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)

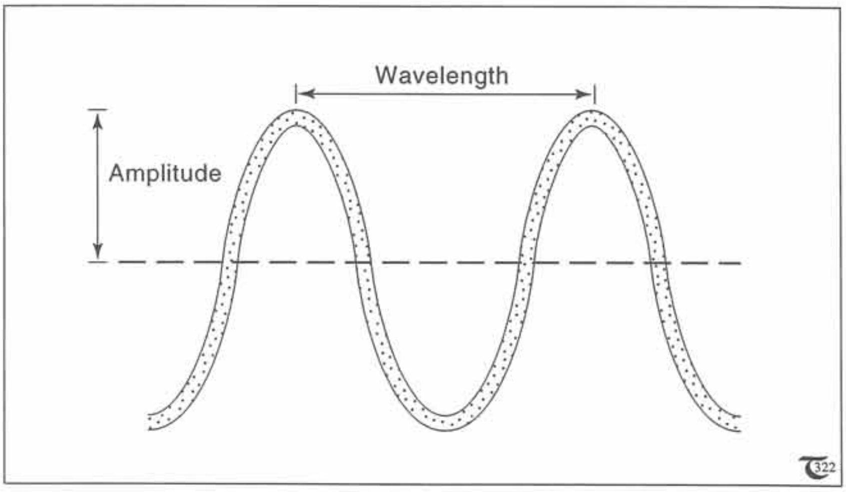


Figure 7-1: *Section perpendicular to the fold axes, defining wavelength and amplitude of the individual folds in a fold train.*

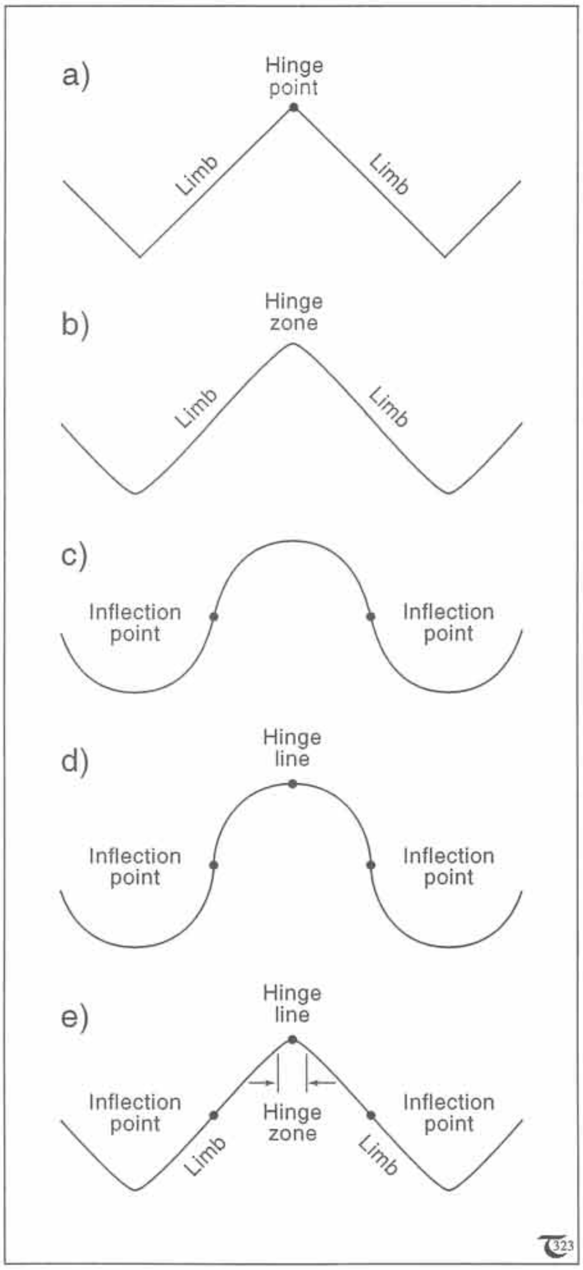


Figure 7-2: The geometry of folds. a) Zig-zag or chevron fold with straight limbs meeting in a single hinge line. b) Chevron fold with limbs connected by a hinge zone of gradually changing curvature. c) Gently curved folds with inflection points marking the points of minimum curvature. d) Hinge point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

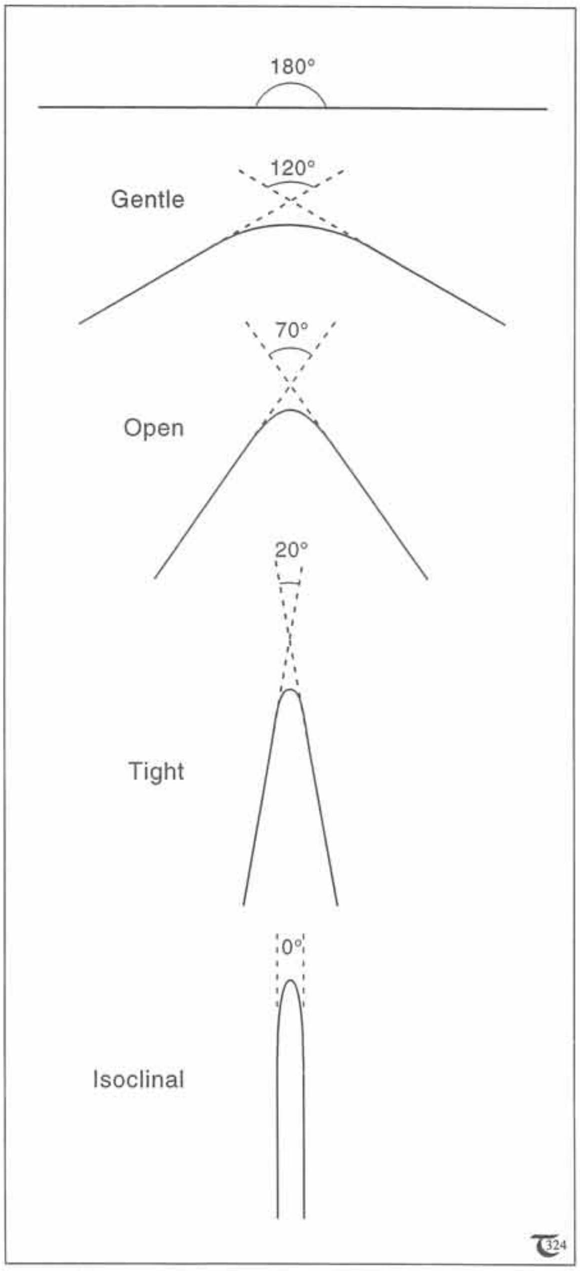


Figure 7-3: Classification of folds on the basis of the interlimb angle.

