(Fig 1). Hardcastle and King (1972) showed that for both sites the most frequent wave period (T_z) is between 10.0 and 10.5 seconds while 50% of the significant waves (H_s) (Tucker, 1963) exceed 0.26 m at Wyke and 0.23 m at West Bexington.

Earlier studies (Carr, 1969) had examined the grading of indigenous pebbles above low water mark (Fig 2). They had also shown that, when comparing the spherical and oblong flints and cherts with the discoid quartzites for any given position on the beach, the only identical dimension, ratio or shape index was the short axis (c). Thus a linear regression line drawn between the short axis of the two geological types had a slope of 45° (Carr, Gleason and King, 1970).

Three experiments at Chesil are summarised in this paper. Two, using introduced geological tracers, previously subject to marine processes elsewhere, are reported more fully in Carr (1971). The other study, based on the local material, is described by Gleason and Hardcastle (1973).

For both geological tracer experiments wave heights were slightly above average, but did not exceed 1.2 m. In the first of these experiments wave periods were somewhat longer and for the second somewhat shorter, than normal. During the February 1971 indigenous pebble study wave heights were representative of the yearly pattern although wave periods were rather longer, the mode falling at 13.0 seconds.

The first tracer experiment, begun in October 1969, used quartz granulites taken from the beach at Rosemarkie, Scotland. This material, like the indigenous sediment, has a specific gravity of about 2.6. Long diameter (a) ranged from approximately that of the local material at the site (2.5 x 10^{-2} m) to a maximum of 1.1 x 10^{-1} m. Some 17,200 pebbles and cobbles were placed at mid-tide level on the surface of the beach at Wyke (Fig 1) since the purpose of the experiment was primarily to relate transport of the introduced tracer to the wave parameters, rather than to sum the overall movement of that part of the beach subject to wave action.

The results showed:

i) That tracer of a comparable size to the background material was incorporated within it. Somewhat larger material tended to remain on the surface possibly by 'rejection' (Moss, 1962, 1963) upwards or inability to be drawn downwards. This effect was most pronounced under periods of long, low swell where turbulence was at a minimum and where percentage recoveries were higher. Gross discrepancies in size were accommodated by very large material being combed down below low water mark, there to remain.

ii) There was a clear relationship between greater longshore transport and increasing size of particle (Table 1 and Fig 3a). Taking the whole recovered sample for any day, best correlations were marginally given with the short axis; (c). While in the short term this relationship appeared linear, over the longer term it took a logarithmic form similar to the exponential grading of the local material, and the long axis (a) became best correlated. On one occasion (24 November 1969) given consistent wave approach from an easterly direction and low wave height (< 0.3 m) (so that only the top few layers of pebbles were moved), the grading of the surface tracer was reversed with the coarsest recovered tracer particles towards the northwest. Table 1 shows that this sorting mechanism is even more evident where recoveries at high, mid, and low water mark are analysed separately. All the tables in this paper utilise standard statistical procedures and assume (correctly) an essentially normally distributed

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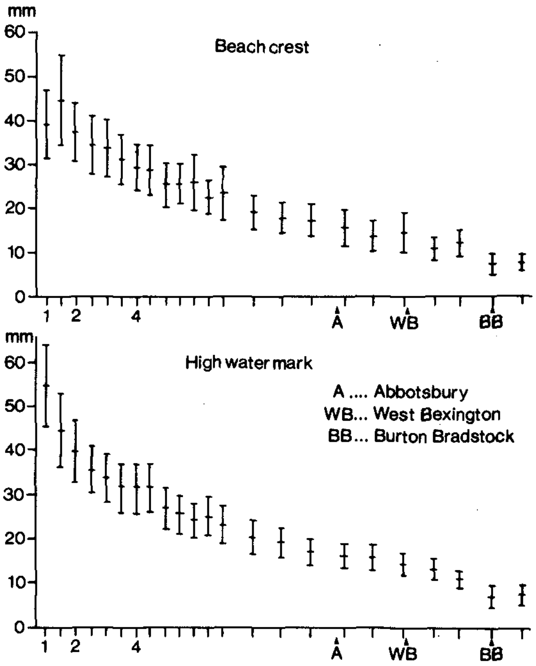

Figure 2
Chesil Beach:
Comparison of means and standard deviation for pebble long diameter (a) along the beach crest and at high water mark, July 1965. Note the basically exponential curves joining the means.
For location, see Figure 1.
(After Carr,1969).

population for both tracer (at the time of introduction) and indigenous material.

iii) Rates of movement at Wyke reached 343 m after the first day but after 165 days, often with much more severe conditions, the farthest recorded material was only 3952 m southeast of its origin. This reflects the proportion of time that material is out of circulation by being above or below the zone of wave action; by burial; and by intermittent transport opposite to the prevailing direction. Data show that lateral movement of individual pebbles is not necessarily greater under storm conditions even with the same angle of wind-wave or swell approach because of the effect of depth of mixing.

