SEDIMENTATION OF BEACH GRAVELS:
EXAMPLES FROM SOUTH WALES

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ABSTRACT

On the basis of particle shape the surface layers of some South Wales beaches are subdivided into four zones—a large disc zone landward, typified by cobble sized discs, having on its seaward side the imbricate zone composed mainly of imbricate disc-shaped pebbles. Seaward of the imbricate zone lies the infill zone where spherical and rod shaped pebbles (drawn from a reservoir, underlying the large disc zone, and in which there are particles with a shape and size making them potentially capable of rapid seaward transport) infill a framework of spherical cobbles fringing the seaward margin. The spherical cobbles framework is called the outer frame.

Particle shapes are not so much made as used on these beaches; and particle shape differentiation is related to settling velocity, pivotability, and ability to filter through the porous gravels. Discs are not produced by a special feature of marine abrasion: the most oblate discs are found in areas least worked on by the sea.

Composition is a function of particle size and shape; particle size and shape vary systematically across the beach; so composition and maturity indices are also seen to vary in a similar way. In the reworking of the boulder clays, which forms a source for much of these marine gravels, two processes are recognised: the post glacial weathering of the boulder clays and abrasion on the beach. Both are selective in that they affect the labile (in this case a subgreywacke) more than the stable (in this case, quartzites). Weathering and abrasion work to split greywackes into discs. At the same time destruction of this kind in always reducing the number of large and increasing the number of small particles, produces a size maturity correlation where the coarser grains are more mature than equivalent sizes in the original boulder clay, but possibly the finer are less mature than equivalent sizes in the original boulder clay. As abrasion further continues, (exemplified here on one beach) the composition shape function begins to disappear, and maturity greatly increases with size.

Particle size parameters vary across the beach. Changes in standard deviation and skewness are, to a considerable extent, effected by either the removal from, or addition of small coarse modes to large fine. Size frequency and shape frequency are combined in an attempt to understand more fully the type and extent of sediment movement taking place in these gravels.

The beaches are divided into two types: the one on breakdown building up to the seaward a succession of coarse spherical cobbles infilled with spherical and rod shaped pebbles; the other an alternation of beds containing spherical and rod-shaped grains with beds of disc-shaped grains.

INTRODUCTION

Numerous well developed gravel beaches of believed storm origin are found on the South Wales (U.K.) coastline which faces the dominant westerly winds. This study is concerned with the particle shape, size, and lithological composition of six of these beaches positioned between Sker Point and Nash Point (fig. 1). The coastline is at present one of submergence (Strahan, 1896; Strahan and Cartrill, 1904, p. 104), but oscillations of the post glacial shoreline have been a marked feature. The gravels of the present day beaches are backed by Recent gravel whose level is several feet higher. This older gravel is overlain by sand dunes.

The Ogmore gravel beaches are backed by low cliffs of Triassic breccias and Carboniferous Limestone or low sand dunes, and they face open sandy beaches. The Newton beaches, on the other hand are backed by fairly high dunes, face wide stretches of sandy beach, and lie adjacent to the Ogmore River. Much of the gravel on the Newton beaches is mixed with sand, some of which is known to have come from the dunes. Sker beaches are situated on a rocky coastline, and are usually found in small coves backed by low dunes. Sker Point beach is situated on a headland, is backed by low lying dunes, faces a rock platform of Triassic conglomerate, and is one of the highest beach bars studied. Cwm Nash beach is situated in a small cove in a coastline which has high cliffs of Liassic limestone. The beach is backed by a small valley and has a rock platform in front of it. Like Sker Point, Cwm Nash receives relatively intensive wave attack, and the beach bar is correspondingly high.

In all, six beaches were sampled, and many more studied; but the beaches at Sker Point and Newton were sampled more intensively than the others.

PARTICLE SHAPE

The gravel beaches at the outset were sampled for particle shape using the method suggested by Krumbein (1953) and Krumbein and Miller.
SEDIMENTATION OF BEACH GRAVELS, SOUTH WALES

(1953), but once it became apparent that a zonal arrangement of particle shape existed on the beach, further sampling was not based on a statistical plan, but rather directed towards those parts of the investigation which would throw more light on the means of particle movement.

The shape of the particle was classified according to the Zingg (1935) classification, while sphericity, calculated according to Krumbein (1941b), is determined in only a few samples, since this measure is inherently ambiguous (van Andel, Wiggers, and Maarleveld 1954, p. 105; Sneed and Folk, 1958, p. 122; Bluck, 1965, p. 241). Approximately 50 particles were measured from each of the size grades and each of the localities shown in figures 1 and 4. The samples included particles of various lithology; in these gravels the type of source rock exerts very little control over the essential particle shape make-up of the beach.

The data are presented in two ways: the proportion of particle shapes are recorded for each size grade (fig. 2), and the size frequency measurements are combined with the particle size shape data to give an estimate of the actual numbers of variously shaped particles there are in a sample (fig. 3). In figure 2 the proportion of differently shaped particles for each size is given for all beaches, but is obtained from only those samples collected by means of a grid; other samples were biased towards certain zones. Whilst significance has not been calculated on any of these data, there is clearly an abundance of spherical and disc shaped grains in all sizes (cf. Bluck, 1965, p. 241, fig. 14), with the exception of the 20-30 mm. grade where there is an abundance of rod shaped fragments. Although the proportion of differently shaped particles varies from size to size, there is a general trend to these variations with an increase in the proportion of discs with increasing size, and a corresponding decrease in rods and blades. In comparison with the particle shape composition of the boulder clays, beaches have smaller proportions of spherical shaped fragments in many of those size grades common to both deposits. A marked decline in the proportion of rod shaped particles takes place in the 70-80 mm. sizes of the boulder clays which also have a slightly higher proportion of blades in the larger sizes; this latter characteristic would follow from the observations of Holmes (1960, p. 1653), if blades are assumed to be an "immature" shape. A combination of shape size frequency is given for all

Fig. 1.—Location of gravel beaches.

Fig. 2.—Shape composition of beaches and glacial boulder clay. Beach sample, 5,300; boulder clay, 600 particles.
beaches studied (fig. 3), including only those samples collected with the aid of the grid. Disc shaped fragments are by far the most abundant, and the highest percentage of discs is found in the size class which is also the modal size class of the gravel. This is not the case with any other shape; spherical grains, for example, are present in greater proportion in a size class which is larger than the modal size class of the sediment and rods in a smaller size class. The reasons for these features are not yet understood.

