PALAEOCURRENT ANALYSIS

7.1 Introduction

The measurement of palaeocurrents is a vital part of the study of sedimentary rocks, since they provide information on the palaeogeography, palaeoslope, current and wind directions and they are useful in facies interpretation. The measurement of palaeocurrents in the field should become a routine procedure; a palaeocurrent direction is an important attribute of a lithofacies and necessary for its complete description.

Many different features of a sedimentary rock can be used as palaeocurrent indicators. Some structures record the direction of movement (azimuth) of the current whereas others only record the line of movement (trend). Of the sedimentary structures, the most useful are cross-bedding and sole structures (flute and groove casts), but other structures also give reliable results.

7.2 Palaeocurrent Measurements

The more measurements you can take from either a bed or a series of beds, the more accurate is the palaeocurrent direction you obtain, although an important consideration is the variability (spread) of the measurements.

First, assess the outcrop. If only one lithofacies is present measurements can be collected from any or all of the beds. If measurements from one bed (or many beds at an outcrop) are all similar (a unimodal palaeocurrent pattern, Fig. 7.1), there is little point in taking a large number of readings. Some 20 to 30 measurements from an exposure would be sufficient to give an accurate vector mean (Section 7.4). You should then find other outcrops of the same lithofacies in the immediate vicinity and farther afield, so that the palaeocurrent pattern over the area can be deduced.

If readings vary considerably within a bed, you will need to collect a large number (more than 20 or more than 50 depending on the variability) to ascertain the mean direction.

Measurements collected from different sedimentary structures should be kept apart, at least initially. If they are very similar they can be combined. Also keep separate measurements from different lithofacies at an exposure; they may have been deposited by different types of current, or by currents

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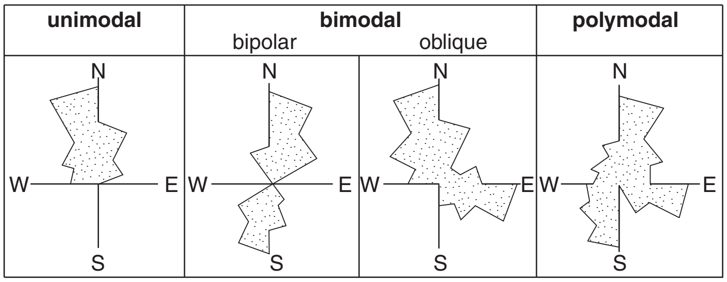


Figure 7.1 *The four types of palaeocurrent pattern, plotted as rose diagrams (with 30° intervals). The convention is to plot palaeocurrent azimuthal data in a 'current-to' sense, so that, for example, in the unimodal case shown here, the current was flowing from the south towards the north.*

from different directions. Readings should be tabulated in your field notebook (see Fig. 7.2).

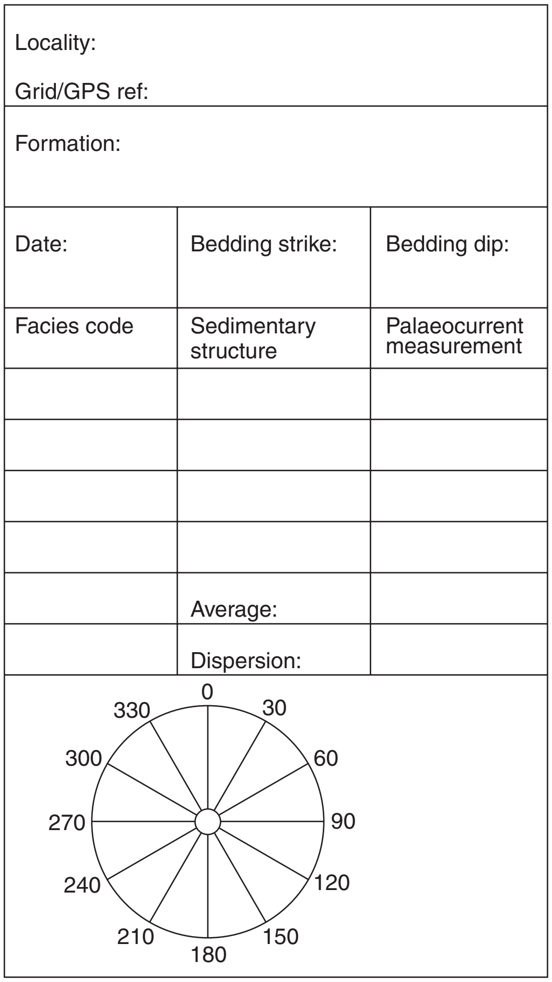
The measurements you have taken may not represent the current direction if either the shape or the orientation (or both) of the sedimentary structures has been changed by tectonism. It is important to appreciate that two changes can occur: tilt and deformation. A simple change in the inclination of the plane, of which the sedimentary structure is a part, is described as the tilt. Tilt does not change the shape of a sedimentary structure. Processes which change the shape of a sedimentary structure are described as deformation.