Only one aspect of the second tracer study, in late 1970, will be discussed here.

The experiment used 12,350 quartzitic conglomerates with a specific gravity of about 2.7 and 5,350 basalts with a S.G. of 2.83 - 2.90. As before, the particles had been rounded by beach processes elsewhere. The basalts, and approximately half the conglomerates, were injected at the Wyke site. The proportions recovered of the former geological type to the latter varied from 15 to over 50%. This is what would be expected if the heavier specific gravity pebbles worked their way into the beach (low recovery) and the beach was combed down afterwards resulting in their re-exposure (high recovery). Longshore travel was less for the basalts probably because of the compounded effect of greater burial time and smaller movement even when on the surface because of the relatively greater specific gravity.

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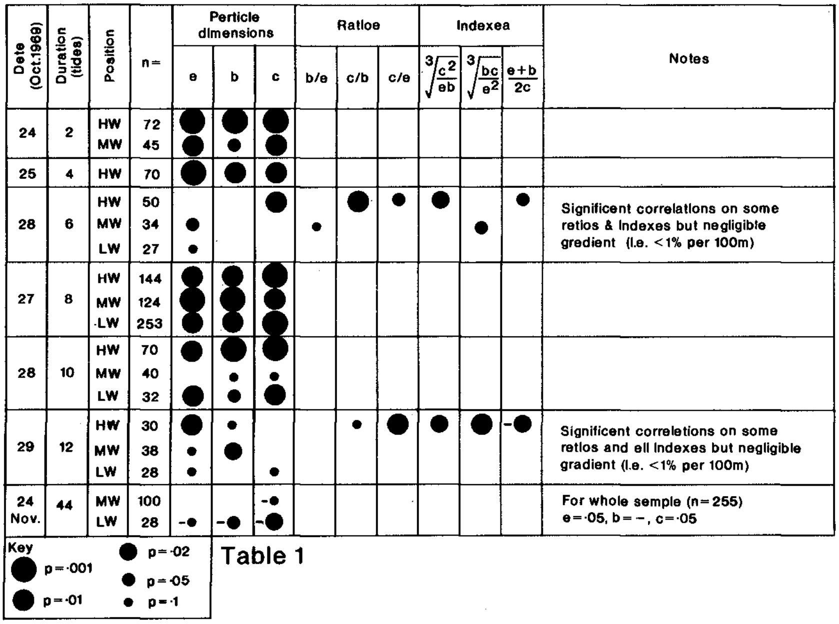

Date (Oct.1969)	Duration (tides)	Position	n=	Particle dimensions			Ratios			Indexes			Notes
				e	b	c	b/e	c/b	c/e	$\sqrt[3]{\frac{c^2}{eb}}$	$\sqrt[3]{\frac{bc}{e^2}}$	$\frac{e+b}{2c}$	
24	2	HW MW	72 45	● ●	● •	● ●							
25	4	HW	70	●	●	●							
28	6	HW MW LW	50 34 27	 • •		●	 •	●	•	●	 •	•	Significant correlations on some ratios & indexes but negligible gradient (i.e. <1% per 100m)
27	8	HW MW LW	144 124 253	● ● ●	● ● ●	● ● ●							
28	10	HW MW LW	70 40 32	● ●	● • •	● • ●							
29	12	HW MW LW	30 38 28	● • •	• ●	 •		•	●	●	●	-●	Significant correlations on some ratios and all indexes but negligible gradient (i.e. <1% per 100m)
24 Nov.	44	MW LW	100 28	 -•	 -●	-• -●							For whole sample (n=255) e=·05, b=–, c=·05

Key
● p=·001
● p=·01
● p=·02
• p=·05
• p=·1

Table 1

Chesil Beach: tracer experiment 1969. Probability levels for correlation coefficients (where $p \leqslant 0.1$) between pebble axis/index (y) against distance travelled alongshore in metres (x). Coarsest material always travelled furthest. Direction of grading is reversed for 24 November. n = Number of individuals. For all tables; a, b, c = long, intermediate, short axis in mm; HW, MW, LW = high, mid, low water; p = probability level. $p \leqslant .001$ means that there is 1 possibility in 1000 or less of such a result occurring by chance. As n increases the same significance level may be obtained by a lower correlation coefficient (r) but the level of explanation (r^2) will also be lower.

