CHAPTER

13

OBJECTIVE METHODS FOR CONTRUCTING PROFILES AND BLOCK DIAGRAMS OF FOLDS

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13-1 INTRODUCTION

A slice or section through any three-dimensional object provides a useful visual image of its interior. Geologists often construct sections of the earth to illustrate its internal structure. A section that is oriented perpendicular to the surface of the earth is called a *cross section* (Appendix 1). Block diagrams (Appendix 1) combine data from maps and cross sections to provide a perspective image of a three-dimensional block of the earth.

Cross sections and block diagrams are influential tools that you can use to convey your ideas about the geologic structure of an area to other geologists. They are also often used *as data* when analyzing the tectonic history or resource potential of an area, so it is important that they be as accurate and truthful as possible. Constructing cross sections and block diagrams tests your understanding of the geometry of deformed rocks. The central problem that you encounter when constructing a cross section or block diagram is, How can surface data be extrapolated to depth? Extrapolation, as you will see, depends in part on objective geometric techniques of projecting structures and in part on subjective interpretation.

In this chapter we examine some of the objective geometric techniques (Busk method, kink method, dip-isogon method, and down-structure projection) used to project surface data on fold geometry to depth. We will also see how to incorporate drill-hole and seismic data in such sections. Finally, we will describe how to represent accurately the three-dimensional configuration of rock structures in block diagrams that have geologic maps on their upper surfaces and geologic cross sections on their sides. Additional aspects of cross-section construction are introduced in Chapter 14. It is important to emphasize at the outset that the ***reproducibility*** of cross sections and block diagrams drawn using the techniques described in this chapter must not be confused with the *truthfulness* of these representations. Natural geologic structures rarely conform to ideal geometries; thus, real geology may deviate markedly from sections drawn using geometric models.

13-2 FOLD STYLES AND SECTION LINES

Cylindrical and Cylindroidal Folds

Objective techniques for projecting fold geometry to depth can be applied only to folds whose shapes have a certain degree of regularity. *Cylindrical* or *cylindroidal* folds are two types of folds whose shapes are sufficiently regular that data on fold shapes at the surface can be used to characterize fold shapes at depth. The techniques are not feasible in regions where fold shapes are very irregular (folded layers thicken or thin dramatically, and fold trains are disharmonic); in such regions, knowledge of fold geometry at the surface will not help us predict fold geometry at depth.

As described in Chapter 8, the axis of a cylindrical fold is a straight line that, when moved parallel to itself, can "trace out" the folded surface (Fig. 13-1). Because of this

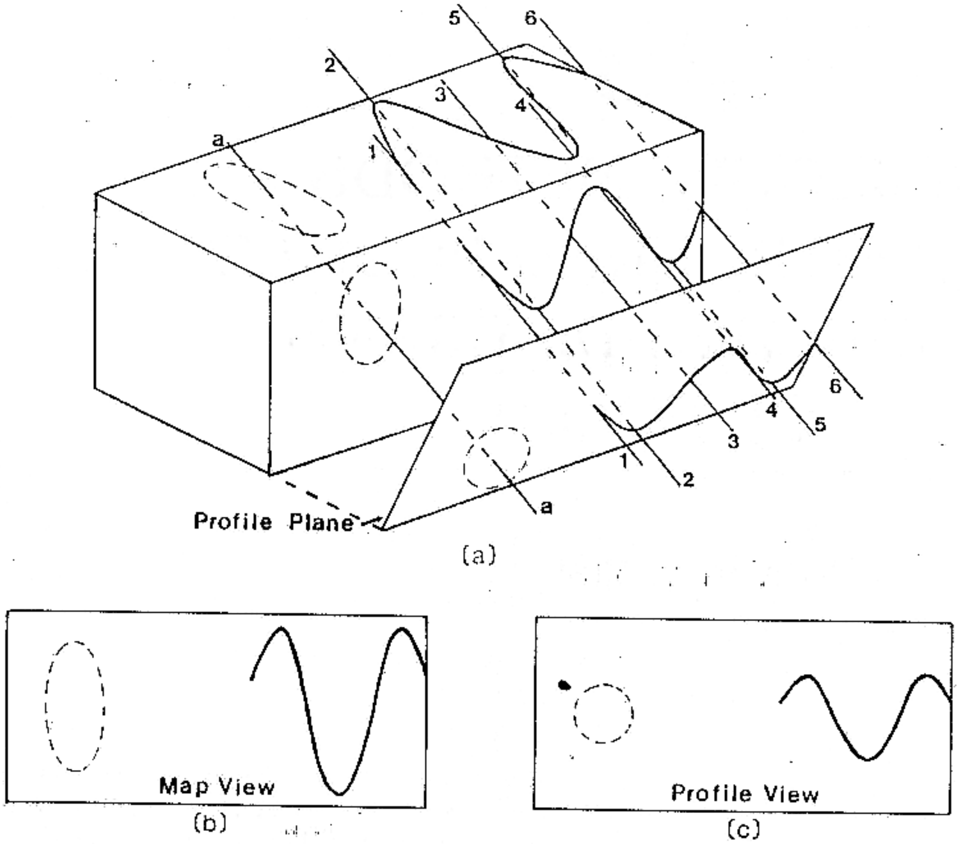


Figure 13-1. Map, cross section, and profile views. (a) If the axis of a circular cylinder (line a) plunges, the map pattern of the cylinder on a horizontal surface is an ellipse, and the intersection of the cylinder with a vertical cross-section plane is an ellipse. Likewise, the shape of a plunging fold is distorted in the map and cross-section planes; (b) distorted shapes in the map plane; (c) true shapes in the profile plane.

property, the shape of a cylindrical fold can be projected orthographically along the fold axis onto a plane that is normal to the axis. Few real folds are cylindrical, but many real folds are *cylindroidal*. In a cylindroidal fold, segments of the hinge line are nearly straight lines, but no single straight line can trace out the entire fold. In practice, we can construct representations of cylindroidal folds by assuming that they are composed of several cylindrical segments, where the axis of each segment is not exactly parallel to the axes of the adjacent segments (Ramsay and Huber, 1987; Langenberg and others, in press).

Choosing the Line of Section

You will recall from earlier chapters that the inclination of a dipping layer in a vertical section equals the layer's true dip only if the section is oriented perpendicular to the layer's strike. Likewise, the truest representation of any cylindrical fold is a section taken perpendicular to the fold's axis (Fig. 13-1; see also Suppe, 1985). A section that is oriented perpendicular to fold axes in a region is called a *profile section* or, more commonly, a *profile*, and a section that is oblique to the axis of a structure is called an *oblique section*. The traces of the folded layers exhibit their maximum curvature in a profile plane. The profile plane of a nonplunging cylindrical fold is vertical and strikes perpendicular to the strike of the folded layers. The profile plane of a plunging cylindrical fold must be an inclined plane. Since the fold is cylindrical, profiles drawn at all points along the fold axis must be identical. If a fold is cylindroidal, folded layers exhibit different shapes in different sections along the length of the fold. Sections that show the maximum curvature of the folded layers at different points along the fold axis have different strikes and dips. There is, therefore, no such thing as a single profile of a cylindroidal fold. We can draw a section that approximates a fold profile for an individual segment of a cylindroidal fold by positioning the section normal to the local fold hinge.

In a given map area it is best to draw sections of folds so that the surface trace of the section, called the *line of section*, crosses regions where surface geology is well constrained and/or there are seismic or drill-hole data available. The line of section should intersect several attitude measurements; the spacing between attitude measurements along the line of section must be less than the wavelength of the folds.

Parallel and Nonparallel Folds

In some geologic settings layered sequences of rock are folded in such a manner that (1) individual layers are not appreciably thickened or thinned during folding, and the thickness of an individual layer measured perpendicular to its local dip is nearly the same at all points around the fold; and (2) successive layers in the fold are conformable or harmonic. Folds that fit these criteria are called *parallel folds*. Some parallel folds have smoothly curved broad hinge zones (Fig. 13-2a), whereas others have narrow angular hinge zones that separate domains in which layers have nearly constant dips (Fig. 13-2b). The Busk method of section construction (Busk, 1929) is appropriate for smoothly curved parallel folds, whereas the kink method (e.g., Suppe, 1985) is appropriate for parallel folds with angular hinge zones and straight limbs. These methods produce reliable cross sections only if the assumption of parallel folding is valid; they cannot be used for extrapolation to depth in regions of nonparallel or disharmonic folding. If we cannot assume that folds are parallel, we use the dip-isogon method or one of several orthographic projection techniques to construct sections. Keep in mind that there are geologic settings where none of these techniques yields a truthful representation of subsurface structure.

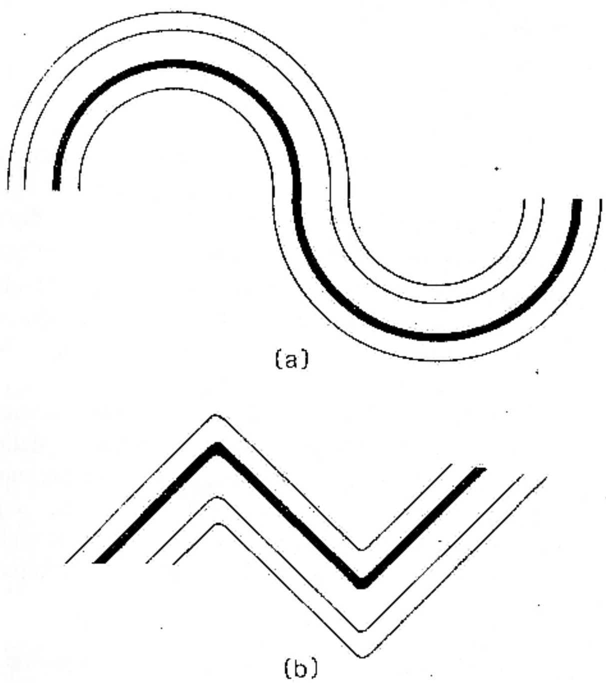


Figure 13-2. Styles of parallel folds referred to in the text. (a) Concentric parallel folds; (b) angular parallel folds.

13-3 BUSK METHOD OF CONSTRUCTING SECTIONS OF NONPLUNGING FOLDS

The Busk method is the most popular method for constructing sections of parallel folds with smooth, rounded hinges. An alternative method that uses "evolutes" and "involutes" (types of curves; see Bronshstein and Semendyayev, 1973) was proposed by Mertie (1947; see also Roberts, 1982), but this method is considerably more difficult and usually does not yield cross sections that are sufficiently more accurate than those constructed with the Busk method to be worth the trouble.

The Busk method permits us to reconstruct the traces of layers in a section plane from surface or subsurface measurements of the attitudes of the folded layers. The geometric basis of this method is the assumption that folded layers are everywhere tangent to circular arcs. In practice this assumption means that (1) the trace of each folded layer in a profile plane can be divided into a number of segments each of which is either a portion of a circular arc or a straight line. Along each circular-arc segment, dip values change smoothly and continuously. Adjacent circular-arc segments are connected either by inflection points or by straight-line segments; and (2) Folding is harmonic and the traces of adjacent layers in profile are concentric arcs of different radii (Fig. 13-2a).

Busk Method for Two Points

Problem 13-1 (Busk method using data at two points)

Stations A and B lie 140 m apart along a N45°W-trending section line across a horizontal parallel fold; the elevation of A is 5 m higher than the elevation of B. The attitude of bedding at A is N45°E,10°SE, and the attitude at B is N45°E,35°SE. Use the Busk method to reconstruct the segments of folded layers that pass through A and B.

Method 13-1

Step 1: Draw a profile plane to scale. In this problem the plane is vertical and is perpendicular to the axis of the fold. If stations fall directly on the section line, as in this problem, just plot them at their appropriate relative elevations and lateral spacing. (If a station does not fall directly on the section line, plot its projection on the section line by drawing a projection line parallel to the fold axis from the station to the section line. The intersection of the projection line with the section line gives the station's relative position along the section line; plot a projected station at the same elevation as the original station.)

Step 2: In this problem the section line is perpendicular to the strike of the the beds, so the true dips of the beds can be shown in the profile plane. If the section line is not perpendicular to strike, we can still carry out a Busk construction, but the dips indicated in the profile plane must be apparent dips. Once the appropriate apparent dip value in the profile plane has been determined, indicate the dip values on the profile plane by short line segments drawn in ink (e.g., line segments 1 and 2 in Figure 13-3a).

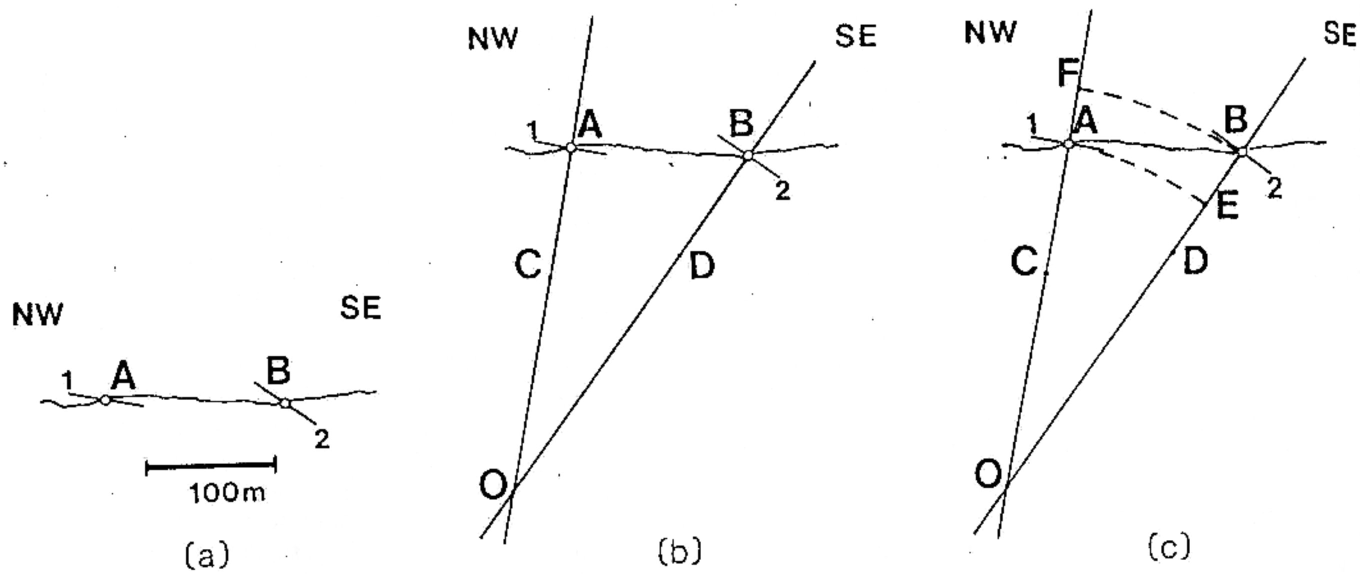


Figure 13-3. Illustrations for Busk construction Problem 13-1. (a) The location of stations A and B plotted along a line of section. Line segments 1 and 2 give the dip values in the plane of section at A and B, respectively; (b) cross section completed in step 3; (c) completed Busk reconstruction of layers passing through A and B. The dip value increases from A to B, so the circular arcs are antiformal.

Step 3: We assume that the traces of beds passing through A and B are segments of concentric circular arcs. We must now find the common center of these circular arcs. To do this, recall that the radius of a circle is perpendicular to the trace of the circle at all points along the circle. Draw line AC perpendicular to line segment 1 at A and BD perpendicular to line segment 2 at B. Extend lines AC and BD to intersect at point O (Fig. 13-3b). Point O is the center of the concentric circular arcs.

Step 4: Next, obtain a compass and place its anchor needle on point O. With the compass's pencil, draw one circular arc that passes through point A and intersects radius OB at point E, and a second circular arc that passes through point B and intersects the extension of radius OA at point F. The two circular-arc segments, AE and BF, are the profile traces of bedding that we desire (Fig. 13-3c). Note that arc segments AE and BF are concentric, but have different radii, and that points A and B do *not* lie on the same arc segment. It is important that the arc segments not be extended beyond their intersections with rays OA and OB, for the traces of layers outside the rays are fixed by dip readings at other station locations.

In Problem 13-1 note that if, for example, point A was the outcrop of a stratigraphic contact, arc segment AE would be the Busk reconstruction of that stratigraphic contact. Note also that the layer thickness is uniform along the fold segment between stations A and B (i.e., AF = BE). The relative dip values at stations A and B determine whether the center of curvature for circular-arc segments passing through the two points lies below the ground surface (as in Figure 13-3c, where the dip at B is greater than the dip at A) or above the ground surface (as in Figure 13-4a, where the dip at B is less than the dip at A). The circular arcs representing the folded layers drawn using these centers will be either antiformal (Fig. 13-3c) or synformal (Fig. 13-4a).

In Problem 13-1 the dips at our two stations were different. If the dip readings at two adjacent stations are identical, the normals to the line segments representing the dipping layers do not intersect. The "arc" segments connecting these two dip stations will be straight lines (i.e., they will have an infinite radius of curvature; Fig. 13-4b).

Busk Method for Three or More Points

Problem 13-2 (Busk method using data at three points)

Stations A, B, and C lie on a N45°W-trending section line across a horizontal parallel fold. The horizontal distance between A and B is 190 m, and the horizontal distance between B and C is 200 m. The elevation at A is 150 m, at B is 160 m, and at C is 170 m. The attitude of bedding at A is N45°E,10°SE, the attitude at B is N45°E,35°SE, and the attitude at C is N45°E,70°SE. Use the Busk method to construct the traces of the folded beds passing through A, B, and C.

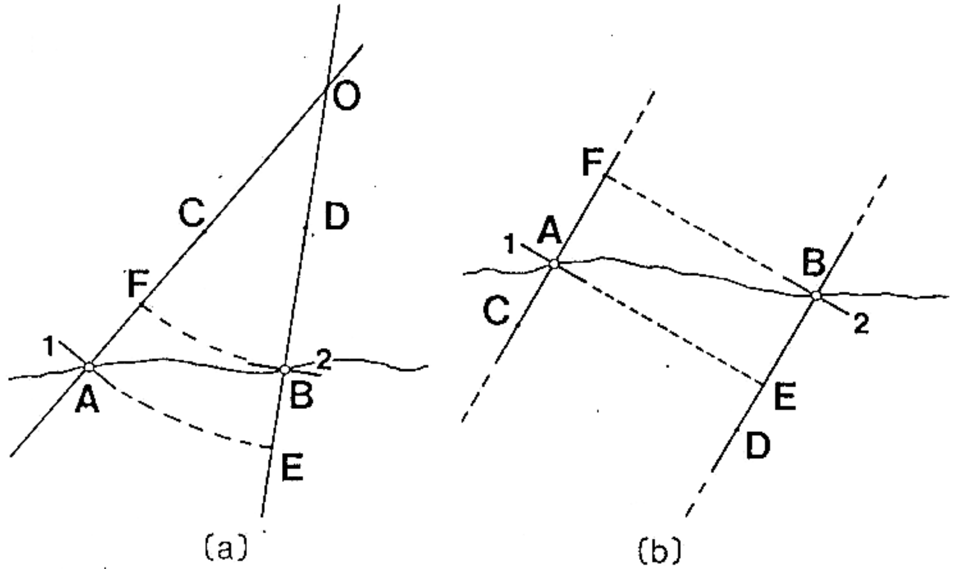


Figure 13-4. Busk construction, continued. (a) If dip values decrease from A (where the attitude is N45°E,40°SE) to B, (where the attitude is N45°E, 10°SE), the center of curvature for the arc segments passing through A and B lies above the points, and the folded surfaces are synformal; (b) if strike and dip readings at two adjacent stations along a line of section are the same (N45°E, 30°SE at both A and B), the limb segments between the two points are straight-line segments.

Method 13-2

Step 1: Draw your section line, locate the positions of the stations along the section line, and plot line segments representing the dips at these stations (Fig. 13-5a). In this problem the dips indicated on the line of section are true dips.

Step 2: Draw the normals to line segment 1 at A and line segment 2 at B, lines AD and BE respectively (Fig. 13-5b). Extend these lines to intersect at point O.

