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Flume experiments on the alignment of transverse, oblique, and longitudinal dunes in directionally varying flows

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ABSTRACT

For more than a century geologists have wondered why some bedforms are orientated roughly transverse to flow, whereas others are parallel or oblique to flow. This problem of bedform alignment was studied experimentally using subaqueous dunes on a 3·6-m-diameter sand-covered turntable on the floor of a 4-m-wide flume.

In each experiment, two flow directions (relative to the bed) were produced by alternating the turntable between two orientations. The turntable was held in each orientation for a short time relative to the reconstitution time of the bedforms; the resulting bedforms were in equilibrium with the time-averaged conditions of the bimodal flows. Dune alignment was studied for five divergence angles (the angle between the two flow directions): 45°, 67·5°, 90°, 112·5° and 135°. The flow depth during all experiments was approximately 30 cm; mean velocity was approximately 50 cm s^{-1}; and mean grain diameter was 0·6 mm. Each experiment continued for 30–75 min, during which time the flume flow was steady and the turntable position changed every 2 min. At the end of each experiment, water was slowly drained from the flume and dune alignment was measured. Transverse dunes (defined relative to the resultant transport direction) were created when the divergence angle was 45° and 67·5°, and longitudinal dunes were created when the divergence angle was 135°. At intermediate divergence angles, dunes with both orientations were produced, but transverse dunes were dominant at 90°, and longitudinal dunes were dominant at 112·5°.

One experiment was conducted with a divergence angle of 135° and with unequal amounts of transport in the two flow directions. This was achieved by changing the orientation of the turntable at unequal time intervals, thereby causing the amount of transport to be unequal in the two directions. The dunes formed during this experiment were oblique to the resultant transport direction.

These experimental dunes follow the same rule of alignment as wind ripples studied in previous turntable experiments. In both sets of experiments, the bedforms developed with the orientation having the maximum gross bedform-normal transport (the orientation at which the sum of the bedform-normal components of the two transport vectors reaches its maximum value). In other words, the bedforms develop with an orientation that is as transverse as possible to the two flows. In those cases where the two flows diverge by more than 90° and transport equal amounts of sand, bedforms that are as transverse as possible to the two separate flows will be parallel to the resultant of the two flow vectors. Although such bedforms have been defined by previous work as longitudinal bedforms, they are intrinsically the same kind of bedform as transverse bedforms.

INTRODUCTION

As early as 1870, geomorphologists became puzzled as to why some aeolian dunes are orientated roughly transverse to flow, whereas others are parallel or oblique to flow (Frere, 1870). Since then, this problem of bedform alignment has been the subject of considerable field observation and speculation. This paper reports results of an experimental study using subaqueous dunes to investigate this problem of bedform alignment.

Many workers have presumed that dunes and other bedforms tend to be aligned relative to some flow parameter such as prevailing winds (Bagnold, 1933;

Glennie, 1970), predominant sand-transporting winds (Glennie, 1970), strong winds (Twidale, 1981), flow at various elevations within an atmospheric Ekman spiral (Mabbutt, Wooding & Jennings, 1969; Warren, 1976; Brown, 1983), flow deflected by the dunes (Lancaster, 1983; Tsoar, 1983), or resultant sand-transport directions (Fryberger, 1979). Various theories have been proposed to explain why some dunes form with a longitudinal alignment (roughly parallel to the transport direction) whereas others are transverse (roughly normal) or oblique (defined by Hunter, Richmond & Alpha (1983) to be 15–75° to the resultant transport direction). These theories have proposed that the formation of dunes with a longitudinal trend or linear morphology is induced by bidirectional or directionally variable wind regimes (Bagnold, 1941; Fryberger, 1979; Tsoar, 1983), by net erosion or scarcity of sand in a dune field (Mainguet & Chemin, 1983; Wasson & Hyde, 1983), by deposition in the lee of obstacles (Melton, 1940), by paired helical vortices in the wind (Hanna, 1969; Cooke & Warren, 1973; Tseo, 1986), or by high wind speeds, which have been hypothesized to favour formation of such vortices (Glennie, 1970; Folk, 1976). The merits of some of these theories have been discussed by Lancaster (1982), McKee (1982), Tsoar (1983), Rubin (1984), and Rubin & Hunter (1985).

Despite the fact that geologists are often more interested in determining palaeocurrent directions than palaeocurrent velocities, few experimentalists have examined the effects of varying flow directions on bedforms and cross-bedding. Although some laboratory studies have examined bedforms and cross-bedding in flows that reverse by exactly 180°, other directional changes are difficult to produce in laboratory flumes because the confined flows generally parallel the walls of the narrow channels. To simulate natural directionally varying flows such as occur in aeolian dune fields, tidal and shelf marine environments, and within unsteady eddies in rivers, experimental flows must be free to vary by all angles—not just 180°. One technique to produce such directional variability experimentally is to rotate the bed beneath a unidirectional flow. This technique was used in a previous study of wind ripples (Rubin & Hunter, 1987) and was used in this study of subaqueous dunes.

Study of bedforms in directionally varying flows is important because directional properties of a flow can determine whether bedforms are transverse, oblique, or longitudinal. In a previous study, Rubin & Hunter (1987) created transverse, oblique, and longitudinal wind ripples in bidirectional flows merely by changing the two flow parameters defined in Fig. 1: the divergence angle (the angle between the two alternating flow directions) and the transport ratio (the ratio of transport in the dominant direction to transport in the subordinate direction). The main finding of the wind-ripple experiments was that regardless of whether the bedforms could be defined as transverse, oblique, or longitudinal (relative to the vector resultant), the bedforms in each experiment had the maximum gross bedform-normal transport (i.e. the bedforms had the orientation that was subject to more transport crossing the bedform crestline than any other possible bedform orientation). The implications of these results are considered in the discussion of the results of the new flume experiments.

