two points on the primitive circle that represent the surface axial trace (Fig. 7.5).

Often the surface axial trace cannot be reliably located on a geologic map. If the folds are well exposed, then a profile view can be constructed (as explained in the next section), and the axial trace can be located in the profile plane and transferred to the geologic map.

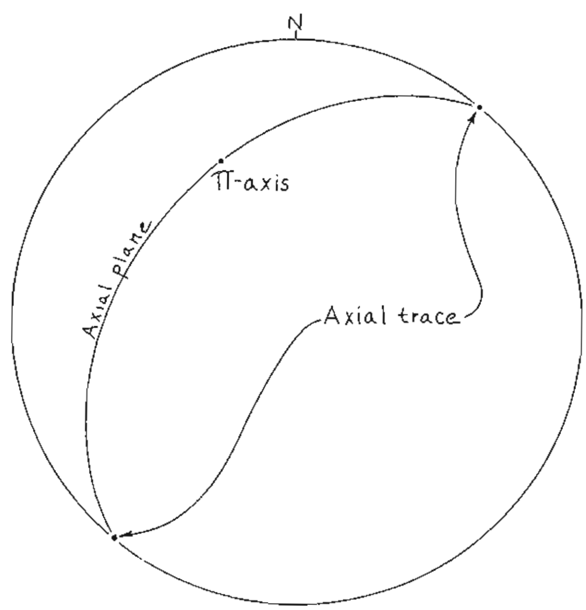

Fig. 7.5 Equal-area net plot. The axial plane is the great circle common to the π-axis and the two points on the primitive circle that represent the axial trace.

Constructing the profile of a fold exposed in flat terrain

To find the orientation of the axial plane of a fold, it is very useful to know the orientation of the axial trace. This is most reliably located on a profile view of the fold. If the trend and plunge of the fold axis are known and if the fold is well exposed in relatively flat terrain, then a profile view can be quickly constructed. Consider the fold shown in plan view in Fig. 7.6a. The profile view and surface axial trace are constructed as follows.

1 Draw a square grid on the map with one axis of the grid parallel to the trend of the fold axis (Fig. 7.6b). The length of the sides of each square, d_s (surface distance), is any convenient arbitrary length, such as 1 cm or 10 cm.

2 The surface distance d_s when projected on a profile plane will remain the same length in the direction perpendicular to the trend of the fold axis. The sides parallel to the trend, however, will be shortened in the profile view (except in the case of a vertical fold). This is easily confirmed by viewing down-plunge in Fig. 7.6b. The shortened length parallel to the trend of the fold axis we will call d_p (profile distance). Length d_p can be determined trigonometrically with the following formula:

$$d_p = d_s \sin \text{plunge}$$

It can also be determined graphically, as shown in Fig. 7.6c.