Measurements of particle shape-size of gravels from two selected beaches are shown in figure 4, where a general increase in the percentage of spherical and rod shaped particles takes place towards the seaward margin. Only in one of the six beaches studied is there an increase in the proportions of spherical and rod shaped fragments in a perpendicular direction, for instance, along the beach. The most landward margins of all the beach bars are composed of gravels which have a high proportion of disc shaped grains in the larger size classes, spherical and rod shaped fragments being almost confined to the lower size ranges. Since the modal grain size of the sediment is lower than sizes in which there is a high proportion of discs, disc shaped fragments are not the most abundant variety in these gravels (fig. 7). Deposits with the characteristics listed above make up the large disc zone. Immediately seaward of the large disc zone are deposits characterized by a high proportion of disc shaped grains in all sizes studied. And, in addition, the modal grain size of the deposit falls in the same size range which contains the highest proportion of discs. Moreover, the deposits flanking the seaward margin of the large disc zone are the only ones where grain imbrication is particularly well displayed, and these gravels consequently constitute the imbricate zone, although imbrication may be seen in deposits occurring elsewhere on the beach. Outside the imbricate zone, is an area composed of gravels which have a large proportion of spherical and rod shaped fragments in all the sizes studied. This area normally has a sheet of sand bordering the imbricate zone (that is on the landward fringe), over which particles move very rapidly, and in view of this the sheet of sand is referred to as the "sand run." The particles moving across the sand run accumulate on the seaward side to form a narrow band composed of spherical and rod shaped pebbles, where the modal grain size of the deposit is also the size having the highest proportion of either rod or spherical grains. Seaward of this again is an area where the spherical and rod shaped pebbles are infilling a framework of larger cobbles. Trenching has shown that all three deposits described represent the stages of infilling a cobble frame, and for this reason the three deposits comprise the infill zone; but all three are not always present in the infill zone. All zones in figure 4 refer only to the surface layers of the beach.

The cobble sized deposits, composed primarily of spherical grains, which fringe the very seaward gravel bar margin is called the outer frame. Here, the size grade with the highest proportion of spherical particles is coincident with the modal grain size of the sediment.

Landward Particle Movement; Build up of the Bar

The gravel bars were built up during storm conditions (Lewis, 1931). In nearly all the beaches studied, the presence of gravel (which often contains disc shaped boulders, up to a metre across) above or on the high water mark confirms this view. Net landward movement during normal sea conditions is small (cf. Kidson and Carr, 1959, p. 386) and mainly confined to disc shaped pebbles. Fleming (1964, p. 115), in tank experiments, demonstrated a migration of "non spherical" grains up the beach.

It is suggested that during storm conditions fragments of all shapes were thrown forward by the waves, but discoidal particles being easily plucked from the sea floor; being lighter than, for example, a sphere of similar median diameter; and when in suspension having a lower settling velocity than any other shaped particle (Wadell, 1934; Krumbein, 1942; McNown and Malaika, 1950; Albertson, 1953; Briggs and others, 1962) were larger than, or, if of the same size, thrown further than any other particle being moved by the wave.
Fig. 4.—Showing the distribution of particle shapes and zones on two of the beaches studied. Top diagram, Sker; bottom, Newton.
Conversely, the presence of large spherical shaped fragments at the foot of the bar may be partly due to their high settling velocity. During storm conditions, when moved, they were either smaller than or, if of the same size, thrown a shorter distance than other shaped grains. Spherical and disc shaped grains are end members of series of shapes all having different settling velocities; rods and blades falling somewhere between the two extremes (Krumbein, 1942; McNown and Malaika, 1950; Albertson, 1953; Briggs and others, 1962).

On one occasion, after moderately rough seas, spherical particles were found blanketing the various zones already established on the beach. The paucity of disc shaped fragments in this blanketing deposit is believed to be due to the lack of discs on the seaward bar margin, from where the deposit had been derived, that is from the infill and outer frame zones.

Seaward Particle Movement; Breakdown of Storm Beach

Particle movement during the erosive period of the gravel beach development takes place within the beach on the landward side, and also on the beach surface, normally seen on the seaward areas.

Movement within the beach.—Movement within the beach has been demonstrated by a study of the distribution of painted particles from known positions. And such movement is most common in the gravels underlying the large disc zone. The backwash of waves breaking on the porous frame travels through the gravel, rather than on the gravel surface and in its passage combines finer material seaward the size and shape of which depend upon the size and geometry of the gravel pore space: the gravel in this upper part of the beach therefore acts as a sieve on the infiltering particles (fig. 26). Insufficient data are as yet available to describe fully the shape sorting mechanism taking place in this sieving process, but it is known that spherical particles, on some beaches at least, move more quickly through the pores than do other shapes. The large disc zones of these beaches have aprons of spherical pebbles a few feet seaward of bands of seaweed, which mark the turning points of the flood tides; and these spherical pebbles are interpreted as having moved through the cobble frame of the large disc zone. The pore geometry not only varies with position on the beach (since shape and size of beach gravels vary in an areal fashion), but also varies in the same spot with changing sea conditions. Thus on some gravel beaches there is a tendency for rod shaped grains to orientate themselves in a direction perpendicular to beach strike; in others the gravel is seen to slump seaward, and in these a random particle orientation is likely. It might well be that the condition of rod particles, with their long axes dipping towards the sea precedes the slumping in that it provides a fabric facilitating mass movement.

Movement on the surface.—In traction spherical and rod shaped particles tend to move faster than the discoidal (Krumbein, 1942, p. 625); discs have a lower pivotability than rods and spherical (Shepard and Young, 1961, p. 198; Kuenen, 1964a, p. 207). These facts were demonstrated on the beach by painting particles of various shapes and size, placing them in a line parallel to the shore, and noting their distribution after a tide. Thus, on all the beaches studied spherical and rod shaped particles are transported seaward by the backwash and accumulate on the seaward fringe of the gravel bar (fig. 4, 5).

Generally speaking spherical and rod shaped fragments respond in a similar way to the forces applied to them by the water; this is demonstrated by the close positive correlation between the number of rod and spherical grains present in the samples (fig. 6). Moreover, most samples have more spherical than rod shaped fragments. But in parts of the imbricate zone at Sker Point, the lower sizes particularly have more rod than spherical particles (fig. 4). This fact is in evidence elsewhere, although is not true at Cwm Nash (fig. 3). The reason for the higher percentage of rods in the imbricate zone of the many beaches is clearly displayed in the field, where rod shaped pebbles are caught up in the irregular surface offered by the imbricate fabric. Here they lie with their long axes parallel to the beach strike lodged in hollows which face the land (since imbricate pebbles normally dip towards the sea.) Observations made on the beach during sediment movement showed that spherical grains, on the other hand, move with greater ease through this picket of imbricate particles. When the direction of imbrication is reversed, the hollows between the discs face the sea and the rods are released.

This lateral filtering of particles according to their shape also takes place in the outer frame, and can be demonstrated at Sker Point. At localities 9, 10, 11, (fig. 4, Sker), situated in the infill zone and outer frame, there is a seaward decline in the proportion of rods, but an increase in the proportion of spherical particles. This, again, can be related to the nature of the floor over which the grains are transported: the spherical grains are better suited to travel through cobble frame, since the rods, being moved with greater speed when they are orientated with their long axis parallel to the beach, are least capable of moving through the pores of the cobbles when in this alinement.
There is a seaward decline in the size grade which has the highest proportion of disc shaped pebbles. The modal grain size of the gravel is smaller than that size with the highest proportion of discs on the landward bar margin, and greater than the modal size with the highest proportion of discs on the seaward bar fringes. Both modal grain size of the gravel and the size grade with the highest proportion of discs are coincident in the sediments of the imbricate zone, which is situated somewhere between the two other locations (fig. 7). These features concerning the disc shaped particles are common to all the beaches. In addition, there is an overall change in the shape of the discs from land to sea; the discs on the landward side are more oblate than those on the seaward, thus giving the impression of a very gradual change in the shapes of fragments across the beach.