PROCEDURE

Theoretical considerations

The aim of these flume experiments was to create bidirectional flows, observe the orientation of the resulting dunes, and determine what flow properties control dune orientation. Specifically, do subaqueous dunes follow the same rule of alignment as wind ripples? A critical design requirement for the experiments was to produce bedforms that were in equilibrium with the time-averaged conditions of each bidirectional flow. Depending on the period of the

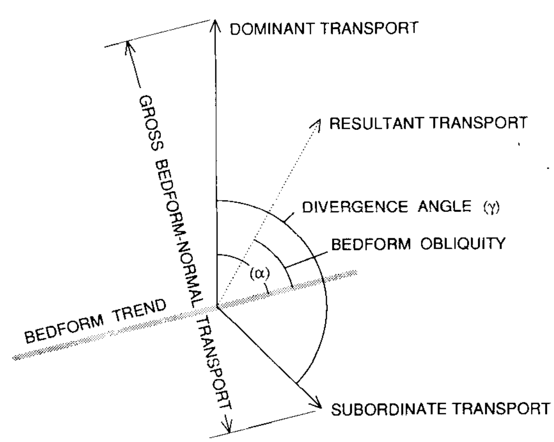

Fig. 1. Diagram showing definitions of dominant transport vector, subordinate transport vector, resultant transport vector, divergence angle, and gross bedform-normal transport. The angles are defined in a clockwise direction. Where the transport ratio is 1:1, as in all but one of these flume experiments, the dominant and subordinate transport vectors are of equal magnitude.

flow fluctuations relative to the reconstitution time of the bedforms, three kinds of equilibrium or disequilibrium are theoretically possible for any bedform in a periodic bidirectional flow. Where bedform reconstitution time is short relative to the length of a single flow-fluctuation cycle, bedforms will tend to be in instantaneous equilibrium with the present flow conditions (Fig. 2A). Current ripples in a tidal flow can exhibit this kind of equilibrium. Within a relatively short time after the flow reverses, ripple morphology may depend only on the present flow conditions; the effect of previous flow conditions is erased. This kind of instantaneous equilibrium is unsuitable for the present experiments because bedform alignment would change through time. At any one time, bedform morphology would reflect only the more recent half of the bidirectional flow cycle.

A second type of equilibrium/disequilibrium (also unsuitable for these experiments) occurs where bedform reconstitution time is comparable to the period

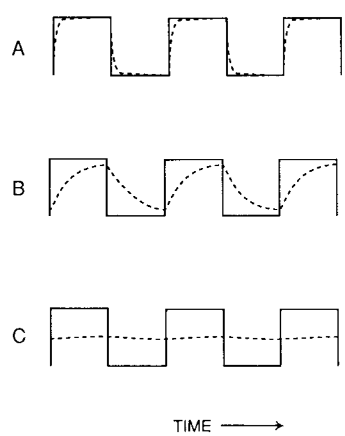

Fig. 2. Conceptual diagram illustrating three types of equilibrium and disequilibrium in a cyclic flow that alternates instantaneously between two directions or velocities (solid line). The morphological response of the bedforms, which may be any change in orientation, height, or plan-form geometry, is illustrated in purely diagrammatic form by the dashed line. (A) Bedform reconstitution time is short relative to the period of flow cyclicity; shortly after the flow changes, bedforms are in equilibrium with the new flow conditions. (B) Bedform reconstitution time is roughly comparable to the period of flow cyclicity; bedforms are continuously out of equilibrium because the flow repeatedly changes before bedforms can readjust to the new conditions. (C) Bedform reconstitution time is long relative to the period of flow cyclicity; bedforms respond so slowly that they are in equilibrium with time-averaged properties of both parts of the bidirectional flow cycle. This is the type of equilibrium desirable for experimental study of bedform alignment.

of flow fluctuations (Fig. 2B). In such a situation, bedforms are almost continuously in disequilibrium. For example, small tidal dunes that require many hours to adjust to new flow conditions may not approach equilibrium until it is nearly time for the flow to reverse. Such bedforms are unsuitable for the alignment experiments because the bedforms are not in equilibrium with either the instantaneous or the time-averaged conditions.

The third type of equilibrium—which is appropriate for these experiments—occurs where the length of each flow fluctuation is short relative to the bedform reconstitution time (Fig. 2C). In such a situation, any one half of the bidirectional flow cycle will have no appreciable effect on bedform orientation; the bedforms are in equilibrium with the time-averaged properties of the flow. Large tidal dunes or sand waves commonly respond so slowly relative to a single tide cycle that they exhibit such behaviour. In this experimental study, the period of the complete bidirectional flow cycle was kept to 4 min (< 2 min in each position) so that the period would be short relative to the bedform reconstitution time. Although the bedform reconstitution time was not measured directly, the fact that the results of duplicated experiments were independent of the position of the turntable at the end of the experiment indicates that the turntable rotation period was in fact short relative to the reconstitution time. If the period of the flow cycles had been too long (approaching or exceeding the bedform reconstitution time), the bedforms would have tended to be transverse to the last flow in each experiment.

