Cross Sections, Data Projection and Dip-Domain Mapping

6.1 Introduction

A cross section shows the relationships between different horizons and allows the information from multiple map horizons to be incorporated into the interpretation. Cross sections may categorized as illustrative or predictive. The purpose of an illustrative cross section is to illustrate the cross section view of an already-completed map or 3-D interpretation. A slice through a 3-D interpretation is a perfect example. The purpose of a predictive cross section is to assemble scattered information and, utilizing appropriate rules, predict the geometry between control points. A predictive cross section can be used to predict the geometry of a horizon for which little or no information is available.

Data projection is typically part of the cross-section construction process. Relevant data commonly lie a significant distance from the line of section. Rather than ignore this information, it can be projected onto the section plane. The quality of the result depends on selecting the correct projection direction. This chapter describes how to select the projection direction and gives several techniques for making the projection by hand or analytically. Projection within a dip-domain style structure involves defining the 3-D axial-surface network and so becomes a blend of mapping, data projection, and section construction.

6.2 Cross-Section Preliminaries

6.2.1 Choosing the Line of Section

Cross sections constructed for the purpose of structural interpretation are usually oriented perpendicular to the fold axis, perpendicular to a major fault, or parallel to these trends. The structural trend to use in controlling the direction of the cross section is the axis of the largest fold in the map area or the strike of the major fault in the area. Good reasons may exist for other choices of the basic design parameters. For example, the cross section may be required in a specific location and direction for the construction of a road cut or a mine layout. If other choices of the parameters, such as the direction of the section line or the amount of vertical exaggeration, are required, it is recommended that a section normal to strike be constructed and vali-

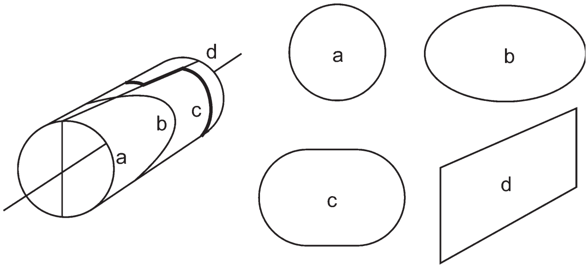


Fig. 6.1.
Cross sections through a circular cylinder. **a** Normal section. **b** Oblique section. **c** Offset section. **d** Axial section

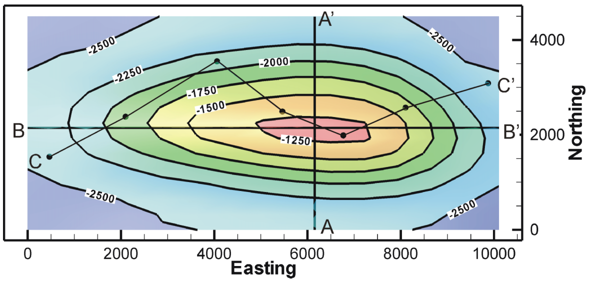


Fig. 6.2.
Structure contour map of an anticline showing the section lines. *A–A'*: normal (transverse) cross section perpendicular to the trend of the anticline. *B–B'*: longitudinal cross section. *C–C'*: well-to-well cross section

dated (Chap. 10 and 11) first. A grid of cross sections is needed for a complete three-dimensional structural interpretation.

The reason that a structure section should be straight and perpendicular to the major structural trend is that it gives the most representative view of the geometry. The simplest example of this is a cross section through a circular cylinder (Fig. 6.1). If the entire cylinder is visible, then it would readily be described as being a right circular cylinder. The cross section that best illustrates this description is Fig. 6.1a, normal to the axis of the cylinder, referred to as the normal section. Any other planar cross section oblique to the axis is an ellipse (Fig. 6.1b). An elliptical cross section is also correct but does not convey the appropriate impression of the three dimensional shape of the cylinder. A section that is not straight (Fig. 6.1c) also fails to convey accurately the three-dimensional geometry of the cylinder, although, again, the section is accurate. Section c in Fig. 6.1 could be improved for structural interpretation by removing the segment parallel to the axis, producing a section like Fig. 7.1a. A section parallel to the fold (or fault) trend (Fig. 6.1d) is also necessary to completely describe the geometry.

Predictive cross sections are constructed using bed-thickness and fold-curvature relationships that are appropriate for the structural style. In order to use these geometric relationships, or rules, to construct and validate cross sections, it is necessary to choose the cross section to which the rules apply. Such a rule, in the case of the circular cylinder in Fig. 6.1, is that the beds are portions of circular arcs having the same center of curvature. In this simple and easily applicable form, the rule applies only to section a. More complex rules could be developed for the other cross sections, but it is quicker and less confusing to select the plane of the cross section that fits the simplest rule than to change the rule to fit an arbitrary cross-section orientation.

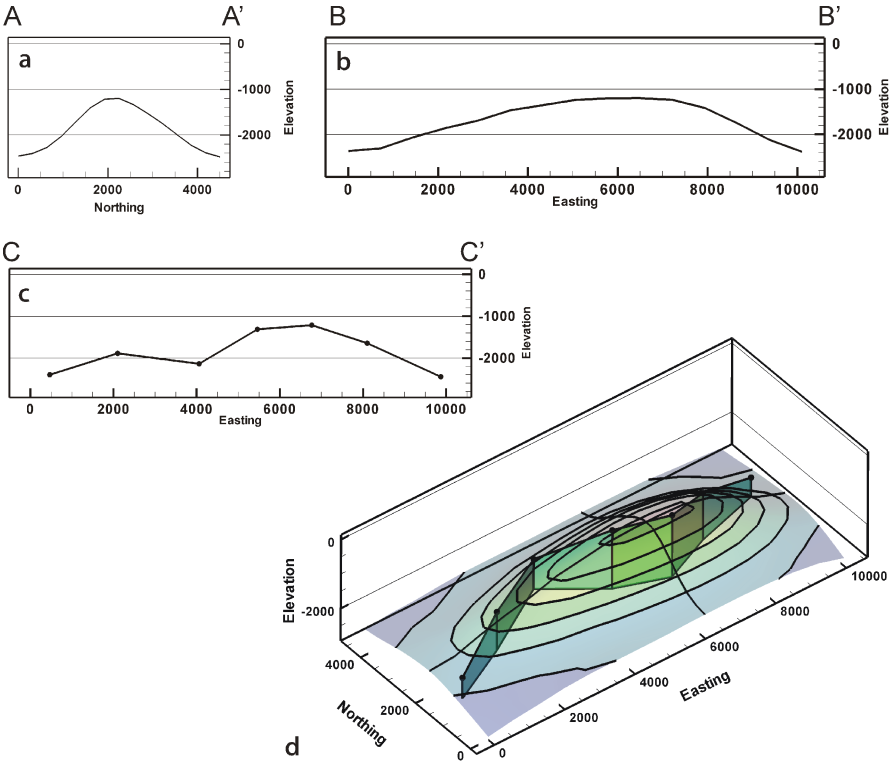
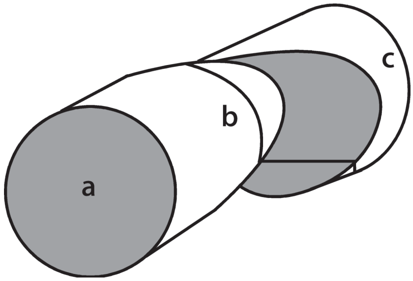


Fig. 6.3. Sections through the map in Fig. 6.2. **a** Normal section perpendicular to the fold crest. **b** Longitudinal section parallel to the fold crest. **c** Zig-zag or well-to-well cross section. **d** Oblique 3-D view of the structure showing the three cross sections

The effect of a curved section (Fig. 6.2) on the implied geometry of an elongate dome is shown in Fig. 6.3. The correct geometry of the structure is shown by the normal section, a straight-line cross section perpendicular to the axial trace of the structure (Fig. 6.3a) and the longitudinal section (Fig. 6.3b) parallel to the crest of the structure. A line of section that is not straight, such as one that runs through an irregular trend of wells or a seismic line that follows an irregular road, produces a false image of the structure. The zig-zag section across the map (Fig. 6.3c) incorrectly shows the anticline to have two local culminations instead of just one. This is a serious problem if the cross section is used to locate hydrocarbon traps or to infer the deep structure using the predictive section drawing techniques described in Sect. 6.4.

The first line of section across a structure chosen for interpretation should avoid local structures, like tear faults, oblique to the main structural trend. Oblique structures introduce complexities into the main structure that are more easily interpreted after the geometry of the rest of the structure has been determined. Returning to the cylinder, now shown offset along a tear fault (Fig. 6.4), cross sections at a and c will

Fig. 6.4.
Cross-section lines across a cylinder offset along an oblique fault



reveal the basic geometry of the cylinder. A cross section at b that crosses the fault will be very difficult to interpret until after the basic geometry is known from sections a or c. The simplest method for constructing the structure along section b would be to project the geometry into it from the unfaulted parts of the cylinder.

6.2.2 Choosing the Section Dip

Only a cross section perpendicular to the plunge (the normal section) shows the true bed thicknesses. In all other sections the thicknesses are exaggerated. This is important if the section is going to be used for predictive purposes. The plunge of a cylindrical fold is the orientation of its axis, which can be found from the bedding attitudes using the stereonet or tangent diagram techniques given in Sect. 5.2. A conical fold does not have an axis and so, in the strict sense, there is no normal section. The orientation of either the crestal line or the cone axis is an approximate plunge direction for a conical fold. On a structure contour map the trend and plunge of the crestal line is readily identified. The plunge angle is given by the contour spacing in the plunge direction.

Within a domain of cylindrical folding, changing the dip of the section plane is equivalent to changing the vertical or horizontal exaggeration. This relationship is the basis of the map interpretation technique known as down-plunge viewing. The map pattern in an area of moderate topographic relief represents an oblique, hence exaggerated, section through a plunging structure. Viewed in the direction of plunge, the map pattern becomes a normal section (Mackin 1950).

The down-plunge view of a fault should give the correct cross-section geometry and the sense of the stratigraphic separation. The plunge direction of a fault is parallel to the axis or crest or trough line of ramp-related folds or drag folds. If the fault is listric or antilistric, the plunge direction should be the axis of the curved surface, just as if it were a folded surface. If the fault is planar and there are no associated folds, the appropriate plunge direction is parallel to the cutoff line of a displaced marker against the fault (Threet 1973).

If a vertical cross section is constructed normal to the trend of the plunge, the vertical exaggeration due to the plunge angle can be removed by rotating the section using the method given in Sect. 6.5. The same approach can be used to convert a map view into a normal section.

6.2.3
Vertical and Horizontal Exaggeration

Both vertical and horizontal exaggeration are used to help visualize and interpret the structure on cross sections. Vertical exaggeration is a change of the vertical scale (usually an expansion) while maintaining a constant horizontal scale and is a common mode of presentation of geological cross sections. Vertical exaggeration makes the relief on a subtle structure more visible on the cross section (Fig. 6.5a). Horizontal exaggeration is a change of the horizontal scale while maintaining a constant vertical scale

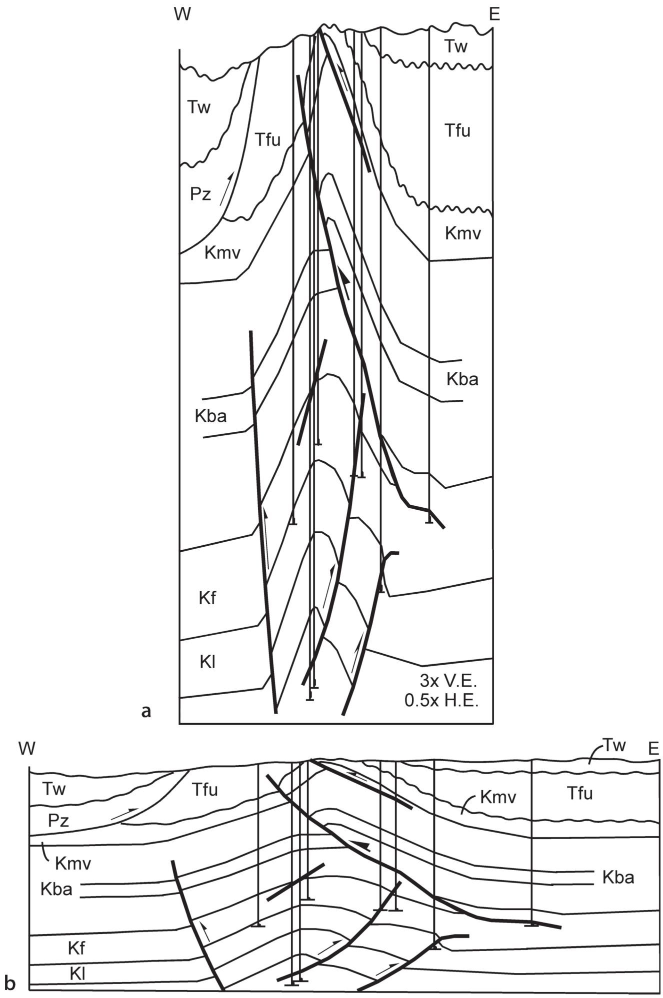


Fig. 6.5. Cross sections across Tip Top field, Wyoming thrust belt. **a** 3:1 vertical exaggeration and a 0.5:1 horizontal exaggeration, as might be seen on a seismic reflection profile. **b** Unexaggerated cross section. (Section modified from Groshong and Epard 1994, after Webel 1987)

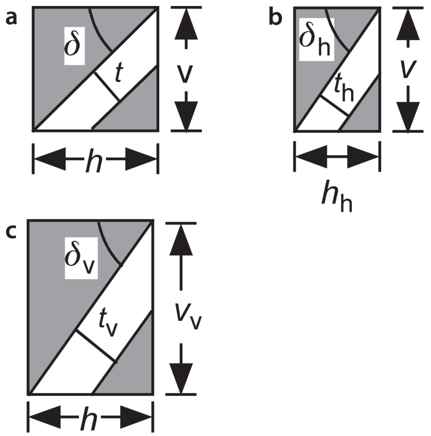


Fig. 6.6.
Vertical and horizontal exaggeration. A bed of original thickness t is shown in *white*.
a Unexaggerated cross section.
b Horizontally exaggerated (squeezed) cross section.
c Vertically exaggerated cross section

and is common, along with vertical exaggeration, in the presentation of seismic lines (Stone 1991). Reducing the horizontal scale (squeezing) makes a wide, low amplitude structure more visible and makes the break in horizon continuity at faults more obvious. Squeezing exaggerates the structure without producing an unmanageably tall cross section.

Vertical exaggeration (V_e) is equal to the length of one unit on the vertical scale divided by the length of one unit on the map, and horizontal exaggeration (H_e) is the length of one unit on the horizontal scale divided by the length of one unit on the map (Fig. 6.6):

$$V_e = v_v / v \quad , \tag{6.1}$$

$$H_e = h_h / h \quad , \tag{6.2}$$

where v_v = exaggerated vertical dimension, v = vertical dimension at map scale, h_h = exaggerated horizontal dimension, and h = horizontal dimension at map scale. As derived at the end of the chapter (Eqs. 6.21 and 6.22), the true dip is related to the exaggerated dip by

$$\tan \delta_v = V_e \tan \delta \quad , \tag{6.3}$$

$$\tan \delta_h = \tan \delta / H_e \quad , \tag{6.4}$$

where δ_v = vertically exaggerated dip, δ_h = horizontally exaggerated dip, and δ = true dip. Equation 6.3 is plotted in Fig. 6.7. In its effect on the dip, a vertical exaggeration is equivalent to the reciprocal of a horizontal exaggeration (from Eq. 6.24 at the end of the chapter):

$$V_e = 1 / H_e \quad . \tag{6.5}$$

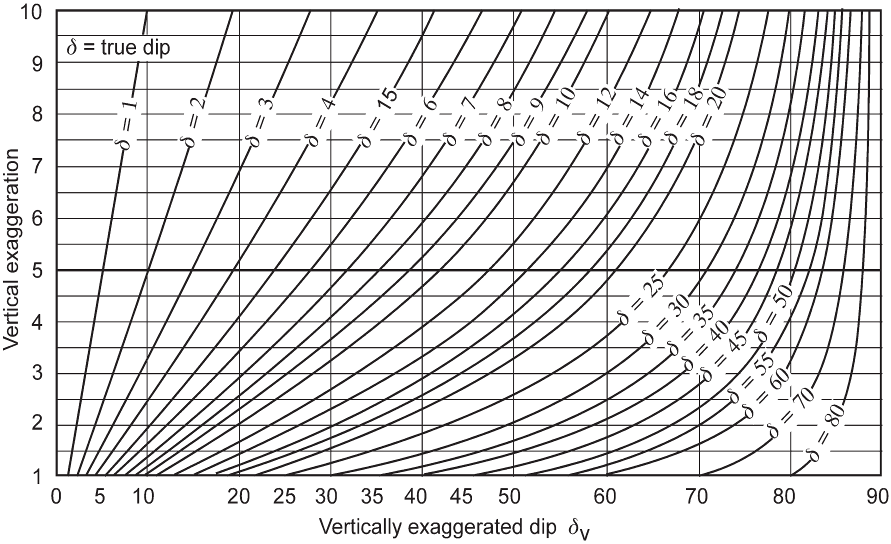


Fig. 6.7. Relationship between true dip and vertically exaggerated dip (Eq. 6.3) for various amounts of vertical exaggeration. (After Langstaff and Morrill 1981)

The effect of exaggeration on the thickness of a unit is given by (derived as Eqs. 6.26 and 6.28)

$$t_h / t = \cos \delta_h / \cos \delta \quad , \tag{6.6}$$

$$t_v / t = V_e \ (\cos \delta_v / \cos \delta) \quad . \tag{6.7}$$

The symbols are the same as in Eqs. 6.1–6.4. Horizontal exaggeration has no effect on the thickness of a horizontal bed, whereas vertical exaggeration changes the thickness of a horizontal bed by an amount equal to the exaggeration. Horizontal exaggeration changes the thickness of a vertical bed by the full amount of the exaggeration, whereas vertical exaggeration has no effect on the thickness of a vertical bed. For beds dipping between 0 and 90°, both horizontal and vertical exaggeration cause the apparent thickness to increase.