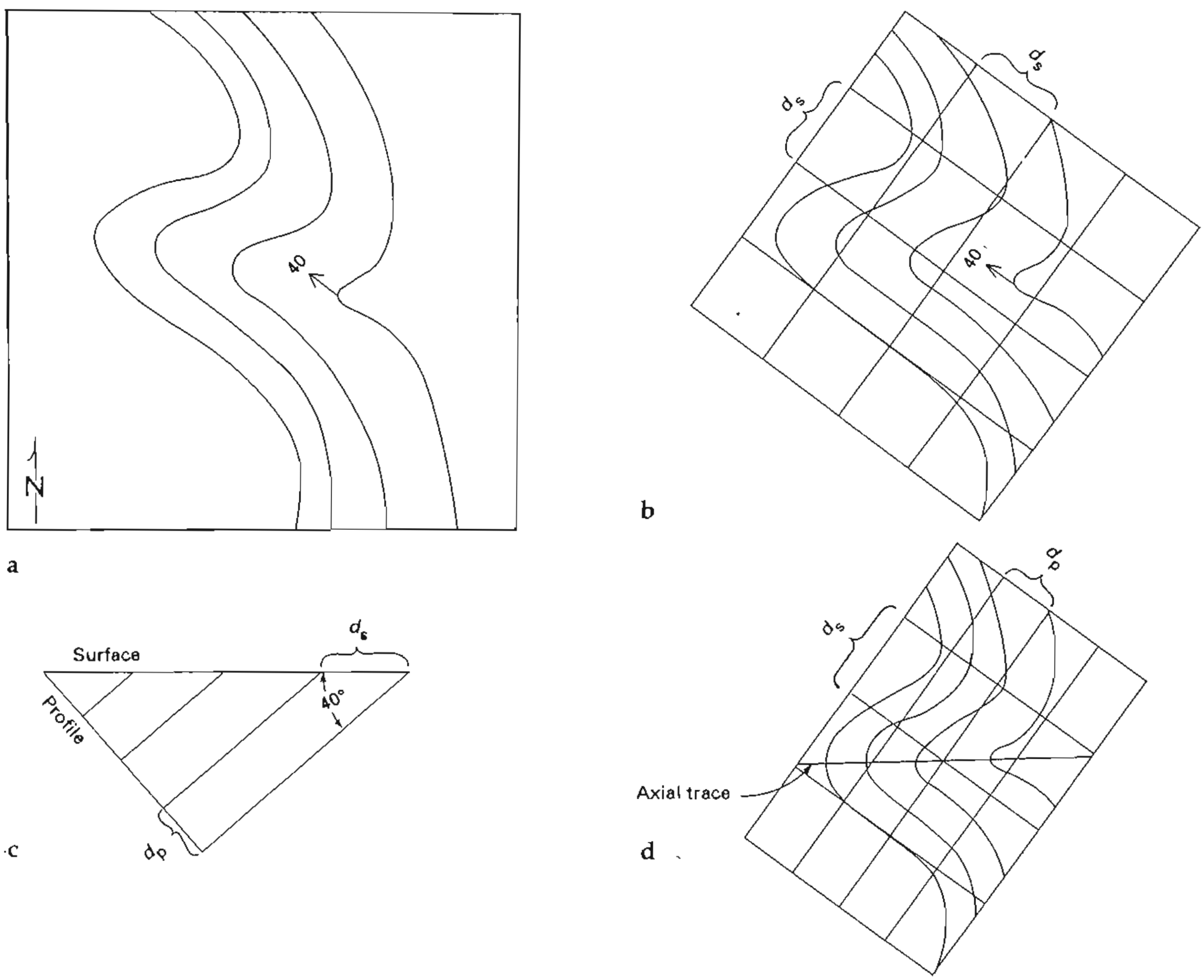

Fig. 7.6 Method for constructing the profile view of a fold exposed in flat terrain. (a) Map view. (b) Square grid drawn on map with one axis parallel to trend of fold axis. (c) Graphical relationship between surface distance (d_s) and profile distance (d_p). (d) Profile view. Fold is drawn using grid intersections for control. Axial trace is drawn onto fold.

3 With d_p now determined, a rectangular grid is drawn which represents the square grid projected onto the profile plane. Points on the square grid in the map view are then transferred to corresponding points on the rectangular grid. The profile view of the fold is then sketched freehand, using the transferred points for control (Fig. 7.6d).
4 The axial trace can now be drawn on the profile plane (Fig. 7.6d), and then transferred back to corresponding points on the square grid.

Simple equal-area diagrams of fold orientation

The orientation of a fold can be simply and clearly characterized by an equal-area diagram showing the axial plane and fold axis. Examples of various folds are shown in Fig. 7.7. Picture in your mind's eye what each of these folds would look like. What characteristics of a fold are *not* displayed in such a diagram?

Problem 7.1

1 On separate pieces of tracing paper construct a β-diagram and π-diagram for the folds in Fig. 7.10. Determine the trend and plunge of the fold axis.
2 Construct a profile view as shown in Fig. 7.6, and draw surface axial traces on the plan view. Determine the strike of the axial plane.
3 Draw a simple equal-area diagram such as those in Fig. 7.7 showing the orientation of these folds.
4 Concisely but completely describe these folds. Include the attitude of the fold axis, attitude of the axial plane, interlimb angle, symmetry, and fold class.

