

CHAPTER 49

DIFFERENTIAL MOVEMENT OF COARSE SEDIMENT PARTICLES

by

Alan Paul Carr¹

ABSTRACT

This paper mainly describes experiments that have been carried out on two shingle beaches on the south coast of England.

The results for the higher energy environment of Chesil Beach showed that largest tracer material travelled farthest, and best correlations tended to be with the short axis. At Slapton, however, different sediment parameters appeared significant at various times. Where linear parameters were relevant correlations were again best with the short axis, but smaller material travelled farthest. This may reflect different wave regime, a less efficient sediment rejection mechanism, finer grades of sediment or better adjustment of tracer to indigenous background material at Slapton.

There was a marked degree of selectivity at both sites between material recovered along a particular zone of the beach as compared with the overall recovery on the same day, and between the overall recovery for a particular day as compared with the originally injected tracer. Attempts have been made to correlate wave data from f.m. pressure recorders with longshore transport of the coarse grades of sediment in the inter-tidal zone. While at Chesil wave direction, frequency and height were all important there were no obvious relationships at Slapton. The results have relevance in respect of beach stability and in the conclusions drawn from tracer studies using coarse grades of sediment.

INTRODUCTION

The differential transport and sorting of varying sediment sizes has been widely observed in aeolian, fluvial and marine environments. The phenomenon has economic importance particularly in the realms of natural and induced stability of the sea bed and the foreshore. For example, artificial beach replenishment is accepted as being more effective if particular grades of sediment are chosen in relation to specific beach conditions (e.g. Krumhein and James, 1965).

As Wood (1970) has observed: 'The extensive literature on the engineering properties of a natural beach is principally concerned with fine to medium sand foreshores. In consequence, a number of generalisations have been made concerning the properties of a beach that do not apply ... to a shingle or even a coarse sand beach'. It is with such grades of sediment that this paper is concerned.

To some extent investigations using these coarse particles are simplified by the diminishing importance of tidal currents relative to waves, and suspension and saltation relative to bedload. The actual samples are also more readily physically measurable. However, considerable problems remain. For example, there are the differing effects of waves offshore, in the breaker zone, and onshore where permeability adds yet a further complication to wave height, period, and steepness. Similarly, for the sediment, there are questions of relevance of shape, roundness and specific gravity; the manner of the vertical distribution of tracer through the disturbed part of the beach, and the further complication of the inter-relationship of different ranges of sizes of particles within samples having the same mean.

¹Principal Scientific Officer, Institute of Oceanographic Sciences, Taunton, England.

Even in the apparently simpler situation of uni-directional flow Kellershals and Bray (1971) have written: 'Describing the (gravel) bed material ----- in quantitative terms is a difficult task which presently involves a series of largely subjective decisions about sampling locations, time of sampling, and sampling procedure. Different investigators can therefore arrive at widely different results ----'.

Castenho (1970) has demonstrated a similar diversity of opinion relating to differential longshore transport within the sand fraction.

There is also argument as to the importance of biological processes, such as kelp-rafting (e.g. Emery and Tschudy, 1941), within the coarse sediment grades.

On a more detailed scale there are problems of terminology, in particular that of the use of the words 'shingle' and 'gravel' and some of the disagreements in the literature may stem from this cause. Emery (1955) preferred 'gravel beach' ----- 'to avoid the term "shingle" which' (he thought connoted) 'imbrication and flat shape'. Wood (1970) wrote: 'By definition, a shingle beach is one in which the mean particle size D_{50} is larger than 10 mm. The mean size is most often in the range 10 - 40 mm'. Carr (1971) used 'shingle' to refer to material at least partly rounded and sorted by marine processes, and falling within the range 4 mm to 256 mm long diameter or equivalent. It thus included the pebble and cobble categories of the Wentworth Scale. It is in this sense that the term is used here.

This paper describes work carried out by two component bodies within the UK government's Natural Environment Research Council, initially by the (then) Nature Conservancy and latterly by the Institute of Oceanographic Sciences. The study is primarily concerned with the results obtained from two contrasting English shingle beaches, Chesil and Slapton, although reference is also made to a third beach at Budleigh Salterton (Fig 1). The data from Chesil Beach tend to emphasise the relationship between gross wave characteristics and sediment sorting; those from Slapton demonstrate the apparent variability of sediment parameters.