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

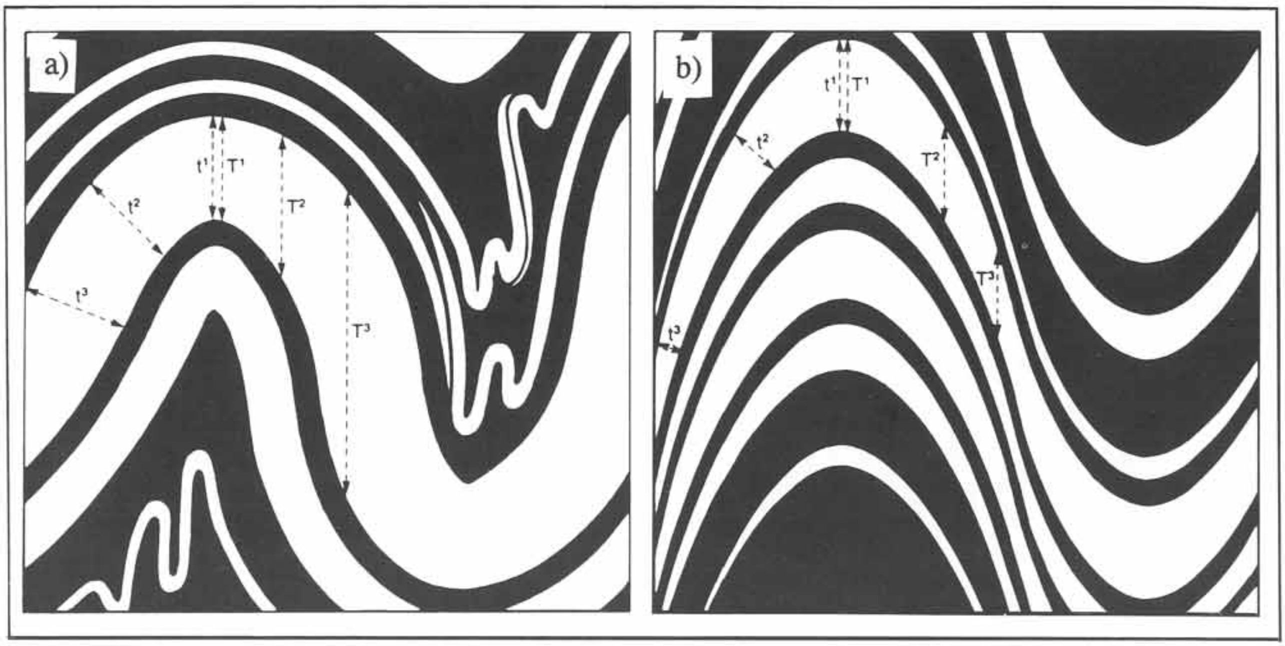


***Figure 7-4:** Fold classification on basis of layer thickness. a) Parallel or concentric folds with constant layer thickness. b) Similar folds with variable layer thickness.*

□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.

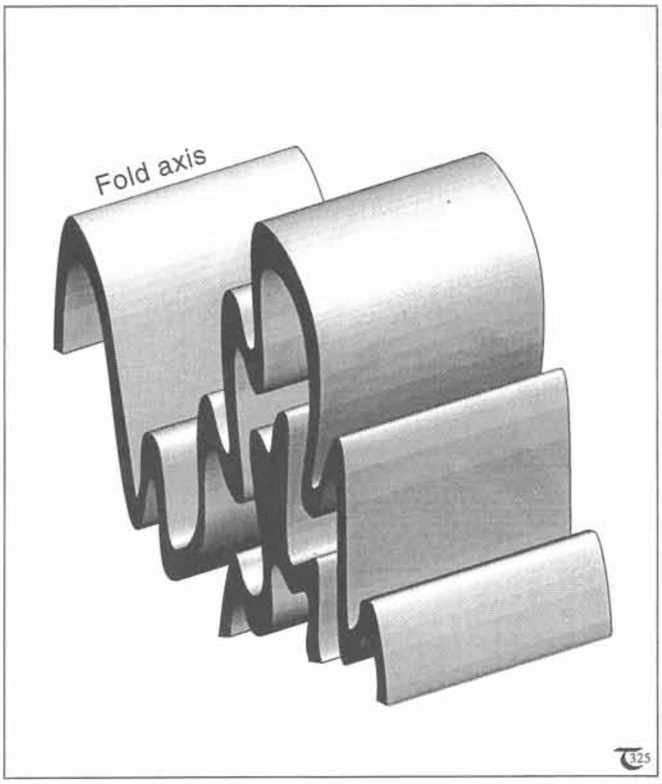


Figure 7-5: Cylindrical folds.

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).

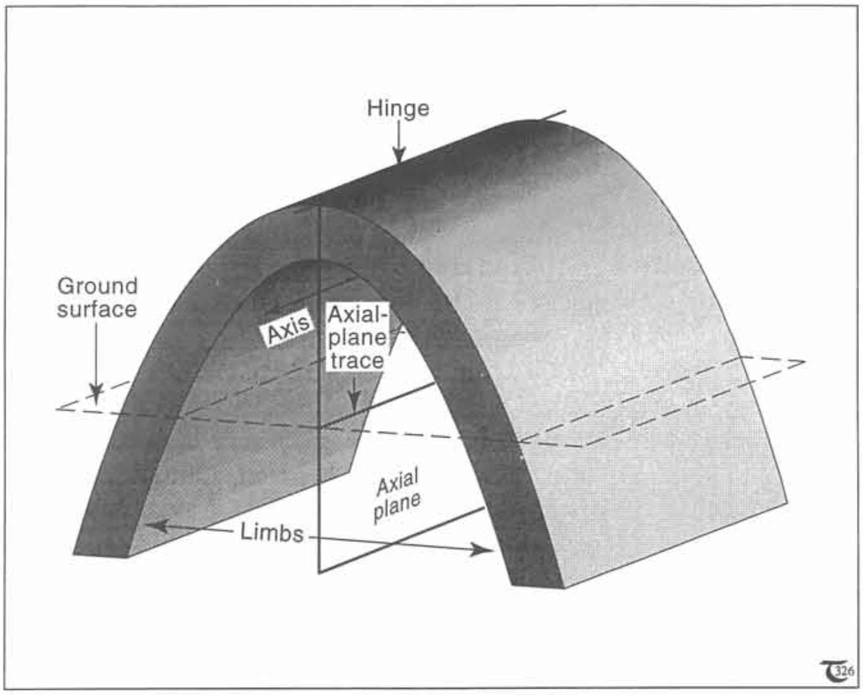


Figure 7-6: Upright, horizontal fold.

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 7-7a: 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-

