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Lateral Grading of Beach Sediments: A Commentary

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ABSTRACT

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Lateral grading of beach sediments can be achieved by downdrift attrition and/or longshore drifting. Chesil Beach (England) is graded from small to large pebbles and cobbles south-eastward in the direction of increasing wave energy. Attrition is very slow, and grading seems to have been achieved by alternations of longshore drifting, with selection of coarser from finer particles by the stronger south-eastward movement. Wave energy gradients may have contributed by moving smaller particles westward, and by conserving the lateral gradation. Hawke Bay beach (New Zealand) is graded in the reverse direction. It is fed with sand and gravel by the Mohaka River, near the western end, and lateral grading has been attributed to downdrift attrition eastward. Longshore sorting has probably also contributed, and a method of separating attrition from sorting is proposed. The two systems are compared as a basis for elucidating the causes of lateral drifting, which can evidently develop in different ways.

ADDITIONAL INDEX WORDS: *Lateral grading, beach granulometry, longshore drifting, wave energy gradients, attrition.*

INTRODUCTION

Lateral grading of beach sediments generally takes the form of progressive longshore changes in the size, shape or density of pebbles and sand grains, and has been observed and discussed on beaches in various parts of the world. The topic was of much interest to the late R.W.G. Carter, who discussed it on the Magilligan Foreland beach (CARTER, 1975) and elsewhere on the coast of Northern Ireland, and contributed a brief review of 'beach grading' in his book *Coastal Environments* (CARTER, 1988, pp. 240–244). It is evident that several factors have contributed to lateral grading, and that there is no single, simple explanation for the phenomenon. Among the many beaches that show lateral grading by particle size the longest and most impressive are Chesil Beach on the south coast of England and the Hawke Bay beach on the east coast of North Island, New Zealand. Both are gently curved beaches with a southerly aspect, but they show lateral grading in opposite directions. This commentary will refer primarily to these two beaches in considering some of the problems that have to be solved before a comprehensive explanation of lateral grading of beach sediments can be achieved.

CHESIL BEACH

Chesil Beach is a shingle beach on the Dorset coast in southern England, stretching about 28 kilometres from the harbour breakwaters at West Bay, near Bridport, and curving south-eastwards until it terminates beneath the high limestone cliffs at Chesilton, on the west coast of Portland Bill (Figure 1: inset, and Plate 1). Towards the western end the beach runs in front of vertical cliffs of layered sandstone, but at Burton Cliff, a kilometre east of the mouth of the River Bride, it diverges to form a shingle barrier about 150 metres wide, rising 7 metres above high tide level, fronting a series of marshy meres and then the shallow tidal lagoon known as The Fleet (Plate 2). The shingle barrier widens south-eastwards to approximately 200 metres, increasing in crest height to 14.7 metres above high tide level at the south-eastern extremity. It faces south-west, and receives ocean swell from the Atlantic as well as waves generated by wind action in the English Channel. Mean spring tide range is 3.7 metres at Lyme Regis, to the west, but diminishes eastward to about 3 metres on Chesil Beach.

Evolution of Chesil Beach

The shingle barrier rests upon a gentle bedrock slope that declines seaward to a depth of 15 metres below Ordnance Datum, the shingle being underlain by lagoonal deposits. These indicate that Chesil Beach has moved landward during and since the Late Quaternary (Flandrian) marine transgression: the inner shore of The Fleet has only minor cliffing, and has never been exposed to the open sea at its present level, a point first noted by BADEN-POWELL (1930). There is still intermittent landward movement as the result of overwashing of beach material during occasional south-westerly storm surges, and lagoonal deposits exposed low on the seaward side are the source of lumps of clay and peat thrown up on the beach south-east of Abbotsbury during storms. The accompanying short-term variations in beach crest height and location have been documented by CARR and GLEASON (1972) and CARR and SEAWARD (1990).

Chesil Beach consists of well-rounded brown pebbles, more than 98.5% of which are flint and chert derived from Creta-

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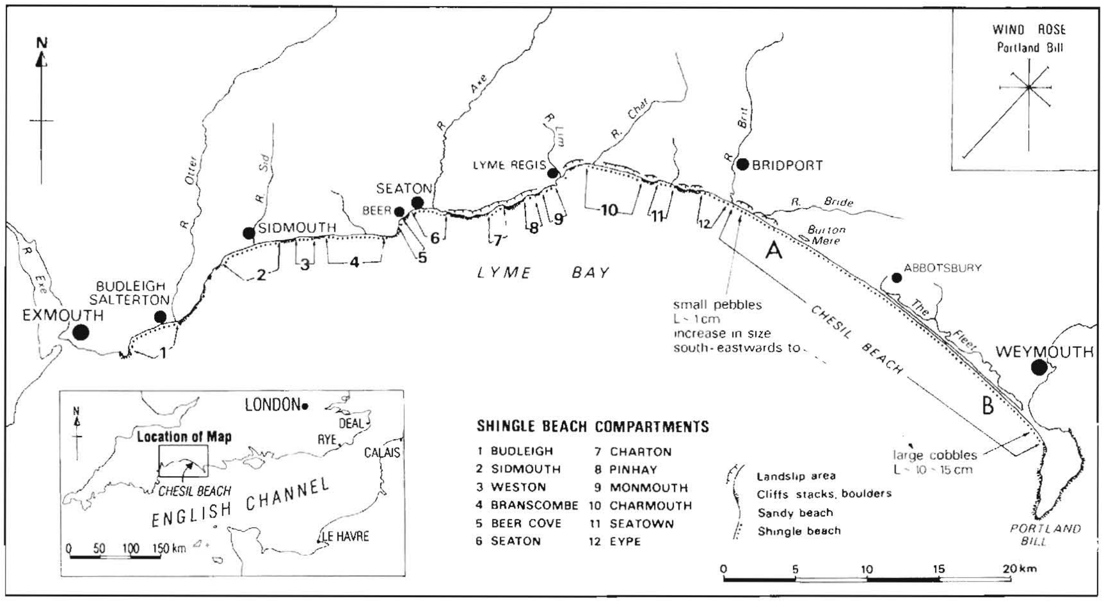