The positive correlation between the number of discs and the number of blades in each of the samples indicates that both shapes respond in a similar way to the forces applied to them by the water (fig. 6). Discs are known to possess a low pivotability and therefore tend to move more slowly in traction. But pivotability is also a function of size as well as shape, and in these beaches the landward increase in the size grade with the highest proportion of discs is believed to be an expression of the two factors, shape and size, controlling pivotability.

The reason for the greater abundance of disc shaped particles in the imbricate zone is related to the amount of sediment reworking taking place there. Of the lag gravels, this is the one nearest to the sea, and is therefore subjected to more intensive current action; and since spherical and rod shaped particles are continually moving seaward and disc tending to lag, the more reworking by the sea the fewer spherical and rod shaped particles will remain on the imbricate zone. There are always the by-passing grains extracted from gravels to the landward, but these are few in number (fig. 7). A state of equilibrium is therefore approached when, in these lag gravels, the grain size of the sediment is coincident with that size class having the highest proportion of discs. It follows, therefore, that the deposits to the landward (the large disc zone) have not reached a condition of equilibrium, in the sense that given the same conditions of reworking and a long period in which seaward particle movement takes place, the spherical and rod shaped grains will continue to be removed from the zone. The large disc zones, and the deposits underlying them, are reservoirs of spherical and rod shaped grains which are potentially capable of rapid seaward transport.

Whilst the discs lag, they are by no means stationary—although the mechanism of seaward movement is not easily detected. Discs are seen to move like wheels (Owens, 1908, p. 418;
FIG. 6.—Correlation between the numbers of variously shaped particles found in each sample of size range 16–48 mm.

Bagnold, 1940; Kuenen, 1964a, p. 37), but this is not considered to be the important method of disc transportation here, and is commonly seen taking place on sandier beaches. The discs in the imbricate zone move in a number of ways, the most important of which are not yet determined. Imbricate discs nearest the sea often dip at a lower angle than those immediately landward (see also Krumbein, 1939, p. 702); and, as diagrammatically shown in figure 8, this, by means of a caterpillar-like action, allows the imbricate zone to move slowly seaward. The movement is irregular, with the result that disc pebbles in this zone have highly irregular dip values, from 0°–85° (see also Krumbein, 1939, fig. 18). The backwash is observed to play a major role in the formation of imbrication (but see Frazer, 1935, p. 980). The percolation of the backwash downward through the underlying porous gravel produces imbrication dipping seaward; but where there is a strong backwash or an impermeable bed below the discs, imbricate pebbles may sometimes dip landward, or in some cases imbrication is completely destroyed. On the other hand, where the discs are particularly large, and the gravel very porous, there is insufficient strength in the backwash to effect the imbrication of the discs (fig. 30 B, C).

The change in the dip of imbrication at the seaward end of the imbricate zone, is related to the change in the permeability of the underlying beds where they are more permeable towards the
landward regions, being underlain by gravel, and relatively impermeable on the seaward side being underlain by sand (fig. 26). Thus the concentration of water along the sand surface in the backwash, displaces the foot of the pebbles which are in contact with the sand surface.

The "broken-up" imbrication (fig. 8) is also considered to be a form of disc movement. It may be due to a strong backwash flipping over the discs (Twenhofel, 1950, fig. 24), or the rotation of the underlying spherical pebbles (fig. 8B). But it is also conceivable that the orbital movement of passing waves may induce this reversal in disc dip.

SPHERICITY

The changes in the sphericity/size relationship across the beach is given in figure 9, where a general increase in sphericity is indicated in a seaward direction (Krumbein and Griffith, 1938, fig. 6) for particles of the same size; and an increase in sphericity with size. The standard deviation of sphericity (fig. 9) shows a general increase with increasing size, and in a seaward direction for all sizes studied. The facts presented in figure 9 may well indicate that selective shape sorting is indeed less selective when large grains are being moved, and when turbulent conditions are presumably present; and that shape sorting is more selective in what it leaves behind than in what it removes: or that particles which roll have a wider range of sphericity than those which lag.

In respect to the gravels found on these beaches where the initial deposit was laid down by storm waves of high energy, and with a large suspended load, the following points may be made:

1. Where the highest proportion of discs falls in a size grade larger than the modal

FIG. 7.—An example of the combination of shape/size/frequency across a beach at Sker Point. 'Mode' refers to the size range containing the highest proportion of the stipulated shape, and is determined by the use of a moving average. The scale on the left of the frequency curves indicates the numbers of all the particles.

FIG. 8.—Mechanism of disc migration. (A) successive stages in the movement are represented by 1, 2, 3, 4. By displacing a few of the discs at the seaward end of the column (1), and with the others conforming to this new dip (2), the particles are able to move past stationary points, A and B as in 3. The process begins again as in 4. The arrows in (B) represent the direction of backwash movement.
Fig. 9.—Variation of mean sphericity ($M\psi$) with size and position across the beach. Standard deviation of sphericity ($\sigma\psi$) is plotted against mean sphericity, where Eq. 1 is $\sigma\psi = 1.8M\psi - 0.003$; Eq. 2 is $M\psi = 0.64\psi + 0.438$; and $r = +0.85; n = 12; p < 0.001$. The example is taken from Cwm Nash at stage 3 (of the Sker type beach).
size of the sediment, reworking is not complete, and in that sense the sediment in question is not in equilibrium with its new conditions.

(2) Where the highest proportion of discs falls in a size grade which is the same as the modal size grade of the sediment, reworking is complete, and in that sense the sediment is in equilibrium with its new conditions.

(3) Where the highest proportion of either spherical or rod shaped grains is found in the same size grade as the modal size of the sediment, then uniform deposition by a similar means of transport is indicated.

(4) Where the disc mode falls in a size grade lower than the modal size grade of the sediment, either the deposit is made up of a coarse tractive load sediment (spherical and rod) and a fine suspended load sediment (which includes many discs); or two modes of tractive transport has taken place—rapid movement of spherical and rod shaped grains to the site of sediment accumulation, and a slower movement of discs (e.g. by shuffling) to the same site. In both instances the discs are found above the spherical and rod shaped fragments in the succession.

LITHOLOGICAL COMPOSITION

The beach pebbles lithologically resemble the rock types which compose the adjacent cliffs. Thus the beach at Cwm Nash is composed almost exclusively of Liassic limestones (with the anticipated marked absence of shales); the beach at Sker Point of particles found in the surrounding boulder clay and Triassic conglomerate; and the beaches near Ogmore of fragments similar to those found in the nearby boulder clay, Triassic breccias, and also fragments of adjacent Carboniferous Limestone. With the possible exceptions to be noted later, in each beach there is no reason to suspect the presence of an additional source whose general composition is dissimilar to those now found fringing the beaches. Nevertheless, shoreward migration of exotic pebbles (?ships ballast) on a nearby beach at Newton is evident. Lithological composition is given in figures 10, 11, 12.