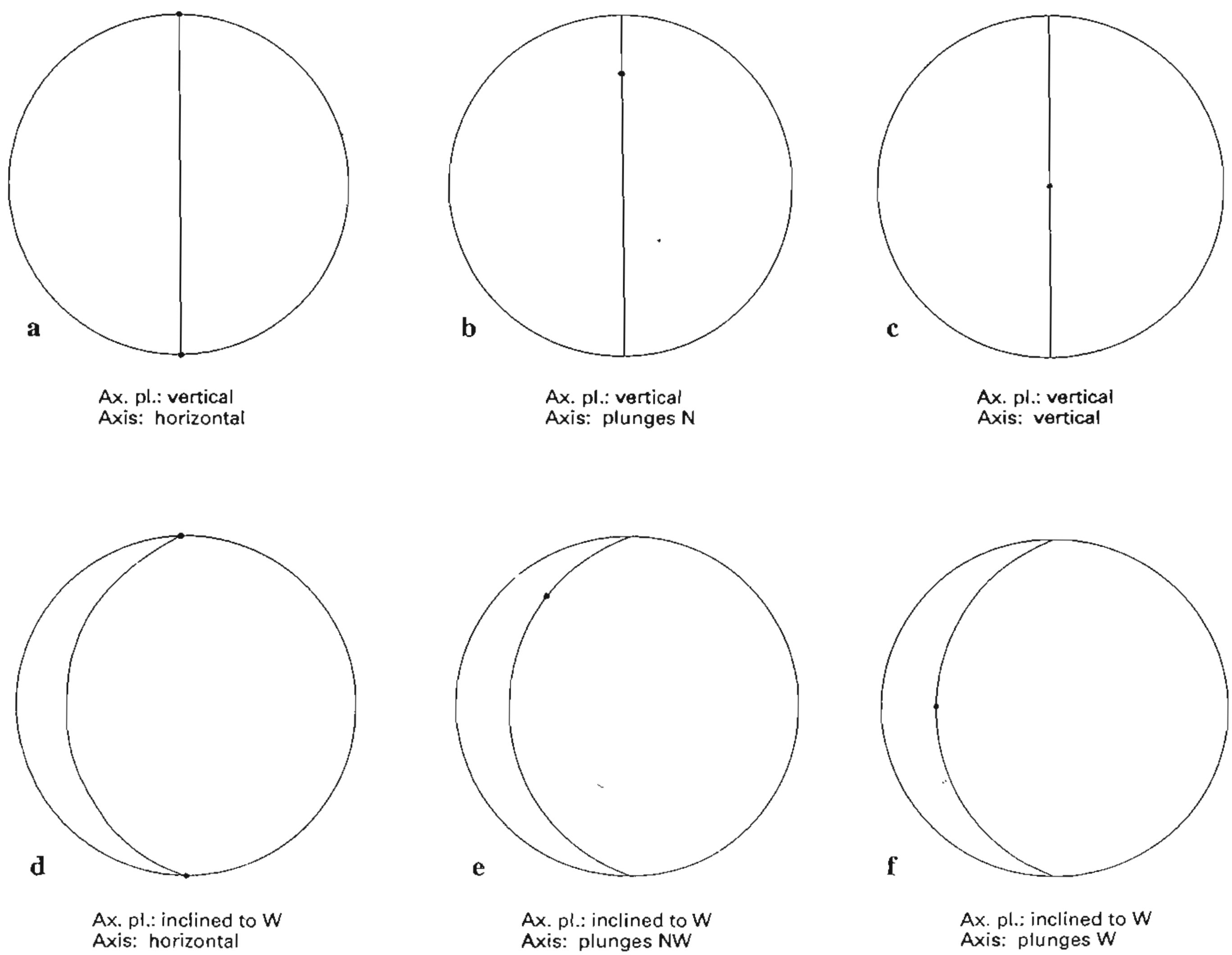

Fig. 7.7 Simple equal-area diagrams showing orientation of folds. Ax. pl. is axial plane.

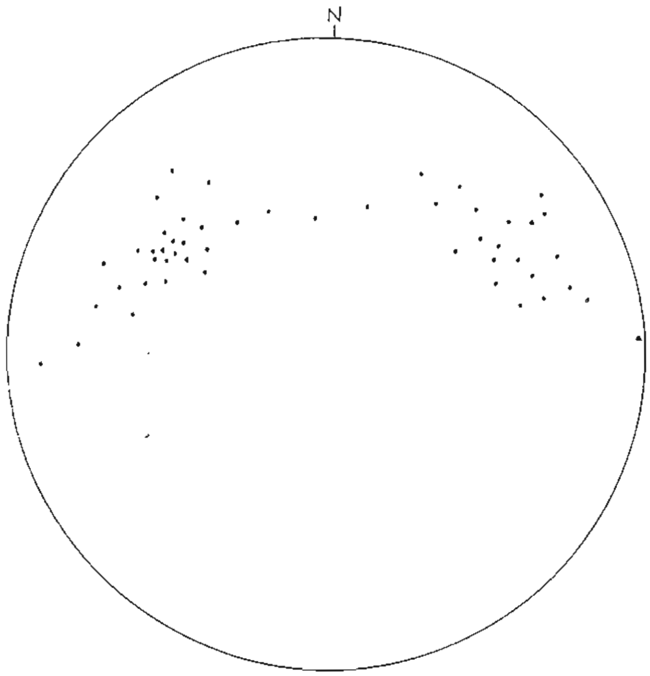

Fig. 7.8 Point diagram with 50 attitudes plotted.

Contour-diagrams

Because real folds are not exactly cylindrical, when a β-diagram or π-diagram is made no single β-axis or π-axis emerges. If a large number of data are available the orientation of the hinge line can be determined statistically through the use of a contoured equal-area diagram.

Figure 7.8 is an equal-area diagram showing poles to 50 bedding attitudes. This is called a *point* or *scatter diagram*. You could approximately locate a π-circle through the highest density of points, but contouring makes the results repeatable and reliable, as well as providing additional information.

A point diagram is contoured as follows:

1 Cut out the center counter and peripheral counter in Fig. 7.15 at the end of this chapter. With a razor blade, carefully cut out the holes in the counters and cut a slit in the peripheral counter as indicated. The holes in the counters are 1% of the area of the equal-area net provided with this book.

2 Remove the grid in Fig. 7.16, also at the end of this chapter, and tape it to a piece of thin cardboard to increase its longevity. The distance between grid intersections is equal to the radius of the holes in the counters.

3 Tape the tracing paper containing the point diagram onto the grid such that the center of the point diagram lies on a grid intersection. Tape a second, clean piece of tracing paper over the point diagram. The two pieces of tracing paper do not move while you are counting points.

4 You are now ready to start counting points. This is done by placing the center counter on the point diagram such that the hole is centered on a grid intersection (Fig. 7.9a). Count the number of points within the circle, and write that number in the center of the circle on the clean sheet of tracing paper. Systematically move the counter from one grid intersection to the next, recording the number of points within the 1% circle at each intersection. Each point will be counted several times.

