Appendix D: Solutions to Exercises

The interpretation of geological maps and sections is an exercise in visualizing and understanding the complex shapes of rock structures in the subsurface. Developing a good grasp of this subject requires exercises. This book includes a variety of exercises, the solutions to which are listed below. Some exercises require the construction of structure contours on maps or the completion of cross-sections. The graphic solutions are not included here. Thus, students can demonstrate independently how their solutions were obtained.

Chapter one

1-1: a) Well number six in the block diagram of Figure 1-4 has the largest yield. Well number two has the smallest yield. b) The water trapped in the fault zone of well number one comes from the residual soil and fractured granite above it. c) Emplacement of the aplite dike is likely to have fractured the host rock, which may now act as a water reservoir, while the aplite itself is an effective seal rock.

1-2: a) Color the map of Figure 1-7b, as requested. b) The slide mass moved due north down the steepest slope of the terrain after its destabilization by gravity forces. The motion ceased when the mass lost momentum in flat terrain, as can be inferred from the increased spacing of the topographic contours. c) The Old Bierer cabin was covered and destroyed by the 1925 Gross Ventre slide.

Chapter two

2-1: The average slope of the north flank of the volcano in Figure 2-2b is about 20 degrees.

2-2: For example, the geographical coordinates for King Fahd University of Petroleum and Minerals are 26° 19' N latitude and 50° 08' E longitude.

2-3: The map of Figure 2-13 shows a sequence of horizontal layers, labeled O (old) to P (young). a) O is the oldest unit. b) The gravel unit in the stream channels is the youngest deposit. c) The gravel is deposited in stream channels, disconformably cut into the horizontally layered sequence. d) Elevation contours follow the O-S contact at 1,000 meters, S-D contact at 1,100 meters, D-M contact at 1,200 meters, M-P contact at 1,300 meters. e) & f) The highest point is occupied by unit P, located in the center of the map.
between 1,300 and 1,400 meters elevation. In fact, this map is from a North American locality, and the letter code stands for a Paleozoic sequence: Ordovician (O), Silurian (S), Devonian (D), Mississippian (M), and Pennsylvanian (P).

2-4: a) All strata in the map of Figure 2-14 are horizontal, because the boundaries of the rock units either coincide with or are parallel to the topographic elevation contours. b) Because all layers are horizontal, specific lithological contacts can be traced at the same elevation everywhere. c) The area below 200 meters in the southeast corner of the map cannot be completed, because it is uncertain whether the conglomerate, exposed elsewhere at 300 meters elevation, extends to this depth. d) The bottom of the conglomerate and the top of the limestone are not exposed. They are the oldest and the youngest units, respectively, outcropping in this area. Only their minimum thickness can be estimated; their total thickness cannot be inferred from the map pattern.

2-5: Construct the cross-section A-B across the map of Figure 2-14 with equal horizontal and vertical rules. Take one centimeter to be one hundred meters. Section A-B crosses two hills, separated by a central valley. The lithological boundaries below the ground surface in the cross-section are all horizontal. The thicknesses of the rock units are from old to young: conglomerate, minimum thickness of 60 meters; coarse-grained sandstone, 150 meters; shale, 50 meters; mudstone, 150 meters; fine-grained sandstone, 100 meters; limestone, minimum thickness of 110 meters. The cross-section should include lithological symbols, a legend, horizontal and vertical scale bars, geographical orientation marked at either end above the section line (together with the letters A and B).

2-6: The columnar section for the stratigraphic units in the map of Figure 2-14 can be quickly abstracted, using their thickness, as already determined in exercise 2-5. The relative resistance to erosion can be indicated by relief in the column, using the common observation that limestone and sandstone are resistant and form cliffs and benches, while mudstone, shale, and conglomerate are less resistant and commonly recede in the relief. Include the vertical scale and appropriate symbols, and write the rock type adjacent to the relief in the columnar section.

Chapter three

3-1: Layer attitudes in Figure 3-7 are: a) For location A: N160E/42SW (clockwise strike/dip), N20W/42SW (counterclockwise strike/dip), and 250/42 (azimuth/dip). b) For location B: N160E/64NE (clockwise strike/dip), N20W/64NE (counterclockwise strike/dip), and 070/64 (azimuth/dip).

3-2: The geological sketch map of Figure 3-7 must include a north arrow, scale bar, approximate lithological boundaries, strike/dip symbols, lithological symbols, and a legend.

3-3: The cross-section of Figure 3-11b shows a layer with an apparent dip of 38 degrees and the apparent thickness is about 1.1 times that seen in the section of Figure 3-11a.

3-4: a) Complete the five sections across the map of Figure 3-12, transferring the lithological boundaries and surface dips from the map to the section, correcting for apparent dip in oblique sections. b) The most representative subsurface structure is seen in section P-Q, normal to strike. It shows a synform and an adjacent antiform. c) Section P-U is probably the least representative section, because it is taken parallel to the strike of the layers, which appear perfectly horizontal in the section, disguising their folded nature. Section P-T is, also, misleading, because it shows layers dipping homoclinally northeastward at 10 degrees.

3-5: a) The cheapest pathway for the trench planned across the area of Figure 3-12 connecting P and S cuts normal to strike of the resistant unit C but cuts obliquely through the other units, staying close to the straight line connecting locations P and S. b) The cost saving is calculated by integrating the cost for both alternatives. Following the more economic pathway, despite it being longer than the straight line between P and S, is about 10 percent cheaper.

3-6: a) The true thickness of layers A, B, and C in Figure 3-17b is 26, 71, and 100 meters respectively. b) A cross-section at 45 degrees to strike of layers A, B, and C, shows them with apparent dips of 11, 35, and 90 degrees. Their thicknesses, also, appear as apparent thicknesses of 26, 85, and 155 meters, respectively.

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3-7: a) The cross-section A-B across the map of Figure 3-18 shows a sequence of uniformly, shallowly dipping strata. The lithological symbols should be ruled parallel to the dipping boundary, not horizontal as is sometimes done by novices. b) The columnar section can be constructed with a vertical scale exaggerated, if preferred. The Lower Greensand, Gault, and Upper Greensand units have true thicknesses of 42, 11 and 5 meters, respectively. c) The difference between the true thickness and the layer width appearing on the map is rather large, due to the small dip of the layers. The true thickness is only nine percent of the outcrop width exposed at the surface.

3-8: The true thickness of the aquifer described is 285 meters.

Chapter four

4-1: To complete the section of Figure 4-4c choose symbols given in Figure 2-16.

4-2: The sections across the four different maps of Figure 4-12a to d show: a) A southward sloping ground surface with horizontal layers in the subsurface. b) A gently west sloping ground surface with a vertical dike in the subsurface. c) A gently south sloping ground surface with a homoclinal north-dipping sandstone bed. d) An assumedly flat terrain with an asymmetric synformal fold closure, cut perpendicular to strike.

4-3: The seismic section of Figure 4-9a shows an overall, vertical exaggeration of approximately 1.6 times.

4-4: The true thickness of the aquifer in Figure 4-12a is 21.3 meters.

4-5: The true dip at the base of the Silurian in the Michigan Basin of Figure 4-15 is less than one degree.

4-6: The true dip of the base of the cover sequence of the Arabian shield in Figure 4-16 is approximately one degree. b) The cross-section of Figure 4-16 includes all of the visual distortions, outlined in section 4-3.

4-7: Canyon wall exercise. No map provided. a) The apparent dip is 50 degrees. b) The true thickness is 100 meters. c) The outcrop width is 116 meters. d) The apparent thickness is 255 meters.

4-8: The Paleozoic layers in the Grand Canyon viewed from Lipan Point in Figure 4-19 are cut parallel to strike in the right part of the picture, therefore, all the layers appear horizontal and concordant. However, in the left part of the picture, layers are cut normal to their trend and the angular unconformity between them is obvious. b) Apparent thickness changes are negligible for layers of shallow dip (see Table 4-2).

Chapter five

5-1: a) The average slope of the Precambrian basement of the northeastern Arabian Peninsula of Figure 5-3 is about one degree. b) The corresponding azimuth/dip varies between 045/01 and 062/01.

5-2: For the structure-contour maps in Figure 5-6a and b: a) Azimuth/dip in location 1 is: 090/40; location 2: 135/35; location 3: 135/65; location 4: 135/35. b) Cross-section A-B shows a surface dipping uniformly, 40 degrees toward the east. Cross-section C-D illustrates a surface that dips southeasterly at 35, 65, and 35 degrees. c) This is a tilted monocline with sharply defined hinges (see chapter seven).

5-3: On the map of Figure 5-7a, the color notation for gold-bearing deposits should appear only on the area outside the horseshoe-shaped enclosure, outlined by the limestone bed. In the cross-section of Figure 5-7b, the area between limestone bed and ground surface should be colored.

5-4: The azimuth/dip of the coal bed on the map of Figure 5-9 is 090/29. b) The cross-section has horizontal and vertical scales equal and shows the ground surface in topographic profile and coal bed in the subsurface, dipping uniformly toward the east at 29 degrees. c) On the map of Figure 5-9, the area west of the outlined coal exposure contains no coal in the subsurface.

