Hydrodynamic Factors Controlling the Distribution of Heavy Minerals (Bristol Channel)

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Based on a knowledge of the Bristol Channel hydrography, the quantitative heavy mineral distribution, and the individual mineral threshold values, a model for equivalence/inequivalence values and heavy mineral enrichment is presented. Hydraulic inequivalence in the Channel is a result of (1) preferential mineral size from the source; this controls the mineral suite changes created by (2) differential entrainment of minerals by density and size. Differential mineral transport of heavy minerals depends upon the hydraulic conditions of unidirectional and oscillatory flow, separately and in combination, acting on a seabed of certain roughness. Such a model can be used to explain the development of heavy mineral enrichment found on the open (high energy) beaches and in the areas of local tidal current enhancement.

Introduction

Mineralogical studies of mobile seabed sediments can, by their very nature, reveal certain hydraulic and boundary roughness characteristics of an area (Slingerland, 1977). Heavy minerals, specifically, will be located throughout a sedimentary basin in a distribution which is related to both source areas and the modern prevailing superimposed hydraulic regime. These processes will be reflected by the individual mineral distributions and concentrations, and their associations with the light minerals. Hydraulic equivalence, defined by Rubey (1933), states that the hydraulic conditions which would permit the deposition of a particular quartz grain would also be conducive to the deposition of a heavy mineral of the same settling velocity, though smaller in size. The size of such a grain is inversely proportional to a power of its density. Subsequent studies have revealed that standard hydraulic equilibrium, as defined by Rubey (1933) and Rittenhouse (1943), is inapplicable to most natural non-cohesive sands because of the interaction and complexity of grain size, density, shape and mode of sediment transport (Lowright *et al.*, 1972; Slingerland, 1977). Recent investigations have defined two possible explanations for this divergence, as outlined by Lowright *et al.* (1972). They are (1) size restriction inherent in certain minerals from source and (2) differential entrainment of mineral grains. Whether it is the first or

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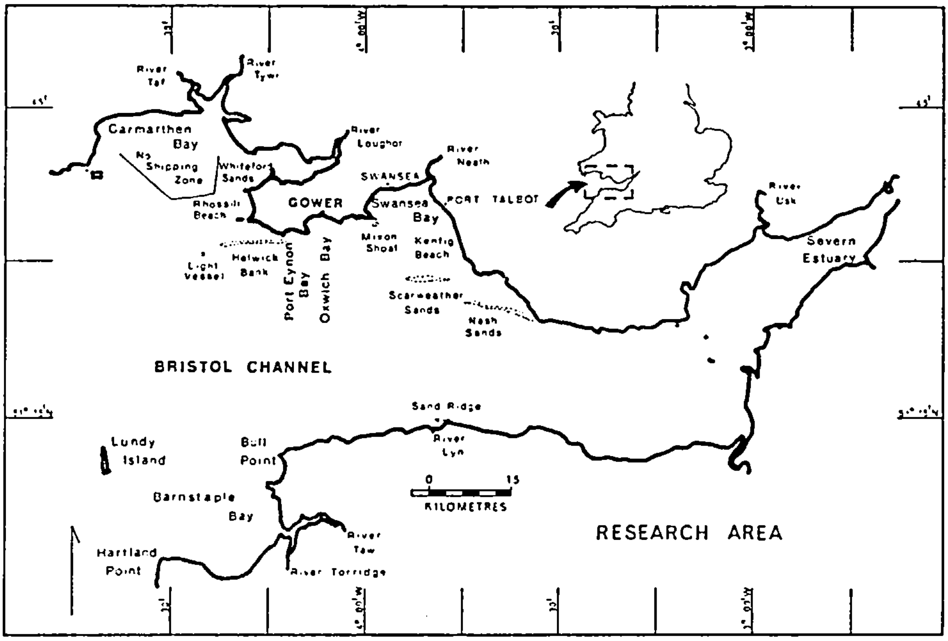

Figure 1. Area of research.

second explanation, or both mechanisms, which is operative, it is nevertheless an understanding of the hydrodynamic parameters acting on the sediment at the boundary layer which delineates the respective distribution and concentration effect of either.

