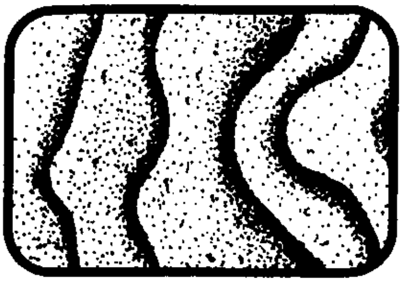

Preservation of Cross-strata Due to Migration of Subaqueous Dunes Over Aggrading and Non-aggrading Beds: Comparison of Experimental Data with Theory

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SUMMARY

An experimental study of the preservation of cross strata during the migration of dunes under aggrading and non-aggrading conditions was conducted in order to test the Paola-Borgman (1991) theory for distribution of cross-set thickness as a function of the distribution of bed-wave height. The theory needed to be modified to deal with aggrading conditions (Bridge and Best, 1997). The geometry and migration characteristics of the dunes (determined using an ultrasonic depth profiler and visual observations) are typical of sinuous-crested dunes observed in rivers and other flumes. These characteristics do not vary systematically with aggradation rate. As part of the test of theory, a two-parameter gamma density function was fitted to histograms of dune height and dune trough elevations relative to two different reference datums. The parameters of these fitted functions do not vary in the way predicted by Paola and Borgman because: 1) dune height does not correlate very well with dune trough elevation, and; 2) choice of reference datum has a major, unanticipated effect on parameter values.

Most cross sets were formed by only the highest 10% of the dunes. Mean cross-set thickness/mean *formative* bed-wave height ranges from 0.18 to 0.3. Cross-set thickness does not vary systematically with aggradation rate in these experiments because the primary control of set thickness is the variability of dune height. Mean cross-set thickness is predicted quite well using the modified Paola-Borgman theory if:1) dune height is used as a proxy for dune trough elevation but certain parameter values are modified, or; 2) an appropriate datum is used for defining dune trough elevations. A simple method is proposed for estimating the height distribution of dunes from the thickness of their sets of medium-scale cross strata.

RÉSUMÉ

Une étude en laboratoire a été menée pour étudier la préservation des sets sédimentaires pendant la migration de dunes, en milieux d'aggradation et de non-aggradation ; cette étude visait à tester la théorie de Paola-Borgman (1991) sur la variation de l'épaisseur des sets sédimentaires en fonction de l'amplitude des éléments topographiques du plancher sédimentaire. La théorie doit être modifiée pour tenir compte des conditions particulières des milieux d'aggradation (Bridge and Best 1997). La géométrie et les caractéristiques migratoires des dunes (données d'observations visuelles et de levés par profileur ultrasonique) sont typiques des caractéristiques des dunes à crêtes sinueuses observées, autant dans les chenaux artificiels que dans les rivières. Ces caractéristiques ne varient pas directement avec le taux d'aggradation. Parmi les mesures visant à tester la théorie, une fonction de densité gamma a été adaptée pour rendre compte du profil des histogrammes de répartition de la hauteur des dunes et de l'élévation de leurs cuvettes d'affouillement, mesurées à partir de divers niveaux de référence. Les paramètres de ces fonctions adaptées ne varient pas selon les prévisions de Paola-Borgman parce que : 1) la corrélation observée entre les hauteurs de dune et l'élévation de leurs cuvettes d'affouillement n'est pas adéquate, et 2) le choix des niveaux de référence influence de manières importante et imprévue la valeur des paramètres.

La plupart des sets sédimentaires ont été formés par les 10 % les plus élevées des dunes. Les valeurs du rapport de l'épaisseur moyenne des sets sédimentaires sur la hauteur moyenne des dunes dont elles sont issues s'étendent de 0,18 à 0,3. Dans ces expériences, l'épaisseur des sets sédimentaires ne varie pas directement selon le taux d'aggradation, l'épaisseur des sets sédimentaires variant surtout avec la hauteur des dunes. L'épaisseur des sets sédimentaires peut être prédite de manière fiable en se basant sur la théorie modifiée de Paola-Borgman, à condition 1) que la hauteur des dunes soit le facteur utilisé plutôt que l'élévation de la cuvette d'affouillement et que certains paramètres soient modi-

List of Symbols

a	Inverse of mean value of exponential tail of probability density function of topographic height
c	Bed-wave celerity (downstream migation rate)
d	Mean flow depth
h	Bed-wave height
h_m	Mean bed-wave height
h_{sd}	Standard deviation of bed-wave height
i	Volume of sediment (plus pore space) transported in a bed form per unit width and time
l	Length (spacing) of bed waves
$p(s)$	Probability density function of stratal thickness
$p(h)$	Probability density function of bed-wave height
r	Aggradation rate
s	Thickness of cross-stratal set
s_m	Mean thickness of strata
s_{sd}	Standard deviation of stratal thickness
α,β	Parameters in gamma density function
Γ	Gamma function
δ	Angle of climb of bed waves relative to mean bed level

fiés, ou 2) qu'un niveau de comparaison approprié soit choisi pour établir l'élévation des cuvettes d'affouillement. Une méthode simple est proposée permettant d'estimer la distribution de la hauteur des dunes à partir de l'épaisseur de leurs sets sédimentaires.

INTRODUCTION

Cross strata formed by the migration of subaqueous ripples and dunes are very common in sands and sandstones. Despite this, we do not yet have a good quantitative understanding of what controls the geometry of sets of cross strata. It has been established that the thickness of cross-strata sets within cosets, as seen in cross sections parallel to the mean flow direction, depends on: 1) average deposition rate relative to the downstream migration rate of the bed waves; 2) the succession of bed waves of varying height (or scour depth) passing through the cross section, and; 3) changes in the height and migration rate of individual bed waves as they migrate (reviews in Allen, 1982; Rubin and Hunter, 1982; Paola and Borgman, 1991; Best and Bridge, 1992; Bridge and Best, 1997).

In the case of bed waves of constant (in time and space) geometry and downstream migration rate under conditions of steady deposition (see control 1 above), the thickness of cross sets, *s*, is constant and given by:

$$s = l\, r / c = l \tan \delta \qquad (1)$$

where *l* is length (spacing) of bed waves, *r* is mean vertical deposition rate, *c* is mean bed-wave migration rate, and δ is the angle of climb relative to mean bed level. For bed waves that are approximately triangular in cross section parallel to the mean flow direction, the volume of sediment (including pore space) transported per unit width and time, *i*, is approximately

$$i = h\, c / 2 \qquad (2)$$

where *h* is bed-wave height. Substituting for *c* in Equation (1) gives

$$s = l\, h\, r / 2\, i \qquad (3)$$

Equation (3) is the basis for the common assumption that cross-set thickness is related to bed-wave height. However, bed-wave height is only one of several variables involved. Furthermore, the geometry and migration rate of bed waves cannot be assumed constant, and Equation (1) is not generally applicable.

Paola and Borgman (1991) addressed control 2 above, and developed a theoretical equation for the probability density function (PDF) of bed-wave heights that could be related to the PDF of cross-set thickness. They did not consider controls 1 and 3, assuming no net deposition and that bed waves did not change in height as they migrated. Their equation for the PDF of cross set thickness, *p(s)*, is:

$$p(s) = a\, e^{-as} \left(e^{-as} + as - 1 \right) / \left(1 - e^{-as} \right)^2 \qquad (4)$$

where 1/*a* is the mean value of the exponential tail of the PDF of topographic height relative to a datum, and *a* is inversely related to the breadth of the tail of the height distribution. The mean value of *s* is 1.64493/*a* and the standard deviation is 1.44997/*a*. In order to test the applicability of Equation (4), it is necessary to measure distributions of cross-set thickness and bed-wave height at a specific location on the bed under conditions of no net aggradation. As explained by Paola and Borgman, when *a* is derived from bed-wave height data, its value must be doubled before it is used in Equation (4) to predict the distribution of stratal thickness. Thus, the mean stratal thickness, s_m, will be 0.8225/*a* and the standard deviation, s_{sd} is given by 0.725/*a*. Paola and Borgman pointed out that it is useful to fit a two-parameter gamma density function to the measured distribution of bed wave heights, *h*:

$$p(h) = h^{\alpha - 1}\, e^{-h/\beta} \;/\; \beta^{\alpha}\, \Gamma(\alpha) \qquad (5)$$

where α and β are parameters and Γ is the gamma function. This particular density function is useful because $\beta = 1/a = h_{sd}^2 / h_m$, $a = h_m^2 / h_{sd}^2$, and therefore the expected stratal thickness and standard deviation are $0.8225\, h_{sd}^2 / h_m$ and $0.725\, h_{sd}^2 / h_m$, respectively. Here, h_m and h_{sd} are the mean and standard deviation of the bed-wave height distribution, respectively.