5-5: a) The structure contours for the top and bottom of the sandstone formation in Figure 5-11a coincide and trend N-S. b) The vertical thickness of the sandstone bed follows from the difference in elevation between coinciding structure contours: 300 feet. c) The azimuth/dip of the formation is 090/21. d) The true thickness of the formation is 260 feet. e) The ground surface can be outlined in the cross-section, using the elevation contours on the map. f) The entire area between the two sandstone outcrops is not underlaid by the sandstone and is, therefore, colored on the map.

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5-6: a) The V-rule suggests the sandstone formation on
the map of Figure 5-13 dips southeasterly. b) Use
different colors for the two sets of structure contours,
thus distinguishing the contours for the bottom and top
of the bed. c) The azimuth/dip is 120/38. d) The
cross-section shows the ground surface and the attitude
and thickness of the sandstone formation in the subsurface.

5-7: a) The structure contours, for the map of Figure
5-14, trend E-W. The azimuth/dip of the sandstone
unit is 180/10. b) Vertical thickness of the sandstone
unit, inferred from the structure contours, is 300
meters. The true thickness is 295 meters. c) The area
north of the sandstone outcrop is not underlaid by
sandstone.

5-8: a) The V-rule suggests that all the stratigraphic
units on the map of Figure 5-15 dip due west, so that
the youngest bed is the (second) sandstone unit above
the mudstone. b) Structure contours indicate that the
azimuth/dip of all units is 270/22. c) The vertical
thickness of the limestone and shale units is 100
meters; their true thickness is 92 meters. The vertical
thickness of the mudstone unit is 200 meters; its true
thickness is 185 meters. The columnar section repre-
sents these thicknesses and reads from old to young:
older sandstone, limestone, shale, mudstone, and
younger sandstone. d) Section A-B illustrates a homo-
clinal sequence, dipping westerly at 22°. Section C-D
shows the stratigraphy apparently horizontal, because
it is taken parallel to strike.

Chapter six

6-1: a) The inliers on the map of Figure 6-2 occur
below the 500-meter elevation contour. Outliers occur
above the 800-meter contour in the northern part of
the map and above 700 meters in the southern part of
the map. b) The columnar section shows a scaled drill
hole section. The relative thickness of the horizon-
tal layers can be estimated from elevation differences
in the map.

6-2: a) The beds in the map in Figure 6-3 have
azimuth/dip: 090/11. b) The cross-section Y-Z shows
a ground surface, outlining a gentle hill with an adja-
cent valley. The subsurface comprises concordant
layers uniformly inclined to the east at 11 degrees.
c) The vertical thickness for these gently inclined
layers is almost identical to their true thickness: A:
thickness unknown, as the bottom of this unit is not
exposed; B: 150 meters; C: 100 meters; D: 100
meters; E: 50 meters; F: thickness unknown, as the
top of this unit is not exposed. d) The triangular
outcrop of unit B is an inlier. The circular outcrop
of unit E is an outlier.

6-3: a) The coal outcrop on the map of Figure 6-5 can
be traced across intersections of topographic contours
and structure contours at the same elevations. b) The
azimuth/dip is 150/30. c) Rocks overlie the coal bed
outside the ellipse-shaped area, outlined by the coal
outcrop at the surface.

6-4: a) On the map of Figure 6-6, the structure
contour for 1000 meters is a straight line through
points B and C. The structure contour of 900 meters
is parallel to line BC and contains point A. Interme-
tiate contours for 25-meter spacing are all mutually
subparallel and occur at proportionally spaced dis-
tances. b) The base of the sandstone formation can be
traced across the map, adding topography contours of
25-meter spacing and marking their intersections with
structure contours of corresponding elevation. c) No,
the sandstone is not found at location D. d) Cross-
section X-Y shows a ground surface, outlining a valley
and adjacent hillsides, with a sandstone formation in
the subsurface, uniformly inclined to the north at about
20 degrees.

6-5: Completion of the map of Figure 6-7 requires the
construction of structure contours at 50 meters spacing
and interpolation of topographic contours with similar
spacing.

6-6: The limestone bed in Figure 6-8 has azimuth/dip:
203/23.

6-7: a) The azimuth/dip of the coal bed on the map of
Figure 6-10 is 180/34. b) The coal outcrop on the map
of Figure 6-10 can be traced across intersections of
topographic contours and structure contours at the
same elevations. c) At location D, you have to drill
100 meters deep to reach the coal seam.

6-8: a) The azimuth/dip of the coal seam on the map of
Figure 6-11: 227/27. b) & c) The coal outcrop on the
map of Figure 6-11 can be traced across intersections of
topographic contours and structure contours at the
same elevations.

6-9: a) The azimuth/dip of the bed on the map of
Figure 6-12: 130/37. b) & c) The coal outcrop on the

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map of Figure 6-12 can be traced across intersections of topographic contours and structure contours at the same elevations. d) Choose your colors at convenience.

6-10: Bore hole exercise. No map provided. The azimuth/dip of the sandstone unit is 220/38. The vertical thickness is 200 feet. The true thickness is 157 feet.

Chapter seven

7-1: The structural elements of the folds in Figure 7-1 can be named, following the definition given in the text.

7-2: Exercises on Figure 7-2. a) This is a tricky question, because chevron folds fulfill the requirements of both similar and parallel folds. b) The limestone bed is not a parallel fold, but a similar fold. c) Such folds would be somewhat disharmonic.

7-3: a) The folds of Figure 7-1 and 7-4a and b all are examples of tight folds. Some of the smaller parasitic folds in Figure 4-4a are isoclinal. b) This is a tricky question. An important characteristic of similar folds is that both wavelength and the amplitude are constant for all layers in the fold. Therefore, none of the folded layers in Figure 7-4b has the largest wavelength or amplitude.

7-4: No map provided. The fold described is commonly asymmetric.

7-5: No map provided. a) Drawing of an antiform with younger rocks in the core. This antiform is not an anticline. b) Drawing of a synform with older rocks in the core. Such a synform is not a syncline. Such folds occur in the lower limb of large-scale recumbent folds (see section 7-6) when refolded into antiformal and synformal closures with upright axial planes.

7-6: The geological maps for the area viewed in the block diagram of Figure 7-10 must include a north arrow, scale bar, approximate lithological boundaries, lithological symbols, strike/dip symbols, axial plane traces, and a legend.

7-7: a) The traces of the axial planes, in the block diagram of Figure 7-16, trend N-S. b) The dip of the fold limbs can be inferred, using the V-rule, where beds are intersected by the drainage channels. The map contains two antiformal closures, separated by a synformal closure. c) All the folds plunge toward the north. d) The section normal to the strike shows the fold structure. The section parallel to the strike shows layers dipping uniformly toward the north, parallel to the plunge of the fold hinge. e) The oldest rocks are found in the core of the antiformal closures, assuming the antiforms are anticlines, too.

7-8: a) to c) The transparency of the photograph in Figure 7-17 cannot show a map, because the aerial view is oblique. What must be sketched is a panoramic view of the landscape. Indicate the major plunging anticline of Sheep Mountain, the dip direction of the layers, and the smaller syncline in the lower corner of the picture. The area exposes a sequence of sedimentary rocks, deformed into open plunging folds with upright axial planes. The more resistant beds form ridges in the landscape. The youngest rocks of the area occur in the core of the small syncline adjacent to Sheep Mountain.

7-9: a) Section A-A', across the map of Figure 7-18, shows a flat ground surface and an open asymmetric synformal closure in the subsurface. Section B-B' shows a similar structure but with shallower dip, due to the oblique angle between the section line and the trend of the structure. The transferral of the map data for the northern limb requires correction for apparent dip. b) Color the layers to classify the map pattern and section. c) The fold plunges at an average of ten degrees toward the north-west. d) The plunge/trend of the fold hinge ranges between 10/305 and 20/305.

7-10: The satellite image, of Figure 7-21 of the Fars platform in the Zagros Mountains, contains numerous doubly-plunging antiforms of the Tertiary Asmari limestone, breached by plugs of infracambrian Hormuz salt. The salt creeps down the flanks of the anticlines in salt glaciers or namakiers. Include a north arrow, scale bar, approximate lithological boundaries strike/dip symbols, lithological symbols, and a legend.

7-11: The dip direction of the fold limbs in the radar image of Figure 7-23 can be inferred where they are intersected by stream channels. The map pattern suggests that the folds are tight to isoclinal, but this is a cutting effect. Most folds plunge very gently, so that their limbs tend to be subparallel in map view, even in open folds. Include a north arrow, scale bar, approximate lithological boundaries, lithological symbols, strike/dip symbols, axial plane traces, and a legend.
Chapter eight

8-1: Structure contours for fifty-meter intervals can be interpolated on the map of Figure 8-1 between existing contours, using their spacing and the additional points of known elevation. The best prospect for a good hydrocarbon trap is below the NE-SW trending anticlinal ridge, particularly near its 960 meter culmination.

8-2: The form lines on the map of Figure 8-4 must everywhere be parallel to or tangential to the trend of the outlined form surface. An attempt can be made to convert this map into a structure-contour map by using the dip to estimate the elevation of form lines, adjacent to the 5000 foot structure contour.

8-3: a) The form lines of the sedimentary beds of the seismocrop map of Figure 8-5 are quite well-outlined by the black curves on the seismocrop map. These form lines enclose depressions, that formed while the adjacent salt stocks rose upward. The diffuse seismic signature of the salt masses precludes the drawing of form lines within them. b) A cross-section across the seismocrop map shows diapiric salt stocks and pillows, separated by mini-basins of layered sedimentary rocks.