FIELD EXPERIMENTAL STUDIES

(a) Chesil Beach, Dorset

Chesil Beach is one of the three major shingle structures on the coast of Great Britain, and the only one primarily of barrier form, being backed by the shallow Fleet lagoon for much of its length. The beach extends more than 18 km from Chesilton in the east, where it terminates against the cliffs of the so-called Isle of Portland, to an essentially arbitrary limit in the west. Opposite the Fleet, Chesil Beach is between 150 and 200 m wide, but is narrower at both ends. For much of its distance there is a picture of a progressively increasing crest height, the maximum of +14.7 m O.D. (Ordnance Datum, which is approx. mean sea level) being found near Chesilton. Pebble size above low water mark also increases in the same direction (Fig 2). During the studies described mean pebble size for long diameter (a) in the experimental area fell between 6.4×10^{-3} and 6.3×10^{-3} m. Taking the whole beach nearly 98.5% of the pebbles and cobbles are of flint and chert (Carr and Blackley, 1969) and 1.2 per cent of quartzite. Both types have a specific gravity of about 2.6.

Offshore, the beach drops at a gradient broadly similar to that of the seaward face above low water mark - 1 in 10 overall but exceeding 1 in 3 - for a horizontal distance of approximately 70 m (Neate, 1967). Thereafter, it shelves gently to about -18 m O.D. some 270 m offshore opposite Wyke Regis.

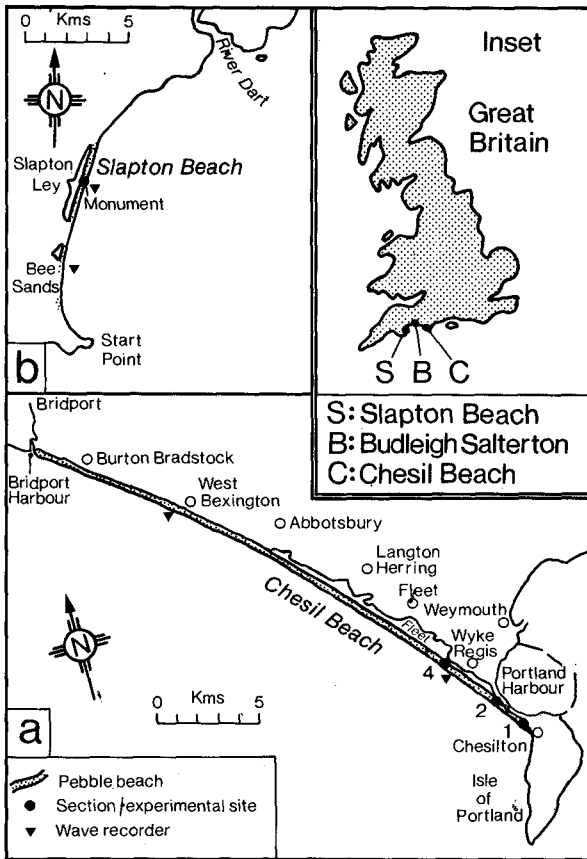


Figure 1

Site map (a) Chesil Beach, Dorset

(b) Slapton Beach, Start Bay

Inset map shows overall location

Only minor coast protection works exist, none of which are within the experimental area.

The tidal range varies from about 1.3 m at neaps to 3.5 m at springs. Tidal velocities do not exceed 1.0 ms^{-1} . Wave data were obtained from two f.m. pressure units located offshore and linked to analogue recorders on land. The wave recorder at Wyke was 100 m and that at West Bexington 250 m offshore

(Fig 1). Hardcastle and King (1972) showed that for both sites the most frequent wave period (T) is between 10.0 and 10.5 seconds while 50% of the significant waves z (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 (2.5×10^{-2} m) to a maximum of 1.1×10^{-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

