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.

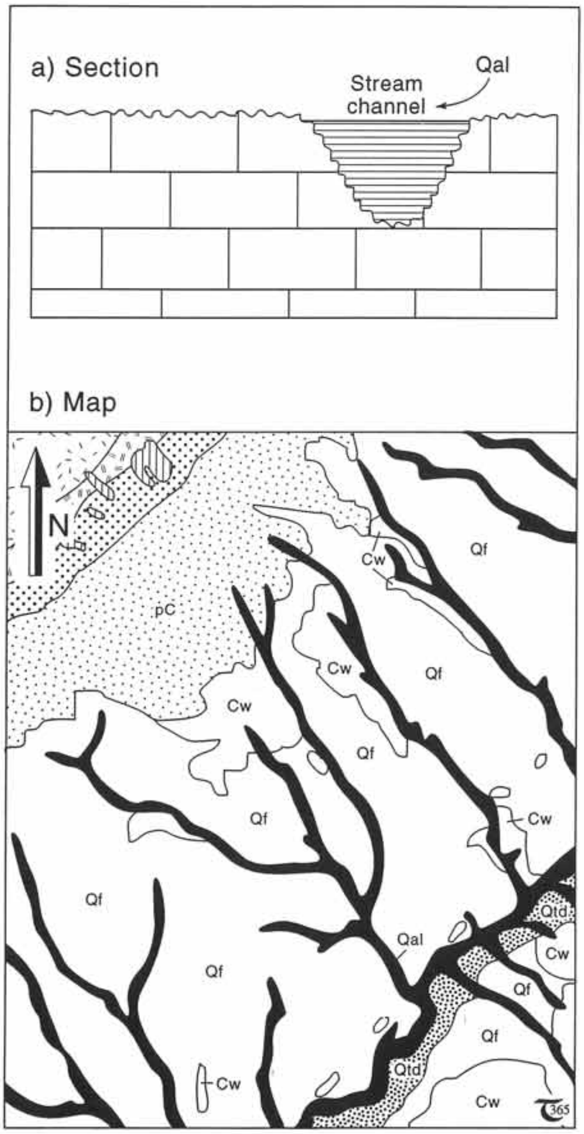

Figure 9-1: a) & b) Disconformities of horizontal sedimentary beds due to channel erosion. a) Section of stream channel filled with sediment. b) Map view of stream channel deposits (Qal).

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.

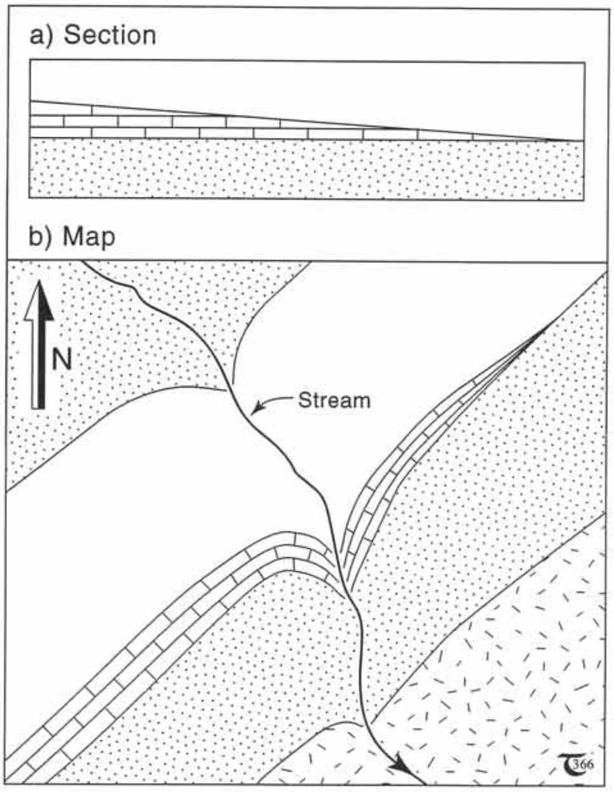

Figure 9-2: a) & b) Disconformity due to local hiatus, commonly involving erosion. a) Cross-section of limestone bed, shown to thin laterally and disappear. b) Map view, after later tilting.

