Chapter 1

STRUCTURAL PLANES

1.1 INTRODUCTION

Especially in the early stages of an investigation of the geology of an area, much attention is paid to determining and recording of the location and orientation of various structural elements. Planes are the most common of these. They are also a useful starting point in the introduction to the geometrical methods of structural geology.

1.2 DEFINITIONS

Plane: a flat surface; it has the property that a line joining any two points lies wholly on its surface. Two intersecting lines define a plane.

Attitude: the general term for the orientation of a plane or line in space, usually related to geographic coordinates and the horizontal (see Fig. 1.1). Both trend and inclination are components of attitude.

Trend: the direction of a horizontal line specified by its bearing or azimuth.

Bearing: the horizontal angle measured east or west from true north or south.

Azimuth: the horizontal angle measured clockwise from true north.

Strike: the trend of a horizontal line on an inclined plane. It is marked by the line of intersection with a horizontal plane.

Structural bearing: the horizontal angle measured from the strike direction to the line of interest.

Inclination: the vertical angle, usually measured downward, from the horizontal to a sloping plane or line.

True dip: the inclination of the steepest line on a plane; it is measured perpendicular to the strike direction.

Apparent dip: the inclination of an oblique line on a plane; it is always less than true dip.

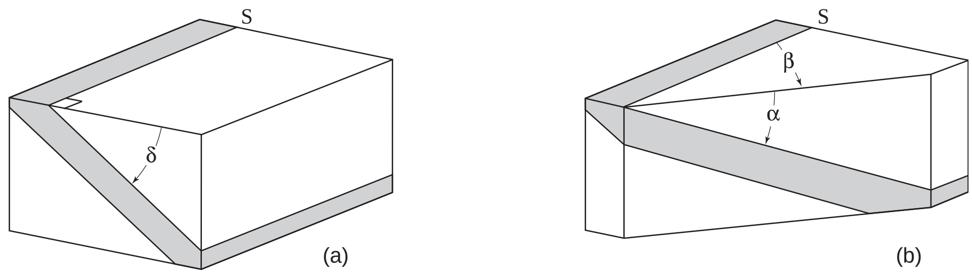


Figure 1.1: Strike S, true dip δ (delta), apparent dip α (alpha) and structural bearing β (beta).

1.3 DIP & STRIKE

The terms *dip* and *strike* apply to any structural plane and together constitute a statement of its *attitude*. The planar structure most frequently encountered is the bedding plane. Others include cleavage, schistosity, foliation and fractures including joints and faults. For inclined planes there are special *dip and strike map symbols*; in general each has three parts. The only exception is the special case of a horizontal plane which requires a special symbol.

1. A *strike line* plotted long enough so that its trend can be accurately measured on the map.
2. A short *dip mark* at the midpoint of one side of the strike line to indicate the direction of downward inclination of the plane.
3. A *dip angle* written near the dip mark and on the same side of the strike line.

The most common symbols are shown in Fig. 1.2 and their usage is fairly well established by convention. However, it is sometimes necessary to use these or other symbols in special circumstances, so that the exact meaning of all symbols must be explained in the map legend.

Attitude angles are also often referred to in text, although the usage is considerably less standard. There are two basic approaches. One involves the trend of the strike of the plane and the other the trend of the dip direction. Each of the four following forms refers to exactly the same attitude (for other examples see Fig. 1.3).

1. Strike notation
   (a) N 65 W, 25 S: the bearing of the strike direction is $65°$ west of north and the dip is $25°$ in a southerly direction. For a given strike, there are only two possible dip directions, one on each side of the strike line hence it is necessary only to identify which side by one or two letters. If the strike direction is nearly N-S or E-W then a single letter is appropriate; if the strike direction is close to the $45°$ directions (NE or NW) then two letters are preferred (see Fig. 1.3 for examples).

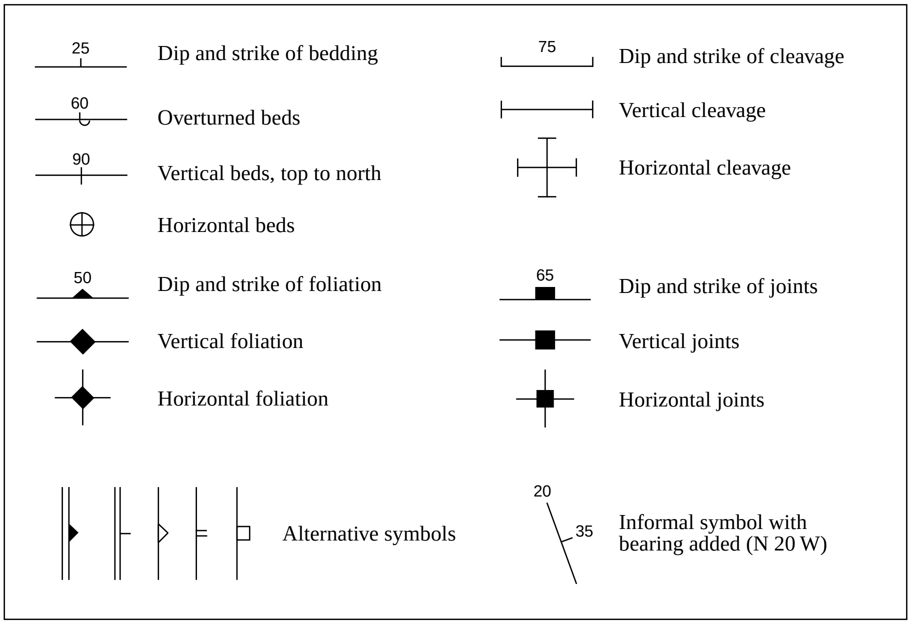


Figure 1.2: Map symbols for structural planes.

   (b) 295, 25 S: the azimuth of the strike direction is $295°$ measured clockwise from north and the dip is $25°$ in a southerly direction. Usually the trend of the northernmost end of the strike line is given, but the azimuth of the opposite end of the line may also be used, as in 115, 25 S.

2. Dip notation

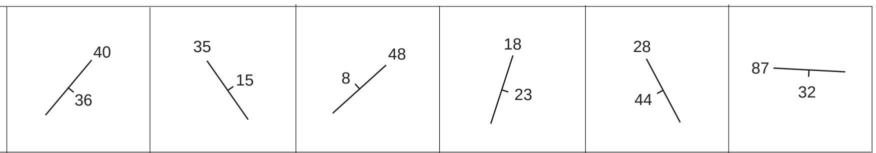
   (a) 25, S 25 W: the dip is $25°$ and the trend of the dip direction has a bearing of $25°$ west of south.

   (b) $25/205$: the dip is $25°$ and the trend of the dip direction has an azimuth of $205°$ measured clockwise from north. The order of the two angles is sometimes reversed, as in 205/25. To avoid confusion, dip angles should always be given with two digits and the trend with three, even if this requires leading zeros.

As these dip and trend angles are written here the degree symbol is not included and this is a common practice. However, this is entirely a matter of individual preference and taste.

The two forms of the strike notation are the most common with the difference usually depending on whether the compass used to make the measurements is divided into quadrants or a full $360°$ and on personal preference. The advantage of the quadrant method of presentation is that most people find it easier to grasp a mental image of a trend more quickly with it.

The forms of the dip notation are more generally reserved for the inclination and trend of lines rather than planes, although when the line marks the direction of true dip, it may apply to both. The last method gives the attitude unambiguously without the need for letters and, therefore, is particularly useful for the computerized treatment of orientation data. For this reason it is becoming increasingly common to see the attitudes of planes written in this way.



SYMBOL						
Strike (a)	N 40 E, 36 SE	N 35 W, 15 NE	N 48 E, 8 NW	N 18 E, 23 E	N 28 W, 44 SW	N 87 W, 32 S
Strike (b)	040, 36 SE	325, 15 NE	048, 8 NW	198, 23 E	332, 44 SW	273, 32 S
Dip (a)	36, S 50 E	15, N 55 E	8, N 42 W	23, S 72 E	44, S 62 W	32, S 3 W
Dip (b)	36/130	15/055	08/318	23/108	44/242	32/183

Figure 1.3: Examples of the strike and dip notations.

It is essential to learn to read all these shorthand forms with confidence and to this end we will use them in examples and problems. However, they are not always the best way of recording attitude data in the field. It is a common mistake to read or record the wrong cardinal direction, especially for beginners. For example, it is easy to write E when W was intended for a strike or dip direction.

One way to avoid such errors is to adopt a convention such as the *right-hand rule*. There are two versions.

1. Face in the strike direction so that the plane dips to the right and report that trend in azimuth form.
2. Record the strike of your right index finger when the thumb points down dip (Barnes, 1995, p. 56).

Alternatively, record the attitude by sketching a dip and strike symbol in your field notebook and adding the measured bearing or azimuth of the strike direction (see the informal symbol in Fig. 1.2).[1] This permits a visual check at the outcrop — stand facing north and simply see that the structural plane and its symbolic representation are parallel. Recording attitudes in this way also reduces the chance of error when transferring the symbols to a base map.

Strike and dip measurements are commonly made with a compass and clinometer. A variety of instruments are available which combine both functions. In North America, the Brunton Compass is widely used. In Europe and elsewhere the Silva Ranger, Chaix and Freiberg compasses are favored (McClay, 1987, p. 18, 21). The methods of measuring attitudes in a variety of field situations are given in some detail by Davis & Reynolds (1986, p. 662–669), McClay (1987, p. 22–30), and Barnes (1995, p. 7–9).