Exaggeration creates several problems in the interpretation of a cross section. The first is that a large vertical exaggeration or horizontal squeeze may so distort the structure that the structural style becomes unrecognizable. This will lead to difficulties in interpretation or to misinterpretations. For example, the exaggerated cross section in Fig. 6.5a looks more like a wrench-fault style than the correct thin-skinned contraction style. Cross-section construction and validation techniques and models for the dip angles and angle relationships do not apply to the exaggerated geometry. Exaggeration also causes thicknesses to be a function of dip (Fig. 6.8). Care must be taken not to interpret exaggerated thicknesses as being caused by tectonic thinning

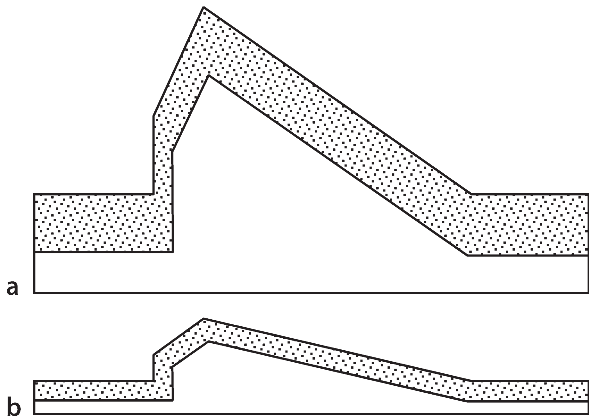


Fig. 6.8.
Effect of a 3:1 vertical exaggeration on thickness. **a** Profile vertically exaggerated 3:1. Bed thickness increases as the dip decreases. **b** Unexaggerated profile. Bed thickness is constant

or thickening or by structural growth during deposition. The profile can be easily corrected when the true horizontal and vertical scales are known. The correction factor is the inverse of the horizontal or vertical exaggeration. Create an unexaggerated profile by multiplying the correction factor times the scale of the exaggerated axis. If the cross section is in digital form, this is a simple operation using a computer drafting program.

Seismic time sections are commonly displayed with both horizontal and vertical exaggerations (Stone 1991). Horizontal exaggeration may be applied to obtain a legible horizontal trace spacing. The amount of horizontal exaggeration is most conveniently determined by comparing the distance between shot or vibration points marked on the profile with the scale between the corresponding points on the location map. The vertical scale on a time section is in two-way-travel time, and the determination of the vertical exaggeration requires depth conversion as well as scaling. A few simple techniques can provide the necessary scaling information without geophysical depth migration. If the depth to a particular horizon is known independently, as from a well, then the vertical exaggeration at that well can be determined directly from the definition (Eq. 6.1). If the true dip is known for a unit or a fault, then the vertical exaggeration can be found by solving Eq. 6.3, given the exaggerated dip from the profile.

If there is a unit on a seismic time section that can be expected to have constant depositional thickness and minimal structural thickness changes, then any observed thickness change in the unit is caused by the exaggeration (Fig. 6.9a,b). The vertical exaggeration of the time section can be removed by restoring the bed thickness to constant (Stone 1991). A package of reflectors should be chosen that retains its reflection character and proportional spacing regardless of dip. The reflectors should be parallel to one another and not terminate up or down dip. The thickness changes of such a package are more likely to be caused by exaggeration than by deposition. A simple procedure for removing the vertical exaggeration is to change the vertical scale until the unit maintains constant thickness regardless of dip (Fig. 6.9c). This provides a quick depth migration that applies to the depth interval over which the unit

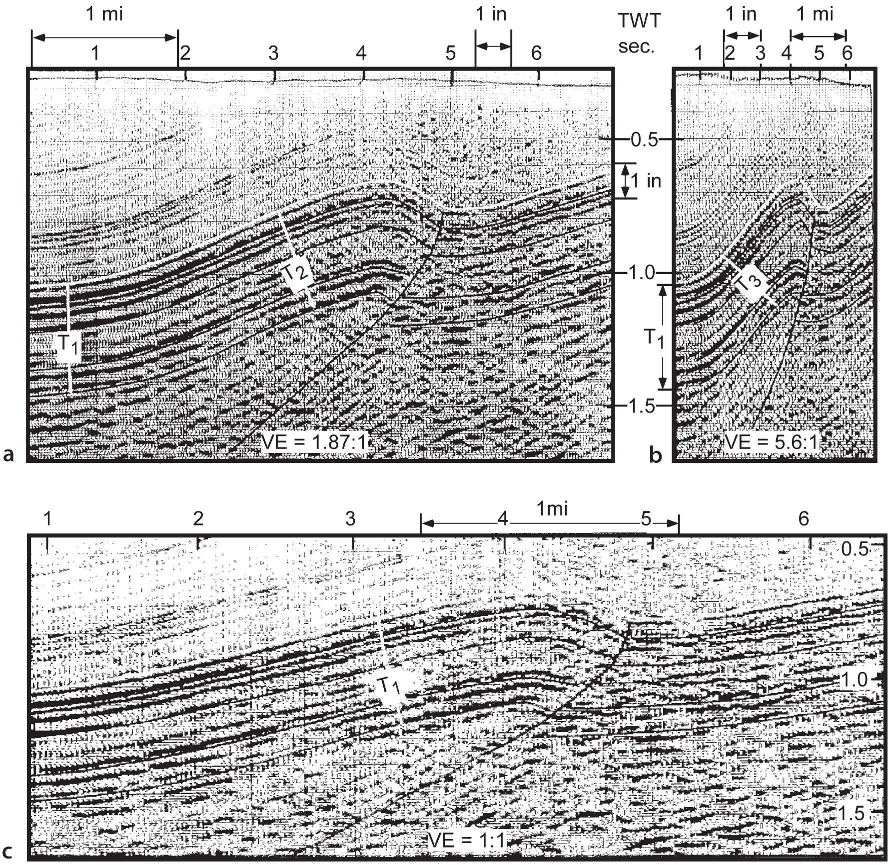


Fig. 6.9. Time migrated seismic profile from central Wyoming. *TWT:* Two-way travel time; T_i: interval thickness. **a** Original profile having a vertical scale of 7.5 in per second and a horizontal scale of 12 traces per in. Vertical exaggeration (*ve*) is 1.87 : 1. **b** The vertical scale is the same as in **a**, the horizontal scale is reduced by two-thirds. Vertical exaggeration is 5.6 : 1. **c** Unexaggerated version produced by expanding the horizontal scale. Thickness T_1 is now constant across the profile. (After Stone 1991)

occurs. Because seismic velocity varies with depth, the profile might remain exaggerated at other depths. Normally seismic velocity increases with depth and so the vertical exaggeration decreases with depth. This method does not take into account horizontal velocity variations. A further caution is that the thickness variations seen in Fig. 6.9a are just like those that are caused by deformation. The inferred vertical exaggeration should always be cross checked by other methods whenever possible. If the profile is also horizontally exaggerated, then this method will give the correct exaggeration ratio of 1 : 1, but both the horizontal and vertical scales could be exaggerated. Eliminate the horizontal exaggeration while maintaining the ratio constant to produce a depth section.

6.3 Illustrative Cross Sections

The purpose of an illustrative cross section is to illustrate the geometry present on a structure contour map. It is comparable to a topographic profile in concept and construction.

6.3.1 Construction by Hand or with Drafting Software

Begin by drawing the line of section on the map (A–A', Fig. 6.10a). The line of section in Fig. 6.10a has been selected to be perpendicular to the crest of the anticline. Clearly show the end points of the section because they will serve as the reference points for all future measurements. The section will be compiled on a graph where the vertical axis represents elevations and the horizontal axis is the distance along the profile (Fig. 6.10b). For an unexaggerated profile, the vertical scale should be the same as the map scale and the lines spaced accordingly. To construct a vertically exaggerated profile, let the vertical scale be some multiple of the map scale.

Cross sections are usually drawn either to be vertical or to be inclined such that the plane of the section is perpendicular to the direction of plunge of the structure of

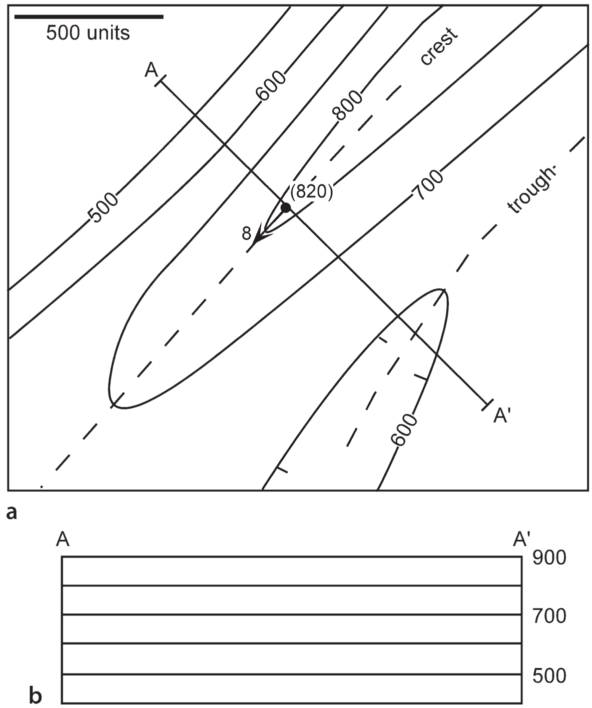


Fig. 6.10. Initial stage of cross-section construction from a map. The line of section is *A–A'*. **a** Structure contour map and a dip measurement (at elevation 820). **b** Graph for cross-section construction. For no vertical exaggeration both the horizontal and vertical scales are the same as the map scale

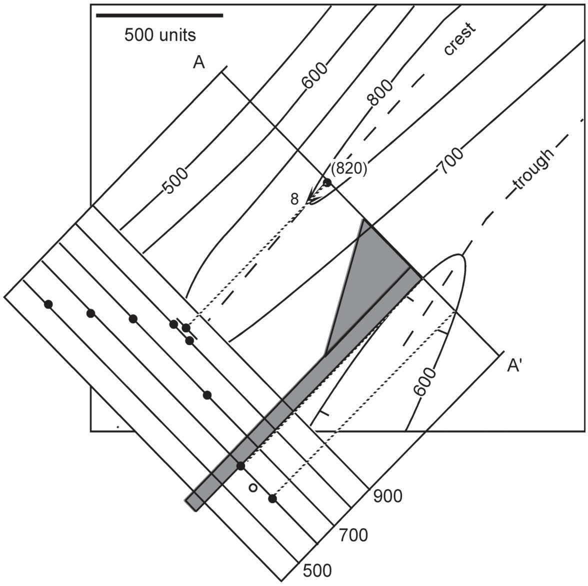


Fig. 6.11.
Direct projection of data from structure contour map to cross section. *Dotted lines* are right-angle projection lines. *Circles* show projected points: *filled circles* are projected from known elevations; the *open circle* is an interpolated elevation. The drafting tools are *shaded*

interest. For many purposes, it is most convenient to construct a vertical profile. For a cylindrical structure, a vertical profile is easily transformed into a normal section (Sect. 6.5). The techniques of section construction will begin with vertical profiles. Construction of an initially tilted profile is considered in Sect. 6.6.1.

The next step in constructing the cross section is to transfer the data from the map to the profile. One convenient projection method is to align the cross-section graph parallel to the line of section, tape the map and section together so that they cannot slip, and project data points at right angles onto the cross section with a straight edge and a right triangle (Fig. 6.11). Any type of map information can be transferred to the cross section by this method. In computer drafting it is usually more convenient to draw straight lines vertically or horizontally; therefore the map should be rotated so that the projection direction is either horizontal or vertical. Data points are located at their correct distances from the ends of the section and at their proper elevations. The probable locations of turning points of the structure contour map are also marked as points (Fig. 6.11), for example, between the two adjacent 600 contours. The location of a turning point is constrained to be between the next higher and lower elevations.

An alternative method is to mark the locations of the data points on a strip of paper for working by hand (Fig. 6.12a) or on a line drawn on top of the section line in a drafting program. After marking, the line of data locations is rotated to be parallel to the cross-section horizontal (Fig. 6.12b). In a drafting program, group the points before rotating. Then project the data points from the line onto the cross section (Fig. 6.12c). The points can be projected with a right triangle as in the previous method, or the overlay can be moved to the correct elevation on the section and each point marked at the appropriate distance from the end of the section. After compiling the

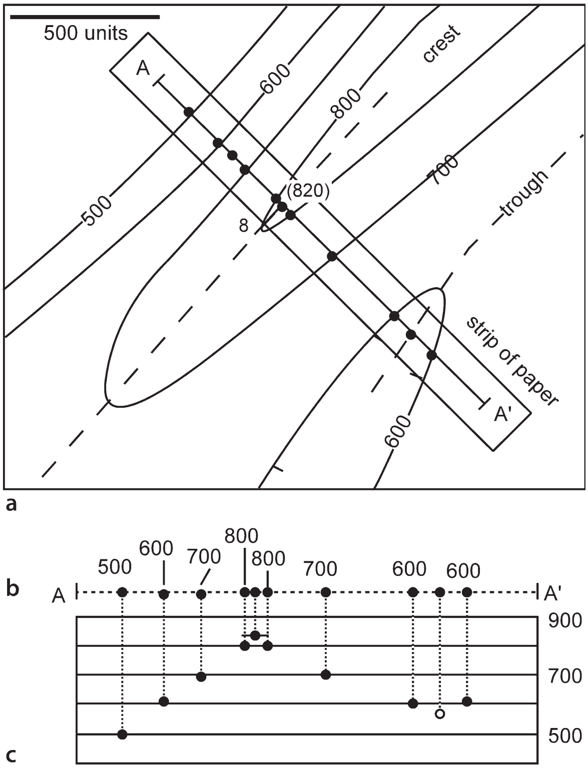


Fig. 6.12. Transferring data from map to cross section using an overlay (*dashed line*). **a** Data points are marked on the overlay. **b** The overlay is aligned with the section. **c** Points are projected onto the section (*dotted lines*). *Filled circles* are projected from known elevations; the *open circle* is an interpolated elevation

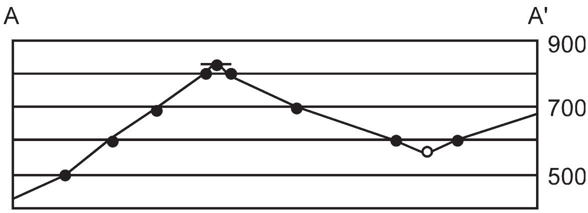


Fig. 6.13. Cross section *A–A′* from the structure contour map of Fig. 6.12. Vertical section, no vertical exaggeration. The *short horizontal line* is the apparent dip from the bedding attitude on the map

data onto the profile, it should be checked. Then the profile is constructed by connecting the dots (Fig. 6.13). If the correct shape of the profile is not clear, points can be added by interpolation between contours on the map.

6.3.2 Slicing

With 3-D software a cross section can be constructed by slicing the 3-D model (Fig. 6.14). The slice automatically shows the apparent dips of beds and faults, contact locations, and the apparent thicknesses of the beds.