Data required to test the Paola-Borgman theory (measured distributions of cross-set thickness and formative bed-wave height) are extremely rare. However, Best and Bridge (1992) and Bridge and Best (1997) measured time series of bed-wave height at a point for low-relief (mm in height) bed waves on upper-stage plane beds, under conditions of net deposition, and then directly related each preserved lamina (equivalent to a cross set) to its formative bed wave. Thus, the effects on lamina (or cross-set) thickness of controls 1 and 2 above were explored. It was determined that only the largest-height bed waves in a population leave a depositional record, and that the thickness of sediment preserved is generally only a small fraction of formative bed-wave height (less than 50% in this case). Thus, it is difficult to relate lamina (or cross-set) thickness to the geometry of the *average* bed wave in a population. Bridge and Best (1997) adapted Paola and Borgman's (1991) theoretical model for the PDF of stratal thickness in terms of the PDF of bed-wave heights for aggrading conditions:

$$\begin{aligned} s_m &= l\, r / c + 0.8225 / a = \\ &\; l\, r / c + 0.8225\, h_{sd}^2 / h_m \end{aligned} \qquad (6)$$

This revised model agreed remarkably well with experimental data.

The type of experimental-theoretical study performed by Bridge and Best (1997) has not been performed for migrating dunes or ripples, and the simultaneous effect on cross-set thickness of all three controls mentioned above has never been examined experimentally or theoretically. In this paper we report on an experimental-theoretical study similar to that of Bridge and Best, but for the case of dunes migrating under aggrading and non-aggrading conditions. Cross strata formed by ripples will be examined in a subsequent paper (Storms, Van Dam and Leclair, submitted), as will control 3 above.

EXPERIMENTAL APPARATUS AND PROCEDURE

Experiments were conducted at the Department of Geological Sciences, Binghamton University, using a hydraulic flume 7.6 m long, 0.6 m wide, and 0.4 m deep that recirculates water and sediment (see Best and Bridge, 1992). The sediment used was moderately well-sorted silica sand with a median diameter of 0.42 mm. A conveyer belt at the flume entrance allowed sediment to be added to the channel at different, accurately controlled feed rates. This sediment-feed method results in steady sediment aggradation throughout the length of the flume (see Bridge and Best, 1997). Four experiments were conducted with different aggradation rates, including one run with no net deposition. Flow condi-

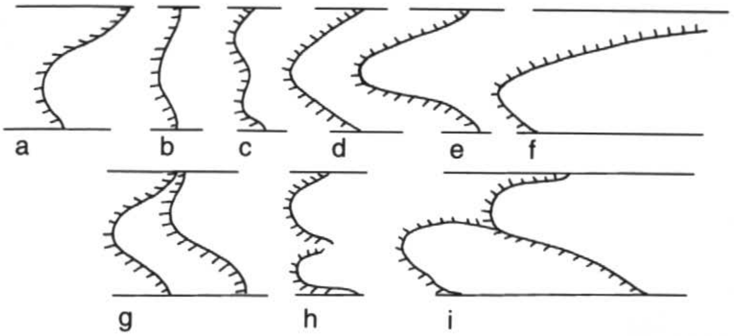

Figure 1 *Examples of crestline shapes and orientation of dunes as observed in plan. The most frequent dune shape is illustrated in* (**a**). *Dune crests do not always extend across the flume width* (**e**, **f**, *and* **h**) *and dunes are generally not evenly spaced* (**g** *and* **i**).

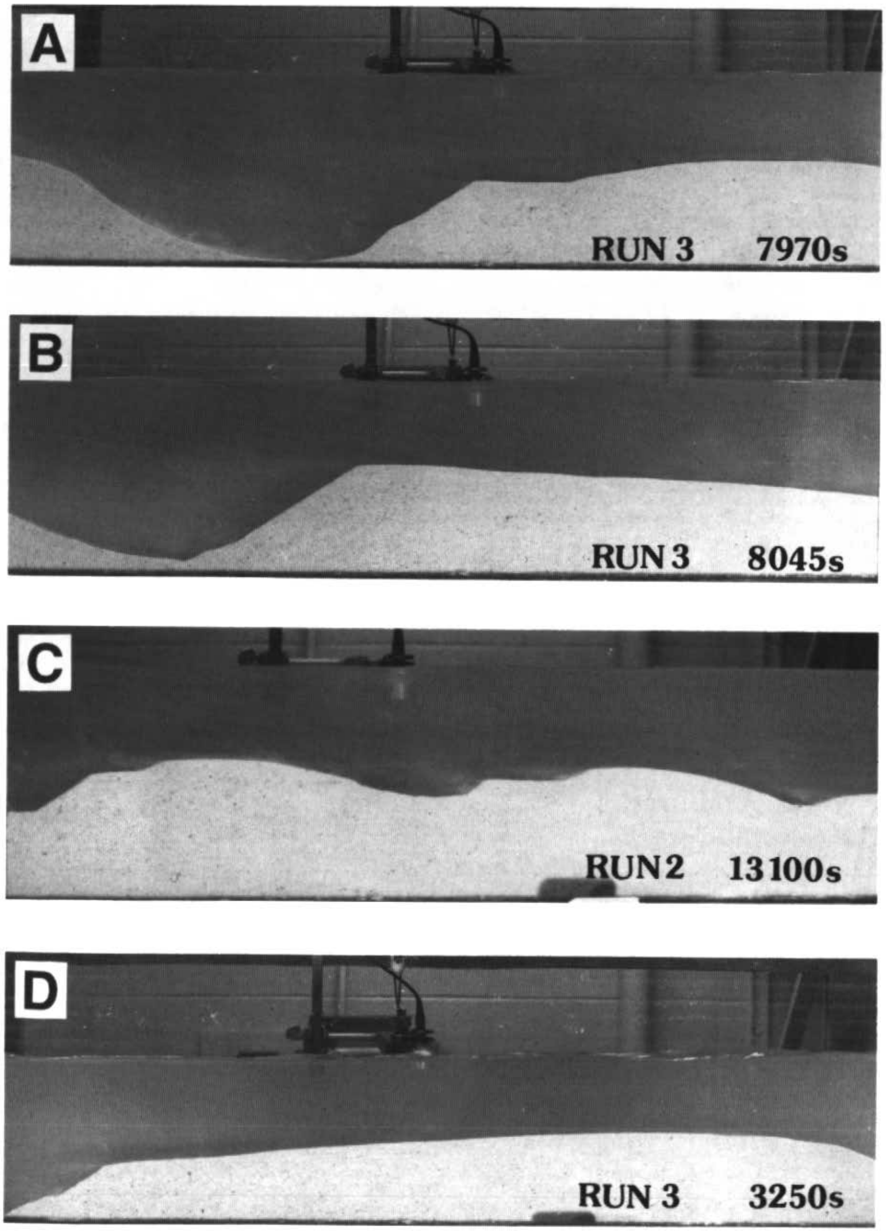

Figure 2 *Alongstream profiles of dunes.* (**A**) *dune with superimposed bedwave that is migrating faster than the host dune.* (**B**) *superimposed bedwave in* (**A**) *has migrated to the crest of the host dune, adding to its height.* (**C**) *dunes with smaller superimposed bedwaves.* (**D**) *humpbacked dune. Run number and time in seconds from beginning of run are indicated.*

tions were similar for all experiments: water temperature ranged from 18° C to 20° C, flow depth was 0.13 m, and mean flow velocity was 0.6 $m \cdot s^{-1}$. These flow conditions correspond to the middle of the dune existence field (Southard and Boguchwal, 1990).