The most direct method is to hold a compass directly against an exposed plane surface at the outcrop. We illustrate the procedure using the Brunton Compass but the methods with the other

[1] It is not necessary to plot this strike line in your notebook using a protractor. With a little practice any trend line can be sketched with an accuracy of $\pm 5^\circ$ or better. In combination with the labeled strike direction this is sufficient.

instruments are similar. The Freiberg compass is an exception because the dip and dip direction are measured in a single operation, and this has some advantages.

1. Strike is measured by placing one edge of the open case against the plane and the compass rotated until it is horizontal as indicated by the bull's eye bubble (Fig. 1.4a). The measured trend in this position is the strike direction.

2. Dip is determined by placing one side of the compass box and lid directly against the exposed plane perpendicular to the previously measured strike. The clinometer bubble is leveled and the dip angle read (Fig. 1.4b).

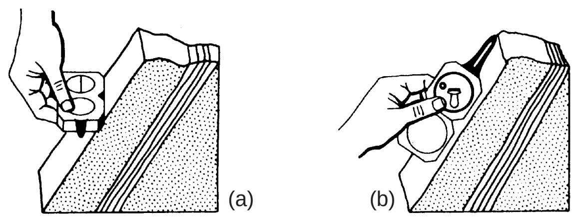


Figure 1.4: Measurements with a Brunton Compass (from Compton, 1985, p. 37): (a) strike; (b) dip.

1.4 ACCURACY OF ANGULAR MEASUREMENTS

The goal of making dip and strike measurements is to record an attitude which accurately represents the structural plane at a particular location. With reasonable care, horizontal angles may be read on the dial of the compass to the nearest degree, especially if the needle is equipped with damping. Vertical angles may also be read on the clinometer scale to the nearest degree, or better if a vernier is used.

There are two reasons why such accuracy does not automatically translate into accurately known attitudes. First, even if the plane is geometrically perfect it is not possible to place the compass in *exactly* the correct position when making a measurement. Second, the present of local irregularities means that a result will depend on the precise placement of the instrument on the exposed surface. In everyday terms, the first is an error, while the second introduces an uncertainty. In practice, however, it is difficult or impossible to separate these two effects. Thus *error* and *uncertainty* are essentially synonymous when applied to any scientific measurement (Taylor, 1997, p. 3).

It is, of course, easy to make a *mistake* when measuring or recording an angle of dip or strike. Almost everyone has had the unfortunat experience of finding an attitude which seems out of place in a notebook or on a map. If the mistake is small it may be difficult to identify, but then its presence may not make much difference. On the other hand, if the mistake is large, then some effort should be made to avoid or correct it. There are statistical methods for identifying *outliers* and discarding them, but the question always remains: is the exception real or not? A better approach is to identify them while it is still possible to correct it in the field. A good way to do this plot the attitude symbols on a sketch map as they are made. Then seemingly anomalous attitudes can be quickly confirmed or discarded by additional observations.

Because all measurements are subject to such errors or uncertainties there will generally be a *discrepancy* between any two angles measured on the same plane. There are two main types of errors: *random* and *systematic*.

The difference between these two may be illustrated with a simple "experiment" consisting of a series of shots fired at a target (Taylor, 1997, p. 95–96). Accurate "measurements" are represented by shots which cluster around the center of the bull's eye: they may tightly clustered (Fig. 1.5a) or not (Fig. 1.5b). An important cause of random errors is the marksman's unsteady hand. In either case, if there is a sufficient number of shots and their distribution is truly random, the mean location of the shots will define the center of the target with acceptable accuracy.

Systematic errors are caused by any process by which the shots arrive off-center, such as misaligned sights. As before, the random component may be small (Fig. 1.5c) or large (Fig. 1.5d). In both cases, the mean will depart significantly from the center of the target.

While the pattern of shots is a good way of illustrating the difference between random and systematic errors, it is misleading in an important sense. Knowing the location of the bull's eye is equivalent to knowing the true value of the measured quantity. In the real world we do not know this true value; indeed if we did we would not have to make any measurements. A more realistic illustration would be to examine the pattern without the target. Then the random errors would be easy to identify but systematic error would not be.[2]

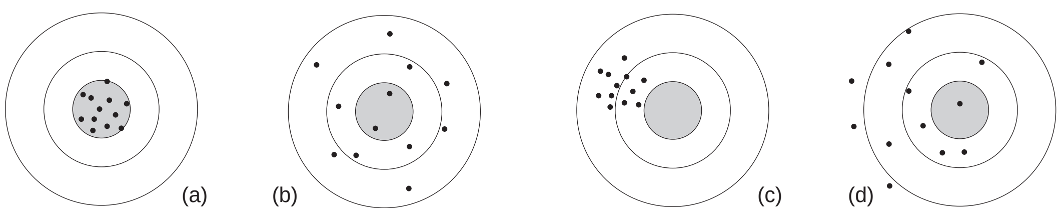


Figure 1.5: Combinations of small and large random R and systematic S errors (after Taylor, 1997, p. 95): (a) R small, S small; (b) R small, S large; (c) R small, S large; (d) R large, S large.

For horizontal trend angles measured in the field, systematic errors arise if the magnetic declination is improperly set on the compass or an incorrect angle is used to manually correct a reading. The compass needle may also be deflected by magnetic materials, such as magnetite, in the rock or a piece of magnetized iron, such as a rock hammer, near the compass. A similar effect may be produced by the electromagnetic fields associated with nearby power lines. The standard approach to controlling systematic errors is the use equipment which has been tested and calibrated, but this

[2] Then there is the *Texas Sharpshooter Fallacy:* a fabled marksman randomly sprays the side of a barn with bullets and then paints a circle around a cluster. Epidemiologist call this fallacy to the *clustering illusion*, the intuition that random events which occur in clusters are not really random events at all. To such clusters politicians, lawyers and, regrettably, some scientists assign a causal relationship, such as a link of some environmental factor and a disease, when they are actually due to the laws of chance (Carroll, 2003, p. 375).

has rather limited application for the field geologist. With awareness and care, these systematic errors may be minimized.

Random errors of both dip and trend arise from the actual process of making the measurements. Even for a geometrically perfect plane, it is never be possible to align the compass and read the angles *exactly*. Further, inevitable natural irregularities on the surface of naturally occuring planes make this process even more difficult. Measuring the attitude of a stiff field notebook, map case or a small aluminum plate held tightly against the rock surface helps eliminates the effect of small-scaled features.

There is also a way to reduce the effect of such irregularities. Stand back from the outcrop several meters and determine the trend of a horizontal line of sight parallel to the bedding (Fig. 1.6a), and then measure the inclination of the bedding perpendicular to the this line (Fig. 1.6b). Although it takes practice to become proficient, this is probably the most accurate field method of determining dip and strike at the scale of a single outcrop.

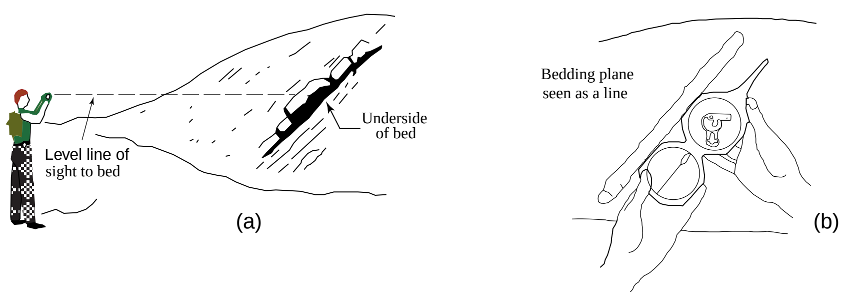


Figure 1.6: Avoiding minor irregularities (Compton, 1985, p. 35): (a) sighting a level line; (b) dip measured perpendicular to this line.

Because of such inevitable random errors there will generally be a *discrepancy* between any two measured values of the same angle on the same plane. To evaluate such random errors, the standard procedure is to make multiple measurements. For dip angles or any such measured quantities, the simple *arithmetic mean* $\bar{x}$ of a series of N measurements $x_1, x_2, \ldots, x_N$ is found from

$$\bar{x} = \frac{x_1 + x_2 + \cdots + x_N}{N} = \frac{1}{N}\sum_{i=1}^{N} x_i. \tag{1.1}$$

This mean is almost always the *best* estimate of the true value (Taylor, 1997, p. 10, 98, 137). That is,

$$x_{best} = \bar{x}.$$

The discrepancies d_i associated with a set of measurements x_i are then

$$d_i = x_i - \bar{x}, \quad (i = 1 \text{ to } N).$$

These are positive or negative, depending on whether the value of x_i is greater or less than $\bar{x}$.

These discrepancies gives a valuable indication of the uncertainty associated with the measurements (Taylor, 1997, p. 10). The measure of this uncertainty is most simply approximated as the magnitude of the largest discrepancy

$$\Delta x = |d_i|_{large}.$$

The positive number Δx is termed the *uncertainty*, or *error*, or *margin of error*. Then the result of any measurement is expressed in the *standard form* as

$$(\text{measured value of } x) = x_{best} \pm \Delta x.$$

This means that we can be confident that the correct value *probably* lies between $x_{best} - \Delta x$ and $x_{best} + \Delta x$, though it is *possible* that it lies slightly outside this range, absent systematic errors, as we have been assuming.

