Chapter 6: Three-Point Problems and Insertion of Outcrops

THE INTERPRETATION of map patterns, using structure contours, is further explored in this chapter. Incomplete map patterns of poorly exposed areas can be completed by constructing structure contours for the geological contacts already shown on the map. The method of structure contours can, also, be applied to determine the strike and dip of strata in the subsurface from drill-hole data only. The orientation of any flat, inclined geological surface can be determined using the elevation of at least three points on that surface. Such situations are traditionally referred to as three-point problems, and many examples are included in this chapter.

Contents: Section 6-1 introduces the terms inlier and outlier, commonly used to describe map patterns. The insertion of outcrops, using structure contours, is explained in section 6-2. The determination of azimuth/dip from three elevation points of a rock surface and the completion of the associated map patterns are discussed in sections 6-3 and 6-4 for surface and subsurface data, respectively.

6-1 Inliers and outliers

Shallow dipping rock strata tend to give very intricate outcrop patterns on the map in terrains of pronounced topography (Fig. 6-1). Closed out-

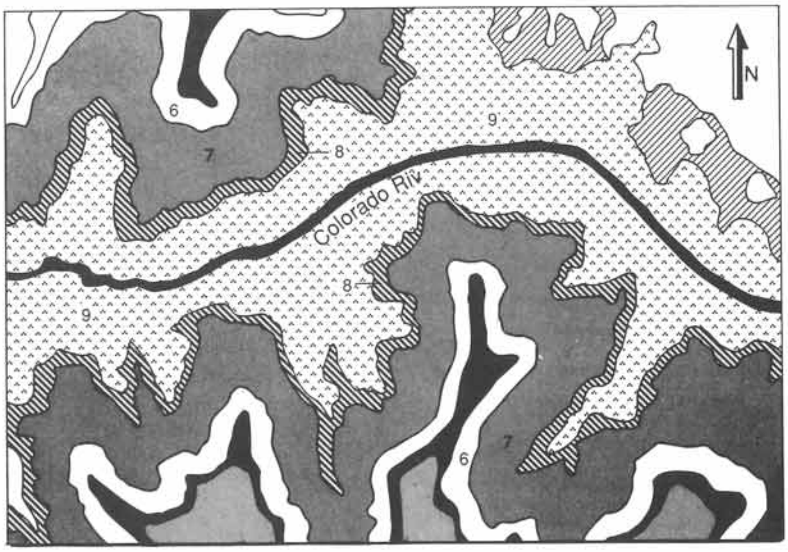


Figure 6-1: *Geological map of the Grand Canyon, mainly comprised of subhorizontal strata. Correlated units are labelled with corresponding numbers.*

crop traces, occurring at the tops of mountains and in the deeper canyons (Fig. 6-2), deserve special attention. The assessment of such outcrop patterns may help to establish an understanding of the *stratigraphic succession* of the rocks exposed in the area. A general rule is that closed outcrop patterns, occupying areas of relatively high elevation, identify the youngest rock units in the area. Such outcrops of younger rock, entirely surrounded by older beds, are called *outliers* or *onliers*. Another general rule is that closed outcrop patterns, occupying topographically low areas, commonly outline the oldest rock formation in the area. Such outcrops of older rock, entirely surrounded by outcrops of younger beds, are called *inliers*. The definitions given here should be used with caution and may not apply to tectonized regions. Folded rock units, with closed outcrop patterns on hill-tops, do not necessarily need to be younger than the underlying rocks. The stratigraphic succession, therefore, is usually determined by internal evidence, such as fossils, graded bedding, and other way-up criteria, and not solely by relative topographic position.

☐Exercise 6-1: Examine the outcrop pattern of the map in Figure 6-2. Beds are horizontal and apparently right-way-up. a) Color the inliers in red and outliers in blue. b) Establish the stratigraphic succession for the area in a columnar section.

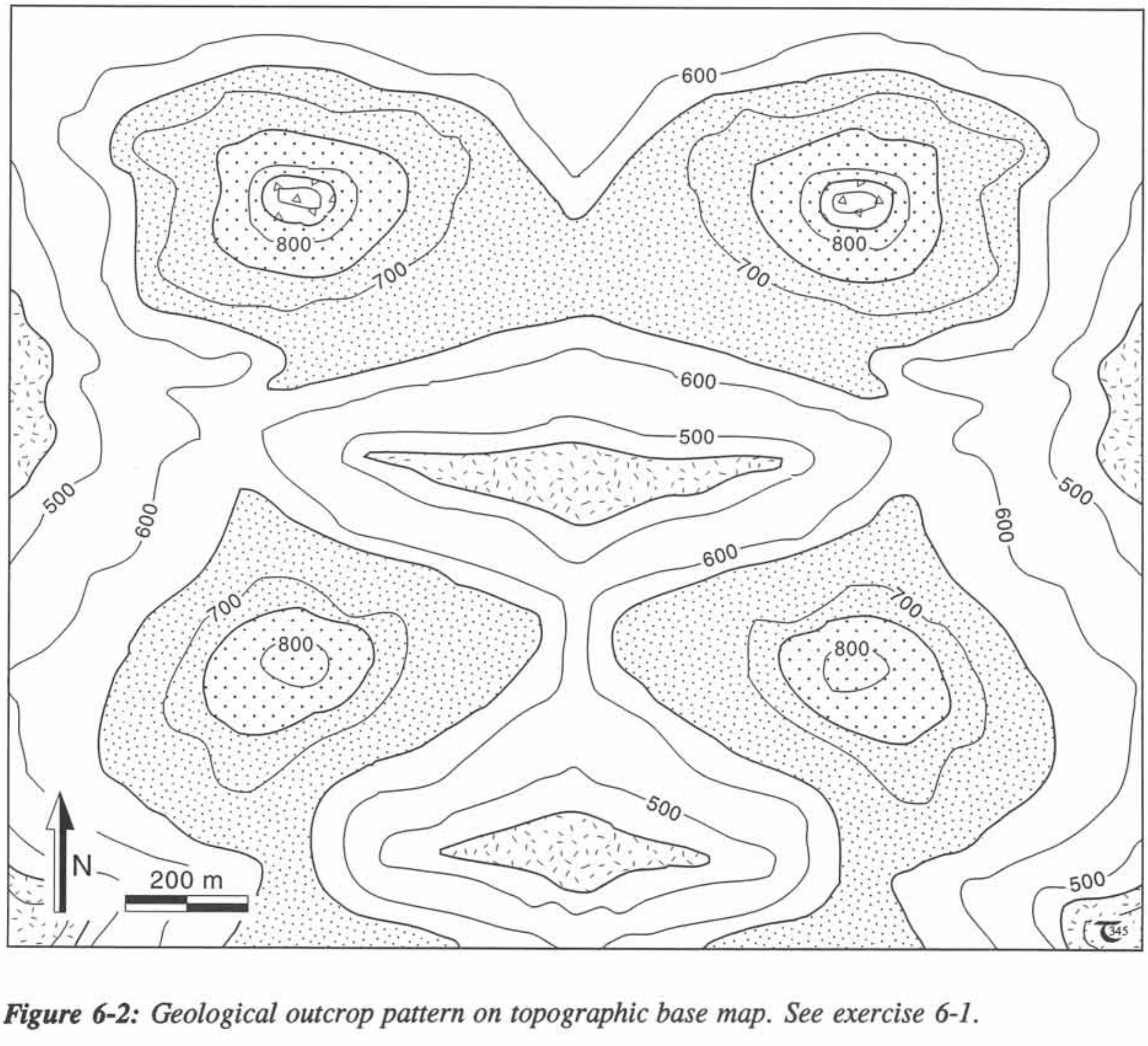


Figure 6-2: *Geological outcrop pattern on topographic base map. See exercise 6-1.*

☐Exercise 6-2: Refer to the geological map of Figure 6-3. a) Determine the azimuth/dip for the uniformly oriented succession, using structure contours. b) Draw a cross-section along line Y-Z. c) Calculate the true thickness of the layers, and make a columnar section. d) Color any inliers in red and outliers in blue.

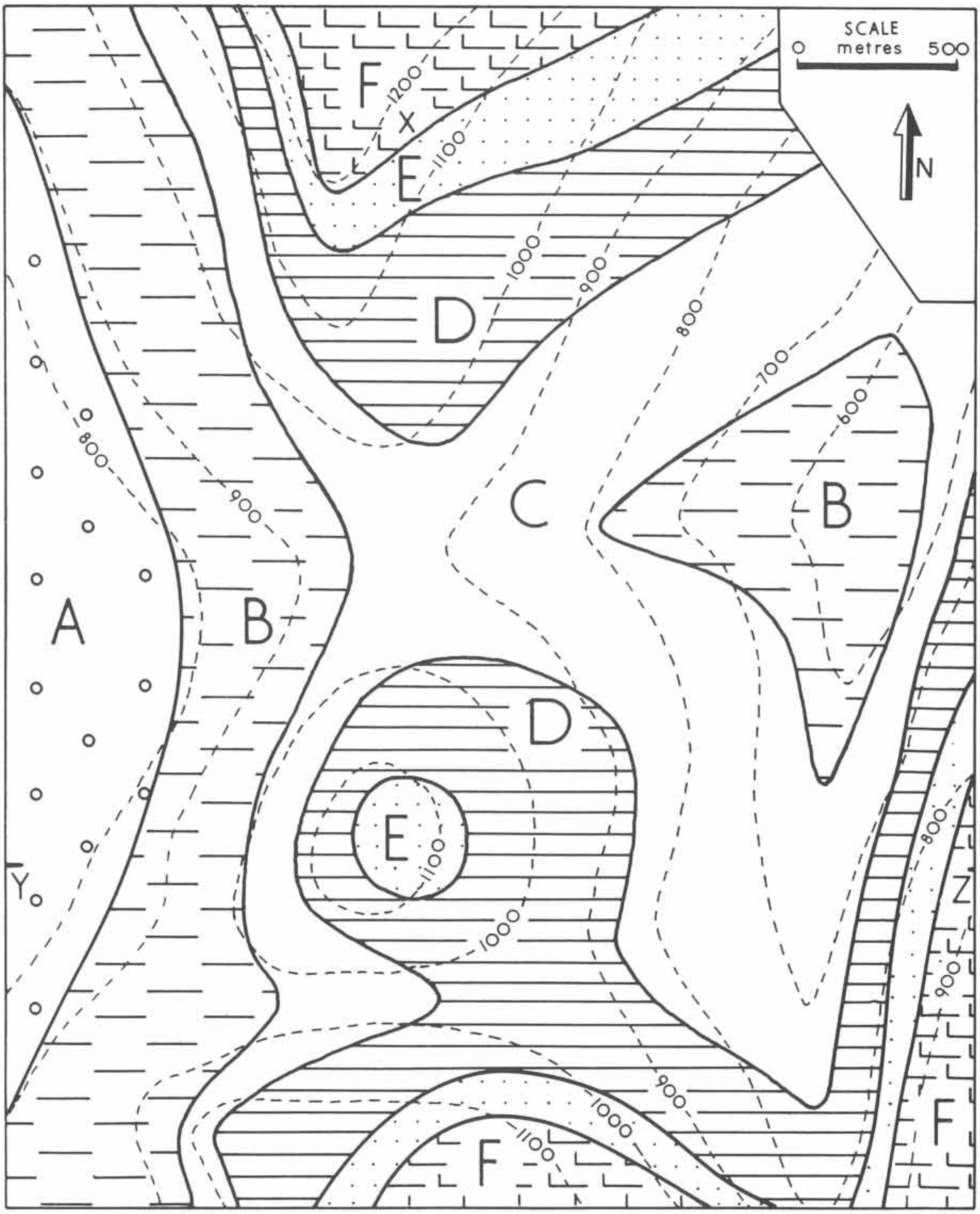


Figure 6-3: Map of geological outcrops on topographic base map. See exercise 6-2.

6-2 Insertion of outcrops

A stratigraphic layer reaches the surface in any location where the topographic contour cuts a structure contour. This fact can be utilized to complete the outcrop pattern of a geological stratum if the structure contours and the topography contours are both known. Figure 6-4 illustrates a geological boundary inserted where its structure contours intersect the topography. However, if a terrain is mapped, for example, from aerial photographs, structure contours will not be known initially, and the outcrop pattern itself may still be incomplete. *Finding, at least, a few locations, where the boundary of a bed is exposed at the same elevation, may allow the construction of its structure contours.* The remainder of the geological map can then be completed by inserting the geological boundaries where the structure contours intersect the topography. Join the intersection points in a smooth continuous curve to complete the outcrop pattern.

☐Exercise 6-3: A uniformly oriented coal bed is exposed at three locations - A, B, and C, as indicated on the map of Figure 6-5. Two structure contours are included to start you off. a) Complete the outcrop pattern of the coal bed for the entire map area. b) What is the orientation of the coal bed (azimuth/dip)? c) Color blue all rocks overlying the coal bed.

If the exact trend of the outcrop between two points is doubtful, determine the outcrop location by interpolation. Sketch a topographic contour half-way between two existing ones, and draw the corresponding strike line. This gives an additional outcrop point and facilitates the completion of the interconnected outcrop-pattern. Also, remember that an outcrop boundary can cross a topographic contour line only where it is, also, crossed by a structure contour and nowhere else.

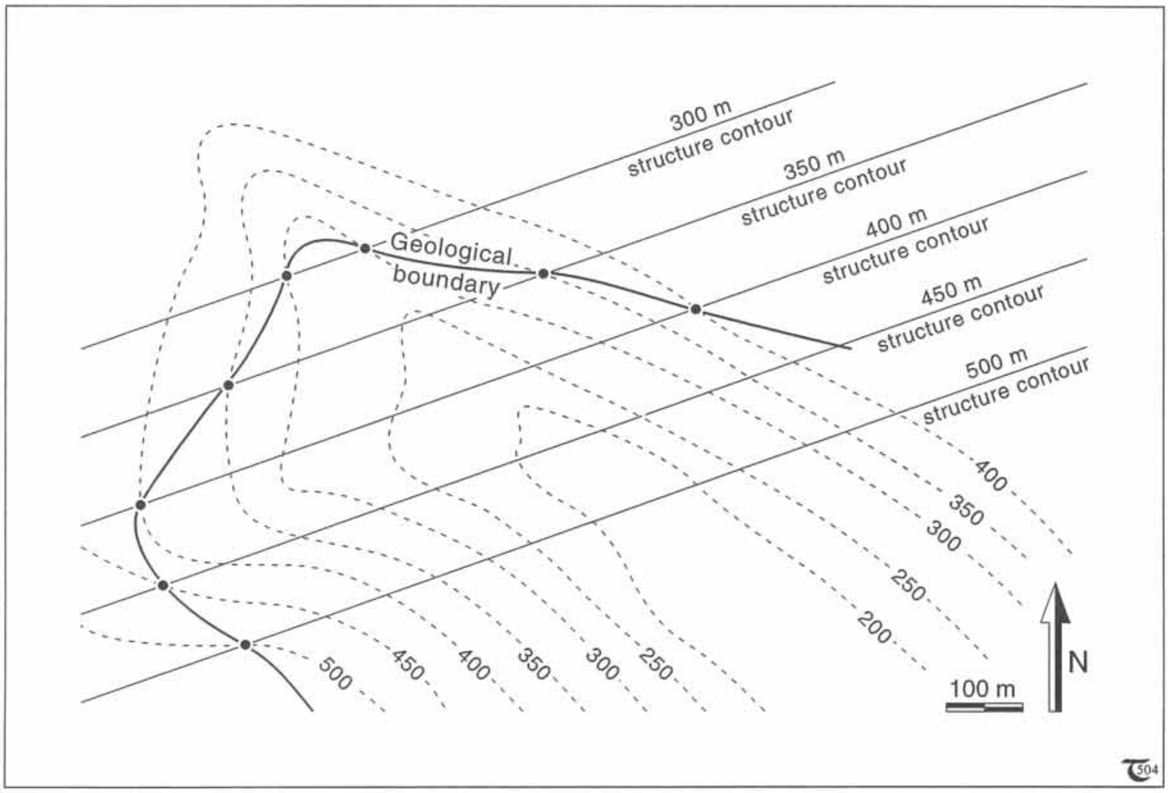


Figure 6-4: A geological boundary can be constructed at the intersections of structure and topographic contours.

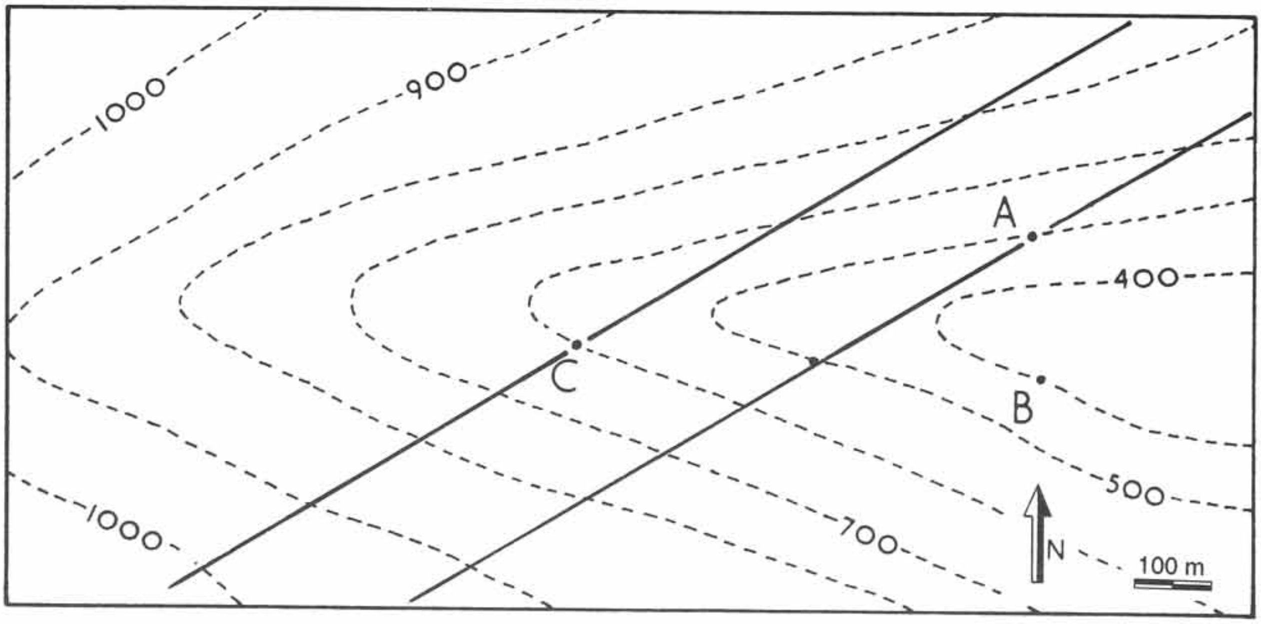


Figure 6-5: Incomplete outcrop pattern of coal bed on topographic base map. See exercise 6-3.

☐Exercise 6-4: The outcrop of a thick, uniformly oriented sandstone formation is shown in the map of Figure 6-6. The base of the sandstone is, also, exposed at location A. a) Construct structure contours for the base of the sandstone, using 25 m contour spacing. b) Complete the outcrop pattern. c) Does the grit crop out at D? d) Construct a section X-Y across the map, as indicated.

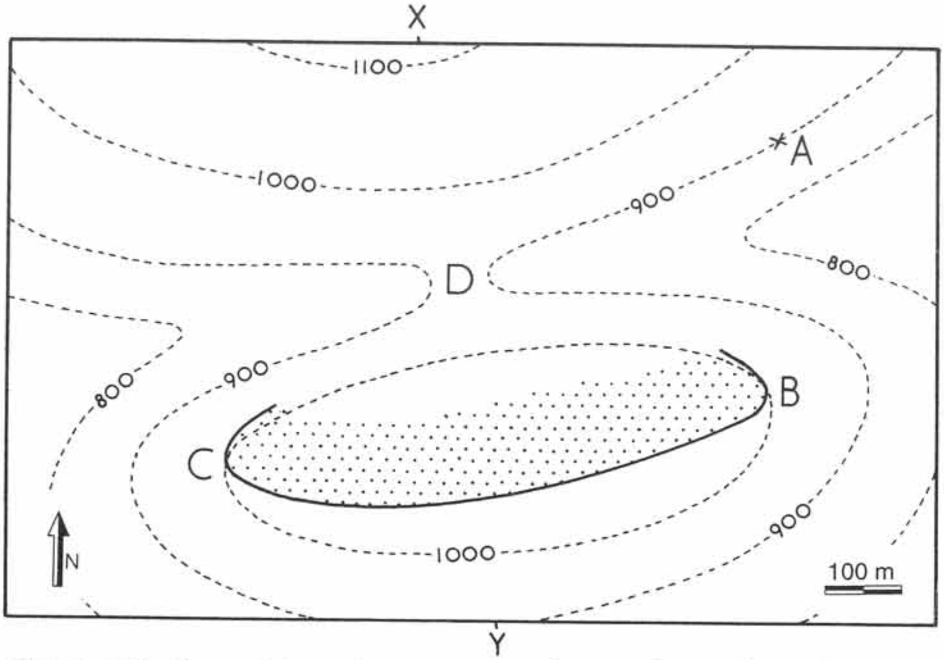


***Figure 6-6:** Incomplete outcrop pattern of a sandstone formation on a topographic base map of 100 m contour spacing. See exercise 6-4.*

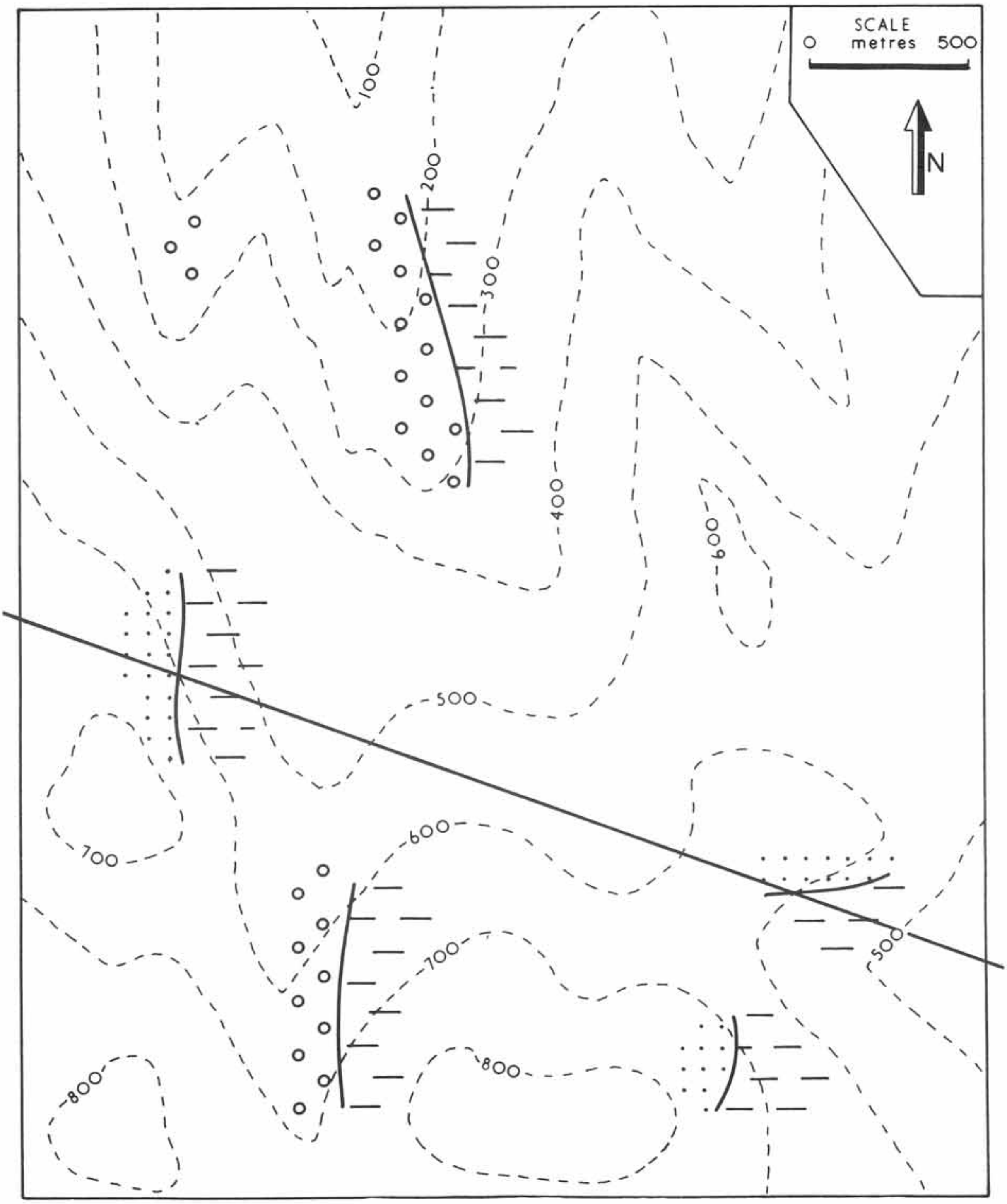


Figure 6-7: Incomplete geological map on topographic base map. Contour spacing is 100 m. See exercise 6-5.

☐Exercise 6-5: The incomplete map of Figure 6-7 shows all the geological information that could be mapped from the aerial photographs of a heavily forested area. Field reconnaissance has further revealed that the three rock types identified are conglomerate, shale, and sandstone. It is, also, known that all strata in this area have a uniform orientation. Complete the geological map by inserting the boundaries between all the beds, using the principle of structure contours. Remember that structure contours of uniformly dipping layers are always parallel. One structure contour, inferred from the outcrop pattern, is drawn on the map to get you started. Construct the other structure contours, and then complete the continuation of the geological boundaries and insert lithologic symbols.

6-3 Three-point problem technique

The simple geometric fact that three points define a plane is exploited extensively in the preparation and interpretation of geological maps. In geology, the *three-point problem* refers to the situation where the stratum orientation needs to be abstracted from three points of known elevation. If the elevation of a bed is known at three or more points, defining two crossing lines in the same plane, it becomes possible to calculate the strike/dip or azimuth/dip of such planes. Two points of equal elevation can be connected to define the strike line. A third point, either up or down dip, will be sufficient to determine the dip of the surface.

Consider a particular three-point problem, defining the top of a limestone bed in three locations A, B, and C (Fig. 6-8). The respective elevations of these points are 450, 525, and 650 meters above the sea level datum. The strike line has to be found by construction, because none of the three points is at similar height. Take the lowest and the highest of the three points, in this case points A and C, and connect them by a straight line. Subdivide the length AC into equally scaled distances to find a point of the same elevation as the intermediate point B. The strike line is now fixed on the map by connecting the two points at 525 meters. This, also, is the 525 m structure contour for the top of the limestone bed. Assuming that the limestone

☐Exercise 6-6: Determine the azimuth/dip of the limestone bed of the three-point problem in Figure 6-8.

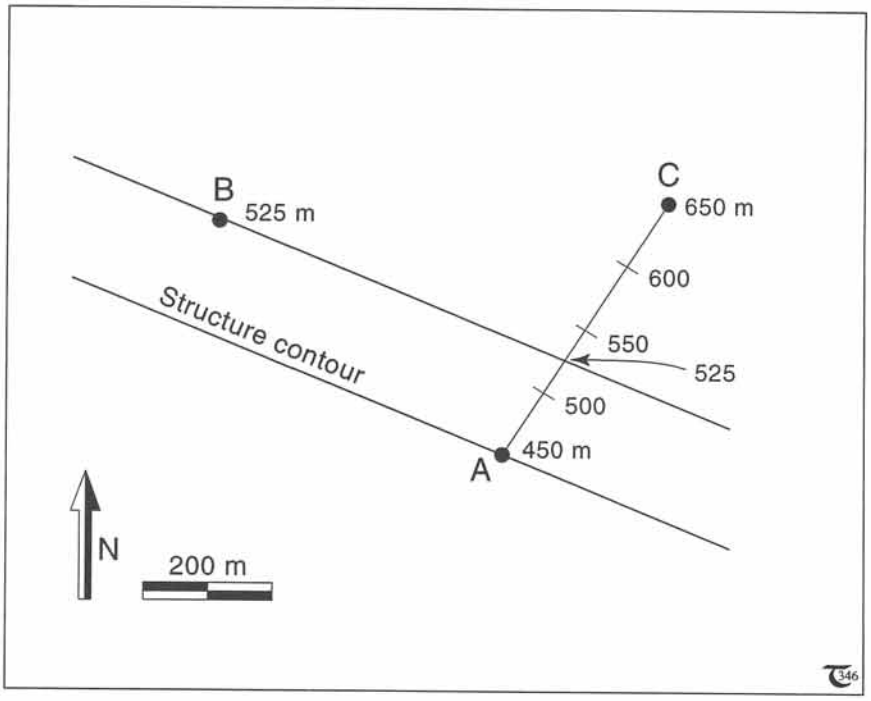


Figure 6-8: Construction of structure contours from three points on the structure with known elevations (A,B,C).

bed dips uniformly, all other structure contours will be parallel to the strike line constructed. Structure contours of convenient spacing can be constructed accordingly.

The three-point problem is usually combined with a topographic base map, which allows the insertion of outcrop patterns. Figure 6-9a shows a base map with a coal bed observed in outcrops A, B, and C. It is essential, in order for the method to work, that all layers are homoclinal - they must possess uniform dips. The three points of observed coal outcrops are all located on topographic elevation contours. These points, also, lie on structure contours of corresponding elevation. Interpolation fixes the strike of the structure contours (Fig. 6-9b). Subsequently, the outcrop boundaries can be inserted where the structure contours and topographic contours meet (ringed points). Join the ringed points by a smooth curve to complete the outcrop pattern.

☐Exercise 6-7: The continuous line on the map of Figure 6-10 indicates the outcrop pattern of a two-meter, thin coal seam. The coal is exposed in three locations - A, B, and C. All coal seams in the area are known to be uniformly dipping. a) Determine the azimuth/dip of the exposed coal seam. b) Complete the outcrop pattern of the coal seam, assuming that the thin layer can be represented as a single line on the scale of the map. This implies that structure contours for the top and bottom of the coal seam coincide. c) At what depth would the coal layer be struck in a borehole sunk at location D?

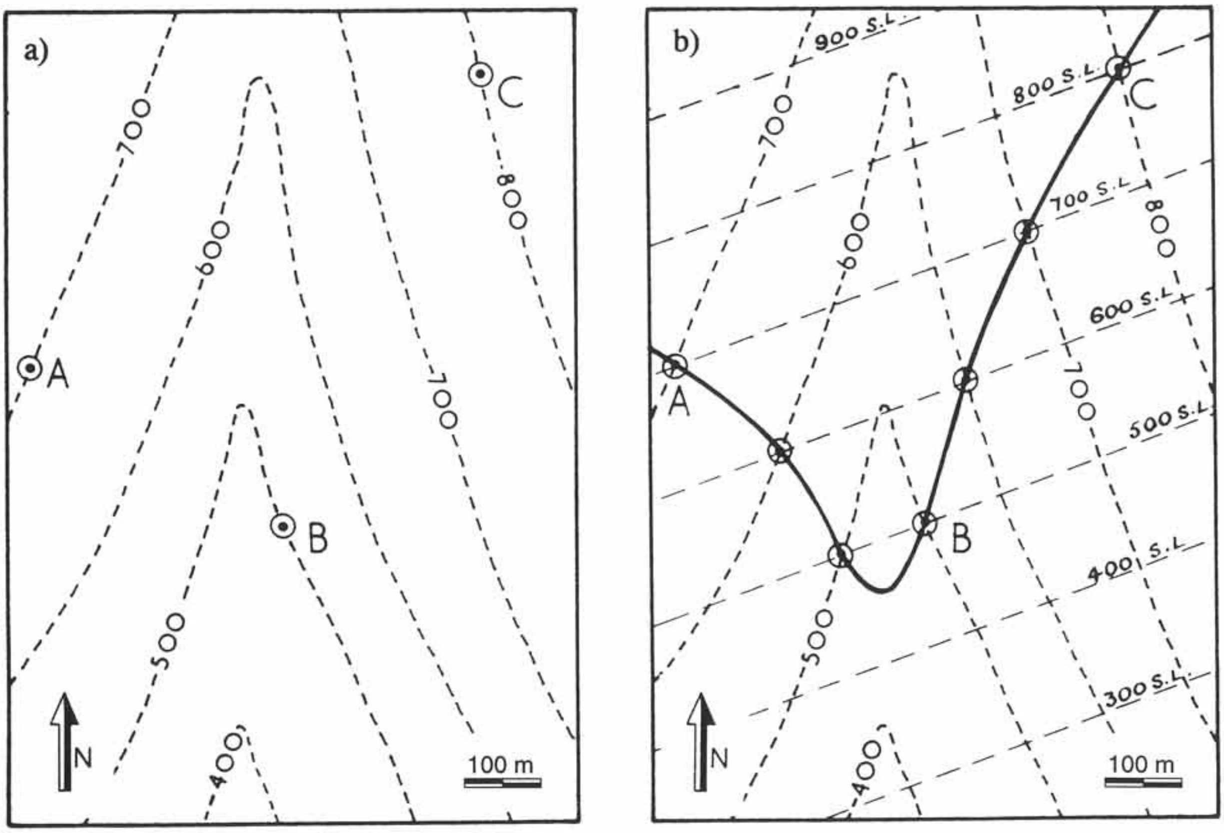


Figure 6-9: a) Topographic base map with three observed coal outcrops: A,B,C. b) Construction of structure contours allows completion of coal outcrop pattern by interpolation in a smooth curve.

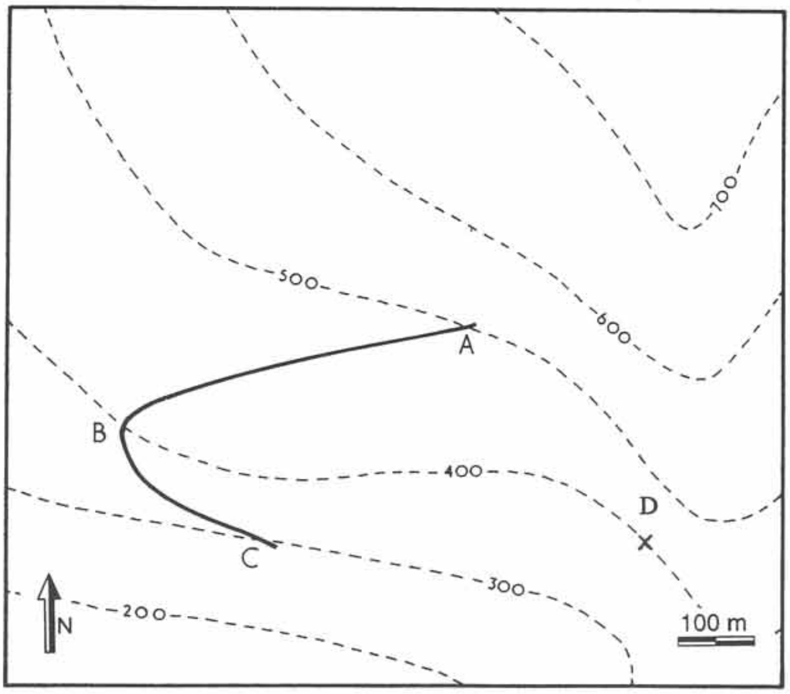


Figure 6-10: *Incomplete outcrop pattern of coal seam on topographic base map. See exercise 6-7.*

☐Exercise 6-8: Refer to the map of Figure 6-11. a) Determine the attitude of the coal seam. b) Complete the outcrop pattern. c) Also, complete the outcrop pattern of two other coal seams, which are, respectively, two hundred meters vertically above and below the one first mapped.

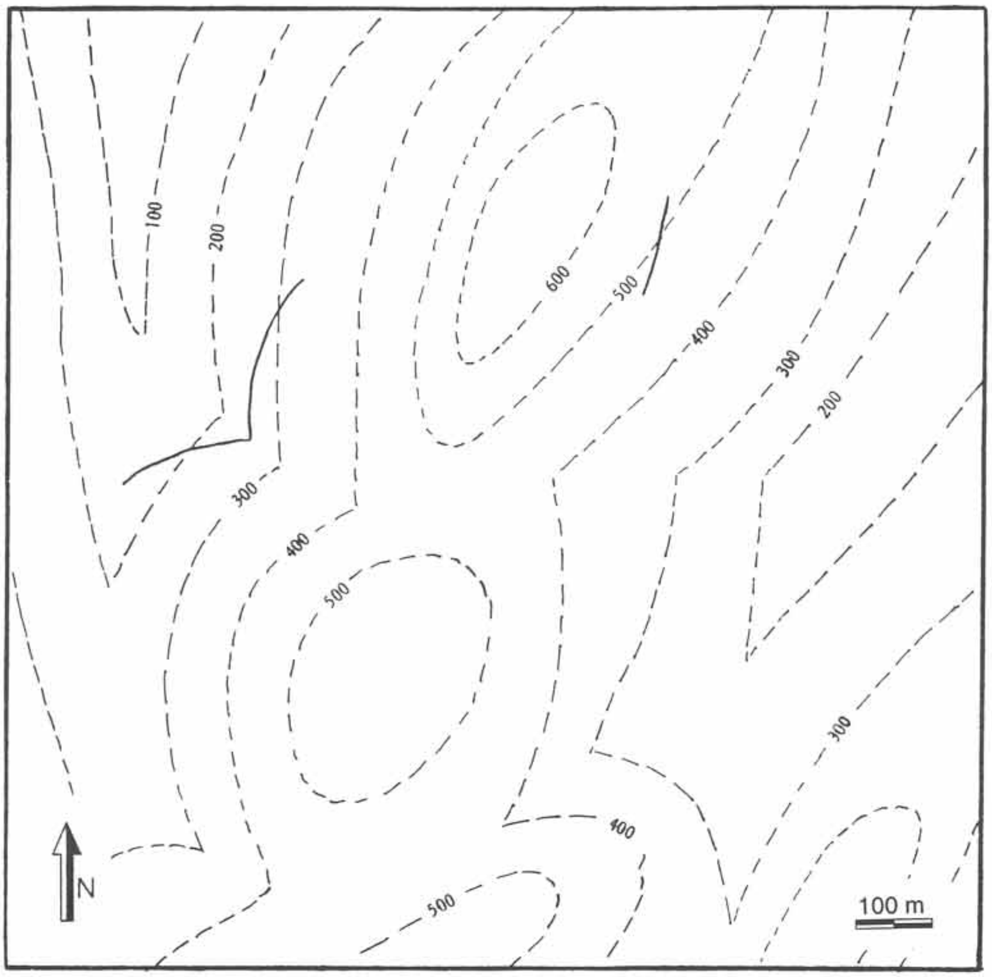


Figure 6-11: *Incomplete outcrop pattern of coal seam on topographic base map. See exercise 6-8.*

6-4 Three-point problems for borehole data

Three-point problems need not necessarily be limited to surface data only. The principle has many applications to mining and to petroleum and engineering geology, through usage of borehole data. The line of argument used to solve three-point problems from subsurface data is the same as that used for points exposed at the surface. The depth at which layers are encountered in boreholes is commonly measured downwards from the ground surface - the drilling depth. For the solution of three-point problems, the elevation of the layers needs to be calibrated to sea-level datum. This is simply achieved by substracting the drilling depths from the topographic elevations of the drill sites.