The purpose of this investigation is to interpret the present sediment distribution of the Bristol Channel (Figure 1) in relation to Pleistocene and Holocene processes, with particular reference to the heavy mineral/hydrodynamic process mechanisms. As the majority of heavy minerals of the Channel are derived from relict glacial seabed material, from both the Wolstonian (Saalian, Illinoian) and Devensian (Weichselian, Wisconsin) glacial periods of the late Pleistocene (Barrie, 1980), the relationship of modern hydrodynamic conditions to a homogenous suite of minerals can be examined. It was not until the late Flandrian that the modern hydrodynamic regime of the Channel was attained, causing a rapid redistribution of the Quarternary deposits into something approaching the present day pattern of sediment distribution (Culver & Banner, 1979).

This study augments a complementary study of the heavy mineral distribution in Bristol Channel bottom sediments in which mineral associations are related to the Pleistocene and Holocene development of the Bristol Channel (Barrie, 1980). The method of data collection has been described in that paper. The present study, based on this information, presents a qualitative model for the association of heavy minerals in a marine basin, subjected to both tidal and surface gravity-wave-induced (oscillatory) motion.

Bristol Channel hydrodynamics

Tidal current circulation

The three-dimensional tidal current pattern of the Bristol Channel is essentially rectilinear with a large vertical range and associated high current velocities. The rectilinear currents run basically parallel to the main axis of the Channel. The surface current distribution presented by Sager (1968) compares very favourably with the computed (using a finite difference technique) tidal current model of Pingree (1980). Generally, there is an increase of maximum current speeds from the outer Channel (1·0 m s^{-1} at surface) up to the Severn Estuary (2·25 m s^{-1} at surface); these are intensified between Hartland Point and Lundy Island.

The simple rectilinear tidal situation is modified within the embayments. 'Eddies' within the Gower embayments of Oxwich and Port Eynon, and Swansea Bay (Figure 1) have been suggested by Rees (1940). Recent investigations in Swansea Bay (Collins *et al.*, 1979) have confirmed that a quasi-permanent tidal eddy exists on the western side of the embayment, causing a flow past Mumbles Head for approximately 9 h. As the current passes the Mumbles promontory, it is deflected by the main rectilinear Channel stream. The deflection is to seawards during ebb, and it is returned to the anti-clockwise eddy system during flood. This pattern causes reinforcement of the tidal currents around Mumbles Head. Collins *et al.* (1979) further postulate similar gyres (eddies) in Oxwich and Port Eynon Bays. Current velocities and patterns within the embayments, but outside the dominant tidal gyres, are less discernible or significant. Within Swansea Bay, Ferentinos (1978) has demonstrated that the bottom tidal current velocities of the central and eastern portions of the bay are very low (i.e. approximately 0·15 m s^{-1} at springs and 0·15 m s^{-1} on neaps) in comparison to the higher values of the main Channel. This can also be inferred within Carmarthen Bay from the Admiralty Publications [Chart 1076 and Tidal Stream Atlas of the English and Bristol Channels (1973)]. However, the restricted entrance and configuration of the Loughor Estuary gives rise to fast tidal currents. Speeds, at 1 m above the seabed, of 1·6 m s^{-1} (Moore, 1976) at the entrance, increase towards the River Loughor.

Wave hydrodynamics

Records of the direction of swell, as those of height and period, are very limited for the Bristol Channel. However, wave approach in the Bristol Channel can be generally considered to be directly related to the wind directions shown in the meteorological records. The main wind directions, based on records from the north coast of the Bristol Channel are from the north-west to south-west (Collins *et al.*, 1979). Some 50% of the winds came from the south-west quadrant during the year 1973/1974 (Tyler & Banner, 1977), the north-east quadrant accounted for 22·45% and the north-west for 20·30% of the wind. Wind records from the Victoria Park, Swansea, meteorological station demonstrate similar characteristics over the period from 1921 to 1940. The prevailing wind direction over this period is from the south-west (240°).