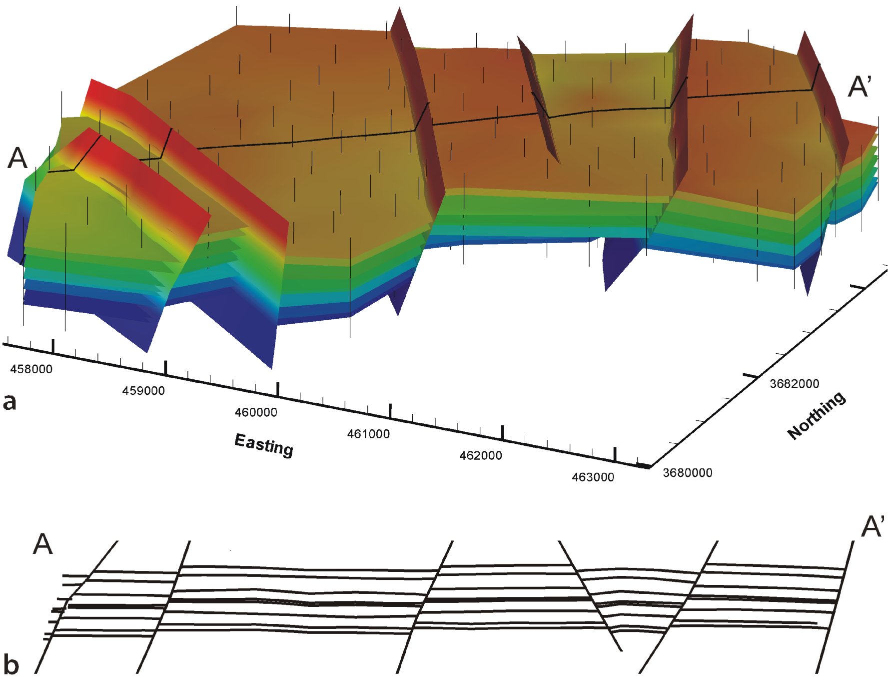


Fig. 6.14. 3-D map of coal-cycle tops and normal faults in the SE Deerlick Creek coalbed methane field, Black Warrior Basin, Alabama. *Vertical black lines* are wells (data from Groshong et al. 2003b). **a** Oblique view to the NW. *Wide line* crossing the region is the slice line. **b** Vertical slice from SW (*left*) to NE (*right*) across the area

6.4 Predictive Cross-Section Construction

A predictive cross section uses a set of geometric rules to predict the geometry between scattered control points. This process requires interpolation between data points and perhaps extrapolation beyond the data points. The best method depends on the nature of the bed curvature and on the nature of the bed thickness variations, or the lack of bed thickness variations. Where closely spaced control points are available, any method of interpolation will produce similar results. Where the data are sparse, the model that best fits the structural style will provide the basis for drawing the best cross section.

Two predictive methods will be presented here. The first method, here termed the dip-domain technique, is based on the assumption that the beds occur in planar segments separated by narrow hinges or faults (Coates 1945; Gill 1953). Easily done by hand, this method is also widely used in computer-aided structural design programs and in structural models. The second method is the method of circular arcs, which is based on the assumption that the beds maintain constant thickness and form segments of circular arcs (Hewett 1920; Busk 1929). Most cross sections published before the 1950s use this method.

Begin either technique by compiling the hard data onto the line of section. The cross section that shows just the original data will be called the *data* section. The cross-section interpretation should be done as an overlay on the data section. The interpolation between the control points may change dramatically during the interpretation process, but the locations of the control points and bedding attitudes should remain the same. Including the data section along with the final interpretation separates the data from the interpretation, a fundamental distinction that should always be made. The data may be subject to revision, of course. For example, inconsistencies in the cross section may indicate that a geologic contact has been mislocated or that a fault is required. This is one of the important reasons for constructing a predictive cross section. In the best scientific procedure, the original data and the interpreted result are both presented in the final report.

Data to be compiled will include dips and contact locations. If the section is not perpendicular to the fold axis, all dips shown on the cross section must be the apparent dips in the plane of the section. Measured attitudes must be converted using Eq. 2.18 or with a tangent diagram or stereogram. On an exaggerated profile (not recommended), the dip must be the exaggerated dip from Eq. 6.3 or 6.4. When the data have been transferred to the cross section, the section should again be checked against the information seen along the line of section on the map. A common mistake is to produce a cross section that fails to match the map along the line of section. All elevations, geological contacts, attitudes (apparent dips), and attitude locations must match exactly along the line of section. Projection of data to the line of section is commonly required and is discussed in Sect. 6.6.

It is useful to summarize the stratigraphic thicknesses in a "stratigraphic ruler" which will greatly speed up the drawing of an unexaggerated cross section. Draw the stratigraphic section at the scale of the cross section on a narrow piece of paper or, in computer drafting, make it a group of its own. This can be used as a ruler to mark off the stratigraphic units on the cross section and provides a quick check to see if the thickness of a unit is consistent with its dip. This only works on unexaggerated cross sections and is one of the important reasons for not using vertical or horizontal exaggeration.

Many structural interpretations are based on seismic reflection profiles which are already displayed in the form of a cross section. A seismic line that is to be interpreted structurally should satisfy the same criteria with respect to the choice of the plane of section and vertical exaggeration as a geological cross section. If geological data are available, transferring the data from maps to the seismic line will provide constraints that will help in the construction or validation of the depth interpretation. A successfully depth-converted seismic line must follow the same geometric rules as a geologic cross section.

6.4.1 Dip-Domain Style

The dip-domain method is based on the assumption that the beds occur as planar segments separated by narrow hinges. This method was originally proposed as section construction technique by Gill (1953) who called it the method of tangents. The basis for the technique lies in the relationship between the bedding thickness and the symmetry of the hinge (discussed previously in Sect. 5.4.2). For constant thickness

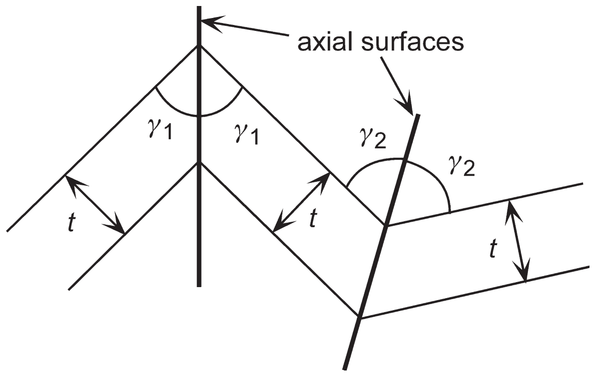


Fig. 6.15.
Dip-domain fold hinges in a constant thickness layer. t Bed thickness; γ_l-half-angles of the interlimb angle

beds, the axial surface bisects the interlimb angle between adjacent dip domains (Fig. 6.15). This maintains constant bed thickness. If the beds change thickness across the axial surface, then the axial surface cannot bisect the hinge. The technique is described here in the context of constant thickness beds. The technique is the same for beds that change thickness except that the axial surfaces do not bisect the hinges. See Eq. 5.13 for a method to calculate the axial surface orientation in folds that do not maintain constant bed thickness (see also Gill 1953).

6.4.1.1
Method

The following steps outline the dip-domain construction technique.

1. On the map or cross section, define the dip domains and locate the boundaries between domains as accurately as possible (Fig. 6.16a). A certain amount of variability from constant dip is expected in each domain (perhaps a 2–5° range).
2. Define the axial surfaces between domains (Fig. 6.16b). If bed thickness is constant, the axial surfaces bisect the hinges, but if bed thickness changes are known, use Eq. 5.13 to find the dips of the axial surfaces. Where axial surfaces intersect, a dip domain disappears and a new axial surface is drawn between the newly juxtaposed domains (for example, locations X in Fig. 6.16b). Note that a single fold is likely to have multiple hinges, as illustrated in Fig. 6.16.
3. Draw a key bed or group of beds through the structure, honoring the domain dips and the stratigraphic tops (Fig. 6.16c). Sometimes the data do not allow a single key bed to be completed across the whole structure. Shifting up or down a few beds to a new key bed will usually allow the section to be continued. Note that axial-surface intersections do not necessarily coincide with named stratigraphic boundaries. It is usually helpful to draw an horizon through the axial-surface intersection points (Fig. 6.16c).
4. Complete the section by drawing all the remaining beds with their appropriate thicknesses (Fig. 6.16c).
5. If desirable on the basis of the structural style, round the hinges an appropriate amount using a circular arc with center on the axial surface, or a spline curve.

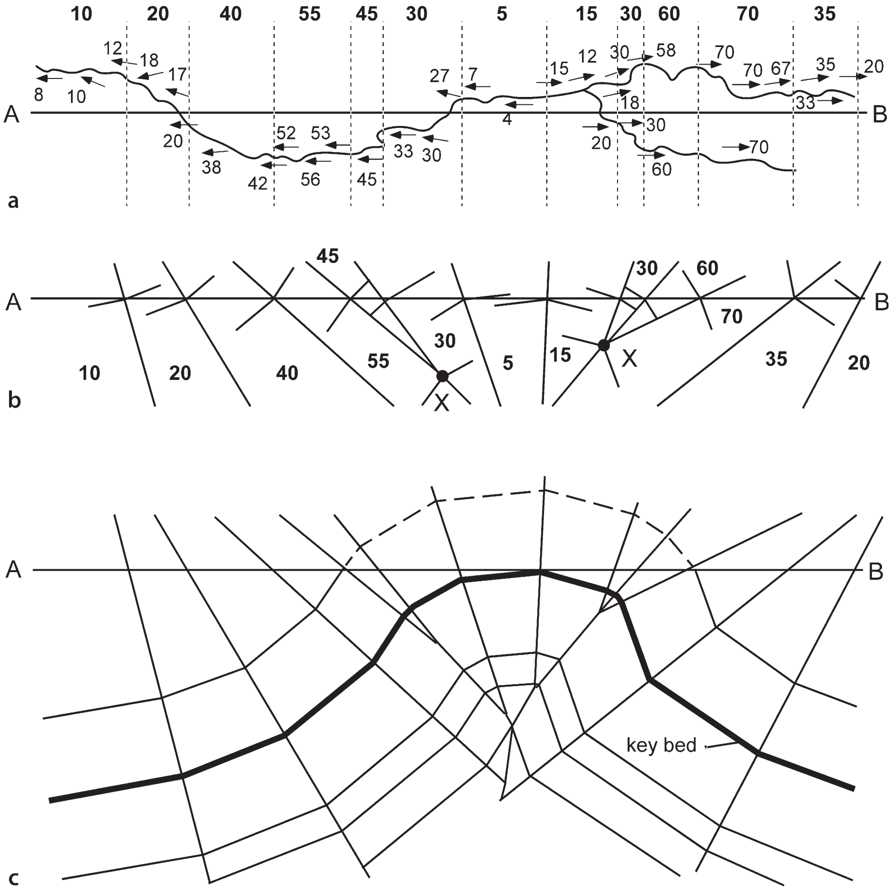


Fig. 6.16. Dip-domain cross-section construction technique. **a** Map of dips measured along a stream traverse and the boundaries (*dotted lines*) between interpreted dip domains. **b** Initial stage of cross-section construction showing domain dips and hinge locations with axial surfaces that bisect the hinges. *X:* axial-surface intersection points. **c** Completed cross section. (After Gill 1953)

6.4.1.2
Cylindrical Fold Example

The steps in building a cross section and interpolating the geometry using the constant bed thickness dip-domain method is illustrated with the Sequatchie anticline (Fig. 6.17). The map is characterized by domains of approximately constant dip, making it a good candidate for a dip-domain style cross section. The fold is nearly cylindrical within the map area and so the geometry of the structure should be constant along the axis. The crestal line is horizontal (Fig. 5.8b), making a vertical section the most appropriate. Prior to drawing the section, the stratigraphic thicknesses are determined and summarized in a stratigraphic ruler at the same scale as the map (Fig. 6.18).

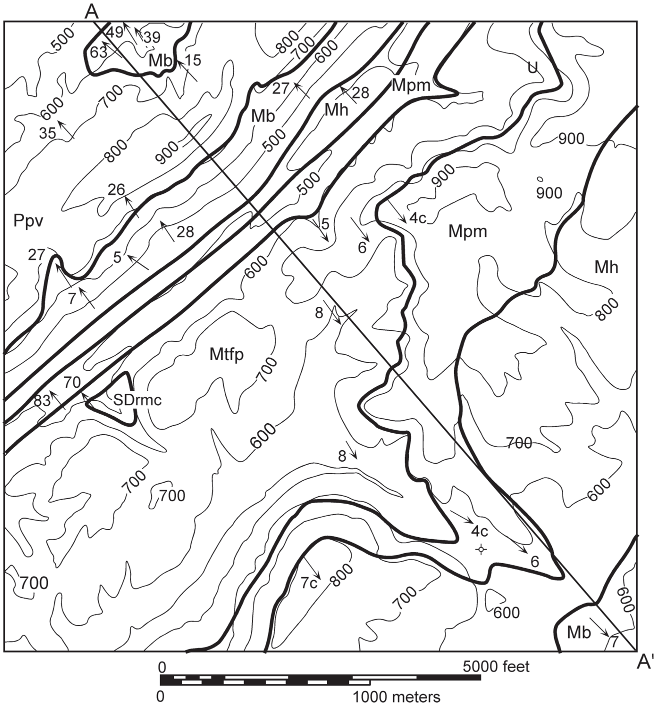


Fig. 6.17. Geologic map of a portion of the Sequatchie anticline at Blount Springs, Alabama, showing the line of cross section. Geologic contacts: *wide lines*, topographic contours (ft): *thin lines*, measured bedding attitudes are shown by *arrows*. *c:* Attitude computed from three points

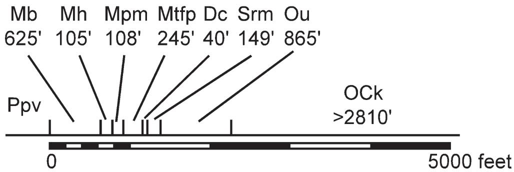


Fig. 6.18. Stratigraphic column for the Sequatchie anticline map area at the same scale as the map, to be used as a stratigraphic ruler. Thicknesses are in feet. Thicknesses of Ppv through Mpm are from outcrop measurements. The top of the Ppv is not present in the map area. Thicknesses of Mtfp through OCk are from the Shell Drennen 1 well (Alabama permit No. 688) interpreted by McGlamery (1956), and corrected for a 4° dip. The well bottomed in the OCk and so the drilled thickness is less than the total for this unit

The first step is to transfer the data from the map to the cross section. The line of section is drawn on the map (Fig. 6.17), at right angles to the fold axis. The topography is drawn using the method of Fig. 6.12, with the vertical scale equal to the map scale (Fig. 6.19). The geologic contacts are shown by arrows and the dips close to the line of section are shown as short line segments. The stratigraphic ruler is shown intersecting the topography at the projected surface location of the well that provided the thicknesses of the subsurface units. The geological data in solid lines on Fig. 6.19 form the data section which should not be subject to significant revision.

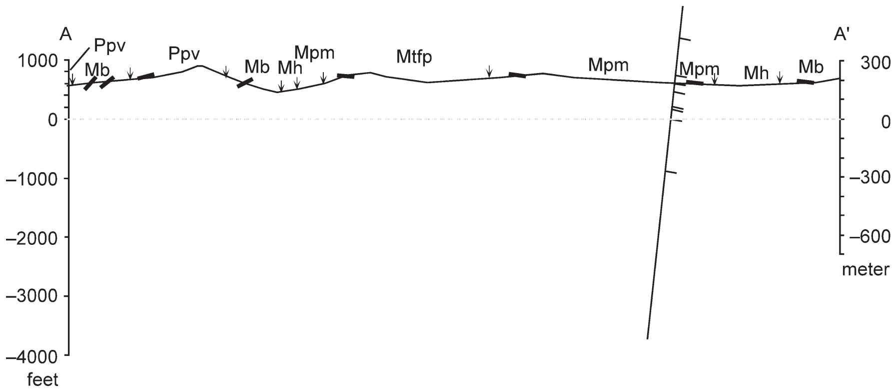


Fig. 6.19. Data section along the line *A–A′* (Fig. 6.17). No vertical exaggeration. The stratigraphic column is shown where the trace of the well projects onto the line of section. *Short arrows* at the topographic surface are the geological contact locations. *Wide short lines* are bedding dips

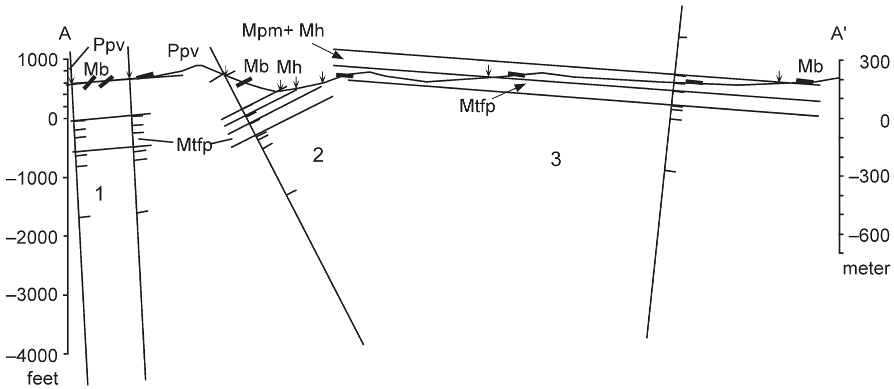


Fig. 6.20. Comparison between domain dips, stratigraphic thicknesses, and contact locations. *Short arrows* at the topographic surface are the geological contact locations. *Wide short lines* are bedding dips. Dip domains are *numbered*

The next step is to establish the domain dips and see how well the domains fit the locations of the formation boundaries (Fig. 6.20). As a first approximation, the fit to one backlimb and two forelimb domains is tested. (The forelimb is the steeper limb.) The dip of domain 1 (3NW) is given by the dip of the line connecting the base of the Ppv on opposite sides of the Mb inlier. The steeper dips of Mb within the inlier are caused by second-order structures and do not apply at the scale of the cross section. The domain 2 dip is the 27NW dip seen at the surface. The domain 3 backlimb dip of 6SE is seen in outcrop but is selected primarily because with this dip the unit thicknesses match the contact locations. Portions of the beds are drawn in with constant bed thickness to compare with the contact locations. The domain 2 dip fits both contacts of the Mh, even though this information was not used to define the dip.