☐Exercise 6-10: Draw your own map for the following situation. Borehole B in an oilfield is 5,000 feet due north of borehole A, and borehole C is 10,000 feet due east of borehole A. The top and bottom of a reservoir sandstone bed are reached at the following altitudes relative to sea level:
A) -2,500 and -2,700 feet,
B) -2,800 and -3,000 feet, and
C) -3,000 and -3,200 feet. Determine both the azimuth/dip and the true thickness of the sandstone.

☐Exercise 6-9: Refer to the map of Figure 6-12. The top of a five-meter-thick hydrocarbon reservoir is encountered in drill cores at locations A, B, and C, at respective depths of 450, 350, and 250 meters. All pay-zones in the area are known to dip uniformly. a) Determine the azimuth/dip of the hydrocarbon reservoir. b) Determine if the reservoir is cropping out anywhere, and, if so, complete the outcrop pattern, assuming that the thin layer can be represented as a single line on the scale of the map. c) An important one meter thick stratigraphic marker horizon is found in borehole A at a fifty-meter depth. Map the outcrop trace of this marker horizon. d) Color the rocks in the map area on top of the marker horizon.

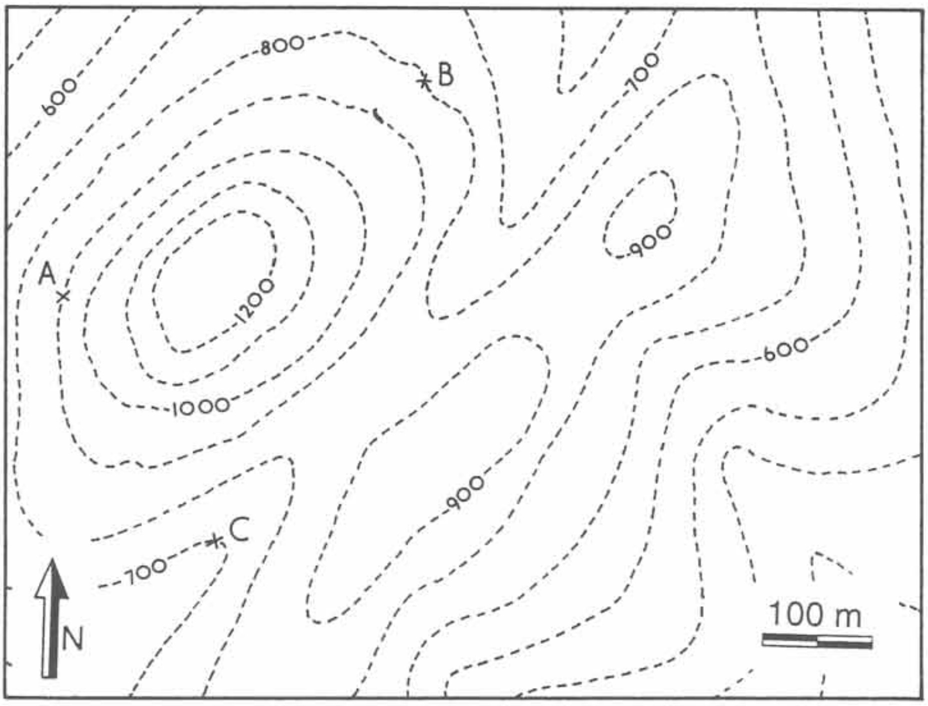


Figure 6-12: Topographic base map with location of three boreholes (A, B, and C). See exercise 6-9.

Chapter 7: Maps of Folds

FOLDS ARE contortions of originally planar layers. They are, also, inspiring geometrical objects and have been studied extensively by structural geologists. Folds are presumably so exciting because they have an endless variety of shapes and sizes, as can be seen in the field. Anticlinal folds may be of economic significance when forming structural traps for oil and gas accumulations. Various mechanisms may lead to folding of initially horizontal planar beds, but our description concentrates entirely on basic geometric features and the map appearance of folds.

Contents: Terms to describe the structural elements of fold profiles are outlined in section 7-1. Cylindrical, upright, horizontal folds and their map patterns are discussed in section 7-2. Folds may further be asymmetrical, overturned, upright plunging, or doubly plunging, and these terms are introduced in sections 7-3 through 7-5. The final section, 7-6, illustrates reclined folds, recumbent folds, and monoclines.

7-1 Fold-shape in section

A folded sedimentary layer ideally resembles a sinusoidal wave, forming a *fold train*. Seen in profile normal to the wave crest, such fold trains possess a *wavelength* and *amplitude* (Fig. 7-1). The points of largest curvature are termed the *hinge points*, and the sections separated by the hinge points are the *fold limbs*. The fold limbs can be either straight (Figs. 7-2a&b)

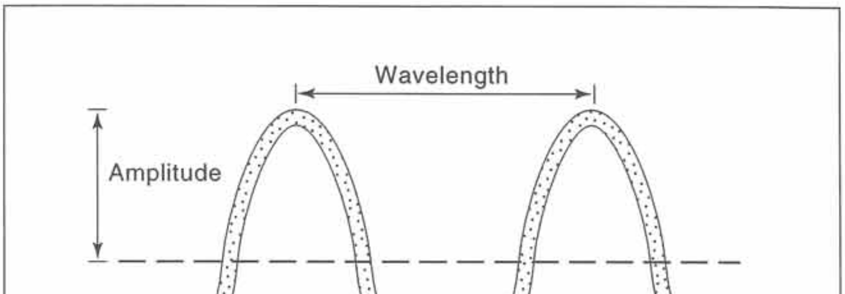


Figure 7-1: *Section perpendicular to the fold axes, defining wavelength and amplitude of the individual folds in a fold train.*

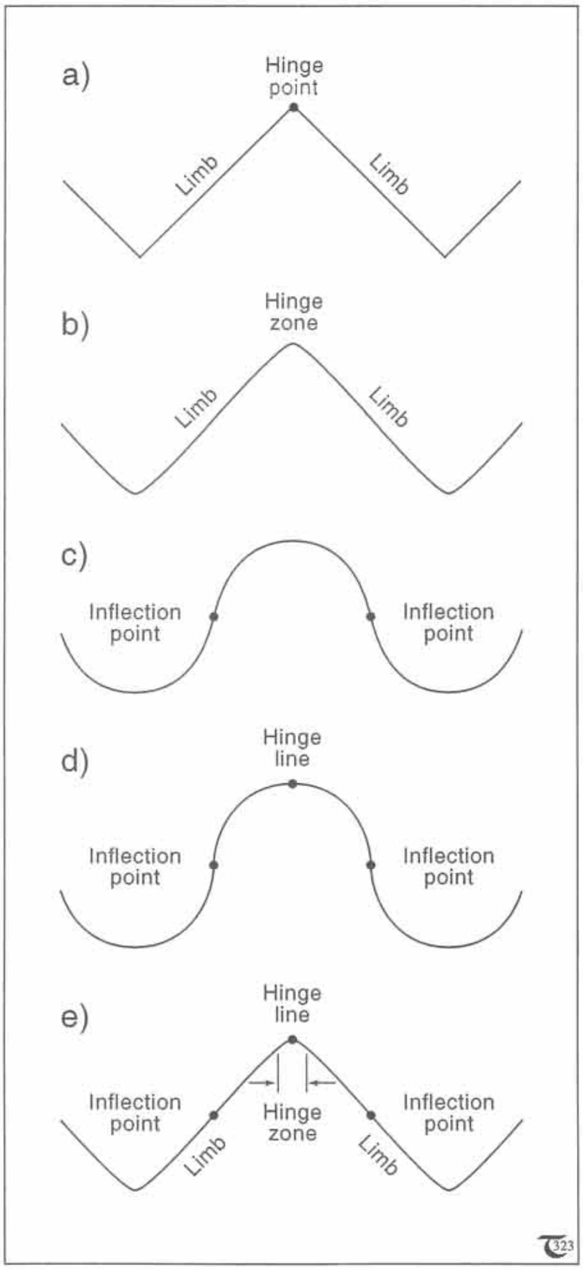


Figure 7-2: *The geometry of folds. a) Zig-zag or chevron fold with straight limbs meeting in a single hinge line. b) Chevron fold with limbs connected by a hinge zone of gradually changing curvature. c) Gently curved folds with inflection points marking the points of minimum curvature. d) Hinge point in curved folds is a point of maximum curvature. e) Inflection points on straight fold limbs.*

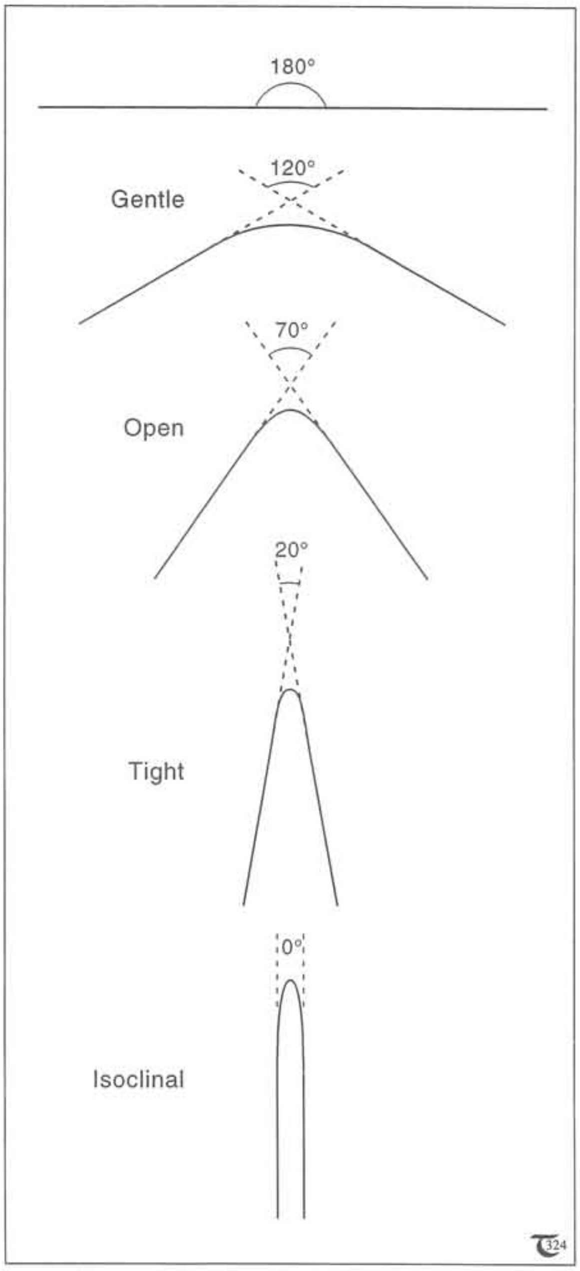


Figure 7-3: *Classification of folds on the basis of the interlimb angle.*

☐**Exercise 7-1: Indicate in Figure 7-1 all hinge points, inflection points, and the hinge zone and limbs in the fold train.**

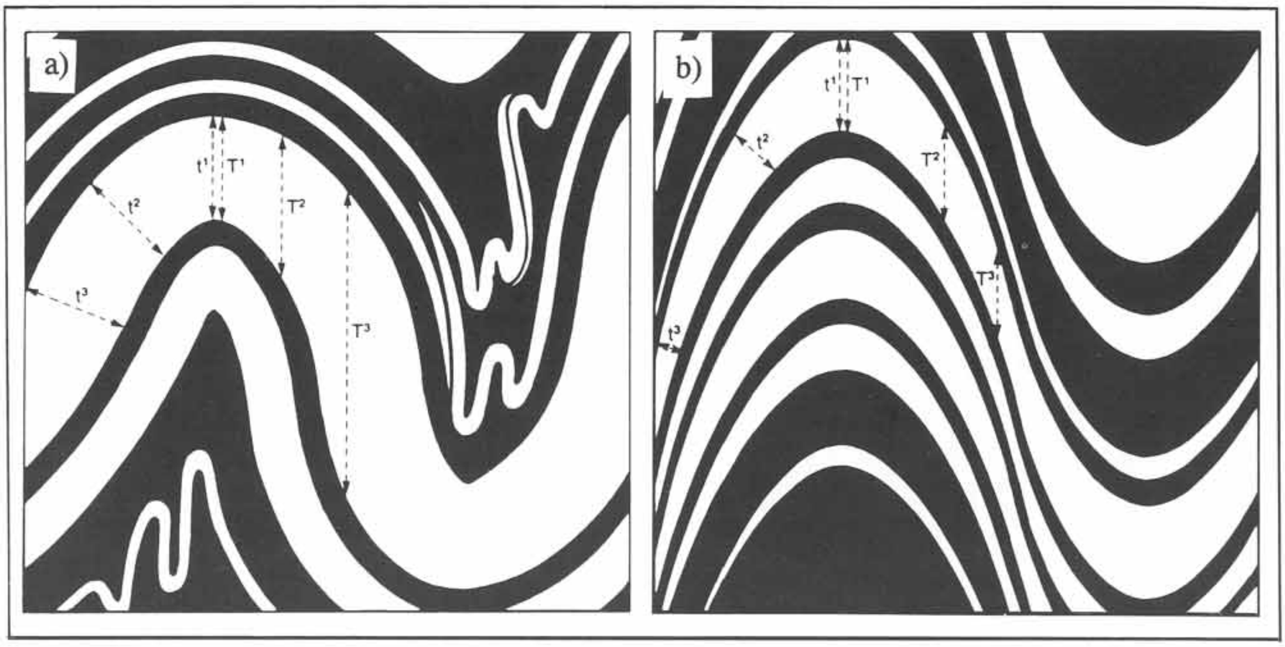


Figure 7-4: *Fold classification on basis of layer thickness. a) Parallel or concentric folds with constant layer thickness. b) Similar folds with variable layer thickness.*

☐Exercise 7-2: Refer to Figure 7-2. Assume that the lines in Figure 7-2a and b represent the top and bottom surface trace of a sandstone bed. Color the layer in red, and learn that the special folds of straight limbs are termed chevron or zig-zag folds. Likewise, assume that the curves in Figure 7-2c and d are the top and bottom of a limestone bed, and color it in blue. Now answer the following questions: a) Is the chevron fold in the red sandstone bed a special case of a similar or a parallel fold? Why? b) Is the blue limestone bed displaying a similar or a concentric fold? c) If all layers seen in Figure 7-2 are part of one sequence, are the folds harmonic or disharmonic?

☐Exercise 7-3: a) Classify whether the folds shown in Figures 7-1 and 7-4 are open, tight, or isoclinal. b) In Figure 7-4b, which layer, if any, has the largest wavelength and the smallest amplitude?

or gently curved (Figs. 7-2c & d). *Inflection points* are points along the fold profile, where the curvature is zero. In upright, curved folds, the inflection points occur at the locations of largest dip on the fold limbs (Fig. 7-2d). The *hinge zone* is the area near the hinge point, within which the layer curvature is largest (Fig. 7-2e). Points of highest and lowest position on a folded surface, with respect to the horizontal, are the fold crests and fold troughs, respectively. The crests and troughs of folds coincide with the fold hinges of upright folds, but this need no longer be so in overturned folds (see later).

The *interlimb angle*, which is the angle between the fold limbs, may vary between 0° and 180°. However, it is impractical to quantify this angle for any particular fold train, as the interlimb angle may vary across the fold train. The interlimb angle, therefore, is commonly described in qualitative terms, distinguishing gentle (180°-120°), open (120°-70°), tight (70°-20°), and isoclinal (20°-0°) folds, as illustrated in Figure 7-3.

Figure 7-4 not only takes into account the fold shape, but also illustrates that layer thickness may vary along the layer. Two basic types of folds are distinguished on the basis of the variations of layer thickness, as seen in the fold profile. *Parallel* or *concentric* folds have constant layer thickness if measured perpendicular to the bedding surface (Fig. 7-4a, i.e., $t^1=t^2=t^3$ and $T^3>T^2>T^1$). *Similar folds* have constant thickness if measured parallel to the axial plane (Fig. 7-4b, i.e., $t^1>t^2>t^3$ and $T^3=T^2=T^1$). If measured normal to the bedding, the thickness of similar folds is largest in the hinge zone and decreases on the fold limbs to attain a minimum thickness at the inflection points. Similar folds are commonly *harmonic*, which means that the shape, wavelength, and amplitude of each layer in the fold train is more or less the same for the observed section (Fig. 7-4b). However, parallel or concentric folds tend to develop *disharmonic* features because the thinner beds in the sequence always tend to develop *parasitic* or *minor folds* of smaller wavelength (Fig. 7-4a).

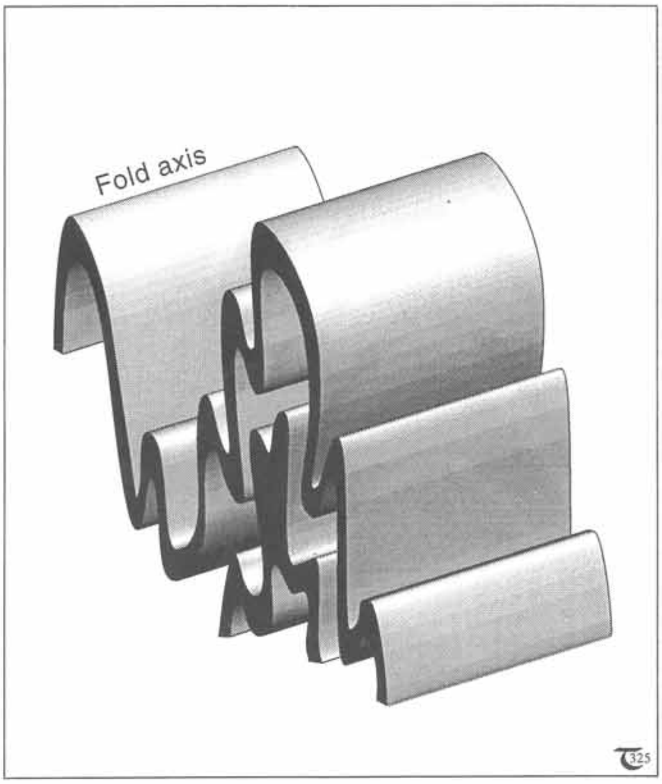


***Figure 7-5:** Cylindrical folds.*

7-2 Cylindrical, upright, horizontal folds

Many folds have a simple geometry, not only in profile, but also in the direction normal to the section of profile. One assumption usually made is that folds are *cylindrical*. This means that their form surface can be thought of as being generated by moving a line through space, keeping that line parallel to its previous positions and describing surfaces which are parts of cylinders (Fig. 7-5). This line is termed the fold axis. The essence of this concept is that all fold axes of cylindrical folds will be mutually parallel. There are,

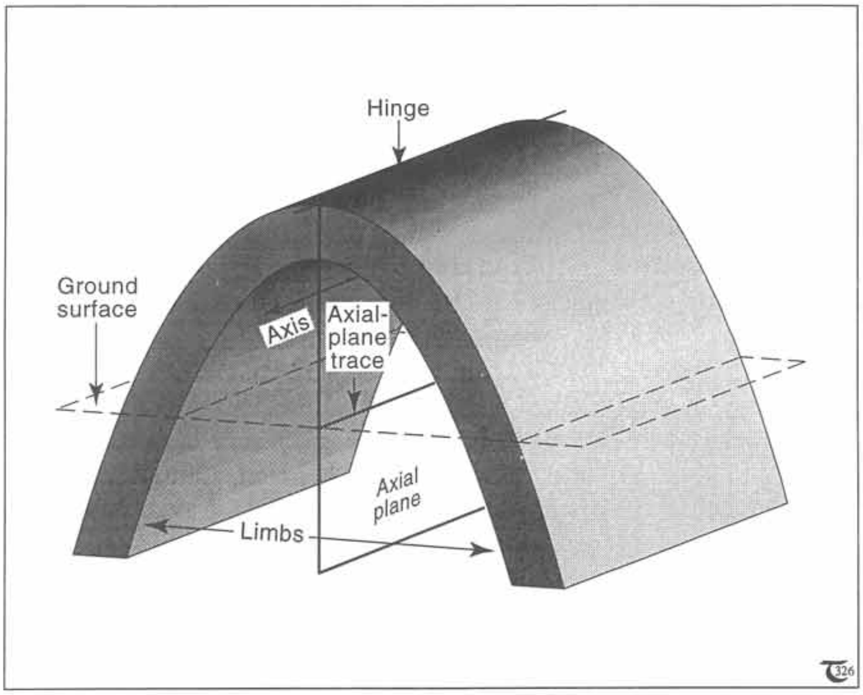


***Figure 7-6:** Upright, horizontal fold.*

Figure 7-7a: *Chevron folds in Cambrian shales, western Main Ranges, Canada.*

Figure 7-7b: *Small-scale folds in Paleozoic schist with marble intercalations, Saltfjord, Norway. Hammer for scale.*

also, conceptual models of other, non-cylindrical folds, such as conical folds. These can be theoretically generated by a fold axis, pivoting about a point in space, outlining surfaces which are parts of cones, but these are less common in nature.

Figure 7-6 illustrates a segment of a three-dimensional cylindrical fold. The fold limbs are separated by a hinge line. The fold hinge line may differ from the fold axis for the following reason. The hinge line joins points of maximum curvature on the folded surface, and need not be straight. The hinge line thus is a material line, as opposed to the fold axis, which is an imaginary straight line that, when moved parallel to itself in space, traces out the fold surface.

The hinge lines in the top and bottom of successive folded layers define the *axial surface* of a fold. The axial plane usually bisects the interlimb angle but not necessarily so (see exercise 7-4). The *axial trace* is the imaginary line marking locations where the axial surface intersects the ground surface of a map area. The fold of Figure 7-6 is termed *upright and horizontal*, meaning that the axial plane is subvertical and the fold axis is horizontal. Examples of upright folds are illustrated in Figures 7-7a and b.

The important distinction between *antiforms* and *synforms* is schematically explained in Figure 7-8. An antiform is a fold that closes upward. Conversely, a synform closes downward. However, the map views of upright horizontal antiforms and synforms in terrains of low relief are identical. The ground surface is intersected by a set of subparallel lithological boundaries. Their map views are, therefore, similar but can be distin-

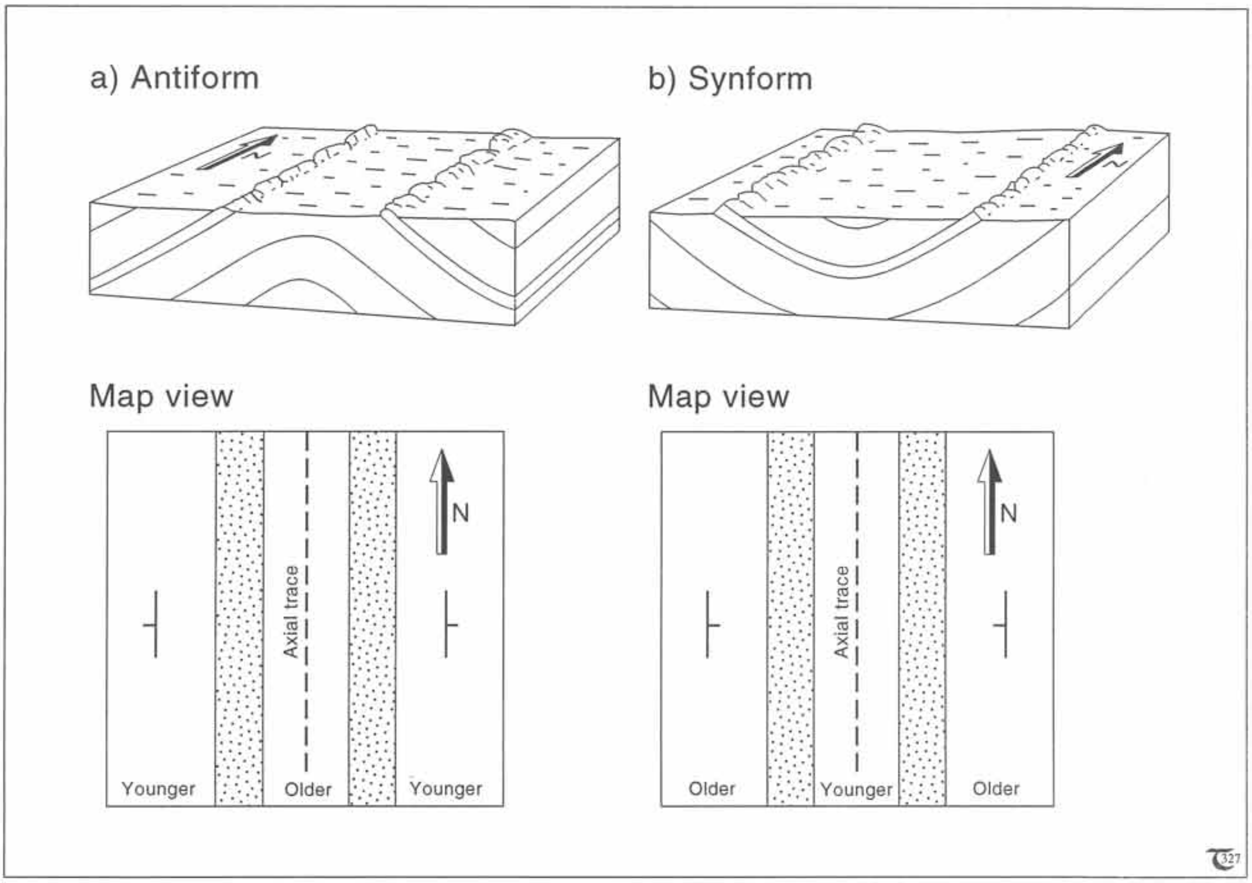


Figure 7-8: *Perspective diagrams and map views of: (a) antiform and anticline, and (b) synform and syncline. All are upright.*

guished (1) if the direction of dip is indicated at either side of the axial plane traces, or (2) if repetition of beds is seen and if their relative ages are known. For example, the rocks along the antiformal axial trace in the map of Figure 7-8a are older than those further away from the trace and the same rocks are found going west and east. Conversely, rocks along the synformal axial trace of the map in Figure 7-8b are younger than those to the east and west in the map area.

The antiform of Figure 7-8a can, also, be termed an anticline, but there are examples in nature where antiforms have been formed in sequences which were lying upside down before the folding. Consequently, the youngest rocks are found in the core of such antiforms. It has been suggested that such antiforms should not be termed anticlines, reserving the term only for those antiforms in which the oldest rocks really occur where one expects them: in the fold core. Similarly, the synform of Figure 7-8b can be termed a syncline but only if the youngest rocks really occur along the axial trace of the synform, as portrayed in Figure 7-8b. The existence of folded upside-down sequences was not recognized until the early 1900's. Before that time the terms antiform and synform did not exist, because all folds were thought to be anticlines and synclines in normal stratigraphic successions.

7-3 Inclined and overturned horizontal folds

Upright horizontal folds are widespread in fold belts, but not all axial planes need necessarily be upright. Figure 7-9a illustrates the common upright horizontal fold. Figure 7-9b has an

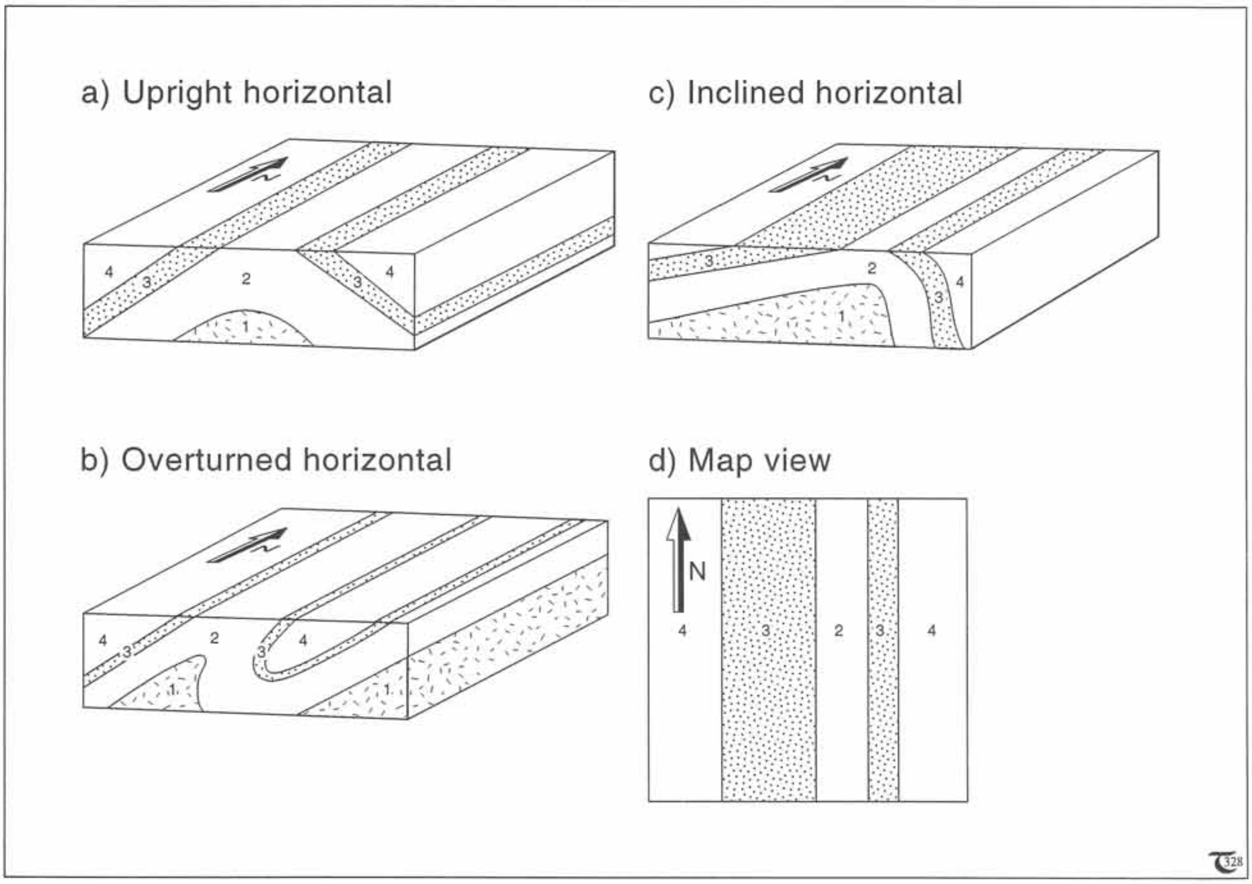


__Figure 7-9:__ a) to d) Horizontal folds with particular orientation of fold limbs and axial plane: (a) upright fold, (b) overturned fold, (c) inclined fold, and (d) map view of inclined fold.

☐Exercise 7-4: Draw a fold where the axial plane connects the hingelines of successive layers but is not the bisector of the interlimb angle.

☐Exercise 7-5: a) Illustrate an antiform which is not an anticline. b) Illustrate a synform which is not a syncline.

inclined axial plane, horizontal fold axis, and tight fold limbs, thus termed an *overturned horizontal fold*. The peculiar aspect of overturned folds is that layers at both limbs dip in the same direction. Figure 7-9c illustrates an inclined horizontal fold, not yet overturned, possessing asymmetric fold limbs of different length and different inclination. Because of apparent thickness effects, the map pattern of *inclined folds* shows different outcrop width for the same layer at either side of the trace of the axial plane (Fig. 7-9d).

7-4 Upright, plunging folds

Upright folds, i.e., folds with vertical axial planes, do not necessarily need to have horizontal axes. Fold axes may be inclined so that they *plunge* beneath the horizontal ground surface (Fig. 7-11). The orientation of any fold axis can be specified in terms of plunge/trend notation. This notation helps to distinguish measurements of linear features from planar features. For example, the fold axis of the upright, plunging fold in Figure 7-11 is oriented at 40/070.

The surface expression or map pattern of upright, plunging folds is different from that of horizontal folds. Figures 7-12a and b show the block diagrams of an upright, plunging antiform and synform, respectively. The aerial views of upright, plunging antiforms and synforms in terrains of low relief are identical; both form a *V- or U-shaped intersection pattern* with the ground-surface. Their map views are, therefore, similar but can be distinguished (1) if the direction of dip of the beds is indicated at either side of the axial plane traces (Figs. 7-12a & b), or (2) if the relative age of the beds is known. For example,

☐Exercise 7-6: Prepare a geological surface map of the area in Figure 7-10, which itself is seen looking due north. Color the map, include a legend, north arrow, strike-dip symbols, and amount of dip.

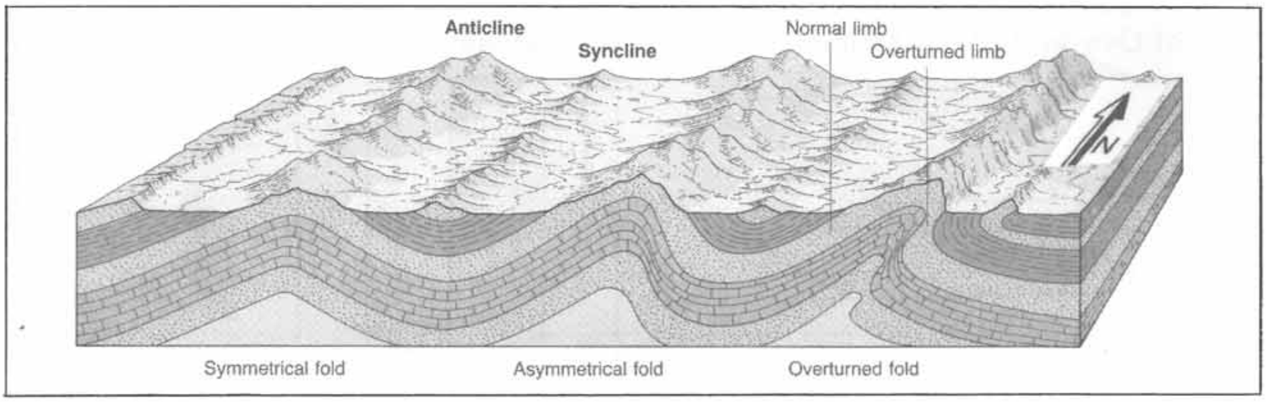


Figure 7-10: *Block diagram of terrain with horizontal folds. The dip of the east limb of the antiformal closures becomes progressively steeper towards the east and is overturned in the easternmost antiform.*

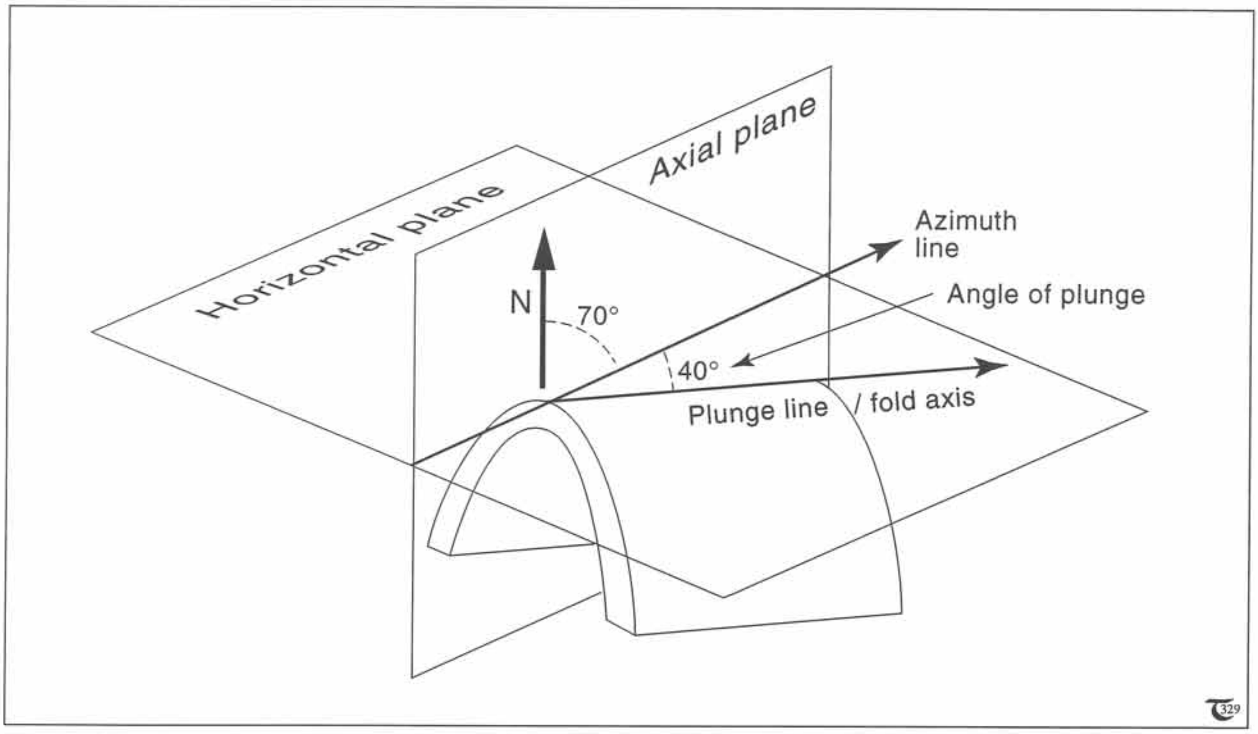


Figure 7-11: *Upright, plunging fold.*

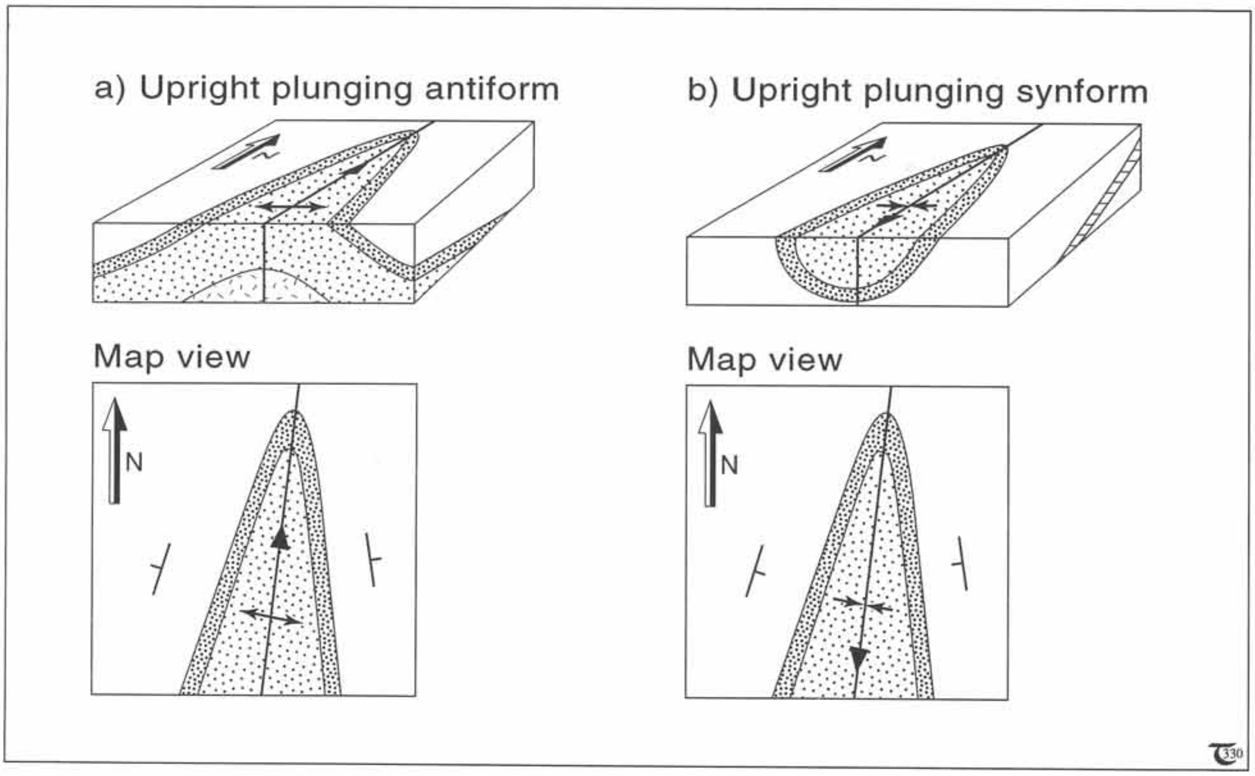


Figure 7-12: *Perspective diagrams and map views of: (a) upright, north-plunging antiform, and (b) upright, south-plunging synform. Note the similarity in the map patterns of both folds.*

if rocks in the core of the fold closure are older than those farther away from the axial trace, the structure is an anticline (Fig. 7-13a). Conversely, if rocks occupying the fold closure are younger than rocks seen along the limbs, the structure is a syncline (Fig. 7-13b).

