Chapter 4. Orientation Description

4.1 Introduction

Definitions
In structural geology, we need to describe the orientations of real and/or imaginary lines, planes, and surfaces in three-dimensions and to define how those features change orientation through time. Linear features in a rock are called **lineations** and planar features include **foliations, bedding planes,** and **faults**. We use **trend** and **plunge** to describe the orientations of linear features. We describe the orientations of planar features or portions of surfaces by: 1) **Strike**, **dip,** and **dip direction**; or 2) **Dip** and **dip bearing**. If a line is associated with a plane, we can define its orientation by defining a **pitch** and a **pitch direction** that relates to the strike and dip of the plane.

Relevance
Describing the orientation of geological structures is the basis of structural geology. Despite the advent of digital techniques, the magnetic compass remains the most practical, simple and commonly used instrument to record orientations in the field, and every structural geologist (indeed, every field geologist) needs to become thoroughly proficient in the use of the compass. This chapter therefore gives the key concepts behind describing orientations and measuring them with a compass: An Appendix to this chapter gives a thorough exposition of the practicalities of compass use.

4.2 Directions on the surface of Earth and maps

An **azimuth** is one way of designating a direction, or bearing, on a horizontal plane, in space (Figure 4.1a). We use the geographic North pole, the point where the Earth's axis of rotation intersects its surface, as our reference for reckoning directions. We call the direction along which one would need to travel to reach the geographic North pole 'North.' Azimuths range from 0 (North) to 360 (also North), in a clockwise fashion. Consequently, 090 is East, 180 is South, and 270 is West. Note that we use 3 digits (002, 087, 120 etc.) to define an azimuth and that we drop the º sign. North is upwards, toward the top of the page on maps. Azimuths are commonly used by navigators of all sorts, but particularly by sailors who are unconstrained by obstacles and can go in any direction. This is the system that is used by most geologists and is used in this book.

An alternative method for determining direction on a horizontal plane is the **quadrant measure** (Fig. 4.1b). It uses a system of 4 **quadrants**, or sections of the compass: NW, NW, SW, and SE. A bearing specifies any cardinal direction (N, S, E, W) by a letter (i.e., N). For any direction between the cardinal directions, a quadrant direction is given in the form N34E or S30W. The first letter gives the reference direction (N or S), the number gives the angular variation from that reference direction (say 34), and the last letter gives the direction toward which to measure the angle (E). So, N34E is a line oriented 34° from North, towards the direction of East. N34W is a line oriented 34° from North, towards the direction of West. Note that N34E (bearing) is the same as 034 (azimuth), and N34W (bearing) is the same as 326 (aximuth = 360 - 34). Similarly, S30W (bearing) is the same as 210 (azimuth = 180 (= S) + 30).

4.3 Earth's magnetic field

Earth's magnetic field is extremely useful for determining directions in the field. For our purposes, Earth's magnetic field is a *geocentric dipole*, meaning that the field is consistent with a strong, two-ended (di-polar) magnet positioned at the center of Earth (Fig. 4.2). The non-dipolar components of Earth's magnetic field are sufficiently small that we can ignore them for this discussion. The lines surrounding the globe in Fig. 4.2 are called *magnetic field lines*; a small magnetic dipole (i.e. a bar magnet) placed anywhere on Earth would align itself with the magnetic field lines if it were able to move freely. Magnetic field lines go directly out of Earth at the magnetic South pole and directly into Earth at the magnetic North pole (which means, from a physics point of view, Earth's magnetic South pole is equivalent to the North pole of a magnet). At all other places on Earth, magnetic field lines have a finite horizontal component. It is this horizontal component of the magnetic field that induces a compass needle to point toward the magnetic poles and allows you to determine the direction of North. The vertical component of Earth's magnetic field is related to the *inclination* of a magnetic field line, the angle between a horizontal plane and the magnetic field line. Note, as is shown on Fig. 4.2, magnetic field lines are inclined relative to the horizontal at most locations on Earth, pointing upward in the southern hemisphere and downward in the northern hemisphere. Only near the equator are magnetic field lines horizontal. The different inclinations in different hemispheres give rise to a difference in vertical component of the magnetic pull in the northern and southern hemispheres (Figure 4.2). For this reason, compasses from the Northern hemisphere will not work in the Southern hemisphere, and vice versa.

The axis of Earth's magnetic field does not coincide with Earth's rotation axis, so the magnetic North pole does not coincide with the geographic North pole. Because the compass points to the magnetic North pole, there is at most locations on Earth an angular difference, called the *magnetic declination* (Fig. 4.2), between the direction in which the compass needle points and North. The magnetic declination is the angle, measured in a horizontal plane, between the direction toward the geographic North pole and the direction between the magnetic North pole. A declination of 10° west means that the magnetic North pole is oriented 10° west of north (counterclockwise) from the geographic North pole. Figure 4.3 shows that the declination changes from point to point around the globe; the declination at any one point will also change from time to time.

Many maps use the direction to the geographic North pole as the basis of their reference frame (although you may encounter maps that use a 'grid North' that is close to but not precisely parallel to geographic North as their reference). Therefore in order to show directions measured with a compass on a map, it is essential to adjust or correct magnetic bearings for the declination (the difference between magnetic and true North). Imagine that the magnetic pole is 10º due West of the geographic pole, as in the above example (the declination is 10º west). If your compass needle points to 000 (*magnetic N*), then it is pointing towards 350º (*true N*). A simple rule can be deduced from this example: to convert magnetic directions to geographically correct directions, 10º must be subtracted for west declinations, and vice-versa for east declinations.