The quartzite particles vary in their composition and texture, and are, for the most part, probably derived from the Namurian, Lower and Middle Coal Measures of the South Wales Coalfield. These highly quartzose rocks have grain sizes ranging from fine sand to fine pebble, and in nearly all examples seen in thin section the grains are pressure welded. The subgreywacke is a fairly friable, poorly sorted quartz rich rock with
some evidence of pressure welding. The intergranular pore space is filled with clay minerals, but the most important attribute of the subgreywacke is the ease with which it splits along the bedding planes. The rock, quite singular in character, is derived from the Upper Coal Measures of South Wales, where it is known as the Pennant Sandstone. The limestones vary considerably in texture; the Liassic ones are aphanitic, and the Carboniferous ones are mostly bioclastic with grain size varying mainly from fine to coarse sand. Triassic particles are calcareous silts ones, and the Old Red Sandstones are tough, and quartzitic with some pressure welding, although some have a calcite cement.

A trial test was conducted on the quartzites in order to determine whether they behaved more or less as a single unit. That they did behave in a similar way was confirmed by subdividing them into dark (with fine grain size) and light (with coarse grain size) and comparing their variability when plotted against size, although the finer grained group seemed to be the more labile. However, with the distribution of both types of quartz being fairly uniform, grouping them together is not considered to be a serious error.

Composition is a function of size (Davis 1938), and in Newton, Ogmore and Sker (figs. 10, 11), quartzite increases with increasing size, whilst limestone and subgreywacke percentage decrease with increasing size. The percentage of large limestone fragments is high in Ogmore, which is backed by limestone cliffs. Quartzites are the most abundant lithology (fig. 12). Figure 13 shows that in the gravels of Newton beach there is a strong positive correlation between the number of disc shaped particles and the number of subgreywacke particles per sample, and in the same way for spherical and quartzite. There is no significant correlation of the same type and magnitude were obtained from Ogmore, the gravels at Sker Point yielded a diminished, and not always significant correlation between similarly paired observations. In the samples of boulder clay so far studied, there is no significant correlation between the number of disc shaped particles and the number of subgreywacke particles per sample; the same thing is plotted with spherical and quartzite. Particle sizes range from 16-128 mm.
of spherical and quartzite particles, nor between the number of discs and subgreywacke per sample. It seems reasonable to assume that even after more boulder clay samples have been taken, these correlations will, at the very most, be small—although perhaps significant.

The reasons why the subgreywacke makes disc shaped particles are to be found in the ease with which it splits along the bedding planes, rather than any mineralogical attribute. Weathering taking place during the interval between glacial deposition and marine erosion is an important factor in controlling size (Davis, 1951, p. 187) and shape of particles being made available to the beach. Observations have shown that sometimes the post-Glacial interval flat disc or blade shaped particles are produced from spherical and rod shaped subgreywacke grains; weathering opens the planes of weakness in these particles so that on slightest impact they break into a number of platy fragments. The quartzites on the other hand show little or no effect of weathering in the boulder clay, and although no significant correlation is found in the boulder clay between spherical and quartzite grains, it is evident that shape sorting has incidentally produced a sorting out of particles in terms of their lithological composition.

Where the migration seaward of beach gravels brings about a succession comprising deposits of different zones there is also a succession of gravels with quite different composition (fig. 28). It is clear therefore that any vertical change in the particle composition of a gravel or conglomerate, even when particles of the same size are being compared, cannot without due caution be ascribed to changes in provenance: and if shape sorting is or has been effective in the deposit examined, then a rapid lateral change in lithological composition is also to be anticipated in any sampling programme.

Maturity of the Gravels: the Reworking Process

Maturity is calculated on the basis of including limestone and subgreywacke as being labile, and quartzite and Old Red Sandstone as being stable. The maturity index is therefore:

\[ \text{Maturity} = \frac{\text{Quartzite} + \text{O.R.S.}}{\text{Limestone} + \text{Subgreywacke}} \]

As to be expected from compositional variations, maturity increases with increasing grain size, and changes with position on the beach (fig. 16, 17, 18). The imbricate zone has the lowest maturity, and the infill zone and outer frame the highest. Included in the figures 16 and 17 is the maturity of the boulder clay also plotted against grain size, where there is little or no definite maturity changes over the size ranges studied. Limestones are not present in the boulder clay, so that given no additional source of gravel, the difference between the maturity (excluding limestone) of the boulder clay and the marine gravels, for each grain size, will give some indication of the combined effects of weathering processes which have affected the particles in the boulder clay since its laying down, and the processes of marine abrasion on particles released to the beach.

The respective effects of weathering and marine abrasion on the maturity are difficult to isolate. Both weathering and abrasion, in preferentially breaking down the subgreywacke particles to a greater number of smaller sizes, is continually increasing the maturity of the higher size grades, but reducing the maturity of the...
Fig. 14.—Showing the distribution of lithological types, and how this distribution changes between zones. O.R.S. = Old Red Sandstone. Top diagram, Sker; bottom, Newton.
lower. The rate of supply of labile constituents to the lower size grades is probably logarithmic and, when all things are taken into account, might well produce a maturity curve similar to figures 16 and 17. Also abrasion generally increases with increasing size (Daubree' 1879; Marshall, 1927; Krumbein, 1941a, Kuenen, 1956), so the increase in maturity with size in figures 16 and 17 may also reflect this factor (although Kuenen, 1964b, p. 34, found no increase with size, in the erosion of particles subjected to surf-like action). Considering now the differences in maturity (excluding limestone) of different shaped particles, it is known from observation that in the weathering process subgreywacke particles become more oblate: gravel lying at the foot of one boulder clay exposure contained many large subgreywacke discs. Since the number of discs so produced is a multiple of the number of other shapes from which they are derived, such as spherical and rods, one would therefore expect the disc fraction of the marine gravels to be

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Fig. 15.—Diagram to illustrate the differences in lithological types between zones on a sector of the Newton beach.

Fig. 16.—Maturity of the beach and boulder clay gravels plotted against size: data for Sker Point.

Fig. 17.—Maturity of the beach and boulder clay gravels plotted against size: data for Newton and Ogmore.

In Newton Eq. 1 is $M = -0.624 S - 2.761$; and Eq. 2 is $S = -0.9954 M - 4.989$; where $r = +0.79$; $n = 9$; $p = <0.02$. In Ogmore Eq. 1 is $M = -0.357 S - 1.13$; and Eq. 2 is $S = -1.279 M + 4.859$; where $r = 0.677$; $n = 9$; $p = <0.02$. 

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either less mature than that of the boulder clay, or if more mature, the difference between the maturity index of the two deposits to be far smaller in the case of discs than in the case of spherical. That this is so is demonstrated in figure 19. But the maturity of the beach disc particles is much higher than one would have expected from weathering alone: small samples of disc fragments, rather angular in outline and in a part of the large disc zone immediately backed by boulder clay, gave maturity values of 2 for −5.5φ and 2.9 for −6.5φ (fig. 19). This deposit, little worked on by the sea, is believed to be fairly representative of the material supplied to the beach after the weathering of the boulder clay, and the differences between the maturity values of this deposit and the maturity values for the beach is a result of beach abrasion. Meager though this information is, it assumes a greater importance when it is considered in the light of foregoing conclusions. Large discs move only during storm conditions when they are ultimately thrown forward in the advancing storm waves. And in order to account for the increase in disc maturity with increasing size, it is suggested that abrasion takes place mostly during storm conditions. Under these conditions impact breakage would be high, and even higher.