While dip angles can be treated directly in this way, horizontal trend angles in general and strike angles in particular present special problems and a different method for calculating their mean direction must be used (see §7.4).

Rondeel & Storbeck (1978) performed a series of experiments to evaluate the magnitudes of the dip uncertainties. Multiple measurements were made on a 10×10 cm single, slightly irregular bedding plane surface which was rotated into different inclinations ranging from 5–$88°$. For moderate to steep inclinations they found that 90% of the angles were within $2°$ of the mean. For bedding planes with greater irregularities, Cruden & Charlesworth (1976) found that the uncertainties were also greater, and ranged up to about $10°$. For more formal purposes, the *sample standard deviation* is used to express the uncertainty and is defined as

$$\sigma_x = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(d_i)^2} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2}. \tag{1.2}$$

For large N the denominator $N-1$ can be replaced with N (Taylor, 1997, p. 97–101), and this equation then becomes the statement of the *root mean square* (commonly abbreviated RMS) of the deviations.[3]

In most general field mapping projects, we probably can accept carefully made single measurements recorded to the nearest degree because the uncertainties are probably modest. However, if these attitude measurements are to be used for special purposes, greater care and possibly other methods may be required.

There are certain situations where the uncertainty may be much greater. The case of a gently dipping plane poses special problems.

If the dimension of the outcrop is sufficiently large the inclination of a smooth plane as small as one degree, then both the dip and the dip direction can be visually identified and estimated. However, if the plane is irregular it is possible that one or more measurements might yield a result such that $\Delta x > x$, implying that the dip may be in the opposite of the observed direction, which would be a huge error.

Further, the measurement of the strike direction on such a gently dipping plane, even a slightly incorrect placement of the compass may result in a large error. By definition, the strike is the

[3] For large N dividing by $N-1$ or N makes almost no difference. The advantage of using $N-1$ is that it gives a larger estimate of the uncertainty, and especially for measurements made in the field environment this is a good thing.

trend of a horizontal line on an inclined plane. If the compass is not exactly horizontal then a direction other than the true strike will be recorded. The geometry of this situation is shown in Fig. 1.7a where a *maximum operator error* ε_o, the largest angular departure from horizontal, goes uncorrected. The result is that a trend OS' rather than the true strike OS is recorded. The angle between these two directions is the *maximum strike error* ε_s and its magnitude as a function of the dip angle δ may be evaluated. The three right-triangles in this figure yield the trigonometric relationships

$$w = d/\tan\delta, \quad l = d/\tan\varepsilon_o, \quad \sin\varepsilon_s = w/l.$$

Substituting the first two into the third gives[4]

$$\boxed{\sin\varepsilon_s = \frac{\tan\varepsilon_o}{\tan\delta}} \tag{1.3}$$

This result, first obtained by Müller (1933, p. 232; see also Woodcock, 1976), is solved for values of ε_s and the results displayed graphically for $\varepsilon_o = 1$–$5°$ in Fig. 1.7b. It is important to note that for very small dip angles, the maximum possible strike error is large and approaches $90°$ as $\delta \to 0$.

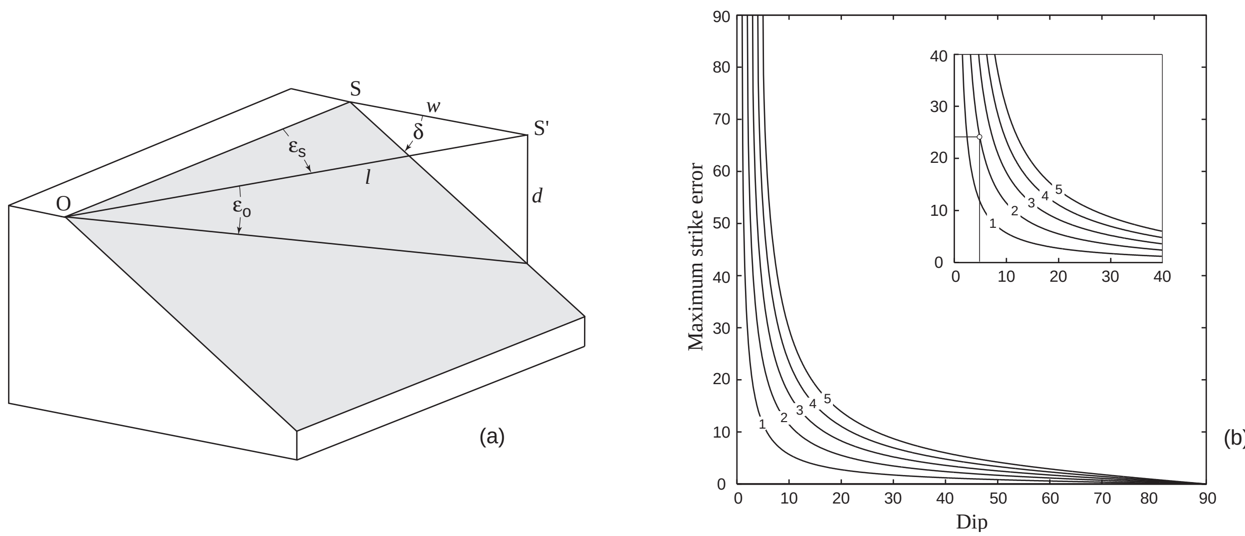


Figure 1.7: Maximum strike error: (a) geometry; (b) ε_s as a function of dip for values of $\varepsilon_o = 1$–$5°$. (The inset shows an example $\varepsilon_o = 2°$, $\delta = 5°$, with the result that $\varepsilon_s \approx 24°$).

1.5 GRAPHIC METHODS

Indirect methods are also available for determining the various angles and these are the subject of the remainder of this chapter. All the techniques dealt with here are concerned with the relationships between the components of the attitude of planes — the angles of true and apparent dip, and the strike.

[4] As we will see later, this equation is just a specialized version of a more general description of the relationship between dip δ, apparent dip α and structural bearing β (compare Eq. 1.7).

Of several possible approaches to solving these problems we choose at the outset an entirely graphical technique — the method of *orthographic projection* (see Appendix A). There are two reasons for this choice. First, with it we may readily and simply obtain solutions to a wide variety of problems. Second, it allows the various components of the problems to be visualized in a three-dimensional setting. This visualization is of crucial importance in developing the ability to solve geometrical problems in geology.

By way of introduction, consider a simple geological situation shown in the two block diagrams of Fig. 1.8. In order to follow the description of their geometric properties it will be helpful to assemble *Block A* and *Block B* at the end of the book and have them in front of you.

Problem

- The trace of an inclined plane is exposed on a flat, horizontal surface. The plane strikes east-west and dips $36°$ to the north. Construct a vertical section showing the angle of true dip. What is the depth to this plane at a map distance of $w = 100$ m measured perpendicular to the strike line?

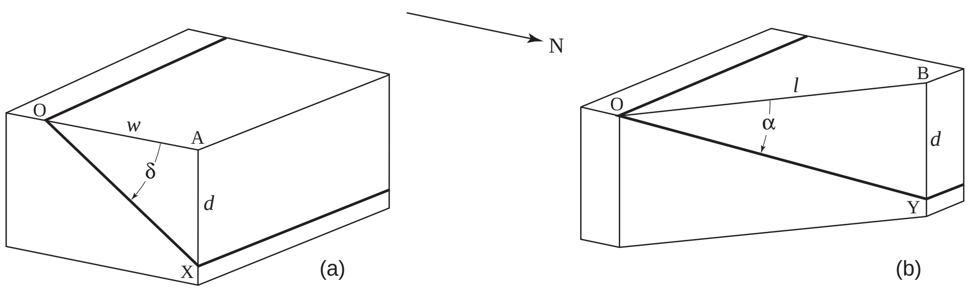


Figure 1.8: Block diagrams: (a) true dip δ; (b) apparent dip α.

Approach

- On the top of the block the trace of the inclined plane is a line of strike (Fig. 1.8a). The goal is to construct a vertical section showing the angle of true dip δ. To do this we imagine standing at a point O on the surface trace of the plane and then walking a distance $w = 100$ m due north to another surface point A. As we make this traverse, the vertical distance to the inclined plane steadily increases from zero to a depth d directly below A. With the dip angle and the traverse length known, we can easily make a scaled drawing of the top surface of the block showing its proper dimensions. To depict the vertical side, we imagine turning it upward as if it were hinged along edge OA. This hinge is called a *folding line,* abbreviated *FL* (see §A.2). We can now easily construct the required view.

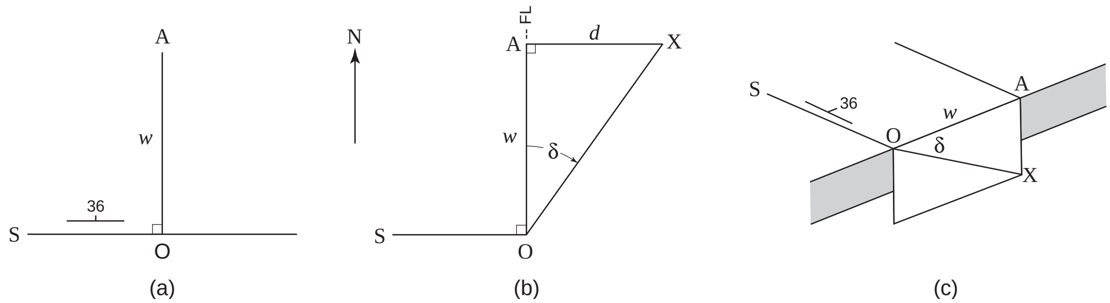


Figure 1.9: True dip: (a) map; (b) section with OA as *FL*; (c) visualization.