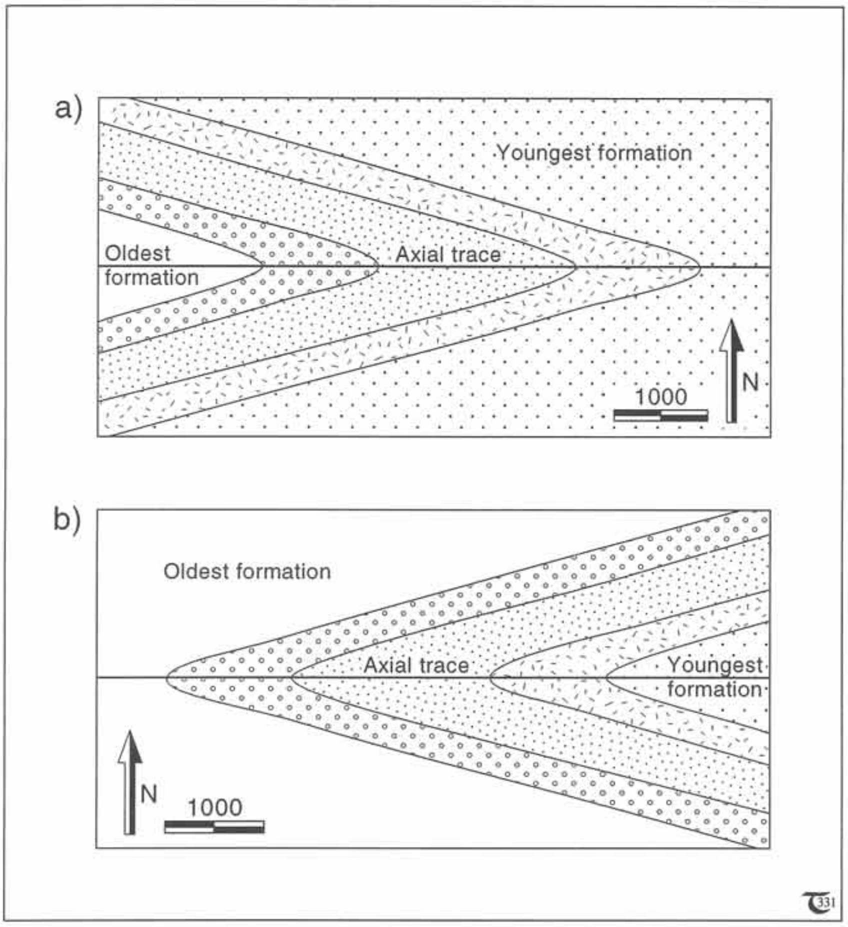


Figure 7-13: *a) & b) Map patterns of plunging folds: (a) east-plunging anticline, and (b) east-plunging syncline.*

Antiforms and synforms can be distinguished on the basis of the map pattern, even if only the direction of fold plunge is known. The symbols for indicating the plunges of the axes of antiforms and synforms are shown in Figure 7-14. *Synforms of plunging folds close, on the map, in a direction opposite to the plunge of their fold axes* (Fig. 7-12b). In contrast, the outcrop pattern of *plunging antiforms close in the plunge direction* (Fig. 7-12a). A plunging fold train of antiforms and synforms will intersect the terrain in an en-echelon pattern of opposite pointing V's (Fig. 7-15a & b).

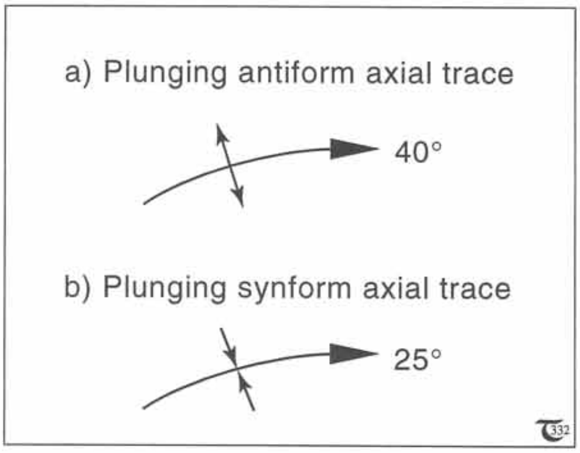


Figure 7-14: *a) & b) Map symbols used for indicating the surface trace of the axial planes of: (a) plunging antiform, and (b) plunging synform.*

☐Exercise 7-7: Complete the two vertical sections of the block diagram in Figure 7-16 compatible with the surface map. a) Draw the traces of the axial planes by connecting the hinge points. b) Indicate strike and dip symbols. c) Indicate the direction of plunge of the fold axes using arrows. d) Complete the sections. Start with the section normal to the strike; then complete the section parallel to the strike. e) Indicate where the oldest rocks are found at the surface.

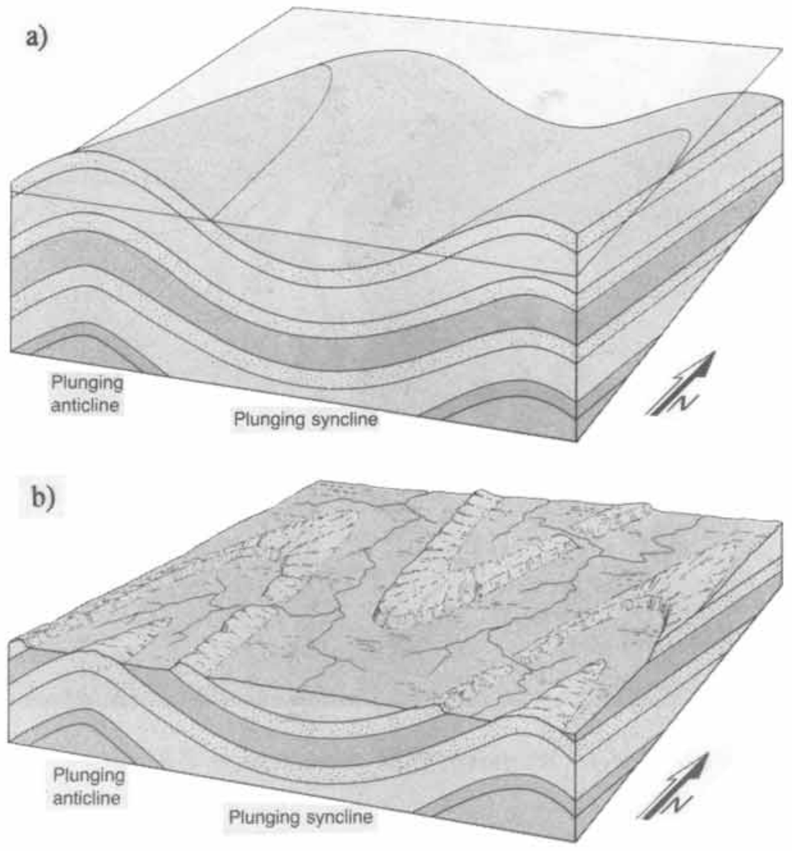


Figure 7-15: a) & b) Plunging folds: (a) before erosion, and (b) after erosion. The outcrop pattern of the eroded beds forms V-shapes alternately pointing north and south.

☐Exercise 7-8: Figure 7-17 shows an oblique aerial view of Sheep Mountain in Wyoming, USA. Erosion has cut the flanking sedimentary beds into low ridges, in places cut into V-shapes by transecting drainage patterns.
a) Use a transparent overlay, and outline all the major structural features.
b) Describe the structure of Sheep Mountain in as much detail as possible, using all the terms introduced in this chapter.
c) Where are the youngest rocks in the field of view?

☐Exercise 7-9:
a) Construct profiles along section lines A-A' and B-B' on the map of Figure 7-18.
b) Color both the map and section.
c) Outline on the map the trace of the axial surface, and indicate the plunge direction of the fold axis with the appropriate symbol.
d) What is the plunge/trend of the fold hinge?

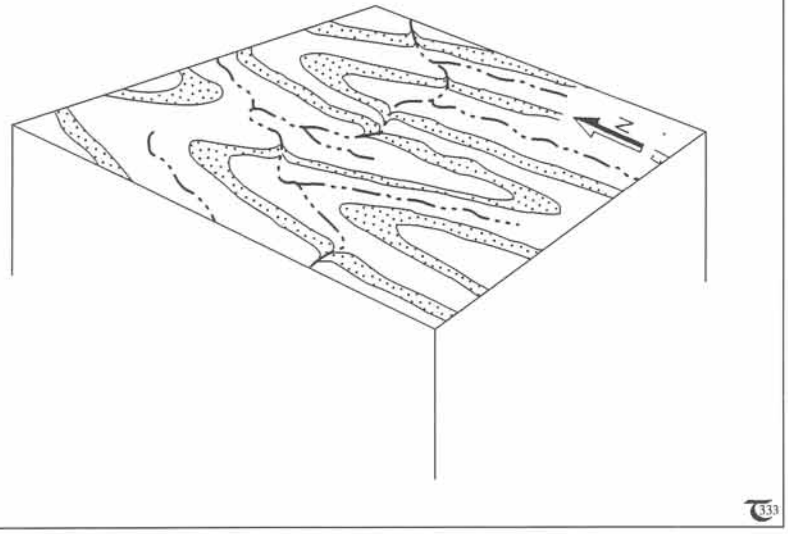


Figure 7-16: Perspective diagram to be completed in connection with exercise 7-7.

Figure 7-17: Sheep Mountain in oblique aerial view, Wyoming, USA. See exercise 7-8.

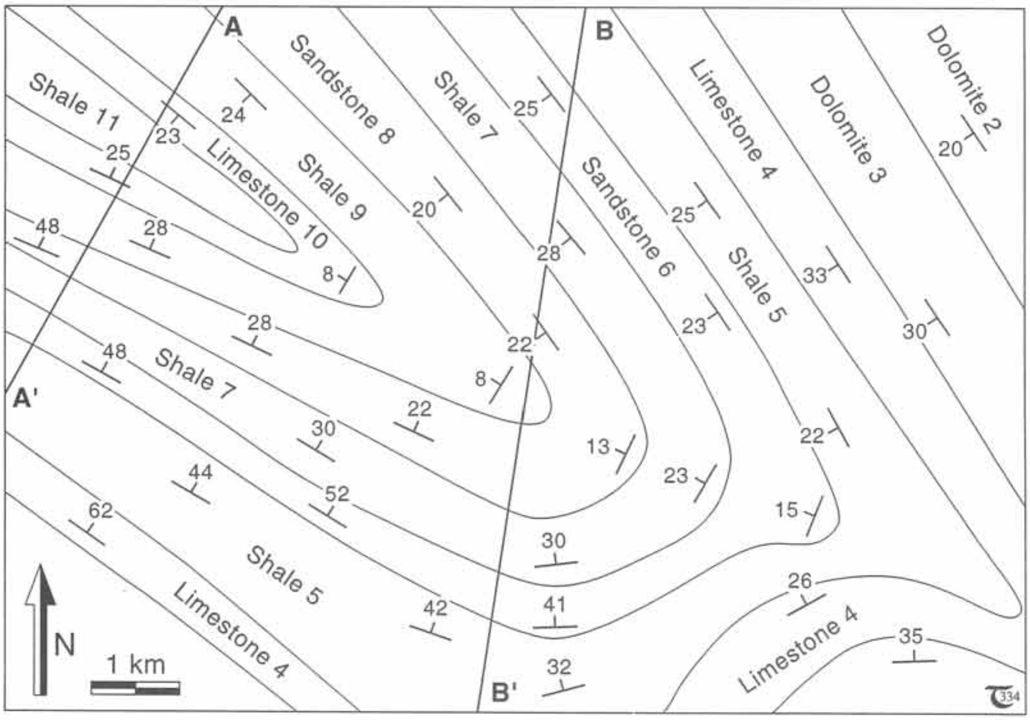


Figure 7-18: Map of flat terrain with plunging folds. See exercise 7-9.

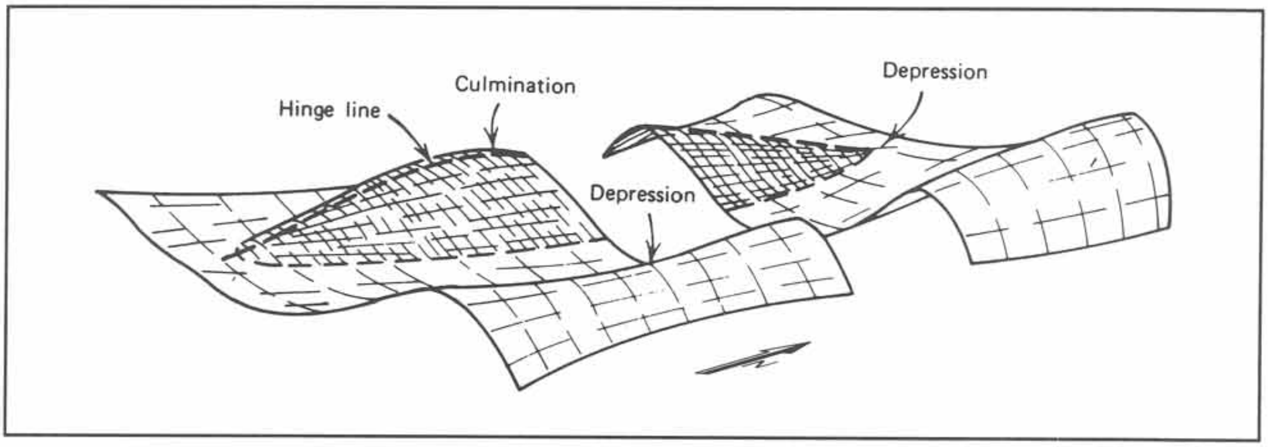


Figure 7-19: Structural surface, marking doubly plunging fold. The axial culmination separates the segments of opposite plunge directions.

7-5 Doubly plunging folds

Natural fold structures may be approximately cylindrical but many have undulations along the direction of their fold hinges. Fold hinges are then no longer straight lines but gentle curves of variable attitude, which may change plunge direction at either side of an *axial culmination* (Fig. 7-19). The folds described by such axes are *doubly plunging*. The map pattern of doubly plunging folds resembles that of an elongated dome, such as exposed in the Black Hills, South Dakota (Fig. 7-20). The basement-uplift in the Black Hills is caused by Laramide deformation and Late Tertiary to early Eocene uplift of Precambrian schist. The Precambrian granite, hosted in the core of the dome, was emplaced before the uplift. Doubly plunging folds, also, may occur in regular patterns, such as seen in a satellite image of the Zagros fold belt, southeastern Iran (Fig. 7-21). The coastline in the south is black. The structures seen are due to an en-echelon network of doubly plunging folds. The black spots inland are glaciers of salt, emanating from the crests of fold closures that are pierced by vertical salt stocks.

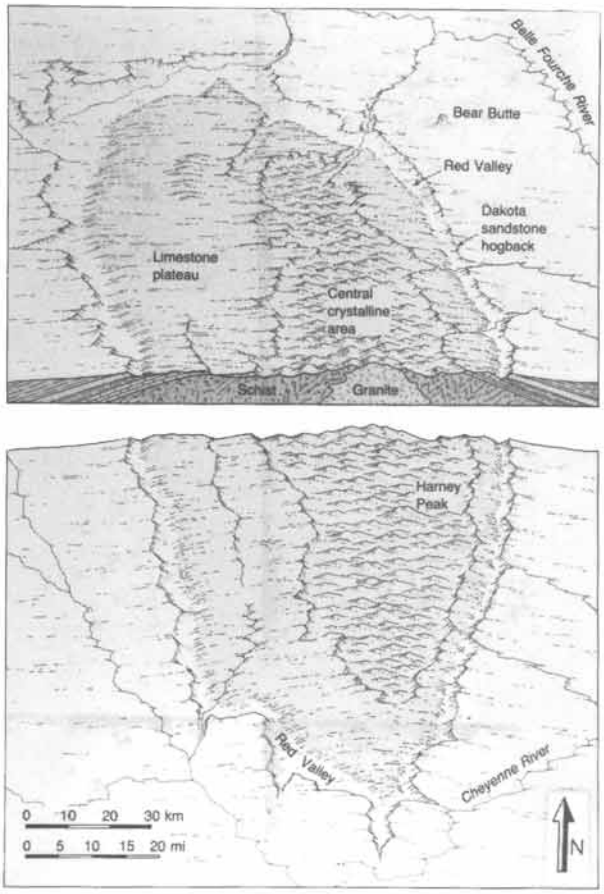


Figure 7-20: Oblique map view of the doubly plunging anticline or elongate dome of the Black Hills, South Dakota.

☐Exercise 7-10: a) Construct a geological map of the southern half of the area covered by the image of Figure 7-21. Use a transparent overlay, and indicate the structural symbols. b) Figure 7-22 illustrates the bifurcation point, occurring where three plunging antiforms meet. Mark the bifurcation points on your map.

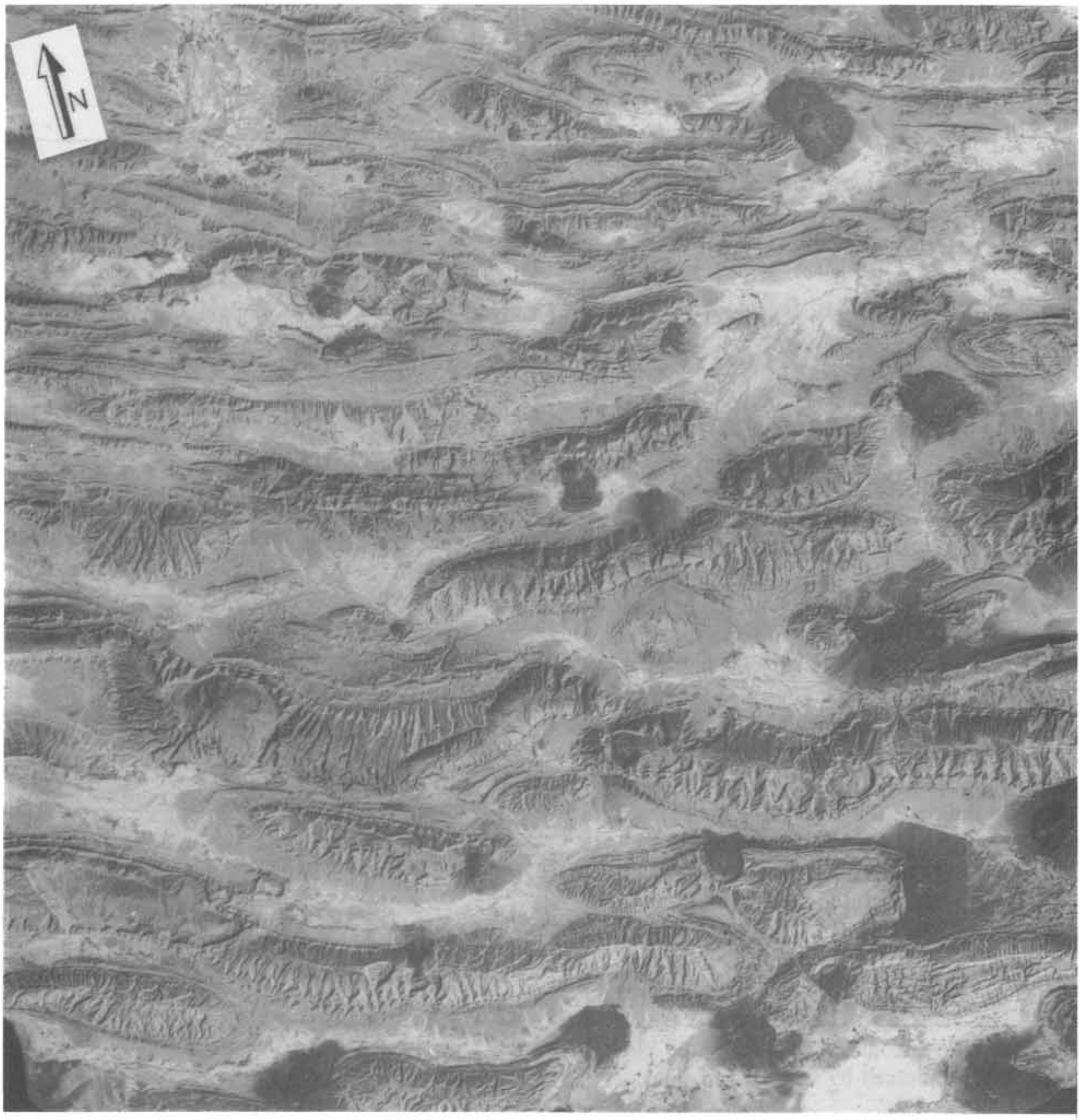


Figure 7-21: *Satellite image of doubly plunging folds in the Zagros Mountains, southeastern Iran. This landsat image covers about 180 by 180 square kilometers.*

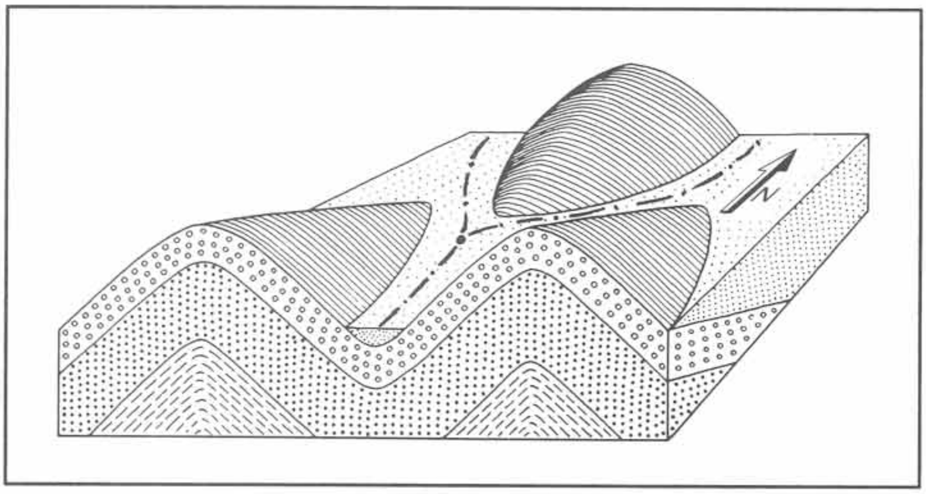


Figure 7-22: Perspective diagram of doubly plunging folds and the bifurcation point in the map pattern where three plunging anticlines meet.

☐Exercise 7-11: Figure 7-23 is a radar image of the Valley-and-Ridge province of the Appalachian. Interpret the fold structures on a transparent overlay.

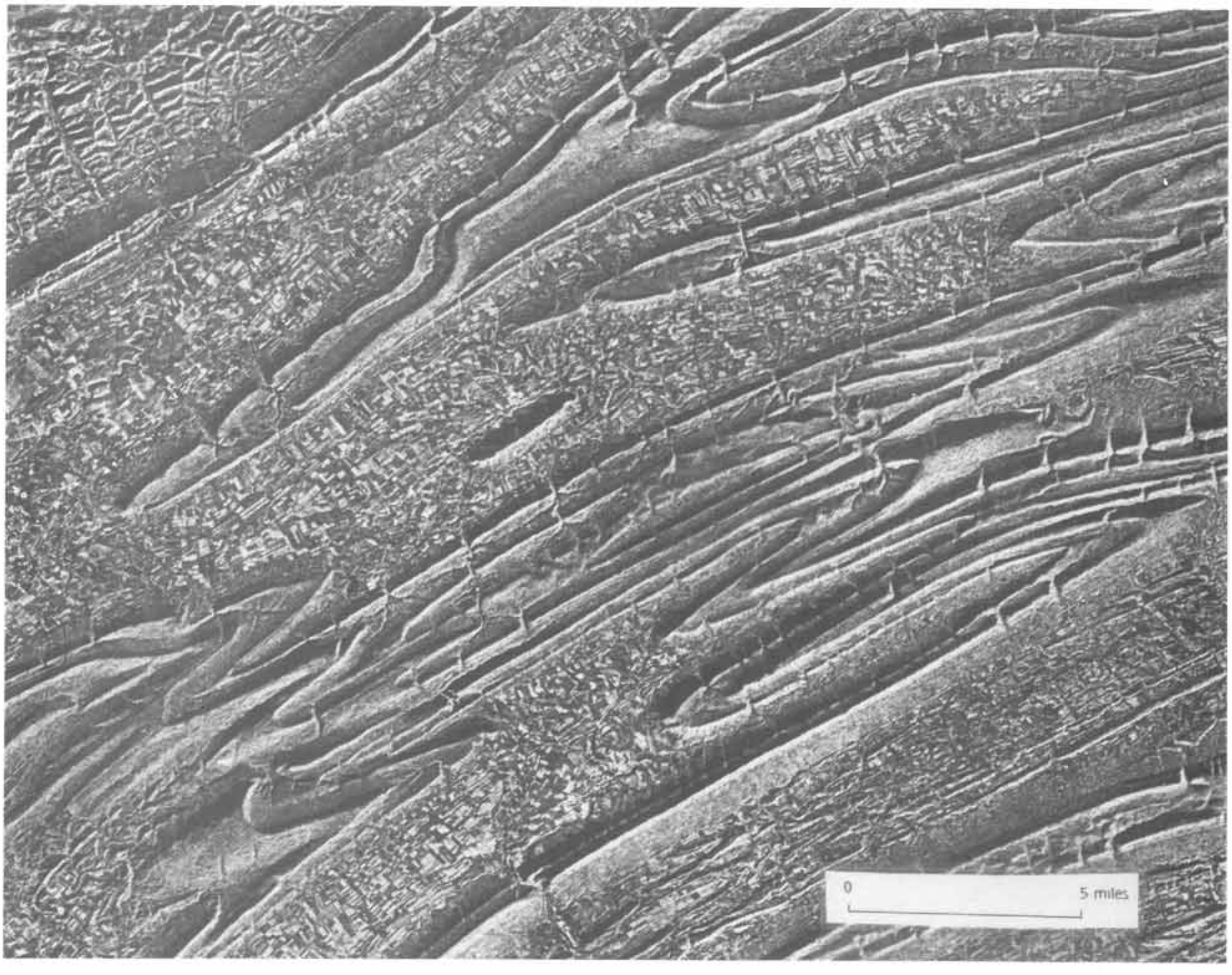


Figure 7-23: Radar image of the Valley-and-Ridge province of the Appalachians.

7-6 Recumbent folds, reclined folds, and monoclines

In extreme cases, folds are neither upright horizontal nor upright plunging but possess awkward orientations of the axial plane and the axis of the folds. Figure 7-24a illustrates the ordinary upright plunging fold, which becomes inclined plunging if the axial plane is tilted (Fig. 7-24b). Figure 7-24c illustrates the *reclined fold*, a special case of inclined plunging folds, where the azimuth of the fold axis is the same as the dip direction of the axial plane. Figure 7-24d shows a *recumbent fold*, which typically has a subhorizontal axial surface. Beautiful examples of recumbent folds occur in the eroded walls forming the coast of Greenland (Fig. 7-25a & b).

Another distinctive type of fold is the *monocline*, which is not a fold in the strict sense, because it has only one limb (Fig. 7-26a). Monoclines are local distortions of otherwise homoclinal strata and are caused by basement faults. The Waterpocket monocline, Utah, is a famous example of this structure (Fig. 7-26b).

☐Exercise 7-12: Vertical drill cores taken from recumbent folds show an upside-down stratigraphy at one side of the axial surface. Make a cross-section to sketch the situation.

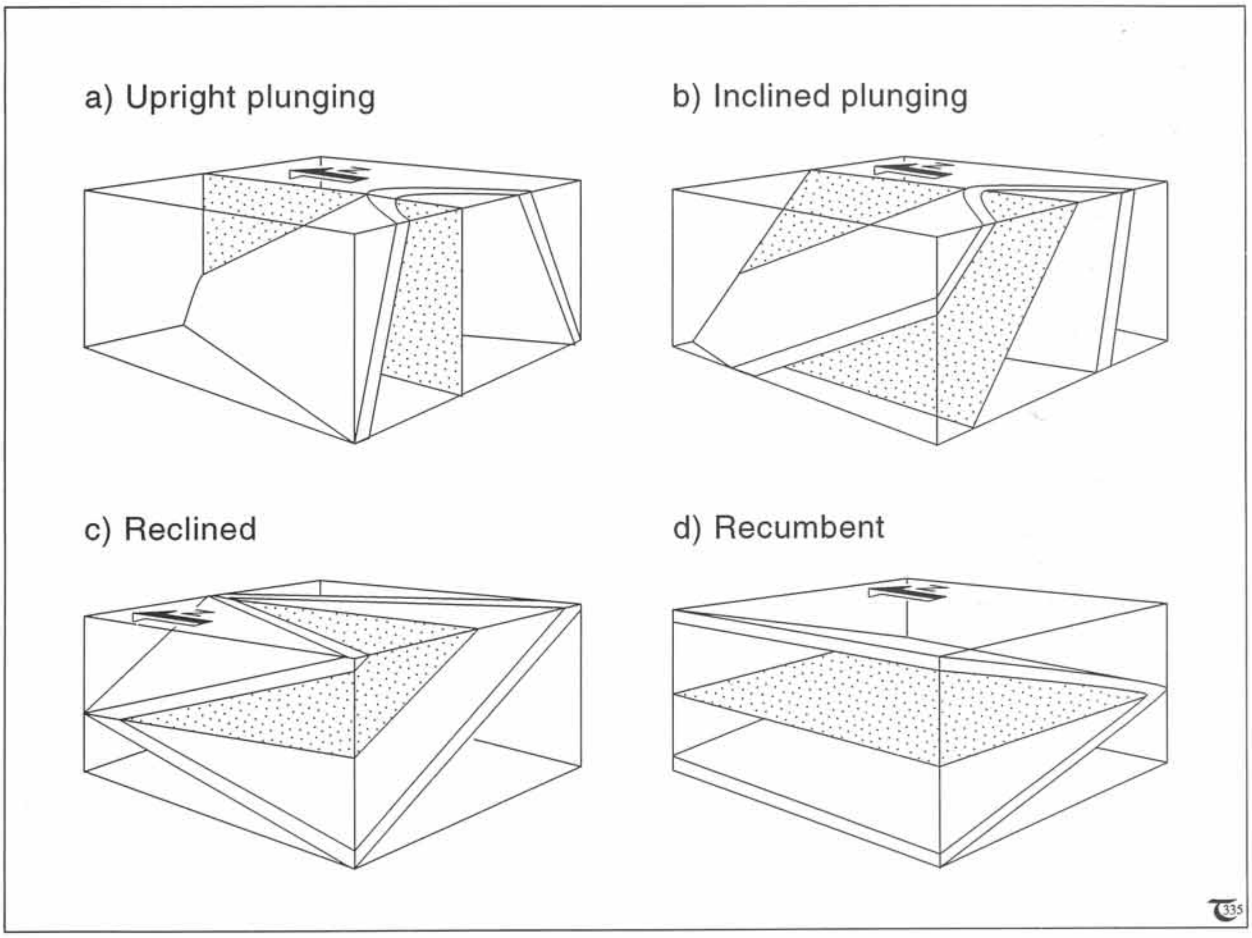


Figure 7-24: *a) to d) Four major fold orientations, deviating from that of upright horizontal folds. Fold orientations shown are: (a) upright horizontal, (b) inclined plunging, (c) reclined, and (d) recumbent.*

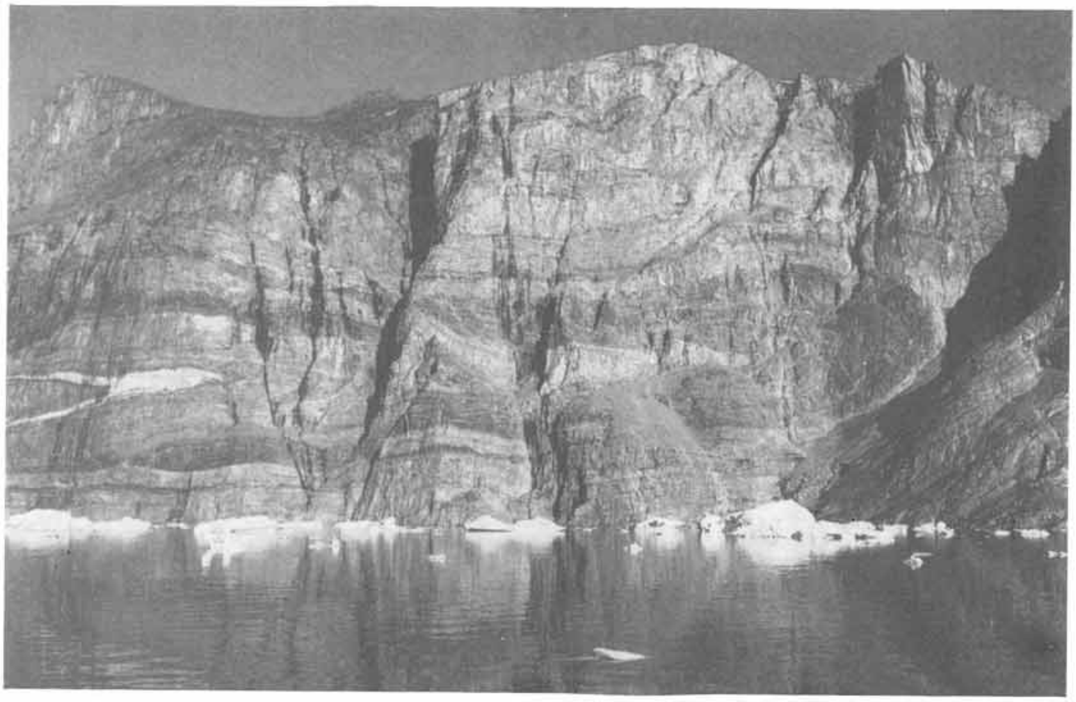


Figure 7-25a: *Recumbent fold in steep cliffs of Precambrian gneisses at the Umanak area, Greenland. Cliff height is about 1.5 kilometers.*

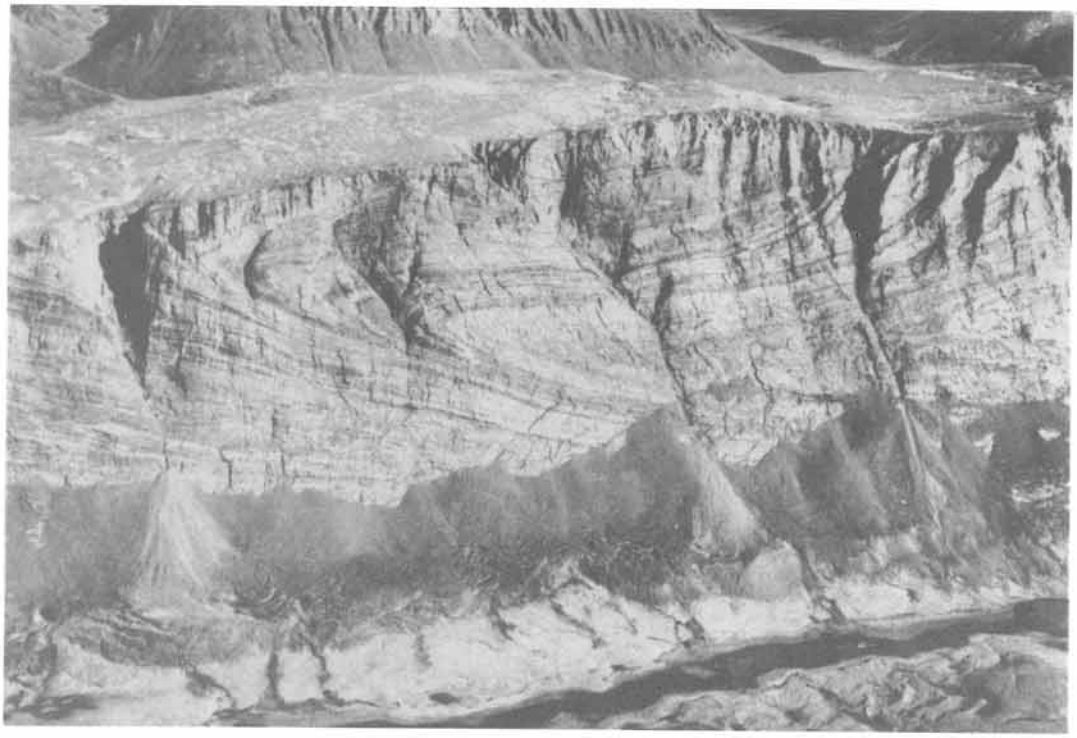
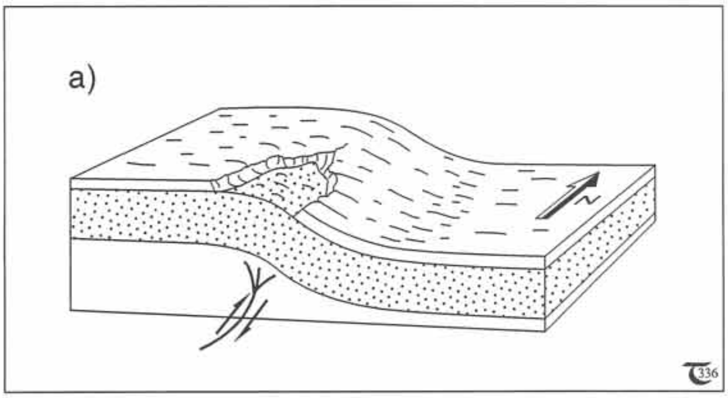
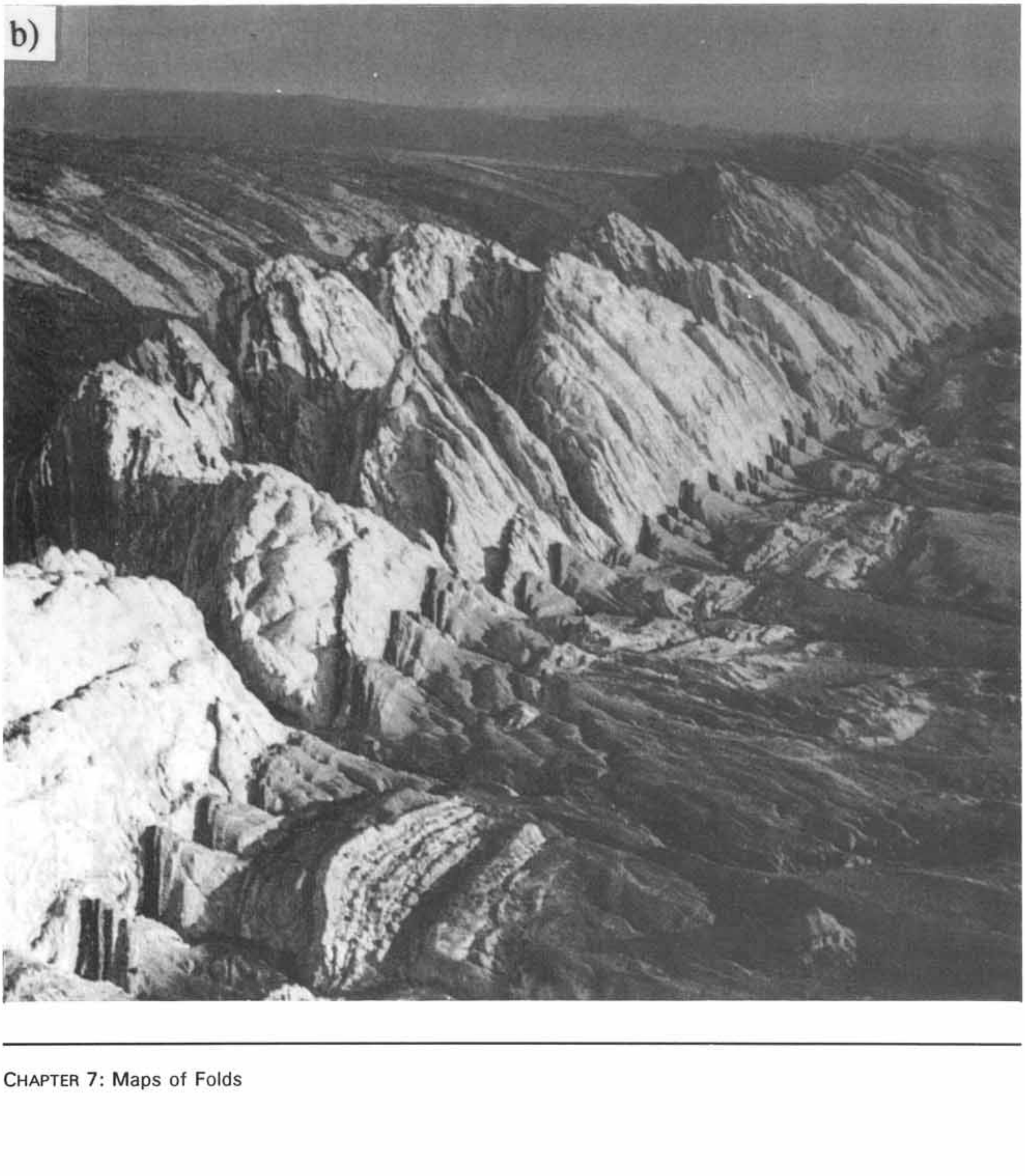


Figure 7-25b: *Recumbent fold in Caledonian gneisses of western Greenland. Cliff height is about 800 meters.*

Figure 7-26: *a) Perspective diagram of a monocline. b) View along the flexure in the terrain that defines the Waterpocket monocline, Utah.*





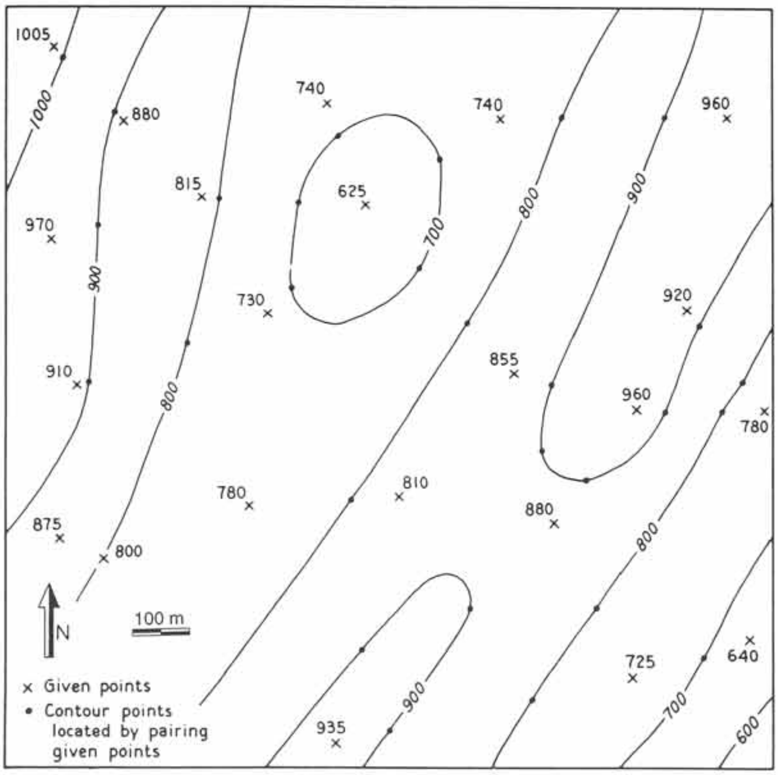
Chapter 8: Structure Contours for Complex Surfaces and Folds

THE CONCEPT of structure contours is further advanced in this chapter. Chapter five outlined how structure contours can be used to infer the strike and dip of rock strata by constructing structure contours on outcrop maps. Chapter six used structure contours to complete outcrop patterns on geological maps of poorly exposed areas. This chapter expects the reader to exercise the ability to think clearly in three dimensions. This is a primary requirement for the successful interpretation of geological maps and for visualizing the subsurface attitude of geological surfaces, such as homoclinal and folded rock strata.

