

Transport Direction and Bedform Orientation

Transport direction inferred from cross-bed dips

One of the most important applications of cross-bedding analysis is the determination of paleocurrent directions. The traditional approach has been to measure large numbers of cross-bed dips and to presume that the mean cross-bed dip direction represents the paleocurrent or paleotransport direction. This approach is probably quite reliable for the deposits of transverse bedforms and for many three-dimensional longitudinal bedforms. It is also quite likely that if a deposit was produced by a diverse assortment of bedforms or by bedforms with three-dimensional superimposed bedforms, then the divergence between the paleocurrent direction and the cross-bed dip direction in individual beds will, in many cases, merely cause scatter to the data, rather than introducing a systematic bias. Oblique bedforms, however, can deposit cross-beds that dip with a systematic divergence from the direction of sediment transport (Figs. 42-46 and 69-74).

Determining the paleotransport direction solves only half the problem of distinguishing the deposits of transverse, oblique, and longitudinal bedforms; bedform orientation must also be determined. The most straightforward technique for determining bedform orientation is by inspecting sections that parallel the generalized depositional surface. Such sections contain indications of bedform orientation, such as aligned fingertip structures (Figs. 38 and 46) or foresets that extend laterally for distances that are large relative to the bedform spacing. Distinguishing the deposits of transverse, oblique, and longitudinal bedforms is useful in determining fluctuations in flow direction, because some kinds of bedforms such as longitudinal dunes tend to form in reversing flows. Moreover, recognition of the different kinds of bedforms is the first step toward understanding how bedform alignment is controlled in directionally varying flows.

Transport direction inferred from trends of trough axes

Trends of trough axes are commonly used to infer paleotransport directions. As illustrated by many of the computer images, trough axes have the same trend as the displacement direction of the bedform surface, but the displacement direction of the bedform surface does not necessarily parallel the transport direction. The divergence between the trough-axis trend and the resultant bedform transport direction is most pronounced where a trough-shaped set is produced by migration of a scour pit that is bounded on one side by the lee slope of the main bedform and on the adjacent sides by much smaller lee-side spurs or superimposed bedforms. In such a situation, a unit distance of scour-pit migration in an along-trough direction represents less transport than an equal distance of transport in a direction normal to the main bedform because of the difference in size of the bedforms migrating in bedform-normal and bedform-parallel directions. The following section considers this problem in detail.

Transport direction inferred from along-crest and across-crest transport

Bedforms can be classified as transverse, oblique, or longitudinal by their orientation relative to the long-term resultant sediment-transport direction. Transverse bedforms trend roughly normal to the transport direction, longitudinal bedforms trend roughly parallel to the transport direction, and oblique bedforms have intermediate trends.

The usual approach to classifying bedforms using this scheme has been to use current-velocity measurements and transport-rate equations to calculate the transport direction and then to measure the deviation between the calculated transport direction with the bedform trend. An alternative is to use the sediment transport represented by bedform migration to determine the relative rates of across-crest and along-crest sediment transport. The use of bedform height, shape, and migration speed to determine the rate of sediment transport is well known, having been proposed in 1894 (work by Deacon referenced in Goncharov, 1929; Hubbell, 1964), applied in fluvial studies in 1955 (Benedict et al.), tested in flumes in 1965 (Simons et al.), and applied to the study of paleotidal flow velocities from tidal-bundle thicknesses in the 1980s (Allen, 1981; Allen and Homewood, 1984). The rate of sediment transport represented by bedform migration (called the bedform transport rate by Rubin and Hunter, 1982) is given by

$$i = VHk \quad (1)$$

where i is the bedform transport rate (expressed in units of bulk volume per unit time per unit width), V is the rate of bedform migration, H is bedform height, and k is a dimensionless shape factor equal to A/HL ; A is bedform cross-sectional area (measured in a vertical plane parallel to the transport direction), and L is bedform spacing. Bedforms that are triangular in profile have a shape factor (k) equal to $1/2$. Equation (1) is correct only if bedforms are transverse to the transport direction or if i , V , H , and k are measured in a plane that parallels the transport direction. Where bedforms are not transverse and where i , V , H , and k are measured normal to the bedform trend, equation (1) must be modified to

$$i = \frac{VHk}{\sin \alpha} \quad (2)$$

where α is the angle between the bedform trend and the resultant transport direction (90° for a transverse bedform and 0° for a longitudinal bedform).

