FOURTH EDITION

Stephen M. Rowland, Ernest M. Duebendorfer, Alexander Gates

STRUCTURAL ANALYSIS & SYNTHESIS

A LABORATORY COURSE IN STRUCTURAL GEOLOGY

with website

WILEY Blackwell

Structural Analysis and Synthesis

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A Laboratory Course in Structural Geology

Fourth Edition

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Preface

This manual is intended to serve as the primary resource for the laboratory portion of an introductory course in structural geology for undergraduate students. It is designed to accompany any of the available structural geology textbooks. It supports both the descriptive and quantitative parts of a course at approximately the same level of detail as most of the textbooks. The book retains 17 chapters to cover the standard 12–14 weeks of a semester, and several chapters have specialized themes. The organization by the authors places most of the areas deemed necessary to structural geology at the front of the manual, followed by a synthesis of most of them, and then the more specialized topics at the end.

One of the most challenging aspects of structural geology for introductory students is visualizing three-dimensional structural features and objects and representing them or projecting them on two-dimensional diagrams for analysis. This is still the case even with computer programs to solve simple to complex problems. Students are strongly encouraged to use props to help visualize the real-world features rather than trying to imagine them. The exercises are much easier to solve and the methods understood using this approach.

The other challenge for students is that many techniques build upon previously learned techniques. It is imperative for students to complete the supporting exercises and fully understand them before moving to the next level of rigor, or the deficits will snowball. This is especially true with the equal-area projections which are used in multiple chapters. For this reason, all of the exercises should be done manually at their introduction. After students master the manual techniques, they are encouraged to use computers.

The final challenge for which many students find problems is with the quantitative aspects. The quantitative requirements are not rigorous, but many students cannot remember basic trigonometric relationships, which are used extensively. Many exercises require only SOHCAHTOA and inverse functions for solution, but instead of sketching the geometry of the situation, many students try to imagine it and make errors. It is recommended that triangles are drawn and angles and sides labeled so errors can be avoided. Use of a protractor should also be reviewed prior to the class.

This is the fourth edition of the classic and popular laboratory manual in structural geology that was first introduced in 1986 by Stephen Rowland. Each edition follows trends in the field and this edition is no exception. It retains most of the exercises from previous editions, so that faculty who regularly adopt previous versions of the manual may continue to do so. There are minor changes to some chapters and the addition of several new chapters, but most chapters are composed of previous material that has been edited or expanded upon to adjust the focus and provide structural techniques that were not previously available.

The general changes include several themes:

1. Many geology graduates are employed in the environmental industry. Exercises have been adapted to include environmental applications as well as traditional techniques of structural geology.
2. Many of the exercises have been revised to be more quantitative, especially with regard to determining depth to subsurface features. Techniques are introduced for more quantitative

analysis. Several computer programs are available to solve quantitative problems. Although students are taught to perform techniques manually, the computer programs are described and locations are provided.

3 Chapters and exercises that were primarily descriptive and overlapped strongly with lecture content of most courses in structural geology were revised to be more quantitative. This is especially true for stress and strain measurements. Although many strain techniques were developed several decades ago, they provide necessary quantitative constraints on processes and relationships to make them realistic. This manual includes several additional quantitative techniques.
4 All quantitative techniques have limitations. Without certain requirements and assumptions, the techniques will not yield useful results. It is important that students understand these limitations so they can appropriately apply the techniques and properly evaluate their trustworthiness.
5 Many techniques of structural geology, both in the field and in the lab, are better taught through visual demonstration. Even with classroom demonstration, students require individual demonstration, which is very time-consuming for the professor. Online videos are few and incomplete. This edition includes accompanying videos to demonstrate complex techniques.
6 Figures for the Problems are now included on separate pages at the end of each chapter and labeled with a "P" in the text for ease in identifying and locating them.
7 With limitations on accessing appropriate structural field locations from many urban areas and schools in areas with inappropriate geology, structural geology field trips must be eliminated from the curriculum. In addition, students with physical disabilities and illnesses may be limited in access to field locations. For these reasons and other possible restrictions, two virtual field trips from classic structural geology areas have been added to the manual. These virtual field trips are made from the perspective of a student making observations and measurements in the field. There are even erroneous measurements included so students will need to evaluate and eliminate them.

Many of the ideas in this revision have been refined during the offering of structural geology courses since the late 1980s. However, the direct influence of structural geology faculty members including James Granath, David Gray, Carol Simpson, and David Valentino is acknowledged in this revision. In addition, Richard Allmendinger and Frederick Vollmer provided guidance and permission to reference their excellent computer programs available on their websites. The influence of Ben van der Pluijm and Stephen Marshak is also acknowledged.

About the Companion Website

This book is accompanied by a companion website:

www.wiley.com/go/structuralanalysis4

The website includes:

- Powerpoints of all figures from the book for downloading
- Web links from the book for downloading

1

Attitudes of Lines and Planes

Objectives

- **Measure planes and lines in the field using standard techniques.**
- **Become familiar with the azimuth and quadrant methods for defining the orientations of planes, lines, and lines within planes.**
- **Draw and read back orientations on maps.**

This chapter investigates the orientations of lines and planes in space. The structural elements that we measure in the field are lines and planes, and analyzing them on paper or on a computer screen helps us visualize and understand geologic structures in three dimensions. In this chapter, we examine nomenclature, measurement, and representation of these structural elements. Solving apparent-dip problems is commonly also included in a chapter on lines and planes, but these problems are much more easily solved using a stereonet and will be included in Chapter 3.

All orientations contain two components: an inclination and a declination. The declination is a horizontal angle of rotation from a reference point, most commonly true north. Declinations include the strike of a planar feature (Figure 1.1) and the trend of a linear feature (Figure 1.2). Inclination is the angle that a plane or line is sloped relative to the horizontal plane of the earth's surface. For planes, this quantity is the dip (Figure 1.1), and for lines, it is the plunge (Figure 1.2).

The orientation of planar features is measured with a strike and dip. By convention, they are labeled strike, dip, and dip-direction, though there are variations. The dip direction is the quadrant toward which the dip is inclined. Dips must be perpendicular to their corresponding strike and are indicated by the dip direction. A northeast (NE) strike, for example, can only have a southeast (SE) or northwest (NW) dip direction. The orientation of linear features is measured with trend and plunge and is reported as plunge/trend. Lines do not require a dip direction, so the written orientation is readily distinguished from that of a plane.

There are two ways of expressing the strikes of planes and the trends of lines (Figure 1.3). The azimuth method is based on a 360° clockwise circle

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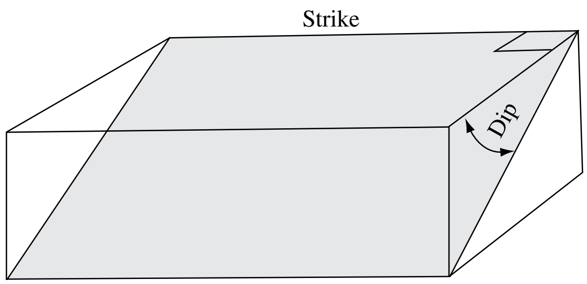


Figure 1.1 Strike and dip of a plane.

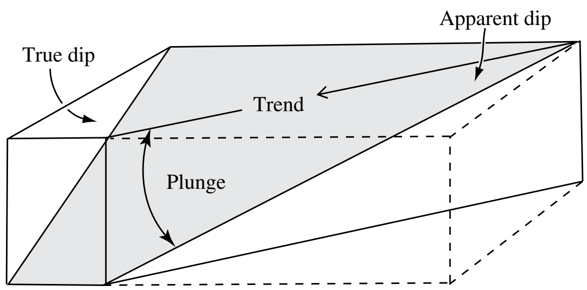


Figure 1.2 Trend and plunge of an apparent dip.

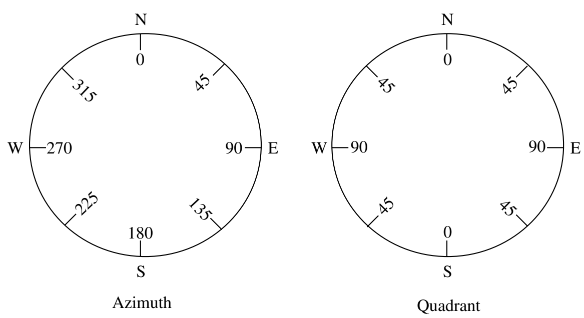


Figure 1.3 Azimuth and quadrant methods of expressing compass directions.

and the quadrant method is based on the four 90° compass quadrants – north, south, east, and west. The quadrant system is the most commonly used in the United States, but in other countries the azimuth system is the convention. Strikes are traditionally measured from the north-half of the transit or compass, but it is understood that the line extends in both directions. Unless horizontal, trends must be measured from the direction that they plunge, so they can be in any direction.