Contents: Section 8-1 outlines how structure-contour maps for complex surfaces are obtained. The related concept of form-line contour maps is introduced in section 8-2. Subsequently, the principal features of structure contours are discussed for horizontal folds in section 8-3 and for plunging folds in section 8-4. The effects of topography on the map patterns of folded sequences are highlighted in the final section, 8-5.

8-1 Structure-contour maps for complex surfaces

Structure contours for many common rock-deformation patterns, such as tilted and folded layers, can be inferred either from outcrop patterns or by solving three-point problems from subsurface data. However, these methods are less suitable for obtaining the structure contours for complex deformation patterns. Complex structures require the input of many elevation data on a geological surface, which are subsequently contoured by extrapolation. The principle is similar to the early method for fabrication of topographic contour maps. The elevation of the land surface was measured in a number of locations, and the contour lines were then sketched by extrapolating between the surveyed points.



☐Exercise 8-1: Refer to Figure 8-1 and draw the interpolated structure contours for fifty-meter intervals. Color in red the closed reservoir highs which have shapes that could be good hydrocarbon traps.

Figure 8-1: Structure contours, above sea-level, for the top surface of an undulating hydrocarbon reservoir.

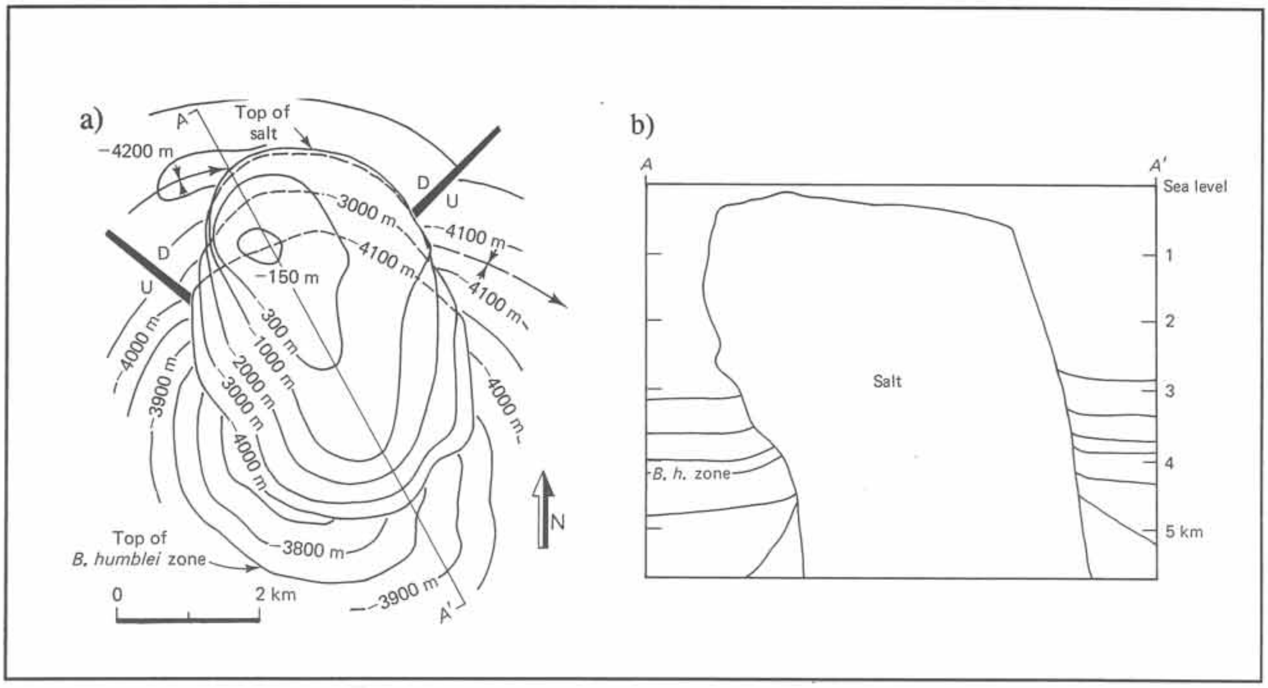


Figure 8-2: a) Structure-contour map of Cote Blanche Island salt dome, Louisiana. b) Section along line A-A' across the dome.

The data for structure contours of complex deformation surfaces may come from drillholes and depth-converted seismic reflection profiles, detailing the elevation of the surface in many locations. The structure-contour maps of the Arabian and Canadian Precambrian basements are outlined on the basis of elevation data of the subsurface (Figs. 5-2 and 5-3). Software for the construction of contour maps from elevation data is commercially available (see chapter seventeen).

Structure contours are important in locating hydrocarbon accumulations. Figure 8-1 shows a map with elevation data of the top of a potential hydrocarbon reservoir, and the extrapolated structure contours outlined are based on these elevation data. Gas and oil tend to migrate through the porous reservoir rock until they become trapped in the higher portions of the reservoir, assuming there is a sealing cap rock. Structural highs of such reservoirs appear on structure-contour maps in locations where the contours form closed loops. Also, the volume of the best reservoir traps can be estimated from structure-contour maps. The volume below the top of such reservoirs, outlined by structure contours, is approximated with simple geometry, such as a cylinder or a cone, or by applying automated integration.

The 3-D shape of salt domes may be represented by a projection map of the structure contours on the dome surface (Fig. 8-2a). Figure 8-2b shows a section across the upper part of the salt dome, which pierces the surrounding stratigraphic sequence. The rock layers pulled up by the rising salt may act as reservoirs for migrated hydrocarbons, and salt itself is good seal rock.

8-2 Form lines

Structure contours represent the shape of structures and are curves or lines connecting points of similar altitude on a particular structural surface. A closely related type of contour is the form line or form-line contour, which is constructed by tracing the strikes of the structures visualized in a horizontal map. For example, Figure 8-3a shows the strike/dip symbols for sedimentary beds dipping gently away from a central elongated dome. A form line can be constructed as a curve, everywhere tangential to the strike of a particular geological surface, thus accentuating its form as seen in map projection (Fig. 8-3b). Form lines resemble structure contours, but adjacent form lines trace different geological surfaces rather than one surface as is

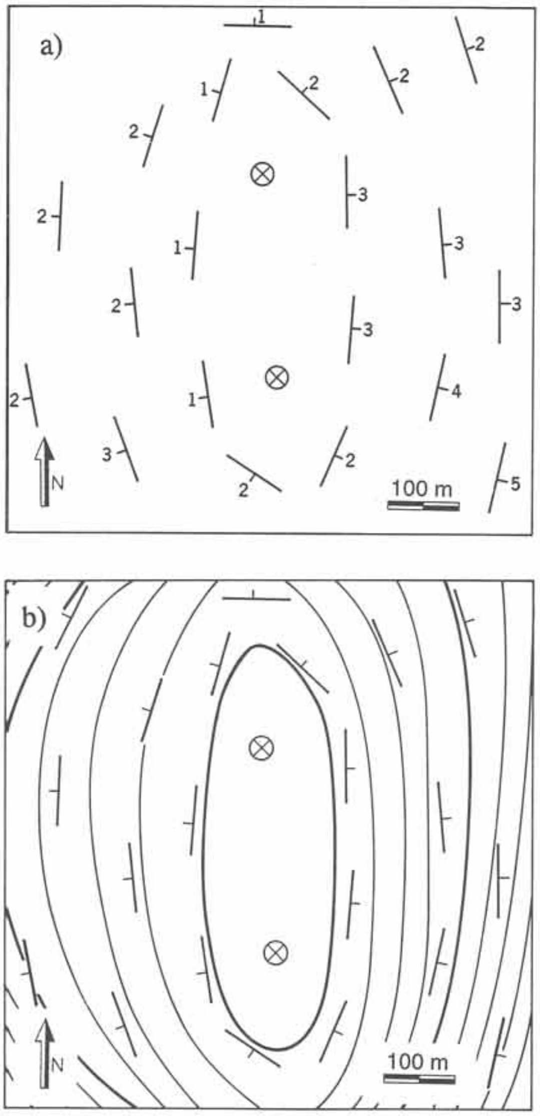


***Figure 8-3:** a) Structure map indicating strike and dip of sedimentary beds. b) Form-line contour map of the same area.*

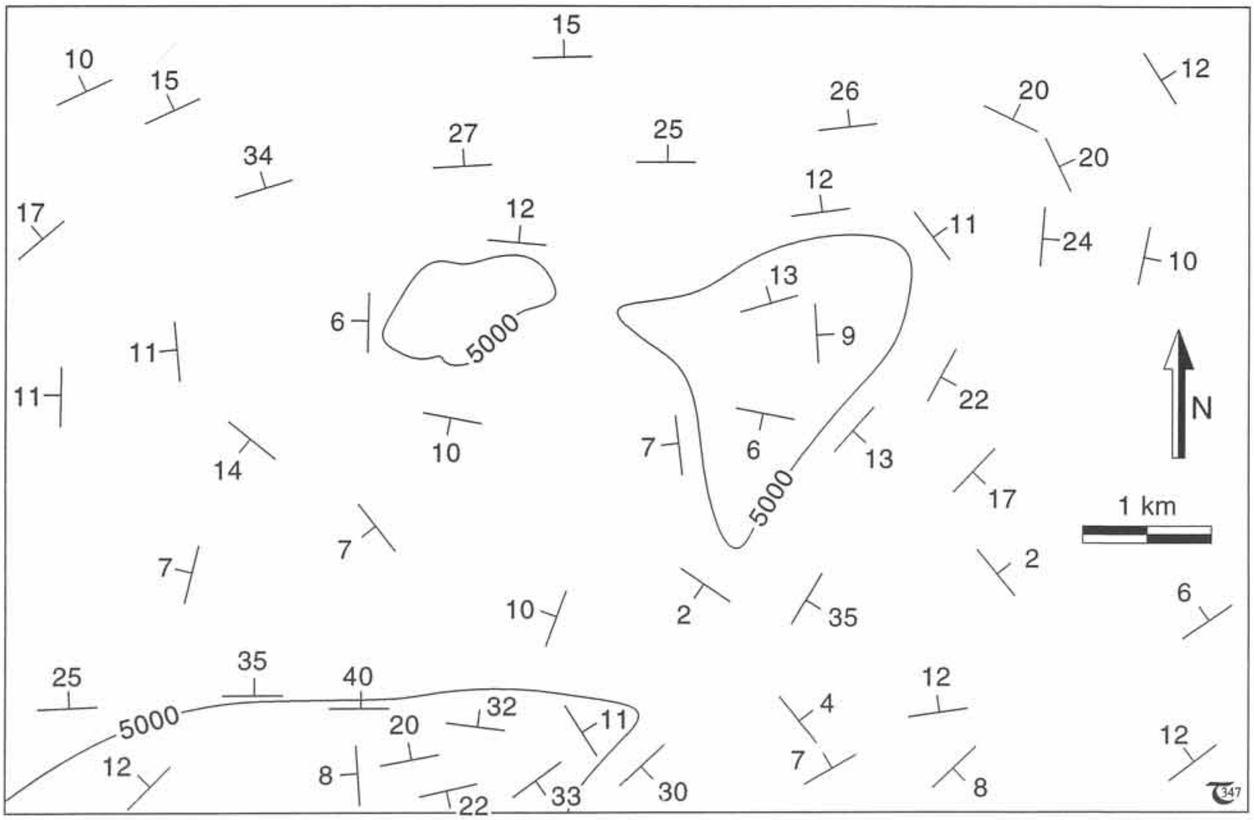


Figure 8-4: Structural map with 5,000 foot structure contour. See exercise 8-2.

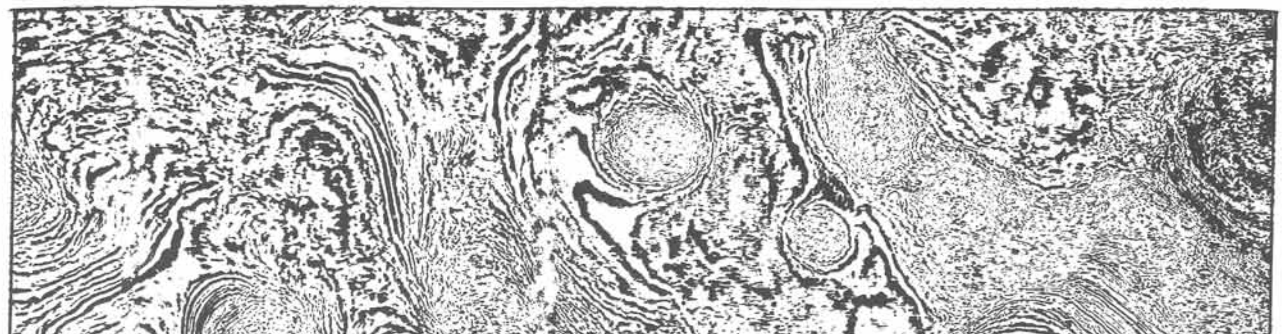


Figure 8-5: Seismocrop or time-slice map of salt domes below the floor of the Gulf of Mexico, south of New Orleans, Louisiana. This horizontal seismic map is synthesized by 3-D migration.

the case for structure contours. Additionally, the absolute elevation of form lines is unknown, for, if their elevation or depth were known, they would immediately become structure contours. Because adjacent form lines represent no single stratigraphic horizon, their spacing is arbitrary and includes no information on the steepness of structural slopes. Nonetheless, form lines are useful to obtain a qualitative impression of the subsurface structure. Form lines commonly closely resemble structure contours. Consequently, form lines on horizontal slices through a regional structure can be transformed into structure contours for a particular geological surface after calibration with depth estimates to that surface.

☐Exercise 8-2: Consider the structural map of Figure 8-4, and extrapolate the form-line contours. Because form lines have no absolute value, they may start anywhere.

☐Exercise 8-3: Figure 8-5 shows a seismocrop map approximately three kilometers below sea level in the Green Canyon area, Gulf of Mexico. The sub-circular features with poor internal resolution are salt stocks. The smoothly curved reflectors are sedimentary layers. a) Construct a form-line contour map for the area. b) Attempt a cross-section.

8-3 Horizontal chevron folds

Structure contours for folds of continuously changing limb curvature cannot be obtained easily. Their contour maps have to be obtained by extrapolation from drillholes or by depth calibration of form-line contours. However, folds with relatively straight limbs, i.e., chevron type or box folds, allow the construction of structure contour-lines from a few strike/dip measurements only. Figures 8-6a and b are structure-contour maps of an upright horizontal and inclined horizontal fold, respectively. The traces of the axial planes separate regions of opposite dip. *Structure contours on opposite limbs of folds with horizontal hinge lines typically map as a pattern of parallel lines.* Symmetric, upright, horizontal folds have structure contours with the same spacing at either side of the axial plane trace (Fig. 8-6a). Asymmetric, horizontal folds have structure contours of different spacing at either side of the axial plane trace (Fig. 8-6b).

☐Exercise 8-4: a) Indicate strike and dip symbols on the maps of Figures 8-6a & b in order to bring out the orientation of the fold limbs. b) Draw cross-sections normal to the trend of the hinge lines of the folds.

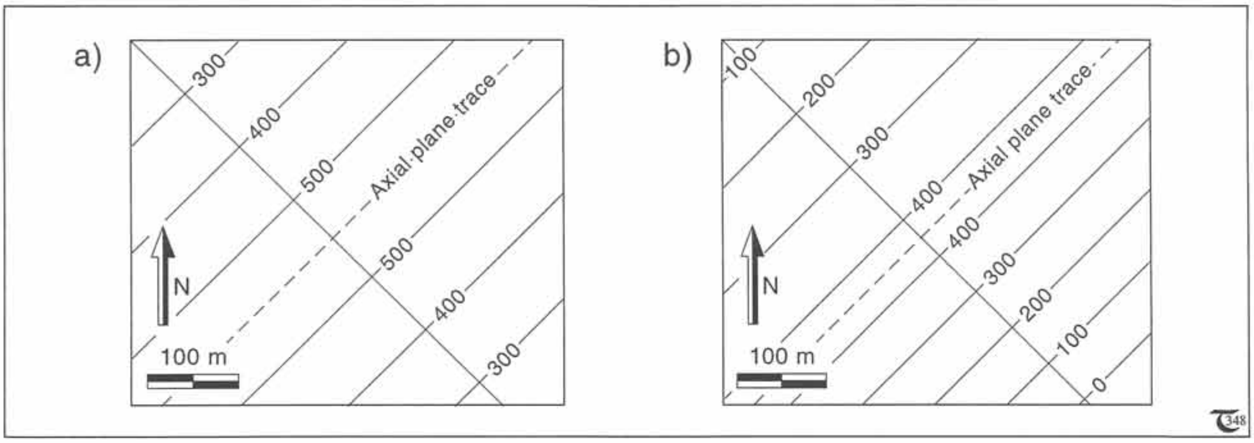


***Figure 8-6:** a) & b) Structure-contour maps. Contours are in meters above sea-level. See exercise 8-4.*

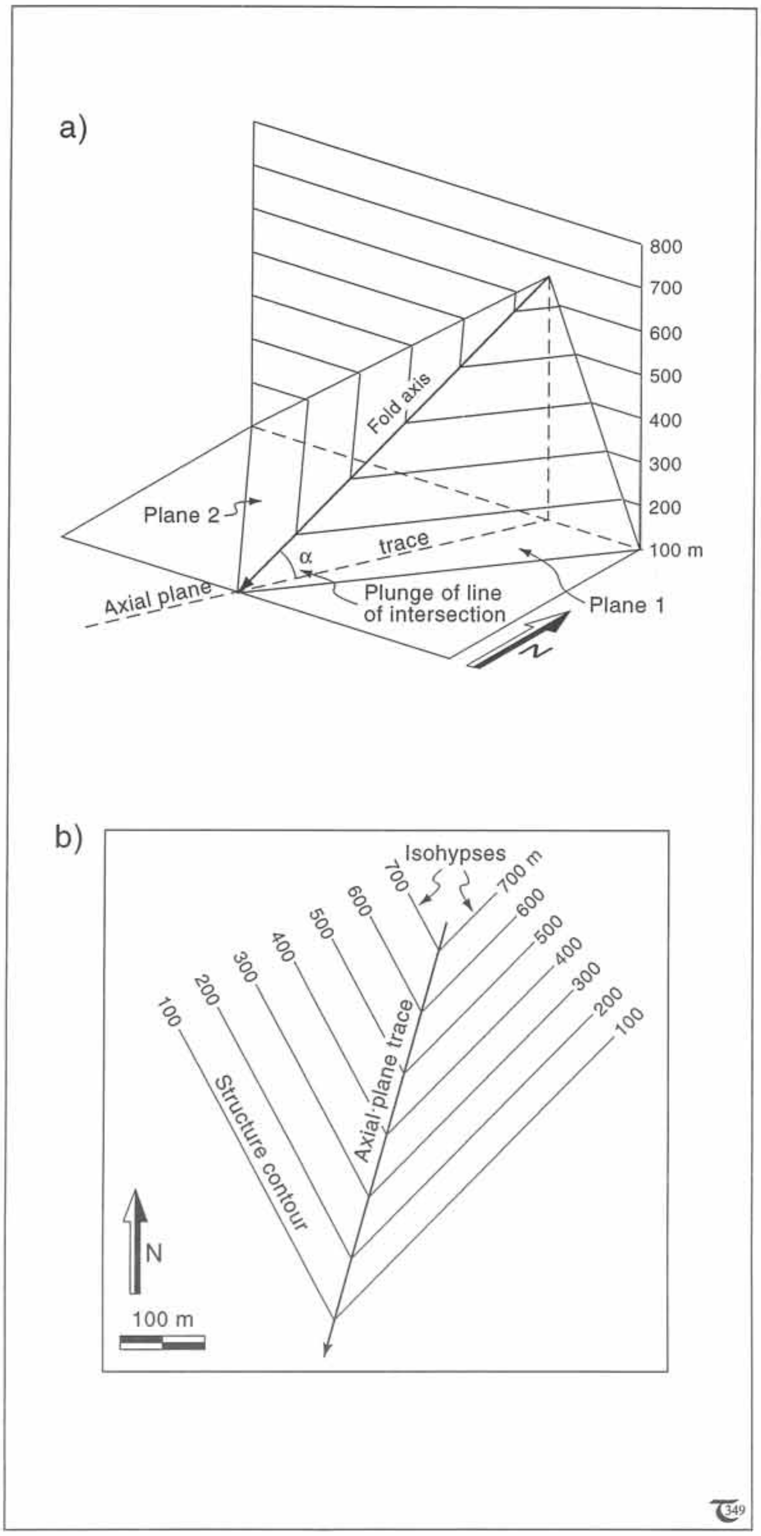


Figure 8-7: a) Perspective view of structure contours on south-plunging chevron fold. b) Map projection of structure contours for plunging chevron fold shows typical herring-bone pattern.

8-4 Plunging chevron folds

Figure 8-7a shows a plunging chevron fold with a hinge zone so narrow that it can be approximated by the intersection of two planes representing the fold limbs. The structure contours on the limbs are not parallel, but oblique, to the plunging fold axis. Figure 8-7b is a structure-contour map or projection of the structure contours of the 3-D fold perspective of Figure 8-7a. *The structure contours of plunging folds typically map as herring-bone patterns.* The trace of the axial plane coincides with the projection of the hinge line of the folds, provided the axial plane is upright or vertical. The plunge of this hinge line can then be inferred from the spacing of the contours along the trace of the axial plane.

☐Exercise 8-5: Determine the trend/plunge for the hinge line of the fold in the structure-contour map of Figure 8-7b.

☐Exercise 8-6: Refer to the structure-contour maps of Figures 8-8a & b. a) Draw the trace of the axial planes on both maps, and indicate the direction of plunge of the hinge lines of the folds in each of them. b) Give the plunge and trend for both hinge lines. c) Draw cross-sections, keeping horizontal and vertical scales equal, for both maps perpendicular to the axial planes as outlined.

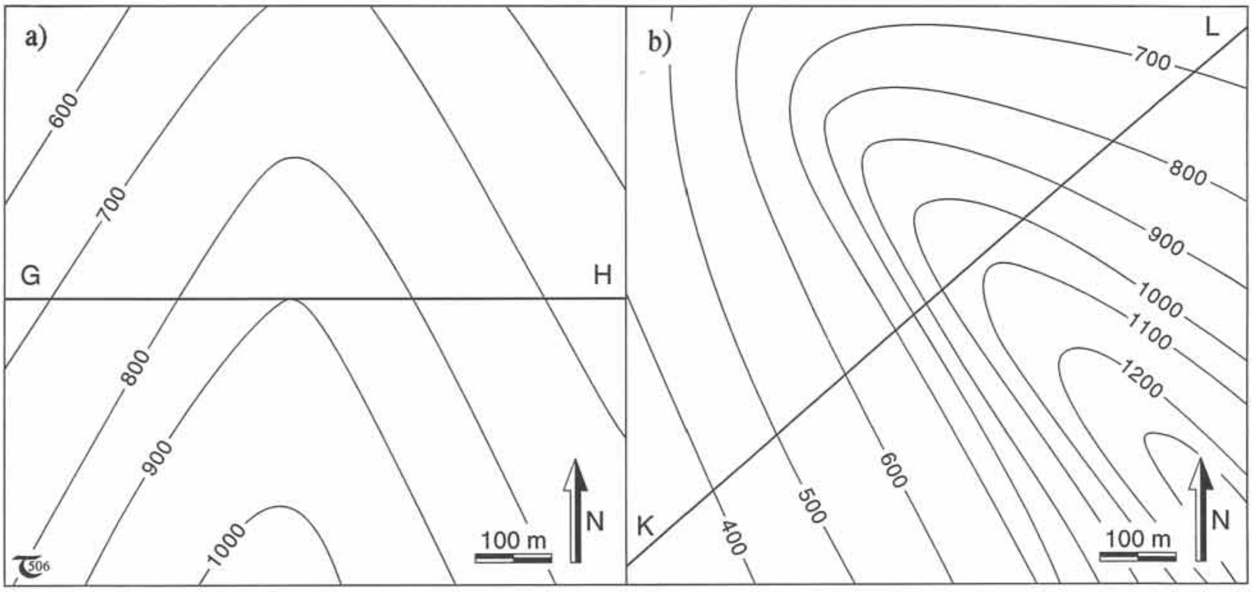
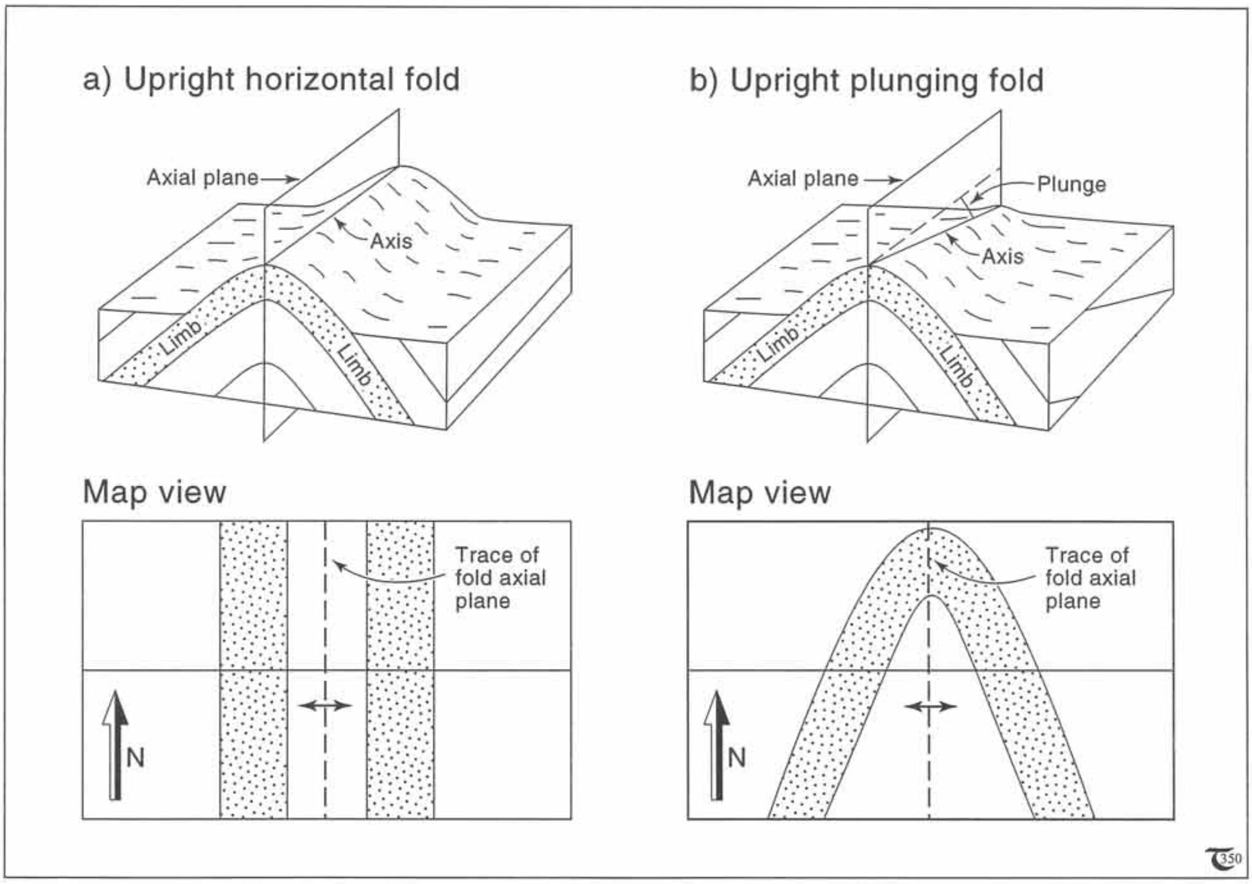


Figure 8-8: *a) & b) Structure-contour maps. Map (a) is contoured in meters below sea-level. Contours in map (b) are in meters above sea-level. See exercise 8-6.*


a) Upright horizontal fold

b) Upright plunging fold

Figure 8-9: *a) & b) Perspective diagrams and typical map views for: (a) upright, horizontal folds, and (b) upright, plunging folds. The map views show horizontal slices through these structures after erosion.*

8-5 Single-layer folds and topography effects

The presence of significant topographic relief may greatly affect the appearance of rock outcrop patterns on geological maps. Rather complex map patterns have been illustrated earlier for horizontal beds (chapter two) and for uniformly dipping strata (chapters five and six). Similarly, the outcrop pattern of folded strata may, also, be significantly affected by the incision of the erosion surface. The map patterns of folded strata in terrains of negligible topographic relief have been discussed in detail in chapter eight. The main features of upright horizontal and upright, plunging folds are illustrated in Figures 8-9a and b.

The sharp distinction between the outcrop patterns for horizontal and plunging folds may disappear in terrains of high topographic relief. For example, upright horizontal folds, typically mapping as subparallel beds in terrains of low relief (Fig. 8-10a), may form sharp fold closures in terrains of high relief (Fig. 8-10c). Consequently, upright, horizontal folds cannot so easily be distinguished from upright plunging folds, as their fold closures appear similar on the map (Fig. 8-10c & d). However, structure contours provide a simple means to distinguish these two major fold types. This is because the characteristic herring-bone pattern of structure contours appears only for plunging folds. Horizontal folds always have subparallel structure contours irrespective of whether or not there is any topographic relief (compare Figs. 8-10b and d).

☐Exercise 8-7: The map of Figure 8-11 shows the outcrop pattern of a coal seam. a) Use structure contours to establish the structure of the coal seam. b) Complete the map pattern where necessary. c) How deep is the coal layer at P? d) Color red all rocks above the coal bed.

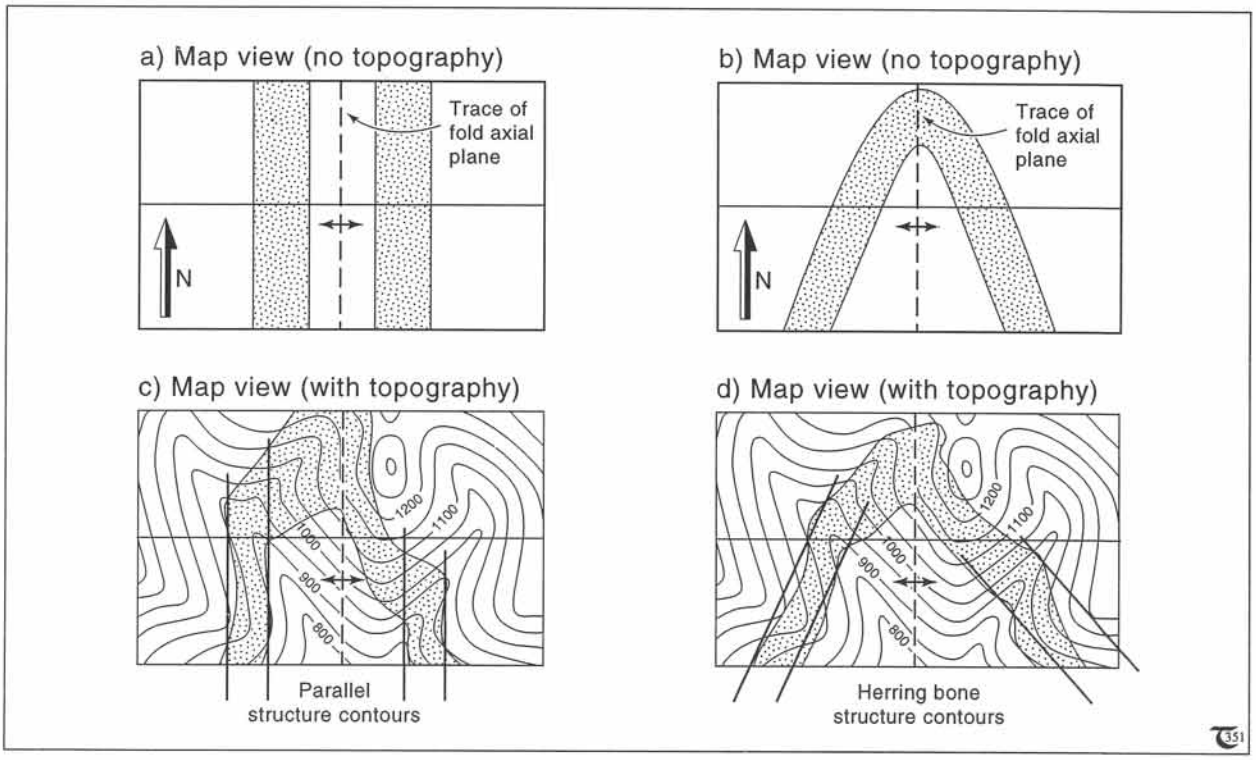


Figure 8-10: a) & b) Map views of upright, horizontal and upright, plunging folds in flat terrains. c) & d) Map views of upright, horizontal and upright, plunging folds in terrain of high topographic relief.