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

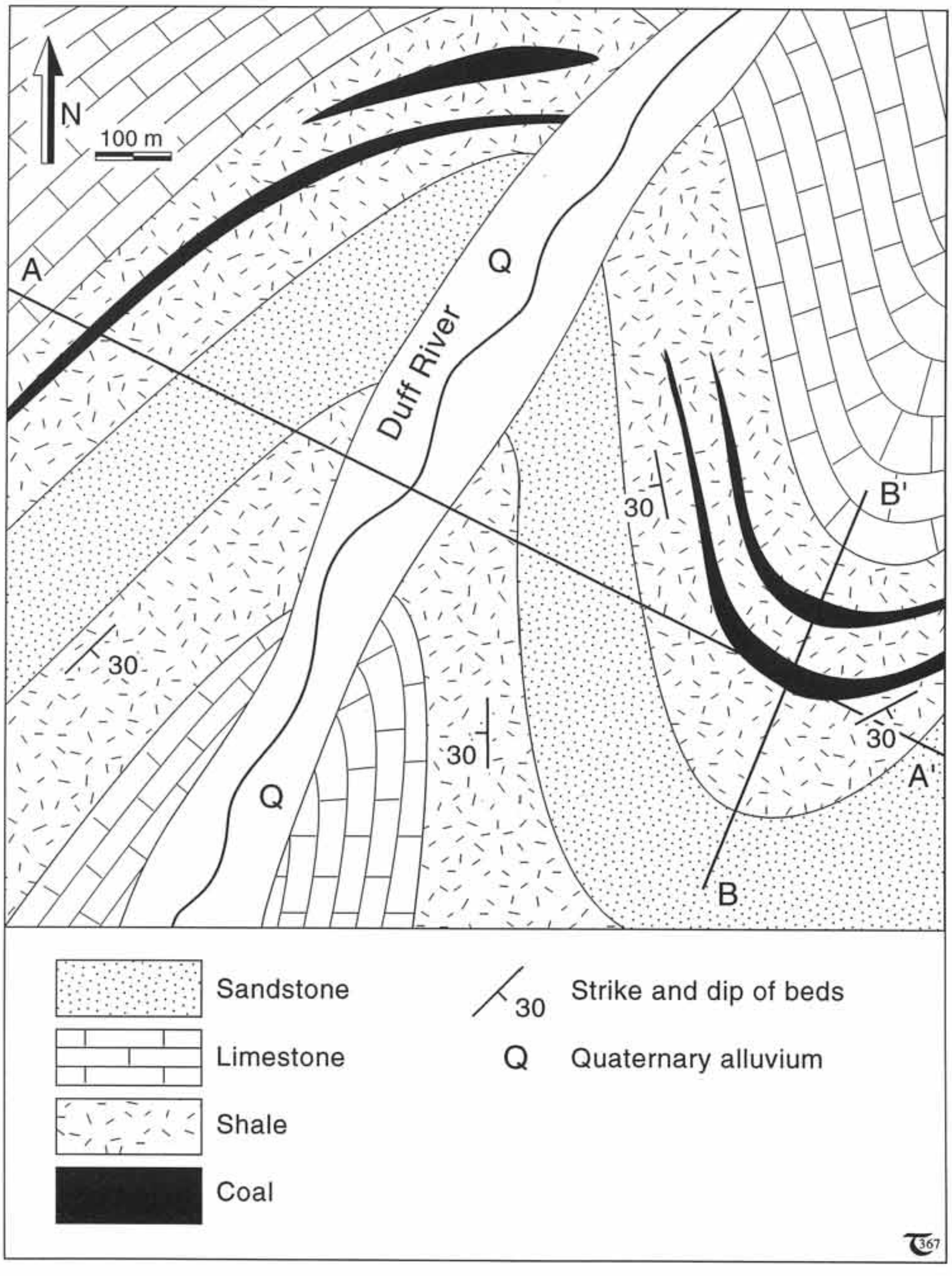

***Figure 9-3:** Map for exercise 9-1. The legend represents a lithological key only and is not in stratigraphic order.*

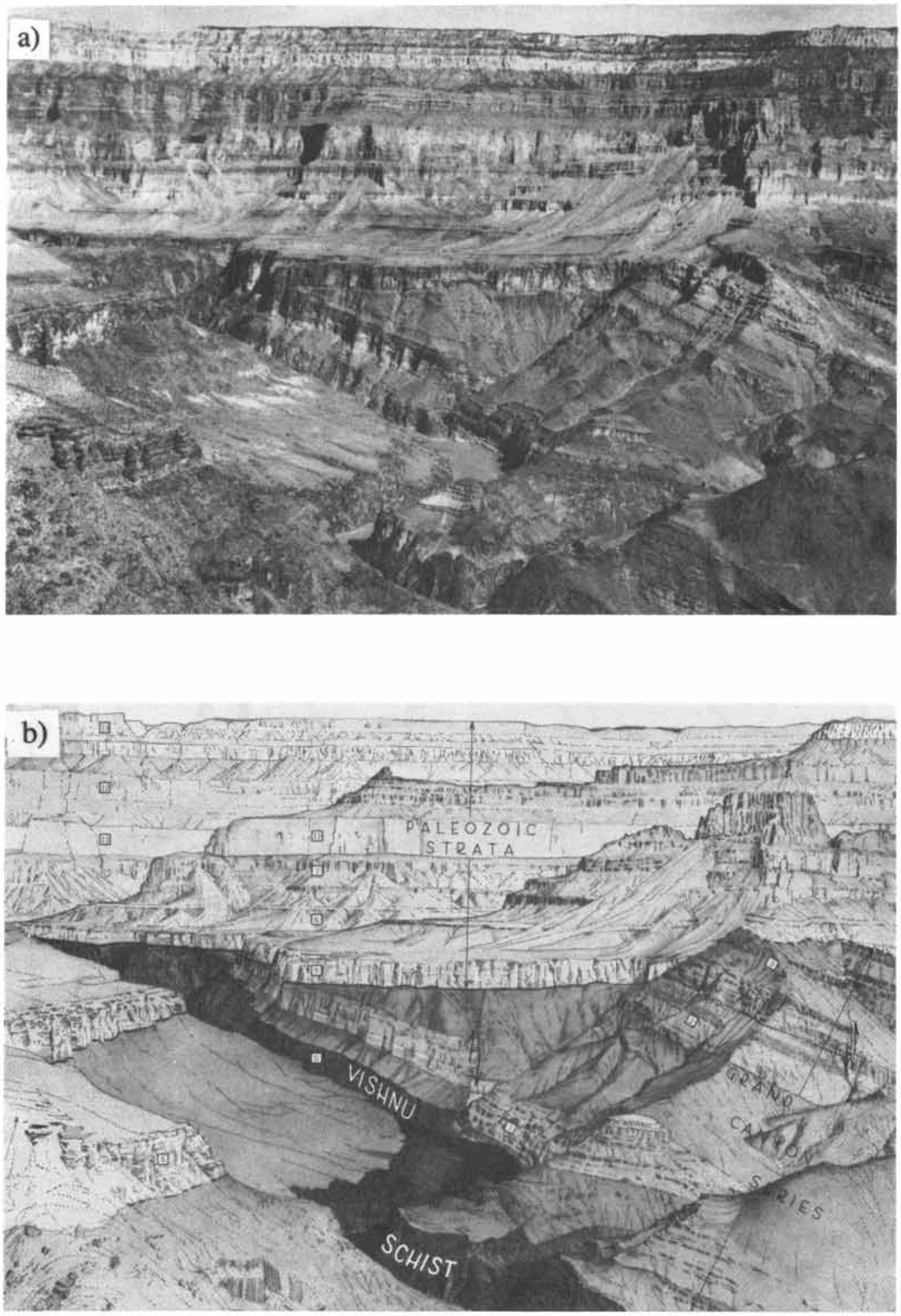

Figure 9-4: *a) & b) Angular unconformity between the Precambrian Grand Canyon Series and the Paleozoic cover. a) Photograph. b) Geological panoramic sketch, viewed toward the northwest near Shinumo Creek.*

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.