At the start of each experiment, the flume was set to produce the desired hydraulic conditions and allowed to run for a few hours without sediment feed to establish uniform, equilibrium flow. In order to ensure that the hydraulic conditions remained constant during the runs with sediment aggradation, it was necessary from time to time to add water to the flume (to replace that lost in the pore spaces of deposited sediment) and to increase the pump power of the flume (as there was more water to recirculate).

Bed height was measured at 5 second intervals in the centre of the test section (located in order to avoid flume entrance and exit effects: see Best and Bridge, 1992) using an ultrasonic depth profiler that gives bed height to within 0.1 mm (details of profiler in Best and Ashworth, 1994). These bed-height records allowed measurement of the height and scour depth of all bedforms passing under the profiler, plus the rate of aggradation. In addition, visual observations were made, and 35 mm photographs were taken through the side walls of the flume, in order to determine dune length and celerity, dune shape in plan and profile, spatial relationships among different dunes, and the nature of smaller superimposed bedforms. The time when each dune crest was under the transducer was also noted.

The flow was stopped when sediment thickness in the test section reached about 200 mm, and the flume was drained. Box cores (200 mm x 150 mm x 80 mm) were taken from the test section and epoxy-resin peels were made from the cores. We measured cross-set thicknesses at five different vertical sections on each box-core peel, including one immediately beneath the transducer. The vertical sequence of cross sets beneath the transducer position could then be compared with that expected from the bed-height records and each set could be matched with a specific formative bedform. Furthermore, the distribution of observed cross-set thicknesses could be compared with theory. The other vertical-section measurements would show how individual and mean cross-set thickness vary downstream and laterally.

RESULTS AND ANALYSIS

Visual Observations of Bedform Geometry and Migration

Dunes had crestlines that were curved in plan, and parts of crestlines were commonly oblique to the flume walls (Fig. 1). The elevations of the crest and trough of any dune varied across the width of the flume, and flow-parallel spurs occurred commonly in dune trough regions. Dune crestlines did not always extend across the full width of the flume (Fig. 1). Alongstream profiles of dunes were rarely simple triangular shapes (Fig. 2). Smaller bedforms were commonly superimposed on the stoss sides of the larger forms. Humpbacked dunes occurred at times (Fig. 2).

The geometry and migration rate of dunes varied markedly in time and space. New dunes may arise by creation and growth of bedforms on the stoss sides of existing dunes, and relatively rapidly migrating dunes may catch up with downstream dunes, thereby replacing them (see also Gabel, 1993). This made it difficult to define dune height, length and celerity very accurately. For practical purposes, dunes were defined as those asymmetrical bedforms with lengths greater than 600 mm (Allen, 1982; Gabel, 1993) and periods greater than 250 s. They were observed as they passed through the test section over a distance of approximately 0.30 m. As mean dune migration rates were typically around 2 mm·s^{-1}, and mean lengths were around 900 mm (Table 1), their mean periods were on the order of 450 s.

Analysis of Time Series of Bed Height

Time series of bed height (Fig. 3) indicate that aggradation rate was constant in each run and that dunes did not systematically vary in height with time. Aggradation rate was determined from the slope of the linear regression of bed height versus time (Table 1). Expanded versions of these bed-height time series (*e.g.*, Fig. 4) were used to define distributions of dune height and scour depth. Under certain conditions, the ultrasonic depth profiler recorded reflections from the base of the flume rather than the sediment surface. Such clearly erroneous data points were removed prior to definition of dune heights and scour depths. Determination of dune trough elevations (scour depths) is straightforward, in contrast to dune height. Time series of bed height will only represent alongstream profiles of dunes if the dunes do not change shape or celerity as they migrate. In fact, the shape and celerity of dunes varied in time markedly (see previous section, and Fig. 2), making it difficult to define their height accurately.

The bed-height time series (Fig. 4) show fluctuations of bed height of different height and period. The highest, longest period fluctuations ($h > 30$ mm; period > 250 s) with asymmetrical shapes are clearly dunes. The top of the steep lee slope (brink point) of each dune was identified on the time series (Fig. 4), and this time of occurrence was checked against the time when the brink point of that dune was actually observed to pass under the transducer. For the purposes of this study, the height of the dune was taken as the difference in elevation between the brink point and the immediately preceding trough (Fig. 4). The brink point was used rather than the crest because it is difficult to define the crest elevation when there are superimposed bedforms, and when bedforms are changing height with time.

The bedforms superimposed on the backs of dunes, with smaller heights and

Table 1 Bedform characteristics

Run number	**1**	**2**	**3**	**4**
Run period (sec)	42,140	75,135	32,350	17,840
Aggradation rate (mm/sec)	0	0.001	0.003	0.009
Number of dunes (and scours) in bed profiler records	76	100	61	26
Mean height (h_m) from bed profiler records (mm)	48.3	53.1	46.9	52.29
Variance ($h_{sd}{}^2$) (mm^2)	463.85	684.58	422.58	426.9
Co-efficient of Variation (h_{sd}/h_m)	0.45	0.48	0.44	0.39
$a = h_m/h_{sd}{}^2$ (from bed profiler records) (mm^{-1})	0.104	0.082	0.111	0.122
Mean scour depth (sc_m) below upper datum	59.1	62.9	58.9	71.9
Variance ($sc_{sd}{}^2$) (mm^2)	587.2	853.8	480.2	930.4
Co-efficient of Variation (sd_{sd}/sc_m)	0.41	0.46	0.37	0.42
$a = sc_m/sc_{sd}{}^2$ (from bed profiler records) (mm^{-1})	0.101	0.074	0.12	0.077
Number of scours under mean bed height datum	64	94	54	25
Mean scour depth (sc_m) (mm)	27.7	35.9	29.9	40.7
Variance ($sc_{sd}{}^2$) (mm^2)	492.2	792.5	392.5	824.4
Co-efficient of Variation (sc_{sd}/sc_m)	0.80	0.78	0.66	0.71
$a = sc_m/sc_{sd}{}^2$ (from bed profiler records) (mm^{-1})	0.056	0.045	0.076	0.049
Mean length (l_m) from side-wall observations (mm)	861	834.6	890	938
Standard Deviation	275	280.3	298	341
Co-efficient of Variation	0.32	0.34	0.33	0.36
Mean celerity from side-wall observations (mm/sec)	2.2	1.4	1.5	2.7
Standard Deviation	0.7	0.63	1.02	1.2
Co-efficient of Variation	0.32	0.45	0.68	0.44
h_m/l_m	0.056	0.064	0.053	0.056
h_m/d	0.37	0.41	0.36	0.40
l_m/d	6.6	6.4	6.8	7.2

periods, can be recognized fairly easily on the time series (Fig. 4). However, some of the smaller fluctuations could be due to the migration of trough spurs under the transducer, or migration of the edge of a dune into and out of the plane of the profiler. The smallest fluctuations in bed height are possibly due to turbulent fluctuations in the height of the bedload layer. These smaller scale bed-height fluctuations were not considered in this analysis because most are not dunes, and Paola and Borgman's theory only applies to single classes of bedforms (not superimposed bedforms).

In determining the distribution of dune trough elevations (scour depths), it is necessary to define a datum from which measurements are made. One datum used was the linear regression line calculated for all bed height: time data for a given run. This is more-or-less equivalent to the mean bed elevation, which rises gradually through time due to aggradation. Another datum line that was used is parallel to the regression-line datum but passes through the crestlines of the highest dunes (Fig. 6).

