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.

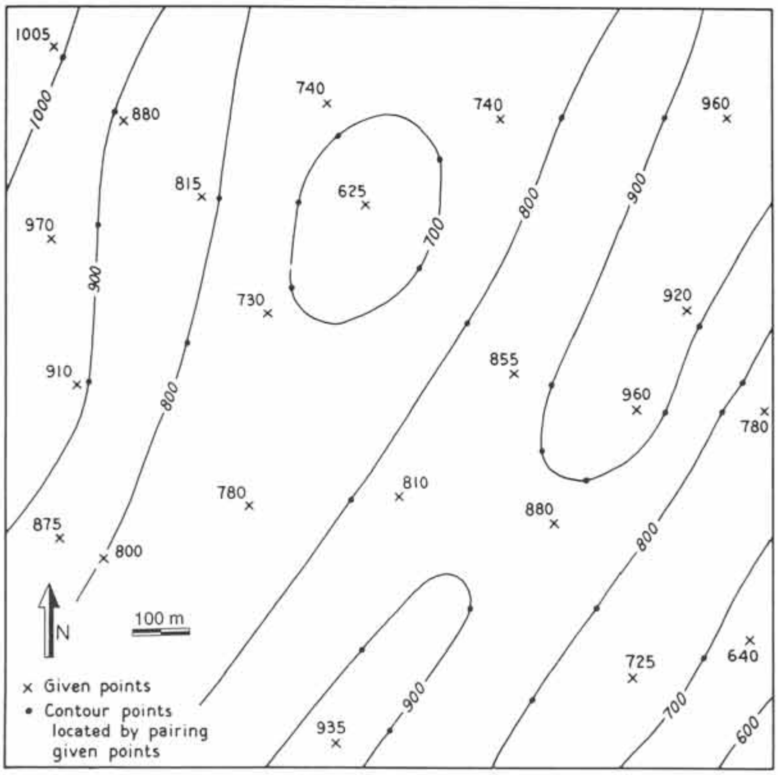

Figure 8-1: *Structure contours, above sea-level, for the top surface of an undulating hydrocarbon reservoir.*

□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.

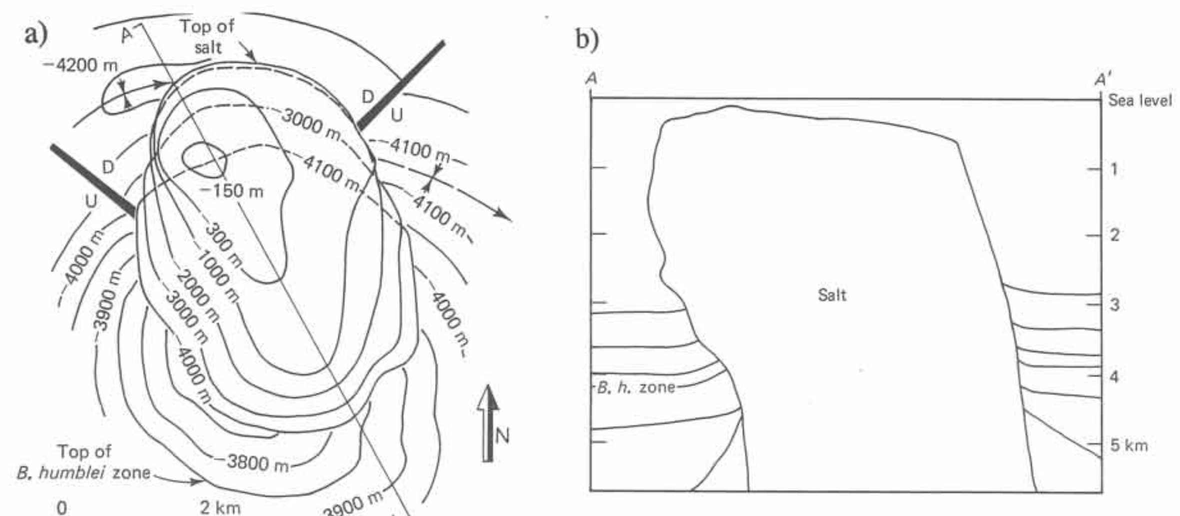

Figure 8-2: *a) Structure-contour map of Cote Blanche Island salt dome, Louisiana. b) Section along line A-A' across the dome.*

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.

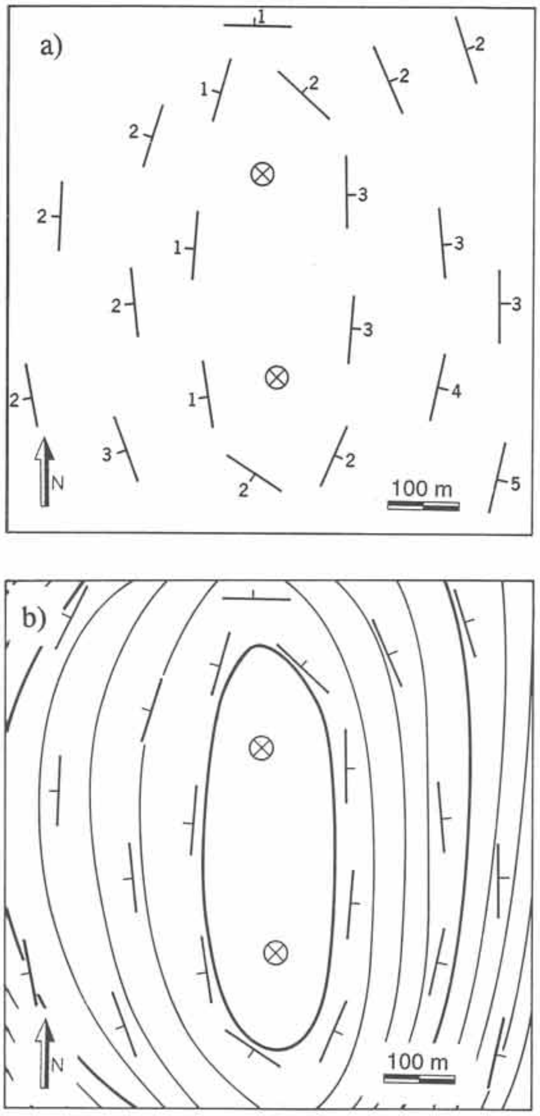

Figure 8-3: *a) Structure map indicating strike and dip of sedimentary beds. b) Form-line contour map of the same area.*