Experimental equipment

These experiments were conducted on a 3·6-m-diameter turntable which was installed on the floor of a 4-m-wide, 160-m-long, flume at the Environmental Research Center, University of Tsukuba (Fig. 3). The slope of the bed was adjusted by introducing approximately 600 m^3 of sand and running the flume until the flow at the turntable site was nearly uniform, with a depth of approximately 30 cm, a mean velocity of approximately 50 cm s^{-1}, and a thickness of 10–20 cm of sand covering the turntable. Flow was not perfectly uniform, however; the velocity decreased slightly downstream, so that the plywood surface of the turntable would not be exposed by erosion. During some experiments, the velocity was noticeably faster along one side of the flume. This cross-channel velocity gradient, however, did not produce a systematic

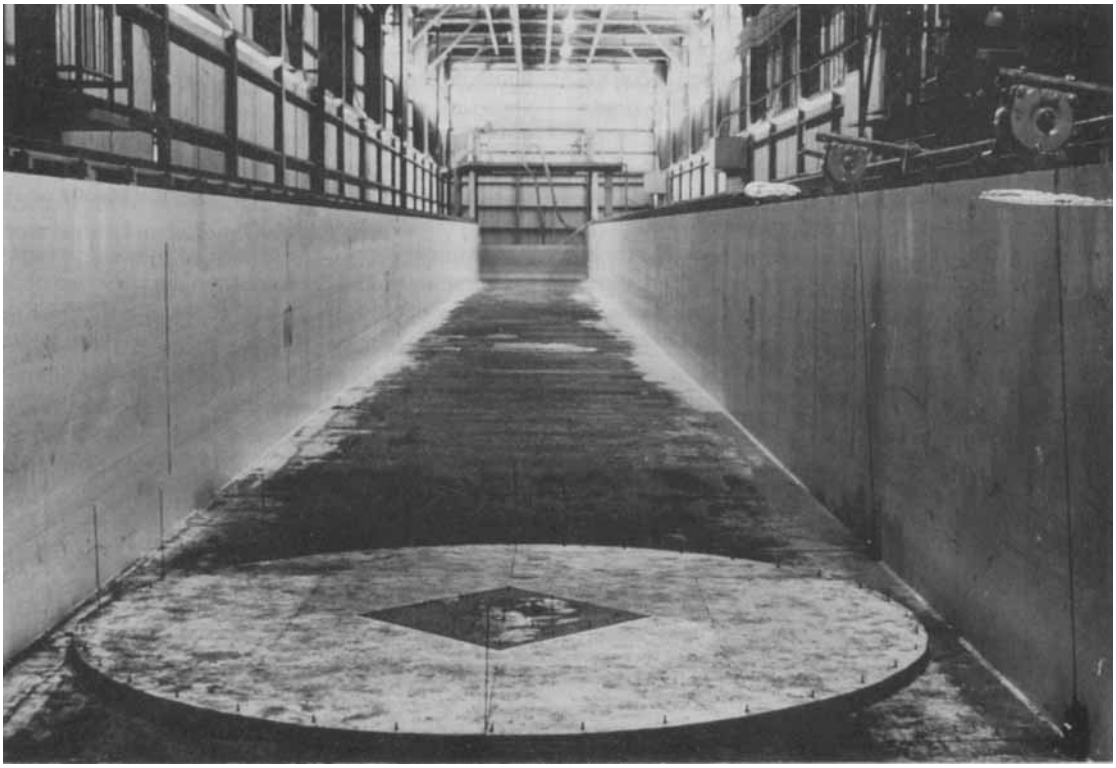

Fig. 3. Photograph of the turntable before sand was introduced. The turntable is 3·6 m in diameter; flume width is 4·0 m.

skewing of the dunes upstream or downstream from the turntable.

During the experiments, the turntable was loaded with approximately 2000 kg of sand. To rotate this mass, a remote-controlled electric car was used to pull a pair of cables that ran through a pulley system and wrapped around the turntable. The rotation direction of the turntable was reversed by reversing the direction of the car. Orientation of the turntable was monitored by observing markers mounted on metal rods attached to the turntable. The rods extended above the water surface and were monitored using a closed-circuit television camera that was mounted above the turntable.

Experimental approach

In the previous turntable experiments with wind-ripples, experimental conditions included a wide range of divergence angles (0–180°) and transport ratios (1:1–16:1). Orientation of the experimental wind ripples could be determined very precisely, not only because they were relatively straight-crested, but also because the turntable diameter was large (120 cm) relative to the ripple spacing (5–10 cm), and the turntable therefore contained a large sample of ripples. As a result, it was possible to determine ripple orientation relative to the transport direction with a high precision, and repeated experiments were in close agreement (Fig. 4).

In contrast to those experiments, these flume experiments produced bedforms that were more three-dimensional and so large that only a few could fit on the 3·6-m-diameter turntable. Consequently, dune orientation could not be determined with great precision. Moreover, the possibility that the cross-channel differences in flow strength might introduce a systematic bias in the dune orientations called for a different experimental approach. As a result, the experiments were designed to explore the transition from transverse to longitudinal dunes in flows having a transport ratio of 1:1 (i.e. only the conditions represented by points close to the lower horizontal axis in Fig. 4). It was then only necessary to determine