Figure 1. Chesil Beach and other shingle compartments in Lyme Bay, Dorset, on the south coast of England. The wind rose (inset) indicates that south-westerly wind-generated waves are dominant, but that southerly, south-easterly and westerly waves also occur in coastal waters. There is also a south-westerly swell arriving from the Atlantic Ocean.

ceous formations, which overlie Jurassic rocks in the Dorset hinterland, and are exposed in cliffs along the coast to the west, capped by derived Pleistocene flint and chert gravels (BIRD 1995). The remaining 1.5% are Triassic quartzites, a few pebbles of Jurassic limestone and sandstone, and fragments of granite, vein quartz and metamorphic rock derived from formations that outcrop farther west, on the coasts of Devon and Cornwall. Towards the south-eastern end of the beach there is an increasing proportion of limestone pebbles and cobbles derived from the cliffs and quarry waste of the Isle of Portland. All of the beach material has come from eroding cliffs beyond either end of the beach, and from the sea floor: the rivers of southern England are small and deliver very little sediment to the coast other than fine material (silt and clay), and there has been no fluvial input to Chesil Beach. Petrological variations within the beach are a function of the durability and initial size of the stones, their source and their history of migration (CARR and BLACKLEY, 1969).

Chesil Beach has been regarded as essentially a relict formation, which originated during Pleistocene oscillations of sea level, when successive marine transgressions collected gravel from earlier fluvial and periglacial deposits on what is now the sea floor and built them into a barrier formation. STEERS (1953) concluded that 'the present Chesil [Beach] may be regarded as one last stage in a slow landward movement of sea floor material in front of the breaking waves; a sea level slowly but surely rising on a shelving land and, as it were, driving before it shingle, rather as a broom sweeps dust from a floor'. Chesil Beach is no longer receiving gravelly material from the sea floor (NEATE, 1967), but limestone pebbles and cobbles are still being added at the south-eastern end, and there have been occasional accessions of pebbles and cobbles from the west, derived mainly from cliff-top weathered gravelly Pleistocene drift deposits. They are assembled in beach compartments on the coast of Lyme Bay, and as intervening headlands are cut back they are drifted eastward by the predominating south-westerly waves towards Chesil Beach. The building of the West Bay harbour breakwaters at the mouth of the River Brit in 1742 reduced beach drifting, but some gravelly material is moving eastward across the sea floor. Although there are none of the irregular white-coated flint nodules or well-rounded bluish flint cobbles of the kind found, freshly derived from Chalk or Jurassic limestone outcrops, on beaches further west in Lyme Bay (BIRD, 1989), it has been calculated that the recession of cliffs to the west is yielding over 4,000 m^3/year of gravel to the beaches between Lyme Regis and Bridport (BRAY 1992). The proportion of this moving on to and along Chesil Beach is difficult to determine, but the preservation of lateral grading indicates that any material arriving must move quickly to the sector dominated by pebbles of similar size.

Lateral Grading

Chesil Beach shows remarkable lateral size grading (Plate 3), especially between high and low tide lines, where there is a gradual increase in calibre from small pebbles (mean diameter about 1.0 cm) at West Bay (south of Bridport) to large cobbles (mean diameter 10 to 15 centimetres) at the extreme south-eastern end (Figure 1). The gradation is so obvious that it is possible for boatmen to come ashore in fog or at night and know how far along the beach they are by the size of the pebbles. CARR (1969) illustrated this gradation by detailed measurements, thereby confirming observations made by

Plate 1. Chesil Beach, looking south-east towards the limestone cliffs of Portland Bill.

CORNISH (1898), and found that as the grain size increased south-eastward the shape of the pebbles and cobbles showed little variation. Below the low tide line the beach material is less well sorted, with a few larger pebbles and cobbles and some sand, and on the crest of the beach is a scatter of larger stones thrown above high tide level by occasional storms.

Such lateral grading is only possible where there is a range of grain sizes: as CARTER (1988) remarked: 'whether or not grading develops is controlled by the inherent characteristics of the sediment mass'. The evolution of lateral grading on Chesil Beach has been much discussed, and numerous papers have been published: there are useful reviews by ARKELL (1947) and CARR and BLACKLEY (1973).

Wave Energy

It has been noted that the increase in pebble size south-eastward along Chesil Beach accompanies an increase in mean wave height in that direction (ARKELL, 1947; CARR, 1971; CARR and BLACKLEY, 1974). The nearshore profile is smooth, and certainly steepens south-eastwards, the 10 metre depth contour being nearly a kilometre offshore at West Bay and less than 60 metres at the eastern end. Measurements of waves have shown that long-period swell ($T > 12$ seconds) is commoner towards the south-east, and statistical predictions indicate a larger maximum wave height in that direction (HARDCASTLE and KING, 1972). Recent storm surges have produced waves large enough to overwash the beach crest only towards the south-eastern end, in a sector which lacks even the sparse vegetation seen further west. Analyses of wave regimes have dealt more with wave height than with wave refraction and energy dissipation, and it would be interesting to develop the approach used by STONE *et al.* (1992) on laterally graded beaches on the Gulf Coast of the United States to an anlaysis of wave energy on Chesil Beach.

