SEDIMENT CIRCULATION
IN
MIXED GRAVEL AND SHINGLE BAYHEAD BEACHES
ON THE SOUTH EAST DORSET COAST

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ABSTRACT :

This thesis investigates and attempts to clarify the morphological characteristics, processes and sedimentology of five local mixed gravel and shingle beaches. A conceptual framework of process-response has been adopted which considers energy inputs, sediment transport and coastal morphology, under conditions of limited sediment supply and a "closed cell" situation.

Onshore field investigations using conventional methods of surface sediment sampling, together with beach profiling, platform and cliff measurements provided quantitative data with respect to contemporary sediment inputs, sediment characteristics and transport. Extensive and intensive measurements of beach sections described spatial and temporal morphological and volumetric change and revealed a neutral sediment budget at the scale of 12-14 months. The beaches are in equilibrium with prevailing and dominant south westerly wave regimes; prolonged periods of south easterly wave climates influence the foci of wave energy and cause significant littoral drift and exposure of the chalk platform.

The offshore data used were derived from available sources and supplemented by fieldwork by the author. Investigations in the nearshore zone by side-scan sonar and echosounder revealed the morphological and sedimentological nature of the seafloor along the northern shore of Weymouth Bay. Sediment distribution and bedforms suggested preferred sediment transport paths. Within each bay sediment sampling by grab and/or divers elucidated the nature of each sediment cell. The distinct differences of textural composition and the presence of natural offshore barriers to sediment movement highlighted the sedimentological/morphological containment of each bayhead unit.

Theoretical considerations and field data have helped to gain a better understanding of the relationship between cliff, beach, platform and nearshore processes and illustrate that selected embayments along the northern shore of Weymouth Bay are morphologically contained sediment cells sharing the same hydrodynamic system.

I declare that while registered as a candidate for the degree of Doctor of Philosophy I have not been registered for another award of the Council for National Academic Awards or of a University during the research programme, nor has any of the material contained within this thesis been submitted for any other award.Any assistance received has been duly acknowledged.

CONTENTS

VOLUME 1.

VOLUME 2 .

VOLUME 2:

LIST OF FIGURES

LIST OF TABLES:

LIST OF PLATES:

LIST OF APPENDICES:

APPENDIX 1: WAVERLEY SIDE SCAN SONAR SPECIFICATION.

APPENDIX 2: BEACH PROFILES-DURDLE DOOR BEACH,ONE MONTH SURVEY,FEBRUARY 1983.

APPENDIX 3: BEACH PROFILES-WORBARROW BEACH,STORM EVENT SURVEY,SEPTEMBER 1983.

APPENDIX 4: WIND ROSES AND BEACH PROFILES - RINGSTEAD, DURDLE DOOR,MAN O'WAR,MUPE AND WORBARROW BEACHES,MONTHLY BEACH SURVEYS 1983/1984.

CHAPTER 1

PROCESS - RESPONSE MODELS AND APPROACHES TO COASTAL GEOMORPHOLOGY

Most coastal researchers have attempted to relate nearshore processes with foreshore responses in order to gain better understanding of coastal behaviour for purposes of coastal zone management. In an attempt to structure such relationships in the search for "generalizing principles, it is a useful philosophical device to recognise models - actual or conceptual frameworks to which observations are referred as an aid to identification and as a basis for prediction", (Krumbein and Sloss, 1963). Thus, a conceptual model is the abstraction of key factors to represent relationships within a system. That system involves :-

(i) interaction of a large number of variables, and

(ii) simultaneous variation of all or most of the variables.

The structuring of a conceptual model is only a beginning, where factors are recognised or inferred relevant to the problem. Despite the problems of applying statistics to coastal geomorphology, especially sampling restrictions and the multiplicity of variables in even the simplest situations, most problems are answerable to quantitative analysis. With the collection of more data and quantification of all the relevant characteristics of the model they may be incorporated into a single equation for accurate description and prediction in a deterministic model.

Despite the wealth of literature and research into beach/nearshore processes, observational data is still a main consideration but is gradually being supplemented by quantitative data. A fully deterministic beach process - response model is still an eventuality, (although significant developments are being made with regard to predicting profile response by the Hydraulics Research Station, e.g. Price, Tomlinson and Willis, 1972; Brampton and Motyka, 1985). The main problem in the development of a universal model (whether conceptual or deterministic) is the relative isolation of research into separate subject areas (e.g. shallow coastal water hydraulics, nearshore circulation, littoral zone sedimentology and cliff stability). Leonard (1981) highlighted the multi-interdisciplinary nature of coastal zone processes by the inclusion of his article, "The Moving Seacoast" in the journal, "Perspectives in Computing", thereby adding computer-aided analysis to the broad spectrum of disciplines involved. Unfortunately there has been little concern for the overlap of research interests despite the necessity to consider a total coastal environment from continental shelf waters through the intertidal zone to the hinterland. It is also pertinent to note the lack of quantitative field data under storm conditions and as a result, inferences have to be made based on theoretical conclusions and laboratory controlled experiments.

Krumbein (1964) provided much of the groundwork for the concept of beach process-response by advocating a "Conceptual Beach Model". The model was based on the simplified identifications of a set of complex relationships. The key factors were divided into two elements (Figure 1) :

(i) process elements
(ii) response elements

The response elements include two main items :

(i) geometry of the beach deposit
(ii) properties of beach materials controlled by the kinds of material originally available at the beach site or brought in by currents and tides. Krumbein (1964) recognised a feedback process where close relations occur among the process elements, in that geometry of the beach site, as expressed by nearshore bottom slope, influences the pattern of energy distribution on the

shore. The feedback loop is a vital link in the model (Figures 1, 2 and 3).

The conceptual model does not take into account several factors including swash zone dynamics, rates of erosion, quantities of shore drift, but stressed that the model provides information and a base for a more formal quantitative treatment of data to be developed.

Whitten, (1964), considering process-response models in geology used Krumbein's (1964) beach model to illustrate the objectives and relevance of such model developments. He made it clear that the process model includes overall regional controlling factors and local factors peculiar to the particular population studies; any complete analysis involves separation of these two groups. A response model produced by the simultaneous effect of several factors (some of which maybe response elements) raises important questions in the evaluation of the relative effects played by each of the contributing factors. The importance of the beach profile in influencing beach process-response relationships led Sonu and Van Beek (1971) to propose a beach profile transition model based upon data collected from the study of nearly 300 beach profiles. The derived model function took into account beach width, sediment storage and surface configuration, in an attempt to predict the development of successive beach profile changes on the premise that the initial profile stage and configuration was known.

The inter-relation of hydraulic and energy characteristics across the swash zone and the initial morphology and structure of the beach surface recognised by Krumbein's (1964) model has been fundamental to the development of beach facies models. Bluck's (1967) facies model was based on the selective sorting of beach pebbles according to particle shape and sphericity. Problems inherent in this first attempt to recognise zonational behaviour of pebbles across the swash zone were highlighted by Orford (1978), who provided a modified version of Bluck's (1967) initial model, by using profile configuration as a discriminant between differing deposition environments he was able to observe the re-arrangement of sediments in relation to beach morphology. Orford, (1978), asserted that sorting processes could operate in both onshore and offshore directions under different littoral conditions. He also recognised that sediment differentiation was taking place on two scales; a daily basis and a long term genesis associated with gradual evolution.

One of the major aims of developing a conceptual beach process-response model is to gain some understanding of the mechanisms of processes at work. Observations on bayhead beaches along the south-east Dorset coast allowed modifications to be made to the basic conceptual beach model so that it could be applied to an idealised bayhead beach. The model considers energy inputs, sediment transport processes and coastal morphology under conditions of limited sediment supply and an inferred closed-cell environment. An attempt is made, in the following text, to identify and elucidate the key factors affecting morphological change in such environments.

In any such study the selection of an appropriate timescale is an important factor; some purpose may require selection of one set of timescales rather than another; Carr, (1980), considered the relation of short term change to longer term trends in determining coastal change by raising the question of the validity of experimental field techniques of limited duration. He states, (p.75), "Longterm records have the effect of averaging the changes that have occurred over the corresponding timespan. They may well include the effects of extreme events but are not explicit in so doing. Thus they represent the sum but not the range of conditions that have been experienced and may partially reflect factors and circumstances that have been superseded ... short term records and experiments may show a new or recent trend at variance with earlier conditions and thus be valid and significant." It must be remembered that the coastal geomorphologist has to work under considerable temporal restrictions but at the same time short term observations have an important role to play in the search for a more satisfactory spectrum of observations. In addition to the choice of an appropriate timescale in the investigation of coastal zone form and processes the actual spatial scale of the study must be decided upon. Hayes et al, (1973) discussed the issue of spatial scale and classified coastal studies into three categories dependent upon the scale and detail of the study :

1. reconnaissance of a large section of the coast.
2 studies at the intermediate level which involve some systematic process measurements.
3. detailed time series studies of a small area, e.g. beach cusps.

The authors suggested that the overall analysis of coastal forms and littoral processes should be a consequence of data obtained from studies at each of the three scales. The collection of data at all three scales enables comparisons of processes and forms in regions characterised by different environmental parameters to be made. The data obtained from such a hierarchical development is necessary for model development, from the conceptual through to the deterministic stage. The model making procedure is such that reconnaissance studies are necessary to provide the basic framework of the model by defining the key elements. The use of individual projects, whether at the intermediate level or at the detailed scale, ensure that the data can be used to provide answers related to the problem under investigation, in addition to providing the continuum of relationships between the key elements. The ultimate objective is the derivation of a deterministic, predictive model that can be applied to any similar situation and considers process/response in the offshore and onshore zone.

CHAPTER 2

INTRODUCTION

Compartmental type beaches with distinct headlands separating predominantly mixed gravel and single foreshores are a major feature of the south-east Dorset coast, although previous work in the area has concentrated on the unique feature, Chesil Beach, (Carr 1969, 1971, 1974, 1982).

This study aimed to further the investigation into the morphological characteristics, processes and sediments of local mixed gravel and shingle bayhead beaches by identifying the range of physical processes contributing to the process of sediment circulation with respect to a "closed cell" hypothesis. The underlying theme was the study of the interaction between the atmosphere, lithosphere and hydrosphere. The investigation had a number of objectives :

1. **Local importance** : The south east Dorset coast is a valuable resource to the tourism and recreation industry as well as a popular area for geological field studies. However, no quantitative research has been applied to the coastal sediment system, only brief qualitative statements being made by Arkell (1947).

2. **Wider Objectives** :
   - (i) to identify the processes responsible for the transport of sediment within the coastal zone (from cliff top to nearshore).
   - (ii) to organise processes into a conceptual beach model of sediment transport in self-contained cells.
   - (iii) to determine the sedimentological and morphological nature of potentially self-contained sediment cells thereby gaining a better understanding of processes at work in the context of a process-response model.

(iv) to develop field techniques suited to the gathering of relevant data for the needs of the research objectives.

RESEARCH PROGRAMME

A suite of five fringing, mixed beaches was chosen for study (Figure 4) :

1. Ringstead
2. Durdle Door - Bat's Head
3. Man O'War
4. Mupe
5. Worbarrow

The beaches were selected because they embody a set of common features, yet each may be described as morphologically distinct :

(i) Compartments : Each beach may be described as a discrete morphological unit because they are terminated by distinct boundaries; with the exception of Ringstead Bay (which is bounded by a headland to the east and an offshore ledge to the west) the beaches are bounded by major headlands.

(ii) Beach material : Each beach is predominantly silica, (>99%), with some chalk despite great lithological variation along the coastline.

(iii) Sediment sizes : Each beach is made up of sediment grades ranging from fine sand to boulders.

(iv) Sediment input : Each beach has a potential chalk and flint input.

(v) Hydrography : All the beaches lie on the northern edge of the shallow plateau that extends from Weymouth to St. Albans Head.

Each morphological unit is part of the same integrated system sharing the same tidal regime, the same wind and wave regime and, consequently, the same potential energy input. The general aspect of the coastline is south-west, its generally straight trend reflected by the 5m., 10m. and 15m. bathymetric contours. Each of the bay units is semi-circular or oval in shape.

The research programme was approached on two levels :

(i) pilot study
(ii) main study

The objectives were interactive and wide ranging and the results are an attempt to provide a starting point for the quantification of hydrodynamically powered, morphologically contained units.

CHAPTER 3

PHYSICAL BACKGROUND

Geomorphology and geology of the south-east Dorset coast.

The coastal zone between Bran Point and Worbarrow Tout displays great variety in lithology and structure. The coast from White Nothe to Worbarrow Tout forms the southern boundary of the physiographically distinct Isle of Purbeck. Lithologically the Isle of Purbeck consists of Upper Jurassic strata, (Kimmeridge Clay, Portland Sand and Stone, and Purbeck Limestone), and cretaceous strata, (Wealden Clays, Lower Greensand, Gault, Upper Greensand and Chalk). Steers (1964), stated : "In Purbeck we find some of the best and most interesting cliff scenery, not only on the south coast but also in England and Wales. In few places is the relation between structure, rock type and erosion so well seen."

The northern boundary of Purbeck is formed by the narrow, but distinct chalk hog's back of the Purbeck Hills that swings inland from the coast at Lulworth towards the Foreland of Swanage. Although Ringstead Bay lies just west of this region, it is included in the study area because of its close proximity to the active chalk cliffs of White Nothe. It also provides for a useful comparison, as, unlike the beaches that extend from White Nothe to Worbarrow it is not backed by chalk, but by low, mobile clay cliffs.

The geology of this area is well-documented; pioneering work by Strahan (1898), followed by a comprehensive study by Arkell (1947), remains the standard texts referred to. Other accounts by Davies (1956), House (1958) and Perkins (1977), provide useful, quick reference guides.

The coast is divided into a number of discrete units for ease of description :

1. Ringstead Bay (Bran Point to White Nothe), Figure 5, Plate 1.

   A shallow bay, orientated south-west (183^{o}) and backed by Upper Jurassic 'waxy clay' cliffs that form a low, wide terrace of mobile material behind a pronounced mixed gravel and shingle beach ridge. Ringstead Coral beds (Jurassic), form the foreshore for some distance around the bay and can be found exposed along the backshore of the beach and as an ironstone in the upper part of the cliff (Strahan, 1898). Harder Corallian Beds form the Ringstead Ledges, a succession of reefs that are exposed at low tide and form the western boundary to the bay unit. These Ledges are part of the elongated, flat, Ringstead Anticline which runs parallel to the cliffs and passes a little way inland, (Arkell 1947). Travelling eastward the low, clay cliffs give way to the impressive chalk headland of White Nothe. Kimmeridge Clay rises from the beach but is mostly obscured by landslips of Chalk and Greensand due to a fault running just west of Holworth House. A complete section of Portland Beds in the eastern corner of Ringstead Bay mark the last episode of marine Jurassic; Purbeck and Portland Beds are planed off and directly overlain by Gault.

   The chalk cliffs forming the headland of White Nothe rise to 150m. with Lower, Middle and Upper Chalk zones represented. Hard Chert beds form a prominent ledge at sea level, whilst above, the cliff consist of alternations of smooth chalk and marl with layers of flint (Strahan 1898). The form of the cliff is doninated by large rotational slumps in the Chalk and Greensand that have slipped over the unstable Kimmeridge Clay. The inter-tidal zone is strewn with large boulders and chalk fragments forming an extensive apron around the headland and up to 10m. beyond L.A.T.

2. White Nothe to Man O'War Cove

This section of the coast is structurally dominated by the Purbeck Fold. Vertical chalk cliffs rise up to 100m along this section, the beds being almost horizontal at first but an easterly dip appears, steepening towards Middle Bottom, which marks a syncline in the Purbeck Fold. The foresyncline of the middle limb of the fold forms the headland of Bat's Head, and the western boundary of a gravel beach that extends eastwards to Durdle Door (Figure 6, Plate 2). The bay is wide, shallow, orientated to the south west (185°) and backed for most of its length by vertical chalk cliffs. Bat's Head is hard chalk that has been penetrated to form a small cave - Bat's Hole. The chalk is severely crushed and sheared due to tectonic pressure, whilst movement in a westerly direction has inverted the chalk between Bat's Head and the deep recess at the centre of the bay known as Scratchy Bottom. The recess marks a dry pass in the surrounding chalkland; on the eastern side of the recess the beds are inverted, having been tilted through more than 90° to dip seaward 75° (Davies, 1956).

Durdle Cove is dominated by a southerly dipping slide plane that cuts across the vertical chalk zones. Marine erosion has taken advantage of the plane of weakness by carving out a series of small caves, the roof of each cave has pushed northward relative to the floor. Durdle Door, a natural arch cut in Portland stone protects the cove, the Portland stone itself protecting the Purbeck, Wealden and Greensand Beds that form the narrow col linking Durdle Door Cove to Man O'War Cove to the east.

The shingle ridge is at its steepest at the apex of the cove where it is fully exposed to the dominant and prevailing waves. The beach is at its narrowest towards Bat's Head and the underlying chalk platform is often exposed after storm events; a notch defines the cliff-platform junction. A discontinuous offshore reef (Portland Stone) runs across the bay from Durdle Door and extends westwards beyond Bat's Head. Isolated sections of the reef stand above the water as "the Bull, the Blind Cow and the Calf".

Man O'War Cove (Figure 7, Plate 3) lies to the east of the promontory. The small, semi-circular bay, orientated 162° is sheltered from the dominant and prevailing winds and waves and is also protected by the reef of Portland Stone (Man O'War Rocks) that run across the entrance of the bay. The cliffs at the back of the bay are exposed Purbeck and Wealden Beds, the latter towards the centre of the cove have slipped and slumped. The eastern boundary of the bay is marked by high chalk cliffs of Man O'War Head, separating Man O'War Cove from St. Oswald's Bay. At the point intense crushing has taken place in the Middle Chalk, resulting in inverted bedding that dips 120° (Davies, 1956).

The steep shingle ridge is often marked by large cusps, especially between mid and low water. Their form is best appreciated from the cliff top where the complex wave refraction patterns, a consequence of the filtering effect of Man O'War Rocks, can be seen.

3. Mupe and Worbarrow Bay

"These two bays, with Arish Mell, constitute a wide bight with chalk at the back, Wealden Beds forming most of the sides and Purbeck Beds and Portland Stone at the points." (Davies, 1956).

Mupe Bay (Figure 8, Plate 4) to the west, faces south-east (147°). The cliffs forming the back of Mupe Bay display an excellent section from the Wealden Beds down to Portland Stone. The Mupe Rocks and Ledges, some with a Lower Purbeck capping provide a natural breakwater at the western boundary of the bay. They too are remnants of the discontinuous Portlandian ridge that can be traced above water from Mupe Rocks in the east to the Cow and the Calf off Bat's Head. Acoustic surveys have revealed that this natural barrier also extends across Worbarrow Bay as a submerged reef of varying dimensions. The Wealden Beds of Mupe Bay have slipped and slumped in the western half of the bay and are, in parts, densely vegetated. Eastwards, the junction of the Lower Greensand and Wealden Beds is concealed by a mass of chalk talus that has fallen from the vertical chalk cliffs that rise to form Bindon Hill. The debris also covers the relatively thin succession of Gault and Upper Greensand.

The eastern section of the bay is backed by very steep cliffs of Cockpit Head; Black Rock provides the eastern boundary of the bay. The beach presents a steep, but narrow shingle ridge to the south-east. The coarsest sediment grades are found at the apex of the bay along a section fully exposed to south-easterly gales.

High chalk cliffs, dipping steeply north extend beyond a small headland to Arish Mell. Arish Mell is a dry pass through the chalk ridge; a small stream enters the bay behind a shingle ridge. The beach is out of bounds to the general public and therefore remains undisturbed by human interference. To the west of the pocket beach the intertidal zone is strewn with large chalk boulders up to 4m. long.

Worbarrow (Figure 9, Plate 5), is a more open bay facing south-west (206°). It is bounded to the west by a shear chalk cliff that runs from Cover Hole to Cow Corner. The chalk cliffs here are the western exposure of the sinuous ridge that runs inland across the Isle of Purbeck. Scree slopes mask the cliff face and rock falls litter the storm beach above the high water mark. Towards Worbarrow Tout, the eastern boundary to the bay, Wealden clay cliffs back the shingle beach. As in the clay cliffs of Mupe landslips and mudslides dominate the lower cliff sections; after prolonged rainfall tongues of mobile clay move onto the beach only to be removed by storm waves. The most exposed sections of the beach present a high storm ridge to prevailing and dominant south westerly winds and waves, whilst to the east the beach form is planar, with little berm development, and finer sediment grades.

Worbarrow Tout provides a natural eastern boundary to the beach and main study area. The Tout itself is mainly Middle Purbeck strata and is separated by a narrow neck of land from the main mass of Gad Cliff that runs eastwards towards St. Alban's Head. The Tout presents a vertical face to the sea with a northerly dip slope falling to the neck that lies above Pondfield Cove.

THE OFFSHORE GEOLOGY OF WEYMOUTH BAY (Figure 10)

A most comprehensive geological map constructed by Donovan and Stride in the early 1960s illustrated the submerged geology and relief between the Isle of Portland and Durlston Head and southwards to the junction of the Jurassic and Cretaceous rocks. The map was drawn up from data recorded by A.S.D.I.C. equipment. The relief data was supplemented with samples obtained by free swimming divers and a gravity corer. The divers also examined areas close inshore that were not readily accessible to the acoustic equipment. A map summarising the main geological features of Weymouth Bay is reproduced along with a summary of the main geological features examined by Donovan and Stride (1961).

The Isle of Purbeck Anticline lies 'en echelon' to the east and south of the Weymouth Anticline. On land the overturned northern limb extends from Swanage westwards until a point between Bat's Head and White Nothe, whereupon it passes out to sea (Arkell 1947). Donovan and Stride (1961) show that the submerged part of the structure is an elongated asymmetrical dome bounded on the south by the Shambles syncline. The outermost ridge on the northern side of the Lulworth Banks is presumed to be Sandsfoot Grits (Kimmeridge - Upper Jurassic) and within it, samples show that a large area is occupied by Osmington Oolite. The inner ridge is Bencliff Grits and the hollow in the middle is floored by Nothe Clay (Corallian mudstones, Upper Jurassics). The lower boundary of the Kimmeridge Clay around the Lulworth Bank is placed just beyond the outermost ridge of the Corallian Rocks. East of the Lulworth Banks remnants of roughly concentric outcrops within the Kimmeridge Clay mark the position of a dome. The eastern part of the Purbeck Anticline has two subsidiary crests passing through Broad Bench and Chapman's Pool, divided by a shallow syncline.

The Isle of Portland is a fragment of the Shambles Syncline which plunges south-easterly. East of the Shambles an outcrop of Portland Beds is marked by a belt of 30m soundings (Admiralty Chart 2610). The Shambles itself is a bank of sand, shingle and shell, the accumulation a consequence of tidal stirring (Pingree, 1978). Two prominent ridges lie at its eastern end, one Portland Stone, the other Portland Sand. West of Portland Bill a deep hole has been eroded in the Upper Kimmeridge Clay, whilst immediately to the west stands a shoal of stone banks found in the middle part of the Kimmeridge Clay. To the south of the Bill a belt of ridges lies to the east of a featureless outcrop of Portland Sand, whilst Purbeck beds are inferred south east of the Bill (Donovan and Stride, 1961).

The westward overstep of the Upper Cretaceous rocks along the Dorset coast is well documented. At Swanage there appears to be complete conformity throughout the Upper Jurassic and Cretaceous and this continues westward to Worbarrow Bay (Arkell, 1947). However, at Lulworth, Strahan (1895) recorded "a strong line of erosion", whilst Arkell (1947) suggested possible "angular discordance". North of Durdle, Lees and Tait (1946) proved Gault resting on Lower Purbeck Beds, an indication of unconformity. West of Durdle Door the coast is formed of vertical overturned chalk whilst the Calf marks the westernmost offshore reef of Portland Stone. There is no evidence of Portland Stone beyond 60m west of the Calf.

Donovan and Stride's (1961) survey located the southern limb of the Purbeck Anticline which is shown to be strongly asymmetrical. The survey also showed that the western end of the Purbeck Anticline passes into the Weymouth Anticline not as a single anticlinal crest but as a series of major folds with a north-westerly trend. The Burning Cliff Fault west of White Nothe is considered to be part of a system of tear faults which must occur where one monocline is replaced 'en echelon' by another.

DENUDATION CHRONOLOGY - REGIONAL PERSPECTIVES

RELIEF AND STRUCTURE

Like much of Southern Britain the structure of Dorset has developed upon Mesozoic and Cainozoic sediments mantled by superficial deposits. South Dorset (Isle of Purbeck and the Weymouth Lowland), is only a small area of the much more geologically complex region, the Hampshire Basin. Many of the structures seen in South Dorset are due to the most recent tectonic events (Alpine Orogeny), but the general relief of the area may be understood in terms of the interaction of subaerial denudation on the macrostructure and lithology (Jones 1981). The area is also part of the Southern Fold Belt that may be traced from the Isle of

Portland through the Isle of Purbeck to the Isle of Wight. The folding is seen as a number of short, parallel anticlines forming narrow hog's back ridges such as the Purbeck Hills (Lees 1952). Phillips (1964). even considered the Purbeck Fold to be located above yet another fault, the tightly crumpled Jurassic rocks exposed on the Lulworth coastal stretch being the product of gravity tectonics and not drag as originally postulated by Arkell (1933).

Arkell (1947), noted that intra-Cretaceous movements were important in southern Dorset resulting in intense folding and faulting between the deposition of the Wealden Beds and Gault in the Weymouth area. Thus the Ringstead (Arkell, 1947) and Weymouth folds (House. 1961) are considered to originate from this time. Both Phillips (1964) and Drummond (1970). provide evidence for the initiation of the Purbeck Fold during Mesozoic times; the whole area appears to have suffered pulsed tectonism with activity possibly reaching a peak in the late Oligocene, early Miocene. More recently it has become apparent that the accordant chalk summits, previously attributed to marine erosion, are most probably subaerially modified marine surface, the area having experienced frequent transgressions and tectonic disturbances (Jones, 1981).

In fact, the greater part of the landscape is a product of Quaternary denudation, an oscillating sea level is considered to have been the most important influence upon landform development, particularly the Flandrian transgression. This transgression resulted in both the separation of Britain from the main continental mass (by 8600 BP) and the creation of the existing coastal physiography.

COASTAL DEVELOPMENT

The south-east Dorset coast is considered to be a classic example of marine action acting upon rocks of unequal resistance. Fluctuating sea levels caused the periodic exposure of extensive tracts of sea floor. For example, during the Devensian the sea almost certainly abandoned the whole of the English Channel with a fall in sea level of at least 100m. The temporarily emergent channel floor was drained westwards by an enlarged Seine-Solent river (Jones, 1981).