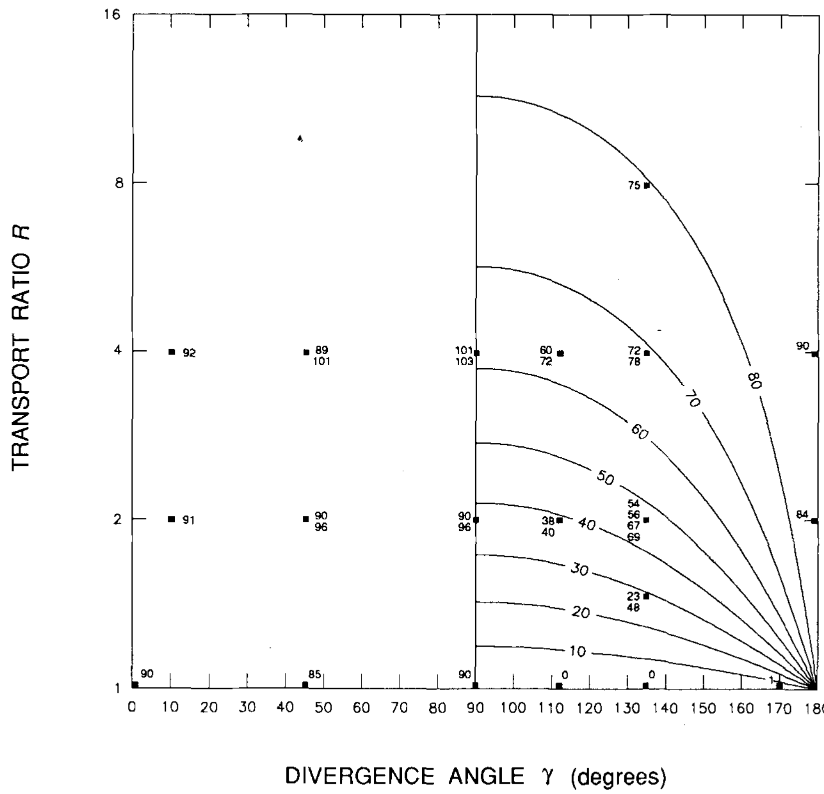

Fig. 4. Plot showing bedform obliquity as a function of divergence angle (the angle between the two flow directions) and transport ratio (the ratio of the amount of sand transport in the dominant direction to the amount in the subordinate direction). Bedform obliquity is defined relative to the resultant transport direction (Fig. 1), not relative to the dominant transport vector as in Eq. (1). Perfectly longitudinal dunes have an obliquity of 0°, and transverse bedforms have an obliquity of 90°. The plotted points are the experimental results; contours show the bedform obliquity predicted using the rule of maximum gross bedform-normal transport. Transverse bedforms form in all flows having divergence angles $<90°$, in flows having transport ratios $>8:1$, and in flows having divergence angles that approach 180°. Longitudinal bedforms form only in flows having divergence angles $>90°$ and transport ratios that approach $1:1$. Oblique dunes form in flows having divergence angles $>90°$ and transport ratios beween $1:1$ and $8:1$. From Rubin & Hunter (1987).

whether the resulting dunes had a transverse or longitudinal trend, a simple distinction even where bedforms have sinuous plan forms (Fig. 5).

For the purpose of these experiments, 'transverse', 'oblique', and 'longitudinal' were defined relative to the resultant transport direction that was calculated by summing the two flow vectors of the bidirectional cycle. Because the flow velocities were constant during each experiment, it was not necessary to use a sediment transport model to calculate transport rates; the magnitude of any transport vector was proportional to the time that the turntable remained fixed in position. This method correctly gives the resultant transport direction prior to development of the bedforms and can therefore be used to characterize the flow that was responsible for producing the bedforms. In effect, this method gives a value that could be termed the 'flat-bed resultant'. After the bedforms develop, however, the near-bed flow may become deflected by the bedforms, causing a rotation in the resultant transport direction.

This effect of bedforms on the transport direction of a flow is analogous to the more thoroughly studied effect of bedforms on shear stress of a flow. Because bedform roughness can effect shear stress—even when mean velocity and depth remain constant—it has been argued that mean velocity rather than shear stress should be used to characterize flow strength in studies of bedform equilibrium (Middleton & Southard, 1984, p. 282). Similarly, if bedform orientation is to be studied as a function of the directional properties of a flow, the directional properties should be character-

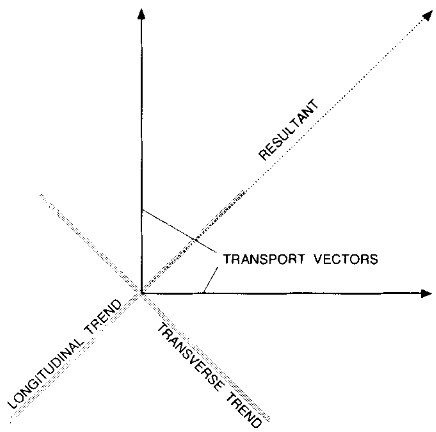

Fig. 5. Diagram illustrating transverse and longitudinal bedform trends in a bidirectional flow with a divergence angle of 90° and transport ratio of 1:1. The longitudinal trend bisects the angle between the two flow vectors; the transverse trend lies outside that angle. Bedform trend bisects the angle between the two flow vectors where the angle is 180° (oscillation ripples, for example). Where the angle between the two flow vectors is zero (a unidirectional flow), bedforms lie outside the angle. As the divergence angle increases gradually from 0° to 180°, the bedform trend must make a 90° jump—from a transverse trend to a longitudinal trend. The focus of these turntable experiments was to determine the divergence angle at which this jump occurs.

ized independently of the bedforms produced by the flow. The technique used in these flume experiments (measuring the turntable position through time) satisfies this condition. For field measurements to be comparable, the field measurements must also be independent of the bedforms; flow directions and velocities should be measured high above the bedforms or over a flat bed outside of the bedform field. Similarly, transport rates should be calculated for a flat-bed. For the different problem of calculating the actual transport through a bedform field—rather than the present problem of characterizing a bedform-producing flow—the deflection of the flow by the bedforms and the variation of bedform roughness as a function of flow direction must be considered.

Experimental procedure

Each experiment consisted of 7–18 bidirectional flow cycles (28–72 min of flow). A typical cycle (a 90° divergence angle, for example) consisted of 102 s of flow toward the first direction, 18 s to rotate the turntable to produce the second flow direction, 102 s of flow toward that direction, and 18 s to rotate back to the first flow direction (Fig. 6). At the end of each experiment the tailgate of the flume was raised rapidly. Within 10–20 s, flow at the turntable site stagnated, and flow into the headgate was stopped. To drain the flume without disturbing the bedforms, the tailgate was lowered gradually.

