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 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 geographical 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.

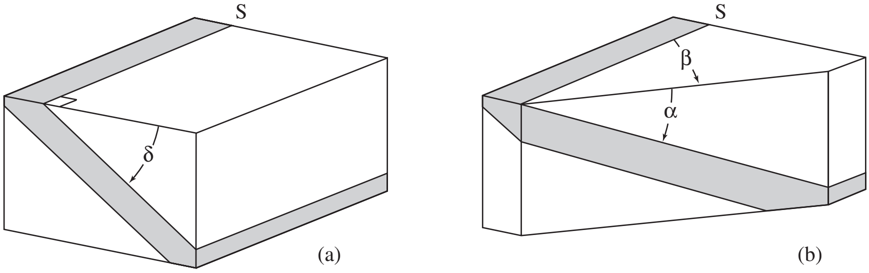


Figure 1.1 Strike S, true dip δ (delta), apparent dip α (alpha) and structural bearing β (beta).

1.3 Dip and 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).
   (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 north-

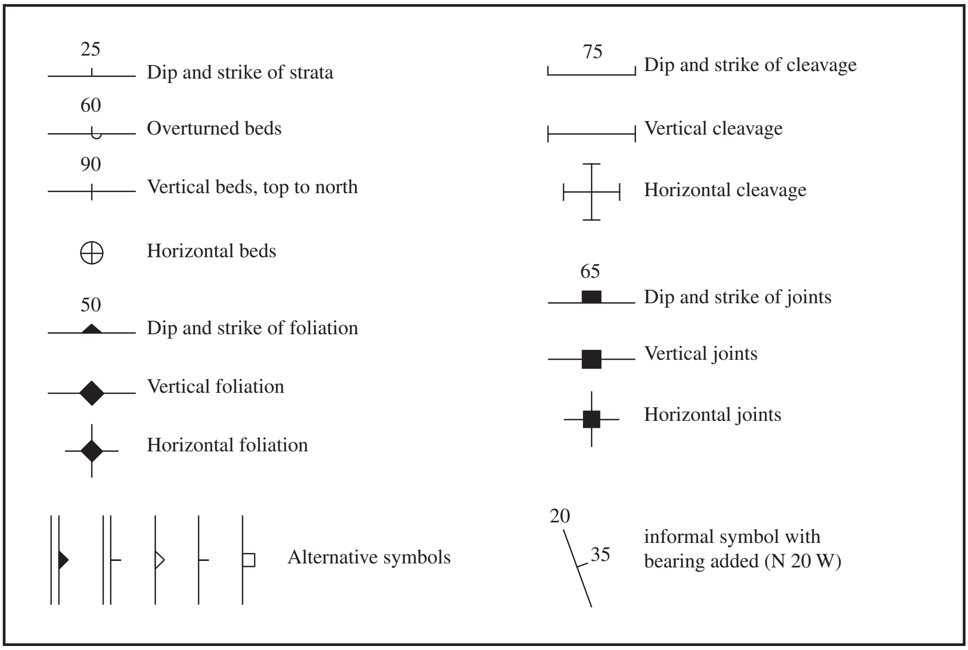


Figure 1.2 Map symbols for structural planes.

ernmost 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

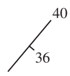
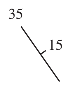
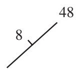
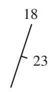
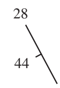
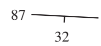
SYMBOL						
Strike (a)	N 40 E, 36 SE	N 35 W, 15 NE	N 48 E, 8 NW	N 18 E, 23 E	N 28 W, 44 SW	N 87 W, 32 S
Strike (b)	40, 36 SE	325, 15 NE	48, 8 NW	198, 23 E	332, 44 SW	273, 32 S
Dip (a)	36, S 50 E	15, N 55 E	8, N 42 W	23, S 72 E	44, S 62 W	32, S 3 W
Dip (b)	36/130	15/055	08/318	23/108	44/242	32/183

Figure 1.3 Examples of the strike and dip notations.

data. For this reason it is becoming increasingly common to see the attitudes of planes written in this way.

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,

[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 ±5° or better. In combination with the labeled strike direction this is sufficient.

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 Barnes (1995, p. 7–9), Davis and Reynolds (1996, p. 662–669) and McClay (1987, p. 22–30).

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 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).