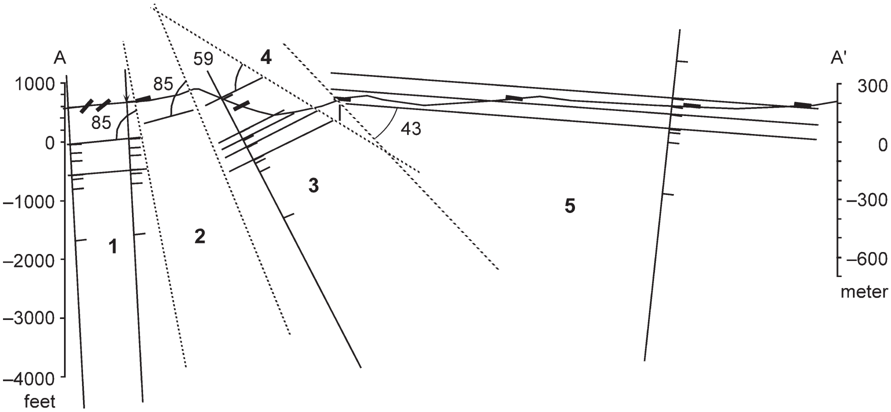


Fig. 6.21. Axial surface traces (*dotted lines*) that bisect the interlimb angles. Exact locations of the axial surfaces are not yet fixed in this step. Dip domains are *numbered*

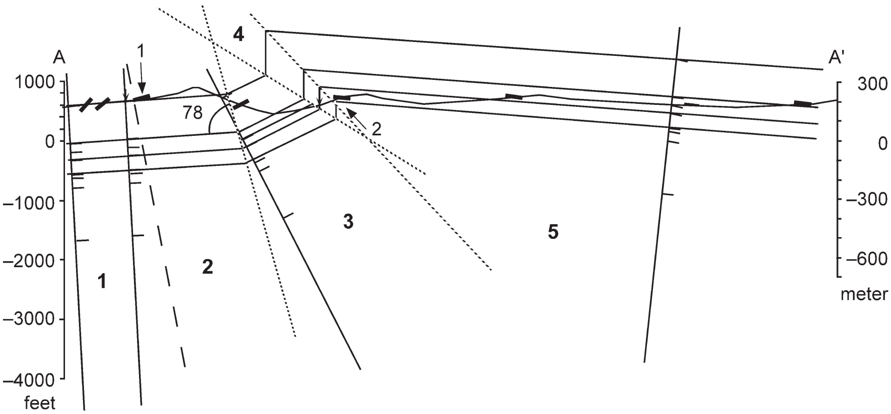


Fig. 6.22. Dip-domain cross section with axial surfaces (*dotted lines*) moved so that the dip domains match the stratigraphic contact locations. The *dashed* axial surface will be deleted and domains *1* and *2* combined

The axial surface orientations are determined next (Fig. 6.21). Following the relationship in Fig. 6.15 for constant bed thickness, the axial surfaces bisect the hinges. The interlimb angles are measured, bisected and the axial surfaces drawn between each domain. Two dip domains (2 and 4) are added to those shown in Fig. 6.20 so that the dips can be honored at the ground surface. It is tempting to insert a fault at the location of domain 4, but the map (Fig. 6.17) shows a vertical to near-vertical domain to the southwest in the same position as on the vertical dip on the cross section. Not far to the southwest of the map area, the units are directly connected across the two limbs (Cherry 1990) with no fault present. The positions of the axial surfaces in Fig. 6.21 are only approximate; the next step is to determine their exact locations.

The locations of the axial surfaces are now adjusted until the dip domains match the stratigraphic contacts (Fig. 6.22). The dip change of the Ppv at location 1 must be ignored and the corresponding axial surface between domains 1 and 2 removed in order to match the locations of the stratigraphic contacts. A new axial surface dip is determined as the boundary between the two domains in contact (1 + 2 and 3) after the incorrect axial surface is removed. The vertical dip selected for the forelimb provides a good match to all the contacts except for the top of the Dc at location 2. A slight rounding of the contact at this location will provide a match to the map geometry. The internal consistency of the section based on constant thicknesses, planar domain dips and the mapped contact locations and depths in the well is strong support for the interpretation.

Axial surfaces are shown as crossing in Fig. 6.22, an impossibility. Where two axial surfaces intersect, the dip domain between them disappears and a new axial surface is defined between the two remaining dip domains (Fig. 6.23). The final cross section (Fig. 6.23) is an excellent overall fit to the dips and contact locations. Locations 1 and 2 are the only misfits. The misfits are quite small. At location 1, the base of the Mh does not match the mapped outcrop location which could be caused by a second-order fold at that point or by the mislocation of a poorly exposed contact. A very small domain of thickened bedding is required at location 2 in order to keep the top of the Dc below the surface of the ground and so that the contacts of the Dc and the Sm meet across the axial surface. It is no surprise that bed thickness is not perfectly constant in such a tight hinge. The surprise is that such a small region of thickening is required in the hinge. The effect of the thickening of the Mtfp is to round the hinge, a feature that might continue upward along the axial surface as well, but is shown as ending within the Mtfp. Both the vertical domain and the thickened domain disappear at point 3 where a new axial surface bisects the angle between the remaining two domains (2 and 4). The match of the top of the OCk across this axial surface is an additional confirmation of the cross-section geometry because the location of the axial surface is defined by intersection point 3, not by projection of the OCk contact.

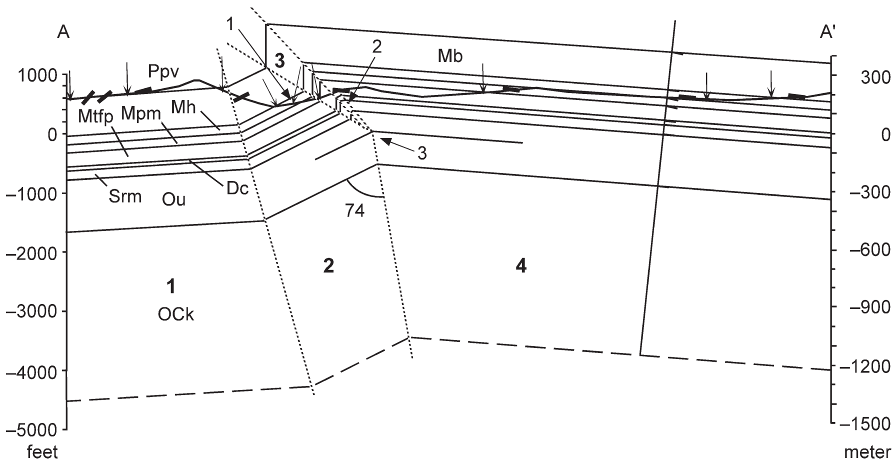


Fig. 6.23. Final constant-thickness, dip-domain cross section across the Sequatchie anticline. No vertical exaggeration. The *numbered arrows* are explained in the text. *Small arrows* mark the contact locations. The *dashed line* is the level of the deepest horizon drilled

This example illustrates the importance of the cross section to structural interpretation. The rule of constant bed thickness allows a few dips and the formation contact locations to tightly constrain the geometry of the cross section. The rule works well even though there is a small amount of thickening in the tightest hinge. The cross section can, in turn, be used to revise the geologic map and the composite structure contour map. The cross section provides the needed control for mapping the deeper geometry. Extrapolation to depth using the composite-surface technique breaks down if vertical lines through the control points pass through axial surfaces, as happens in the forelimb of the Sequatchie anticline (Fig. 6.23). Composite surface maps (Sect. 3.6.2) provide a good first approximation, but the final interpretation should be controlled directly by cross sections based on multiple horizons.

6.4.2 Circular Arcs

The method of circular arcs is based on the assumptions that bed segments are portions of circular arcs and that the arcs are tangent at their end points (Hewett 1920; Busk 1929). This type of curve can be drawn by hand using a ruler and compass. The resulting cross section will have smoothly curved beds. The method of circular arcs produces a highly constrained geometry in which both the shape of the structure and the exact position of each bed within the structure are predicted. When these predictions fit all the available data, the cross section is very likely to be correct. If the stratigraphic and dip data cannot be matched by the basic construction technique, as often happens, dips can be interpolated that will produce a match. The basic method is given first, then two techniques for dip interpolation.

6.4.2.1 Method

If the dips are known at the top and bottom of the bed (Fig. 6.24), the geometry of a circular bed segment is constructed by drawing perpendiculars through the bed dips (at A and B), extending the perpendiculars until they intersect (at O) which defines the center of curvature. Circular arcs are drawn through A and B to define the top and bottom of the bed.

This process is repeated for multiple data points to draw a complete cross section (Fig. 6.25). The first center of curvature (O) is defined as the intersection of the normals to the first two dips (A and B). The marker horizon located at point A is extended to the bedding normal through B along a circular arc around point O. The next center of

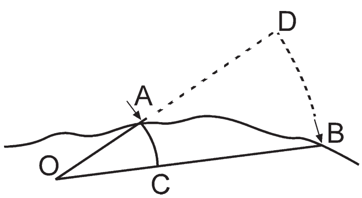


Fig. 6.24. Cross section of a bed that is a portion of a circular arc. (After Busk 1929)

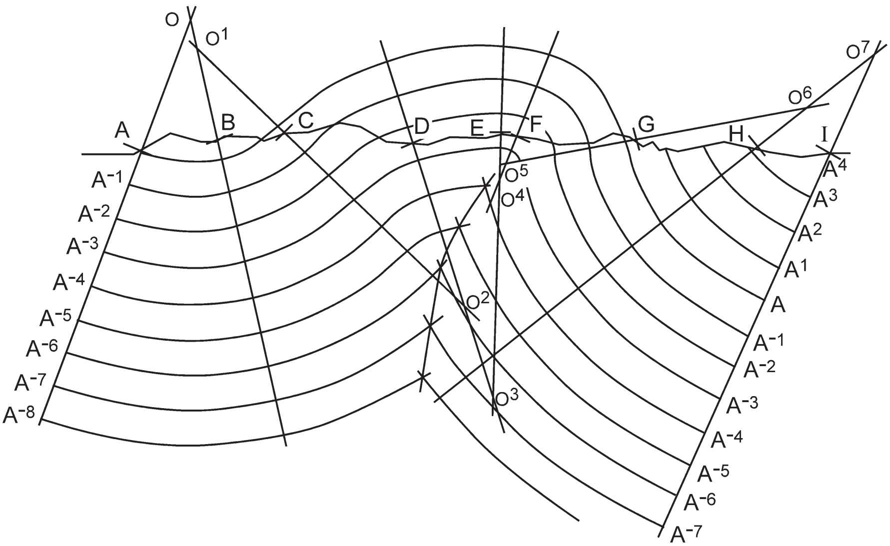


Fig. 6.25. Cross section produced by the method of circular arcs. *A–I:* outcrop dip locations; A^i: marker horizons; O^i: centers of curvature. (After Busk 1929)

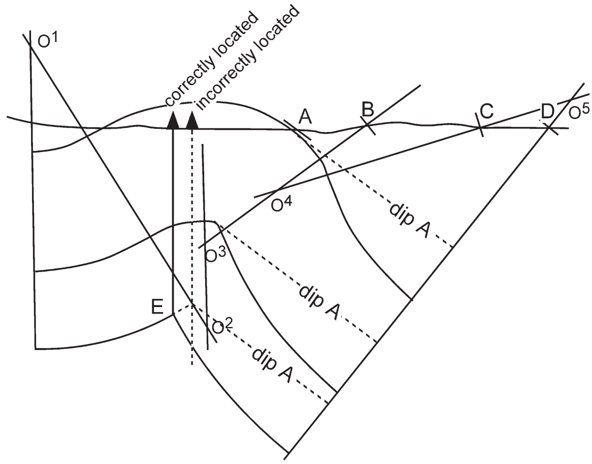


Fig. 6.26. Sensitivity of the crest location on a circular-arc cross section to the dips in the adjacent syncline. *A:* Dip on surface anticline used for linear projection of the fold limb; *B–D:* dips in adjacent syncline used for circular-arc construction of the limb; O^i: centers of curvature. Wells attempting to drill the lowest unit at the crest are shown. (After Busk 1929)

curvature is located at O^1. The marker horizon is extended to the normal through C as a circular arc with center O^1. The same procedure is followed across the section to complete the key horizon A–A (Fig. 6.25). The remaining stratigraphic horizons are drawn as segments of circular arcs around the appropriate centers. Constructed in this fashion, the beds have constant thickness. To maintain constant bed thickness, the beds form cusps in the core of the fold.

To properly control the geometry of a cross section at depth, data may be needed at a long distance laterally from the area of interest (Fig. 6.26). For example, in order to correctly locate the crest of an anticline at depth, dips are needed from the adjacent synclines. If the last dip in the anticline (Fig. 6.26) was collected at A, then the steep limb of the structure would be drawn with the long dashed lines and the crest on the lowest horizon would be at the location of the incorrect well. Using the dips at B, C, and D, the structure is drawn with the solid lines, and the crest is found to be at E (Fig. 6.26). This is a general property of cross-section geometry and also applies to dip-domain constructions.

6.4.2.2
Dip Interpolation

Frequently the predicted geometry and the bed locations do not agree. The predicted location of horizon A (Fig. 6.27) on the opposite limb of the anticline is at B, but that horizon may actually crop out at B' or B". This result means that insufficient data are available to force a correct solution. It is necessary to modify the data or to interpolate intermediate dip values between A and B in order to make the horizon intersect the section at B' or B". Two methods of dip interpolation will be given; the first is to interpolate a planar dip segment and the second is to interpolate an intermediate dip.

The simplest method is to insert a straight line segment (AY, Fig. 6.28) between the two arc segments that produce the disagreement. This method is usually successful and provides an end-member solution. The procedure is from Higgins (1962):

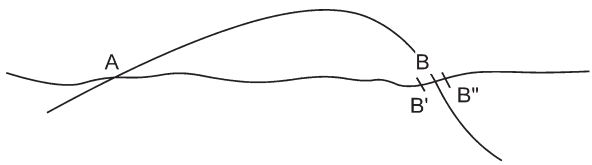


Fig. 6.27.
Cross section showing the mismatch between the predicted location of the key bed at *A* and its mapped location (*B′* or *B″*) at *B*. (After Busk 1929)

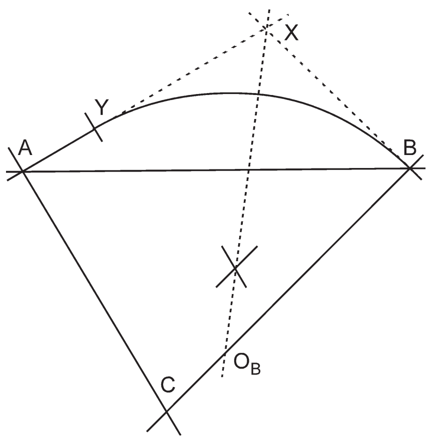


Fig. 6.28.
Interpolation using a straight line with a circular arc. (After Higgins 1962)

1. Extend the dips at A and B so that they intersect at X.
2. On AX locate point Y such that YX = XB.
3. Bisect angle YXB. The bisector will intersect BC, the normal to B, at O_b.
4. With center O_b and radius BO_b, draw the arc from B to Y. This arc is tangent to AY, the straight-line extension of the dip from A.