The available observed information on wave approach is for the calendar year of 1976, from the St. Gowan Light Vessel; these are accompanied by wind directional data. In these records, the prevailing direction of approach is from the south-west (230°) and persists over 38% of the year. The comparative frequency of approach from the north-west (320°), particularly during the summer months, was high (i.e. over 24% annually). As the St. Gowan Light Vessel is positioned just outside the western boundary of the area under investigation, along the northern coastline, the north-westerly wave approach could be associated with the commonly occurring north-westerly winds, which follow the warm and cold meteorological fronts through the Lundy area (Tyler & Banner, 1977). Over the remainder of the year, the St. Gowan records from 1976 show that wave approach from the north-east and south-east was over 17% and 20% of the time, respectively.

In view of the fact that the swell direction from the south-west is predominant, and that it is this direction which is that of the longest fetch, wave energy acting upon the mobile

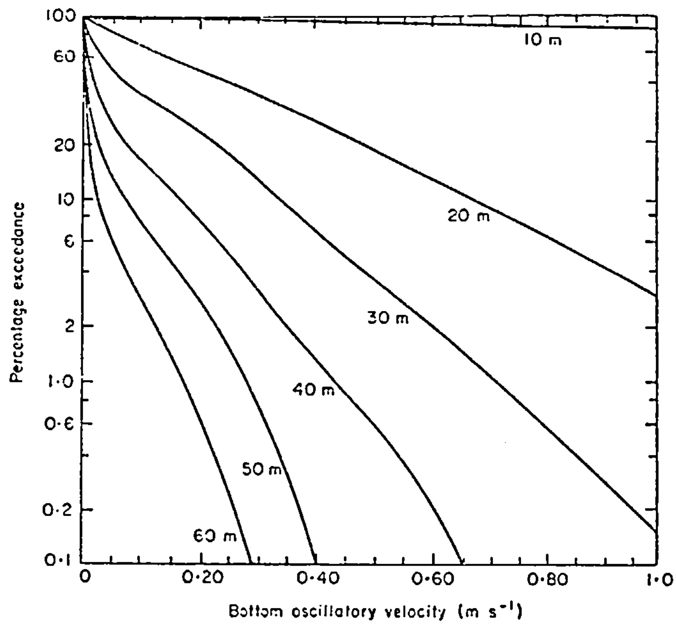

Figure 2. Percentage exceedance of bottom oscillatory velocities at certain depths, based on the data recorded from September 1960 to May 1961 (Darbyshire, 1962) at the Helwick Light Vessel.

sediment cover is considered to be the most effective from the south-west. Using the wave records from the Helwick Light Vessel (Darbyshire, 1962) and the Airy wave theory (Inman, 1963), it is now possible to calculate near bed oscillatory currents for the Channel as a whole. Subsequently, a diagram (Figure 2) representing these oscillatory currents in terms of percentage exceedance was produced for the period September 1960 to May 1961.

Heavy mineral distribution

Eight minerals account for 75–88% of the total non-opaque heavy mineral assemblages in the Bristol Channel. Factor analysis has indicated three mineralogical patterns which are hydrodynamically controlled and a further pattern which is controlled by source (Barrie, 1980). Dividing one of the factor analysis patterns (zircon, rutile) into three groups, five modes of mineralogical association were defined (Barrie, 1980). The associations are: (i) Group A—Tourmaline, epidote, amphibole; (ii) Group B—garnet; (iii) Group C—zircon, rutile; (iv) Embayment Group—chlorite, zircon, rutile; and (v) Beach Group—tourmaline, zircon, rutile (Figure 3). In the south-westerly area of the region and along the south coast of the Bristol Channel, is the Barnstaple Bay Province (chlorite, siderite) which is controlled by source.

Hydraulic inequivalence, with the heavy minerals being smaller than predicted (low heavy/light mineral ratio), was observed in Group B. Inequivalence increased in the Group C minerals, where it was almost four times what is expected by standard hydraulic equivalence (from offshore depths of approximately 35 to 10 m below chart datum (Barrie, 1980). The mineralogical changes throughout the Channel are reflected partially by the distribution of zircon and rutile, both restricted to the fines, and amphibole, dominant in the coarse