A plane that strikes due northwest–southeast and dips 50° southwest could be described as 315°, 50°SW (azimuth) or N45°W, 50°SW (quadrant). Similarly, a line that trends due west and plunges 30° may be described as 30°/270° in azimuth (sometimes written as 30° → 270° or 30°, 270°) or 30°/N90°W in quadrant. For azimuth notation, always use three digits (e.g. 008°, 065°, 255°), so that a bearing cannot be confused with a dip (one or two digits). In this book, the strike is given before the dip, and the plunge is given before the trend. We recommend that you use the azimuth convention in your work. It is much easier to make errors reading a bearing in quadrant notation (two letters and a number) than in azimuth notation (a single number). In addition, when entering orientation data into a computer program or spreadsheet file, it is much faster to enter azimuth notation because there are fewer characters to enter.

The method for measuring planes and lines in the field is to use a pocket transit or a modified compass with a clinometer. Video 1 https://youtu.be/QSrmwSot7Os contains instructions on how to measure lines and planes in the field using both devices. An alternative method of measuring and representing strike and dip is the right-hand rule. The right-hand rule requires that you view and measure the strike direction so that the surface dips to your right. For example, the attitude of a plane expressed as 040°, 65°NW could be written as 220°, 65° using the right-hand rule convention because the 65°NW dip direction would lie to the right of the 220° strike bearing. The system eliminates the need for dip direction. A third but less popular method is dip/dip direction. In this case, the dip angle and its direction (declination) are measured. The dip direction is perpendicular to the strike, so no dip direction is required for this method either. In areas of low dip angles, this can be a simpler and more accurate system because the strike of planes with low dip angles can be difficult to measure and may result in significant errors.

There is a problem measuring declinations because they are meant to be from the geographic North Pole, but a compass or transit measures from the magnetic North Pole. These devices must be adjusted to correct for the difference in location between the poles. The closer the measurement is made to the poles, the more pronounced the correction may be, and the current rapid wandering of the magnetic North Pole is further complicating data collection. There are apps available for smartphones to measure orientations that do not require corrections, but they tend to be less accurate and subject to cell phone coverage. Because inclinations are relative to the earth surface at a specific location, they are only comparable locally. Relative to a fixed point in space, a 30° dip at one location would not be parallel to a 30° dip measured 1000 km away.

Definitions

The following terms are used to describe the orientations of lines and planes. All of these are measured in degrees, so values are typically followed by the degree symbol (°).

Attitude The orientation in space of a line or plane. By convention, the attitude or orientation

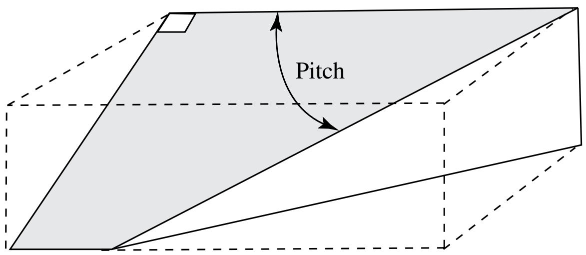


Figure 1.4 Pitch (or rake) of a line in an inclined plane.

of a plane is expressed as its *strike* and *dip*; the attitude of a line is expressed as *trend* and *plunge*. (syn: orientation).

Bearing The declination or horizontal angle between a line and a specified coordinate direction, relative to compass directions or in azimuth.

Strike The bearing of the line of intersection of an inclined plane with the horizontal plane or surface (Figure 1.1). The strike is a line of equal elevation on a dipping plane.

Dip The vertical angle between an inclined plane and a horizontal line perpendicular to its strike. The maximum angle of inclination on an inclined plane. The direction of dip can be thought of as the direction water would flow down the plane (Figure 1.1).

Trend The bearing (compass direction or declination) of a line (Figure 1.2). Non-horizontal lines trend in the down-plunge direction.

Plunge The vertical angle of inclination between a non-horizontal line and the horizontal (Figure 1.2).

Pitch The angle measured *within* an inclined plane between a horizontal line and the line in question (Figure 1.4). Also called **rake.**

Apparent dip The vertical angle between an inclined plane and a horizontal line that is not perpendicular to the strike of the plane or in true dip direction (Figure 1.2). For any inclined plane, the true dip is always greater than any apparent dip. Note that an apparent dip may be defined by its trend and plunge *or* by its pitch within a plane.

Problem 1.1

Translate the azimuth convention into the quadrant convention, or vice versa.

a) N12°E	f) N37°W
b) 298°	g) 233°
c) N86°W	h) 270°
d) N55°E	i) 083°
e) 126°	j) N3°W

Problem 1.2

Circle those attitudes that are impossible (i.e. a bed with the indicated strike cannot possibly dip in the direction indicated).

a) 314°, 49°NW	f) 333°, 15°SE
b) 086°, 43°W	g) 089°, 43°N
c) N15°W, 87°NW	h) 065°, 36°SW
d) 345°, 62°NE	i) N65°W, 54°SE
e) 062°, 32°S	

Problem 1.3

Fault surfaces can contain slip lineations (fault striae). Such slip lineations can be used to determine the orientation of a slip on a fault and, therefore, whether the motion on the fault was strike-slip, dip-slip, or oblique-slip. A geology student who was just learning to use a pocket transit recorded the orientations of five slip lineations on one fault surface. The strike and dip of the fault surface is 320°, 47°NE. The student's five recorded lineation orientations are recorded in the table below.

Determine which lineation orientations are feasible and which ones must represent a mistake on the part of the student because the given orientation does not lie within the fault plane. Give a brief explanation for each of your five answers. For the valid lineation orientations, indicate which type of fault motion is indicated.

Lineation (plunge and trend)	Feasible? (yes or no)	Explanation	Type of motion indicated (strike-slip, dip-slip, or oblique-slip)
a) 34°, due north			
b) 0°, 140°			
c) 33°, N66°W			
d) 47°, 050°			
e) 75°, due north			

Structural Elements

The structural elements observed in an outcrop must be carefully discerned as actual components of the rock before they are measured. Many students attempt to take measurements from the surface of outcrops which generally are not suitable data. In most cases, it is better to extend the observed feature away from the outcrop surface with a book for planar features or a wooden pencil for linear features. This smooths uneven surfaces and eliminates the influence of magnetite or other magnetic minerals on the magnetic compass needle. Care must be taken that the tools used to extend the elements are not themselves magnetic.

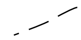
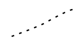
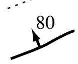
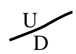
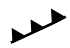
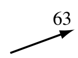
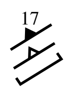
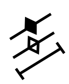
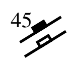
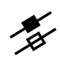
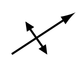
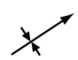
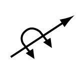
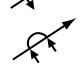
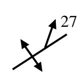
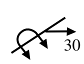
Planar and linear elements have standard notations for use on geologic maps (Table 1.1). Planar elements include primary features such as bedding and dikes, as well as secondary features such as foliations including cleavages, faults, and joints. By convention, bedding is designated S_o as the most basic of surfaces. The foliations that overprint bedding are labeled S_1–S_n, with S_1 the earliest tectonic cleavage (typically slaty), followed by successive overprinting crenulation cleavages S_2–S_n. In metamorphic rocks, foliations such as schistosity and gneissosity cannot be related to bedding so cannot follow the S_1–S_n system. Instead, the oldest recognizable surface can be designated S_x and subsequent foliations designated S_{x+1} and so on.

There are primary planar features that can be used to reconstruct areas and document strain but don't have S surface designations. For example, foresets in cross bedding can be used to determine flow directions and strain in some cases. They should be measured and documented.

Structural or secondary linear elements can be divided into two types, intersection lineations and stretching lineations. The intersection of any two planar surfaces produces a lineation. These can range from discrete features like pencil cleavages to more subtle features like wrinkles on foliation surfaces. It is best to measure the two planar features that create the lineation in most cases. These lineations can be designated by the two intersecting surfaces such as $L_{1\times2}$ (S_2 crossing S_1) for reference. Stretching lineations are of more common interest. They can be slickensides on faults or any linear fabric in an L or LS tectonite. In particular, lineations in shear zones are important because they can show movement sense, like slickensides. If needed, these can also be labeled by generation such as L_1. Fold axes/hinge lines are measured as lineations (intersection).

There are also primary linear features that should be documented for reconstruction of a field area. In sedimentary rocks, parting lineations, flute casts, and groove casts among others can be documented and measured to help determine flow direction and strain in some cases. Plutonic and volcanic rocks can contain flow foliations that are also useful.

Table 1.1 Common symbols used on geologic maps.