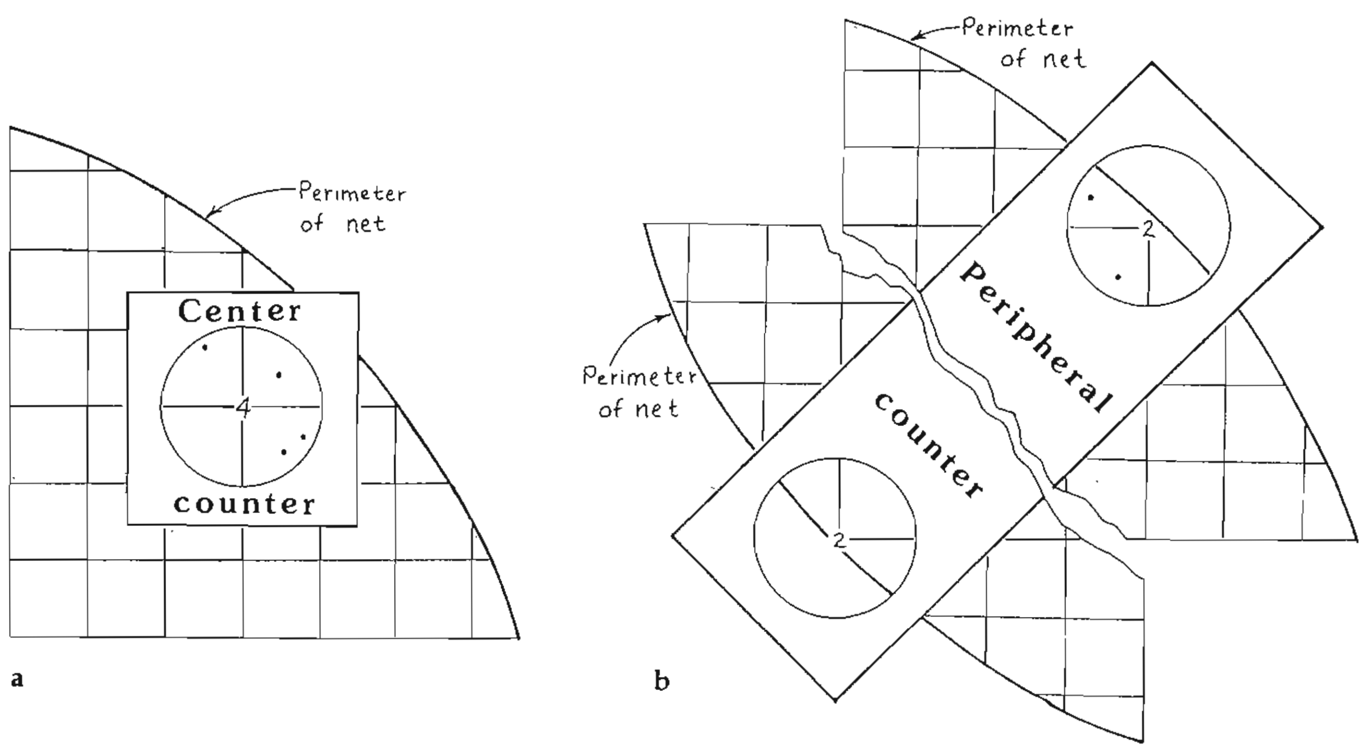

Fig. 7.9 Technique for counting points for the purpose of contouring. (a) Use of center counter. (b) Use of peripheral counter. Total number of points in both circles is written at the center of both circles.

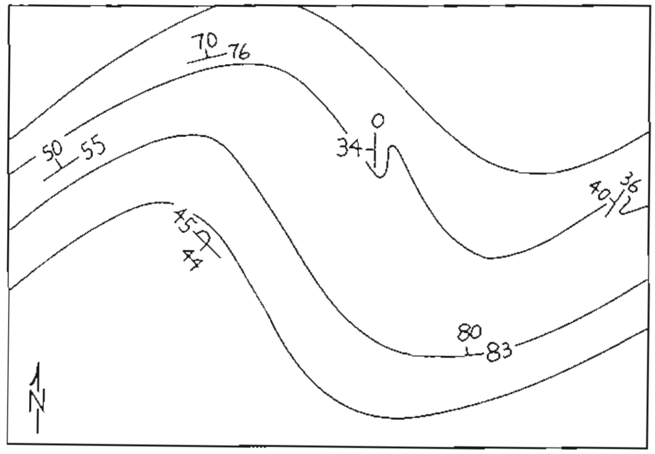

Fig. 7.10 Geologic map for use in Problem 7.1.

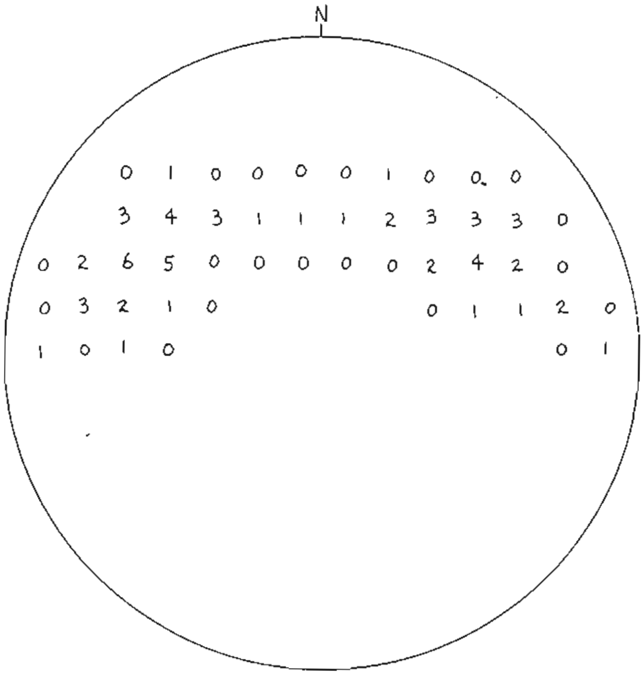

Fig. 7.11 Results of counting point diagram in Fig. 7.8.