7.2.1 Correction of measurements for tectonic tilt

To ascertain the direction of palaeocurrents from structures in dipping beds it is necessary to remove the effects of tilting, a straightforward process that is described below. To do the same with deformed sedimentary structures is not simple and requires an accurate assessment of the strain the rock mass containing the sedimentary structure has undergone; a description of how this is done is beyond the scope of this book but accounts can be found in structural geology textbooks. The tell-tale signs of deformed rock masses are the presence of such features as cleavage, minor folding, metamorphic fabrics and deformed fossils.

7.2.1.1 Linear structures

The following steps should be taken to correct the trend of a *linear structure,* such as a flute or groove cast or parting lineation, that has been changed by a tilt of more than 25° (also see Fig. 7.3).



Locality: Grid/GPS ref:		
Formation:		
Date:	Bedding strike:	Bedding dip:
Facies code	Sedimentary structure	Palaeocurrent measurement
	Average:	
	Dispersion:	

Figure 7.2 *Proforma for palaeocurrent data. If dip of cross-beds is required, add another column. Corrections for tectonic tilt are required for linear structures such as groove marks if the strata are dipping more than 25° and for planar structures such as cross-bedding if the strata are dipping more than 10°. If this is the case, then add columns for the pitch and down-dip trend of linear structures or the dip and strike of cross-beds.*

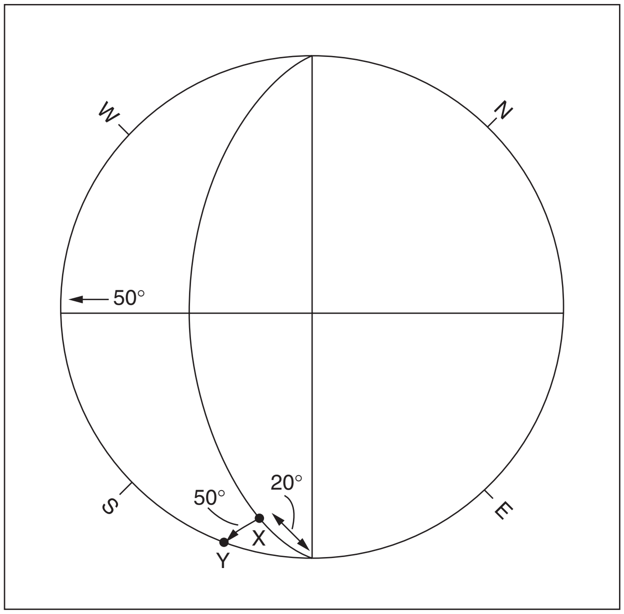


Figure 7.3 *An example of correcting the orientation of a linear structure for tectonic tilt. A bed dips at 50° to 225° and has a linear structure, such as a groove mark or parting lineation, with a pitch of 20° to the south-east. The bed is plotted as a great circle on a stereonet and the pitch of the structure is marked on that circle (X). The bed is restored to the horizontal and with it the structure along a small circle to give its original orientation at point Y. On rotating back, the azimuth of Y is given: 155°. See text for details.*

1. First measure the direction of dip (or strike) and the angle of dip of the bedding surface (or undersurface); then measure the acute angle between the elongation of the structure and the strike of the bedding (this is the pitch or rake of the structure) and note the down-dip direction of the structure.
2. With the angle of dip and the direction of dip of the bed, plot the bedding surface as a great circle using the stereonet inside the back cover of this book. To do this, place tracing paper on the net, draw the circle and mark north, south, east and west and the central point; mark the direction of dip on the circle (circumference of the net) and then rotate the paper so this mark is on the east–west (equatorial) line of the net; count in the

angle of dip of the bed from the mark on the circumference and draw the great circle using the line already there on the net.