8-4: a) The attitude of the limbs of the folded surface, portrayed in the structure map of Figure 8-6a, are: 315/45 and 135/45. It shows a symmetric chevron fold with vertical, upright axial plane and horizontal hinge line. The attitudes of the limbs in Figure 8-6b are: 315/45 and 135/60. It is an asymmetric chevron fold with a horizontal hinge line with an axial plane inclined towards the northeast (if bisecting the inter-limb angle). b) There is no information about the level of the ground surface. The shape of the single surface outlined by the structure contours of Figure 6a shows in a cross-section: A symmetric, upward-closing chevron fold with both limbs dipping at 45 degrees in opposite directions. The section across Figure 8-6b shows an other, asymmetric, anticlinal chevron fold with the NW limb dipping at 45 degrees and the SE limb dipping at 60 degrees. Both folds have narrow hinges.

8-5: The plunge/trend of the fold hinge line outlined by the structure contours of Figure 8-7b is 51/195.

8-6: a) The axial plane trace of the fold in Figure 8-8a trends N-S, and the hinge line of this synform plunges toward the south. The axial plane trace of the fold in Figure 8-8b trends NW-SE, and the hinge line of this antiform plunges northwestern. b) Figure 8-8a: 21/184; Figure 8-8b: 41/323. c) There is no information about the level of the ground surface. Only the shape of the folded surface can be outlined. A symmetric synform is seen in section G-H. An asymmetric antiform appears in section K-L.

8-7: a) The difficulty is to decide whether structure contours on the map problem of Figure 8-11 should be straight lines connecting ab and cd or bm and cn. The lines through ab and cd would not be strictly parallel. Consequently, these are less likely to be the correct contours. The alternative solution of structure contours with E-W trends is correct. The coal seam turns out to be folded into an antiformal closure about E-W trending axis. b) The coal is further exposed at the surface in the eastern part of the map as follows from intersections between the structure lines and topographic contours. c) The coal layer occurs at 100 meters depth below surface point P. d) The entire area outside the core of the antiformal closure is underlaid by the coal bed.

8-8: Both maps of Figure 8-12a and b are tricky, because the map patterns are suggestive of fold structures. However, both maps represent homoclinal beds, as follows from the construction of structure contour lines. The topographic relief for both maps is identical, but the bed on the map of Figure 8-12a has a shallower dip (010/20) than that of the bed in Figure 8-12b (350/32).

8-9: a) On the map of Figure 8-13, the structure contour of opposite limbs intersect in a herring-bone pattern. The horizontal spacing of the contours on the eastern limb is narrower than that of the western limb. Consequently, the eastern limb (295/48) dips more steeply than the western limb (080/29). b) The hinge line of the fold plunges northeasterly at 12/015. c) The structure seen is that of a northeasterly-plunging synform.

8-10: a) On the map of Figure 8-15, structure contours remain parallel only if intersection points of the outcrop pattern and topographic contours are connect-
ed by N-S-trending lines, as opposed to E-W-trending ones, which are incorrect. b) The layers strike N-S everywhere, even where the outcrop pattern of fold limbs appears curved on the map. c) The axial plane traces occur in a synformal closure occupying the western part of the map and in an antiformal closure occupying the eastern half. d) Both folds have horizontal fold axes and upright axial planes, because structure contours are mutually parallel everywhere and equally spaced. The limbs are straight, so they are chevron folds. e) All strike lines are N-S and alternating limbs dip 30 degrees in opposite directions. f) Cross-section X-Y is normal to the trace of the folds and shows the relief of the ground surface, which slopes gently eastward. The surface of the section is occupied by an open antiform and an adjacent open synform, both with vertical axial planes.

8-11: a) On the map of Figure 8-17, it is more practical to draw structure contours only for the boundaries of units A and H. All structure contours trend N-S. Both units host fold closures. The dips of the layers on individual limbs are constant (20° and 50°, resp.), because the spacing of the structure contours on the fold limbs is constant for each layer. However, all limbs dip eastward and are part of overturned folds. The fold hinges are horizontal, the axial plane dips 35 degrees eastward. The folds are tight chevron folds. b) Two axial plane traces should appear on the map, and both are curved. A north-south trending, concave-east curve can be traced between the two limbs, outlined by unit C and through the fold hinges reflected in the outcrops pattern of the two exposures of unit A. This is the synformal axial plane trace. Another axial trace should be drawn farther eastward, separating the two limbs of formation G and bending similarly as the one explained previously. This is an antiformal axial plane trace. c) Bed H is an inlier, because it is surrounded by younger beds. d) The hinge lines of the folds are horizontal, because all structure contours are subparallel and the herring-bone pattern, typical for plunging folds, is not seen. e) The axial planes dip eastward. f) The cross-section illustrates a gently eastward-sloping ground surface, below which occurs one overturned synformal and one antiformal chevron fold.

Chapter nine

9-1: On the map of Figure 9-3, the outline of the Quaternary deposit of the Duff River corresponds to an unconformity surface. Each of the subparallel coal seams may have been discontinuous, even before folding, if unconformably deposited into separate depressions or if partly eroded and unconformably overlaid by shale. In the latter case, unconformity surfaces may be traced, following the top of the coal layers and across their separation below the Duff River.

9-2: The sections of Figures 9-5b and 9-8b can be completed, using the instructions of chapter four. The transferal of map data to the section line is relatively straightforward. Correction for apparent dip is not necessary for layers of shallow dip, cut here at a large angle to their strike. The unconformity surface below the Kenley grit dips similarly to the beds above it. The sandstone bed should appear in the section below the unconformity surface.

9-3: On the map of Figure 9-9, the Fort Union Formation and Wasatch Formations are mostly conformable, but the base of the Fort Union Formation is a distinct angular unconformity surface. The disconformity surface below the Quaternary gravels is a third unconformity in the Meeitee area. The Wasatch and Fort Union Formations were subhorizontal after deposition and were tilted about an axis trending N10°W effectively to cause the structural strike in that direction with an east dip at 4 to 10 degrees. Earlier, the Mesaverde, Meeitee, and Lance Formations have been tilted together about a NE-SW-trending axis, that tilted the formations to dip gently toward the SE.

9-4: a) On the map of Figure 9-10, an unconformity surface occurs at the base of unit Y. b) The strata above the angular unconformity dip gently due north with an azimuth/dip of 000/08. c) Beds below the unconformity dip gently toward the westnorthwest with azimuth/dip of 290/11. d) The unconformity surface dips similarly to the overlying strata. e) The sequence of the beds, from old to young, is: L: conglomerate; M: sandy shale; - coal seam ; N: fine-grained sandstone; O: shale; P: coarse-grained sandstone; Y: mudstone; Z: limestone.

9-5: a) Concerning the coal seam on the map of Figure 9-10: Location A, 600 m high itself, is cut by the coal structure contour of 150 m. The unconformity surface is at 450 m. Conclusively, coal is found in bore hole A at 450 m below the ground surface. Location B, 500 m high itself, is cut by the coal structure contour of 300 m. Henceforth, coal is found in bore hole B at 200 m below the ground surface. Location C, 550 m
high itself, is cut by the coal structure contour of 400 m. Coal is not found in bore hole C, because the unconformity surface occurs just a little below 400 m elevation in bore hole C. b) The coal seam is missing in borehole C, because it has been eroded away before the deposition of unit Y.

9-6: a) On the map of Figure 9-12, an angular unconformity occurs at the base of unit X. b) The strata above the unconformity surface dip gently toward the NNE with an azimuth/dip of 020/05. c) Unit A is exposed in an inlier; unit X is an outlier where surrounded by unit E. Unit E rests on underlying units and, therefore, would be an inlier itself were it not for the presence of the unconformable unit X. d) Beds below the unconformity are folded about horizontal N-S trending axes. The limbs dip at 17 degrees in opposite directions. Inlier A is in the core of an eroded antiform. Unit E occurs in the core of an eroded synform. e) Cross-section P-Q shows the relief of the ground surface, the angular unconformity surface with an apparent horizontal dip, and the symmetric fold structures farther below. f) The stratigraphic sequence is: A, B, C, D, E, - angular unconformity X, and Y.

9-7: No map provided. The isochore map shows contours, trending NE-SW, with spacing progressively diminishing in the southeasterly corner, where the reservoir thickness increases significantly.

9-8: a) On the map of Figure 9-18, the Cretaceous sequence is more than five-kilometer thick in the core of the graben, except for a local circular depression along its axis, where the thickness is less than four kilometers. b) The progressive thinning toward the margins of the central graben suggest that the deposition of the Cretaceous sequence was syntectonic. c) The isopach map shows only the thickness of the Cretaceous sequence and yields no information on its absolute depth.

Chapter ten

10-1: The construction requested for Figure 10-3 is similar to that shown in Figure 10-2b.

10-2: The construction requested for Figure 10-6 is similar to that shown in Figure 10-4.

10-3: There are many different ways in which the parallel perspective of Figure 10-1 can be transformed into an angular perspective diagram. Choose any of the possibilities shown in Figure 10-5.