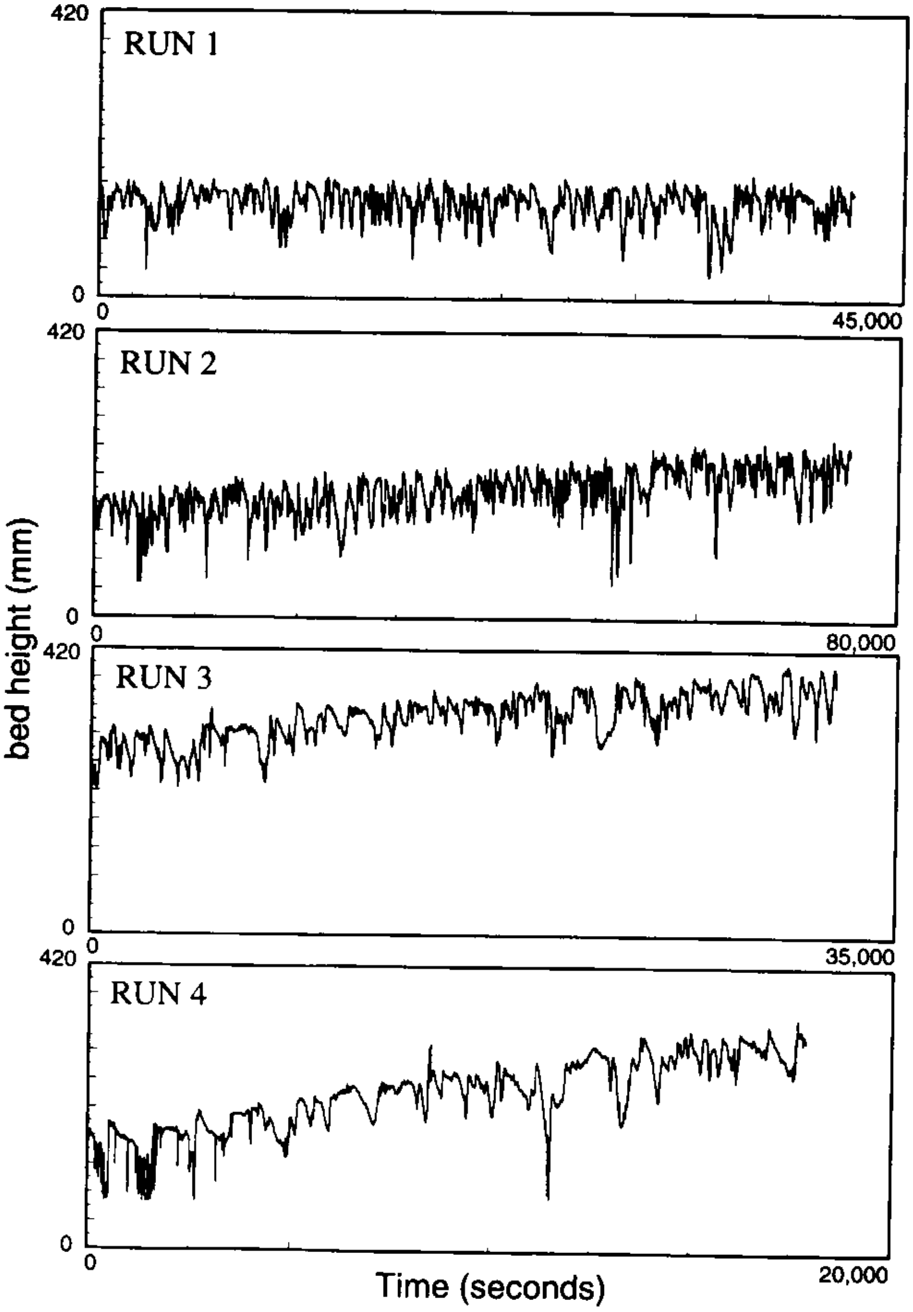

Figure 3 *Time series of bed height obtained using the ultrasonic depth profiler for runs 1 to 4. Bed-height fluctuations are due to passage of dunes and superimposed bedwaves under the transducer. Overall linear trend indicates constant aggradation rate, increasing from run 1 to run 4.*

Dune Characteristics

The ratios of mean height/depth, mean length/depth, and mean height/mean length of dunes range from 0.37 to 0.41, 6.4 to 7.2, and 0.053 to 0.064, respectively (Table 1). These values are typical of sinuous-crested dunes observed in rivers and laboratory flumes (Allen, 1982; Gabel, 1993; Yalin, 1992). There appear to be no systematic variations in these geometric parameters, nor mean celerity, with aggradation rate (Table 1).

Variations in the height, length and celerity of dunes observed at any cross section reflect lateral and temporal variation in these parameters for individual dunes, as well as variation between dunes. The coefficients of variation of these parameters are similar to those observed by Gabel (1993) for river dunes, and they do not appear to vary with aggradation rate (Table 1).

The number of dune troughs (scours) below the mean-height datum is less than the total number of dunes measured (Table 1) because some dune troughs lie above this datum. Thus, the choice of datum may influence the variance of the dune trough elevations. As with dune height, there is no systematic variation in the means and coefficients of variation of the trough elevations with aggradation rate.

Theoretical Distribution of Dune Height and Scour Depth

The two-parameter gamma density function (Equation 5) was fitted to histograms of observed dune height and scour depth in order to determine the a value in Equations 4 and 6 (Figs. 5 and 6). For each run, we defined different class intervals for the histograms and used least squares minimization techniques for fitting (Powell, Marquadt-Levenberg and Simplex). The fitting techniques usually gave similar results, although the Powell technique was not always successful and the Marquadt-Levenberg technique gave more variability in the fitted parameters as class interval was varied. Therefore the Simplex method was used in most cases. Values of the parameters of the fitted gamma density function are critically dependent on the shape of the exponential tail of the histogram, that is dependent on the number of class intervals used. However, the variation in parameter a for different class intervals and fitting methods was usually not very great (Table 2). The range of values of *a* in Table 2 for each run reflects the variation of histogram shape with varying class interval.

Values of *a* determined for dunes average 0.1 mm^{-1}. There is no systematic variation in *a* with aggradation rate, as was the case for low-relief bedwaves on upper stage plane beds (Bridge and Best, 1997). Values of *a* for these low-relief bedwaves ranged from 0.26-0.41 mm^{-1}, much greater than the values determined here. Values of *a* for ripples are typically 0.15-0.2 mm^{-1} (Storms *et al.*, submitted; Paola and Borgman, 1991). Thus *a* systematically decreases as the heights of bed waves increase.

Histograms of scour depths depend on the choice of datum (Fig. 6). If the datum is taken as the least-square regression line for bed height (local mean bed height), some of the dune troughs are above the datum, and will not be included in the analysis. If the datum is raised to and above the crests of the dunes, all dune troughs are included in the analysis. Thus, the effect of raising the datum is to increase the mean scour depth markedly but to increase the variance only slightly (Fig. 6; Table 1). The result is an increase in *a* as the datum is raised (Fig. 6; Table 1).

According to Paola and Borgman (1991), the value of *a* based on dune height should be twice the value based on scour depth for a datum at the mean bed level. The basis for this assertion is that, with the idealized geometry shown in Figure 7, dune heights will be twice as large as their scour depths below the datum. Thus, the variability of dune height will be twice as much as the variability of scour depth, and the value of *a* will be half as much for dune height as it will be for scour depth. However, Figure 3 shows that the deepest dune troughs are not necessarily associated with the greatest elevations above local mean bed level. The deepest scours are actually associated with the largest-height dunes that migrate in temporarily low regions of the bed. Thus, use of dune height to estimate scour depth leads to underestimation of scour depth, and overestimation of *a* in Equation 6. Indeed, values of *a* based on dune height are not half as much as those based on scour depth below mean bed level (Table 2). Therefore, it may be necessary to increase the value of the constant 0.8225 in Equation 6 if using dune height as a proxy for scour depth. If a datum for scour depth is used parallel to the mean bed elevation but near the crests of most dunes (Fig. 7), the correlation between dune height and scour depth is better (Fig. 6). Furthermore, use of this datum has the advantage of including all dune troughs. Not surprisingly, *a* values for scour depths relative to this datum are similar to those for dune height.

A final point here is that the fitted values of *a* may not represent the extreme tails of the distributions of dune height or dune trough elevation very well because the gamma density function is fitted to the whole histogram. However, it is these extreme tails that are of most concern when predicting the preservation of cross strata.