Step 3: Place the anchor needle of your compass at point O and draw circular arcs AF and GB. These arcs represent the segments of the folded layers between stations A and B.

Step 4: Draw the normal to line segment 3 at C, line CH. Extend line CH to intersect the radius OB at O' (Fig. 13-5c). The point O' is the center of concentric circular-arc segments that are tangent to line segment 2 at B and line segment 3 at C. The centers of the two sets of circular-arc segments must lie on a single straight line normal to line segment 2 at B (e.g., line OB in Fig. 13-5c).

Step 5: Move the anchor needle of the compass to point O', and draw arc segments BJ and CI. To finish the drawing, return the anchor needle back to point O and draw arc segment IL (Fig. 13-5c).

Once again, the relative spacing of stations A, B, and C and the relative magnitudes of the dips at these stations determine the locations of the centers of concentric circular arcs passing through three stations along a single line of section (see Fig. 13-6).

So far, we have not worked with problems where a single marker bed is exposed at several localities along a line of section. If we have an insufficient number of surface or subsurface dips along the line of section, the Busk method may predict surface exposures of a horizon that do not correspond with known surface exposures. If a particular marker bed appears at the ground surface two or more times long the line of section, it is possible to test the consistency of the Busk construction of the fold with the surface data. The following method is taken from Billings (1972).

Problem 13-3 (Busk method applied to a marker horizon)

We know the attitude of bedding at four points along a N45°W-trending line of section across a horizontal parallel fold: N45°E,15°NW at point A, N45°E,40°SE at point B, N45°E,60°NW at point C, and N45°E,15°SE at point D. A distinctive conformable stratigraphic contact crops out at points A and D along a section line. Use the Busk method to reconstruct the folded layers between points A and D. Be sure that your solution conforms with known positions of the contact.

Method 13-3

As we will see, if we simply apply the steps of Method 13-2 to the data given here, we obtain a cross section that cannot be correct (Fig. 13-7a). The arc segment that passes through point A does not connect with the arc segment passing through point D. Next, we illustrate how such a mistake can be corrected.

Step 1: Draw the line of section, locate the measurement stations, and plot the appropriate line segments 1, 2, 3, and 4 representing the dip values at each station.

Step 2: Draw the normal to line segment 1 at A and the normal to line segment 2 at B, and extend them to intersect at O. Place the anchor needle of a compass at O, and draw circular-arc segment AE. Point E does not coincide with point B, but based on the field data that we

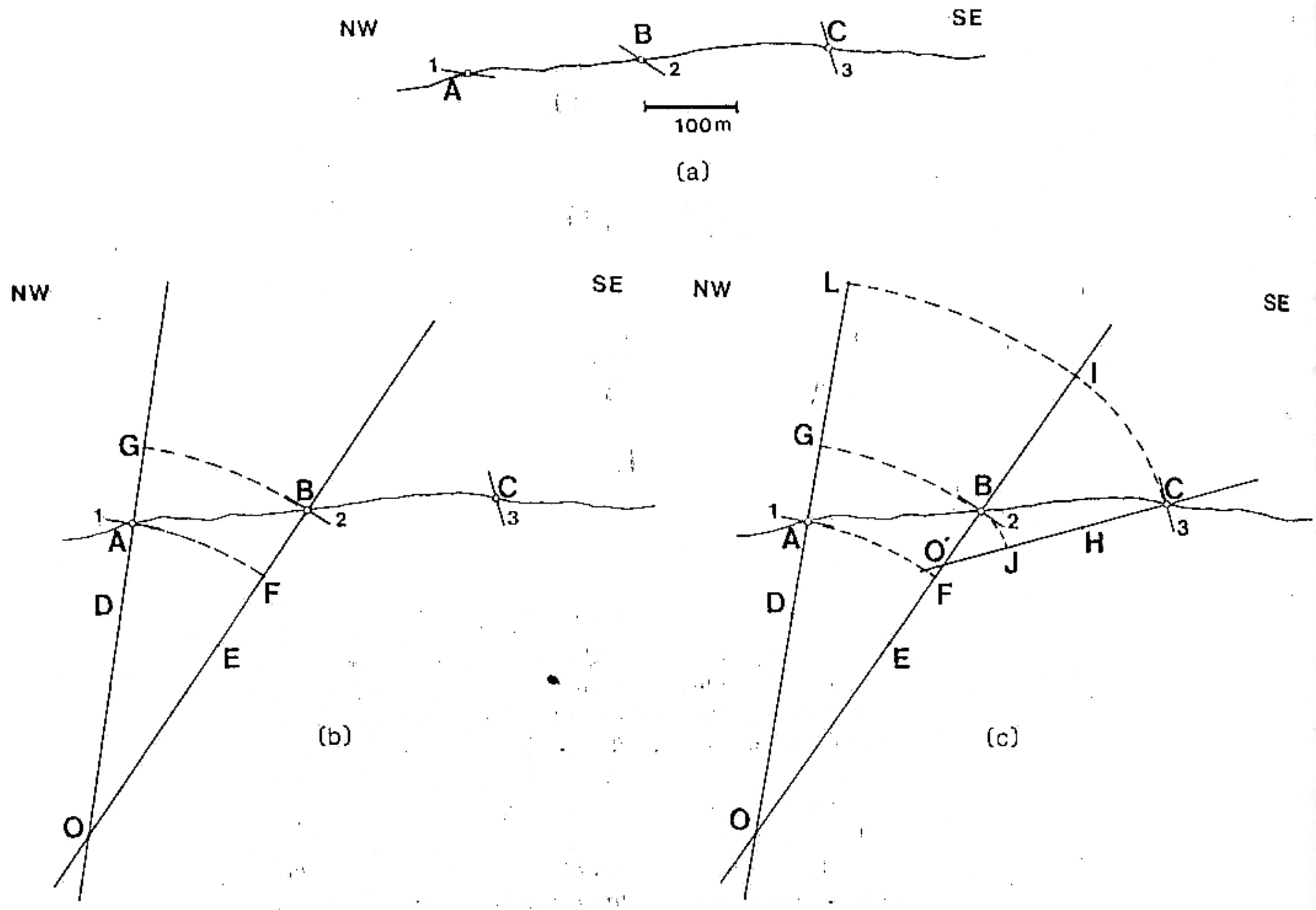


Figure 13-5. Busk construction for Problem 13-2. (a) Stations A, B, and C, plotted on a cross section plane; (b) partial construction after completing step 3 of Method 13-2; (c) completed cross section.

have, we do not expect the layer passing through A to crop out at B.

Step 3: Draw the normal to line segment 3 at C, and extend the normal to line segment 2 at B (line OB) to where they intersect (point P). Use a compass to draw circular-arc segment EF. Once again, F and C do not coincide, but this is consistent with our field data.

Step 4: Draw the normal to line segment 4 at D, and extend it to intersect the normal to line segment 3 at point Q. Place the anchor needle of your compass at Q, and draw circular-arc segment FG (Fig. 13-7a). G does not coincide with D. Field data indicate, however, that the same contact crops out at both points A and D. Therefore, barring faults, point G *should* coincide with point D. Obviously, our section at this stage is not correct, and we must modify it.

We alter the construction to conform with surface data by interpolating a dip value between the two stations that are most widely spaced (B and C) and by replacing the single arc segment (EF) between those two stations with two arc segments.

Step 5: Place the anchor needle of your compass at Q, and draw arc DW (Fig. 13-7b).

Step 6: Draw line WX perpendicular to QP, and draw line EY perpendicular to OP. Lines WX and EY intersect at point R.

Step 7: Draw a straight line between points E and W. Drop a perpendicular from the line EW to point R, and extend it to intersect the ground surface at U. The inclination of the line EW is, in effect, an interpolated dip value at U for the layer passing through A and D.

Step 8: Extend line RU upward to intersect the extension of OB. The intersection of these two lines is point S. Line SR, which is perpendicular to the interpolated dip at U, intersects line PQ at point T.

Step 9: With the compass anchor at S, draw circular-arc segment EH. With the compass anchor at T, draw circular-arc segment HW. Curve AEHWD (Fig.

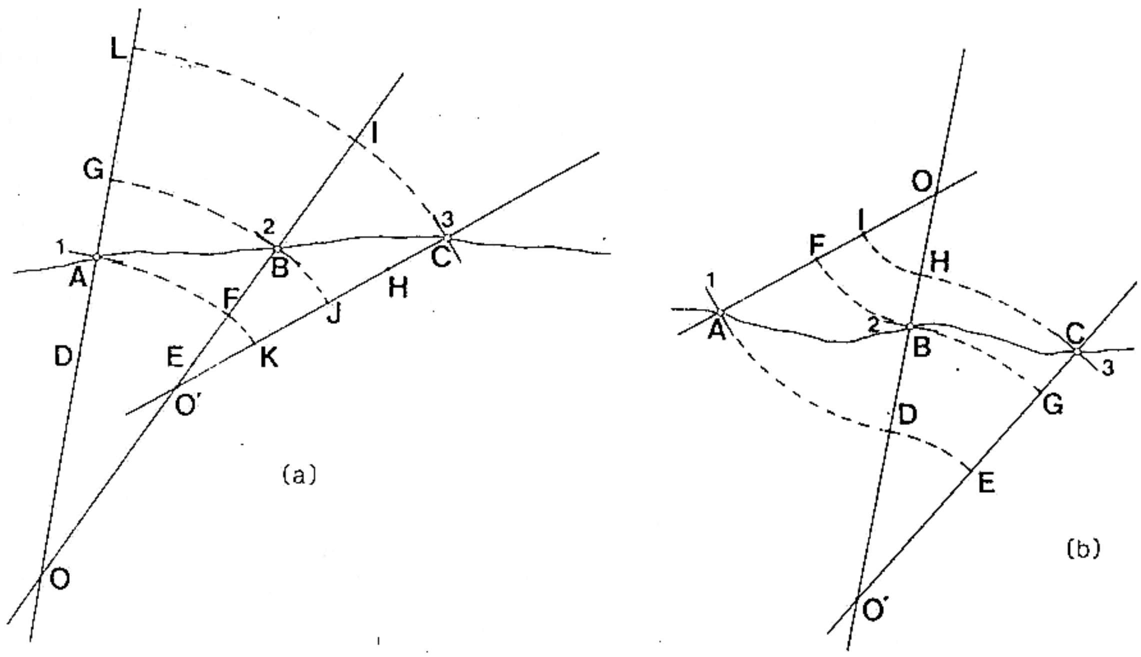


Figure 13-6. Illustration showing that the relative positions of the centers of concentric arc segments passing through three stations in a Busk construction change as distances between stations and dip values at the stations change. (a) Dip values in the plane of section increase from A (10°) to B (35°) to C (60°). Comparing this figure with Fig. 13-5c, we note that the center O' may fall between points F and B or between points O and F, depending upon the dip values at stations and the spacing between stations; (b) construction for the case where the dip at the intermediate station (station B) is less than the dip values at the two ends. Dip values are 60° at A, 10° at B, and 40° at C. Curvature changes from synformal to antiformal. Curvature will change from antiformal to synformal if the dip at a station is greater than dips at the two adjacent stations.

13-7b) is the trace of a surface that fits the known dip data and passes through both points A and D.

Problems with the Busk Method

Figure 13-8 shows a cross section drawn by applying the Busk method to seven dip readings along a line of section. Remember that, by definition, the hinge of a fold is the line along which the curvature of the fold is a maximum. If the trace of a layer is drawn as a circular arc (i.e., OP in Fig. 13-8), the curvature of the layer is constant, so technically, we cannot define a unique hinge. In Busk constructions, we arbitrarily place the hinge at the midpoint of an arc. ZZ' is the trace of one antiform's hinge surface in Figure 13-8.

Look again at Figure 13-8. At points U and X along line ZZ', concave-up arc segments of adjacent synforms intersect (there is no intervening antiformal arc). The t of the the folded layer has infinite curvature at such poi Points of infinite curvature, called *singularities*, o appear in Busk constructions of folds whose waveleng are short relative to the thickness of the layered seque Singularities, such as those that occur at points U and are a consequence of the assumptions that folded layers concentric circular arcs. Singularities are rarely observe outcrop, so we must question whether Busk-construc folds actually represent reality. Badgley (1959) sugges replacing singularities in Busk reconstructions with cur line segments, but, as Ragan (1985) noted, this alters appearance of the reconstruction without necessa making it more truthful. If several singularities appear Busk construction of an area but none are observed surface exposures, we probably should find an alterna method to reconstruct the subsurface geology of the area

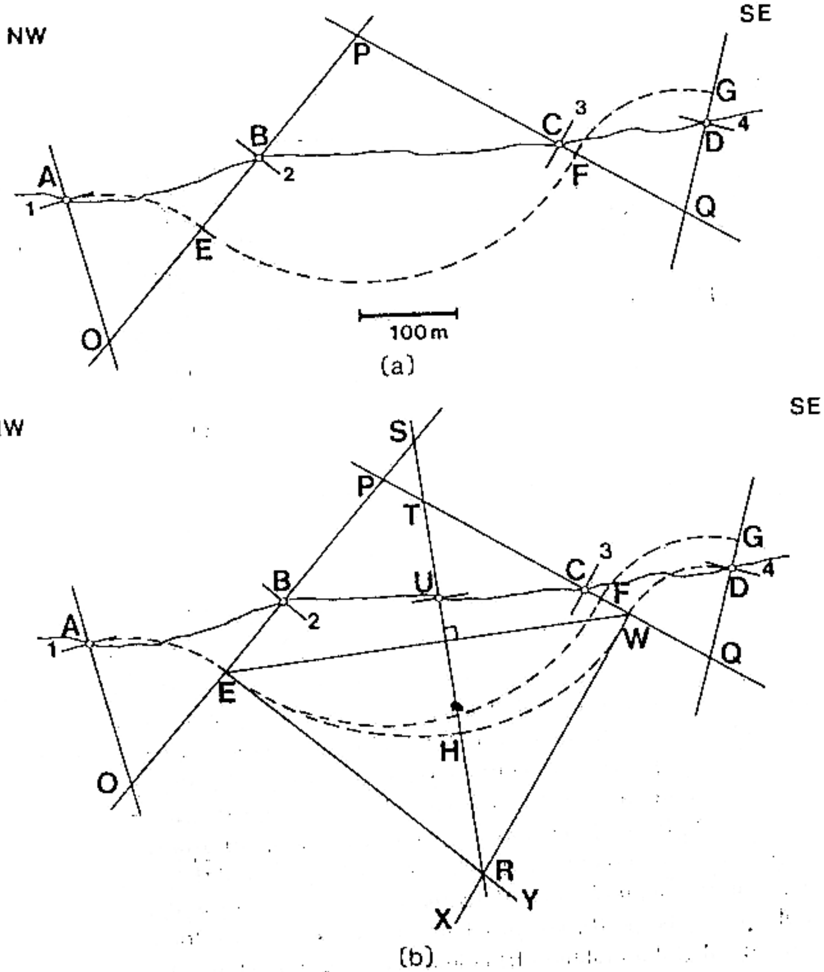


Figure 13-7. Steps in the Busk construction of Problem 13-3. (a) Incorrect cross section drawn using dip values at four stations; (b) interpolating a dip reading at an intermediate location in the Busk construction (after Billings, 1972).

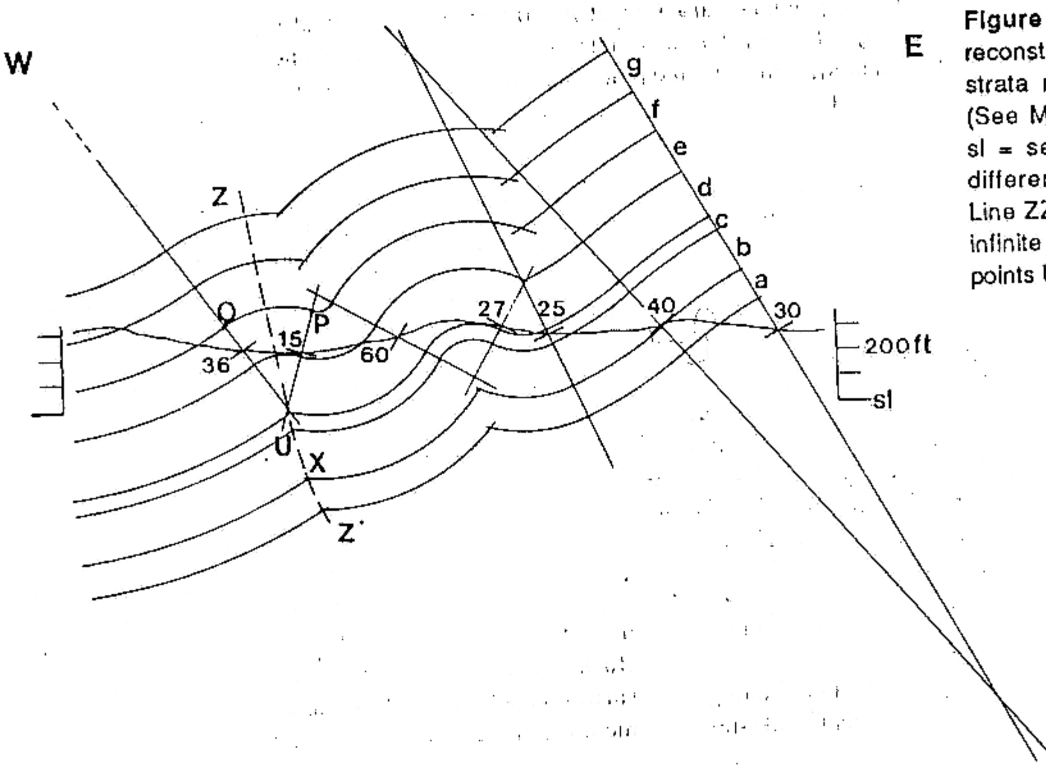


Figure 13-8. Completed Busk reconstruction of folded Devonian strata near Kingston, New York. (See Marshak and others, 1986.) sl = sea level; a through g are different stratigraphic horizons. Line ZZ' is a fold hinge. Note the infinite curvature (singularities) at points U and X along the hinge.

13-4 KINK-STYLE CONSTRUCTION OF NONPLUNGING FOLDS

Kink Geometries

In recent years geologists have recognized that many folds, particularly those in fold-thrust belts, have straight limbs and angular hinges (cf. Faill, 1969, 1973; Laubscher, 1977; Thompson, 1981). Angular folds produce *domainal dip patterns* on maps. A *dip domain* on such a map is an area in which strata have nearly constant dips. Adjacent dip domains are separated by narrow belts in which dips change abruptly (Fig. 13-9). The formation of these angular folds is often accommodated by interlayer slip, and it often occurs without appreciable thickening or thinning of strata. We model these angular folds as kink folds and use a method that relies on the geometric properties of kink folds to draw cross sections of regions exhibiting domainal dip patterns.

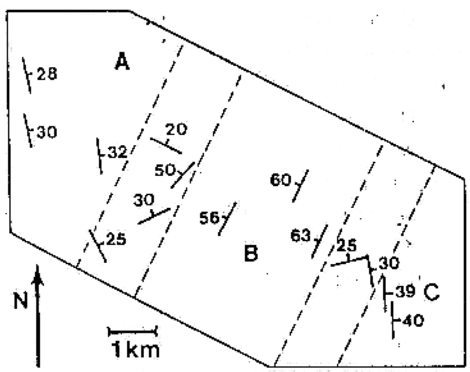


Figure 13-9. Dip domains on a map of angular folds. The map in this figure shows attitude measurements on bedding in a small area. The map can be divided into three distinct dip domains (A, B, and C) where layer dips are fairly constant. Belts between domains are fold-hinge zones (i.e., domain boundaries).

In an ideal kink fold, layering abruptly changes its attitude across an imaginary planar boundary called a *kink plane* (Fig. 13-10), which is the fold's axial surface. Layers in adjacent limbs of a kink fold meet along a *kink axis*; the change in attitude between adjacent limbs can be described by a rotation around this axis. If layers do not thicken or thin during folding, the kink plane bisects the angle between adjacent limbs. If the layer thickness does change, the kink plane does not bisect the angle between adjacent limbs.