10-4: a) To complete the isometric projection of Figure 10-9b, draw first, onto the map of Figure 10-9a, a grid spaced similarly to that seen on the top surface of Figure 10-9b. Next, transfer the surface geology at grid-line crossings from the map to the corresponding points in the block diagram. The outcrop pattern is further completed by sketching curves between the transferred data points. b) The geology in the vertical walls of the block diagram use the surface data to infer the most likely subsurface structure. Both sections should be identical but are visually distorted by the isometric projection, each in a different way. c) A practical coordinate system is chosen parallel to the edges of the block, using length units corresponding to those used on the original surface map. The origin of the coordinate system is fixed best in one of the corners of the block diagram.

10-5: a) The block diagram of Figure 10-13 is constructed by first elevating topographic contours from the map in Figure 10-13d to elevated contours, according to the instructions illustrated in Figures 10-12a to f. b) The surface geology is transferred from the map of Figure 10-13d to the elevated-contour block diagram by extrapolation. The two sections P-Q and R-Q are slightly distorted to fit with the squinted vertical walls of the block diagram.

Chapter eleven

11-1: a) The extension in Figure 11-3 between points A and B has a stretch of 1.04. It involves crustal extension of 4 percent. b) The extension in Figure 11-4 between points C and D has a stretch of 1.08. It involves a horizontal extension of 8 percent. It is worth noting that the amount of stretch and extension estimated varies with the choice of reference points (i.e., A and B, C and D). But the extension estimates made here emphasize that normal faults commonly accommodate crustal extension.

11-2: The crustal shortening, in Figure 11-6 between points E and F, has a stretch of 0.88. It involves a horizontal shortening of 12 percent. Reverse faults help to accommodate crustal shortening.

11-3: The minimum displacement of the rock units in the nappe sheet of Figure 11-7b can be inferred from
the maximum distance between a fenster and a klippe. That distance suggests a minimum displacement of several kilometers for the thrust unit of Figure 11-7b.

11-4: a) The Alpine fault of Figure 11-10 is a right-lateral wrench fault. b) Right-lateral or dextral or clockwise. c) The transform fault at the spreading ridge of Figure 11-10 shows left-lateral apparent offset. d) Left-lateral or sinistral or counterclockwise.

11-5: a) & b) To fault the layers in the map of Figure 11-14, use the same principles as shown for the reverse fault in Figure 11-13. If equal off-sets are chosen for the east dipping and west-dipping reverse faults, both maps will look identical. This exercise demonstrates that it is difficult to determine the type of faulting if only a surface map is available. In such cases, further information on the direction of dip of the fault is required in order to distinguish whether the fault is of normal or reverse type.

11-6: Most students, who consider fault movement and its effect on map appearance an easy topic, become intrigued by the unexpected complexity of this exercise in Figure 11-16. Draw the solution in perspective diagrams for three stages (prefaulting, post-faulting, and post-erodional). a) A reverse fault, dipping east-ly more steeply than the layers, will cause a stratigraphic repetition. b) A west-ly-dipping reverse fault causes a stratigraphic gap in the sequence. These two results for reverse faults are complementary to the effects of normal faulting, illustrated in Figures 1-15a and b.

11-7: a) Cross-section A-B, across the map of Figure 11-17, illustrates three subparallel normal faults (assume an eastward dip of about 60 degrees), that caused a repetition of the stratigraphy. The principle is similar to that illustrated in the sequence of block diagrams of Figure 11-15a. The eastern part of the section is unconformably covered by a limestone unit of shallow dip. Complete the subsurface structure below the limestone, as much as possible, by transferring data from the southern basement outcrop to the section line. b) A brief tectonic history, that explains the map pattern is as follows: A basement sequence of planar parall strata has apparently been tilted by block rotation. The tilted sequence was subsequently cut by three, ESE dipping normal faults associated with an episode of crustal extension in ESE-NNW direction. This episode of extension, commonly associated with basin subsidence, was followed by a regression (due to either a local tectonic uplift or global eustatic sea-level drop). The regression exposed the block-faulted basement units in a land surface, that eroded into a peneplain. Subsequently, the limestone unit was deposited by transgression over a low-relief surface. The transgression could be due to either local tectonic subsidence or global sea-level rise at the end of a glacial. Finally, renewed regression exposed the land surface once again and, possibly, has eroded away parts of the overlying limestone, so that the angular unconformity surface and basement units are exposed anew.

11-8: The construction requested to explain the map pattern of Figure 11-20 is similar to that shown in Figure 11-19, except that the vertical slip is now much larger. Consequently, the intersection line of the two rock units in the west block is below the ground surface, while it would be above the ground surface in the east block, were it not removed by erosion.

11-9: a) The transverse fault in Figure 11-21a has no dip indicated. In such cases, assume the fault surface to be subvertical. The map pattern implies that the east wall of the fault has dropped down relative to the west wall (similar to that seen in the sequence of block diagrams of Figure 11-18a). Erosion leveled the ground surface, and the marine regression implied by the erosion was followed by a marine transgression to deposit the new limestone unit. Finally, renewed regression exposed the angular unconformity on the land surface. b) Cross-section A-B across the map of Figure 11-21a shows all basement units as apparently horizontal, because the section is parallel to strike. The western block is uplifted relative to the eastern block. The eastern basement block is unconformably overlaid by the limestone unit.

11-10: a) The map of Figure 11-22 illustrates strata, homoclinally dipping toward the SSE. A central fault block has dropped, relative to the wall rock at either side. The subsided structure is a graben, and, therefore, the two faults are most plausibly interpreted as inward-dipping, normal faults. Such faults record a period of extension. Although the same map pattern could alternatively be explained by two outward-dipping, reverse faults, such reverse faults of opposite dip are extremely rare and, therefore, are less likely. b) Cross-section C-D shows subhorizontal strata at the same elevation in the west and east block. The central fault block has dropped, and the amount of displacement can be determined, projecting the boundaries of
the strata on the map to the appropriate depth in section C-D, using the 30-degree surface dip.

11-11: For the map of Figure 11-23, the assumption of dip-slip faulting and exclusion of strike-slip faulting is reasonable. Field studies have shown that closely spaced faults, separating correlatable rock strata, are more likely to be dip-slip faults, rather than strike-slip faults. The latter faults commonly occur as discrete, individual faults and sply only if displacements are large so that rock units cut by the fault can no longer be found within short distances. a) These are oblique normal faults, formed by E-W extension of the area. The shallow dip of the fault blocks may be due to block rotation coeval with the faulting, rather than prior to the faulting. b) Cross-section E-F shows west-dipping normal faults, separating strata gently dipping toward the east. Displacements follow from the construction.

11-12: No map provided. This is a very simple exercise, but beware that the arrows used are half-arrows, showing relative sense of shear only. These half-arrows differ from full arrows which would be vectorial and wrongly suggest absolute sense of movement. Solutions: a) A sinistral set of strike-slip arrows, showing clockwise sense of shear. b) A dextral set of strike-slip arrows, showing clockwise sense of shear. It is worth noting that the displacement seen on dip-slip faults is sometimes referred to in terms of sinistral or dextral sense of shear. How-ever, this terminology is never used by experienced structural geologists for dip-slip faults. They realize that the same dip-slip fault, where cut by a canyon, shows opposite sense of shear on opposite vertical canyon walls. Consequently, the terms sinistral and dextral are unambiguous only for strike-slip faults, which can be viewed on horizontal surfaces only and thus have a unique sense of shear.

11-13: The map pattern of Figure 11-25 suggests the presence of a folded sandstone layer to the untrained mind. This interpretation is false, as follows immediately from the construction of structure contours. a) The sandstone formation in the western block dips uniformly to the south with azimuth/dip: 185/18. b) The fault plane is strictly vertical, because it cuts across different elevations without curving on the ground. c) The attitude of the sandstone formation in the eastern block is the same as in the western block, because the spacing of structure contours is the same.

The dip-separation follows from the vertical elevation difference of laterally-matching structure contours at either side of the fault trace: 50 meters. Assum-ing the dip-separation is entirely due to dip-slip, the eastern block has subsided, relative to the western block. The strike-separation follows from the horizontal separation of structure contours of the same elevation at either side of the fault: 200 meters (measured along the fault trace). g) If due to strike-slip alone, the fault is sinistral (or left-lateral or counter-clockwise). It is important to realize that the true sense of fault-slip cannot be inferred without reference points, known previously to be in continuous contact across the fault plane, now separated by fault displacement. However, exercise 12-10 gives an example of a problem where fault-slip can be reconstructed unambiguously.

Chapter twelve

12-1: a) The western part of the map of Figure 12-3a includes a repetition of stratigraphic units in reverse order. This is characteristic for folded sequences. The vertical sequence trends NE-SW between the fold limbs and across the fault line. The single strike/dip symbol on the map helps to decide that the fold closure is a synform, rather than an antiform. The synform is displaced by the faults. The dip of the fault is unknown, so assume it is steep. The displacement of the synformal closure (analogous to that portrayed in the series of block diagrams of Figure 12-12a to c) indicates that the NE block is downthrown with respect to the SW block. If the fault dips NE, it is a normal fault. In contrast, a reverse fault must be concluded if the fault were to dip to the SW. Both interpretations are possible on the basis of the data provided. b) Section A-B shows the faulted synform with apparent dips for the fold limbs, and the west limb is steeper than the east limb, as suggested by the different outcrop widths for either limb on the map. The basement is covered in the east by discontinuous conglomerate units, overlaid by limestone and sandstone. c) A brief geological history: The basement sequence was folded about NE-SW-trending fold axes. Subsequently, it was faulted transversely by a NW-SE-trending dip-slip fault that threw the NE block down relative to the SW block. Subsequently, erosion leveled the ground surface. The conglomerate may be a remnant of a braided river deposit on a coastal plain. A marine transgression deposited limestone and sandstone onto the basement. Marine regression and
subsequent erosion of the land surface exposed both the cover and the underlying basement structure, as well as the unconformity surface that separates them.