4.4 Compasses

Geologists most commonly use a compass to determine direction in the field. Three basic types are now routinely used: Transit (e.g. Brunton), Stratum (e.g. GeoBrunton, Breipthaupt, Freiberg), or Silva type (Fig. 4.4). A description of how the compasses work, with step-by step instructions, is given in the Appendix to this chapter. If you have not used a professional compass before, please read the Appendix before you continue reading the rest of the chapter. It will also help to have a compass with you while reading the chapter, if that is possible. Otherwise, the descriptions of how to measure the orientations of lineations and foliations will make little sense.

The variety of compasses in use can be perplexing at first. Each type has features that are advantageous for specific types of work: for example the transit compass for surveying; the stratum compass for rapid and accurate collection of structural data. Apart from their specific features, familiarity probably dictates choice of compass as much as anything, and practice rapidly brings skill in collecting orientation data with all types of compass.

4.5 Lines: Trend and Plunge

We use two numbers to describe the orientation of a linear element or **lineation** in space: **Trend** and **plunge** (Fig. 4.5). The **trend** (also called the *plunge bearing*) is the angle between a horizontal line and the projection of the linear element onto the horizontal plane (what you would see when looking vertically down on the linear element from above) (Fig. 4.5a). We usually give the trend as an azimuth, varying from 000 to 360, and always written with three numbers (e.g., 005). For example, if you place a pencil on the ground, with the point oriented toward N, the linear element (i.e. pencil) would have a trend of 000. If the pencil were oriented NE, it would have a trend of 045.

The **plunge** (or inclination) of any linear element is the angle measured <u>downward</u> from the horizontal to the line in a vertical plane. As is clear in Figure 4.5, that vertical plane will also contain the direction of the trend (Fig. 4.5b). That is, the plunge is the deviation from the horizontal in the vertical plane that contains the linear element. The value of the plunge varies from 0 to 90. So, a pencil that is oriented horizontally has a plunge of 0, a pencil that is oriented vertically has a plunge of 90, a pencil that is oriented halfway has a plunge of 45. In structural geology, the plunge is always downward into the Earth.

Lines that plunge between 0 and 30 are *shallowly plunging*. If lines plunge between 30 and 60, they are *moderately plunging*. If lines plunge between 60 and 90, they are *steeply plunging*.

In this book, we will always define the trend of the line as the direction in which the line plunges. Thus, there is only one possible trend for any given line. You should be aware that this convention is not universally followed, so you need to examine carefully the description of orientation data presented elsewhere. The only exceptions to the rule that a line has only one possible trend are horizontal lines, which can have either one *or* two orientations in space. Horizontal lines have two orientations in space if there is no preferential direction to the line. The trend of a NS-oriented, horizontal pipe is either 000 or 180, since the pipe has no distinctive or "sharp" end. If the horizontal line is a pencil or a direction that you need to walk to in space, then there is only one correct trend for the line.

There are many conventions for writing down the orientation of a trend and plunge. One common convention is to write the plunge, followed by an arrow, and then the trend (e.g., 45 $\rightarrow$ 065). This order of numbering implies "a line plunging 45 in direction 065." On a geological map, a lineation is shown an arrow with no tail (Figs. 4.6a and b). The arrow is oriented in the direction of the trend. The plunge amount is written by the front tip of the arrow. If the lineation has no plunge, we depict it with a two-headed arrow (Fig. 4.6c). Instructions for how to measure lineations are given in the Appendix.

4.6 Planes

4.6.1 Strike, dip and dip direction,

Most geologists use one of two different conventions to describe the orientation of a planar surface in space: 1) **Strike**, **dip,** and **dip direction**; or 2) **Dip** and **dip bearing**. It is probably more common to use strike, dip, and dip direction to define the orientation of a planar element. We describe strike, and dip and dip direction measurements in this section, and dip and dip bearing measurements in the following section. We will use a book as our standard for a planar marker.

The **strike** is the most difficult of the spatial orientation measurements to comprehend. The **strike** is the direction of any and all horizontal lines on a plane. Every inclined plane will contain an infinite number of strike lines, each of them different distances above or below a horizontal datum. All strike lines on that plane must, however, be parallel to each other. That is, all strike lines of a plane will have the same bearing or orientation in space. That is why we can define a single strike for any plane. By this definition, a horizontal book has no strike line, since there is more than one horizontal line. Figure 4.7 shows a book that is tipped up in an aquarium (We recommend, despite the temptation, not to try it with this book). If you fill the aquarium with water, the intersection of the water line with the book will show you one of the many strike lines on this plane. For the specific scenario in Fig. 4.7, the long direction of the aquarium is oriented NS and the strike line of the book is oriented NS. Since the strike line is a horizontal line in space, as discussed above, the trend is both 000 and 180. Imagine a slightly different orientation of the book in the aquarium, with the book standing on a corner (Fig. 4.7b). In this case, the strike line trend is still both 000 and 180. This is a critical point: The strike line does not need to be parallel to the edge (or binding) of any planar surface.