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

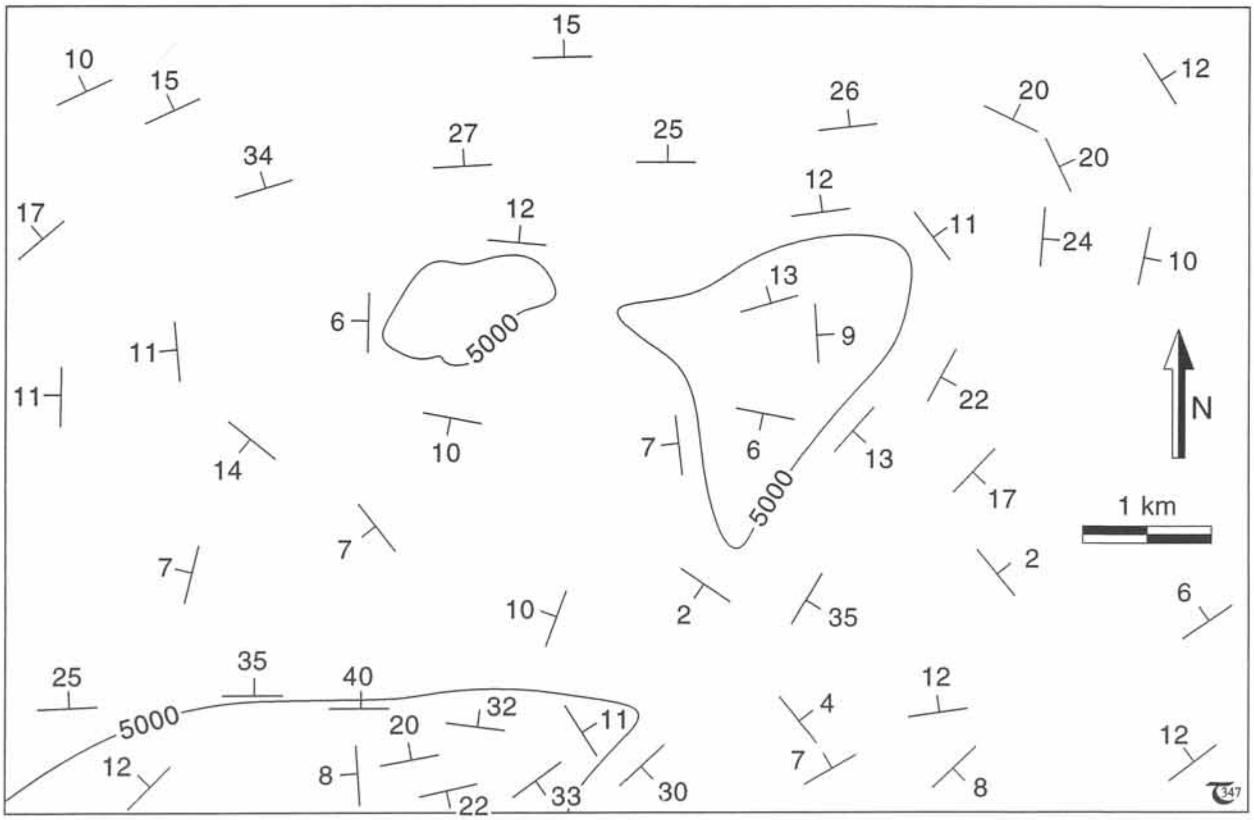

Figure 8-4: Structural map with 5,000 foot structure contour. See exercise 8-2.

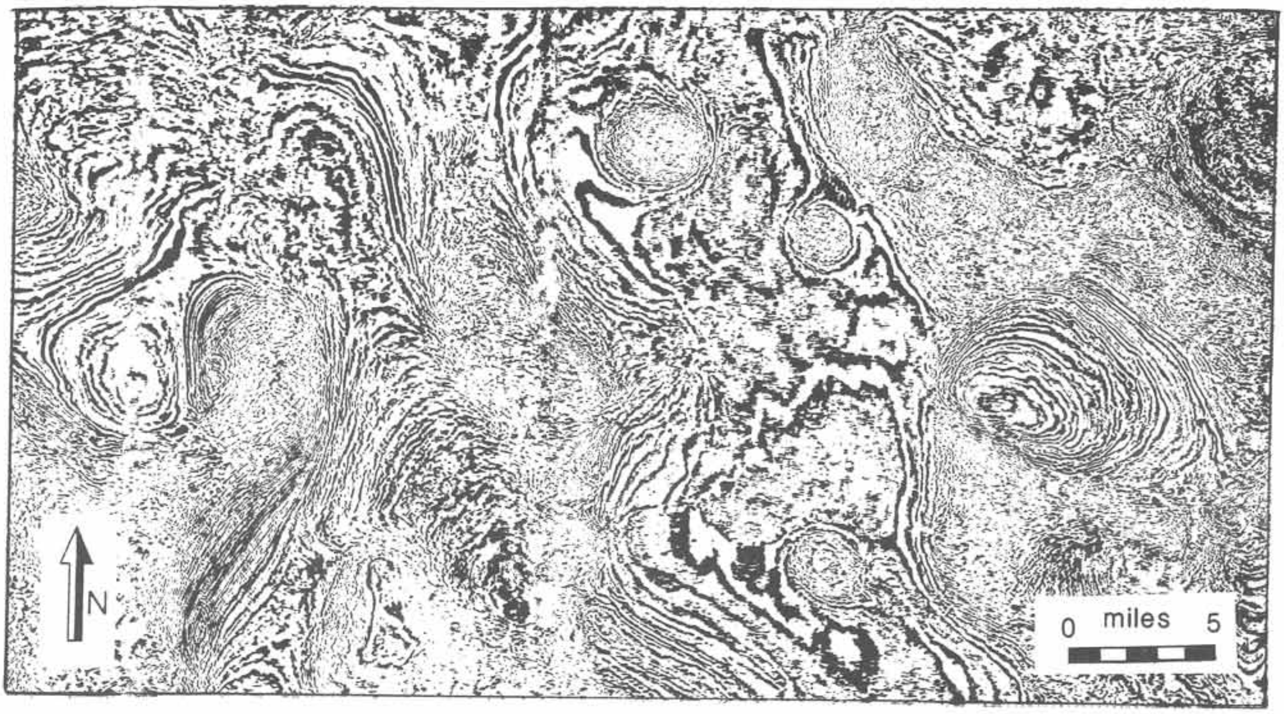

Figure 8-5: Seismocrop or time-slice map of salt domes below the floor of the Gulf of Mexico, south of New Orleans, Louisiana. This horizontal seismic map is synthesized by 3-D migration.

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.