12-2: a) The triangular area, enclosed by the three faults on the map of Figure 12-4, is downthrown with respect to the east and west walls. The displacement by each of the transverse faults is similar to that portrayed in Figures 12-2a to c. The block to the north of the third, WSW-ENE-trending fault is downthrown with respect to the southern structures. b) The map shows a transversely faulted antiform, plunging ENE, covered by horizontal conglomerate. A longitudinal fault juxtaposes the conglomerate in the north against unit A. The stratigraphic sequence from old to young is: M, R, T, A, - angular unconformity - , O, c) A basement sequence has been deformed by crustal shortening in NNW-SSE direction into a gentle antiform, plunging toward the ENE. A central section of the fold is downthrown between two transverse faults, possibly in a graben structure, bounded by normal faults. (Extension normal to the shortening direction is quite common, and faults transversely across folds are mostly of normal type). The entire structure was leveled by erosion and unconformably covered by a basal conglomerate. The conglomerate is cut by a ENE-WSW-trending fault, which represents the latest geological event recorded in the map area. d) The oldest rocks of unit M are exposed in the core of the antiform. e) The highest part of the plunging antiform, occurring to the east of the two transverse faults, is the best target for hydrocarbon exploration. Upward migrating gas and oil may have accumulated into a reservoir below the fold hinge and are sealed by the N-S-striking fault. An exploration drill hole should be sunk into the fold closure about 100 meters to the NE of the 600-meter high peak.

12-3: a) Repetition of the stratigraphic units in reverse order in the central part of the map of Figure 12-7 indicates that the basement sequence is folded about N-S-trending axes. Both the E-W-striking stream channel and outcrop pattern of the unconformable limestone unit suggest that the central section of the map area is a topographic low. The curvature of the fault, convex toward the east, suggests it dips eastward. The beds to the west of the longitudinal fault dip westward, as indicated by the intersection at the stream channel crossing and by the single strike/dip symbol. This fixes the stratigraphic sequence, so that the sandstone is overlaid by the shale unit. Consequently, the fold structure to the west of the longitudinal fault is a synform. It leans against a faulted antiform in the west, where conglomerate is exposed in the fold core. The more complete stratigraphic section in the west wall of the antiformal structure indicates that the west wall is upthrown relative to the east wall. This situation is similar to that portrayed in Figure 12-6a to c. b) Cross-section A-B shows the ground surface gently sloping westward. The subsurface structure shows an open antiform in the western part of the section, separated by a normal fault from an open synform in the central part of the section. The basement is unconformably overlaid by a horizontal limestone unit. The conglomerate in the basement can be traced below the limestone cover in the section. Include a legend with the section, placing the units in their appropriate sequence: old below, young above. c) The area was shortened in E-W direction, which led to deformation of the basement units into N-S-trending open folds with upright axial planes and horizontal hinges. If the longitudinal fault were to dip westward, it would be a reverse fault and, thus, could be coeval with the shortening episode, that led to folding. However, the curvature of this fault suggests that it dips eastward, which makes it more likely a normal fault, and the west block was upthrown. The normal fault postdates the folding and may be indicative for crustal relaxation and extension after horizontal shortening. The ground surface of the faulted fold sequence was denuded by erosion and covered by a transgressive limestone unit. A later regression exposed the land surface shown in the map. The maximum elevation of 83 meters indicated on the map, is much greater than the maximum global sea-level drops of about 200 meters recorded in geological history. This knowledge leads to the conclusion that the regression, which exposed this area above sea-level, is mostly due to local tectonic uplift, rather than sea-level changes.

12-4: The map of Figure 12-8 includes two longitudinal faults. One of the faults separates the sandstone from the conglomerate unit in the western part of the map. The other fault occurs between the white marl and limestone units. a) The section shows a flat ground surface, and the subsurface shows a central, gentle, upright, horizontal synform with a core of limestone. Both limbs are longitudinally faulted. Younger units of the faulted limbs lean against older units of the central synform. This indicates that the central section of the map is upthrown. If the faults dip outward, it is a horst structure. If the faults dip inward, it is a pop-up structure with reverse faults, indicative of shortening. Such reverse faults could be
formed coeval with the folds of the area. Each of the alternative interpretations could be valid, and no conclusive evidence is given here to rule out either of them. b) The central block moved upward relative to the limbs downthrown at either side of the synformal core.

12-5: a) The map of Figure 12-11 illustrates a transversely faulted, SE-plunging, antiformal fold closure. The rocks in the fold hinge of the SE block are juxtaposed against older rocks in the NW block. The NW block, therefore, must have been upthrown relative to the SE block. This situation is reverse to that illustrated in Figures 12-10a to c, where the block containing the nose of the fold is upthrown instead of being downthrown, as shown here. b) Cross-section A-B shows an apparently asymmetric antiform, but this asymmetry is largely due to the way the section line cuts the fold. The west limb is cut parallel to the strike, and layers on that limb, therefore, appear with a very shallow apparent dip. The NW block is upthrown. Consequently, if the fault surface is drawn dipping southeastward, it would be a normal fault. Conversely, if the fault were to dip northwestward, then it must be a reverse fault. Each of the alternative interpretations could be valid, and no conclusive evidence is given here to rule out either of them.

12-6: a) The map of Figure 12-12 illustrates a SSE plunging synform, displacing a transverse dip-slip fault. The rocks in the fold hinge lean against older rocks in the southern block. The southern block, therefore, must have been upthrown, relative to the northern block. This situation is reverse to that illustrated in Figures 12-9a to c, where the block containing the nose of the fold is upthrown instead of being downthrown, as shown here. The basement fold is unconformably overlaid by a limestone unit in the NE corner of the map area. b) Cross-section A-B shows a southward-sloping ground surface. The basement layers in the subsurface appear with nearly horizontal apparent dips; the northern block is downthrown. The basement in the northern end of the section is covered by a subhorizontal limestone unit. c) This area was deformed by shortening in ENE-WSW direction into a synform fold, plunging south-southeastward. The fold is cut by a transverse fault, the northern block is downthrown. Consequently, if the fault were to dip northwestward, it would be a normal fault. Conversely, if the fault were to dip southeastward, it must be a reverse fault. Each of the alternative interpretations could be valid and no conclusive evidence is given here to rule out either of them.

12-7: a) The area in the map of Figure 12-13 exposes gently folded sedimentary rocks. A western synform adjoins an eastern antiform. Both folds plunge northerly. The two subparallel transverse faults in the central part of the map enclose an upthrown fault block, possibly a horst structure, bounded by outward-dipping normal faults. The transverse fault in the SE corner of the map separates a southeastern block, that was upthrown relative to the northern block. The longitudinal fold cutting the antiform nose in the NE corner of the map has an eastern wall, upthrown relative to the western wall. This dip-slip is opposite to that illustrated in Figures 12-15a to c. b) Cross-section A-B shows a gentle synform in a horst block, sandwiched between a downthrown east-dipping limb in the westernmost block and another east-dipping limb in the easternmost, downthrown block. c) The area, which comprises coal seams, has been folded into gentle synforms and antiforms, plunging northerly. The folds are block-faulted by what are, most likely, transverse normal faults. These faults have accommodated extension, normal to the direction of shortening, indicated by the folds. The longitudinal fault in the NE corner of the map may be an east-dipping reverse fault, formed coeval with the folding event.

12-8: a) The map of Figure 12-16a exposes a doubly plunging synform, displaced by longitudinal normal faults. The axial plane trace trends E-W. Each of the four normal faults has its northern wall upthrown relative to the southern wall. b) Cross-section A-B shows normal faults dipping southward. The southern limb of the synform in the northern end of the section is faulted and repeated three times in the southern part of the section. c) Lava of "Old Red Sandstone" age are overlaid by Devonian rocks, including sandy mudstone, marl with coal intercalations, and shale. The Devonian sequence was folded into a doubly plunging synform by N-S-shortening. The folded sequence was then stretched by block-faulting, involving normal faults.

12-9: If the structure on the map of Figure 12-19 were to be a synform, then the southern block was downthrown. But if the structure is an antiform, then the northern block was downthrown instead. The strike-separation indicates a component of dextral strike-slip was, also, involved in the fault movement.

APPENDIX D: Solutions to Exercises
12-10: For Figure 12-19: If it is the type of fold specified in exercise 12-10, the net-slip can be constructed as follows: The strike-slip component, measured between the map projection of the axial plane traces, is 120 meters. The vertical dip-slip component can be determined from the elevation difference between the fold hinge at either side of the fault; it amounts to 210 meters. The amount of net-slip of 242 meters follows from vector addition.