After the flume was drained enough that the bed was visible, the test illustrated in Fig. 5 was used to determine whether the dunes were transverse or longitudinal with respect to the resultant transport direction. For this crude distinction, it was not necessary to consider sediment transport while the turntable was rotating, although such transport must be considered if high accuracy is desired in quantifying bedform obliquity (Rubin & Hunter, 1987). Transport during turntable rotation slightly reduces the nominal divergence angle, because some transport occurs toward intermediate directions. In addition, if the transport ratio is not 1:1, transport during rotation changes the nominal transport ratio and rotates the resultant transport direction. A computational technique for evaluating these effects in complicated multidirectional flows is discussed and illustrated with an example in a later section.

RESULTS

Bedform orientation was studied for 10 runs with nominal transport ratios of 1:1 and divergence angles of 45°, 67·5°, 90°, 112·5°, and 135°. Transverse dunes were created when the divergence angle was 45° and 67·5° (Fig. 7), and longitudinal dunes were created when the divergence angle was 135°. At intermediate divergence angles, dunes (or dunes and spurs) with both trends were produced, but transverse trends were

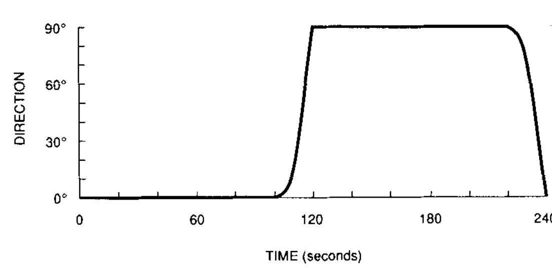

Fig. 6. Diagram illustrating a single experimental bidirectional flow cycle. One complete cycle consists of 102 s of flow toward the first direction, 18 s to rotate to the second direction, 102 s of flow toward that direction, and 18 s to rotate back to the first direction. Each experiment consisted of 7–18 such cycles.

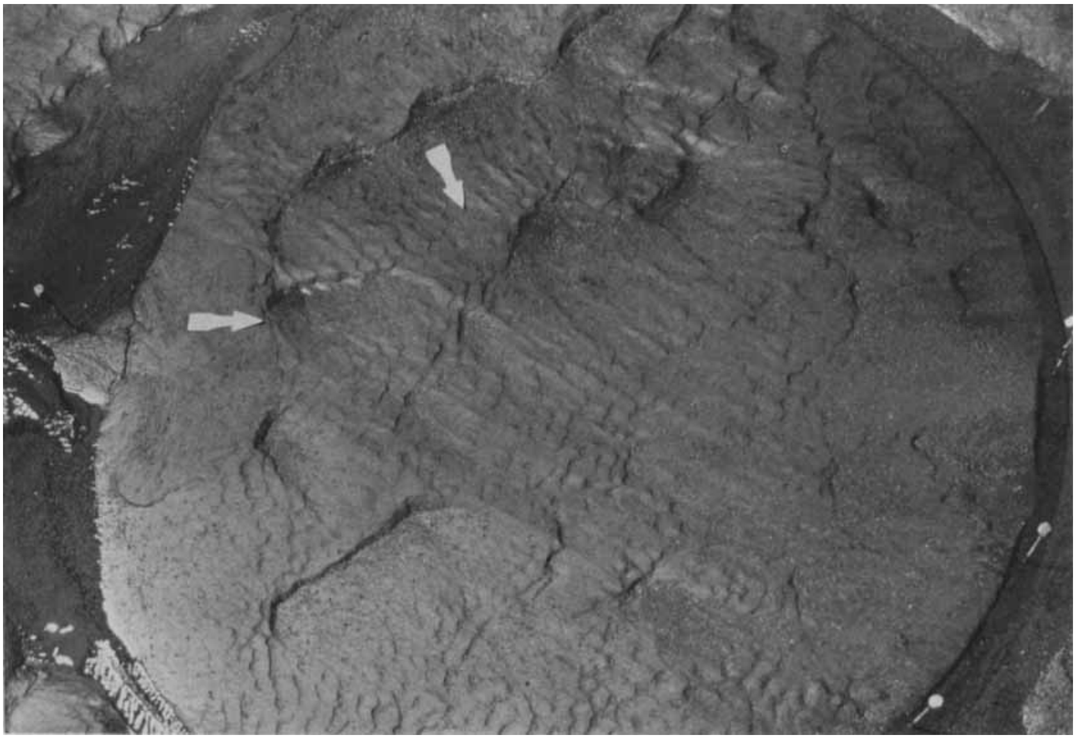

Fig. 7. Photograph of transverse dunes formed by a bidirectional flow with a nominal (excluding transport during rotation) divergence angle of 67° and transport ratio of 1 : 1. Transport directions are indicated by arrows; the resultant direction is from upper left to lower right. Although the dominant dune trend is transverse to this direction, some longitudinal lineations are present also. Turntable diameter is 3·6 m.

dominant at 90°, and longitudinal trends were dominant at 112·5° (Fig. 8). These results indicate that subaqueous dunes follow the same rule of alignment as wind ripples (Fig. 4), although the nature of the phase boundary between transverse and longitudinal bedforms (at a divergence angle of 90°) differs somewhat for the two kinds of bedforms. For wind ripples the phase boundary is abrupt, whereas for subaqueous dunes the transition is a gradational dominance of one trend over the other. It is not known whether this difference in the phase boundary results from an intrinsic difference between subaqueous dunes and wind ripples (such as longitudinal spurs being less stable on wind ripples) or results from differences in experimental conditions (such as the period of the bidirectional flow cycles relative to the bedform reconstitution time).