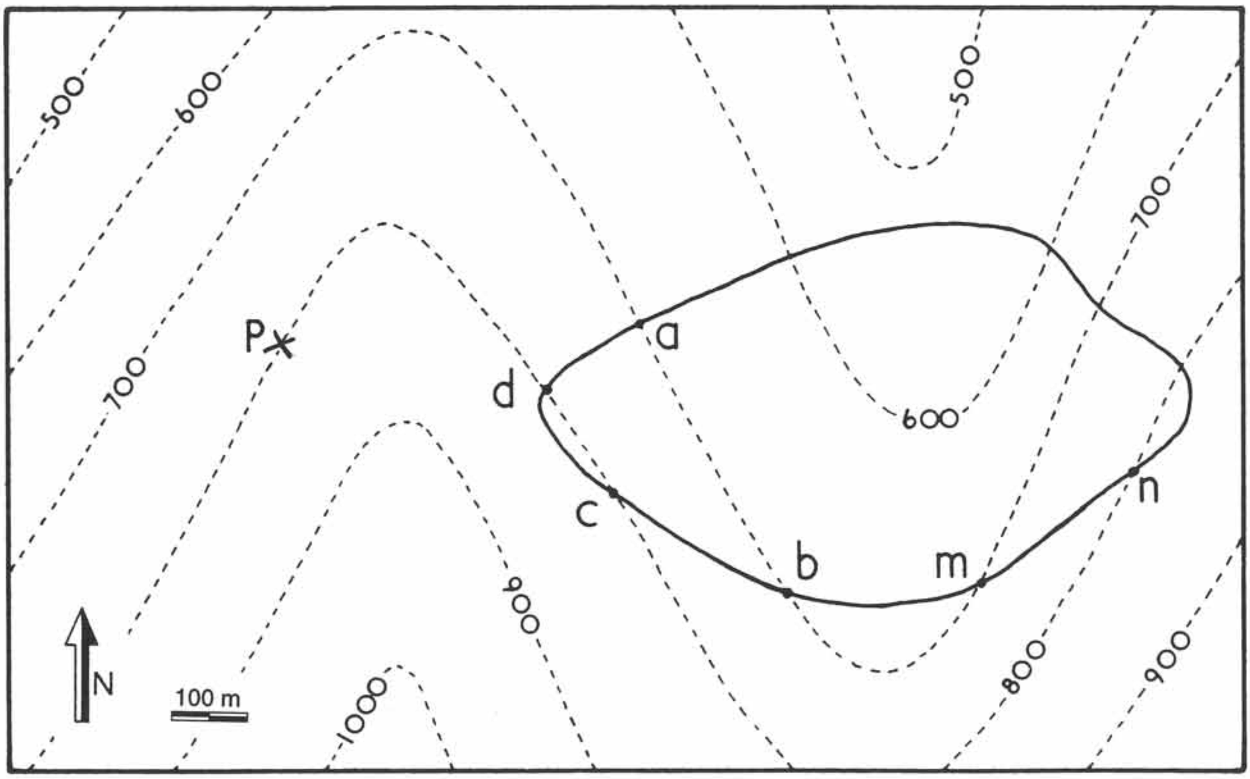


Figure 8-11: Outcrop pattern of coal seam on topographic base map. See exercise 8-7.

☐Exercise 8-8: The marker beds of the maps in Figures 8-12a and b have different orientations. Describe both the *orientation(s)* (azimuth/dip) and *shape* (homoclinal, folded, etc.) of the marker bed for each of the maps.

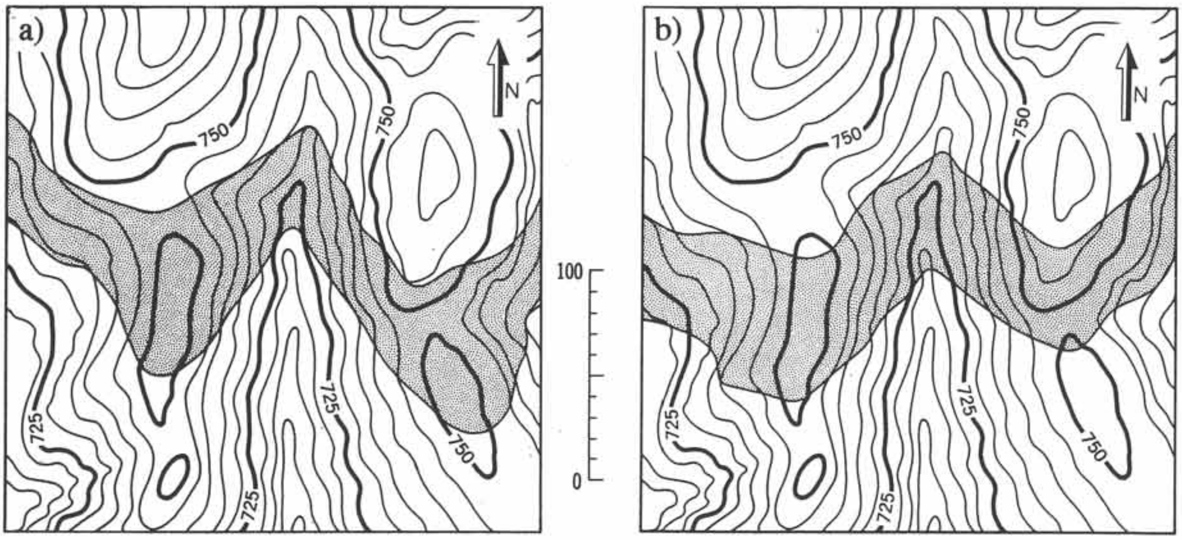


Figure 8-12: a) & b) Outcrop pattern of sandstone formation in two different areas of identical topography. Contours are in meters.

☐ **Exercise 8-9: The sandstone formation in the map of Figure 8-13 cannot be horizontal. a) Draw strike lines or structure contours for each surface. b) Determine the plunge and trend of the fold hinge. c) Is this a plunging antiform or synform?**

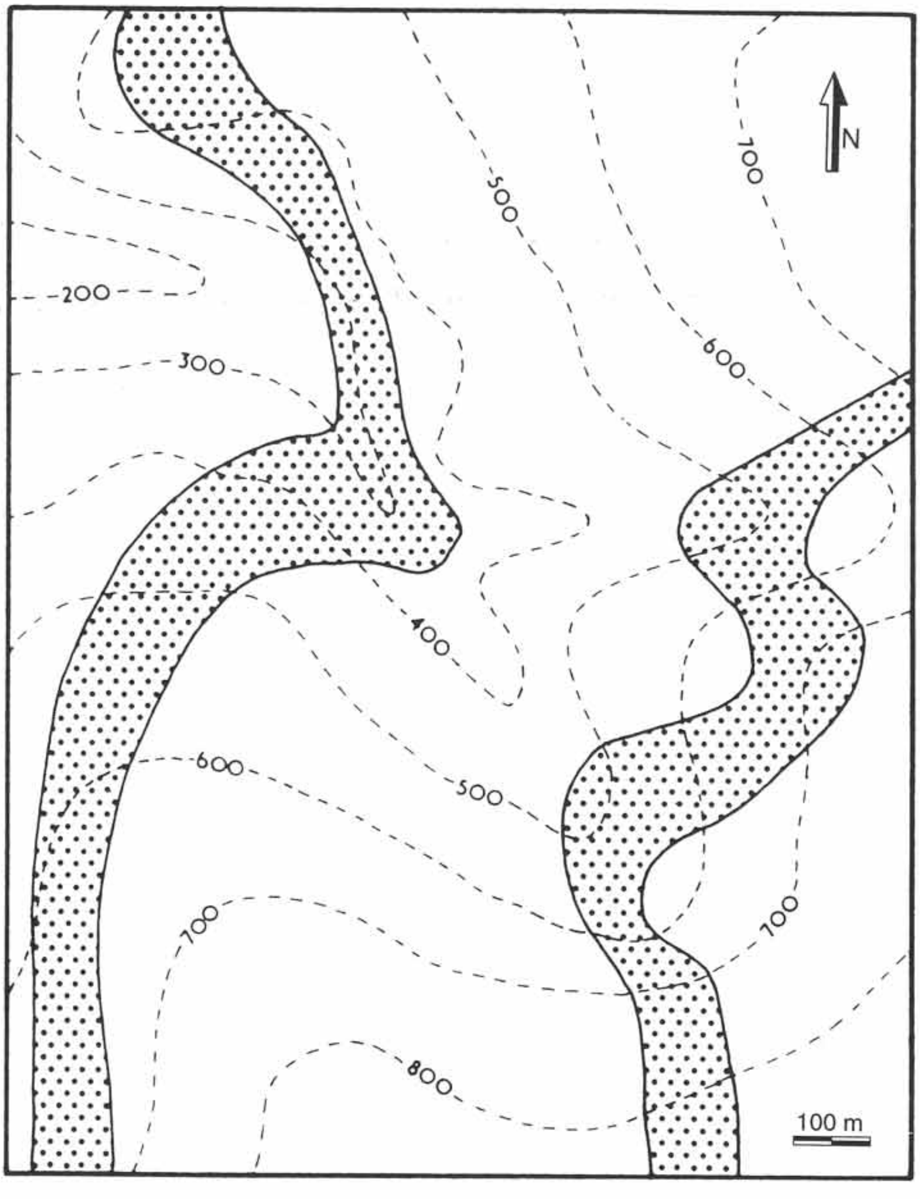


Figure 8-13: Outcrop pattern of sandstone formation on topographic base map. See exercise 8-9. Contours are in meters.

8-6 Multiple-layer folds and topography effects

The outcrop pattern of folded sequences display the interplay of the topography with geological boundaries. Figure 8-14a is a map of upright, horizontal folds. The outcrop pattern resembles mirror-image symmetry about an imaginary east-west axis across the center of the map. The map pattern is best understood by concentrating on the structure contours for one lithological boundary (Fig. 8-14a). The structure contours (for the bottom of the sandstone: *aa', bb', cc', dd', ee'*) fix the strike and dip of the fold limbs. The strata in this area are folded about horizontal fold axes with vertical axial surfaces, because all the structure contours remain subparallel and evenly spaced. However, the symmetry of the map pattern exists only because the surface topography is nearly symmetric about the east-west axis. The landscape portrayed in the map is comprised of a single east-west trending valley so that the map shows the projection of the geological structure in the north and south walls of the central valley. The east-west section across the map illustrates the structure of the upright, horizontal folds transected by the valley (Fig. 8-14b).

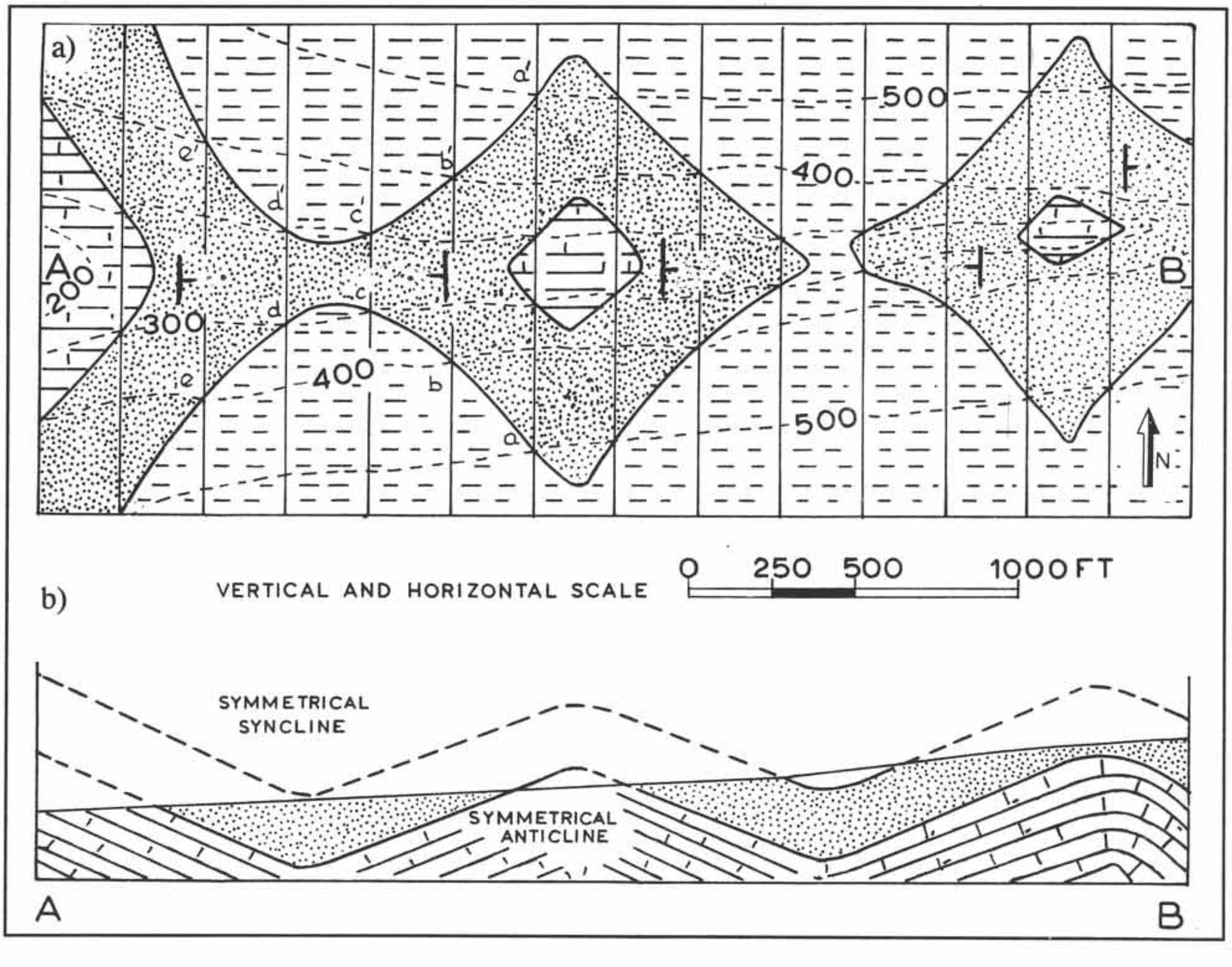


Figure 8-14: *a) Map pattern of upright, horizontal folds in sedimentary sequence, transected by a westward draining stream valley. b) East-west section across the map, as indicated.*

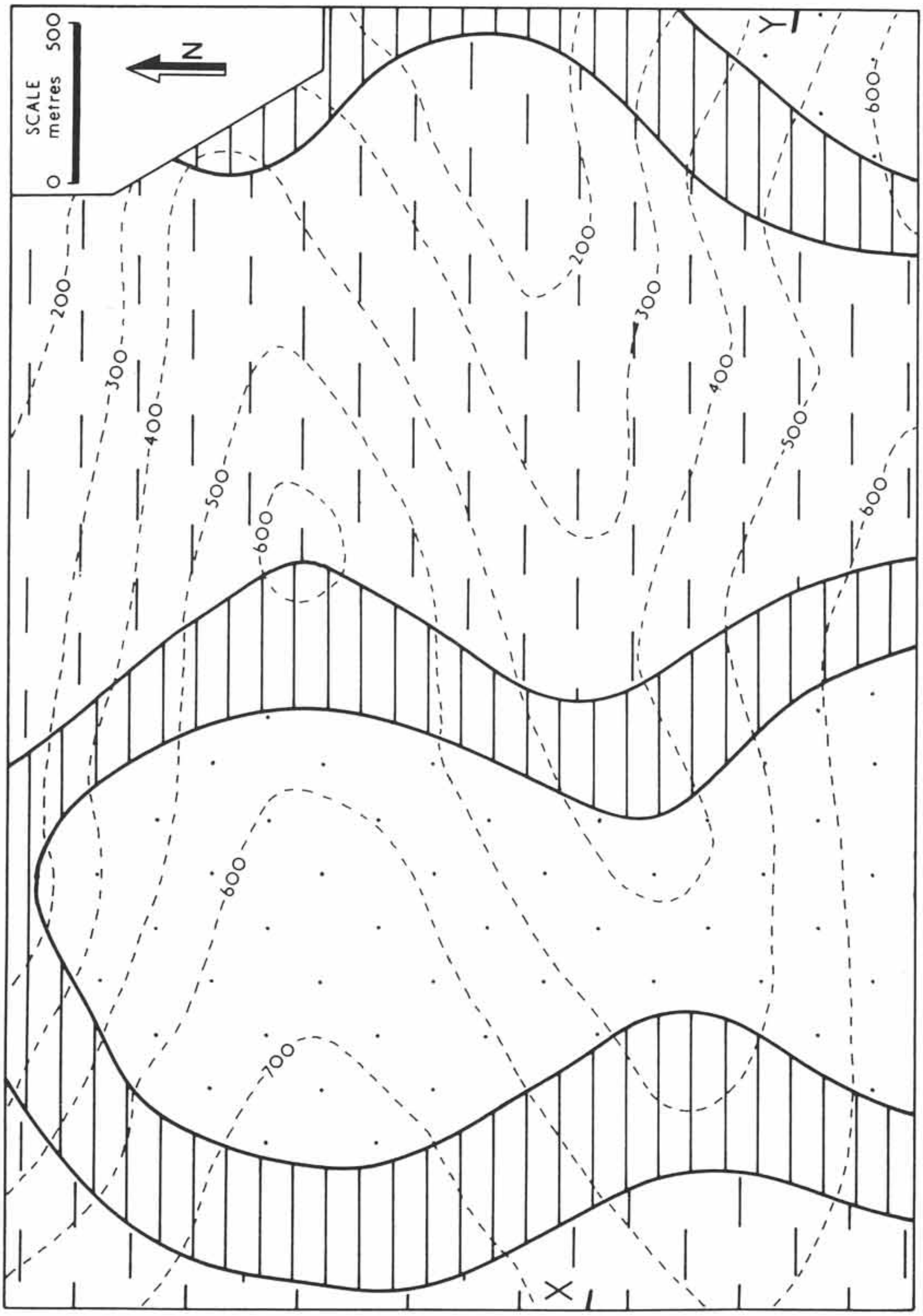


Figure 8-15: Complete geological outcrop pattern on topographic base map. See exercise 8-10.

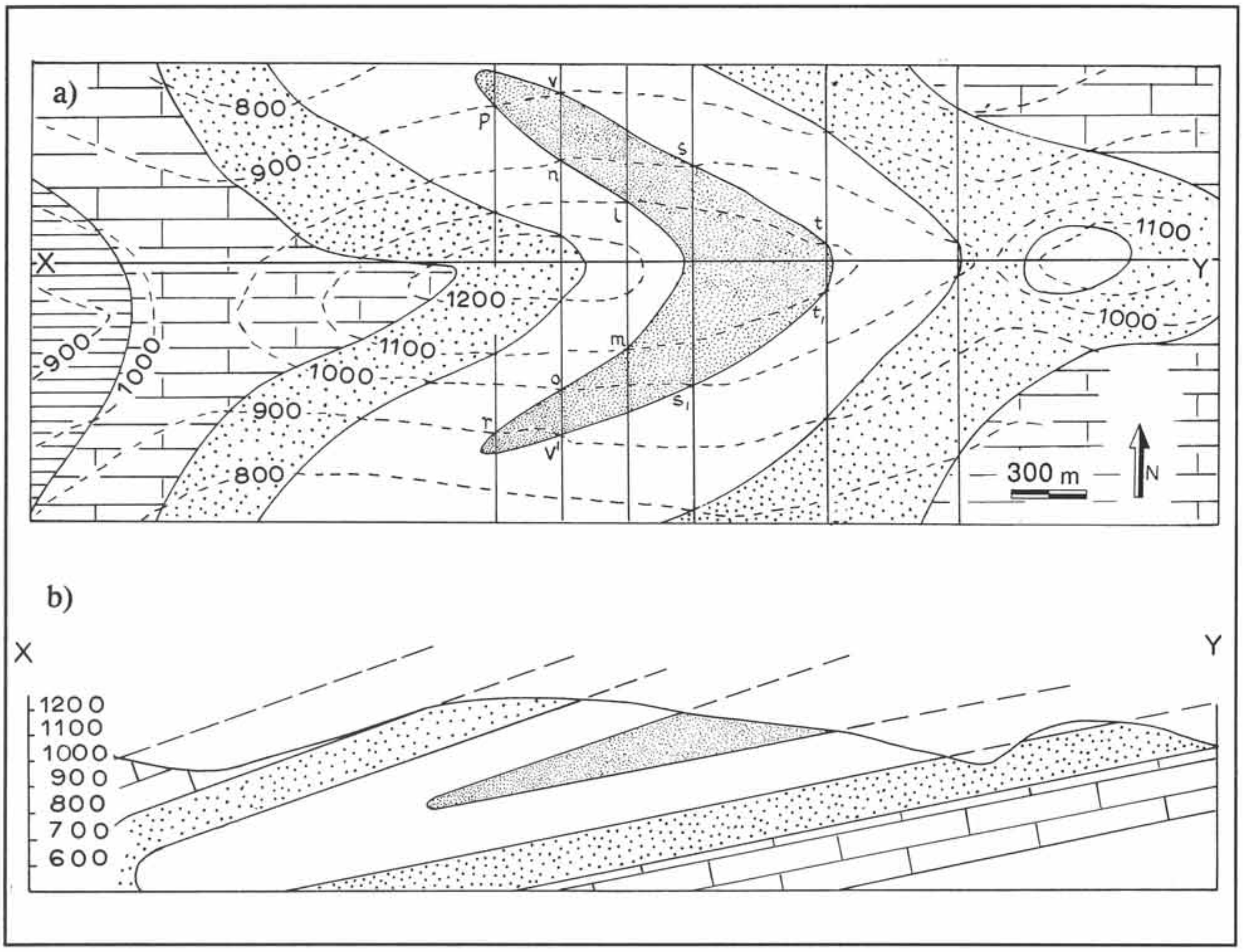


Figure 8-16: a) Map of overturned, horizontal folds in sedimentary sequence, preserved in an E-W trending mountain range. b) E-W section across the mountain range of the map, along section line X-Y.

☐Exercise 8-10: Refer to the map in Figure 8-15. a) Draw structure contours for the upper and lower surface of the horizontally ruled bed of shale (use different colors for top and bottom contours. b) Is the direction of strike of the layers approximately N-S or E-W? c) Indicate the trace of axial planes, and mark them as synforms or antiforms. d) Are the folds upright horizontal or plunging? e) Indicate strike/dip symbols on the map to illustrate the structure. f) Draw a section along line X-Y.

The outcrop pattern of Figure 8-16a arises from rock strata folded about horizontal axes, such that the fold limbs are overturned and all layers dip westward. The detailed structure follows quickly from structure contours (east limb: *tt'*, *ss'*, and *vv'*; west limb: *lm*, *no*, and *pt*) constructed on the surface of the boomerang-shaped outlier in the center of the map. The hinge line of the fold trends north-south. The topography of the area is an east-west trending ridge, so that the profile of the fold structure appears both on the north and south slopes of the ridge. Compare this fold profile with that seen in the accurate east-west cross-section of Figure 8-16b.

☐Exercise 8-11: Refer to the map in Figure 8-17. a) Draw enough structure contours to deduce the strikes and dips of all the beds in the map area. b) Indicate the trace of the axial plane(s), and mark them as synforms or antiforms. c) Is bed H an inlier or outlier? d) Are the hinge lines of the folds horizontal or plunging? e) Are the axial planes of the folds upright or inclined? f) Draw a section along line X-Y.

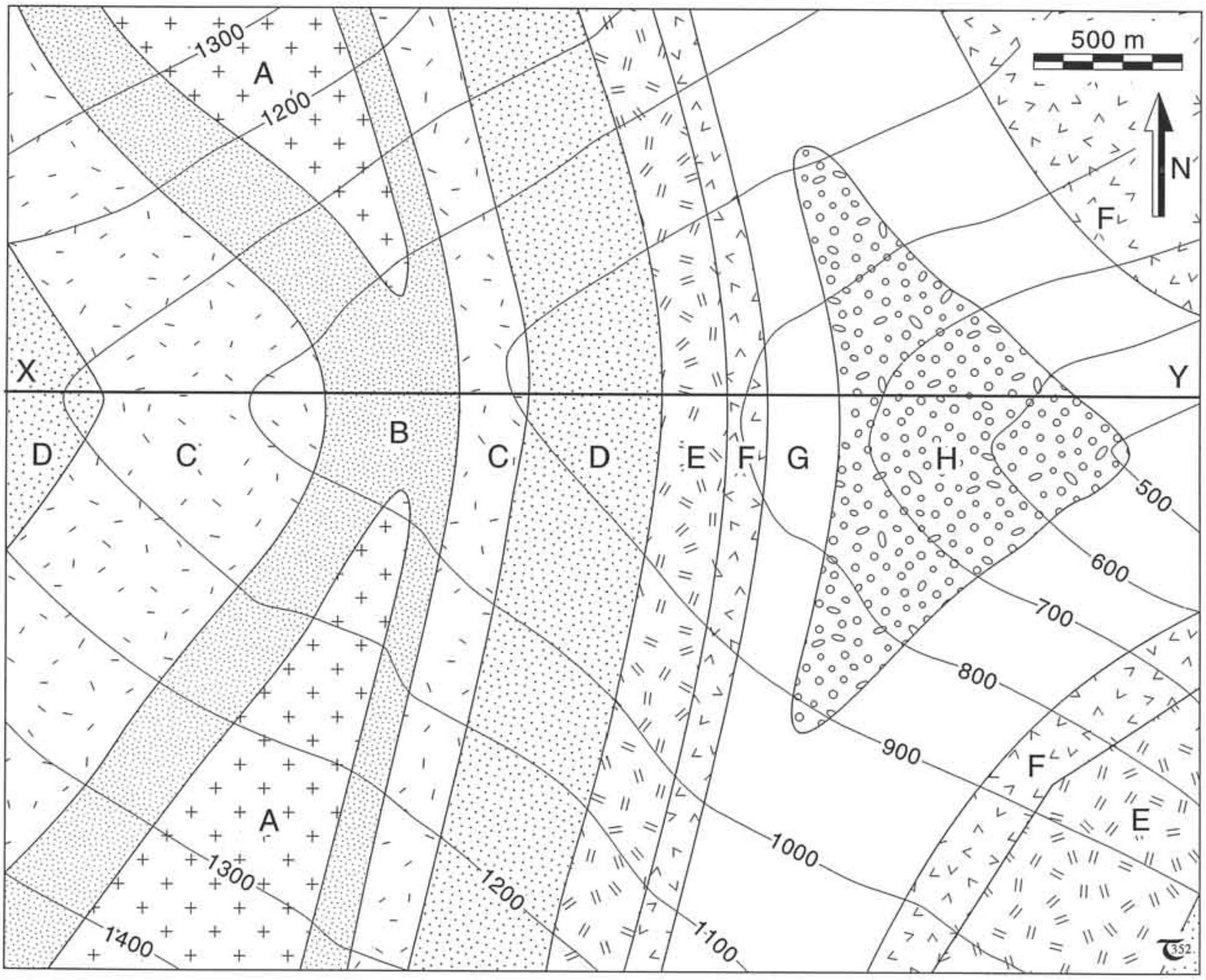


Figure 8-17: Geological outcrop pattern on topographic base map. See exercise 8-11.

Chapter 9: Unconformities and Isopach Maps

It is commonly assumed that the individual strata of sedimentary sequences are laterally continuous and of constant thickness. Unless field observations show otherwise, the boundaries of individual layers are traced as subparallel or conformable curves in the landscape. However, changes in the lateral continuity of rock units may result in non-parallel or unconformable outcrop patterns on geological maps. Therefore, the early recognition of the presence of unconformities in the terrain is important, and the subsequent interpretation needs to be professionally sound.

Contents: The three basic types of unconformities - all treated in separate sections - are disconformities (section 9-2), angular unconformities (sections 9-3 and 9-4), and nonconformities (section 9-5). Isopach and isochore maps are introduced in section 9-6.

9-1 Unconformities

Many sedimentary strata on geological maps represent a continuous sequence. Younger rocks are the product and record of younger geological events and were gradually deposited on top of the older strata. But, sometimes, younger rocks are separated from older ones by an erosion surface or non-deposition surface. Such boundaries are termed unconformities, and they may indicate that a significant portion of the stratigraphic record is missing. For example, in the Grand Canyon, USA, the Temple Butte Limestone of Devonian age rests directly on top of the Muow Limestone of Cambrian age. Between these two formations, no deposits of Ordovician and Silurian age are preserved. It can be concluded that the unconformity surface between them represents a time-gap of one hundred million years. The nondeposition period causes a discontinuity of, or *hiatus* in, the stratigraphic record. The contact between the Temple Butte Limestone and the Muov Limestone is an example of a *disconformity*. Two other types of unconformities distinguished are *angular unconformities* and *nonconformities*, as discussed in sections 9-3 through 9-5.

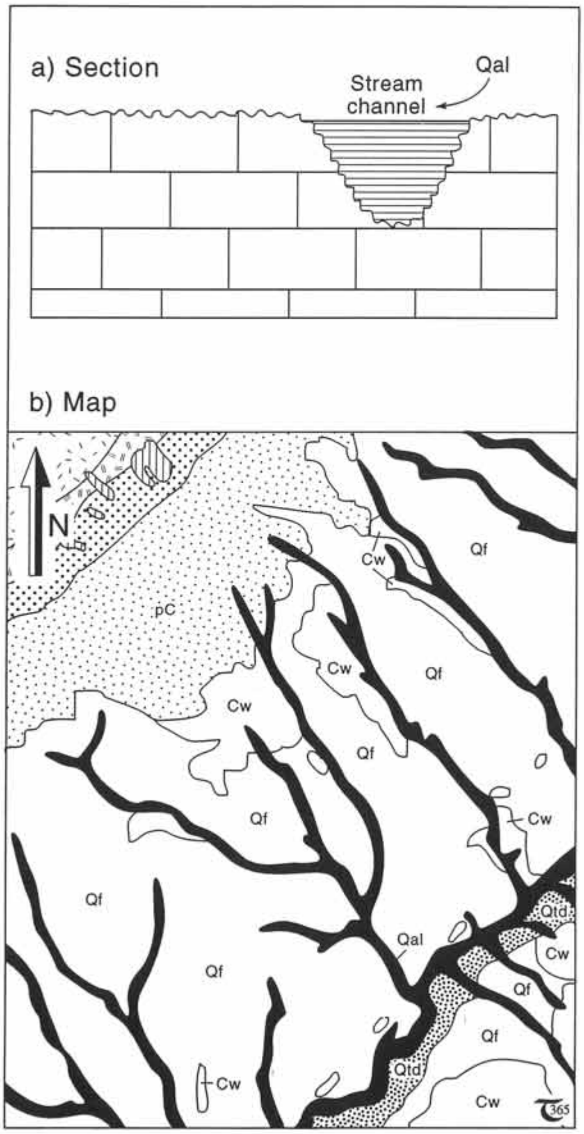


***Figure 9-1:** a) & b) Disconformities of horizontal sedimentary beds due to channel erosion. a) Section of stream channel filled with sediment. b) Map view of stream channel deposits (Qal).*

9-2 Disconformities

Disconformities are the type of unconformity where essentially parallel sets of sedimentary layers are separated by an internal unconformity surface. For example, stream channels, filled with sediment and carved into an older floor of horizontal sedimentary rocks, are deposited disconformably over underlying rock units (Fig. 9-1a). The map pattern typically displays a dendritic outcrop pattern for disconformable stream channel or alluvial deposits (Fig. 9-1b). Another type of disconformity occurs where a particular horizontal layer is found to thin laterally and disappear, due to erosion in part of the region before the overlying deposits could accumulate (Fig. 9-2a). However, such discontinuous layers may be difficult to distinguish from lateral facies changes, which could, also, lead to lateral differences in the stratigraphic sequence. The map pattern of sharp lateral facies changes and some disconformable layers are quite similar (Fig. 9-2b). Field observations can establish whether the disconformable layer has vanished due to lateral facies changes or due to erosion. Unlike the erosional disconformity, facies changes are not necessarily connected to a time-gap in the sedimentation record.

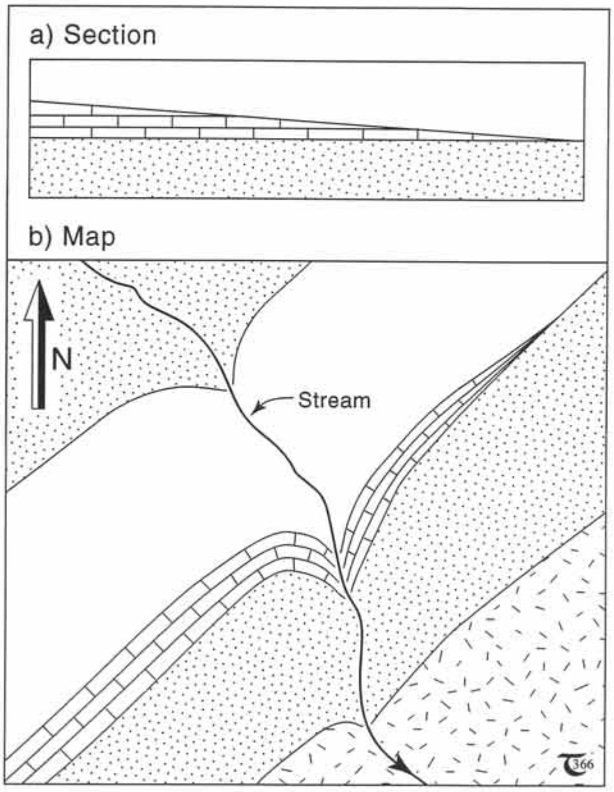


***Figure 9-2:** a) & b) Disconformity due to local hiatus, commonly involving erosion. a) Cross-section of limestone bed, shown to thin laterally and disappear. b) Map view, after later tilting.*

☐Exercise 9-1: Examine the map of Figure 9-3, and identify one unambiguous disconformity and two more possible disconformities.

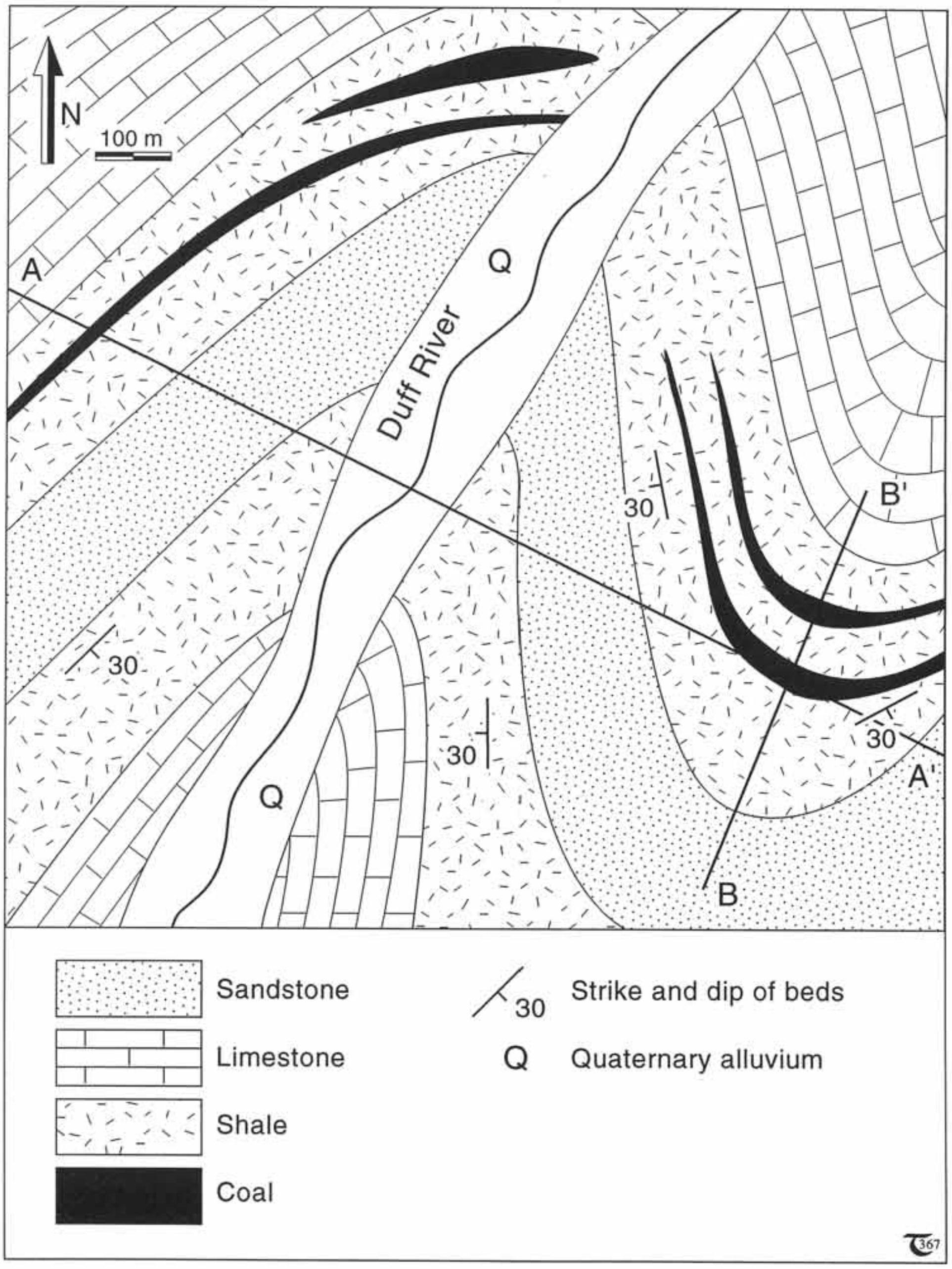


Figure 9-3: Map for exercise 9-1. The legend represents a lithological key only and is not in stratigraphic order.

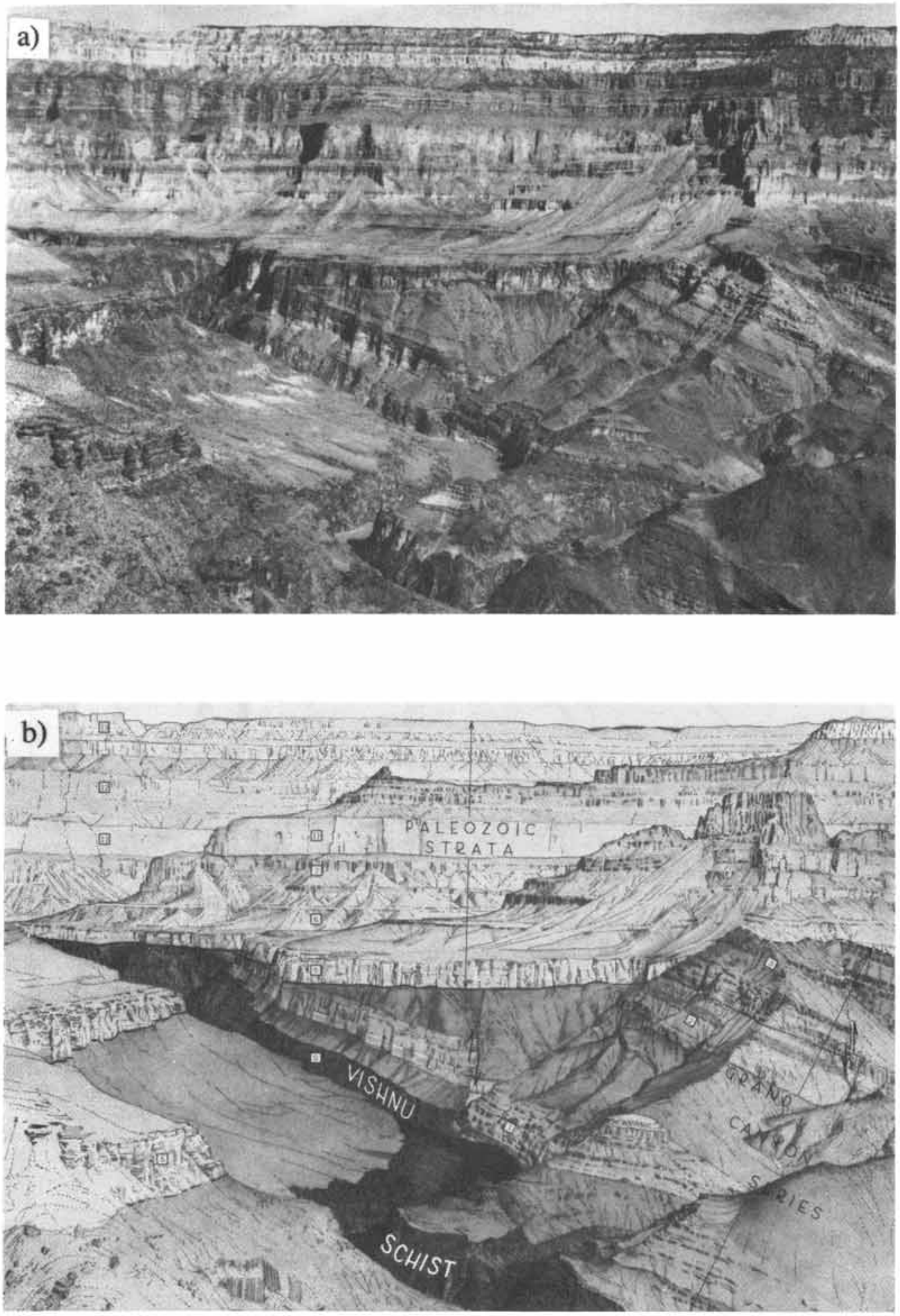


Figure 9-4: *a) & b) Angular unconformity between the Precambrian Grand Canyon Series and the Paleozoic cover. a) Photograph. b) Geological panoramic sketch, viewed toward the northwest near Shinumo Creek.*

9-3 Angular unconformities of tilted layers

Angular unconformities are breaks in the stratigraphic record, which separate younger sedimentary rocks from underlying, tilted sedimentary or low-grade metamorphic lithologies. A classical angular unconformity occurs between the Precambrian Grand Canyon Series and the base of the overlying Paleozoic sequence (Fig. 9-4a & b). This angular unconformity represents an erosional surface, that leveled the tilted Grand Canyon Series before deposition of the Paleozoic rock units.