Several authors have reported a correlation between lateral grading of shingle and longshore gradients in wave energy. KING (1972) found 'a positive relationship between wave energy and size of shingle. . . the largest particles tend to accumulate in the zones of greatest energy', and CARTER (1988) concluded that 'longshore size sorting tends to mirror spatial gradients in wave energy' with 'a propensity for coarse grains to congregate under the more energetic breaker zone'. The lateral grading on Chesil Beach is consistent with the observation by BRYANT (1982) that on steep, reflective beaches longshore drifting diminishes (or alternating longshore drifting becomes balanced) and longshore size-sorting tends to mirror spatial gradients in wave energy. However, a correlation between increasing grain size and increasing wave

Plate 2. Chesil Beach, near Abbotsbury, with the Fleet lagoon on the left. The crest profile is indicated by the line of World War II tank traps.

energy is not a full explanation of lateral grading. It is necessary to separate cause from consequence, and to clarify the mechanism whereby sorting has been achieved.

Attrition

An early view was that lateral grading on Chesil Beach was due to progressive attrition (defined as mechanical reduction in size of rock particles) of shingle as it moved along the shore, the progressive wearing down of cobbles to pebbles indicating a predominant westward drift. This was the view of PRESTWICH (1875), who thought that the shingle came from the raised beach, of which a remnant survives on Portland Bill, to the south-east. However, there is little evidence of such attrition, and the concept of predominant westward drifting has not gained general acceptance. The pebbles are of resistant materials, which rarely break, and although some wearing must have taken place as the result of repeated wave agitation (the pebbles are well-rounded), it is probably a very slow process. The exception, as BADEN-POWELL (1930) noted, is that the less resistant limestone cobbles derived from the Isle of Portland cliffs are quickly worn down as they drift north-west along the beach in response to occasional southerly waves in the waters immediately west of Portland Bill.

Lateral grading occurs along both sides of the shingle barrier, and although the material on the ridge crest and inner slope is less well sorted than on the intertidal beach face it is not noticeably coarser, as it would be if attrition were rapid on the more exposed seaward side. If beach face pebbles diminished by attrition are being transported westwards, and immediately replaced by slightly larger shingle arriving from the east, there should be continuing accretion of small pebbles at the western end, and a deficit developing in the coarser material towards the south-eastern end of the beach. There is indeed a minor accumulation of small pebbles against the West Bay harbour breakwaters during episodes of southerly and south-easterly wave action, but no sustained accretion at the western end. Nor is there any obvious deficit at the south-eastern end, although the rate of supply of limestone cobbles from the cliffs of the Isle of Portland to the beach at Chesilton and the extent of their westward movement should be investigated further.

The landward migration of Chesil Beach implies that when beach material is washed over the crest from the seaward face during a major storm there will be exposure of shingle that has resided within the beach for some centuries. There is no indication that shingle exposed in this way after storms is noticeably coarser than that which previously occupied the beach face, implying that attrition has been very slow, even compared with the rate of landward migration of the shingle barrier.