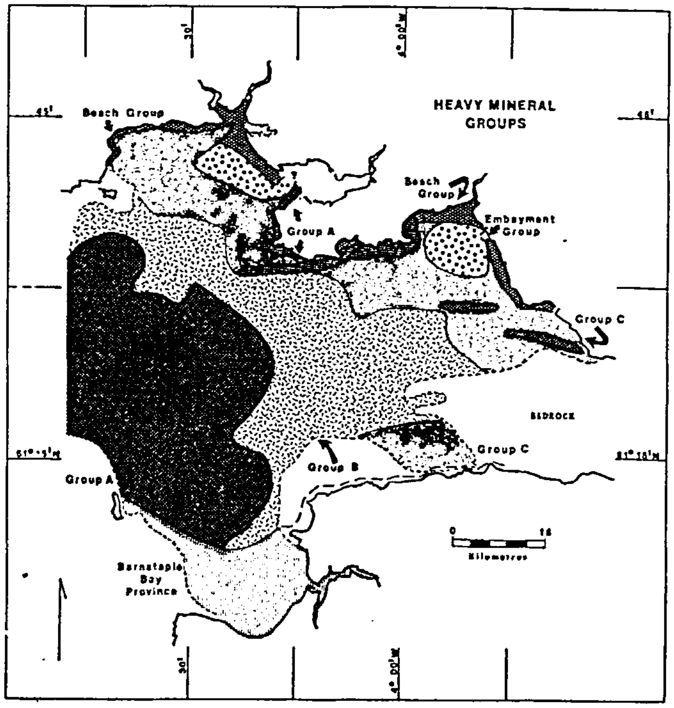

Figure 3. Distribution of the Heavy Mineral Groups in the Bristol Channel (after Barrie, 1980).

fraction, inferring type (1) of the explanations for the hydraulic inequivalence, namely, that of mineral size restriction from the source. This explanation, however, is not adequate to explain totally the results but is only sufficient to suggest some significant mineral changes, determined by hydrodynamic sedimentary selection. Therefore, the second explanation [type (2)] for hydraulic inequivalence, i.e. differential transport, can be postulated as the governing factor controlling the heavy mineral distribution in the Bristol Channel.

Certain areas also respond to increased tidally-induced currents or reinforced current gyres with altered mineralogically equivalent suites and placer concentrations. For example, at the mouth of the Loughor Estuary, in the upper reaches of the Severn Estuary, and in an area to the north of Hartland Point (along the southern coastline), the heavy mineral concentrations are abnormally high. The areas are those of high tidal current activity. On a slightly smaller scale, the two embayments of the Gower coastline (Port Eynon and Oxwich), and the area on the eastern side of Mumbles Head (in Swansea Bay), also reveal this same anomaly. Heavy mineral concentrations increase on the eastern sides of Port Eynon Point, Oxwich Point, and Mumbles Head, but end abruptly in the region around the promontories. An area of such localised concentration, Mumbles Head, was sampled in detail (Barrie, 1980) so as to correlate with available tidal current measurements. These high concentration areas are protected from the predominant swell direction (SSW. to NW.). There is conclusive correlation, then, between the deposits and the enhanced tidal currents.

The explanation of the mechanisms creating the heavy mineral groups and the corresponding placer concentrations cannot, then, be undertaken without assessing the superimposed hydrodynamics of the Bristol Channel, with respect to differential mineral transport at the bottom boundary layer.

The threshold of heavy minerals under undirectional flow

The threshold of natural sediment movement has been considered by most geologists in relation to such empirical curves as those of Shields, Hjulstrom, Sundborg or Inman (these are summarized in Miller *et al.*, 1977). The limited seabed current measurements available for the Bristol Channel show that for long periods (up to 70% of the tidal cycle) conditions of threshold exceedance exist. Lowright *et al.* (1972) have predicted that the differential entrainment of minerals of differing densities can be explained by unidirectional threshold conditions. This entrainment difference can then explain the differences in hydraulic equivalence.