Figure 9-5a shows a typical map pattern from the British coal measures. The gently inclined Paleozoic mudstones with inter-bedded coal seams are separated - by an angular unconformity - from the subhorizontal Mesozoic limestone. The boundaries of the tilted Paleozoic layers are truncated on the map where covered by the limestone. The occurrence of such angular unconformities represents a time-gap in the stratigraphic record.

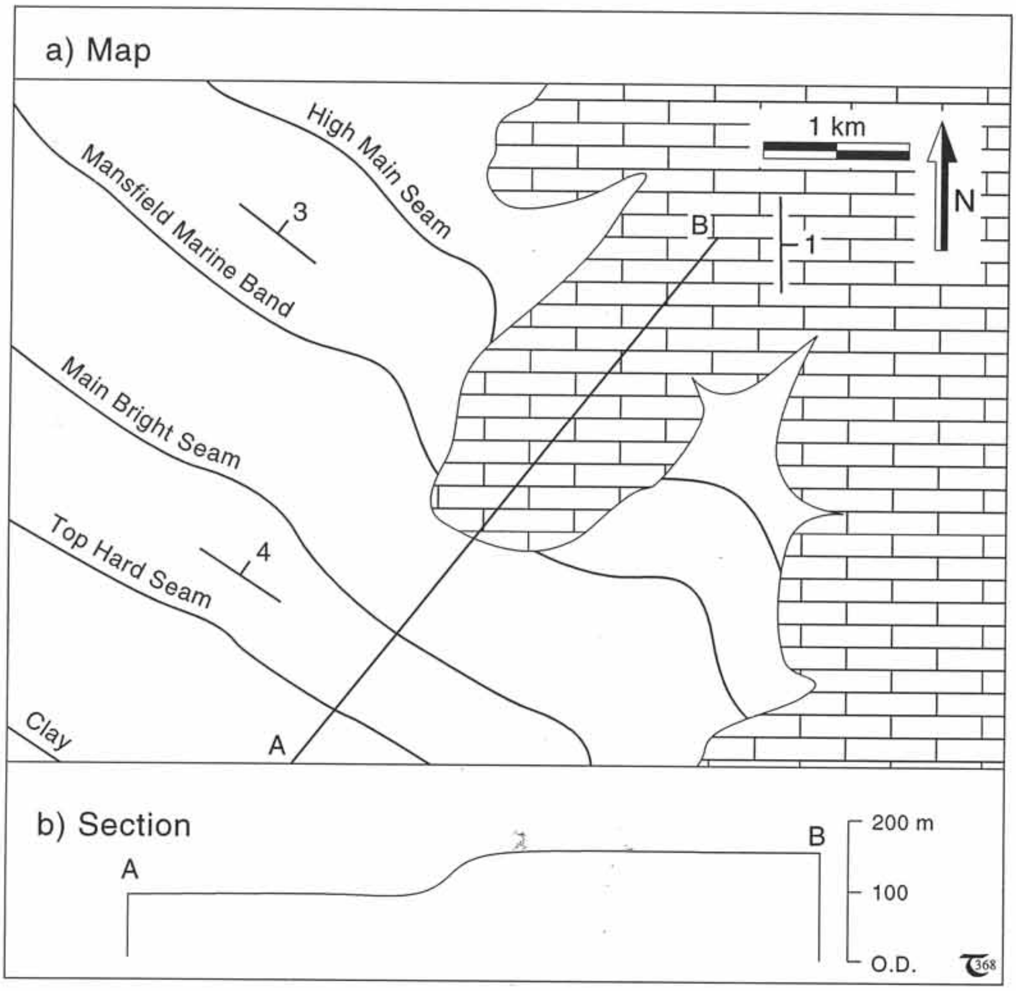


Figure 9-5: *a) Map of terrain in the British coal measures. b) Incomplete section. See exercise 9-2.*

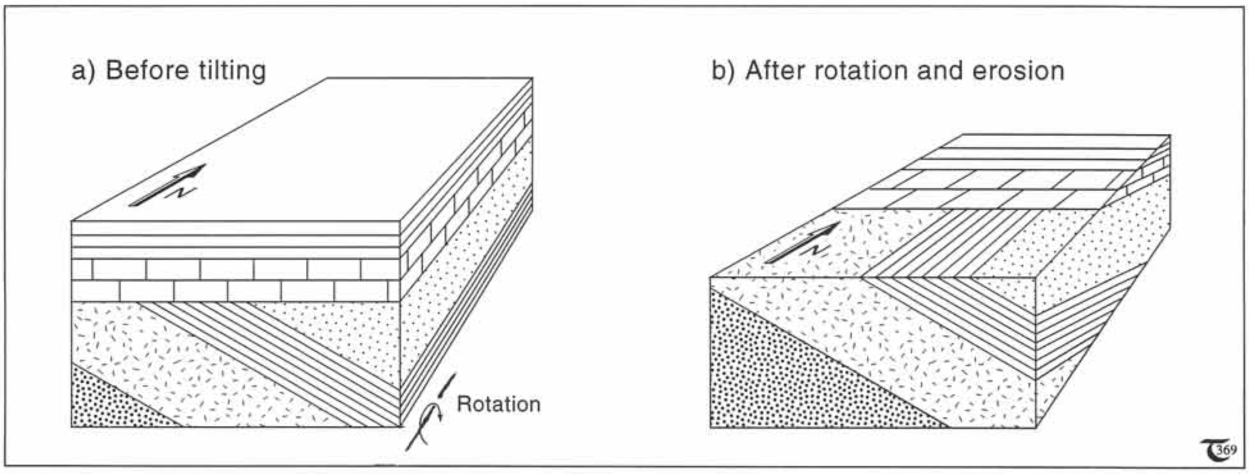


Figure 9-6: *a) & b) The cover rocks above an angular unconformity may be tilted themselves. a) Cover sequence before tilting. b) Final appearance after block rotation and subsequent erosion of the cover rocks.*

The rocks overlying an angular unconformity are originally deposited horizontally but may later be tilted. Consequently, they can display a direction of dip which is different from that of the rocks beneath the unconformity (Figs. 9-6a & b). The limestone bed in Figure 9-6b strikes differently from the beds below the unconformity. Consequently, the limestone rests on beds of different ages, and can be said to *overstep* these older beds. The strata which are overstepped are older and were tilted and eroded before deposition of the younger strata.

Figure 9-7 illustrates an angular unconformity where the younger layers are laid down during a progressive transgression of the land surface. The sedimentary rocks above the unconformity are said to *onlap* or *overlap* the older sequence. Stratigraphic overlaps are commonly accompanied by *oversteps*. In other episodes of geological history, the sea may have regressed rather than transgressed the land surface. The regression may be only local, due to gradual tectonic uplift of the area. But global regressions have, also, occurred in the geological past due to global sea-level drops. Whatever the underlying cause, such events commonly lead to *offlapping*, rather than *onlapping*, of layers.

The map of Figure 9-8a shows a geological map of a doubly-tilted region, with Cambro-Ordovician shales tilted towards the east and Silurian shales tilted towards the northeast. The outcrop pattern of the older shales is abruptly truncated by the subparallel bands of the gently inclined younger series. An other example of *double tilting* is shown in Figure 9-9.

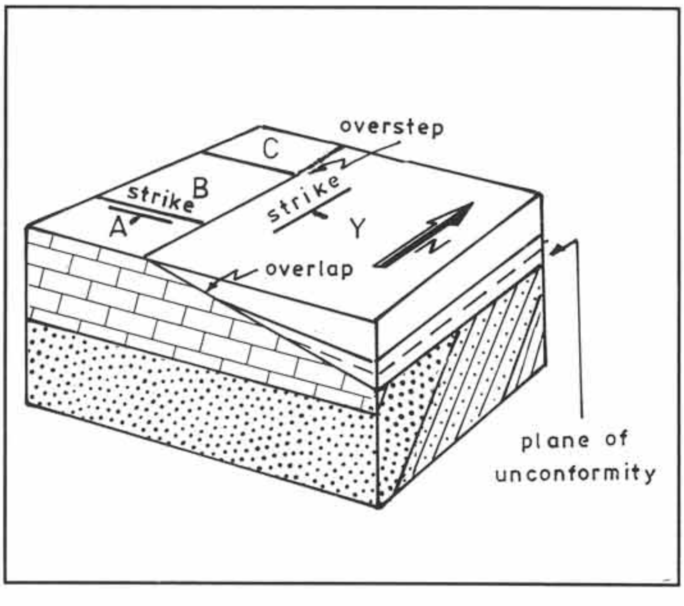


Figure 9-7: *Angular unconformity with overstepping and overlapping cover sequence.*

☐Exercise 9-2: Complete the cross-sections of Figure 9-5b and 9-8b. Include legends, geographical orientations, and symbols, so as to give the sections a professional appearance. For the section of Figure 9-8b, pay particular attention to the position of the basement sandstone in the cross-section.

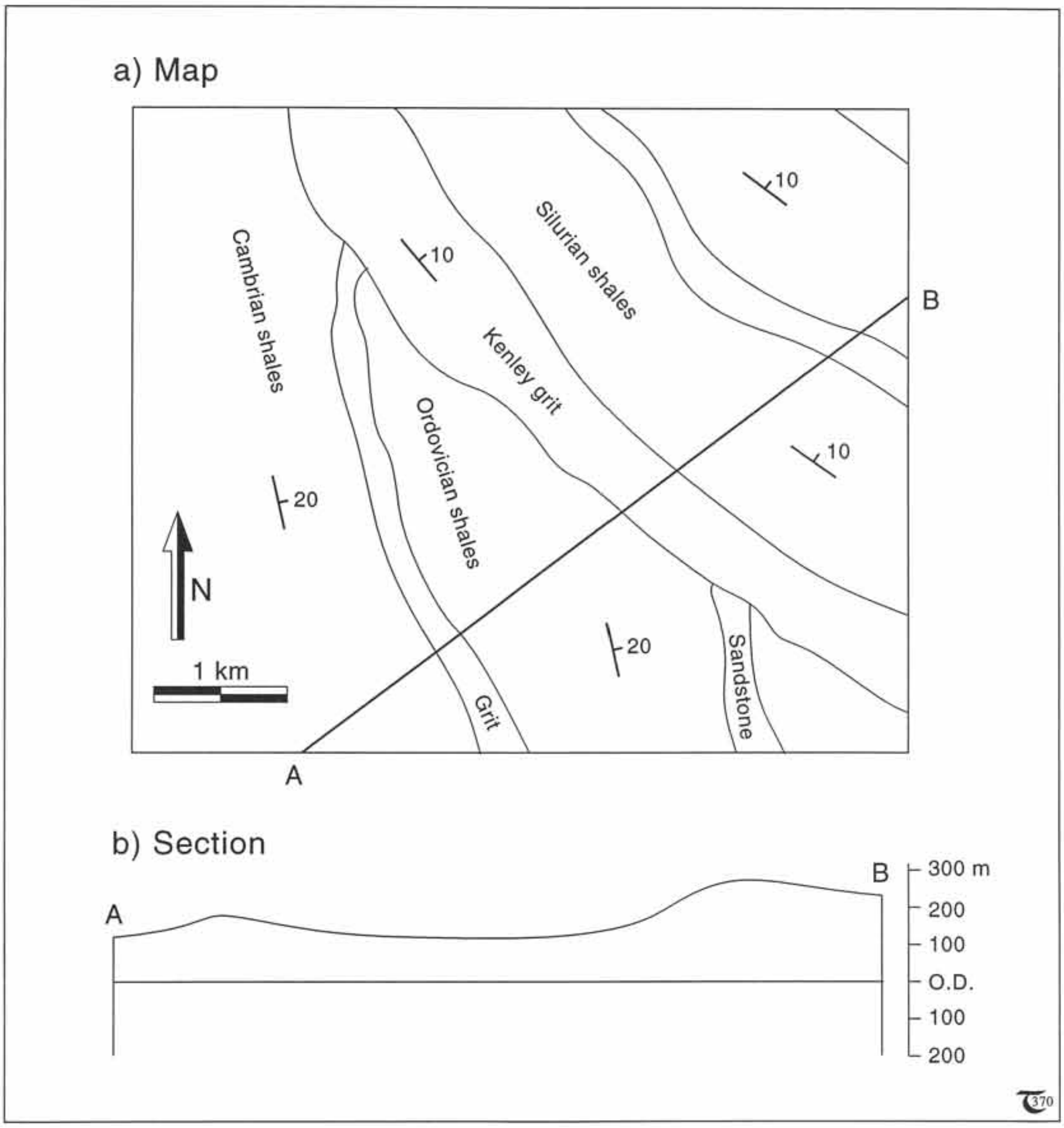


Figure 9-8: a) Map of angular unconformity between Cambro-Ordovician shales overlain by Silurian shales. b) Incomplete cross-section. See exercise 9-2. (O.D. is the British Ordnance Datum of mean sea-level.)

☐Exercise 9-3: Study the map pattern of Figure 9-9, and mark in red the angular unconformities of the Meeteetse area, Wyoming. Discuss the tilting history of the terrain.

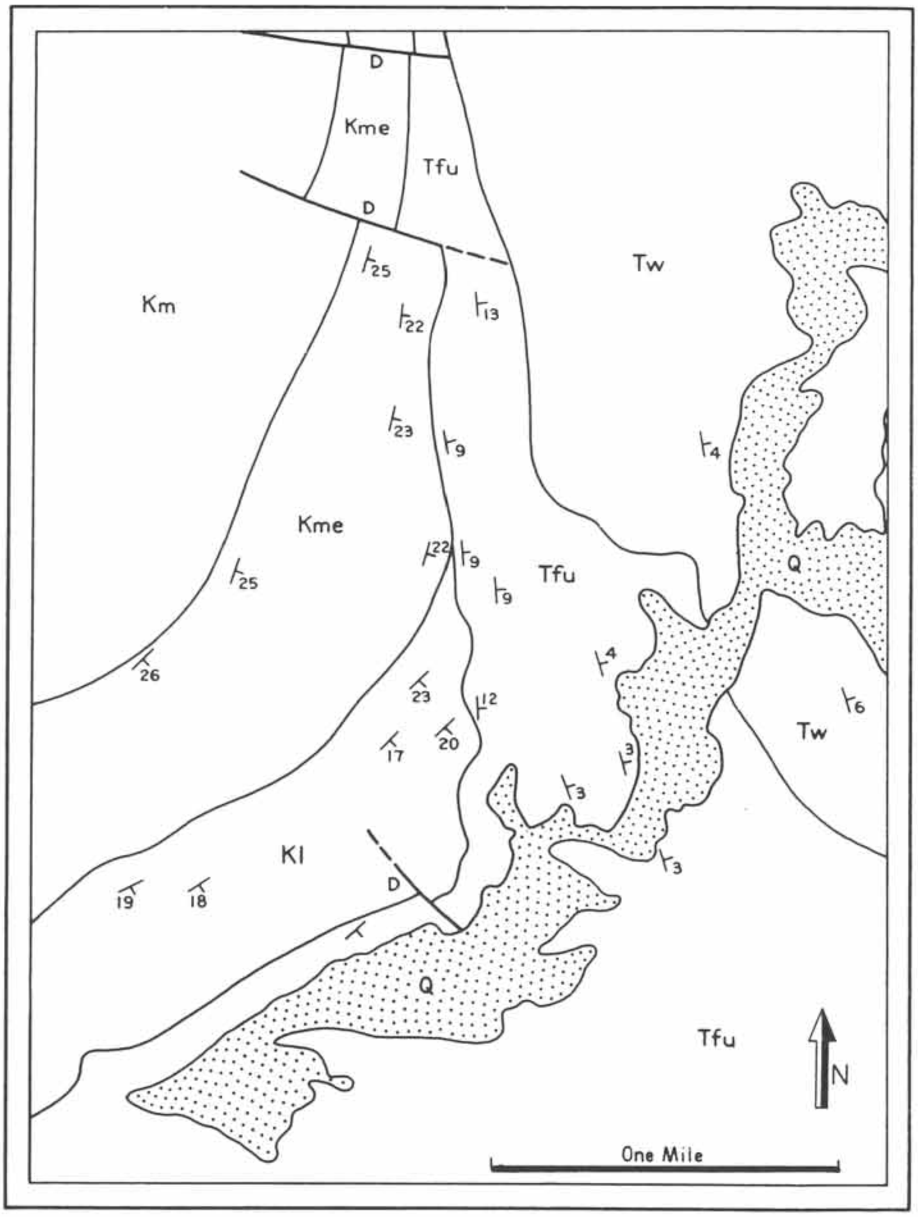


Figure 9-9: Angular unconformities, Meeteetse area, Wyoming. Legend: Km-Mesaverde Fm., Kme-Meeteetse Fm., Kl-Lance Fm., Tfu-Fort Union Fm., Tw-Wasatch Fm., Q-gravel, D-downthrown side of normal faults.

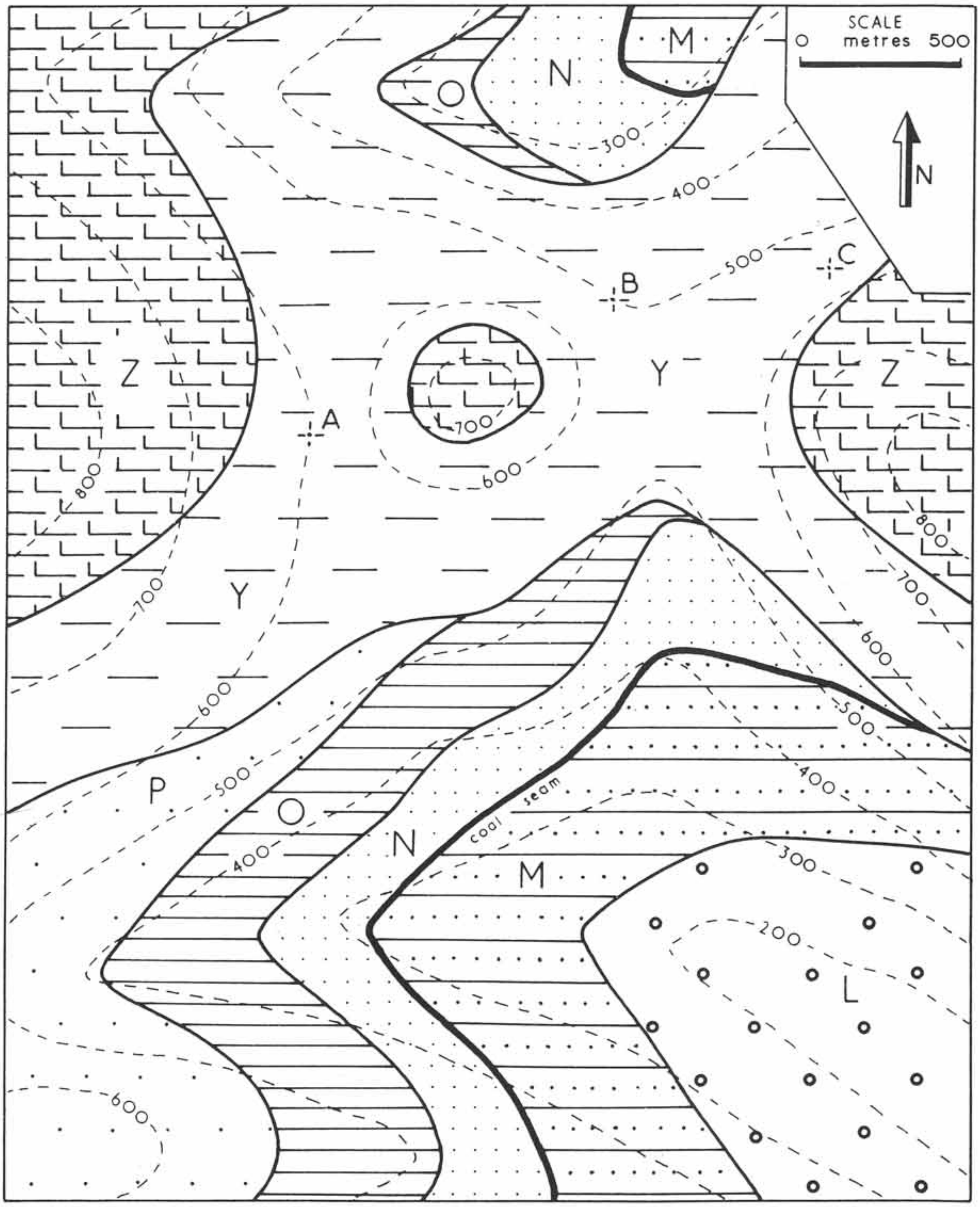


Figure 9-10: *Geological outcrop pattern on topographic base map. See exercises 9-4 and 9-5.*

☐Exercise 9-4: On the map of Figure 9-10: a) Trace in red any unconformities. Use structure contours to solve questions (b) to (d). b) Determine the orientation of the strata above the unconformity (azimuth/ dip). c) Determine the orientation of the beds below the unconformity. d) Determine the orientation of the unconformity surface. e) Establish the key for this map in the appropriate stratigraphic sequence.

9-4 Angular unconformities above folded layers

Folding of a region's rock strata leads to coeval uplift of the ground surface and, thus, invokes progressive erosion of the folded layers. Deposition of new rocks at the ground surface is inhibited as long as the folding and uplift continue. When the folding ceases, the uplifted area rapidly erodes to sea-level through erosion, weathering, and sediment transport. Any rise in global sea-level during interglacial periods or tectonic subsidence of the eroded area may lead to a new sequence of deposition. The folded base-

☐Exercise 9-5: Referring again to the map of Figure 9-10, answer the following questions: a) Would the coal seam be encountered in the boreholes located at points A and B? Calculate the depth of the coal seam below the ground surface, if present in any of the vertical drill-holes in A and B. b) If you conclude the coal seam cannot be found in any of the two holes, explain why the coal would be missing.

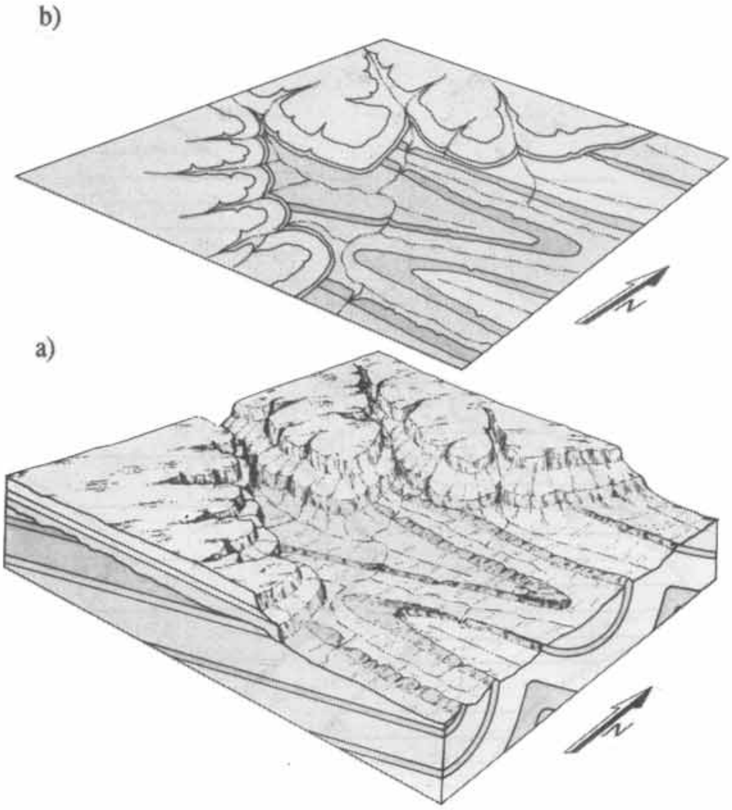


Figure 9-11: a) & b) Angular unconformity between folded basement rocks and subhorizontal cover sequence. a) Perspective diagram. b) Map view.

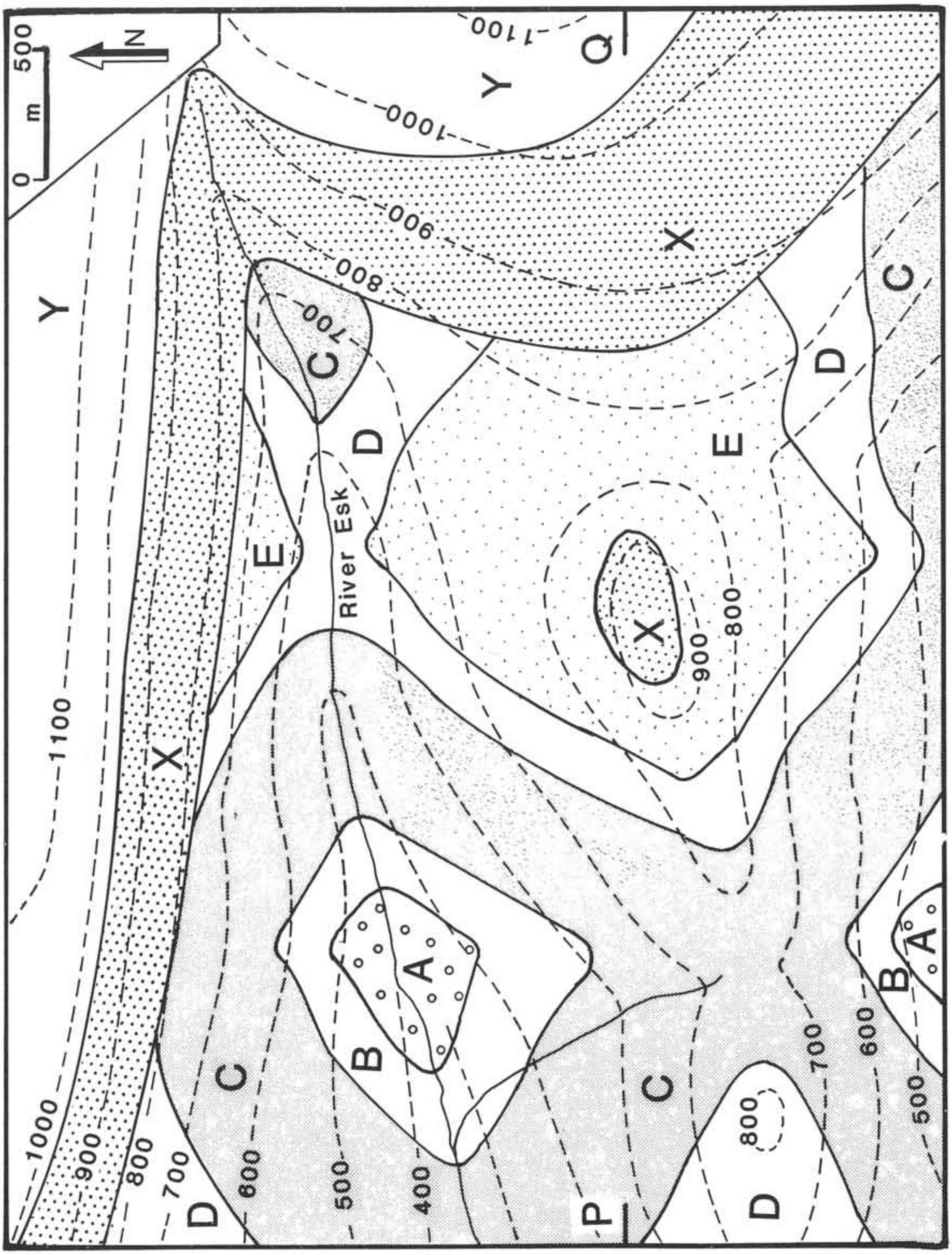


Figure 9-12: Geological outcrop pattern on topographic base map. See exercise 9-6.

ment rocks will then be separated from the subhorizontal cover sequence by an angular unconformity. Finally, the folded basement rocks and the associated unconformity can be seen reappearing at the ground surface only when renewed uplift allows erosion of the cover rocks themselves.

The block diagram of Figure 9-11a displays an exposed angular unconformity above a folded basement. The associated map of Figure 9-11b illustrates how the pattern of plunging folds is truncated by the unconformity. The folds below the unconformity may, also, have horizontal, rather than plunging, hinge lines but may still display complex map patterns if the topographic relief is significant.

☐Exercise 9-6: On the map of Figure 9-12: a) Trace in red any unconformities on the map. b) Use structure contours to determine the orientation of the strata above the unconformity (azimuth/dip). c) Trace in blue the boundaries of any inliers and outliers (see chapter six). d) Determine the orientation of the beds below the unconformity. e) Construct a cross-section along line PQ. f) Establish a complete key for this map in the appropriate stratigraphic sequence.

9-5 Nonconformities

Nonconformities are unconformities between younger sedimentary strata overlying a basement of either igneous or high-grade metamorphic rocks. The important implication is that the sedimentary rocks are deposited onto an old erosion surface at the top of the basement. The erosional truncation of the basement is often marked by a basal conglomerate, containing fragments of the eroded basement rock (Fig. 9-13). If no inclusions are encountered in the beds directly above the nonconformity surface of an igneous basement, then it may be difficult to prove the erosional origin of the truncation of the basement. In such cases, the sedimentary rocks could be older than the underlying igneous rocks. Sedimentary rocks that are intruded by igneous rocks may show contact metamorphism rather than containing fragments of eroded basement rocks. This would imply a discordant contact between the sedimentary cover sequence and the crystalline basement, due to magmatic activity.

Many geological boundaries result from a mixture of discordant igneous intrusions into a cover sequence that was earlier nonconformably deposited onto the basement rock. But clear-cut examples of nonconformity surfaces can be encountered in the field. For example, the photograph of Figure 9-14 shows interbedded Tertiary basalts and sedimentary rocks, resting nonconformably on Precambrian gneiss, as exposed in the 1.5 km high cliff of the Gaaserfjord, eastern Greenland. The time-gap represented by the nonconformity spans at least half a billion years. Figure 9-15 illustrates the nonconformity between the Vishnu schist and the Grand Canyon Series, representing another time-gap in the stratigraphic record of several hundred million years.

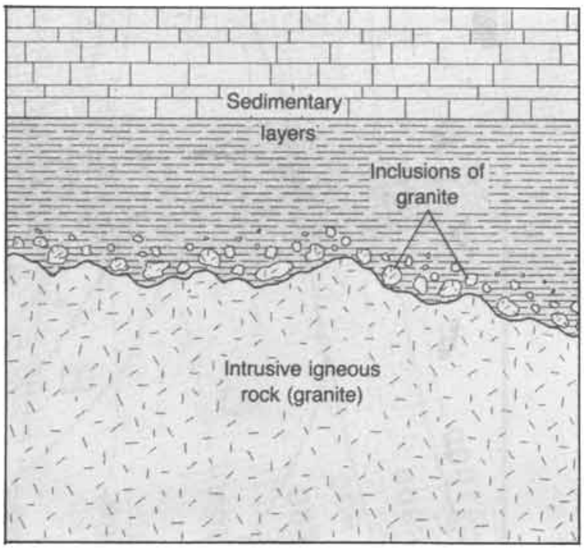


Figure 9-13: Nonconformities occur beneath sedimentary strata, overlying an eroded basement. The igneous inclusions shown may reach boulder size.

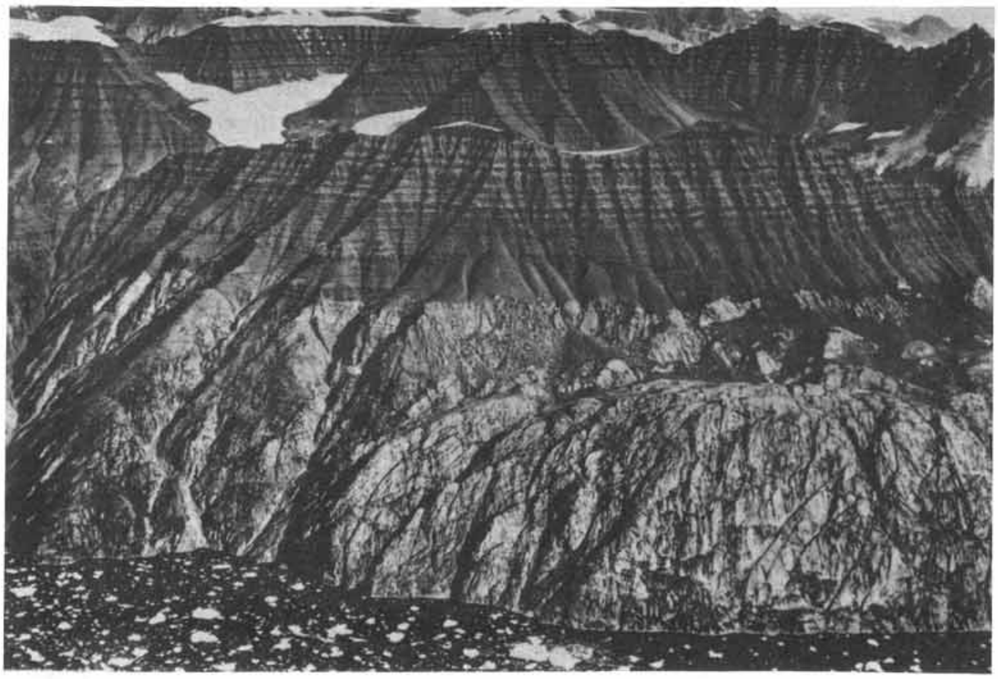


***Figure 9-14:** Nonconformity between gneisses of the Precambrian basement and overlying Tertiary basalt flows, Gaaserfjord, eastern Greenland. Cliff height is approximately 1.5 kilometers.*

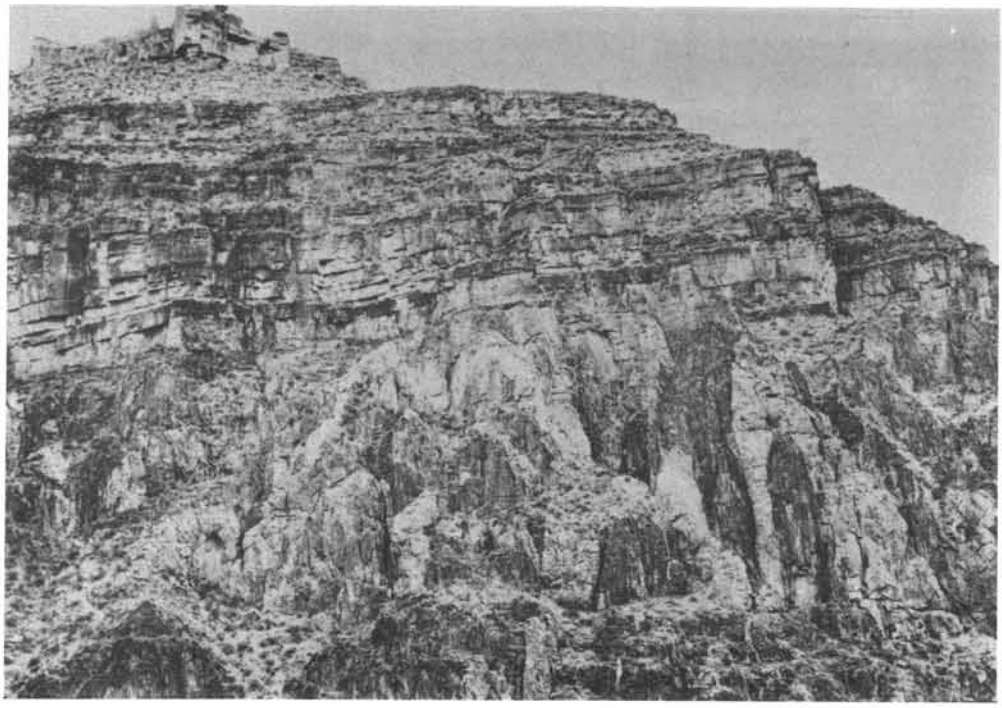


***Figure 9-15:** Nonconformity between the vertically foliated Vishnu schists and the layered Grand Canyon Series, Kaibab Trail. Height of the cliff is about 250 meters.*

9-6 Isopach and isochore maps

Sedimentary beds may show lateral changes in thickness, either in connection with an erosional episode that created an unconformity or due to lateral facies changes. Figure 9-16 shows the lateral facies changes in the Billefjorden trough on Svalbard in the Barents Sea. It is of crucial importance to the hydrocarbon industry to document such lateral changes in layer thickness. Regional variations in the thickness of the source, reservoir, and cap-rock control the way in which hydrocarbons are maturing, migrating, and subsequently trapped.

The regional change in thickness of essentially undeformed, subhorizontal layers can be documented by *isopachs*, i.e., contours connecting points where the beds have the same thickness. Two reference surfaces are needed to draw isopach maps: the top and the bottom of the bed(s) concerned. Figure 9-17a illustrates the structure contours for the top (solid curves) and bottom (dashed curves) of an oil-bearing limestone formation. The lateral variation in the thickness of the limestone follows directly from the difference in elevation of the two sets of structure contours. In Figure 9-17b, the intersection points of the structure contours of the top and bottom of the limestone are utilized to construct thickness contours or isopachs (fat dashed curves). The zero-thickness isopach of a unit may reflect the ancient shoreline, although parts of the formation may have been eroded, thus shifting the zero isopach farther seaward. Figure 9-17c shows two mutually perpendicular cross-sections across the limestone reservoir and emphasizes the thickness variations and approximate shape of the reservoir.