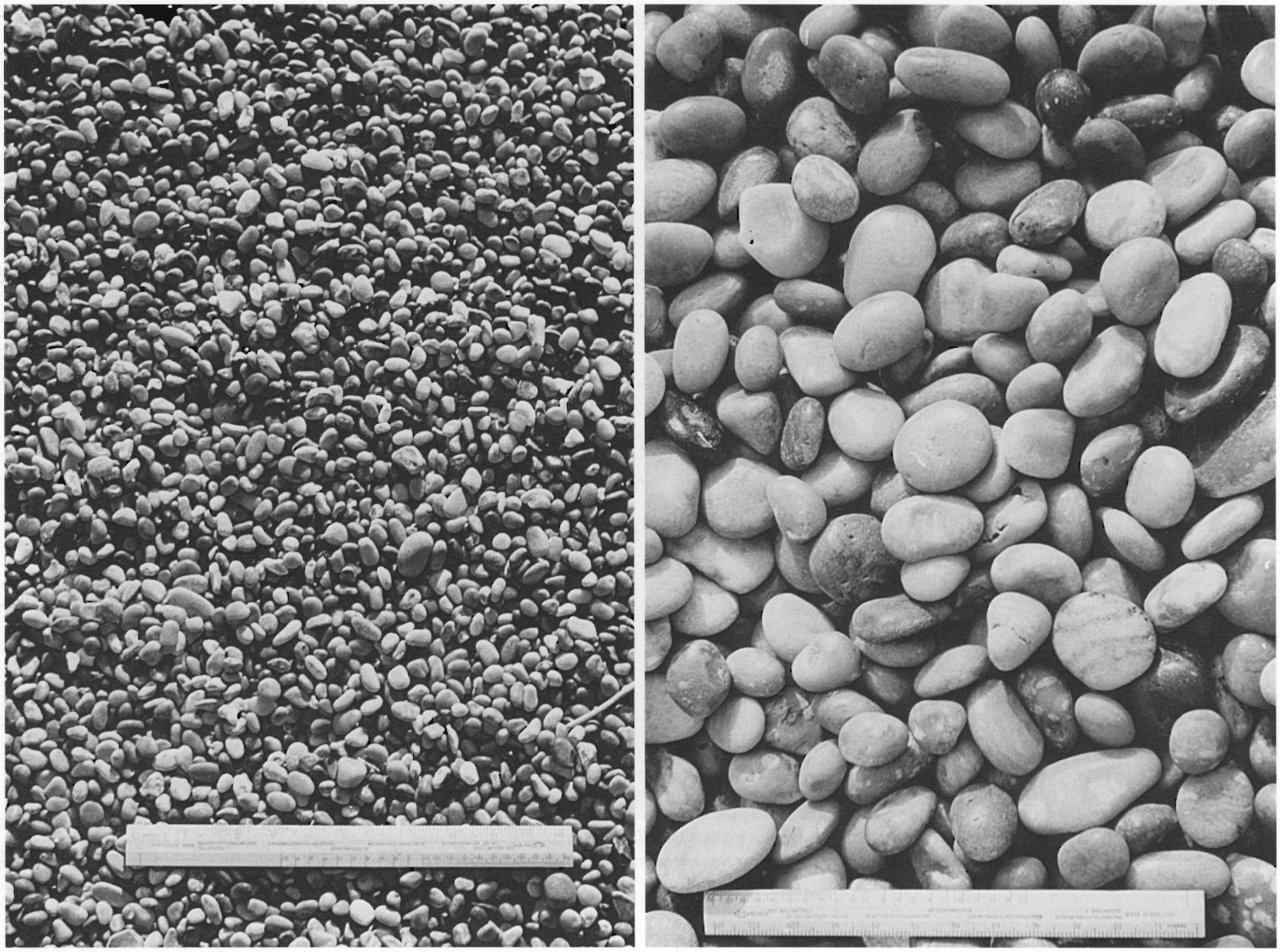

Plate 3. Contrast in shingle size on Chesil Beach. The scale in both photographs is a one foot (approximately 30 centimetre) ruler. On the left is the beach near the western end (A in Figure 1), where mean pebble diameter is between 1 and 2 centimetres, and on the right the beach towards the south-eastern end (B in Figure 1), where mean pebble diameter is about 5 centimetres.

Longshore Sorting

Most authors have accepted that attrition has played little part in the development of lateral grading on Chesil Beach, preferring the hypothesis of sorting (selection). This could have been achieved by a process, or combination of processes, which have carried beach material of particular size, shape and density, with a specific hydraulic equivalence, along the shore until it congregates on a particular beach sector.

As CARTER (1988, p. 241) observed, 'there is a prevailing assumption in reports of size-grading that grain selection results in the fining of sediments downdrift [and] that fines—at least within the gravel-sand size ranges—are more mobile, and will thus migrate further, faster'. Examples of this have been documented by EVANS (1939), TUTTLE (1960), CUNNINGHAM and FOX (1974), SELF (1977), and STAPOR and MAY (1983). It was the basis of a deduction by PRESTWICH (1875) that Chesil Beach had been sorted by a predominance of westward longshore drifting, with gradual attrition from cobbles to pebbles. However, many beaches show coarsening downdrift (SEIBOLD, 1963; MCCAVE 1978), and on Magilligan Foreland in Northern Ireland CARTER (1975) deduced that longshore drifting had moved relatively coarse sediment more rapidly than finer material: a phenonemon also noted on Chesil Beach by COODE (1853). PALMER (1834) had previously concluded that the larger pebbles travelled further and faster south-eastward along Chesil Beach, and Coode noted their interception by the Isle of Portland, acting as a huge natural groyne. Later workers have accepted that predominant longshore drifting on Chesil Beach has been south-eastward in the direction of coarsening beach gravel (CARR 1969).

On Cape Cod SCHALK (1938) attributed a similar increase in beach sediment size downdrift to a progressive loss of finer material seaward, leaving the beach as a coarse lag deposit, but there is no evidence of such rejection of smaller pebbles as shingle size increases south-eastward along Chesil Beach. STONE et al. (1992) concluded that westward coarsening of the beach sediments between Grayton Beach and Pensacola Pass on the Florida coast resulted from an increase in wave energy in that direction, which seems to be true of Chesil Beach, but requires closer analysis.

Persistence of Lateral Grading

Lateral grading may develop as the result of longshore drifting, but once attained it is likely to persist only if the volume and rate of longshore drifting diminish, or take the form of more or less balanced alternations. CARTER (1988, p, 243) suggested that once the shingle has become graded, each sector of beach consisting of pebbles or cobbles of uniform size forms a homogeneous surface from which they are not easily dislodged by wave action. Arriving pebbles of the same size are assimilated in the beach mass. Larger pebbles, moved by storm waves, roll or slide quickly across such a beach face, and smaller ones are liberated as the beach surface is reworked by wave action, rejected, and carried away alongshore by angled swash. DAVIES (1974) found that on an essentially relict beach such sorting persists because of the lack of new material, and remains in equilibrium with wave energy gradations or process regimes.

As CARTER (1988, p. 243) remarked: 'It should be clear that every particle has a most favoured position, and that gradually through reworking the beach will become graded. These positions will reflect the nil-transport location for that particular grain, which should lie just below an entrainment threshold associated with extreme [wave] energy conditions. The direction of grading should be an artefact of the net transport vector'.

Experimental Work

RICHARDSON (1902) put brick fragments of various sizes on Chesil Beach and found that they drifted along the shore at rates of up to 550 metres per day until they arrived in the sector where there were pebbles of a similar size. There was some doubt about the validity of this experiment because the brick fragments were initially angular, and differed in shape and hardness from the mainly flint and chert pebbles. However, the results were confirmed by CARR (1971), who imported pebbles from Scotland of rock types not naturally present on Chesil Beach, so that their movement could be readily traced, and put them on sectors where they were larger than the local pebbles. These also drifted south-eastward, at rates of up to 343 metres per day, until they reached the sector where they matched the ambient shingle size. These experiments demonstrated that longshore drifting can be generated by waves arriving on Chesil Beach: it may have little effect now on the laterally graded shingle, but it could have produced this lateral grading.

JOLLIFFE (1964) carried out experiments with painted pebbles and synthetic shingle tracers at Deal and Rye in south-eastern England, and found that the larger waves moved the largest pebbles most rapidly, while small waves moved only the finer beach particles, leaving the larger ones more or less stationary. He suggested that a predominance of stronger south-westerly wave action could thus have sorted Chesil Beach laterally.

