Relations Between Cross-Bedding, Bedforms, and Flow

Approach

The usefulness of cross-bedding as a flow indicator results from the connections between cross-bedding, bedforms, and flow conditions. As a result of empirical and theoretical studies in the past few decades, it is now possible to predict crudely what bedform morphology results from flow conditions for many two-dimensional flows that are steady through time and uniform through space and for many two-dimensional oscillatory flows. Eventually, it may become possible to predict bedform morphology and behavior accurately for more complicated flows such as those that vary in strength or direction or the geologically more important flows that decelerate downcurrent (Rubin and Hunter, 1982). Ultimately, it may be possible to use cross-bedding to recreate current-meter-type records of paleocurrent directions and velocities. Even without quantitative fluid dynamics models, however, it is possible to infer bedform morphology and behavior from cross-bedding and to relate those interpreted characteristics qualitatively to flow conditions. The following section considers the controls of flow on bedform morphology and behavior and considers some of the general properties of the cross-bedding that is produced.

Plan-Form Geometry

Degree of three-dimensionality

The extent of two-or three-dimensionality of cross-bedding is an important geometric property because three-dimensionality of bedding is an indicator of bedform three-dimensionality, and bedform three-dimensionality is an indicator of flow conditions. Interpreting flow properties from bedform three-dimensionality is complicated, because many processes influence the extent to which bedforms are two-or three-dimensional.

(1) Some kinds of bedforms, such as wind ripples, are inherently two-dimensional.

(2) Bedforms that are produced by reversing flows tend to be more two-dimensional than their unidirectional counterparts. For example, wave ripples are more two-dimensional than current ripples; sand waves in reversing tidal flows are more two-dimensional than sand waves or dunes in unidirectional flows such as in rivers; and linear eolian dunes, which tend to form in reversing winds (Tsoar, 1983; Fryberger, 1979), are more two-dimensional than the barchanoid or crescentic dunes that form in unidirectional winds.

(3) Some workers have reported that the three-dimensionality of subaqueous bedforms increases with flow strength. According to some reports, current ripples are more three-dimensional at higher flow velocities—keeping mean depth constant—or at shallower depths—keeping mean velocity constant (Allen, 1968, 1977; Harms, 1969; Banks and Collinson, 1975). Middleton and Southard (1984, p. 7.59), however, disputed these findings and concluded that no definitive or unified picture of spacing, height, velocity, and plan geometry has emerged. There seems to be better agreement that large-scale subaqueous bedforms (dunes and sand waves) tend to be more three-dimensional at relatively high shear velocities or at relatively high velocities for any fixed depth (Allen, 1968; Southard, 1975).

(4) Ripples tend to be more two-dimensional where rapid deposition from suspension is occurring (Harms et al., 1982).

(5) Immature ripples have been reported to be more two-dimensional than more fully developed ripples (Ashley et al., 1982).

Although deposits of stoss-erosional two-dimensional bedforms are readily recognizable because their cross-beds dip toward the same direction (dispersion of dip directions is low), dispersion of cross-bed dip directions is not controlled entirely by bedform three-dimensionality; dispersion of dips is also influenced by bedform variability, behavior, and angle of climb. For example, reversals in the along-trough migration direction of lee-side scour pits increase the dispersion of cross-bed dips without changing bedform morphology or three-dimensionality (compare Figs. 38 and 59). Similarly, dispersion of cross-bed dips depends on the relative migration speeds of main bedforms and superimposed bedforms in situations where bedform morphology is constant (Fig. 46E and M). Because the dispersion of cross-bed dips depends on such factors as bedform variability and on the angle of climb (that is, dispersion is not determined uniquely by bedform morphology), much work remains to be done before three-dimensionality of bedforms can be quantitatively related to the dispersion of cross-bed dips.