Construction

1. On a map view draw an east-west line of strike S and locate point O on it. From O draw a line in the dip direction to locate point A at a distance of $w = 100$ m using a convenient scale (Fig. 1.9a).

2. With OA as a *FL* draw a line on this now upturned section making angle $\delta = 36°$ with the horizontal. This is the required trace of the inclined structural plane (Fig. 1.9b).

3. At surface point A on this section, draw a vertical line downward to intersect the trace of the inclined plane at point X. Distance AX is the depth $d = 73$ m to the plane at this point.

Accuracy is an important part of these constructions (see §A.3 for some general guidelines). Its particularly important that lines, such as OA, be long enough so that their orientations can be measured easily to within one degree. In the previous problem this can be accomplished by using a scale of 10 mm $= 10$ m. As a general rule, a single diagram should occupy the central part of a letter-size sheet of paper. Beginners commonly make their constructions too small.[5]

A very useful aid in this kind of problem is to actually bend the drawing along the folding line over the edge of a table top (Fig. 1.9c). You can then actually see the relationship between the map and the vertical section in three dimensions.

Once this three-dimensional visualization can be made with some confidence, we can, of course, relate the angle δ and the lengths of sides w and d of the vertical right-triangle OAX with the simple formula

$$\tan\delta = d/w. \tag{1.4}$$

A closely related situation involves depicting the trace of an inclined structural plane on an oblique vertical section as illustrated in the block diagram of Fig. 1.8b.

[5]All of the figures here and throughout the book were originally constructed at such a scale, but they have been reduced to conserve space.

Problem

- Depict the same north-dipping structural plane on a vertical section whose trend is N 60 W. In this direction the apparent dip $\alpha = 20°$. What is the depth to the plane at a horizontal distance of $l = 200$ m from the strike line measured in this oblique direction?

Approach

- In similar fashion, the goal now is to construct the vertical section showing the angle of apparent dip. As before, we imagine starting at a point O on the strike line and walking in this direction (Fig. 1.8b). As we do this the depth to the plane now increases from zero to the *same* depth d at point Y directly below surface point B. With the known apparent dip angle and the traverse length we draw the vertical section using as the folding line OB.

Construction

1. Through surface point O on an east-west line of strike S draw a line in the direction N 60 W and on it locate point B at a distance $l = 200$ m using a convenient scale (Fig. 1.10a).

2. With OB as *FL* draw a line inclined at the angle $\alpha = 20°$ (Fig. 1.10b). A vertical line downward at B then intersects this inclined line at point Y. Distance BY is the depth $d = 73$ m to the plane.

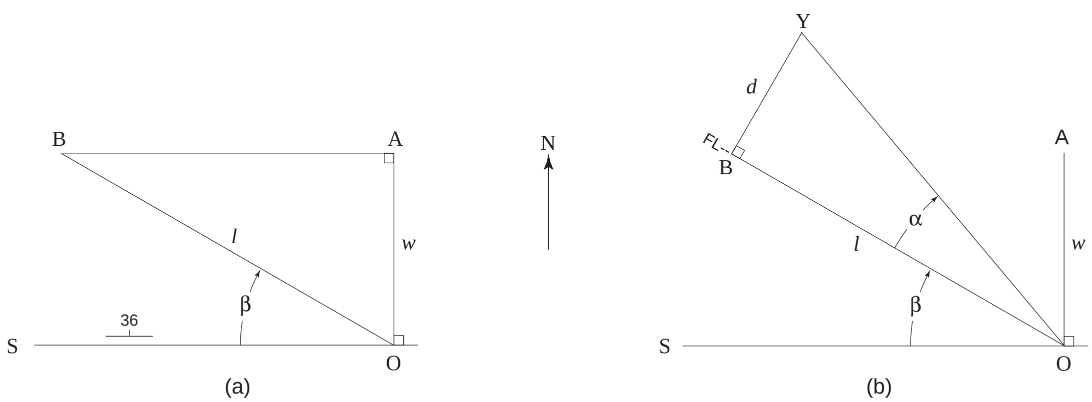


Figure 1.10: Apparent dip: (a) map; (b) section with OB as *FL*.

Again, as an aid to visualization we may convert this drawing to a three-dimensional block diagram by folding the paper over the edge of a table top along the *FL*. We may also relate the three elements of the vertical right-triangle OBY with the formula

$$\tan\alpha = d/l. \tag{1.5}$$

Note that the essential features of these oblique sections remain the same no matter how the map is oriented. For this reason it is convenient to express the trend of the apparent dip relative to the strike direction. For this reason we refer to this angle β as the *structural bearing* of the line. The length l of the oblique traverse required to arrive at B can be obtained from the horizontal right-triangle OAB with

$$\sin\beta = w/l. \tag{1.6}$$

1.6 FINDING APPARENT DIP

In the previous problem, the apparent dip was given. However, this angle cannot always be measured in the field. If inclined planes are to be depicted on such oblique sections we need a method for finding it.

Problem

- If $\delta = 36°$ and $\beta = 30°$, what is α?

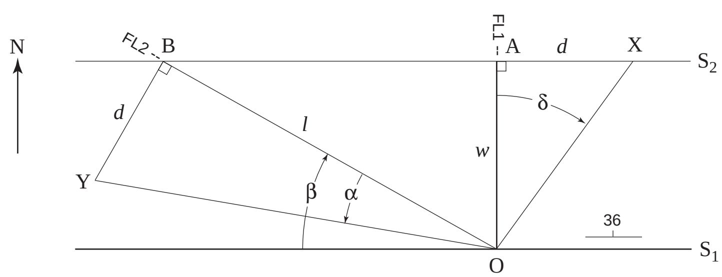


Figure 1.11: Apparent dip from true dip and strike.

Approach

- The solution of this problem involves two steps: first draw the true-dip section (Fig. 1.10a); then draw the apparent-dip section (Fig. 1.10b). As is the general practice we combine the map and sections on a single diagram. This eliminates the need to replicate most angles and lengths and this reduces the chance of error.

Construction

1. Through a point O on strike line S_1 draw a line in the dip direction (Fig. 1.11). On this line locate surface point A at an arbitrary but conveniently large distance w.

2. Construct a vertical section with OA as *FL1* showing the trace of the inclined plane at angle $\delta = 36°$ and thus determining the depth d of point X below A.

3. Through surface point A, draw a second strike line S_2.

4. A line from point O making angle $\beta = 30°$ with S_1 intersects S_2 at surface point B.

5. Construct a second vertical section with OB as *FL2* to locate point Y at the *same* depth d below B. Then OY represents the trace of the plane and its inclination is the angle of apparent dip.

Answer

- The angle BOY is $\alpha = 20°$.

Beginners are often confused by this jumping back and forth between map and section on the same drawing. Folding the drawing over the edge of a table top is a powerful aid in distinguishing the two distinct views. Using different colors for lines on the map and on the section also helps.

Several additional points should be noted. First, we need never know the actual depth d. Its scaled length may be transferred directly from sections OA to OB on the drawing with compass or divider. Second, in all such constructions, the direction of upward folding is immaterial, though it is usually best to choose it in the direction of the greatest open space on the drawing in order to avoid interfering lines.

As defined and used here, the angle of apparent dip is unambiguous and with reasonable care no difficulties should be encountered. There are, however, some situations where an "apparent" apparent dip may be observed (see Exercise 1.6) and this may be confusing. For this reason some prefer to speak of a *dip component* rather than an apparent dip, as we will do in §1.9.

1.7 ANALYTICAL SOLUTIONS

By combining the two-dimensional views of maps and sections, the methods of orthographic projection are an invaluable tool in learning to visualize the geometry of structures in three dimensions.

Analytical solutions also have their place. A word of caution: both the calculator and computer do exactly what they are told and it is remarkably easy to enter the wrong number, use the wrong parameter or the wrong formula. The invariable result is the display of an impressive-looking number which is utterly wrong. Be careful!

The present problem involving α, β and δ may be solved with the aid of a trigonometric equation (Herold, 1931). From Eq. 1.4 $w = d/\tan\delta$ and from Eq. 1.5 $l = d/\tan\alpha$; substituting these into Eq. 1.6 and rearranging yields

$$\boxed{\tan\alpha = \tan\delta\sin\beta} \tag{1.7}$$

Obtaining an answer to this type of problem is a procedure called, fondly, *plug* and *chug*. Plugging in the values $\delta = 36°$ and $\beta = 30°$ gives

$$\tan\alpha = (0.72654)(0.50000).$$

Chugging out these values, your calculator displays

$$\tan\alpha = 0.36327 \quad \text{or} \quad \alpha = 19.69463.$$

Now what do we write down? For a proper answer we need two things: a way of identifying the figures which are significant, and then a way of eliminating the non-significant ones.[6]

As we have seen in §1.4, there is an inevitable uncertainty associated with any measured angle; we expressed such an angle together with its uncertainty in the form $x \pm \Delta x$. On the other hand, if we represent an angle by a single number, as we almost always do, there is an *implied uncertainty*. For example, consider the angle $\delta = 36°$: As written, this is taken to mean that the angle which best represents δ is probably closer to 36 than to 35 or 37, that is, it lies in the range $36 \pm 0.5°$. This in turn means that the uncertainty is at least 0.5. This number is called the implied *absolute* uncertainty because it is expressed in the same units as the measured value.