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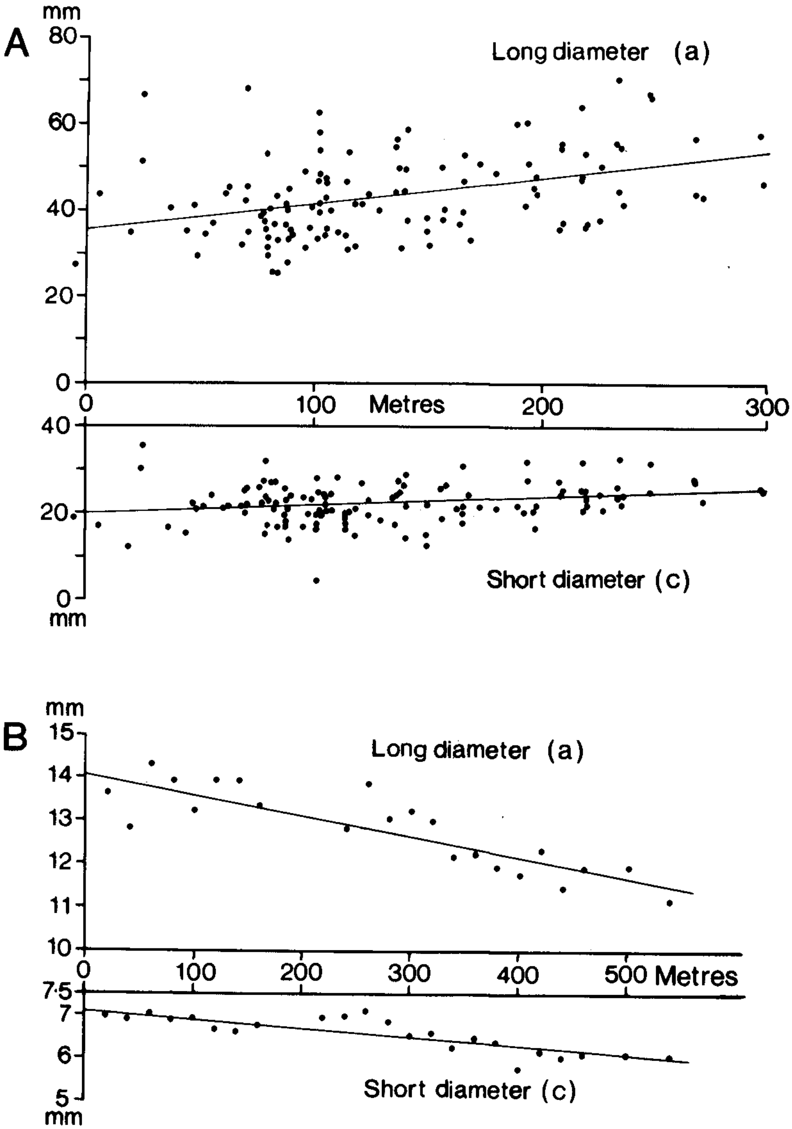

Figure 3
Relation of particle size (y) to distance travelled alongshore (x) in tracer experiments.
(a) Chesil Beach. Data for 27 October 1969, mid-tide zone.
n = 124 individuals.
(b) Slapton Beach. Data for 8 October 1973, high tide zone.
n = 23 group mean samples.