![Graph](image-url)
SEDIMENTATION OF BEACH GRAVELS, SOUTH WALES

for larger discs where a greater weight is involved.

Since it is an observable fact that under normal sea conditions, spherical and rod shaped particles of the diameter about \(-5\phi\) move more rapidly than any other sizes, all spherical and rod shaped fragments which were collected for mechanical analysis were plotted on probability paper on the chance that a size deficiency would appear; a size deficiency rather higher than the expected one is seen (fig. 20), but the reason for this is not certainly known.

The beach at Sker Point is markedly more mature than those at Ogmore and Newton; and if the supply of limestone to all beaches is assumed to be fairly constant (by leaving out limestone, all three beaches give essentially the same maturity curves as before) there are a number of other possible explanations for this relationship which readily present themselves. Undoubtedly, the Ogmore River has brought in some subgreywacke particles; samples of the gravels of this river obtained less than a mile from the river mouth contained well over 80 percent subgreywacke in all size grades from 35-95 mm. Also, Newton and to a lesser extent Ogmore have a high sand content which could well serve to hinder erosion (Kuenen, 1964b, p. 35, showed this effect of high sand concentration in experiments). The Sker Point beach, on the other hand, being situated on an exposed headland, is more vulnerable to wave attack (the storm beach is far higher here than anywhere else) and also has less sand mixed in with the gravel than seen elsewhere. There is not obvious contamination by a gravel source other than the boulder clay. But, in the lower size grades, the maturity of the Newton and Ogmore beaches is lower than the maturity of the adjacent boulder clays. This may be due either to contamination or to the increase in smaller labile particles consequent on the breakdown of large.

The observed maturity differences across the beaches follow from selective shape sorting already referred to in the discussion of lithological composition.

From the foregoing data and discussion, the following points may be made in respect to these gravels. Where there has been little abrasion or no prolonged weathering of this mixed rock suite there is only a minor correlation between lithology and shape, and maturity and size. But in the early stages of weathering and/or erosion there is a marked correlation between lithology and shape and a somewhat less marked correlation between maturity and size; the shape-lithology correlation is partly the expression of how this maturity-size correlation is being achieved, by the splitting of subgreywacke particles along bedding planes to form discs. At this stage there may even be a decrease in the maturity of the smaller grains: Ogmore and Newton might (with the reservations already referred to) be examples of this stage. With more intensive weathering or, as in the case studied here, erosion, the shape/lithology correlation becomes smaller, and confined to the smaller sizes (since the number of labiles are reduced by becoming smaller in size) and the shape lithology correlation of the stable lithological types, if such a correlation exists, will remain. Sker Point beach is an example of this phase. Maturity-size correlation will produce a steep curve which will, as erosion proceeds, continue to steepen to approach parallelism to the size axis as a power function. (see table 1).
**Table 1.** The maturing process of the marine gravels intensity and/or period of weathering and/or abrasion

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) No variation of maturity with size</td>
<td>(i) Maturity varies with size</td>
<td>(i) Maturity greatly increases with increasing size</td>
</tr>
<tr>
<td>(ii) No correlation between shape and lithology</td>
<td>(ii) Smaller sizes are less mature than equivalent size grade in source rock</td>
<td>(ii) All size grades larger than granule are more mature than same size grades in source rock</td>
</tr>
<tr>
<td>e.g. BOULDER CLAY</td>
<td>(iii) Good correlation between lithology and shape.</td>
<td>(iii) Correlation between lithology and shape best developed in the smaller size grades.</td>
</tr>
<tr>
<td>e.g. NEWTON and OGMORE</td>
<td></td>
<td>e.g. SKER POINT</td>
</tr>
</tbody>
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**PARTICLE SIZE PARAMETERS**

Beaches were sampled for size parameter data in a similar way as outlined for the study of particle shape. The intermediate axis of the particle was used to describe the size attributes. The relevant statistics of the total random beach sample is given in figure 21, where the standard deviation compares well with the recorded values of Krumbein and Griffith (1938, p. 636), Emery (1955, p. 47), where his Trask sorting values have been transformed to standard deviation using the graphs of Friedman (1962, fig. 9) and Steinmetz, (1962, p. 65), who utilized the long axis of the particle. However, the values of standard deviation are not uniformly distributed over the beaches; this measure changes markedly in a direction perpendicular to beach strike (Krumbein and Griffith, 1938, fig. 4).

Skewness is derived from the third moment, and is calculated in the way outlined by Krumbein and Pettijohn (1938) and (Griffith, 1960, p. 574), and also shows a marked change in value across beach strike. Kurtosis, derived from the fourth moment, varies in a similar direction.

An estimate of the particle size parameters of the gravels as originally laid down by the advancing storm waves, was obtained for four samples (table 2). This original or parent deposit, undoubtedly modified by the backwash of the depositing storm waves, has its coarser frame infilled with granules and sand (fig. 31), and is found near the high tide mark. Seaward of this parent deposit there were no extensive spreads of gravel, as is common when reworking of the storm beach has taken place. These four samples are amongst the worst sorted seen on the beach.

The particle size parameters will be discussed within the framework of the zones already established on these beaches.

**Large Disc Zone**

The average grain size of gravels in the large disc zone ranges from -6.6φ on the landward to 5.7φ on the seaward side. The gravels are comparatively well sorted, display symmetrical frequency curves, and generally a high positive kurtosis (fig. 22). The sediment has an open framework, with a poorly developed preferred orientation; discs often lie flat on the surface, and occasionally rod shaped grains have long axes dipping seaward.

The large disc zone is least worked on by the sea; it straddles the high tide mark. But this zone, although retaining some of the characteristics of the parent deposit, is distinctive by virtue of the small amount of reworking which has taken place here. Figure 7, which shows two typical size-frequency-shape curves for this deposit, illustrates the presence of two important components: a coarse grained disc fraction, and a frequency mode predominantly composed of spherical and rod shaped particles; the finer

**Table 2.** Particle size parameters of parent gravel

<table>
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<th>Mdφ</th>
<th>σ</th>
<th>Skφ</th>
<th>Kφ</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4.436</td>
<td>0.5701</td>
<td>-0.599</td>
<td>-1.05</td>
</tr>
<tr>
<td>-3.991</td>
<td>0.7121</td>
<td>-1.062</td>
<td>+0.54</td>
</tr>
<tr>
<td>-4.317</td>
<td>0.6312</td>
<td>+0.285</td>
<td>+2.83</td>
</tr>
<tr>
<td>-5.125</td>
<td>0.5189</td>
<td>-0.279</td>
<td>+0.18</td>
</tr>
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</table>
grades comprise a similar mixture of shapes as does the mode.