The **dip** is the direction angle of maximum inclination on the plane. The direction of the dip is necessarily perpendicular to the strike line. As with a plunge, we always measure the dip *downward* from horizontal. The value of the dip varies from 0 to 90. So, a horizontal book has a dip of 0, a vertical book has a dip of 90, a book that is oriented halfway between these end-members has a dip of 45. Planes that dip between 0 and 30 are *shallowly dipping*, between 30 and 60 are *moderately dipping*, and between 60 and 90 are *steeply dipping*. The only complication with a dip measurement is that it requires a dip direction. The **dip direction** is necessarily perpendicular to the strike line, and is usually approximated by one of the 8 directions N, NE, E, SE, S, SW, W, NW In the aquarium example, the books in Figs. 4.7a and b strike NS, and dip 60° to the East (specified as 60 E). The book Fig. 4.7c strikes NS and dips 60°, given by the measurement 000, 60 W.4.

There are different conventions for strike and dip. One convention is to give the azimuth or quadrant measure of either end of the strike line (i.e. as 000 or NS), a comma, and then followed by the dip and the dip's direction (60E): NS, 60 E or 000, 60E (For Figs. 4.7a or b). In this case, Fig. 4.7c could be characterized as 000, 60W or NS, 60W. Another common convention is the use of a slash to separate the strike from the dip and dip direction e.g. 000/60E. An alternative convention is the **right-hand rule**. In the right-hand rule convention, the dip is always oriented to the right hand (clockwise) side of the designated strike line when looking downwards. In practical terms, this means that you identify one end of the strike by determining which you must face to have your right hand point in the direction of the dip; you record the direction in which you are facing as the strike direction. The advantage of this system is that no dip direction is necessary. So, Figs. 4.7a and b are characterized as 000, 60 and Fig. 4.7c is characterized as 180, 60. This is the most common version of the right hand rule, but it is as well to note that one textbook (Barnes 1991) suggests the opposite convention for the right-hand rule.

On a geological map, the strike line is shown as a line with a small dash coming out in the middle of it on one side (Figs. 4.6d and e). The dash is oriented in the direction of the dip and the dip amount is written by that dash. Special symbols are used if the bed is flat-lying or vertical (Figs. 4.6f or g). If the planar feature has a facing direction, such as sedimentary bedding, we reserve the strike and dip symbol for the general case where the stratigraphy dips between 1° and 89°. If the bedding is overturned, another loop is added to the dip symbol to indicate that fact (Fig. 4.6h).

4.6.2 Dip and dip bearing

An alternative way to measure the orientations of planes is to use their dip and dip bearing. Dip bearing means the accurate direction of dip (measured either by an azimuth, e.g. 050, or quadrant measure, e.g. N50E) rather than the general direction (e.g. NE). Technically the dip and dip bearing measure a line in space rather than a plane. In fact, the dip bearing is the orientation of the steepest line on a plane and the dip is the plunge of that line. That line uniquely defines a plane only because it is specified to be the steepest line on that plane.

The dip bearing is, by definition, 90° different from the strike. Thus, for our example in the book in the aquarium example (Fig. 4.7a), the steepest line has a bearing of 090. Thus, the dip direction is 090. The dip of the plane is 60. For Fig. 4.7b, the dip direction is also 090 and the dip of the plane is 60. For Fig. 4.7c, the dip direction is 270, not 090, because the bearing of the line is to the W. The dip of the plane is still 60.

The dip and dip bearing can be reported by: dip, dip bearing or dip/dip bearing. For the examples of Figs. 4.7 a and b, it is 60, 090. For the example in Fig. 4.7c, the measurement is 60, 270 or 60/270. This way of writing the dip and dip bearing removes confusion whether the measurement is a strike and dip (with right hand rule, since no direction is given, e.g., 000, 60) or a dip and dip direction (e.g., 60, 090).

4.6.3 Apparent dips

Any line that lies within an inclined plane and has a trend other than the trend of the strike must be inclined relative to the horizontal. Since the dip is the line of maximum inclination, all other inclined lines must have inclinations less than the value of the dip. An analogy is given in Fig. 4.8a: the skier traveling directly from start to finish is going down slope in the true dip direction; the others are traveling down lower slopes along apparent dips. We often underscore the distinct character of the dip line by saying that its inclination is the **true dip** of the plane (δ). Since the inclination of a line other than the dip is not equal to the value of the dip, we often refer to its inclination as an **apparent dip** (α) of the plane in a given direction. It is important to recognize that any apparent dip is a line in space, and so we must define both its trend and plunge values in order to 'fix' or describe that apparent dip. Note also that the magnitude of an apparent dip is not arbitrary. Lines with trends parallel to the strike will have inclinations of zero (their apparent dip is zero). Lines with trends parallel to the trend of the dip will have an inclination equal to the true dip of the plane. Any line oblique to the strike or the dip will have an inclination between zero and the true dip. You can calculate the value of the apparent dip (α) of a line if you know both the angle between the trend of the strike and the trend of the line of apparent dip (β) and if you know the value of the true dip (δ) of the plane (Fig. 4.8c):

$$\tan \alpha = \tan \delta \ \sin \beta$$

Clearly, if you know two pieces of information, such as the orientation of the strike and an apparent dip in a particular direction, you can determine the true dip of the plane. A more typical situation is that in which one knows the trends and plunges of two apparent dips. With this information, one can determine the strike and dip of the plane. This can be very useful in situations such as the base of cliffs (if it is safe!) or underground, where a plane can be seen on several vertical faces, but there is no accessible horizontal exposure to determine the strike.