Even where V , H , and k are known, equation (2) cannot be used to solve for the orientation of the transport direction relative to the trend of a two-dimensional bedform, because an infinite number of transport vectors can produce a given migration rate; a small vector normal to the bedform crestline can produce the same migration rate as a larger vector that more nearly parallels the bedform trend. Although equation (2) cannot be used to solve for α where bedforms are perfectly two-dimensional, that equation can be modified for such use where bedforms are three-dimensional. Conceptually, the

approach is to determine the unique transport vector that simultaneously would cause the observed migration of two sets of bedforms. Algebraically, this is accomplished by solving equation (2) simultaneously for the transport represented by two sets of bedforms. The solution is given by

$$\alpha_1 = \tan^{-1} \left[\frac{V_1 H_1 \sin \beta}{V_1 H_1 \cos \beta - V_2 H_2} \right] \quad (3)$$

where the subscripts refer to the two sets of bedforms, and β is the angular divergence of the migration directions of the two sets of bedforms.

Equation (3) can also be applied to a single set of bedforms, if they are three-dimensional. In such a situation, β is equal to 90° , V_2 is the along-crest migration speed of the plan-form sinuosities, and H_2 is the mean height of the bedforms measured along profiles parallel to the generalized trend of the bedforms. In the computer-generated depositional situations, H_2 was measured from contour maps of the bedform topography. Although equation (3) cannot be used with perfectly two-dimensional computer-generated bedforms, most real bedforms, including many that would be considered two-dimensional, are probably three-dimensional enough to use this approach.

Note that the transport direction given by equation (3) considers only the fraction of transport that is represented by bedform migration. That transport direction will parallel the direction of total transport only if the bedforms are equally effective traps for sediment transported in different directions across their surfaces. This property is less likely to be met where the two sets of topographic features have grossly different morphology. For example, plan-form sinuosities may be less effective traps for sediment transported along-crest than are the main lee slopes for sediment transported across-crest.

A second difficulty can arise when using equation (3) to determine the transport direction in those situations where transport is represented by more than two sets of topographic features: different pairs of features give different calculated transport directions. Such a discrepancy occurred in several of the situations modeled in this publication; in those cases, preference was given to transport directions calculated with respect to pairs of bedforms with similar morphology. Despite these limitations, the technique represented by equation (3) is a useful approach for determining the transport direction from bedform migration.

The relative heights and migration speeds of main bedforms and superimposed bedforms can rarely be determined from cross-bedding, and along-crest and across-crest components of transport must be treated qualitatively rather than quantitatively. The transport direction represented by the migration of perfectly two-dimensional bedforms cannot be determined more accurately than approximately 180° (within 90° of the bedform migration direction); transport toward any direction within this range will cause lateral migration of the bedforms. In contrast, where superimposed bedforms are present and are migrating toward a direction different from that of the main bedform, the transport direction can be limited to a single quadrant (limited to one hemisphere by the migration of the

main bedforms and limited to one-half of that hemisphere by the right-hand or left-hand migration of the superimposed bedforms). Along-crest migration of superimposed bedforms is recognizable merely by inspection of some outcrops (particularly in sections that parallel the generalized depositional surface) and by an asymmetric distribution of cross-bed planes relative to bounding-surface planes (computer images in Figs. 42-46 and 69-74).

Controls of bedforms alignment

Compared to the numerous studies of equilibrium bedform size and shape, the study of how bedform orientation varies as a function of flow conditions has received surprisingly little work. With the exception of longitudinal eolian dunes, many workers believe that ripples, dunes, and sand waves are inherently transverse bedforms. All of these kinds of bedforms, however, can be oblique to the resultant transport direction. Obliquity can result from nonuniform flow conditions that cause one end of a bedform crestline to outrun the other end (Dietrich and Smith, 1984) or from nonuniform conditions that cause the transport direction to rotate downcurrent over a distance that is too short for the bedform to respond (Rubin and Hunter, 1985).

Oblique bedforms can originate even in uniform flows. Experiments conducted on a rotatable sand-covered board (Rubin and Hunter, 1987) have shown that transverse, oblique, and longitudinal wind ripples can be created in bidirectional winds merely by varying two parameters: the angle between the two winds (the divergence angle) and the proportions of sand transport in the two directions (the transport ratio). Transverse bedforms were created when the divergence angle was less than 90° , when the transport ratio was large, or when the divergence angle approached 180° and the transport ratio was not equal to unity; longitudinal bedforms were created when the divergence angle was greater than 90° and the transport ratio approached unity; and oblique bedforms formed when the divergence angle was greater than 90° and the transport ratio was between unity and approximately eight (Appendix B, Fig. B-1). In all experiments, the bedforms followed the rule of maximum gross bedform-normal transport: the bedforms had the trend that was subject to the maximum gross (transports in opposite directions are summed as two positive numbers) transport across bedforms.

In these experiments, the fact that some bedforms were longitudinal (parallel to the resultant transport direction) was merely coincidental. Such bedforms are more properly thought of as bedforms that are as transverse as possible to the separate transport vectors. These experimental results are compatible with previous field studies in which it was shown that longitudinal dunes can form without flow parallel to their crestlines (Tsoar, 1983) and that linear dunes tend to form in reversing wind regimes (Fryberger, 1979; Twidale, 1981).