	Strike and dip of bedding
	Overturned bedding
	Vertical bedding
	Horizontal bedding
	Crumpled bedding
	Trace of contact
	Less well-located contact
	Covered contact
	Fault contact with dip
	Sense of slip on strike-slip fault
	Sense of slip on dip-slip fault (D = down, U = up)
	Thrust fault, barbs on upper plate
	Bearing and plunge of fold axis or lineation
	Strike and dip of foliation, cleavage, or schistosity
	Vertical foliation, cleavage, or schistosity
	Strike and dip of joints or dikes
	Vertical joints or dikes
	Trace of axial surface or crest of anticline, with plunge
	Trace of axial surface or trough of syncline, with plunge
	Anticline with overturned limb
	Syncline with overturned limb
	Trace of axial surface with bearing and plunge of fold axis
	Overturned anticline with bearing and plunge of fold axis

Symbols for Common Structural Elements

Plotting or reading back any structural element requires determining the declination angles. This can be done digitally using a number of computer drafting programs. However, for this chapter, the exercise will be done by hand for better understanding. The procedure requires first to determine the reference direction (usually north) on the map in question. Next, a protractor is used to measure the angle between the reference direction and the strike or trend line to be measured or drawn (Figure 1.5). Students may need to watch online videos on the use of a protractor if they cannot remember how to use one. Finally, the proper symbol is chosen for drawing or determined for reading back and the angle of dip or plunge is written or read. Dip direction is shown by the tick mark on the side of the strike line and the dip is written next to it. The plunge angle is written on the plunging end of the trend line. Symbols for elements are shown in Table 1.1.

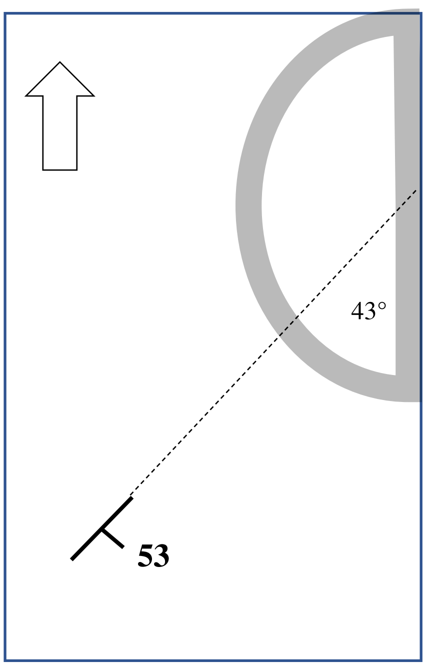


Figure 1.5 Measuring the strike or trend of a structural symbol using a protractor.

Structural Grain

In many areas, the structural geology controls the formation of the landscape. The alignment of ridges and valleys across an area can be controlled by the structural alignment of the bedrock. Such alignment is called *structural grain*. Structural grain is measured as a declination or bearing the same way as a strike or trend. A line can be drawn along or parallel to the general alignment of a ridge, expressed by the contours on a topographic map, as structural trend. The lines of structural grain are measured using a protractor, like strike or trend (Figure 1.6). Ridges are formed by more resistant units like quartzite, whereas valleys are more commonly underlain by less-resistant rock such as shale. There can be several structural grains across a map depending upon the structural complexity of the bedrock in the area. By determining their orientations, the geology of an area may be more easily interpreted. Geologists use structural grain as a standard method to generalize the strike of units in geological interpretation.

Faults can also be recognized by topographic features. Faults are typically linear features on maps that can offset other topographic features such as ridges and valleys. They can also appear as

Problem 1.4

Plot the following structural elements on the map in Figure P1.1. Use the proper symbol (see Table 1.1) and label each (a, b, c, etc.).

a) N21°E, 57SE bedding
b) 288°, 13 N joints
c) N26°W, 42SW cleavage
d) 055°, 41SE foliation
e) 017°, 68NW cleavage
f) 233°/12° fold axis
g) 270°/81° stretching lineations
h) 083°/9° slickensides

Problem 1.5

Read back the structural elements on the map in Figure P1.2 and determine what the symbol represents. Fill in the table below with the results.

Location	Strike/trend	Dip/plunge	Element
a			
b			
c			
d			
e			

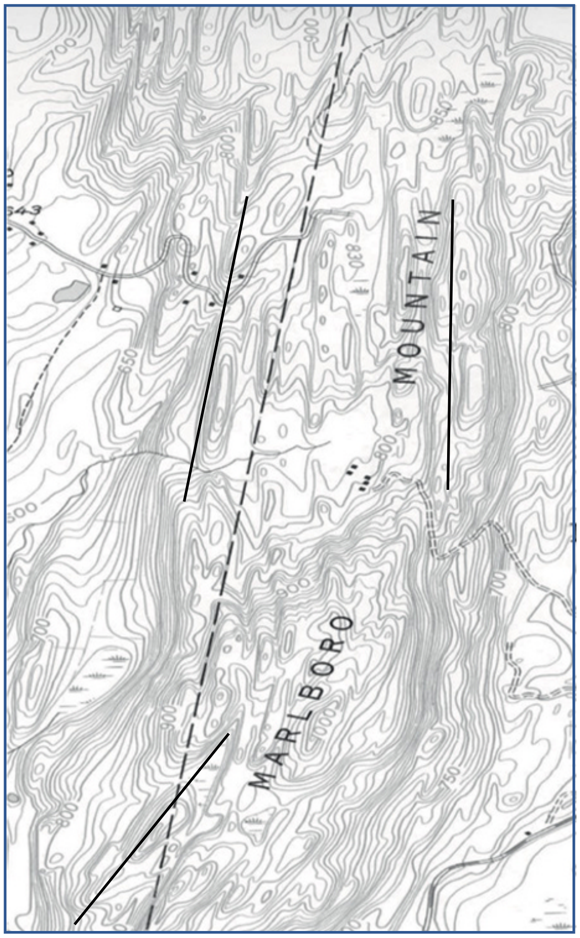


Figure 1.6 Topographic map showing linear ridges and the line to measure structural grain of a ridge.

profound breaks in topographic styles, juxtaposing hilly areas with flat areas. Active faults can offset rivers and other modern features. These fault lines are measured the same way as the structural grain with a protractor.

Karst topography is common in temperate areas underlain by limestone. One of the main features of karst is the formation of sinkholes. In many cases, the location of sinkholes is controlled by joints, joint systems/fracture trends, and brittle faults. In particular, sinkholes are common at the intersection of joints or faults. Aligned sinkholes can define zones of joints (fracture zones). By measuring the bearing of aligned sinkholes, the alignment of such brittle features may be determined.

In some cases, an indication of dip can also be determined from the topography. If the more resistant units that make up the ridges are shallowly dipping, there will typically be a dip slope and a strike or scarp slope. The steeper side of the ridge results from erosion of the unit face and is the strike slope. The shallower side of the ridge generally follows the dip of the bed. The dip direction is in the direction of the shallow side and the strike approximately follows the structural grain of a ridged area.

Problem 1.6

Using the map in Figure P1.3, determine the structural grain of the areas indicated. Also, determine the dip direction where possible.

Location	Structural grain	Dip direction?
a		
b		
c		
d		
e		

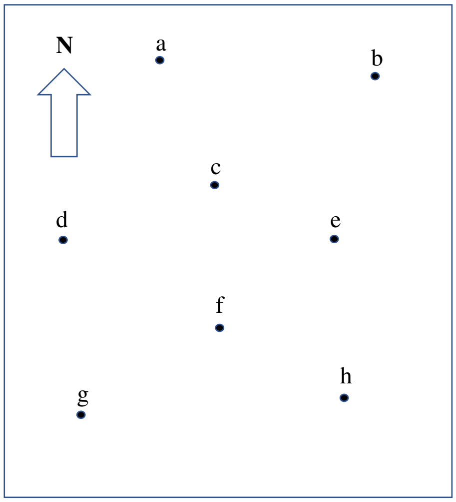


Figure P1.1 Base map on which to plot structural symbols in Problem 1.4.

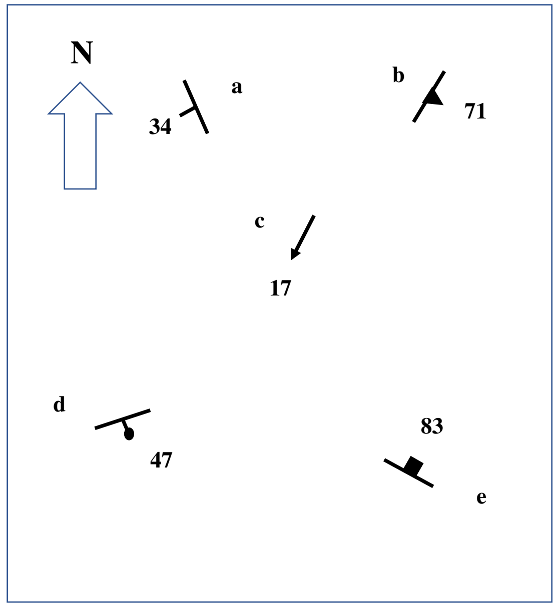


Figure P1.2 Map with structural symbols to be read back in Problem 1.5.