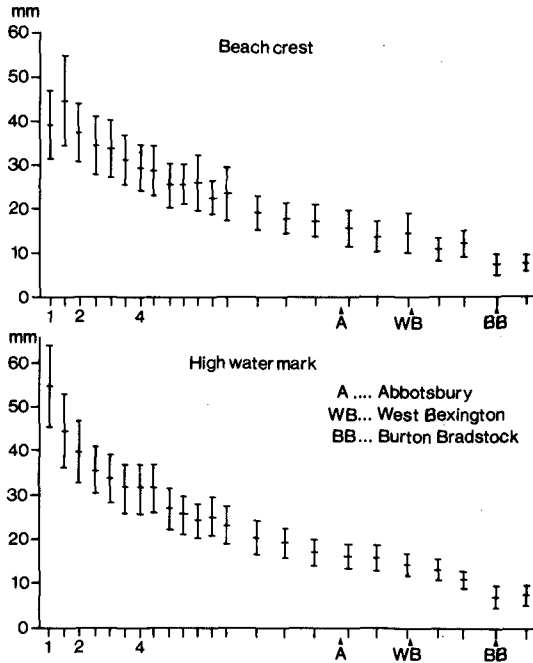


Figure 2
Chesil Beach:
Comparison of means
and standard deviation
for pebble long
diameter ($\bar{a}$) along the
beach crest and at
high water mark,
July 1965. Note the
basically exponential
curves joining the
means.
For location, see
Figure 1.
(After Carr, 1969).

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.

Date (Oct 1968)	Duration (tides)	Position	n	Particle dimensions			Ratios			Indexes			Notes
				a	b	c	b/a	c/b	c/a	$\sqrt[3]{\frac{c^2}{ab}}$	$\sqrt[3]{\frac{bc}{a^2}}$	$\frac{e+b}{2c}$	
24	2	HW	72	●	●	●							
		MW	45	●	●	●							
25	4	HW	70	●	●	●							
28	6	HW	50			●		●		●		●	Significant correlations on some ratios & indexes but negligible gradient (i.e. <1% per 100m)
		MW	34	●			●				●		
		LW	27	●									
27	8	HW	144	●	●	●							
		MW	124	●	●	●							
		LW	253	●	●	●							
28	10	HW	70	●	●	●							
		MW	40	●	●	●							
		LW	32	●	●	●							
29	12	HW	30	●	●			●		●	●	●	Significant correlations on some ratios and all indexes but negligible gradient (i.e. <1% per 100m)
		MW	38	●	●								
		LW	28	●	●	●							
24 Nov.	44	MW	100			●							For whole sample (n=255) a=0.05, b=0.05, c=0.05
		LW	28	●	●	●							

Table 1

Key

● p=0.001 ● p=0.02

● p=0.01 ● p=0.05

● p=0.1 ● p=1

Chesil Beach: tracer experiment 1969. Probability levels for correlation coefficients (where $p \leq 0.1$) 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. $p \leq 0.001$ 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.