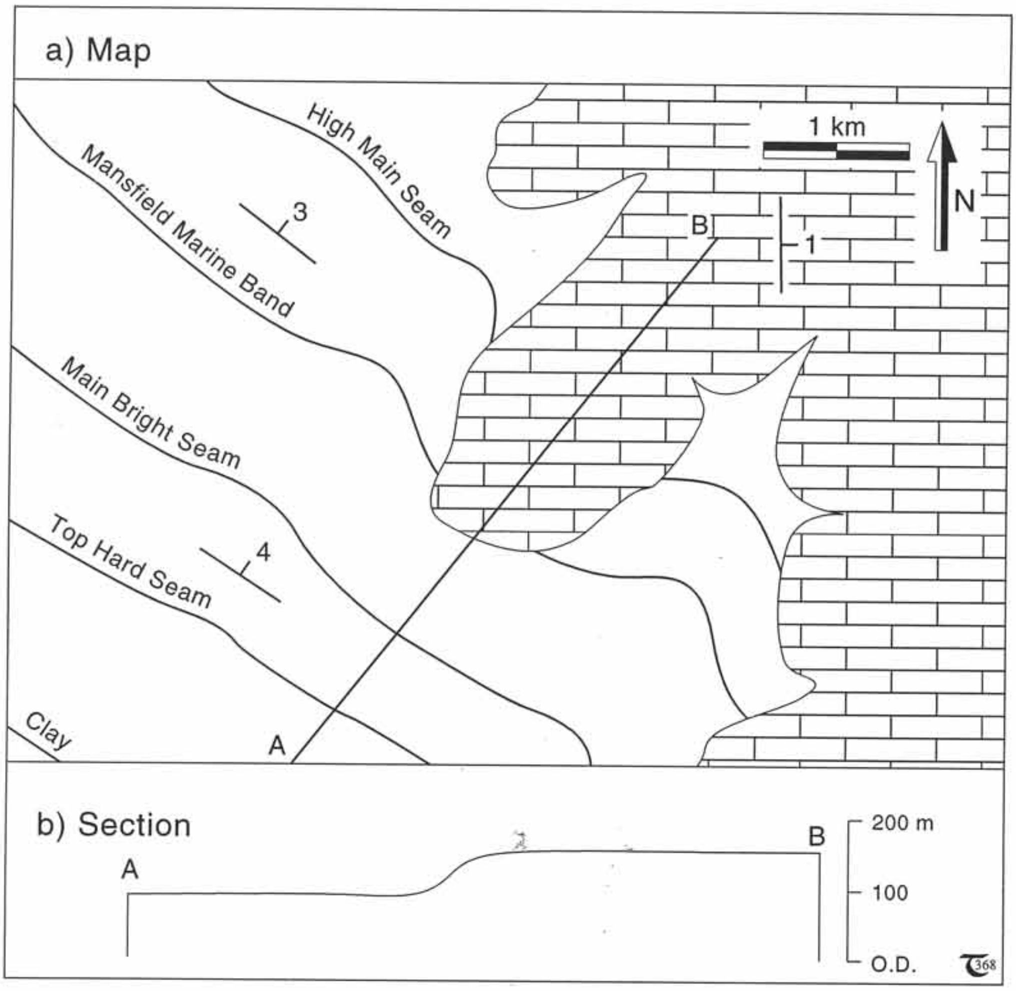

Figure 9-5: *a) Map of terrain in the British coal measures. b) Incomplete section. See exercise 9-2.*

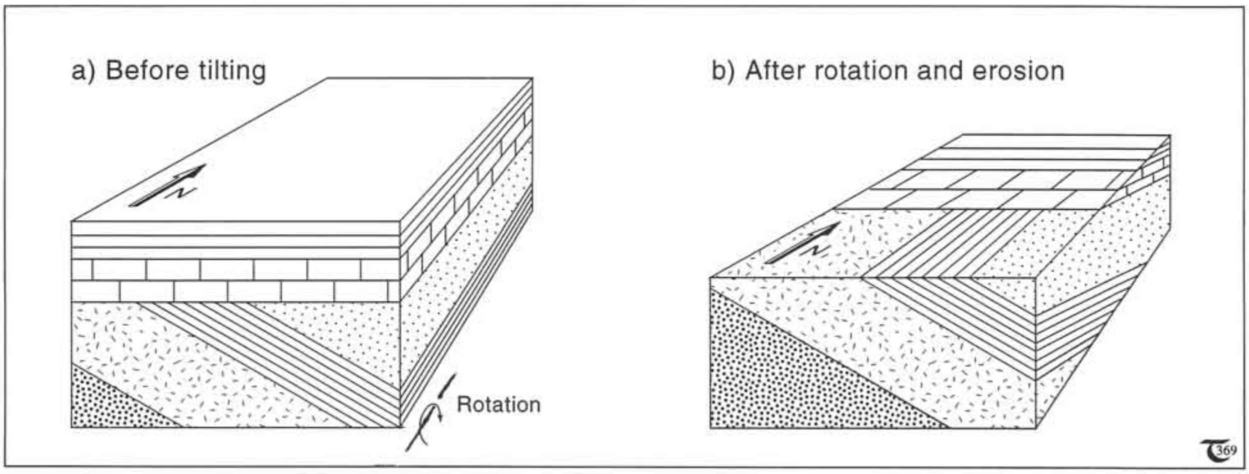

Figure 9-6: *a) & b) The cover rocks above an angular unconformity may be tilted themselves. a) Cover sequence before tilting. b) Final appearance after block rotation and subsequent erosion of the cover rocks.*

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.

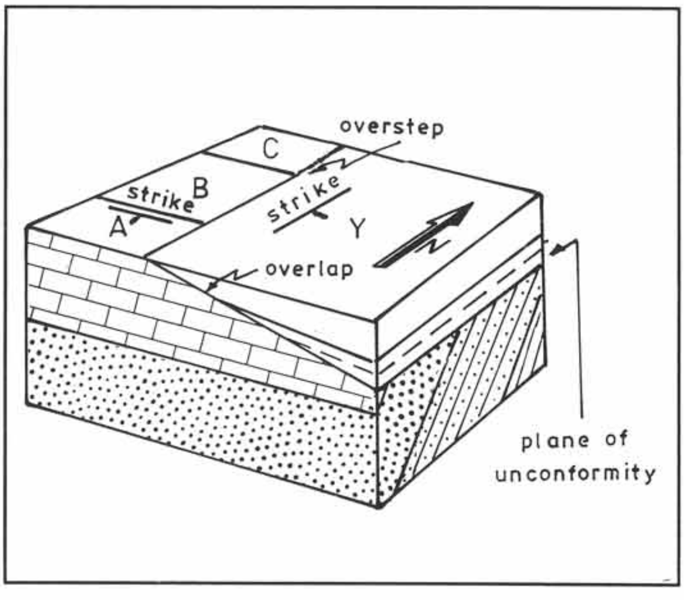

Figure 9-7: *Angular unconformity with overstepping and overlapping cover sequence.*

□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.