The threshold of heavy minerals under oscillatory flow

Heavy minerals and other mobile surficial sediment will move, initially, under oscillatory water movement as expressed by the critical threshold equation:

$$\frac{\rho(U_m)^2}{(\rho_s-\rho)gD}=0{\cdot}21\,(d_0/D)^{\frac{1}{2}}$$

where ρ is the density of water and d_0 is the orbital diameter of wave motion (derived from Komar & Miller, 1974). In developing this equation, Komar & Miller (1973, 1974) used previously published laboratory flume data. Nevertheless, the equation is regarded as conservative in comparison to the situation which would be expected in the oceans (Komar & Miller, 1974). A computer program, utilizing the above equation has been presented by Komar & Miller (1975). In this, an input of grain diameter (D) and grain density (ρ_s) is used to compute the period (T) and the orbital velocity (U_m) needed for sediment movement. This section of the program is followed by one which combines wave height (H), water depth (h) and period (T) into an equation for orbital velocity (U_m), the linear Airy wave equation.

$$U_m=\frac{\pi H}{T\sinh(2\pi h/L)}\,.$$

Substituting the individual mineral densities of the eight significant minerals from the Bristol Channel bottom sediments, and their corresponding mean grain sizes, enables the conditions of threshold exceedance to be computed and compared with the wave conditions recorded at the Helwick Light Vessel (Darbyshire, 1962). The different particle densities and their respective mean grain sizes predict similar threshold conditions, over a range of wave height and wave period combinations for the Channel. This would be expected, with reference to the theory of hydraulic equivalence.

The deviations from hydraulic equivalence in Groups A, B and C, in the offshore area, were compared with Komar & Miller's (1974) threshold equation, in order to determine if hydraulic inequivalence, due to differential entrainment of heavy minerals, can be predicted from oscillatory motion as was suggested by unidirectional threshold equations (Lowright *et al.*, 1972). Three samples were used to represent Groups A, B and C minerals, respectively. The threshold exceedance values in relation to the Helwick Light Vessel wave records (Darbyshire, 1962) of six minerals (tourmaline, garnet, zircon, rutile, epidote and amphibole) with their respective mean size and density were calculated for the three respective groups. The first point of interest is that individual mineral exceedance values for the period of September 1960 to May 1961, over the offshore depth range of each group, were so close to one another that the standard deviation never exceeded 2·85% exceedance. For this reason,

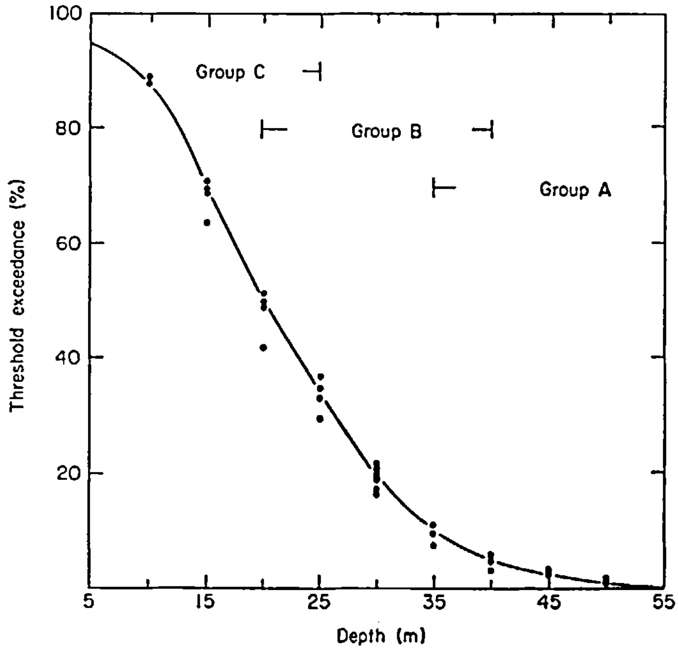

Figure 4. Threshold exceedance curve for heavy minerals within the Bristol Channel under oscillatory motion, based on the data recorded from September 1960 to May 1961 (Darbyshire, 1962) at the Helwick Light Vessel. See text for meaning of Groups A, B and C.

the results for individual minerals were averaged and compared with the threshold exceedance values of their host light (quartz) minerals. Combining the heavy/light threshold exceedance relationship for Groups A, B and C, over the water depths at which they are found (Figure 4) leads to two conclusions. Firstly the close heavy/light threshold exceedance relationship confirms the assumption that differential entrainment can be explained by oscillatory threshold equations. Secondly, the curve of best fit for Figure 4 approximates the sediment exceedance values, in relation to depth, for the greater part of the central and outer Bristol Channel.