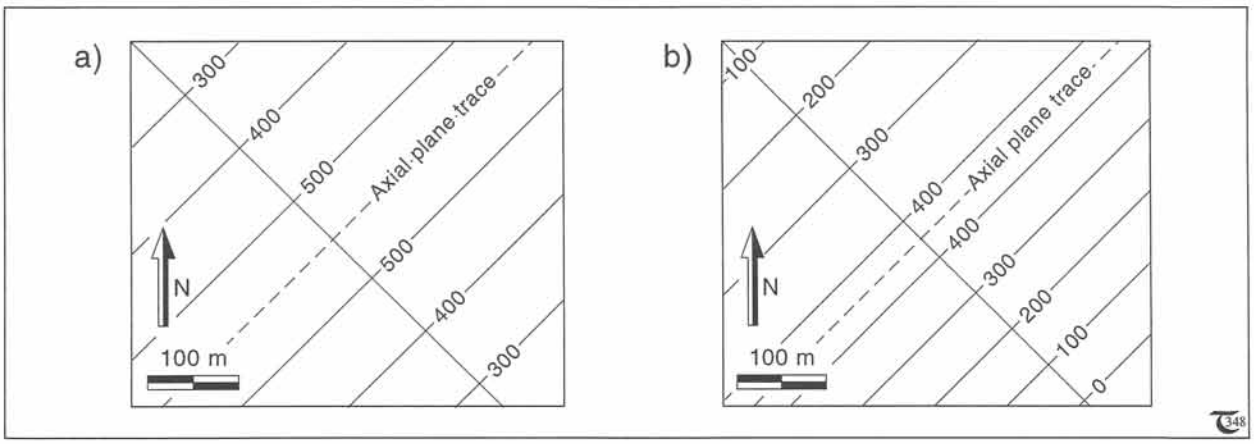

***Figure 8-6:** a) & b) Structure-contour maps. Contours are in meters above sea-level. See exercise 8-4.*

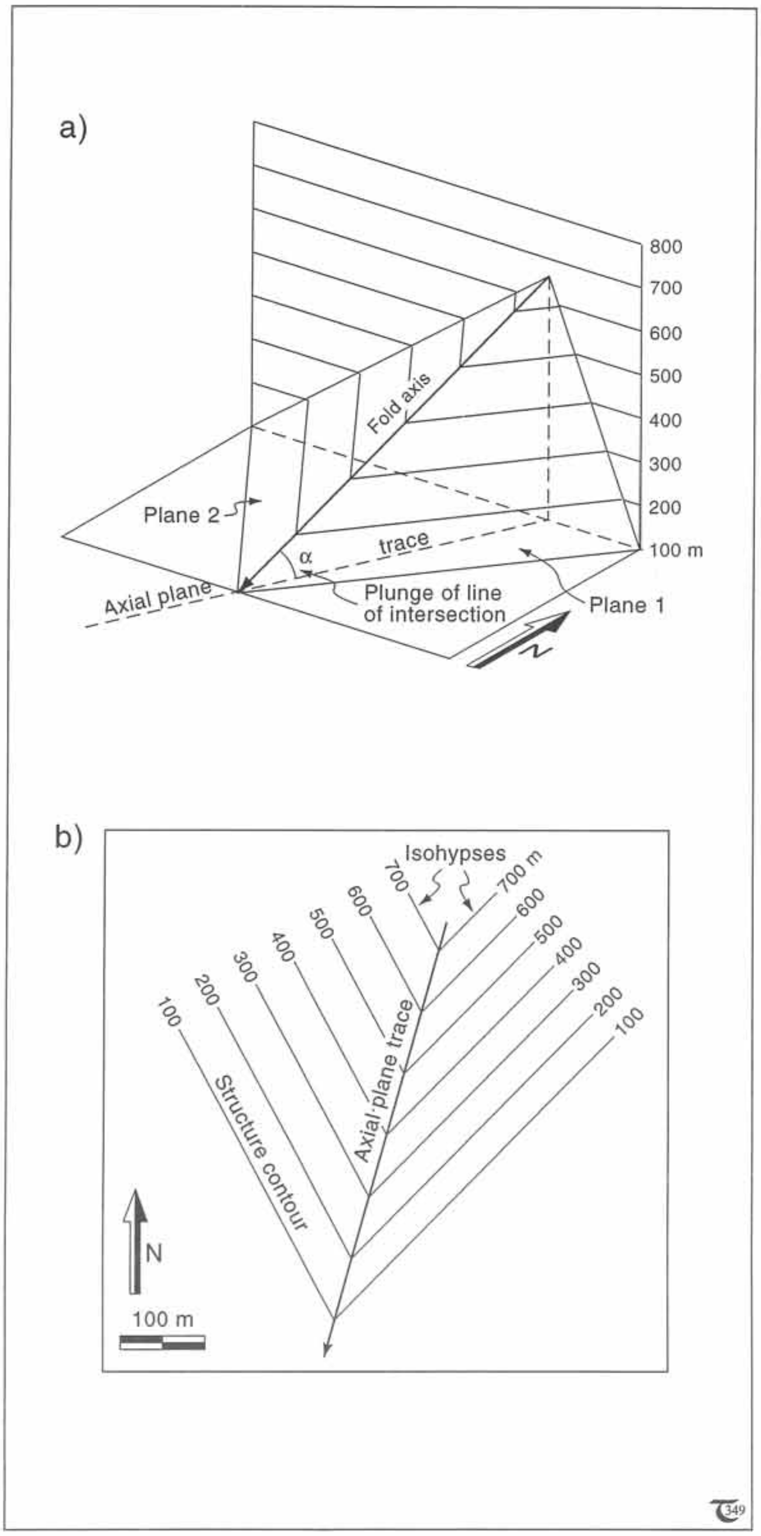

Figure 8-7: a) Perspective view of structure contours on south-plunging chevron fold. b) Map projection of structure contours for plunging chevron fold shows typical herring-bone pattern.

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.