4.7 Lines within Planes: Pitch and pitch direction

A **pitch** records the orientation of a linear element that is associated with a plane, such as striation or a slickenfiber on a fault plane. The pitch is usually defined to vary between 0 and 90 and must always be given with a **pitch direction** (see below). Pitch is synonymous with a rake.

Figure 4.9 shows an example of a plane that strikes 000 and dips 60 E. The black pencil pitches at an angle of the 30 from the South end of the strike line. Therefore, the pitch measurement is: 000, 60 E: 30S. The red pencil pitches at an angle of 80 from the North end of the strike line. Therefore, the pitch measurement is: 000, 60 E; pitch: 80N. Some students find the pitch direction, but not the pitch amount, difficult to understand. In the example of the red pencil, the trend of that pitch in space is almost E. The pitch, however, must be measured from one end of the strike line, which defines its orientation. Some conventions use a 0 – 180 scale for pitch, defining 0 as the end of the line given by a strike measurement.

4.10 Summary

Linear features in rocks are called lineations. We describe their orientation by a trend and plunge. The trend can be given as an azimuth (000-360) or bearing (N, N45E, S12W, etc.). The plunge is a number between 0 (for horizontal lines) and 90 (for vertical lines).

Planar features in rocks include bedding, faults and foliations. Planar features are described by their orientation using either: 1) a strike, a dip value, and dip direction; or 2) a dip value and a dip bearing. We can use an azimuth or a quadrant measure to give a strike or dip bearing. The dip value is a number between 0 (horizontal) and 90 (vertical). The dip direction is a cardinal direction in space (N, NE, E, etc.).

A pitch (or rake) characterizes a line that is associated with a plane. The pitch is measured as an angle in the plane, taking the acute angle from the strike line. The pitch is a number between 0 and 90. The pitch must also be given with a pitch direction that determines which end of the strike line was used as a reference from which the pitch angle is measured.

Appendix 1: The professional compass

Geologists use a compass to determine direction in the field (Fig. 4.4). The quality of your geological data, and thus your geological interpretations, are based on your ability to use a compass. Thus, it is worth knowing the names for the critical parts of the compass and understanding how it works. Three basic types are now routinely used: The pocket transit (or Brunton), the stratum compass, and the Silva.

The needle of the compass contains a bit of magnetic material, often magnetite, which aligns to the Earth's magnetic field. The transit compass has two levels: a round bulls eye level and a cylindrical level. The bulls eye level, used to measure azimuthal (horizontal plane) directions, must be level to get accurate measurements. The cylindrical level, used to measure deviations from horizontal (inclinations), must: 1) lie in a vertical plane (compass be upright); and 2) be on the top side of the compass. The cylindrical level is moved using a lever on the back (vernier adjustment) of the compass. As the lever moves, the level and the vernier moves, and the center of the vernier points to the clinometer scale that is located on the bottom of the compass. You always want to use the scale that goes from 0 (horizontal) to 90 (vertical). The other scale is for road grade and runs from 0 to 100% (over a 45° angle). The stratum or Silva compass may come with a single bulls eye level.

The metal case of the transit compass is the basis for taking measurements. The brass or black metal piece that can be folded out is called a pointer. Depending upon the manufacturer, there may or may not be a pointer on a stratum compass. A stratum compass also has graduated hinge scale between the top and bottom parts of the compass. You use this hinge scale to measure dip values.

Finally, there is a ring on inside, perimeter part of the compass to which the magnetic needle will point. This is the graduated circle, and we use it as the basis for azimuthal measurements. The rings come in two types, depending whether the compass reads in azimuth or quadrant. Transit or stratum azimuth compasses read from 0 to 360, marked in sequential order counterclockwise around the ring. Quadrant compasses read from 0 to 90 in four separate sections (quadrants) of the compass. On the bottom of the compass, there is an "E" on the left hand side and a "W" on the right hand side.

Here is the tricky part: The azimuth markings on transit or stratum compasses run in the opposite directions (i.e. they increase anticlockwise) from azimuth in space (which increases clockwise: compare Fig. 4.1 to Fig. 4.4). This is required because it is the edge of the compass matters, not the magnetic needle, that matters. Here are two examples of how that arrangement works (Fig. 4.A1). Imagine that you are aligning the compass toward a feature that is oriented toward 045 (or NE in the quadrant system). As you point your compass in toward 045, the magnetic needle still points at the magnetic North pole. That means, if you ignore your spatial orientation and consider only the compass, the needle has moved <u>counterclockwise</u> 45° with respect to the zero mark. On a map, however, NE is oriented <u>clockwise</u> 45° from N. For this reason, the ring in the compass is marked opposite the azimuthal orientation in real space. Here is another example. Imagine another feature that is oriented 10° west (counterclockwise) of north (an azimuth of 350). If you orient the compass in that direction, and look only at the compass, the magnetic needle will have moved clockwise with respect to the ring.