The low standard deviation and the high positive kurtosis are the result of the reworking of a parent deposit with particle size parameters somewhat similar to that as shown in table 2 and figure 23. Particles which were mostly of a size smaller than $-5\phi$, and probably also less pivotable particles of a larger size than this, were at an early stage lost during the period when the open framework was formed; the lag concentrate of large discs (fig. 4) left particularly on the top layer of the sediment is thought to indicate the removal of spherical grains from the coarse end of the frequency distribution. With the development of an open frame, the backwash in percolating through the gravel pores, could no longer concentrate sufficient energy to move the gravel with any speed even though the gravel contained particles normally capable of rapid movement in traction, that is spherical and rods. The formation of a porous frame prohibited the development of a negatively skewed distribution typical of lagged gravel.

The Imbricate Zone is typified by gravels which have an average grain size of $-5.2\phi$, are comparatively well sorted and have variable skewness and kurtosis values which by and large average out ‘normal’ (fig. 22). The modal size grade of the gravel contains the highest proportion of discs. These pebbles normally form an open framework, but there is very little downward and lateral filtering due to the proximity of the sand floor (fig. 26).

In comparison with those of the large disc zone the gravels of the imbricate zone are far more worked on by the sea, and for that reason reflect less the nature of the parent deposit; but many of the discs were probably derived from the areas now occupied by the large disc zone, and therefore transported seawards (see fig. 23). The disc part of the frequency distribution represents a lag deposit (in the sense that it moves seaward a lot slower than any other group of particle shapes), whilst spherical and rod shaped grains are only in transit from the landward beach bar to the seaward margin. The frequency distribution may therefore be looked upon as a large and basic or stable population of discs, upon which is superimposed a minor and transient population of spherical and rods; the size parameters of the discs change when traced.

![Fig. 22.—Variation in particle size parameters across the beaches. M\phi= mean diameter in phi; \phi = phi standard deviation; Sk\phi = phi skewness; K\phi = phi kurtosis. The disc 'mode' and the spherical 'mode' represent an average of the size classes which have the highest proportion of these respective shapes for several samples taken from the zones indicated.](image-url)
seaward, and those of the spherical and rod pebbles vary with the availability and selection of these grains from the reservoir situated landward.

The particle size parameters across the imbricate zone are given in figure 24. The samples were obtained from a beach which had just been worked on by a receding tide. Grain size diminishes seaward, this being due to a decline in the size of the discs more than compensating for a slight increase in the number of spherical and, to a lesser extent, rod shaped grains which slightly increase in size in that direction. The seaward increase in the standard deviation is mainly due to the spread produced by a disc population decreasing in size, mixing with a population of mainly spherical and some rods, increasing in size. The spherical and rod shaped particles being larger in size and smaller in number than the discs at the seaward end, tend to impart a negative skew to the frequency distribution. But on the landward side the gravels have a positive skew due to the presence of a minor amount of particles, particularly rods (of slightly smaller size than the imbricate discs) being wedged in the disc picket. Kurtosis is difficult to interpret in figure 24 but seems to become negative when traced towards the sea, probably due to the spherical and rod shaped grains, accumulating on the seaward end producing a second, albeit smaller, size mode.

**Outer Frame Zone**

Gravels of the outer frame have a mean size $-6.6\phi$, and are the best sorted gravels on the beach; their frequency distributions have skew-
NESS VALUES which vary considerably, but as a generalisation may be said to be positive skew and negative kurtosis. The modal size grade has the highest proportion of spherical and rod shaped fragments. The particles form a framework which is up to 2 feet thick and which is underlain by sand or rock. Little is known about the formation of this deposit other than it was derived from the landward, and in that event it may be that the larger fragments were removed off the storm beach in preference to small (see King, 1959, Joulieff, 1964, p. 80, although this latter writer records 4'-5' particles travelling slower than 2'-3'). But there is always the possibility that both large and small fragments were taken off the gravel bar, and the smaller have since been removed. The positive skew present in some of these gravels would perhaps indicate this former mechanism. Observations made on the beach indicate that pebble or granule material with a low standard deviation tends to move en mass, and creep along towards the sea; but any material larger than this creeping gravel moves rapidly in traction, overtaking the finer grained constituents. It is conceivable that this difference in type and form of movement of different sized gravel happened during the early stages of beach bar breakdown, and so led to the accumulation of the outer frame. Such forms of movement would be particularly helped where the beach slope is high: the larger grains having a greater momentum than the small; or may be partly due to the fact that the larger grains are not hindered by being caught in the pores between smaller. This latter origin implies a bimodal grain distribution in the lower part of the beach bar to where these cobbles were moving; and it is significant that gravel of the size range about −5.5 to −6.5φ is retained in the large disc zone as an open framework in the way already outlined, thus leading to a deficiency of this size, and a relative pebble and cobble abundance on the seaward fringe (fig. 20).

Infill Zone

This zone contains gravels which fall into two groups: those which form a thin band of spherical and rod shaped pebbles on the seaward side of the imbricate zone, and those to seaward again, where spherical and rod shaped pebbles, infill the outer frame (fig. 26).

The spherical and rods accumulating to the immediate seaward of the imbricate zone have an average grain size of −5.1φ. Their size frequency curves have comparatively high standard deviation of 0.4φ, negative skew, and a negative kurtosis. These pebbles are drawn from the landward situated reservoir (which underlies the large disc zone (fig. 26), and across the imbricate zone, which acts as a picket. The sizes of particles in this zone depend upon what is made available for transportation from the reservoir, the sea conditions, and the nature of the openings between the imbricate discs in the imbricate zone. Where the migrating particles have the same size as the openings offered by the discs, movement is hindered (this being strong in the case of rods). Particles larger or, perhaps to a lesser degree, smaller than this size tend to make a more important contribution to the deposits accumulating on the seaward fringe of the imbricate zone. It follows then that these particular deposits of the infill zone have a fairly high standard deviation, and a negative kurtosis with a tendency towards bimodality (fig. 22, 23). The negative skew of the distribution is acquired in two possible ways: finer constituents tend more to remain trapped in the imbricate picket or the finer particles are more rapidly moved than coarse on the flat surface (around 3-5°) and transported out of the gravel and seawards.

Seaward, spherical and rod shaped pebbles and granules infill the outer frame to give rise to a deposit with an average grain size of −5.1φ with (excepting the 'parent' gravel) the poorest sorting in the beach, and having a strong negative skew, and a positive kurtosis.

Since at least two distinctive sediments of widely different average grain size are mixed to form the gravels of the infill zone, the high value of standard deviation is to be expected. Moreover the negative skewness is the result of an excessive amount of fine gravel infilling the pore space within a coarse sediment; and the positive kurtosis is possibly the result of lateral filtering through the pores. However when this pore filling takes place, grain to grain contacts of the outer frame are sometimes lost: cobbles are found dispersed throughout the gravel and entirely surrounded by the finer, seaward moving gravels. But the absence of a frame does not imply the simultaneous deposition of the cobbles and the pebble-granule sized material (Plumley, 1948, p. 542-545, Potter, 1955, p. 17); the cobbles of the outer frame were present on this seaward fringe long before the finer grained material arrived. Whilst there may be more than one way in which this framework of cobbles is broken down, the mechanism of its disintegration has been observed operating in one instance. The infilling of the outer frame zone is sometimes accomplished by the seaward movement of a wedge of fine gravel which may be preceded by a thin veneer of spherical and rod shaped, medium sized pebbles. Backwash, concentrated on the surface of this fine gravel mass grows turbulent around the projecting cobbles of

SEDIMENTATION OF BEACH GRAVELS, SOUTH WALES 147
the frame, effects the removal of some of them, leaving others dispersed in the matrix of finer material. Dispersive stress, increasing with increasing grain size (Bagnold, 1954, p. 62), could also be a factor in frame disintegration (see fig. 30D, E).

