Reports

Bedform Alignment in Directionally Varying Flows

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Many kinds of sediment bedforms are presumed to trend either normal or parallel to the direction of sediment transport. For this reason, the trend of bedforms observed by remote sensing or by field observations is commonly used as an indicator of the direction of sediment transport. Such presumptions regarding bedform trend were tested experimentally in bidirectional flows by rotating a sand-covered board in steady winds. Transverse, oblique, and longitudinal bedforms were created by changing only two parameters: the angle between the two winds and the proportions of sand transported in the two directions. Regardless of whether the experimental bedforms were transverse, oblique, or longitudinal (as defined by the bedform trend relative to the resultant transport direction), they all had trends that yielded the maximum gross transport across the bedforms. The fact that many of the experimental bedforms were neither transverse nor parallel to the resultant transport direction suggests that transport directions cannot be accurately determined by presuming such alignment.

FOR MORE THAN A CENTURY GEOLOGists have wondered why some sediment bedforms trend roughly normal to flow and others trend roughly parallel to flow, but, despite considerable controversy and speculation, the factors that control bedform orientation have never been investigated experimentally, as far as we know. The lack of a general understanding of what controls bedform trend is summarized in three specific questions: (i) What are the directional parameters of a flow that control bedform trend? (ii) What factors determine whether a bedform takes a transverse or longitudinal trend? (iii) Do oblique bedforms (those at an angle between transverse and longitudinal) always require special conditions without which the bedforms would be either transverse or longitudinal?

The difficulty of relating bedform trend to the various directional parameters of a flow is not apparent for unidirectional flows because the resultant (vector-mean) flow direction, peak flow direction, and resultant transport direction all coincide in such flows. The difficulties arise for flows that vary in direction (such as tidal flows, wave-generated flows, and eolian flows), because the different directional parameters can diverge. For example, the peak flow direction diverges from the resultant flow direction in any situation where the flow jumps back and forth between two directions that differ by an angle other than 180°. In flows where such directional parameters diverge, there is no general agreement on those parameters responsible for controlling the bedform trend. Nowhere is this lack of agreement as pronounced as in the study of eolian dunes. Eolian dunes have been interpreted to trend parallel or normal to prevailing winds (*1, 2*), to predominant sand-transporting winds (*2*), to strong winds (*3*), to flow at various elevations within an atmospheric Ekman spiral (*4–6*), to flow deflected by the dunes (*7, 8*), to resultant sand-transport directions (*9*), and to winds that occurred in the past (*2, 4*).

Although sedimentologists disagree about which flow parameters control bedform trend, bedforms can be classified descriptively by the relation between their trend and the resultant transport direction (either measured or calculated from flow data). Transverse bedforms lie roughly normal to the resultant transport direction, longitudinal bedforms lie roughly parallel to that direction, and oblique bedforms have intermediate trends [15° to 75° to the transport direction, according to the definition in (*10*)]. Many factors have been proposed to explain why a longitudinal bedform trend might develop in place of a transverse trend. Several of these factors follow: (i) bidirectional wind regimes (*7, 11*), (ii) wind regimes with a relatively large gross transport but with a relatively low consistency ratio (*9*) (gross transport is defined as transport in which the backward amount is added to, rather than subtracted from, the forward amount), (iii) net erosion or a scarcity of sand in a dune field (*12–14*), (iv) paired helical vortices in the wind (*15, 16*), and (v) strong winds, which have been suspected to favor the formation of such vortices (*2, 17*).

Disagreement exists about the significance of oblique bedforms. Most workers ignore the possible existence of such bedforms or consider them merely to be improperly aligned transverse or longitudinal bedforms, but other workers consider them as a distinct kind of bedform or part of a continuum that includes transverse and longitudinal bedforms (*18, 19*).

We report the results of an experimental study of bedform trend in directionally varying flows. In these experiments we created transverse, oblique, and longitudinal bedforms; determined the flow conditions that produce the different kinds of bedforms; and developed a model that predicts the trend of the bedforms.