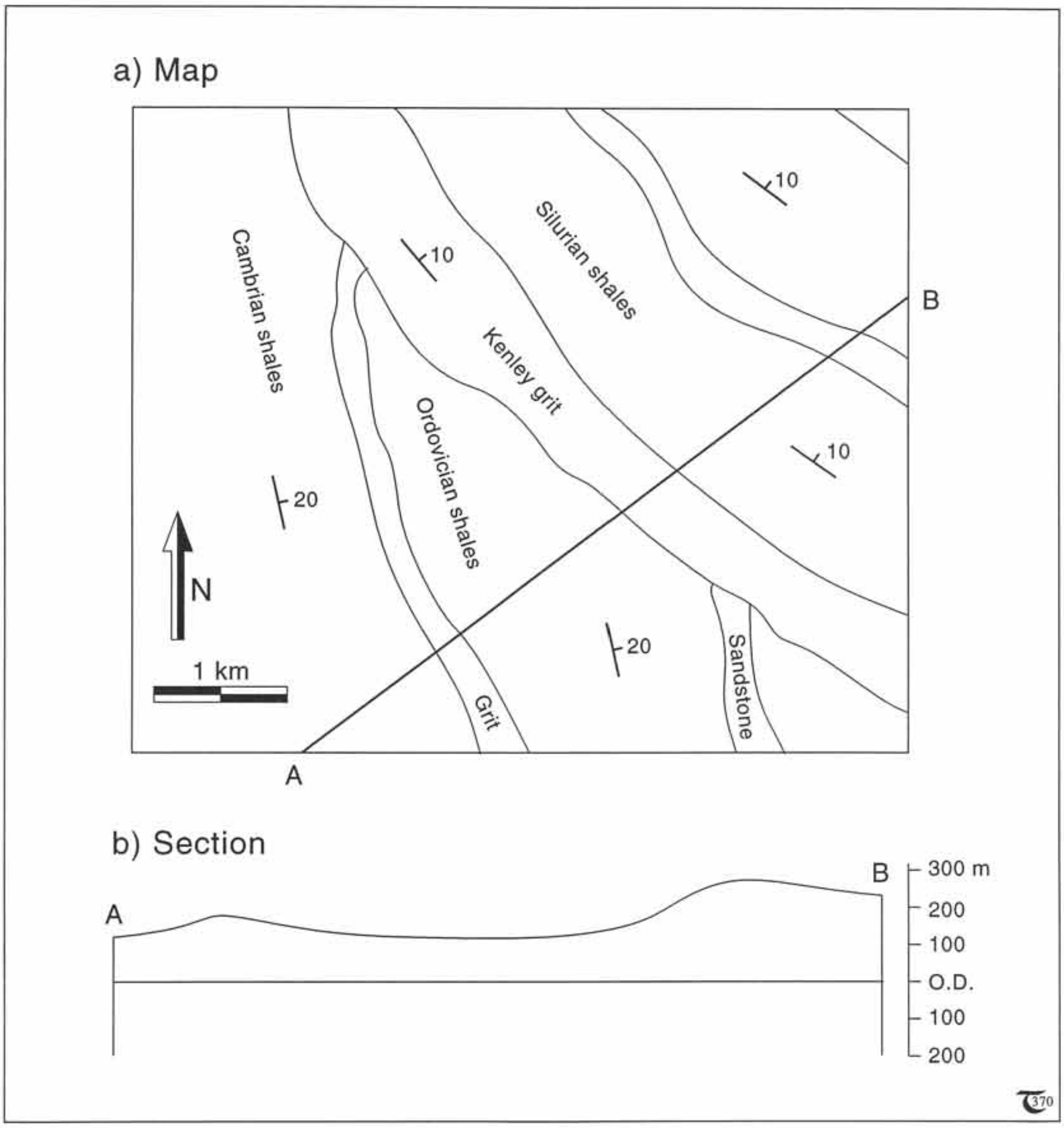

***Figure 9-8:** a) Map of angular unconformity between Cambro-Ordovician shales overlain by Silurian shales. b) Incomplete cross-section. See exercise 9-2. (O.D. is the British Ordnance Datum of mean sea-level.)*

☐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.

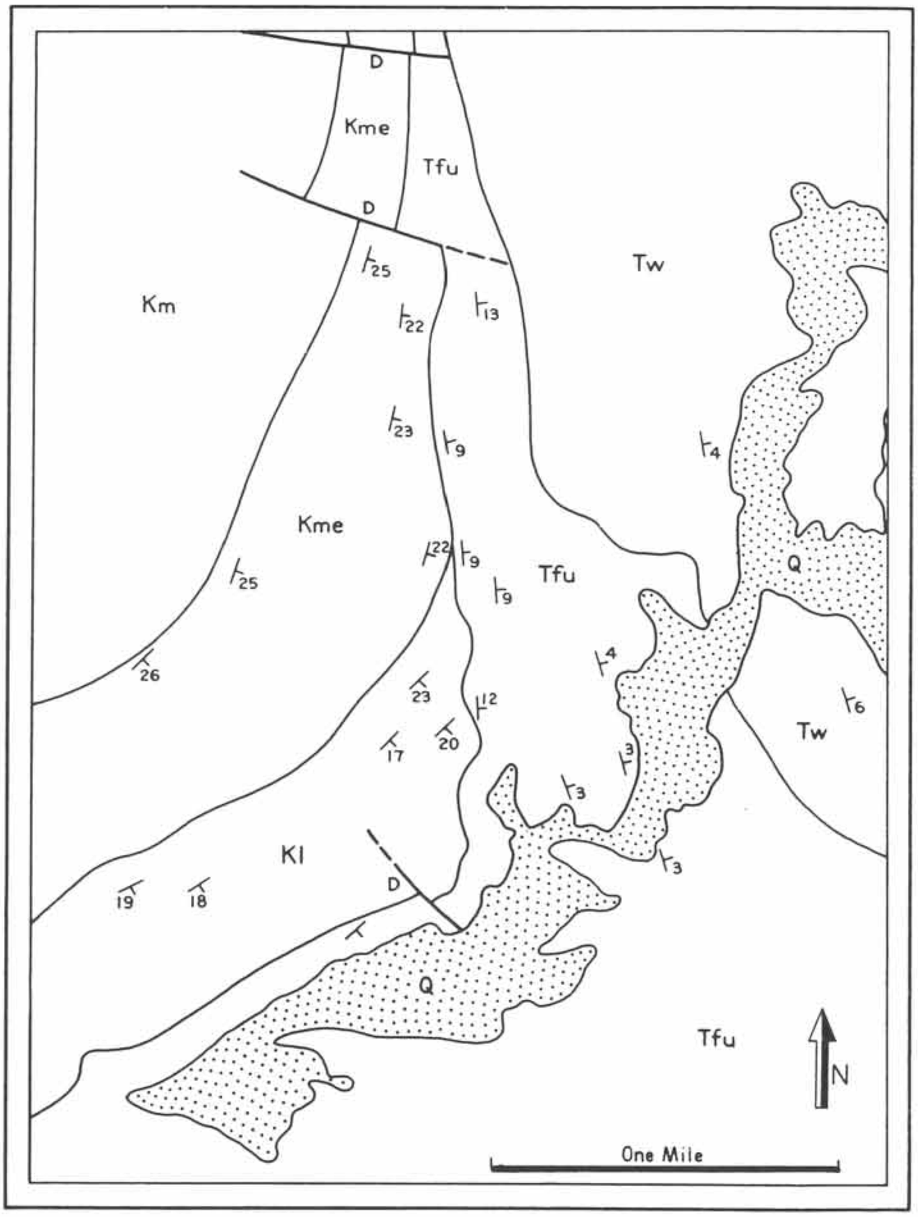

Figure 9-9: Angular unconformities, Meeteetse area, Wyoming. Legend: Km-Mesaverde Fm., Kme-Meeteetse Fm., Kl-Lance Fm., Tfu-Fort Union Fm., Tw-Wasatch Fm., Q-gravel, D-downthrown side of normal faults.