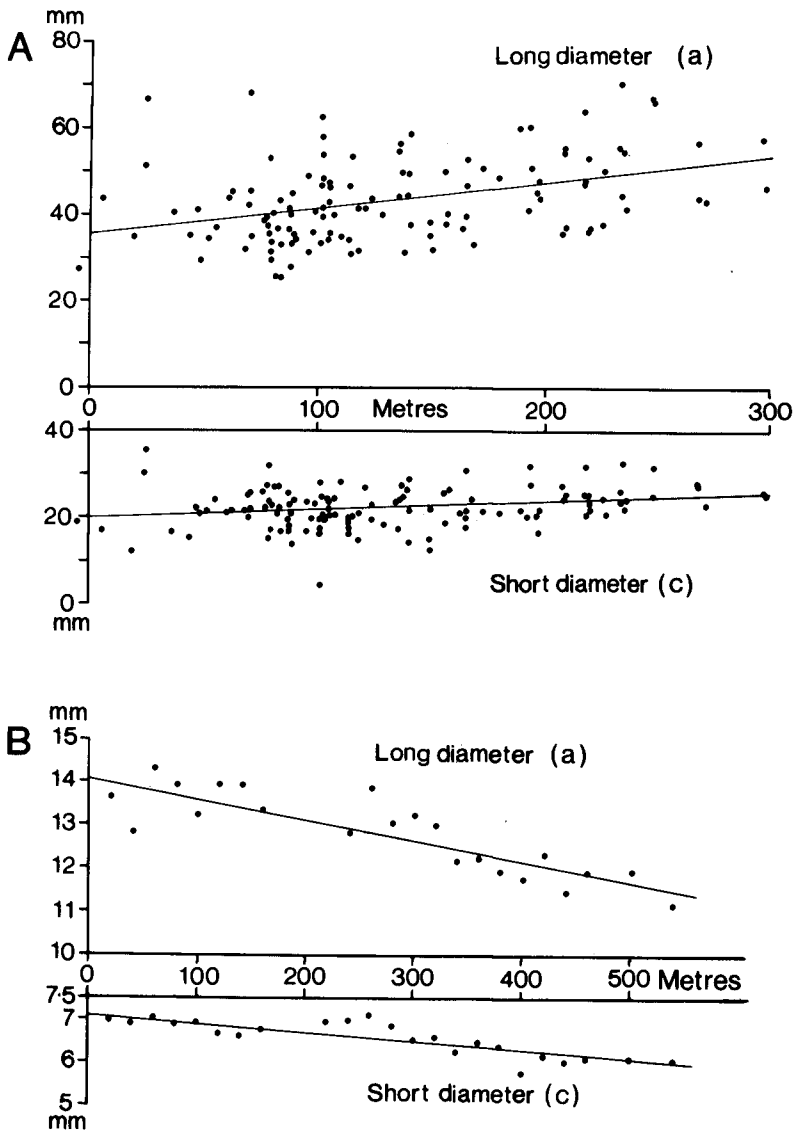


Figure 3

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.

Section No.	Mean dimension	Frequency = $1/T_z$	Signif. wave height (H_s)	$H_s^{1/2}$	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	
●	$p = .001$
●	$p = .01$
●	$p = .02$
●	$p = .05$

Table 2

Chosil 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 (θ°); frequency ($1/T_z$); significant wave height (H_s); (H_s^2); and Sine 2θ , where θ is the angle of swell approach relative to a

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 ($1/T$ and H_s^2) appear to be the most significantly correlated factors. Wave frequency ($1/T_s$) was important in vertical sorting of material; wave direction (ϕ°) and $\sin 2\theta$ in longshore transport, H_s^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 $\pm$ 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 -2 ϕ) and small pebbles (-2 to -4 ϕ) categories (where ϕ (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 -4 ϕ 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_s) 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

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 -2.40ϕ . Slightly larger pebbles, having a mean of -2.98ϕ , 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 1.5×10^7 and one of 6.0×10^6 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 ϕ 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 y and the distance travelled 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 a , b and 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.

Table 3

Date (February 1973)	Duration (tides)	Position	Particle dimensions										Notes	Key			
			a			b			c								
			Linear	Log	d ²	Linear	Log	d ²	Linear	Log	d ²						
13am	1	HW														p = .001	
13pm	2	HW														p = .01	
15	5	HW														p = .02	
		MW													p = .05		
16	7	LW														p = .007	
		LW													p = .01		
17	7 + 9	HW														p = .02	
		LW													p = .05		
18	3 + 11	MW															
		LW															
19	5 + 13	HW															
		MW															
		LW															
		LW															
20	7 + 15	MW															
		LW															
21	9 + 17	MW															
		LW															

Slapton Beach: tracer experiment, February 1973. Probability levels where $p \leq 0.05$ for correlations between $-\phi$ ($\phi = -\log_2$ 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.