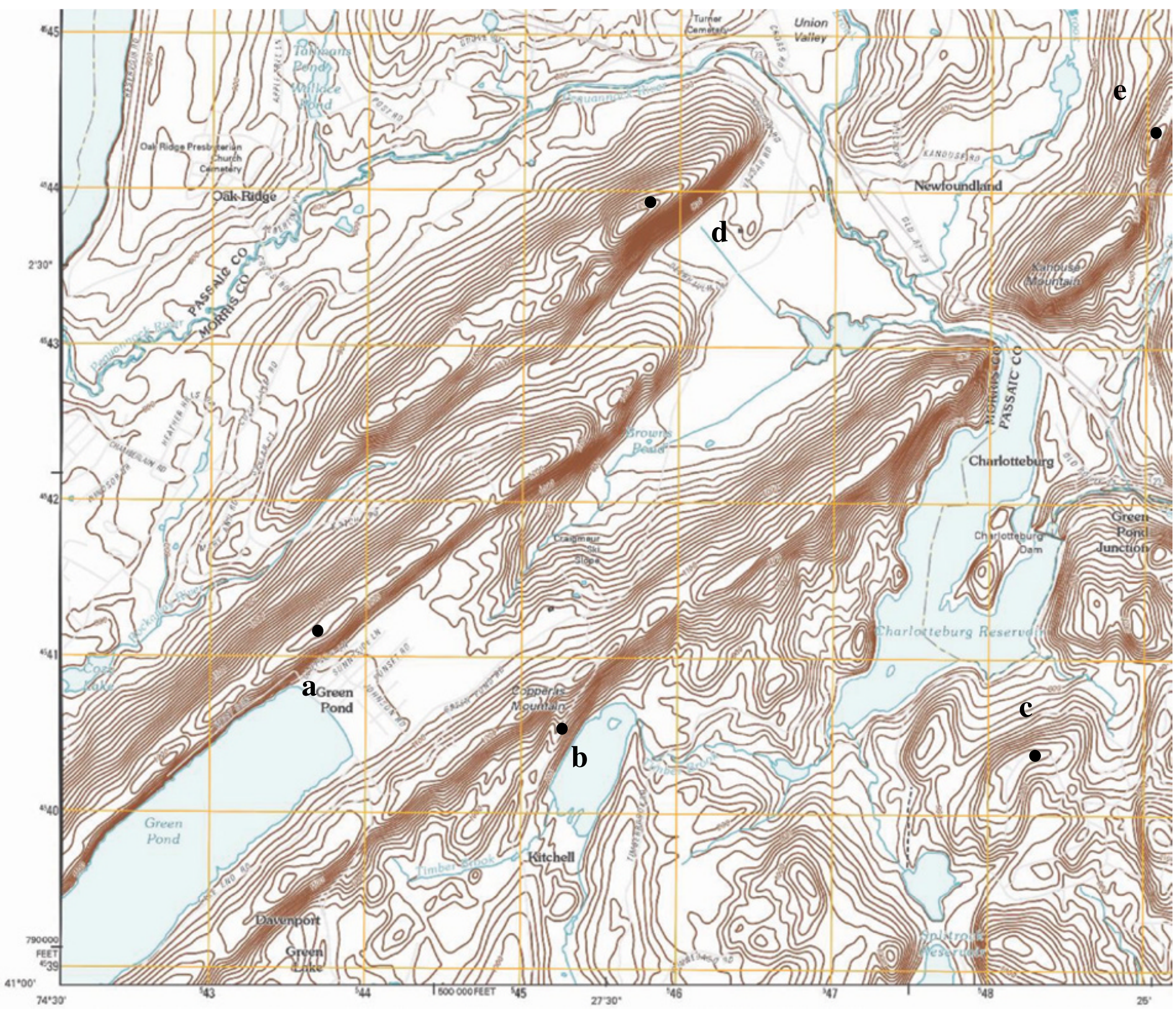


Figure P1.3 Topographic map showing linear ridges with uneven slopes to measure structural grain and possible dip direction in Problem 1.6.

2

Outcrop Patterns and Structure Contours

Objectives

- **Determine the general attitudes of planes from outcrop patterns.**
- **Draw structure-contour maps.**
- **Solve three-point problems.**
- **Determine outcrop patterns of planar layers from attitudes at isolated outcrops.**
- **Determine the nature of contacts from outcrop patterns and attitudes.**
- **Determine stratigraphic thickness from outcrop pattern.**

One of the primary roles of a geologist is to quantitatively determine subsurface structural relations from surface and/or well data. Your skills to address this will be developed starting with planar features and progressing to more complex structures. Planar structural elements such as contacts between monoclinal beds, dikes, and faults form irregular outcrop patterns on the uneven earth's surface. In situations where strike and dip symbols are not provided (such as on regional, small-scale maps), outcrop patterns can serve as clues to the orientations of the planes. These relations should also be used for constructing maps from field data. The following are seven generalized cases showing the relationships between topography and the outcrop patterns of planes as seen on a map. As you examine Figures 2.1–2.7, cover the block diagram (parts a) and try to visualize the orientation of the bed from its outcrop pattern in map view (parts b). Note the strike and dip symbols that indicate orientation.

1. Horizontal planes/contacts parallel topographic contour lines. They also "V" or point upstream but this is not unique (Figure 2.1).
2. Vertical planes/contacts are not deflected at all by valleys or ridges (Figure 2.2).
3. Moderate to steeply inclined planes "V"/point opposite to the direction of dip across horizontal or shallowly inclined ridges (Figure 2.3).
4. Planes/contacts that dip upstream also "V" upstream (Figure 2.4).
5. Planes/contacts that dip downstream at the same dip angle as the stream gradient appear parallel to the stream bed (Figure 2.5).

Structural Analysis and Synthesis: A Laboratory Course in Structural Geology, Fourth Edition.
Stephen M. Rowland, Ernest M. Duebendorfer, and Alexander Gates.

Companion website: www.wiley.com/go/structuralanalysis4

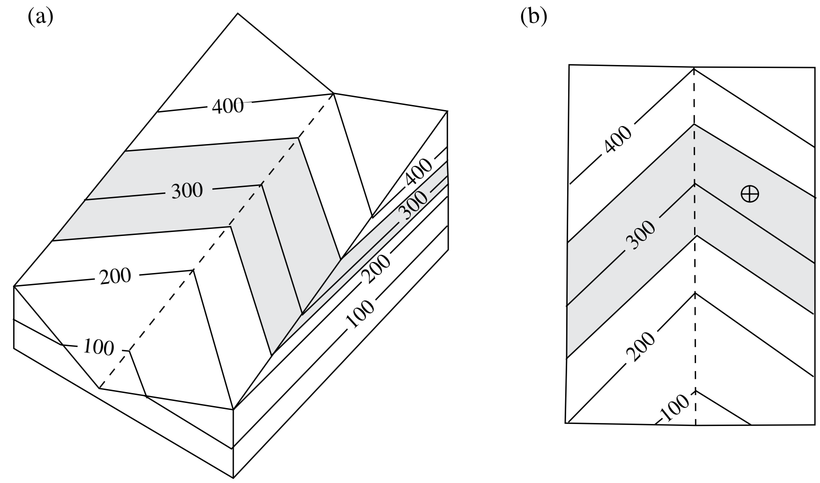


Figure 2.1 Horizontal layer in a stream valley. (a) Block diagram. (b) Map view.

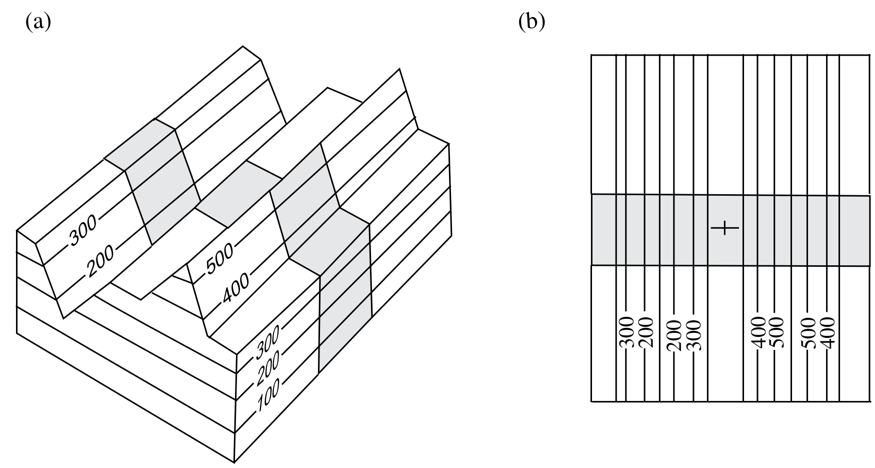


Figure 2.2 Vertical layer strikes perpendicular across a ridge and valley. (a) Block diagram. (b) Map view.