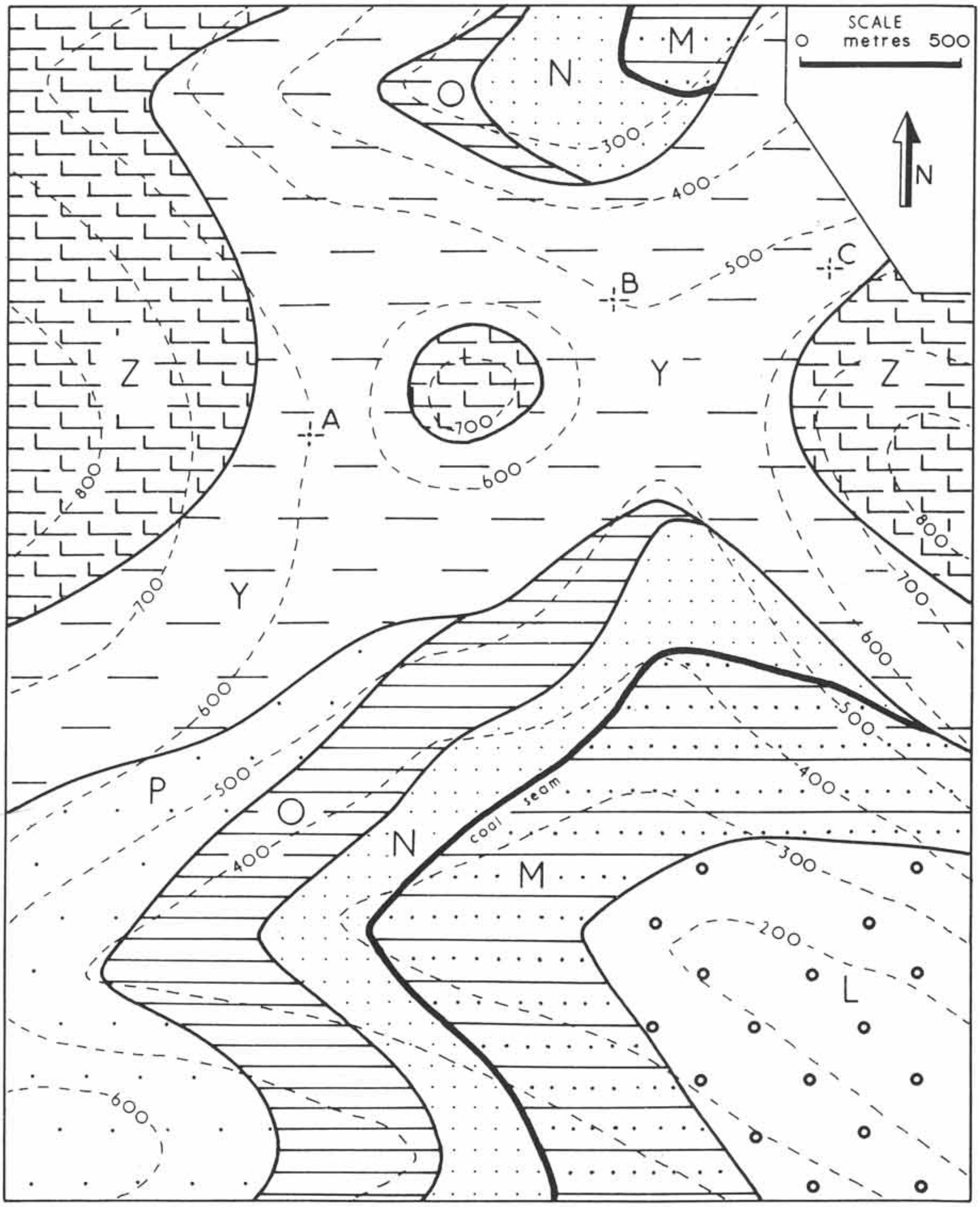

Figure 9-10: Geological outcrop pattern on topographic base map. See exercises 9-4 and 9-5.

□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.

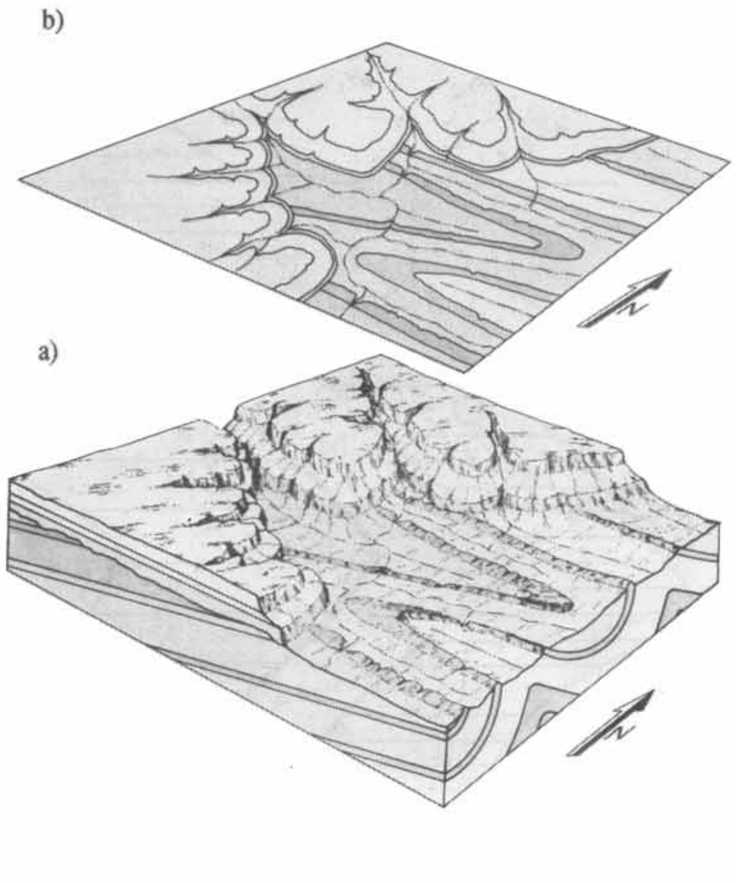

Figure 9-11: a) & b) Angular unconformity between folded basement rocks and subhorizontal cover sequence. a) Perspective diagram. b) Map view.