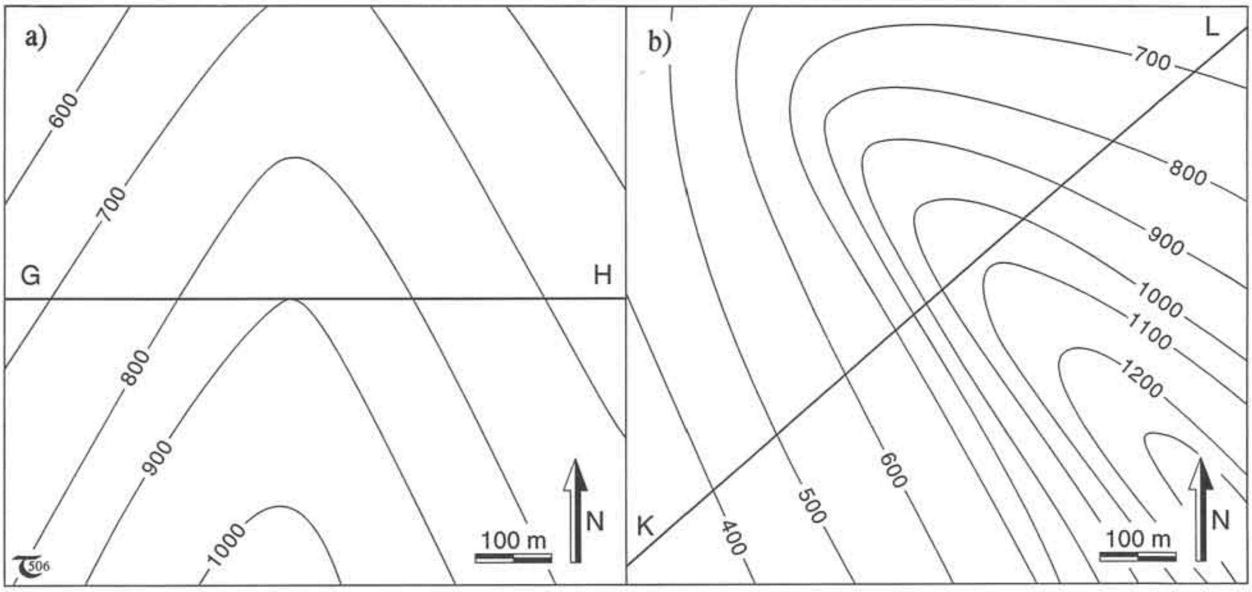

Figure 8-8: *a) & b) Structure-contour maps. Map (a) is contoured in meters below sea-level. Contours in map (b) are in meters above sea-level. See exercise 8-6.*

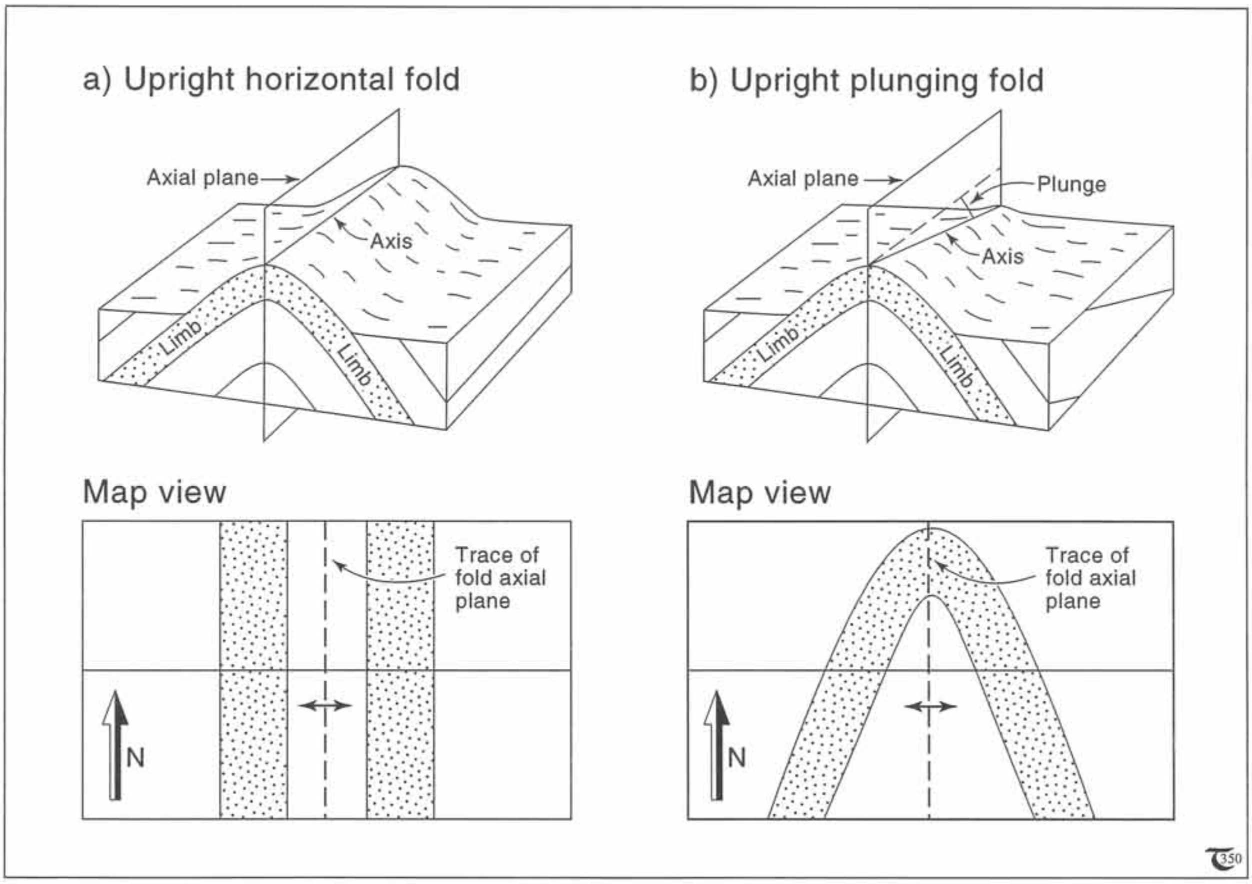

Figure 8-9: *a) & b) Perspective diagrams and typical map views for: (a) upright, horizontal folds, and (b) upright, plunging folds. The map views show horizontal slices through these structures after erosion.*

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.