The retreat of the Devensian ice sheets resulted in a marked marine transgression with a sea level rise greater than 100m in the last 14000 years. 45m of this rise occurred during the Flandrian transgressian (Akeroyd, 1972), there being an early rapid rise with the sea advancing up the Channel and through the Dover Strait. A direct consequence of this was the final separation of the mainland from the continent. Coastline retreat continued to be rapid resulting in steep active clifflines and extensive shore platforms. The literature dealing with the South Dorset coast emphasises that the bays owe their development to the breaching of the Portland Stone and subsequent erosion of the Purbeck and Wealden Beds.

St. John Burton (1937), accounted for bay development by using Lulworth Cove as an example. He suggested that marine erosion was not the sole process for the development of either Lulworth Cove or Worbarrow Bay. He implicated that a confluence drainage system was responsible for the initial erosion that allowed for further penetration by marine erosion. Bury (1936), also considered anomalous river pastures in the Isle of Purbeck in connection with bay development, especially Worbarrow Bay. The stream that flows southward from East Lulworth to Arish Mell is opposite the direction of dip. Bury (1936) did not regard this stream as a direct consequence of the Miocene disturbances but that it originated under conditions independent of the Miocene folds. He also considered the narrow col that separates Worbarrow Tout from the surrounding upland to mark the floor of an old river valley.

Tyneham Brook enters Worbarrow bay a little to the north. It rises in Tyneham and flows down a steep sided valley bordered by a broad, flat floor of a more mature valley. Evidently, 'recent' rejuvenation has taken place and the stream has adjusted the bottom of its valley to a new level caused by a change in sea level. Bury (1936), provided evidence for the connection between Tyneham Brook and Pondfield Cove. He suggested that the Pondfield stream, after receiving the waters of Tyneham Brook flowed southwards and that present geography resulted from the capture of this combined stream, just at the elbow, owing to the advance of the sea in Worbarrow Bay. Linton (1932), had already suggested that the hills on either side of Arish Mell were submerged under a Pliocene sea, and on re-emergence the slightest inequality of the sea bottom might determine in which direction the new streams would flow. The connection between drainage and a changing sea level may also have aided the development of the Durdle Door - Bat's Head bay with evidence provided by dry passes at Scratchy Bottom and at a point on the eastern side of the Bat's Head promontory.

Present day coastal configuration suggests that either cliff retreat in the past must have been a great deal more rapid or that the sea has re-occupied and re-fashioned previously developed marine features. However, not all of the chalk that has been removed from above the present sea floor was denuded during the Holocene (Figure 11). Large volumes of sediment must have been removed by marine erosion, particularly over the last 5000 years. It is during this time that the breaching of the Frome-Solent valley between Purbeck and the Needles occurred, separating the Isle of Wight from the mainland (Everard, 1954).

The Flandrian Transgression is considered accountable for the formation of depositional features around the South coast. Erosion has provided the mobile sediments that could be moved by waves and currents to form major shingle structures such as Chesil Beach and Hurst Castle Spit. It is reasonable to assume that the smaller fringing gravel and shingle beaches around the coast have originated from the same source, given that present day cliff erosion rates are not substantial enough to have formed these features.

HYDROGRAPHY

Admiralty Chart 2610 describes the areal extent of the shallow plateau of Weymouth Bay. Geographically it is bounded on two sides by land; the northern boundary extends as an almost straight coastline between Weymouth in the West and St. Albans Head in the east, whilst the Isle of Portland provides the western boundary. The bathymetric character of bay is largely controlled by geology; to the south and east a geological boundary may be used to delineate the area (Figure 12). This natural boundary takes the form of a ledge that runs from a point due south of Portland Bill extending north-eastwards to St. Alban's Head and is marked on the chart by a 30m. contour (Donovan and Stride, 1969). The ledge itself is of resistant Portland Beds whilst the bay area to the north is floored by softer Kimmeridge Clay (containing resistant stone bands), and the area to the south is floored by Purbeck and Wealden Beds. Donovan and Stride mapped the area during 1959-1960. They were particularly interested in the occurrence of apparently "closed basins" which were located along the strike of Upper Kimmeridge Clay on the northern side of the Portland ridge. These basins correspond to the strongest tidal streams in the area and the authors attributed their development to erosion by those streams, especially during times when the sea was shallower.

The relatively flat expanse of the central area of the bay enhances the change in relief presented by the Shambles Bank, Adamant Shoal and Lulworth Banks. The Shambles Bank and Adamant Shoal are contemporary surficial sediment features formed by tidal stirring (Pingree, 1978). The Shambles Bank to the south east of Portland Bill has been well documented by Pingree (1978) and is a more significant relief feature than the much smaller Adamant Shoal that lies to the northeast. Directly north of Adamant lies a series of rocky outcrops that make up the morphologically distinct Lulworth Banks, a geological feature that presents the remains of the eroded Purbeck Anticline.

Moving shoreward the 15m. bathymetric contour reflects the apparent straightness and south-west aspect of the coastline, while the 10m. and 5m. contours highlight the small semi-circular and oval embayments and coves that indent the Isle of Purbeck coastline.

CHAPTER 4

COASTAL SEDIMENT TRANSPORT

Sediment motion in relation to fluid dynamics is a complex area of study best left to physicists and mathematicians, but cannot be ignored by the coastal geomorphologist. The understanding of water induced sediment movement is increasing; equations developed under laboratory conditions to describe such thresholds of movement are becoming increasingly modified in order to quantify and predict real world situations. A brief review of theoretical and natural observations of nearshore water motions and induced sediment movement is presented.

Basically, there are two types of induced water motion, both effect sediment transport :

1. current induced water motion - regular motion.

2. wave induced water motion - irregular motion.

Both may be superimposed upon each other although one type of motion will dominate. Thus both processes need to be recognised and understood in order to assess potential sediment transport.

There are a number of fundamental papers on wave generation - Franklin et al (1774), Jeffreys (1925), Sverdrup and Munk (1947). Theories have become increasingly complicated and although there is still no definitive physical insight into wave generation, characteristics can be estimated sufficiently accurately to be of practical value. In deep water the profile of ocean swell is very nearly sinusoidal with long, low crests ($d > 0.5$ Lo, where d = depth, Lo = wavelength), the water particles following nearly orbital paths. As they enter shallow water they undergo a transformation. The water particle orbits flatten out, the wave becomes trochoidal with flatter troughs and more peaked crests, resulting in a mass transport of water shoreward. Shallow water waves may be defined as those that are travelling in water depth less than half the wavelength, ($d < 0.5$ Lo) velocity and length progressively decrease and the height increases, only wave period remains constant. Shoaling will not occur uniformly along a wave front; as wave speed decreases the wave front bends as a result of the variations in celerity along the front. The combination of shoaling and wave front bending is known as refraction and the wave crests tend to become parallel to the bathymetry. The interaction of the water wave and seabed topography may modify both the seabed (if the orbital velocities near the bed are sufficient to cause sediment motion), and the waves (possibly causing a proportion of the energy of an incident wave to be reflected). Wave steepness also varies in shoaling waves. The steepness temporarily drops slightly below its deep water value as the waves pass through intermediate water depths and then rapidly increases. The steepness increases until a point is reached where the waves become unstable and break. Particles no longer move quickly enough to complete their respective orbits and the crest collapses.

Putnam and Johnson (1949) have shown that the dissipation of energy by bottom friction and/or percolation can bring about a significant loss of wave energy with a possible reduction of wave height, particularly for high waves of long period which are propagated into a shallow region of very gentle bottom slope. Long waves effectively "feel" bottom sooner than short period waves and consequently are subject to frictional dissipation over a greater distance.

Davies (1980), made a study of the interactions between surface water waves and ripples and dunes on the seabed. He concluded that a transmitted wave may experience a small phase shift, even in cases of zero reflection. Examples are presented which indicate that relatively few bottom undulations may give rise to a very substantial reflected wave. However, it is also the dynamic interaction between detrital particles and moving fluids that give depositional landscapes. In turn, the nature of detrital sediments depends on the properties of the environments in which they form.

BASIC PRINCIPLES OF THE INITIATION OF SEDIMENT MOVEMENT UNDER FLUID MOTION

A number of fundamental references detail theoretical analysis of the initiation of sediment movement - Bagnold (1966), Graf (1971), Yalin (1972), Allen (1973, 3rd ed.). Basically, when a fluid and a solid are in relative motion a velocity gradient is set up at right angles to the direction of flow. Shear stress at the solid surface opposes the motion of the fluid past the solid (or vice versa). There will also be shear stresses where the velocity gradient exists. As the velocity gradient diminishes in magnitude with decreasing distance from the bed, the shear stresses also diminish in the same direction. The region of velocity gradient is called the boundary layer of the flow.

Reynolds (1965) recognised two types of fluid flow - laminar and turbulent. As a result of his investigations he developed a scale of Reynold's numbers based on the fact that fluid near the bed will impart momentum to solid particles and is, therefore, best described as the relationship between inertial and viscous forces in fluid motion.

Therefore :

$$\mathrm{Re} = \frac{\text{Inertial force}}{\text{Viscous force}}$$

Drag occurs when a fluid and a solid body are in relative motion and describes the forces which oppose the motion and enforce equilibrium. There are three types of drag which can be described in terms of the Reynold's number :

viscous - surface - form
(increasing Reynold's number)

SEDIMENT ENTRAINMENT

Experiments show that as the velocity of fluid flow over a bed of sediment is increased there comes a stage where the intensity of the applied force is large enough to cause sediment to moved from the bed into the flow. This is termed the "threshold of movement" and can be further specified in terms of a value of the boundary shear stress - the critical boundary shear stress. The value of the critical boundary shear stress depends on whether the bed sediment is cohesionless or cohesive. It is obvious that if a fluid stream can entrain sediment from a bed then it can also carry it along for some distance. Sediment particles are therefore set in motion when the critical shear stress at the bed is exceeded. Factors governing sediment motion include grain diameter (d), relative density of grains (ps) and water (p), the kinematic viscosity of water (v) and the shear stress the water exerts on the bed. The calculation of sediment transport can be carried out in two ways (Table 1) :

1. The velocity profile method based on boundary layer measurements.
2. Quadratic Stress Law

The prediction of grain movement is based upon Shield's (1936) diagram. He produced an empirically derived curve showing the threshold of movement of quartz density solids expressed in terms of grain diameter and the dimensionless threshold stress criterion. Using this curve a further curve can be generated relating critical shear stress to grain diameter for quartz clasts in water (Figure 13).

Shields used the dimensionless entrainment number Θ, which is roughly the ratio of the bed mean tractive force divided by the immersed weight of the sediment particle, (Hammond, 1982), (Table 2). Unfortunately there are no satisfactory measurements in the tidal environment which could be used to verify the Shield's curve at high grain Reynold's number, >1000, (Heathershaw and Hammond, 1982). The Shield's curve does not calculate the transport rate of a particle but this is covered by Bagnold's Bedload Transport Rate (1963), which relates the mass transport of sediment as bedload to the power expended by water moving over the sediment/water boundary, (Table 2). The use of Bagnold's equation requires direct measurement of near bottom currents. Problems in the use of the equation are related to evaluation of the coefficient k and w. Inman et al (1966) used the shear velocity U^* instead of mean velocity $w = U^{*3}p$. Whereas Bagnold (1963) assumed k to be relatively constant, Kachel and Sternberg (1971), suggested k varied as a function of excess boundary shear stress.

It must be stressed that the above equations have been developed from flume based experiments and although observed data from river measurement correlates well with those predicted in the laboratory there have been few attempts to compare them in the sea. This is largely due to the difficulty of making sediment transport measurements in the sea and of obtaining contemporaneous hydraulic data, (Heathershaw, 1980). Sediment transport equations for use in the sea under oscillatory tidal currents and surface wave motions are still in the very early stages of development and this must be taken into account when discussing or inferring sediment movement in coastal waters.

Sediment transport in the offshore zone can be divided into three types according to two major processes :

1. unidirectional currents alone.
2. wave action.
3. unidirectional currents superimposed on wave action.

SEDIMENT TRANSPORT DUE TO CURRENTS

Much attention has been paid to the attempt to explain the processes responsible for eroding, transporting and depositng sand in the offshore zone (continental shelf areas). Bed forms such as sand patches, sand ribbons, sand ripples and sand waves are often found longitudinal or transverse to peak currents. They reveal preferred sand transport directions which show a relationship with tidal currents in some areas and non-tidal currents in others. Although tidal currents are bi-directional, rectilinear or rotary they develop essentially uni-directional transport paths. Reading (1975) suggests a number of reasons :

(i) tidal current ebb and flood velocities are usually unequal in maximum strength and duration.

(ii) ebb and flood currents may follow mutually exclusive transport paths.

(iii) the lag effect associated with a rotating tide delays the entrainment of sediment.

(iv) a single tidal current may be enhanced by other currents such as wind driven currents.

Measurements of tidal streams show that bottom currents are often considerably stronger than those only a few feet above the bed (Carruthers, 1962). Stronger velocities on the bottom are particularly important if the bed is cohesionless and mobile, as it may change configuration with changing steam direction. Bed forms may not only indicate direction of transport but also velocities (for example, sand wave assymetry may reverse with the tide), and amounts of sediment available for transport.

SEDIMENT TRANSPORT DUE TO WAVES

Waves are an important agent of sediment transport, by waves alone and also by waves with superimposed unidirectional currents. It is generally believed that in shallow water waves alone can produce onshore movement of sediment because of the assymetry of their orbital notions; in shallow water the wave crests are sharp and separated by long flat troughs. The orbital motion under the crest is of high speed but low duration, where as the offshore return flow under the troughs is of lower speed but longer duration. Some grain sizes may be of sufficient size that they are transported only by stronger orbital motion and are not moved at all by the return offshore flow. Each crest passage would shift the grain onshore and it would progressively 'hop' towards shore with no intervening offshore motion. A finer grain might be moved both during the onshore motion and offshore flow, but would only shift offshore a small distance during the return orbit since most of the current of the return orbit is not sufficient to move the grain. Presuming there is no unidirectional current superimposed on the system the waves may selectively drive pebbles and cobbles towards the beach but not produce a shoreward transport of the fines. Bagnold (1940) showed, in a wave tank study, that the bigger the particle the more pronounced is the onshore creep.

If the bottom is sloping offshore there would be a gravity component acting on the grains that might oppose the onshore shift. A balance could be achieved between the two forces for a certain grain size so that the grain size would be at a null point and would move back and forth in equilibrium but with no net transport. This situation is known as the "null point hypothesis" and is well documented in literature concerning coastal processes (e.g. Komar 1976; King 1972, 2nd ed.). The null point is an unstable equilibrium, for a particular grain at null point would, in slightly deeper water, move offshore and in slightly shallower water would move onshore. However, according to the model all grains coarser than this critical equilibrium size would have a

stronger offshore component because of gravity and would tend to shift offshore while the finer grains would move onshore. Thus there is slight conflict within the hypothesis.
Komar (1976) concluded that because the hypothesis does not consider unidirectional currents, even those induced by waves, and because it probably over-rates the importance of the offshore gravity component acting on the grains, the null point hypothesis does not present a valid model for sediment transport or equilibrium non-transport under wave motion.

Bagnold (1963) developed a model of sediment transport produced by coupling of wave action with superimposed linear currents. According to the model the stress exerted by the wave motion supports and suspends sediment above the bottom but without causing a net transport since the wave orbits are closed. Superimposed on this to and fro motion is any unidirectional current that produces a net transport of the sediment, the direction of the transport being the same as the current. Komar and Miller (1975) were able to compare the threshold of sediment motion under waves with the threshold under unidirectional steady currents. The oscillatory threshold data was found to fit the curve given by Shields (1936) for unidirectional threshold with about the same degree of scatter. Therefore, Shields' threshold curve could be used for oscillatory water motions as well as for unidirectional flow. They derived curves for orbital velocity under waves for thresholds of sediment motion as well as water depths to which sediment can be set in motion by surface waves of a given period. However, they stress that under shoaling wave conditions care must be taken when using the equations for deriving curves.

Nearshore currents may cause an intermittent flushing of the nearshore water column and may be wave induced . Such systems may take the form of :

(i) a cell circulation system of rip currents and associated longshore currents.

(ii) longshore currents produced by an oblique wave approach to the shoreline.

It is well-documented that when waves approach a straight coastline at an oblique angle a longshore current is established flowing parallel to the coastline in the nearshore zone and may account for a net transport of material along the shore. Cell circulation depends mainly on the variations in wave height along the shore. Such variations may be a result of wave refraction which may concentrate wave rays in one area causing high waves and at the same time spread rays in another area of the beach to produce low waves. Thus cell configuration is directly influenced by offshore topography. Shepard and Inman (1950, 1951) noted, however, that circulation cells are not in all cases a product of refraction. Bowen and Inman (1969) have shown theoretically and experimentally that the ordinary incident swell waves may generate standing waves on the beach that have the same period as incoming waves. Interaction of incoming and edge waves produces alternatively high and low breakers along the shoreline and therefore gives rise to a regular pattern of circulation cells with evenly spaced rip currents.

WEYMOUTH BAY WAVE CLIMATE

Two components are basically responsible for the spectrum of surface waves arriving at any location :

(i) locally generated seas.

(ii) longer period swell waves refracting into the area which may originate far outside the area of interest.

Fetch and duration characteristics are succinctly described by Heathershaw, Carr and King (1980, p.1) :

> "The range of heights present in a locally generated sea will be a function of the wind speed, fetch and duration. If either fetch or duration are limited then the sea will not reach a fully developed state .... it is not sufficient to consider the geometric fetch alone as being a true measure of the wind's effectiveness in generating a sea. This is because the wind transfers energy to the sea over a range of angles up to 45° on either side of the direction in which it is blowing and thus open ocean fetches are a measure of the wave energy arriving at a point from a similar range of angles 45° on either side of the wind. In effect this assumes a fetch of infinite width whereas on an irregular coastline, or in estuaries, rivers and lakes, the fetch width may limit contributions from the full range of angles. Under these conditions wave height prediction is normally carried out in terms of an effective fetch which, usually is less than geometric fetch."

For Weymouth Bay, the effective fetch characteristics are calculated for a point in Worbarrow Bay. This bay was chosen due to its open exposure, as opposed to bays further west which are partially protected by Portland Bill. Effective fetch was calculated using the method given by the Coastal Engineering Research Center (Shore Protection Manual, volume 1, 1973). The effective fetch (X eff), characteristics are shown in Figure 14, and were calculated using measured geometric fetches (XL), and for angles out to 45°, in steps of 5° on both sides of the assumed wind direction. Effective fetch bearings were taken in the same way. The spectrum of geometric fetches measured were contained within and including 116°(T) and 266°(T), this being the range of angles occluded by land. The results are shown in Table 3.

Effective fetch characteristics were calculated in order to predict and hindcast wave heights at Worbarrow using the method developed by Darbyshire and Draper (1963) and reproduced in Figure 15. Wave hindcasting has been employed in this study as a surrogate for direct wave measurement. Table 4 provides predicted wave heights at Worbarrow Bay for a $5.0ms^{-1}$, $10.0ms^{-1}$, $15.0ms^{-1}$ and $20.0ms^{-1}$, wind blowing for variable duration. It must be noted that values extrapolated for bearings 116° to 136° are fetch limited, resulting in similar wave heights irrespective of wind speed and duration.

LOCAL WIND CLIMATE

Long term records (> 10 years) indicate that prevailing and dominant winds are south west (Brachi, Collins and Roberts, 1978). However, data extracted from detailed meteorological records kept by H.M.S. Osprey, Royal Naval Base, Portland, for the duration of this study (September 1982 to September 1984) show that the prevailing and dominant winds were westerly (Figure 16). Wind strengths over the winter periods were largely in excess of Beaufort force 4, but gale force winds were most common during early autumn and spring. The northern shore of Weymouth Bay being orientated south to south westerly is exposed to the strongest prevailing winds. However much of the shore west of Lulworth is partially protected from the full force of Atlantic swell by Portland Bill.

Wave action can be severe along this stretch of coastline and is undoubtedly a major influence on its geomorphology. Wave action is more responsible for the movement of sediment in the nearshore zone than transport by currents. The effect of storm swell can be seen in the offshore gravel ripples, their long ridges at right angles to prevailing and storm waves, (Brachi, Collins and Roberts, 1978). Waves tend to be of a plunging nature due to the steep break of slope that is characteristic below the low water mark. Breaking wave heights up to 4m., with swash lengths up to 25m. are not uncommon during severe storm conditions.

WAVE REFRACTION IN WEYMOUTH BAY

Wave refraction is a consequence of wave crests aligning with the bathymetric contours and is dependent on the relation of water depth to wavelength. Refraction is important for several reasons (Shore Protection Manual, volume 1, 1977) :

1. Refraction, coupled with shoaling, determines the wave height in any particular water depth for a given set of incident deepwater wave conditions, that is, wave height, period and direction of propagation in deep water. Refraction therefore has significant influence on the wave height and distribution of wave energy along a coast.

2. The change of wave direction of different parts of the wave results in convergence or divergence of wave energy.

3. Refraction contributes to the alteration of bottom topography by its effects on the erosion and deposition of beach sediments; Munk and Traylor (1947) indicated the possible inter-relationships between refraction, wave energy distribution along a shore and the erosion and deposition of beach materials.

Refraction analysis is based on several assumptions:

(i) Wave energy between wave rays or orthogonals remains constant.

(ii) Direction of wave advance is perpendicular to the wave crest, that is, in the direction of the orthogonals.

(iii) Speed of a wave of given period at a particular location depends only on the depth at that location.

(iv) Changes in bottom topography are gradual.

(v) Waves are of constant period.

(vi) Effects of currents, winds and reflections from beaches and underwater topographic variations are considered negligible.

Refraction diagrams for Weymouth Bay were constructed, by hand, using the orthogonal method prescribed in the Shore Protection Manual (volume 1, 1977). The range of wave periods and wave directions investigated was determined by observations during the pilot study, hindcasting and historical records relating to wave direction. Prevailing and dominant south westerly wave trains, often with origins in the South Atlantic reach Weymouth Bay with a 10 second period. Wave trains from the south east have a characteristic 5 second period under a restricted fetch. Mixed wave trains are common, particularly when the wind direction swings from a westerly to easterly sector; locally generated waves from the south east are superimposed on decaying swell from the south west. Due to its limited fetch a south easterly sea rapidly decays if the wind climate backs to either the south west or the northerly sectors. Few wave refraction techniques are able to account for such mixed wave trains because of the unpredictable attenuation and/or intensification of wave energy.

Wave refraction diagrams for Weymouth Bay are illustrated in Figures 17, 18, and 19).

1. Wave Trains Approaching from the South West

Figure 17 illustrates the calculated refraction of a south westerly wave train with a 10 second period. The effect of the Shambles Bank is particularly pronounced; much of the wave energy entering the western section of the bay is attenuated by the Bank which also causes marked refraction and divergence of the waves to the north. South westerly waves that do not cross the Shambles Bank continue on their heading towards the east of the bay. The south western extent of St. Albans Ledge causes some refraction but the bathymetry close inshore (15m. - 5m. contours) has the greatest effect, refracting the incoming waves to such a degree that they are normal to the shore before breaking. The diagram illustrates a tendency for wave rays to converge at a point just south of Worbarrow Bay suggesting a complex interaction of energy in that area and is reflected by a concentration of wave energy along the western sections of the beach. Figure 18 shows an expanded section of the Worbarrow-Mupe embayment; incoming wave trains appear to be little affected by the submerged offshore barrier and reach both beaches normal to the shore. Under such conditions little lateral movement of beach material is expected, an onshore/offshore exchange of material will be the dominant process. Returning to Figure 17, a concentration of wave energy is apparent along Gad Cliff that runs eastward from Worbarrow Tout and is therefore just beyond the limits of the main study area. The overall impression gained is that wave energy is most concentrated towards the eastern and western limits of the study area, whilst the central section (Bat's Head to Lulworth) is sheltered by the effects of the Shambles Bank.

2. Wave Trains Approaching from the South East

Wave regimes approaching from the south east are not uncommon but are generally short-lived due to a limited fetch. Five second period waves typify a south easterly sea but are often superimposed upon a prevailing south westerly swell. Waves approaching from the south east undergo little refraction until they reach the 10.0m bathymetric contour, (Figure 19); despite refraction close inshore the waves reach the shoreline at an oblique angle, providing conditions capable of causing a lateral drift of beach material. Their presence may be short-lived but their effect is often pronounced causing longshore transport to the west. Mixed wave trains, with a south easterly and south westerly component may produce significant counter-drifts of foreshore sediment.

TIDAL REGIME

The tidal regime in the study area is complex, having a double tidal wave which results in a characteristic asymmetric tidal curve. George (1983) provides an explanation for the phenomenon by analysis of the effects of a degenerate amphidrome that exists in the English Channel. The channel co-oscillates with tide in the Celtic and North Seas so as to produce an antinode at each end and a node in the middle. The Earth's rotation converts this mode into an amphidromic system and by tidal propagation the amphidrome is displaced to the north. Instead of an area with no semi-diurnal tide there is an area stretching from Portland to the Isle of Wight in which the mean spring range is <2.0m. The reduced semi-diurnal amplitude causes the quarter diurnal and higher species of the tide to become more important. George (1983) carried out tidal predictions of the tide height at hourly intervals during the whole of 1983 for 6 ports (Portland, Swanage, Poole entrance, Bournemouth, Nab Tower and Cherbourg). He found that on 10 occasions during the year (with extreme neap tides), the calculated position was in the sea between Portland and Swanage. The axis of amphidromic movement has been shown to reach the sea in the vicinity of Lulworth Cove. When the amphidrome becomes real the tide will contain virtually no semi-diurnal component.

Published tidal data for the study area refers to the main port of Portland; tidal data for Portland is in turn referred to Devonport, (Admiralty Tide Tables, volume 1, 1982, 1983, 1984). High water at Portland occurs about one hour later than at Devonport and is followed by a first low water after 4.5 hours and a second 4 hours later still (these intervals may vary slightly between spring and neap tides).

The Tidal Stream Atlas "Approaches to Portland" (Admiralty Publication No.257, 1973) shows the direction and magnitude of tidal streams for each hour of a tidal cycle. It is apparent that at almost all phases of the tide there is a southerly drift along the east coast of Portland and that soon after the drift past the Bill has set eastwards a large eddy develops around the Shambles. Along the central section of the survey area the main tidal currents flow parallel to the coast in an easterly direction on the flood, veering to westerly on the ebb. Generally, there tends to be a shoreward drift that is a consequence of the Shambles eddy. The anti-clockwise drift within Weymouth Bay results in a mixing of water from mid channel off Portland Bill. During neap tides flooding and ebbing occur at a maximum speed of between 1.7 and 3.1 knots. In general, the tide ebbs slightly faster than it floods and this results in a residual east to west flow along the coast. Close inshore the currents are modified by coastal topography.