The similarity of behaviour of the subaqueous dunes and wind ripples at a transport ratio of 1 : 1 raised the question of whether the same rule of alignment describes subaqueous dunes at other transport ratios. This was investigated with only a single run having a nominal transport ratio of 2 : 1 and divergence angle of 135°, but the results of this experiment suggest that the same rule does, in fact, hold under those conditions also. The dunes formed in this experiment (Fig. 9) were oblique dunes; they were orientated at 37° to the resultant transport direction (calculated including the transport during rotation). This result is also compatible with the results of the wind-ripple experiments; for these experimental conditions, an obliquity of 47° is predicted from the rule of maximum gross bedform-normal transport (discussed in the following section).

DISCUSSION

Ripples and dunes in many natural environments are subject to flows having high-frequency directional variations and can be expected to follow the same rule of alignment as the experimental wind ripples and subaqueous dunes. Examples of such bedforms include

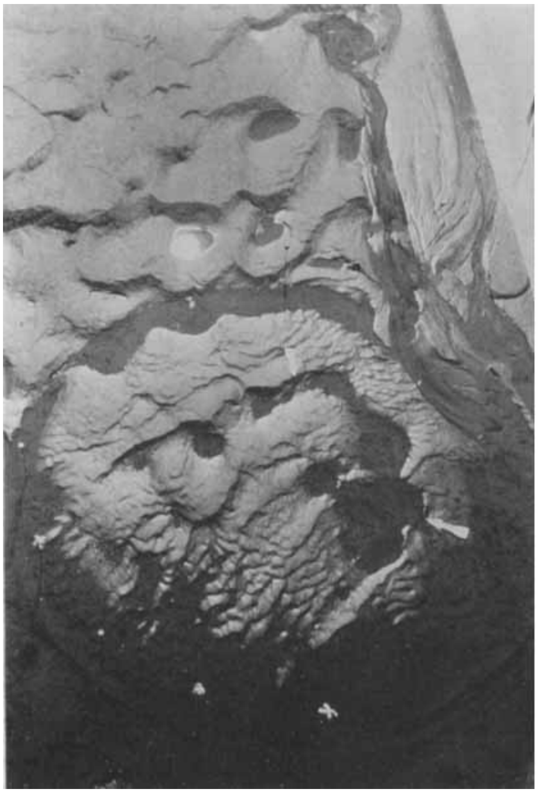

Fig. 8. Photograph of dominantly longitudinal dunes formed by a bidirectional flow with a nominal divergence angle of 112° and transport ratio of 1:1. Transport directions are shown by arrows. The dominant bedform trend parallels the resultant transport direction (upper right to lower left), but as the experimental conditions are near the transition to transverse bedforms, transverse bedforms are present also. Turntable diameter is 3·6 m.

Fig. 9. Photograph of oblique dunes formed by a bidirectional flow with a nominal divergence angle of 135° and transport ratio of 2:1. The dominant transport direction is from top to bottom. Turntable diameter is 3·6 m.

aeolian dunes that experience flow fluctuations caused either by periodic events such as daily sea breezes, seasonal winds, or by non-periodic events such as the passage of weather fronts; ripples that experience wave-generated oscillatory flow (possibly combined with a unidirectional component); dunes in tidal flows; and ripples in unsteady directionally varying flow within river eddies. These experiments suggest that where the flow fluctuations are rapid relative to the bedform reconstitution time, bedforms will form with the orientation that is subject to the maximum gross bedform-normal transport. As noted previously (Rubin & Hunter, 1985, 1987) other factors can affect bedform alignment; these experiments do not prove that bedform alignment is not influenced by such factors as sediment supply, sediment cohesiveness, or spatial flow variations in a field of bedforms.

Rule of maximum gross bedform-normal transport

In nearly all previous field studies of bedform alignment, sediment transport toward varying directions has been characterized by the resultant transport vector. Although the vector resultant is the appropriate parameter for describing the net rate and direction of sediment transport, the problem of bedform genesis is so different that another parameter is needed to characterize flow conditions. When sediment is transported toward opposing directions, the opposing transport cancels out—a physical process that is accurately described when the resultant is calculated. In contrast, when bedform genesis is being considered, opposing vectors should not be cancelled out, because the two opposing vectors may be creating a single bedform orientation (normal to the two vectors). It can be argued that all transport should be considered to have a positive effect, because all transport may be involved in creating bedforms. For example, consider a wave-generated onshore–offshore flow combined with a small unidirectional alongshore flow. If the onshore and offshore components are equal, then they cancel out, and the resultant of the system is equal to the unidirectional vector. Regardless of the strength of the onshore–offshore flow, it has no effect on the resultant—yet it is typically this stronger wave-generated oscillatory flow that is responsible for producing bedforms. For problems of bedform alignment, a new parameter is needed to characterize a multidirectional flow in such a manner that flow toward opposing directions is represented rather than cancelled.

One such parameter is 'gross bedform-normal transport' (Rubin & Hunter, 1987). Transport over any bedform can be resolved into two components, one normal to the bedform trend (Fig. 1) and one parallel to the bedform trend. In a purely unidirectional flow, all transport over perfectly transverse bedforms is bedform-normal, and no transport over longitudinal bedforms is bedform-normal. Where a bedform is subject to two or more transport vectors, bedform-normal transport is defined as the sum of the bedform-normal components. *Net* bedform-normal transport is the sum of the bedform-normal components, considering forward transport across the bedforms to be positive and reverse transport to be negative. *Gross* bedform-normal transport is the sum of the bedform-normal components, considering all transport to be positive. By treating all transport as positive, no transport is lost to the cancellation of opposing vectors.