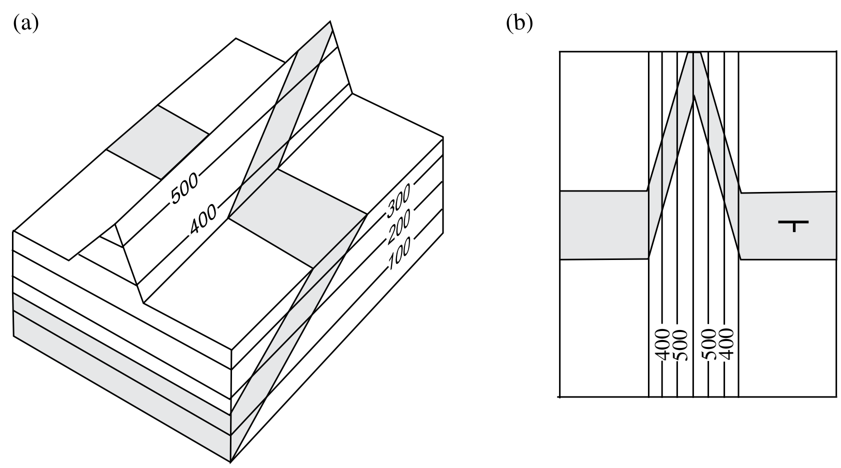


Figure 2.3 Inclined layer strikes perpendicular across a horizontal ridge. (a) Block diagram. (b) Map view.

6 Planes/contacts that dip downstream at a gentler angle than the stream gradient "V"/point upstream (Figure 2.6).

7 Planes/contacts that dip downstream at a steeper angle than the stream gradient (the usual case) "V"/point downstream (Figure 2.7).

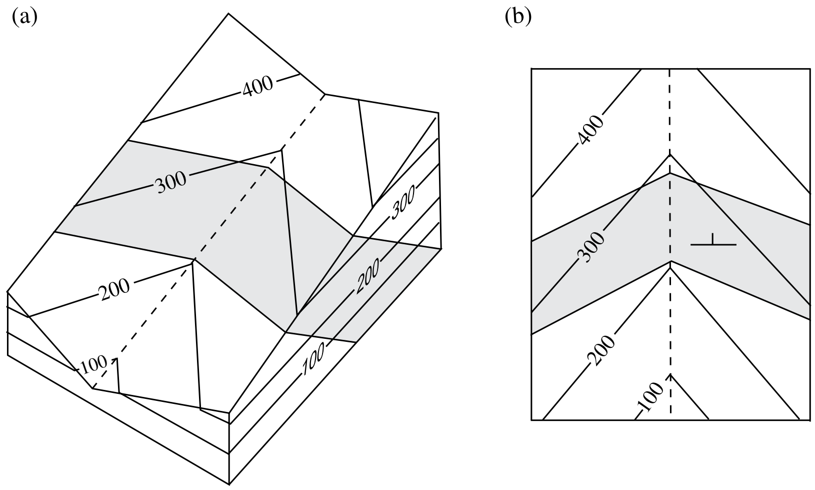


Figure 2.4 Inclined layer dipping upstream that flows 90° to strike. (a) Block diagram. (b) Map view.

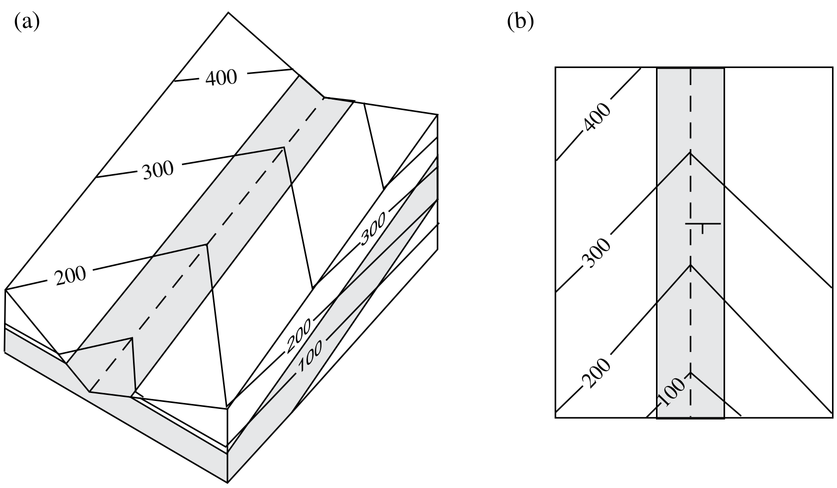


Figure 2.5 Layer dipping parallel to stream gradient (perpendicular strike). (a) Block diagram. (b) Map view.

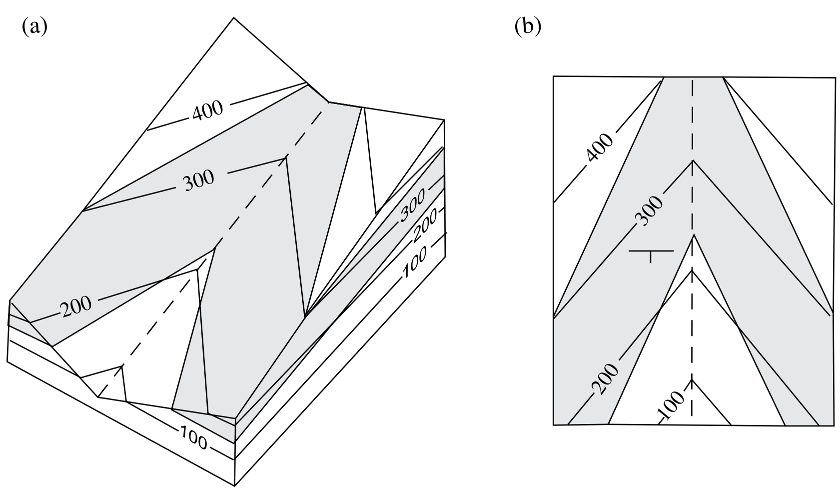


Figure 2.6 Layer dipping downstream more gently than the stream gradient with strike perpendicular to stream. (a) Block diagram. (b) Map view.

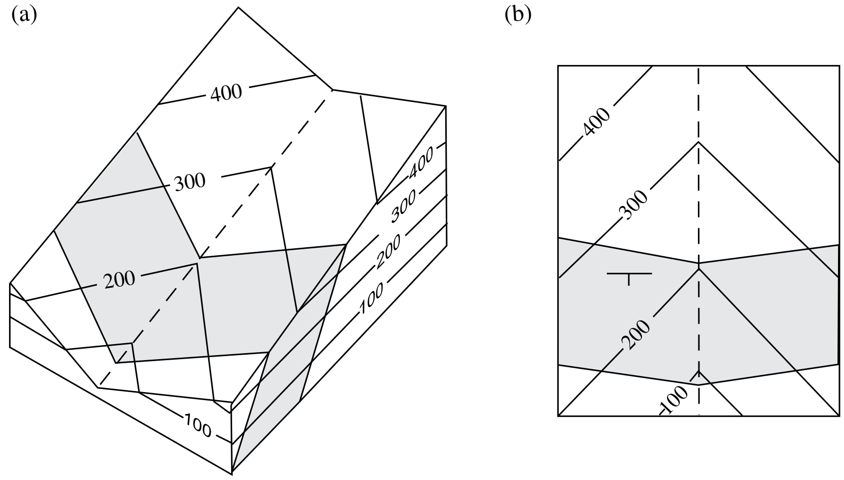


Figure 2.7 Layer dipping downstream more steeply than the stream gradient; stream perpendicular to strike. (a) Block diagram. (b) Map view.

Problem 2.1

On the geologic map in Figure P2.1, draw the correct strike and dip symbol in each circle to indicate the attitude of Formation B and each dike. To verify your attitude symbols, Figure P2.2 can be cut out and folded to form a block model of this map. Table 1.1 shows standard symbols for geologic maps.

Structure Contours

On a topographic map, contour lines connect points of equal elevation on the earth's surface. In contrast, *structure contour* is a line that connects points of equal elevation from sea level on a *structural surface*, such as the top of a bed or formation (Figure 2.8). This means that the orientation of a structure contour is parallel to the strike of the bed or other structural element. Dip direction is perpendicular to the structure contour and directly downslope. Structure contours are read and analyzed the same way as topographic contours, in most cases. For example, calculating dip angles is done the same way as calculating slope angles from topographic contours. Both use the formula:

$$\tan\delta = \frac{\text{change in elevation}}{\text{map distance}}$$

Structure-contour maps are used for depiction and recognition of features in the subsurface. They are used extensively in petroleum exploration to identify structural traps and in hydrology to characterize the subsurface configurations of water tables and aquifers. Although there are more sophisticated methods to model the hydrogeology of an area, structure contouring of the water table is an invaluable skill for all geologists working on environmental delineation/remediation projects.