The United Kingdom Atomic Energy Authority carried out an extensive study of tidal currents in 1956 (Exercise Mermaid). The study was necessary due to the proposed siting of an effluent discharge pipeline (from the Winfrith Heath Research Establishment) through Worbarrow Bay. One of the main objectives of the exercise was to supplement Admiralty data on tidal streams to the east of Arish Mell Gap. They also studied bathymetry and sediments in order to define obstacles which might be encountered in laying such a pipeline. From the survey the following inference was made (Exercise Mermaid, 1958, p.4) :

> "As there is a large left-handed eddy to the east of Portland Bill and centred near the Shambles, by analogy a right-handed eddy might be expected to the west of St. Alban's Head. If this is so, there should be a neutral line separating these eddies and approaching the shore somewhere between these headlands. Evidence implies that the neutral line should meet the shore close to Arish Mell, say at Worbarrow Tout."

The report concluded that a complicated secondary eddy existed in the vicinity of the Kimmeridge Ledges (east of Worbarrow).

SEDIMENT TRANSPORT PATTERNS IN WEYMOUTH BAY

Sediment movement in the nearshore depths is the critical factor to the closed cell hypothesis, so an attempt was made to examine the offshore morphology and sedimentological characteristics in order to identify or infer possible sediment transport paths. An area stretching from Bran Point to Worbarrow Tout, and seaward to a point approximately 4kms offshore was delineated for further study. Morphologically it was necessary to identify possible barriers to free sediment movement, not only from the deeper water offshore to the intermediate depths closer inshore, but also in the bays themselves, where the potential movement of large amounts of sediment may be critical to beach development and modification.

Detailed study of the seabed morphology in the selected area was made by dimensional computer graphic representation of extrapolated bathymetric data (Admiralty Chart 2610). The computer program, written by Ringrose (U.W.I.S.T., Cardiff, 1984) for use on a BBC Model B microcomputer was still in its early development stage and Weymouth Bay was used as one of the test sites.

A bathymetric grid using a rectangular xy matrix was established over the area of interest (x axis aligned parallel to the shoreline, y axis normal to the shoreline). The grid was physically produced by overlaying the chart with a suitable grid, in this case 0.5cms by 0.5cms, and noting the depth values at grid line intersections. The Admiralty Chart 2610 with depth soundings in fathoms was used because it details more soundings than the equivalent metric chart; each sounding was converted into feet. Due to the detailed coverage of grid lines it was necessary to interpolate some data points. For each grid line intersection three values were obtained; x and y values denoted the position on the horizontal and vertical axes whilst the third value (z) recorded the depth. Due to the limitations of disc space and the computer program the study was divided into 24 'tiles', each with a maximum of 156 depth values, each tile being executed individually. By triangulation each x, y and z value was plotted in relation to the others. Azimuth and elevation valves were selected to highlight the importance of selected morphological features. The printed 'tiles' were then pasted together to provide a complete mosaic of seabed morphology within a selected area of Weymouth Bay, (Figure 20).

Using the bathymetric imagery or mosaic several hydrographic zones were considered :

1. Deep water zone : a generally flat or gently undulating seabed with depths >15m. The southern edge of the study area is dominated by the morphologically and geographically defined Lulworth Banks that rise up to 3m. above the surrounding seabed.

2. Intermediate zone : The 10m. and 15m. bathymetric contours provide the boundaries to this zone, characterised by its narrow width and steep gradients.

3. Outer inshore zone : Bounded by the 5m. and 10m. bathymetric contours this zone is characterised by a terrace-like feature that falls away sharply to the 10m.contour.

4. Inshore/breaker zone : Bounded by the chart datum and the 5m. contour this zone is characteristically the most dynamic zone in which waves shoal, break and dissipate their energy. Morphologically this zone displays a step-like feature below the point of lowest astronomical tide which gives way abruptly at the base to the gently sloping 5.0m terrace.

Admiralty Chart 2610 presents, to a limited extent, an indication of the quality of the bottom which can be used to give an overall 'feel' for the sedimentary environment. Close inspection reveals that much of the area is covered by a thin veneer of fine sands, shell (whole and broken), gravel and shingle. Due to tidal stirring (Pingree, 1978) large accumulations of broken shell and sand have been concentrated into tidal banks to the east of Portland Bill. The Shambles Bank (south east of Portland Bill) is the larger of the two tidal banks found in Weymouth Bay, the Adamant Shoal (to the north east of Portland) being only a relatively minor feature. The high percentage of shell fragments in the area was confirmed by Langhorne, Heathershaw and Read (1982). In a study of the physical processes governing the movement of gravel on the seabed a preliminary assessment of the seabed was made in Weymouth Bay with a view to research site selection for a more detailed study. The survey was carried out around the Adamant Shoal; sonar records gave a very high acoustic return indicative of gravel but bottom samples showed that the high return was given by shell material. No gravel samples were obtained and it was concluded that if gravel exists in the area surveyed it lies beneath the surface sands and shell screened from the flow.

1. Deep Water Zone :

The central section of the bay towards the Lulworth Banks is dominated by fine sand and shell; shingle and gravel deposits tend towards the shore but are sparsely distributed around bare rock outcrops such as the Lulworth Banks. Fine clays and muds are to be found off areas where clay cliffs dominate the shoreline (e.g. within Weymouth embayment).

Side scan sonar records (supplied by Waverley Electronics of Weymouth) of a track across the Lulworth Banks from a point approximately 1.6kms off Bat's Head to a point 1.6kms seaward of White Nothe show that the seabed is densely covered by ripple features. High reflectivity suggests that the material is shelly sands and gravels like those found further south. Few patches of flatbed sands or gravels exist, those that do, tend to lie in troughs separated by the rock outcrops that form the Lulworth Banks. The ripples are not of uniform size; ripples with wavelengths in the order of 1.5m are interspersed with ripples <1.0m wavelength. The ripples tend to run over the lower rock ridges and their extent does not appear to be disrupted by the nature of the bedrock. The track was run during spring tidal conditions preceded by one week of southerly winds, Beaufort force 1-3. Meteorological conditions and previous observations suggest that a long, low swell with a 10 second period prevailed at the time of the survey. Using the equation $0.78 \times (p)^2$ (May, 1973) waves with a ten second period require a depth of 78.0m before they begin to 'feel' bottom, that is, a point is reached shoreward of which interaction with the bottom causes a significant drain of energy from the wave. The energy lost from the wave to the bottom is used in the generation of heat and in the transport of bottom sediments. Waves of this type will, therefore, be feeling bottom and capable of moving sediment as they enter Weymouth Bay.

Flemming and Stride (1967) defined three main facies along converging sediment transport paths in the English Channel between the Lizard and Start Point. Strongest tidal currents in the area being >1 knot are capable of transporting most of the sand grades present although they are too weak to move gravel unaided. Spring tidal currents throughout Weymouth Bay are often in excess of 1 knot, even at locations near the shore and over the Lulworth Banks. Such currents are assumed to be capable of transporting the sand, shell and fine gravel material that covers much of the area, whilst the effect of wave action on the floor will produce the extensive areas of ripples. Sediment movement and morphological features in the deeper waters of Weymouth Bay therefore appear to be dominated by wave motion aided by peak tidal currents. Hodographs constructed by UKAEA (1958) for standard points of tidal stream measurements indicate that there is a net shoreward drift in addition to the oscillatory tidal movement parallel to the shore, the shoreward drift being a consequence of the tidal stirring around the Shambles. Long waves can be expected to cause the finer sands and shells to ripple and bring about an increased influence on coarser materials as water depth decreases. Theoretically, under the action of waves alone sand transport should occur up to depths where the limiting conditions under which sand ripples develop cease to apply, (sand of grain size 0.5mm in depth of 36.0m should ripple and commerce to move when waves 122.0m long raise their height to >2.0m - Jolliffe, 1978).

In a broad context there is evidence to suggest that there is a progressive decrease in average grain size in the direction of net sediment transport. In the North Sea for example, sediment streams tend to head from medium and coarse sand to areas of silt and clay (Stride, 1963). Davies (1980) also used particle size (and sand wave assymetry) to infer sediment transport in the Bristol Channel and discovered a progressive fining towards a deposit axis. Further work by Parker (1982) in the Severn Estuary also used the distribution and assymetry of sand banks, ribbons and dune bedforms to postulate an eastward transport of sand.

2. Intermediate Zone :

Unlike the irregular bathymetry of Weymouth Bay in depths >15m., the landward contours are largely a reflection of coastline configuration. Processes within this zone are also dominated by tidal currents and wave action. The increasing effect of shoaling waves in decreasing water depths towards the shore raises fundamental questions pertaining to the relationships between littoral zone and offshore sediment transport. It has already been noted that, in general, sediments in Weymouth Bay coarsen towards the shoreline; wave and current motions are capable of mobilising fine sediment in the deepest waters of the bay but the potential movement of shingle grades is not readily discernible by sonograph and surface current data. King (1959) provided evidence for strong tidal currents necessary for substantial movement of shingle at depth, and that moderate waves can move shingle in depths of about 6.0m. The Hydraulics Research Station derived limiting depths of shingle transport under laboratory conditions (Russell, 1960). Using a wind-wave flume they indicated that waves equivalent to a height of 2.5m and a period of 8 seconds moved 25.5mm pebbles (-4 Ø) down to 8.0m, 51.0mm (-5.0 Ø) down to 4.0m and 76.0mm (-6.0 Ø) only in the breaker zone, although if these pebbles lay on a hard, horizontal bottom the larger grade pebbles would have moved to 11.0m. Further work by Rance and Warren (1968), in a pulsating water tunnel at H.R.S. resulted in a working diagram giving the wave conditions necessary to move a particle of a given size moving from its initial position to some new position (Figure 21). They showed that a 10 second wave in 20.0m water depth would move 20.0mm (-4.0 Ø) shingle, if the wave height measured 3.5m; with an 8 second wave 3m high, fine shingle of 6.5mm (-2.0 Ø) would be on the threshold of movement in 20.0m of water. There have been a number of field investigations using radio-active, fluorescent and paint-coated pebbles. In 1956 Steers and Smith devised an experiment at Scolt Head, Norfolk, to measure the movement of shingle over the sea floor and to determine whether the offshore material is supplied to local beaches. The experiment was also designed to test the suitability of radio-active marking for such experiments. In short, the experiment indicated that pebbles did move over the sea floor in depths of 3-4 fathoms. Crickmore et al (1972) devised an experiment to obtain quantitative data on the movement of shingle under wave action in depths of 10-20m by tracking radio-active marked material. Seeding of tracer material in depths of 9.0 to 18.0m was carried out by divers and detection was carried out using a towed vehicle. The experiment showed an increase in bed mobility with a decrease in depth and that there was evidence of landward movement of shingle inshore of the 12m. bathymetric contour. Radioactive methods of marking shingle for offshore tracer experiments have proved to be successful but fluorescent tracers are more suited to the finer grades despite difficulties of seeding (dispersion within the water column), and retrieval (by ultraviolet light or grease-coated cards; Jolliffe, 1963).

The "intermediate zone" of the study area forms much of the area that was surveyed by the author, using side-scan sonar in 1984 (Chapter 5). Briefly, running parallel to the shore the topographical detail of the seabed is one of gentle undulations with areas of exposed bedrock. Like southern Weymouth Bay surficial sediments are predominantly fine gravels, shell and sand. Areas dominated by fine gravels and shelly material tend to be rippled with flat bed sands between. Boulder fields are restricted in extent and appear to be associated with actively eroding cliffs that plunge directly into the sea without a beach apron (e.g. between Durdle Door and Lulworth Cove). Much of the central section of Worbarrow Bay lies within the intermediate zone classification. Within this zone lies the distinct morphological feature presented by the Portland Stone "barrier" that can be traced from Worbarrow Tout to Mupe Rocks. Towards the centre of the bay the barrier stands up to 8.[illegible] m above the surrounding sea bed. Towards the eastern and western margins of the bay the height of the barrier decreases to 5.0m but retains its morphology; a vertical landward side and a more gently sloping lee slope made up of a number of parallel ridges.

The ridges act as sediment traps whilst on either side of the barrier lie extensive areas of fine gravels and shell. Not only does the barrier restrict mobility of surficial sediments but must affect the attenuation of incoming wave trains. The fine gravels and shelly sand contain little shingle (Hamworthy Sub-Aqua Club, personal communication 1984). The nature of substrate may affect the potential mobility of any shingle on the surface. Jolliffe (1978) notes that shingle is most mobile over "clean" rock, less over other shingle and through weed, and least across sand/silt deposits. Local divers have observed evidence of scour on the landward, bottom edge of the Portland Stone barrier suggesting that there is mobility of fine abrasive materials close to the barrier. Considerations of tidal currents and wave motion suggest that the sand/shell/gravel ripples are wave controlled and therefore have a tendency to move shoreward. There is no evidence to suggest that this fine material cannot be transported over the ridge into the bay even where the barrier is highest. Tidal currents are not strong enough, however, to reverse the situation and exchange sediment from inside the barrier to outside. Even at its lowest points the exchange of material over the barrier will be restricted.

3. Outer Inshore Zone

Within this zone there is widespread coarsening of sediment size compared to the deep/intermediate zones. Dense weed growth occurs throughout the late spring and summer months, but is halted by the first storms of autumn when vast amounts are torn up and washed up on the beaches, where it may alter permeability and percolation of water through the beach. The importance of weed growth over shingle beds is debatable. The phenomena of weed rafting is often treated with great scepticism but is not a new discovery, (Johnson 1919). A number of papers have appeared on the subject, but as yet the process has not been universally accepted as an important one in the process of shingle transport. Beach sampling on Ringstead and Worbarrow beaches has confirmed that shingle is transported onshore by kelp rafting. Significant transport rates by rafting have been recorded (Jolliffe and Wallace 1973; Jolliffe, 1976, 1977). Jolliffe is an enthusiastic supporter of the process and provides evidence to suggest that the bulk of some coastal shingle deposits have originated in this way (1977), including the beaches of Weymouth Bay. The presence of weed rafted gravel and pebbles along the south east Dorset coast has been noted, especially following periods of storm activity, but there has not been enough quantitative evidence to suggest that significant volumes of beach material have come to rest in the littoral zone by this process. That is not to say that the process must be ignored or dismissed as whimsical as it indeed raises interesting new implications for the concept of sediment circulation.

Within this zone the effect of tidal currents is negligible with a corresponding increase in the effect of changing wave motions. The approaching wave crests which are not originally parallel with the coastline are slowly refracted over the shelving topography. Observations of wave approach suggest that waves reach the beach with a small angle of incidence having been orientated parallel to the offshore bathymetry. Wilkinson (1980) warns that care must be taken when estimating this angle visually because it will always be strongly biased towards the most visible frequency rather than the most energetic. The effects of shoaling and refraction can be estimated by linear wave theory. The propagation of surface waves into shallower water may be analysed by consideration of the wave energy between vertical planes which are orthogonal to the wave crests and which intersect with the surface to produce wave rays. Energy is assumed to be transmitted between these planes, it does not travel along wave crests or cross wave rays, (Heathershaw et al, 1980).

A theoretical study of wave induced energy flow and reflection of incident wave energy over seabed topography by Davies (1980) enabled the velocity field to be calculated beneath surface waves progressing over a rippled bed structure. Although a number of limited assumptions were placed on the theory they did not prevent use of the theory over wide and practically important ranges of both surface wave and seabed parameters. The theory predicts an enhancement of the orbital velocity amplitude above each ripple crest and reduction above each trough. It also predicts a steepening of the surface wave crests and a lengthening and flattening of the troughs. It was found that the interaction of progressing incident surface waves and undulations on the bed gave rise to the new waves whose wave numbers are the sum and difference of those of the incident wave (k) and the bed (l). Theoretical consideration of the relationships of these parameters indicate that reflection of incident wave energy may tend to gradually reduce the wave height of an incoming swell wave and thereby reduce its potential for erosion at the seabed.

INSHORE/BREAKER ZONE

As a wave progresses into shallow water the various changes become more pronounced until at some critical point the wave breaks. The critical limit of instability has been expressed by the wave steepness $\frac{H}{L} = 0.147 = \frac{1}{7}$ (Pethick, 1984).

In very shallow water Airy wave theory does not adequately predict wave movement and Solitary wave theory is often used to express the celerity of the wave at the crest and trough. Breaking is initiated by steepening of the free surface at the crest. Speed at the crest exceeds that of the intervening troughs, waves become asymmetrical leading to instability and the wave breaking. The crest pitches forward and forms a jet. A vortex is formed as the jet closes with the surface and penetrates into the body of the flow. As the vortex progresses forward and downward bubbles are entrained and turbulence generated (Thornton, 1975). Experiments by Thornton (1979) measured the kinematics of various types of breaking wave. Results showed that most of the kinetic energy is coherent with the surface and that breaking occurs when the transfer of energy to higher frequencies is not fast enough to balance the increase in the energy density of the waves during shoaling. The important factor is the water depth relative to wave height at the break point; Galvin (1972) proposed a critical ratio between depth and wave height to be a constant 0.78 although recent work by Tucker et al.(1983) produced lower values around 0.5, reaching a maximum of 1.3 . Galvin (1965, 1972) proposed a breaker coefficient which incorporated the dependence of the break point upon the beach slope and wave characteristics. The breaker coefficient (Bo) has been used to describe the form of the breaking wave. Four basic types of breaking wave form are generally recognised: surging, collapsing, plunging and spilling. Flat low waves are associated with surging breakers whilst high, short waves often form spilling waves. Webber and Bullock (1970) attribute a long swell with a steepness of < 1/200 and an offshore wind conducive to the formation of plunging breakers.

The run-up of waves on a sloping beach face is the culmination of a process that begins offshore; each stage of wave motion is influenced by the preceding stage. The extent and nature of the run up is very dependent on the mode of breaking and by reflection and gravitational backwash of the preceding wave (Webber and Bullock, 1970). Theories have developed and experimental data is available concerning the run up of waves on beaches (eg Schiffman, 1965; Kemp 1970; Svensden et al, 1978; Thornton, 1979; Caldwell, 1983). Schiffman (1966) made the first attempts to measure energy in the swash-surf zone by electro-mechanical means. By using a dynamometer he was able to measure bottom velocities within the intertidal zone. His results of velocity and grain size distribution indicate three distinct zones inside of the breaker zone; a surf zone and a swash zone divided by a zone of transition. The transition zone corresponds to the area where the backwash reaches its maximum velocity. It is an area of turbulence due to the interference of backwash with the uprushing surf. Single energy regimes exist on either side of the transition zone. Kirk (1971) developed the instrumentation first used by Schiffman (1965) to study energy of the swash zone on shingle beaches as well as sample sediment moving in the water columns. More recently, Caldwell, Williams and Roberts (1982) provided new instrumentation to replace the dynamometer. They used force transducers rather than dynamometers; the amount of displacement applied to a central rod was measured electronically from the resulting change in capacitance between a number of electrodes.

Kemp (1960) also noted that the general character of swash and backwash describe two separate parts of a flow cycle but did not attempt to produce energy values for these flow conditions. Instead, he described a relationship between the duration of onshore water movement caused by a single wave (run-up) and wave period. The derived ratio (of run up duration to wave period) he called the "phase difference"

$$- P = \frac{t}{T}.$$

On the basis of this ratio he classified wave beach relationships into three categories :

(i) surge (surging waves)
(ii) transition (plunging waves)
(iii) surf (spilling waves)

The breaker type transition from surging to plunging using this ratio stands at 0.5 and 1.0 for plunging to spilling. Huntley and Bowen (1975) made observations on a steep beach under small plunging breakers (0.3m) and found that the uprush and backwash velocities were of similar magnitude. They also observed the interference of backwash on many beaches; backwash has an important influence upon the manner in which succeeding waves break. High backwash velocities tend to promote plunging breakers by a "tripping" action.

Mixing of water in the surf zone is not only associated with breaking waves. Wave induced currents in the surf zone also provides an effective advective mechanism that transports not only water alongshore and offshore but also plays an important part in longshore movement of material. Wave-induced current systems may be subdivided into :

(i) cell circulation of rip currents and associated longshore current.
(ii) longshore currents produced by an oblique wave approach to the shoreline.

Much of the theoretical work on longshore currents has been carried out by Putnam, Munk and Traylor (1949) and Longuet-Higgins (1956, 1970) and aimed to consider velocity values. Sonu, McClay and McArthur (1966) assessed the validity of seven analytical formulas in addition to linear and non-linear multiple regression schemes by using field data. The data indicated that longshore currents are a velocity field consisting of a multitude of velocity vectors, the basic pattern of which varied according to the regimes of wave - topography interaction in the surf zone. Sonu and

Russell (1966) stressed the need to recognise topography as a responding variable as well as a process variable in the physical scheme of longshore currents. Under natural conditions the nearshore topography participates in the longshore current mechanism as a dynamic variable, not only redistributing the breaker influx but also undergoing displacements and transformation due to waves and currents. It was originally thought that wave refraction over an irregular bottom provided an energy gradient for longshore currents to flow from areas of highest breakers to lowest breakers where the waters flow seaward through the breaker zone as rip currents (Inman et al, 1971). The movement of longshore and rip currents forms a nearshore circulation cell. Each cell has the dimension of surf zone width and spacing between rip currents. Thus the cells produce a continuous interchange of water.

CHAPTER 5

SIDEWAYS-LOOKING SONAR

DEVELOPMENT

Modern sonars are the present day equivalents of A.S.D.I.C. (Antisubmarine Detection Investigation Committee, 1919) equipment. The basic task of ASDIC was to search and locate underwater objects by acoustic methods, for purposes of defence and attack during war time. The period 1945-1965 was one of great innovation in the electronics industry and the military implications and potential of ASDIC were recognised. From these developments sophisticated modern SONAR (Sound, Navigation and Range) systems have evolved. However, the capability of acoustic imagery by sonar devices is not confined to military use; in particular side-scan sonar is increasingly used for mapping sea floor morphology and sedimentology.

PRINCIPLES

Any sonar system depends on the propagation of sound in water and the properties of sound waves. Acoustic signals are the only feasible method of transmitting information through the water column beyond a few metres, and electro-acoustic transducers are the only practical solution for sensing underwater sounds as well as producing them. Thus sonar transducers can act as transmitters and receivers and the sidescan sonar relies on this principle. Acoustic energy is transmitted as a focused, conical beam. The transducers emit short pulses of acoustic energy at regular intervals and listen for echoes between the pulses. The period between pulses is governed by two-way travel time - the time it takes for sound waves to reach the target and be returned to the transducer. This is known as backscatter because sound waves are scattered by an object in their path, the sonar detects those thrown back at it. The detected echoes of a transmitted pulse are recorded and presented on a sonograph. On a side-scan sonar the transducer is tilted to give a conical beam with a very narrow horizontal direction (1.5 - 3.0°) and a wide vertical plane (50-60°) (Figure 22). This allows the transducer to emit lobes of energy to its port and starboard side. Side-scan sonar is usually towed behind the vessel giving the system portability and also reducing background noise caused by the vessel. The transducer unit ("fish") is linked to a recording unit and printer.

The vessel underway provides scanning in the direction parallel to the track providing a continuous ship record. It is the strength of the returned echoes that provides information about the seafloor. The effects of the changing angle of incidence of the sound rays dominate the variations in reflection or backscatter. Both morphology and texture of the seabed will influence backscattering strength (Figure 22).

SHADOW FORMATION

If the object width is greater than the width of the received beam then it is possible for some of the seabed to be obscured, the area will be displayed as an acoustic shadow, there being no backscatter from this area. For example, a pronounced rock outcrop or large boulder will obscure the seabed behind it from transmitted beams. In practical terms this results in a light patch (no reflectivity) on the sonograph.

MORPHOLOGY AND SEDIMENT TEXTURE

Features such as rock ridges will be picked up by the sonar beam due to the change in angle of incidence. Rock outcrops with steep faces presented towards the sonar will scatter sound energy back to the receiver very strongly, the lee slope being in a shadow zone. However, the shape of the sea floor is not always the main factor in determining the appearance of the sonograph. Sediment texture and forms may influence the image by reflecting acoustic energy in different degrees :

(i) Rocky floor - an irregular rocky outcrop has good reflective properties. A high percentage of acoustic beam is returned by upstanding ridges to give a definite trace.

(ii) A flat sandy floor will have a reflection coefficient less than for rock and often give a specular, light coloured trace on the sonograph.

(iii) Mud and fluid clays may reflect energy into the distance instead of returning it to the receiver, giving bright patches (poor reflectivity) on the sonograph.

(iv) Gravel and shell both give a similar return. Individual particles act as point sources of very good reflectivity, giving a very definite return.

(v) Debris from cliff falls and boulder-sized blocks will scatter sound energy very strongly and are often attended by definite shadow zones in the lee of each boulder.

Sediment forms are often indicative of sediment transport paths and are easily identified on a sonograph. Sand waves, sand ribbons and ripples (and their gravel and shell equivalents) present on the seafloor have good surface reflectivity and their dimensions can often be quantified. Large scale features such as waveforms often indicate their preferred direction of migration by their cross-sectional profile. Sand waves are large scale forms with lower limits of 30.0m wave length, 1.5m wave height. Sand ribbons commonly develop where the sediment cover is thin and vast amounts are not readily available. They are generally aligned parallel to the main flood and ebb directions. They are capable of changing orientation in response to changes in tidal currents (direction and velocity). Ripples tend to be small scale features and may be classed as megaripples, (lower limits 60.0cms wavelength, 4.0cms wave height, the upper limits being 30.0m wavelength and a wave height of 15m) and ripples, which are any wave forms below those limits (Reading, 1975). In this way side-scan sonar is useful for describing textural and gross morphological change.

Although side-scan sonar is now being widely employed in seabed surveys (geological, morphological, sedimentological studies as well as wreck and debris detection) little work is being carried out on replicability of surveys. Documented data is usually obtained from only one survey and there is no published data to suggest that repeat surveys of a predetermined track, over a protracted length of time have been attempted. In terms of assessing sediment movement by side-scan sonar, replicability of survey over a predetermined track is essential.

DISTORTIONS

Side-scan sonographs suffer from geometric and pictorial distortions :

(i) Slant range distortion results from the fact that the sonar measures differences in travel time along the slanting ray path from vehicle to sea floor, whereas the user wishes to interpret the record in terms of horizontal range. The principle is based upon Pythagoras' Theorem (Figure 22). Thus at short range, when the rays are slanting steeply, a given increment of travel time corresponds to a much larger increment of horizontal range than it would at far range when the rays are almost horizontal (Somers and Searle, 1984). This can be compensated and corrected for within the recording equipment. Slant range distortion can also be reduced by using a suitable depth to range ratio, the optimum being no more than 1:10.