It is also possible to set the declination of the compass, to compensate for the fact that geographic and magnetic North poles are not aligned. To do this, you must first loosen the screw on the bottom of the compass (note: some compasses do not have a loosening screw). Then, rotate the large screw on the side of the compass (called the magnetic declination adjustment screw). You will notice that the entire ring moves. The reference is to the index point on the pointer side of the compass. If the magnetic declination is zero, or is unknown, the index pin should point to 000 (Fig. 4.A2a). For an east declination, the zero mark on the ring must lie east (clockwise) of the point (Fig. 4.A2b). For a west declination, the zero mark on the ring must lie west (counterclockwise) of the point (Figure 4.5c). Remember to tighten the loosening screw when done. You can check that you have performed the correct adjustment form the rule that was deduced in 4.3. For example, West declinations require subtraction. If you adjustment has reduced the bearings from their un-adjusted value, it is correct.

An additional adjustment may be necessary on some stratum compasses (e.g. Freiberg). This is to compensate for the inclination of Earth's magnetic field (Fig. 4.2). For use in the Northern hemisphere, a small weight (typically a strand of copper wire) needs to be mounted on the South compass needle at the correct distance from the fulcrum to bring the needle back to horizontal, and visa versa for the Southern hemisphere. The closer your field area is to the pole, the greater the combination of weight and distance from the fulcrum is necessary. In the case of Silva compasses, it is vital to buy the correct model for the latitude and hemisphere of the field area.

To read an azimuthal direction, point the pointer of the compass in the correct orientation, level the bulls eye level, and read off the number to which the white or North end of the magnetic needle points. To read a quadrant direction, point the compass in the orientation of feature, level the bulls eye level, and read off the number. Then, you must add an "E" or "W" to all measurements that are not in a cardinal direction. Using the example (045 or NE) above, the compass would read 45. You would read N45 and then add the letter (E) that was on the same side of the compass as the compass needle. In the first case, you would read N45E. In the second case (350 or 10° W of N), you would read "10", see that it was from the N side and W was the closest letter, and read "N10W". The same is true for measurements in the southern part of the compass. For example, SE would be oriented S45E and 210 is S30W.

There are a few general guidelines for use of a compass. First, you should recall that metal objects, including mechanical pencils, belt buckles, rings, watches, and clipboards are often magnetic and will affect the compasses. Second. some other things that you might not notice or think about, such as powerlines and metal pipes below ground, also affect the measurement. Using compasses in mines can be particularly difficult because of the magnetic mine infrastructure. Do not take measurements near iron-bearing objects.

Last, some rocks are very magnetic and affect the compass needle. For these rock types – banded iron formation, highly serpentinized peridotites, and even some oxidized granites etc. – one must use a sun compass. It is advisable to test for possible effects of rock magnetism by bringing a small sample of rock up to the compass and observing its effect on the needle as it is moved around. As a double check in all of the above, it is best to have some independent concept of the direction toward N (for example, using the sun, the orientation of a road, or a GPS unit), to make sure that any measurement makes sense.

The trend on a compass is measured with the graduated circle (Fig. 4.4). The bulls eye level must be level to get accurate azimuth (horizontal plane) measurements. If one needs to site at an object, there are several methods for simultaneously siting and reading the compass. One method is to bend up the pointer with the slot. Then, bend up the mirror so that, holding the compass near your waist, you can look down into the mirror. If the bulls eye level is level and you can look down into the mirror, and the center of the line on the mirror goes through the slot on the pointer, you are looking in exactly the direction that the compass reads. Most field geologists can site to within 1 degree on a distant object.

The plunge or dip is read on the clinometer scale, with a range of 0 (horizontal) to 90 (vertical), with the vernier. (Do not confuse clinometer scale with the grade % scale that goes from 0 to 100 over 45°). This vernier is moved to the correct position by leveling the attached cylindrical level, by using the vernier adjustment lever on the back of the compass.

Appendix 2: Step-by-step instructions for using compasses.

A2.1 How to measure a linear object: trend and plunge

We will use a pencil as our example of a linear marker, with its orientation given in Figure 4.5. The first task is to determine the trend (Fig. 4.A3a).
Transit:

- Point your compass in the direction of the pencil, making sure that the pencil plunges downward away from you.
- Level the bulls eye level.
- Standing directly above the compass and having folded the pointer out fully, make sure you can see the entire pencil through the slot in the pointer.
- Make sure the bulls eye level is still horizontal.
- Record the measurement reading off the white end of the arrow.
- Point your compass toward N and make sure that your measurement makes sense.

The second task is to measure the plunge (Fig. 4.A3b). The two long sides of the compass – informally called the measuring edges (Fig. 4.A4) – are critical.

- Line up a measuring edge with the lineation.
- Rotate the compass (about the measuring edge aligned with the lineation) until it lies in a vertical plane

- Using the lever on the base of the compas, adjust the cylindrical level until the clinometer level becomes level. If the clinometer level is not on top, you must turn over the compass and start over.
- Read off the number and record it.
- Double check that your trend is correct for the case of very shallow or very steep lineations.