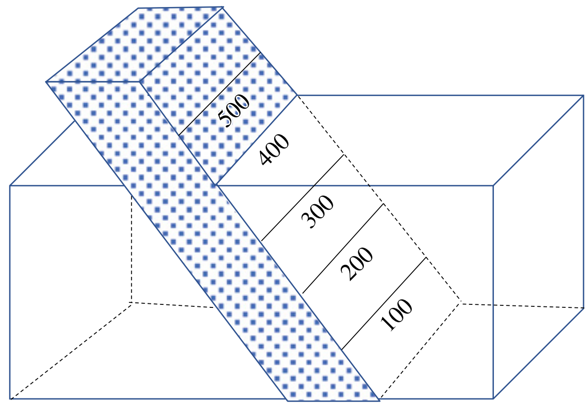


Figure 2.8 Example of structure contours on a structural surface.

Structure-contour maps are commonly constructed from drill-hole data. See Figure 2.9, for example, which shows a faulted dome. Notice that, unlike topographic contours, structure contours can terminate abruptly. Gaps in the map indicate normal faults, and overlaps indicate reverse faults.

There are various techniques for contouring elevations. In the case of structure contours, there are usually not enough data to produce an unequivocal map, so experienced interpretation is valuable. Although there are computer programs that draw contour lines between data points, such programs cannot substitute for the judgment of an experienced geologist.

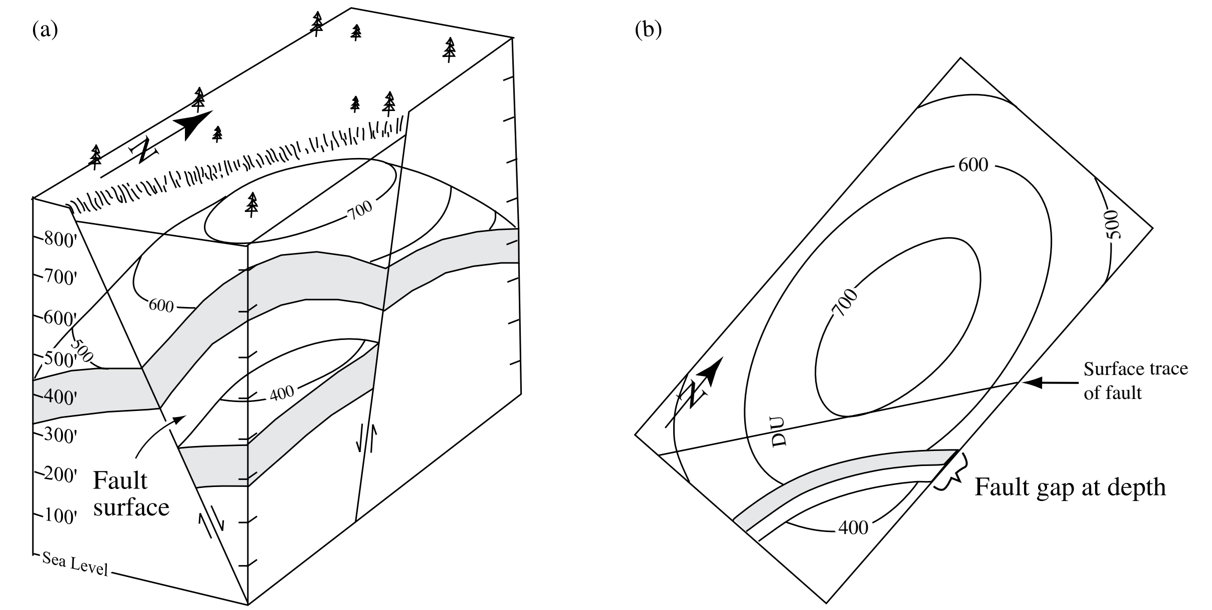


Figure 2.9 Block diagram (a) and structure-contour map (b) of a subsurface faulted structural dome with contours on the top of shaded layer. D, down; U, up.

The Three-Point Problem

In many geologic situations, a planar bed or fault surface may crop out at several locations. If the elevations of three points on the surface are known, then the "three-point problem" solution can be used to determine the orientation of the bed or fault (see technique in Video 2 at https://youtu.be/GBpY_Vi0zMw). Figure 2.10a shows three points (A, B, C) on a topographic map. These three points lie on the upper surface of a sandstone layer. The problem is to determine the attitude of the layer.

Step-by-Step Solution

1 Label the three known points A, B, C and their elevations on the map.
2 Draw lines connecting the three points and making a triangle.
3 One of the lines connects the highest to the lowest of the three points. Scale this line with a ruler and find the point along it that is equal in elevation to the point of intermediate elevation. In Figure 2.10b, point B has an elevation of 160 ft, so point B′, the point on the AC line that is equal in elevation to point B, lies 6/10 of the way from point A (100 ft) to point C (200 ft).
4 Draw a line from the intermediate elevation point to equivalent scaled elevation on the highest to lowest line. This is the strike line. In Figure 2.10c, there are two points, B and B′, of equal elevation lying in the plane of the bed and defining the strike of the plane. The structure-contour line B–B′ is drawn, and the strike is measured with a protractor to be 048 (N48°E).
5 A series of strike lines can now be drawn on the map parallel to the strike line at selected regular elevations. Use the scaled line from highest to lowest elevation to determine the structural contours to be drawn (Figure 2.10d). The spacing (d) between the structure contours of chosen elevation increments is replicated across the map to complete the structure contour map (See Figure 2.13a).
6 The spacing (d) reflects the angle of dip and the dip direction is perpendicular to strike in the direction of lower elevations. The dip angle can be determined trigonometrically like slope on a topographic map as shown for Figure 2.10 and 2.13a:

$$\tan\delta = \frac{\text{change in elevation}}{\text{map distance}} = \frac{60'}{104'} = 0.57$$

$$0.57 = \tan 30^\circ,\ \delta = 30^\circ$$

More commonly, three-point problems are applied to well data. The procedure is the same as described for surface exposures except the elevations used in the analysis are from depth below the surface. The elevation for each well is the drilling depth subtracted from the surface elevation to yield an elevation relative to sea level, the datum. There is a difference