Bidirectional wind regimes were created experimentally by rotating a sand-covered plywood board in relatively steady sea breezes of the California coast. The bedforms produced on the board were wind ripples that had spacings of 5 to 10 cm. The diameter of the board was large enough (1.2 m) that the ripples across most of the surface were not disturbed by edge effects. Two parameters were varied (Fig. 1): the angle between the two winds (the divergence angle) and the ratio of transport in the two wind directions (the transport ratio, defined as always greater than or equal to unity). The divergence angle was controlled by rotation of the sediment-covered board; divergence angles ranged from 0° to 180°. The transport ratio was controlled by the length of time that the board remained in each of its two positions; transport ratios ranged from 1:1 to 8:1. Thirty-one experiments were conducted for 20 combinations of divergence angles and transport ratios. In all experiments the board was left in each of its two positions for time intervals that were short relative to the time required for ripples to form. For the wind conditions during the experiments (typically 5 to 10 m sec^{-1} at an elevation of 2 m above the bed), the board was turned at time intervals ranging from 6 to 54 seconds. We assumed that the natural small fluctuations in wind speed and direction were not in phase with the rotation of the board, and we verified that there was no systematic change in wind direction during an experiment. Because the transport ratio was controlled by time rather than wind speed, the need for calculating sediment transport as a function of wind speed was eliminated. In addition to reducing errors introduced by imperfect equations of transport rate, this approach to controlling the transport ratio simplified the experimental technique. However, the results might differ if flow velocity rather than time were used to control the transport ratio.

After 10 to 30 minutes, ripples were well established on the board, and their average trend relative to the wind directions was estimated visually and measured by a pro-

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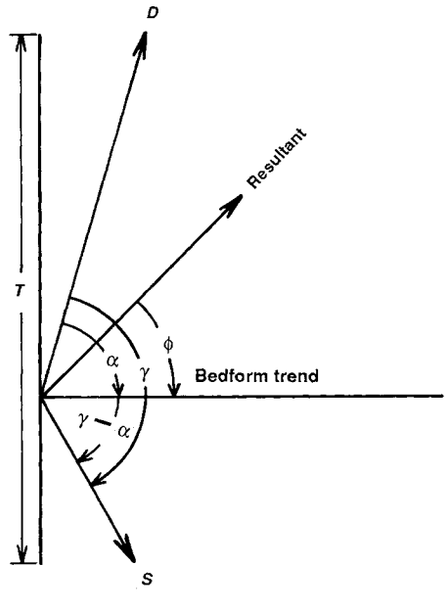

Fig. 1. Diagram of transport vectors and bedform trend. The vectors D and S are the dominant and subordinate transport, respectively; α is the angle between D and the bedform trend; γ is the angle between D and S (the divergence angle); and T is the gross bedform–normal transport. The resultant transport is the vector sum of D and S, and ϕ is the angle between the resultant and the bedform trend.

tractor. Twenty of the 31 experiments were conducted under conditions that duplicated those in another experiment. Experiments that were repeated for constant values of the controlling parameters had a maximum disparity of 13° from the mean of the experiments under the given conditions; the standard deviation of disparities for repeated experiments was 6.0°. In the duplicated experiments, the placement of the dominant and subordinate winds was reversed, but no systematic differences resulted from the reversals. For all experiments, the resultant transport direction was calculated from the two wind vectors, and the bedform trend relative to the transport direction was plotted as a function of the two experimental variables.

The most notable feature of the experimental results (Fig. 2) is an abrupt change in bedform trend when the divergence angle crosses a critical value between 90° and 112°. In order to explain this change, we concentrated on the conceptually simple case in which the transport vectors were equal (the transport ratio was 1.0). In this case transverse ripples form when the divergence angle is less than the critical value, and longitudinal ripples form at greater angles (Fig. 2). These transverse and longitudinal ripples both have the trend that yields the maximum gross bedform–normal transport. (Gross bedform–normal transport is defined as the amount of sediment transported normal to the bedform trend, measured without regard to direction of transport; that is, transports in opposite directions do not cancel but rather are summed as two absolute numbers.) The shared property of maximum gross bedform–normal transport in these simple flows suggested the possibility that the bedforms had such a trend under all experimental conditions.