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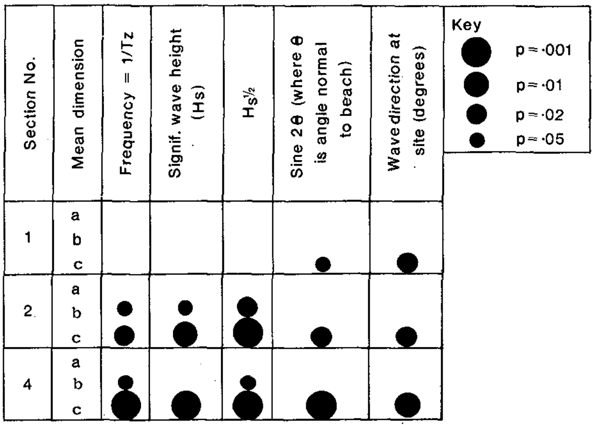

Table 2

Section No.	Mean dimension	Frequency = 1/Tz	Signif. wave height (Hs)	Hs½	Sine 2θ (where θ is angle normal to beach)	Wave direction at site (degrees)
1	a					
	b					
	c				●	●
2	a					
	b	●	●	●		
	c	●	●	●	●	●
4	a					
	b	●		●		
	c	●	●	●	●	●

Key

●	p = ·001
●	p = ·01
●	p = ·02
●	p = ·05

Chesil Beach: daily sampling of indigenous material over a one month period (February 1971). Probability levels for correlation coefficients between pebble axes and wave parameters. n = 28 (days). (After Gleason and Hardcastle, 1973).

The month-long experiment in February 1971 which employed the local material, was designed to show the change in particle size with varying wave conditions at each of three sampling sites (Fig 1) (Gleason and Hardcastle, 1973). Since the beach is graded alongshore, with the smallest material towards the western end, (Fig 2) it follows that waves from the prevailing direction of fetch (southwest) should cause a decrease in pebble size at the sampling sites. The best correlation would be expected at Wyke where the angle of wave approach would be most oblique to the beach.

Table 2, modified slightly from Gleason and Hardcastle (1973), gives the probability levels for the correlations between linear parameters against wave direction ($\varphi°$); frequency ($^1/T_z$); significant wave height (H_s); ($H_s^{\frac{1}{2}}$); and Sine 2θ, where θ is the angle of swell approach relative to a

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line normal to the beach (Longuet-Higgins, 1970a, b). It shows, firstly, that as in the case of the earlier studies, the short diameter (c) gives the best correlations and, secondly, that the modified wave parameters ($^1/T_z$ and $H_s^{\frac{1}{2}}$) appear to be the most significantly correlated factors. Wave frequency ($1/T_z$) was important in vertical sorting of material; wave direction ($\varphi°$) and Sine 2θ in longshore transport, $H_s^{\frac{1}{2}}$ in both processes.

b) Slapton Beach, Devon

Start Bay extends from Start Point in the south to the mouth of the River Dart in the north, a distance of some 13 km (Fig 1). The largest unit within the bay is Slapton barrier beach which is nearly 5 km long and between 100 and 140 m in width at high tide. Its crest generally falls within the range 6.0 m ± 0.5 m O.D. As in the case of Chesil this is affected by waves only rarely.

There is an overall trend throughout the coastline of Start Bay for the natural beach material to become coarser from north to south but this is liable to be obscured both by variations within the four component units and from month to month. About 85% of beach particle analyses taken in 1971 - 72 fell within the granules (-1 to -2ϕ) and small pebbles (-2 to -4ϕ) categories (where phi (ϕ) = $-\log_2$ diameter in mm), although a considerable number of the samples contained some coarser material generally of a siliceous, quartzitic or schistose nature. Within the -1 to -4ϕ range about 85% of the shingle is flint, chert or quartz. Sediment size falls abruptly away from the coastline.

In the centre of the Bay the exposed beach has an overall slope of 1 in 15 reaching as much as 1 in 7. The gradient of the beach below low tide level continues at the same order of slope until approximately -7.5 m; thereafter it shelves gently to reach -14.5 m O.D. about 600 m offshore. Still further offshore the topography is influenced by the coarse sand and shell of the Skerries Bank which extends from near Start Point some 6.5 km towards the northeast. The minimum depth of the Bank below sea level is -4.7 m O.D., although most of the crest is between -7.5 m and -9.0 m O.D.

Again, as in the case of Chesil, only minor coast protection works exist; none of these affect the Slapton experimental area of the Bay.

The tidal range varies from about 1.8 m at neaps to 4.4 m on springs. For the Slapton wave recorder site, some 200 m offshore, the most frequent wave period (T_z) is between 6.0 and 6.5 seconds with 50% of the significant waves (H_s) exceeding 0.16 m. (June 1972 - 73 data). The Skerries Bank has the effect of causing marked variations in the height, period, and direction of waves reaching the shore at high, as compared with low water.