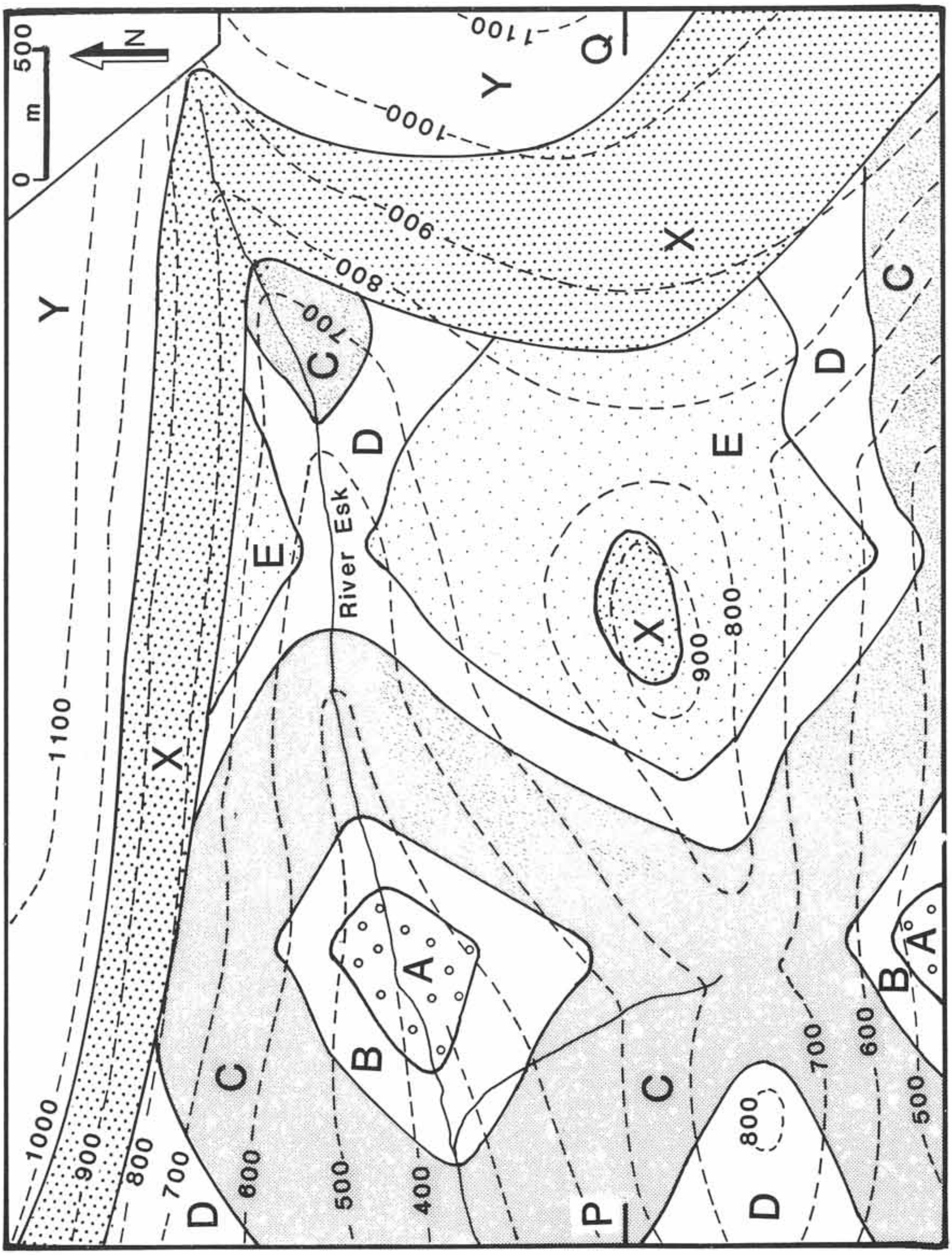

Figure 9-12: *Geological outcrop pattern on topographic base map. See exercise 9-6.*

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.

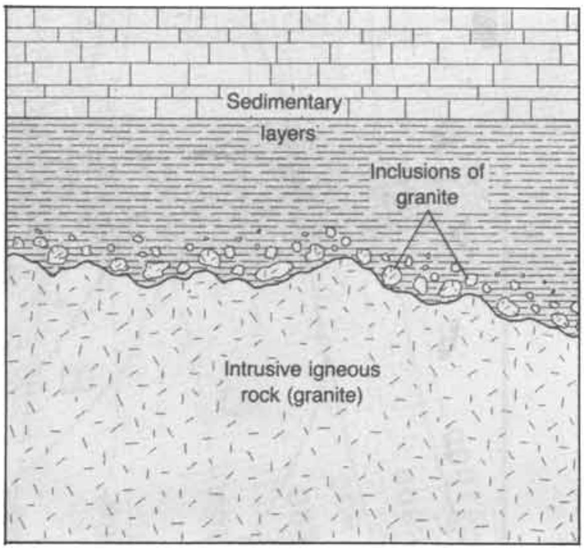

***Figure 9-13:** Nonconformities occur beneath sedimentary strata, overlying an eroded basement. The igneous inclusions shown may reach boulder size.*