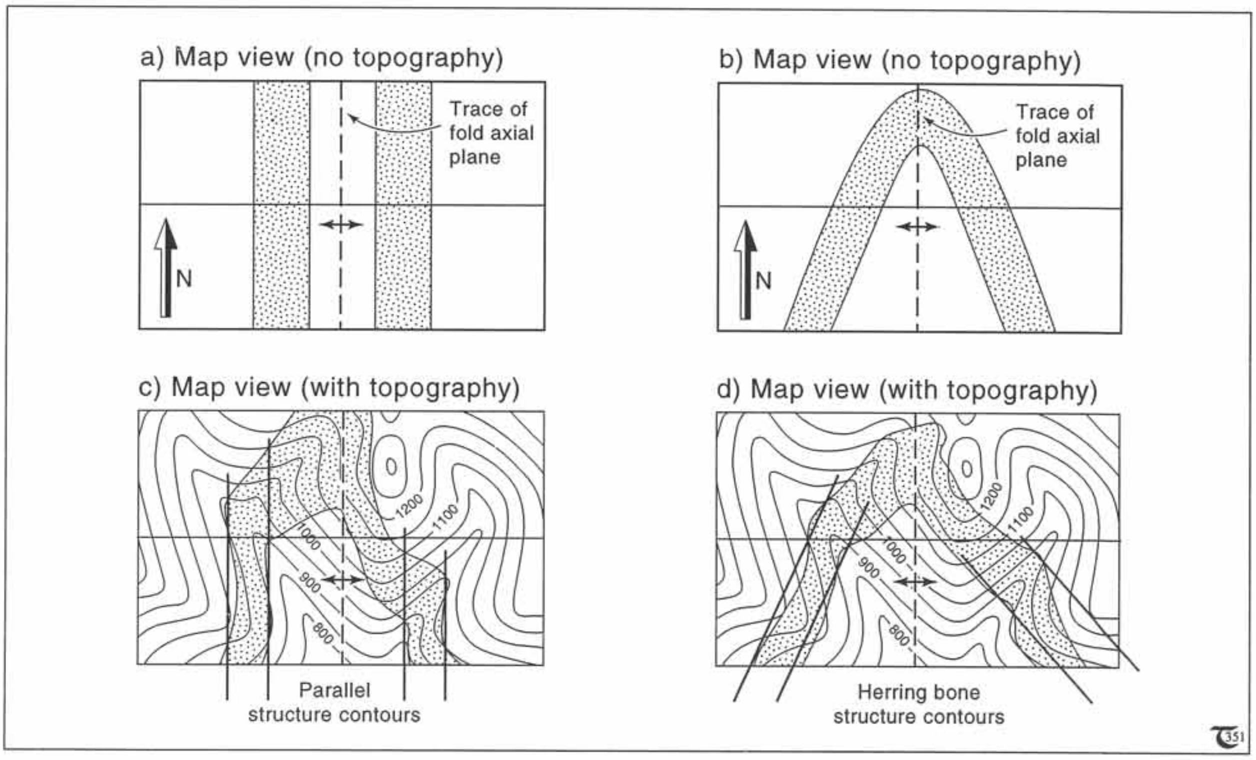

***Figure 8-10:** a) & b) Map views of upright, horizontal and upright, plunging folds in flat terrains. c) & d) Map views of upright, horizontal and upright, plunging folds in terrain of high topographic relief.*

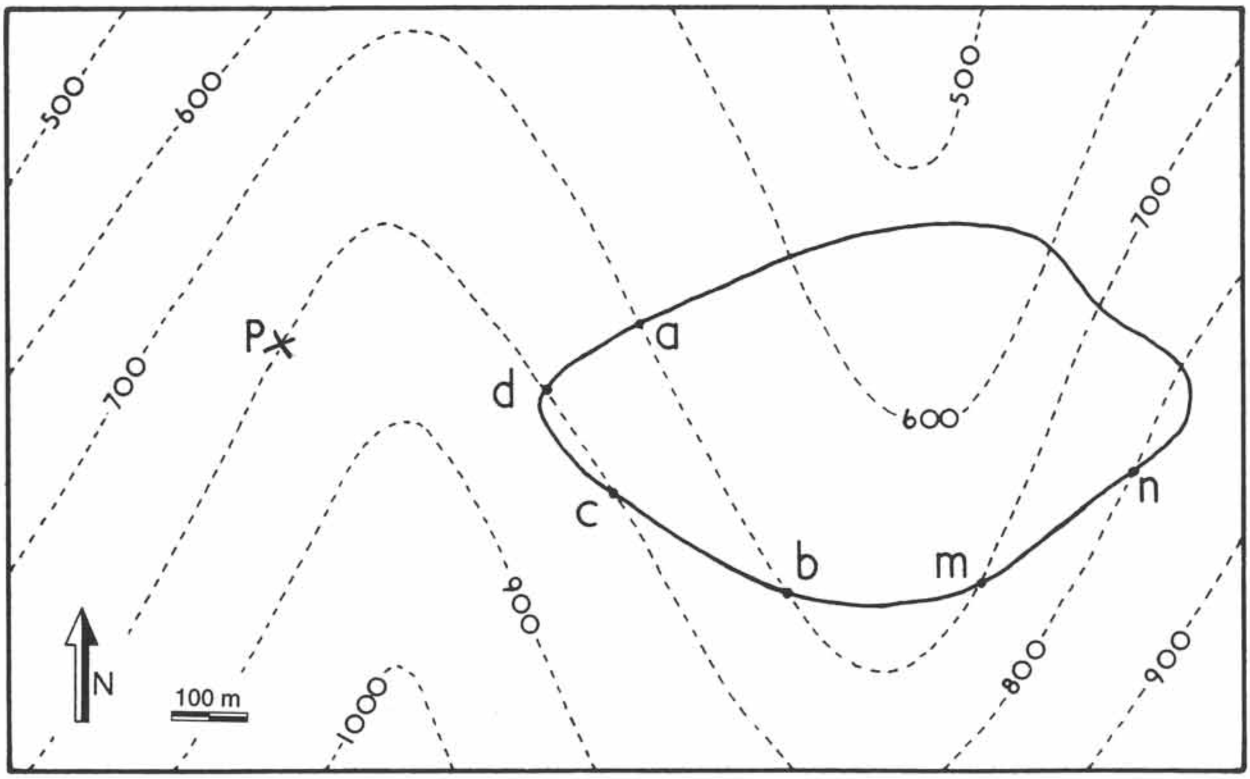

Figure 8-11: Outcrop pattern of coal seam on topographic base map. See exercise 8-7.

☐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.

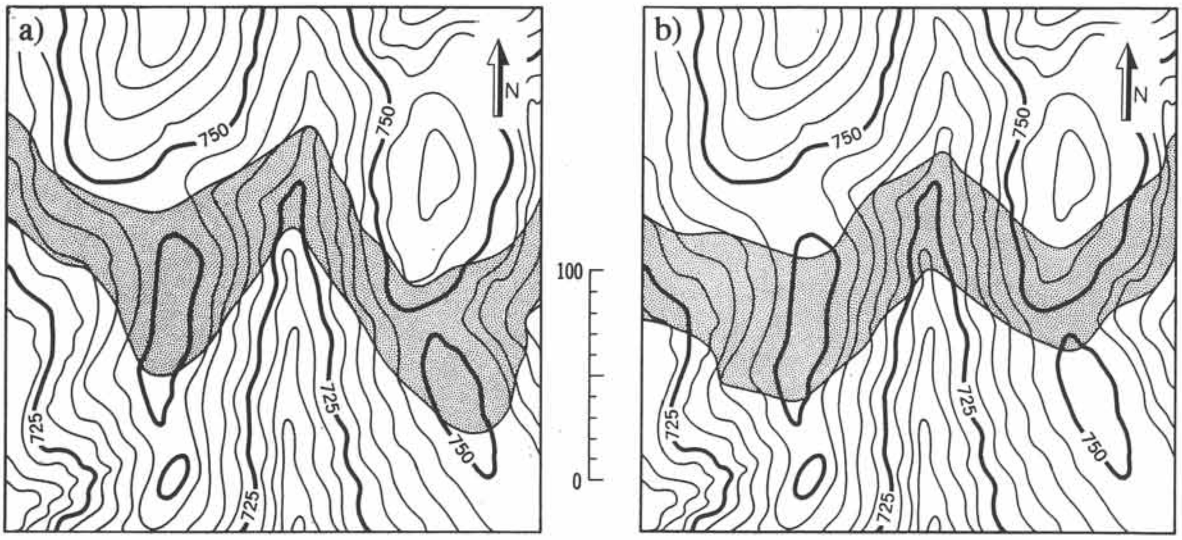

Figure 8-12: a) & b) Outcrop pattern of sandstone formation in two different areas of identical topography. Contours are in meters.