A complexity arises when determining bedform-normal transport of a flow because the quantity cannot be determined independently of bedform orientation; a single multidirectional flow has different amounts of bedform-normal transport for different arbitrary bedform orientations. Results of the present experiments with subaqueous dunes and the previous experiments with wind ripples indicate that the bedforms take the orientation that for the given pair of flow vectors has the 'maximum gross bedform-normal transport'. This orientation can be determined for any pair of flow vectors using the equation

$$\tan\alpha = \pm\frac{R + |\cos\gamma|}{|\sin\gamma|}, \tag{1}$$

where α is the angle between the dominant transport direction and the bedform trend subject to the maximum gross bedform-normal transport, R is the transport ratio, and γ is the divergence angle (Rubin & Hunter, 1987). The angles are defined in a clockwise direction as indicated in Fig. 1. The minus sign in $\pm$ gives the correct value of α for divergence angles ranging from 0° to 90°, and the plus sign gives the correct value for divergence angles from 90° to 180°. Two solutions (equal maxima) occur for a divergence angle of 90°, as illustrated by the discontinuity at $\gamma = 90°$ in Figs 4 and 10.

Although Eq. (1) cannot be applied to flows with more than two flow vectors, another technique can be used to predict bedform trend in complex natural and experimental flows with any number of flow vectors. For any bedform trend, gross bedform-normal transport can be calculated by resolving every transport vector in the flow cycle into bedform-normal and bedform-parallel components and then summing the absolute values of the bedform-normal components. By calculating this quantity for a large number of arbitrary bedform trends (such as 180 trends in 1° increments, as in the computer code in Appendix 1), the bedform trend having the maximum gross bedform-normal transport can be identified. This technique works for any complex cyclic flow—including complex experimental flows where transport during rotation is considered (Fig. 11).

These experiments have examined bedform alignment only in high-frequency bidirectional flows. Many questions have yet to be investigated regarding the alignment of bedforms in more complex multidirectional flows or in flows that fluctuate with a period comparable to the bedform reconstitution time, so that bedforms are continuously changing throughout each flow cycle. These more complex situations may be responsible for creating such diverse features as star dunes, trains of intersecting and interfering bedforms, and some kinds of superimposed bedforms. Finally, the effects of changes in flow direction on bedform behaviour and internal structure have yet to be examined.

CONCLUSIONS

The dunes studied in these experiments all follow a single rule of alignment: the dunes were formed with the orientation that for the given flow conditions was subject to the maximum gross bedform-normal transport. The orientation of the resulting dunes can be transverse, oblique, or longitudinal to the resultant transport direction. Combined with the previous experiments with wind ripples, the results indicate

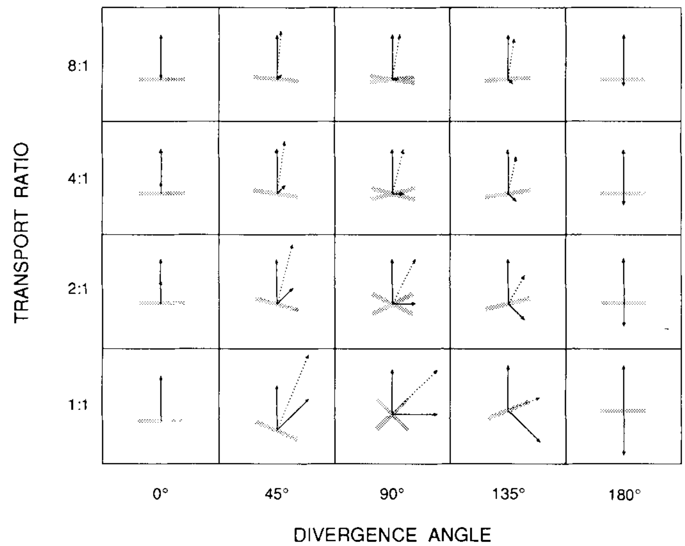

Fig. 10. Diagrammatic version of Fig. 4, illustrating bedform trend as a function of divergence angle and transport ratio. Solid lines are individual transport vectors, dotted lines are resultant transport vectors, and wide grey lines represent the bedform trends subject to maximum gross bedform-normal transport.