Lateral Grading and Wave Energy Variations

There is no doubt that Chesil Beach as a whole is related to wave energy gradients, for it is aligned orthogonally to the approach of the largest storm waves (LEWIS, 1938), but the relationship between size sorting and wave energy variations needs elucidation. It would be interesting to develop a numerical model to explore this process. CARR (1971) suggested that the tracer pebbles he deposited on Chesil Beach had migrated to the sector where they were in equilibrium with the prevailing wave energy, but longshore drifting was due to waves arriving at an angle to the beach.

The correlation of shingle size trends with wave energy gradients could be explained by the moving away from high wave energy sectors of pebbles up to a certain size, only the coarsest remaining. Such selection could take place slowly and intermittently, as the beach face was reworked by storm waves. The implication is that waves refracted by the sea floor in such a way as to anticipate and fit the outline of a beach, arriving parallel to the shoreline, but producing higher breakers on one end than the other, could sort a heterogenous beach into a graded one by generating longshore drifting from the higher to the lower energy sector without actually breaking at an angle to the shore. The paradox is that on Chesil Beach this implies westward drifting, conditioned by diminishing pebble size mobilisation thresholds as maximum wave energy declines in that direction, on a beach where the prevalence of south-westerly wave action, arriving obliquely to the shoreline, would suggest a predominant drifting to the south-east. The hypothesis of sorting by wave energy contrasts needs testing by injecting tracer pebbles smaller than the ambient size and determining whether they move westward. Such counter-drifting of smaller pebbles may well have been a contributory factor to sorting, but experimental work has shown that pebbles are moved quickly by waves arriving obliquely to the shore in either direction. The potential longshore drifting in either direction could have produced lateral grading.

Grading by Drift Alternations

CODDE (1853) was the first to suggest that lateral grading on Chesil Beach developed as the outcome of two interacting wave trains, south-eastward drifting by the stronger and more frequent westerly and south-westerly waves in Lyme Bay alternating with westward drifting by occasional south-easterly and southerly wave action. Given an initially heterogeneous (unsorted) Chesil Beach, the predominant westerly and south-westerly waves would have carried all grades of shingle south-eastward, while the occasional south-easterly and southerly waves, being less powerful, would have carried only the smaller pebbles back to the west. This could have achieved the sorting, pebbles of a particular size being moved to and fro until they settled in a sector where they conform with the average. CORNISH (1898) supported this hypothesis, but his suggestion that tidal currents had contributed to the sorting is unlikely because alongshore tidal currents do not here attain velocities capable of moving even the smaller pebbles. LEWIS (1938) concluded that there was now no net longshore drifting on Chesil Beach because its alignment had become adjusted to the pattern of the dominant south-westerly storm waves, but that occasional waves from the west-south-west had carried shingle of all sizes south-eastward, whereas southerly waves had taken only the smaller pebbles back towards the west, thereby contributing to lateral grading.

Most attempts to explain the evolution of lateral grading on Chesil Beach seem to have been based on what would happen on an initially heterogenous Chesil Beach in its present position, but this could be misleading. Lateral grading was achieved within the shingle deposit as it was driven landward by recurrent storm wave episodes, during and since the Late Quaternary (Flandrian) marine transgression. There may well have been a heterogeneous mass of gravel about 10,000 years ago on what is now the floor of Lyme Bay, which the rising sea mobilised, initiating the process of lateral sorting as it rolled landward. There may have been a still earlier beach formation, shaped in Pleistocene times, of which the shingle raised beach on Portland Bill is a remnant.

A Beach in Equilibrium?

The indications are that, lateral grading having been achieved, Chesil Beach is in equilibrium with the incident wave regime. Swell from the Atlantic Ocean generally breaks parallel to the beach, but locally generated waves result from the wind rose shown in Figure 1. The westerly, south-westerly and southerly components of this indicate a potential for longshore drifting in either direction, and although this needs refining against data of actual wave regimes it agrees with the results of the various experimental studies. Some longshore drifting takes place whenever waves arrive at an angle to the shore, but a with the achievement of lateral grading a balance could have been achieved whereby net actual longshore drifting is zero. The implication is that, left undisturbed and without any change in wave climate, Chesil Beach will continue to move landward intermittently as the result of storm surge overwash, and that it will retain its lateral grading, perhaps with gradual attrition over a long period.

Other Dorset Beaches

It is noteworthy that other beaches occupying compartments between headlands and rocky or bouldery shore protrusions along the coast of Lyme Bay also show lateral grading (Bird, 1989). This grading is less perfect than on Chesil Beach because these beaches are still receiving occasional accessions of flint and chert gravel of varied size falling from cliff-top Pleistocene periglacial drift deposits, as well as rock fragments, chiefly limestone, eroded from cliffs and rocky foreshores. Nevertheless, each of these smaller beaches is low, with poorly sorted sand and shingle to the west and higher, often wider, coarser and better sorted to the east. The Seatown beach (Figure 2) is an example. Grading here seems to have been the outcome of sorting by alternations of longshore drifting, beach material being moved eastward by strong prevailing south-westerly wave action, and the finer fractions returned westward by gentler and less frequent south-easterly wave action. Moreover, as Arkell (1947) observed, the direction of lateral grading reverses to the east of Portland Bill, where the beaches have larger pebbles westward and smaller eastward. This he attributed to the sheltering effect of the Portland peninsula, which excludes south-westerly wave action and allows south-easterly waves to move the larger pebbles westward, as on Ringstead beach. Farther east, beyond the shelter of Portland Bill, the lateral grading of beaches reverts to the pattern seen on Chesil Beach.