12-11: The map of Figure 12-20a shows a NE-SW trending breccia zone, marking a discontinuity in the outcrop pattern of the strata at either side of the zone. The strike-dip data on the map indicate a gentle antiform is left-laterally displaced by the breccia zone, which, therefore, is a fault zone. Consequently, the breccia must be of tectonic, rather than of sedimentary, origin. The map of Figure 12-20b shows a tight NE-SW-trending synform, left-laterally displaced by a NW-SE-striking fault.

12-12: a) Structure contours for the fault plane on the map of Figure 12-21 indicate its azimuth/dip is 090/34. b) The azimuth/dip of the sandstone layer in the hanging wall is 090/18. c) The fold hinge line in the foot wall, which hosts a synform, trends N-S and is horizontal. d) The west limb of the synform has azimuth/dip: 090/18. The east limb has azimuth/dip: 270/34. e) Cross-section A-B shows an asymmetric synform in the foot wall of a fault and an east-dipping limb in the hanging wall. f) The fault is longitudinal to the fold structure. It is most certainly a reverse fault, that cuts through the hinge zone of an antiform, that occurs east of the synformal closure seen on the map.

Chapter thirteen

13-1: This question requires students to think more independently to search for geological information. Consult your fellow students or instructor for help in finding nearby tectonic settings with modern magmatic activity.

13-2: Ring dikes are igneous intrusions, typically emplaced along conical surfaces, the diameter of which widens downward. The vertical block surrounded by the ring fracture is commonly subsided into a magma chamber. Cross-section M-N across the map of Figure 13-15a shows a ring dikes of constant width. This implies that the dip of the ring fault is everywhere equal. The space for the intrusion is created by lowering the central block. Figure 13-15b is a map with discontinuous ring dikes of variable thickness. Cross-section O-P should show a smaller cauldron block, lowered inside a bigger cauldron block. Both blocks are bounded by ring faults, that are subvertical in the east. No dikes is formed there, because lowering of the central cauldron block(s) creates no space if walls are subvertical. However, in the western part of the map area, ring fractures dip outward, so that lowering of the cauldron block creates space for the igneous intrusion of ring dikes.

13-3: Cross-section Q-R, across the map of Figure 13-16, illustrates that all the igneous rocks on the map are interconnected in the subsurface and form part of a single pluton. The pluton is intruded into country rock, that made up of a folded sequence. The coal-bearing sandstone unit occupies the core of a synform. The conglomerate is exposed in the eroded cores of antiformal closures, occurring at either side of the central synform.

13-4: Section X-Y, across the map of Figure 13-17, shows dikes A and B are subvertical, as can be inferred from structure-contour rules. The attitude of dikes C and D is more ambiguous, but their straightness suggests they are, also, steep. Although all dikes have the same width at the surface, their apparent thicknesses in the cross-section are all different.

13-5: The igneous complex of Mull, Scotland, in the map of Figure 13-20, hosts an interesting collection of ring dikes. From the cross-cutting relationships in the map patterns, it appears that a suite of earlier acid ring dikes is locally truncated by basic ring dikes. The center of intrusion for both sets of ring dikes is in the southeast of the map. This early set of ring dikes is truncated in turn by the Glenn Cannel granophyre intrusion. The Loch Ba felsite is a late cone sheet, that cuts across all other intrusions.

13-6: The section, across the Anstruther gneiss-dome of Figure 13-6, can, on the basis of the map data, be drawn only in very speculative fashion. The important notion is that the supracrustals are layered volcanoclastics and sedimentary rocks, that are draped, more or less, concordantly around the gneiss-dome.

13-7: The form lines, for the satellite image of Figure 13-27, follow the trend of the layers, discernable in the supracrustals, wrapped around the plutons. The foliation within the plutonic gneiss-domes themselves is less well-defined. The form lines in the supracru-
Chapter fourteen

14-1: Interpretation of the geological history implied in the section of Figure 14-4: The oldest rocks in the sequence are the basement rocks, which are overlaid by unconformable lake and river deposits. All these rock units are buried by a flood basalt sequence. Each episode of basalt flooding was followed by weathering and erosion, as can be inferred from the incision by stream channels, lake deposits, and fossil soils in the top of each basalt flow. The remains of cinder cones are locally preserved as pyroclastic aggregates near feeder dikes, cutting through older layers of basaltic lava. Subsidence must have occurred after the cessation of the magmatic epoch, so that the postvolcanic succession could accumulate.

14-2: Using the legend of Figure 14-17c, it seems that the lava flows at Kilauea originate from fissures, that slowly propagate laterally from a common point of origin. For example, in 1956, eruption was first observed in location A near Puu Honuaula, after which the fissure eruption propagated northeastward to B, C, D, E, and F. A little back-tracking took place when renewed eruption occurred at location G between D and E. But the general trend was that of a fissure, propagating from A to P, to vent the Kii flow of 1955. Later that year, a fissure opened further southeastward, venting basalt flows between locations U and Q. In 1960, the northwestern tip of the fissure system reactivated and vented a lava flow near the Kapoho Crater.

14-3: The sections of Figure 14-21b to d suggest that slide masses, involved in the 1980 collapse of Mount St. Helens, moved northward for several kilometers.

14-4: Many more geological hazard maps are still needed. Study the example set by USGS Special Publication L-836.

14-5: The formula for estimating the rock volume involved in the collapse of a volcanic cone is: \( V = \frac{\pi h^2}{3(\tan \alpha)} \). The collapse of a cone 300 m high and sloping 30 degrees involves a rock volume of 85\( \times 10^6 \) cubic meters.

14-6: The speculative map of the Valles Caldera area, five million years into the future, would probably expose basalts and rhyolitic ring dikes. Fifty million years from now, the entire magma chamber below the caldera floor will be exposed as a subcircular pluton.

Chapter fifteen

15-1: The search for impact structures near your home region requires literature study. Ask your instructor and librarian for references.

15-2: a) Coloring of the slide masses, on the drift map of Figure 15-17a, reveals that the tiny village of Turrillas, Spain, is built on prehistoric landslides. b) The cross-section of Figure 15-17b illustrates a reverse fault (NBF), that has moved a hanging wall of Paleozoic and Mesozoic basement rocks onto a foot wall of Neogene strata. The schist, phyllite, and carbonate rock of the uplifted basement have all supplied material for various landslides, strewn around the northern slope of the Sierra Alhambilla. Cerro Minuto threatens to bury Turrillas village if it follows the slide path of earlier, prehistoric slides, on which the village is built. A device for monitoring movements and ground creep urgently needs to be installed at Cerro Minuto to protect the villagers and their dwellings.

15-3: a) Karst areas are prone to sudden collapse of the ground surface into sinkholes. b) Sinkholes are generally unsuitable for waste disposal, because they are surrounded by porous rocks, that would soak up liquid waste, thus risking contamination of aquifers in the subsurface. Special preparations of the site could reduce the risk of subsurface contamination of waste repositories, hosted in sinkholes.

15-4: The end-moraines deposited during the Illinoian glacial (550,000 to 400,000 years ago) are less prominently preserved than the those of the Wisconsinian glacial (180,000 to 10,000 years ago). The Wisconsinian end-moraines of Figure 15-23 include various stages, as is evident from the sinuous ridges. What is seen in the map is a pattern of glacial retreat. The youngest end-moraines occur farthest north.

Chapter sixteen

16-1: The frequency of visible light is of the order of \( 10^4 \) Hertz. Thermal infrared waves have frequencies ranging between \( 10^6 \) and \( 10^9 \) Hertz. The frequency of radar waves ranges between \( 10^3 \) and \( 10^4 \) Hertz. For comparison, the frequency of FM radio waves is of the order of 100 MegaHertz, and the AM radio band

APPENDIX D: Solutions to Exercises
occupies frequencies ranging between 531 kHz and 1,602 kHz.

16-2: a) One of the strengths of remote-sensing methods is that they provide instantaneous access to any place in the world. No permission is required to enter the terrain. Cumbersome ground logistics are thus avoided. Remote-sensing images reduce the ground surface to a scale that can be managed and analyzed in desk studies. Conventional aerial photographs are commonly panchromatic and analog, and cover areas of up to one hundred square kilometers in each frame. In contrast, satellite images are multispectral and digital and cover areas of several thousand to ten-thousand square kilometers in each frame. Satellite images can be digitally merged with other databases or even transformed into virtual reality images with three-dimensional perspective of the terrain, but the ground resolution of aerial photographs is still up to a hundred times better than that of any digital satellite image. b) Detailed field investigations by geologists on the ground are costly and time-consuming. Only rocks in their immediate vision can be studied. A synoptic mental picture of the spatial distribution of rock units and structures is obtained only after completing the geological map. Some areas are inaccessible for geological ground personnel, due to political, strategic, logistical, or bad weather limitations. However, the advantage of ground studies over remote-sensing methods is that rock samples and fossil specimens can be identified and, if so required, collected for further study. Mineralization zones and the attitude of structural fabrics can be measured in detail. Also, field geology is a lot of fun!