(ii) Scale distortion results from the difficulty of maintaining a constant speed over ground, due to a number of environmental constraints (e.g. head seas, cross currents). Position fixes are often taken at a fixed time interval and are marked on the sonograph by an "event mark". The distance between event marks on the sonograph will not necessarily be of uniform distance (over ground) apart. It must also be remembered that position fixes relate to the position of the navigation antenna on board and not to the position of the "fish". This can be corrected for by measuring the lay-back of the fish from the antenna. (Some side-scan sonars are now being manufactured which have their own tail buoy equipped with position fixing electronics so that the sonograph is directly related to the position of the fish.) The towed fish itself may suffer severely from a third type of distortion :

(iii) Yaw distortion results from the difficulty in stabilising the fish against sea conditions such as roll, currents and wave motion. It is assumed that the towed fish is on the same heading as the vessel, but cross currents may cause the fish to be towed at an angle to the heading. Wave motion, particularly in shallow water, may cause the fish to bounce and yaw, resulting in distortions on the sonograph which are readily detectable to the trained eye.

SIDE-SCAN SONAR SURVEY

A side-scan sonar survey was carried out along a transect from Bran Point to Worbarrow Tout. The Waverley 3000 dual channel side-scan sonar, manufactured by Waverley Electronics Limited, Weymouth, was deployed from their own research vessel, "Sea Searcher". The survey was carried out on 31st July, 1984, under the supervision of Mr M. Seymour of Waverley Electronics Limited. The specifications of the complete system are given in Appendix 1.

AIM OF THE INVESTIGATION

The main aims of the survey were :

(i) to classify the nature and topography of the seabed close inshore.

(ii) to investigate the extent and morphology of the submerged Portland Stone "barrier" that crosses the mouth of Worbarrow Bay (Plate 6).

(iii) to classify the surficial seabed in terms of sediment type and bedforms in relation to inferred sediment transport paths and to analyse the effect that the barrier might have upon such mobility. Figure 23 depicts the track followed by the survey vessel.

The track has been divided into three "legs" for clarity :

(1) The first transit ran parallel to the coastline along a course approximating to the 10m bathymetric contour from Bran Point to Worbarrow Tout.

(2) Several tracks were run in Worbarrow Bay in an attempt to reveal the extent of the submerged Portland barrier that runs across the bay.

(3) The third track began south of Durdle Door, running towards the arch before turning portside and following a return track almost identical to the outward track of (1).

The vessel maintained a speed of 4 knots whilst the survey was in progress, (the recommended towing speed of a side-scan sonar being in the range 3-10 knots), in a force 3 west to north-westerly wind and a tidal range of 1.9m with low water at approximately 1430 the complete survey was carried out on an ebbing tide. Position fixing was by Decca Navigator equipment, the Weymouth Bay area being covered by the south west regional main chain. Decca is a hyperbolic type radio navigational aid which operates by recording the differences in phase of the continuous wave signals received from three transmitters. The phase of these transmitters is controlled by a master transmitter and the digital output corresponds to "red, purple and green" lanes. Special Decca charts are available on which the lanes are overprinted for position fixing.

During the survey fixes were taken every minute and recorded by an event mark on the sonar recorder. A Furuno FE-600 echosounder was run in conjunction with the sonar to provide additional topographical information. Event marks on the echograph were made simultaneously with those on the sonograph. In deriving the course from the navigational data it was assumed that speed over ground was constant and that the course between fixes was straight. Taking fixes at one minute intervals provided for greater accuracy in relation to sonograph interpretation. Lay-back from the Decca antenna to the tow point was 6.8m and the fish was towed on a cable length of 26.6m. Slant range distortion was minimised by using a depth to range ratio of 1:10.

MORPHOLOGY AND SEDIMENTS

TRANSIT 1 - BRAN POINT TO WORBARROW TOUT

The western boundary of Ringstead Bay is marked by two distinct rocky ledges, 4.5m high, separated by a small trough 1.5m deep. They are extensions of the Corallian Ringstead Ledges. The surrounding sediments are flat bed coarse gravels and pebbles at a depth of 15m. - 17m. grading into sand across Ringstead Bay. Another small ledge, standing 1.5m above a gravel bed lies at the eastern end of the bay. The seabed in front of the Great White Nothe landslides is dominated by an undulating seafloor with an average depth of 18m. and intensely folded rocky outcrops trending north east to south west. These outcrops are partially covered by small sand ripples. Another small rock outcrop trending north west to south east corresponds to the fault described by Donovan and Stride (1961). They describe this feature as an offshore extension of the fault near Holworth House, also postulated by Strahan (1878). This whole section with its sinuous ridges and channelled sand ripples compares favourably with Donovan and Strides (1961) ASDIC records and is part of the westernmost extent of the foresyncline of the Purbeck monocline which passes out to sea between Bat's Head and White Nothe, (Plate 7).

Towards Bat's Head the bedrock is overlain by fine sediment forming small ripples trending north eastwards towards the shore. At a point just east of Bat's Head the sea bed plunges to 21m. before rising sharply to form a large dome-shaped feature surrounded by patchy gravel and pebble beds and a small boulder field. The crest of the dome lies at a depth of 15m. and runs out from Swyre Head. Moving eastwards a 3m. depression corresponds to Durdle Door Cove before rising sharply as a series of rocky pinnacles separated by troughs floored with gravels and coarse sediment. The outcrop runs across Man O'War and St. Oswald's Bay. The coarse sediment and small boulder patches of this section of coast are interspersed by isolated patches of gravel ripples.

The area in front of Lulworth Cove is dominated by a series of well-defined parallel outcrops that can be followed as three distinct but not high ridges that run parallel to the coast before swinging north east towards the shore. The outcrop encloses a gently sloping area on its landward side. This plain-like area is covered in sand ripples migrating across the outcrop. At a point directly seaward of Lulworth Cove entrance the parallel outcrops are buckled or faulted (Plate 8). These features may have an important link with the development of the Cove itself. The outcrop then swings north eastwards before swinging south east once again. In effect the outcrop forms a large "S" shaped feature (about an east west axis) that dominates seabed morphology between

Stair Hole and Mupe Rocks. Parts of the outcrop are faulted with a displacement of up to 5m. (e.g. off Bacon Hole, near Mupe Rocks). Between the outcrops lie depressions infilled with small sand ripples and flat bed sand patches, (Plate 9).

Travelling across Worbarrow Bay the "barrier" is well displayed as it swings south easterly, easterly and then north-easterly. The submerged reef appears to describe an arc from Worbarrow Tout to Mupe Rocks with its apex opposite Arish Mell Gap (Plate 10). The barrier stands as a series of prominent ridges and troughs separating a flat plain to its landward and seaward sides. The flat areas are dominated by a surficial cover of bifurcating and sinuous sand and shell ripples.

A second reef feature trending south west - north east was located south of Worbarrow Tout, and can be aligned with Gad Cliff that ends abruptly above Pondfield Cove. It appears that this feature is quite distinct from the main Portland Stone barrier running across the bay and is in fact the seafloor outcrop that is part of the Gad Cliff structure. The outcrop although only 1.5m in height at this point is made up of a series of very jagged, parallel ridges, crossed by numerous small faults. The area separating the two reef structures are floored with sand and shell ripples.

TRANSIT 2 - WORBARROW BAY

Several tracks were run within Worbarrow Bay itself in order to map the Portland barrier and sediment types on either side. A further track was run as close inshore as possible, around the bay from Worbarrow Tout, past Arish Mell Gap and out of the bay past Mupe Rocks. The purpose of the latter track was to provide information regarding sediment characteristics close inshore in order that any relationship between beach and nearshore sediments might be exposed. It is known that the high chalk cliff at the western end of Worbarrow beach (Cow Corner) is an active "feeder zone", large boulders litter the base of the debris fan and it was assumed that the nearshore zone may also be dominated by a boulder field. This was investigated during the survey.

The eastern limb of the barrier is a substantial morphological feature rising up to 9m. above the seafloor. The ridge itself is a rugged feature, its crest marked by a series of parallel ridges separated by troughs up to 3.0m deep. The reef presents an almost vertical wall to its landward side, the lee slope presenting a more gentle slope. Landward of the reef the surficial sediments, dominated by sand and shell ripples grade into finer flat bed sediments (Plate 11). Westward, the reef decreases in height (7.5m), but retains its vertical landward wall, lee slope and jagged morphology (Plate 12). The average depth inside (landward) the barrier is 18m. whilst outside the depth increases to 23m. Opposite Arish Mell Gap the barrier stands at 6m. The parallel ridges are not so well defined possibly due to sediment infill. The western limb of the barrier increases in height (7.6m) and the vertical wall dominates. Here the seaward slope is more concave in form with a smoother outline than further east. Fine sediments lie on both sides of the barrier, both the echograph and sonograph traces suggest the presence of fluid mud that can be associated with the Wealden clay outcrops.

Most of the transit run close inshore in Worbarrow Bay was recorded on a 75m. range. Due to increased wave motion in the shallowing water the sonograph was affected by yaw distortion (Plate 13). From a point close to Worbarrow Tout the track follows the general curvature of the bay at an average depth of 9m., before entering deeper water past Mupe Bay (13.7m) and traversing the barrier close to Mupe Rocks (Plate 14). The inner bay from the Tout to Cow Corner is dominated by a surficial cover of a mixed nature. Small boulders and cobbles interspersed with flat bed sands, shells and gravels are widespread, some of the shell and gravel material appearing as dense ripples. The sea bed off Cow Corner to Arish Mell Gap is dominated by an extensive boulder field on a fine sand bed. Many of the boulders are large rectangular blocks surrounded by smaller, more irregular boulders and fragments. The area from Arish Mell to Mupe Rocks is dominated by patches of flat bed sands, gravels and shingle.

TRANSIT 3 - DURDLE DOOR TO WHITE NOTHE

The final track began at a point due south of Durdle Door arch. A transit run directly towards the arch shows a highly irregular seafloor consisting of a series of rises and depressions. A number of rocky ridges stand up to 4.5m above the sea bed. Like the barrier in Worbarrow Bay, they stand with almost vertical walls to the landward side. The depressions fall to a depth of 21m. separated by 6m. high pinnacles. Evidence provided by transits 1 and 3 show a large basin bounded on all sides by a rising seafloor associated with Durdle Door Cove (Plate 15). Between Durdle Door and Bat's Head the sediment type and morphology is well displayed, ranging from sand and gravel ripples to small boulders (Plate 16). Towards Bat's Head a rock outcrop emerges from beneath a sediment cover before disappearing again just west of the headland. From this point to White Nothe transits 1 and 3 followed almost identical tracks; transit 3 highlights the presence and dominance of the Purbeck monocline between Bat's Head and White Nothe. The main morphological features and sediment types are diagramatically presented in Figure 24.

CHAPTER 6

CLIFFS AND SHORE PLATFORMS

CLIFFED COASTLINES

Studies of hard cliffed coastlines are few and far between, (Steers 1962), those that do exist tend to neglect the role that cliffs play in the total coastal process regime. Many studies of sea cliffs have concentrated only upon their plan or map form with respect to morphological development and classification of coasts, (Johnson, 1919, 1925). Steers (1962), expressed the view that little was known of the relationship between eroding cliffs and beaches associated with them; most studies of eroding coasts have emphasised either the cliffs or the beaches. May (1976), however, has provided one of the few papers that presents a direct link between cliff erosion and beach development at a site on the south western shore of Poole Harbour. Cliff top recession is a more favoured topic and detailed surveys (with the aid of historical maps) have been carried out - May (1966), So (1965) and Trenhaile (1971). Trenhaile (1971), estimated rates of retreat of whole cliff faces whilst others have looked at the processes of cliff profile development (Cambers, 1976; Hutchinson, 1973; Paskoff, 1985), and the form and development of intertidal shore platforms at the cliff foot - Bartrum (1926, 1935, 1938); Jutson (1949, 1950a, 1950b); Hills (1949); Edwards (1951); Cotton (1963); So (1965); Gill (1967); Wright (1967, 1970); Trenhaile (1967, 1969, 1971, 1972, 1974, 1980); Wood (1968).

PROCESSES AND PROFILES

The general profile of sea cliffs is controlled by relative rates of erosion by marine and subaerial processes, as well as by positions of more resistant strata in the cliffs

(Figure 25). Emery and Kuhn (1982) developed a matrix of active sea cliffs to be expected from bedrock of three different limiting degrees of homogeneity with respect to relative erodability at the bottom and top. They recognised that sea cliffs undergo three main stages, active, inactive and former, the profiles being controlled by marine and subaerial erosion. Their control over cliff profiles is more a function of their relative effectiveness than their absolute effectiveness. The matrix is made up of lateral divisions for differing degrees of homogeneity and vertical divisions denote relative effectiveness of marine versus subaerial erosion. The model assumes that structure is not important and ignores the presence or absence of shore platforms and notches, considering them transient features. Such a matrix provides a generalised view of profile development but ignores the features that are important in terms of short term profile change and sediment inputs to the beach system.

In terms of the coastal erosion regime the cliff foot is an important feature. The cliff face and cliff top are subjected to subaerial erosive processes whilst the cliff foot is exposed to dynamic marine processes. The two processes are inter-dependent but actual rates of cliff erosion are difficult to monitor and measure. Cliff top retreat is often studied in an historic context using cartographic methods (Carr, 1962), (May, 1966), or by photography (Trenhaile, 1971). Those methods tend to study erosion on a long term basis, but in terms of changing beach volumes, attrition on the shore platform and contrived erosion and sculpturing of the cliff foot, studies in the short term are critical. The most effective method of making continuous and direct measurements of erosion on bare, solid rock surfaces is that advocated by Robinson (1976), who made extensive use of a micro-erosion meter.

The main processes at work at the cliff foot have been classified by King (1972), as follows :

corrosion
attrition
corrasion
hydraulic action (quarrying)

Robinson (1977), in a study of marine erosive processes at the cliff foot emphasised differences in the erosive processes and morphology between those parts of the cliff foot with a beach, and those without. Erosion at the cliff foot is primarily controlled by wave energy, which tends to be greatest during winter months. Erosion rates were as much as 18.5 times greater (at the cliff foot) where a beach was present, quarrying being the dominant process. Further erosion of the cliff face will take place by waves armed with small rock particles and beach materials, although its influence will be restricted vertically and will also depend on the amount of material carried. A not too variable beach surface allows corrasion and wedging to erode a notch in the cliff foot, (Robinson, 1970).

CHALK COASTLINES

Recent increased attention to the study of cliff erosion has been brought about by the number of cliff falls along chalk coastlines, many of which are popular areas of recreation and leisure. Despite the extent of the chalk outcrop, not only in south and east England, but also north west Europe, the stability of coastal chalk slopes has been overlooked in favour of their inland counterparts; only a dedicated minority have published papers (May, 1971; Hutchinson, 1971, 1980, 1983, 1984; Middlemiss, 1983). Another problem is that hard cliffs are often associated with intertidal platforms and it is the latter that have received most attention. The general profile of any cliff is partly a function (to varying degrees), of its geology, chalk cliffs being no exception.

PETROLOGY OF THE CHALK

A comprehensive study of chalk petrology is provided by Hancock (1976). Changes in chalk coastlines vary considerably due to lithological differences in the chalk as well as localised tectonic differences, but it is certain that the abundance of joints, fractures and solution channels play a critical role in the development of chalk coastal landforms. Chalk is an unusually pure limestone being distinguished from most other limestones by "its whiteness, its friability and its extent over several continents continuously for half a geological period", (Hancock, 1976).

The high porosity of white chalk is a measure of its softness and friability and is in the range of 37-47%. However, chalk has exceptionally low permeabilities for a rock with such high porosities. Chalk is often described as being massive, but bedding can be recognised especially in flint bearing chalk, as for example along the Dorset coast and Isle of Wight.

Dorset chalk tends to be homogeneously harder than others (Rowe, 1901) due to burial, diagenesis, high heat flow and local tectonic stresses.

CHALK CLIFFS

The most comprehensive studies of chalk cliffs have been carried out by two French workers Girard (1907), and Prêcheur (1960). Girard (1907), attempted to link the processes of cliff erosion, transport and deposition of shingle and modification by human activity. Prêcheur (1960), used a cliff profile classification approach based on detailed study of the coast betwen Ault and Le Havre. His classification produced five types of cliff profile (Figure 26) :

Type A - simple, homogenous unresistant to erosion.
Type B - similar to A, but marked by a resistant pedestal and affected by jointing. Stacks, arches and caves are common.
Type C - upper abrupts, variable material, weak at base, more resistant above. Often major landslips.
Type D - alternating bands of marly and flinty chalk. Complex profile.
Type E - capped by Tertiary sands and clays.

May (1964) adapted Prêcheur's (1960) classification to the chalk coastlines of south England and has provided measures of the length of each cliff type present and compared them to those of Normandy (Table 5). It can be seen that type A cliffs predominate in both Normandy and southern England. Naturally there is great variation within the broad classification which will be dependent on localised variations in geological structure.

Middlemiss (1983) noted that instability of chalk cliffs was related to geological structure and made a detailed survey of jointing within the chalk structures of the Kent coastline. Jointing was considered the most important factor, leading to variability of the cliffs being worked upon by two main processes:

(i) wave erosion working on master joints.
(ii) effect of percolating water in the joints.

The main joints act as channels for downward flow of water from above. Evidence that larger cliff falls have tended to follow periods of hard frost suggests that one of the main factors inducing falls is the freezing of this water and exertion by pressure. High energy wave action and occasional frost action accounted for the generally rapid cliff retreat at Birling Gap, East Sussex. May (1971) confirmed that winter is the main period of cliff retreat, but large changes could take place at any time. Summer changes are normally reduced by subdued wave attack and in some years winter fall debris offers slight protection to the cliff foot. Hutchinson (1971) also noted that falls in chalk cliffs are frequent and often large (up to 250,000 tonnes). He compared the incidence of 40 recorded chalk falls along the Kent coast (1810-1970), with the average monthly effective rainfall and average number of days of air frost per month. Correspondence between climatic factors and the incidence of falls was close. The majority of falls were concentrated within the winter months (October-April), and evidence suggested that rainfall has greater influence during the earlier part of this period and frost during the latter. Middlemiss (1983) agreed that transient water in the jointing system affects cliff instability,; frozen water will prise open the joints whilst temporarily blocking the exits of the joint system.

Storm waves have an important effect on the lower cliff face and partly account for notch formation. The smooth, concave profile of many notches suggests that they are formed chiefly by corrasion, whilst irregular notches may be largely due to quarrying. In Joss Bay,Isle of Thanet, Hutchinson (1971, 1984) recorded that a notch 1m. deep was cut within 5 years. Slower rates of notch development have been recorded in Dorset by May and Heeps (1985). A fall at Ballard Down in 1969 measured $500m.^3$ but by early 1977 had been reduced to about 90. m^3. By August 1984 no chalk blocks remained at the cliff foot, which was marked instead by a deep notch. A further $35m.^3$ of chalk had been removed from the cliff profile.

CHANGES IN S.E. DORSET CHALK CLIFFS

A variety of cliff forms is represented along the chalk coastline of south east Dorset, and in common with the chalk coastline of S.E. England is marked by changes far from regular in time or space (Figure 27). The chalk dominates the coastline at three locations in south east Dorset: between Studland and Swanage, at Worbarrow, and from Lulworth

Cove to White Nothe. The lithology and structure of the chalk in south Dorset was first described by Rowe (1901), but Arkell's (1947) description still remains the main geological reference. Much of the chalk has been hardened by local tectonic stresses whilst a study of the relationship between the dip and the mean rock density (Mimran, 1975), revealed a density increase of 30% from horizontal to vertical layers.

A number of issues arise when considering the role that the chalk cliffs of south east Dorset play in the total process regime from cliff top to nearshore zone :

1. What forms do changes in chalk coastlines take?

2. Are there preferred locations for rapid change and/or rock falls?

3. What effects do the beaches and cliff foot debris have upon further changes in the cliffs?

4. How important are contemporary rock falls in providing a supply of beach material?

Cliffs are affected by a spectrum of changes of varying magnitudes and frequencies. Many small, frequent events at the cliff foot or face may be as important as a single large change in the cliff top (May, 1979). This is certainly true of the chalk cliffs of south east Dorset. Erosion of the cliff face is an intermittent process, changes may be imperceptible over prolonged periods. Micro erosion by salt crystallisation, dessication, heating and cooling, expansion and contraction, may be attributed to seasonal changes in the climate, which in turn has a direct influence on the type of erosion that will predominate during that period.

Observations along the lower cliff face along the chalk section between Durdle Cove and Bat's Head provide evidence for the interdependence of marine and subaerial erosion and how they adjust seasonally. Erosion at the cliff foot is primarily controlled by wave energy which is greatest during the period September-April when gale force conditions are more frequent. Under calm weather conditions (Beaufort force 1-2) the tidal range is insufficient (< 2. m) for waves to reach the cliff face. Under a large swell, storm waves frequently hit the cliff face between Swyre Head and Bat's Head at high tide. Even at low tide swash run-up under such conditions reaches the cliff foot. Data collected daily between 25.1.83 and 22.2.83 indicated that waves reached the cliff base at Swyre Head (where the beach is at its narrowest) at high water on 19 occasions (65%). (Beach) profile height variablility was greatest between Swyre Head and Bat's Head. This also indicated that wave action was an influential process up to the cliff base. Conversely, in the deep recess of Scratchy Bottom, and within the shelter of Durdle Door Cove, no recordings were made of wave action at the cliff base.

Observations of the lower cliff surface indicated that the erosive effects of spray are often underestimated. The effect of spray on the cliff face depends on the droplet spectrum - the size of individual droplets and the intensity with which they hit the cliff face. The potential effects of spray induced erosion may be discussed using two hypothetical situations :

(i) direct wave action on the cliff face. The force of a wave breaking directly onto a cliff face will result in the disaggregation of water droplets from the main water mass. Two phases of action follow; the main mass of water will run down the cliff face under natural gravitational force; the second phase of action takes place when any disaggregated droplets hit the surface. Large droplets will act like heavy raindrops and run down the cliff face. The overall effect of this process (separate from hydraulic action), will be to wash away unconsolidated fragments on the cliff face. These fines may be carried away in suspension or may become incorporated into the beach system.

(ii) indirect wave action. In the coastal zone spray may be carried great distances inland. In such a situation it is most likely that the smaller droplets will be carried furthest. The smaller droplets act like fine mist and tend to be absorbed by the chalk face (rather than running down it) and saturate the surface layers. The end result is a thick chalk paste (up to 3.[illegible] mm thick) that can be removed by subsequent downwash, revealing a fresh surface for the process to continue. The chalky paste may then be carried away in suspension into the offshore zone and/or may be redeposited into the beach system.

The effects of spray micro-erosion are most frequently seen during winter periods when waves are most likely to reach the cliff and winds are strong enough to carry spray great distances. Micro-erosion of surface layers by wind borne spray may affect the whole cliff face but is concentrated at lower levels. Erosion of the surface layers may also be attributed to frost action. Long periods of frost action weaken the chalk surface resulting in flaking. Prolonged dessication also produces chalk fines in flake form, and the evidence for the process is most visible during the summer period (but also occurs during the winter period). Removal of moisture from the surface layers of chalk results in minute flaking. Much of the finer particles are removed by wind but the larger flakes tend to accumulate at the cliff foot or on small ledges, to be washed away by rainwash or wave action. Quantifiable amounts of chalk are eroded from the lower chalk face by frost action during winter periods and dessication during summer months (Plate 17). Evidence is provided by measurements obtained during the period June 1984 to January 1985; calculations indicate that during the period June - August 1984 (inclusive), up to 3.75m^3 of chalk accumulated at the cliff foot (along the whole chalk section), due to dessication of the cliff surface. Measurements taken during January 1985 indicated an accumulation of 3$m.^3$. However, removal of fines is potentially greatest during winter months so there will not be a prolonged accumulation of fines as during summer months. From the data available it has been inferred that erosion (by frost action and dessication), during the winter may be up to three times as great as erosion (by dessication alone) during the summer.

The main forms of measurable change are :

(1) rock falls.
(ii) mass movements within pre-existing landslide zones.
(iii) notching of the cliff platform junction.
(iv) accumulation of debris, usually smaller than 4 cms, at the cliff-foot where a beach or larger calibre debris inhibits removal by wave activity.

The largest volumes are removed from the cliff slopes by the first two processes. Notching is very important, both in reducing the stability of chalk cliffs (Hutchinson, 1971), and by accentuating the expansion of caves or arches.

At the end of May 1983 a small chalk rockfall occurred below Swyre Head. Approximately $70m.^3$ of flint bearing chalk fell from the lower cliff face leaving a scar extending about 10m. up the cliff face, (Figure 28, Plate 18). Undermining of the cliff at the cliff/platform junction by marine erosion and subaerial erosion, particularly frost action and alternate wetting and drying, is thought to have accentuated inherent weaknesses in the chalk. Slickenslides visible through the cliff face and in cliff fall debris after the event suggest earlier movements within the cliff and it is postulated that the fall took place along existing lines of weakness which were taken advantage of by contemporary subaerial and marine processes. The fall debris included a small number of very large boulders up to $9.0m^3$. The majority of these large boulders remained against the cliff face below the point which they had sheered and slid down to rest on the beach (Plate 19). Smaller boulders lay at the seaward edge of the fall (Plate 20), but the majority of particles (by number) were smaller than shingle size and partially filled spaces between the larger boulders. During the following three months some of the fine particles were removed by surface run-off but storm waves breaking up to 4m. high during a storm in early September 1983 removed all but the larger boulders (Plates 21 and 22). Within 18 months of the event all traces of chalk debris had been removed from the beach. Table 6 indicates the size distribution of randomly selected boulders down the central line of the rockfall on a number of dates. Despite the rapid rates of change in the size distribution, there was no significant increase in the proportion of chalk pebbles in the adjacent beach sections, it being thought that most of the debris from the fall was moved offshore and directly attacked by solution processes. Some larger boulders came to rest below the low water mark but after 24 months no trace of boulders can be found offshore in the vicinity of the fall.

At White Nothe and in Worbarrow Bay (Cow Corner), much larger mass movements in the chalk take place and large numbers of large boulders litter the shoreline. The behaviour of the debris of these falls is quite different from that of the fall witnessed at Swyre Head. At Cow Corner the debris forms a talus (Plate 23). At the base of the cliff the inclination is about 40^{o} and very large boulders ($10m^3$) line the upper limits of the beach, extending 100m. eastwards where they protect clay cliffs behind. As cliff height increases the angle of inclination also increases. The debris (small boulders and many small chalk fragments) appear to "flow" from the upper cliff (70m) over the larger boulders beneath. Thus the debris is carried to the beach where it is removed by downwash and wave action. This cliff section is very active and a large boulder field offshore (located by side-scan sonar) suggests that the cliff has been actively eroding for some time. At White Nothe vast amounts of chalk (with flint),are gradually reaching the intertidal zone due to massive rotational mass movements that have, and still are, occurring on the 150m. high headland (Plate 24). Multiple, successive slumps subjected to subaerial weathering produces debris from boulder to gravel size. When the debris reaches the cliff toe it has already been worked upon and in many cases small talus cones spill into the intertidal zone (Plate 25). Prolonged supply of chalk to the intertidal zone has produced a large boulder field skirting the headland (Plate 26). Extremely large boulders (up to 15m^3) reduce wave energy protecting the boulders towards the backshore. A continuous supply of material to the boulder field has a two-fold effect; extending the boulder field, which, in turn protects the cliff base from direct marine attack. At certain points around the headland pocket storm beaches of small rounded chalk pebbles and angular flint fragments lie among large boulders.