The second method is to insert a dip such that the two data points are joined by two circular arcs that are tangent at the data points and at the interpolated dip. The result is a cross section with continuously curving beds. This method is given by Busk (1929) and Higgins (1962). Beginning with the two dips A and B (Fig. 6.29):

1. Draw AA' perpendicular to the lesser dip at A; draw BB' perpendicular to the greater dip at B.
2. Draw the chord AB. Angle CAB must be greater than angle CBA; if not, switch the labels on points A and B.
3. Erect the perpendicular bisector of AB. This line intersects AA' at Z.

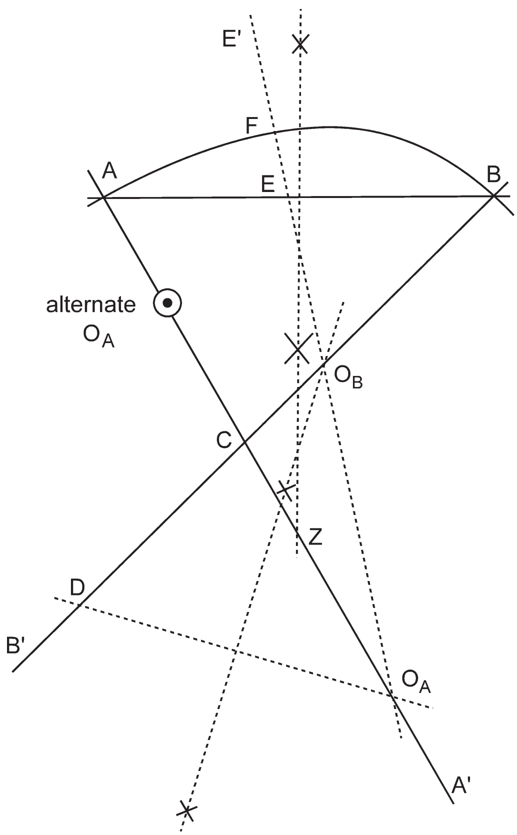


Fig. 6.29. Interpolation using circular-arc segments. (Modified from Higgins 1962)

4. Choose point O_A anywhere on line AA' on the opposite side of Z from A. (If the length O_A–Z is very large, it is equivalent to drawing a straight line through A.)
5. On BB' locate point D such that BD = AO_A.
6. Draw DO_A connecting D and O_A.
7. Erect the perpendicular bisector of DO_A. This line intersects BB' at O_B.
8. Draw O_AE' through O_A and O_B, intersecting AB at E.
9. With center O_A and radius AO_A, draw an arc from A, intersecting O_AE' at F.
10. With center O_B and radius BO_B, draw an arc from B intersecting O_AE' at F. This completes the interpolation.

If a correct solution is not obtained, it may be because the sense of curvature changes across an inflection point, causing the centers of curvature to be on opposite sides of the key bed. Modify step 4 above by using the alternate position of O_A (Fig. 6.29: alternate O_A), located between C and A.

6.4.2.3 Other Smooth Curves

Interactive computer drafting programs provide several different tools for drawing smooth curves through or close to a specified set of points. Typically they are parametric cubic curves for which the first derivatives, that is the tangents, are continuous where they join (Foley and Van Dam 1983). In this respect the curves are like the method of circular arcs, for which the tangents are equal where the curve segments join, but cubics are able to fit more complex curves than just segments of circular arcs. Two different smooth curve types are widely available in interactive computer drafting packages, Bézier and spline curves. The two curve types differ in how they fit their control points and in how they are edited. Both types are useful in producing smoothly curved lines and surfaces (Foley and Van Dam 1983; De Paor 1996).

A Bézier curve consists of segments that are defined by four control points, two anchor points on the curve (P_1 and P_4, Fig. 6.30a) and two direction points (P_2 and P_3) that determine the shape of the curve. The curve always goes through the anchor points. The shape is controlled in interactive computer graphics applications by moving the direction points. In a computer program the direction points may be connected to the anchors by lines to form handles (Fig. 6.30b) that are visible in the edit mode. At the join between two Bézier segments, the handles of the shared anchor point are colinear, ensuring that the slopes of the curve segments match at the intersection.

A spline curve only approximates the positions of its control points (Fig. 6.31) but is continuous in both the slope and the curvature at the segment boundaries, and so the curve is even smoother than the Bézier curve (Foley and Van Dam 1983). The shape is controlled in interactive computer graphics applications by moving the control points that are visible in the edit mode. This curve type should be drawn separately from the actual data points because editing the curves changes the locations of the points that define the curve. The control points can be manipulated until the match between the curve and the data points is acceptable.

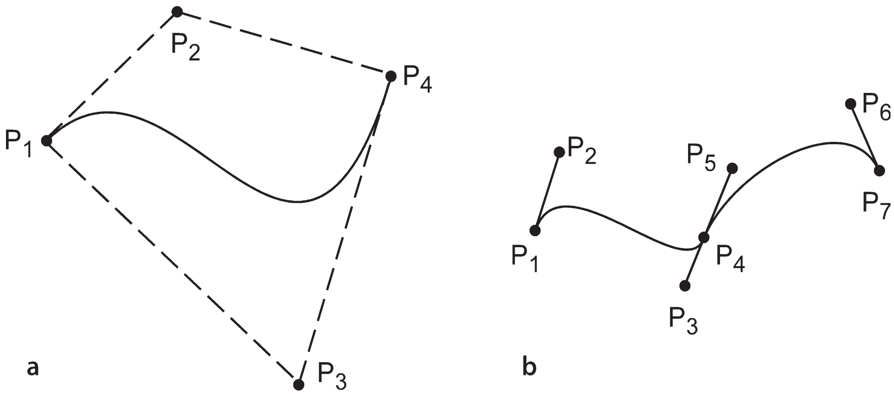


Fig. 6.30. Bézier curves. **a** The four control points that define the curve. **b** Two Bézier cubics joined at point P_4. Points P_3, P_4, and P_5 are colinear. (After Foley and Van Dam 1983)

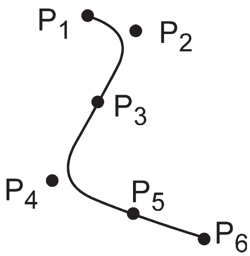


Fig. 6.31.
Spline curve and its control points

Drawing a cross section (or a map) using the smooth curves just described requires care to maintain the correct geometry. Constant bed thickness, for example, is not likely to be maintained if the section is drawn from sparse data. The appropriate bed thickness relationships can be obtained by editing the curves after a preliminary section has been drawn. The cross section of the Sequatchie anticline illustrates the problems. The original section (Fig. 6.23) was redrawn by changing the lines from polygons to spline curves in a computer drafting program. The resulting cross section (Fig. 6.32) may be more pleasing to the eye than the dip-domain cross section, but it is less accurate. The unedited spline-curve version (Fig. 6.32a) is much too smooth. Each bedding surface is defined by 4 to 6 points, a data density that might be expected with control based entirely on wells. Bedding thicknesses are not constant as in the dip-domain version, and the amplitude of the structure is reduced. These are the typical results of analytical smoothing procedures, including the smoothing inherent in gridding as used for map construction. Editing the spline curves produces a better fit to the true dips (Fig. 6.32b). A more accurate spline section can be produced by introducing many more control points, which is the appropriate procedure for producing a final drawing of a known geometry. The addition of control points to improve an interpretation based on a sparse data set requires additional information, such as the bedding dips, or the requirement of constant bed thickness.

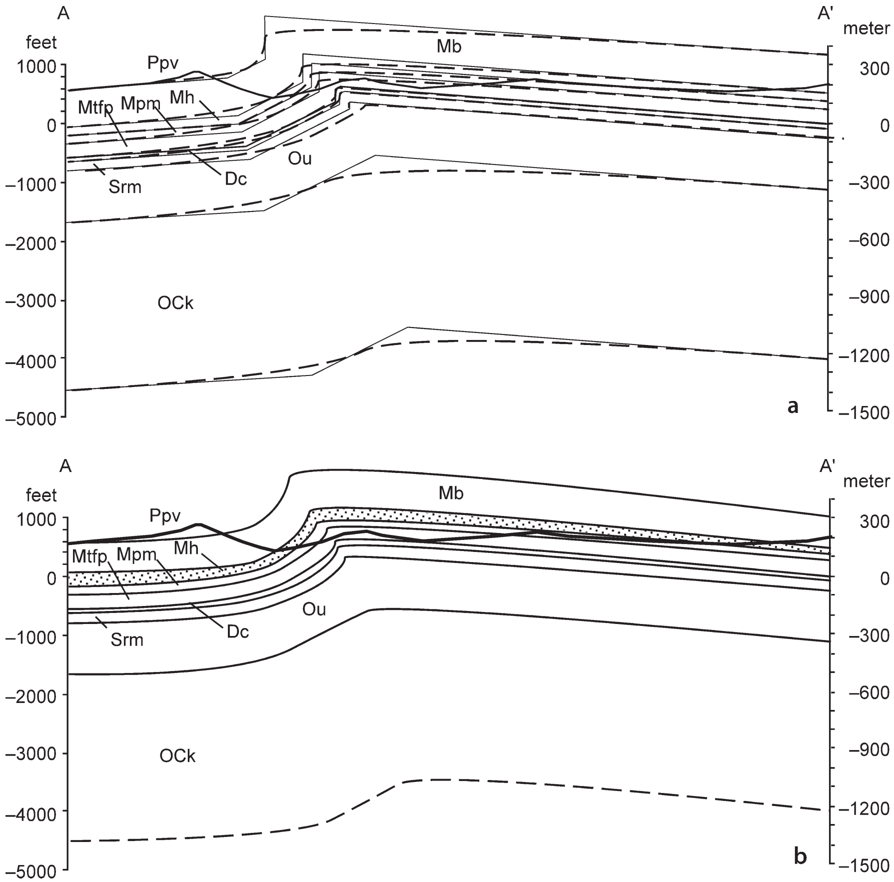


Fig. 6.32. Cross section of the Sequatchie anticline interpreted with spline curves. No vertical exaggeration. **a** Dip-domain cross section (*thin solid lines* from Fig. 6.23) and computer-smoothed spline interpretation (*thick dashed curves*). **b** Spline curve section edited to more closely resemble the dip-domain section

6.5 Changing the Dip of the Section Plane

If a cross section is not perpendicular to the fold axis, it is helpful for structural interpretation to rotate the section plane until it is a normal section. Alternatively, it might be necessary to rotate a normal section to vertical. The necessary relationships are equivalent to removing (or adding) a vertical exaggeration, as done in the visual method of down-plunge viewing.

From the geometry of Fig. 6.33, the exaggeration in a vertical section across a plunging fold (Eq. 6.1) is

$$V_e = t_v / t = 1 / \cos \phi \quad . \tag{6.8}$$

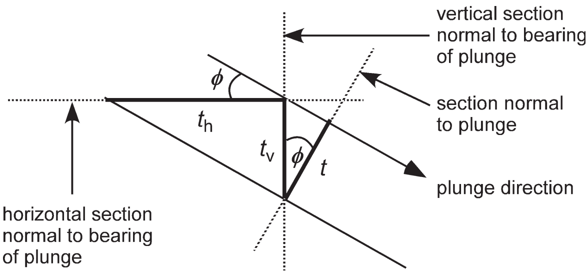


Fig. 6.33. Vertical exaggeration in cross section parallel to the plunge direction, caused by a plunge angle of ϕ. The true thickness is t; the exaggerated thickness is t_h in the horizontal plane and t_v in the vertical plane

The section is changed from a normal section to a vertical section by exaggerating the vertical scale with Eq. 6.8. The vertical exaggeration on a vertical section due to the plunge is removed by multiplying the vertical scale of the section by the reciprocal of the vertical exaggeration, cos ϕ.

The exaggeration on a horizontal section (map view), t_h / t, (Fig. 6.33) is

$$V_e = t_h / t = 1 / \sin \phi \quad . \tag{6.9}$$

The exaggeration on a horizontal section due to the plunge is removed by multiplying the vertical scale of the section by the reciprocal of the vertical exaggeration, sin ϕ.

The same procedure can be used to rotate the plane of a cross section around a vertical axis. Treat Fig. 6.33 as being the map view and the vertical exaggeration as being a horizontal exaggeration. Equation 6.8 then gives the horizontal exaggeration of the profile, with ϕ = the angle between the normal to the line of section and the desired direction of the section normal. Rotate the section by multiplying the horizontal scale by the reciprocal of the horizontal exaggeration, cos ϕ.

6.6 Data Projection

In order to make maximum use of the available information, it is usually necessary to project data onto the plane of the cross section from elsewhere in the map area. Data from a zig-zag cross section or seismic line should be projected onto a straight line to correctly interpret the structure. Wells should be projected onto seismic lines for best stratigraphic correlation and to confirm the proper depth migration of the seismic data. The additional data that are obtained by projection from the map to the line of section help constrain the interpretation of the cross section and help ensure that the interpretation is compatible with the structure off the line of section. Projection of data to the line of section is an important step in the geological interpretation, not a simple mechanical process.

Incorrect projection places the data in the wrong relative positions on the cross section and renders the interpretation incorrect or impossible. The effect of the projection technique is illustrated with an example (Fig. 6.34) originally presented by Brown (1984). A cross section of the structure in Fig. 6.34a has been constructed by projecting the wells onto the line of section along the strike of the structure contours (Fig. 6.34b). The resulting profile is poor in terms of structural style. The cross section shows multiple small faults instead of a single smooth fault. Note that no well shows

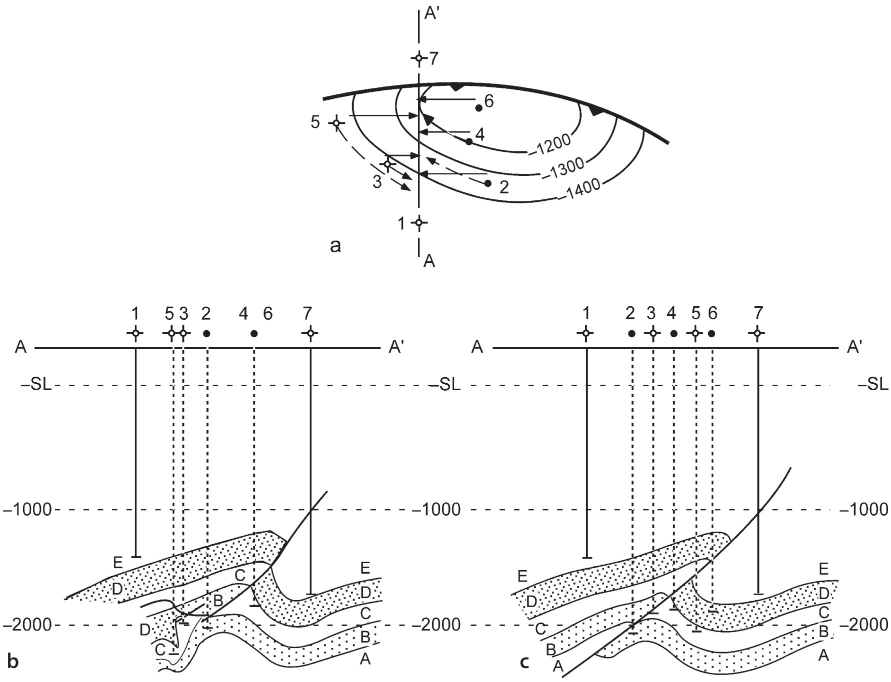


Fig. 6.34. Different cross sections obtained by different methods of data projection. **a** Structure contour map of horizon *E*, showing the alternative projection directions. *Solid lines* are parallel to the fold axis; *dashed lines* are parallel to structure contours. **b** Cross section produced by projecting wells along structure contours. **c** Cross section produced by projecting wells along the plunge of the fold axis. *SL* sea level. (After Brown 1984)

more than one fault, yet the cross section shows locations where a vertical well should cut two faults. Projection along plunge (Fig. 6.34c) significantly improves the cross section. The west half of the structure has a uniform cylindrical plunge to the west and so projection along plunge produces a reasonable cross section. Only one fault is present and it is relatively planar, as expected.

Three general approaches to projection will be presented: projection along plunge, projection with a structure contour map, and projection within dip domains. For structures where the plunge can be defined from bedding attitude data, projection along plunge is effective. Where formation tops are relatively abundant, but attitudes are not available, projection by structure contouring is straightforward and accurate. Computer mapping programs usually take this approach. It must be recognized that the structure contours themselves are interpretive and may not be correct in detail until after they have been checked on the cross section. Iterating between maps and the cross section in order to maintain the appropriate bed thicknesses is a powerful technique for improving the interpretation of both the maps and the cross section. For dip-domain style structures, defining the dip-domain (axial-surface) network is an efficient method for projecting the geometry in three dimensions.