We need a way of insuring that any calculated number we use takes advantage of the information content of the original measurement, while at the same time avoids any suggestion that it is more accurate than is justified. We do this by retaining only the significant figures and there are several convenient, well-established *Rules of Thumb* for accomplishing this.

1. When numbers are added or subtracted, the result should have the same number of decimals places as the number with the fewest decimal places.

2. When numbers are multiplied or divided, the result should have the same number of significant figures as the number with the fewest significant figures.

3. The presence of zeros requires special care. All these numbers have two significant figures: 20, 2.0, 0.20, 0.020, 0.0020.[7] Sometimes there is a question of just how many significant figures are there — how many are there in 320? A simple way of resolving this ambiguity is to write $320 = 3.2 \times 10^2$ or $320 = 3.20 \times 10^2$, depending on what is intended.

4. Exact numbers are treated as if they have an infinite number of significant figures (2 and π in the expression $2\pi r$ are examples).

Next, we need to have a systematic way of eliminating the non-significant figures. The process of doing this is called *rounding off*, which is simply a way of estimating or approximating the value of the final number as accurately as possible. First, we define the *rounding digit* as the rightmost significant number. Then the general rules are:

[6] Vacher (1998a) gives a good treatment of the use and abuse of significant figures.

[7] We use the International System of Units (SI) throughout the book (for more details see `http://physics.nist.gov/cuu/`). Its application here is the rule that a zero should be placed in front of the decimal marker in decimal fractions (for example $2/100$ is written as 0.02 *not* $.02$).

1. If the number just to the right of the rounding digit is *less* than 5, *round down* by dropping all the non-significant figures. The number is now slightly less that the calculated one.

2. If the number just to the right of the rounding digit is *greater* than 5, *round up* by adding 1 to the rounding digit and then dropping the non-significant figures. The number is now slightly greater than the calculated one. Note that rounding 9 up gives 10, not 0.

3. If the number just to the right is *equal* to 5 then there are two cases.

   (a) If the numbers following the 5 are all zeros, or there are no numbers round so that the rounding digit is even, that is, round up if it is odd and down if it is even. Zero is treated as even for this purpose. This practice insures that on average we round up or down half of the time.

   (b) If there are any non-zero numbers to the right of the 5 this means that the total number is greater than 5, so always round up.

In our problem the specified values of β and δ have only two significant figures, the answer should also have only two significant figures. Rounding then gives $\alpha = 20°$, which is the same as obtained graphically.

Unfortunately, these conventional rules sometimes gives misleading uncertainties. This is especially the case then numbers are multiplied or divided. An effort to improve the rounding rules is described by Mulliss & Lee (1998) and Lee, et al. (2000).[8] A workable alternative is to simply accept the fact that these rules are, and were always meant to be, only approximate (Earl, 1988).

An additional complication occurs when numbers are combined: the uncertainties are propagated to the final answer. An investigation of such errors is a superior way of evaluating uncertainties, and we return to this important matter in §2.10.

1.8 COTANGENT METHOD

There is a useful short-cut method for determining the relationships between α, β and δ which combines a simple geometrical construction with trigonometric data (Kitson, 1929).

Problem

- If $\delta = 36°$ and $\beta = 30°$, what is α?

Construction

1. From point O on strike line S_1 measure distance $\cot\delta = 1/\tan\delta = 1.37638$ in the true dip direction using a convenient scale and plot point A (Fig. 1.12a).

[8] These two articles can be found at `http://www.angelfire.com/oh/cmulliss/index.html`.

2. Construct strike line S_2 through point A parallel to S_1.

3. An oblique line through O making an angle β with S_1 intersects S_2 at point B.

4. Using the same scale, measure distance $OB = \cot\alpha$.

Answer

- Length $OB = \cot\alpha = 2.75$ and therefore $\alpha = \arctan(1/2.75) = 20°$.

In problems such as these which involve lengths calculated from angles, the plots and measurements should generally be accurate to at least two decimal places so that angles can be determined to the nearest degree. There are, however, some situations where greater accuracy is desirable.

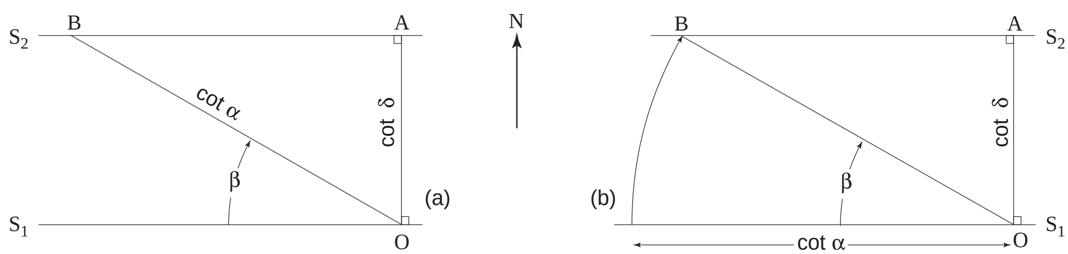


Figure 1.12: Cotangent method: (a) apparent dip; (b) structural bearing.

In terms of the fully graphical technique with folding lines, the use of the cotangent function is equivalent to choosing depth $d = 1$. This short-cut gives a solution more quickly, while still retaining the visual advantages of the completely graphical approach. It is especially useful when dealing with small dip angles which are difficult to construct accurately at any reasonable scale.

If an apparent dip is known, it is a simple matter to reverse this construction to find the angle of true dip. A closely related problem involves finding the structural bearing of a line whose apparent dip angle is specified.

Problem

- If $\delta = 36°$ and $\alpha = 20°$, what is β?

Approach

- To determine the structural bearing of a line we must construct the horizontal right-triangle OAB of Fig. 1.12a. We may easily find the length of side OB from the angle of apparent dip. The problem is then reduced to discovering its trend. This may be done simply with the cotangent method.

Construction

1. On a map draw a strike line S_1 and line OA in the direction of true dip (Fig. 1.12b).
2. In this dip direction measure a distance $OA = \cot\delta$ using a convenient scale. Through A draw a second strike line S_2.
3. We now need a line whose length is equal to $\cot\alpha$ using the same scale. It does not matter where we draw this line, but it is convenient to measure it along the existing line S_1.
4. With point O as center and length $\cot\alpha$ as radius, swing an arc to locate point B on S_2. Line OB is then the trend of the line of apparent dip and the angle it makes with S_1 and S_2 is β.

Answer

- The structural bearing $\beta = 30°$. Note that two trends satisfy this angle, N 60 W and N 60 E.

1.9 TRUE DIP & STRIKE

In some field situations it may not be possible to measure the true dip and strike directly. However, if apparent dips in two different directions are known, the attitude of the plane can be determined.

Problem

- From the two apparent dips $20/296$ and $30/046$ determine the true dip and strike of the plane.

Approach

- Two lines on the plane whose inclinations are the apparent dip angles α_1 and α_2 intersect at a point. Three points determine a plane, so two additional points must be found. A second point is located from a vertical triangle containing one of the apparent dips using a folding line. A third point, associated with the second apparent dip, could be found in like manner. However, it is advantageous to locate this third point at the same elevation as the second. A line joining these points of equal elevation is, by definition, a line of strike. The true dip is then measured perpendicular to this line.

Construction

1. From a local origin O plot the trends of the two apparent dip directions in map view (Fig. 1.13).
2. Construct vertical sections in each of these apparent dip directions.

(a) With the first line as *FL1* locate B_1 at an arbitrary distance l_1. Construct the vertical triangle B_1OY_1 using α_1 and thus determine the depth d to Y_1 on the plane below surface point B_1.

(b) With the second line as *FL2*, construct the vertical triangle B_2OY_2 using α_2. This time the traverse length l_2 is determined by using the same depth d and this locates surface point B_2.

3. Because Y_1 and Y_2 have identical depths below the common point O they also have equal elevations. A line through the two corresponding surface points B_1 and B_2 is then a line of strike.

4. From O a line perpendicular to the strike and intersecting it at point A establishes the direction of true dip. At the same depth d below A, point X lies on the horizontal line Y_1Y_2. With this true dip direction as *FL3* locate X at the same depth d below A. Angle AOX is the true dip angle.

Answer

- The plane strikes east-west and dips $40°$ north.

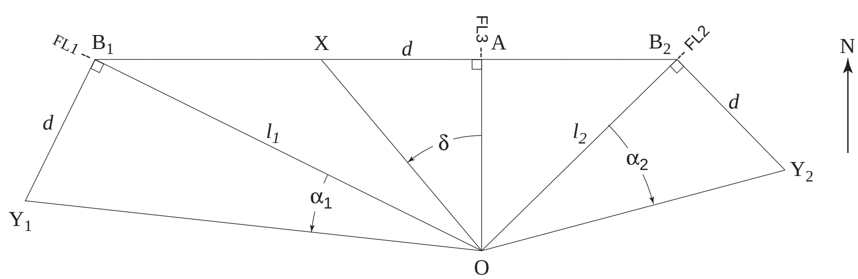


Figure 1.13: True dip and strike from two apparent dips using folding lines.