☐**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?**

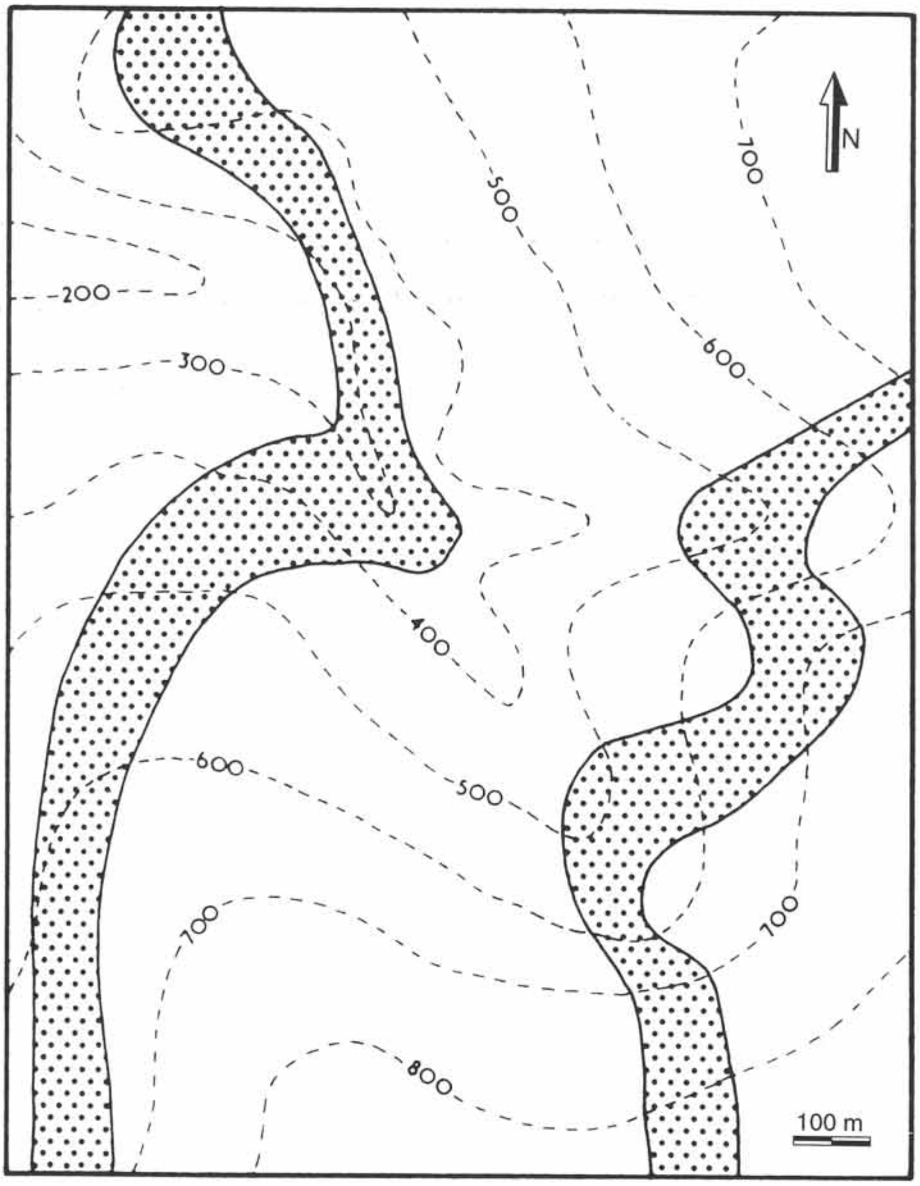

Figure 8-13: *Outcrop pattern of sandstone formation on topographic base map. See exercise 8-9. Contours are in meters.*

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).