If the sedimentary beds are not subhorizontal, but inclined at a significant angle, the vertical thickness of the beds will be larger than the true thickness. In such cases, the preparation of an

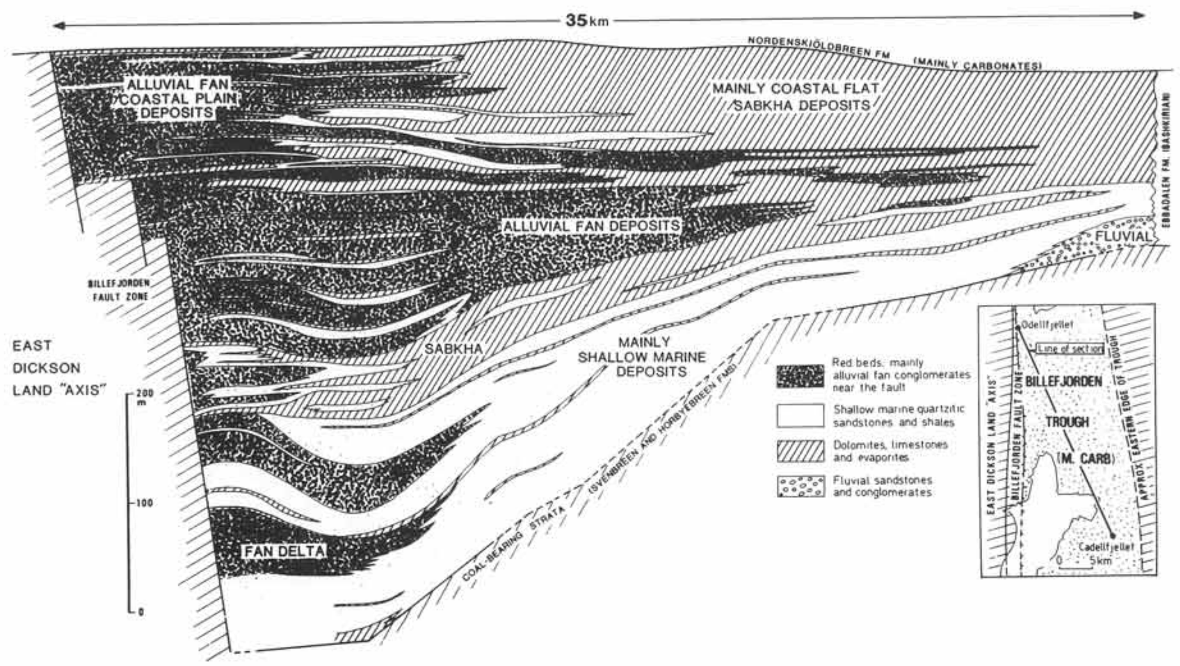


Figure 9-16: *Cross-section of the Billefjorden trough, Svalbard.*

isopach map, showing the true stratigraphic thickness of the layers, would be very elaborate, as vertical thicknesses need to be converted to stratigraphic thicknesses. If the vertical thickness is greater than the stratigraphic thickness, the contours of equal vertical thickness are preferably termed *isochores*, rather than *isopachs*, to emphasize the difference between vertical and true thickness.

Isopach maps allow estimation of the rate of subsidence in an area. If isopach contours consistently outline thickening of successive formations in the same region, the lateral thickening may reflect lateral changes in subsidence rates. A succession of isopach maps for each of the important stratigraphic units in a hydrocarbon basin provides a basis for the reconstruction of its subsidence history. Knowledge of the detailed subsidence history and the sedimentological characteristics will assist in identifying likely migration routes for the hydrocarbons. If a reservoir of the migrated hydrocarbons has been discovered, isopach maps - together with data on porosity and water saturation - can be used to calculate the oil and gas reserves by simple volumetric principles.

☐Exercise 9-7: An important hydrocarbon reservoir is present in the subsurface of a square area of one hundred square kilometers. The vertical, drilled thickness of the reservoir is not constant. Extensive exploration drilling has established the following thicknesses. In the corners of the area: NW 100 meters, SW 400 meters, NE 300 meters, and SE 1,000 meters. In the middle of each of the sides of the square area: N 150 meters, E 500 meters, S 600 meters, and W 250 meters. Prepare an isochore map for the hydrocarbon reservoir.

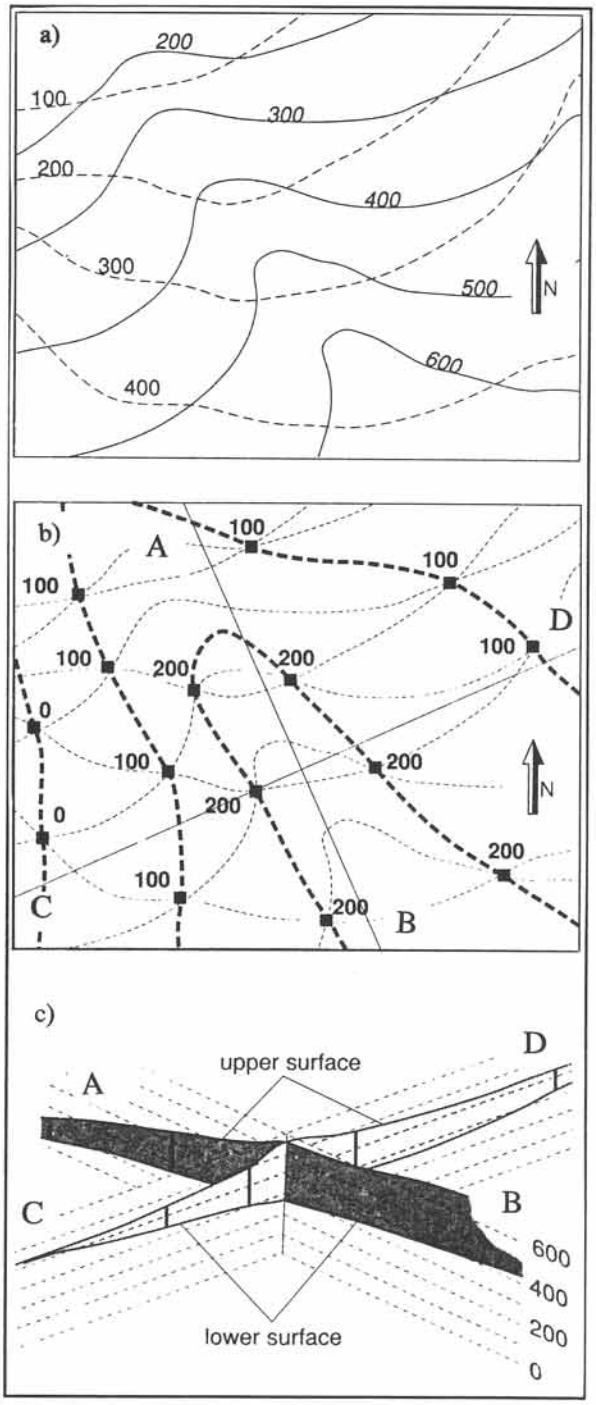


Figure 9-17: Construction of isopachs from structure contour maps. a) Structure contour of top (solid curves) and bottom (dashed curves) of limestone unit. b) Isopach map with contours for 0, 100, and 200 meter thickness. c) Sections across the limestone unit.

☐Exercise 9-8: Figure 9-18 is an isopach map for a Cretaceous hydrocarbon reservoir beneath the floor of the North Sea, due north of the Statfjord production area. a) Color in red the subsurface area where the Cretaceous section is more than five kilometers thick. b) What could explain the shape of the Cretaceous sediment body? c) Can you infer anything about the absolute depth of the top of the Cretaceous on the basis of this map?

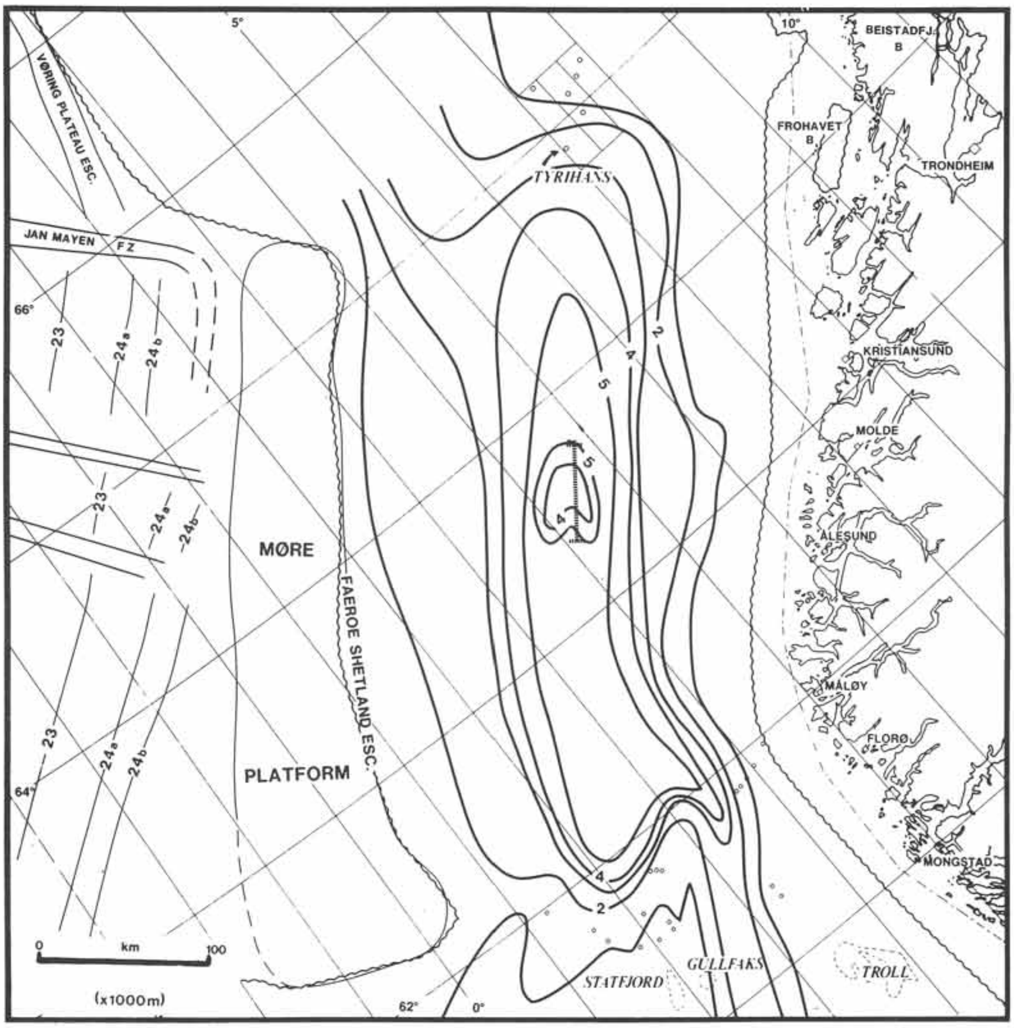


Figure 9-18: Isopach map for Cretaceous reservoir rocks, off-shore Norway. Thickness is in kilometers. Magnetic anomalies are included west of the Moere platform. See exercise 9-8.

Chapter 10: Three-Dimensional Perspective Diagrams

THREE-DIMENSIONAL PERSPECTIVE diagrams combine information from maps and cross-sections into a single illustration to enhance understanding of their relationship. Such diagrams are presented as various types of perspective blocks. The top of the blocks shows an oblique aerial view of the geological and topographic features of the upper surface. This upper surface is typically that of the Earth's surface but, also, may be a horizontal slice through several tilted or deformed layers in the subsurface. The sides of the blocks provide a simultaneous view of the subsurface geology. The geological structure of an area thus displayed can be understood by non-specialists, involved in mining, petroleum, and engineering operations. This chapter concentrates on the graphical variety of 3-D display methods to aid professionals, such as engineers and geologists, in deciding which type of diagram is most appropriate for each particular application.

Contents: Two types of perspective diagrams are outlined in sections 10-1 and 10-2. Isometric block diagrams with flat top surfaces are discussed in section 10-3. Isometric diagrams, including the topographic relief of the ground surface, are introduced in section 10-4. The final section, 10-5, summarizes additional display methods, including fence, cabinet, coulisse, and structure-contour diagrams.

10-1 Parallel perspective

The illusion of a 3-D view in a 2-D picture can be created by graphically distorting the

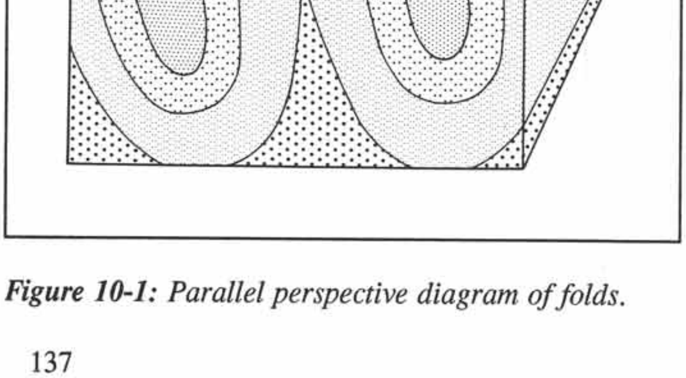


Figure 10-1: Parallel perspective diagram of folds.

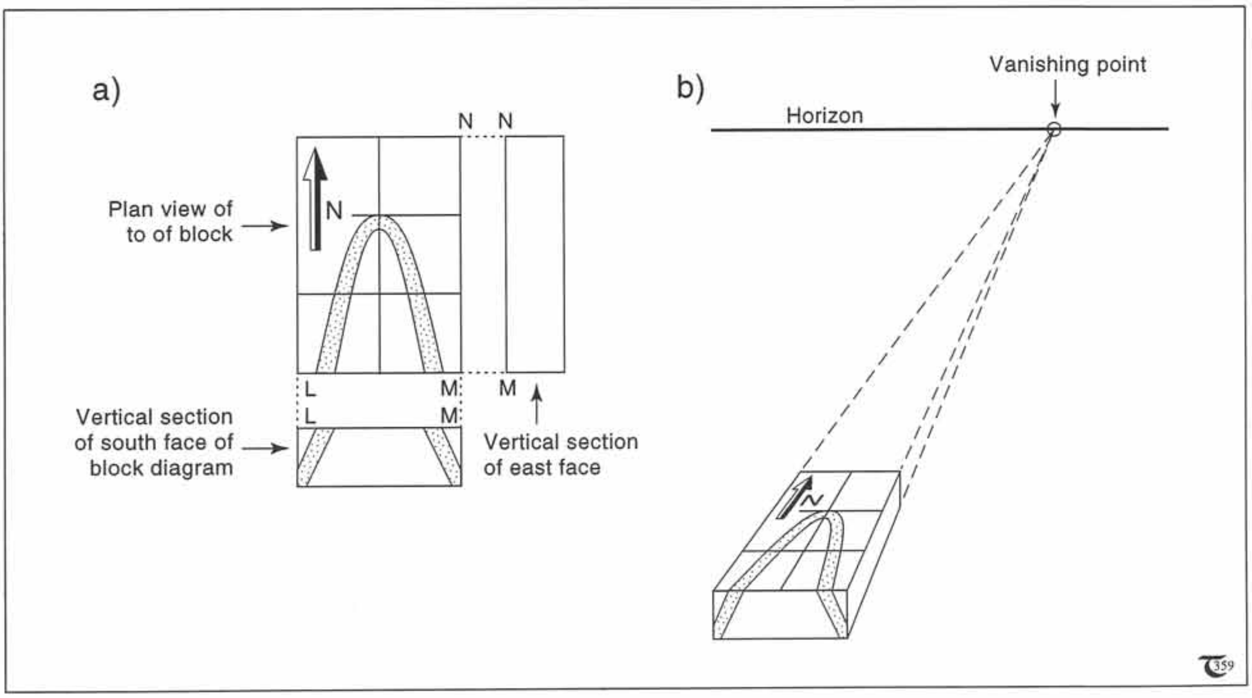


Figure 10-2: a) & b) Construction of parallel perspective diagrams. See text.

various parts of crustal cut-outs in a carefully controlled fashion (Fig. 1). One class of perspective diagrams show imaginary crustal blocks with the perception of depth and distance enhanced by means of one or more perspective vanishing point(s) at an imaginary horizon (Fig. 10-2b). Consequently, the front of the map appears larger than its back. Distances and angles of the structure in different parts of the diagram are distorted in a gradually shifting fashion. If only one vanishing point is used, the diagram is termed a *parallel perspective*, sometimes referred to as one-point perspective or single-vanishing point perspective. Perspective diagrams involving two vanishing points, termed *angular perspectives*, are discussed in section 10-2.

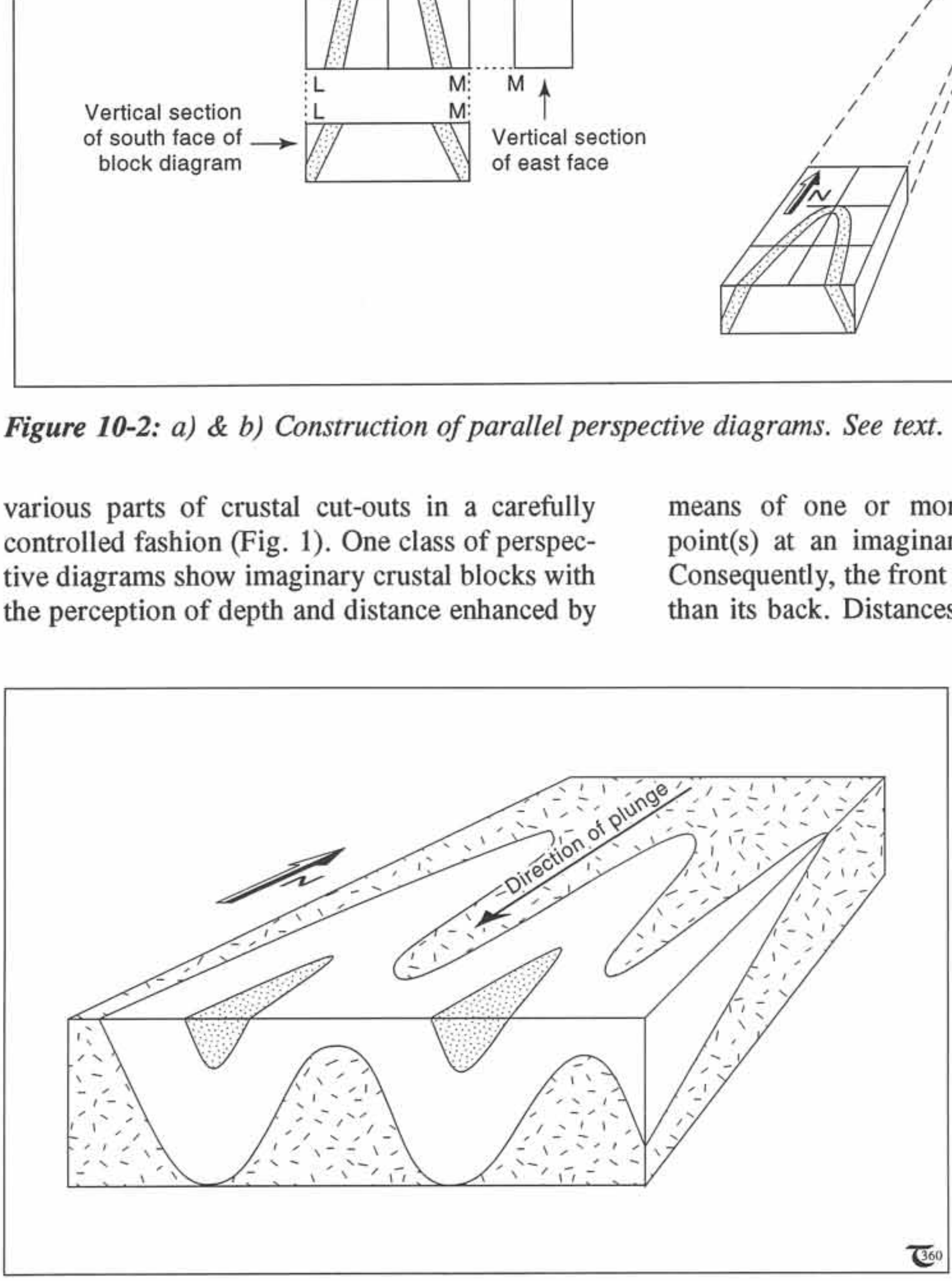


Figure 10-3: Parallel perspective diagram of upright, south-plunging folds. See exercise 10-1.

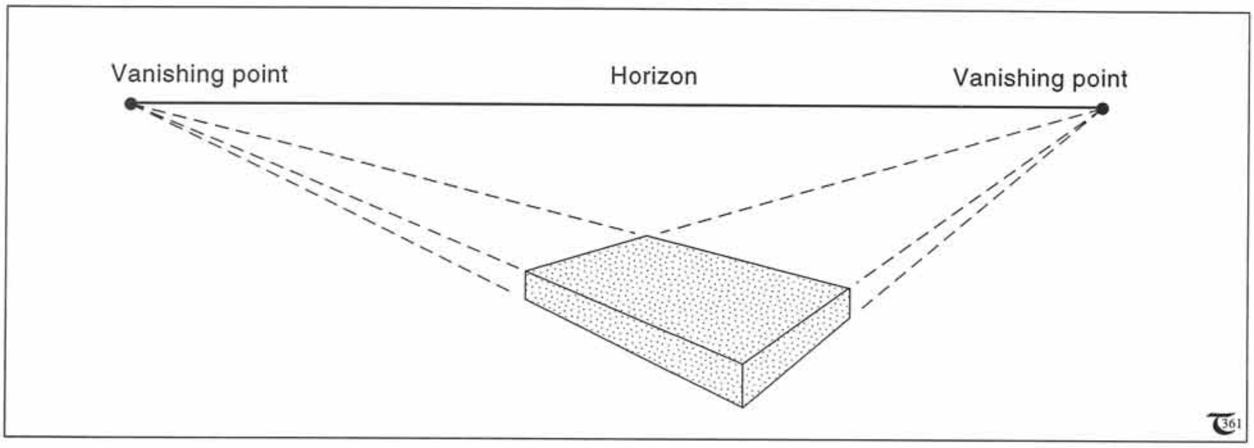


Figure 10-4: Angular perspective diagram.

The geology of the crustal perspective block can be completed only if the ordinary map view and two cross-sections - mutually perpendicular along the side lines of the map - are available or constructed as starting material (Fig. 10-2a). The outlines of the perspective diagram are drawn, choosing a vanishing point at an imaginary horizon. The geological information is transferred to the surfaces of the perspective diagram, visually deforming two of the panels of the perspective diagram to create the sense of depth (Fig. 10-2b). To achieve this manually, the map is subdivided into equal squares, which are then proportionally deformed, together with the geological bound-

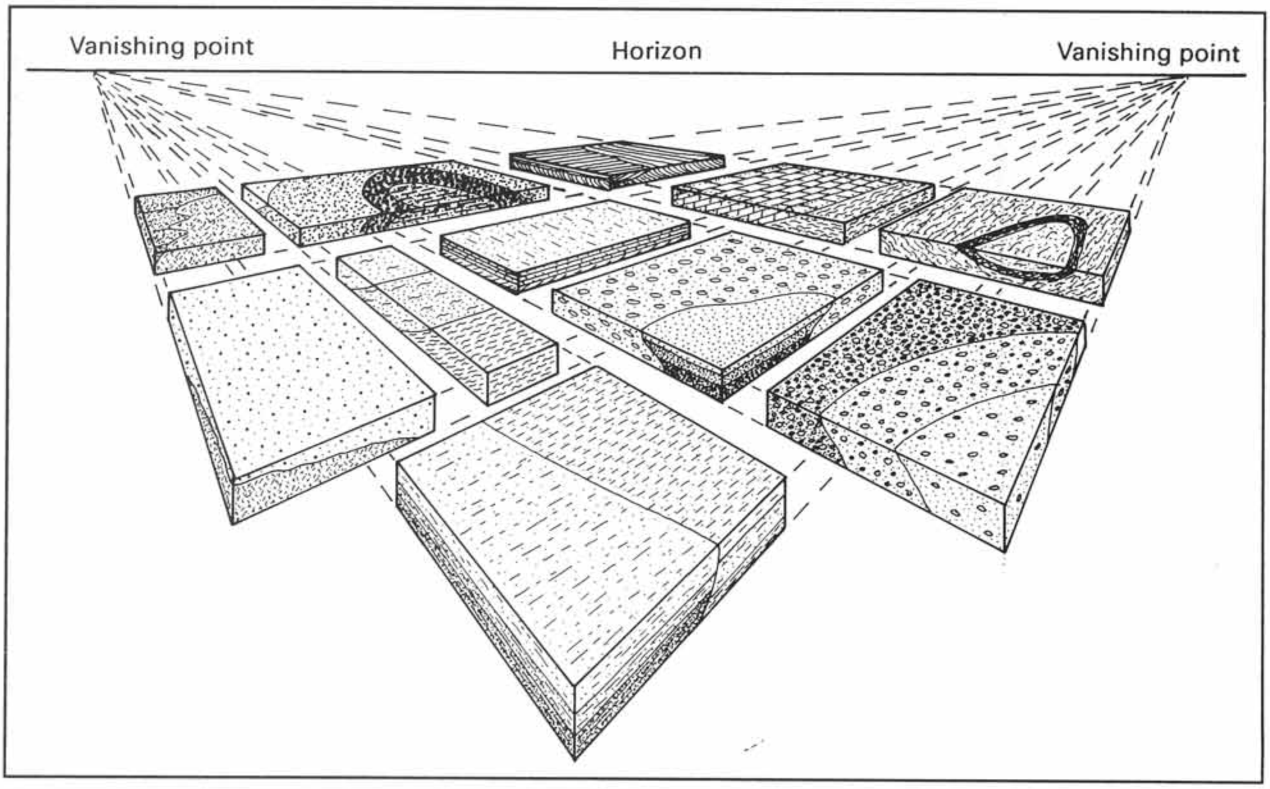


Figure 10-5: Family of angular perspective diagrams.

aries, into the finite units of the perspective diagram's top surface. Perspective diagrams with one vanishing point have undistorted front panels. However, the other visible side panel is deformed in a fashion controlled by the location of the perspective point, so as to create the suggestion of a 3-D view. All lines that are vertical in reality remain vertical in the perspective diagram. But much of the quantitative information on angular relationships and distances is obscured.

☐Exercise 10-1: Examine the parallel perspective diagram of Figure 10-3, and construct both the vanishing point and the imaginary horizon line.

10-2 Angular perspective

Slightly more realistic is the perspective diagram with two vanishing points at the horizon (Fig. 10-4). Such *angular perspective diagrams* are, also, referred to as two-point perspectives or double-vanishing-point perspectives. Figure 10-5 illustrates an array of angular perspective diagrams, all at different rotation and distances with respect to the same horizon and vanishing points. The distance between the two vanishing points is arbitrary, as is the relative position of the block itself. The orientation of the block can be selected so that the relevant structure is displayed in the most suitable fashion. Evidently, of all 3-D display methods available, perspective diagrams have the most realistic appearance and, therefore,

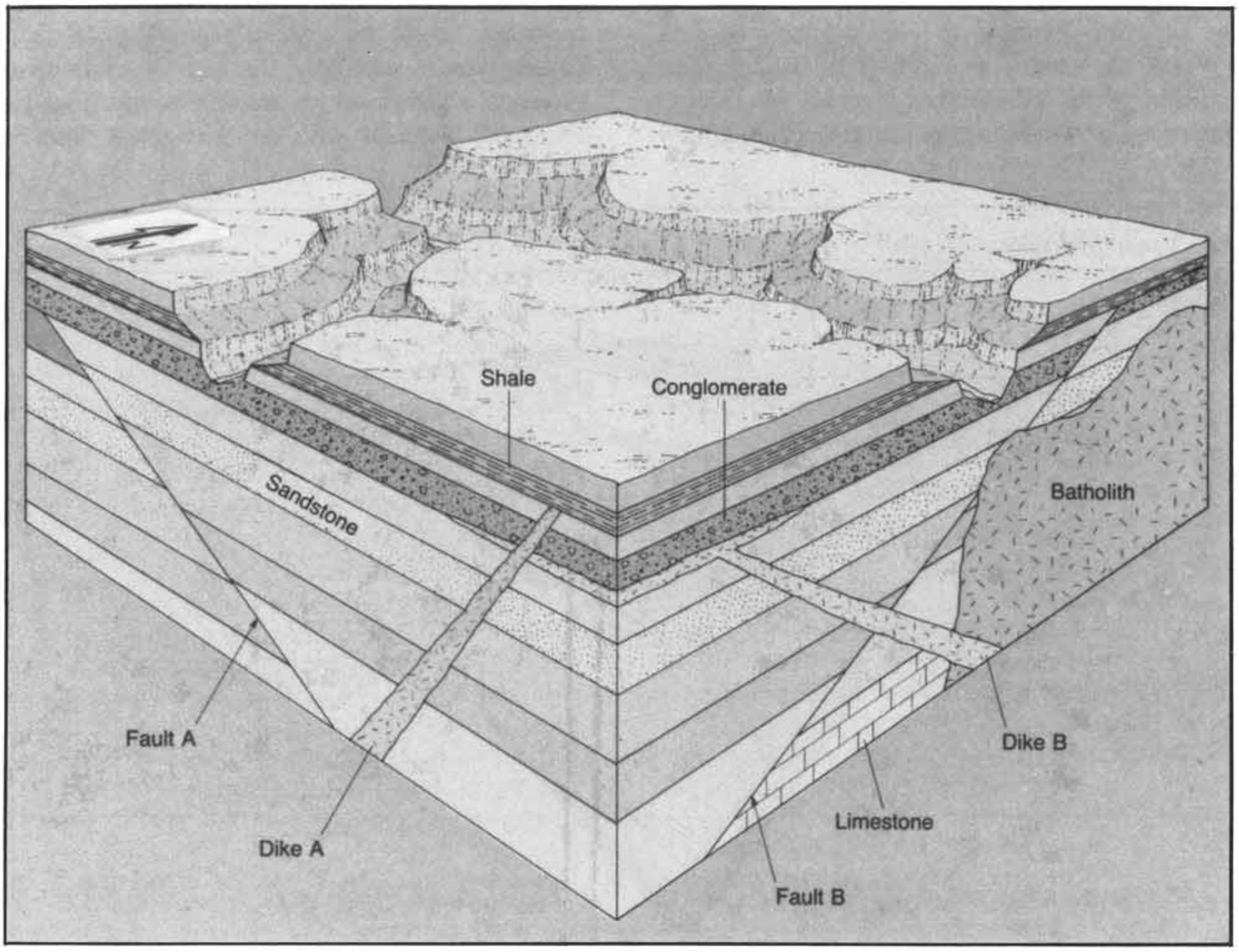


Figure 10-6: Angular perspective diagram for exercise 10-2.

are very suitable for rapid communication of the general three-dimensional structure of crustal blocks. Perspective diagrams are good qualitative tools, but the increasing foreshortening towards vanishing points makes them less suitable for any quantitative measurement of either distances or angles.

☐Exercise 10-2: Examine the angular perspective diagram of Figure 10-6. a) Construct the vanishing points and the imaginary horizon line. b) If the canyon system at the surface were to be displayed more prominently, how would you change these perspective points? c) How could the visual prominency of the canyon system be reduced? d) Why is an angular perspective block better than a parallel perspective for displaying the faults and dikes of this region?

☐Exercise 10-3: Transform the parallel perspective of Figure 10-1 into an angular perspective diagram.

10-3 Isometric perspective without topography

Isometric block diagrams differ from parallel and angular perspective diagrams in that there are no vanishing points involved with the former. The blocks are constructed by drawing three sets of lines, each set differently oriented, but all lines of the same set remaining exactly parallel (Fig. 10-7a to c). Consequently, the front- and rear-panels of an isometric block have the same area, even in the drawing plane. The dimensions of the block diagram can be defined by a Cartesian coordinate system, with the Z-axis pointing downward. The orientation of the other two axes can be fixed in an arbitrary fashion. Figures 10-7a to c illustrate three different, arbitrary orienta-

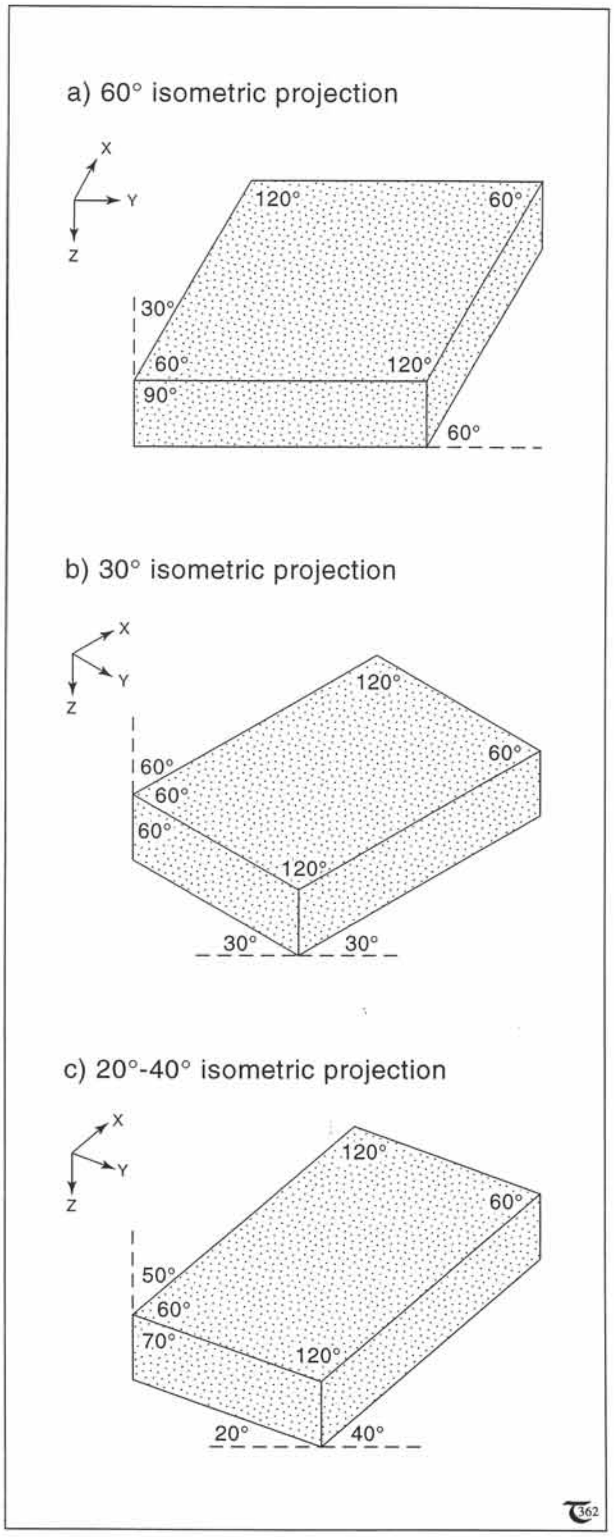


Figure 10-7: a) to c) Isometric block diagrams for a range of tilt angles with respect to the horizontal.

tions for the Cartesian coordinate system, resulting in different views of the isometric block. All the distances measured along the three axes of the block are equal to the dimensions of the original map and vertical section scales used. All lines parallel in the block will be parallel in reality. All

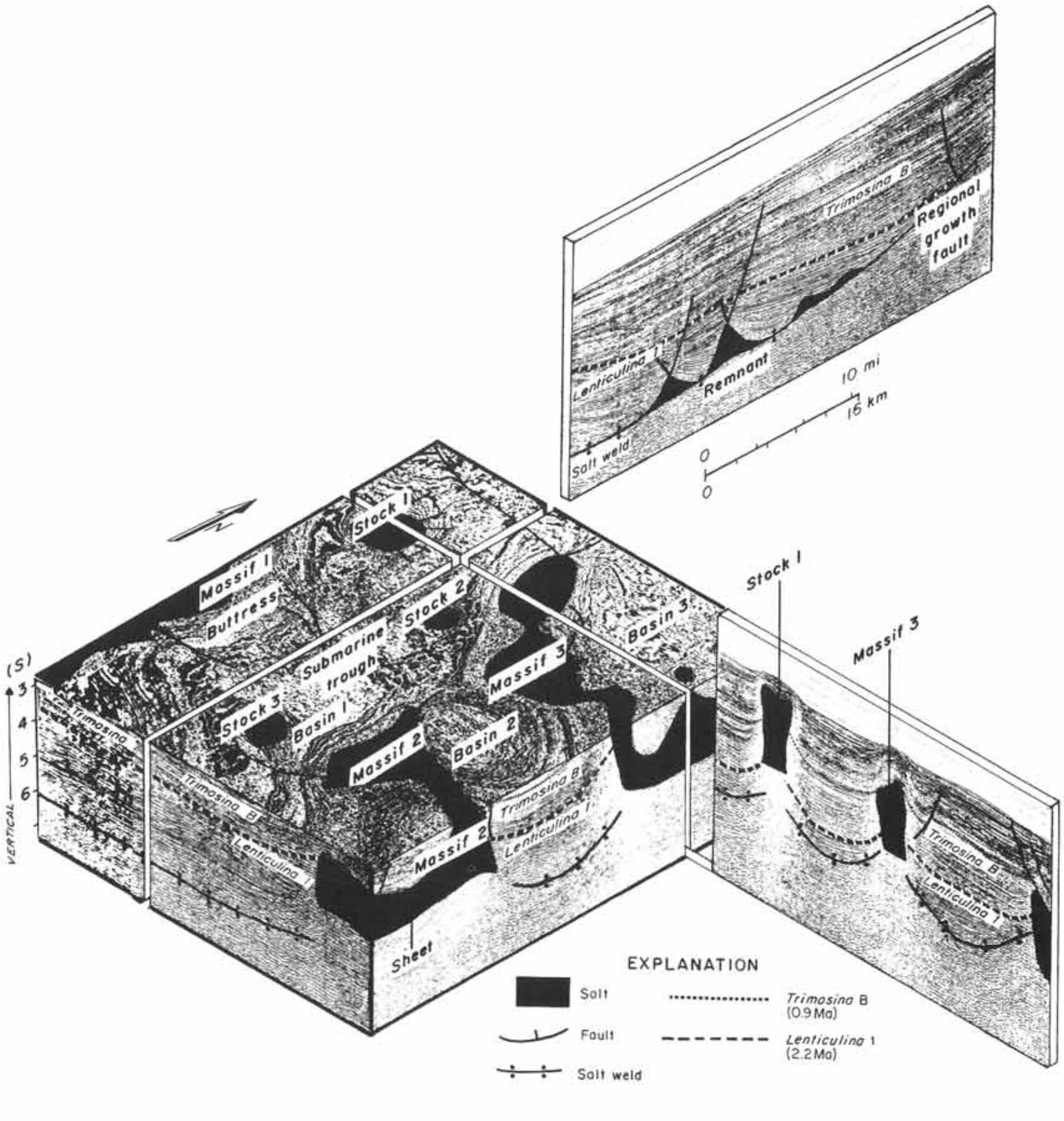


Figure 10-8: *Isometric block diagram of seiscrop map and sections of salt domes in the Gulf of Mexico, off-shore Louisiana. The pull-out panels visualize the structure in the rear parts of the block.*

angles in isometric blocks are distorted, except for those seen in the front-panel of the projection of Figure 10-7a.