Plots of various parameters of the size frequency distribution are given in figure 25. Standard deviation decreases with increasing size and this is to be expected since the lag gravels (with the exception of the outer frame, which may not be a lag deposit) are normally coarse and have lost size grades during reworking. In comparison, the curves of a similar plot made by Folk and Ward (1957, p. 17, fig. 10) show gravel of about $-3\phi$ to be fairly well sorted for a fluvial gravel. Skewness versus size shows no well developed correlation (cf. Folk and Ward, 1957, p. 19, fig. 12; Friedman, 1961, p. 518, fig. 2, for sand sized material. Friedman, ibid, p. 517, coarse sand and gravel), and neither does kurtosis versus size. Standard deviation increases with the approach of high negative skewness values. This follows from the fact that the increase in the standard deviation is accomplished by adding a small amount of coarse material to a greater popula-

![Figure 25](image-url)
tion with a finer mode such as imbricate zone. There are variants of this: the removal of the coarser part of a distribution lowers standard deviation, and produces positive skew such as large disc zone. And the addition of a large amount of fine to a small amount of coarse material produces the same effect of increasing standard deviation and giving a negative skew such as infill zone. For a similar plot Folk and Ward, (1957, fig. 14) found a circular distribution over a much wider range of standard deviation values. But even taking same ranges (converting Folk and Ward’s data by means of the graphs produced by Friedman, 1962), the nature of the correlation is evidently different.

In comparing standard deviation of sphericity (fig. 9) with standard deviation of size frequency both appear to increase seaward (excluding the outer frame); and this might well indicate that where there is strong size sorting, there is also strong shape sorting.

Whatever the ultimate cause may be of these changes in the statistical parameters associated with size sorting, it is evident that they are less useful in subdividing the beach bar than the shape-size procedure adopted here and elsewhere (Bluck, 1965); and since it is from an analysis of the beach bar zonal development that the mechanics of sediment movement is deduced, mechanical analysis can only be regarded as an inferior tool to the point of being supplementary. These shortcomings of the particle size parameters may be due either to their relative insensitivity or acute sensitivity to the recording of such a variety of hydrologic and other factors which are known to exist on the beach. The imbricate zone, for example, has a wide range of standard deviation, skewness and kurtosis (figs. 22, 24), which fall well within the ranges of such values obtained from other zones; yet the essential nature of this zone is easily ascertained from the size-shape data, and size-shape-frequency data. The relative ease with which the size frequency responds to conditions of the environment is therefore demonstrated by this example. But mechanical analysis does not itself possess the means by which these changes in standard deviation, skewness and kurtosis may be elucidated: within the size frequency distribution are lumped together different shaped particles each of which respond differently to different conditions, or respond differently to the same condition. This defect is overcome by the use of the shape-size-frequency technique, the great advantage of which is that it dissects the frequency curve in such a way as to permit a more direct analysis of where, to what extent, and how gravel movement is, or has taken place in the area represented by the sample.

DEVELOPMENT OF THE GRAVEL BEACHES

The gravel beaches studied in detail can be conveniently subdivided into two groups: the Sker type and the Newton type, each of which behaves in a slightly different way during break down, but they were both built up in essentially the same way.

Sker Type

This type of gravel beach is found at several localities in the Sker district, Ogmore and Cwm Nash, and includes five of the six beaches studied. They all have a large disc zone, an im-

STORM BEACH: SKER POINT

![Composite diagram showing a part of the Sker Point storm beach. The diagram is based partly on a number of trench sections.](image-url)
bricate zone, an infill zone and an outer frame. Observations made over a period of 3 years have shown that the development of the Sker type beach bar is as follows:

(a) The 'initial' form comprises a ridge of gravel positioned on or about the high tide mark, and a thin fringe of gravel on the seaward side. The whole bar is composed of variously shaped fragments the inter-pore space of which is infilled with sand and granules. The large discs are only beginning to be further concentrated. On the seaward side the imbricate zone is only impersistently developed, and well mixed with spherical and rod shaped fragments. Imbrication is only weakly developed. The outer frame is normally fairly well established at this time.

(b) After a while four zones become fairly well established; the large disc, imbricate, infill and outer frame. The large disc zone has a considerable residuum of large discs and an open framework, which slows down the abstraction of spherical and rod shaped particles. Underneath this zone is a reservoir of sand and gravel (fig. 26) which is subjected to movement through the developing frame; the frame acts as a sieve on this moving material. The imbricate zone is now fairly well established and has a fairly short, steep asymptotic profile, and a seaward decline in disc size. On the seaward side of this imbricate zone the infill zone comprises the sand run, the thin strip of spherical and rod pebbles, and an area where infilling is taking place. At this stage in the bar development the outer frame is filled, and the sequence resulting is as shown as one in figure 27 and is found on several beaches. The beach bars shown in figures 3, 4 and 5 were sampled at this stage.

(c) Following the creation of the zones, further modification is apparent by the growth of the large disc zone. This growth entails further removal of spherical and rod shaped grains on the landward, with the accumulation of a residuum of discs. But seaward extension is affected by the migration of discs as shown in figure 29 out over the infilled frame, or even as a component of frame infill. The extension
of the imbricate zone introduces a further hindrance to the rapid seaward transport of spherical and rod shaped grains.

Smaller and/or less spherical cobbles and large pebbles, released from the reservoir underlying the disc zone, move seaward and extend the outer frame ahead of the migrating pebble and granule sized material, or adds another outer frame above the already existing infill zone.

A model for the succession built up during the breakdown of a storm beach of this type is given in figure 29. Although part of this modal succession has been proved to exist on one beach (for 1 and 2 of figure 29, see figure 28), that part designated 3 has not been seen on the present day beaches, but has been seen in some marine gravels related to an earlier sea level. These older gravels were excavated to a maximum depth of 15 feet by a mechanical shovel. In the exposed sections there were some beds of cross bedded gravel, with the cross bedding dipping towards the land. However, the landward movement of a flat topped gravel bar, whose particle shape composition compared well with the particle shape composition of the older cross bedded gravel, was seen seaward of the infill zone at Newton: it was not seen to migrate over the infill zone, but it does seem likely that bar migration of this type would give rise to the landward dipping cross bedded gravels.

In the excavated sections of the older beach deposits, thick beds of gravel were seen to dip seaward at slight angles: this seaward dip of gravels also obtains on the present day beach during the bar breakdown, and with a higher content of sand in the bar, this angle of deposition is possibly higher. Dune sands, following on top of these inclined gravels produce a succession which appears to be unconformable, but which is in fact the normal succession of regression with offlap.