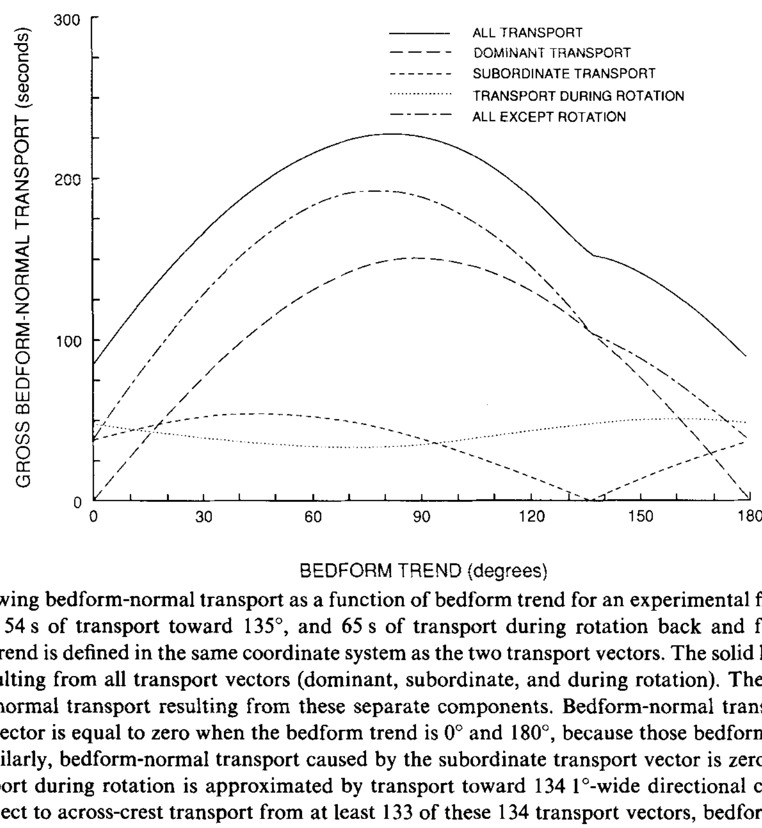

Fig. 11. Diagram showing bedform-normal transport as a function of bedform trend for an experimental flow cycle of 151 s of transport toward 0°, 54 s of transport toward 135°, and 65 s of transport during rotation back and forth between those directions. Bedform trend is defined in the same coordinate system as the two transport vectors. The solid line shows bedform-normal transport resulting from all transport vectors (dominant, subordinate, and during rotation). The dashed and dotted lines show bedform-normal transport resulting from these separate components. Bedform-normal transport caused by the dominant transport vector is equal to zero when the bedform trend is 0° and 180°, because those bedform trends parallel the transport vector. Similarly, bedform-normal transport caused by the subordinate transport vector is zero when the bedform trend is 135°. Transport during rotation is approximated by transport toward 134 1°-wide directional classes. Because any bedform trend is subject to across-crest transport from at least 133 of these 134 transport vectors, bedform-normal transport during rotation is greater than zero for all bedform orientations. For these experimental conditions, the resultant transport direction is 33°, and the predicted dune trend—the trend having the maximum gross bedform-normal transport—occurs for a bedform trend of 80°. This is in good agreement with the observed bedform trend of 70°.

that transverse bedforms are created where the divergence angle is less than 90°, where the transport ratio is large, or where the divergence angle approaches 180°. Longitudinal bedforms are created where the divergence angle is greater than 90° and the transport ratio is 1:1. Formation of longitudinal bedforms does not require flow to be parallel to the bedform; the experimental longitudinal bedforms formed without such flow. Oblique bedforms are created where the divergence angle is greater than 90° and the transport ratio has moderate values (between approximately 1:1 and 8:1, depending on the divergence angle).

The fact that some natural bedforms have been observed to be transverse, oblique or longitudinal to transport does not demonstrate that the bedforms are dynamically different. The experimental transverse, oblique, and longitudinal dunes all follow the same rule of alignment and are intrinsically the same kind of bedform; their alignment relative to the transport direction depends solely on the directional properties of the flow. The fact that the experimental ripples and dunes form with the orientation that is subject to the maximum gross bedform-normal transport is not surprising because ripples and dunes are known to form with transverse orientations in unidirectional flows. Although these results demonstrate that directional properties of a flow can control dune alignment, the results do not consider such effects as flow strength, sediment abundance, sediment cohesiveness, or the possibility that other kinds of bedforms may tend to form with longitudinal orientations in unidirectional flows.

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APPENDIX 1

FORTRAN program to use transport data to calculate the bedform trend having the maximum gross bedform-normal transport.

```
      PROGRAM TREND
c Uses transport data to calculate the resultant transport direction and
c the bedform trend subject to the maximum gross bedform-normal
c transport.

      REAL data(0:359), gross(0:179)
      REAL ewxprt, nsxprt, center, rsltnt, trans, max, pi
      INTEGER i, j, sectrs
      CHARACTER* 32 infil, outfil

c Initialize variables.
      pi=3.14159
      ewxprt=0.0
      nsxprt=0.0

      WRITE(9,*)'Type name of input file to be used, then RETURN'
      READ(9,*) infil
      OPEN (3,file=infil,status='old')
      WRITE(9,*)'Type name of output file to be created, then RETURN'
      READ(9,*) outfil
      OPEN (4,file=outfil,status='new')

c The first line of the input file must list the number of sectors into
c which transport is divided.  The maximum number of sectors is 360.
c The first line must also contain the angle from north to the central
c value of the first sector (for example, 5° if the first sector ranges
c from 0° to 10°).
c The data array is read from an input file and gives the amount of
c transport TOWARD each sector, starting with the first sector and
c proceeding clockwise around the compass.
      READ (3,*) sectrs, center

      do 10, j=0,sectrs-1
c Read transport vectors.
        READ (3,*) data(j)
c Resolve transport vectors into north-south and east-west components.
        ewxprt=ewxprt+data(j)*(sin(((j*2*pi)/sectrs)+
     &     (center*pi/180.0)))
        nsxprt=nsxprt+data(j)*(cos(((j*2*pi)/sectrs)+
     &     (center*pi/180.0)))
10    CONTINUE

c Calculate and write direction and magnitude of resultant transport
c vector.
      rsltnt=atan2(ewxprt,nsxprt)*(180.0/pi)
      WRITE (4,*) 'Resultant transport direction =', rsltnt,' degrees'
      trans=SQRT((ewxprt**2)+(nsxprt**2))
      WRITE (4,*) 'Net transport =',trans,' units specified in input'

c Write heading for table.
      WRITE (4,*) 'BEDFORM TREND (DEGREES)
     &       GROSS BEDFORM-NORMAL TRANSPORT'
c Calculate gross bedform-normal transport for all possible bedform
c trends (at 1° increments).
      do 100, i=0, 179
        gross(i)=0.0
        do 90, j=0,sectrs-1
          gross(i)=gross(i)+(ABS(sin(((+(center*pi/180)+((j*2.0*pi)
     &        /sectrs))-(i*pi/180.0))))*data(j))
90      CONTINUE
        WRITE (4,*) '        ', i, '
     &    gross(i)
100   CONTINUE

c Identify maximum value of gross bedform-normal transport.
      max=0.0
      do 150, i=0,179
        IF(gross(i).gt.max)max=gross(i)
150   CONTINUE

c Identify all bedform trends having a value of gross bedform-normal
c transport equal to the maximum.
      do 180, i=0,179
      IF(gross(i).eq.max)THEN
        WRITE (4,*) 'TREND WITH MAXIMUM BEDFORM-NORMAL TRANSPORT ='
     & ,i , '   degrees'
      ENDIF
180   CONTINUE

      CLOSE(3)
      CLOSE(4)

      END
```

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