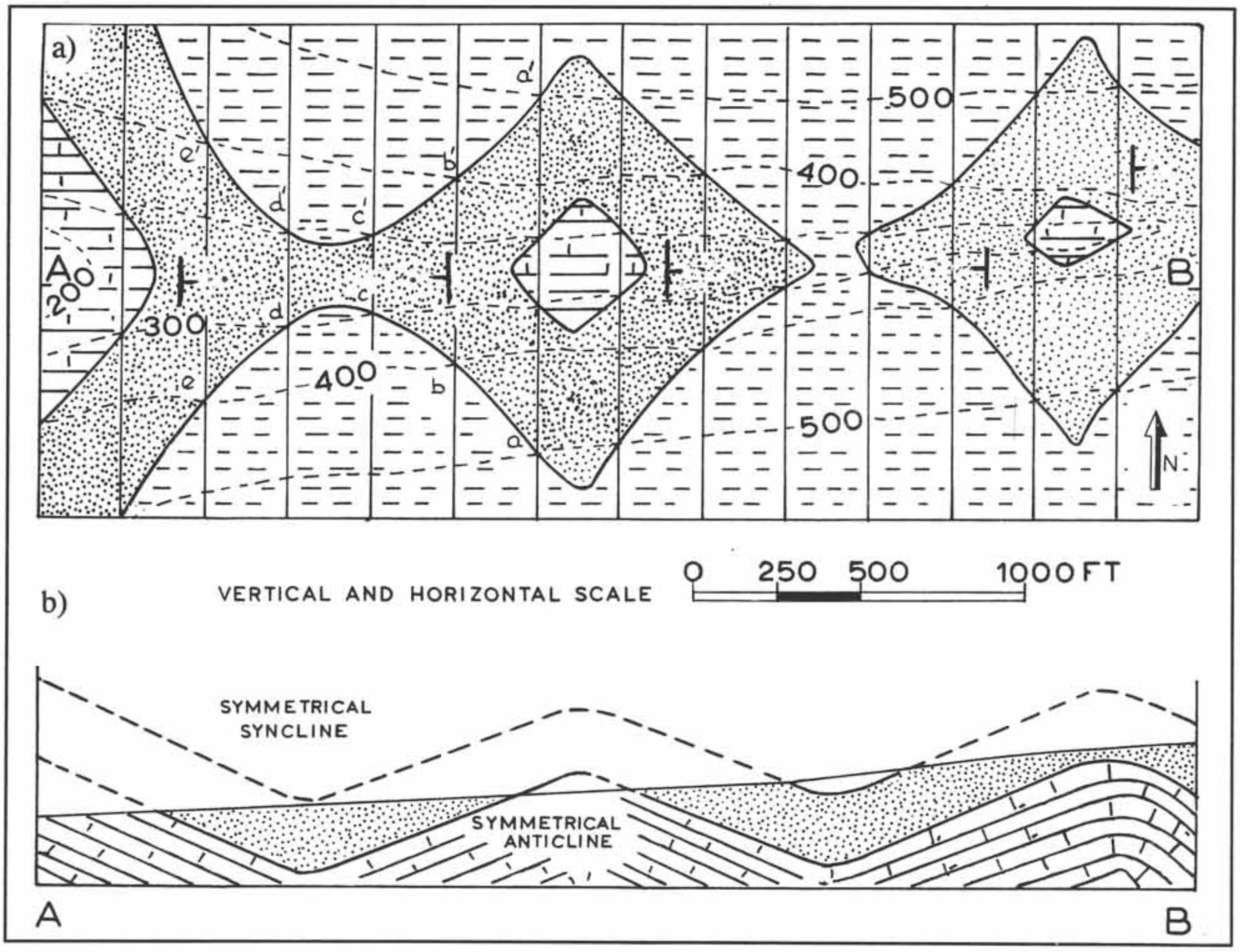

Figure 8-14: a) Map pattern of upright, horizontal folds in sedimentary sequence, transected by a westward draining stream valley. b) East-west section across the map, as indicated.

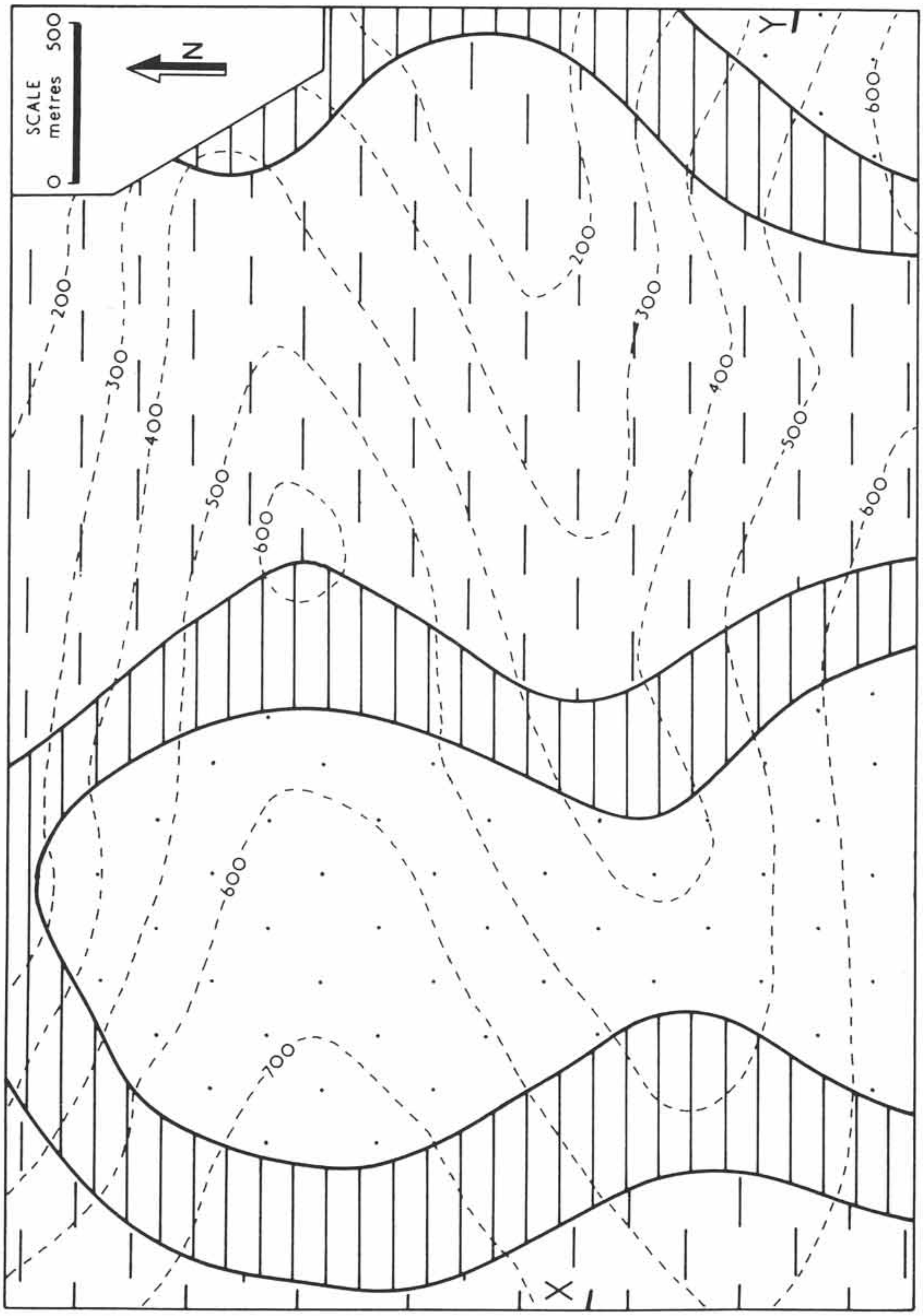

Figure 8-15: Complete geological outcrop pattern on topographic base map. See exercise 8-10.