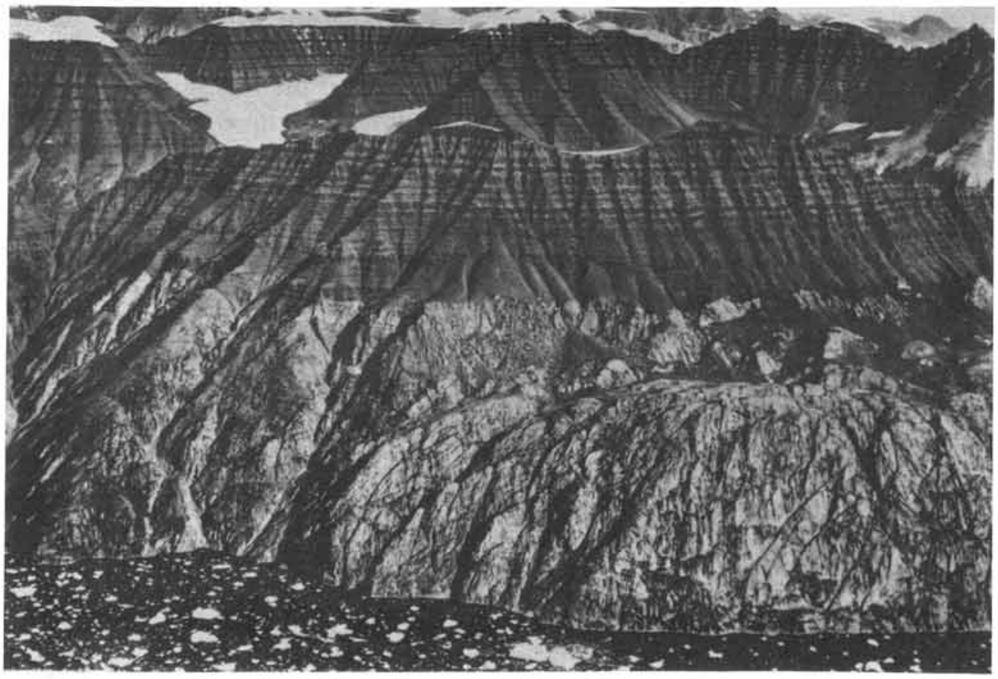

Figure 9-14: Nonconformity between gneisses of the Precambrian basement and overlying Tertiary basalt flows, Gaaserfjord, eastern Greenland. Cliff height is approximately 1.5 kilometers.

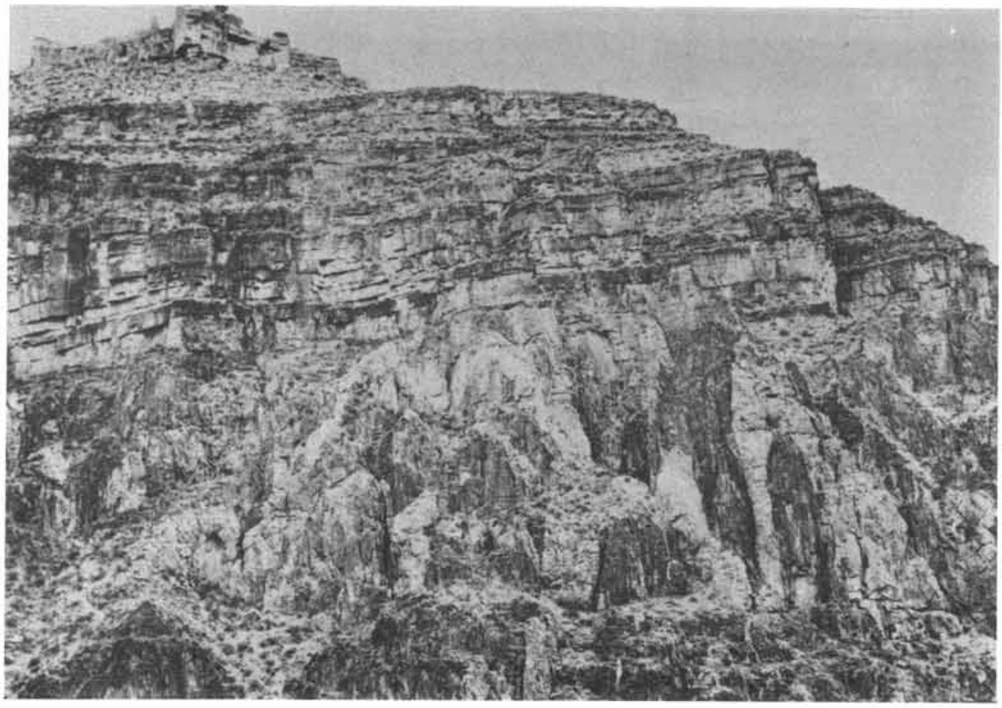

Figure 9-15: Nonconformity between the vertically foliated Vishnu schists and the layered Grand Canyon Series, Kaibab Trail. Height of the cliff is about 250 meters.

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

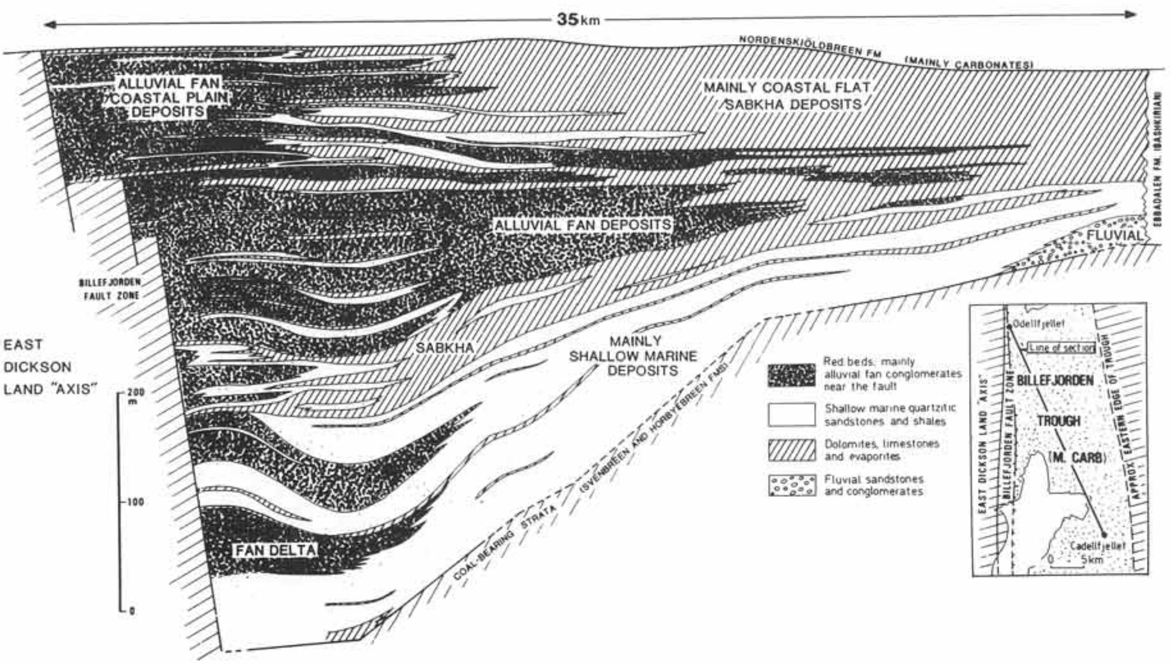

Figure 9-16: Cross-section of the Billefjorden trough, Svalbard.

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.