16-3: Oblique and vertical aerial photographs appeared on the cover of this book and in Figures 1-2a, 1-6a, 1-7a, 1-8a & b, 1-9a, 2-6, 2-8, 2-10, 2-12, 7-17, 7-26, 13-1b, 13-6, 13-11a & b, 13-14, 14-3b, 14-11a, 14-32, 14-34c, 15-10, 15-12, and 15-20a & b. Panoramic photographs taken from ground-based vantage points appeared in Figures 3-1b, 4-19, 7-7a, 7-25a & b, 9-4a, 9-14, 13-4, 14-11b, 14-25, 14-28a, 15-4, 15-9a & b, 15-15, 15-16b, and 15-18. Landsat images were used in Figures 7-21, 13-1a, 13-27, and 15-6b. The photograph of the lunar crater in Figures 15-3a & b were taken from aboard the Apollo spacecraft. A radar image was used in Figure 7-23. Seismic maps were used in Figures 4-9a, 8-5, and 10-8. More remote sensing images appear in chapter sixteen: Figures 16-11 to 16-14 (aerial photographs); Figures 16-19a, 16-23a & b, 16-24a & b, and 16-27b (Landsat); Figure 16-20 (SPOT); Figure 16-27a (Space Shuttle radar); Figure 16-29 (Magellan radar).

16-4: Remember that aerial photographs are commonly printed at a quadrangular format of 22.9 by 22.9 inches. Standard aerial photographs at 1:60,000 scale, therefore, cover an area of 14 by 14 kilometers. Those taken at 1:40,000 cover an area of 9 by 9 kilometers. Aerial photographs of scale 1:30,000 cover 7 by 7 kilometers on the ground in each frame.

16-5: a) The stereopair of Figure 16-11 illustrates an arid landscape, devoid of any vegetation. The area is relatively flat, except for a number of barchanoid dunes, resting on a desertscapes. Any drainage pattern is absent. The dominant erosional agent is a northerly wind, as can be inferred from the shape of the barchanoid dunes. Settlements and cultivation centers are absent. b) The stereopair of Figure 16-12 covers an arid area, largely devoid of any vegetation. The landscape is dominated by a series of ridges, formed by resistant bedrock in a folded sequence of sedimentary strata. The flanks or limbs of the folds are transected by parallel stream channels. The drainage network is dry, but its extent suggests that the area is occasionally inundated by torrential rains. The main stream runs roughly from the south toward the north. The map shows a NW-plunging synform in the north of the image. The attitude of the limbs can be inferred by applying the V-rule, where stream channels intersect resistant beds. The folds are gentle to open. Brief geological history: A sedimentary sequence was buried, folded, and uplifted to give rise to the present morphology. c) The stereopair of Figure 16-13 covers an arid landscape. A dendritic drainage pattern runs off to the southeast corner of the photograph. The main wadis are floored by light-toned gravels and lined by trees and shrubs of dark albedo. The region is arid but occasionally receives torrential rains. The bedrock includes a steeply foliated, dark-toned metamorphic belt, trending NW-SE. This metamorphic belt of schists is adjacent to light-toned granitic plutons. The regional structure is transected by NNE-SSW trending fissures. These fissures form shallow ridges in the landscape. They are, in fact, intruded by basic dikes of dark albedo. One of the fissures shows dextral strike-slip displacement of the metamorphic belt. The sequence of supracrustals, including schists, has been sandwiched between two buoyant plutons. The foliation in the supracrustals is discordant to the boundaries of the adjacent plutons and was formed during their emplacement. The penetrative foliation indicates

APPENDIX D: Solutions to Exercises
formation under metamorphic, deeper crustal conditions, perhaps below ten kilometers depth. The fissuring indicates brittle deformation, which commonly occurs only at shallow crustal depths. In fact, the basement is 600 million years old, and the fissures and the basic dike swarm are much younger, only about 30 million years old. d) The stereopair of Figure 16-14 covers an arid landscape. The drainage pattern varies locally from dendritic and trellis on the light-toned basement to radial off the dark-toned plateau of basaltic lava. The region occasionally receives torrential rains. The bedrock below the basalt plateau is made up of E-W-foliated granite or gneiss. The basement is cut by N-S fissures, invaded by basic dikes. These fissures possibly are the conduits that allowed for the extrusion of the flood basalts.

16-6: It takes about nine SPOT images to cover the same area as a Landsat image. Total coverage of the US requires about 4,500 SPOT images.

16-7: The SPOT image of Figure 16-20 covers an arid region. The Draa Plateau hosts a centripetal drainage pattern, that runs off toward the east. The plateau is floored by sedimentary rocks of Carboniferous age. The basal layers of the Carboniferous sequence form ridges in the landscape and are cut by parallel valleys. The shallow basin, made up of gently-dipping Carboniferous beds in the southern part of the image, contrasts with the tightly folded Devonian beds just north of the Draa Valley. Directly to the south of the Draa Valley, one must interpret an E-W-trending fault contact between the Carboniferous and the Devonian sequence. The asymmetry of the folds in the Devonian beds indicates a dextral sense of shear for the Moroccan Border fault.

16-8: The digital pixel map of Figure 16-22a can be converted into a false color image by choosing arbitrary colors for a particular range of digital numbers. The resolution is poor, but the image includes a highway, highlighted by the array of digital numbers between 48 and 56.

16-9: The coloring of Figure 16-28 helps to examine how the distinguished features correspond to the radar image of Figure 1-27a.
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Multilingual Abstracts
الجيولوجيا البنائية وتحليل الخرائط:

د. رود ويجلمرس
قسم علوم الأرض - جامعة الملك فهد للبترول والمعادن
ترجمة: د. عبداللطيف أحمد قحوش

يدرس نظام الجيولوجيا البنائية معمارية الأرض وبعض الكواكب الأخرى. إن أنماط تكوين الصخور ملحم مثيرة بسبب جمالها الفني وأهميتها الاقتصادية للإنسان. إن معرفة البنية تحت سطحية حيوية للنجاح في برامج الهندسة وبرامج استكشاف المعادن. إن الفهم الكامل لبيئات الصخور ضروري للتخطيط في صناعات البترول والتعدين، وفي عمليات البناء، وفي تصريف النفايات، وفي استكشاف المياه. لبيئات التكوين في الصخور أهمية بالغة في تحديد المناطق الخطرة مثل الكتل الصخرية المحتملة إنهيارها، وفي إنشاء الأرض والقوى الجيولوجية. يركز نشاط البحوث على بيئة تكوين الصخور في قشرة القارات القريبة من السطح.

صمم كتاب الجيولوجيا البنائية وتحليل الخرائط لطلاب البكالوريوس في الهندسة المدنية، هندسة البترول، تقنية التعدين، علم المياه، دراسات البيئة، والجيوفيزياء، والجيولوجيا. ولقد عرضت مبادئ الجيولوجيا البنائية بحرص، وتم عرض وشرح المواضيع بنظام منساق ومدعوما بصور توضيحية وتمارين متدفقة في تفسير الخرائط. وتم استخدام كتابة هذا الكتاب في دراسة واحد ومساعد على تحقيق التعلم إنساني بين الطلاب ومدربهم، وترويده بثقة مشتركة في تقنيات ومبادئ علم الجيولوجيا البنائية. بما أن النظرية مدعومة بالتمارين التطبيقية، لذا يمكن استخدام هذا الكتاب للمحاضرات والمعلمين. وإن استخدام كتاب واحد يشمل على جزئيتي متكاملتين أفضل عمليا من كتابين متفردين، كما أنه يبقى التكلفة الشرائية في مقدور الطالب.
Структурная геология и интерпретация карт
Автор: Вайермарс, Руд
Аннотацию перевел канд. геол-мин. наук В.Б.Алексеев
Текст аннотации состоит из двух абзацев

Структурная геология изучает строение твердой Земли и других планет. Деформации горных пород очаровывают и возбуждают фантазию благодаря своей красоте и практическому значению для человека. Знание структуры земной коры необходимо для успеха в большом количестве различных программ, связанных с инженерной геологией и полезными ископаемыми. Ясное понимание структуры горных пород важно для стратегического планирования в нефтяной и горной промышленности, строительстве, захоронении отходов и гидрогеологии. Деформационные структуры вмещающих пород влияют на размещение зон повышенной опасности, таких как оползни, области усадки грунта и сейсмичные разломы. Исследования концентрируются на изучении деформационных структур приповерхностной континентальной коры.