Kinds of three-dimensionality

It is obvious from examining bedforms in the field—and equally obvious when attempting to simulate bedforms mathematically—that there are at least two kinds of three-dimensionality: three-dimensionality caused by plan-form curvature and three-dimensionality caused by the superpositioning of positive or negative topographic features on bedforms that otherwise might be straight-crested. The effects of these different kinds of three-dimensionality on the geometry of cross-beds and bounding surfaces have not been adequately distinguished in previous studies. Regardless of the geometric details of the three-dimensionality, cross-beds deposited by three-dimensional bedforms vary in direction of dip, and traces of these cross-beds are curved in horizontal sections. Bounding-surface geometry depends, however, on the geometric details of the three-dimensionality. Where bedform troughs contain closed depressions (scour pits) such as those that occur between out-of-phase crests, lee-side spurs, or superimposed bedforms, the resulting bounding surfaces are shaped like troughs or truncated troughs, as illustrated in Figures 34 and 46. In contrast, bedforms with plan-form curvature but with troughs that do not vary in elevation produce bounding surfaces that are more nearly planar, as illustrated in Figure 32. Although the bounding surfaces produced by bedforms with scour pits thus differ considerably from those produced by bedforms lacking scour pits, distinguishing the deposits of bedforms with sinuous, linguoid, and lunate plan-form geometries is virtually impossible without exceptionally revealing horizontal sections (Figs. 32 and 34) or without unusually complete preservation of bedforms.

Despite considerable study, the hydraulic significance of specific plan-form shapes has not yet been quantitatively documented. Allen (1968) reported that ripples with in-phase crestlines form in weaker flows than ripples with out-of-phase crestlines, but as yet there is poor understanding of what flow conditions produce sine-shaped, linguoid, or lunate plan-form geometries or what flow conditions control the phase relations of bedforms with these different plan-form geometries.

The three-dimensionality of many bedforms results from superpositioning of bedforms or other topographic features, rather than from bedform plan-form curvature. The superimposed topographic features include spurs and scour pits in bedform troughs, peaks and saddles on bedform crests, and small bedforms that may be superimposed at restricted or widespread locations on the main bedforms. Several experimental studies have found that lee-side spurs become more closely spaced with increasing flow strength (Allen, 1969, 1977; Banks and Collinson, 1975), but the results are difficult or impossible to apply to ancient bedforms, not merely because of disagreement about which is the proper measure of flow strength (Froude number or shear stress) but because spacing of spurs has also been found to depend upon both flow strength and channel width (Allen, 1977).

Small bedforms are commonly superimposed on larger bedforms, and the migration directions of the two sets of bedforms often diverge. Two models have been proposed to explain bedform superpositioning: a fluctuating-flow model (Allen, 1978) and a multiple-boundary-layer model (Rubin and McCulloch, 1980). In the fluctuating-flow model, superimposed bedforms arise when flow conditions change and new bedforms are created before the old bedforms are destroyed. Superimposed bedforms that migrate in the same direction as the main ones are believed to indicate changes in flow strength (Allen, 1978), whereas superimposed bedforms that migrate in a different direction are believed to indicate changes in flow direction (Hereford, 1977; Elliott and Gardiner, 1981).

In the boundary-layer model, large bedforms create boundary layers (Smith and McLean, 1977) in which smaller bedforms can exist. The surface of the large bedform, like any sediment surface, is acted on by the overlying flow and is molded into a flat bed, ripples, dunes, or another bed configuration, depending upon the local flow conditions near the bed (Rubin and McCulloch, 1980). Superimposed bedforms formed in such steady flows are common in flumes (Guy et al., 1966), but most flume flows are so shallow that the resulting bedforms are small, and the superimposed dunes or sand waves, which are even smaller, are the size of ripples (Davies, 1982). In larger flumes, such as those that are on the order of a meter deep, large bedforms can be created, and the superimposed bedforms are large enough to be recognized as dunes or sand waves (Bohacs, 1981).

Many of the computer images in this publication illustrate depositional situations where two sets of bedforms simultaneously migrate in different directions. Although such behavior might seem unlikely, if not impossible, deposits produced by bedforms with this kind of behavior are common and can be readily explained by both fluctuating flow and multiple boundary layers. First, fluctuations in flow direction might alternately maintain two sets of bedforms. If the individual flow fluctuations transport small enough amounts of sediment relative to the sizes of the bedforms, then the two sets of bedforms will have the appearance of migrating simultaneously. Second, where the large bedforms are oblique to the flow direction, local flow on the lee side may take the form of a helix with an axis parallel to the bedform crestline (Allen, 1968). Bedforms created on the bed below such helical flow will develop in response to those local flow conditions and could be expected to have a different trend from the main bedforms. In addition to these processes that can maintain two sets of bedforms for long periods of time, two or more sets of bedforms can also exist temporarily at a site where flow conditions change and one set of bedforms is replaced by another (Fig. 79).