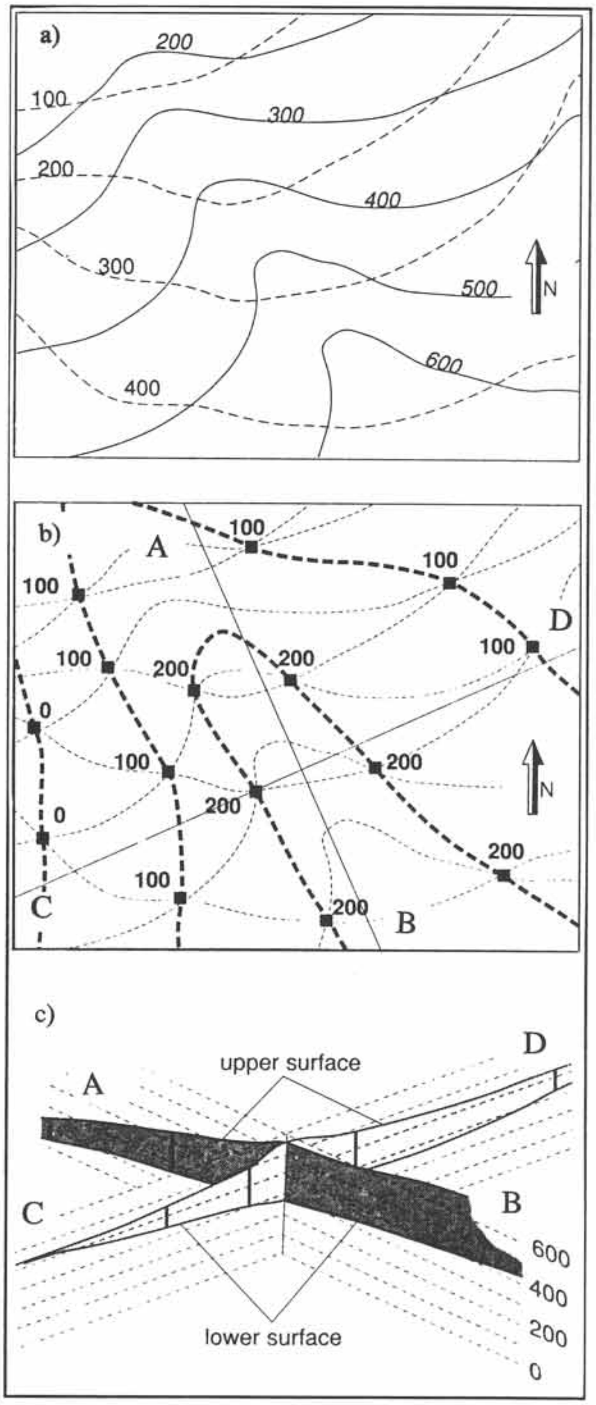

Figure 9-17: *Construction of isopachs from structure contour maps. a) Structure contour of top (solid curves) and bottom (dashed curves) of limestone unit. b) Isopach map with contours for 0, 100, and 200 meter thickness. c) Sections across the limestone unit.*

□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?

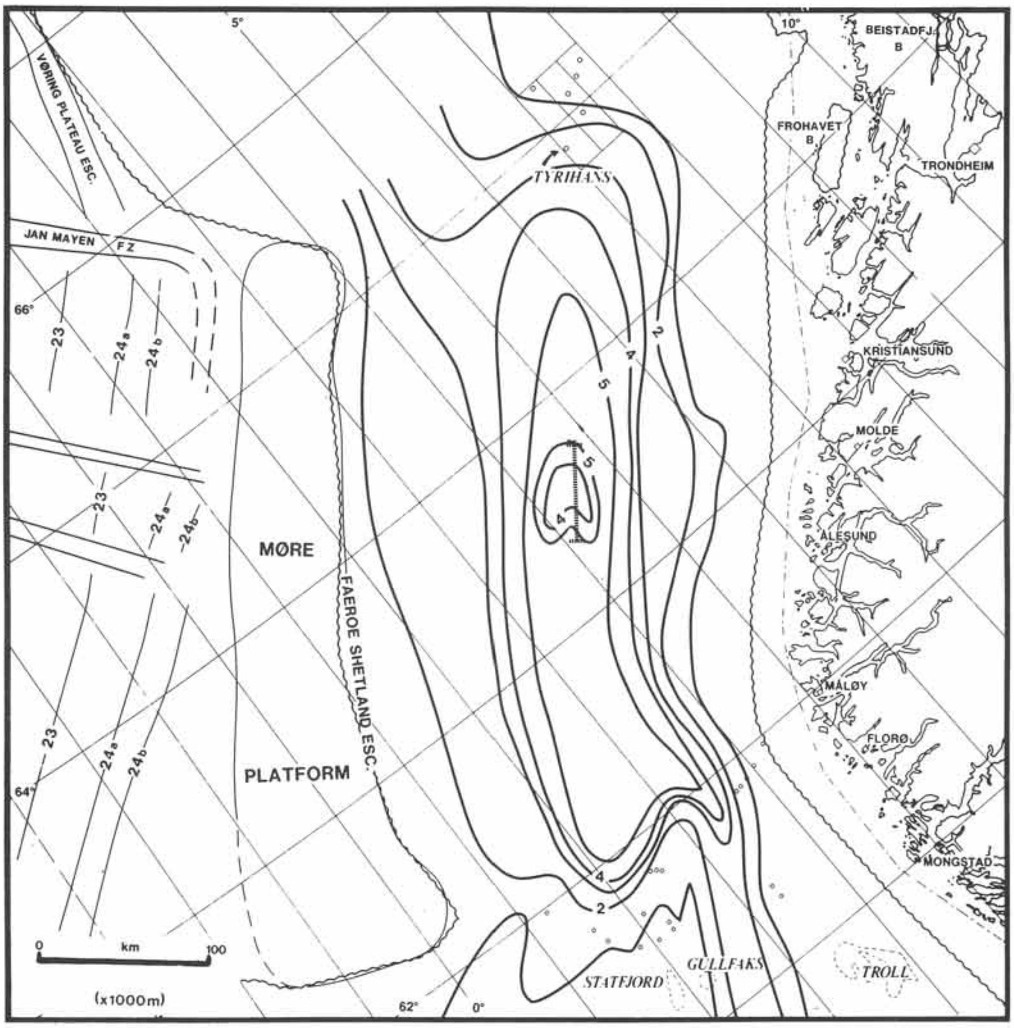

Figure 9-18: Isopach map for Cretaceous reservoir rocks, off-shore Norway. Thickness is in kilometers. Magnetic anomalies are included west of the Moere platform. See exercise 9-8.