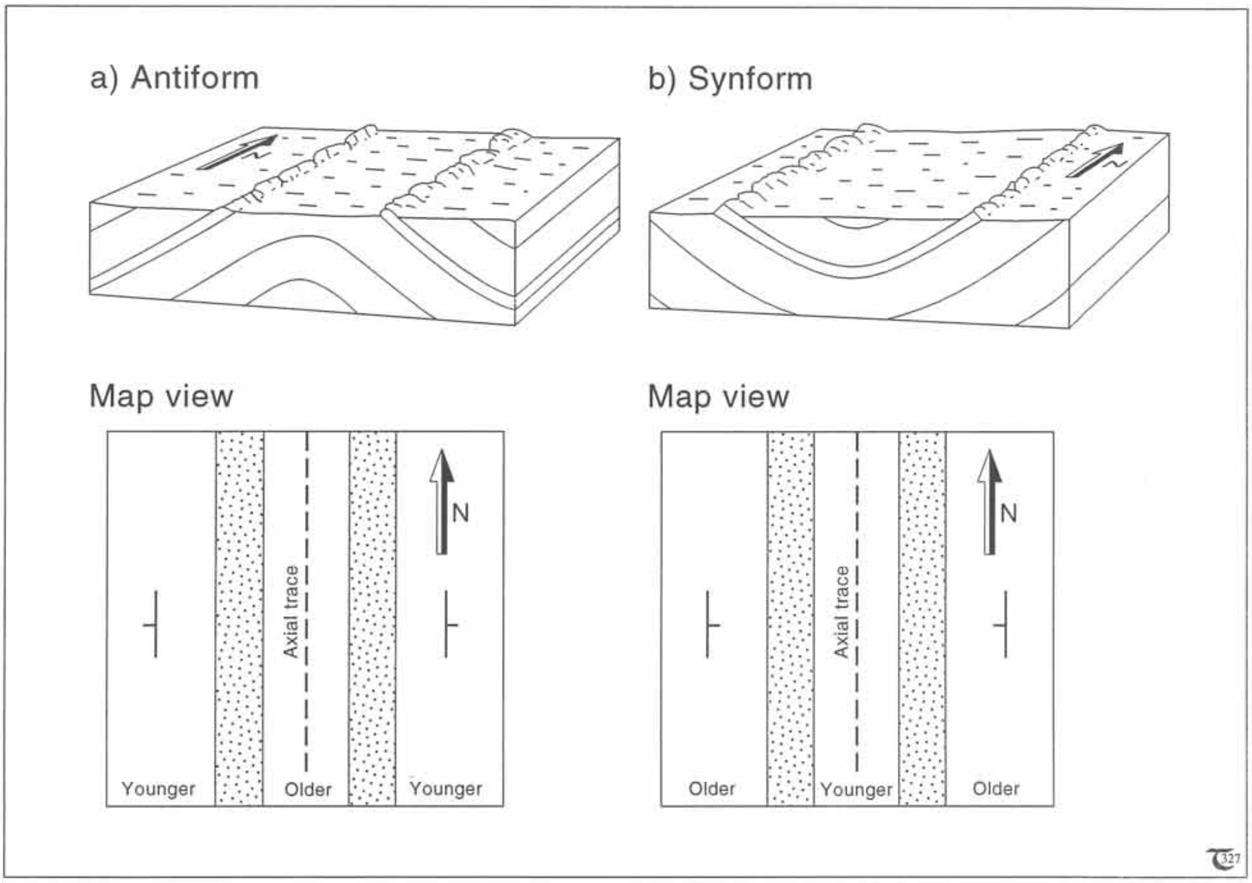


Figure 7-8: *Perspective diagrams and map views of: (a) antiform and anticline, and (b) synform and syncline. All are upright.*

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

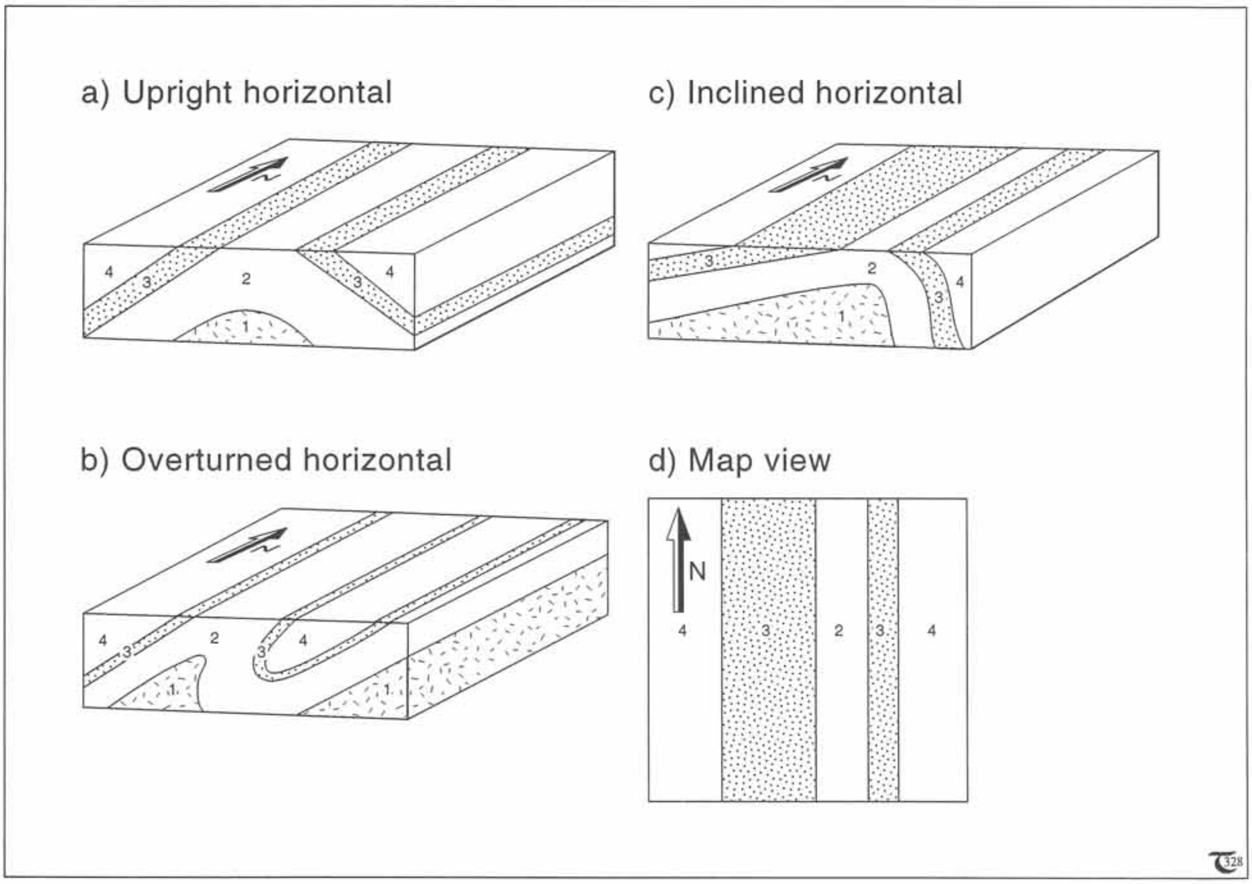


***Figure 7-9:** a) to d) Horizontal folds with particular orientation of fold limbs and axial plane: (a) upright fold, (b) overturned fold, (c) inclined fold, and (d) map view of inclined fold.*

□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.

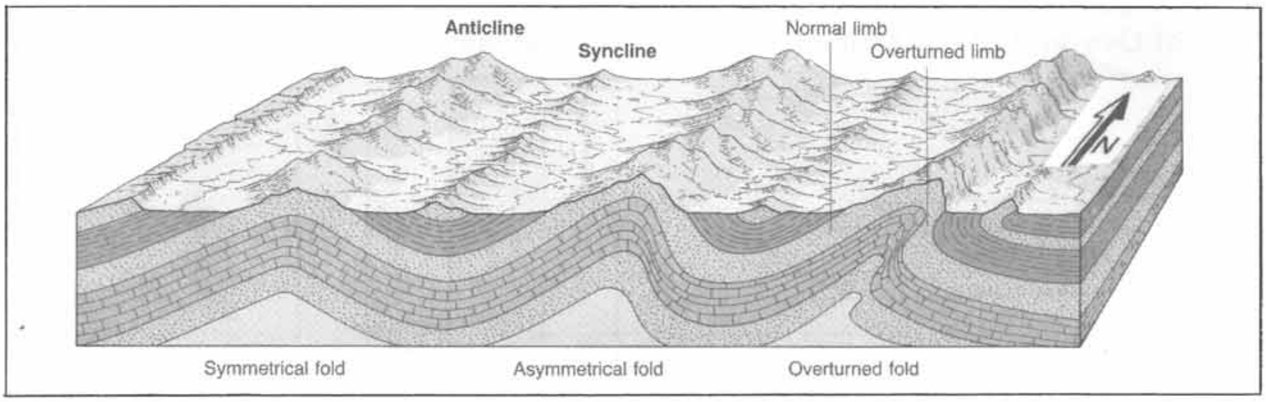


Figure 7-10: *Block diagram of terrain with horizontal folds. The dip of the east limb of the antiformal closures becomes progressively steeper towards the east and is overturned in the easternmost antiform.*