Discussion

Slingerland (1977), in assessing quantitative, theoretical and experimental support for deviations from hydraulic equivalence, stated that changes in both the Reynolds Number of the flow at the bed (R_*) and d/BKs, the ratio of the grain size in question (d) to the bottom roughness grain size (BKs), control changes in equivalence values, by means of differential entrainment. He used the Karman-Prandtl equation, with the modification by Einstein (1950), to examine hydraulically smooth ($R_*<5$), transitional ($5<R_*<70$) and rough boundaries ($R_*>70$) under unidirectional motion.

Measured values of the Reynolds Number related to tidal flow are not available for the offshore area of the Bristol Channel and only an assessment of the value (based on estimated flow type) can be presented here. However, Channon & Hamilton (1971, 1976) have demonstrated, from near seabed current records from the South-west Approaches, that derived

Reynolds Numbers relate to predominantly transitional boundary layers over the complete tidal cycle. These values correspond to surface tidal current speeds which are an order of magnitude less than those in the area under study. At the other geographical extreme, within the inner Channel, a single station maintained by Channon & Hamilton (1971) relates to fully rough conditions with a very high Reynolds Number at peak velocity conditions, on a tidal range between spring and neap tides. From the previous discussion of the Bristol Channel tidal currents, and the present considerations, it can be assumed that fluid flow in the bottom boundary layer, in the region outside of the embayments, is transitional to rough over the peak and near-peak tidal currents. Within the inner Channel, there is a region where a fully rough hydrodynamic regime becomes dominant, for the same tidal range. The Reynolds Number, developed near the bed, will be further increased by bottom wave oscillatory motion as the water depth decreases and bed roughness increases, as is demonstrated by Kamphuis (1975).

Slingerland's (1977) classification of hydraulic characteristics, using the critical bed and suspended material velocity equations, indicates that an increasing Reynolds Number (i.e. from transitional to rough flow conditions), in association with coarse grained poorly sorted sediment, will lead to the development of hydraulic inequivalence. Under these conditions heavy minerals will be found which are up to four times smaller in size than those which might be predicted from standard hydraulic equivalence. This reduction in grain size is accompanied by a general increase in the percentage of minerals of greater density. As expressed by Slingerland (1977), 'entrainment equivalent heavy sizes or heavies that are small enough to lodge within the larger population will remain, since fluid turbulence will act to remove all suspension equivalents'. On the Channel bottom in the areas of Group B and C offshore, grains are moved by the increased flow until the interparticle geometry provides stable positions. The increasing bed roughness will accommodate the smaller heavy minerals by their ability to lodge, while larger heavies will be entrained along with their equivalent sized light minerals.

Group A minerals, in the offshore zone at depths greater than 35 m below chart datum, are subject primarily to the input of energy from the tidal regime. Here, the oscillatory wave threshold exceedances are very small. The smaller Reynolds Numbers and the fact that the ratio of the grain size of the heavy minerals is slightly smaller than the bottom roughness grain size explain the hydraulic equivalent state.

One reservation in extrapolating Slingerland's (1977) classification into deeper areas, other than the nearshore and the beach environments, is that the boundary between transitional and rough flow is related to the configuration of the seabed. Thus, complex beds such as sand waves develop fully rough flow characteristics at higher Reynolds Number than the smooth, or simply patterned, beds (Sternberg, 1968). This could be an explanation of the apparent non-bathymetrical control on the total placer concentrations, and of tourmaline and epidote concentrations (of the Group A minerals) (Barrie, 1980) to be distributed along the area defined by sand waves (Belderson & Stride, 1966). The distribution of garnet, conversely, increases laterally, away from this area.

Within the shoaling areas of the Group A region of minerals, maximum wave energy and the superimposed tidal currents have created well-sorted sediment. This results in small quantities of heavy minerals, where entrainment equivalence is equal to hydraulic equivalence. Smaller grains of heavy minerals are extracted from the homogeneous sand deposit by a vertical velocity component of the flow, at a high Reynolds Number.

On the minerals within the eastern-central zones of Carmarthen and Swansea Bays (i.e. the Embayment Group), the tidal current influence is very much reduced (Ferentinos, 1978).