Newton Type

The beach at Newton, similar to the Sker type in many ways, has the same stages in breakdown; but differs in having a higher proportion of sand and no outer frame on the immediate seaward side of the infill zone (fig. 31 A). There is a rather poorly developed frame some 60 yards seaward of the gravel beach, but it is not certain if this is genetically related to the beach bar itself; it might be related to gravel movement at the mouth of the Ogmore River. Instead of there being one imbricate zone and one area of spherical and rod pebble accumulation, there are up to three of each in the stage corresponding to (c) of the Sker type. And with the seaward migration of these three or less zones a succession, as shown in figure 28 is produced (see also figure 29). Once again the succession in figure 29 is hypothetical in that it assumes no

Fig. 28.—Section obtained from trenches cut into the gravel beach at Newton. S=spherical; R=rod; D=disc; B=blade. Sg=subgreywacke; L=limestone; Q=quartzite; ORS=Old Red Sandstone.
landward migration of gravel during a period of complete breakdown of the bar. In marked contrast to the succession produced by the breakdown of the Sker type bar, this Newton type shows an increase in the size of the spherical and rod shaped fragments upward in the succession (fig. 28).

CONCLUSIONS

Differently shaped particles react differently to water flow, and this is an important characteristic of these marine gravels which permits a subdivision of the beach into zones. Disc shaped fragments behave quite differently from either spherical or rod, but behave in a similar way to blade. These features may be related to settling velocity or 'flume behaviour,' where on a smooth, unobstructed floor, spherical and rod shaped grains move faster than discs or blades. But the beach surface is seldom smooth and unobstructed, and in the reaction between particle and floor, another shape sorting factor is seen to operate—shape filtering. In this process, particles, because of their shape, cannot easily move through the obstructions, and therefore constitute a lag deposit.

Size frequency analysis, itself of secondary importance in the study of marine gravels, can be used with advantage when combined with shape. In combining shape-size-frequency it is possible to assess the degree to which the deposit in question has come to terms with those factors of the environment which are acting on the sediment at the time of sampling. Where the modal size of the sediment is coincident with the size having the highest proportion of discs, then a state of equilibrium is achieved in a gravel undergoing lag; where the modal size of the sediment is coincident with the size having the highest proportion of spherical or rod shaped particles, then fairly uniform conditions of deposition from the tractive load are taking place.

Tractive transport on the beach is seen to take three forms: the most common is rolling, where the particle caught in the force of the backwash moves along the surface with which it is predominantly in contact. Disc shaped grains shuffle along, and some grains move collectively in a form called surface creep. Surface creep is found in gravels with a low standard deviation, and occurs when the backwash water, percolating through the sediment, mobilises the layer and effects its slow movement seawards. This form of movement is achieved in two ways—(a) No effective turbulence is caused by large grains being surrounded by finer: there is an even distribution of the energy expended on the sediment surface by the water movement. (b) The sizes of the pores within the sediment mass and on the surface of the sediment are such that few grains are either large enough to roll on the surface and bridge the gaps between grains, or small enough to migrate through the pores.

The anomalous situation is seen where coarse
SEDIMENTATION OF BEACH GRAVELS, SOUTH WALES

<table>
<thead>
<tr>
<th>LARGE DISC</th>
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<th>INFILL</th>
<th>OUTER FRAME</th>
<th>ZONES</th>
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Fig. 30.—A. Gravel beach and bar, Sker Point. Stage 2 of breakdown. B. Large disc zone Sker Point. C. Imbricate zone, Sker Point; pebbles do not show imbrication. D. Outer frame, Sker Point. E. Infill zone, Sker Point, spherical and rod shaped particles are infilling a frame of cobbles, which is partly broken up.
FIG. 31.—A. Gravel beach, Newton, at stage 2 of breakdown. B. Imbricate zone, Sker Point, showing the large spherical particles concentrating on the seaward side, and the finer grains trapped within the picket of imbricate pebbles on the landward side. The photograph was taken after particles of the outer frame had been thrown up over the imbricate zone. C. Section cut into the parent gravel, showing lag of discs at the top (large disc zone) underlain by beds rich in spherical and rod shaped pebbles and granules, and finally a sand filled gravel at the bottom. Newton. D. Gravel beach at Newton in stage 1 of its development. Beach cusps of the type shown are common in this phase of bar development.
grains outstrip fine. On the beaches this phenomenon is believed to be due to: (a) If it is considered that the weight, and the discoidal shape of a particle are factors hindering its movement in traction, then it follows that large spherical grains will move when smaller discs will remain. (b) Large grains will move on the surfaces of small by bridging the gap between these smaller grains. This factor is extremely important where the small sized sediment moves either by shuffling (imbricate discs) or by creep.

Both composition and maturity are a function of size and shape on these beaches, and for that reason vary markedly and systematically within the beach environment. There is no correlation between maturity and size in the source rocks of these gravels, and the value of maturity is low. Weathering of this source gravel (boulder clay) produces an increase in maturity with increasing size, and abrasion on the beaches accentuates this trend by further reducing the numbers of large labile fragments. It seems likely that erosion would continue to produce a maturity-size power function. Shape-lithology correlation is believed to be a characteristic of a phase in the maturing process of these gravels. The sequence of gravels in order of increasing maturity is: boulder clay—the Newton and Ogmore beaches—the Sker beaches. This sequence correlates with an increase in energy supplied to effect the erosion of the gravels: this being based on inference in the case of the glacial environment, and for that reason vary markedly and systematically within the beach environment. There is no correlation between maturity and size in the source rocks of these gravels, and the value of maturity is low. Weathering of this source gravel (boulder clay) produces an increase in maturity with increasing size, and abrasion on the beaches accentuates this trend by further reducing the numbers of large labile fragments. It seems likely that erosion would continue to produce a maturity-size power function. Shape-lithology correlation is believed to be a characteristic of a phase in the maturing process of these gravels. The sequence of gravels in order of increasing maturity is: boulder clay—the Newton and Ogmore beaches—the Sker beaches. This sequence correlates with an increase in energy supplied to effect the erosion of the gravels: this being based on inference in the case of the glacial environment, but based on evidence in the case of the beaches. The main landward part of the storm beach may be looked upon as being a reservoir of sand and gravel slowly being released to the sea. This reservoir is capped by a zone of large discs representing the lag product of gravel leaching. In time a shape differentiation takes place throughout the bar with discs travelling seaward far slower than spherical and rod: the stage of bar breakdown can be ascertained from the length of the imbricate zone, which increases with the continued reworking of the gravel. The history of bar breakdown is written, in converse, in the deposits accumulating at its foot, and these sequences have been observed in older post-glacial deposits.

The possibility of disc shaped fragments being made by special features of marine abrasion is not supported by the data obtained here. The largest discs are the most angular and the most oblate; and the most oblate discs are found in areas which are least worked on by the sea, such as in the large disc zone, near the high tide mark. The most oblate discs have the least independent evidence of the type abrasion envisaged by some as effecting a flattening of particles. Selective sorting controls the shape distribution of a population of grains, and impact breakage during storm conditions is the favoured means of beach particle abrasion for discs at least.

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