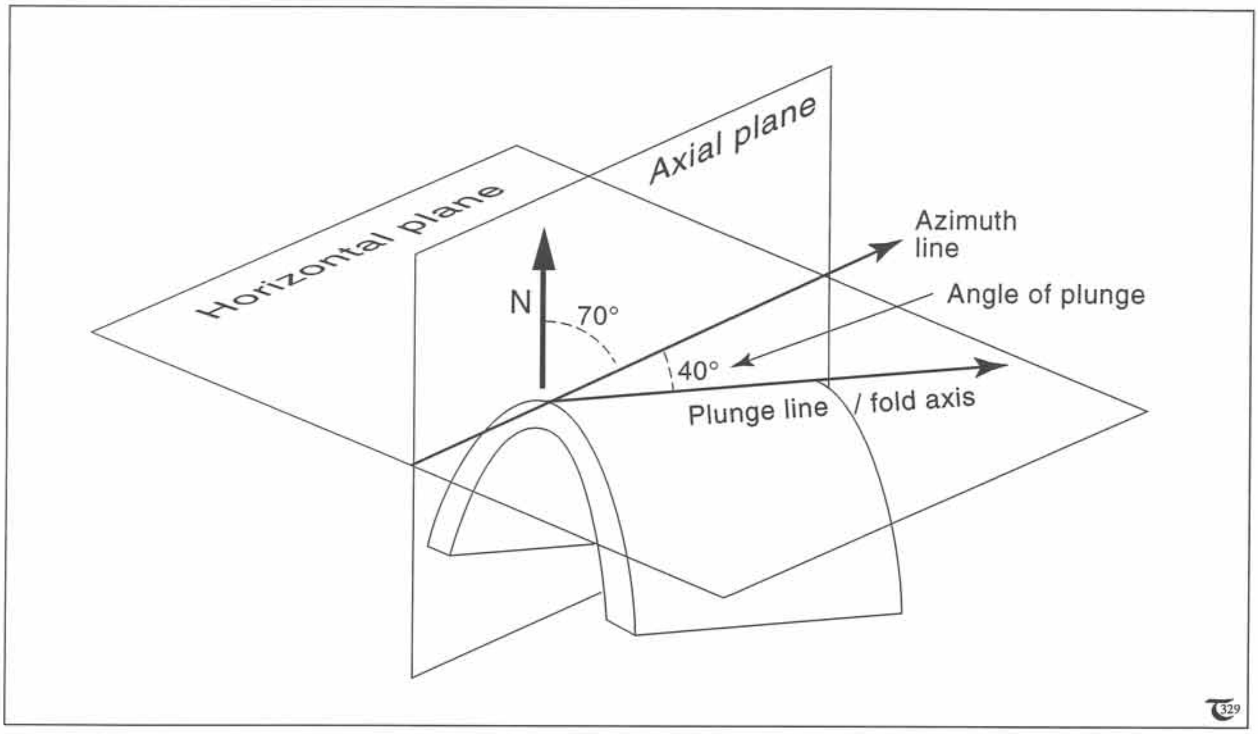


Figure 7-11: *Upright, plunging fold.*

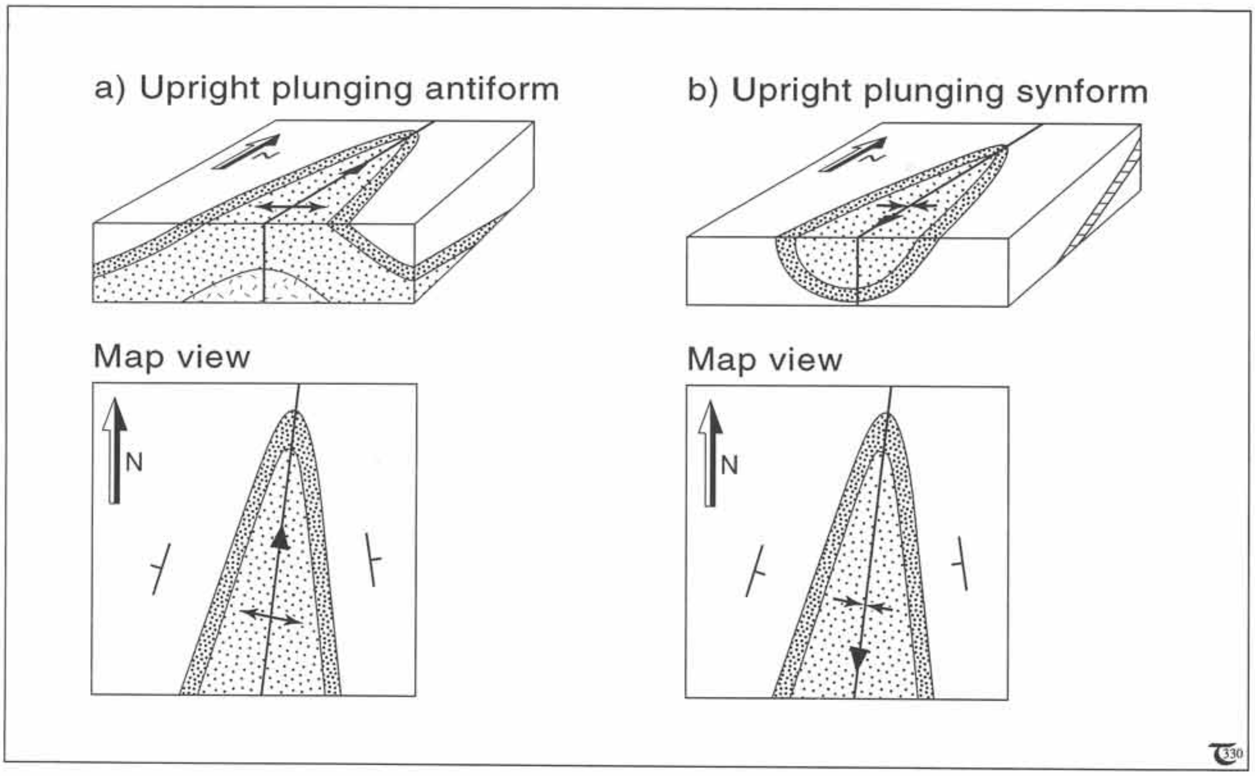


Figure 7-12: *Perspective diagrams and map views of: (a) upright, north-plunging antiform, and (b) upright, south-plunging synform. Note the similarity in the map patterns of both folds.*

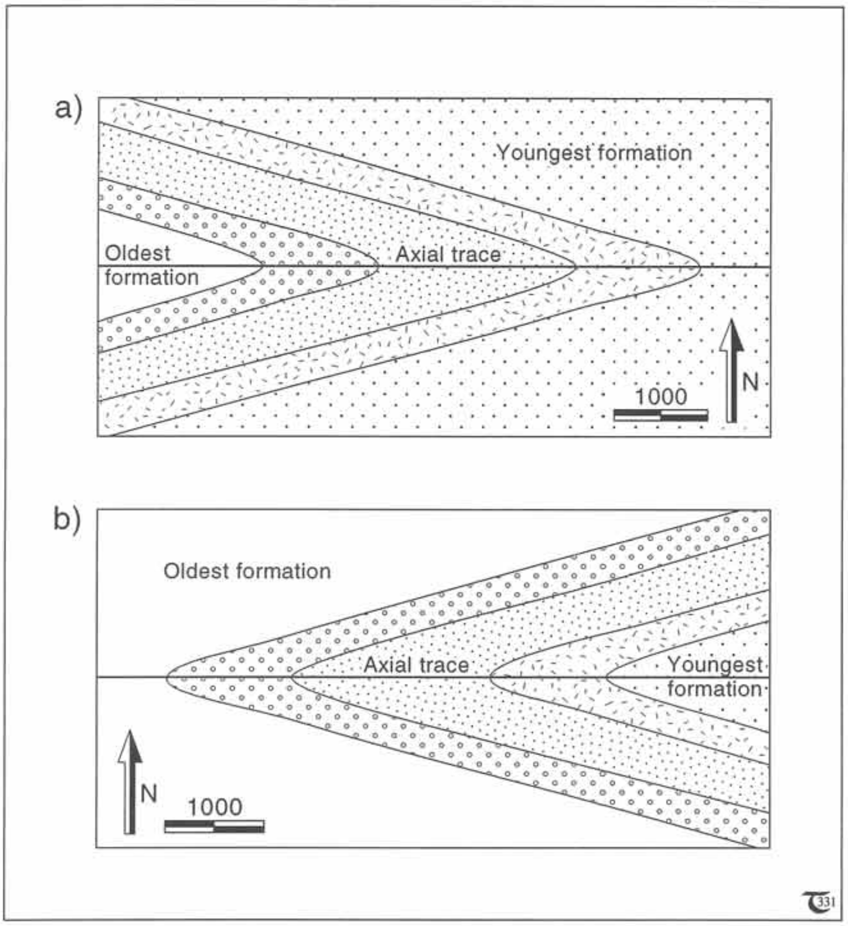


***Figure 7-13:** a) & b) Map patterns of plunging folds: (a) east-plunging anticline, and (b) east-plunging syncline.*

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).