3. On the great circle, from the appropriate end, mark the acute angle between the trend of the sedimentary structure and the strike of the bedding surface (i.e., the pitch). To do this, have the paper in the same position as when you drew the great circle (dip direction on the net equatorial line) and then count the pitch angle from the end of the great circle to which the structure is directed down-dip.
4. From this point of the pitch angle on the great circle, move along the small circle to the nearest point on the circumference of the net and mark this place.
5. Finally, rotate the tracing paper back to its original position with regard to the stereonet (north on north) and read off the new direction for the structure. For asymmetric linear structures such as flute marks the azimuth is obtained, whereas with structures giving a trend such as groove marks and current lineation, the current could have been in the opposite direction too.

See Fig. 7.3 for a worked example.

7.2.1.2 Planar structures, especially cross-bedding

The following steps should be taken to determine the original orientation and angle of dip of a planar structure (principally cross-bedding) that has been changed by a tilt of more than 10°.

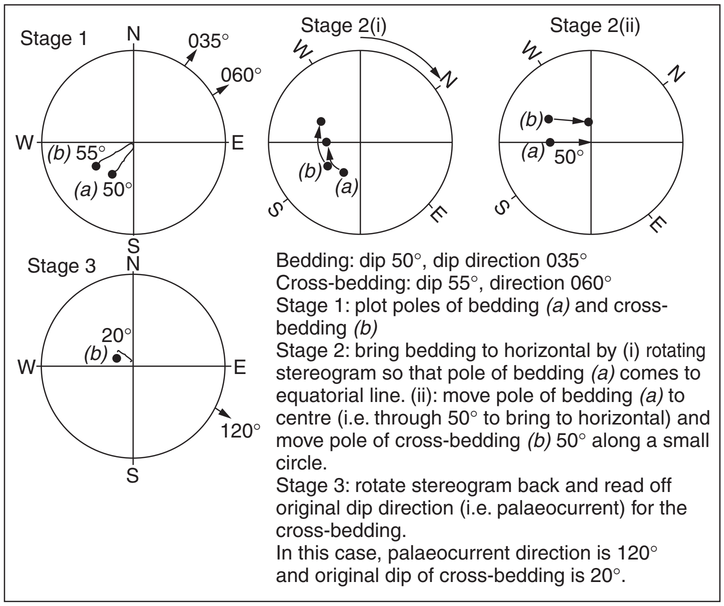
1. First measure the direction of dip (or strike) and the angle of dip of the bedding surface, and then the direction of dip (or strike) and angle of dip of the cross-bedding.
2. Plot the pole for the bedding surface using the stereonet inside the back cover of this book. To do this, place tracing paper on the net, draw the circle and mark north, south, east and west and the central point. Mark the point of the direction of dip on the circle (circumference of the net) and then rotate the paper so this point is on the east–west/equatorial line of the net; count the angle of dip of the bed from the net central point along the equatorial line *away* from the point of the dip direction on the circumference. This point is the pole to the bedding on the lower hemisphere.
3. Plot the pole for the cross-bed surface in the same way as the pole to the bedding (so start with the tracing paper back at north, coinciding with the stereonet).
4. Restore the bedding to the horizontal by rotating the tracing paper to bring the pole of the bedding to the equatorial line of the net and (notionally)

moving the pole to the centre of the net; then move the pole of the cross-bedding along the small circle it is now situated upon, in a similar direction, by the same number of degrees as the angle of dip of the bedding, to give a new point.

5. Rotate the tracing paper back to its original position relative to the net (north on north) and read off the new direction by drawing a line from the central point, through the new pole position for the cross-bedding, to the circumference. This azimuth is the original orientation (direction of dip) of the cross-bedding, i.e., the direction to which the current was going.
6. The original angle of dip of the cross-bedding can be obtained by rotating the tracing paper so that the new pole position for the cross-bed is on the equatorial line, and then noting the number of degrees from the net centre to the new pole position.