This type of problem may be solved even more quickly by the cotangent method. This is particularly useful in situations where measurements have been made by tape because they do not have to be converted to degrees (Rich, 1932). For example, if the map distance l and the vertical distance d are measured then

$$\cot\alpha = l/d,$$

and this length can be used directly to construct a diagram. This is also a useful way of handling small dip angles which are difficult to plot accurately at any reasonable scale.

Problem

- From the two apparent dips $20/296$ and $30/046$ determine the true dip and strike of the plane using the cotangent method.

Construction

1. In map view, plot rays from a single point O in each of the two apparent directions (Fig. 1.14).
2. Locate point B_1 at a distance $l_1 = \cot\alpha_1 = 2.74748$ and point B_2 at a distance $l_2 = \cot\alpha_2 = 1.73205$ along their respective rays using a convenient scale.
3. Line B_1B_2 represents the strike direction.
4. The perpendicular distance OA to this strike line is $\cot\delta = 1.19$ using the same scale.

Answer

- The strike is east-west and the dip $\delta = \arctan(1/1.19) = 40°$ due north.

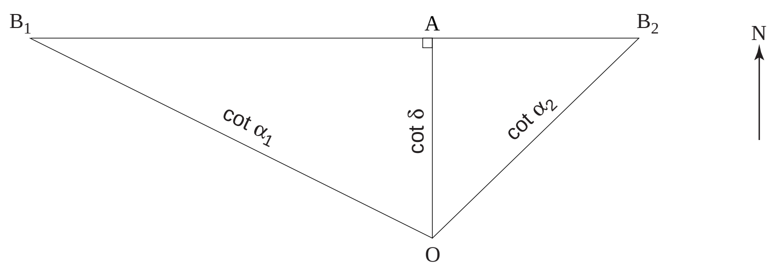


Figure 1.14: Dip and strike from two apparent dips by the cotangent method.

1.10 DIP VECTORS

An alternative way of representing and manipulating angles of true and apparent dip is with vectors (Harker, 1884; Hubbert, 1931). Not only does this make use of the well-established concepts and methods of vector algebra, but it also opens up other possibilities which we explore in later chapters. Accordingly, we represent the attitude of a inclined plane on a map with the *true dip vector* $\mathbf{D}$. This vector is horizontal and points in the direction of true dip. Its magnitude or length is equal to the slope of the dip angle

$$D = \tan\delta. \tag{1.8a}$$

Similarly, we define the magnitude of the *apparent dip vector* $\mathbf{A}$ as

$$A = \tan\alpha. \tag{1.8b}$$

These vectors, like the conventional dip and strike symbols, are two-dimensional representations of lines on an inclined plane.

We may now determine the angle of apparent dip in any direction specified by a unit vector $\hat{\mathbf{u}}$ from the *scalar* or *dot product* of $\mathbf{D}$ and $\hat{\mathbf{u}}$. By definition

$$\mathbf{A} = \mathbf{D} \cdot \hat{\mathbf{u}} = Du \cos \phi \tag{1.9}$$

where ϕ is the angle between $\mathbf{D}$ and $\hat{\mathbf{u}}$. Geometrically, the scalar product represents magnitude of the projection of one vector onto another (Halliday & Resnick, 1978, p. 22). Because $D = \tan \delta$ and $u = 1$, Eq. 1.8 becomes

$$\boxed{\tan \alpha = \tan \delta \cos \phi} \tag{1.10}$$

Because $\phi = 90 - \beta$ this is equivalent to Eq. 1.6.

Problem

- If $\delta = 36$ and $\phi = 90° - \beta = 60°$, what is α?

Construction

1. From a point O draw $\mathbf{D}$ in the dip direction with scaled length $\tan \delta = 0.72654$ (Fig. 1.15a).
2. Vector $\hat{\mathbf{u}}$ from O with unit length and making an angle of ϕ with $\mathbf{D}$ represents the direction of $\mathbf{A}$.
3. The projection of $\mathbf{D}$ onto $\hat{\mathbf{u}}$ fixes the magnitude of $\mathbf{A}$.

Answer

- $A = \tan \alpha = 0.36$ and therefore $\alpha = 20°$. As this construction shows, $\mathbf{A}$ is clearly a *component* of $\mathbf{D}$.

We can, of course, reverse this construction to determine the magnitude of $\mathbf{D}$ and the angle it makes with $\hat{\mathbf{u}}$ from a known apparent dip vector $\mathbf{A}$ (Fig. 1.15b).

A straight-forward extension of this construction then allows the true dip vector $\mathbf{D}$ to be found from two apparent dip vectors $\mathbf{A}_1$ and $\mathbf{A}_2$. The following procedure solves the problem of Fig. 1.13 or Fig. 1.14.

Problem

- From apparent dip vectors $\mathbf{A}_1(20/296)$ and $\mathbf{A}_2(30/046)$ find the true dip vector $\mathbf{D}$.

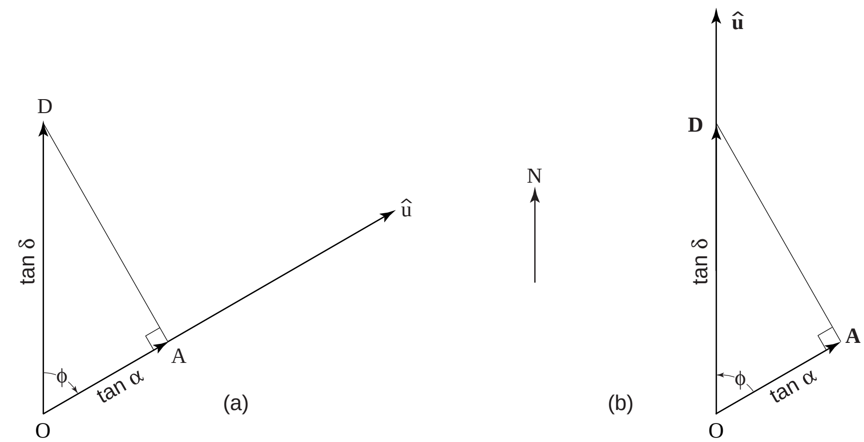


Figure 1.15: Dip vectors: (a) $\mathbf{A}$ from $\mathbf{D}$; (b) $\mathbf{D}$ from $\mathbf{A}$.

Construction

1. In map view draw vectors $\mathbf{A}_1$ and $\mathbf{A}_2$ radiating from point O with lengths $A_1 = \tan\alpha_1 = 0.36397$ and $A_2 = \tan\alpha_2 = 0.57735$ using a convenient scale (Fig. 1.16).
2. Draw perpendiculars from the tips of each of these apparent dip vectors.
3. These projection lines intersect to locate the tip of the dip vector $\mathbf{D}$ and its scaled length is $\tan\delta = 0.84$.

Answer

- The dip vector $\mathbf{D}$ makes an angle $\phi_1 = 64°$ with $\mathbf{A}_1$ and $\delta = \arctan(0.84) = 40°$.

This vector approach also leads to a simple analytical solution. Representing the two apparent dips by vectors $\mathbf{A}_1$ and $\mathbf{A}_2$ then

$$\tan\alpha_1 = \mathbf{D}\cdot\hat{\mathbf{u}}_1 \quad \text{and} \quad \tan\alpha_2 = \mathbf{D}\cdot\hat{\mathbf{u}}_2$$

where the unit vectors $\hat{\mathbf{u}}_1$ and $\hat{\mathbf{u}}_2$ represent the directions of the known apparent dips. Labeling the angles which the unknown vector $\mathbf{D}$ makes with each of these ϕ_1 and ϕ_2 then with Eq. 1.9 we have

$$\tan\alpha_1 = \tan\delta\cos\phi_1 \quad \text{and} \quad \tan\alpha_2 = \tan\delta\cos\phi_2.$$

Solving each for $\tan\delta$ and equating the two results gives

$$\frac{\tan\alpha_1}{\cos\phi_1} = \frac{\tan\alpha_2}{\cos\phi_2} \quad \text{or} \quad \tan\alpha_2\cos\phi_1 = \tan\alpha_1\cos\phi_2. \tag{1.11}$$

Labeling the total angle between $\hat{\mathbf{u}}_1$ and $\hat{\mathbf{u}}_2$ as ϕ we can express angle ϕ_1 in terms of ϕ and ϕ_2. There are two cases.

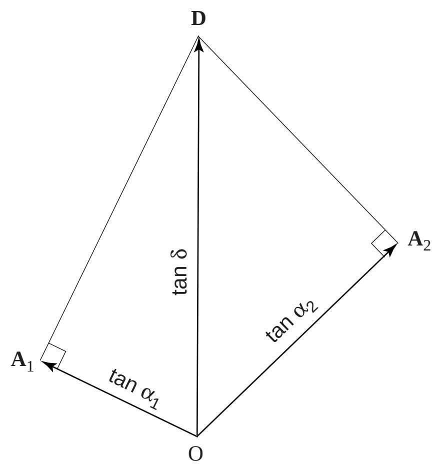


Figure 1.16: Vector solution of true dip and strike.

1. If $\mathbf{D}$ lies between $\mathbf{A}_1$ and $\mathbf{A}_2$ (Fig. 1.17a), then $\phi = \phi_1 + \phi_2$ or $\phi_2 = (\phi - \phi_1)$.

2. If $\mathbf{D}$ lies outside $\mathbf{A}_1$ and $\mathbf{A}_2$ (Fig. 1.17b), then $\phi = \phi_1 - \phi_2$ or $\phi_2 = (\phi_1 - \phi)$.