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).

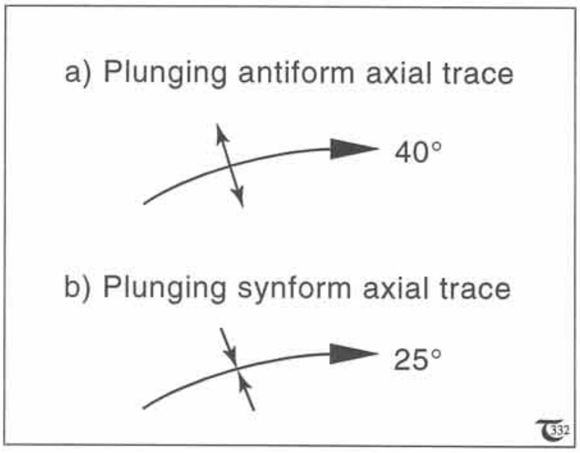


***Figure 7-14:** a) & b) Map symbols used for indicating the surface trace of the axial planes of: (a) plunging antiform, and (b) plunging synform.*

□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.

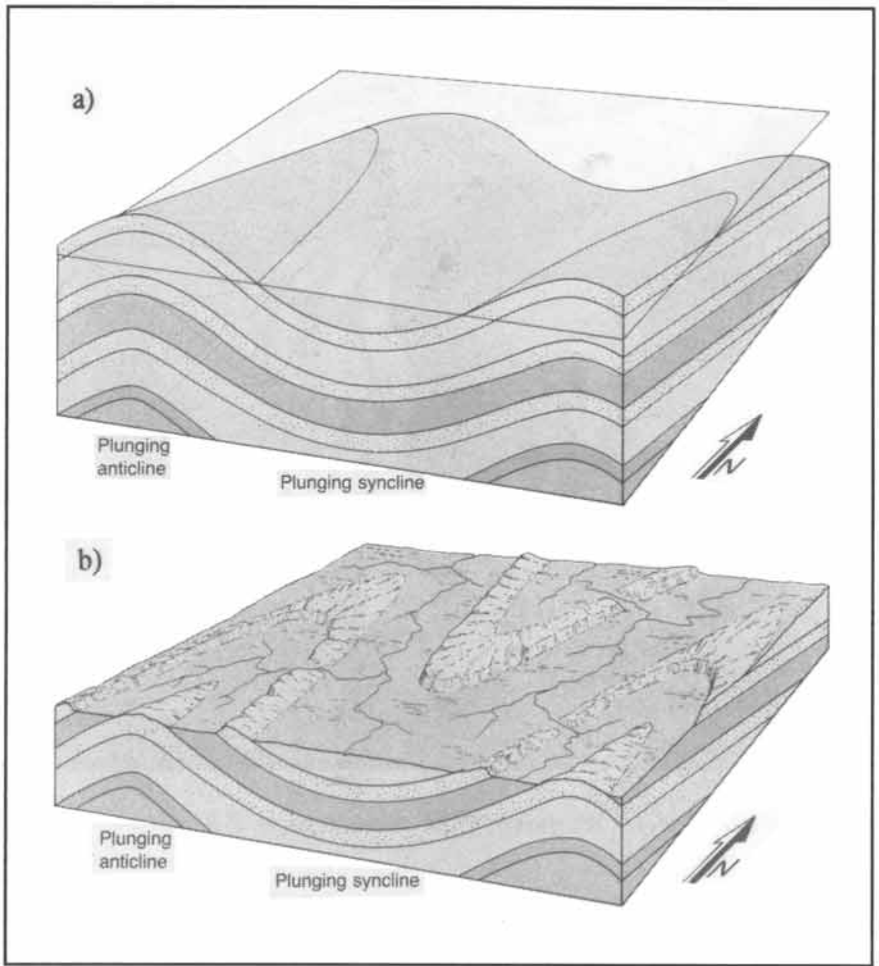
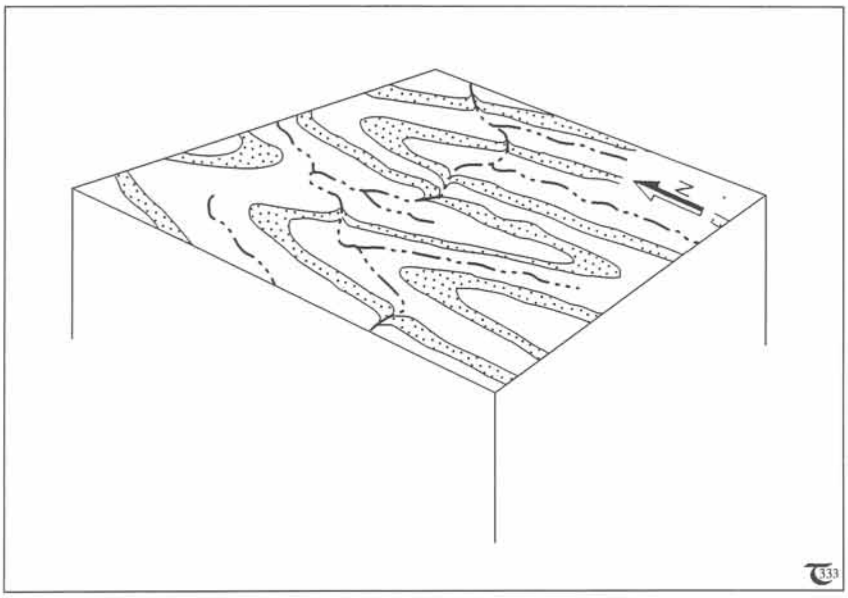


Figure 7-15: *a) & b) Plunging folds: (a) before erosion, and (b) after erosion. The outcrop pattern of the eroded beds forms V-shapes alternately pointing north and south.*