SOUTH EAST DORSET CHALK CLIFF PROFILE CLASSIFICATION

The preceding discussion notes the variety in profile form displayed by the chalk cliffs of south east Dorset. Such variety is, apparently, a function of the lithological variety of the chalk itself and its mechanical properties due to local tectonic differences. Three profile forms are recognised based on the relationship between geological structure and the relative rates of marine and subaerial erosion.

1. Cliff profile controlled by mass movement (horizontal strata)

White Nothe headland presents a profile that is the result of mass movement within the chalk due to an unstable basement rock (Kimmeridge Clay), resulting in deep seated rotational failure. The size of debris entering the system is controlled by jointing within the chalk; it is then worked upon by subaerial processes as it moves slowly downslope. Marine erosion has minimal control over this profile, and the small, but continuous addition of chalk debris to the intertidal zone further reduces the potential effects of marine erosion on the cliff toe.

2. Cliff profile in vertical bedding

(a) Marine erosion dominant

Much of the chalk between Bat's Head and Worbarrow Bay has been greatly affected by localised tectonics and beds have suffered intense crushing and inversion. The degree and direction of inversion processes all affect the development of profile form.

At Bat's Head the promontory is made up of alternate zones of vertically bedded hard and soft chalk. The hard chalk that caps the lower 12m. of the seaward face of the promontory remains resistant to marine and subaerial erosion. The softer chalk behind is severely crushed and marine erosion has exploited weaknesses in the bedding resulting in the formation of a small arch (Plate 27) whilst a deep notch has developed in the corner where the promontary joins the cliffs backing the beach. Subaerial erosion has taken advantage of the seaward edge of the upper cliff face where the chalk is already crushed and very friable, resulting in a concave upper profile. A similar process is acting upon the small headland to the east of Scratchy Bottom (Plate 28).

The consequences of the interaction of marine and subaerial processes taking advantage of inherent weaknesses in the structure of the chalk has already been discussed by the consideration of a fall that occurred in May 1983 at Swyre Head (Plate 29).

(b) Subaerial erosion dominant

Erosion and mass movement of steeply dipping chalk at Mupe and Worbarrow has resulted in cliff profiles dominated by scree material. The base of the cliff is protected by large boulders and a high storm beach. Mass movement from above, caused by subaerial erosion is the dominant process, ensuring a continuous supply of material to the intertidal zone.

3. Cliff controlled by horizontal strata

At Studland, the eastern extent of the chalk in the Isle of Purbeck, the chalk remains horizontally bedded. The cliffs are relatively low compared to those that form the coastline between Worbarrow and White Nothe and with a northerly aspect they are greatly sheltered from marine action. Here, subaerial processes , particularly frost action, are most active, taking advantage of the regular jointing in the chalk. Vegetation may also aid cliff erosion; growing root systems prise open joints and cause blocks of chalk to fall onto the platform beneath, or open the way for increased water penetration and subsequent seasonal affects of frost action, wetting and drying. Blocks remain for prolonged periods on the platform beneath.

SHORE PLATFORMS

Intertidal and submarine platforms are characteristic, not only of much of the chalk coastline in southern England, but also of a significant proportion of many coasts. However, the literature dealing with them is scanty and generally refers to a few well studied areas in Australia, southern Japan and southern Britain (where they occur along 35% of coastline). Trenhaile (1982) goes as far as describing the shore platform as a "neglected coastal feature". The processes at work within the zone of platform development and subsequent rates of erosion are extremely difficult to measure, especially if they are only temporarily exposed from beneath a beach accumulation. In many cases a qualitative approach has to be adopted. The processes identified as being attributable to shore platform development may be broadly classified under mechanical wave erosion and weathering. Mechanical wave erosion encompasses a number of parameters, the most important (but most restricted in extent), being breaking wave shock, water hammer, and air compression in joints. Hydrostatic pressure, cavitation and abrasion also account for erosion of a rock surface particularly in the winter months. Weathering of exposed platform surfaces will occur by water layer levelling wherever spray and splash accumulate, (Hills, 1940). The process is associated with wetting and drying and consequently, salt crystallisation, but may also be partly solutional in origin. Water layer weathering will be inhibited however by low rates of evaporation and a sloping platform surface. Weathering by solution will be active on lithologies with a significant carbonate content and will be enhanced by water flow and turbulence in the surf zone. The role of frost weathering in coastal areas is, in general, poorly understood and although a recognised process at work on cliff profiles its importance in the intertidal and surf zone has not been questioned sufficiently.

The most important factor governing the processes operating on shore platforms is that of lithology and structure. As shore platforms are interdependent with cliff profiles the two features cannot be considered in isolation. On the contrary, it is the inter-relationship of these morphological features that may determine the type of surficial deposit at the cliff foot. Robinson (1977), found that sandy beaches at the base of the cliff are most favourable for the development of wide platforms, followed by a bare cliff foot, a boulder beach and a talus cone. The observations were confirmed by Trenhaile (1977), in his study of platforms on the Glamorgan coast, where greatest abrasion is associated with sand and pebbles, quarrying where the cliff foot is bare whilst the presence of boulders or talus at the cliff foot provides a degree of protection from further erosion. These common observations, by two authors working in very different areas, confirms the relationship between cliffs and shore platforms. Similarly, platform profiles will be strongly influenced by rock hardness which are inherited features of structure and lithology, whilst dip plays an important part in determining surface roughness. Gill (1967, 1972) and Trenhaile (1969) described how mean elevation increases with rock hardness suggesting that platforms become steeper and narrower as rock hardness increases. Further investigations by Trenhaile and Layzell (1982), implied that the relationship between platform and rock hardness may be more complex than first thought and requires further intensive study.

Descriptions of platform morphology have provided many theories accounting for their development and continuing development. Each author emphasises different processes, ranging from aspect, fetch, wave energy to tidal duration and changes in sea level. Trenhaile (1969) suggested that platforms in both southern and northern hemispheres are related features representing opposite ends of a tidally regulated, wave erosional spectrum of forms which may be classified in a similar way to Davies' (1964) world morphogenic environments. Several workers have attempted to relate platform width to wave energy by estimating the energy environment (So, 1965), wave refraction (McLean, 1967), wave forecasting (Trenhaile, 1974) and fetch (Flemming, 1965). These factors imply that platform width is greatest on exposed coastlines although others disagree (e.g. Johnson, 1933; Bartrum, 1935; Hills, 1949). They suggested that platform width is greatest in sheltered environments. Edwards (1941) and Trenhaile (1972, 1978) discovered a negative correlation between platform width and cliff height. Davies (1964) emphasised the relationship of tidal range in determining coastal characteristics, a process that has been highlighted as making a substantial contribution to platform development. Wright (1969) and Edwards (1971) agreed that platform width increases as tidal range increases. More recently, detailed studies of the influence of the tidal range have been executed by Trenhaile and Layzell (1980, 1981). They considered tidal duration curves as a means of describing how wave energy is distributed within the tidal range and how long still water level coincides with each intertidal elevation. From the curves they deduced that storm wave action is much more likely to occur (and therefore affect platform morphology), when still water is at mid tide level than when it is close to the tidal extremes. This accounts for platform development being best at mid tide level. Carr and Graff (1982) disagreed on the basis that the tidal duration curve was an incorrect interpretation of the distribution. They suggested that emersion curves were a better means of displaying the data and that because tidal level varies most rapidly at the mid tide position, wave action is least effective there. Platform development will indeed be best at mid tide level because more intense erosion will take place at the tidal extremes (e.g. high water wave ramp, and low tide cliff separated by a convex platform profile). In reply, Trenhaile (1982), agreed with Carr and Graff's argument and thought it a welcome addition to the model as it did not affect that basic form of the simulated profiles.

CLIFF/PLATFORM JUNCTION

The cliff platform junction is an easily recognisable morphologic feature of the shoreline and emphasis has been placed on its spatial height variation. Bartrum (1935) noted that such junctions may be higher or lower on headlands than in adjacent embayments according to geology and wave exposure. So (1965), Wood (1968) and Wright (1970) agreed that the height of the junction varies with its position relative to the bayhead and bounding headland and that the height of the cliff may affect the level of the junction. However, they did not agree as to the height of the junction in relation to tidal range. So (1965) indicated that within any one locality detailed studies reveal a relationship between height and aspect, the general levels concentrated about MHWN. Wright (1967), discovered that in the majority of cases along the south coast of England the junction is developed below the uppermost level of expectable marine action and that it does, in some cases (e.g. Studland, Dorset) correspond to MHWN. Further investigations by

Wright (1970) by means of precise levelling of the junction revealed a 4.0m variation in height (relative to Ordnance Datum) but within the limits of MHWS and MHWN, possibly due to aspect, geology, or local variations in marine conditions (e.g. tidal range).

Few workers have attempted to model platform development. Flemming's (1950) model assumed a cliff made of uniform rock with no subaerial weathering and no beach formation. He concluded that cliff recession decreased with time but did not reach zero. Sunamura (1978), developed a mathematical model to account for submarine platform development under a static sea level. By considering wave induced cliff recession and shallow water wave dynamics the model showed that the development approaches equilibrium with time. Sunamura made it clear that physical processes of cliff erosion are of vital importance in considering the platform development. The model assumed that waves recede from a cliff made of homogeneous rock with no subaerial weathering, leaving behind a uniformly inclined submarine platform, and material produced by cliff erosion does not form a wave built terrace. While waves at the foot of the cliff have sufficient force to cause cliff erosion, a submarine platform continues to grow. The platform width increases and the gradient decreases with time. When the wave force becomes insufficient to erode the cliff due to the wave and topography interaction, i.e. due to negative feedback, the platform development halts.

CHALK PLATFORMS ON THE SOUTH COAST OF ENGLAND

Steers (1962) drew attention to the extensive platforms of the south coast, particularly those that front the high chalk cliffs that dominate much of the south coast shoreline. They range from being small outcrops beneath a beach cover to very broad, exposed features. A number of researchers have commented on the main features of distribution, width and height of the platforms, with particular emphasis on the height of cliff/platform junctions in relation to tidal conditions. Wright (1967) considered the importance of the unique tidal conditions in the English Channel as the major influence on the height of the junction. He considered a junction at MHWN to be typical of chalk platforms. Wood (1968), in a study of Kent beach platforms noted a difference in the height of the notch between the headland and the bay that he attributed to exposure; the further the headland projected seaward, the lower the height of the notch. Likewise, the platform in the bays sloped more steeply seaward than that off headlands. Wright (1970), in a similar study reported a difference of nearly 2.0m between headlands and bayheads. However, Wright attributed geology to be the most important factor influencing the height of the cliff/shore platform junction at the local scale; erosion being primarily by mechanical processes (abrasion, wave quarrying, hydraulic action). Wright indicated that the height of the cliff may affect the level of the junction first suggested by Sparks (1960) who argued that, on theoretical grounds, the rate of retreat of a high cliff is slower than that of a low cliff composed of similar materials. Provided that down wearing processes acting on the shore platform at the cliff base are not overwhelmed by the supply of debris, the junction will be lowest where the processes of erosion have most time to act, that is where cliff retreat is slowest (Wright, 1970).

So (1965) in a study of Isle of Thanet chalk platforms placed pitting by solution and mechanical abrasion as the major marine agent responsible for post planation modification. He suggested that the presence of boulders, chalk fragments and flints on the platforms pointed to the importance of storm wave action in platform formation. He also linked variation in the height of the notch to differences in exposure. May (1984,pers. comm.) observed the role of flint armouring on some Isle of Thanet platforms. In situ flints form the platform surface because of the gentle dip of the bedding; the flint acts as a structural control on the platform. The rugged surface of the platform acts as a dissipator of wave energy thus reducing wave energy at the cliff/platform junction, and protecting the basal chalk beneath. Robinson (1977), recognised two morphological zones on a wide intertidal platform, its morphology primarily controlled by the presence/absence of relatively resistant strata. The two zones recognised were classified as the plane, (characterised by no beach sediment), and a ramp (at the cliff foot and covered by a beach). Many of the platform features described in the literature lie exposed at low tide; very few have a beach cover. Beaches that do occur tend to be accumulations of sediment and have an abrupt low tide cliff. The chalk platforms on the south east Dorset coast do not conform to the general characteristics reported elsewhere.

CHALK PLATFORMS ON THE SOUTH EAST DORSET COAST

Chalk platforms outcrop at two main locations along the coastline :

(i) between Durdle Door and Bat's Head.
(ii) at Studland, the eastern extremity of the chalk on Isle of Purbeck.

It is not known whether platforms are well-developed in front of the chalk cliffs of Man O'War, Mupe and Worbarrow Bay due to the depth of beach accumulations. During the study period, chalk platforms were not exposed at these locations.

The low chalk cliffs that run from the corner of Studland Bay towards Old Harry Rocks mark the easternmost extent of the chalk outcrop on the Isle of Purbeck. A narrow chalk platform (15m. wide, with an inclination of approximately 2°) skirts the cliff base. In the corner of the bay the platform is covered by a small storm beach accumulation of rounded chalk pebbles and angular flint nodules. Towards Old Harry Rocks, the platform is littered with small rectangular chalk blocks and large flint nodules (up to 0.25m length), much larger than any seen on the shoreline of western Purbeck. Many of the flint nodules fall from the cliff face unfragmented, having a rounded form rather than the fragmented, very angular flints found at the other main chalk locations. The north facing cliffs are sheltered from prevailing and dominant south westerly winds and notching at the cliff/platform and the chalk blocks rapidly become rounded as they are rolled back and forth over the platform. The whole flint nodules are extremely resistant to erosion, particularly those nodules that do not present any fragmented edges for further attrition. Erosion of the cliff face is predominantly by frost action and rainwash.

Between Durdle Door Cove and Bat's Head the chalk platform is a more pronounced feature of the coastline despite its limited and infrequent exposure. The chalk platform cut into almost vertical bedding is characterised by its narrow width (20m. between Swyre Head and Bat's Head but up to 55m. into the Scratchy Bottom recess), and its steep (5-10^{o}) planar slope. The platform can be traced in this form from the small headland east of Scratchy Bottom to Bat's Head. Trenhaile and Layzell (1982) suggested a strong relationship between platform extent and rock hardness; platforms become steeper and narrower as rock hardness increases. Local tectonic-induced hardness of the chalk along this stretch of coast may therefore be a major influence on the platform morphology. Spatial variations in morphology are small, the greatest differences can be seen in the form of the cliff-platform junction. The plan form of the cliff platform junction along cliff line is influenced by geology and structure; close to Bat's Head the junction has a stepped profile (Plate 30). Further east the cliff platform junction is marked by a smooth notch cup up to 1.0m into more massive chalk (Plate 31). Figure 29 shows the variety of cliff-platform junctions along the Durdle Door chalk. It can be seen that the height of the junction ranges from 1m. O.D. to 5m. O.D. A number of factors may affect and influence the variation in junction form and height :

(1) Tidal range
(2) Beach cover
(3) Wave energy

Tidal Range: Tidal range in the area is no more than 2.0m at spring tide. Wright (1970), and Trenhaile (1972), both agreed that tidal range is significant in determining the height of cliff-platform notches although they are also very sensitive to geological factors. As a result Wright and Trenhaile put the notch at a height close to the MHWST. Along the Durdle Door cliff-line only two preselected profiles display a notch into the cliff at the approximate height of MHWST - profiles 8 and 9, in Figure 29. Profiles 7,6 and 3 display notches/junctions at a point above MHWST, but not out of reach of storm wave action. Only the junction at profile 4, always under a beach cover and marked by vegetative growth, is rarely reached by swash or direct wave action.

Beach Cover: The depth of beach cover may have an important influence on the extent and type of erosion both at the cliff-platform junction and along the platform profile. Beach cover may provide important protection to the cliff base from direct wave action, particularly with increasing depth; beach sediment itself is potentially a strong erosive agent (by corrasion and attrition) and there will be a threshold (depending on depth of cover, size of sediment, nature of sediment) where the beach ceases being protective and becomes erosive. Beach cover may be described in terms of mean depth, a function of cross sectional area divided by beach length. Mean depths reach a minimum during the period October to April, when wind strength and wave energy is greatest. Mean depths of beach cover measured along selected profiles between Swyre Head and Bat's Head were as little as 0.11m to 0.24m. Minimum mean depths were closely related to minimum beach gradients (measured by Bruun Index - chapter 8).Minimum mean beach depth was observed to correspond with the period of high wave energy.It is reasonable to assume that under such conditions the beach is in a highly mobile state. Small beach gradients without berm developments will allow large waves (up to 4m.), and swash armed with sediment to attack the cliff face directly,and may result in corrasion at the cliff base, and subsequent attrition of eroded fragments and particles. Quarrying by wave action alone on the exposed cliff face will also be greatest at this time (Plate 32).

Maximum mean beach depths, beach gradients and pronounced berm development occurred during the early summer months when the extent of wave action and wave energy was at a minimum. The steep gradient provides a reflective surface for waves to act upon. Calm sea conditions, a reduction in effective tidal range, increased beach volumes, beach widths, steep gradients and berm formation help protect both the platform and its cliff junction from marine erosion. Only the upper layers of the beach surface will be mobile and and will be confined to the intertidal zone, up to 8.0m seaward of the cliff face.

Wave Energy: Bartrum (1935), So (1965), Wood (1968) and Wright (1970) attributed the height differences of cliff-platform junctions to geology and/or wave exposure and suggested that platform width is greatest on exposed coastlines. Trenhaile (1974), found a relationship between platform gradient and fetch in southern Britain, but this has not been confirmed elsewhere.

Most workers do agree, however, that mechanical wave erosion is the basic platform process and that quarrying is possibly the most powerful mechanism. The quarrying of rock by wave action may be produced by wave shock, wave hammer or air compression (Trenhaile, 1980). Sunamura (1978), considered three types of breaking wave occurring in front of the cliff face as a mechanism of shore platform formation on the Izu peninsula. The type of breaking wave depends on the relative magnitude of breaking depth of incoming waves (db) and water depth at the cliff base (d).

Waves breaking in front of the cliff are the most effective agent in platform cutting. The important issue is whether waves have enough force to run over the platform surface to the main cliff face where erosion may take place. Breaking wave heights of 0.25 - 0.75m are experienced on the Durdle Door coastline during calm conditions. During storm conditions breaking wave heights can be as much as 4.0m and the abnormal sea level rise caused by such storm events will produce breaking waves at and in front of the cliff face. Large scale offshore exchanges of material during extreme events may leave the platform with only a thin veneer of sediment (e.g. 0.11m to 0.24m) on sections that are fully exposed to the full force of mechanical wave erosion. The sections of platform most frequently exposed display cliff platform junctions that lie above MHWST, at a height corresponding to the range of storm wave action (2.0 - 3.5m O.D.).

THE EXPOSED PLATFORM

Platform profiles are strongly influenced by structural and lithological factors and this relationship is best displayed when the platform is fully exposed, free of any beach sediment. Only sections of the platform are exposed at any one time, it being apparent that the platform towards Bat's Head is not exposed simultaneously with the platform in front of Swyre Head. Exposure of the platform is a consequence of storm wave action or prolonged easterly wave climates.

The platform surface is strongly influenced by the vertical bedding of the chalk between Swyre Head and Bat's Head, highlighted by bands of flint running east-west (Plate 33). The hard bands of flint form distinct jagged ridges on the platform surface. Scouring at the base of the flint results in gully development which becomes more pronounced westwards along the platform (Plate 34). Gully development may concentrate erosion further by scour and corrosion, the latter occurring by water becoming trapped in small depressions. Spray and splash accumulating in the solution notches and gullies is a potential agent for water level weathering. During storm conditions the platform is not wide enough to be free of swash for any length of time and the surface is not given time to dry out for hydration and salt crystallisation to occur. However, there is often a lag effect, with the platform remaining exposed for a short period during the return to calmer sea conditions. It is during this period that water layer weathering may occur. Due to the double low tide the upper reaches of the platform and cliff base may dry out and allow salt crystallation to occur resulting in granular disintegration of the surface (Mottershead, 1982). Major joints running north south are also exploited by marine erosion to give a grid-like pattern of ridges and runnels over the platform surface. Fragments produced by attrition of the flint bands tend to accumulate in the gullies from where they become incorporated into the beach system. Observations suggest that the amount of flint eroded from the platform and incorporated into the beach may be greater than that from cliff erosion. Indeed, when the beach veneer is at a minimum, attrition of the flint bands is possibly at its greatest, but occurs virtually undetected. The eastern extent of the platform is only infrequently exposed. The platform within Durdle Cove was only exposed during an intense, prolonged period of north easterly winds and easterly seas. Morphologically the chalk platform differed from that further west by having an irregular nodular surface not affected by direct marine attack (Plate 35).

General Considerations

The study of chalk cliffed coastlines is not extensive although chalk platforms have proved to be a more popular study. Much of the work relates to estimated rates of cliff retreat over long periods by cartographical methods. The role of marine versus subaerial erosion on the cliff face is recognised, particularly on a seasonal basis. Further investigations along the chalk cliffs of south east Dorset have attempted to identify the processes at work and their degree of interdependence. Profiles are largely dependent upon the resistance of geology and structure to marine and subaerial erosion and their relationship was used to classify profile form; three profile types were recognised along the chalk cliffs of south east Dorset.

The role of cliff erosion in the "process response" situation is shown by the variation in cliff form along the coastal zone. The fall at Swyre Head proved to be a very transient feature with rapid removal of material. Very little debris was incorporated into the beach system in contrast to the chalk falls at Mupe and Worbarrow where much of the input is reworked and incorporated into the beach system. At White Nothe the chalk input becomes incorporated into a boulder field thus increasing the protection of the cliff foot from direct marine attack. At White Nothe contemporary cliff erosion may be attributed to subaerial processes, whereas at Durdle Door, Mupe and Worbarrow, cliff erosion is a consequence of the inter-relation of subaerial and marine processes; the importance of frost action has been highlighted and the influence of spray on the cliff surface discussed as an important agent of erosion.

The wave refraction diagrams constructed for Weymouth Bay (Chapter 4) suggest that areas of active erosion may be associated with the concentration of wave energy along parts of the coast as a result of wave refraction. The scree slopes of Mupe and Worbarrow may have been initiated by direct marine attack at the cliff foot; Figure 17 suggests that a concentration of wave energy is probable along the western section of Worbarrow beach and at Cow Corner (where a scree slope is well developed) under prevailing south westerly swell. However, the cliff foot is now protected from direct wave attack by its own boulder debris and a narrow, but very steep storm beach. Mupe also receives energy from the south west due to refraction over Mupe Ledges, but because of its south east aspect the highest energy waves received are from the south east. Like the chalk slope at Worbarrow the scree slope at Mupe is protected from all but the highest storm waves by a steep storm beach and large boulders masking the cliff foot.

White Nothe headland receives wave trains from both the south west (as a consequence of refraction over the Shambles Bank) and the south east, but the protection afforded by an extensive boulder field has already been discussed in detail. The chalk cliffs backing Durdle Door beach do not apparently receive an abnormal concentration of wave energy but marine erosion is nevertheless an active process; the narrow, planar beach cannot migrate inland to a position where increased shoaling would lower wave energy levels because it is restrained by the cliffs, thus allowing direct marine erosion along the cliff foot.

Studies of the chalk platforms along the south coast have been largely concerned with the processes of their formation. The majority of platforms studied lay exposed during the tidal cycle, having little or no beach cover. In contrast, the platforms in the chalk of south east Dorset are infrequently exposed despite only a relatively thin sediment cover. A study of the narrow chalk platform between Durdle Door and Bat's Head highlighted the importance of the beach cover, both as an agent for erosion and as a protector to both the platform and cliff foot. The variation in height of the cliff-platform junction suggests a relationship with exposure and storm wave action. Only sheltered profiles show a correlation between junction height and MHWST, the others being best developed above this point. The surface morphology of the platform is greatly influenced by variations in hardness between the chalk and flint bands. Flints eroded by scour and attrition provide weapons for further attrition at the cliff base, whilst mechanical wave action at the base accounts for quarrying and the loosening of small chalk blocks. Undercutting of the cliff foot ultimately leads to a weakening of the lower cliff face and mechanical failure.

Variations in platform morphology are ascribed chiefly to differences in tidal range (Trenhaile and Layzell, 1981), the rate of recession at each elevation being directly related to tidal duration. Such a process at work along the Dorset coast would produce a tidal duration maxima at low water and a wide low water section of gentle gradient and a high concave upper section where wave processes are of restricted duration (but of greatest energy). Measured platform morphology reveals that where the platform is most frequently exposed it exhibits an upper, slightly concave ramp (up to 5m. wide) and a lower section with a tendency to a convex form. The morphology of that section of platform which is very rarely exposed and normally lies beneath > 2m. of beach material, is quite different; the surface is highly irregular and nodular, marine erosion has not had sufficient opportunity to produce a ramp-like surface as is seen less than 100m. further west.

In terms of the "process-response" model the platform acts as a pathway for sediment transport, thereby linking processes at work on the cliff and within the intertidal zone. Fieldwork indicates that sections of chalk platform between Swyre Head and Bat's Head are frequently exposed during the winter period. However, it was noticeable that the entire stretch of platform was never exposed at any one time. That section of platform exposed at any one time is a reflection of differences in wave energy and wave climates acting upon the beach. It appears that sections of exposed platforms are a result of high energy concentrations removing the beach material, so that in effect, they act as "parting" zones. The result is a division of the contained beach unit into a number of smaller, discrete but interdependent cells of sediment movement. The ramp-like platform allows easy mobilisation of beach material, particularly when the beach cover is thin (<1m.). The platform acts as an impervious surface thereby influencing the level of the water table. Saturation of the beach is common under such small depths of sediment cover and the water table will increase the effectiveness of the backwash (under certain conditions), and its implications will be reflected in the amount of erosion. A similar process can be seen at work on the storm ridge within Durdle Cove, where rainwash has produced an internal concentration of clay approximately 2m. below the beach surface. This layer not only adds support to the internal structure of the beach but will also affect the passage of water through the beach and mobilisation of the sediment above.