5 On the periphery of the point diagram, where part of the circle of the center counter lies outside the net, the peripheral counter is used (Fig. 7.9b). When the peripheral counter is used the points in both circles are counted, added together, and that number is written at the center of both circles. Figure 7.11 shows the results of counting the points in the point diagram in Fig. 7.8. Each number is a sample of 1% of the area of the point diagram.

6 The numbers are contoured as shown in Fig. 7.12a. The result is much like a topographic map, except that the contour lines separate point-density ranges rather than elevation ranges. In the interest of simplicity and clarity some of the contours can be eliminated. Figure 7.12b shows contours 3 and 5 eliminated and a stippled pattern of varying density added. Fifty points were involved in this sample, so each point represents 2 % of the total. The contours in Fig. 7.12b, therefore, represent densities of 2, 4, 8, and 12% per 1% area. The contour interval and total number of points represented (n) are always indicated either below the plot or in the figure caption (Fig. 7.12c).

7 The highest density regions on such a diagram are called the π-maxima. The great circle that passes through them is the π-circle, and its pole is the π-axis (Fig. 7.12c). For mildly folded, symmetric folds the axial plane bisects the acute angle between the π-maxima, as shown in Fig. 7.12c. The attitude of the axial plane is most reliably determined from a combination of the π-axis attitude and the strike of the surface axial trace, the latter being determined by the technique shown in Fig. 7.6.

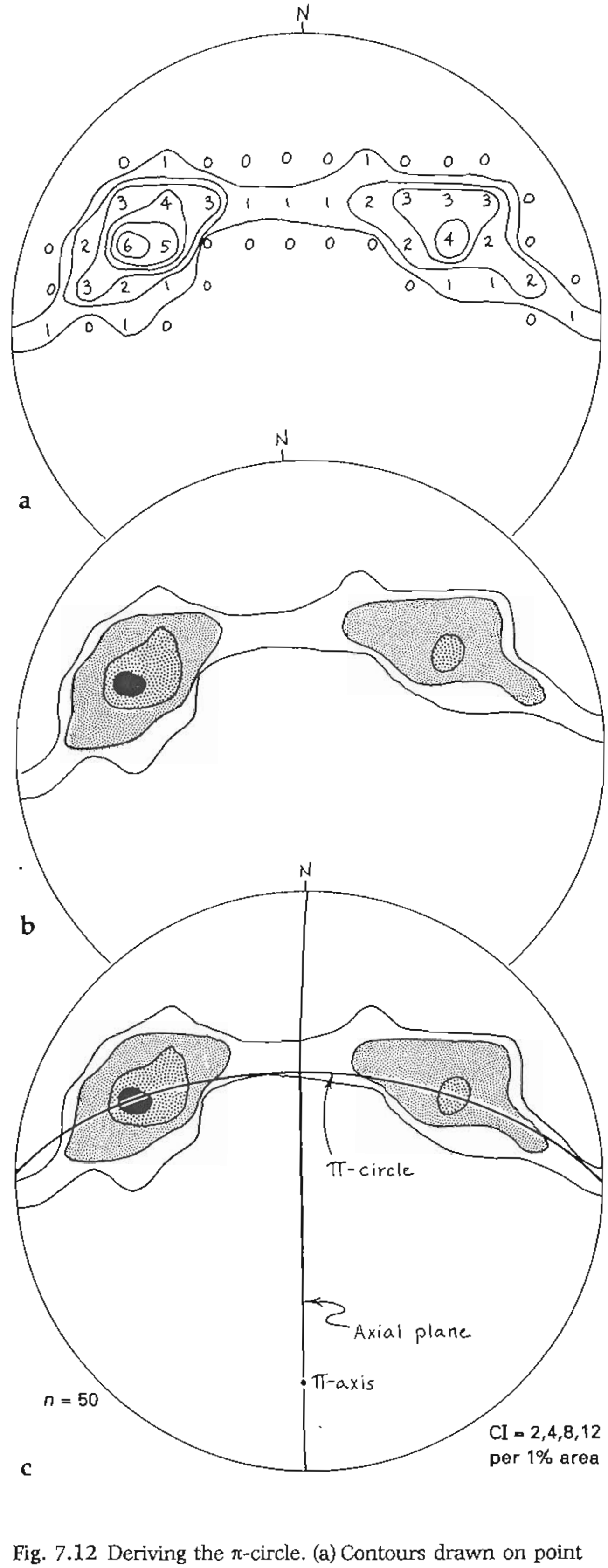

Fig. 7.12 Deriving the π-circle. (a) Contours drawn on point grid. (b) Selected and shaded contours. (c) π-axis and π-circle determined from contour diagram. Axial plane cannot be located with certainty without additional information. CI, contour interval.

Folding style and interlimb angle from contoured π-diagrams

In addition to providing a statistical π-axis, contoured π-diagrams indicate the style of folding and the interlimb angle. The band of contours across the diagram is referred to as the *girdle*, and the shape of the girdle reflects the shape of the folds. Figure 7.13a shows a profile and π-diagram of an extreme case of long limbs and narrow hinge zones. Figure 7.13c shows asymmetric folds whose eastward-dipping limbs are longer than the westward-dipping limbs. Figures 7.13b, d, and e are other examples of different styles of folding and corresponding contoured π-diagrams.

The interlimb angle of a fold can be measured between the two maxima along the π-circle directly off the contoured π-diagram.