A kink band is composed of two parallel kink planes whose kink axes are parallel but have the opposite sense of rotation (Fig. 13-10). Intersecting kink bands produce folds with straight limbs and angular hinges (Fig. 13-11a).

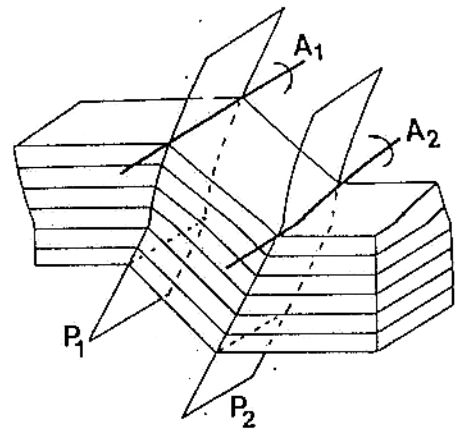


Figure 13-10. Idealized kink band, showing folded layers, two kink planes (P_1 and P_2) and kink axes A_1 and A_2. (From Faill, 1969.)

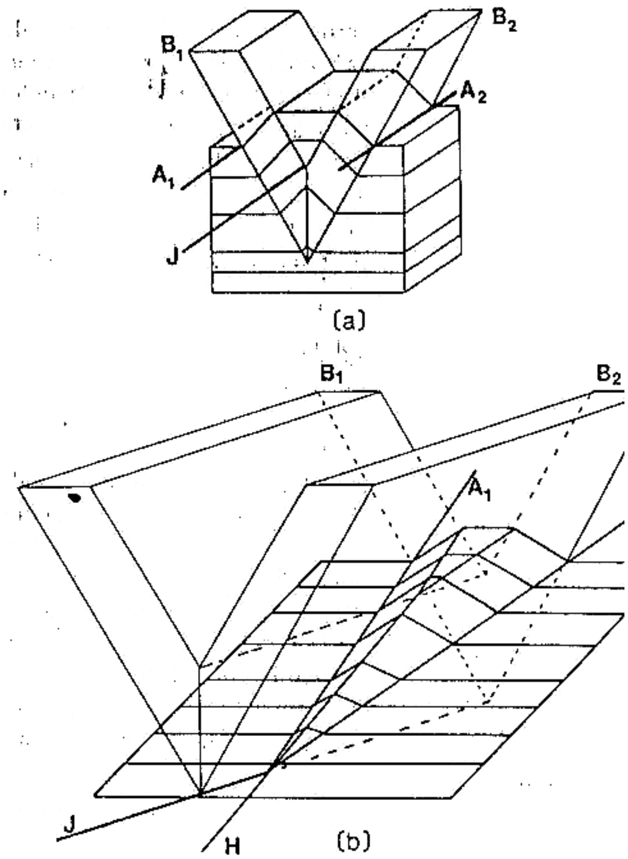


Figure 13-11. Geometry of folds formed by intersecting kink bands. (From Faill, 1969.) (a) A cylindrical angular fold is generated when two kink bands, B_1 and B_2, with kink junction axes A_1 and A_2 intersect along a kink junction axis J that lies in bedding; (b) if the kink junction axis J is oblique to bedding, intersecting kink bands form noncylindrical folds.

The line at which the two kink bands join is called the *kink junction axis* (line J in Figure 13-11a). If the kink junction axis lies in the plane of layering (Fig. 13-11a), the resulting fold is cylindrical, but if the kink junction axis is not in the plane of layering, noncylindrical folds result (Fig. 13-11b). In a section through either type of angular fold, the traces of contacts are straight, parallel lines whose inclinations change abruptly at fold hinges (the kink planes).

We can use the Busk method to construct sections of kink-style folds, but by doing so, we disregard the unique properties of kink folds. The kink method (Faill, 1969, 1973; Suppe, 1985) takes advantage of the unique properties of kink-style folds. In the kink method we draw the traces of layers as straight-line segments between adjacent fold hinges. As we will see, we locate and use known stratigraphic contacts to draw our cross section at the outset, thereby avoiding difficulties like those encountered in Problem 13-3. Because the kink method allows us to construct cross sections of angular folds rapidly and reliably, it has become popular in recent years. The boundary-ray method of section construction (Badgley, 1959, after Coates, 1945, and Gill, 1953) was also developed to accommodate angular folds, but because it requires data other than strike and dip readings and because it is quite complex, it is not widely used. The kink method is the method of choice for drawing sections of angular folds.

Kink Method Applied to Folds with Constant Layer Thickness

Problem 13-4

The stratigraphic contact between a limestone and a shale crops out at points X and Y along a N75°W-trending line of section across an angular parallel fold (Fig. 13-12a). The contact between the shale and a sandstone crops out at points W and Z, and the top of the sandstone crops out at point V. Line segments 1, 2, and 3 at points A, B, and C, respectively, give the dip values of different domains. Points V and W fall in dip domain 1 (N15°E,50°W), point X falls in dip domain 2 (N15°E, 10°W), and points Y and Z fall in dip domain 3 (N15°E,25°E). Use the kink method to draw a profile of the fold.

Method 13-4

Step 1: First, we locate the fold hinges. We assume that the limestone/shale contact that passes through point X is a straight-line segment. This line must have an inclination in the plane of the section that corresponds to the dip value of this domain, so we draw this segment of the contact parallel to line segment 2 at B. Likewise, draw the segment of the limestone/shale contact that passes through point Y parallel to line segment 3 at C. The two segments of the limestone/shale contact intersect at point L (Fig. 13-12b). Point L is the intersection between the trace of a kink hinge plane and the limestone/shale contact.

Step 2: To determine the trace of the hinge plane that passes through point L, bisect angle XLY. The hinge-plane trace is line ab (Fig. 13-12b).

Step 3: Draw the segment of the shale/sandstone contact trace passing through Z as a straight line parallel to YL. This line intersects hinge ab at point M. To continue the trace of this contact beyond the hinge, draw a line from M that is parallel to XL.

Step 4: Next, we position the second hinge-plane trace. The segment of the shale/sandstone contact passing through W must have an inclination in the plane of section that corresponds to the dip value for its domain. Draw the segment of this shale/sandstone contact passing through W as a straight-line segment parallel to line segment 1 at A. This portion of the shale/sandstone contact intersects the segment of the contact passing through M at the point N. Bisect ∠ WNM to determine the orientation of the second hinge-plane trace, which is line cd (Fig. 13-12c).

Step 5: Now we can complete the outer portion of the fold. The limestone/shale contact intersects line cd at point O. We can extend this contact beyond hinge cd as line segment OP, where angle POd = ∠ XOd. Draw the upper contact of the sandstone (QV parallel to PO, etc.).

Step 6: When any two kink-fold hinge traces intersect, they are supplanted by a single hinge trace that bisects the angle between the remaining opposing limbs (provided the layers' thicknesses remain constant). Hinge traces ab and cd intersect in the subsurface at point e. To position the traces of layers in the core of the fold, draw eS parallel to OP and eT parallel to LY. Draw fold hinge ef so that it bisects the angle between eS and eT.

Kink Method Applied to Folds with Changing Layer Thickness

In many cases surface data indicate that corresponding layers on opposing limbs of folds have different thicknesses. In these cases the fold hinges cannot bisect the interlimb angle, so the *axial angle* between each limb and the fold hinge is different for opposing limbs. Consider a kink fold where layer thickness changes abruptly from T on one limb (Fig. 13-13) to T' on the other limb. The two axial angles are γ and γ', where

$$\gamma = MBD \neq \gamma' = MBE.$$

A comparison of triangles MBD and EMB indicates that

$$T/\sin \gamma = BM = T'/\sin \gamma' \qquad \text{(Eq. 13-1)}$$

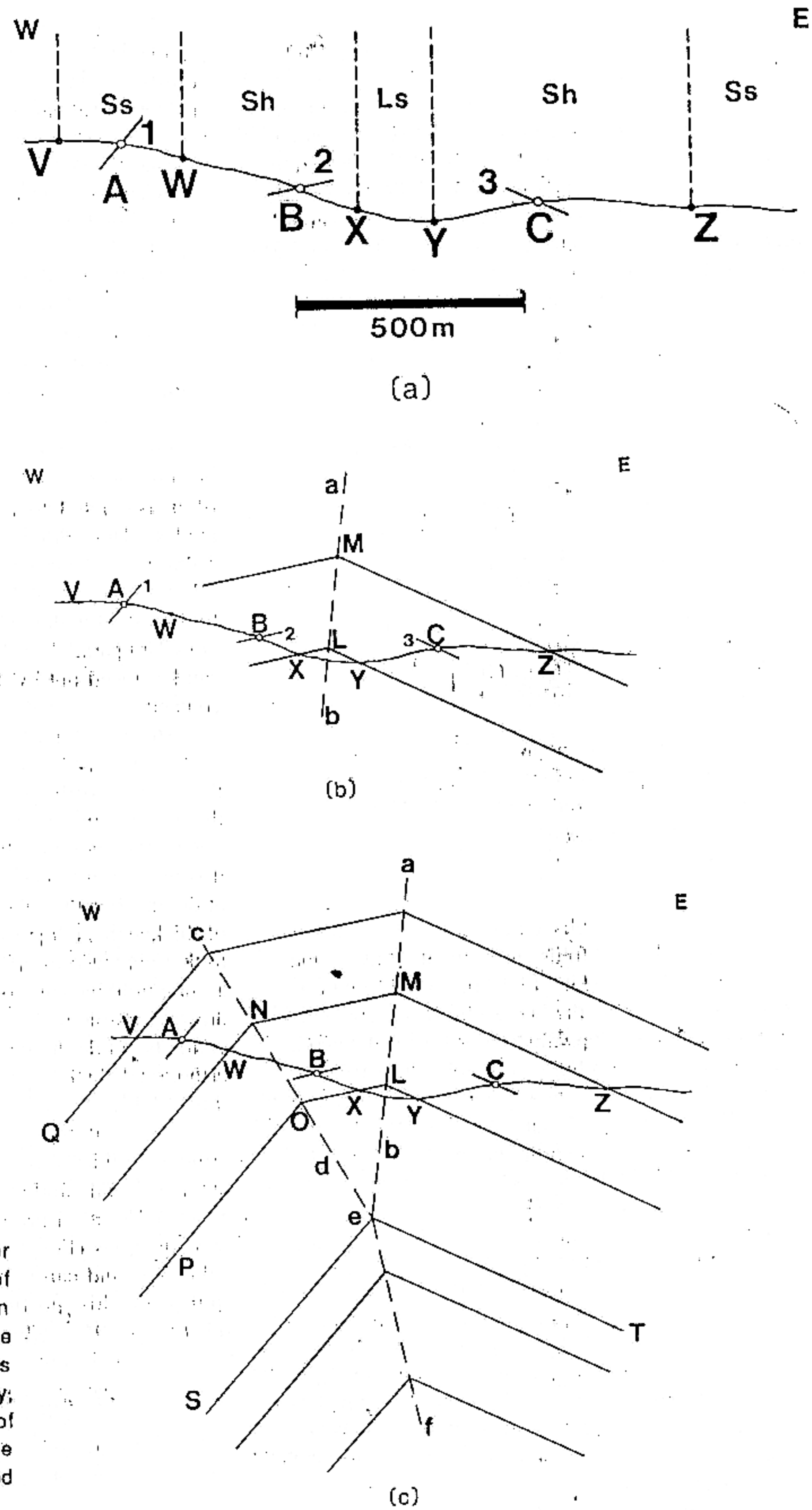


Figure 13-12. Illustrations for kink-method construction of Problem 13-4. (a) Raw dip data on a cross-section plane. Line segments 1, 2, and 3 give the dips at points A, B, and C, respectively; and represent the attitudes of different domains; (b) fold profile after completing step 3 in Method 13-4; (c) completed fold profile.

or,

$$T'/T = \sin \gamma'/\sin \gamma \qquad \text{(Eq. 13-2).}$$

If we can locate a fold hinge and we know the dips of the opposing fold limbs, we can measure the axial angles γ and γ' and can use Equation 13-2 to find the relative orthogonal thicknesses of layers on opposing limbs. If, alternatively, we know T and T' from field data, we can use Equation 13-2 to calculate the axial angles and orient the fold hinge in our reconstruction.

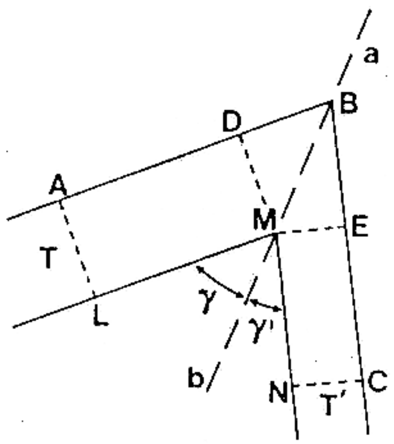


Figure 13-13. An angular fold with different layer thicknesses (T and T') on opposing limbs and unequal axial angles ($\angle$ DBM $\neq$ $\angle$ MBE).

Problem 13-5

Field mapping has established that a single stratum in a region of angular parallel folds crops out at points A and C along a line of section (Fig. 13-14a). A fold hinge is exposed at point h between the two limbs. Line segments 1, 2, and 3 give domainal dip values at points A, B, and C, respectively. Dipmeter readings in the borehole at D are also plotted on the figure. Note that two distinct dip domains are defined by the measurements in the drill hole. Use the kink method to draw a profile of the fold.

Method 13-5

Step 1: First, draw the trace of the fold hinge passing through point h. Locate point i in the drill hole halfway between two nonparallel dip measurements in the bore hole, and draw line ih. Extend this line into the sky.

Step 2: Draw a straight-line segment parallel to line segment 3 through point C, and extend it to intersect the fold-hinge trace at point G. Draw a straight line parallel to line segment 2 through point B, and extend it to intersect the fold-hinge trace at E.

Step 3: Draw line GJ parallel to BE and line EF parallel to CG. Note that the axial angle JGE is not equivalent to the axial angle CGE and that layer thickness JB is not equivalent to layer thickness CF. By inspecting Figure 13-14b, we see that the eastern limb was thinned to 83% of the thickness of the flat-lying limb during folding.

Step 4: To complete the outer portion of the fold profile, we must position the fold hinge between dip domains 1 and 2 in the western portion of the profile. Changes in layer thickness in the eastern portion of the profile make us wary about applying the parallel folding assumption elsewhere in the profile. We need field data, however, on the relative thicknesses of layers in the limbs of this open fold to draw this western fold hinge. Lacking such data, we *assume* here that layering neither thickened nor thinned as this open fold formed. This is reasonable because changes in layer thicknesses in angular folds are often restricted to folds with relatively tight interlimb angles. Thus, draw a straight line parallel to line segment 1 through A, and extend it to intersect the continuation of GJ at K. Bisect angle AKJ to find the trace of the second fold hinge (line lm). Extend BE to intersect lm at N, then draw NO parallel to AK. The shallower levels of the fold can be traced out by drawing lines parallel to established contacts.

Step 5: A problem arises below the depth at which fold-hinge traces hi and lm intersect (point S). Because of the thinning of the eastern limb, we cannot simply bisect the angle between opposite limbs to determine the hinge trace below point S. In order to complete the fold profile, it is necessary to know how much layer thinning occurred at depth. For the sake of argument, assume that the ratio of thicknesses in opposing limbs in the subsurface is equal to that observed in the outer portion of the fold. With this assumption, we can position the fold hinge graphically by drawing lithologic contacts at depth parallel to established contacts while maintaining a fixed ratio between the orthogonal thicknesses of the eastern and western limbs (Fig. 13-14c).

Alternatively, we could substitute this ratio of orthogonal thicknesses into Equation 13-2. We know that the two axial angles together must equal angle RST, measured (with a protractor) to be 94°. We have, then, two equations (Equation 13.2 and $\gamma + \gamma' = 94°$) with two unknowns and can solve for the values of the two axial angles in this portion of the fold. We begin by substituting $94° - \gamma$ for γ' into Equation 13.2. Using the trigonometric identity for the sine of the difference between two angles, we can rewrite this equation in terms of $\sin \gamma$ and $\cos \gamma$. Combining terms and rearranging, we have $\gamma = \arctan [\sin 94°/(0.84 + \cos 94°)]$, or $\gamma = 52.3°$ and $\gamma' = 41.7°$, the same values we determined graphically.

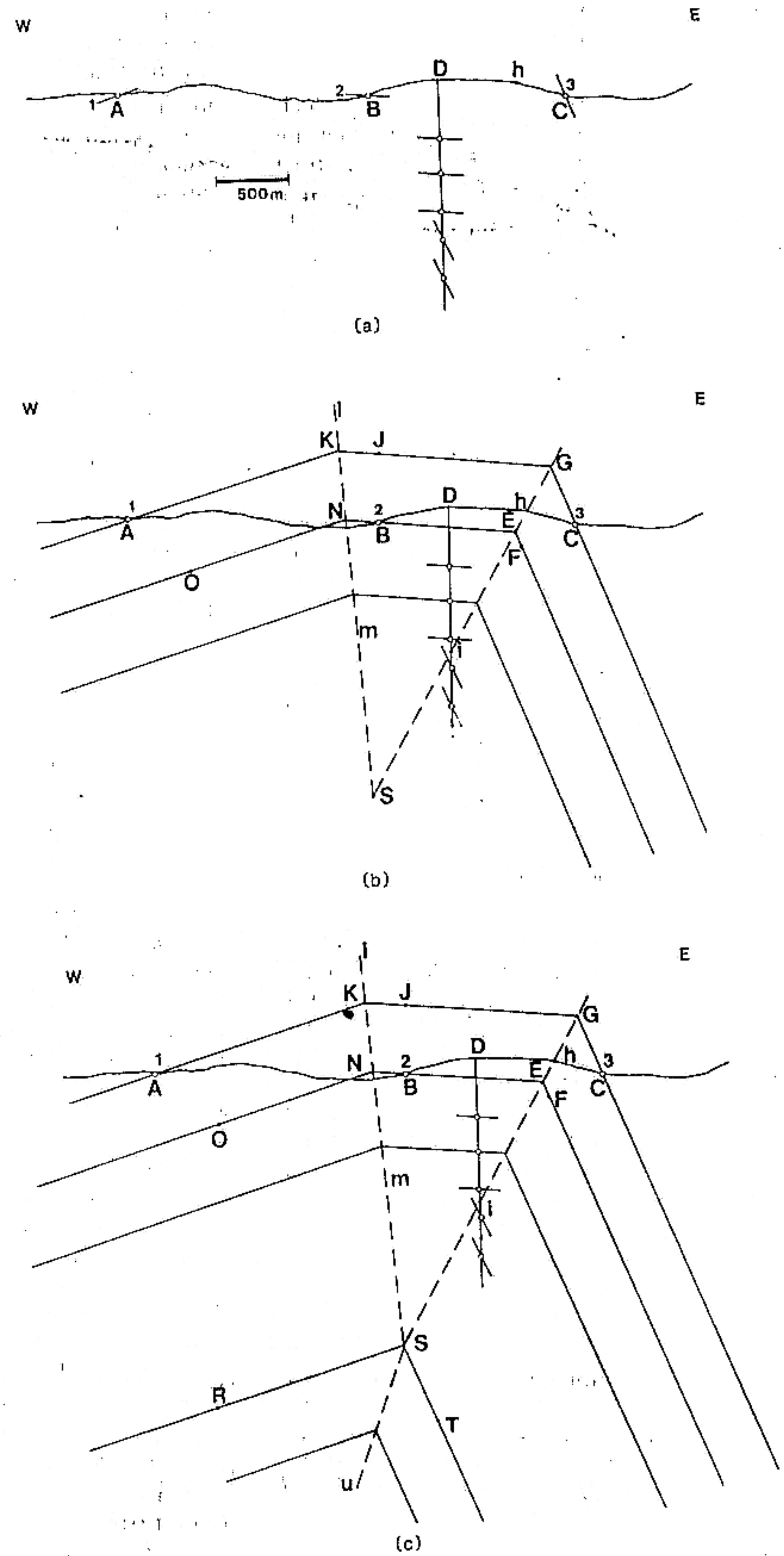


Figure 13-14. Illustrations for kink-method construction of a fold with nonconstant layer thickness, described in Problem 13-5. (a) Raw data plotted on a cross-section plane. A drill hole at point D provides subsurface data; (b) partially completed fold profile after step 4 in Method 13-5; (c) completed fold profile.