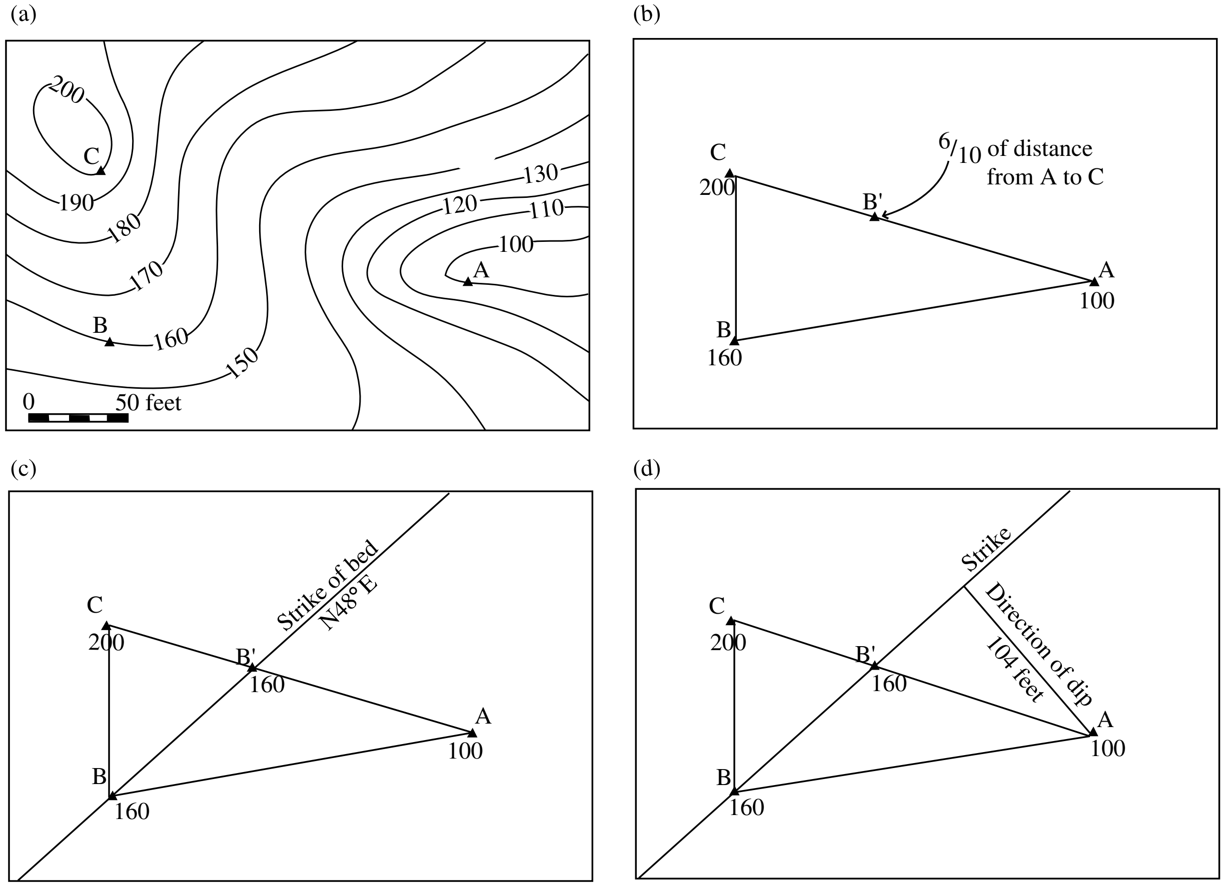


Figure 2.10 Solution of a three-point problem using a combination of graphical and trigonometric techniques. (a) Three coplanar points (A, B, and C) on a topographic map. (b) Connect by lines to make a triangle. Locate of a fourth point, B′ on the AC line, at the same elevation as point B. (c) Line B–B′ defines the strike of the plane. (d) Dip-direction line perpendicular to the line B–B′; dip angle determined using Step 6.

between solid elements such as beds, faults, or dikes and the water table which is commonly independent of them. The dip angle and its direction show the direction of groundwater movement and possibly some indication of relative velocity.

Problem 2.2

Points A, B, and C in Figure P2.3 are oil wells drilled on a level plain, and all of the wells tap the same oil-bearing sandstone. The depth (*not the elevation!*) of the top of this sandstone in each well is as follows: A = 5115 ft, B = 6135 ft, and C = 5485 ft.

1 Determine the attitude of the sandstone.
2 If a well is drilled at point D, at what depth would it hit the top of the sandstone?

Drawing a Topographic Profile

Topographic profiles are the first step in drawing a geologic cross section. The profiles show the relief at the earth's surface along the top of the geologic structure section. Usually you will have to construct your own topographic profile. Cross sections must be drawn on topographic profiles with no vertical exaggeration. The technique for drawing a topographic profile is as follows:

1 Draw the section line on the map (Figure 2.11a).
2 Lay the edge of a piece of paper along the section line, and mark and label on the paper each contour, stream, and ridge crest (Figure 2.11b).
3 Scale off and label the appropriate elevations on a piece of graph paper (Figure 2.11c). Graph paper with 10 or 20 squares per inch is ideal for 7.5-minute quadrangle maps because the scale is 1 in = 2000 ft. Notice that the map scales on Figures 2.11a and 2.11b are the same as the vertical scale on Figures 2.11c and 2.11d. *It is very important that the vertical and horizontal scales are the same on structure sections*. This is a very common oversight. If the scale of the structure section is not the same as the scale of the map then the dips cannot be drawn at their normal angle.

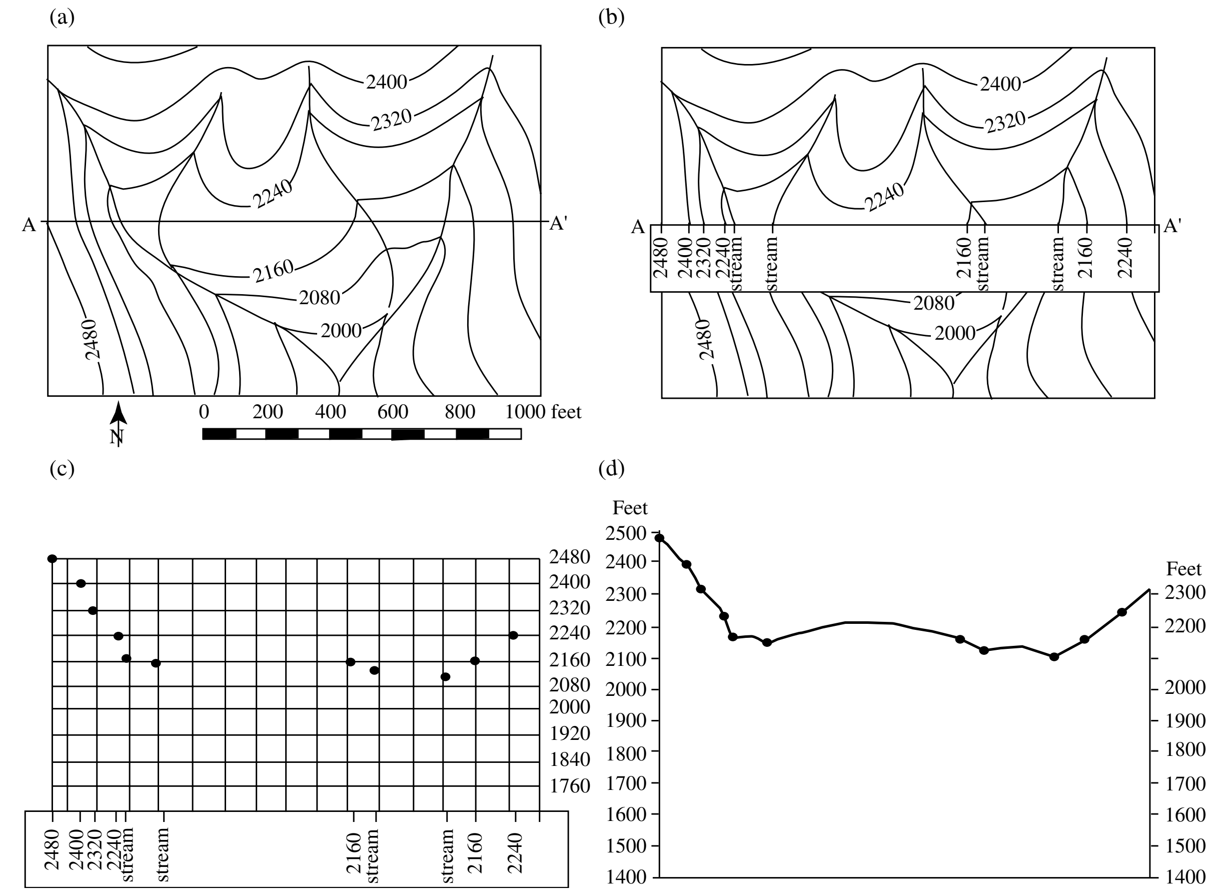


Figure 2.11 Technique for drawing a topographic profile. (a) Draw section line on map. (b) Transfer contour crossings, streams, and other features to another sheet of paper. (c) Transfer points to proper elevation on cross section sheet. (d) Connect points in a way that reflects the topographic subtleties recorded on the map.

4 Lay the labeled paper on the graph paper and transfer each contour, stream, and ridge crest point to the proper elevation on the graph paper (Figure 2.11c).
5 Connect the points (Figure 2.11d).

Drawing Cross Sections of Structure Contour Maps

A geologic cross section can now be added to the topographic profile. The procedure is essentially the same as the topographic profile except structure contours are used instead of topographic contours. This is a very simple procedure for planar features because they will appear as straight lines and, unlike complex topography, only two points are needed to define a straight line.

1 Construct a topographic profile (Figure 2.12).
2 Lay the edge of a piece of paper along the section line, and mark and label on the paper at least two structural contour elevations for each contact.
3 Lay the labeled paper on the graph paper and transfer each structure contour point chosen to the proper elevation on the graph paper/profile (Figure 2.12).
4 Connect the points and draw the planar features using a ruler (Figure 2.12).