Not all features in the same area will necessarily have the same projection direction. For example, stratigraphic thickness changes may be oblique to the structural trends and should therefore be projected along a trend different from the structural trend. Folds and cross-cutting faults may have different projection directions. The respective trends and plunges should be determined from structure contour maps (Chap. 3), isopach maps (Sect. 4.3.1) and dip-sequence analysis (Chap. 9).

6.6.1 Projection Along Plunge

Projection of information along plunge is most appropriate where the local data are too sparse to generate a structure contour map, but where the trend and plunge can be determined from bedding attitudes, for example, from a dipmeter.

6.6.1.1 Projecting a Point or a Well

The projection of a point, such as a formation top in a well, along plunge to a new location, such as a vertical cross section or a seismic line (Fig. 6.35) is done using

$$v = h\ \tan\phi \quad , \tag{6.10}$$

where v = vertical elevation change, h = horizontal distance in the direction of plunge from projection point to the cross section, and ϕ = plunge. For example, if h = 1 km and the plunge is 15° (Fig. 6.35), the elevation of the projected point is 268 m lower on the cross section than in the well.

6.6.1.2 Plunge Lines

Projection along plunge is conveniently done using plunge lines, which are lines in the plunge direction, inclined at the plunge amount (Wilson 1967; De Paor 1988). Plunge lines

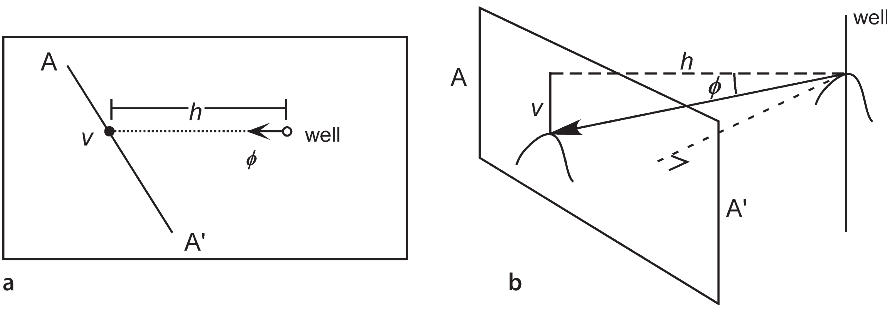


Fig. 6.35. Projection of a well along plunge to a cross section or seismic profile. **a** Map view of the projection of the well to cross section *A–A'*. The *arrow* gives the plunge direction; ϕ plunge amount; *h* horizontal distance in direction of plunge from projection point to cross section; *v* vertical elevation change. **b** 3-D view

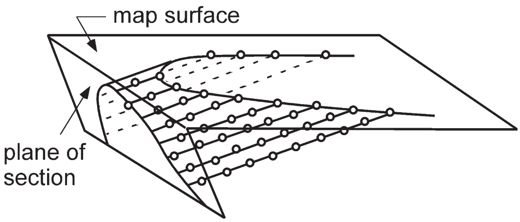


Fig. 6.36.
Plunge lines in a cylindrical fold. The lines are parallel to the plunge and points along the lines mark elevations. (After De Paor 1988)

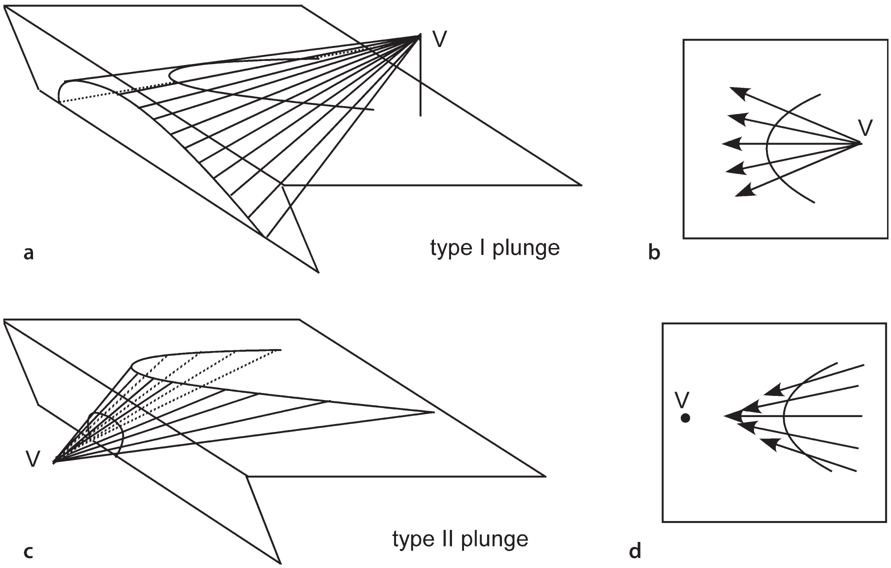


Fig. 6.37. Plunge lines in conical folds. *V* Fold vertex. **a** Perspective view of type I fold. **b** Map view of plunge lines in type I fold. *Arrows* point down the plunge direction. **c** Perspective view of type II fold. **d** Map view of plunge lines in type II fold. *Arrows* point down the plunge direction

provide an effective means for quantitatively describing and projecting the 3-D geometry of a fold. A series of plunge lines defines the shape of the structure (Fig. 6.36). The plunge line for a cylindrical fold is parallel to the fold axis and is the same direction for every point within the fold (Fig. 6.36). Each plunge line in a conical fold has its own bearing and plunge (Fig. 6.37). The plunge lines fan outward from the vertex. In a type I conical fold (Fig. 6.37a,b) the plunge is away from the vertex and in a type II fold the plunge is toward the vertex (Fig. 6.37c,d). Plunge line directions in conical folds are best determined from the tangent diagram as described previously (Sect. 5.2.2).

A plunge line lies in the surface of the bed. Begin the projection by drawing a line on the map parallel to the plunge through the control point to be projected. Starting from the known elevation of the control point, mark spot heights (Fig. 6.38) spaced according to

$$H = I / \tan \phi \quad , \tag{6.11}$$

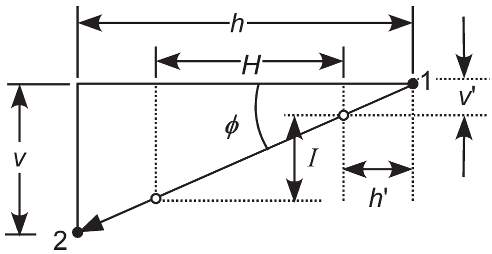


Fig. 6.38.
Projection along plunge in a vertical cross section. The projection is parallel to plunge along the plunge line from point *1* to point *2*. *Open circles* are spot heights along the plunge line. For explanation of symbols, see text

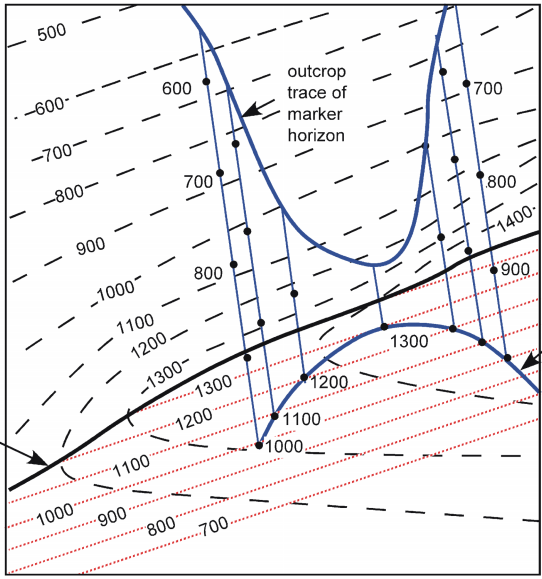


Fig. 6.39. Projection of a marker horizon to a fault plane along plunge lines. *Dashed lines* are topographic contours above sea level. *Dotted lines* are subsurface structure contours on the fault. Plunge lines are *solid* and marked by spot elevations. (After De Paor 1988)

where H = horizontal spacing of points, I = contour interval, and ϕ = plunge. If the control point is not at a spot height, the distance from the control point to the first spot height is

$$h' = H\,v'/I \quad , \qquad (6.12)$$

where h' = the horizontal distance from the control point to the first spot height and v' = the elevation difference between the control point and the first spot height.

Projection along plunge lines is particularly suited to projecting data from an irregular surface, such as a map, onto a surface, such as a cross section or fault plane, that itself can be represented as a structure-contour map. Figure 6.39 shows plunge lines derived from a map of a folded marker horizon on a topographic base. The fold

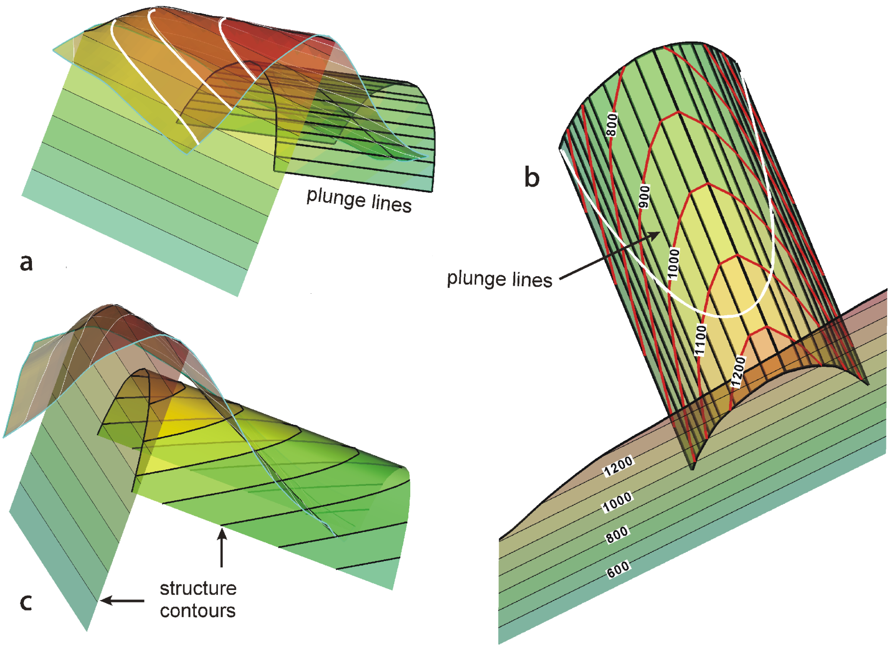


Fig. 6.40. 3-D views of the map in Fig. 6.39. **a** Oblique view to NW. Topographic surface with *white contours*, fault with *thin black contours*, fold with *thick black plunge lines*. **b** Vertical view, N up. Structure contours (with elevations) and plunge lines on the fold, structure contours (with elevations) only on the fault. *White line* is outcrop trace of fold. **c** Oblique view to NW. Same as **a** except fold shape indicated by structure contours

is projected south, up plunge, along the plunge lines onto the structure contour map of a fault. The intersection points where the plunge lines have the same elevation as the fault contours are marked and then connected by a line that represents the trace of the marker horizon of the fault plane (Fig. 6.39). In 3-D (Fig. 6.40a), the outcrop trace is projected up and down plunge from the outcrop trace to more completely illustrate the fold.

A structure contour map can be constructed from the plunge lines by joining the points of equal elevation (Fig. 6.40b). Figure 6.40b demonstrates that the plunge lines are not parallel to the structure contours and that projections should be made parallel to the plunge lines, not parallel to the structure contours. The structure contours provide an additional cross check on the geometry of the structure and on the internal consistency of the data. Once the fold geometry is constructed the plunge lines can be deleted and the shape shown by structure contours alone (Fig. 6.40c).

This technique can be performed analytically using the method of De Paor (1988). An individual point P (Fig. 6.41), given by its xyz map coordinate position, can be projected along plunge to its new position P' $(x', 0, z')$ on the cross-section plane (defined by $y' = 0$). Select the map coordinate system such that x is parallel to the line of cross section and y is perpendicular to the line of section. Choose $y = z = 0$ to lie in the plane

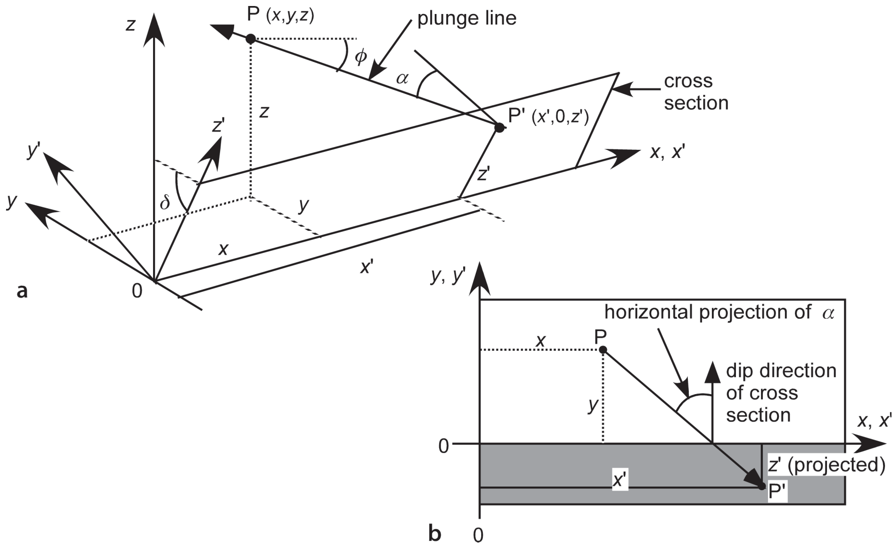


Fig. 6.41. Projection along plunge into the plane of the cross section. **a** Perspective diagram. **b** Horizontal map projection. The projection of the section plane onto the map is *shaded*

of the cross section. The sign convention requires that the positive (down) plunge direction be in the negative y direction. The elevation of a point is z. The dip of the plunge line $= \phi$, the angle between the plunge line and the normal to the cross section $= \alpha$, and the dip of the cross section $= \delta$. The plunge line is constant in direction in a cylindrical fold but may be different for every location in a conical fold.

The general equations for the projected position of a point P', derived at the end of the chapter (Eqs. 6.36 and 6.41), are:

$$x' = x + y \tan\alpha + \tan\alpha\ (z \cos\alpha - y \tan\phi) / (\tan\phi + \tan\delta \cos\alpha) \quad , \tag{6.13}$$

$$z' = (z \cos\alpha - y \tan\phi) / (\tan\phi \cos\delta + \sin\delta \cos\alpha) \quad . \tag{6.14}$$

For a vertical cross section, from Eqs. 6.42 and 6.43,

$$x' = x + y \tan\alpha \quad , \tag{6.15}$$

$$z' = z - (y \tan\phi) / \cos\alpha \quad . \tag{6.16}$$

A cross section perpendicular to the fold axis is possible only for a cylindrical fold. The equations for projection to the normal section are (from Eqs. 6.44 and 6.45)

$$x' = x \quad , \tag{6.17}$$

$$z' = z \cos\phi - y \sin\phi \quad . \tag{6.18}$$

In a conical fold the plunge amount and direction changes with location. A cross section perpendicular to the crestal line will be closely equivalent to a normal section in slightly conical structures. Substitute the plunge of the crestal line in Eqs. 6.17 and 6.18 to approximate a normal section. The shorter the projection distance, the better the approximation.

6.6.1.3 Graphical Projection

The concept of projection along plunge is the basis of the graphical cross-section construction technique of Stockwell (1950). This method makes it possible to project data onto cross sections that have steep dips, such as vertical sections or sections normal to gently dipping fold axes. The graphical method is given by the following steps. Refer to Fig. 6.42 for the geometry.

1. Create the graph on which the cross section will be constructed at the same scale as the map and align it perpendicular to the plunge direction. Draw the line AC parallel to the plunge direction at the edge of the map. AC represents a horizontal line on the plunge projection. The plunge projection will be constructed from this line.
2. Begin the projection with the point that is to be projected the farthest (P_1). Project this point along the dotted line P_1A, perpendicular to the line AC to point A. From point A, draw the line AB at the plunge angle, ϕ, from AC.
3. Draw the orientation of the plane of the cross section (line CB) at the desired orientation to the vertical (angle ACB). In Fig. 6.42 the plane of the cross section has been chosen to be perpendicular to the plunge (angle ABC = 90°). The plane of ABC represents a vertical cross section in the plunge direction through point P_1.
4. The length CB is the distance in the plane of the east-west section from the map elevation of P_1 to its location P_1' on the cross section. Draw a vertical construction line (dotted line P_1C') through P_1 onto the line of section and measure the length C'B' (solid line) = CB down from the map elevation of the point to find P_1'.
5. Repeat step 4 to project all other points, for example P_2 is projected to P_2'.