13-5 DIP-ISOGON METHOD OF CONSTRUCTING FOLD PROFILES

If we have information on the characteristic way in which layer thicknesses vary in a region (variations that are commonly a function of lithology), we can construct reasonable profiles of the folds in the region, even when it is not possible, because of the layer-thickness variation, to use Methods 13-3, 13-4, or 13-5. Variations in layer thickness are readily described by *dip-isogon patterns* (Ramsay, 1967), which indicate the relative curvatures of the outer and inner arcs of folded layers (see Chapter 11). Remember that a *dip isogon* is a line in the profile plane that connects points with equal dip values on successive contacts. Characteristic dip-isogon patterns can be derived by examining well-exposed minor folds in the region of interest or by studying well-constrained profiles in the region. Once the characteristic dip-isogon pattern is known for a sequence of beds at one location in a region, it can be used as a guide in constructing profiles of folds involving similar sequences of beds elsewhere in the region.

The following problem/method (based on procedures outlined by Ramsay and Huber, 1987) illustrates how to use characteristic dip-isogon patterns to reconstruct fold profiles. In the problem we refer to two angles: (1) δ is the angle between a specified reference line and the tangent to any folded layer at a point. We use the same reference line to measure all δ values in a single profile. The reference line may have any attitude, but normally we choose a horizontal line or a normal to the fold hinge as a reference line (Fig. 13-15a). If a fold-hinge plane is vertical, the normal to the hinge is horizontal, and δ values equal the local dip values. (2) $\emptyset$ is the angle between the normal to a folded layer at a point and the dip isogon that passes through that point (Fig. 13-15a). We call $\emptyset$ the *deflection* of the isogon. By convention, angles that open in a clockwise sense are negative, and angles that open in a counterclockwise sense are positive. The deflection angle usually changes as we trace an isogon from one rock type to another; $\emptyset$ is usually greater in less-competent layers (Fig. 13-15b). In plots of $\emptyset$ against δ, the curves connecting ($\emptyset$, γ) pairs for points on the surfaces of different layers are generally different.

Problem 13-6a (Characterizing dip-isogon patterns)

Figure 13-15b is a profile of folded quartzites and phyllites seen in a vertical roadcut. Assume that this profile indicates how quartzites and phyllites typically behaved during folding in this area, and determine the characteristic dip-isogon patterns for folded quartzites and phyllites in this area.

Method 13-6a

Step 1: Draw the hinge-surface trace ab on the profile. Draw a reference line for measuring δ values at different points on the layers. In Figure 13-15b the reference line RL is perpendicular to the fold hinge ab.

Step 2: At several points around the fold (at regular intervals, such as 5° or 10° increments, along each lithologic contact), draw a short line segment tangent to the contact. Measure the angle between this line segment and the reference line (Fig. 13-15a). In Figure 13-15b, for example, the outer arc of the phyllite bed has a dip value of $\delta = +60°$ at point X, the outer arc of the quartzite bed has a dip value of $\delta = +60°$ at point Y, and the inner arc of the quartzite bed has a dip value of $\delta = +60°$ at point Z.

Step 3: Draw straight-line segments across layers connecting equal dip (δ) values. These segments are the layers' dip isogons. In Figure 13-15b XY, is the +60° dip isogon for the phyllite bed, and YZ is the +60° dip isogon for the quartzite bed. Draw normals to layering where each

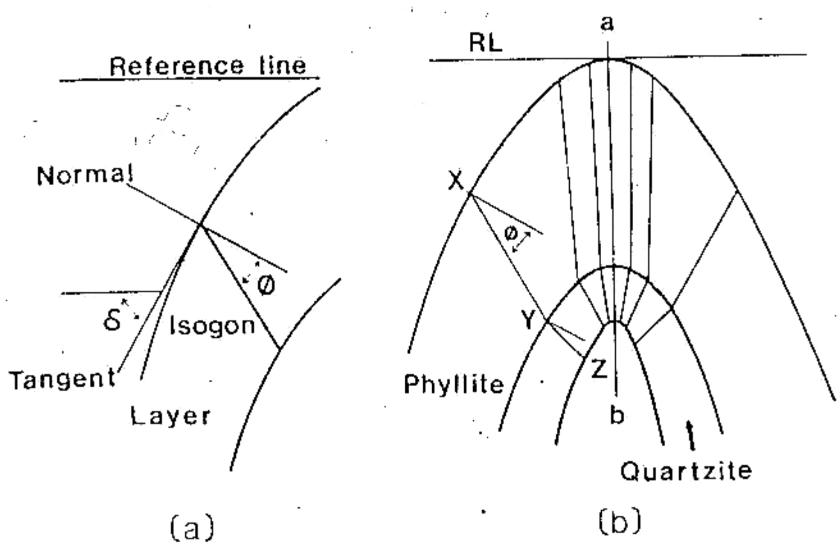
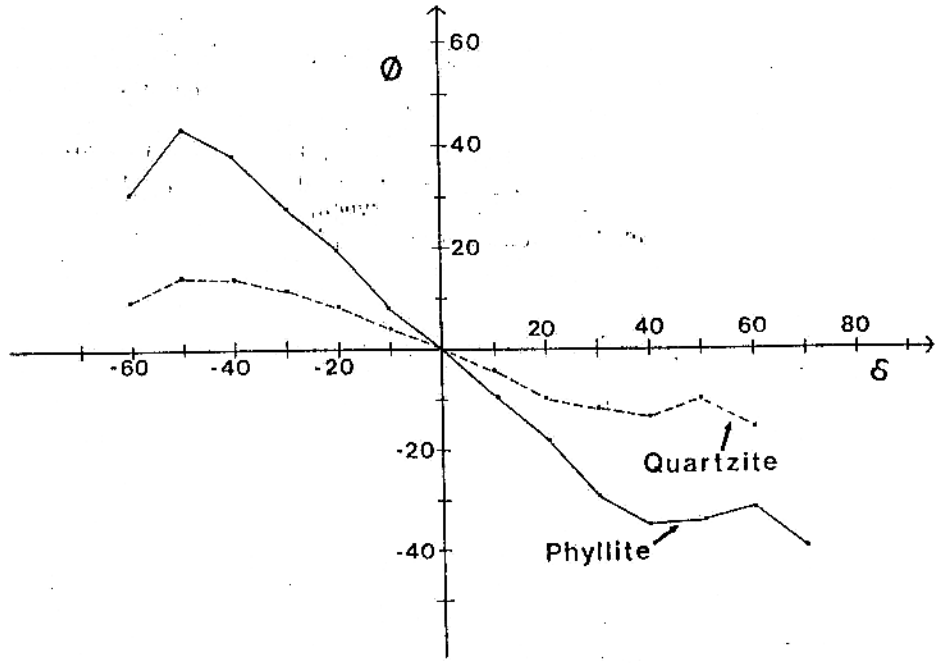
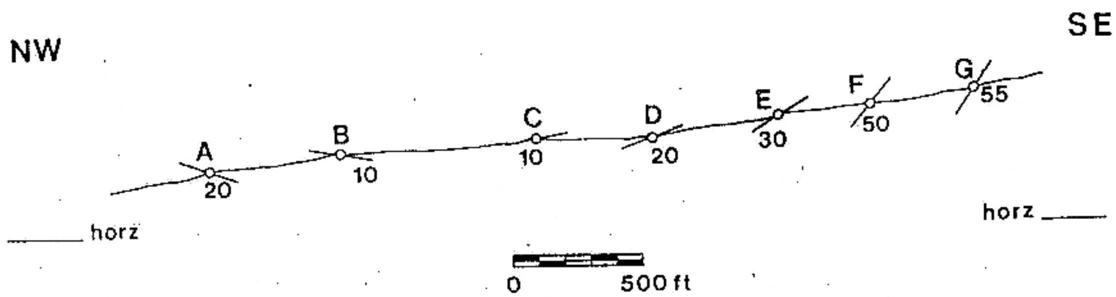


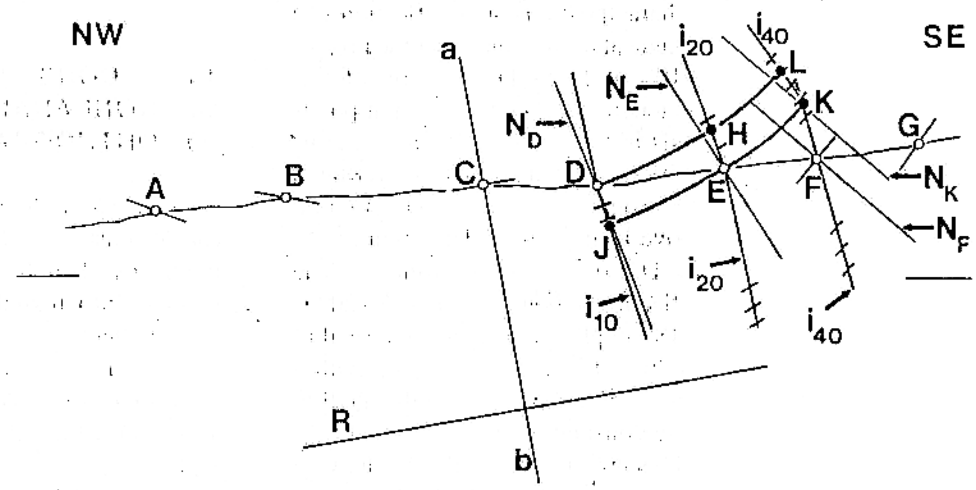
Figure 13-15. Illustrations of dip-isogon method of fold construction described in Problem 13-6. (a) Convention for measuring dip (δ) values with respect to a given reference line and dip-isogon deflection $\emptyset$; (b) profile of a well-exposed minor fold in the western portion of the Great Smoky Mountains, Tennessee Appalachians, involving a quartzite layer and a phyllite layer. The fold hinge is ab; several isogons are shown. XYZ is the +60° isogon in this fold; (c) plot of dip-isogon



(c)



(d)



(e)

deflection (ø) versus dip values (δ) for the quartzite layer (dashed line) and the phyllite layer (solid line) in (b); (d) topographic profile across Bates Mountain (from King, 1964), which is near the location of the fold shown in (b), with dip values at several locations. Quartzites crop out between D and E, a distinctive phyllilte layer crops out at G, and the fold hinge (with strike and dip N60°E,80SE) crops out at C; (e) profile after step 5 in Method 13-6b.

isogon intersects a lithologic contact, and measure the deflection angle of each isogon. In Figure 13-15b, ø = -32° for isogon XY, and ø = -15° for isogon YZ.

Step 4: Tabulate values of δ and ø for each layer in the profile, and plot these data on a graph with δ on the horizontal axis and ø on the vertical axis. Note that the the ø-versus-δ curve for phyllite is different from the ø-versus-δ curve for quartzite in Figure 13-15c. If we assume that the dip-isogon pattern in Figure 13-15b is typical of folds in this area, this graph *characterizes* the dip-isogon patterns for folded quartzite/phyllite sequences in this area. We use this graph to reconstruct a fold profile from dip data along a line of section.

Problem 13-6b (Dip-isogon construction of a fold profile)

Figure 13-15d is a topographic profile showing outcrop patterns and dip values along a N30°W-trending line of section across a folded quartzite/phyllite sequence near the location of Figure 13-15b. The fold's hinge crops out at point C; the strike and dip of the hinge is N60°E, 80°SE. The top of a quartzite bed crops out at point D; its base is exposed at E. A distinctive phyllite layer crops out at G. Assume that the fold does not plunge, and construct a profile of this fold.

Method 13-6b

Step 1: First, draw a reference line on the section with an orientation comparable to that in our characteristic profile (i.e., normal to the fold hinge). Draw the trace of the hinge surface, ab, on the profile, and draw reference line R perpendicular to ab.

Step 2: Measure the angle δ between the dip mark at each station along the line of section and the reference line R, and tabulate the measurements. For example, δ = +10° at point D, δ = +20° at point E, and δ = +40° at point F.

Step 3: Find the characteristic isogon deflection that corresponds to the dip value at each point along the profile. For example, δ = +10° at point D. Figure 13-15c indicates that the characteristic isogon deflection at points where δ = +10° in folds in this area is -5° in quartzite layers and -9.5° in phyllites. Draw a normal to layering at D (N_D). Draw the +10° isogon (i_{10}) with a deflection of -9.5° in the phyllite above D and with a deflection of -5° in the quartzite below D. δ = +20° at point E. The characteristic isogon deflection at points where δ = +20° is -10° in quartzites and -18° in phyllites. Draw a normal to layering at E (N_E), and draw the +20° isogon (i_{20}) with ø = -10° in the quartzite above E and ø = -18° in the phyllite below E. Dip values are constant along any isogon. As Ramsay and Huber (1987) suggest, indicate this by drawing several small tick marks, each parallel to the local dip, across each isogon.

Step 4: We assume that the isogon pattern in the fold in our section in Figure 13-15d is comparable to that in the characteristic profile. The phyllite/quartzite contact that crops out at D must have a δ value of +20° when it crosses isogon i_{20} above E. Using a french curve or a flexible ruler, extend the phyllite/quartzite contact to point H on the +20° isogon, making sure that this contact parallels the tick marks across the isogon at H. Similarly, the quartzite/phyllite contact exposed at E must have a δ value of +10° when it crosses isogon i_{10} below D. Extend the quartzite/phyllite contact from E to point J on the +10° isogon, making sure that this contact parallels the tick marks across the isogon at J.

Step 5: Draw a normal to layering through point F (N_F), and then draw the +40° isogon through this point (i_{40}) with the appropriate deflection angle for phyllites (-33°). Extend the quartzite/phyllite contact to point K on the +40° isogon, making sure that it is parallel to the tick marks across the isogon. The deflection of the +40° isogon must change from a value appropriate for phyllite to one appropriate for quartzite above K. Draw a normal to layering at K (N_K), and extend the +40° isogon above K with ø = -13°. We can then extend the phyllite/quartzite contact from H to L. Repeat steps 4 and 5 until you have completed the profile of the fold.

Fold profiles constructed by the dip-isogon method will show changes in layer thickness similar to those seen in the characteristic profile. Because the dip-isogon method uses the shapes of folds seen in well-constrained profiles as models for other profiles instead of assuming that layer thickness does not change around folds or changes abruptly across fold hinges, this method is conceptually more attractive than the Busk and kink methods. As Ramsay and Huber (1987) note, however, fold profiles drawn by the dip-isogon method become less reliable as we extend our profiles farther from data constraints.

13-6 CONSTRUCTING PROFILES OF NONPARALLEL FOLDS BY ORTHOGRAPHIC PROJECTION

Accurate and well-constrained profiles of nonplunging folds can be constructed directly from observational data obtained in regions where folds are cylindrical and topographic relief is sufficiently high that large portions of folds are exposed.

The technique introduced next involves orthographic projection and can be used for either parallel folds or nonparallel folds. It is particularly useful for nonparallel folds, for which the Busk and kink methods cannot be applied.

To visualize how a cross section of a nonplunging fold can be constructed, consider the patterns defined by the intersections between a cylindrically folded surface and the ground surface. A cylindrically folded surface intersects a horizontal ground surface in a series of straight lines that parallel the fold axis (ab, ef, and ij are parallel to cd and gh in Fig. 13-16a). This map pattern, a series of straight lines, tells us little about the shape of the fold in profile. If the folded surface intersects a vertical quarry wall,

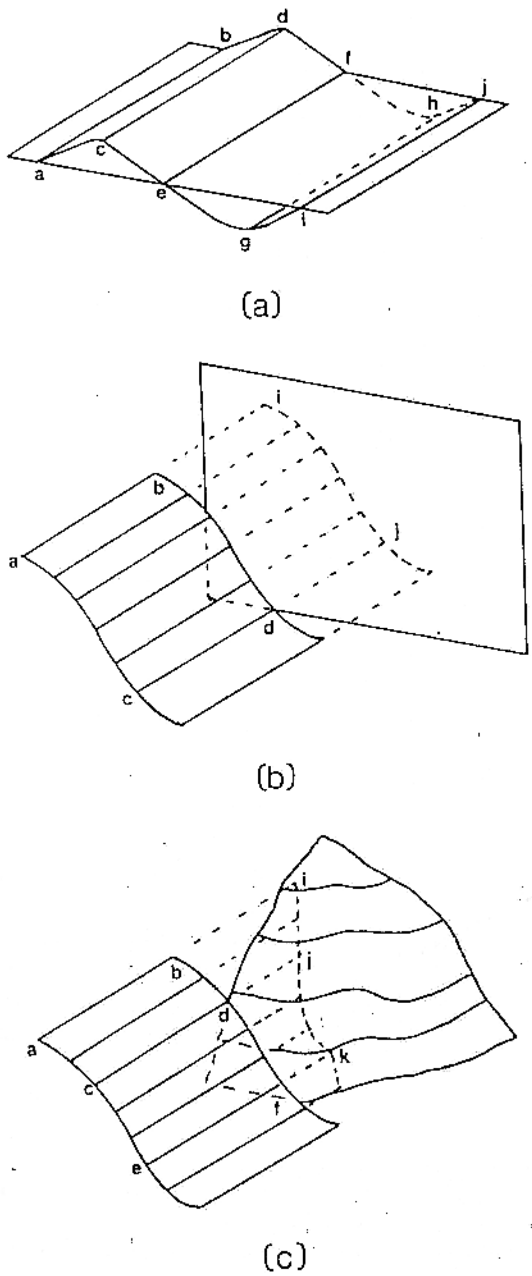


Figure 13-16. Traces of folds. (a) The traces of nonplunging cylindrical folds on a horizontal surface are straight lines; (b) trace of a cylindrically folded surface abdc on a vertical face is curve ij; (c) trace of cylindrically folded surface abfe on an irregular topographic surface is curve ijk.

however, the trace of the fold on the vertical surface gives the true shape of the folded layer (Fig. 13-16b). If the ground surface is irregular, the folded surface intersects the ground along an irregular trace (Fig. 13-16c). The shape of each segment of this irregular trace is controlled by the strike and dip of one portion of the folded layer. We can use this map trace to construct a profile of that folded contact. To define a folded layer, we need to know the map trace of both the upper and lower boundary of the layer.

Next, we show how to construct a profile of a folded contact from its trace on an irregular topographic surface. This problem is the inverse of the problem of calculating outcrop traces that was described in Chapter 2. Note that this method can also be used for parallel nonplunging folds that are exposed in regions of high relief.

Problem 13-7

Figure 13-17a is a map of a cross-bedded quartzite (stippled) that is overlain by marble (M) and is underlain by slate (S). The attitude measurements on the map indicate that this meta-sedimentary sequence has been folded, and a stereogram of the poles to bedding (not shown) indicates that folding is cylindrical around a horizontal axis. The arrow FA above the map gives the bearing of the fold axis. Draw a profile of the folded layers.