See Fig. 7.4 for a worked example.

Finally, a note of warning: if tilted strata are part of a fold whose axis is inclined (i.e., plunging), the fold axis must be brought to the horizontal,



Bedding: dip 50°, dip direction 035°
Cross-bedding: dip 55°, direction 060°
Stage 1: plot poles of bedding *(a)* and cross-bedding *(b)*
Stage 2: bring bedding to horizontal by (i) rotating stereogram so that pole of bedding *(a)* comes to equatorial line. (ii): move pole of bedding *(a)* to centre (i.e. through 50° to bring to horizontal) and move pole of cross-bedding *(b)* 50° along a small circle.
Stage 3: rotate stereogram back and read off original dip direction (i.e. palaeocurrent) for the cross-bedding.
In this case, palaeocurrent direction is 120° and original dip of cross-bedding is 20°.

Figure 7.4 *Correction of cross-bedding for tectonic tilt using stereographic projection. See text for more details.*

so changing the orientation of the tilt, before the tilt is removed. Having completed these corrections, can you be certain that the palaeocurrent direction is that at its time of formation? Unfortunately not, for there may also have been rotations of the strata about a vertical axis; rarely can these be determined accurately.

7.3 Structures for Palaeocurrent Measurement

7.3.1 Cross-bedding

This is one of the best structures to use, but first determine what type of cross-bedding is present (Section 5.3.3). If it has formed by the migration of subaqueous dunes and sand-waves (much is of this type) or aeolian dunes, then it is eminently suitable for palaeocurrent (or palaeowind) measurement. Check whether the cross-bedding is of the planar (tabular) or trough type (Fig. 5.17 and Section 5.3.3.2).

With *planar cross-bedding*, the palaeocurrent direction is simply given by the direction of maximum angle of dip. If the exposure is three-dimensional, or two-dimensional with a bedding-plane surface, there is no problem in measuring this directly. If there is only one vertical face showing the cross-bedding, then taking readings is less satisfactory since it is just the orientation of the face that you are measuring, which is unlikely to be exactly in the palaeocurrent direction. Close scrutiny of the rock face may enable you to see a little of the cross-bed surface and so determine the actual dip direction. If even this is impossible there is no alternative but to measure the orientation of the rock surface.

With *trough cross-bedding,* it is essential to have a three-dimensional exposure or one with a bedding-plane section, so that the shape of the cross-strata is clearly visible and the direction down the trough axis can be measured accurately. Because of the shape of the trough cross-beds, vertical sections can show cross-bedding dipping up to 90° from the real current direction. Vertical sections of trough cross-bedding are thus unreliable for palaeocurrent measurements and should be used only as a last resort.

7.3.2 Ripples and cross-lamination

Palaeocurrent directions are easily taken from current ripples and cross-lamination. The asymmetry of the ripples (steeper lee-side downstream) and the direction of dip of the cross-laminae are easily measured.

Ripples, however, and the cross-lamination they give rise to, are commonly produced by local flow directions which do not reflect the regional palaeoslope. In turbidite beds, for example, cross-lamination within the bed may vary considerably in orientation and differ substantially from the palaeocurrent direction recorded by the sole structures. The cross-lamination forms when the turbidity current has slowed down and is wandering or meandering across the seafloor. In spite of their shortcomings, if there is no other, more suitable directional structure present (cross-bedding or sole structures), it is always worth recording the orientation of the ripples and cross-lamination.

Wave-formed ripples are small-scale structures which record local shoreline trends and wind directions; their crest orientation should be measured, or if visible the direction of dip of internal cross-lamination.

7.3.3 Sole structures

Flute casts provide a current azimuth (Section 5.2.1); some tool marks will also provide a current azimuth, if not at least a line of movement; groove casts provide a line of movement. Flute casts are generally all oriented in the same direction and so several measurements from one bed together with measurements from other beds at the exposure will be sufficient. With groove casts, there can be a substantial variation in orientation and a larger number (more than 20) should be measured, from which the vector mean can be calculated for each bed (Section 7.4).