To test the hypothesis that the bedforms always had the trend that yielded the maximum gross bedform–normal transport, that trend was calculated as a function of the two experimental variables. For an arbitrary bedform trend, the gross bedform–normal transport is given by

$$T = D\,|\sin\alpha| + S\,|\sin(\gamma - \alpha)| \qquad (1)$$

where D and S are the amounts of transport represented by the dominant and subordinate transport vectors, respectively; α is the angle between the dominant transport vector and the bedform trend; and γ is the divergence angle between the two transport vectors. The angles are defined as positive in the clockwise direction (Fig. 1). The bedform trend that yields the maximum value of T is found by the first-derivative test. The value of α for which T is a maximum is

$$\tan\alpha = \pm\frac{R + |\cos\gamma|}{|\sin\gamma|} \qquad (2)$$

where R is the transport ratio (the ratio of D to S). The minus sign in $\pm$ gives the correct value of α for γ ranging from 0° to 90°, and the plus sign in $\pm$ gives the correct value for γ ranging from 90° to 180°. Figure 2 shows the contours of the angle between the resultant transport direction and the bedform trend that yields the maximum value of T (the angle ϕ in Fig. 1).

Comparison of the observed bedform trends and the trends predicted from the rule of maximum gross bedform–normal transport (Fig. 2) shows that the mean observed value minus predicted value is 5.5° and that the standard deviation is 7.8°. (In 8 of the 31 experiments the algebraic sign of the discrepancy cannot be determined because either $R = 1$ or $\gamma = 180°$; results of these experiments were omitted from the statistical calculations.) The close agreement of the observed and predicted values suggests that the experimental bedforms do, in fact, trend in the direction subject to the maximum gross bedform–normal transport. All of the experimental bedforms are so oriented, regardless of whether they are transverse, oblique, or parallel to the resultant transport direction. The fact that some of the experimental bedforms trend parallel to the resultant transport vector is coincidental. In flows having divergence angles between 90° and 180° and a transport ratio of 1.0, the bedform trend that is transverse to the direction of maximum gross transport coincides with the resultant transport direction, but there is no such coincidence where the transport ratio is not equal to 1.0. In sum, the results demonstrate that transverse, oblique, and longitudinal bedforms are not necessarily different kinds of bedforms in a dynamic sense, but rather can be explained by one governing principle.

The importance of gross sediment transport in controlling bedform trend has a physical basis. When net (resultant) trans-

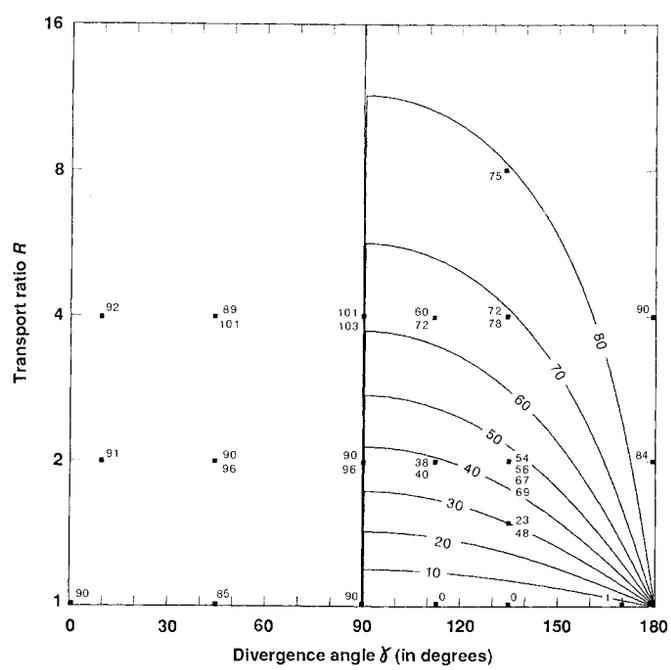

Fig. 2. Plot showing bedform trend relative to the resultant transport direction ϕ as a function of the angle γ between the two wind directions and the ratio R of sand transport in the two directions. The plotted points are the experimental results labeled by ϕ values; contour lines show the value of ϕ predicted from the rule of maximum gross bedform–normal transport (Eq. 2). Bedforms that would plot at the lower-right corner of the figure had the trend that yielded the maximum gross bedform–normal transport (a trend normal to the two opposed winds), but the transport direction is undefinable for those experimental conditions because no net transport occurs.

port is calculated, backward transport across a bedform crest line is subtracted from the forward transport. Therefore, it is treated mathematically as "undoing" the bedform despite the fact that such transport must help create the bedform. In contrast, when gross transport is calculated, transports in both directions across the crest line are summed, or treated as creating the bedform.