Date (October 1973)	Duration (tides)	Position	Particle dimensions						Ratios			Shape indexes						Notes				
			a			b			c			c/a	c/b	b/a	3 $\sqrt{\frac{a^2+b^2+c^2}{3}}$				3 $\sqrt{\frac{abc}{a^2+b^2+c^2}}$			$\frac{a+b}{2c}$
			Linear	Log	Linear	Linear	Log	Linear	Linear	Log	Linear				Linear	Log	Linear		Log	Linear	Log	
5am	1	HW	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	n=12 Material stranded thereafter Correlations : ell except b
6pm	4	HW	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	Stranded thereafter n=27 Good correlations on linear dimensions only
7	5	HW	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	n=16 Fair correlations on two shape indexes only n=24 from origin n=19 from 100m for s, b, c n=29 (ell) for ratios and indexes
		MW	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	Correlations on shape indexes only
		LW	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	Excellent correlations on linear parameters only n=23
8	7	HW	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	Poor correlations on linear parameters only n=10
		MW	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	Good correlations on linear parameters only n=23
		LW	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	Med to good ratio & shape correlations n=28 from origin n=30 (all)

Key ● p=.02 ● p=.001 ● p=.01 ● p=.05 ● n=1

Table 4

Table 4

Key	● p=0.01	● p=0.02
	● p=0.05	● p=0.1

Slapton Beach: tracer experiment, October 1973. Probability levels ($p \leq 0.1$) for correlations between size/ratio/index (y) v. distance travelled alongshore in metres (x). n = no. of group samples. From inflection 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).

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 ϕ 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^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^1) and angle of wave approach (ϕ). (1 occasion at .001, 3 occasions at .01, 1 occasion at .02 for H_s^1 ; 3 occasions at .02 for ϕ^0). 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 1.9×10^{-2} and 1.0×10^{-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 ≤ 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.

DISCUSSION

It was concluded from the Chesil results that when the wave energy flux was high enough, and waves approached obliquely to the shore, the largest material located in the inter-tidal zone travelled farthest. This view has been held by a number of earlier workers in the field (e.g. Richardson (1902) for Chesil; Kidson and Carr (1961) for Bridgewater Bay, and Jolliffe (1964) for Sussex, England). It is not clear, from the Chesil data, however, to what extent the results are influenced by the size of the background sediment ('traction carpet') nor whether the greater movement of larger material is a function of relative or absolute size.

The reduced movement of the higher specific gravity basalts, compared with the other pebble types, suggests that where sources are readily available they might be of significance in beach replenishment schemes although, again, the results may be the effect of the ratio of the quantities of pebbles of different specific gravities rather than the specific gravity as such. There is also the possibility that denser pebbles might be combed down below the area to be protected in a fashion comparable to the 'oversize' granulites.

The best correlations between different geological types, and to some extent for longshore transport, were with thickness (short axis, c) in spite of the greater potential percentage error in measurement of this parameter.

This reflects the prevalent position of rest for the entire beach pebble population, and that the short axis is the most susceptible parameter to swash-backwash movement. As such, pebble thickness should be relevant in beach stability.

At Chesil, shape appeared relatively unimportant as had been shown to be the case in laboratory studies with oscillatory flow (Rance and Warren, 1968; Hydraulics Research Station, 1969). Even when statistically significant correlations occurred in the field the slope of the linear regression line between the shape index and distance travelled was low.

At Slapton sorting appears to be based on different criteria (ϕ frequency and weight; linear parameters; ratios and shape indexes) from time to time. Even where there is an intimate mix of the background population, as was the case during the tracer experiments, it is not easy to isolate the relevant factors which are so highly inter-related. Where linear parameters are relevant, the short axis (c) correlations were again better than for a and b. With greater wave energy, grading only occurred at high water sampling sites and with c. The restriction to high water may be explained by the more consistent wave data then (see below), or by the complicating effect of turbulence and swash-backwash interaction at mid and low-tide levels, particularly with the shorter wave periods characteristic at Slapton. The short axis dominance would correspond to the higher wave energy environment at Chesil. It is interesting that where one parameter has been used in previous work it has almost invariably been the weight, through sieving (ϕ), or the long (a) or intermediate (b) axis (e.g. Kellerhals and Bray, 1971).