With the identity for the cosine of the difference of two angles yields the identical results

$$\cos\phi_2 = \cos(\phi - \phi_1) = \cos(\phi_1 - \phi) = \cos\phi\cos\phi_1 + \sin\phi\sin\phi_1.$$

Substituting this result, Eq. 1.10 becomes

$$\tan\alpha_2\cos\phi_1 = \tan\alpha_1(\cos\phi\cos\phi_1 + \sin\phi\sin\phi_1).$$

We solve this for ϕ_1 by expanding, dividing through by $\cos\phi_1$ and rearranging. The result is

$$\boxed{\tan\phi_1 = \frac{\tan\alpha_2}{\tan\alpha_1\sin\phi} - \frac{1}{\tan\phi}} \tag{1.12}$$

With both ϕ_1 and α_1 known, the true dip can be found from (see Eq. 1.9)

$$\boxed{\tan\delta = \frac{\tan\alpha_1}{\cos\phi_1}} \tag{1.13}$$

For Case 1 (Fig. 1.17a), from the previous problem, $\alpha_1 = 20°$, $\alpha_2 = 30°$ and $\phi = 110°$ and we find that $\phi_1 = 64°$ and $\delta = 40°$.

For Case 2 (Fig. 1.17b), $\alpha_1 = 20°$, $\alpha_2 = 30°$ and $\phi = 18°$ and we find that $\phi_1 = 64°$ and $\delta = 40°$. An ambiguity may arise in this case. By labeling the apparent dip angles so that $\alpha_1 < \alpha_2$ the angle ϕ_1 is always measured from $\mathbf{A}_1$ toward $\mathbf{A}_2$ and this avoids any problem.

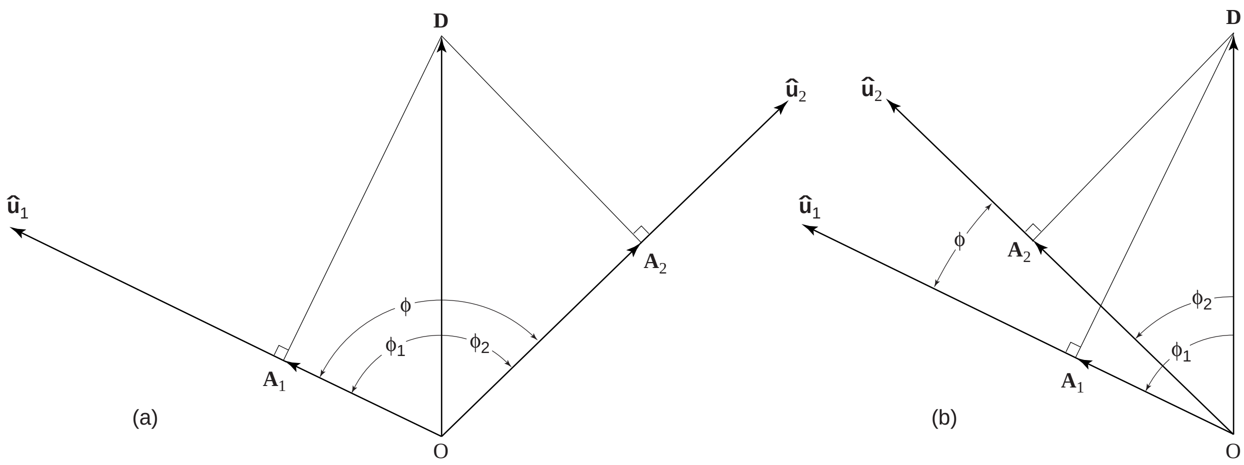


Figure 1.17: Analytical solution of the problem of true dip and strike: (a) Case 1; (b) Case 2.

1.11 THREE-POINT PROBLEM

These methods can also be used to determine the attitude of a plane if the location of *three* points on it are known.[9] It is convenient to label the highest point O. Then the map distances l and elevation difference Δh to each of the other points, the apparent dip in each of these directions is calculated using

$$\tan\alpha = \Delta h/l \quad \text{or} \quad \alpha = \arctan(\Delta h/l). \tag{1.14}$$

With both α_1 and α_2 known, the procedure is then just as before.

In the special case of small elevation differences over large distances, a satisfactory solution requires that the locations of the three points be very accurately known. This can be accomplished with modern electronic surveying equipment.[10]

In these circumstances a graphical solution would require a very large drawing as well as large drafting tools and this is not practical.

Problem

- Three points are located on a structural plane. From the base point O map distance l_1 and l_2 and elevation difference Δh_1 and Δh_2 together with the trends t_1 and t_2 to points P_1 and P_2 are measured using an electronic surveying instrument (see Table 1.1 and Fig. 1.18a). Determine the dip and strike of the plane.

[9] Additional details of this three-point problem are treated in Chapters 3 and 7.

[10] The electronic *total station* is a distance measurement device based on a phase comparison of reflected light from a semi-conducting laser, and an electronic theodolite for measures angles, together with the attendant electronics to reduce and digitally record the data, as well as compute the coordinate geometry. For a typical instrument, the standard deviation of a length measurement is ± 2 mm$+2$ parts per million of the measurement length, and the angular measurement has a standard deviation of ± 3 seconds of arc. For a 1 km measurement, the range has a standard deviation of ± 4 mm. Angles are less precisely determined: ± 24.4 mm in radial distance normal to the measurement direction. For more information see `www.leica-geosystems.com` and click on Products.

	l	Δh	t
P_1	983.3 m	-24.7 m	$23.8°$
P_2	1563.6 m	-48.3 m	$76.4°$

Table 1.1: Data for the three-point problem.

Answer

- From the measured data calculate the magnitudes of the apparent dip vectors in the directions OP_1 and OP_2 using Eq. 1.12: $\tan\alpha_1 = 24.7/983.3 = 0.0251$ ($\alpha_1 = 1.4839$) and $\tan\alpha_2 = 48.3/1563.6 = 0.0321$ ($\alpha_2 = 1.8406$). The angle between these two apparent dip vectors $\phi = t_2 - t_1 = 52.6°$ (Fig. 1.18b). Using these values in Eq. 1.11 we find $\phi_1 = 40.2255°$. Then Eq. 1.12 gives $\delta = 1.88°$ (with three significant figures in the input data, the three figures in this answer are also significant).

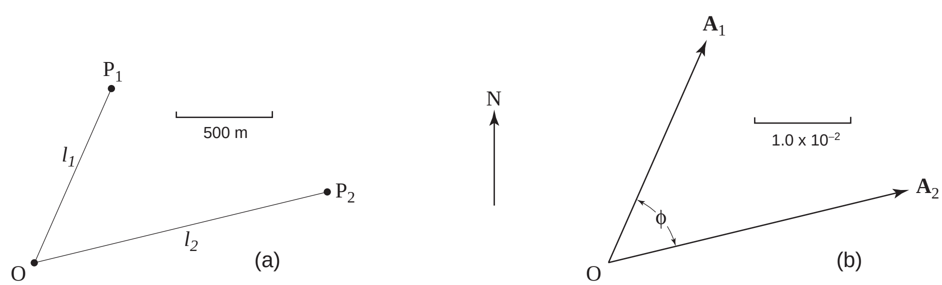


Figure 1.18: Three-point problem: (a) map of surveyed points; (b) apparent dip vectors.

1.12 OBSERVED APPARENT DIPS

The attitude of a structural plane is based on field observation and there is a case that requires special care. Suppose that the trace of a dipping plane is exposed on a vertical plane. With a line of sight perpendicular to this exposure, the observed angle is, in general, an apparent dip. However, if the line of sight is oblique, either to the right or to the left, the observed angle is no longer the apparent dip but rather an "apparent" apparent dip. From Fig. 1.19 we have

$$h = l\tan\alpha, \quad w' = w\sin\beta, \quad \tan\alpha' = h/w',$$

where α is the apparent dip, w is the oucrop width, h is the outcrop height, h' is the apparent height seen in the oblique view, α' is the observed angle and β is the angle the line of sight makes with the exposure plane. Substituting the first two relationships into the third yields

$$\tan\alpha' = \frac{\tan\alpha}{\sin\beta}. \tag{1.15}$$

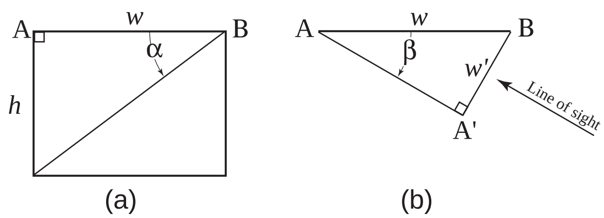


Figure 1.19: Observed apparent dip: (a) direct view of vertical exposure plane; (b) top view of exposure and oblique line of sight in the horizontal plane; (c) observed angle of inclination.

Fig. 1.21a is a graph of this equation, where it can be seen that the observed angle α' is always greater than α and that small angles are distorted relatively more.

Similarly, if the line of sight lies in a vertical plane perpendicular to the exposure but oblique to the plane of the exposure, the observed angle again not the apparent dip. From Fig. 1.20 we have

$$w = h/\tan\alpha, \quad h' = h\sin\gamma, \quad \tan\alpha' = h'/w,$$

where γ is the angle the line of sight makes with the exposure plane and h' is the apparent height. Substituting the first two expressions into the third yields

$$\tan\alpha' = \tan\alpha\sin\gamma. \tag{1.16}$$

Fig. 1.21b is a graph of this equation where it can be seen that the observed angle is always less that α and large angles are distorted relatively more.