Курс "Структурная геология и интерпретация карт" разработан для студентов, обучающихся по специальностям гражданское строительство, нефтяная инженерия, технология шахт, гидрология, защита окружающей среды, геофизика и геология. Принципы структурной геологии тщательно изложены и разработаны систематически. Они сопровождаются иллюстрациями и упражнениями по интерпретации карт. Эта сводка охватывает один семестр лекций и помогает установить легкий контакт между преподавателями и студентами, обеспечивая общий язык по методам и принципам структурной геологии. Поскольку в этой книге теория совмещена с упражнениями, она может использоваться как для лекций, так и для практических занятий. Использование единой книги, освещающей два взаимосвязанных аспекта—теоретический и практический,— вместо двух отдельных книг, практически и позволяет сделать ее цену доступной для студентов.
構造地質學與地圖解讀 (Structural Geology and Map Interpretation)

儒德 魏捷馬斯 著
盧佳鴻 譯

構造地質學的訓練是用來研究地球與其他行星的架構。岩層的
變形圖案是令人興奮的現象，因為它們不但具有美感同時兼具經濟價
值。認識地下構造是各類工程與礦物探勘計劃成功的必要條件。對岩
層構造的徹底瞭解亦是石油與礦冶工業，大型建築，廢料處理及水源
探勘所不可或缺的。圖岩的變形構造對於潛在的岩石滑動，地層下
陷，地震斷層等的定位非常重要。構造地質學的研究集中在大陸地殼
淺部的岩石變形構造。

"構造地質學與地圖解讀"一書是針對大學部，主修土木工
程，礦冶技術，水文學，環境科學，地球物理與地質學等的學生所設
計。文中謹慎的介紹構造地質學原理與系統性的發展，伴隨著說明圖
表與深入淺出的地圖解讀習題。這本運用已知最新知識、技術的教課
書，可以涵蓋一學期的課程，並且可以建立學生與教師間簡化而有效
率的溝通，同時提供了構造地質學原理與方法上的共通語言。因爲理
論與實習的結合，這本書可同時在講堂與實驗室中使用。因此本書也
較一般分為兩冊的教課書更為實用且價錢合宜學生購買。
Geología Estructural e Interpretación de Mapas
(Structural Geology and Map Interpretation)
Autor: Ruud Weijermars
Traducido por: Julia Cuevas

A manera de introducción

La disciplina de la geología estructural estudia la arquitectura de la Tierra sólida y de otros planetas. Los modelos de deformación de las rocas son rasgos apasionantes debido a su belleza estética y a su interés económico para el hombre. El conocimiento de las estructuras del subsuelo es vital para el éxito de muchos programas de exploración minera y de ingeniería. La comprensión minuciosa de las estructuras de las rocas es esencial para una planificación estratégica en la industria minera y del petróleo, en la construcción, en estudios para la ubicación de vertederos y para la prospección de aguas subterráneas. Las estructuras de deformación en la roca encajante son además importantes para la localización de zonas de riesgo, tales como potenciales zonas de deslizamientos de ladera, hundimiento del suelo y fallas sísmicas. Las actividades de investigación se concentran en las estructuras de deformación de las rocas de la corteza continental superficial.

Este libro, titulado Geología Estructural e Interpretación de Mapas, está proyectado para estudiantes de ingeniería civil, ingeniería del petróleo, tecnología minera, hidrología, estudios medioambientales, geofísica y geología. Los principios de geología estructural son introducidos cuidadosamente y desarrollados sistemáticamente, acompañados por ilustraciones informativas y ejercicios perspicaces sobre interpretación de mapas. Esta presentación actualizada cubre un semestre de enseñanza y ayuda a establecer una comunicación más eficiente entre los estudiantes y sus profesores, proporcionando un lenguaje común sobre las técnicas y los principios de la geología estructural. Debido a que la teoría está combinada con ejercicios prácticos, este libro puede usarse tanto para cursos teóricos como para prácticas de laboratorio. El uso de un único libro de texto que integra teoría y problemas es más práctico que dos libros de texto separados y tiene un coste asequible para estudiantes.
Structural Geology an Map Interpretation
Author: Ruud Weijermars
Translated by: Jean Louis Vigneresse

By way of introduction

La discipline de la géologie structurale concerne l'architecture de la Terre et des planètes internes. Les structures des roches déformées sont passionnantes par leur beauté intrinsèque, mais aussi par leur intérêt économique pour l'homme. La connaissance des structures de subsurface est nécessaire à la réalisation et au succès de la planification dans l'industrie minière et pétrolière, lors de la construction d'ouvrages d'art, et à la mise en place de dépôts de déchets ou à la recherche d'eau. Les structures de la déformation des roches sont aussi indispensables pour localiser les zones à risques telles que les glissements de terrain, les affaissements de sols et les failles séismiques. Les activités de recherche se concentrent sur les structures de la déformation des roches dans la croûte continentale superficielle.

L'ouvrage "Structural Geology and Map Interpretation" est destiné aux étudiants de premier cycle en génie civil, génie pétrolier, technologie minière, hydrologie, environnement, géophysique et géologie. Les principes de la géologie structurale sont soigneusement introduits, puis systématiquement développés et accompagnés d'illustrations et d'exercices pertinents sur l'interprétation en carte. Cette somme de connaissances recouvre un semestre d'enseignement et est conçue comme un fil conducteur entre les étudiants et leurs enseignants, sous la forme d'un langage commun sur les techniques et principes de la géologie structurale. Dans la mesure où la théorie est accompagnée d'exercices pratiques, cet ouvrage peut servir à la fois en cours et lors de travaux personnels. L'usage d'un seul manuel comprenant ces deux volets plutôt que deux livres séparés comporte également un coté pratique, et à la fois économique, pour les étudiants.
Structural Geology an Map Interpretation
Author: Ruud Weijermars
Translated by: Stefan Schmid

By way of introduction


Additional Resources
TECHNOLOGICAL ADVANCES have secured an expanding role for computer and remote-sensing applications in geoscience mapping. This directory includes display advertisements by carefully selected suppliers of products and services related to modern mapping technologies. They offer professional solutions for specific problems that can occur in the interpretation, integration, storage, and retrieval of geological information in surface and subsurface maps. The organizations listed here are involved with one or more of the following technologies: remote-sensing methods, satellite imagery, aerial surveys, digital maps, GIS, GPS, image processing, Multimedia, Hypermedia, computer hardware, software, and interfacing platforms.
Mapping-Contouring System (MCS) is a multi-surface geological/geophysical modeling system that can be applied to virtually any task: Geological, geophysical, environmental and mining. The system contours random or ordered data and always honors every data point regardless of clustering. MCS divides the map area into a system of triangles with a data point at each vertex. The original data points are retained throughout all subsequent processing, thereby insuring that all data points are honored. MCS runs on PC's or on workstations, and the maps look hand-contoured!

Multi-Surface Contouring and Cross Sections

MCS can contour one surface or many surfaces simultaneously, thereby making a number of structural maps and isochore maps at the same time. MCS first makes a series of isochore maps and interpolates or extrapolates these maps as necessary to cover the map area. Then these isochore maps are used to reconstruct missing values downward and upward in the stack so that at the end of the processing procedure there is a complete set of structural and isochore maps on all surfaces.
MCS SYSTEM requirements

Personal Computer:
- IBM-PC or compatible.
- DOS, Windows 3.x, Windows 95, or Windows NT
- Math Coprocessor
- 640KB RAM (8MB recommended)
- Hard disk with 20-40MB available
- VGA Monitor
- Mouse

Workstation:
- SUN, DG, HP, IBM, etc.
- UNIX operating system with X/Windows and Motif
- 16MB or greater RAM
- 500MB or greater hard disk
- Monochrome or color monitor
- Mouse

Multi-Surface Faulting

Mapping-Contouring System handles multiple intersecting non-vertical faults among multiple surfaces. In MCS, faulted systems are treated for what they are: sets of three-dimensional blocks containing geological markers (formation tops) which once were continuous surfaces. The boundaries of these blocks are contourable surfaces and are the fault faces. In MCS, both faults and their vertical separations are contoured. MCS uses the fault vertical separations to do a vertical palinspastic reconstruction on the entire system. Multi-surface stacking is performed on the restored (unbroken) system, then MCS generates fault traces as the intersection between structural surfaces and faults.

Integration

Mapping-Contouring System can integrate within any polygon or polygons among any number of extensive surfaces (structure, isochor, etc.) or intensive surfaces (porosity saturation, anti-gross ratio, etc.) to determine productive area, gross volume, net volume, net porous volume, etc.

Reservoir Simulator

Mapping-Contouring System can automatically prepare input for reservoir simulators "untouched by human hands," and MCS can display output from simulators in graphical form.

Depth Conversion

Mapping-Contouring System does an automatic 3-D (multi-surface) time-to-depth conversion using all seismic and all geologic data. The resulting maps honor all well data at all depths and honor all seismic data in between.
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Alboran's Lectures in Geoscience is a textbook series, prepared by experienced earth scientists. The lectures are carefully organized and balanced in approach. Many professionals, students, and instructors have discovered the practical value of these books as user-friendly instruction manuals.

By way of introduction

The discipline of structural geology studies the architecture of the solid Earth and other planets. Rock deformation patterns are exciting features because of their aesthetic beauty and their economic interest to man. Knowledge of the subsurface structure is vital for the success of a variety of engineering and mineral exploration programs. A thorough understanding of rock structures is essential for strategic planning in the petroleum and mining industry, in construction operations, in waste disposal surveys, and for water exploration. Deformation structures in the country rock are important further for localizing hazard zones, such as potential rockslide masses, ground subsidence, and seismic faults. Research activities concentrate on rock deformation structures in the shallow continental crust.

Structural Geology and Map Interpretation is designed for undergraduate students in civil engineering, petroleum engineering, mining technology, hydrology, environmental studies, geophysics, and geology. The principles of structural geology are carefully introduced and systematically developed, accompanied by instructive illustrations and penetrative exercises on map interpretation. This state-of-the-art account covers one semester of teaching and helps to establish a streamlined communication between students and their instructors, providing common language on the techniques and principles of structural geology. Because the theory is combined with practical exercises, this book may be used for both lectures and laboratory sessions. Using a single textbook, comprising two integrated packages, rather than two separate books is practical and keeps the cost affordable for students.

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