Shape-sorting such as that at Slapton, has been widely reported elsewhere, e.g. by Cailleux (1948) for the beaches between the River Var and Antibes and Dobkins and Folk (1970) at Tahiti-Nui. Krumbein (1941) suggested that '--- shape may play its most important role in the selective transportation of the particles'. While it is tempting to argue that shape-sorting may be a response to the generally lower wave energy at Slapton as compared with Chesil there was no valid correlation between shape and wave parameters at Slapton during the 1973 experiments. The overall lack of correlation between sediment parameters and Slapton wave data is almost certainly a result of the east-facing aspect of the site and the increased influence of the Skerries Bank at certain periods in the tidal cycle. This has the effect of preventing equilibrium between sediment and hydraulic processes being obtained before wave parameters are again modified.

However, the basic difference between Chesil and Slapton is the way in which smaller material travelled furthest in both Slapton beach tracer experiments. Any effect of tidal currents is marginal, the gross longshore sediment transport being related to prevailing wave direction. Similar results (where a_{max} varied between approx 1.1 and $7.6 \times 10^{-2} m$) were attributed to 'strong--- longshore currents' operating on indigenous sediment at Duktoth Spit, Alaska (Hayes, 1973). Incidentally, Jolliffe (1972) noted that on the sea bed, in depths of 9-18 m, smallest pebbles also travelled farther than larger. Further research needs to be undertaken in this field.

At both Chesil and Slapton there are many occasions where the t-statistic (Table 6) demonstrates the degree of selection of tracer between the overall and zonal daily recoveries, and between them and the injected population, frequently at a 0.001 probability level. At Chesil it was suggested that such differentiation reached its maximum with the coarsest sediment grades under low, long period, swell but the same order of selectivity has since been shown to occur at Slapton with shorter, wind-driven waves.

While this paper has not been concerned with the detailed processes affecting a coarse sediment beach, it is pertinent to ask to what extent sorting normal to the beach, through the beach (as laminae), and alongshore, are associated. The Chesil experiment by Gleason and Hardcastle (1973) suggested that wave height (as H_s) is relevant in sorting, both alongshore and at right angles to the beach. An oblique angle of wave approach is clearly necessary for longshore selection. Gleason and Hardcastle found that sorting downbeach was also correlated with wave frequency ($\frac{1}{T}$). This conclusion is very much in line with earlier work by Miller (1958) on turbulence, and by Kemp (1960, 1963) on 'phase difference'. It is not clear where 'rejection' of inappropriate grades of particle from the traction carpet fits in (Moss, 1962, 1963). That is, whether, at Chesil, the largest material travels furthest as a function of greater surface area or because it is 'rejected' more frequently either by working its way upwards or being stranded on the surface as smaller pebbles work their way down through the beach.

CONCLUSIONS

Much has been written about the problems of scale in hydraulic model studies. These problems relate to size and form of waves, size and shape of sediment, and the means of representation of geographical areas. However, it is possible to study particular parameters under a controlled, but restricted, range of conditions.

With field experiments on the beach there is a far wider range of potential difficulties stemming, in part, from the inter-action of hydraulic and sedimentary parameters. Studies often do not provide representative environmental conditions. Particularly with shingle there are the complications of cusps and strandlines on the surface and laminae with depth; the legacy of residual grading; a lack of equilibrium with wave data because of the variability of the latter; the effect of the traction carpet; increasing angularity of sediment with diminishing size, and of relation between tracer and background particle size.

Instrumentation of sediment movement, wave data and longshore currents (e.g. by electromagnetic flowmeters) also presents a problem, especially in severe conditions.

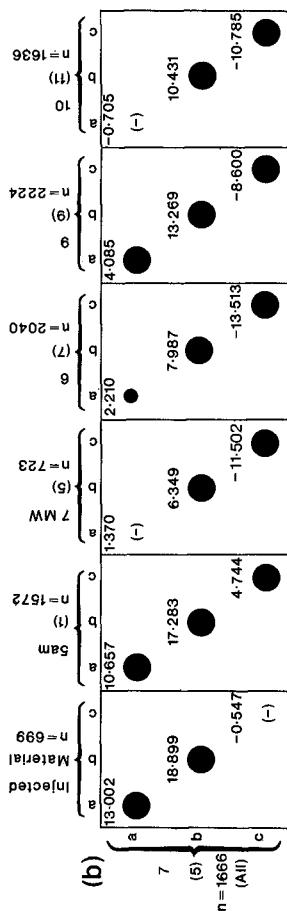
Analysis of the results is complicated by selective recoveries and by the inter-relation of sedimentary parameters which precludes the use of multivariate techniques. More important, selective recoveries also cast doubt on the validity of many tracer experiments which have used coarse grades of material.