The wave refraction diagrams compiled for the study area show that a concentration of wave energy along the western section of Durdle Door beach (under south easterly swell) coincides with the stretch of chalk platform that is most frequently exposed. Field observations verify that, under prolonged periods of south easterly swell, erosion occurs along the beach between Swyre Head and Bat's Head and parts of the platform are exposed. Resumation of prevalent south westerly swell results in aggradation of sediment on the exposed platform. Storm waves from the south west also cause large scale offshore movement of sediment, thereby exposing parts of the platform. Mixed wave trains, a product of a dominant south easterly swell and a prevailing south westerly often prolong exposure of the platform allowing marine erosion to take advantage of the cliff-platform junction. Thus the platform has an important role to play in beach sediment transport, although little research has been carried out in order to examine its importance in the "process-response" model.

CHAPTER 7

BEACH SEDIMENTOLOGY

PARTICLE GEOMETRY

"A description of the basic properties of geomorphological materials is frequently the most important starting point for an explanation of a geomorphological process", (Whalley, 1981). Particle form and particle size are the main sediment descriptors used to study the dynamic behaviour of each individual particle, but despite the growing list of papers there is still concern about the concept of form as an indicator of environmental process. As early as 1898 Cornish observed zoning of different sized, shaped pebbles on a beach, whilst in 1912 Stephenson noted a high proportion of flat pebbles on a beach and proposed that they be used as indicators of beach environments. It was Wentworth (1919) who first assigned a quantitative measurement to sediment particles by measuring the diameter of curvature of the sharpest developed corner and so most of the contemporary concepts of particle shape can be traced back to those pioneering days. Wentworth (1922), also described individual particle geometry by means of three intercepting axes, representing the long (a), intermediate (b) and short axes (c). These three dimensions still form the basis of the concept of shape, size and form. Early workers used shape and form as synonymous expressions although they lacked consistency and exactness and controversy over the definitions still exists. Whalley (1972), defined particle form as an "expression of the external morphology of an object", which can be described by a variety of parameters such as shape, sphericity, angularity, roundness and surface texture. Sneed and Folk (1958), used form to describe overall shape independent of roundness and surface texture. Form parameters are based on the longest, shortest and intermediate orthogonal axes whilst shape parameters should be independent of size and therefore normally take the form of ratios of the axes, (Barrett, 1980). Shape is defined by Pryhor (1971) as the "spatial geometric form of a grain", or in terms of crystal form. However, crystal form descriptors are qualitative and more quantitative geometric parameters are now used, (sphericity, flatness, roundness and elongation). Many of the geometric parameters have received rigorous attention in an attempt to quantify the fundamental properties of sediments and assess their dynamic behaviour. Ehrlich and Weinberg (1970) distinguished shape as a two-part variable - gross shape, described by sphericity and the directional change of the grain surface expressed by roundness and angularity.

The development of formulae to quantify particle geometry is summarised in Tables 7, 8 and 9. Table 7 presents evaluations of sphericity. Basically sphericity measures the ratio between the three major dimensions of a particle and describes the hydraulic behaviour such as settling velocity and depends on surface area. Roundness (Table 8) is a three dimensional property and therefore difficult to measure; quantification is commonly based on comparison charts, ranging from concentric circles (Cailleux, 1947) to photographs (Russell and Taylor, 1937). The main problem in such methods is the provision of a representative number of classes. Pettijohn (1949) did not provide enough divisions in the lower roundness values, a problem rectified by Powers (1953). As with all visual comparison charts there are disadvantages; operator error is the commonest problem in addition to the inherent problem of distinguishing subtle differences in particle rounding, particularly in the lower classes. However, there are also advantages, especially their flexibility; large numbers of particles can be measured with great rapidity not only in the laboratory but also in the field.

Recently more mathematical analysis of grain shape has been attempted. Fourier analysis is favoured by many mathematically-minded sedimentologists, e.g. Ehrlich and Weinberg (1970). Fourier analysis is basically the expansion of a radius about the centre of mass utilising co-ordinates of peripheral points. The technique yields a mathematical model of the grain that will regenerate the grain shape as precisely as required. The grain shape is therefore represented by a linear equation with an indefinite number of terms, with each term representing the contribution of a known shape component.

PARTICLE SIZE

Several reviewers of grain shape methodology and analysis describe the apparent controversy over analysis by graphic statistics and moment statistics (e.g. Folk, 1966; McBride, 1971; Allen, 1975). There are advantages and disadvantages inherent in any method but it is the general opinion that the choice of method depends on the nature of the problem to be assessed. Whichever method is used, the basic aim is to describe a representative sediment sample in terms of mean grain size, standard deviation, skewness and kurtosis. Before grain size parameters can be derived the sediment sample needs to be presented in a quantitative form. There are two common types of particle measurement :

(i) direct measurement by mass measurement using laboratory techniques of sieving, pipette or hydrometer.
(ii) direct measurement of individual particles by measuring the a, b and c axes using rulers and calipers.

There are many opportunities for the introduction of errors during particle size analysis, but certain procedures, if strictly adhered to, can minimise errors introduced into the size distribution during sampling, sample splitting and sample measurement (Table 10).

CUMULATIVE FREQUENCY CURVES

If a sample has been sieved the total sample weight retained on each sieve is measured. From these values the cumulative percentage of the sample coarser than each sieve can be calculated. This is done by summing the percentages retained on each sieve starting at the coarsest and proceeding to the finest. These cumulative percentages are plotted against the appropriate sieve size on arithmetic probability paper if the distribution is open-ended and percentiles in the tails of the distribution are needed for computation the curve must be arbitrarily extended. By using the phi scale the data is transformed to an arithmetic normal distribution. A conversion chart (Figure 30) outlines the relationship between the phi scale and the metric scale. Sediments rarely achieve a perfectly log normal distribution, they merely approximate one. Deviations from log-normality are represented by variation from a straight line and by changes in the slope of the curve.

Cumulative frequency curve statistics were developed to describe the hydraulic action of sediments by relating sedimentation dynamics to texture. Inman (1949), recognised three fundamental modes of transport and utilised existing knowledge to analyse the modes of transport - surface creep, saltation and suspension. Shields (1936), and Bagnold (1941) had already developed the concept of relating fluid mechanics to sediment transport and deposition but it was Moss (1962, 1963), who provided a significant contribution toward an understanding of grain size distributions to depositional processes by recognising sub-populations produced by the three modes of transport. It is now generally believed that the cumulative frequency curve is meaningful with regard to depositional processes. The consistency of the position of truncation points, slopes and other characteristics suggest that meaningful relationships are reflected by log probability plots (Visher, 1969).

The parameters of particle size distribution are routinely used by sedimentologists and can be analysed by :

(i) graphical (percentile) measures.
(ii) moment measures.

Both methods have advantages/disadvantages, but as yet no one has supplied a definite alternative (e.g. Jones, 1970 - the Cumulative Edgeworth Distribution).

GRAPHIC MEASURES

Most graphically derived statistics are approximations of moment statistics and prove useful in distinguishing environments and processes of deposition. Several measures are derived from formulae utilising percentile values, the most common being mean size sorting (standard deviation); skewness and kurtosis, although up to 10 possible parameters have been suggested (Friedman, 1967).

A number of different methods have been advocated for the calculation of each parameter and can only be distinguished by their relative efficiency. Folk and Ward (1957) in their classic work "Brazos River Bar - a study in the significance of grain size parameters", made a rigorous study of statistical measures derived from cumulative frequency curves and recognised the discrepancies resulting from strongly bi-modal samples. Spencer (1963) suggested that nearly all grain size distributions are bi-modal and that clastic sediments are essentially mixtures of three or less populations - gravel, sand, clay. Two main groups of parameters can be derived from the curves - central tendency and scatter (Table 11). Folk (1966) made a thorough review of grain size parameters by assessing the relative efficiency of the most commonly used equations (as determined by the use of percentiles).

MOMENT MEASURES

The method of moments is a technique whereby the entire frequency distribution enters into the determination rather than a few selected percentiles (Van Orstand, 1925). Given a size analysis the frequency (weight %) within each size class is multiplied by some power of the distance that size class is from the mean (Folk, 1966). The method is not without disadvantage.

(i) faulty sieve screens can seriously affect skewness and kurtosis.
(ii) open-ended distributions are not suited to quantification by the method of moments which requires the entire distribution.

The advantages/disadvantages are best described in terms of their real application, the degree of accuracy needed depends on the problem defined. Swan, Clague and Luternauer (1978) made it clear that the two techniques are not comparable whilst Koldijk (1968), Davis and Ehrlich (1970) found that graphic measures were less sensitive. For example, thorough analysis of beach facies would require detailed statistical analysis and the method of moments would be most suitable, for a more general analysis of processes of deposition. Graphical computation may prove advantageous because they can be used to express :

(i) the size frequency distribution of the source rock.

(ii) changes in the nature of the load during transportation to the site of deposition due to abrasion, deposition en route and additions to the load.

(iii) the nature of the movement.

(iv) selective depositional effects at the sampling site.

GRAIN SIZE DISTRIBUTIONS AS ENVIRONMENTAL INDICATORS

Many researchers attempt to describe and interpret sediment transport and deposition with respect to environmental conditions. Some opted to use graphically derived measures, (e.g. Folk and Ward, 1957; Moss, 1962, 1963; Friedman, 1961, 1967; Visher, 1969; McLean and Kirk, 1973; Thomas et al 1973; Sonu, 1972), whilst others preferred the more elegant method of moments (Koldijk, 1968; Hails, Seward-Thompson and Cummings, 1973; Greenwood, 1970; Williams, 1973; Sunamura and Horikawa, 1972). The most common method of displaying environmental significance is to plot the four derived parameters against each other in the form of bivariate scattergrams. Folk and Ward (1957) plotted mean size, sorting and skewness values derived from bimodal samples in three dimensions resulting in a helical trend that has since been described in many other distributions. They showed that skewness and kurtosis values were the result of the mixing of two "normal" populations in various proportions. For example, a dominant fine population and a subordinate coarse population gave negative skewness; a dominant coarse mode gave a positive skewness; a subequal mixture of two populations gave platykurtic distributions and a mix of one very predominant and one very subordinate population gave a leptokurtic distribution.

The four parameters may also give an indication of sediment movement in the littoral zone. Strahler (1966) noted that mean grain size increases, sorting decreases and skewness increases from backshore to foreshore, indicating the movement and sorting by waves as they migrate up and down the beach with each tidal cycle. The decrease in size is therefore due to the migration of energy inputs across the beach. If energy expenditure is greater near the low water mark and decreases towards the high tide swash limit the percentage of coarse material will also increase towards low water to produce high negative skewness values (Greenwood, 1976). Sonu (1972) working on bimodal distributions noted a tendency for negative and positive skewness in fine sediments, the nodal point being at 0.0 phi. He suggested that sediment deposits consist of two groups of sediment, one coarse, one fine, both having a unimodal size distribution with zero skewness. In this way skewness values in bimodal distributions describe relative heights between the dual modes.

Greenwood (1970) stated that particle size is a primary reflection of the transporting agent. Using a random sampling technique with wide coverage he calculated size frequency statistics using moment measures. He noted that higher energy conditions and greater competency mean that particle size in a deposit will be larger than for a deposit associated with lower energy conditions.

Williams (1973) also used moment measures to show variation in size frequency statistics and their application as environmental zone indicators. He showed that mean grain size is a fundamental plot (as did Inman, 1949) having an important control over sorting rather than hydraulic factors. Skewness and kurtosis values indicated that the samples came from non-normal distributions but it was size and sorting values that provided greatest information regarding beach zonation.

Some workers have used grain size parameters to infer the direction of littoral drift, whilst others have used them to describe differences in hydraulic energy across and along the littoral zone. Pickrill (1977) described how a decrease in mean grain size or an increase in the degree of sorting away from a source area may be seen as a product of selective longshore transport and attrition. Sunamura and Horikawa (1972) combined grain size and sorting coefficients to define the preconditions for identifying the direction of drift. However, both Kirk (1969) and McLean (1970) found no discernible longshore trends in size and sorting away from the source area on mixed sand and gravel beaches in New Zealand.

Carr (1969, 1970, 1971, 1974) produced a number of significant papers on linear and shape parameters of coarse sediments on Chesil Beach. He used linear parameters in a rigorous statistical analysis to describe such processes as differential movement of coarse sediment particles, size and shape grading, as well as the significance of pebble size and shape in sorting by waves. Gleason and Hardcastle (1973) tested the correlations between size or shape indices of wave conditions in order to determine the significance of wave parameters in the sorting of pebbles. Results suggested that longshore sorting was dependent on the angle of swell approach and the sine of twice the angle of swell approach relative to a line at right angles to the beach, and the square root of significant wave height. Carr (1971), had already noted this relationship and by comparing linear parameters found that thickness (c - axis) is the critical dimension for lateral movement. Caldwell (1983) working on coarse pebble beaches of South Wales considered particle size to be important in determining sedimentological response to swash processes. Others have used shape indices to describe the sedimentological behaviour of beaches and believed them to be more important than size parameters. Both Bluck (1967), and Orford (1978), presented evidence to confirm the existence of shape sorting although its importance remained questionable. Bluck's (1967) work was based on the modelling of selective sorting of beach pebbles according to particle shape and sphericity. By collecting textural data from six South Wales beaches he was able to develop a model of beach facies sedimentation. His system envisaged a poorly sorted mass initially thrown up by storm waves with shape selection taking place, post storm sediment falling into four zones. Orford (1978), modified Bluck's (1967) model of pebble beach sedimentation by identifying differences in terms of spatial and temporal extent of the beach facies. According to Orford (1978), Bluck (1967) failed to identify a specific facies sequence for storm conditions because he did not fully consider wave dynamics. Using profile configuration as a discriminant between differing depositionary environments Orford (1978) was able to observe a re-arrangement of sediments in relation to beach morphology. The distinction between post-storm swell and fairweather conditions was essentially based upon the spatial extent of certain sub-facies on the lower beach. According to Orford (1978) certain types of facies assemblage depend on onshore movement of selected particles winnowed from lower beach infill zones concluded that sorting processes could operate in both onshore and offshore directions under differing littoral conditions. It is clear, however, that shape sorting occurs on all beaches studied by Bluck (1967), Orford (1978) and Caldwell (1983), but whether this is the main factor determining particle movement is a matter of debate. There are certainly times when shape selection is of greater or lesser importance than size selection. For example, when swash and/or backwash produce entrainment forces which are at the critical threshold for transport, certain particle sizes are more easily suspended and shape may play an important role in zonal deposition. When entrainment forces are no longer marginal, mass rather than shape may be of greater importance (Caldwell, 1983). Carr (1974) also considered the relative merits of shape and size and noted that the comparative unimportance of shape factors at Chesil Beach is probably due to the rather limited range and higher wave energy. Many other beaches where shape sorting has been described are in relatively low energy environments.

Lane and Carlson (1954) attempted to describe the resistance of movement of various shaped particles according to sphericity and Zingg type by making detailed measurements of particle shape and hydraulic measurements of water surface slope, discharge, roughness values and the shear or tractive forces on the seabed. They concluded that flat particles tend to become imbricated and resist movement more than spherical particles of equal weight.

On the basis of the wealth of data available concerning sampling procedure and particle geometry it was considered necessary to prepare a realistic research programme that would provide the data to fulfill the aim of assessing sedimentology within each sediment cell. In this light a pilot study was carried out.

BEACH SEDIMENTOLOGY ON THE DORSET COAST

The study was organised in an attempt to answer a number of fundamental questions :

(1) What were the general sediment characteristics of each beach and was a general pattern of zoning visible?

(2) If there was grading of sediment did it vary over time and/or space?

(3) Was there any relationship between beach morphology and sedimentology?

(4) What were the main differences between sediment characteristics of each beach and could they be accounted for?

In an attempt to answer those questions a number of lines of investigation were necessary :

(i) differences between sediments collected from all study beaches.

(ii) along and down beach variations on each beach.

(iii) assess the link between profile shape and sediment size.

PILOT STUDY

Preliminary investigations, limited to the three most accessible beaches - Durdle Door, Man O'War and Ringstead aimed to :

1. identify and investigate the characteristics of the apparent sediment compartments.
2. develop and evaluate methods and techniques of data collection concerning the quantitative analysis of sediment form and profile variability.
3. determine the most useful techniques in order that a systematic monitoring programme could be developed to assess the variety of parameters making up the total process regime.

SELECTION OF PROFILE SITES : Profile sites were designated at regular intervals of approximately 100 m. This spacing yielded 13 profile sites at Durdle Door, 5 at Man O'War and 12 at Ringstead, (Figure 31).

TEMPORARY BENCH MARKS : Profile sites were located by temporary bench marks. At Durdle Door and Man O'War the hard chalk cliffs provided a suitable surface for establishing bench marks with spray paint. At Ringstead, bench marks were located by wooden stakes driven into the backshore as close as possible to the beach/cliff junction. Permanent stable fixtures such as concrete steps also provided suitable surfaces for the location of temporary bench marks. Figure 31 shows beach sections selected for the pilot study.

BEACH SURVEY METHODS : Surveying of beach sections during the pilot study was carried out by two people using quickset level, staff and tape. Each profile was surveyed from the temporary bench mark (T.B.M.) along a line normal to the shore. It was estimated that beach surveying could be carried out in the time slot three to four hours after the first low water and that in the main study the five beach sites could be grouped so that surveying could be carried out over three days. The pilot study showed, however, that if the number of profiles remained the same (plus profiles at Worbarrow and Mupe), this method of surveying would not be practical.

SEDIMENT SAMPLING : Sediment samples were taken from the surface layer of the beach within a one metre square at the point of the last high water and the mid tide zone, the latter being referred to as Bascom's "reference point", (Bascom, 1951; Williams, 1973). These zones were selected on the basis that they would display greatest variability in response to the energy regime and possibly indicate any relationship between sediment size and beach slope. At each sample site up to 1.0 kg of sediment was collected (in an attempt to adhere to British Standard 1377), and placed in a numbered, self-sealing bag. Where samples consisted wholly of pebble grades (>-2Ø) at least 50 individual particles were collected. Preliminary investigations were limited to two sampling dates, (23.9.1982/14.10.1982).

LABORATORY PROCEDURE

1. **Sieving** : All samples were treated to oven drying and dry sieving. Samples were split into 400g or 50 pebbles and subjected to 15 minutes sieve shaking through screens of whole phi units. Derived percentage data was plotted as a cumulative frequency curve. Size parameters of mean, skewness, sorting and kurtosis were computed using the equations in Table 12. These equations were selected because they consider the tails of the distribution and thus extract the most information.

2. **Particle measurement** : Samples consisting of more than 50% (by weight) pebble grades (>-2Ø) were subjected to individual particle measurement. 50 individual particles were selected, at random, and the following dimensions were measured :

(i) a axis (maximum intercept or length)
(ii) b axis (intermediate intercept or width)
(iii) c axis (minimum intercept or thickness)

The values recorded were subjected to computer analysis in order to derive descriptive statistics of particle shape within each sample (mean elongation, mean flatness, mean sphericity, and classification of the total sample by Sneed and Folk and Zingg classes).

RESULTS

1. 23 September 1982

(i) Ringstead beach

Table 13a indicates that all samples collected produced mean grain sizes within pebble grades, ranging from -2.62 0 (fine pebbles) to -4.58 0 (coarse pebbles). The end profiles displayed mean grain sizes of medium pebble grade whilst samples towards the centre of the beach were more variable, alternating between fine and coarse pebble grades. Down beach variations in mean particle size indicated that profiles 4, 5, 6, 10 and 12 produced the coarsest grades along the midwater zone., elsewhere the coarsest grades were sampled from the high water zone.

Samples ranged from moderately well to very well sorted; no samples proved to be poorly sorted. Lateral variations in sorting values showed that sorting was best developed on the end and central profiles; down beach variations indicated that the end profiles displayed the best sorting values at high water whilst mid water samples were better sorted on the central profiles. According to values of skewness and kurtosis the majority of samples, described normal distributions. Only samples from profiles flanking the central profiles (6 and 7) produced extreme distributions.

Shape values of mean elongation, flatness and sphericity were contained within a relatively small range (Table 13b). Mean elongation and flatness values increased towards the centre of the beach from both ends but sphericity values varied over a small range and no lateral trend was apparent. Downbeach values of the three shape factors increased slightly on profiles 1 to 3 whilst the profiles further east described a decrease in values from high water to mid water. The allocation of individual particles to Sneed and Folk classes showed that very bladed particles dominated the samples particularly towards the centre of the beach, whilst the proportion of very elongate particles increased westwards. Zingg classification also recorded a dominance of bladed particles towards the centre of the beach whilst discs dominated the eastern section of the beach.

(ii) Durdle Door (Table 14a) :

Mean particle sizes ranged from +1.10 0 (fine sand) to -2.78 0 (fine pebbles). The sample set exhibited a marked decrease in mean grain size from east to west, the coarsest grades were sampled within Durdle Cove, the finest between Swyre Head and Bat's Head. Profiles 1, 2, 3, 4, 7, 8 and 10 exhibited mean size values within the same grades at high and mid water, the remaining profiles displayed different sediment grades at high and mid water. With the exception of profiles 9 and 11 mid water samples were a grade finer than those collected from the high water zone.

Sorting values varied from poorly sorted to very well sorted. Lateral variations revealed that the best sorting values were recorded at opposite ends of the beach, within Durdle Cove and towards Bat's Head. The poorest sorting values were exhibited by central profiles, notably, profile 5. Skewness and kurtosis revealed that many samples tended to describe normal distributions, particularly samples from the high water zone. Samples displaying extremely skewed distributions also tended to be platykurtic.

Particle shape analysis (Table 14b) produced a noticeable small range of mean values of elongation, flatness and sphericity. Lateral variations revealed a trend for elongation and sphericity to increase slightly to the western end of the beach. Flatness values described an inverse relationship, decreasing to the west. Sneed and Folk classification noted a dominance of bladed particles despite a proportionate increase of elongated particles to the west (and consequently a reduction in the number of platy particles). Zingg classification was consistent with the findings of Sneed and Folk classes, describing an abundance of bladed particles and highlighting an increase in the proportion of discs and rods to the west.

(iii) Man O'War beach :

Table 15a describes a lateral increase in mean grain size on Man O'War beach from west to east. All the samples produced a mean grain size within pebble grades ranging from fine pebble grades (-2.05 Ø) on profile 1, coarse pebbles at profile 5 (-4.30 Ø). Downbeach variations in mean grain size were negligible; each profile tended to show the same pebble grade at both high and mid water, except profiles 4 and 5 where mid water samples proved to be one grade finer than the high water samples. The small range of mean particle sizes was mirrored by an equally small range of sorting skewness and kurtosis values; sorting was best developed at the western end of the beach, deteriorating slightly to the east. Skewness and kurtosis values indicated that all samples displayed a normal distribution.

Shape distribution (Table 15b) showed little variation in values of mean elongation, flatness and sphericity either along or down the beach face.

Flatness values were inclined to decrease to mid water with sphericity values displaying an opposite trend. Sneed and Folk classes highlighted the dominance of very bladed particles, particularly on the end profiles whilst the proportion of very elongate particles increased at the centre and eastern end of the beach. Zingg classification, however, suggested that disc shapes were the dominant class, particularly along the high water mark. Along the mid water zone a decrease in the proportion of disc shapes allowed for an increase in the proportion of rock and spheres.

2. 14 October 1982

(i) Ringstead

Particle size analysis (Table 16a) described grades ranged from coarse sand (0.44 Ø, profile 9) to medium pebbles (maximum -3.96 Ø, profile 4). Lateral variations in mean grain size indicated that the coarsest grades were sampled from the western section of the beach (profiles 1 to 5) with sands and gravels at the centre and fine pebble grades to the east (profiles 11 and 12). Profiles 1 to 6, 10 and 12 produced a downbeach fining of sediment grade whilst profiles 7, 8 and 9 produced the finest mean grain size along the high water mark.

Mean elongation increased slightly to the east whilst mean flatness increased towards the centre from both ends of the beach, (Table 16b). Sphericity values produced little variation. Sneed and Folk classification indicated a dominance of very bladed particles whilst Zingg favoured disc shaped particles along the western profiles. To the east, Sneed and Folk classes showed an increasing percentage of very elongate particles, Zingg classes noted a marked decrease in the number of spherical shapes whilst the proportion of blades, discs and rods became more even on the eastern profiles.

(ii) **Durdle Door (Table 17a) :**

Mean grain size ranged from 0.62 0 (coarse sand at profile 4) to -2.33 0 (fine pebble grade on profile 1). Samples collected from the high water zone described a decrease in mean grain size from profile 1 to 8 and increasing again towards Bat's Head. Mid water samples also decreased from profile 1 to 8. Between profiles 5 to 9 and 11 and 12 mid water samples were of the same grade as their high water partners. Sorting was well developed along the whole beach, ranging between moderately well sorted and very well sorted; the poorest sorting tended to be displayed by mid water zone samples. Samples collected from Durdle Door Cove were generally very well sorted, samples from the central profiles were well sorted with more variable sorting displayed by profiles at the western end of the beach. The majority of samples produced normal distributions especially along the high water zone. Extreme distributions tended to be confined to mid water samples where sorting was not so well developed.

Mean elongation, flatness and sphericity values showed little variation either along or down the beach face (Table 17b). Sneed and Folk classification produced a dominance of very bladed particles particularly along the eastern section of the beach.

West of the centre of the beach samples produced an increasing percentage of very elongate particles.

Zingg classes revealed a dominance of disc shaped particles throughout the beach but an increase in the proportion of blades and rods towards Bat's Head.

(iii) Man O'War

Mean grain sizes (Table 18a) were confined to pebble grades ranging from fine pebbles (-2.59 Ø minimum, profiles 1 and 2) to coarse pebbles (-4.10 Ø maximum, profile 3). Thus the general lateral trend was for an increase in mean grain size towards the centre from both ends of the beach. Sorting was also best developed towards the centre of the beach, especially on profiles 2 and 3, flanking the profile at the apex of the beach. Kurtosis and skewness values indicate that the majority of samples composed a normal distribution.

Shape indices of elongation and sphericity (Table 18b) produced only a small range of mean values with no marked variation either along or down beach. Flatness values presented greater variation, the general trend being an increase to the east. Sneed and Folk classification exhibited a dominance of very bladed particles despite an eastward increase in the proportion of very elongate particles. Zingg classes presented disc shapes as the dominant particle type throughout the beach, with the exception of profile 5 where spherical shaped particles dominated the sample from the mid water zone.

DISCUSSION

Sediment samples were collected from three selected beaches during the autumn of 1982 in order to make preliminary investigations of both spatial and temporal changes in sediment patterns (over a short period of time, less than one lunar tidal cycle). The pilot study also aimed to determine the most suitable technique for analysing and evaluating the general behaviour of each sediment cell. The methods employed have been described and the statistical results tabulated. In discussion of the results the prevailing wind and wave regime prior to sampling has been taken into account. It should also be noted that all samples were collected after the same tide.