Dune Preservation and Cross-set Thickness

The expected cross-set thicknesses in the deposit under the transducer are given by the difference between the successive elevations of the deepest trough scours, and each cross set can be related to a specific dune (Fig. 8). The mean set thickness does not systematically increase with aggradation rate for the first three runs, but the largest sets are associated with the largest aggradation rate (Table 3). The mean set thicknesses measured on the epoxy peels agree well with expected set thicknesses from the profiler records (Fig. 8, Table 3). Observed mean set thicknesses tend to be slightly larger, and standard deviation is lower, than expected from the profiler records, because thin sets could not always be identified on the peels.

More than 80% of all preserved sets were formed by dunes with heights larger than the 90th percentile of height. There is no evidence that increasing aggradation rate results in preservation of more cross sets from smaller dunes. The ratio of set thickness/formative dune height

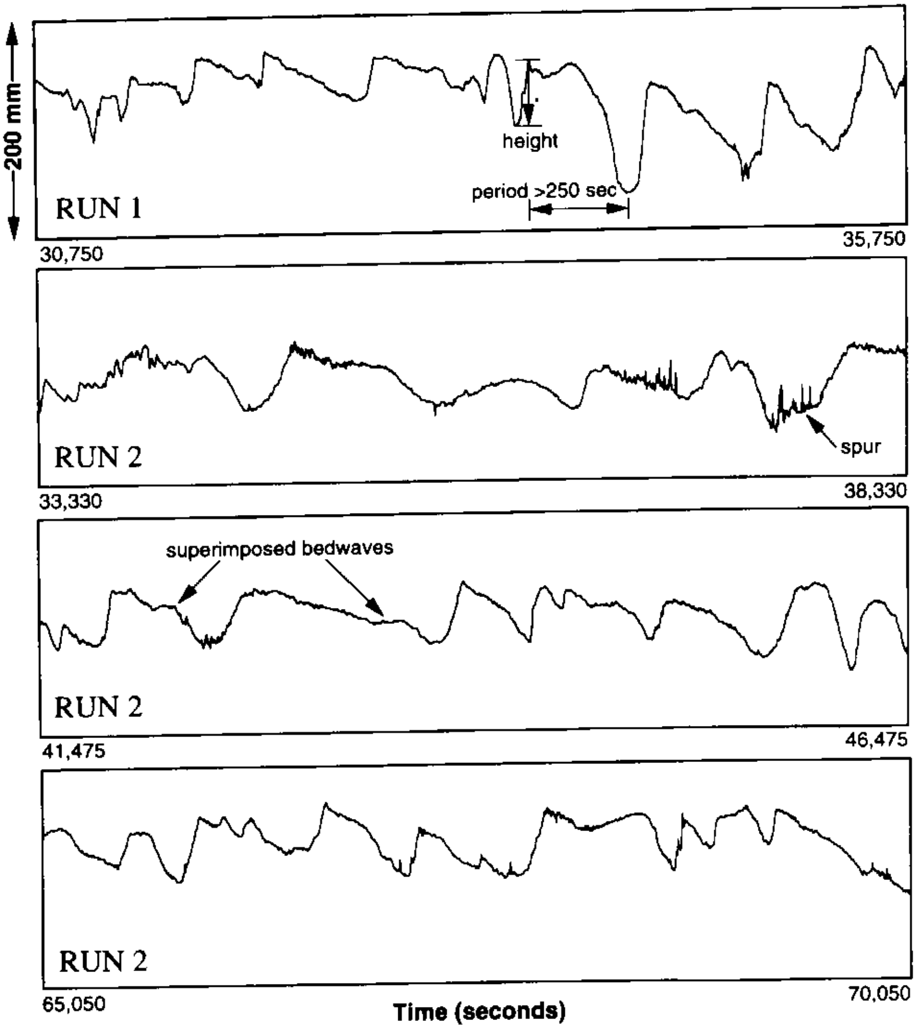

Figure 4 *Examples of expanded bed-height time series, indicating definition of dunes, superimposed bedwaves, dune height and dune period.*

for individual dunes is less than 0.5, and there is a large range (Fig. 9). This ratio shows no clear relationship with aggradation rate. The ratios of mean set thickness/mean formative dune height and mean set thickness/mean dune height (Table 3) do not vary much for runs 1 to 3, but are largest for the largest aggradation rate (run 4). These ratios are similar to those calculated by Bridge and Best (1997) for laminae formed by low-relief bedwaves. However, in the latter case the ratios more clearly increased with aggradation rate. The reason for this difference is probably related to the relative magnitude of the two terms in Equation 6. In the present experiments, the first term (due to aggradation) is generally smaller relative to the second term (due to variance in bedwave height) than in Bridge and Best's experiments.

Along-stream and cross-stream variations in cross-set thickness are shown in Figure 10. Alongstream variations are due to changes in elevation of troughs as dunes migrate downstream. The mean set thickness for all sets in all the verticals measured for a given run is similar to the mean set thickness for the vertical under the transducer (Table 3). Cross-stream variation in set thickness is generally greater than along-stream variation, because these are trough cross strata (Fig. 10, Table 3).

Comparison of Observed Cross-set Thickness with Theory

An initial simple method of establishing whether the distribution of cross-set thicknesses follows Equation 4 is to compare the coefficient of variation for the non-aggradation case with the theoretical value of 0.881 (Paola and Borgman, 1991). The observed value of 0.65 is reasonably close to theory.

If the height distribution of dunes is used to predict the distribution of set thickness with Equation 6, the variance of height is too low, and the predicted mean and standard deviation of set thickness are underestimated (Table 4). However, if the constant 0.8225 is increased to say 1.5, as suggested previously, the agreement improves (Table 4).

If the distribution of scour depths of dunes, using a datum at local mean bed level, is used to predict the distribution of set thickness (using Equation 6 with the constant 0.8225 replaced with 1.645), the mean set thickness is greatly overpredicted because the variance of scour depth is too large (Table 4). However, if the scour depths of dunes are