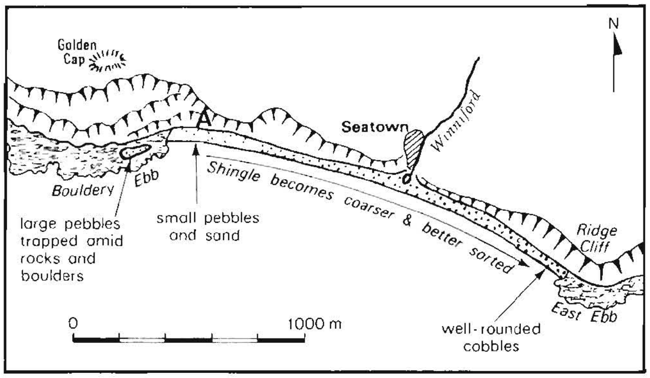

Figure 2. The shingle compartment at Seatown (11 in Figure 1), showing lateral grading similar to that on Chesil Beach.

This evidence suggests that the lateral grading seen on these Dorset beaches is due to sorting, initiated by alternating longshore drifting regimes. Wave energy gradients may have a secondary role in lateral dispersal of pebbles below a threshold size. Once lateral grading has been achieved the presence of beach face congregations of uniform shingle help to conserve it.

HAWKE BAY BEACH

For those whose ideas on lateral grading of beaches are based on the features of Chesil Beach a visit to Hawke Bay, on the east coast of North Island, New Zealand, is salutary, for here a beach of similar aspect and wave climate is graded in the opposite direction (Figure 3). The beach that runs along the northern shore of this bay is, like Chesil Beach, gently curved, and somewhat longer: about 70 kilometres. As in Lyme Bay the hinterland is hilly, and there are a number of cliffed sectors cut back along the gently curved coastline, separated by the mouths of incised valleys, including that of the Mohaka River. Several valley-mouth lagoons occur where river mouths have been impounded behind barrier sectors. The beach is sheltered towards the western end by the high country behind the huge Matangimomoe cliffs (also known as Old Man's Bluff), and at the eastern end the cliffy Mahia Peninsula projects southwards, much like the Isle of Portland, a similarity acknowledged in the naming of the outlying island. Like Chesil Beach, this is a retreating coastline. It is fronted by a sloping nearshore zone which descends smoothly to the 10 metre depth contour about 300 metres offshore, with little alongshore variation. The tide range is small: spring tides rise and fall only 40 centimetres at Napier, to the south-west (Figure 3). The wave climate is dominated by southerly oceanic swell (generated as south-westerly swell in the Southern

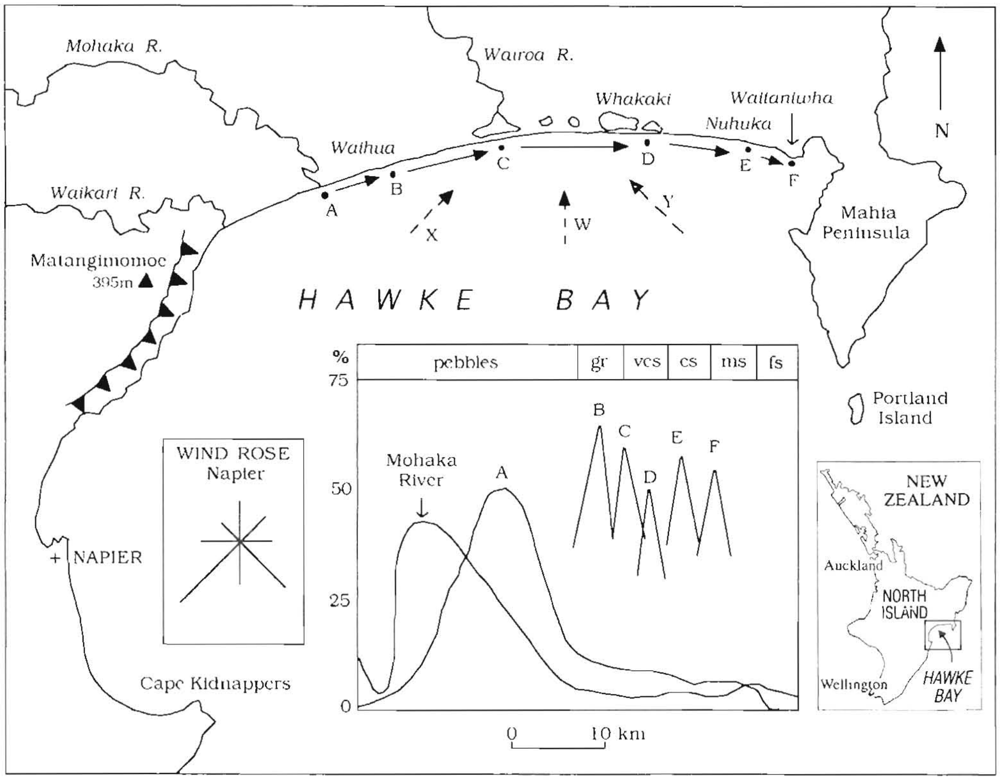

Figure 3. The beach on the north coast of Hawke Bay, on the east coast of North Island, New Zealand, shows lateral grading, the sediment becoming progressively finer eastward from the mouth of the Mohaka River (A to F), as indicated in the graphs. Southerly swell (W) generally arrives parallel to the beach, or from the south-south-west, while wind-generated waves are mainly south-westerly (X) or south-easterly (Y), consistent with the Napier wind regime (inset). Eastward longshore drifting results from this predominance of waves from the south-west.

Ocean and refracted round the South Island of New Zealand), but waves are also generated by winds, notably from the south-west and south-east, over Hawke Bay. Short-term observations indicate that significant wave height is of the order of one metre, but detailed statistics are not yet available.

This coast has not been studied as thoroughly as Chesil Beach, and apart from the early papers by MARSHALL (1929, 1933) has received only incidental mention in textbooks and reviews. The following discussion is based on the author's field reconnaissance and is inevitably rather speculative, the hope being that this commentary will stimulate further research on this important coastal system.