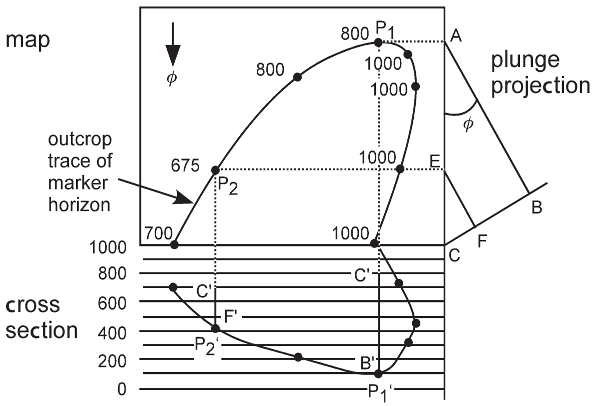


Fig. 6.42. Projection of map data onto a cross section normal to plunge. The plunge is ϕ to the south. *Numbers* on the map (*square box*) are the topographic elevations of the points to be projected

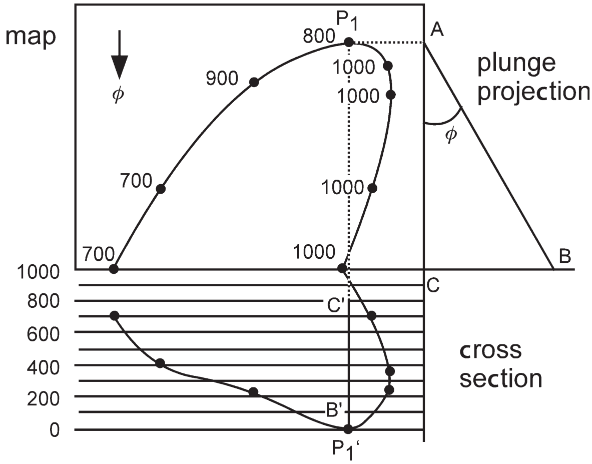


Fig. 6.43. Projection along plunge onto a vertical cross section. *Numbers* on the map (*square box*) are the topographic elevations of the points to be projected

The ratio of the vertical projection length AB to the cross-section projection length CB is constant for all points, CB : CA = CF : CE = sin ϕ. Projection by hand is very rapid if a proportional divider drafting tool is used. Set the divider to the ratio CB / AB; then as the projection length AC is set, the divider gives the required length CB.

The method can be modified for other cross-section orientations by changing the orientation of the line of section on the plunge projection (Fig. 6.43). The orientation of the plane of section on the plunge projection is CB. In Fig. 6.43, CB is at 90° to AC, making the section plane vertical. The ratio CB : CA is constant for all points. Follow steps 1 to 5 above, changing the orientation of the line CB.

The plunge of a fold typically changes along the axis. Cylindrical fold axes may be curved along the plunge and cylindrical folds will change into conical folds at their terminations. Projection along straight plunge lines should be done only within domains for which the geometry of the structure is constant. Variable plunge can be recognized from undulations of the crest line on a structure-contour map or as excessive dispersion of the bedding dips around the best-fit curves on a stereogram or tangent diagram. If the plunge is variable, then the geographic size of the region being utilized should be reduced until the plunge is constant and all the bedding points fit the appropriate line on the stereogram or tangent diagram. If the sequence of plunge angle changes along the fold axis direction can be determined, then the straight line AB (Figs. 6.42, 6.43) could be replaced by a curved plunge line.

6.6.2 Projection by Structure Contouring

Structure contours represent the position of a marker horizon or a fault between the control points. Contouring provides a very general method for projecting data and can be used where the plunge cannot be defined from attitude measurements. This is a convenient method in three-dimensional interpretation. The projection technique is to map the marker surfaces between control points and draw cross illustrative sections through the maps.

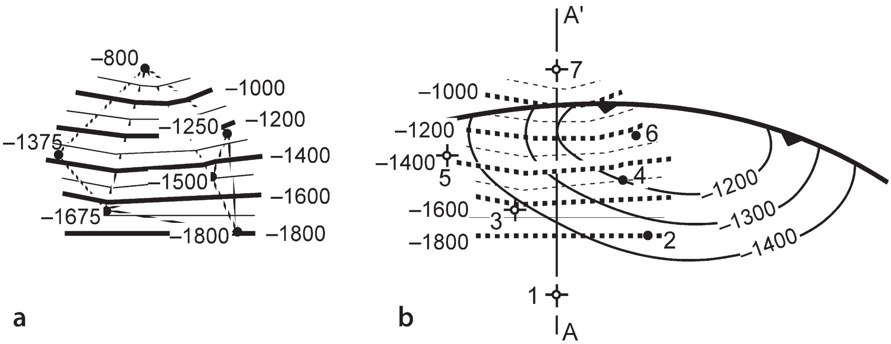


Fig. 6.44. Fault-surface map based on the wells in Fig. 6.34 that cut the fault. **a** *Points* give well locations and depths of fault cuts; *dotted lines* connect the nearest neighbors for contouring. Structure contours (*solid lines*) are derived by triangulation. **b** Structure contours on the fault (*dotted lines*) from a, superimposed on the structure contours of horizon E (*solid lines*) to show their parallelism to the fault trace

Where sufficient data are available, projection by contouring is equivalent to along-plunge projection. For example, the wells in Fig. 6.34 can be projected to the line of section by contouring without knowing the plunge amount or direction. To demonstrate this, the fault in Fig. 6.34 is contoured. The wells are inspected individually to be sure that each one shows only one fault cut, indicating that each well may cut the same fault. The fault contours generated from the elevations of the fault cuts (Fig. 6.44a) are smooth, as expected for a single fault. The fault contours superimposed on the original map (Fig. 6.44b) give the projected elevations of the fault along the line of section. The contours trend almost east-west, parallel to the plunge direction of the fold. A cross section of the fault along A–A' in Fig. 6.44b would be nearly identical to that in Fig. 6.34c. Each map horizon could be mapped to give a 3-D reconstruction of the structure which could then be sliced to create a cross section. When surfaces are mapped separately from sparse data, the spacings between them (thicknesses) are likely to show irregular variations. These variations should be corrected in the final cross section to maintain constant thicknesses (assuming it is geologically appropriate).

6.7 Dip-Domain Mapping from Cross Sections

The construction of maps from cross sections is a valuable technique where the structure is complex and/or the folds are conical. For cylindrical folds and faults the dip domains can be constructed is sections normal to the axis and linked together. Conical folds pose a special problem because no cross section can be drawn that will preserve bed thickness everywhere. The most general method is to define and map the dip domains in three dimensions. The approach will be illustrated here with the simple conical fold introduced in Sect. 5.3.

The horizontal domains in the conical fold (Figs. 6.45, 6.46) show unexaggerated thickness only in a vertical section. Only sections normal to the hinge lines show the unexaggerated thicknesses on the limbs (Fig. 6.46), requiring two different cross-sec-

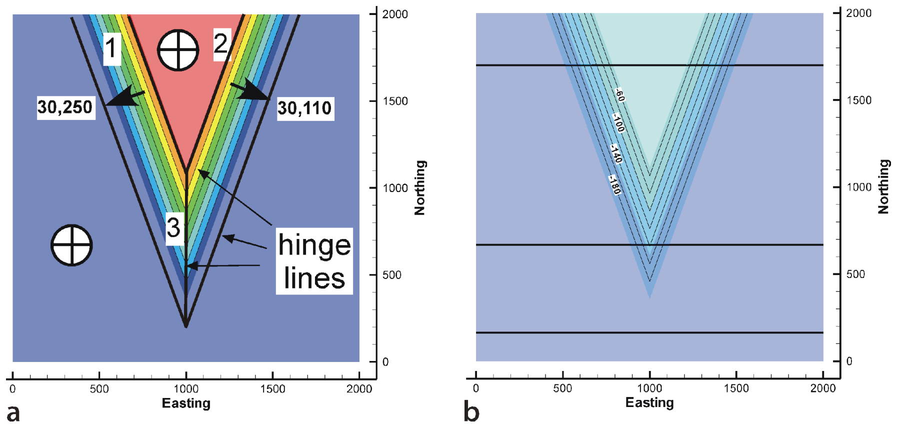
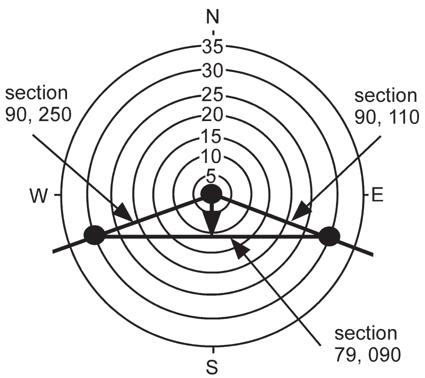


Fig. 6.45. Dip domains in conical fold. **a** Dip-domain map of middle horizon. **b** Structure contour map of middle horizon showing lines of cross section (*heavy EW lines*)

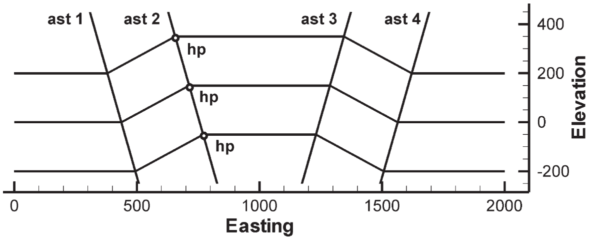
Fig. 6.46.
Tangent diagram of conical fold in Fig. 6.45 showing the directions of the 3 section lines that preserve bed thickness in local areas. In the north the fold crest is horizontal, and in the south it plunges 11, 180



tion trends (110° and 250°). In the region of the 11° south plunge, a section normal to plunge is normal to bedding (Fig. 6.46) but will give an exaggerated thickness where beds are horizontal.

The simplest procedure is to map axial surfaces on straight, vertical cross sections (Fig. 6.47), or from multiple map horizons. An axial surface is by definition the surface through successive hinge lines. This relationship applies regardless of whether or not the profile is perpendicular to the bedding or to the hinge lines. Axial surfaces on successive cross sections are correlated and then mapped in 3-D (Fig. 6.48a). Axial surfaces in conical folds will intersect in three dimensions, and the intersection lines must be located (Fig. 6.48b). Once the axial surfaces and their intersections are constructed, the marker horizons can be mapped across the region (Fig. 6.49). Because a dip domain is a region of uniform dip, once the domain boundaries have been located, bedding attitudes may be projected anywhere within a single domain. Bedding surfaces can be projected throughout the entire domain from a single observation point.

Fig. 6.47.
Axial surface traces defined on a vertical slice oblique to hinge lines (northern section across Fig. 6.45b); *ast:* axial surface trace; *hp:* hinge point



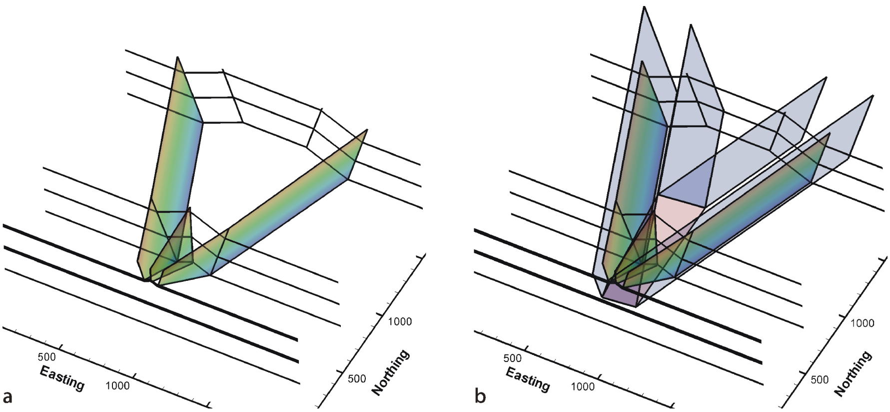


Fig. 6.48. Axial surfaces in the fold of Fig. 6.45. **a** Constructed by linking traces on profiles. **b** Completed axial surface network superimposed on previous construction

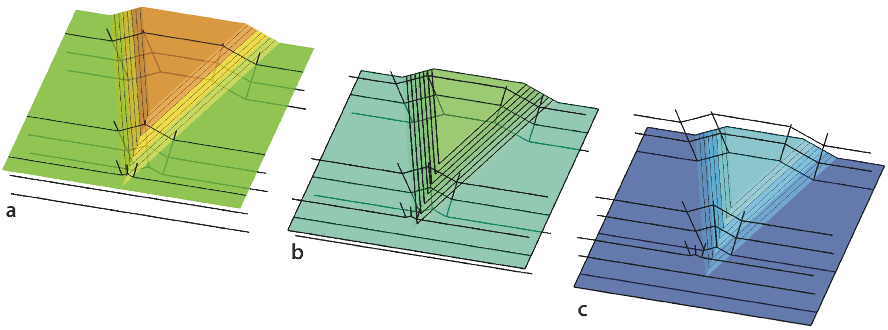


Fig. 6.49. Completed marker surfaces for map in Fig. 6.45. **a** Top. **b** Middle. **c** Bottom

Some types of information, for example fracture density, may be related to the proximity of the observation point to the fold hinge and so should be projected parallel to the closest hinge line. 3-D axial surface maps provide essential information for predicting the deep structure using kinematic models of cross-section geometry (especially using flexural-slip models Sect. 11.6).

6.8 Derivations

6.8.1 Vertical and Horizontal Exaggeration

From Fig. 6.50a, the dip of a marker on an unexaggerated profile is

$$\tan\delta = v/h \quad , \tag{6.19}$$

and the thickness of a unit in terms of its vertical dimension is

$$t = L\,\sin(90 - \delta) = L\,\cos\delta \quad , \tag{6.20}$$

where δ = unexaggerated dip, t = unexaggerated thickness, and L = unexaggerated vertical thickness. Let the vertical exaggeration be $V_e = v_v / v$ and the horizontal exaggeration be $H_e = h_h / h$, where v and h are the original horizontal and vertical scales and the subscripts h and v indicate the exaggerated scale. The equations for the exaggerated dips (Fig. 6.50b) have the same form as Eq. 6.19:

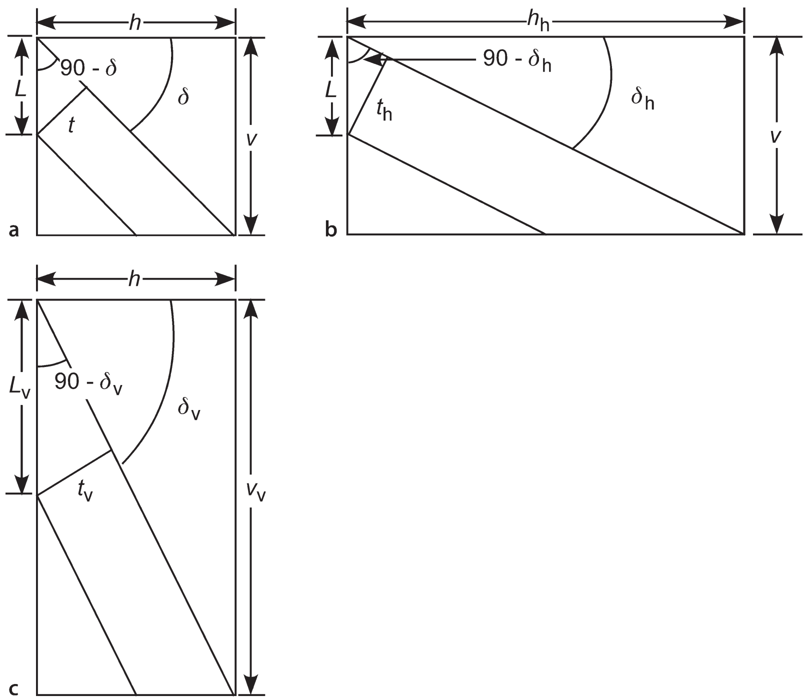


Fig. 6.50. Horizontal and vertical exaggeration. **a** Unexaggerated cross section. **b** Exaggerated horizontal scale; horizontal exaggeration (H_e) = 2 : 1. **c** Exaggerated vertical scale; vertical exaggeration (V_e) = 2 : 1

$$\tan \delta_v = v_v / h \quad , \tag{6.21a}$$

$$\tan \delta_h = v / h_h \quad . \tag{6.21b}$$

Replace h in Eq. 6.21a and v in 6.21b with the values from Eq. 6.19 and use the definition of the exaggeration to obtain the relationship between original and exaggerated dips:

$$\tan \delta_v = V_e \tan \delta \quad , \tag{6.22a}$$

$$\tan \delta_h = \tan \delta / H_e \quad . \tag{6.22b}$$

To relate the horizontal to the vertical exaggeration, substitute the value of $\tan \delta$ from Eq. 6.22a into 6.22b to obtain

$$V_e H_e = \tan \delta_v / \tan \delta_h \quad . \tag{6.23}$$

To obtain the same exaggerated angle by either horizontal or vertical exaggeration, set $\delta_v = \delta_h$ in Eq. 6.23:

$$V_e = 1 / H_e \quad . \tag{6.24}$$

The thickness of a unit on a horizontally exaggerated profile (Fig. 6.50b), t_h, is

$$\sin (90 - \delta_h) = \cos \delta_h = t_h / L \quad . \tag{6.25}$$

Eliminate L by dividing Eq. 6.25 by 6.20:

$$t_h / t = \cos \delta_h / \cos \delta \quad . \tag{6.26}$$

The thickness of a unit on a vertically exaggerated profile (Fig. 6.50c), t_v, is

$$\cos \delta_v = t_v / (V_e L) \quad . \tag{6.27}$$

Eliminate L by dividing Eq. 6.27 by Eq. 6.20:

$$t_v / t = V_e (\cos \delta_v / \cos \delta) \quad . \tag{6.28}$$

6.8.2
Analytical Projection along Plunge Lines

The point P is to be projected parallel to plunge to point P' on the cross section (Fig. 6.51a). The plunge direction makes an angle of α to the direction of the perpendicular to the cross section (Fig. 6.51d) and the plunge is ϕ. Following the method of De Paor (1988), the x coordinate axis is taken parallel to the line of the section and the plane of section intersects the x axis at zero elevation. In the plane of the cross section,