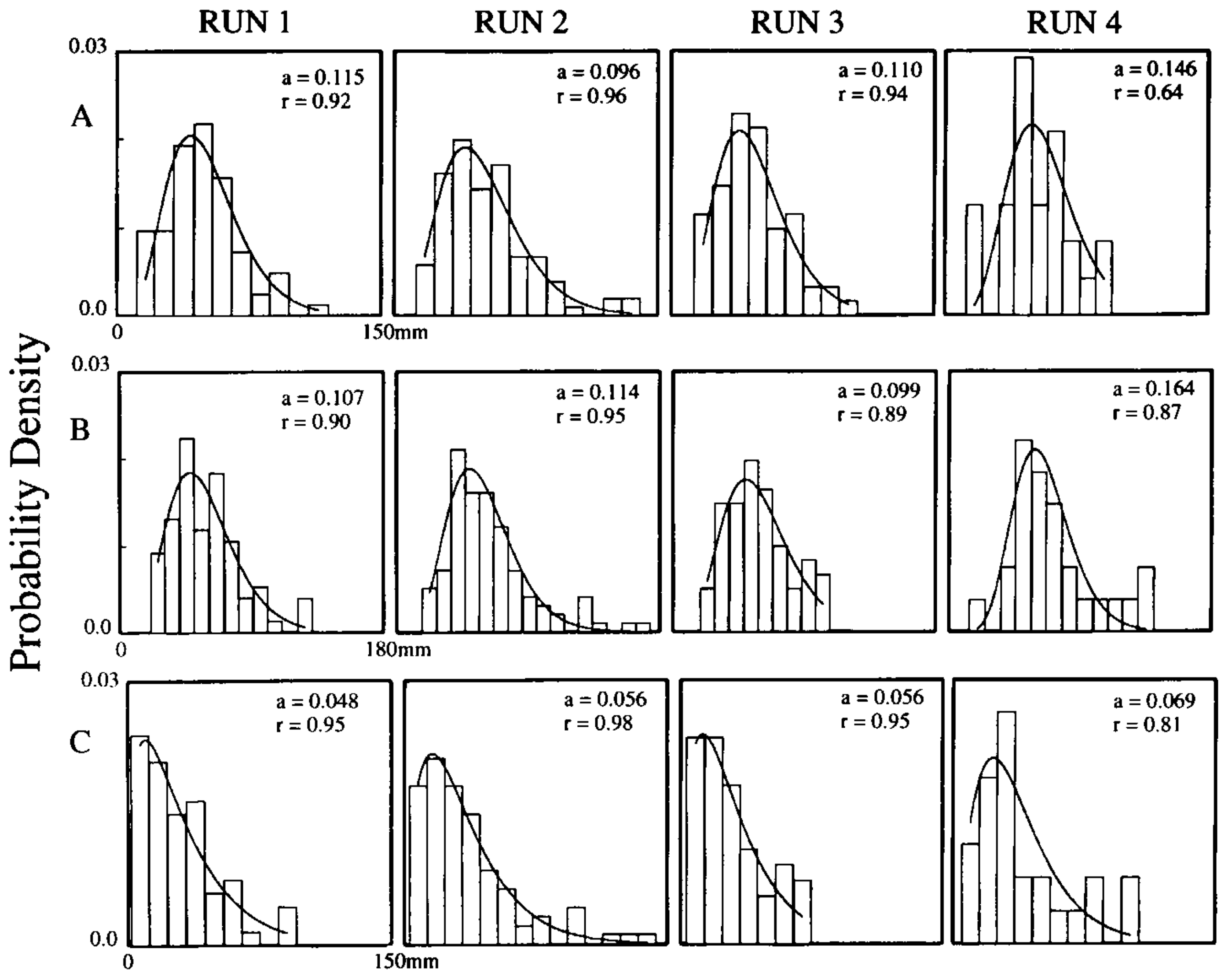

Figure 5 *Histograms of dune height* (**A**) *and dune trough elevation relative to the upper reference datum* (**B**) *and mean bed-height datum* (**C**) *for all runs, with fitted gamma functions.*

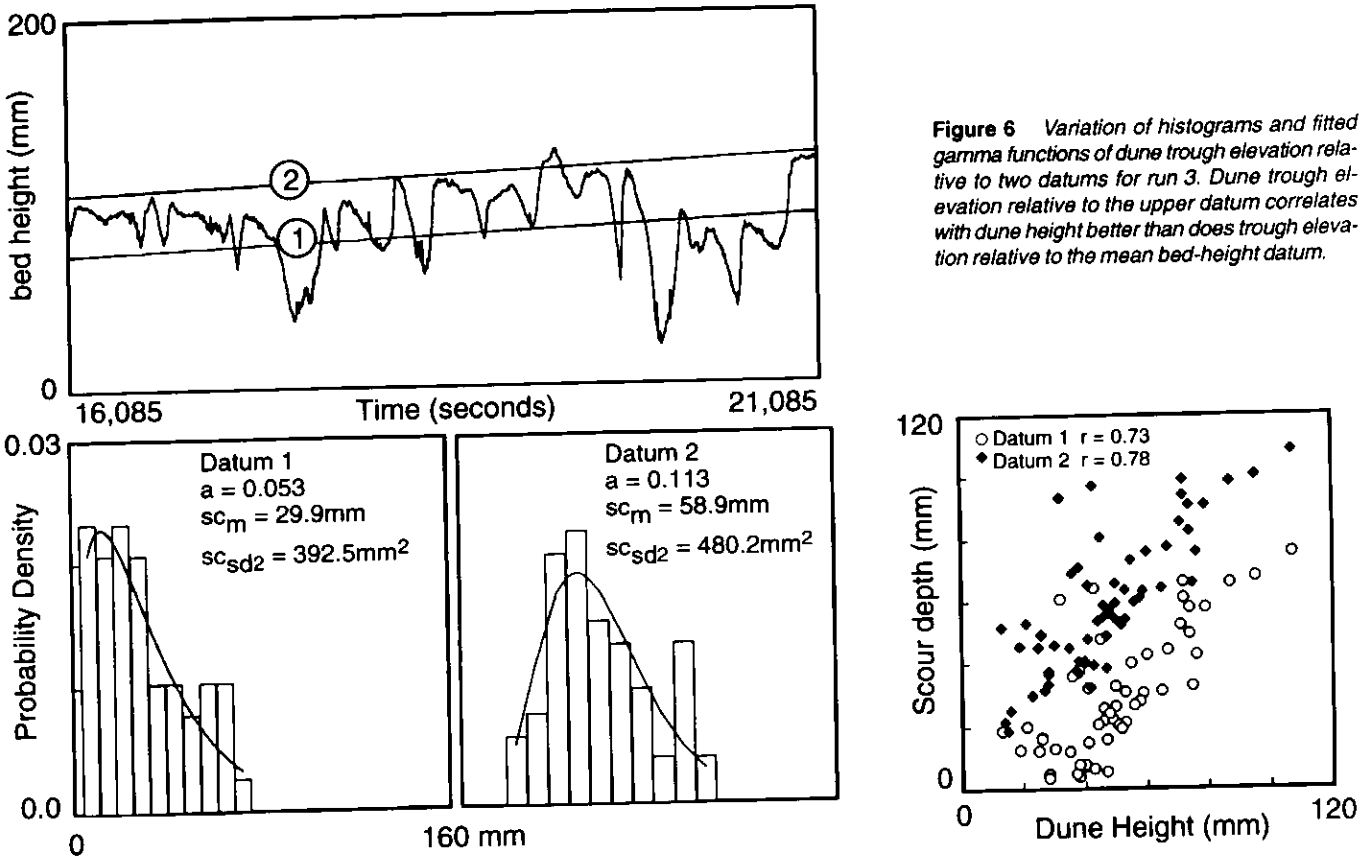

Figure 6 *Variation of histograms and fitted gamma functions of dune trough elevation relative to two datums for run 3. Dune trough elevation relative to the upper datum correlates with dune height better than does trough elevation relative to the mean bed-height datum.*

Table 2 Ranges of gamma density function parameters α, β and *a* (1/β) fitted to histograms of dune height, and scour depths below two datums, using 5 to 15 classes in the histograms.

	RUN 1	RUN 2	RUN 3	RUN 4
Dune height				
α	5.72-5.97	4.5-4.99	4.6504.78	4.85-7.21
β	8.69-8.44	10.37-11.61	10.17-9.99	12.22-7.83
a = 1/β	0.115-0.118	0.096-0.086	0.098-0.10	0.082-0.128
Correlation (r)	0.99-0.89	0.99-0.96	0.96-0.85	0.86-0.45
Scour depth below upper datum				
α	5.81-6.10	6.97-9.42	6.66-6.88	7.26-11.15
β	10.35-9.33	5.41-8.09	8.52-8.47	8.71-5.69
a = 1/β	0.097-0.107	0.185-0.124	0.117-0.118	0.115-0.176
Correlation (r)	0.98-0.89	0.97-0.95	0.86-0.73	0.89-0.81
Scour depth below mean bed level				
α	1.26-1.61	1.61-1.90	1.19-1.93	2.27-2.81
β	21.4-18.63	22.7-18.95	16.67-25.67	18.22-14.86
a = 1/β	0.047-0.054	0.044-0.053	0.06-0.039	0.055-0.067
Correlation (r)	0.99-0.89	0.99-0.98	0.96-0.76	0.91-0.73