Table 6

Date (Oct. 1969)	n	a		b		c		Notes
		t	p	t	p	t	p	
24	194	2.652	●	3.918	●	5.114	●	
25	105	2.824	●	2.806	●	4.213	●	
26	193	1.071		1.063		2.177	●	
27	711	5.403	●	5.481	●	3.221	●	c=nearly .001
28	276	0.729		1.365		2.907	●	
29	137	2.069	●	2.129	●	4.102	●	
24	255	4.252	●	3.584	●	2.077	●	November

Key
● p=.001
● p=.01
● p=.05

(a)



t-statistic: to test whether two samples come from the same population. The greater the value of t the more different the recovered sample. Probability (p) shown when ≤ 0.05 . n = number of individuals. Examples are taken from: (a) Chesil Beach tracer experiment, 1969. Comparison of material recovered to original population injected (After Carr, 1971). (b) Slapton Beach tracer experiment, October 1973. Probability that injected population, sub-population for 7 October MW, and whole recovered populations for other days are the same as the whole recovered population on 7 October. No. of tides shown in brackets. (Negative values result when the sample mean in the column is smaller than the corresponding value in the row). Note the variability from day to day; the selection within a population (7 October all v. 7 October MW) and the change in proportions between the linear parameters (e.g. the positive value of c for 5 October (after 1 tide) compared with the other days).

Wood (1970) wrote: 'With the variation of weather, tide and mobility of a shingle beach profile it is unlikely that any direct general relationship will be found between longshore energy flux and littoral drift even for the same beach, and no reliable quantitative solution of general applicability is foreseeable, without separation of the many parameters'. There is a need to carry out intensive short-term studies to see the precise relation of hydraulic parameters to sediment in the inter-tidal and nearshore zones. Such results could well be of real economic value.

Acknowledgements: I would like to express my appreciation of the invaluable help and support of Peter Hardcastle, Ray Gleason and Mike Blackley over a period of several years. Figure 2 and Table 6^a are based on data originally published in the Journal of Sedimentary Petrology of the Society of Economic Palaeontologists and Mineralogists; Table 2 on data in Estuarine and Coastal Marine Science. Tables 3 and 4 are similar to those published in the Journal of the Geological Society and are reproduced by kind permission.

REFERENCES

- Cailleux, A. 1945. Distinction des galets marins et fluviatiles, Bull. Soc. Geol. France, 5, 375-404.
- Cailleux, A. 1948. Lithologie des dépôts émergés actuels de l'embouchure du Var au Cap d'Antibes, Bull. de l'Institut Oceanographique, Monaco, No. 940, 1-11.
- Carr, A.P. 1969. Size gradinn along a pebble beach: Chesil Beach, England. J. Sedim. Petrol., 39, 297-311.
- Carr, A.P. 1971. Experiments on longshore transport and sorting of pebbles: Chesil Beach, England. J. Sedim. Petrol., 41, 1084-1104.
- Carr, A.P. and M.W.L.Blackley. 1969. Geological composition of the pebbles of Chesil Beach, Dorset. Proc. Dorset Nat. Hist. Archaeol.Soc., 90, 133-140. (Volume for 1968).
- Carr, A.P., Gleason, R. and A.C.King. 1970. Significance of pebble size and shape in sorting by waves. Sediment. Geol., 4, 89-101.
- Castanho, J. 1970. Influence of grain size on littoral drift, 12th Inter. Coastal Engineering Conf., Washington, Proceedings, 2, 891-898.
- Dobkins, J.A. and R. L. Folk. 1970. Shape development on Tahiti-Nui, J.Sedim. Petrol., 40, 1167-1203.
- Emery, K.O. 1955. Grain size of marine beach gravels, J.Geol., 63,39-49.
- Emery, K.O. and R.H. Tschudy. 1941. Transportation of rock by kelp, Geol. Soc. Am.Bull., 52, 855-862.
- Gleason, R., Blackley, M.W.L. and A.P.Carr. 1975. Beach stability and particle size distribution, Start Bay. J.Geol.Soc.Lond., 131.
- Gleason, R. and P.J.Hardcastle. 1973. The significance of wave parameters in the sorting of beach pebbles, Estuar. & Coast. Mar.Sci., 1, 11-18.
- Hardcastle, P.J. and A.C.King. 1972. Sea wave records from Chesil Beach, Dorset. Civil Engineering, 67, 299-300.
- Hayes, M.O. 1973. The investigation of form and processes in the coastal zone, pp. 11-41 in Coastal Geomorphology, ed. D.R.Coates. Proc. 3rd Annual Geomorph. Symposia, Binghampton, N.Y., Sept.1972.
- Hydraulics Research Station. 1969. Threshold movement of shingle subject to wave action. H.R.S., Wallingford, U.K. Notes 15,December.
- Jolliffe, I.P. 1964. An experiment designed to compare the relative rates of movement of different sizes of beach pebbles. Proc.Geol.Ass., 75, 67-86.
- Jolliffe, I.P. 1972. Offshore gravel extraction and coastal regime. International Geography 1972, Vol.1, 643-644. 22nd Inter. Geog. Congress, Montreal.