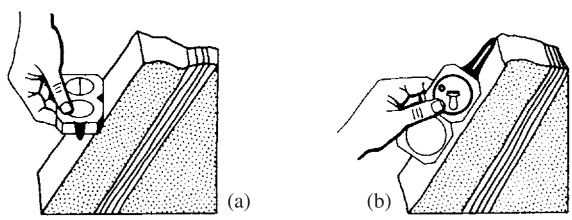


Figure 1.4 Measurements with a Brunton compass (from Compton, 1985, p. 37 with permission of John Wiley): (a) strike; (b) dip.

1.4 Accuracy of angle 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 presence 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 unfortunate experience of finding an attitude which

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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 them in the field. A good way to do this is to 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 be 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 errors would not be.[2]

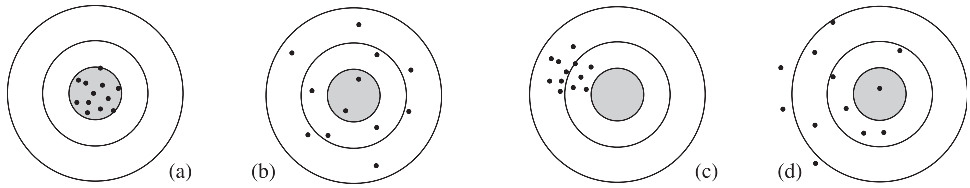

Figure 1.5 Combinations of small and large random *R* and systematic *S* errors (after Taylor, 1997, p. 95): (a) *R* small, *S* small; (b) *R* small, *S* large; (c) *R* small, *S* large; (d) *R* large, *S* large.

[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).

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 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 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 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.

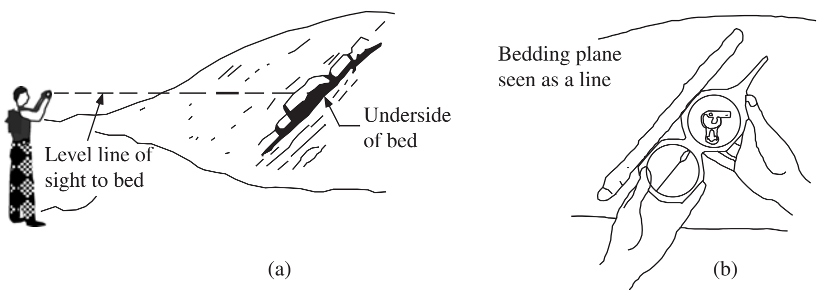

Figure 1.6 Avoiding minor irregularities (Compton, 1985, p. 35 with permission of John Wiley): (a) sighting a level line; (b) dip measured perpendicular to this line.

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 give 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 and 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° to 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 and 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, in 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 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 $\delta \to 0$.

[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.

[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).

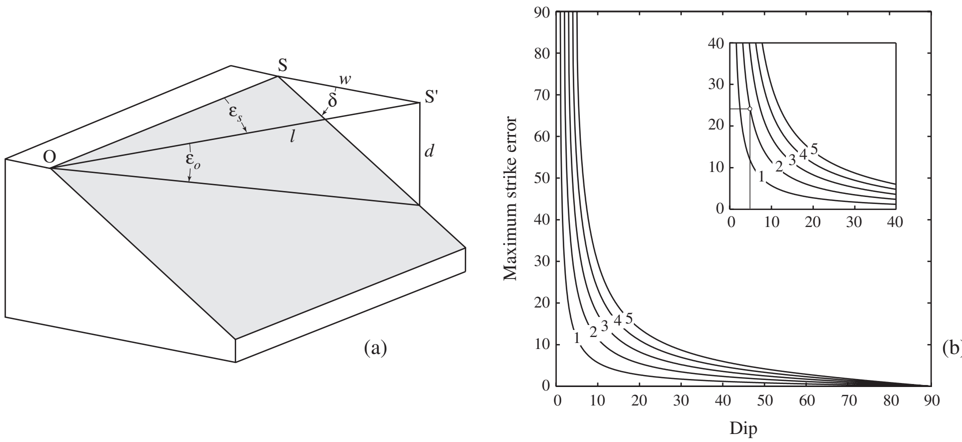

Figure 1.7 Maximum strike error: (a) geometry; (b) ε_s as a function of dip for values of $\varepsilon_o = 1$–$5°$. (The inset shows an example $\varepsilon_o = 2°, \delta = 5°$, with the result that $\varepsilon_s \approx 24°$.)

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.

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.

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?

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