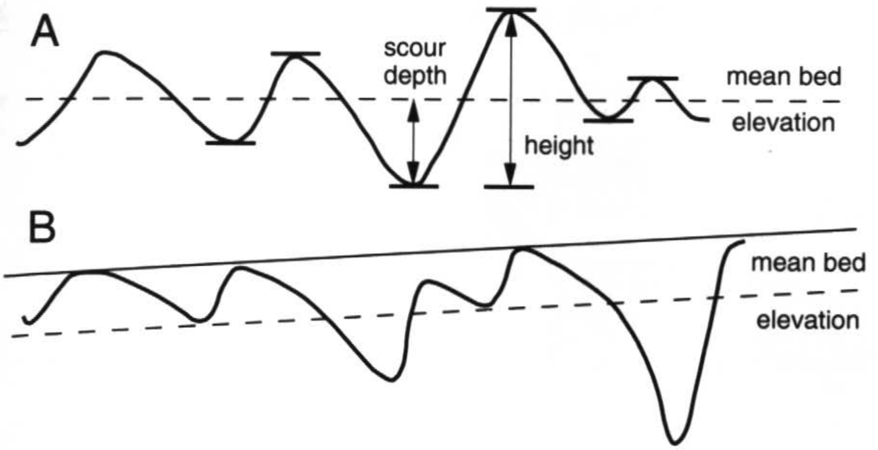

Figure 7 *Relationship between dune height and dune trough elevation below mean bed level for:* **(A)** *idealized geometry described by Paola and Borgman, and;* **(B)** *geometry observed in these experiments.*

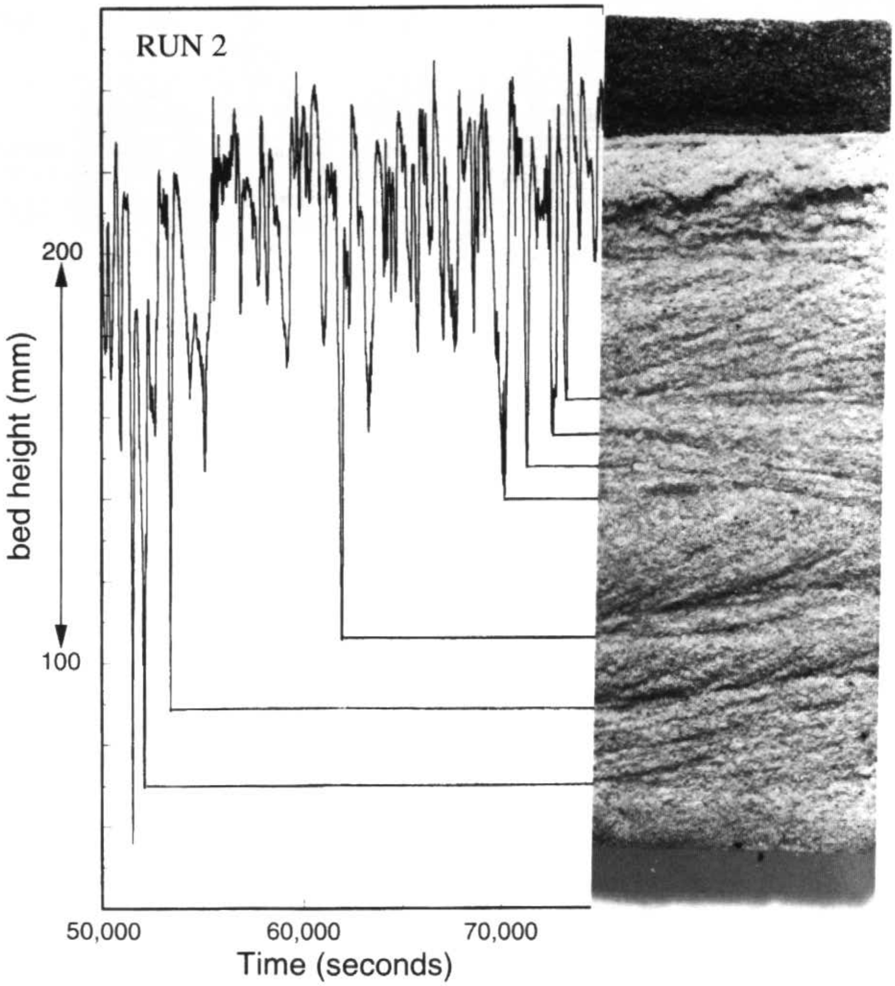

Figure 8 *Details of bed profiler record showing expected positions of cross-set bases for run 2. These are correlated with those observed in box-core peel* **(photo to right)** *from transducer position.*

related to the datum near the crests of the bedforms, the mean set thickness is predicted quite well by the theory (Table 4).

Simple Method for Estimating Dune-height Distributions from Cross-set Thicknesses

This method is based on the premise that the distribution of cross-set thickness is due primarily to variability in dune height, and that variation in aggradation rate plays a minor role. It is also limited to homogeneous cosets of medium-scale cross strata, meaning that there are no obvious spatial changes in the type of strata or mean grain size. The assumption is, therefore, that such cross sets were formed by migration of dunes whose mean geometry did not vary appreciably in time and space. The thickness of cross sets in the coset should be measured over as many closely spaced profiles as possible, such that the mean and standard deviation of cross-set thickness can be calculated. An initial test of the applicability of Equation 4 is that s_{sd}/s_m should approximately equal 0.88 (±0.3). If so, parameters a, α and β of Equations 4 and 5 can be estimated as:

$$\beta = 1/a \sim s_m/1.5$$
$$\alpha = (h_m/h_{sd})^2$$
$$h_m = \alpha\beta$$

In these experiments, if $s_m \sim 15$ mm (run 1), $\beta \sim 10$ mm, and $a \sim 0.1$ mm^{-1}. The coefficient of variation of dune height must be estimated from observations of modern dunes. Data from these experiments and the field data of Gabel (1993) indicate that the coefficient of variation commonly ranges from 0.4 to 0.5, such that α ranges from approximately 4 to 6. Mean dune height in these experiments with $\beta \sim 10$ mm and $\alpha = 5$ is predicted to be 50 mm, close to that observed (Table 1).

The preservation ratio, s_m/h_m, is approximately equal to $1.5/\alpha$, calculated to be 0.3 for these experiments. This agrees with observed values of the preservation ratio (Table 3). However, this preservation ratio is probably a lower limit, because the mean cross-set thickness is underestimated when aggradation occurs. Preservation ratios of up to 0.45 were observed here and by Bridge and Best (1997) when aggradation was proceeding. In cases of extreme aggradation rates on rippled beds, the preservation ratio may approach 1.

Table 3 Cross-strata characteristics

Run number	**1**	**2**	**3**	**4**
Aggradation rate (mm/sec)	0	0.001	0.0035	0.0089
Number of cross-strata sets in bed profiler records	5	8	8	7
Mean set thickness from bed profiler records (mm)	15	18.4	13.0	22.2
Standard deviation (Sd)	9.8	12.3	13.0	22.2
Co-efficient of Variation	0.65	0.67	1.0	0.6
Mean set thickness of vertical section under transducer (mm) (from box-core)	14.6	20.4	13.7	22.2
Standard Deviation	8.9	10.7	8.5	13.2
Co-efficient of Variation	0.61	0.52	0.62	0.59
Mean set thickness from all box-cores in stream direction	16.7	21.4	13.7	22.2
Standard Deviation	9.2	11.4	8.4	13.1
Co-efficient of Variation	0.55	0.53	0.61	0.59
Mean set thickness from box-core across stream	24.9	20.3	17.6	25.1
Standard Deviation	19.4	11.8	11.4	20.4
Co-efficient of Variation	0.78	0.58	0.65	0.81
Mean height of formative dunes (mm)	82.7	104.3	71.3	74.0
Ratio of mean set thickness/mean formative dune height (from profiler records)	0.18	0.18	0.18	0.3
Ratio of mean set thickness/mean height of all dunes (from profiler records)	0.31	0.36	0.33	0.45

CONCLUSIONS

1) Dune geometry and migration characteristics are similar to those of sinuous-crested dunes in rivers and other flumes, and do not vary systematically with aggradation rate.

2) Two-parameter gamma density functions were fitted to histograms of dune height and dune trough elevation relative to two different reference datums in order to define parameter *a*. Parameter *a* based on dune height averages 0.1 mm^{-1}. Parameter *a* based on dune trough elevation increases from 0.05 mm^{-1} to 0.13 mm^{-1} as the reference datum is raised. These results run contrary to the predictions of Paola and Borgman (1991). This is because the troughs of the largest dunes occur at lower elevations than expected, and because dune trough elevations do not correlate very well with dune amplitudes.