- Kellerhals, R. and D.I.Bray. 1971. Sampling procedures for coarse fluvial sediments, J.Hydraul. Div.Am.Soc.Civ.Engrs., 97, 1165-1180.
- Kemp, P.H. 1960. The relation between wave action and beach profile characteristics, 7th Inter. Coastal Engineering Conf., The Hague. Proceedings, 262-277.
- Kemp, P.H. 1963. A field study of wave action on natural beaches, Inter. Assoc. of Hydraulic Research, London. 1, 131-138.
- Kidson, C. and A.P.Carr. 1961. Beach drift experiments at Bridgwater Bay, Somerset, Proc. Bristol Nat.Soc., 30, 163-180.
- Krumbein, W.C. 1941. Measurement and geological significance of shape and roundness of sedimentary particles, J.Sedim.Petrol., 11, 64-72.
- Krumbein, W.C. and W.R.James. 1965. A lognormal size distribution model for estimating stability of beach fill material, Tech.Mem.16, U.S. Army Coastal Engineering Research Center.
- Longuet-Higgins, M.S. 1970a and b. Longshore currents generated by obliquely incident sea waves, 1 and 2. J.Geophys.Res., 75, 6778-6789; 6790-6801.
- Miller, R.L. 1958. A study of the relation between dynamics and sediment pattern in the zone of shoaling wave, breaker and foreshore. Ecologiae. Geol. Helv., 51, 542-551.
- Moss, A.J. 1962. 1963. The physical nature of common sandy and pebbly deposits, 1 and 2. Am.J.Sci., 260, 337-373; 261, 297-343.
- Neate, D.J.M. 1967. Underwater pebble grading of Chesil Bank, Proc. Geol.Ass., 78, 419-426.
- Rance, P.J. and N.F.Warren. 1968. The threshold of movement of coarse materials in oscillatory flow, 11th Inter. Coastal Engineering Conf., London. Proceedings, 1, 487-491.
- Richardson, W.M. 1902. An experiment on the movement of a load of brickbats deposited on the Chesil Beach, Proc.Dorset Nat.Hist. Antiq. Fld.Club, 23, 123-133.
- Sneed, E.D. and R.L.Folk. 1958. Pebbles in the Lower Colorado River, Texas, a study in particle morphogenesis, J.Geol., 66, 114-150.
- Tucker, M.J. 1963. Analysis of records of sea waves, Minut.Proc. Inst. Civ. Engrs., 26, 305-316.
- Wentworth, C.K., 1922. The shape of beach pebbles, U.S.Geol.Surv.Prof.Papers, 131-C, 75-83.
- Wood, A.M.M. 1970. Characteristics of shingle beaches: the solution to some practical problems, 12th Inter.Coastal Engineering Conf., Washington. Proceedings, 2, 1059-1075.