> **Problem 7.2**
> Three of the four fault blocks on the Bree Creek Quadrangle contain folded Paleogene rocks for which bedding attitudes are shown on the map. It may be useful to work in groups of three students, with each student doing all of the following for only one of these three fault blocks. Make copies of your results so that each student in the group has data for all three of the fault blocks. These diagrams will be used in Chapter 11 for a structural synthesis of the Bree Creek Quadrangle.
> 1 Construct a contoured π-diagram.
> 2 Construct a profile view of the folds as shown in Fig. 7.6. In the northeastern block, do not include the beds exposed on the Gollum Ridge fault scarp, because this technique can only be used in areas of low relief.
> 3 Draw dip isogons on your profile view and determine the class of each folded layer.
> 4 Describe the folds as succinctly and completely as possible. Your description should include the trend and plunge of the π-axis, the attitude of the axial surface, interlimb angle, symmetry, class of folds, and age of folding.
> 5 Figure 7.14 is a reference map of the Bree Creek Quadrangle with a circle on each of the three fault blocks involved in this problem. Sketch the contour diagram for each of the three fault blocks in the corresponding circle similar to those in Fig. 7.12c. Draw the π-axis and axial plane on each circle. Such a reference map is an effective way of summarizing the orientation and geometry of folds in separate areas.

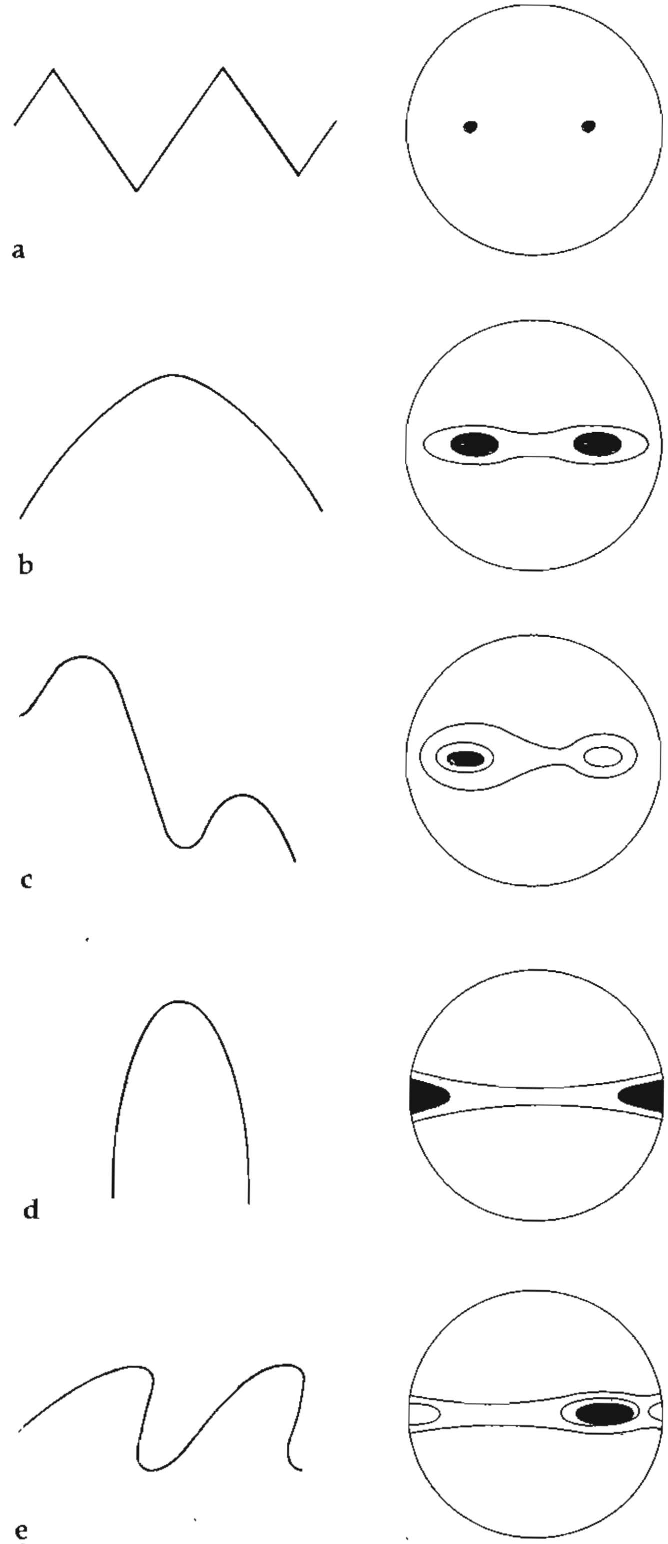

Fig. 7.13 Profiles and corresponding contoured π-diagrams of variously shaped folds (c, d, and e after Ragan, 1985).