3) Most cross sets were formed by the highest 10% of dunes. Mean cross-set thickness/mean *formative* dune height ranges from 0.18 to 0.3, similar to the case for planar laminae formed by low-relief bedwaves on upper-stage plane beds. There is no systematic increase in cross-set thickness with aggradation rate because the dominant control of cross-set thickness is the variability in dune trough elevations, and not aggradation rate.

4) Mean cross-set thickness is predicted fairly well by the modified Paola-Borgman theory only if: 1) dune height is used as a proxy for dune trough elevation, but with constant 0.8225 in Equation 6 replaced with a value around 1.5, or; 2) dune trough elevations are measured relative to a datum near dune crests.

5) The distribution of dune heights responsible for cosets of medium-scale cross strata can be simply estimated from measurements of cross-set thicknesses, assuming that aggradation has a minor influence on cross-set thickness.

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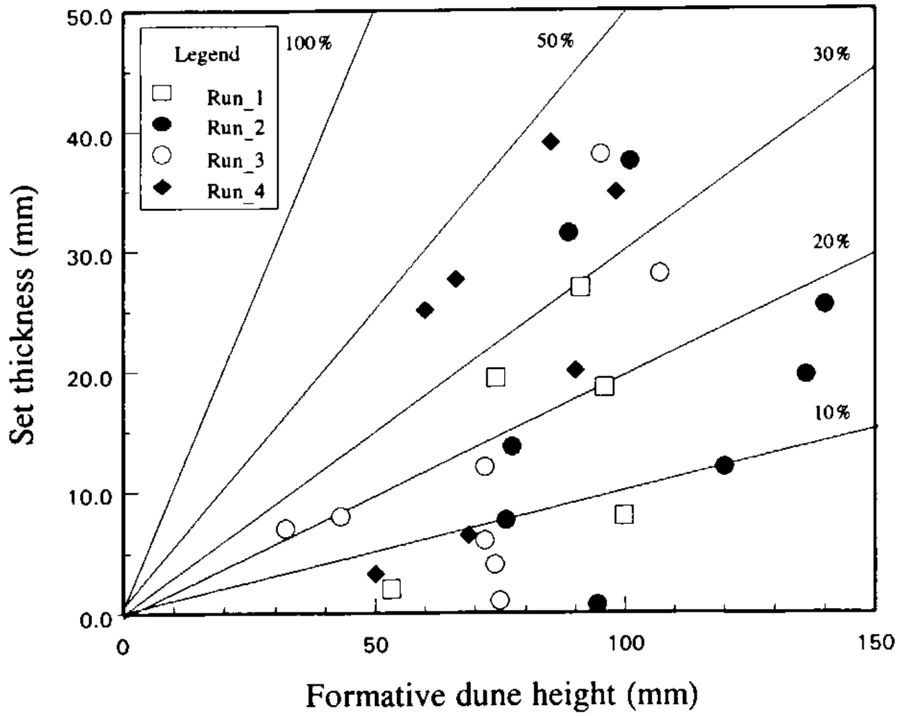
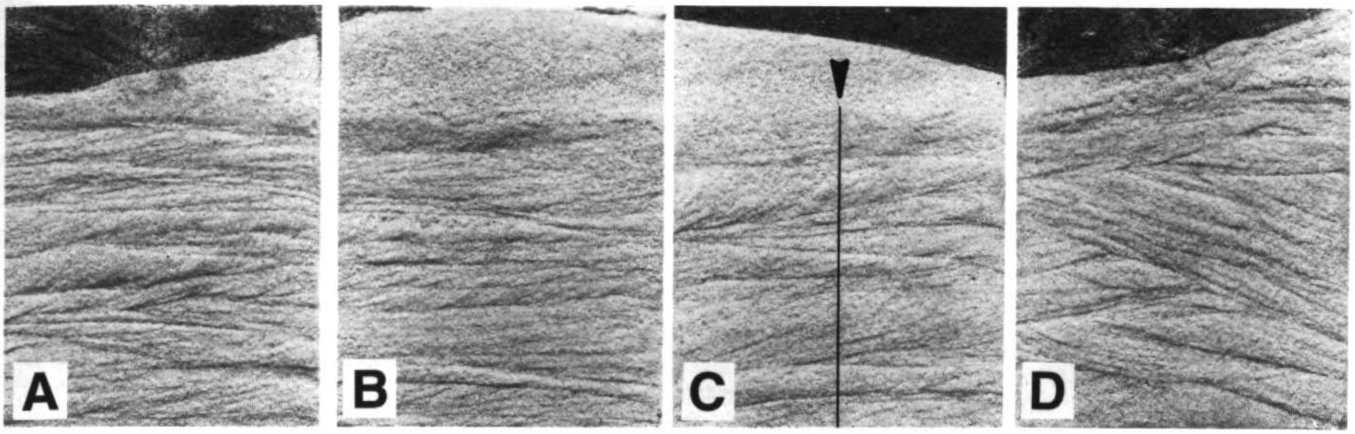


Figure 9 *Cross-set thickness relative to formative dune height for each run. Lines denote percentage of dune height preserved as a cross set.*



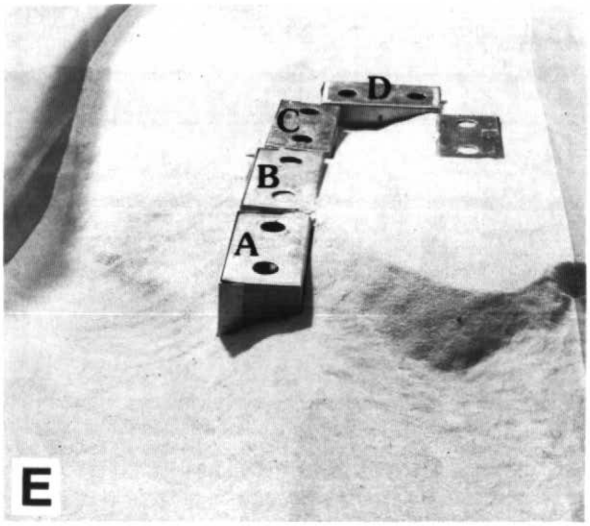


Figure 10 *Box-core peels showing alongstream (**A** to **C**) and across-stream (**D**) variation in cross-set thickness for run 3. All peels are 200 mm high and 150 mm across. Vertical section under the profiler is indicated by arrow. Location of box cores shown in (**E**).*

Table 4 Comparison of observed cross-set thickness with theory

Run number	**1**	**2**	**3**	**4**
Mean set thickness from bed profiler records (mm)	15	18.4	13.0	22.2
Set thickness due to aggradation (*Ir/c*)	0	0.6	1.4	3.3
Predicted set thickness using distribution of dune height:				
Mean set thickness from equation *Ir/c + 0.8225/a* (mm)	6.97-7.15	9.17-10.16	9.65-10.79	9.72-13.33
Ratio of mean predicted set thickness/mean set thickness	0.46-0.47	0.50-0.55	0.74-0.83	0.44-0.60
Mean set thickness from equation *Ir/c 1.5/a* (mm)	12.71-13.04	16.23-18.04	16.4-16.71	15.02-21.59
Ratio of mean predicted set thickness/mean set thickness	0.84-0.86	0.88-0.98	1.26-1.29	0.67-0.97
Predicted set thickness using distribution of scour depth below upper datum:				
Mean set thickness from equation *Ir/c 1.64493/a* (mm)	15.37-16.9	9.49-13.86	15.34-15.46	12.6-17.6
Ratio of mean predicted set thickness/mean set thickness	1.02-1.13	0.52-0.75	1.18-1.2	0.57-0.79
Predicted set thickness using distribution of scour depth below mean bed level:				
Mean set thickness from equation *Ir/c + 1.64493/a* (mm)	30.5-35	31.63-37-98	28.8-43.58	27.85-33.2
Ratio of mean predicted set thickness/mean set thickness	203.0-2.33	1.72-2.06	2.22-3.35	1.25-1.5

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