Stratum:

- Align one edge of the folding top of the compass with the pencil.
- Holding the edge of the folding top against the lineation, open the hinge of the compass and rotate the compass about this edge of the folding top until the bulls eye level is horizontal.
- Free the compass needle and let it reach a stable position.
- Lock the needle in this position.
- Remove the compass and read the trend. Be careful to read the correct end of the needle. In many stratum compasses, the correct end of the needle (e.g. black or red) is the same as the colour of the dip scale that is visible on the top of the compass.
- Record the plunge measurement using the graduated dip scale attached to the folding top.

Silva type:

- Place the edge of a flat non-magnetic surface, such as a hard-backed field notebook, along the pencil.
- Holding the edge along the pencil (lineation), rotate the surface to vertical.
- Place the edge of the Silva along the surface and level the compass.
- Turn the rotating casing until the North of the compass needle is pointing exactly in the direction of the arrows on the base of the rotating casing.
- Record the bearing as the number on the rotating casing beside the mark on the base of the compass,that is in the down-plunge direction of the pencil.

To record the plunge:

- Remove the compass and flat surface.
- Rotate the rotating casing until the 90-270 axis is parallel to the mark on the compass body.
- Place the compass with one edge along the pencil.
- Rotate the compass until it is vertical with the clinometer needle hanging freely. Make sure that the inner scale, used for plunge measurements, is at the bottom of the compass: otherwise, rotate the casing 180º and start again.
- Read the plunge at the tip of the clinometer needle on the inner scale. Be careful to avoid parallax – this means getting your eye close to the needle.

The most common problem with plunge measurements is that the compass is not held in a vertical plane, because it is often requires a small amount of effort to see the face of the compass if it is held vertically. The measurement is incorrect if this mistake is made.

A2.2 How to measure a field lineation

Structural geologists use the word **lineation** to describe a linear *element* in a rock. It might be a specific, individual feature in a rock, a population of elongate minerals, fossils, etc., or the intersection of two planes, which inherently forms a line. There are also lineations, such as grooves on fault surfaces, in which the lineation occurs on a plane. In some cases, such as with striae or other markers on well-exposed surfaces or where erosion has shaped of an outcrop to expose an elongate mineral or fold hinge, you can measure the lineation directly. Where you can see a lineation but cannot place the compass directly on it, the most common technique is to hold a non-magnetic linear marker (a colored pencil, a chopstick, etc.) parallel to the linear element. Then, one uses the protocol given above to measure the orientation of the non-magnetic linear marker.

A2.3 How to measure planar objects

Strike, dip and dip direction with a standard transit compass

Strike, dip and dip direction measurements are generally made with a standard transit compass (e.g. Brunton, Topochaix) and with Silva compasses.

As with linear markers, strike and dip measurements are made with two different placements of the compass (Fig. 4.A5). If you are below the dipping plane (known as an overhanging face), you must use the top part of the compass. The mirror can be quite helpful in measuring strike and dip, particularly when reading a measurement that is above your head. A common mistake, when learning to use a compass, is to use only a corner of the measuring edge on the compass.

If you want to use the right hand rule, make sure that the right hand side of the compass (reckonning that the location of the pointer indicates the front of the compass) is on the side that dips away. That is, on a dipping face, the left edge of the compass must be against the surface.

Here is the protocol for taking a strike measurement with a transit compass:

- Put a measuring edge of the compass on the plane (Fig. 4.A5a) (Make sure that the right side of the compass points in the dip direction if you are using right hand rule convention; this is <u>not</u> the case in Fig. 4.A5a).
- Adjust the compass in order to level the bulls eye level.
- Record the measurement that either end of the needle points to on the circular dial (Read only the white end of the arrow direction if you are using right hand rule convention).
- If you are learning to take strike and dip measurements, mark in pencil the strike line on the planar surface. This is done by drawing a line parallel to the measuring edge, on the planar surface.

For dips that are very shallow or very steep, it is possible that the dip direction is incorrect by 180°. You must keep track of what scale you are using for the hinge, so that if you move past the 0 to 90° range, you will have to make an calculation in your head.

Here is the protocol for taking a dip measurement.

- Place the side of the compass on a plane.
- Make sure that the measuring edges are parallel to the line of steepest dip on the plane.
- Rotate the level until the clinometer level becomes level. If the clinometer level is not on top, you must turn over the compass and start over.
- Read off the number and record it.
- Point your compass in the dip direction and record the approximate bearing of the dip direction. As a double check, make sure that the dip direction is consistent with a direction that is 90° different from your strike measurement. (This step not needed if using right hand rule convention).

In some cases, the dip of the planar surface will be so low that the metal ring on the bottom of the compass will interfere with measurement. In this case, a different technique is necessary, which hinges (pun intended) on the fact that the strike line is a horizontal line on a plane.

Here is the protocol for taking a strike measurement on a very shallowly dipping plane.

- Set the clinometer level to zero.
- Place the entire side of the compass on the planar surface; both measuring edges on the side of the compass (Fig. 4.A4) should be in contact with the planar surface.
- Holding both measuring edges in contact with the planar surface, rotate the compass until the clinometer level goes level.
- Trace a pencil line parallel to the measuring edge on the planar surface.
- Pick up your compass and hold it above your pencil mark.
- Standing directly above the compass, make sure you can see the entire pencil line through the slot (or parallel to the edge) of the pointer.
- Record the measurement reading off the needle.