Following work on the size and geological distribution of the local sediment (Gleason, Blackley and Carr, 1975) and a rather inconclusive experiment along the lines of the work by Gleason and Hardcastle at Chesil, it was decided to carry out short-term tracer experiments on Slapton Beach. These used shingle from the western end of Chesil Beach which meant that, although the specific gravity remained the same as at Slapton, shape varied somewhat, primarily because of the different proportions of geological types. This introduced material was coated with a commercially available polyurethane finish which proved resistant enough for the short-term beach studies and which did not appear to affect the hydraulic properties of the sediment.

A short trial in October, 1972, using 800 kg of labelled material, was intended solely for developing the sampling technique. Two full experiments were undertaken subsequently, one in February and the other in October, 1973. In both experiments surface sampling was carried out along the beach at pre-determined intervals and over a specified areal extent. Samples were collected

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at high-tide and low-tide levels with an additional series at mid-tide level as the tidal range increased from neaps to springs. The techniques are described in greater detail by Gleason, Blackley and Carr (1975) but rely on group mean values, not, as in the case of Chesil, on individual pebbles. Sampling took place alongshore for at least two sites beyond the farthest at which statistically valid data were obtained, to minimise the possibility of 'pulsed' distributions, of which there had been some suggestion at Chesil, escaping notice (Carr, 1971). In the trial and February experiment the tracer had a mean size of -2.40 Ø. Slightly larger pebbles, having a mean of -2.98 Ø, were used in the October experiment. Three tonnes of tracer were employed for each phase in February; five tonnes in October. This represents two batches of approximately 1.5 x 10^7 and one of 6.0 x 10^6 pebbles, respectively. All tracer was deposited on the surface at mid-tide level.

Wave data were obtained from recorders similar to those used at Chesil but with data output on magnetic tape. For the first experiment wave direction was observed by compass from Torcross headland; for the second experiment direction was also abstracted from photographs of the display of a 3.2 cm X-band radar located at the same site.

Wave conditions during the experiments were highly atypical. Thus in the relevant period in February 1973 nearly 50% of the wave periods were between 7.5 and 8.5 seconds with a further 40% longer than this (up to 15.5 seconds). Waves above 0.3 m were almost totally lacking. In October about 75% of wave periods were between 5.0 and 6.5 seconds and none exceeded 8.0 seconds. Waves below 0.3 m were grossly under-represented.

Those occasions where statistically significant longshore grading occurred are shown in Tables 3 and 4, for February and October, respectively. For February the probability levels are given for the calculated linear correlations between negative mean phi values as derived from frequency and weight v. net distance travelled, and for linear, log and distance squared (d^2) correlations between the particle dimensions and net distance travelled. For October the probability levels are for the calculated linear and log correlations between particle dimensions, ratios and shape indexes v. net distance travelled. In all cases the sediment parameter was $\underline{y}$ and the distance travelled $\underline{x}$. The representative shape indexes are those of Sneed and Folk (1958), Krumhein (1941), and Wentworth (1922) - Cailleux (1945).

Furthest travelled material reached 1138 m north of the injection site in the five days of the October 1973 experiment but statistically valid samples were only contained within a distance of -150 m and + 560 m of the origin. The comparable distances for the longer February experiment are -50 m and +230 m.

In all instances maximum longshore transport coincided with smallest particle size (e.g. Fig 3b) hence there was a predominance of negative correlations for the linear parameters. Even where positive correlations occur, as after the first tide following injection of the second tracer in February 1973, this only reflects longshore transport of tracer in the opposite direction because of a reversal in the angle of wave approach relative to a line normal to the beach. The differing signs for the ratio and indexes vis-a-vis linear parameters (for October 1973) is, in part, a response to the relative significance of $\underline{a}$, $\underline{b}$ and $\underline{c}$ in the various functions and to a link between pebble shape and size, for the introduced tracer material. The change in sign for ratios and shape indexes in October after 5 and 9 tides, respectively, may possibly be explained by the limited travel at low water by tide 5 and the legacy of a different direction of wave approach from the beginning of the experiment.