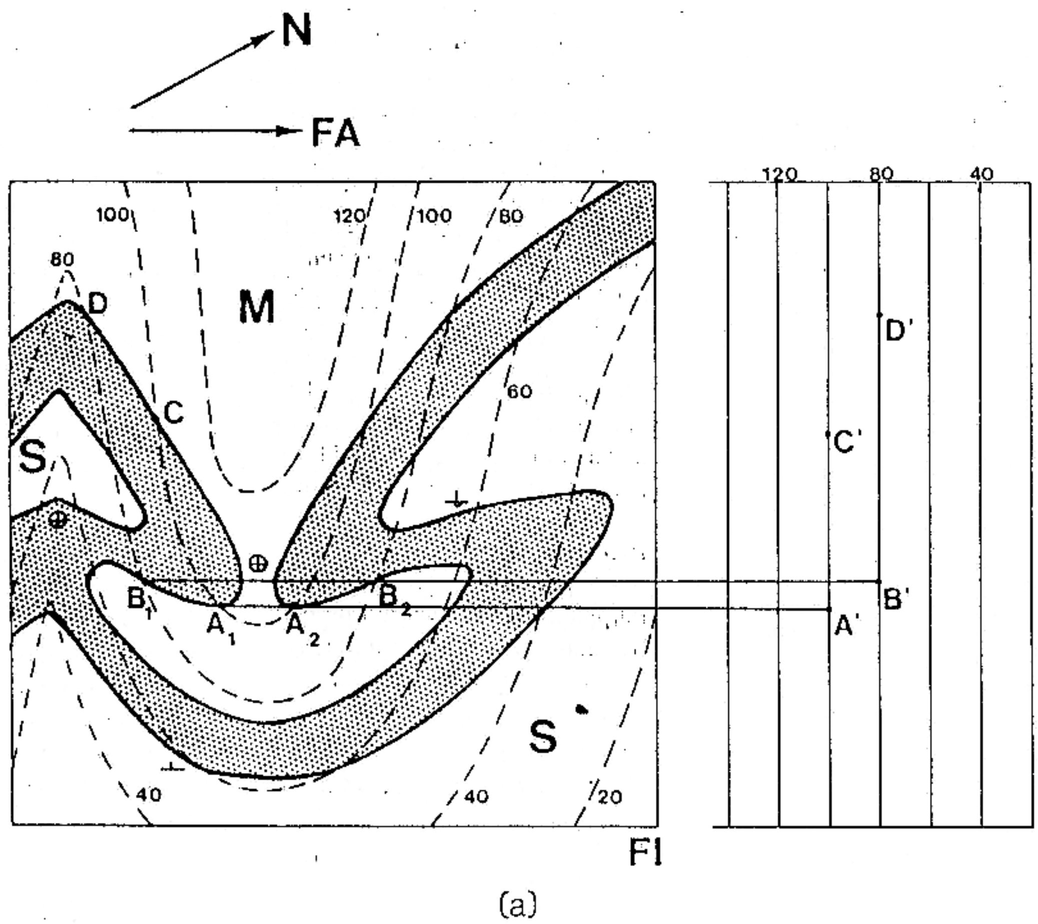
Method 13-7

Step 1: Draw a folding line (F1) perpendicular to the fold axis at the edge of the map, and swing up the cross-sectional view into the plane of the map projection. Draw a suite of lines parallel to the folding line on the rotated cross section. These lines are spaced to represent the difference in elevation between contour lines. The vertical scale on the cross section must be the same as the map scale.

Step 2: Locate the points on the map where the top and bottom contacts of the quartzite layer cross contour lines. From each point, draw a straight line parallel to the fold axis (and, therefore, perpendicular to the folding line) to the corresponding contour line in the rotated cross-sectional plane. For example, the quartzite/marble contact at A_1 on the map projection outcrops at 100 m; we draw a straight line from A_1 across to the 100-m grid line on the rotated cross section. This point plots as point A' on the grid. Notice that point A_2 on the map also plots as A' on the grid. Points B_1 and B_2 on the map plot as point B' on the rotated cross section.

Step 3: Repeat the procedure of step 2 for a sufficient number of points to define the profile trace of the lower contact. (For example, points C and D on the map plot as C' and D' on the rotated cross section). Then, repeat the procedure for points on the upper contact.

Step 4: Connect the points on the rotated cross



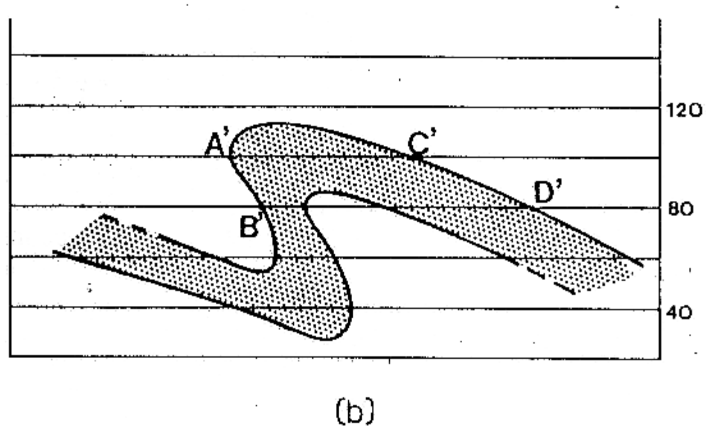


Figure 13-17. Illustration of profile construction of a horizontal cylindrical fold in a region of topographic relief, as described in Problem 13-7. (a) Map showing the outcrop belt of a unit (stipple pattern). The grid at the right is the cross-section plane rotated into the map plane around folding line F1; (b) completed profile of the fold.

section to trace out the upper and lower folded surfaces (Fig. 13-17b). The resulting profile automatically shows the variation in the thickness of the quartzite layer around the fold.

13-7 CONSTRUCTING PROFILES OF PLUNGING FOLDS

We stated earlier that the truest image of the shape of a cylindrical fold is a *profile* of the fold, drawn on a plane normal to the fold axis. The profile plane for a plunging fold is necessarily inclined. Sections other than profiles (e.g., vertical cross sections, oblique sections, or maps) yield fold forms with distorted limb thicknesses, distorted interlimb angles, and incorrect hinge positions (Fig. 13-18; see also Roberts, 1982; Ramsay and Huber, 1987). Fortunately, the very fact that the fold plunges makes it possible for us to see large portions of the fold on a map. Map data can, therefore, allow us to *construct* a profile of a plunging fold. Likewise, subsurface data in a drill hole that is not perpendicular to the fold axis can also be used to construct fold profiles, if it is available. Next, we illustrate how to construct profiles of plunging folds from

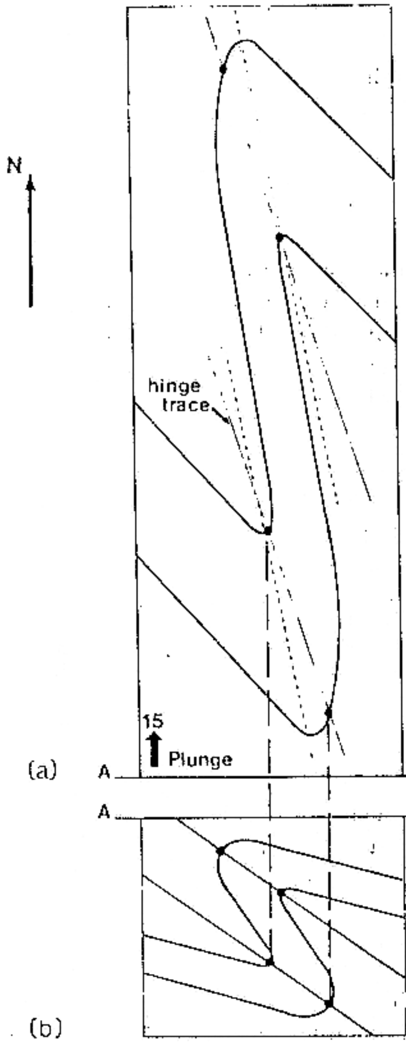


Figure 13-18. Illustration of the distortion of a plunging fold that occurs on a map. (See Schryver, 1966.) (a) Map of a plunging asymmetric fold. The lines connecting zones of maximum curvature in the map traces (thin dashed lines) do not give the true positions of the hinge traces (thin solid lines); (b) profile of the fold.

map and subsurface data. The specific technique that must be used depends on whether the fold is exposed in a region of high topographic relief or in a region of low topographic relief.

Constructing Profiles of Plunging Folds from Maps of Regions with Low Topographic Relief

In regions of low topographic relief (i.e., the heights of hills in the map area are significantly less than the amplitude of the folds in the area), the map plane is essentially an oblique section through the fold. To visualize this principle, refer back to Figure 13-1. Not how the intersection of the plunging circular cylinder wi both the map plane and the vertical cross-sectional plane an ellipse; only on a profile plane oriented perpendicular t the cylinder do you see a circular section. There are tw ways to use the map pattern to construct a profile.

(1) Down-Structure Viewing and Freehan Sketching: The first method is generally referred to a *down-structure viewing.* To obtain a down-structure vie of the plunging circular cylinder in Figure 13-1, simp orient your line of sight so that it parallels the axis of th structure. When viewed from this angle, the ellipse w appear to be a circle. In the field, to obtain down-structure view of a fold, you should place yourself that you are looking down (or up) the hinge of a fold (Fi 13-19a). Sometimes, it is necessary to get into awkward position in order to properly view a structu (Fig. 13-19b)! When positioned properly, you will see t profile form of the fold. It takes practice to down-plunge viewing easily. It may help to relax yo eyes or close one eye and trick yourself into ignoring yo natural depth perception, so that the oblique section of t fold on the outcrop surface appears foreshortened onto single plane that is oriented perpendicular to the hin Sketch the shape of the fold that you see freehand.

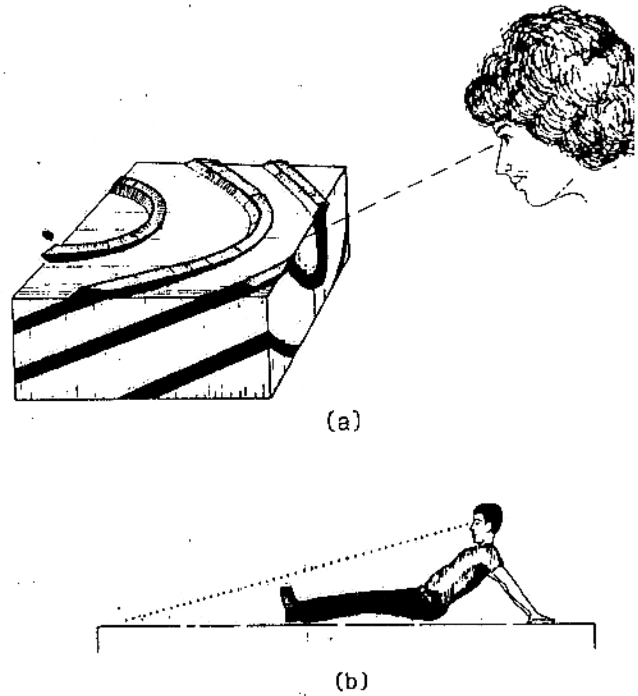


Figure 13-19. Illustration of down-structure viewing. (a) Observer positioned so that her line of sight is parallel is coincident with the hinge of the fold; (b) observer positioned to view a shallowly plunging fold that intersects the ground surface.

We can also use the technique of down-structure viewing to view maps (Mackin, 1950). The only difference between down-structure viewing of a map and down-structure viewing of an outcrop is that in order to orient yourself properly to view the map, you must read the attitude symbols on the map so that you know the plunge direction of the folds. Place the map on a table, and position your line of sight to view it down structure. As before, you can sketch the profile of the fold freehand as you view the map from this angle. Typically, the true amplitude of a fold (the amplitude in profile) will be much less than the apparent amplitude that is indicated in the map plane, and apparent thickening in the hinge may vanish (Figs. 13-1b and c, 13-18). Also, the true symmetry or asymmetry of a fold will be obvious in the profile view.

(2) Grid Method of Profile Construction: The *grid method* (Roberts, 1982; Ragan, 1985) is a graphical technique that allows us to construct *accurate* profiles of plunging folds in regions of low relief from a map of the fold. To understand the basis of this method, again consider the plunging circular cylinder of Figure 13-1. We saw that the map-plane image of the plunging circular cylinder is an ellipse. The line WX across the ellipse (Fig. 13-20), which is perpendicular to the bearing of the cylinder axis, is the same as the diameter (D) of the circular profile of the cylinder, but the line YZ across the ellipse, which has the same bearing as the cylinder axis, is greater than the diameter (D) of the circular profile. If we are given the length of YZ (called D'), we can calculate D from the equation

$$D = D'(\sin \mu) \quad \text{(Eq. 13-3),}$$

where μ is the plunge of the axis of the cylinder.

Now consider a map of a plunging fold. Distances between points on the fold surface measured along lines that are perpendicular to the bearing of the hinge are undistorted, whereas distances measured along lines that are parallel to the bearing of the hinge will be greater than they would be in profile. The distance in profile between any two points along a line on the map that is parallel to the bearing of the fold axis can be found by applying Equation 13-3. In other words,

$$\text{Profile distance between two points on the map} = \text{Distance observed on the map}\,(\sin \mu) \quad \text{(Eq. 13-4).}$$

Keeping this equation in mind, we can transfer contact positions from a square map grid onto a profile grid in which one direction is foreshortened according to Equation 13-3, as demonstrated in the following problem (see also Roberts, 1982; Ragan 1985).

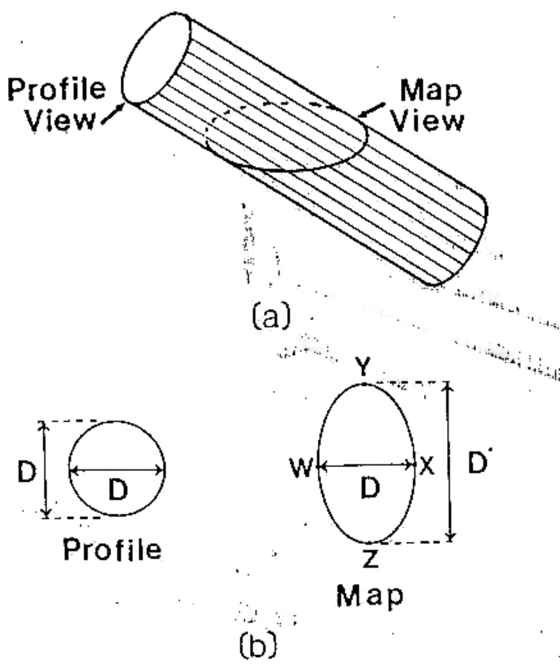


Figure 13-20. Profile versus map views of a plunging circular cylinder. (a) A plunging circular cylinder produces an elliptical trace on a horizontal map; (b) a comparison of the map and profile sections of the circular cylinder.

Problem 13-8

Figure 13-21a is a map of a plunging fold in an area where the topographic relief is small relative to the amplitude of the folds. Stereographic projections of poles to bedding from this map area lie along a single great circle, indicating that the folds are cylindrical. The fold axis (the normal to the great circle on the π-diagram) is oriented 30°,040°. Draw an accurate profile of this fold by using the grid method.

Method 13-8

Step 1: On a transparent overlay large enough to cover the map area, draw a square grid composed of mutually orthogonal suites of lines. The spacing between lines in a suite is an arbitrary distance S (S should be chosen so that a reasonable number of grid lines are drawn; i.e., it should be possible to locate points on the folded contacts accurately with respect to the grid). Use a thicker pen to draw the lines at the left edge of the grid and at the bottom of the grid; these two lines are reference lines.

Step 2: On a separate piece of drafting paper, construct a rectangular grid (here called the *foreshortened grid*) composed of two mutually orthogonal suites of lines. The lines in one suite should be spaced at a distance S apart, and the lines of the second suite should be spaced at a

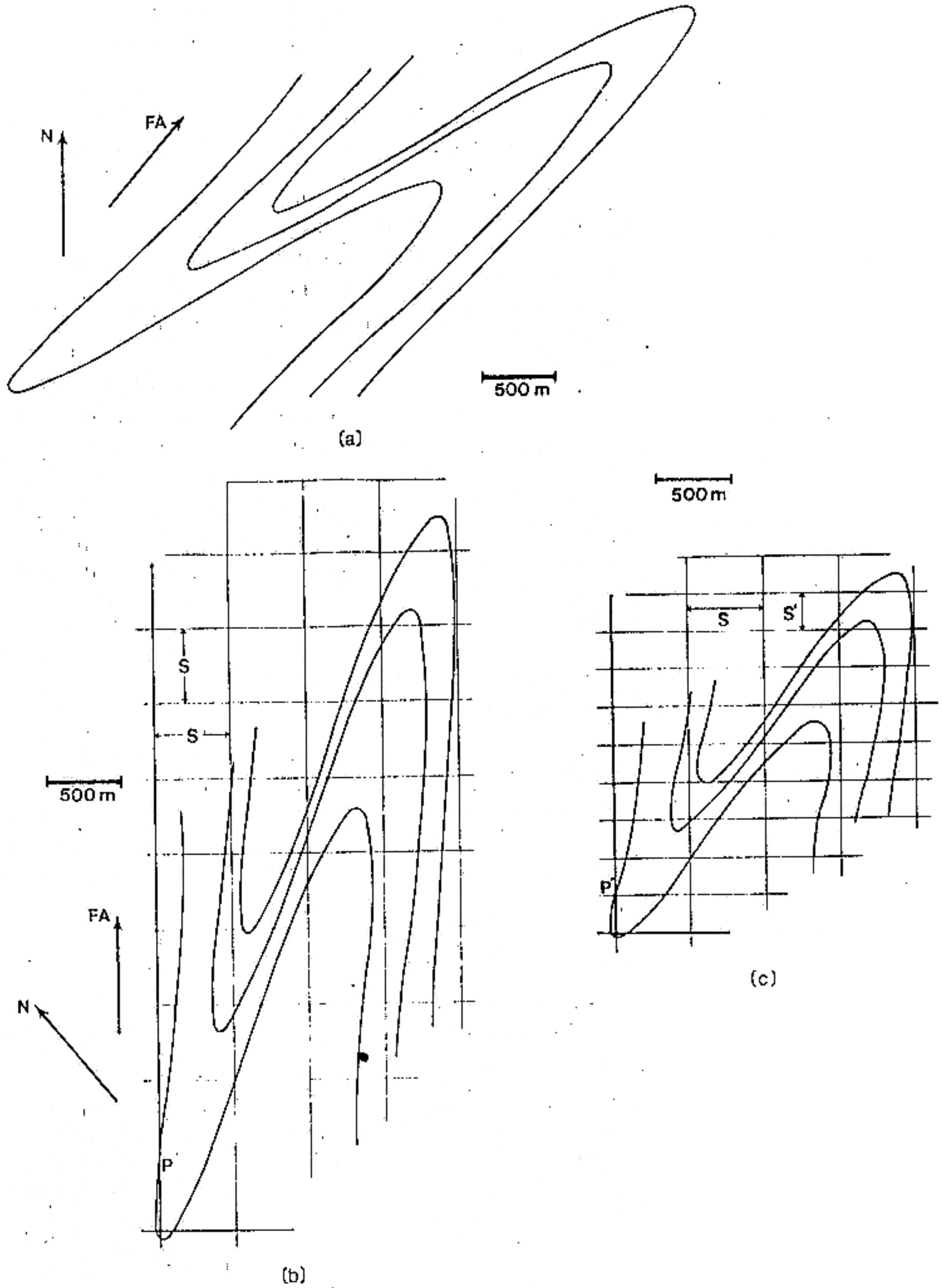


Figure 13-21. Illustration of the grid method for constructing profiles of plunging folds. (a) Map of a fold that plunges 30° in the direction given by FA; (b) map with square grid superimposed on it; (c) the profile plane illustrating the foreshortened grid. See Method 13-8 for more explanation.

distance S' apart, where $S' = S(\sin 30^\circ) = 0.5S$. There should be the same number of lines in the rectangular grid as there are in the square grid. Use a thicker pen to draw the reference lines.

Step 3: Secure the map to your drafting table with the up-plunge portions of the fold nearest to you. Place the square grid over the map with one set of lines parallel to the trend of the fold axis, and secure the overlay in place (Fig. 13-21b). Secure the foreshortened grid to the table next to the map and overlay; the foreshortened grid should be positioned so the suite of lines that are S' apart are oriented perpendicular to the fold-axis bearing (Fig. 13-21c). The lines spaced S' apart are horizontal lines in the profile plane. The lines spaced at a distance S apart are parallel to the bearing of the fold axis; they are parallel to the dip direction of the inclined profile plane--they do not represent vertical lines.