Strike, dip and dip direction with a Silva

- Put a measuring edge of the compass on the plane (Make sure that the right side of the compass points in the dip direction if you are using right hand rule convention).
- Adjust the compass in order to level the bulls eye level.
- Turn the rotating casing until the North of the compass needle is pointing exactly in the direction of the arrows on the base of the rotating casing.
- Record the bearing at either end of the scale against the mark on the compass (read off only at the mark furthest from you if using the right hand rule).

To record the dip:

- Turn the rotating casing until the 90-270 axis is parallel to the marks on the compass body.

- Place the compass with one edge down the steepest dip on the plane.
- Make sure that the inner scale, used for dip measurements, is at the bottom of the compass: otherwise, start again.
- Read the dip at the tip of the clinometer needle on the inner scale.

Dip and dip bearing with a stratum compass

It is possible to take a strike, dip and dip direction measurements and then convert them to dip and dip bearing. Most geologists who take the letter type of measurement, however, are using a stratum compass (Fig. 4.A6; examples include Breipthaupt, Freiberg, GeoBrunton).

The large advantage of these compasses is that you measure both the dip and dip bearing (or plunge and plunge bearing) with a single orientation of the compass (the disadvantage is that you need both hands to do it). The dip bearing is measured by the compass while a calibrated hinge (between the top and the bottom of the compass) measures the dip amount.

The protocol for measuring a dip and dip direction using an appropriate compass.

- Place the folding top of the compass on the planar surface (Fig. 4.A6).
- Holding the entire top of the compass against the planar surface, rotate compass about an axis perpendicular to the planar surface until the hinge of the compass is approximately parallel to the strike of the plane. Open the hinge so that the body of the compass is inclined downward slightly.
- Making sure that you hold the top of the compass against the planar surface, slowly raise the compass body. If you have the hinge of the compass aligned parallel to the strike of the planar surface, the bubble level will move along a path perpendicular to the hinge (and strike of the plane) into the center of the bulls eye level. If the bubble follows a path oblique to the hinge, adjust the orientation of the compast slightly until it does so. This procedure sounds complicated, but with practice it becomes simple, straightforward, and fast.
- Read off the end of the needle to get the dip bearing. In many stratum compasses, the correct end of the needle to read is identified by the colour of the dip meter dial that is visible on the top of the compass - either black or red.
- Read the dip value from the graduated markings on the hinge (Fig. 4.A6).

A2.4 How to measure a field foliation

Structural geologists use the word **foliation** to describe anything about a rock that is planar. Planar *elements* in rocks may be discrete, recognizable surfaces like bedding, joints, or faults, or they can be defined by the collective orientations of a population of planar minerals, joints, etc. To measure a field foliation, the most common technique is to simply use the surface itself, provided that the surface itself is exposed or that a weathered face of an outcrop is parallel to the orientation defined collectively by minerals. Then, use the protocol given above for measuring the orientation of the plane.

Sometimes it is not possible to measure the surface directly, for example because there is not enough room because the weathered faces of the outcrop are not parallel to the orientation of planar minerals. In these cases, you can either (1) hold a non-magnetic planar object (your field book, an aluminum clipboard, etc.) against the rock and line it up with the planar element or collection of planar minerals, or (2) stand some distance from the outcrop, hold your field book or a small board in the same orientation as the planar element, and (3) then measure the orientation of the book or board. Beware of four possible problems of doing this: 1) There is a tendency to move the board during the measurement (while you are learning to measure planar surfaces, have someone else hold the book); 2) The strike line need <u>not</u> necessarily parallel to the edge of the field book (see Fig. 4.7); and 3) Avoid field books if the covers are not planar (warped, for instance, from taking small excursions into nearby bodies of water); 4) Avoid steel clips on boards that may affect your compass.

A2.5 How to measure pitch and pitch direction

You can always measure the trend and plunge of a line to fix its orientation. There are, however, two advantages to fixing the orientation of a line on a plane by measuring its pitch: 1) It requires only that you add one straightforward step to measuring the strike and dip of the plane; and 2) Pitch measurements tend to be more accurate in cases where the planes dip steeply. To measure a pitch, it is easiest to use a protractor (Fig. 4.9), although you can use the graduated markings on the hinge of a stratum compass.

The protocol for measuring a pitch is:

1) Draw the strike line of the plane in pencil.
2) Draw a line that correlates to the lineation, such that it intersects the strike line.
3) Using a protractor, measure the angular difference between the strike line and lineation line. Choose the side of the strike line that makes this measurement less than 90°. This is the pitch measurement.
4) Point the compass in the direction of the end of the strike line that makes an acute angle with the lineation direction (the end of the strike line that you used for the measurement).
5) Record the pitch direction as the compass direction of this end of the strike line

Chapter 4 Figure Captions

Figure 4.1. Conventions for measuring directions (trends) in a horizontal plane. (a) The Azimuth (0-360) system. (b) The Quadrant (NS) system.

Figure 4.2. A cross-section through the Earth's geocentric dipole magnetic field. There are two important aspects to notice. First, the axis of the geomagnetic field does not coincide with Earth's rotation axis, so the magnetic North pole does not coincide with the geographic North pole. This difference requires that one sets a magnetic declination on the compass. Second, there is a vertical component to the magnetic field everywhere except near the equator. Insets show the net force on a compass needle in the northern and southern hemispheres.