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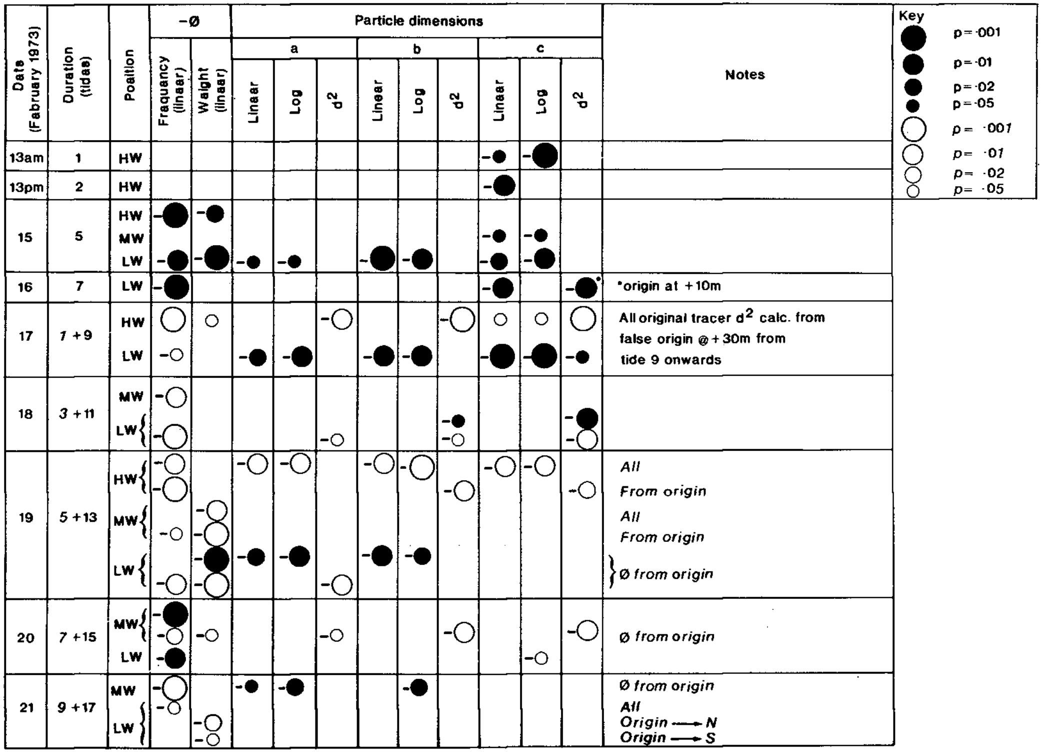
Table 3



Key	
⬤	p = ·001
●	p = ·01
•	p = ·02
∙	p = ·05
◯	*p* = ·001
○	*p* = ·01
◦	*p* = ·02
∘	*p* = ·05

Date (February 1973)	Duration (tides)	Position	−Ø		Particle dimensions									Notes
					a			b			c			
			Frequency (linear)	Weight (linear)	Linear	Log	d^2	Linear	Log	d^2	Linear	Log	d^2	
13am	1	HW									−∙	−⬤		
13pm	2	HW									−●			
15	5	HW	−⬤	−•										
		MW									−∙	−∙		
		LW	−●	−⬤	−∙	−∙		−⬤	−●		−•	−●		
16	7	LW	−⬤								−●		−●*	*origin at +10m
17	*7* +9	HW	◯	∘			−○			−◯	∘	∘	◯	All original tracer d^2 calc. from false origin @ +30m from tide 9 onwards
		LW	−∘		−•	−●		−●	−●		−⬤	−⬤	−∙	
18	*3* +11	MW	−○											
		LW								−∙			−●	
			−◯				−∘			−∘			−○	
19	5 +13	HW	−○		−○	−○		−○	−◯		−○	−○		*All*
			−◯							−○			−◦	*From origin*
		MW		−○										*All*
			−∘	−◯										*From origin*
		LW		−⬤	−•	−●		−●	−•					} *Ø from origin*
			−○	−◯			−○							
20	*7* +15	MW	−⬤											*Ø from origin*
			−◦	−∘			−∘			−○			−○	
		LW	−●									−∘		
21	9 +17	MW	−◯		−∙	−•			−•					*Ø from origin*
		LW	−∘											*All*
				−◦										*Origin ⟶ N*
				−∘										*Origin ⟶ S*

Slapton Beach: tracer experiment, February 1973. Probability levels where $p \leqslant 0.05$ for correlations between $-\emptyset$ ($\emptyset = -\log_2$ diameter in mm) and linear parameters (y) v. distance travelled alongshore in metres (x). Calculated from injection point (= origin) unless otherwise stated. Upright figures represent first, italics second, phase of experiment. n (no. of group samples) averages 6 but varies between 3 and 8. Note the varying significance of different parameters. Finest material always travelled furthest.