Mohaka River

Mohaka River and its tributaries have a large catchment north and west of Hawke Bay, dominated by an uplifted and dissected plateau of gently dipping late Pliocene and Pleistocene conglomerates, sandstones, and soft siltstones and mudstones (KAMP, 1982). These are capped by extensive volcanic ash deposits, notably the Waiohau Ash, deposited about 11,000 years ago and the Taupo pumice, deposited 1,800 years B.P. (PILLANS *et al.*, 1982). Deep valleys have been incised into this terrain, bordered by several dissected terraces, the most prominent of which stands 100 metres above present sea level in the coastal region. The Mohaka River carries a large sediment load derived from generally soft and unconsolidated rock formations exposed in river cliffs cut into the dissected terraces. It flows along braided channels through sand and gravel shoals, down to the shores of Hawke Bay.

The high sediment yield is the outcome of several factors, including the availability of large quantities of unconsolidated material, and rapid runoff (with frequent floods) from catchments where a formerly dense vegetation cover has been largely cleared. There has been Holocene tectonic activity in the country to the west, where major earthquakes have occurred in the subduction zone where the Pacific Plate is passing beneath the Indian Plate, and this has contributed to the production of large quantities of fluvial sediment from the zone of active vulcanicity that runs through the North Island (KAMP, 1982). The 1931 earthquake raised the coastline to the west by up to 2.7 metres, and caused massive landslides, which were subsequently trimmed back by wave action, generating an additional supply of sediment to the beach (MARSHALL, 1933).

Lateral Grading

The Hawke Bay beach consists of generally dark grey sand and pebbles, black when wet. Beach sediments were originally described by MARSHALL (1929), who observed that

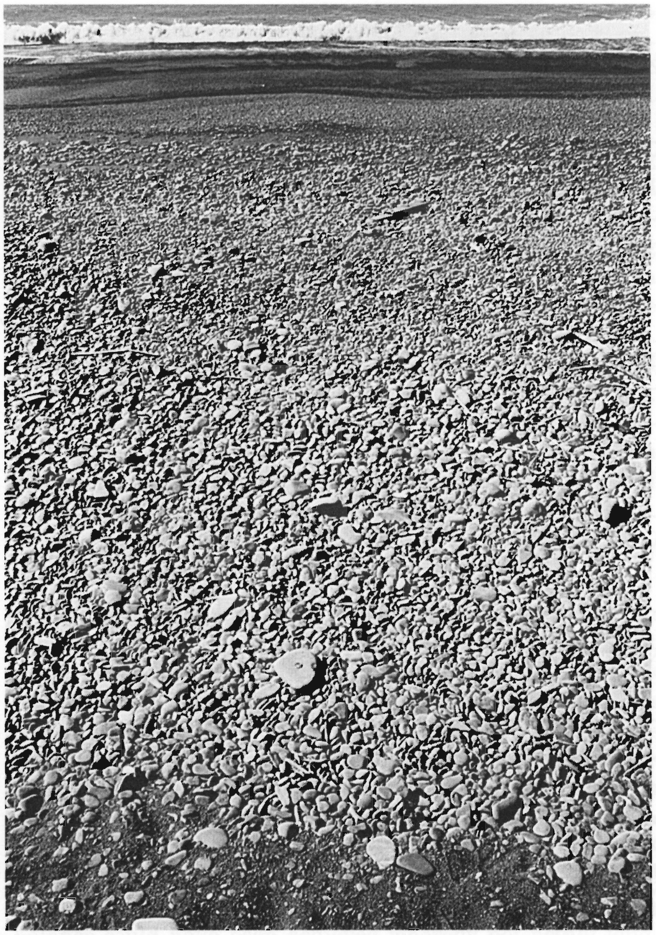

Plate 4. The beach at the mouth of the Mohaka River, Hawke Bay, New Zealand, showing poorly sorted sands and gravels of fluvial origin.

there was a gradual diminution in the modal size of the beach material from west to east, especially east from the mouth of the Mohaka River, which he considered to be the major source of beach material drifting eastward. He noted that the Waihua River, to the east, had contributed small amounts of volcanic sand, that the Wairoa had brought in a little fine sediment, and the Nuhaka also some volcanic sand, but these inputs had been 'almost insignificant' compared with that from the Mohaka River. The rivers generally flow into lagoons ponded behind the beach, but during periods of flooding outlets are cut through to the sea and beach material is temporarily swept offshore.

The sediment supplied to the coast by the Mohaka River is poorly sorted, and ranges from cobbles to fine sand, but the pebble fraction is modal (Plate 4), The cobbles and pebbles are well rounded, but the granules and sand are angular. This sediment arrives in substantial quantities during episodes of river flooding, when a small lobate delta is formed, but is quickly dispersed by wave action. The coarser material, mainly sandstone and mudstone cobbles and pebbles, is soft and readily worn down by wave agitation. The cobbles and pebbles are reduced in size by mutual impact (pieces chip off, leaving percussion marks), disintegration (splitting), and grinding. Similar reduction of beach pebbles by attrition has been demonstrated on another New Zealand shingle beach, in Palliser Bay, by MATTHEWS (1983), who introduced identifiable pebbles and found that they declined in volume by up to 41% in a year. The reduction of drifting pebbles by splitting, crushing and spalling has also been studied in South Wales and Scotland by BLUCK (1969).

Eastward from the river mouth the beach sediment becomes better sorted as the modal size declines from pebbles at the mouth of the Mohaka through granules to very coarse sand, coarse sand and eventually medium sand at Waitaniwha Bay, near the eastern end (Plate 5), after travelling a distance of about 50 kilometres. The angular granules and sand grains become well rounded and polished as they diminish in size in the course of this long transit. East of the mouth of Wairoa River the beach is of sufficiently fine sand to be winnowed to backshore dunes, some of which are spilling into the lagoons.