□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.*

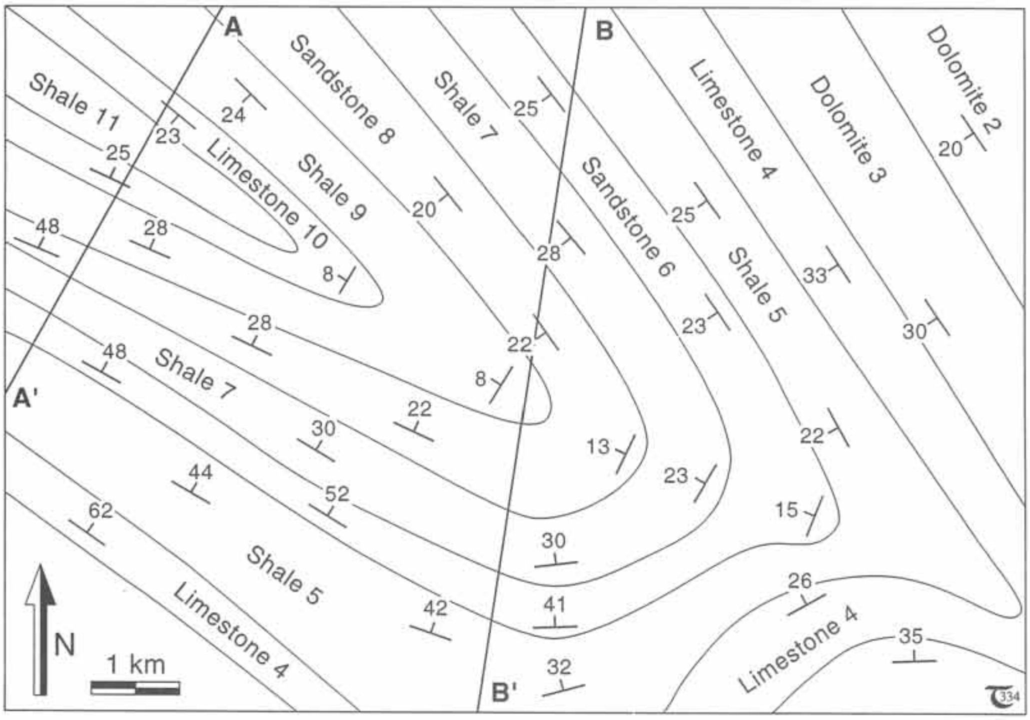


Figure 7-18: *Map of flat terrain with plunging folds. See exercise 7-9.*

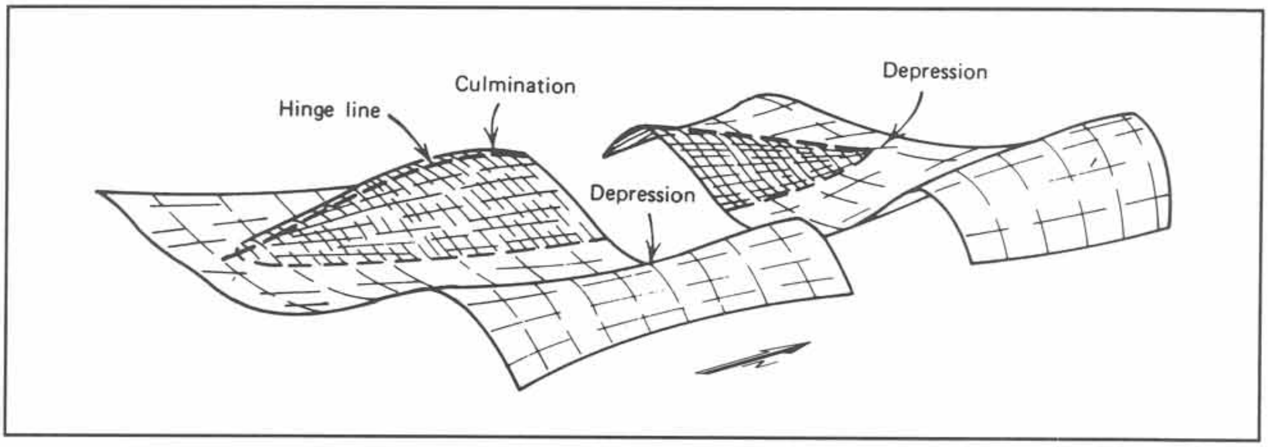


Figure 7-19: *Structural surface, marking doubly plunging fold. The axial culmination separates the segments of opposite plunge directions.*

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.

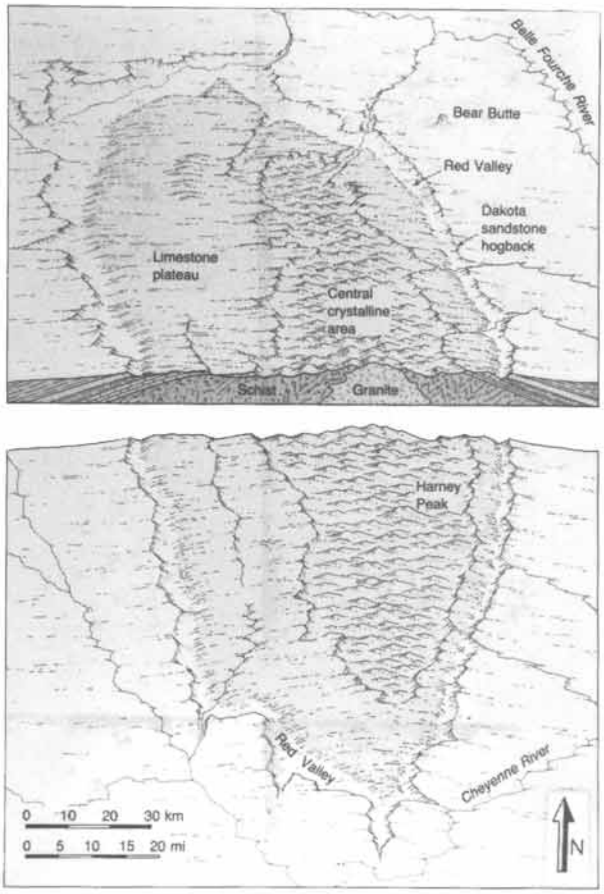


Figure 7-20: *Oblique map view of the doubly plunging anticline or elongate dome of the Black Hills, South Dakota.*

☐**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.**

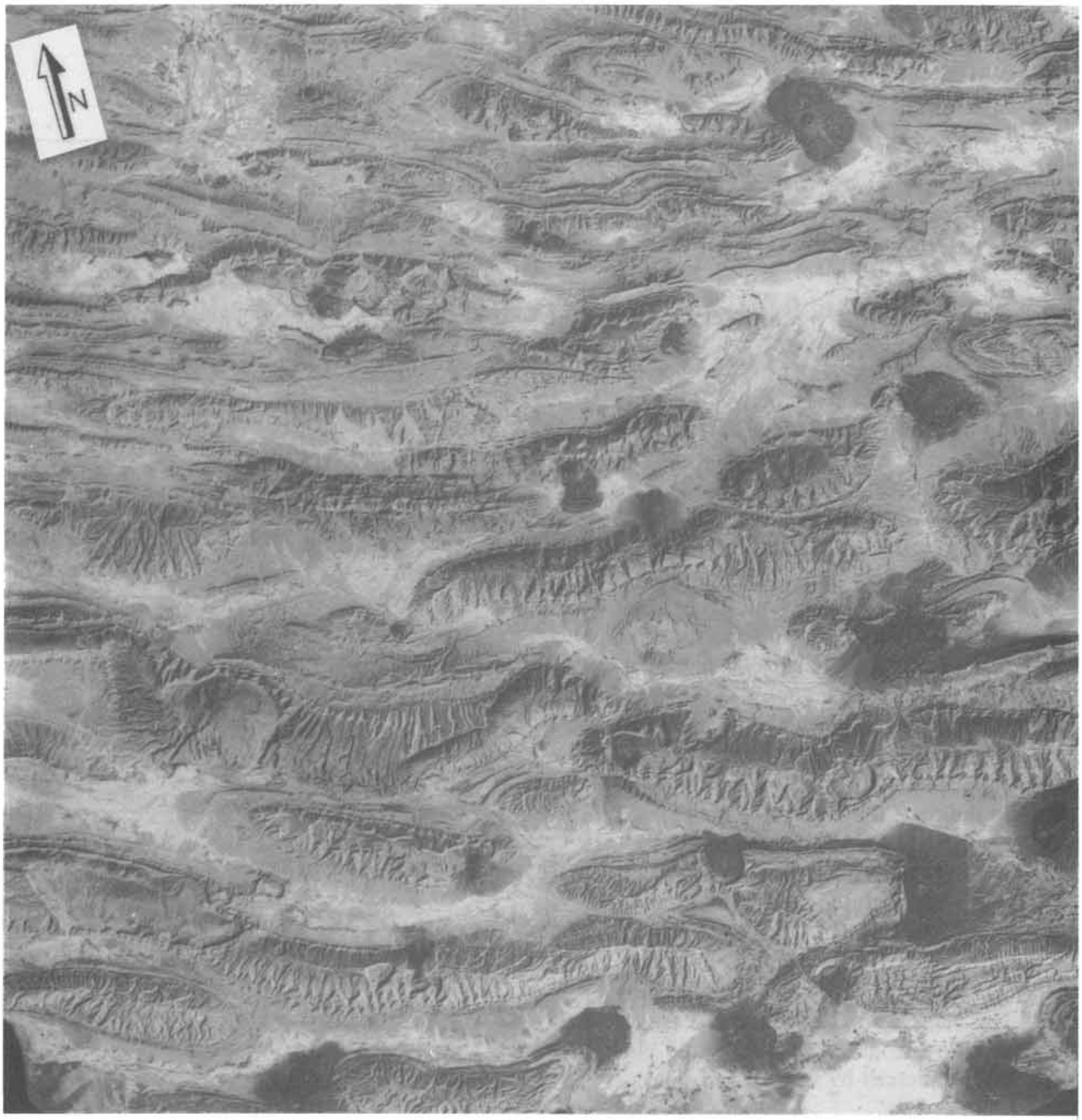


Figure 7-21: *Satellite image of doubly plunging folds in the Zagros Mountains, southeastern Iran. This landsat image covers about 180 by 180 square kilometers.*