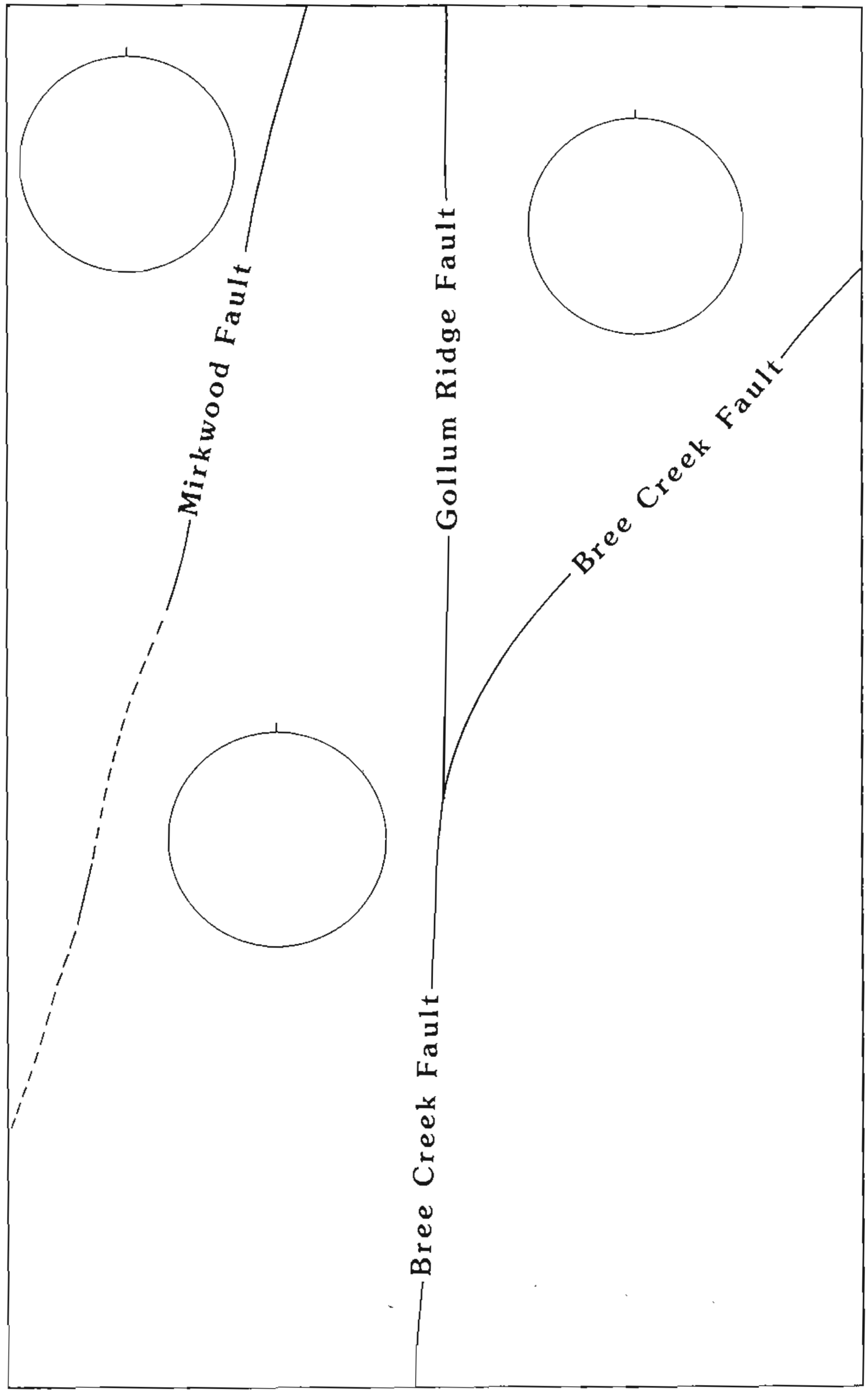

Fig. 7.14 Map of separate fault blocks of the Bree Creek Quandrangle for use in Problem 7.2.