Figure 4.3. Mercator projection map showing the magnetic declination at different points around the world in 2005 (modified from the U. S. National Geophysical Data Center; http://www.ngdc.noaa.gov/seg/geomag/declination.shtml). Red contour lines indicate a positive (east) declination; black contour lines indicate a negative (west) declination. The contour interval is 2°, with every 5th contour line (every 10°) thicker.

Figure 4.4. Cartoon of both the pocket transit ("Brunton") compass and one variety of a stratum compass (the "GeoBrunton"). Both the front side and the back side are shown. Labels are shown only on the pocket transit compass, except for the parts that are unique to the stratum compass. Note that the standard stratum compass (e.g. Beithaupt, Freiberg) in Europe is slightly less bulky, but contains most of the same features.

Figure 4.5. The trend and plunge of a line and space. (a) The trend of a line is its horizontal orientation, taken by projecting the linear element into a horizontal plane. The pencil is pointing toward the ground, as you can tell from its foreshortening. Looking straight down from above, we see its horizontal orientation. (b) The plunge is the angle measured downward from a horizontal line to the linear element. In this case, the angle is 45°.

Figure 4.6. Symbols on a geological map for (a, b, and c) trend and plunge of linear elements, (d, e, f, g, and h) strike and dip of planar elements, and (i and j) strike, dip, and pitch of combinations of planar and linear elements. (a, b) The arrow gives the trend of a lineation. The plunge amount (0-90) is written by the end of the arrow. (c) Use an arrow with heads at both ends to depict horizontal lineations. (d, e, f, g, and h) A strike is a long line and the dip is a tick, with the tick in the direction of the dip. We have separate symbols for flat-lying planes (g) and vertical planes (h). If the planar surface has a facing (such as bedding), we use the symbol in d and e if the bedding is upright and h if the bedding is overturned. (i, j) Since a pitch is a line associated with a plane, a pitch symbol combines the strike and dip symbol with an arrow. The orientation of the pitch arrow, with respect to the strike line, is given by the number at the end of the arrow. Thus, the angle of the arrow with respect to the strike line and it true orientation is not drawn correctly.

Figure 4.7. A cartoon of a book in an aquarium. (a) Book leaning on one edge in water, dipping 60 degrees to the East. The strike line is the water level on the book. (b) Book standing on its corner in water. The strike line is the water level on the book, but is not parallel to any of the edges. (c) Book leaning the other way, dipping 60W.

Figure 4.8. (a) The problem of apparent dips as illustrated by skiers on a slope. Skiers going directly downslope (down dip) go down a 45° incline, while those going back and forth (apparent dip) go down at lower angles. (b) The same slope, now illustrated with compasses. If a dip measurement is not taken directly down dip, there will be a tendency to get shallower measurements. (c) Diagram illustrating the angle β between the trend of the strike and the trend of the apparent dip, the dip angle δ, and the apparent dip α.

Figure 4.9. Examples of pitch measurements on a plane oriented 000, 60 E. The black pencil pitches 20° from the South end of the strike line (pitch = 20 S) and the red pencil pitches 80° from the North end of the strike line (pitch = 80 N).

Appendix Figure Captions

Figure 4.A1. (a) With the pointer of the compass directed toward 045 (N45E) and the compass needle pointing N, you can read the proper azimuth (or bearing) off the graduated circle. (b) With the pointer directed toward 350 (N10W) and the compass needle pointing N, you read the proper azimuth (or bearing) off the graduated circle.

Figure 4.A2. Magnetic declination set, with reference to the index pin and numbers on the graduated circle. The declinations are zero (a), 12 E (b), and 16 W (c).

Figure 4.A3. (a) We measure the trend of a line by placing the pointer (or side) of the compass parallel to the trend line, adjusting the bulls eye to level, and reading the white end of the compass needle. (b) We measure the plunge of a line by holding compass in a vertical plane, with the lineation parallel to a measuring edge of the compass. The cylindrical level is adjusted with the vernier scale, at which point the plunge is read off the clinometer scale by the center of the vernier.

Figure 4.A4. Measuring edges. The top and bottom edges on the sides of the compass are informally known as measuring edges. A major error when first using a compass is to have only a corner or part of a measuring edge on a surface. To acquire good measurements, an entire measuring edge must be on the surface.

Figure 4.A5. How to measure a strike (a) and a dip (b) with a transit compass. a) A strike line is made by holding an entire measuring edge of a level compass against the planar surface. The number is read off the dial. For using right-hand rule, the dip of the surface must by off to the right hand side of the compass and only the white end of the compass is read. b) A dip is measured by placing the entire side of the compass on the surface. The vernier adjustment lever is rotated until the cylindrical level is horizontal. Note that the bubble in the cylindrical level must be on top and the dip must be on the bottom of the compass. The dip is read off the clinometer scale with the vernier.

Figure 4.A6. How to measure a dip direction and dip with a stratum compass. The entire top of the compass is placed on the surface. Both the compass body and the hinge orientation are modified until the bulls eye level is level. The white end of the compass needle points to the dip direction and the hinge records the dip amount. Some care is required in reading nearly horizontal or vertical measurements, as the dip direction may be 180° off.