On the first sampling date (23.9.82), wind direction was westerly, force 4, a prevailing south westerly swell with a 10 second wave period accounted for breaking wave heights up to 0.60m, normal to the shoreline. Before the onset of these conditions a persistent period of easterly winds (10.9.82 - 17.9.82), force 1-3, produced short waves of 5 second period that broke obliquely to the shore at a height <0.50m. The effects of an increase in wave height just before the survey were assisted by a rising spring tide. Both Ringstead and Man O'War beaches displayed a small range of pebble grades over the entire beach face. The similarity did not include patterns of grading; Ringstead displayed a decrease in grain size towards the centre, from both ends of the beach, whilst Man O'War sediment decreased in mean grain size from east to west. Samples collected from Durdle Door beach produced a greater range of sediment grades. Marked alongshore grading described an overall decrease in mean size from east to west. The range of grain sizes on each beach was reflected in the sorting values; the limited range of grades at Ringstead and Man O'War produced a small range of values indicating that all the samples were well sorted. Durdle Door produced a greater range of size and sorting values, but the data from all three beaches indicated that the coarsest grades were the best sorted. Oblate shapes (blades/discs) dominated the majority of samples analysed, irrespective of grain size; the coarsest grades collected from Ringstead (>-4.0 0) proved to be the only exceptions, tending to be more spherical.

Results from the initial survey implied that sediment grading was by size and that lateral grading was best developed, but with only two down beach samples collected from each profile it would be impulsive to remark upon any trends in that direction. Comparing results from Ringstead and Man O'War beaches greater differences within beaches than between beaches were shown. Durdle Door beach samples produced greater differences both between and within the beach. Shape variation was not well developed on any of the beaches,either alongshore or downbeach. The variations and trends displayed by mean grain size was considered a reflection of the configuration and wave energy concentrations within each beach unit. Along Durdle Door beach deviations from the general westward decrease in grain size are seen as a consequence of the bay configuration; the elongate bay is a result of the amalgamation of three separate, smaller units, which is reflected in nearshore topography by a series of rises and hollows (as exposed by a side-scan sonar and echo-sounder survey). The dramatic undulations and the presence of the irregular Portland Stone reef off Durdle Door are expected to have an effect upon the behaviour of incoming waves, which will be manifest by differences in wave energy and sediment behaviour in the intertidal zone. At Ringstead Bay the offshore gradient is relatively uniform and wave energy is comparatively evenly distributed along the shoreline, whilst at Man O'War the offshore reef has an important filtering effect on incoming wave trains.

The second part of the pilot study was carried out on 14.10.82; variable wind direction between 5th and 9th changed to offshore (north to north west), force 1-4, up to, and including the survey date. The offshore wind had a dampening effect on the prevailing south westerly swell, resulting in a period of calm conditions, the maximum breaking wave height being in the order of 0.5m.

Under these conditions Ringstead beach produced a set of sediment samples that were generally of a finer grade but described the same range of size grades. Sediment grading, by size, showed a decrease in grain size towards the centre of the beach. The coarsest grades, on the end profiles, again displayed the best sorting. Man O'War displayed the same range of sediment grades on both survey dates. Sediment grading described an increase in mean grain size to the centre of the beach. Durdle Door beach produced a smaller range of well-sorted sediment grades than in the September survey, but retained a westward decrease in mean grain size (despite minor anomalies on profiles 9 and 11.

Few sediment samples produced bimodal distributions, computed skewness valves suggested that the majority of samples, from all three units and on both sampling dates described normal (unimodal) distributions. A small number of samples from Ringstead beach tended towards bimodality; the larger maximum at the pebble grade and the smaller maximum at the coarse sand grade. Samples from Durdle Door beach tended to describe a mix of one very predominant sediment size (in this case, gravel grade) and one very subordinate grade (usually the grade coarser or finer than the predominant grade). Such samples tended to be leptokurtic. Samples consisting of subequal mixtures of a number of sediment grades were collected on all three beach units and tended to display a platykurtic distribution. Man O'War sediment samples tended to consist of one predominant grade, the subordinate grade comprising 30-50% of the dominant grade.

Both surveys showed that all three beach units produced little shape variation, the majority of samples made up of blade and disc shaped particles. The lack of any significant variation in shape was a factor consistent with the findings of Carr (1971, 1974) during comprehensive research into sediment grading on Chesil beach. Carr found that flint/chert pebbles did not have a well-defined shape and fell marginally into Zingg's spherical class.

In this study mean values of elongation, flatness and sphericity showed little variation whilst bladed and disc shaped particles dominated the majority of samples. The results of the pilot study suggest that silica pebbles retain their proportions irrespective of grain size. The seemingly abherrant results are not a fault of calculation or computation as a manual check was carried out on a selected sample. A similar analysis on a sample of chalk pebbles illustrated that the larger pebbles, >-3.0 Ø, tend to be disc shaped and platy, but rapid attrition results in shape becoming increasingly more spherical with a decrease in grain size. From these results the shape development of silica and chalk pebbles shows an inverse relationship.

It is difficult to correlate specific changes in the patterns of grain size with particular wave climates, although it is likely that even minor variations in grain size are closely linked to the relationship between wave climates, wave refraction and beach orientation. The manner in which silica pebbles retain similar proportions despite attrition and wear may be a function of fracture; flint has a conchoidal fracture and broken fragments tend to be bladed in form. Shape may have a small role to play in the potential mobility of an individual particle, mobility being dependent on the hydraulic processes and nature of the underlying traction carpet. Carr and Blackley (1974) noted that disc shaped pebbles were the most mobile, being able to slide easily over the traction carpet under high energy waves. The predominance of bladed and disc shaped particles on the study beaches suggested that all pebble grades can be readily transported under semi-high/high energy wave regimes.

RECOMMENDATIONS FOR THE DEVELOPMENT OF A SEDIMENT SAMPLING PROGRAMME

1a. **Beach sections** : The designation of beach sections at 100.0m intervals produced a work load too excessive for one field worker. The results of the pilot study noted that neighbouring profiles often displayed similar morphology and sediment grades. A reduction in the number of beach sections was considered necessary and would not result in any significant loss of data (as illustrated by Orford's use of Information Theory 1978). It should be noted that samples obtained during the pilot study were collected after the same tide but the addition of two more study beaches would result in a sampling schedule that would take one person three days to carry out and thus results from all beach units would vary by ± 3 days (ideally all sampling should be carried out at the same time). In this light a reduced, but representative number of beach profiles were designated along each beach, resulting in 6 beach profiles at Ringstead, 9 at Durdle Door and 3 on Man O'War. Using the findings of the pilot study 3 profiles were located at Mupe and 4 at Worbarrow, (Figure 32).

1b. Each section to be located by a temporary bench mark levelled into the nearest Ordnance Survey bench mark.

2a. **Sampling Zones** : The use of only two sampling zones was insufficient to reveal any downbeach grading (by size or shape). Further sampling surveys would produce samples from four arbitrary zones:

(i) the backshore zone (BS) above the swash limit of the last high water. High water at the cliff foot on some occasions would prevent development of a backshore zone.

(ii) the high water zone, (HW).

(iii) the mid water zone, (MW)

(iv) the low water zone, (LW)

2b. **Sampling procedure** : Within the selected zone approximately 1kg. of sediment to be removed from the surface laminar within a one metre square. Samples of material > -2.0 Ø needed to contain at least 50 individual particles

3. **Laboratory techniques** : All samples to be oven dried and split into representative fractions. The representative fraction to be sieved following standard laboratory techniques on screens at 1/2 Ø intervals. The results of the sieving to be constructed as a cumulative frequency curve and the statistical parameters of mean, skewness, sorting and kurtosis to be derived.

A further investigation into reliability of individual particle size measurement to be carried out on a selected set of samples. The pilot study revealed that the technique produced inconsistent data sets because only the coarsest grade samples could be measured efficiently. Samples containing a range of sediment sizes were sieved and the coarser fractions (>-1.0 Ø) removed for further analysis, but with no regard for the finer sediments in the population results were biased towards the coarse grades. A rapid method of grain size analysis involving magnification of individual particles (> 0.0 Ø using an overhead projector (Burke & Freeth, 1978) was tried but was not considered to be a valuable method of analysis; the cuboid nature of sand particles still presented problems of measurement even under magnification. Operator error was potentially high and the method was not as rapid as suggested!

The pilot study implied that shape was not a highly variable parameter and played a limited role in sediment grading, and further investigations into shape development would be limited and treated with caution.

4. **Frequency of sampling** : The objectives of sediment sampling on the five study beaches were primarily concerned with the spatial variations in sediment grade presented by each beach unit, and the possibility of assessing preferred sediment transport directions as portrayed by the relationship between individual particles under identifiable hydraulic conditions. Due to the more general aims of this study regular sediment surveys were not considered necessary; too many sample sets would only confuse the more general trends sought after as well as producing an unnecessarily large workload. These considerations resulted in the decision to carry out an intensive survey over a period of one month on a selected beach. Durdle Door beach was selected because of its accessibility; daily changes of beach morphology to be measured by slope pantometer, but sediment samples were to be collected at approximately weekly intervals.

An additional survey, with samples to be collected from all five study beaches was programmed for the summer of 1984 to coincide with an offshore sampling program.

ONE MONTH SURVEY

DURDLE DOOR BEACH SEDIMENTOLOGY

The pilot study of alongshore variation in pebble size and shape on Durdle Door beach suggested an overall decrease in grain size from east (Durdle Door) to west (Bat's Head). Minor fluctuations in the trend suggested that the beach unit may in fact consist of three secondary circulatory systems that co-exist as a result of bayhead development. A daily beach monitoring and weekly sampling programme was designed to investigate this trend.

METHODS

Nine beach profiles were surveyed daily (over low water), between 25.1.83 and 22.2.83 where practical. Profile stations were surveyed by pantometer from temporary benchmarks down to chart datum. Beach material was sampled from each profile at approximately weekly intervals.

Four arbitrary foreshore zones were sampled along each section yielding a potential complete data set of 36 samples. The zones recognised were :

1. Backshore zone (the area beneath cliff unaffected by last High water).
2. High water zone.
3. Mid water zone.
4. Low water zone

In sandy/gravel area 1kg. of material was scooped from the beach surface within an area approximately 1m. square. In pebble areas, >50 pebbles per sample point were randomly collected from the surface. Complete data sets were not achieved due to a number of reasons :

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(1) storm/post storm conditions with associated long swash run up prevented sampling.
(2) exposure of chalk platform along western sections.
(3) where high water reached the cliff/beach junction no backshore samples could be collected.

LABORATORY PROCEDURE : All samples were treated to standard laboratory routine of drying, splitting and sieving (as described for the pilot study). Samples were dry sieved at 1/2 phi units for 15 minutes, weighed and the data plotted as cumulative frequency graphs. Graphic measures (mean grain size, skewness, sorting and kurtosis were devised using the formulae recommended by the pilot study. Pebble grade samples were subject to shape analysis in terms of the three mutually perpendicular axes, because only coarse samples were analysed the shape analysis data sets were used with reserve.

RESULTS : The results of particle size analysis are presented by Tables 19 (a-f) and 20 (a-f).

ALONGSHORE TRENDS OF MATERIAL SIZE : Alongshore variations in mean particle size for each profile sample site are illustrated in Tables 19a-f.

25.1.83 Along the backshore a marked decrease in pebble size from Durdle Door (fine pebbles) to profile 3 (very coarse sand) was seen, followed by an increase to pebble grade at profiles 4 and 5. Grading along the high water mark described similar pebble grades between profiles 1 and 4 with marked fining to very coarse sand grade on section 5. A similar trend in grading was illustrated by the mid water zone whilst the low water zone displayed the best grading, with a gradual decrease in grain size from profile 1 (medium pebbles) to profile 5 (very coarse sand).

30.1.83 Samples collected from the high water zone displayed a decrease in grain size from profile 1 to 3 (fine pebbles to very coarse sand). All samples from profiles 3 to 8 were coarse or very coarse sand, the finest mean grain sizes from profiles 4 and 8. Mid water zone samples produced a similar trend but with the finest sediment on profile 3, whilst samples from the low water zone also described a decrease in mean grain size from profile 1 to 4, followed by coarser grades on profile 5 and 7 and very coarse sand on profile 8.

8.2.83 Backshore samples showed a marked decrease in sediment grade from profile 1 (fine pebble) to profiles 3, 5 and 6 (gravel). Grading along the high water zone showed a very weak increase from profile 1 to 5 with a distinct change in grade on profiles 6 and 8 and a deviation to coarse sediment on profile 7. Mid water zone samples produced a decrease in mean grain size from profile 1 to 5. The western section of the beach produced a similar pattern with a decrease in sediment grade between profiles 6 and 8 (fine pebbles to very coarse sand). The low water zone produced the best grading with profiles 1 to 5 displaying medium pebble grades, and very coarse sand on profiles 6 and 8, divided by gravel on section 7.

16.2.83 Mean grain sizes along the backshore zone described a small range from gravel to coarse sand with fining to the west. High water samples increased in grain size to profile 5 (fine/medium pebbles), with a distinct change in grade at profiles 6 to 9 (very coarse sand/gravel). Samples from the mid water zone showed a tendency for fine and medium pebbles with deviations towards the ends of the beach (gravel at profile 2, very coarse sand at profile 8). Low water samples showed irregular oscillations along the beach with the coarsest grades found on profiles 1, 2, 6 and 8 (fine to medium pebbles).

21.2.83 Backshore samples indicated a fining westwards to profile 9, whilst along the high water mark grain size increased slightly from profile 1 to 5. Profile 6, being of exposed platform, divided the coarse pebbles of profile 5 from the very coarse sand of profile 7, followed by a marked coarsening of material to profile 9.

A reverse trend was displayed by samples from the mid water zone by sections 1 to 5, with fining from medium pebbles to gravel, whilst sections 7 to 9 displayed a coarsening of sediment (like the high water zone), from coarse sand to fine pebbles. Once again low water samples produced best grading with a fining of material westwards with gravel/very coarse sand grades dominating sections 2 to 5.

1.3.83 High water samples displayed no definite trend with oscillations between fine and medium pebbles along sections 1 to 5, with a change to very coarse sand on profiles 6 and 7 and an increase in grain size to profile 9 (fine pebbles). Mid water samples also displayed an oscillatory trend with fining towards profile 4 and profile 7. Coarsest grades were found at the ends and centre of the beach. Low water samples displayed a simpler trend with fining from both ends of the beach towards the centre.

DOWNBEACH TRENDS OF MATERIAL SIZE

25.1.83 Downbeach trends in mean grain size highlighted the banded nature of foreshore sediments. Greatest variation was found along sections 2, 3 and 4, the best grading along sections 1 and 5. With the exception of profile 1 the finest grade sediments were found in the low water zone, the coarsest grades at high water.

30.1.83 Samples collected on this date showed a definite tendency towards uniformity or gradual grading down the foreshore. Sections 1 and 3 produced total uniformity down their profiles (fine pebbles and very coarse sand respectively); in general coarse grades were found along the mid and low water.

8.2.83 Samples collected from sections 1 to 4 showed marked uniformity with a predominance of pebble grades. The western half of the beach, sections 5 to 8 produced a more banded facies of coarse sands and pebble grades; section 9 showed a more uniform grading within the sand fractions.

16.2.83 Downbeach grading of sediment size produced a more variable pattern than found on the previous sampling date.

Sections produced definite grading trends. Section 1 tended towards pebble fractions with section 2 showing a marked banding of alternate gravel and pebble grades. Sections 3, 4 and 5 all displayed a like pattern with coarse grades along high and mid water, banded by sand grades along the backshore and low water zone. Sections 6 to 9 were of a more variable nature with few similarities in any of the zones. There was, however, a weak tendency for coarser grades to be found towards low water.

21.2.83 Downbeach trends displayed a tendency for consistency of grade in different zones. Pebble grades dominated all 4 zones of section 1 whilst sections 2 to 5 showed a tendency towards pebble grades along high water with gravel or very coarse sand in both the backshore, mid and low water zones. Beyond the exposed platform (section 6) towards Bat's Head sand grades predominated with gravels at the low water mark.

1.3.83 Pebble grades predominated the sample set. Sections 2 to 5 showed a gradual fining of material to low water. Section 7 displayed a reversal of that trend with fining towards the high water mark. Sections 6 and 8 were of a more variable nature ranging from coarse sand to find pebble grades, whilst section 9 produced an identical pattern to that of section 1 (pebble grades).

SORTING, SKEWNESS AND KURTOSIS

25.1.83 55% of the samples collected were very well sorted with a further 25% well sorted. The degree of sorting was well developed both along and down beach, particularly in the mid and low water zones, with nearly all samples in those zones very well sorted. Many of the very well sorted samples also displayed normal kurtosis, whilst samples with extreme values of kurtosis nearly all displayed extreme skewness. With the exception of section 1 the best sorting values were produced by the finer sediment grades that also tended to be mesokurtic. No similar trend was displayed by skewness values, positive values being dominant, especially in the backshore and high water zones where sorting was not so well developed.

30.1.83 The small range in sediment size was not reflected by a similar trend in sorting values. Despite the variability of sorting values 35% of the samples were well sorted; sorting was best developed down the foreshore than along the beach. Better sorting values were associated with down beach uniformity of sediment grade (profile 1), while the poorest sorting values were displayed by samples from the low water zone. Mesokurtic distributions were linked to the better sorted samples whilst extreme skewness was associated with extreme kurtosis. However, samples symmetrically skewed were not necessarily mesokurtically distributed.

8.2.83 Size grading was best developed down each beach section, although along beach trends were also recognised. Pebble grades of sections 1 to 4 displayed the best sorting values (particularly sections 1 and 2). The poorest sorting values were displayed by section 7 where extreme kurtosis and skewness values were also found. The better sorted samples tended to be of mesokurtic distribution although some displayed weak negative skewness.

16.2.83 This sample set produced a very variable size range with weak down/along beach grading. This variation was reflected in the other size parameters. Poor sorting values dominated the data set (34%) particularly samples collected from the mid water zone (and sections 3-6). The poor sorting values were highlighted by extreme kurtosis and skewness values, especially on sections 4 to 8, these values were also associated with fine pebble grades.

21.2.83 Along beach size grading was better developed than down beach grading, with the best sorting values recorded on the end sections (1 and 9), where there was a degree of uniformity of sediment size. Down the foreshore the best sorting values were recorded in the mid and low water zones. As with the other data sets extreme kurtosis and skewness values were linked whilst mesokurtic distribution tended to produce the best sorting values. The degree of sorting could not be associated with any particular sediment grade.

1.3.83 The sediment distribution tended towards down beach grading, especially down the extreme sections (1 and 9 which displayed identical zonal sediment grading). The samples produced a variety of sorting values and despite a majority of very well sorted distributions (39%), poorly sorted samples accounted for 27.5% of the sample population. Nearly all the low water samples displayed the best sorting and mesokurtic/symmetrical distributions, whilst the poorly sorted samples were produced by the high and mid water zones. The majority of the poorly sorted samples also displayed extreme values of skewness and kurtosis.

SHAPE INDICES

Shape indices were used as a means of giving a single descriptive term or value to define the mean shape of each sample. Shape indices were only computed for those samples consisting wholly of pebble grades - data sets are therefore limited. Table 20a-f lists those samples subjected to shape analysis by means of results.

25.1.83 Results for profile 1 indicate that the variation between individual form indices was very small. Elongation values tended to decrease down the profile whilst sphericity increased. Sneed and Folk classification showed a predominance of very bladed and very elongated pebbles at all sample sites, whilst Zingg classes indicated an abundance of disc shapes with an increasing percentage of rod shapes at low water. Along beach variations suggested that elongation values remained stable along the high water zone whilst flatness decreased. The best values of sphericity were found on section 2. Sneed and Folk classes indicated an increase in very bladed pebbles towards section 4 (82%), whilst Zingg classification indicated an increase in disc shapes.

30.1.83 Samples from profile 1 showed a down-beach decrease in elongation and flatness with an increase in sphericity. The decrease in very bladed particles was replaced by an increase in very platy and disc shaped particles. (No other samples were measured.)

8.2.83 Sections 1 to 4 produced measurable samples. Elongation values were unvariable providing no definite trend. Flatness values reached a maximum on profiles 3 and 4 with sphericity at a minimum on profile 3. Sneed and Folk classes revealed that nearly all samples were dominated by very bladed particles with very elongate particles in a subordinate role (except 2 low water and 4 mid water where the reverse was true). In general, however, no definite trend in shape change could be recognised either down or along beach. According to Zingg classes discs dominated all measured samples except for high water profile 2 and profile 4 mid water.

16.2.83 The majority of samples collected were not suited to axes measurement so that not one profile produced a complete down beach profile set. All sections produced a high percentage of very bladed (Sneed and Folk) and disc shaped particles (Zingg). Sphericity values tended to increase to the west.

21.2.83 Profile 1 provided a complete set of samples for shape analysis but further west only high water samples were suited to measurement (profiles 2, 3, 4, 5 and 9). Down beach variations on section 1 showed a decrease in elongation and flatness with an increase in sphericity. Along beach variations showed an increase in elongation and flatness values westward to profile 4. Sphericity values showed an inverse relationship.

1.3.83 Sections 1, 2 and 9 produced complete data sets suitable for shape measurement. Only the high water samples of sections 2, 3, 4 and 5 were suitable for measurement. No definite down beach trend was recognised due to the lack of data. The available data did describe a decrease in flatness and elongation westwards along the highwater zone with a consequent increase in sphericity values. Disc shaped particles dominated the high water zone, decreasing in percentage towards profile 3 but increasing again towards profile 8. Spheres were the dominant shape at high water on section 9.

DISCUSSION

The large amount of data generated by intensive weekly sampling produced complex results. Graphically derived measures have been used in an attempt to infer the characteristic behaviour and environmental significance of the sediment distribution on Durdle Door beach, over a limited period.

Particle size analysis indicated that greater differences in mean grain size existed over the beach unit as opposed to between surveys. The variation in mean grain size on any one survey ranged between -4.0 Ø and 0.12 Ø (medium pebbles to medium sand). The best grading by size/sorting was displayed by down beach samples, especially those collected from the end profiles; it should also be noted that grain size and sorting increased as energy increased, the best sorting was displayed by samples with a mean grain size around -3.0 0. Particle size is regarded as a reflection of the competency of the transporting agent, different size fractions being differently affected by flow processes on the foreshore, the variability of hydraulic conditions highlighted by the spread of grain size. Thus size grading is primarily attributed to a variation in wave energy as determined by such factors as offshore topography and subsequent wave refraction. Selective sorting of sediment is often attributed to the direction of longshore transport, Siebold (1963) stated that the direction of transport may be determined from the grain size distribution if sorting is considered. Sunamura and Horikawa (1972) exploited the situation and produced an improved method for inferring littoral transport by considering sorting (and a defined source area). However, observations on Durdle Door beach suggest that longshore drift is not pronounced under prevailing south westerly swell; waves approaching from the south west quadrant break normal to the shore and a direct onshore-offshore exchange of material is more likely than longshore drift (contrary to findings by Kirk, on mixed beaches on the coast of New Zealand).

Weekly sampling showed that although sediment grading on Durdle Door tends to differ spatially, in a temporal sense it remains relatively stable. The temporal differences experienced by a beach have been linked to the degree of dissipation/reflectance of the beach system, but the relationship is really a complex link between beach morphology and wave characteristics (Kemp, 1960). From the results of particle size analysis on Durdle Door the beach may be described as reflective, particularly within Durdle Cove where the beach is best developed with a steep foreshore, storm crest and coarse sedimentology (pebble grades). Further west, however, the beach is flatter, shallower and experiences a greater variation in grain size and thus tends to be more dissipative in nature. It may in fact, reflect a transition situation between the two extremes of reflection and dissipation.

Sediment distributions also adjust to changing wave climates in an attempt to achieve equilibrium. On Durdle Door small waves of short period (commonly locally generated seas), and where backwash interference is significant, sediments often display a banded distribution over the foreshore; high proportions of coarse material remain stranded resulting in bimodal samples with poor sorting and extreme values of skewness and kurtosis (particularly noticeable along the western section of the beach at high and mid water). The scatter of coarse material over background sediment (traction carpet), may be a result of particle rejection under changing wave conditions (Gleason and Hardcastle, 1977) it being fair to say that under certain conditions only certain sizes are actively transported. A change in the wave regime may be ideal for the drift of coarse material over the surface whilst higher energy conditions tend to hide coarse fractions amongst the most abundant population with an associated reduction in mean grain size (Gleason and Hardcastle, 1970).

Table 21 describes littoral environment observations for the survey dates with additional meteorological data for the rest of the month. The survey of 25.1.83 coincided with a small storm event from the south. Samples collected on this date tended to be unimodal in distribution; many of the upper foreshore samples showed a tendency for subequal dominance of several similar grain sizes, whilst the mid to low water samples were dominated by one grain size.

Samples collected on 30.1.83 coincided with the peak of a small storm event with a dominant south west swell and breaking wave heights up to 1.50m, sediment sampling was difficult and samples tended to display bimodal distributions with maxima at 0.5 Ø and -2.0 Ø (medium sand and fine pebbles). The increase in wave energy, swash and backwash resulted in the exposure of the underlying platform at profile 6.

The remainder of the month was dominated by offshore winds from the north and east which had a damping effect on the prevailing but diminishing southwesterly swell. The change in wave climate resulted in intense erosion of the foreshore and exposure of the platform along profile 9 (8.2.83). Easterly generated seas increased the potential for longshore drift, reflected by poor sorting values and a greater variety of sediment size along and down the beach (16.2.83). Similar conditions prevailed until 21.2.83 but by this time the sediment distribution was reaching equilibrium with the prevailing wave climate. Size/sorting grading was better developed but exposure of the platform at profile 6 possibly highlighted a concentration of wave energy. By 1.3.83 wind direction had swung back to south westerly and the distribution of sediment was not in equilibrium with the prevailing regime. More samples tended to be bimodal with maxima at -4.0 Ø (medium pebbles) and -1.0 Ø (gravel).

The best sorting values were displayed by coarse sediments along steepest, most exposed profiles, (especially within Durdle Cove). Further west the best sorting was produced at low water and may be linked to the existence of a double low water. The low water zone is also the most susceptible region to drift, a changing wave climate may initiate drift and produce bimodal sediment distributions with extreme values of skewness and kurtosis.

Shape grading was not considered significant on Durdle Door beach, although blades and discs dominated the sediment distribution a higher proportion was noted on the upper foreshore where they are concentrated by high energy conditions (Caldwell, 1983).

SUMMER SURVEY 1984

During August 1984 further sets of sediment samples were collected from each study beach in an attempt to evaluate the variation in particle size following a period of calm, stable meteorological and oceanographical conditions.