Wave energy is sufficient to control the sediment distribution, but is only intermittent in relation to the influence of strong south to south-westerly swell wave action. Consequently, the irregular hydraulically rough to smooth boundary conditions (together with the artificial dredging input into Swansea Bay) will result in sediment being supplied and subsequently deposited out of suspension. This complex variation in hydrodynamics is displayed by the structure in the sediment deposits in the box cores of the Institute of Oceanographic Sciences (Taunton) (Barrie, 1980). The settling of the suspended sediment to form different laminae of deposition would presumably then follow Rubey's (1933) law of hydraulic equivalence.

Within the intertidal beach zone, there is a varying amount of shoaling wave energy input which varies with the sample position. The samples analysed in this study were taken from the low water mark of a spring tide. Consequently, the full effect of the advancing and retreating oscillatory motion of the waves will be felt over the seabed with varying turbulence levels. In this portion of the zone, the effect of tidally-induced currents would be generally a secondary process in the selective sorting of sediments. Hydraulic inequivalence, caused by variation in entrainment values in response to differences in the mean wave-induced oscillatory velocities, is most evident on the beaches; those which are exposed to the predominant south-easterly swell showing the greatest inequivalence. On the upper section of the berms of the south-westerly facing open beaches, especially Rhossili Beach in Carmarthen Bay, there are thin laminae of fine heavy mineral concentrations in equivalence with quartz. This is the final result of the differential entrainment created by the waves and surge on the beach shelf (e.g. Everts, 1972; May, 1973; Slingerland, 1977). The inequivalence becomes less apparent in the protected zones of the embayments, until equivalence is reached in the totally protected areas, where tidal currents enhanced by the recirculatory flow become the dominant hydraulic factor in the selective control of the sediment.

Certain areas in the region under investigation are known to have heavy mineral enrichment related to reinforced tidal currents. These areas are, conversely, deficient in wave energy. The tidal current flow in these areas, with currents enhanced by the interaction of the coastal geometry and the offshore rectilinear system, is such that it is equivalent to a rough boundary condition. However, sediments are hydraulically equivalent and the heavy mineral concentrations are large. This finding does not entirely agree with the classification by Slingerland (1977). It is considered by the author that the lighter mineral grains are rolled away within the unidirectional currents, leaving behind the heavier grains. Frequently, based on qualitative field observations, these deposits are raised into suspension, resulting in a density fractionated lag deposit. A model for the development of similar deposits was first proposed by Hand (1964). The efficiency of such a model seems proportional to the intensity of the tidal current in areas protected from the dominant south-westerly swell. This relationship is strengthened when the bottom roughness grain size is close to that of the heavy minerals found.

Summary

From this discussion, a model has been proposed of the effect of wave superimposition on a tidal current regime in creating variations in hydraulic equivalence and total placer concentrations of heavy minerals. Hydraulic inequivalence in the Channel is a result of (i) preferential mineral size from the source, which controls the mineral suite changes, created by (ii) differential entrainment of minerals by density and size. Heavy minerals which are subjected to increasing oscillatory motion over a greater bed roughness, within the Bristol Channel, respond to the flow by becoming increasingly finer in relation to the light minerals. Only at the extreme shoreward end of the dominant swell does the decelerating wave surge enrich the heavy minerals; however, there is still inequivalence with a small heavy/light mineral ratio. Alternatively, the unidirectional motion of the tidal regime concentrates heavy minerals in direct proportion to the intensity of the current, and inversely proportional to the oscillatory penetration at the seabed. The bed roughness is here of lesser importance in the mineral enrichment, but an increased bed roughness size to that of the heavy minerals will result in hydraulic inequivalence at higher Reynolds Numbers. When the effect of wave and tide, within the Channel, are approximately at a maximum (e.g. on the linear sand banks), the entrainment equivalence (which equals hydraulic equivalence for all minerals) results in low concentrations of heavy minerals. It is concluded from this, that any classification to quantitatively predict the equivalence values and the heavy mineral enrichment has to incorporate both the differences between, and the combination of, unidirectional *versus* oscillatory motion acting over the seabed of a certain roughness.

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