7.3.4 Preferred orientations of clasts and fossils, and imbrication

Pebbles and fossils with an elongation ratio of at least 3:1 can be aligned parallel to or normal to prevailing currents (Fig. 4.6). Check for such a preferred orientation and if you either suspect or see its presence, measure and plot the elongation of a sufficient number of the objects (20 or more readings should do). In many cases you will obtain a bimodal distribution with one mode, that parallel to the current, dominant. Pebbles, grains and fossils mostly give a line or trend of movement; with some fossils, for example orthoconic cephalopods, belemnites and high-spired gastropods, a direction of movement can be obtained (the pointed ends preferentially directed upstream). Stromatolite domes and columns may be asymmetric, with growth preferentially taking place on the side facing the oncoming currents/waves.

Flat pebbles in conglomerates and some fossils may show imbrication (Section 4.4), whereby they overlap each other and dip in an upstream direction (see Fig. 4.7).

7.3.5 Other directional structures

Parting lineation records the trend of the current and presents no problem in its measurement. *Channels* and *scour structures* can also preserve the trend of the palaeocurrent. *Slump folds* record the direction of the palaeoslope down which slumping occurred (fold axes parallel to strike of palaeoslope, anticlinal overturning downslope). *Glacial striations* on bedrock show the direction of ice movement.

7.4 Presentation of Results and Calculation of Vector Means

Palaeocurrent measurements are grouped into classes of 10°, 15°, 20° or 30° intervals (depending on number of readings and variability) and then plotted on a rose diagram, choosing a suitable scale along the radius for the number of readings. For data from structures giving current azimuths, the rose diagram is conventionally constructed showing the current-to sense (in contrast to wind roses). For data from structures giving a trend, the rose diagram will be symmetrical. For presentation purposes, small rose diagrams can be placed alongside a graphic log at the location of the readings.

Although the dominant palaeocurrent (or palaeowind) direction will usually be obvious from a rose diagram, for accurate work it is necessary to calculate the mean palaeocurrent direction (that is, the *vector mean*). It is also worth calculating the *dispersion* (or variance) of the data. Vector means and dispersions can only be calculated for a unimodal palaeocurrent pattern (Fig. 7.1).

To deduce the vector means from structures giving azimuths, each observation is considered to have both direction and magnitude (the magnitude is generally considered unity but it can be weighted); the north–south and east–west components of each vector are then calculated by multiplying the magnitude by the cosine and sine of the azimuth respectively. Thus, make a table and simply look up (or use a calculator to find) the cosine and sine of each palaeocurrent reading; add up each column, and division of the summed E–W components (sine values) by the N–S components (cosine values) gives the tangent of the resultant vector. Convert the tangent to an angle with the calculator; this is the vector mean – the average palaeocurrent direction.

$$\text{E–W component} = \Sigma(n \sin\sigma)$$

$$\text{N–S component} = \Sigma(n \cos\sigma)$$

$$\tan\overline{\sigma} = \frac{\Sigma(n \sin\sigma)}{\Sigma(n \cos\sigma)}$$

where

σ = azimuth of each observation from 0° to 360°

n = observation vector magnitude, generally 1, but if data are grouped into classes (0–15, 16–30, 31–45, etc.), then it is the number of observations in each group

$\overline{\sigma}$ = azimuth of resultant vector (i.e. vector mean)

If trends only can be measured then each observation, measured in the range 0° to 180°, is doubled before the components are calculated:

$$\text{E–W component} = \Sigma(n \sin 2\sigma)$$

$$\text{N–S component} = \Sigma(n \cos 2\sigma)$$

$$\tan 2\overline{\sigma} = \frac{\Sigma(n \sin 2\sigma)}{\Sigma(n \cos 2\sigma)}$$

The magnitude (r) of the vector mean gives an indication of the *dispersion* of the data, comparable to the standard deviation or variance of linear data:

$$r = \sqrt{(\Sigma n \sin \sigma)^2 + (\Sigma n \cos \sigma)^2} \text{ for azimuthal data}$$

$$r = \sqrt{(\Sigma n \sin 2\sigma)^2 - (\Sigma n \cos 2\sigma)^2} \text{ for non-azimuthal data}$$

To calculate the magnitude of the vector mean in percentage terms (L):

$$L = \frac{r}{\Sigma n} \times 100$$

A *vector magnitude* of 100% means that all the observations either have the same azimuth or lie within the same azimuth group. In a vector magnitude of 0% the distribution is completely random. There would be no vector mean in this case.