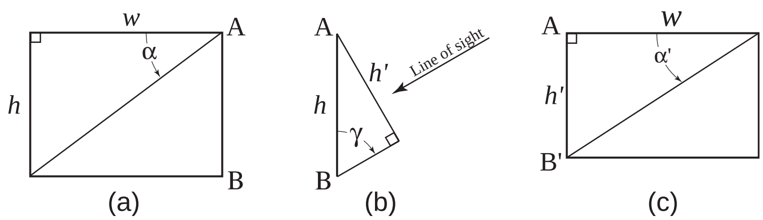


Figure 1.20: Observed apparent dip: (a) direct view of vertical exposure plane; (b) side view of exposure plane with oblique line of sight in vertical plane; (c) observed angle.

More generally, if the line of sight is neither horizontal nor in the plane perpendicular to the exposure the resulting observed angle is mixed — for some apparent dip angles and certain oblique lines of sight the observed angle may be either less or greater. The essential point is that if you find yourself making such observations be careful.

1.13 EXERCISES

These exercise problems are meant to introduce you to the power of graphic methods in geology and to help you learn the basic geometric concepts of structural geology and “see” in 3D. Neatness in the constructions is important. Showing all your construction lines and writing a brief

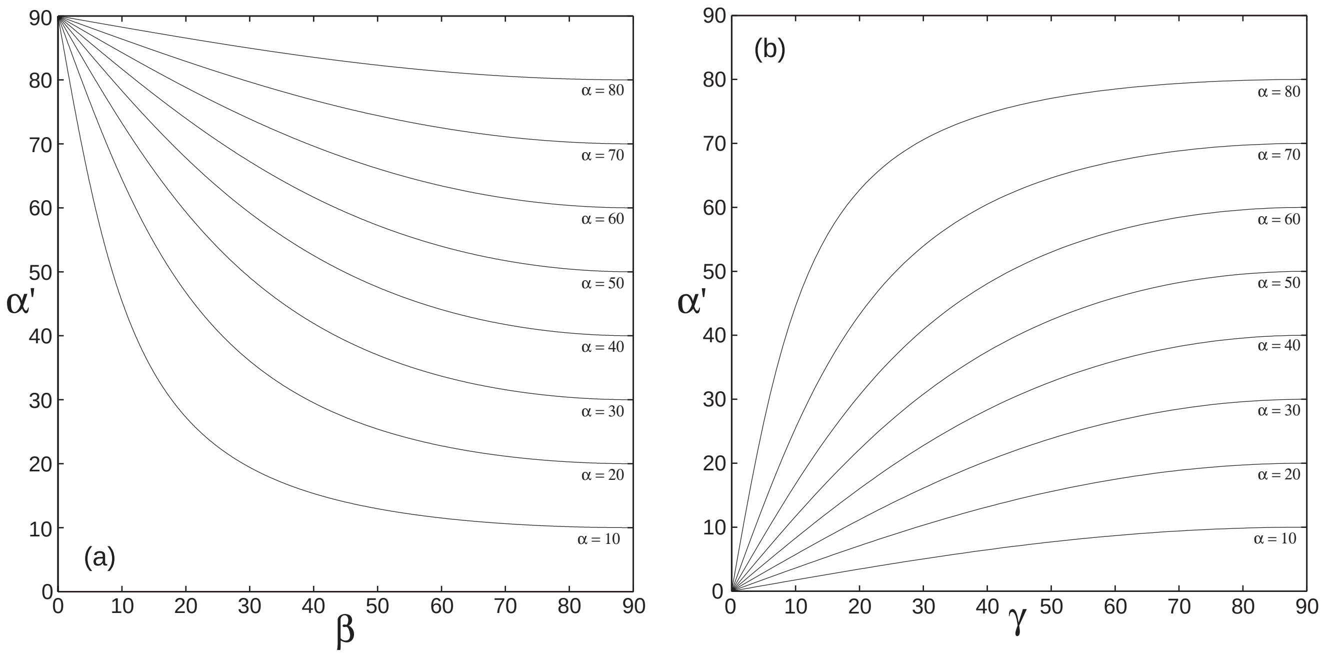


Figure 1.21: Observed apparent dip: (a)α' as a function of β; (b) α' as a function of γ.

explanation of your steps will help make things clearer (such notes will also be an aid for future reference).

1. Using the following data determine the unknown component graphically, and check your results trigonometrically. Each graphical result should be within $1°$ of the calculated value. If it is not then repeat your construction using greater care, making it larger, or both.

   (a) If the attitude of a plane is N 75 W, 22, that is the apparent dip in the direction N 50 E?

   (b) An apparent dip is 33, N 47 E, and the true strike is N 90 E. What is the true dip?

   (c) The true dip is $40°$ due north. In what direction will an apparent dip of $30°$ be found?

2. A certain bed dips $40/000$. In what direction will the apparent dip be exactly half as great. Will this same relationship hold if the bed dips $10°$, $20°$, $50°$, or $80°$? If not, why not?

3. Three points A, B and C on an inclined plane have elevations of 150 m, 75 m and 100 m respectively. The map distance from A to B is 1100 m in a direction of N 10 W, and from A to C is 1560 m in a direction of N 40 E. What is the dip and strike of the plane? (Hint: use Eq. 1.3 to determine two apparent dips).

4. The most important need for the apparent dip arises during the construction of structure sections. Fig. 1.19 is a simple geology map of an inclined sequence of sedimentary strata intruded by a basalt dike and the whole cut by a fault. Construct a vertical section along the line XX' showing the traces of the three structural planes with the correct inclination and proper position.

5. What is the maximum potential error in determining the strike direction if the dip is $5°$ and the maximum operator error is $2°$?

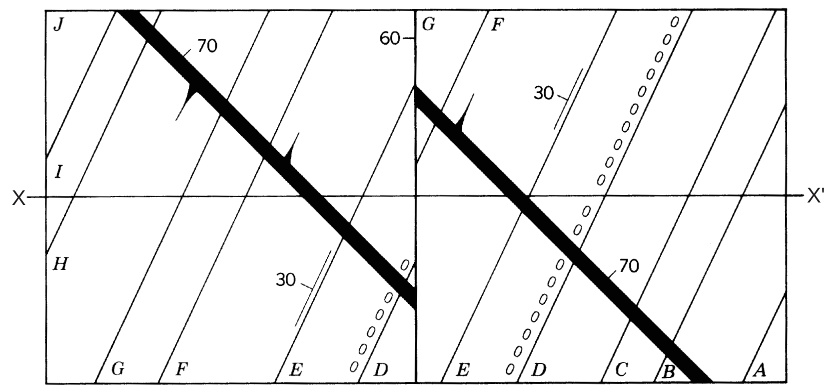


Figure 1.22: Construction of a cross section from a simple map of dipping planes.

6. Using the following data determine the unknown component graphically and check your results trigonometrically. Each graphical result should be within $1°$ of the calculated value. If it is not, then repeat your construction using greater care, making it larger, or both.
   (a) If the attitude of a plane is N85E 25NW, what is the apparent dip in the direction N20E?
   (b) If the strike of a bed 350 and the apparent dip 35 in the direction 300, what is the true dip.
   (c) If the strike and dip of the bed (N45E 30SE) what is the apparent dip in the direction S25W.

7. A distinctive sandstone bed crops out at three localities in a corner of the Edmundsville Quadrangle. Outcrops A and B are on the 240-m contour line, and point C is on the 170-m contour line. Outcrop B is 500 m to the N40E of outcrop A, and outcrop C is 250 m to the N20W of outcrop A. Assuming that the sandstone is homoclinal (constant dip), what is its attitude? 1) Using the following data determine the unknown component graphically and check your results trigonometrically. Each graphical result should be within 1 of the calculated value. If it is not, then repeat your construction using greater care, making it larger, or both. a) If the attitude of a plane is N85W 19NE, what is the apparent dip in the direction N40W? b) Given the strike of a bed 350 and the apparent dip 25 in the direction 280, determine the true dip. c) Given the strike and dip of the bed (N85W 30SW) determine the apparent dip in the direction S60W. 2) A distinctive sandstone bed crops out at three localities in a corner of the Edmundsville Quadrangle. Outcrops A and B are on the 240-m contour line, and point C is on the 180-m contour line. Outcrop B is 400 m to the N40E of outcrop A, and outcrop C is 240 m to the N20W of outcrop A. Assuming that the sandstone is homoclinal (constant dip), what is its attitude?

8. On the attached map, the top of a dolomite unit crops out at points G and H. It is encountered in the drillhole at point I with an elevation of 3000 ft. What is its attitude?

9. Three points A, B, C on an inclined plane have elevations of 150 m, 75 m, and 100 m respectively. The map distance from A to B is 1100 m in a direction of N10W, and from A to C is 1560 m in a direction of N40E. What is the strike and dip of the plane? Solve graphically or analytically.

10. A plane is defined by apparent dip vectors 10/135 and 25/250. What is the strike and dip of the plane? Solve graphically and analytically.

11. On the provided topographic map, the top of a prominent limestone bed is exposed at the surface at points D and E and it is encountered at point F in a borehole at an elevation of 4000 ft. What is the strike and dip of the plane? Solve graphically and analytically.