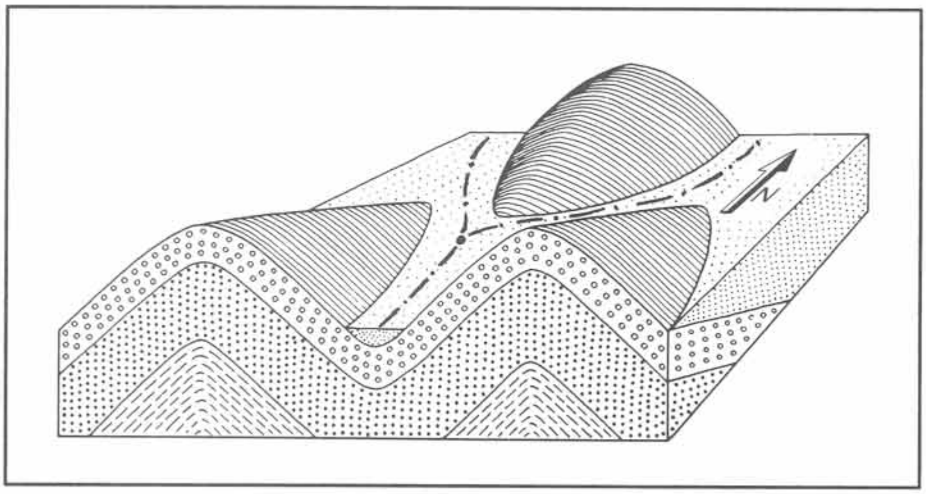


Figure 7-22: *Perspective diagram of doubly plunging folds and the bifurcation point in the map pattern where three plunging anticlines meet.*

□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.

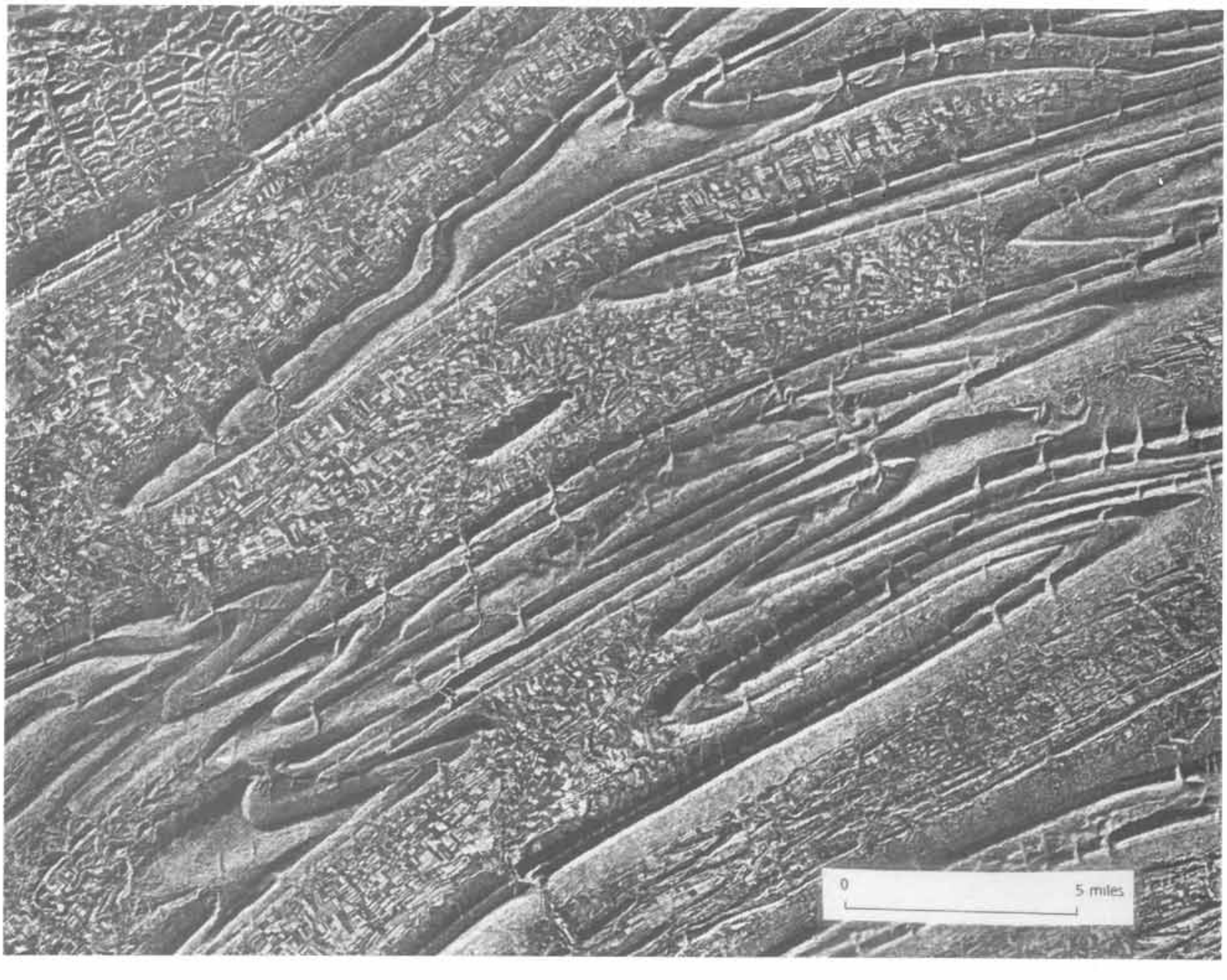


Figure 7-23: *Radar image of the Valley-and-Ridge province of the Appalachians.*

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.