Step 4: Now we use the square grid to locate points on the map traces of the folded layers, and the rectangular grid to position the corresponding points in a profile plane. For example, locate point P in Figure 13-21b. It coincides with the intersection of two grid lines; one line is two lines up from the bottom reference line and the other line is the left reference line. We plot the image of P on the profile plane by finding the corresponding location on the rectangular grid (Fig. 13-21c). Point P' on Figure 13-21c is also located at the intersection of the left reference line with a line two lines up from the bottom reference line.

Step 5: Locate other points on the map of the fold trace with respect to the square grid, and plot the corresponding image points on the profile plane (i.e., the rectangular grid). Using the positions of the points plotted on the rectangular grid as a guide, trace out the image of the folded surface on the rectangular grid. This image (Fig. 13-21c) is the properly foreshortened image of the fold.

An alternative approach is to slide the foreshortened grid over the square grid and, with one of the "horizontal" lines (those spaced distance S' apart) over the corresponding line in the square grid, make tick marks where each contact crosses the line. Repeat this for each "horizontal" line in the profile plane, and use the tick marks to trace out the image of the folded contacts.

Constructing Fold Profiles from Maps of Regions with High Relief

When topographic relief is high (the heights of hills approach or exceed the amplitudes of folds in the area), our map is no longer a single oblique section through a plunging fold. Different portions of the map may be different oblique sections through the fold, but the composite map image is not simply related to the fold shape in profile. If, however, we know the orientation of the fold axis, we can pass a straight line parallel to the fold axis through each point along the map trace of a folded layer and extend these lines to pierce a profile plane. The piercing points collectively define the layer's trace on the profile plane. Next, we introduce a graphical method for finding the piercing points on a profile plane and constructing a profile of the fold. This method works both for parallel and nonparallel cylindrical folds.

Problem 13-9

Figure 13-22 is a map of a folded marble (M), sandstone (Ss), and shale (Sh). An equal-area plot of poles-to-bedding readings from this region (not shown) indicates that the attitude of the fold axis is 30°,045°. Draw an accurate profile of these folded layers.

Method 13-9

Step 1: Align the map so that the plunging fold axis points away from you. Place a sheet of tracing paper over the map.

Step 2: On the right side of the overlay, draw line AB parallel to the bearing of the fold axis. Next, draw lines AD and BC normal to AB, with AD across the up-plunge edge of the map, and BC across the down-plunge edge of the map. Rectangle ABCD outlines that part of the map that we will project onto the profile plane.

Step 3: Let line AB be a folding line (F1), and swing down a vertical cross-sectional plane around F1 (note that we are swinging down an imaginary plane that had extended up into the sky). Draw a suite of parallel lines in the rotated cross-section plane that are parallel to AB and whose spacing, at the scale of the map, equals the map's contour interval. The lowest contour (in this case the 100-m line) should be placed closest to AB. Draw line BQ in the rotated cross-section plane so that it makes an angle of μ (that is, the plunge of the fold) with AB. Line BQ represents the fold axis; note that it plunges to the NE.

Step 4: Find the perpendicular to line BQ that passes through A, and extend it to intersect BQ at point J. We now have right triangle AJB inscribed in our vertical cross-section plane. Line AB is horizontal, and line JB is parallel to the fold axis. Line AJ, which is perpendicular to JB, is the trace of a profile plane on the vertical section. You may wish to erase the contour lines in the cross-section plane that are outside this right triangle.

Step 5: Draw a second rectangle EFGH at the up-plunge end of the map, with EF (farther from you) and GH (closer to you) parallel to DA and equal in length to DA. FG and EH are colinear with CD and AB, respectively. If rectangle EFGH were positioned so that GH coincided with DA and EH coincided with JA, then we could consider EFGH to be a "frame" in the profile plane through which we could view the plunging folds. Because EFGH represents an inclined plane, lines parallel to EF are horizontal, but those parallel to FG are inclined.

Step 6: To draw the fold profile in the "frame" of EFGH we first find a point on the map plane where the trace of the geologic contact intersects a contour line. We choose point L, which lies on the 200-m contour. Through point L we draw two lines; one parallel to AB and one parallel to DA. Extend the line parallel to DA across triangle ABJ to point M, which lies on the 200-m contour line of the rotated cross-section plane. Extend the line parallel to AB across rectangle EFGH; this line intersects EF at N and intersects GH at O.

Step 7: Return to the triangle ABJ. Draw line MP parallel to BJ. Measure the length of segment JP along line AJ. Point L', which is the projection of L in the profile plane (EFGH), lies along line NO; the length of segment NL' equals the length of segment JP.

Step 8: Repeat the procedure for many other points. For example, S' is found by drawing lines SV and ST. Line SV intersects rectangle EFGH at U and V. Line ST ends where it crosses the contour line in triangle AJB in the vertical section plane whose elevation equals the elevation at S. Draw line TW parallel to BJ. Plot point S' along line UV so that the length of segment US' equals the

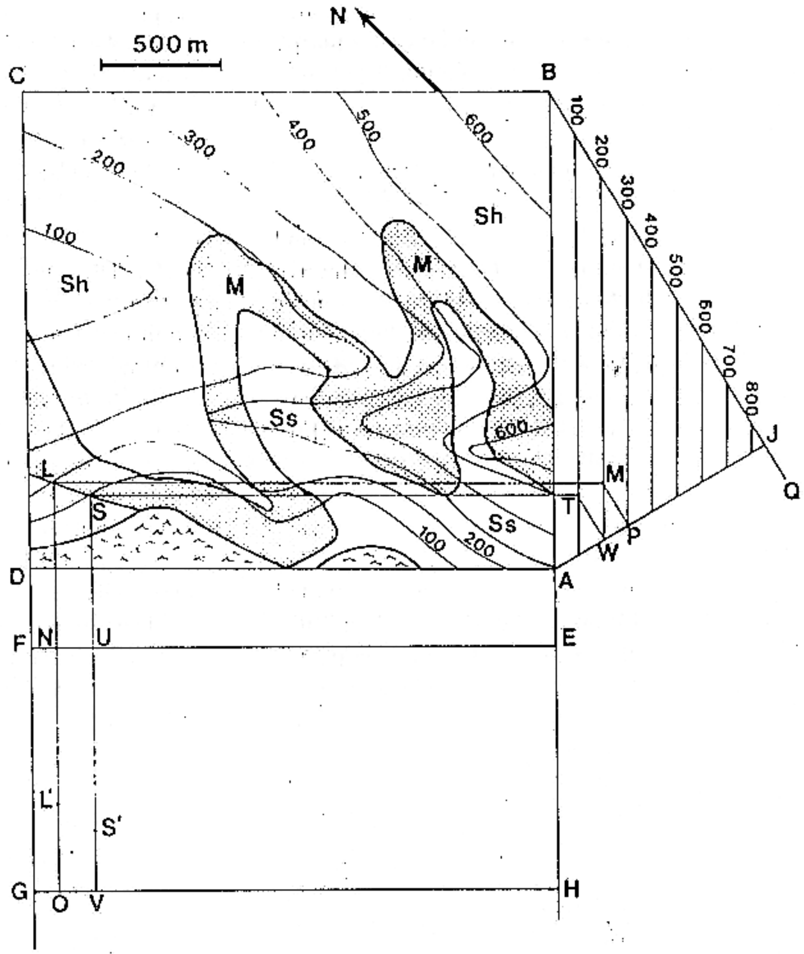


Figure 13-22. Illustration of method for constructing profiles of plunging folds that crop out in areas of high relief, as described in Problem 13-9. Map of folded sandstone (Ss), marble (M and stippled), and shale (Sh) sequence; topographic contours in meters. Triangle ABJ at right is a vertical cross section folded down into plane of the map. Rectangle EFGH is a profile plane positioned in the plane of the map.

length of segment JW along AJ. By connecting the profile images of several points along a particular contact, we can trace out the profile image of that contact (Fig. 13-23).

In the preceding method, lines EF and GH were used as reference lines to determine the positions of points L' and S'. Note that we can draw contour lines on the profile plane, but that the spacing of the contours will not be the same as the spacing on triangle ABJ. Remember that ABJ represents a vertical plane, whereas EFGH represents an inclined profile plane. Therefore, the spacing of contours on EFGH is

$$\text{spacing} = d/\cos \mu \qquad \text{(Eq. 13-5)},$$

where d is the distance between contours in triangle ABJ, and μ is the plunge of the fold axis.

The graphical procedure just described is very tedious if there are many points to be transferred from the map to the profile plane. Section 13-8 provides an algebraic version

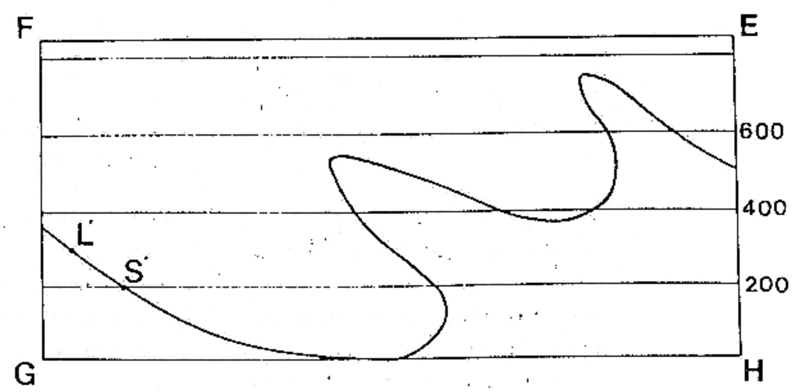


Figure 13-23. Fold profile of the contact between the marble (M) and the sandstone (Ss) shown on the map in Figure 13-22. L' and S' are points determined in Method 13-9.

of the projection procedure, which can be easily converted into a computer algorithm, thereby making it possible for a computer to construct the profile.

13-8 CONSTRUCTING BLOCK DIAGRAMS

A block diagram, with a geologic map on its top face and geologic cross sections along its side faces, is an effective means of portraying geologic structures. In this section we examine how to draw block diagrams with any orientation that correctly portray geologic structures in perspective. We also learn how to plot geologic data on the diagrams. The methods require the use of an *orthographic net* (Fig. 13-24).

The Orthographic Net

An orthographic projection of a sphere can be constructed by simply passing a suite of parallel projection lines through the sphere so that they intersect a projection plane; the projection plane must be perpendicular to the projection lines (Fig. 13-24a). To help you visualize an orthographic projection, consider that the view of the moon that we have from earth is essentially an orthographic projection of half the moon's surface. Imagine a sphere on which lines of latitude and longitude have been drawn. An orthographic projection of this graticule (see Appendix 1) onto any vertical great circle will appear as a grid of lines within the circle. The lines of latitude (which are small circles) appear as straight lines parallel to the equator, and the lines of longitude (which are great circles) appear as elliptical arcs running from pole to pole. This grid is called an *orthographic net* (Fig. 13-24b) or *orthonet*. We can plot lines and planes or rotate geometric elements on an orthographic net exactly like we have done on a stereonet. As is the case with a stereonet, we portray only lower-hemisphere spherical projections on an orthonet, so the projection lines are vertical, and the projection plane is horizontal.

The properties of an orthographic net allow you to rotate figures to simulate the effect of changing your line

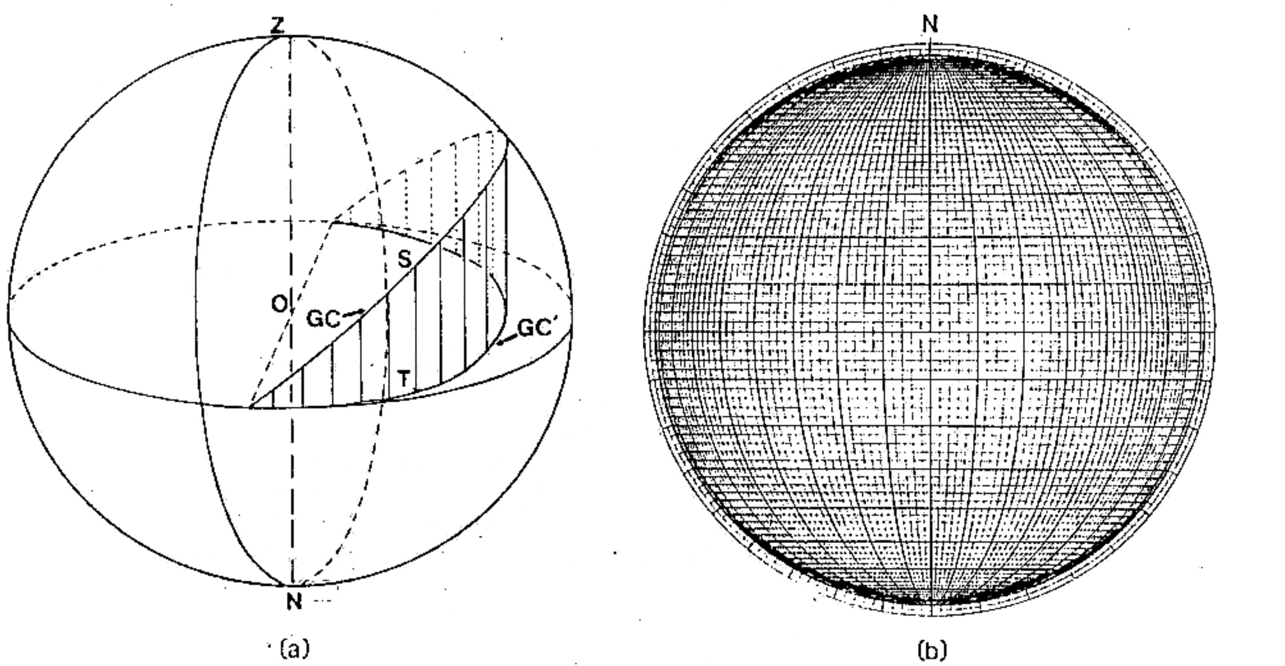


Figure 13-24. The orthographic net. (a) Construction of an orthographic net. O is the center of the projection sphere, Z is its zenith, and N is its nadir. GC is the upper-hemisphere spherical projection of a plane passing through the center of the net. We find the orthographic projection of any point on the surface of the projection sphere (such as point S) by drawing a line that is parallel to ZN through the point and finding where it pierces a plane perpendicular to ZN. In this way we can draw the orthographic projection of the great circle (GC'). We show the upper-hemisphere projection only because it is easier to see in this drawing; (b) a completed orthographic net.

of sight; thus, it is very useful for constructing isometric block diagrams (Appendix 1; also see McIntyre and Weiss, 1956).

Constructing a Cube with an Orthographic Net

Let us begin by examining how to render a cube with a horizontal top face that is viewed along different lines of sight. If we view the cube along a normal to its top face, we see the cube as a square (Fig. 13-25a). Other faces, edges, and vertices on the cube are hidden by this face. We can see the cube's other components only by rotating the cube or by changing our viewing axis. Next, we show a method outlined by Lisle (1980) to draw, in proper perspective, a cube of any orientation viewed along any line of sight.

Problem 13-10

Begin with a cube whose top face is horizontal and whose side faces are aligned northeast and northwest. Draw how the cube would look when viewed along a line oriented 30°,005°.

Method 13-10

Step 1: Prepare an overlay for use with the orthographic net as you did for the stereonet (i.e., push a pin through the center of the net and puncture the overlay with the pin; see Chapter 5). On the overlay, trace the primitive of the orthographic net, and draw a tick mark to indicate north. Place the north mark on the overlay over the north mark on the net.

Step 2: First, plot three points, each representing the orientation of one edge of the cube (these are called the principal directions of the cube). One edge is vertical and is represented by point V at the center of the the net (Fig. 13-25b). The northeast-trending horizontal edge plots as point X on the primitive, and the northwest-trending horizontal edge plots as point W on the primitive. By drawing VX, VW, and line segments parallel to them, we have an image of the cube viewed along a vertical line of sight, with north at the top of the page (Fig. 13-25b).

Step 3: To plot the point representing the line of sight, mark the bearing of the line on the primitive of your overlay. Revolve the overlay so that the bearing (5° east of north) mark lies on the equator (or over the north mark on the grid). Count in from the primitive by 30° to locate point L. Because grid lines are very closely spaced near the primitive, it is useful to check the location of any point by counting out the complement of this angle (60°) from the center of the net. Point L is the lower-hemisphere orthographic projection of the line of sight (Fig. 13-25b).

Step 4: To obtain a cube that appears to be viewe along our new line of sight (L), we rotate L about horizontal axis so that it moves to the center of the n To do this, we let the north-south axis of the net be t rotation axis and revolve the overlay so that point L lies the equator. Move L along the equator by 60° to the cen of the net. This rotation brings the point representing li of sight to the center of the net (i.e., the line of sig becomes vertical). We also rotate V, W, and X through same angle about the same horizontal axis. To do this, V, and W move along small circles by 60° to their rota positions at X', V', and W' (Fig. 13-25c). The spheri angles between L, V, W, and X are not changed by rotat them, but their new positions on the overlay indicate wh the spherical projections of these elements would fal projected orthographically onto a plane normal to the l of sight (L).

Step 5: Draw lines from the center of the net to e rotated edge of the cube (lines OV', OW', and OX' on F 13-25d). These lines have the appropriate attitudes relative lengths to be a perspective rendering of the th principal directions of the cube as viewed along of lin sight oriented 30°,005° when you revolve the overla that OV' appears vertical (Fig. 13-25d).

Step 6: Draw the cube by drawing line segm parallel to, and equal in length, respectively, to OV', C and OX' (Fig. 13-25e).

Constructing Geologic Block Diagrams with an Orthographic Net

Next, we show how to portray geologic features on the of the cube in such a way that angular relationships correctly portrayed. First, we consider how to pr geology onto the top face of the cube, then we con how to project geology onto the side faces of the cube.

Problem 13-11

The trace of a contact is shown on a map 13-26a). Portray this geology on the top surface of a whose principal directions are vertical, north-south east-west. The cube is to be viewed along a line ori 40°,050°.

Method 13-11

Step 1: Draw a square grid on the map. The lines should be parallel to the edges of the proposed (Fig. 13-26a). A point along the map trace of geologic contact has unique coordinates with the squar reference frame.