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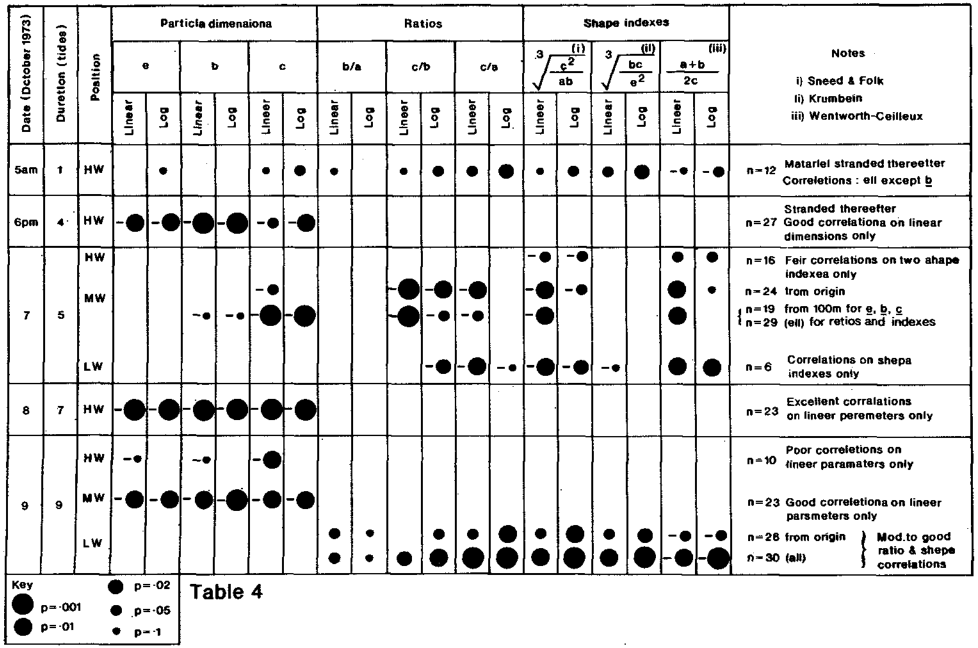

Date (October 1973)	Duration (tides)	Position	Particle dimensions						Ratios						Shape indexes						Notes i) Sneed & Folk ii) Krumbein iii) Wentworth-Ceilleux
			a		b		c		b/a		c/b		c/a		(i) $\sqrt[3]{\frac{c^2}{ab}}$		(ii) $\sqrt[3]{\frac{bc}{a^2}}$		(iii) $\frac{a+b}{2c}$		
			Linear	Log	Linear	Log	Linear	Log	Linear	Log	Linear	Log	Linear	Log	Linear	Log	Linear	Log	Linear	Log	
5am	1	HW		● p=·1			● p=·1	● p=·05	● p=·1		● p=·1	● p=·05	● p=·05	● p=·02	● p=·1	● p=·05	● p=·05	● p=·02	-● p=·1	-● p=·05	n=12 Material stranded thereafter Correlations : all except b
6pm	4	HW	-● p=·01	-● p=·01	-● p=·001	-● p=·001	-● p=·05	-● p=·01													n=27 Stranded thereafter Good correlations on linear dimensions only
7	5	HW													-● p=·05	-● p=·05			● p=·05	● p=·05	n=16 Fair correlations on two shape indexes only
		MW					-● p=·05				-● p=·001	-● p=·01	-● p=·01		-● p=·01	-● p=·05			● p=·01	● p=·1	n=24 from origin
					-● p=·1	-● p=·1	-● p=·001	-● p=·001			-● p=·001	-● p=·05	-● p=·05		-● p=·01				● p=·01		n=19 from 100m for a, b, c n=29 (all) for ratios and indexes
		LW										-● p=·02	-● p=·01	-● p=·1	-● p=·01	-● p=·02	-● p=·1		● p=·01	● p=·01	n=6 Correlations on shape indexes only
8	7	HW	-● p=·001	-● p=·001	-● p=·001	-● p=·001	-● p=·001	-● p=·001													n=23 Excellent correlations on linear parameters only
9	9	HW	-● p=·1		-● p=·1		-● p=·01														n=10 Poor correlations on linear parameters only
		MW	-● p=·01	-● p=·01	-● p=·01	-● p=·001	-● p=·01	-● p=·01													n=23 Good correlations on linear parameters only
		LW							● p=·05	● p=·1		● p=·05	● p=·05	● p=·01	● p=·05	● p=·01	● p=·05	● p=·02	-● p=·05	-● p=·05	n=26 from origin } Mod. to good ratio & shape correlations
									● p=·05	● p=·1	● p=·02	● p=·01	● p=·001	● p=·001	● p=·01	● p=·001	● p=·01	● p=·001	-● p=·01	-● p=·001	n=30 (all)