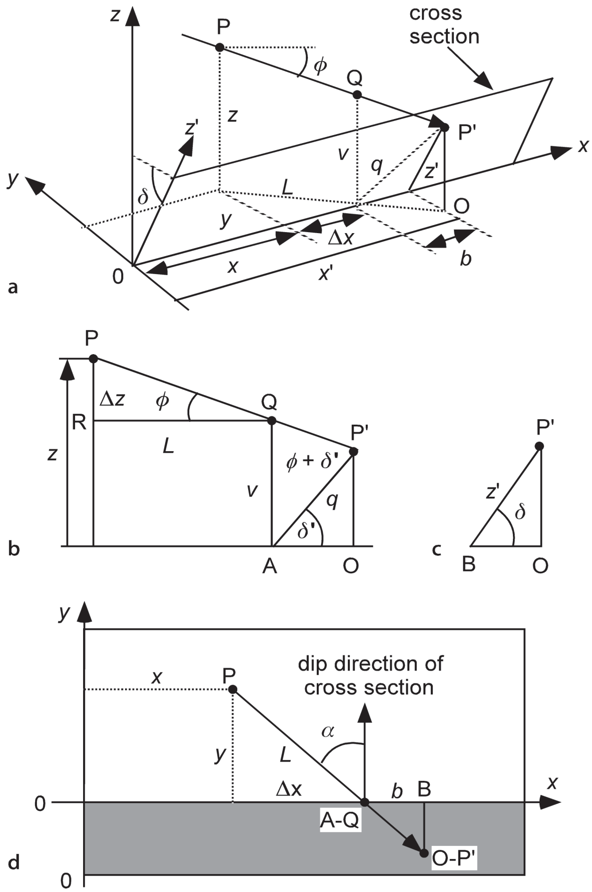


Fig. 6.51.
Projection along plunge. **a** Perspective diagram. **b** Vertical plane through plunge line *PP'*. **c** Vertical plane normal to the cross section through line *OP'*. **d** Plan view. Projection of the cross section is *shaded*. Point *Q* is vertically above *A* at *A–Q* and point *P'* is vertically above *O* at *O–P'*

the position of point P (x, y, z) is P' (x', z'). The apparent dip of the intersection line, q, of the vertical plane through PP' with the cross section is δ'. The relationship between the apparent dip and the true dip, δ, of the z' line, is given by Eq. 2.18 as

$$\tan \delta' = \tan \delta \cos \alpha \quad . \tag{6.29}$$

Begin by finding z'. In the plane normal to the cross section (Fig. 6.51a,c),

$$z' = \mathrm{OP'} / \sin \delta \quad . \tag{6.30}$$

In the plane of the plunge (Fig. 6.51b), using triangles AQP' and PQR,

$$\mathrm{OP'} = q \sin \delta' \quad , \tag{6.31}$$

$$\Delta z = L \tan \phi \quad , \tag{6.32}$$

$$v = z - L \tan\phi \quad , \tag{6.33}$$

and by using the law of sines with angles AQP' and QP'A in triangle QAP', along with $\cos\phi = \sin(90 - \phi)$,

$$q = v / (\tan\phi \ \cos\delta' + \sin\delta') \quad . \tag{6.34}$$

In the plane of the map (Fig. 6.51d)

$$L = y / \cos\alpha \quad . \tag{6.35}$$

Substitute Eqs. 6.29, 6.31, 6.33, 6.34 and 6.35 into 6.30 to obtain

$$z' = (z \cos\alpha - y \tan\phi) / (\tan\phi \ \cos\delta + \sin\delta \ \cos\alpha) \quad . \tag{6.36}$$

The x' coordinate is found from (Fig. 6.51a)

$$x' = x + \Delta x + b \quad . \tag{6.37}$$

In the plane of the map (Fig. 6.51d)

$$\Delta x = y \tan\alpha \quad , \tag{6.38}$$

$$b = \mathrm{OB} \tan\alpha \quad . \tag{6.39}$$

In the plane normal to the cross section (Fig. 6.51c)

$$\mathrm{OB} = \mathrm{OP'} / \tan\delta \quad . \tag{6.40}$$

Substitute Eqs. 6.29, 6.31–6.35 and 6.38–6.40, into 6.37 to obtain

$$x' = x + y \tan\alpha + \tan\alpha \ (z \cos\alpha - y \tan\phi) / (\tan\phi + \tan\delta \ \cos\alpha) \quad . \tag{6.41}$$

For a vertical cross section, $\delta = 90°$ and Eqs. 6.36 and 6.41 reduce to

$$x' = x + y \tan\alpha \quad , \tag{6.42}$$

$$z' = z - y \tan\phi / \cos\alpha \quad . \tag{6.43}$$

For a cross section normal to the plunge line, possible only for a cylindrical fold, $\alpha = 0$, $\delta = (90 - \phi)$ and Eqs. 6.36 and 6.41 reduce to

$$x' = x \quad , \tag{6.44}$$

$$z' = z \cos\phi - y \sin\phi \quad . \tag{6.45}$$

6.9 Exercises

6.9.1 Vertical and Horizontal Exaggeration

Draw the cross section in Fig. 6.52 vertically exaggerated by a factor of 5 : 1. Draw the cross section in Fig. 6.52 horizontally squeezed by a factor of 1 : 2.

6.9.2 Cross Section and Map Trace of a Fault

Draw an east-west cross section across the northern part of the structure contour map in Fig. 6.53. Suppose a fault that dips 40° south cuts the structure in the blank area between the arrows. What would its trace be on the structure contour map? Is the fault normal or reverse? Draw a north-south cross section showing the fault.

6.9.3 Illustrative Cross Section from a Structure Contour Map 1

Draw a cross section perpendicular to the major structural trend in Fig. 6.54. Discuss any assumptions required. What are the dips of the faults? Are the faults normal or reverse?

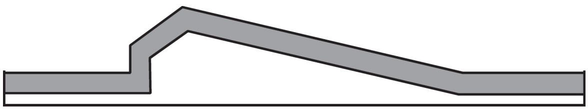


Fig. 6.52. Cross section of a fold having constant bed thickness in shaded unit

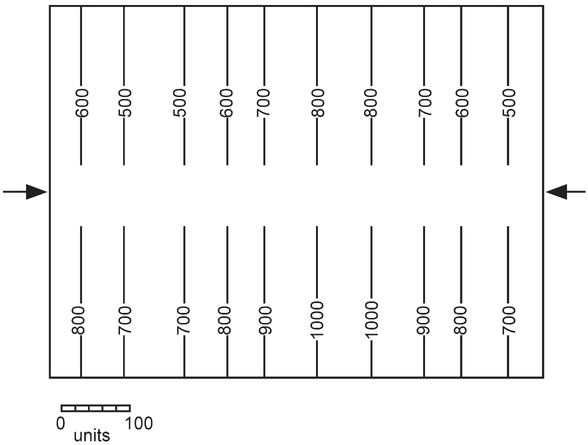


Fig. 6.53. Unfinished structure contour map. *Arrows* indicate the general position of the fault trace

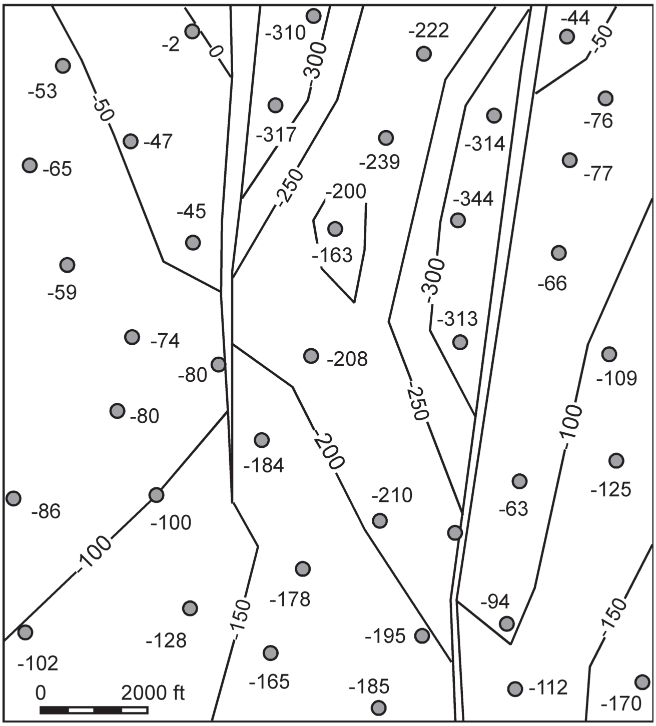


Fig. 6.54.
Structure contour map of the top of the Gwin coal cycle. Elevations of the top Gwin are posted next to the wells. Units are in feet, negative below sea level

6.9.4
Illustrative Cross Section from a Structure Contour Map 2

Draw cross sections along the three lines indicated on Fig. 6.55. Using the fault dip determined from the map, extend the faults above and below the marker horizon until they intersect. Which fault(s) formed last?

6.9.5
Illustrative Cross Section from a Structure Contour Map 3

Draw cross sections along the three lines indicated in Fig. 6.56. Determine the dips of the faults from the map and then extend the faults above and below the marker horizon until they intersect. Which fault is youngest?

6.9.6
Predictive Dip-Domain Section

Complete the cross section in Fig. 6.57 by extending it into the air and deeper into the subsurface. How far can the section be realistically extended?

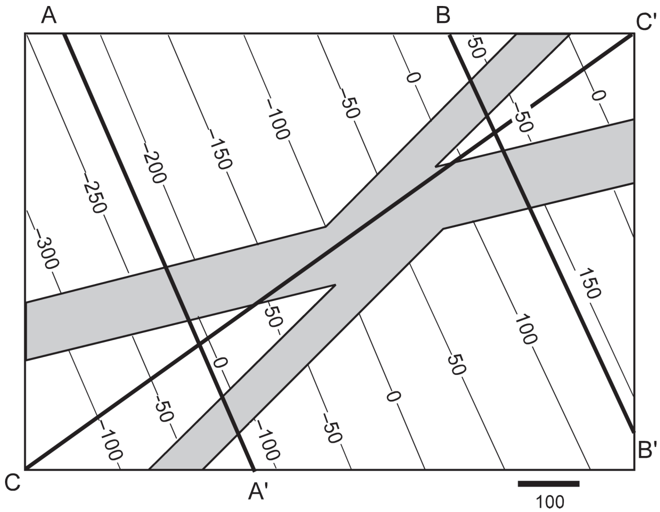


Fig. 6.55.
Structure contour map of a normal-faulted surface. The horizon surface is missing in the *shaded* fault zones. Locations of lines of section *A–A′*, *B–B′*, and *C–C′* are shown

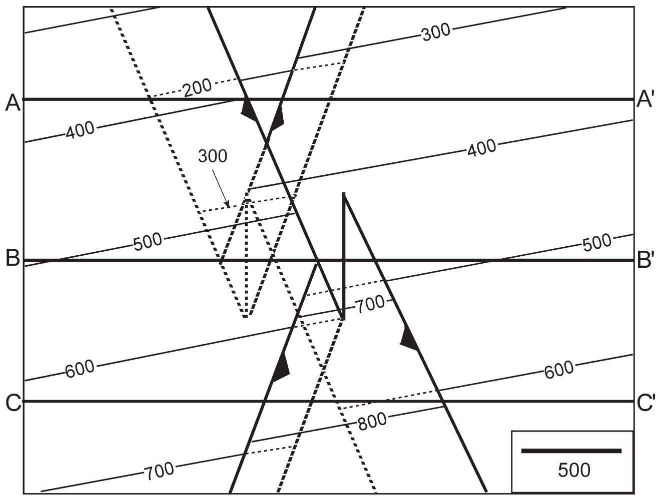


Fig. 6.56.
Structure contour map of a reverse-faulted surface. The horizon surface is repeated by the fault zones. The fault cutoffs are *wider lines*. Hidden contours are *dashed*. The locations of lines of section *A–A′*, *B–B′*, and *C–C′* are shown

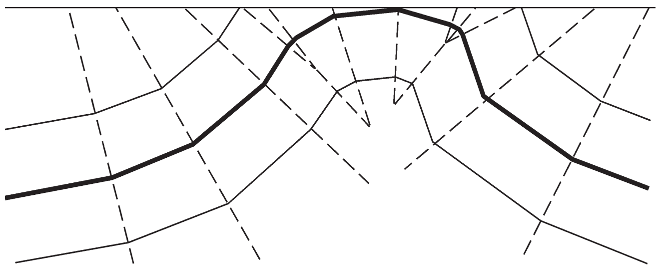


Fig. 6.57.
Partially complete dip-domain cross section. *Dashed lines* are axial-surface traces

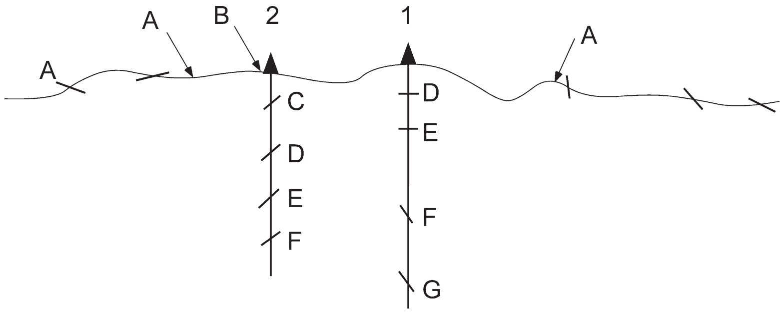


Fig. 6.58. Cross section through the Burma No. 1 and 2 wells. *Short lines* are surface dips. Letters *A–G* are marker horizons seen at the locations of dip measurements that can be correlated. *Arrows* point to locations where markers can be identified in outcrop but the dip cannot be measured. The dips in the wells are from oriented cores

6.9.7
Predictive Cross Sections from Bedding Attitudes and Tops

Complete the cross section in Fig. 6.58, keeping bed thicknesses constant. Use both the dip-domain technique and the method of circular arcs. Scan the section into a computer and complete using the smooth curves provided by a drafting program. Compare the results of the different techniques.

6.9.8
Fold and Thrust Fault Interpretation

Construct illustrative cross section A–A' from the map in Fig. 3.29 using the structure contour map constructed in Exercise 3.7.4. Use the dip-domain technique to construct the same cross section using only the surface geology along the profile. Use the circular arc technique to construct the same cross section using only the surface geology along the profile. What is the plunge of the central portion of the structure from a stereogram or tangent diagram? Project the northern part of the structure onto section B–B' using the method of along-plunge projection. Compare and contrast the cross sections. The wells to the Fairholme were drilled to find a hydrocarbon trap but were not successful. Use the map and cross sections to determine a structural reason for drilling the wells and a structural reason that they were unsuccessful.

6.9.9
Projection

Project the top reservoir onto the seismic line assuming the structure is normal to the seismic line (Fig. 6.59). Project the top reservoir onto the seismic line assuming the structure plunges 10° in the direction 225°.

Fig. 6.59.
Map showing trace of a seismic line and the location of a well