Step 2: Construct the block in the proper orient following Method 13-10. On the top surface of the draw the map grid in the appropriate orientation. I example, the north-south grid lines must parall

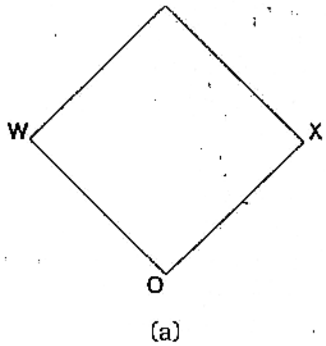
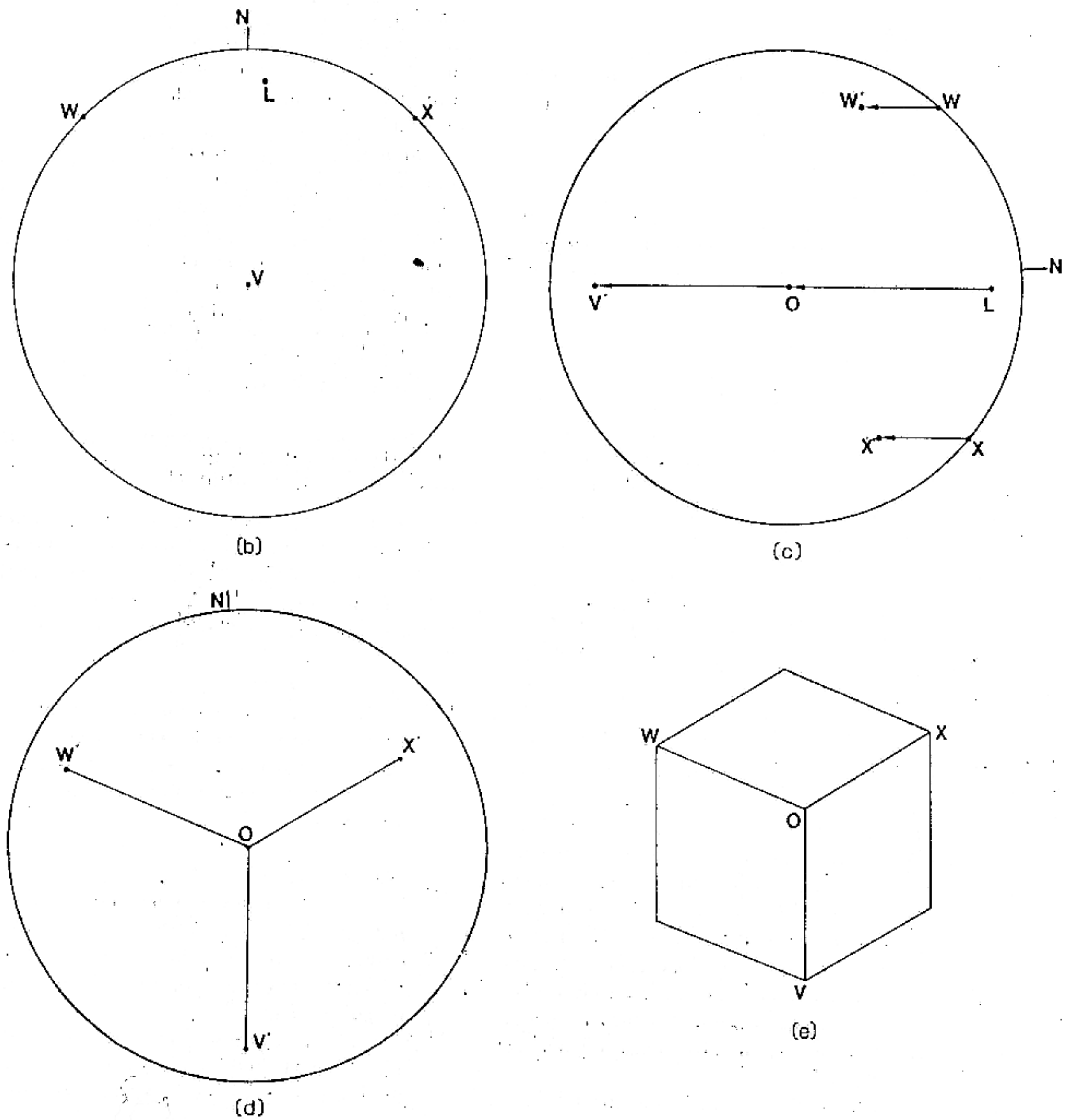


Figure 13-25. Construction of a cube with an orthographic net, as described in Problem 13-10. (a) The cube viewed normal to one face appears as a square; (b) the orthographic projections of a desired line of sight (L) and of the principal directions of the cube (V, W, and X); (c) configuration of projections after rotations; (d) orientations of rays OV', OW', and OX', which give the orientations and relative lengths of the cube's principal directions viewed along the line of sight L, if we align OV' vertically; (e) an isometric projection of the cube as viewed along the line oriented 30°,005°.



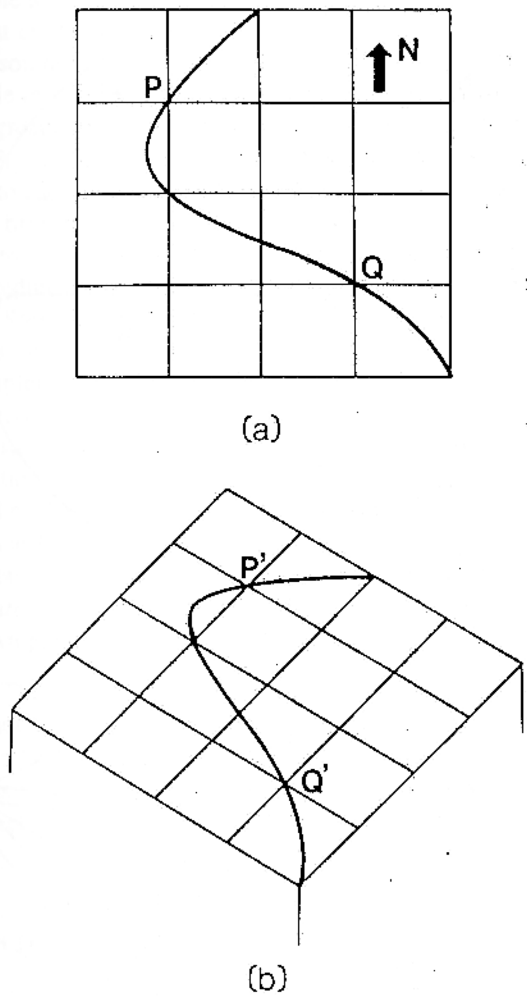


Figure 13-26. Projection of a map onto the top surface of a block diagram, as described in Problem 13-11. (a) Square grid drawn on a map. Points P and Q fall on a geologic contact; (b) the corresponding grid shown in perspective after rotation on an orthographic net. P' and Q' correspond to P and Q, respectively. The geologic contact is shown in perspective on the top of the block diagram.

north-south edge of the block, and east-west grid lines must parallel the east-west edge of the block. The distance between adjacent east-west grid lines is not the same as the spacing of north-south grid lines; the spacing must be proportional to the lengths of the cube edges. In other words, if each edge of the map is divided into four equal segments by construction of the grid, then each segment of the cube edge must be divided into four equal segments by construction of the grid.

Step 3: To determine the trace of the contact on the top of the block, simply determine the coordinates of many points on the contact with reference to the map grid. Transfer these coordinates to the grid on the surface of the cube, and retrace the contact (Fig. 13-26b).

Problem 13-12

Draw an isometric block diagram of the geologic map shown in Figure 13-27a. Show all the geologic features in proper perspective on the sides of the block diagram. The block is to be viewed along a line of sight plunging 30° in the direction 315°. The strike and dip of bedding in the southern limb is N85°E,65°N; the strike and dip of bedding in the northern limb is N37°E,35°S. The azimuth and plunge of the fold axis is 23°,078°.

Method 13-12

Step 1: Prepare an overlay and place it over an orthographic net. Plot the points representing the line of sight and the edges of the cube. In this case the edges of the cube are vertical, east-west, and north-south, respectively. The line of sight plots as point L within the primitive, and the edges of the cube plot as points N and W on the primitive.

Step 2: Plot the points representing poles to bedding in the two limbs of the fold and the fold axis. The southern limb of the the fold plots as Sl, the northern limb plots as Nl on the overlay, and the fold axis plots as F.

Step 3: Rotate all structural elements and principal cube directions by an appropriate amount around a horizontal axis such that L becomes vertical. To do this, revolve the overlay so that L lies on the east-west diameter of the orthonet. Move L by 60° along the diameter to the center of the net. All other points move 60° along appropriate small-circle traces. Remember that if a point reaches the primitive during a rotation, it reappears on the diametrically opposite side of the orthonet. Sl moves to Sl', Nl moves to Nl', F moves to F', etc. (Fig. 13-27b).

Step 4: Draw the properly oriented cube. Transfer the geologic contacts from the map to the top of the cube, using the technique described in Method 13-11.

Step 5: We use a method described by Lisle (1980) to draw lines on the sides of the cube indicating the dipping bedding surfaces. Consider an overlay (Fig. 13-27c) that shows only the points representing the edges of the properly oriented cube (W', X', V'), the now-vertical line of sight (O), and the rotated points representing the structural elements (Sl', Nl', F'). Trace the three great circles that represent the three principal planes of the cube. Each of these great circles is determined by aligning two of the principal axes of the cube along a great circle on the orthonet. Next, draw the great circles that represent bedding in fold limbs as viewed along the desired line of sight. Each great circle is normal to the rotated position of

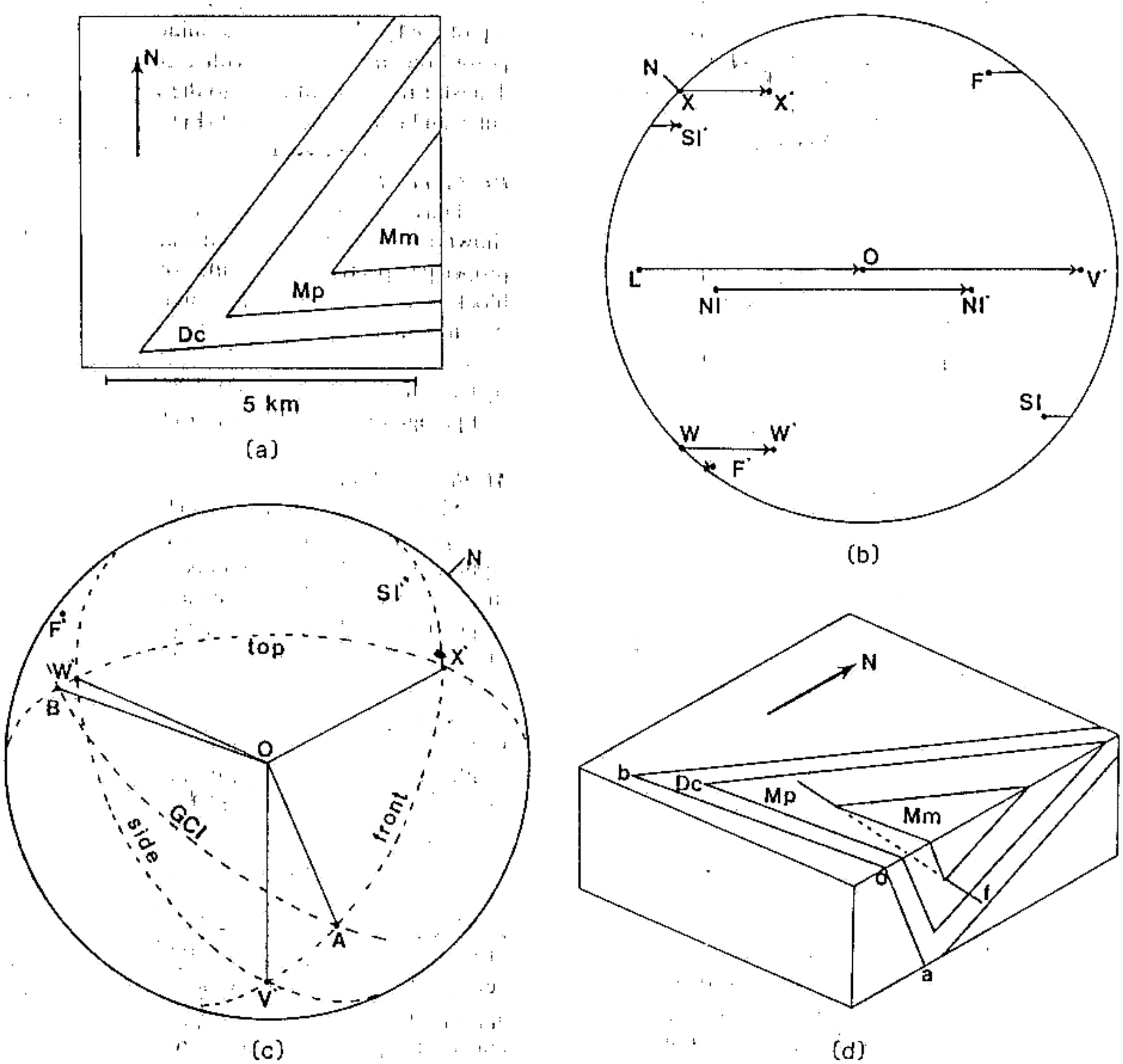


Figure 13-27. Construction of a block diagram of a fold, as described in Problem 13-12. (a) Generalized map of the west end of the Cove syncline, Pennsylvania Appalachians. (After Dyson, 1967.) The dip and dip direction of beds on the northern limb is 35°,127°. The dip and dip direction of beds on the southern limb is 65°,355°. We take the line of intersection of the beds, 23°,078°, to be the fold axis; (b) orthographic projection of elements from the map. V, W, and X are principal directions of the block diagram. F is the fold axis, Nl is the pole to bedding of the northern limb, Sl is the pole to bedding of the southern limb, and L is the line of sight (30°, 315°). All the primed letters have been rotated through 60° around the axis that brings L to the center of the net; (c) rays OV', OW', and OX' are the edges of the block diagram. Great circles denoting top, front, and side face are shown. GCl is the great circle normal to Sl'. GCl intersects the great circle representing the front of the block at A and that representing the top of the block at B. F' is the rotated fold axis; (d) completed block diagram. When OV' is aligned parallel to the vertical edges of the block diagram, oa parallels OA, ob parallels OB, and f parallels OF'.

a pole to bedding in a fold limb. For example, GC1 is the great circle normal to the rotated pole to bedding (SI') in the southern limb. Great circle GC1 intersects the great circle representing the front of the block diagram at A and the great circle representing the top of the block diagram at B (Fig. 13-27c). Rays from the center of the orthographic net to each intersection (OA and OB on Fig. 13-27c) give the orientations, on the block diagram, of the lines representing the intersection of the two planes. Repeat this procedure for bedding in the northern limb.

Step 6: Now that we know the orientations of the beds in the vertical walls of the block, it is easy to complete the block diagram. For example, locate the intersection of the Mp/Dc contact on the southern limb of the fold with the east edge of the block (we know this location from step 4). The trace of this contact in the east wall of the block in Figure 13-27d is a line that is parallel to line OA in Figure 13-27c. The orientations of other contacts are drawn in the same manner. The fold axis in Figure 13-27d, which appears to pass through the block, is drawn parallel to line OF' in Figure 13-27c.

The block diagrams shown in the preceding examples do not show topography on the top surface. Topography, and other embellishments that make a block diagram more realistic, can be added following techniques described by Lobeck (1958) and Goguel (1962).

13-9 APPENDIX: USE OF A COMPUTER FOR DOWN-PLUNGE PROJECTIONS

In order to use a computer to construct down-plunge projections of geologic structures depicted on a map, we must recast the construction process in an algebraic form (Charlesworth and others, 1976; Kilby and Charlesworth, 1980; Langenberg, 1985; Langenberg and others, in press). We first define Cartesian axes with the x-axis parallel to a horizontal north-south line on the map, the y-axis parallel to a horizontal east-west line on the map, and the z-axis vertical (i.e., perpendicular to the map surface). Place the origin of this coordinate frame at one corner of the up-plunge end of the structure and orient the coordinate frame to be right-handed. Any point on the topographic surface or in the subsurface has unique coordinates (x,y,z) relative to these axes. All coordinate values must be measured in the same units (e.g., feet, meters, or miles). It is usually easiest to use the map scale to convert all horizontal distance measurements to those used to measure elevation.

To project a point onto a profile plane, we perform a coordinate transformation to new Cartesian axes x', y', and z'. x' is a horizontal line whose bearing is perpendicular to the bearing of the fold axis. y' has the same bearing and plunge as the fold axis. z' parallels the true dip direction of the profile plane. If the bearing of the fold axis is θ, and the plunge of the fold axis is μ, the point with coordinates (x, y, z) relative to the east-north-vertical coordinate frame has coordinates (x', y', z') relative to the new coordinate axes. The values of x', y', and z' are given by

$$x' = x[\cos\mu\cos(\theta - 90^o)] - y[\cos\mu\sin(\theta - 90^o)] - z\sin\mu \qquad \text{(Eq. 13-A1)}$$

$$y' = x[\sin(\theta - 90^o)] + y[\cos(\theta - 90^o)] \qquad \text{(Eq. 13-A2)}$$

$$z' = x[\sin\mu\cos(\theta - 90^o)] - y[\sin\mu\sin(\theta - 90^o)] + z\cos\mu \qquad \text{(Eq. 13-A3)}$$

or, in matrix form,

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} [\cos\mu\cos(\theta - 90^o)] & [\cos\mu\sin(\theta - 90^o)] & \sin\mu \\ [\sin(\theta - 90^o)] & [\cos(\theta - 90^o)] & 0 \\ [\sin\mu\cos(\theta - 90^o)] & [\sin\mu\sin(\theta - 90^o)] & \cos\mu \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \qquad \text{(Eq. 13-A4).}$$

Since the y'-coordinate axis is parallel to the fold axis, the x'-z' plane is a profile plane. We can project points onto a profile plane by collapsing all points onto a single plane that parallels the x'-z' plane. To do this, we simply ignore the y'-coordinate values and plot all points on a two-dimensional Cartesian coordinate frame with abscissa x' and ordinate z' using only their x'- and z'-coordinate values. The plot of points on the x'-z' frame is the profile of the structure.

Computer construction of profiles involves simply (1) digitizing points along the trace of a structure on a map (i.e., determining their x,y,z coordinates), (2) calculating the coordinates in x', y', z' space, by using the preceding equations, and (3) having the computer plot the transformed x'- and z'-coordinates on an x'-z' profile plane. The algorithms are relatively simple, so the procedure can be accomplished with a desktop computer.

EXERCISES

1. Choose an appropriate line of section across the map in Figure 13-M1.

2. Point A is 150 m northwest of point B along a N45°W-trending section line; the elevation at B is 15 m higher than the elevation at A. The strike and dip of

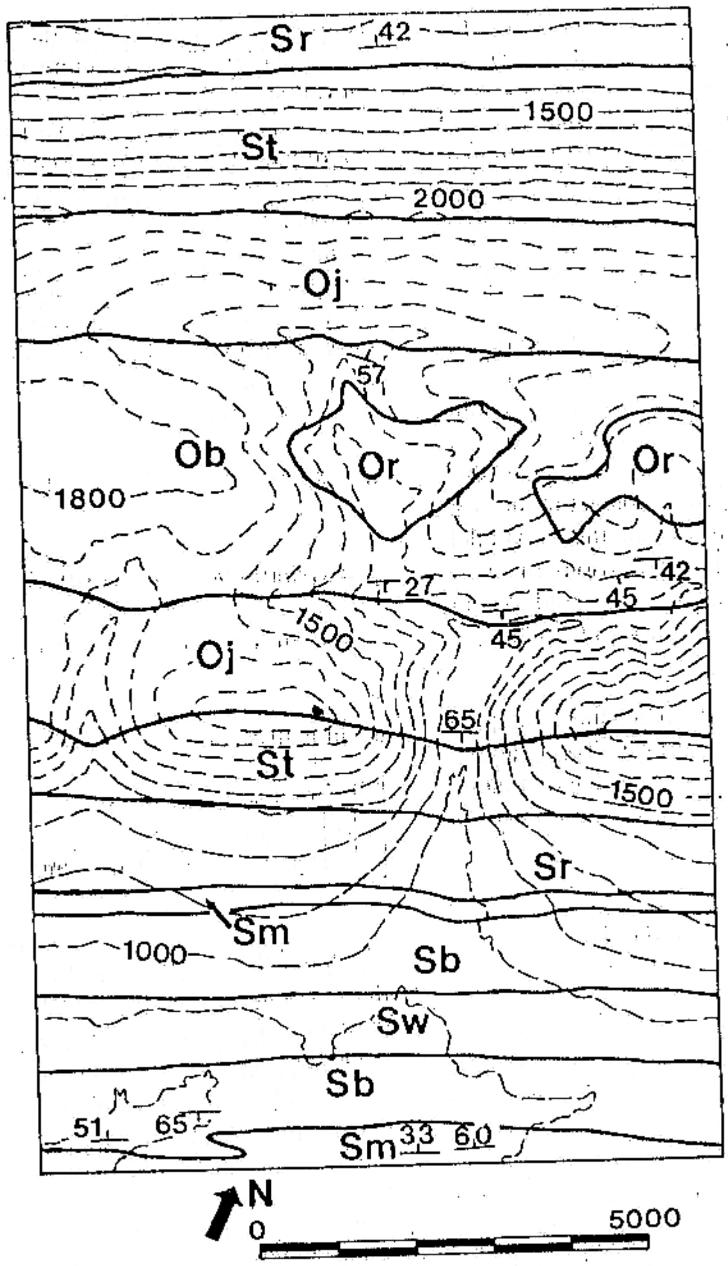


Figure 13-M1. Map of a portion of the Mifflintown Quadrangle, Pennsylvania Appalachians, USA. (From Conlin and Hoskins, 1962.) Or = Ordovician Reedsville Formation; Ob = Ordovician Bald Eagle Formation; Oj = Ordovician Juniata Formation; St = Silurian Tuscarora Formation; Sr = Silurian Rose Hill Formation. Topographic contours in feet.

bedding is N45°E,27°NW at A and N45°E,52°SE at B. Use the Busk method to reconstruct the folded layers passing through points A and B.