MARSHALL (1929) concluded that lateral grading was here the outcome of progressive attrition of beach material as it drifted eastward. Wave action is dominated by the southerly ocean swell (W in Figure 3), which generally breaks evenly and heavily, parallel to the shore, and has been responsible for the shaping of the gently-curving coastline. At times the swell is south-south-westerly, arriving past Cape Kidnappers, and this generates an eastward longshore drift. As in Dorset the predominant winds are south-westerly, producing waves that generate eastward drifting (X in Figure 3), while south-easterly winds occur less frequently, forming waves from the other direction (Y in Figure 3), the beach being sheltered from the east by the large Mahia Peninsula. Thus there are alternations in longshore drifting, with a resultant eastward flow. This is evident in the configuration of river mouths such as the Wairoa, usually deflected eastward, but sometimes westward by spits built by longshore drifting. Although the configuration of this coast is similar to that of Lyme Bay, and the wave regimes are also somewhat similar, the lateral grading of the beach is the reverse of that seen on Chesil Beach.

This example of lateral grading by attrition during longshore drifting has passed into the literature of coastal geomorphology, with brief references in a number of textbooks. It should be noted that although MARSHALL (1929) stated that the beach was 'fed at the western extremity' by sand and gravel from the Mohaka River, the curving Hawke Bay beach actually extends some 20 kilometres west of the mouth of this river, in front of rising cliffs, terminating against the slumping bluffs of Matangimomoe, 395 metres high, which have occasionally been disturbed by earthquakes. In this sector west of the Mohaka River the beach is also of sand and shingle, derived partly from westward drifting of material supplied by the Mohaka and Waikari Rivers and to a lesser extent from the slumping and receding cliffs.

The lateral grading that extends more than 50 kilometres eastward from the mouth of the Mohaka River is less obvious than on Chesil Beach, but can be demonstrated by grain size analyses (as shown by the graphs in Figure 3). It is complicated by the fact that small quantities of sand and gravel are

Plate 5. The eastern end of the Hawke Bay beach at Waitaniwha, where it consists largely of medium sand strewn with driftwood.

added to the beach alongshore from outcrops in the eroding marly cliffs, which contain some gravels (Plate 6), and from the smaller rivers.

The conclusion that lateral grading on the Hawke Bay beach is due to progressive attrition during longshore drifting needs refinement. Although such attrition undoubtedly occurs, there has also been sorting, especially of the finer sand carried eastward along the shore by the predominant southwesterly waves. It is difficult to separate the effects of attrition from those of sorting, as CAILLEUX (1948) found on the laterally graded beach between the mouth of the River Var and Cap d'Antibes in southern France, but perhaps tracer pebbles of coloured rock could be used to measure rates of attrition and longshore transportation, and demonstrate their relative contributions to the attainment of lateral grading on the Hawke Bay beach.

DISCUSSION

CARTER (1988) concluded that 'grading may arise through a number of mechanisms . . . several of [which] may work together'. This is illustrated by the contrast between Chesil Beach in Dorset and the Hawke Bay beach in New Zealand, analysis of which indicates that various factors have influenced the development of beach grading. In deciding why these two beaches show different directions of grading, the following points should be considered:

1. Chesil Beach is a shingle formation with a long history of landward migration and little natural replenishment; the Hawke Bay beach is on a receding coastline, and is actively nourished by an abundance of sediment supplied by rivers and some eroded from cliffs.
2. The Chesil Beach shingle consists mainly of durable flint and chert pebbles, whereas the pebbles on the Hawke Bay beach are of soft rock materials, readily worn down to sand size.
3. Chesil Beach stands on a tectonically stable coast, where the rivers are small and supply very little sediment; the Hawke Bay beach is adjacent to an area of earthquake activity and hinterland vulcanicity, and the Mohaka River in particular delivers a large sediment yield to the coast, particularly during frequent floods.
4. The wave climates of the two coasts are similar, and both show short-term alternations of longshore drifting, the strongest drift being from west to east. Both appear to have configurations well adjusted to the predominant incident wave patterns; both have major upland promontories to the east and cliffs bordering high country to the west.
5. Whereas Chesil Beach has increasing wave energy from west to south-east, correlated with a steepening of the nearshore zone, there is no such longshore energy gradient on the Hawke Bay beach, where the nearshore zone is relatively uniform alongshore.
6. Chesil Beach owes its lateral grading primarily to sorting by alternating longshore drift and perhaps dispersal re-

Plate 6. The central part of the Hawke Bay beach near the mouth of Wairoa River, showing one of the cliffed sectors.

lated to wave energy gradients, with very little attrition of the beach shingle; the Hawke Bay beach has lateral grading produced at least partly by attrition in the course of longshore drifting, although there may also have been longshore sorting.

If Chesil Beach were to be relocated on the north coast of Hawke Bay, would there be changes in its direction of lateral grading? Alternatively, if the rivers draining into Lyme Bay were to begin delivering large quantities of sandstone and mudstone gravel and sand to the coast for deposition along the shore in front of Chesil Beach would the new beach develop the coarse to fine eastward grading seen in Hawke Bay?

CONCLUSION

In order to answer these questions we need a better understanding of the processes that initiate and maintain beach grading. It is evident that there can be no single universally applicable explanation: it is possible to identify several factors that have influenced beach grading, including attrition and sorting developed by longshore drifting and wave energy gradients, the configuration of the coast and adjacent sea floor, and the nature and rate of supply of beach material. This commentary has examined the factors that have contributed to lateral grading on Chesil Beach and the Hawke Bay beach with the aim of stimulating further research and continuing discussion of this phenomenon. It is a debate that Bill Carter would have enjoyed.

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