Determining Outcrop Patterns with Structure Contours

If an important planar horizon is exposed in three places on a topographic map as in Figure 2.13a, its outcrop pattern can be determined on a topographic map. This is done by using the three-point solution and locating the intersections of the structure contours with the topographic contours. This is accomplished using the following technique:

1 Draw structure contours parallel to the line B–B′ (Figure 2.10d). In order to determine the outcrop pattern, these structure contours must have a contour interval equal to (or a multiple of) the contour interval on the topographic map. Because the surface is planar, the structure contours are a series of straight, equidistant, parallel lines. The spacing can be

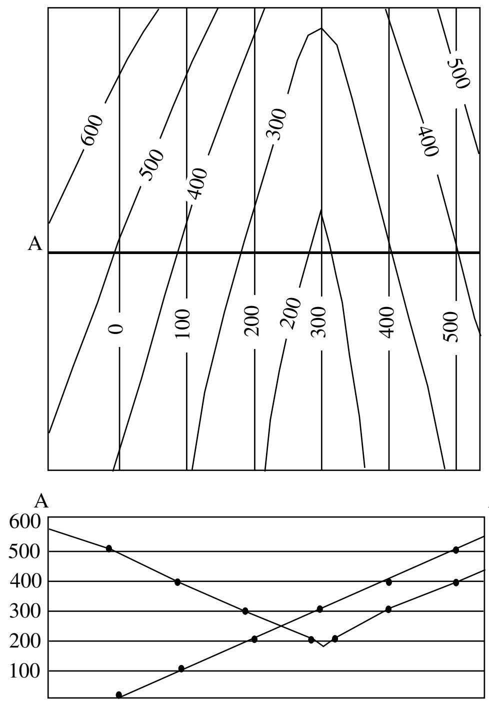


Figure 2.12 Technique for drawing a cross section. The top diagram is a map with surface and structure contours and the bottom is a geologic cross section. Transfer points to corresponding elevations on the topographic profile. Transfer two or more structure contours to another sheet of paper. Connect points to complete the cross section.

determined using the interpolation described or using:

$$\text{map distance} = \frac{\text{contour interval}}{\tan\delta}$$

2 In this example, the spacing (d) is 17.5 ft in map view (Figure 2.13a). Point B is at an elevation of 160 ft, which is conveniently also the elevation of a topographic contour. Points on the bedding plane with known elevations (points A and C in this problem) serve as control points to make sure that the elevations of known outcrop points match their elevations on the structure-contour map. Figure 2.13b shows the completed structure-contour map.

3 On the superimposed structure-contour map and topographic map (Figure 2.13c), every point where a structure contour crosses a topographic contour of equal elevation is a surface outcrop. The outcrop map is made by marking each point where topographic and structure contours of the same elevation cross. Connect the points of intersection to display the outcrop pattern on the topographic map (Figure 2.13d).

This same technique can be used to locate a second surface that is parallel to the first. If the contact

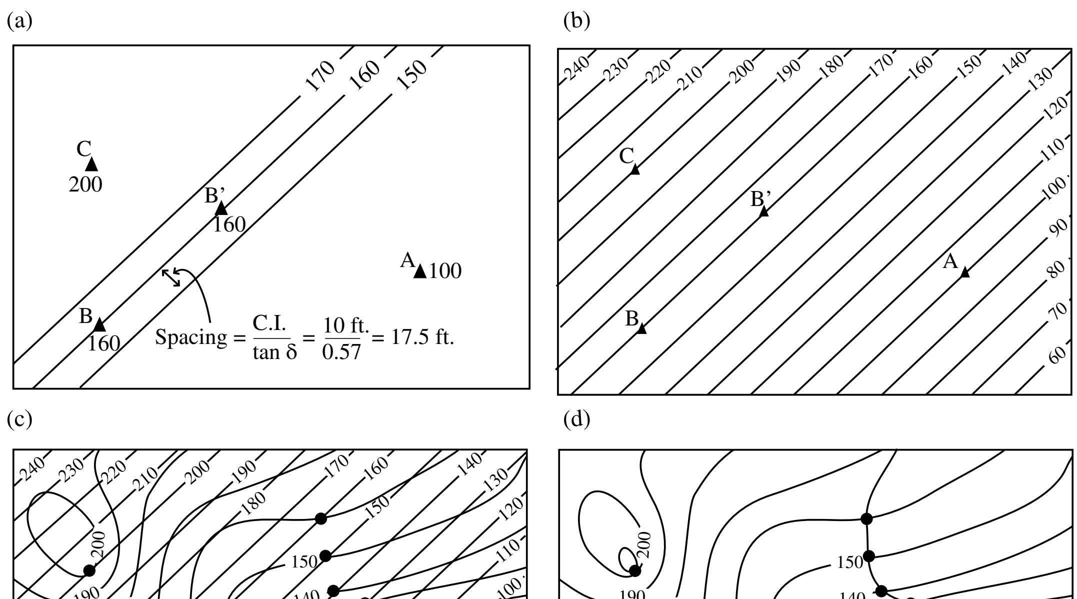


Figure 2.13 Determination of outcrop pattern using structure contours. (a) Three structure contours on a base map (from Figure 2.10c). (b) Structure-contour map. (c) Structure-contour map superimposed on a topographic map. (d) Outcrop pattern of a plane on a topographic map.

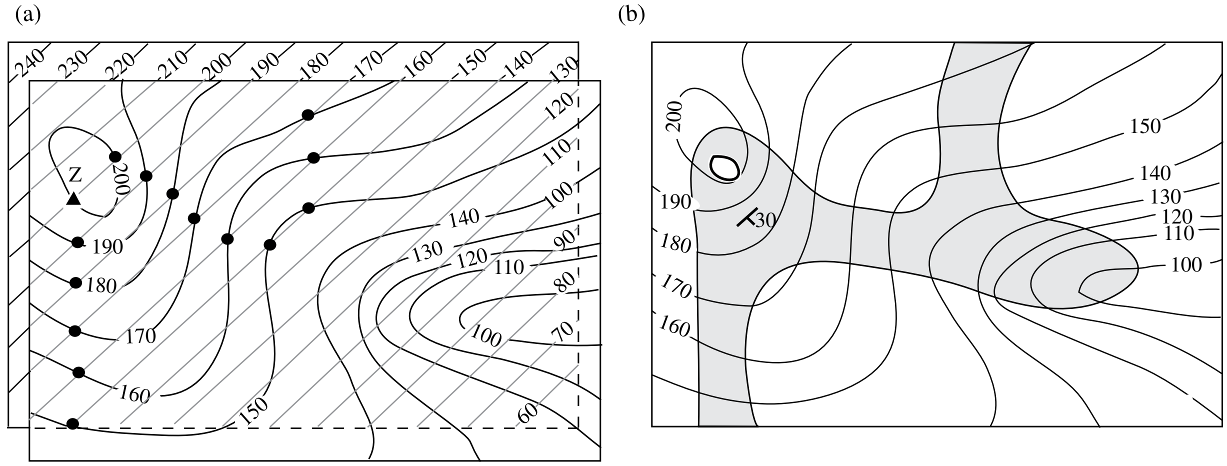


Figure 2.14 (a) Structure-contour map from Figure 2.13 shifted such that the 200-ft structure contour lies on point Z. Point Z is a point where the bottom of a layer is exposed. The top of this same layer is exposed at points A, B, and C from Figure 2.11a. (b) Outcrop pattern of this layer, which dips 30° to the southeast.

shown in Figure 2.13d is the top of a bed, we can determine the outcrop pattern of the bottom of the bed as well. If a single outcrop point on the topographic map is known, then the outcrop pattern can be found using the structure-contour map already constructed for the bed's upper surface as follows:

1 Position the structure-contour map beneath the topographic map such that the bottom surface outcrop point (or points) lies (lie) at the proper elevation on the structure-contour map. With the structure contours parallel to their former position, proceed as before. In Figure 2.14a, point Z, at an elevation of 200 ft, is an outcrop of the bottom of the bed. The structure-contour map has been moved so that the 200-ft structure contour passes through point Z, and the predicted outcrop points have been located as before.
2 Once the upper and lower contacts are drawn on the topographic map, the outcrop pattern of the bed can be shaded or colored (Figure 2.14b).

Problem 2.3

Figure P2.4 is a topographic map of an area that contains an industrial landfill that is leaking leachate into the groundwater system. Points a, b, and c are wells that were drilled at the same time and penetrate the water table. The depth of the water table in each well is 12 ft for a, 10 ft for b, and 27 ft for c. Scale bar is 10 ft. See Video 2 at https://youtu.be/GBpY_Vi0zMw.

1 Assuming that the water table is planar, construct structure contours for the water table.
2 Draw the cross section X to X′, showing the topography and the water table.
3 Shade the area where the properties would be impacted by the pollutant plume.

Gently Bent Layers

The technique of gently bent layers for locating the intersection of a geologic surface with the surface of the earth may be roughly used if the surface has a simple change in dip and a structure-contour map can be constructed. In Figure 2.15a, three attitudes of a marker bed are mapped and all are different. Assuming a constant slope and a gradual change in dip between outcrop points, a structure-contour map may be constructed as follows:

1 Arithmetically interpolate between the known elevation points to locate the necessary elevation points on the surface (Figure 2.15b).
2 Draw smooth parallel structure contours parallel to the strikes at the outcrop points (Figure 2.15c).
3 Superimpose the structure contour map and the topographic map and mark the points where contours of equal elevation intersect (Figure 2.15d).
4 Connect these intersection points to produce the outcrop map (Figure 2.15e).

Problem 2.4

Figure P2.5 is a topographic map. Points A, B, and C are outcrop points of the upper surface of a planar coal seam. Point Z is an outcrop point of the base of the coal seam.

1 Determine the attitude of the coal seam.
2 Draw the outcrop pattern of the coal seam.
3 Determine the thickness of the coal seam. Attach any drawings and computations you use.