3. Points A, B, and C fall along a N88°E-trending section line. The distance from A to B is 550 m, and the distance from B to C is 200 m; all three points have the same elevation. The strike and dip of bedding is N02°W,22°E at A, N02°W,45°E at B, and N2°W, 54°W at C. Use the Busk method to reconstruct the folded layers passing through A, B, and C.

4. Use the Busk method to draw a cross section using the data given in Figure 13-M2.

5. Use the Busk method to draw a cross section from the map in Figure 13-M1.

6. Points A, B, and C fall along a N50°W-trending section line across a region of angular folds. The distance from A to B is 220 m, and the distance from B to C is 370 m; all three points have the same elevation. A falls in a dip domain where the strike and dip of bedding is N40°E, 27°N; B falls in a domain where the strike and dip of bedding is N40°E, 76°S; and C falls in a domain where the strike and dip of bedding is N40°E, 22°N. Use the kink method to reconstruct the folded layers passing through A, B, and C.

7. Use the kink method to draw a cross section using the data in Figure 13-M2. *Hint:* Draw line segments indicating the domainal dips through each point where a kink fold hinge intersects the ground surface (the "h's" on the profile), and bisect that angle to orient the kink fold hinge.

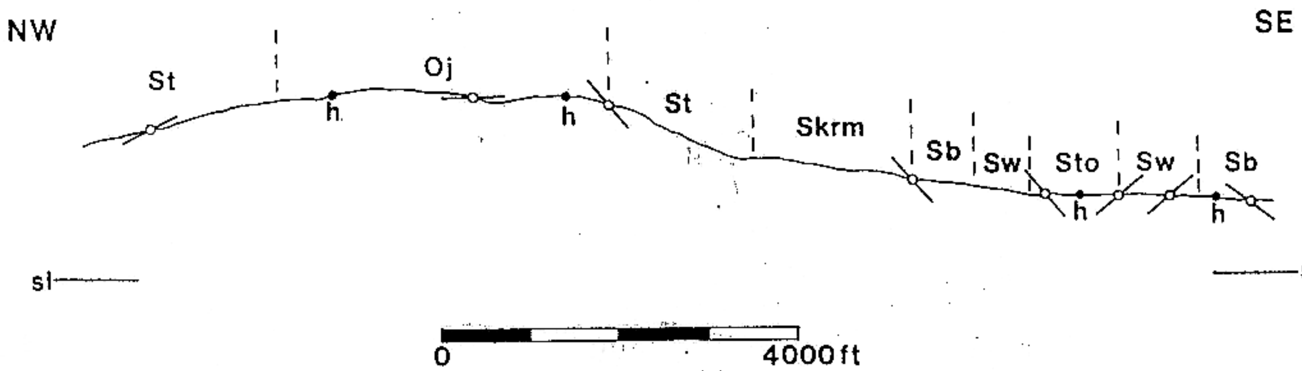


Figure 13-M2. Dip readings along a line of section across folds in the Millerstown Quadrangle, Pennsylvania Appalachians, USA. (After Faill and Wells, 1974.) Dashed vertical lines separate outcrop belts of different stratigraphic units. Each filled circle (h) marks the intersection between a kink plane and the ground surface; use them when completing exercise 7. sl = sea level; Oj = Ordovician Juniata Formation. St = Silurian Tuscarora Formation; Srkm = Silurian Rose Hill, Keefer, and Mifflintown Formations; Sb = Silurian Bloomsburg Formations; Sw = Silurian Wills Creek Formation; Sto = Silurian Tonoloway Formation. The Ordovician Juniata Formation is about 1500 ft thick and is underlain by the 750-ft-thick Bald Eagle Formation and the 1500-ft-thick Reedsville Formation.

8. Use the kink method to draw a cross section of the region illustrated in Figure 13-M3.

9. Use the dip-isogon method to complete the fold profile begun in Problem 13-6.

10. Figure 13-M4 is a map of nonplunging, cylindrical folds. Construct a profile of these folds using the orthographic projection method outlined in Problem 13-7.

11. Use the grid method to draw a profile of the fold in Figure 13-M5.

12. Assume that the folds shown in Figure 13-M6 are cylindrical and plunge 11° toward 015°. Use the method outlined in Problem 13-9 to determine the structure in this region.

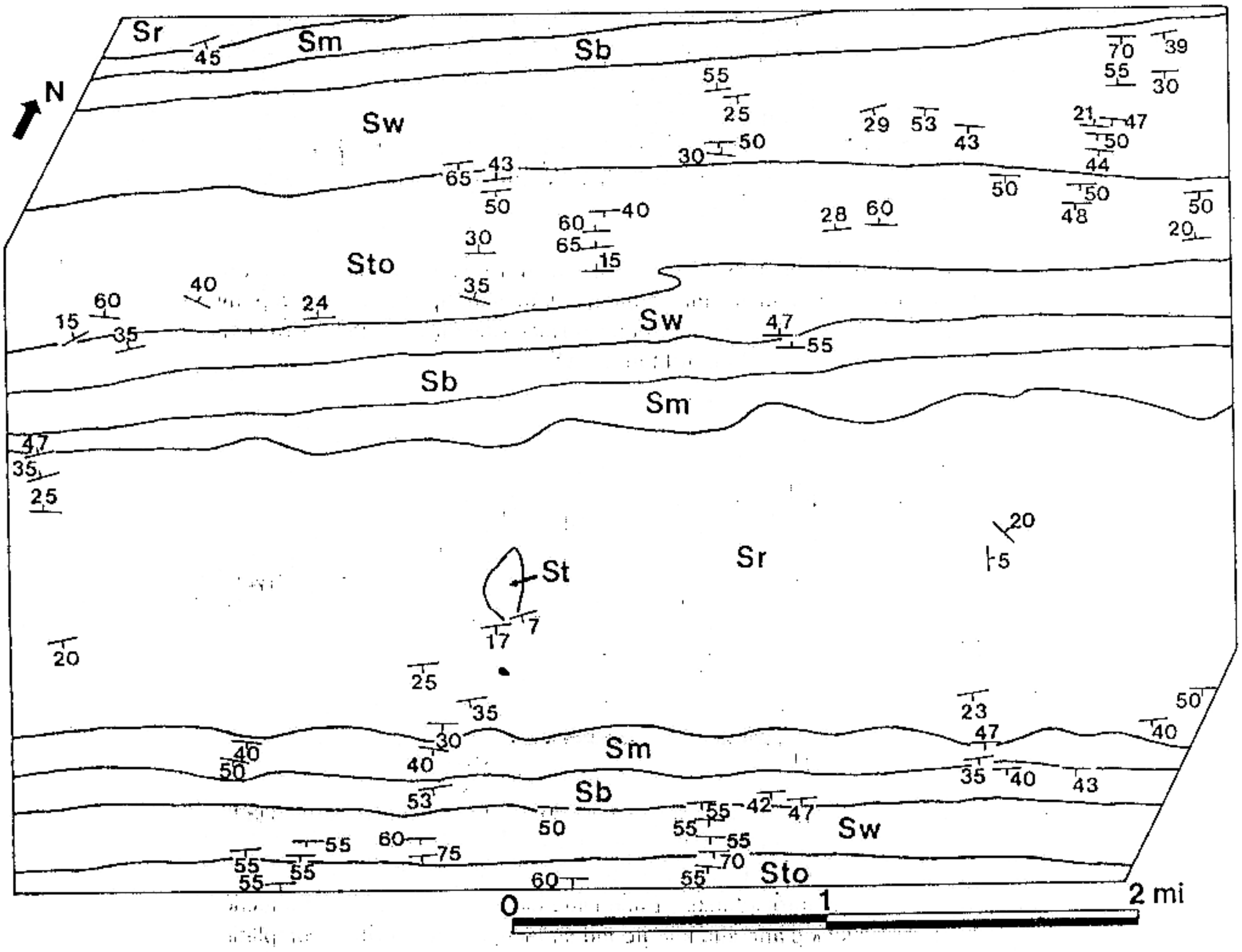


Figure 13-M3. Map of a portion of the Mifflintown Quadrangle, Pennsylvania Appalachians, USA. (From Conlin and Hoskins, 1962.) St = Silurian Tuscarora Formation; Sr = Silurian Rose Hill Formation; Sm = Mifflintown Formation; Sb = Bloomsburg Formation; Sw = Wills Creek Formation; Sto = Tonoloway Formation.

13. Use the orthographic net to draw, in proper perspective, how a cube with a horizontal top and northeast/northwest directed edges would look when viewed along a line of sight 25°,315°.

14. Draw a block diagram viewed along a line of sight 340°,30° of the fold illustrated in Figure 13-M7.

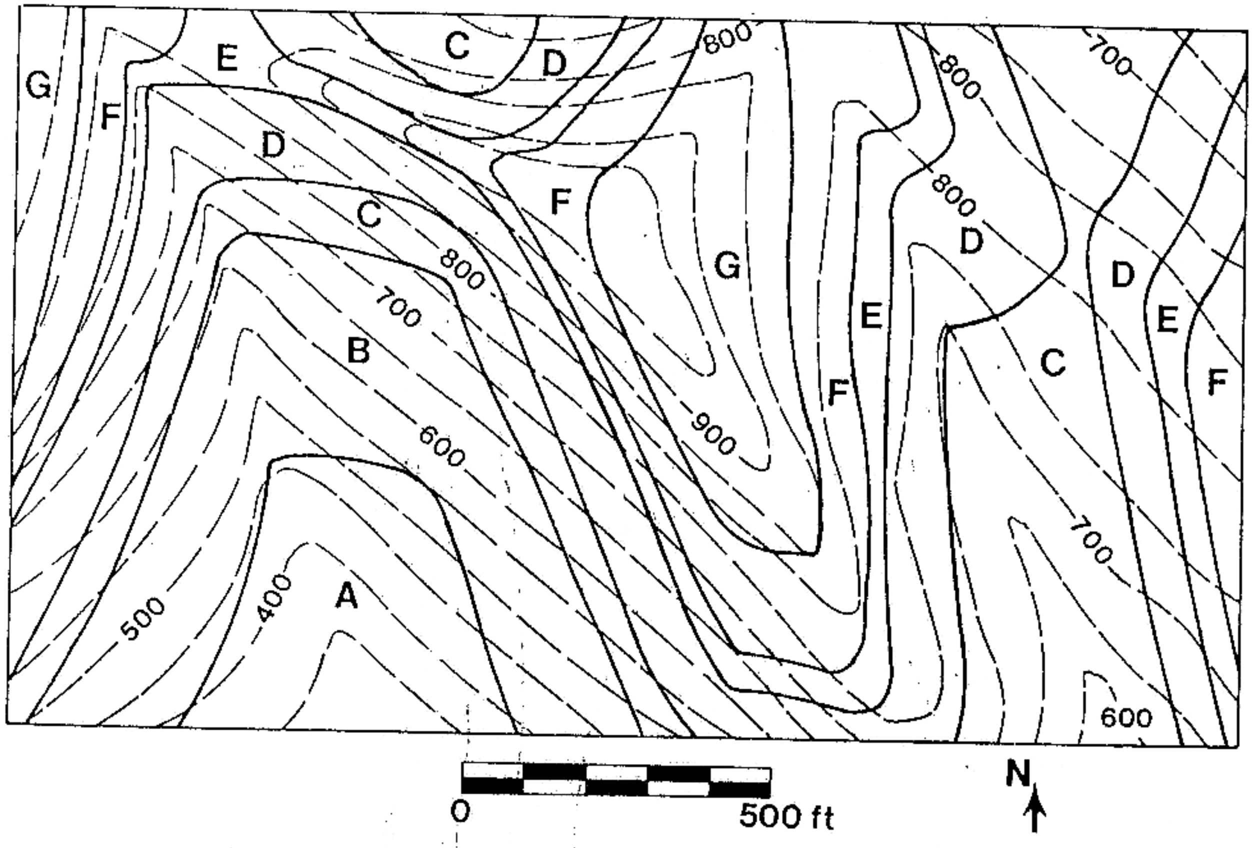


Figure 13-M4. Map of hypothetical nonplunging, cylindrical folds with north-south axes. Topographic contours in feet.

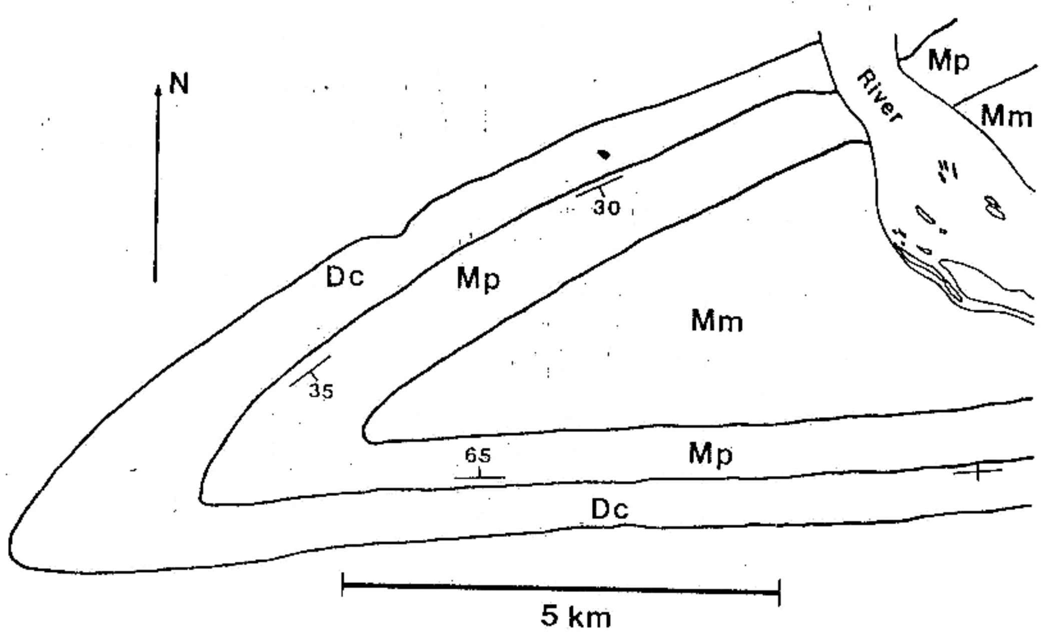


Figure 13-M5. Simplified geologic map of the Cove syncline, New Bloomfield Quadrangle, Pennsylvania Appalachians, USA. (From Dyson, 1967.) Dc = Devonian Catskill Formation; Mp = Mississippian Pocono Formation; Mm = Mississippian Mauch Chunk Formation. Bearing and plunge of fold axis are 085° and 15°.

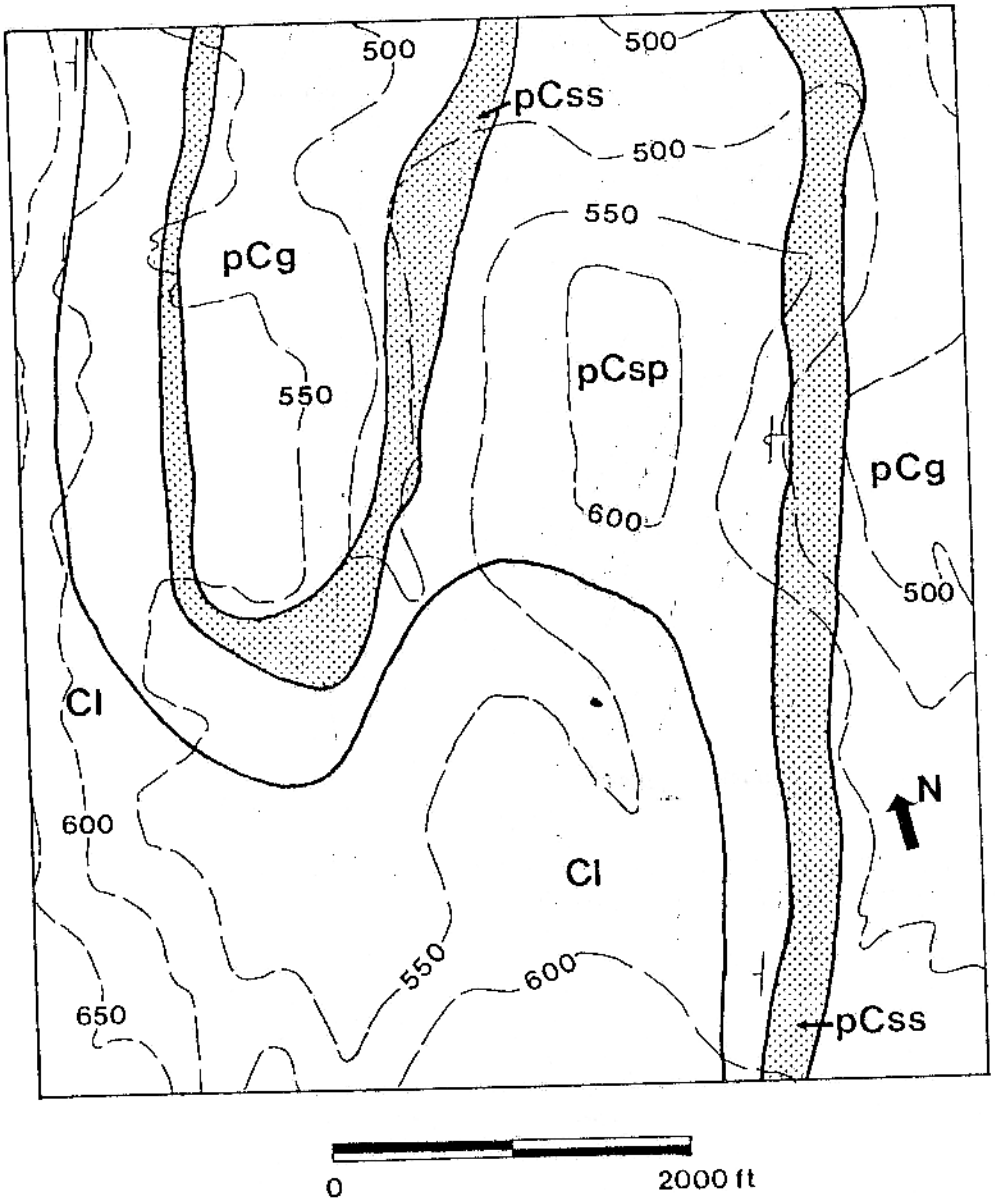


Figure 13-M6. Geologic map of a portion of Blue Ridge, Loudoun County, Virginia, USA. (Adapted from Nickelsen, 1956.) pCg = granitic gneiss; pCss = Precambrian Swift Run Formation sandstone; pCsp = Precambrian Swift Run Formation phyllite; Cl = Cambrian Loudoun Formation. Topographic contours in feet.

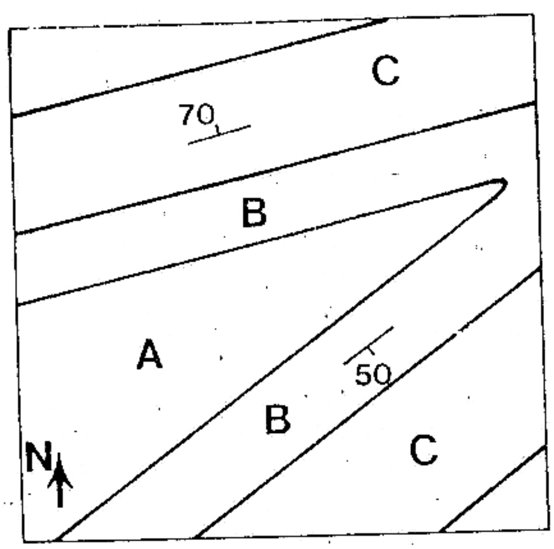


Figure 13-M7. Map of a hypothetical fold. Strike and dip of bedding is N77°E,70°NW in the northern limb and N53°E, 50°S in the southern limb. The fold axis plunges 19° toward 071°.