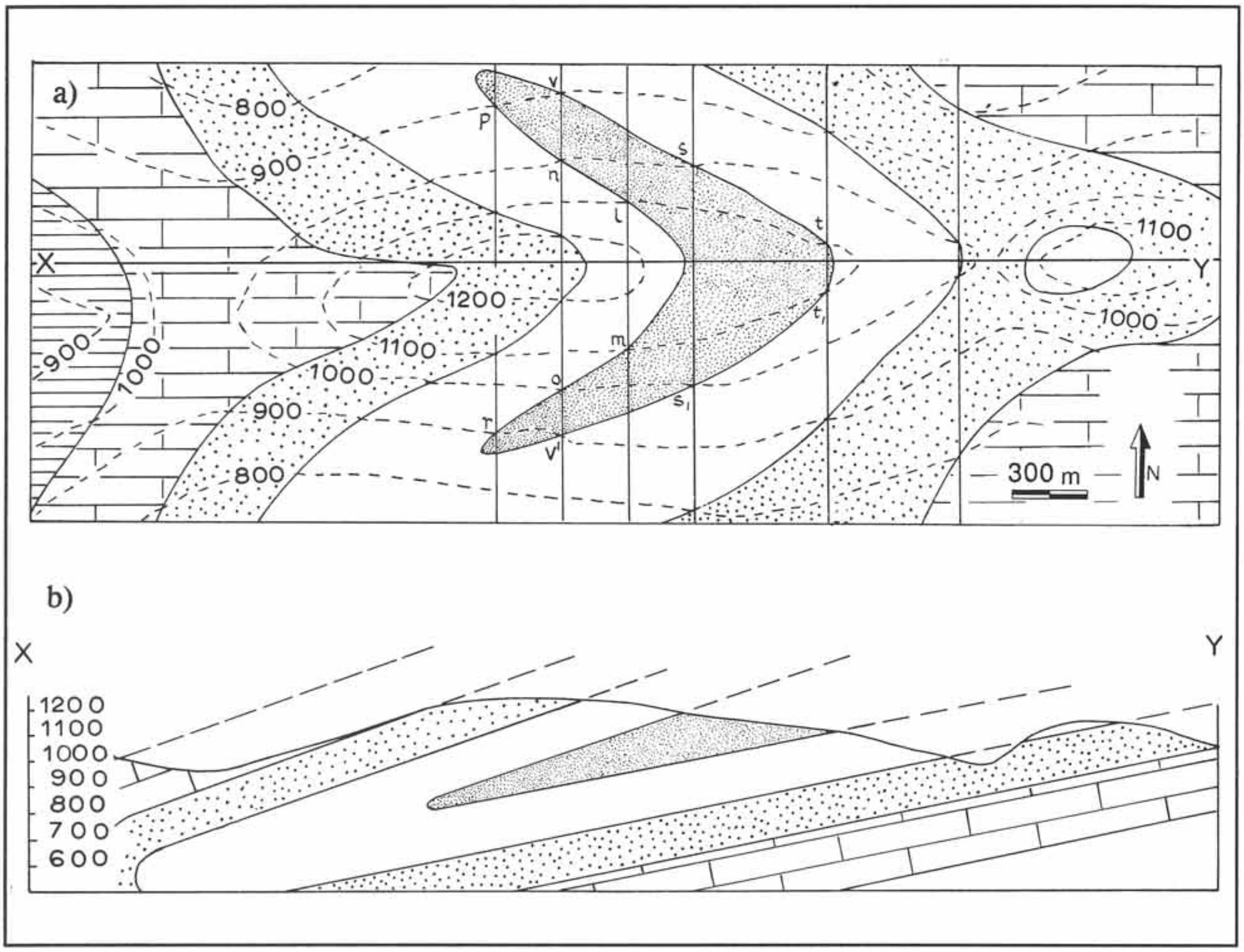

Figure 8-16: a) Map of overturned, horizontal folds in sedimentary sequence, preserved in an E-W trending mountain range. b) E-W section across the mountain range of the map, along section line X-Y.

□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.**

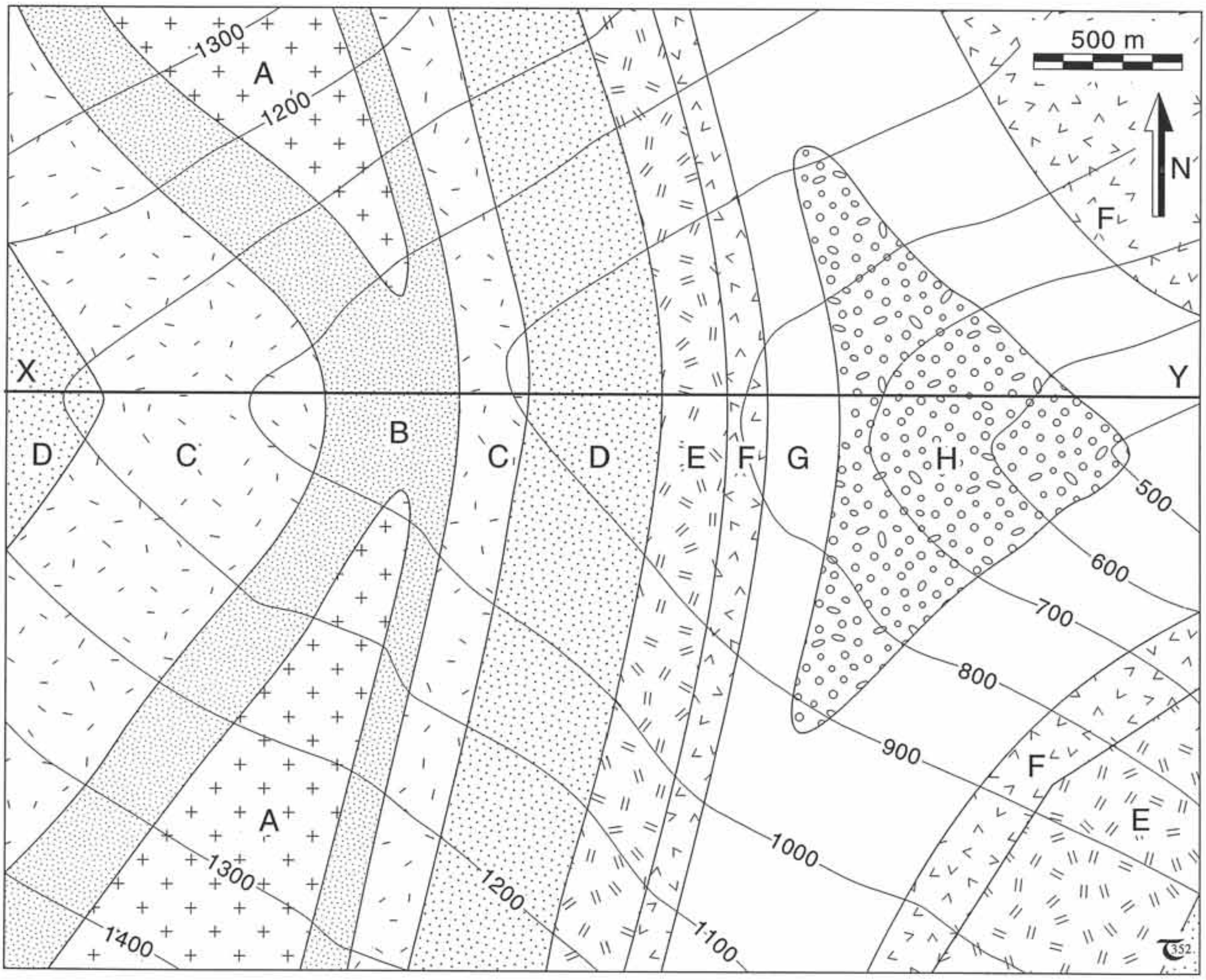

Figure 8-17: *Geological outcrop pattern on topographic base map. See exercise 8-11.*