Key
● p=·001
● p=·01
● p=·02
● p=·05
● p=·1

Table 4

Slapton Beach: tracer experiment, October 1973. Probability levels (p ⩽ 0.1) for correlations between size/ratio/index (y) v. distance travelled alongshore in metres (x). n = no. of group samples. From injection point (= origin) unless otherwise stated. Note the variability of types of sorting and reversal of trends (e.g. between ratios and shapes at 7 and 9 October LW). Finest material always travelled furthest (see text).

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Unlike at Chesil and at Budleigh (see below) gradients of linear regression lines for ratios and indexes are of the order of 1% or more for each 100 m alongshore. In all three sites linear regression lines for axes exceed this gradient.

Equally important is the way in which different factors assume importance on varying occasions. Thus, during the February tracer experiment, there is grading at high water after one tide and at mid-water after five tides, both only on the *c* axis. At high water, after five tides, significant grading is restricted to the Ø scale (which in so far as it reflects anything, should have closest affinities with the intermediate axis, *b*). Phi scale and d^2 are closely linked. Similarly, in the October experiment there are occasions where there is clear preference for grading on linear parameters (e.g. at high water after four and seven tides, and high and mid water after nine tides). At other times, notably at low water, selection by shape appears more important.

Overall, correlations are rather better with the *c* axis than other linear dimensions.

There was a marginally significant correlation (at the 0.1 probability level) for wave period (T_z) v. *c* axis for the February experiment. Apart from this there was no instance of any correlation between wave period, height, direction, spectral width or modified wave parameter (e.g. $H_s^{\frac{1}{2}}$) and any sediment parameter for either experiment even although the study of the indigenous material in May 1972 had shown limited correlations on Slapton Beach for wave height ($H_s^{\frac{1}{2}}$) and angle of wave approach (ϕ). (1 occasion at .001, 3 occasions at .01, 1 occasion at .02 for $H_s^{\frac{1}{2}}$; 3 occasions at .02 for ϕ^o). These results may reflect better adjustment of the local material to wave parameters.

c) Budleigh Salterton, Devon

Budleigh beach is located some 35 km west of Chesil Beach and has a wave regime somewhat intermediate between that of Chesil and Start Bay. However, the principal interest is the way in which the largely discoid quartzites, which form the source of the beach pebbles and cobbles (mean long axis (*a*) falls between 1.9 x 10^{-2} and 1.0 x 10^{-1} m), are supplied by landslips of the Triassic Pebble Beds in the cliffs behind the centre of the beach. The material is ill-sorted, but comparatively well-rounded, prior to becoming available to shoreline processes.

Sampling was carried out on four occasions between October 1971 and October 1972, using 16 section lines spaced at either 200 or 300 m intervals. Initially up to six samples containing 200 individuals were taken on each line to include the cliffs, beach/cliff junction, storm crest, and high, mid, and low water marks. The three linear axes were measured as before and these, plus the ratios and indexes, were correlated against distance alongshore (as linear, log or d^2 regression equations). Distances were computed both from the eastern end of the beach and from the centre, which is coincident with the source of supply. There were no significant correlations for any of the sites to the rear of high water mark at the time of sampling.

Table 5 lists those occasions where probability levels $\leqslant 0.05$ for dimensions, ratios, and indexes v. linear and d^2 relationships for distance alongshore. The most important points are:

i) when significant grading occurs it is generally along the whole beach length with smallest material at the eastern end. However, slips have the effect of both interrupting longshore transport and supplying new material so that in June 1972 grading ran in each direction with mean size increasing from the centre of the beach;

ii) it is possible to have size grading from the centre and shape grading from the end co-existing although, while index v. distance correlations are highly significant, the actual range of shapes available is somewhat limited for this beach and lithology.

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