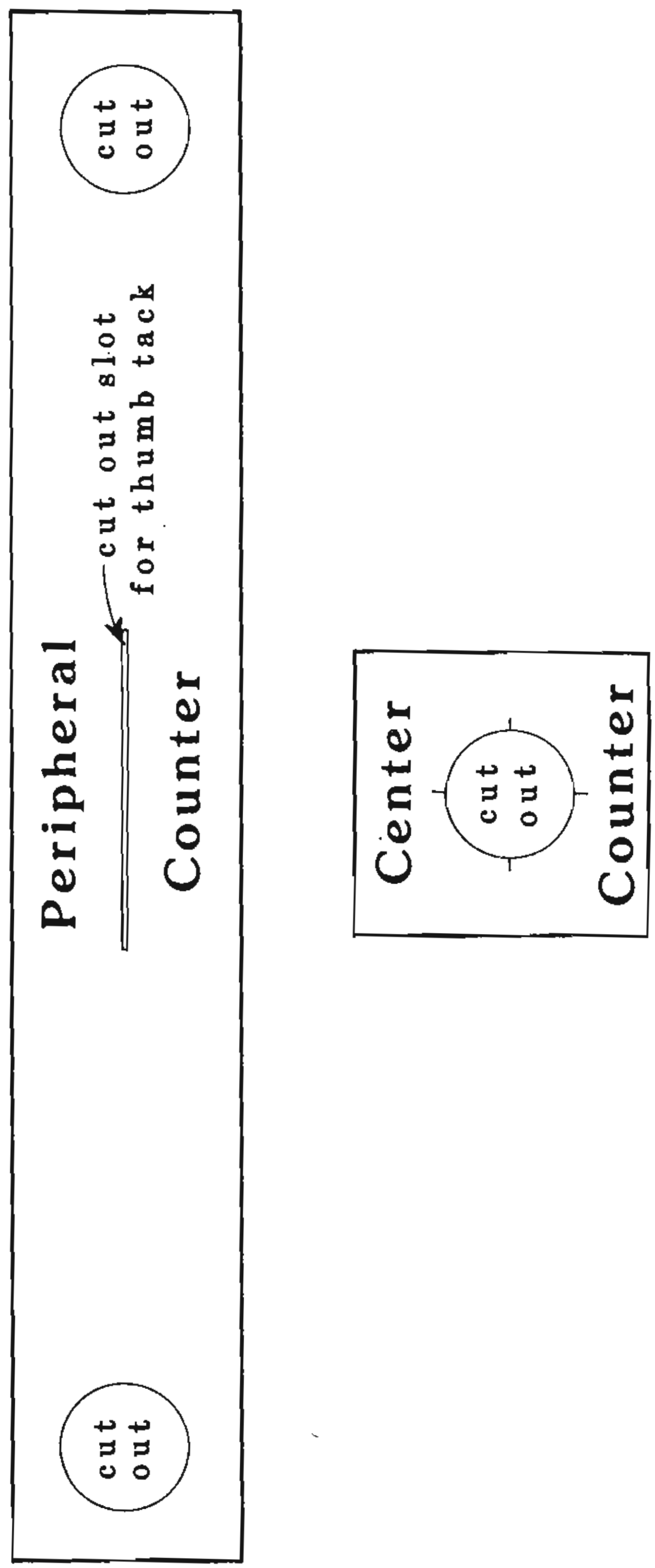

Fig. 7.15 Center counter and peripheral counter to be cut out and used for constructing contour diagrams.

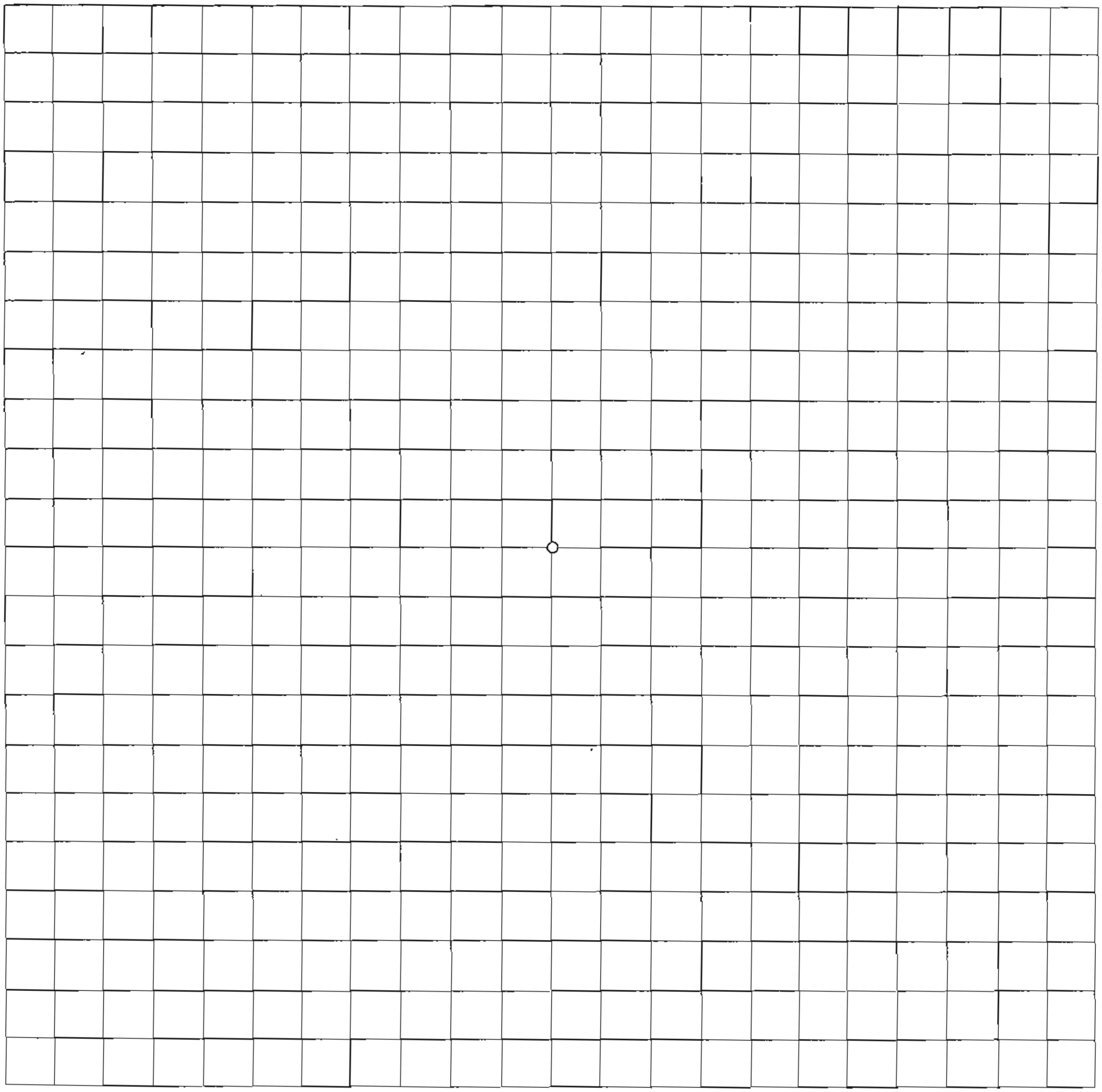

Fig. 7.16 Grid for use in constructing contour diagrams.