Figure 10-8 illustrates an isometric block diagram, constructed from a horizontal seiscrop map and two sets of mutually orthogonal seismic sections. This particular diagram shows the intricate pattern of the interconnected salt masses, seen in various cuts through the subsurface of the Gulf of Mexico. The view of the subsurface structure is enhanced by two accessory panels, pulled from imaginary vertical slots in the interior, as indicated. The vertical scale (Z-direction) is exaggerated and nonlinear, as compared to the horizontal dimensions. In general, if cross-sections, used for constructing block diagrams, have vertical exaggeration, then this exaggeration will be passed on to the block diagram.

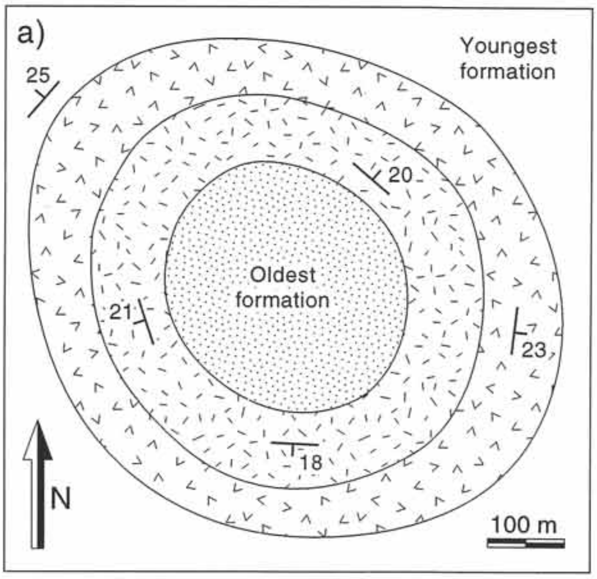


Figure 10-9a: Map view of a dome.

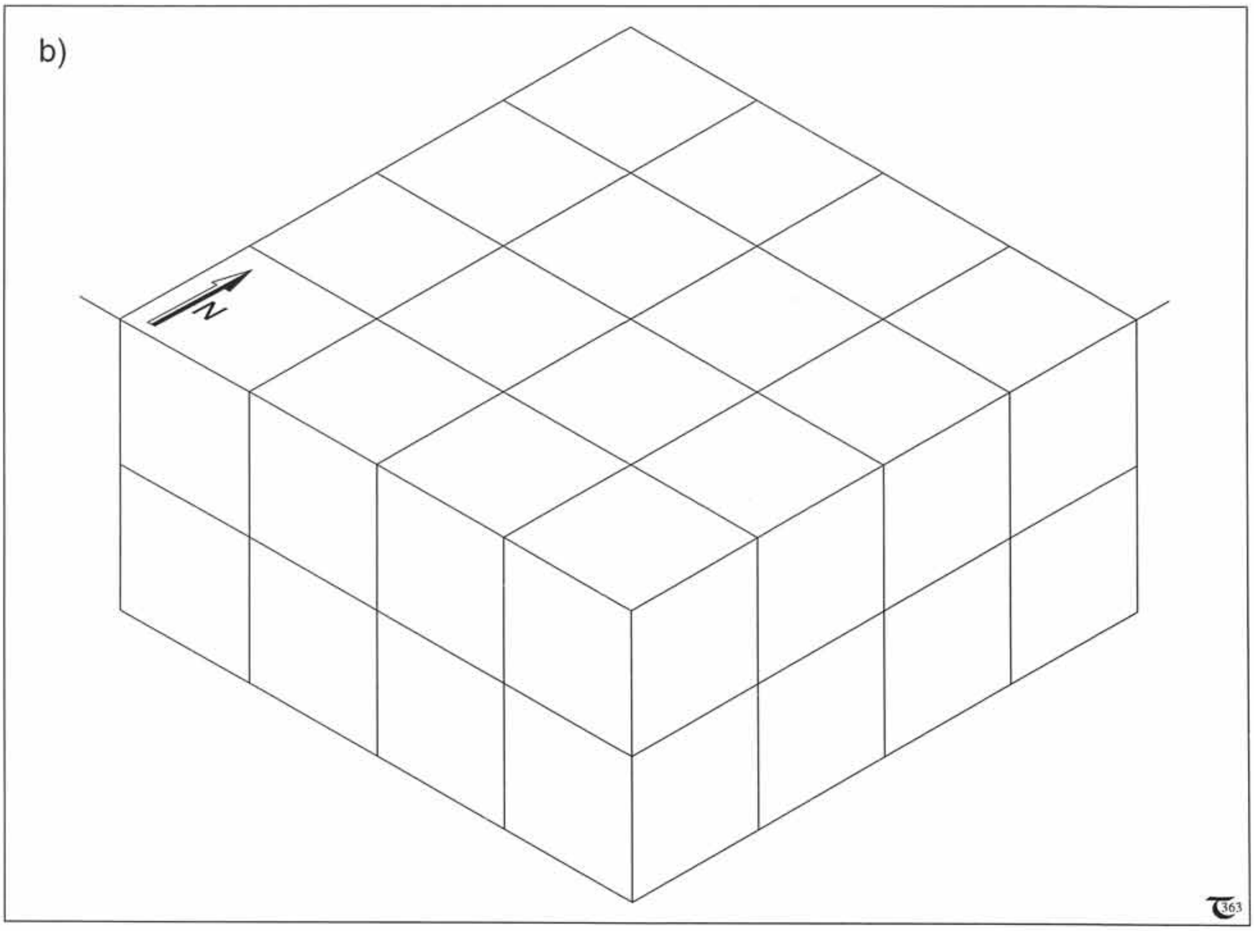


Figure 10-9b: *Isometric frame for exercise 10-4.*

The coordinate system used for any rock body in the subsurface is defined by the axes of the isometric block representation. This coordinate system may be locally defined, either in terms of distances (meters, feet) or in geographical coordinates for the horizontal dimensions (local, national, or international grid), combined with a depth scale. All geological data can then be related to the coordinate system. This allows swift manipulation of the data, particularly if computerized methods are used. Isometric block diagrams are particularly useful for detailed drilling and excavation activities of mining, petroleum, and construction companies. All isometric projections are nonperspective. This makes them less realistic to look at, but this is more than offset by their ability to yield correct lengths along the axial directions. Distances in other directions are not commensurate with the true distances. Angles in isometric projection can be read correctly with a commercially available protractor (e.g., *Linex*).

☐Exercise 10-4: Complete the isometric block diagram (Fig. 10-9b) for the structure seen in the map of Figure 10-9a. Use the following steps: a) Transfer the geology from the map to the block diagram by extrapolation. b) Complete the views of the geology in the vertical walls of the block. c) Define a coordinate system for hydrocarbon exploration in the structure displayed.

10-4 Isometric perspective with topography

All the 3-D views discussed above had flat top surfaces. The topographic surface relief of the landscape will be negligible if the horizontal scale of the diagram is compressed so much that any differences in vertical elevation become invisible. Since the average elevation of continental areas is about two kilometers, vertical elevation shows up as a mere perturbation on a line of one millimeter thickness if the horizontal scale uses one millimeter for one kilometer, i.e. 1:1,000,000 or more. The effect of topography will still be minimal for diagrams in the range of 1:1,000,000 to 1:100,000 but can be enhanced by vertical exaggeration. However, sections and block diagrams of more detailed scale need to take into account the surface topography.

The topographic relief of the ground surface can be included in isometric block diagrams. But the construction of such 3-D diagrams can be

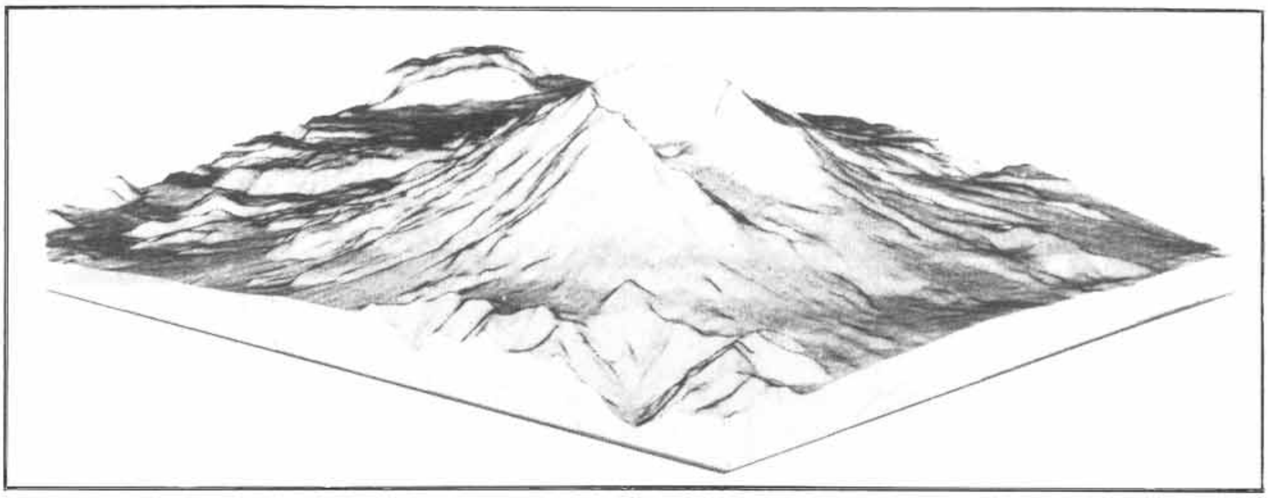


Figure 10-10: Isometric wire-mesh diagram, showing the surface topography of Mount St. Helens with typical horseshoe opening in the summit, which collapsed in a massive landslide during the big 1980 eruption.

elaborate and is greatly facilitated by a range of software packages, which are commercially available and continuously upgraded. If the elevation data are stored in a computer, shaded relief maps can be produced by stacking closely spaced cross-sections at right angles. Figure 10-10 illustrates an isometric block diagram - computer generated - of Mount St. Helens. Software packages for constructing such diagrams are outlined in chapter seventeen, but the basic graphical principles for creating 3-D images are discussed below. Computer methods work along the same principles but partly differ from manual methods in that they speed up the process of graphical representation.

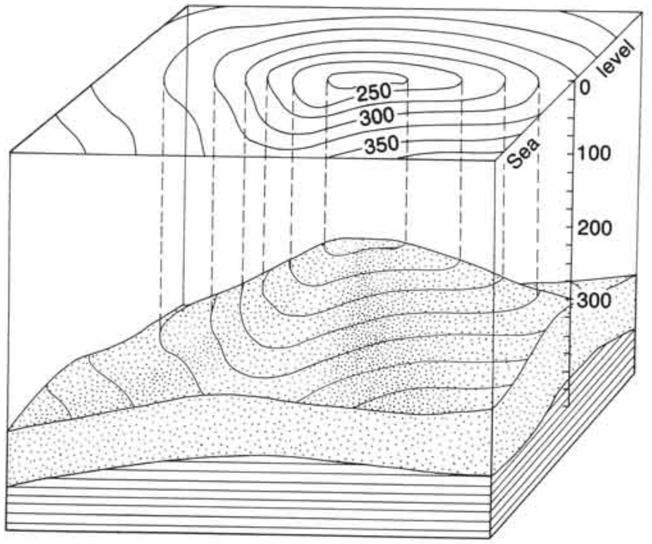
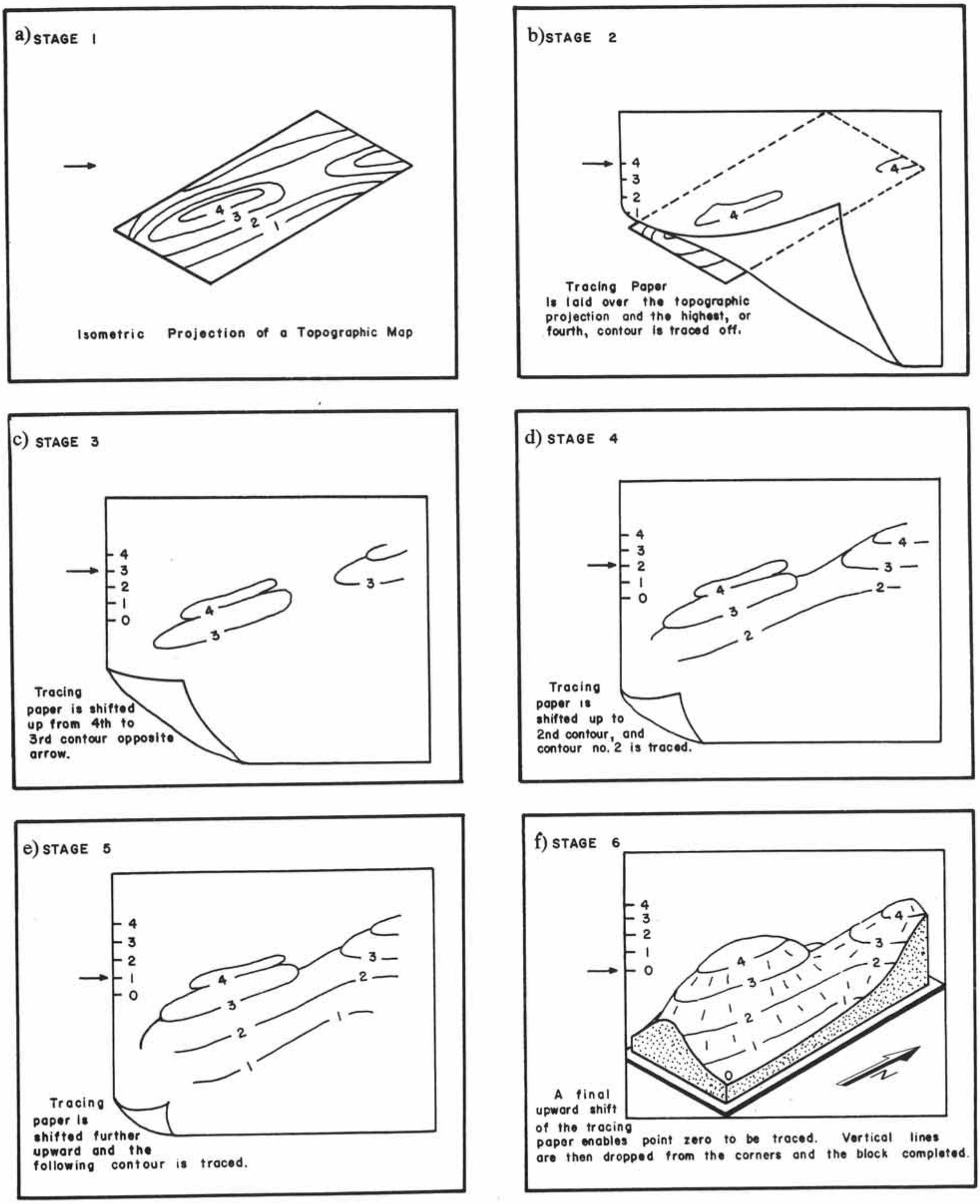


Figure 10-11: *Topographic map and the corresponding isometric block diagram with elevation contours illustrate the landscape in a 3-D perspective.*

Figure 10-11 shows a manually constructed block diagram of a gentle hillside. To show the relief, each of the topographic contours is elevated to its appropriate distance above the base level. The general construction method is illustrated in Figures 10-12a to f. The topographic contour map is the starting point. A sheet of tracing paper is laid over the topographic map, already deformed into isometric format (Fig. 10-12a). An arbitrary reference arrow is drawn on the sheet of the isometric map. This arrow is used to shift the vertical scale on the tracing paper upward, each time a contour of a particular elevation is traced (Figs. 10-12b to e). The spacing on the vertical scale determines whether or not any exaggeration of relief is included. A final shift of the tracing paper enables point zero to be traced. If all the contours are thus transferred to the tracing paper, vertical lines can be drawn from the corners of the original isometric map to border the completed block diagram (Fig. 10-12f). The endings of all contours need to be traced completely towards the edge of the isometric map. Otherwise, the surface profile between the vertical lines, forming the boundaries of the block, cannot be completed.

☐Exercise 10-5: Figure 10-13a shows a merged geological and topographic map. The cross-sections PQ and QR are along the south and east boundaries of the map area (Figs. 10-13b & c). The isometric surface map is given in Figure 10-13d. a) Prepare an isometric block diagram, showing the surface topography of the area. b) Transfer the geological information to the block diagram, using the surface map and the cross-sections.



Isometric Projection of a Topographic Map

Tracing Paper Is laid over the topographic projection and the highest, or fourth, contour is traced off.

Tracing paper is shifted up from 4th to 3rd contour opposite arrow.

Tracing paper is shifted up to 2nd contour, and contour no. 2 is traced.

Tracing paper is shifted further upward and the following contour is traced.

A final upward shift of the tracing paper enables point zero to be traced. Vertical lines are then dropped from the corners and the block completed.

Figure 10-12: *a) to f) Steps involved in the manual construction of an elevated-contour diagram of a landscape.*

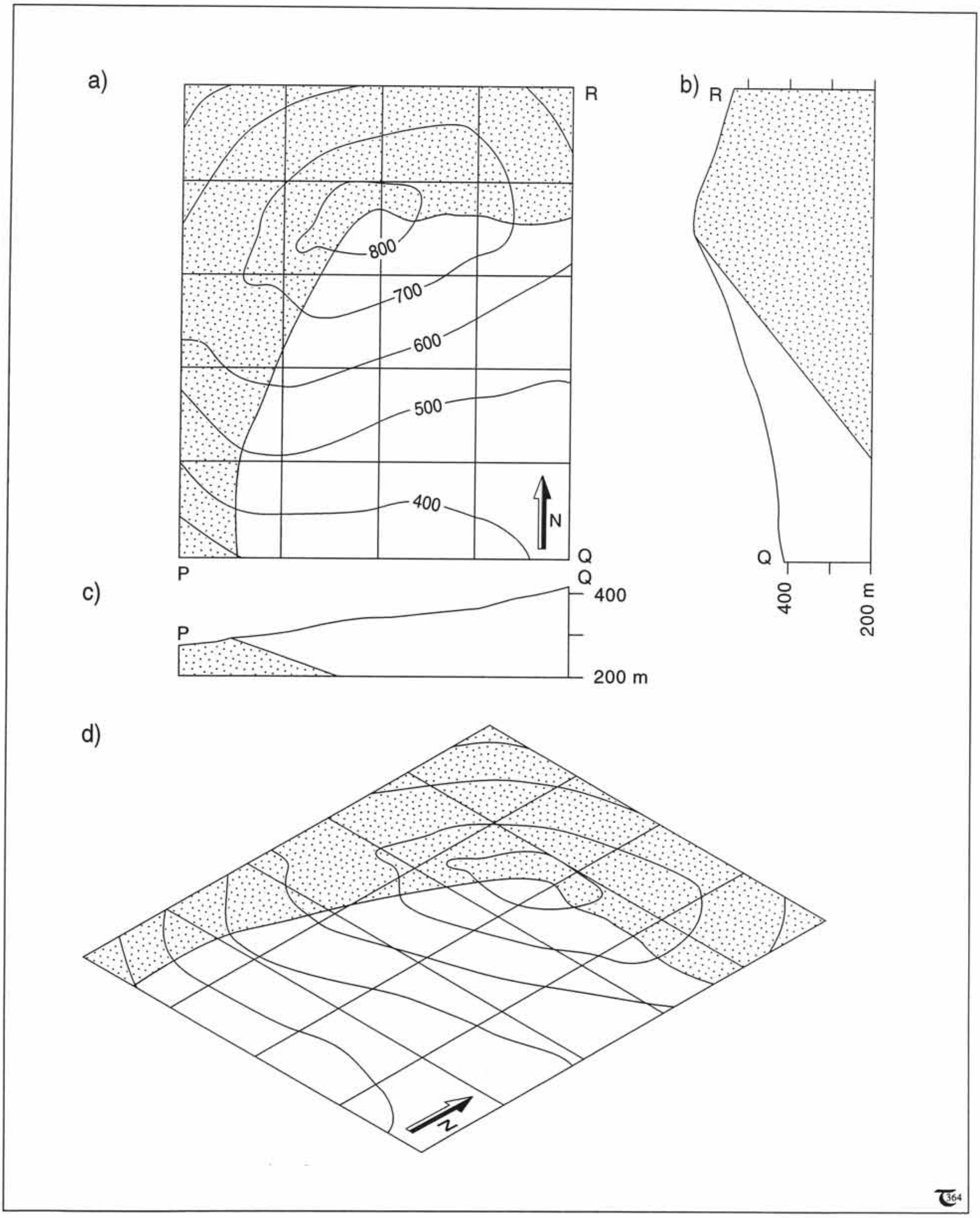


Figure 10-13: Graphics for exercise 10-5. a) Geological map on topographic base. b) N-S section along QR. c) E-W section along PQ. d) Isometrically distorted map view.

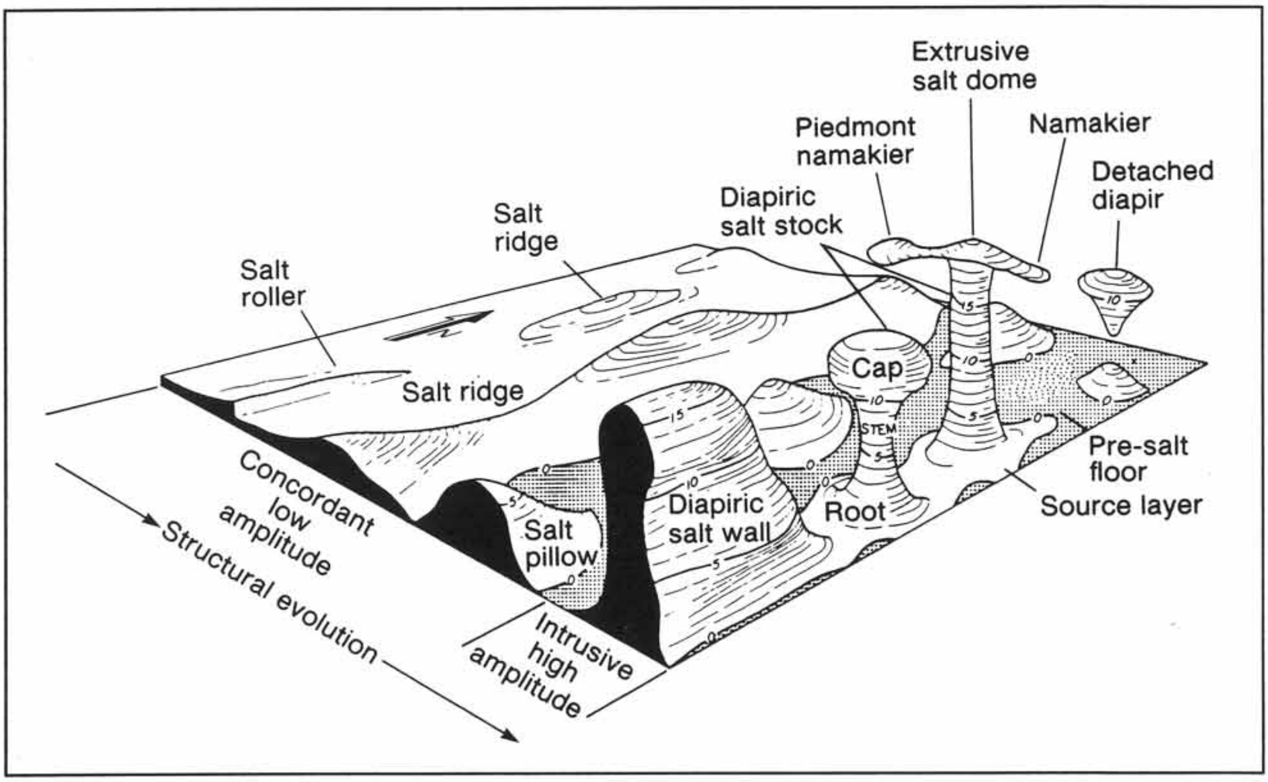


Figure 10-14: *Salt structures, outlined by elevated structure-contours.*

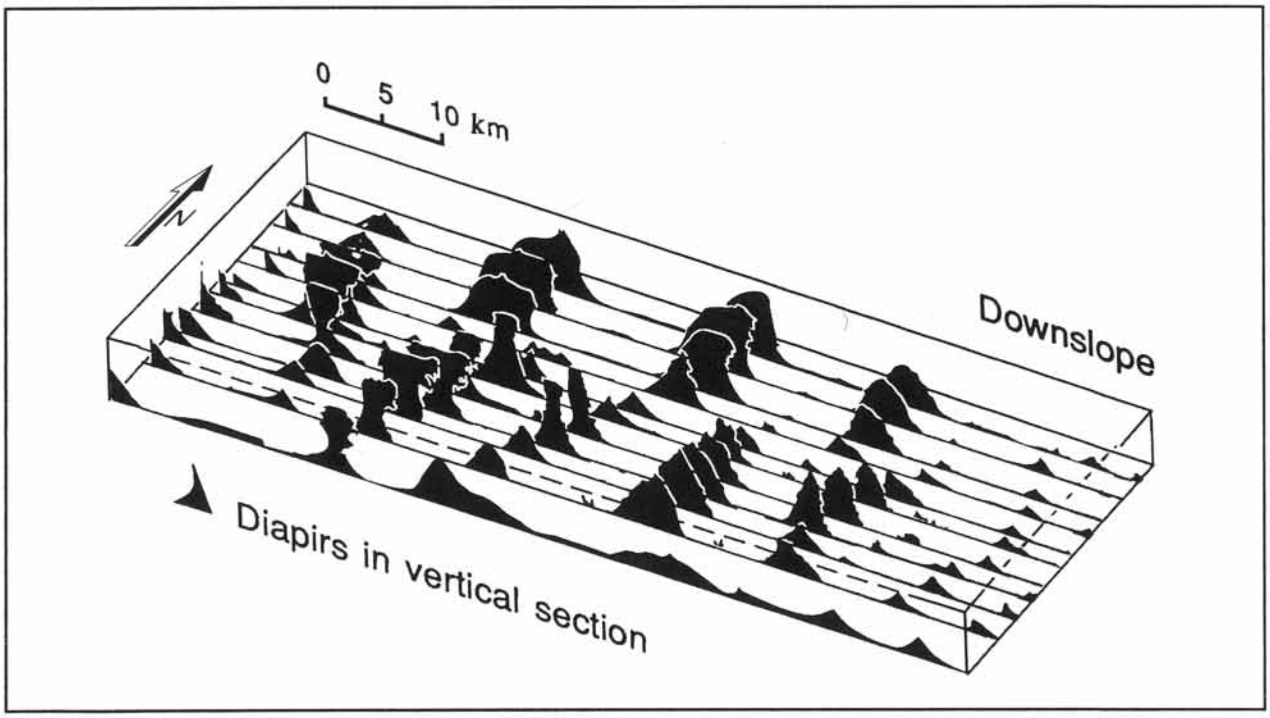


Figure 10-15: *Coulisse diagram of salt ridges.*

10-5 Other perspective diagrams

Additional ways to suggest 3-D views either remove or cut out portions of the isometric projection to visualize the internal structure of the subsurface. Figure 10-14 is an *elevated structure-contour diagram* of the top of large salt structures. The covering rocks have been entirely removed from the block diagram. It has been introduced to illustrate the geometric variety of subsurface salt bodies and the corresponding terms. For completeness, the namakiers or salt glaciers are subaerial and spread laterally over the ground surface. The *coulisse diagram* is an alternative method for illustrating salt domes in the subsurface, using either seismic

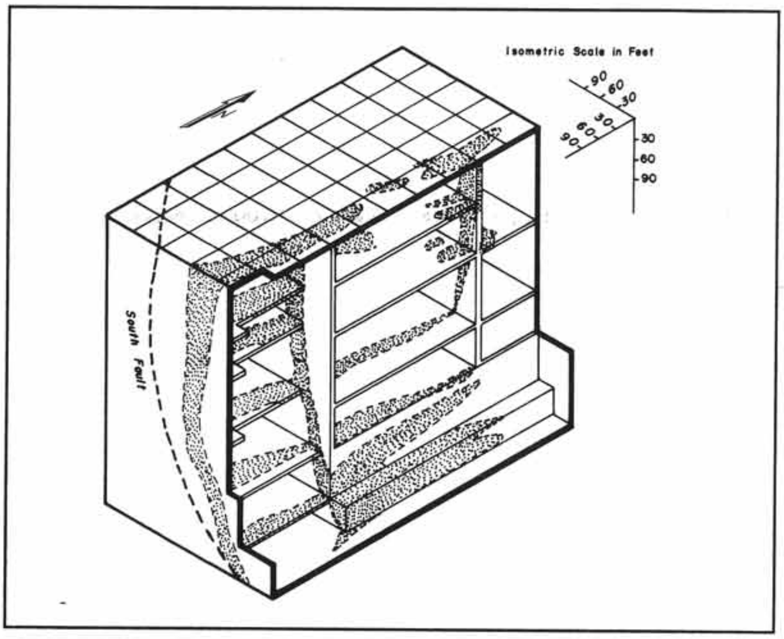


Figure 10-16: *Isometric cabinet diagram of the ore body in the Blinman Copper Mine, Australia.*

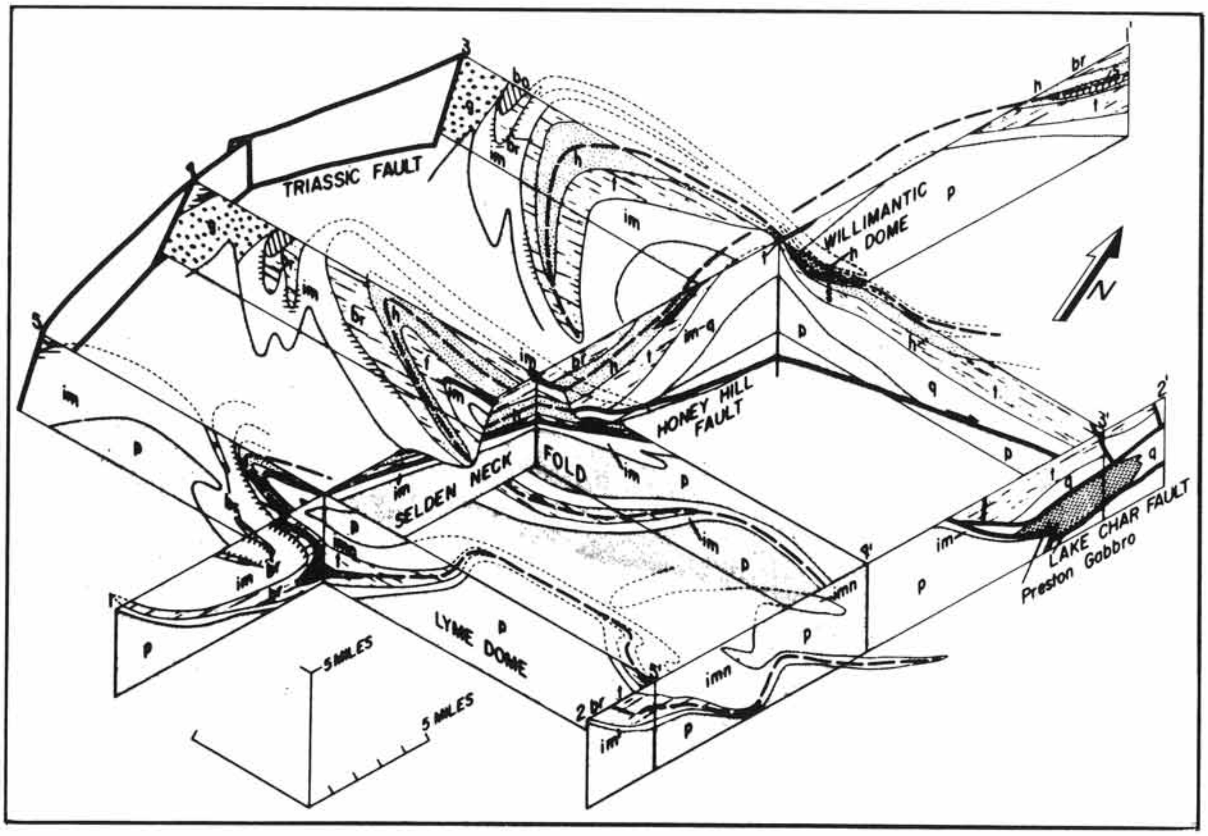


Figure 10-17: *Isometric fence diagram of complex fold structures in Connecticut, USA.*

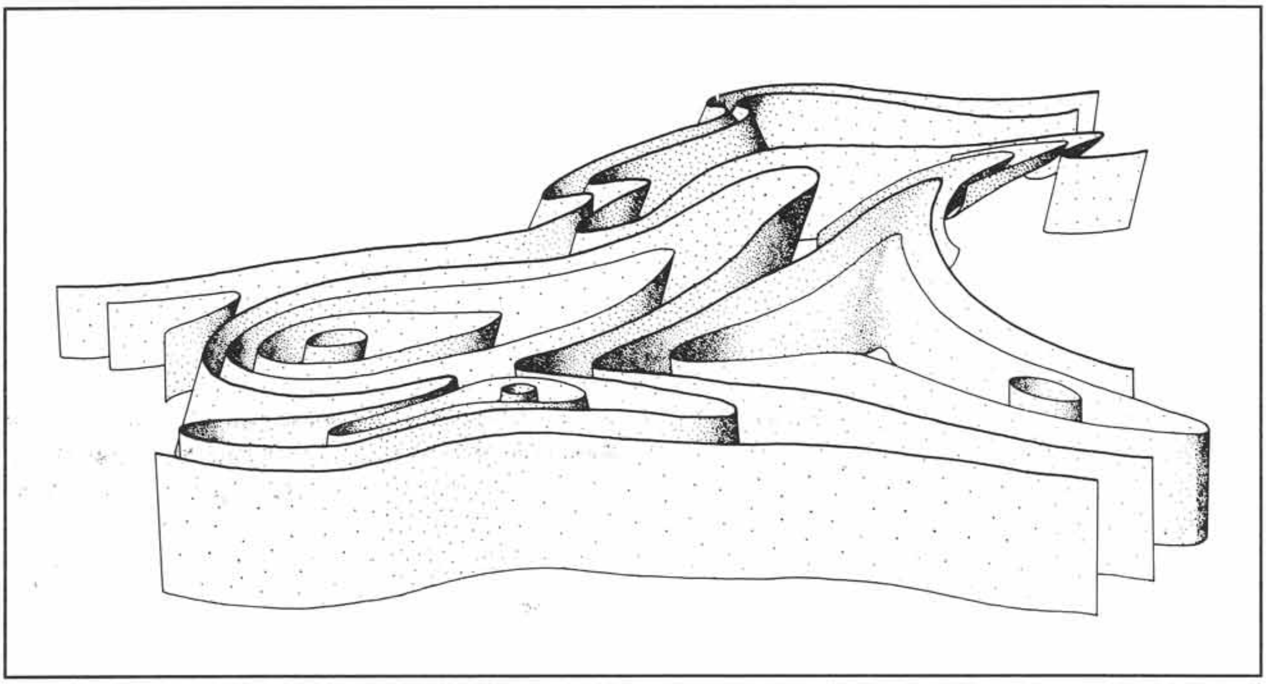


Figure 10-18a: Perspective diagram of dome-and-basin folds of Glen Cannich, Scottish Highlands.

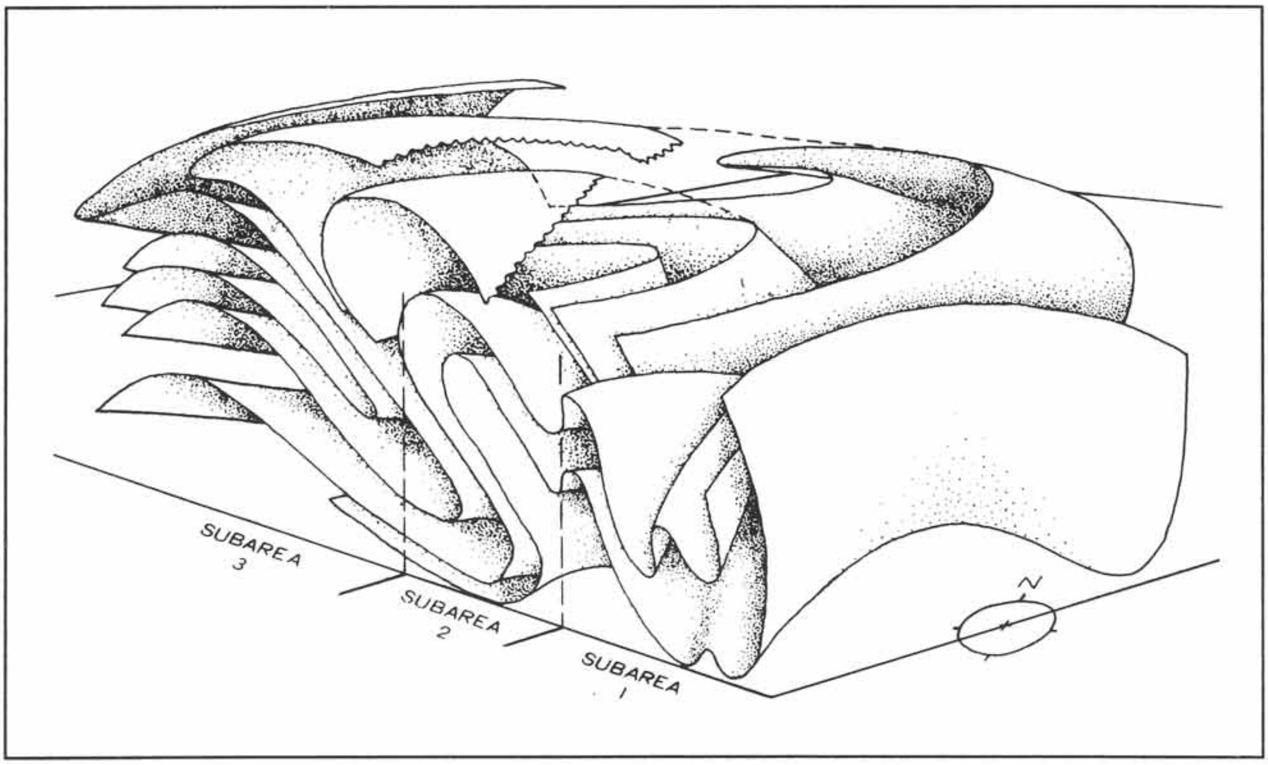


Figure 10-18b: Perspective diagram of non-coaxially refolded folds of the Milton area, Greensboro, North Carolina.

sections or serial cuts through small scale models. The group of narrowly spaced parallel sections is stacked to create the impression of a 3-D view (Fig. 10-15).

Figure 10-16 is an isometric *cabinet diagram*, showing the extent of the ore body of the Blinman Copper Mine, Australia. The ore body forms a vertical sheet and thus cannot be adequately represented by either a structure contour or a coulisse diagram. The isometric *fence diagram* of Figure 10-17 is used for illustrating areas of more complex internal structures. Fence diagrams are, also, widely used for undeformed rocks in sedimentary basins to show the lateral facies changes in otherwise subhorizontal strata.

Some of the most advanced diagrams, commonly used for portraying extremely complex fold structures, use multiple reference surfaces and shading to create 3-D views of the crustal interior (Figs. 10-18a & b). Such hand-drawn diagrams are largely artistic, based on a lot of practice, and no clear guidelines are available for their construction. Modern 3-D visualization software portrays similar artistic realism but is, also, quantitatively precise.