In natural flows, where sediment transport can occur toward any number of directions, the most convenient technique for predicting bedform trend is to compute for the given flow conditions the gross bedform–normal transport for a variety of arbitrary bedform trends (for example, at 1° increments), and to select the trend that yields the maximum value. With this technique we can take into account the transport vectors for the 3 or 4 seconds during which the experimental sediment surface was turned between stationary positions, and it can be shown that our experimental values of ϕ should be approximately 5° greater than if the turning were instantaneous. In addition to explaining the small systematic discrepancy between the observed and predicted values of ϕ, the sand transport during turning explains why the break in bedform behavior was observed to occur at a divergence angle between 90° and 112°, rather than exactly at 90°.

This experimental study does not consider some known causes of bedform obliquity, such as along-crest variations in the rate of bedform migration resulting from variations in local flow conditions (*19, 20*). Also, the results do not prove that other controls, such as sediment availability, flow strength, or helical vortices, have no effect on bedform trend. However, the results do demonstrate that longitudinal and oblique bedforms can be produced independently of such controls. We would expect plots that are qualitatively similar to Fig. 2 to describe the orientation of such natural bedforms as eolian dunes, tidal sand waves, and combined current-wave ripples, provided that the bedforms are large enough (relative to the amount of sediment transported during each flow cycle) to respond only slightly to the individual flow cycles. These natural bedforms are known to be approximately transverse to the resultant transport direction in flows that are effectively unidirectional (corresponding to flows in which either the divergence angle is small or the transport ratio is large). Transverse bedforms are also known to occur where the divergence angle is approximately 180° and the transport ratio is greater than 1.0. In addition, tidal sand waves, oscillation ripples, and eolian dunes will trend parallel to the resultant transport direction when the transport ratio is 1.0 and the divergence angle approaches but does not equal 180°. All of these bedforms of known behavior are in agreement with the trends that were observed in the experiments and predicted from the rule of maximum gross bedform–normal transport. Quantitatively, the relations for different bedforms in different fluids might differ from those in Fig. 2. For example, the abrupt transition from transverse to longitudinal trends that occurs when the divergence angle exceeds 90° might occur at different angles, possibly because of flow separation, which occurs to a different extent over different kinds of bedforms. Possibilities for future work include experimental study of bedform trend in directionally varying subaqueous flows and field studies of larger natural bedforms in flows that produced the bedforms.

In summary, the experimental bedforms had trends that yielded the maximum gross bedform–normal transport. The fact that transverse, oblique, and longitudinal bedforms all followed the same rule of alignment suggests that they do not require differing flow dynamics for their origin (that is, they are basically the same kind of bedform). Longitudinal bedforms were created without flow parallel to the bedform crest line and without alignment with preexisting paired helical vortices in the flow. No bedforms were aligned parallel to the resultant transport direction unless such a trend yielded the maximum gross bedform–normal transport. This study demonstrates that bedforms can trend at any angle relative to the resultant transport direction and that an infinite number of flow regimes can produce the same bedform trend. Until future studies devise techniques for distinguishing along-crest and across-crest components of sediment transport, it will not be possible to determine transport directions from remote-sensing images of dunes in deserts or sand waves on the sea floor; bedforms can no longer be presumed to trend parallel or normal to the resultant transport direction.

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Islet Allograft Survival After a Single Course of Treatment of Recipient with Antibody to L3T4

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Allografts of pancreatic islets of Langerhans were induced to survive for an indefinite period in diabetic mice if, at the time of engraftment, the mice received a single course of treatment with a monoclonal antibody directed against the L3T4 determinant, a nonpolymorphic cell surface glycoprotein present on the cell surface of the murine T helper-inducer lymphocyte subset. This treatment allowed the survival of islets of Langerhans transplanted across a major histocompatibility barrier without additional immunosuppression. The results demonstrate that the lymphocyte subset defined by the expression of the L3T4 molecules is central to the induction of allograft rejection and provides a model for tolerance induction for organ allograft transplantation.

T CELLS SERVE BOTH REGULATORY and effector functions during allograft responses (*1–3*). Although T lymphocytes play a central role in the rejection of allografted tissue (*4–6*), the relative importance of the different T cell populations in graft rejection remains controversial

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