For further discussion and methods for testing the significance of two-dimensional orientation distributions see Potter and Pettijohn (1977). Vector means can easily be calculated in the evenings after fieldwork and then entered on the geological map or graphic sedimentary log. The raw data should always be kept, however.

7.5 Interpretation of the Palaeocurrent Pattern

There are four types of palaeocurrent pattern (Fig. 7.1): *unimodal* where there is one dominant current direction; *bimodal bipolar* (two opposite directions); *bimodal oblique* (two current directions at an angle less than 180°); and *polymodal* (several dominant directions).

Analysis of the palaeocurrent pattern needs to be combined with a study of the lithofacies for maximum information. The features of the palaeocurrent (or palaeowind) pattern of the principal depositional environments – fluvial, deltaic, aeolian sand, shoreline–shallow shelf and turbidite basin – are shown in Table 7.1.

In *fluvial facies*, palaeocurrents are best measured from the largest cross-beds to give the regional palaeoslope. Directions obtained from smaller structures, ripples and parting lineation, will generally show the minor currents

Table 7.1 *Palaeocurrent patterns of principal depositional environments, together with best and other directional structures.*

Environment	Directional structures	Typical dispersal patterns
Aeolian	large-scale cross-bedding	unimodal common, also bimodal and polymodal; depend on wind directions/dune type
Fluvial	*cross-bedding*, also parting lineation, ripples, cross-lamination, channels	unimodal down palaeoslope, dispersion reflects river sinuosity
Deltaic	*cross-bedding,* also parting lineation, ripples, channels	unimodal directed offshore, but bimodal or polymodal if marine processes important
Marine shelf	*cross-bedding*, also ripples, fossil orientations, flutes/grooves on bases of storm beds	bimodal common through tidal current reversals but can be normal or parallel to shoreline; unimodal and polymodal patterns
Turbidite basin	*flutes*, also grooves, parting lineation, ripples	unimodal common, either downslope or along basin axis if turbidites, parallel to slope if contourites

of the river in low stage, and so not reflect the larger-scale palaeogeography. If lateral accretion surfaces are present, measure these too to deduce the direction of meandering. Braided-stream deposits tend to give palaeocurrent directions that have a lower dispersion; meandering-stream facies will show a wider range of directions (see Table 8.2).

Deltaic facies will give a variety of palaeocurrent patterns depending on the type of delta (lobate versus elongate) and the roles of fluvial and coastal processes. In a fluvial dominated system, unimodal patterns will be obtained with dispersion depending on delta type. Where reworking of delta-front sands by marine processes is important, polymodal patterns may be obtained from wave and tidal effects.

Shoreline, shoreface and shelf sandstones are affected by wave, tidal and storm processes and so can have complex palaeocurrent patterns. Where tidal currents dominate, bipolar patterns may be obtained, but often one tidal current direction is stronger so that the pattern is asymmetrical. Tidal currents vary from parallel to oblique to normal to the shoreline. Storm waves and currents generate cross-beds usually directed offshore, but there may be a wide dispersion. Again, measure larger structures where possible (cross-beds, sole structures) rather than ripples which may represent minor reworking.

In basinal successions, palaeocurrents from turbidites are often related to regional basin-ward directed palaeoslopes, but having reached the basin centre, deep-sea currents may then flow along the basin axis. It is useful to know the basin orientation and larger-scale tectonic context of the succession to interpret the palaeocurrent pattern. Flutes and grooves are the best structures to measure, since a turbidity current begins to wander once it is slowing down so that structures within and upon the bed uppersurface (cross-lamination and ripples) may not represent the main current direction. Slump folds are good for palaeoslope orientation. Some deepwater currents flow parallel to the contours of slopes, as in contourite deposits.

Desert sandstones can show very simple or highly complex palaeowind patterns as measured from large-scale cross-bedding. It depends on the nature of the sand deposit – large ridges (seif draas) or sand seas (ergs), the wind system and local topography. Some desert sandstones have unidirectional cross-beds from the effects of persistent trade winds. Palaeowind directions are not related to regional palaeoslope and interpretations of the palaeogeography need to be made with care.