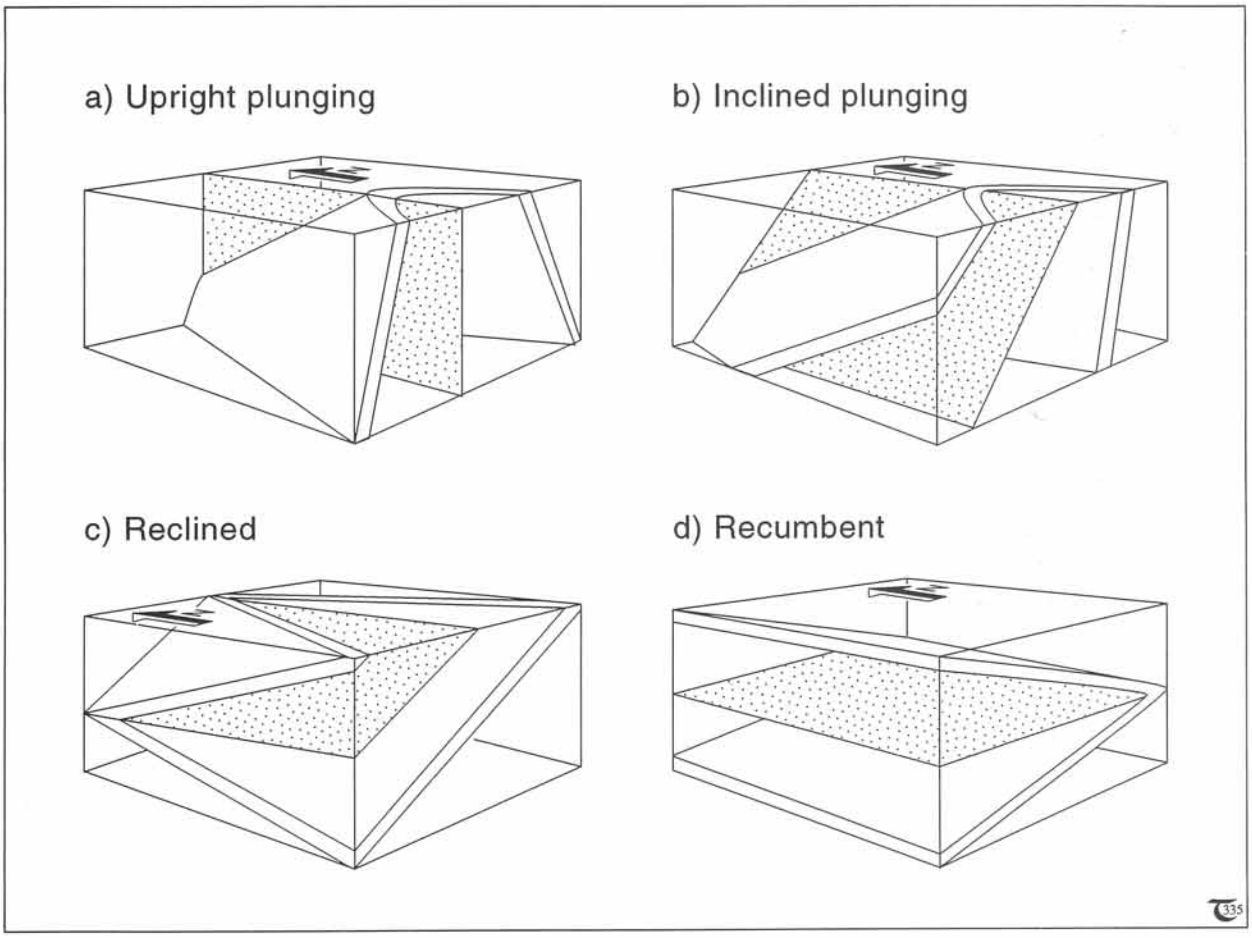


***Figure 7-24:** a) to d) Four major fold orientations, deviating from that of upright horizontal folds. Fold orientations shown are: (a) upright horizontal, (b) inclined plunging, (c) reclined, and (d) recumbent.*

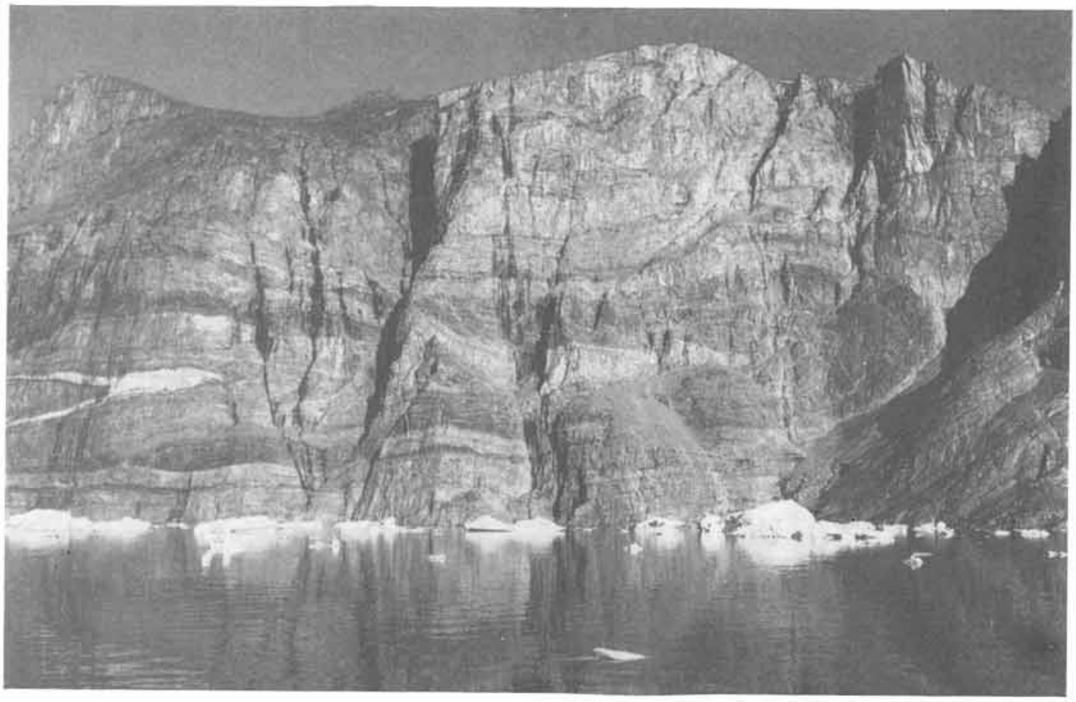


Figure 7-25a: Recumbent fold in steep cliffs of Precambrian gneisses at the Umanak area, Greenland. Cliff height is about 1.5 kilometers.

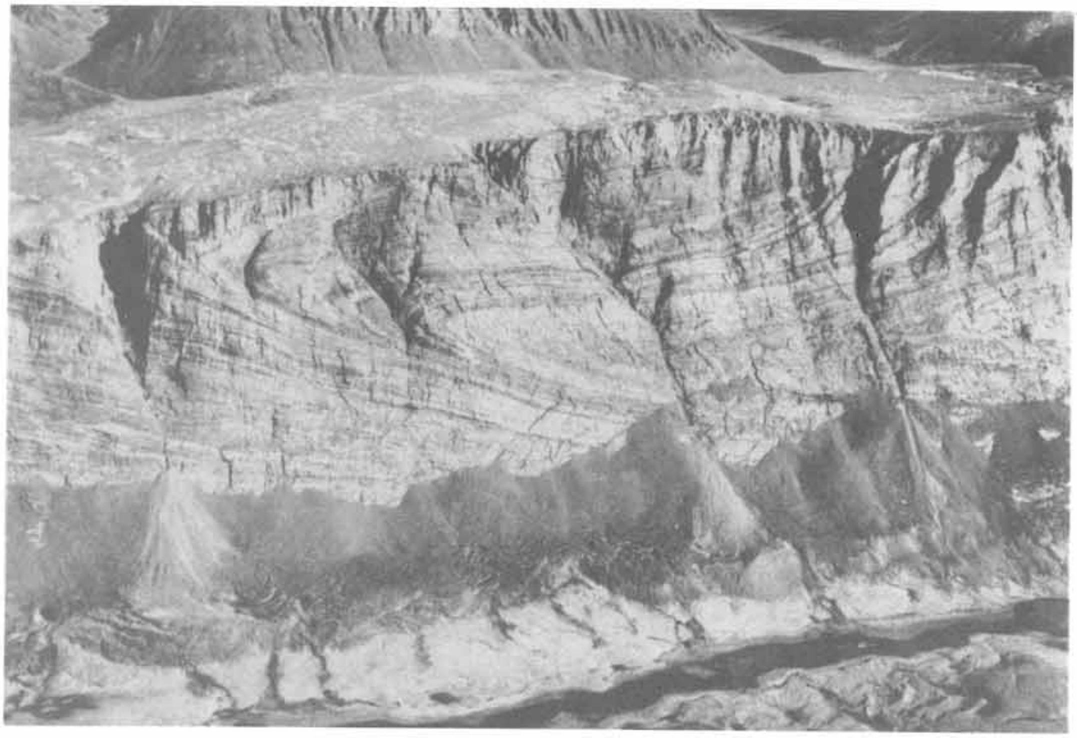


Figure 7-25b: Recumbent fold in Caledonian gneisses of western Greenland. Cliff height is about 800 meters.

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