METHODOLOGY AND RESULTS :

Sediment sampling and laboratory analysis was carried out following the procedure recommended by the pilot study. The results of particle size analysis are presented for each beach in turn :

RINGSTEAD : Examination of the results of particle size analysis (Table 22) reveals that mean grain size of the majority of samples fell within the small range of -4.6 Ø to -2.10 Ø; only the mid water sample from profile 4 produced a mean value out of the pebble grades (+1.82 Ø). Within this small range samples from the high water zone displayed marked grading westwards towards profile 6 (-3.94 Ø to -2.3 Ø). This zone also produced the coarsest sediment grades. Samples from the mid water zone described the greatest variation in longshore sediment grading ranging from -3.95 Ø (profile 2) to +1.82 Ø (profile 4). Downbeach trends showed a uniformity of grade along the profiles towards the ends of the beach, whilst the central profiles (3, 4 and 5) described a weak tendency towards banding with coarse grades along high water and finer grades along the remaining zones.

The small range of mean sediment size was not reflected by the sorting values; the coarsest sediments sampled on profiles 1 and 2 were very well sorted. Sorting values tended to diminish from both ends of the beach towards profile 4, with only profile 5 describing any down beach uniformity, all samples being moderately well sorted. The remaining profiles produced sorting values that tended to diminish seaward with the poorest values recorded along the low water zone. The variation in sorting values was reflected in the extreme values of skewness and kurtosis recorded; skewness values tended to become more extreme seaward, whilst the most extreme kurtosis values were recorded at the high and mid water sampling points of profile 3.

DURDLE DOOR (Table 23) : The main grain size of the majority of samples fell within a small range of pebble grades (-4.21 0 on profile 9 to -2.37 on profile 4), with only 4 samples falling within the finer gravel and very coarse sand grades (backshore zones of profiles 2, 5, 6 and 8). Alongshore variations in grain size showed great uniformity with the greatest range along the backshore, reaching a minimum at profile 5 and a maximum on profile 7, resulting in alternate zones of pebbles and fines. Samples from the high water zone displayed an increase in grain size from both ends of the beach towards the centre (profiles 4 to 7), where mean grain size ranged between -3.85 0 and -4.09 0). The mid water zone produced a small decrease in mean grain size from the central towards the extreme profiles, whilst low water samples displayed the greatest alongshore uniformity producing medium pebble grades on all profiles. Downbeach variations in mean grain size highlighted the banded nature of surface sediments, the finest grades along the backshore and the coarsest grades along the high and low water zones.

Sorting values produced a pattern of best sorting towards the centre and extremities of the beach; profiles 1, 5, 6 and 9 also displayed an increase in sorting in a seaward direction, particularly along the mid water zone. The small range of mean sediment sizes and good sorting values was reflected in the normality of the skewness and kurtosis distributions.

MAN O'WAR (Table 24) : Alongshore variations in mean grain size displayed a marked decrease in grain size (in all zones) to the east, ranging from very coarse and coarse pebbles on profile 1 to fine pebbles and gravel on profile 3. Downbeach uniformity of mean grain size was displayed by all three profiles, particularly profile 2 where the range was very small. Such uniformity was not displayed by the sorting values; profile 2 displayed extreme sorting values, poor sorting on the backshore and very well sorted sediment at high water. A weak trend of diminishing sorting in a seaward direction was noted. Sorting also diminished eastwards along the low water zone. Mesokurtic distributions were produced by samples from profiles 2 and 3 but tended to be positively skewed. Extremes of skewness and kurtosis were produced by samples from profiles 1 and 2 coinciding with the coarsest sediment grades.

MUPE (Table 25) : Particle size analysis indicated a marked similarity of mean grain size on profiles 1 and 3 with an increase in mean size on profile 2. Alongshore and downbeach values of mean grain size highlighted the "mirror" image about a central axis, profile 2. Only the backshore sample from profile 1 disrupts the pattern of downbeach fining from pebbles to gravel. Profile 2 produced coarse pebble grades on all zones.

Sorting, skewness and kurtosis values did not describe the consistency of mean grain size. Sorting diminished in a seaward direction, the best sorting produced by samples from profile 2; the gravel fractions at low water on profiles 1 and 3 produced poor sorting values. Skewness values showed that samples tended to be symmetrical or negatively skewed, but kurtosis values indicated that many of the samples, especially those from profile 2 were not normally distributed.

WORBARROW (Table 26) : Variations in mean grain size indicated that the majority of samples collected fell into the pebble grades within the mean size range -2.01 Ø to -4.49 Ø. Only 2 samples (profile 3, backshore; profile 4, mid water) produced samples with a mean grain size finer than pebble grade. Both alongshore and down beach the coarsest mean grain sizes were found on profiles 3 and 4, whilst profiles 1 and 2 displayed a greater degree of uniformity of grade seaward. Such uniformity was not shown by the sorting values. Profile 3 displayed the best sorting values but extreme values of skewness and kurtosis. The mid and low water samples from profile 1 were poorly sorted, the remaining samples ranging from moderately to well sorted. All the low water samples described positively skewed, platykurtic distributions.

OFFSHORE SEDIMENTOLOGY

A survey of the surficial sediments of each study bay was carried out during the period July to September 1984. The survey was restricted to the shallow water zone (0 - 10m.) and samples were collected by one of two methods :

(i) free swimming divers
(ii) Van Veen grab

Underwater survey by free swimming divers

The general aims of the survey were twofold :

(i) to measure the physical characteristics of each bay along pre-selected profiles. (Each profile was orientated perpendicular to the shoreline as a natural extension of the beach profiles that were already being monitored on a monthly basis.

(ii) to identify, record and collect seabed sediment samples at regular intervals along each 100m transect.

Diving survey techniques : The nature of each dive was largely dictated by local conditions (e.g. weather, tides, currents), all dives being boat-based (inflatable, courtesy of U.W.I.S.T-Maritime Studies Department). Transect lines were marked by a length of weighted rope, staked into the beach at the low water mark and a marker buoy at its seaward limit. The rope length was divided into 10m. sections by numbered plastic tags. The diver was equipped with a prepared dive site log on a writing board. At each location along the transect a number of observations were made with regard to depth, seabed sediment type, seabed morphological features and vegetation. Sediment samples were collected at each location and placed in self-sealing, numbered plastic bags.

It was envisaged that sediment sampling and profiling would be carried out by free swimming divers in all the study bays. However, a number of logistical problems prevented it from being a reality (e.g. limited availability of divers/inflatable, access to a slipway and weather conditions. As a result only three transects were dived; two in Ringstead Bay and one in Worbarrow Bay. Transects were selected by their degree of exposure.

RINGSTEAD BAY (July 1984) : Two transect lines were dived normal to beach profiles 4 and 6 (Figure 33). Two divers worked together along each transect, one to record observations, the other to collect samples. The samples were treated to standard laboratory sieving procedure and the derivation of graphic measures as outlined in the pilot study.

WORBARROW BAY (August 1984) : Only one transect was dived in Worbarrow Bay; accessibility to the bay is limited, even by boat, the nearest slipway being 2.5 nautical miles to the east. Only one diver was available for the survey and due to time constraints and a deterioration in sea conditions only one transect (corresponding to beach profile 2, Figure 34) was surveyed.

RESULTS :

Figure 33 (a;b) shows morphological variation and sediment characteristics along the two transects in Ringstead Bay. Graphic Measures for samples collected at 10 m intervals are tabulated below each profile. Table 27 describes the breakdown of each sample; only the percentage of the dominant grade is given.

Nearshore profile 1 (Figure 33a), the most exposed profile to prevailing and predominant south west winds displayed an undulating profile resulting in a gradual shelving from 0.61m at 10m. to 7.6m at 100m. A small but pronounced "step"

20m.from the low water mark marked the seaward extent of the 'beach'. Pebbles (all grades) and gravel dominated the low water terrace before falling away to flat bed sands and thin sediment veneers over bedrock, that extended up to 100m. offshore. Weed growth was most dense on exposed patches of bedrock (60 - 100m. offshore). Areas with surficial pebble or sand deposits displayed little (25 - 40m.) or no weed (0 - 20m., 40 - 60m.).

Mean particle size values suggested a gradual fining of material to a point approximately 50m. offshore. Sediment size between 50m. and 100m. offshore remained stable, the section dominated by fine to medium pebble grades; many of the coarser pebbles displayed organic coatings (particularly barnacles) and animal borings, suggesting limited mobility.

Sorting values suggested a poorer degree of sorting as sediment size decreased. Samples collected from the section 40m. to 60m. offshore (coinciding with no weed growth) displayed poorest sorting values. Samples shoreward of that point were only moderately sorted whilst those collected between 60m. to 100m. offshore (dense weed growth) produced very good sorting values.

Kurtosis values were all in the leptokurtic range indicating a coarse tail to the distribution. Both the poorest and best sorted samples displayed extremely leptokurtic distributions. Skewness values were more variable although the majority were very positively skewed; only one sample displayed negative skewness - the sand sample from 50.0m offshore.

Nearshore profile 2 (offshore extension of beach profile 6) marked the edge of the boulder field that skirts White Nothe headland. The transect represented the eastern boundary of Ringstead Bay. Morphologically the transect showed a uniform, gradual increase in depth from 0.60m. at 10m. offshore to 4.6m at 100m. offshore. The presence of boulders (up to 3m. in length) from 20m. offshore coincided with very weed growth. Sediments surrounding the boulders ranged from pebbles and gravel to a sand bed. Where boulders were not present the flat bed sands showed rippling, the ripples tending south west - north east, at 45° to the shoreline. Flat bed sands showed little or no weed growth.

In general, mean grain size decreased offshore, with only minor perturbations in the trend, e.g. coarse grades at 40.0m, (Table 26). Sand grades dominated the 80.0 to 100.0m offshore section. Sorting values showed no correlation with grain size with both sand and pebble grades displaying moderately well to very poor sorting values. Skewness and kurtosis values were also variable, no general trend between grain size parameters being discernible.

WORBARROW BAY : Only one transect was surveyed in Worbarrow Bay, an offshore extension of beach profile 2, the most exposed profile. The morphological and sedimentological variations are shown in Figure 34. Morphologically the seabed shelves to a depth of 3.5m at 28.0m offshore where the cobble and pebble ridge (suggesting the seaward extent of the beach) drops away to 4.5m and a rippled sand bed with a scatter of pebbles and exposed bedrock. From this point to 100.0m offshore the seabed shelves gently away to 7.6m. Weed growth is mainly limited to the section 55 - 70 m offshore (on a silt bed) and small lumps grow on patches of exposed bedrock.

Mean grain size values indicated a slight fining offshore, but pebble and gravel grades dominated the whole transect, (Table 27). Medium grade pebbles dominated the 0 - 60 m offshore section with the coarsest mean grain size around 50.0m offshore. Sorting tended to become poorer offshore irrespective of grain size with the coarsest sample displaying the best degree of sorting. All samples, with the exception of that from 40 m offshore displayed very positive or positive skewness indicative of a fine tail to the size distribution.

DISCUSSION

Theoretically the employment of free swimming divers for the collection of nearshore data is a sound idea, but practical problems tended to be logistical in nature - availability of divers and boat, accessibility to a slipway and sea conditions had to be considered. A briefing of divers before each survey and a de-brief session after each dive was of particular importance for accurate records to be maintained. In terms of sedimentological variation, representative samples were the most important consideration of which the divers had to be made aware.

Two divers were insufficient for the number of transects to be measured within the time constraints of the sampling programme; a team of six divers would have been necessary for a complete survey of the nearshore extensions of all beach profiles (assuming that the problems of boat availability, slipway accessibility could be overcome and that tide and sea conditions were suitable for diving).

Supplementary observations were made by the author snorkelling within each bay and the data collected was enough to verify certain inferences that had been made prior to the offshore survey :

(i) the seaward extension of each beach ends abruptly with a steplike feature, a characteristic feature of all the study beaches occurring between 20 - 30 m offshore.

(ii) the nearshore zone displays a distinct change in sediment size from the relatively coarse sediments of the beach extension to the thin veneer of fine sediments over bedrock. Pebbles, of all size grades lie scattered on this fine surficial sediment. The thin veneer of sediment is broken by isolated patches of exposed bedrock which provide suitable surfaces for dense weed growth. Weed growth is prolific during the early summer particularly within Ringstead Bay and Man

O'War Cove where it grows on an undulating rocky bottom and within 5m. of the low water mark. At Durdle Door weed growth is prolific on the chalk platform within the shelter of Bat's Head and on the submerged reef that extends along almost the entire length of the bay. Outside the reef the depth drops to 14.0m and the seafloor is littered with fragmented pebbles and small boulders, kelp does not grow in this more turbulent environment. Within Worbarrow and Mupe bays kelp growth is not so extensive, limited to the patches of exposed bedrock and boulder fields within 100.0m of the low water mark.

Dense kelp growth may be an important factor in preventing mobility of sediment across the seafloor towards the littoral zone, particularly during the summer months. The growth of weed on exposed bedrock may encourage the accumulation of fines around the holdfasts. During storm conditions large amounts of kelp are torn away from the bedrock and are washed up onto the beaches where they may play an active role in beach nourishment; during kelp growth small pebbles become entrapped within the holdfast and when the holdfast is torn off it carries away the small pebbles and fragments of bedrock. Once in the littoral zone the pebbles and fragments are released into the beach system by rotting of the kelp.

GRAB SAMPLE DATA

To supplement the data provided by the diver based survey a further survey of offshore sediments was carried out by grab sampling. Samples were collected from Worbarrow, Mupe, Man O'War and Durdle Door bays during August 1984.

METHOD : A Van Veen grab was used to obtain samples. The grab consists of a bucket which drives into the sediment, closes and retains a sample. The Van Veen relies on the line pull from the boat to achieve closure. However, the use of a Van Veen grab is not without problems :

(1) A sample obtained may not be representative of the general area being sampled.

(2) When sampling heavily consolidated fine clays the grab may be unable to penetrate the surface sufficiently. Any small sample obtained will invariably be washed out as the grab is lifted to the surface by the water trapped in the bucket.

(3) Coarse grained samples will not always be representative by size or weight. Large pebbles trapped in the teeth of the grab may prevent closure of the bucket so that as it is lifted to the surface any other material retained will be washed out.

(4) Dense weed growth will prevent adequate operation of the bucket whilst crevasses in bedrock may trap the grab preventing both closure and recovery.

WORBARROW AND MUPE BAYS : The sampling area was restricted by water depth and no samples were obtained more than 300m offshore. Sample locations were chosen to correspond with the beach profiles that were being regularly surveyed. Additional samples were collected towards Arish Mell. Position fixing was by hand compass bearings on conspicuous points (giving a good angle of cut).

DURDLE DOOR AND MAN O'WAR COVE : Samples from Durdle Door were obtained, where possible, from locations shoreward and immediately seaward of the "barrier". Within Man O'War Cove sampling was prevented by dense kelp.

All samples considered representative by weight were subjected to standard laboratory practice. Samples not considered representative or consisting wholly of shell material were evaluated by visual assessment.

RESULTS : Figures 35 and 36 show sampling sites and Tables 28 and 29 show particle size distribution derived from cumulative frequency curves. Grab samples from Worbarrow Bay displayed a high percentage of sand. In all cases (except sample 2.2 where pebble grades accounted for >40% sample weight and in some cases >90%). The distribution pattern of sediment from grab samples suggests a fining of sediment offshore towards the central section of the bay. Towards the headlands coarser sediments are found, with boulders off Worbarrow Tout and Cow Corner to Cover Hole. The general trend of sediment distribution within the bay indicated a general fining of material in an offshore direction and towards the centre of the bay from east and west. The fine sand grades of the central and western sections of the bay tended to be negatively skewed whilst the coarser grades produced normal to positively skewed distributions. The fine sand grades also displayed the best sorting, only samples collected within close proximity of the offshore boulder fields at the extremities of the bay were poorly sorted and displayed extreme kurtosis values. Along the whole length of the bay sand grades were sampled within 40m. of the low water mark whilst the very central section of the bay (samples 5.1, 5.2 and 5.3) produced samples that consisted wholly of shell (broken and whole).

Size distributions of samples collected from Durdle Door bay indicated a predominance of pebble grades (Table 29). The general trend was one of decreasing grain size with an increase in the percentage of sand grades towards the centre of the bay (off Scratchy Bottom). Samples with the highest percentage (by weight) of pebble grades were obtained from within Durdle Cove. Samples 8, 9 and 10 indicated a decrease in the pebble fraction offshore (>75% at sample 8 approximately 30m. offshore to just over 55% midway between the beach and the barrier). Despite an offshore decrease in grain size sediment size increased towards the extremities of the bay with coarse pebbles to the east and gravel and fine pebble fractions to the west. Computed values of mean grain size tended to emphasise the coarser fractions of each sample. Sorting was not well developed, only sample 12 was well sorted. The coarsest grades tended to be poorly sorted with extreme kurtosis values.

OFFSHORE SEDIMENT DATA FROM OTHER SOURCES

Nineteen samples of seabed deposits were obtained during an Admiralty Survey of Worbarrow Bay in 1956 (in connection with the siting of effluent outfall from the UKAEA site at Winfrith). The samples were examined for their lithological-mineralogical character with particular reference to their clay content. Some samples were only subjected to visual assessment but the majority were sieved. Results of the survey are shown in Figure 37. As a consequence of the siting of the pipeline further surveys have been carried out as part of a general monitoring program in Weymouth Bay. Data regarding the nature of the seabed collected in a 1960/1961 survey and data from a more recent survey has been supplied by UKAEA Winfrith.

RESULTS

1. 1958 AERE Survey, Weymouth Bay

Results from this survey can only be treated in a qualitative manner but provide a pattern of surficial sediments along a line 4 kms. south east from Arish Mell. Coarse sand with shell debris dominated the samples collected to a point approximately 1km. off Arish Mell Gap, (samples 1 to 5 inclusive). Seaward samples were predominantly broken shell with shale or quartz, sand and shell. The general pattern was one of sediment fining seaward, with an increasing proportion of shell material to a point approximately 2km. offshore whereupon the proportion of sand to shell increased.

2. 1960/1961 AERE Survey, Weymouth Bay

By plotting the qualitative results obtained from the surveys a general pattern of surficial sediments within the bay emerges (Figure 38). The inner reaches of Weymouth bay was floored by fine sands and muddy sands with gravelly sand and pebble patches. Towards the Ringstead Ledges mud and sand formed a thin veneer over a rocky bottom. Samples were also obtained along a line running north east from Adamant Shoal towards Mupe Rocks and from a 'block' south and southeast of Worbarrow Bay. Samples from the Adamant Shoal comprised sand with whole or broken shell material (confirmed by IOS survey 1983). Shoreward, samples were sandy gravels, muds and broken shell lying as a thin veneer over a rocky bottom. Bedrock was exposed at all sampling locations from a point immediately south of the Lulworth Banks to Mupe Rocks whilst to the south and southeast of Worbarrow samples consisted of sandy gravels with broken shell.

3. AERE Survey (1984)

Results of a recent survey of sediments taken from the area around the Arish Mell pipeline are reproduced in Figure 39. The general pattern indicates a predominance of broken shell around the pipeline with increasing amounts of sand towards the end of the pipeline. More intensive sampling around the end of the pipeline produced a high percentage of sand.

DISCUSSION

An attempt has been made to illustrate the general pattern of sediment distribution within each bayhead unit. By supplementing data prepared by the author with data supplied by AERE a broad picture of sediment distribution over an area stretching from Weymouth to Worbarrow Tout and south to the Adamant Shoal emerges. Although the AERE survey results at at least 25 years old more recent surveys suggest that a similar distribution still exists. Sonographs (assorted records 1981-1983, Waverley Electronics, personal communication, 1983), illustrate the sediment types found in Weymouth embayment and Worbarrow Bay, whilst the most recent AERE survey along the Arish Mell pipeline confirms a similar distribution to that found in 1960/1961. The investigative survey over the Adamant Shoal carried out by the Institute of Oceanographic Sciences (1980) indicated that surficial sediments were dominated by large amounts of shell material with sand, as discovered by AERE in 1960/1961. Local divers (Hamworthy Sub-Aqua Club, personal communication, 1983) have confirmed the presence of a thin veneer of sands, gravels and shelly material over the Lulworth Banks, much of the sediment being rippled between rock ridges.

The data reveals that Weymouth Bay is floored by a thin veneer of sediment, mainly sands and gravels with large amounts of shell material. The I.O.S. (1980) survey suggested that if large deposits of gravel do exist around the Adamant Shoal and Shambles Bank area they are "screened" beneath the surface sands and shell. Large amounts of broken shell and sand are to be found south of Worbarrow Bay, the proportion of gravel increasing within the bays. West of Worbarrow Bay the Lulworth Banks has a thin sediment cover, with large areas of exposed bedrock. The Banks are the remnants of an eroded dome and the upstanding ridges act as sediment traps. Further west the proportion of sandy sediment increases; large tracts of rippled sand are interspersed with featureless areas of flat bed sands. In the Weymouth embayment sediments become finer and much of the central and southern sections of the embayment are floored by muddy sediments with patches of fine sands and gravels.

The side scan survey carried out in 1984 (by the author) revealed that the coastal section between Ringstead and Worbarrow Tout (seaward of the 10.0m bathymetric contour) is dominated by large areas of rippled sands, gravels and shelly material. Exposed rock outcrops coincided with major geological features such as the Purbeck Anticline and the upstanding Portland Stone ridge. Within each bay sediments became coarser, with an increase in pebble fractions, towards the beach.

Cliffs dominated by large rockfalls and scree material mark areas of submerged boulder fields. Much of the seafloor off Cover Hole (Worbarrow Bay), is littered with large boulders (up to 4m. length). White Nothe headland also produces large amounts of boulder sized material that becomes incorporated into the boulder field that extends from the intertidal zone to a water depth of up to 5m. Vertical cliffs that plunge directly into the sea tend to mark areas of exposed bedrock with only a scatter of fragmented coarse sediment and boulders.

South of Worbarrow Bay much of the shell material present is heavily fragmented, whilst in the bay the shell material collected as grab samples consisted of whole shells. Only shell material sampled in areas dominated by gravels tended to show fragmentation as a result of attrition between the two materials. The presence of whole shell material suggests that the area is not a very high energy environment or that the central section of the bay acts as a sediment sink. Particle size analysis of grab and dive samples indicates that mean grain size increases towards the low water mark. Throughout Mupe Bay pebble grades dominate; the presence of organic growth and animal borings on pebbles sampled suggest that sediment within the bay is not very mobile. Mupe Bay is sheltered from dominant storm waves by Mupe Rocks and Ledges;

only storm waves approaching from the south east will have a significant impact on sediment mobility.

Similar distributions are seen in Durdle Door and Ringstead Bays with the finest sediments found towards the centre of each bay. Pebble grades tend to be found scattered over the seabed up to 100m. offshore whilst close inshore they appear to mark the seaward extent of the beach (up to 30m. offshore) in the form of a distinct pebble ridge.

Evidence of Sediment Mobility

Synthesis of all the available data concerning the distribution of sediment within Weymouth Bay indicates that the area is dominated by fine materials ranging from gravel to muds and silts. The distribution of grain size and sedimentary bedforms may be used as an indicator of sediment transport (Davies, 1980). Sediments get finer the farther they are from their source because they are carried in suspension, with a tendency to move in the direction of the flood tide. The amount in transport and the distance travelled will depend on the current strength. In Weymouth Bay the finest sands and muds are to be found within Weymouth embayment. Some of the muds will have been transported to the bay by the River Wey but its deposition close inshore suggests a decrease in energy and relatively calm conditions. Some of the material will be derived from the clay cliffs north east of Weymouth. However, the high proportion of fine sands imply the end of the transport path and weak currents.

Exposed rock outcrops (such as the Lulworth Banks) imply a shallow surficial sediment cover. Sediment that is available for mobility is concentrated into sand and gravel ribbons and ripples by tidally induced water flow and wave motion. Areas of low current strength are characterised by tracts of featureless flat bed sands and gravels (inner Weymouth Bay, Ringstead Bay). Currents within all the study bays are negligible so that wave action will be the major transport process in the nearshore zone.

Sediment circulation on the Weymouth Bay plateau is only a small part of the much larger, more complex sediment distribution and circulation patterns of the English Channel. The pattern of sediments in the Channel is a complex mixture of gravel, sand and mud in various proportions from a variety of sources. In general coarse material occurs in shallow water around the coast (where wave energy is greatest) and sediments become finer towards deeper water. There are large areas of gravel or rock in the central English Channel which act as a major sediment source. Stride (1959) demonstrated that a zone of divergence (bed load parting), exists south of the Dorset coast, movement of material takes place towards the continental shelf edge in the south west and towards the Dover Straits in the east. Within these sediment transport paths are many smaller eddies such as that in Weymouth Bay. Such smaller sediment transport paths will display their own characteristics, often contrary to the overall trend. Although coarser sediments are pushed shoreward they act as minor sediment sources that in turn describe their own inferred transport paths. This process accounts for the gradual fining of material towards the shore.

CHAPTER 8

BEACHES : PROFILE AND PROCESSES

BACKGROUND

Extensive literature is available on the physical and engineering properties of natural beaches. It is very apparent that the majority of field and laboratory research has been principally concerned with fine to medium sandy foreshores. A limited number of authors have concentrated their interests into the study of shingle beaches (e.g. Carr, 1969, 1970, 1971, 1974), even fewer have studied mixed sediment formations. It is unwise to make direct comparisons of form between sand beaches and mixed beaches as there are a number of fundamental differences, e.g. grain size, mean beach slope. The beach profile is probably the most documented aspect of beach studies but even the concept of the "beach" is difficult to define in a systematic manner because the natural physical boundaries are not well defined. Table 30 describes several definitions of the term beach. It can be seen that the inherent problem is one of defining upper and lower limits and that many definitions confine themselves to that portion of the beach which is visible and fail to mention the dynamic zone over which sediments may be moved. It appears that the choice of definition depends on the terms of reference for the particular beach being studied, a matter of personal choice.

Further problems of definition arise regarding morphological zones within the land-sea interface. Shape is an important geographic concept and individual beaches vary considerably in plan, profile and dynamic behaviour, so that one beach cannot be described as "model". Simple zonation of the littoral zone is possible despite the complex variability that affects our shorelines and a number of authors have attempted to produce a classification.

Any beach study involves the analysis of beach profile data represented as a two dimensional vertical section showing how elevation varies with distance. Changes of beach profile are inter-related and are important to the interpretation of littoral processes. McLean (1967), described the study of beach behaviour as a problem involving an extremely complicated interacting system with many variables, none of which can be controlled. The elements of such a system he defined as :

(i) energy factors
(ii) material factors
(iii) shore geometry

Gourlay (1980), noted the complexity of the processes but provided an even simpler classification :

(i) active factors (waves, tides, wind, temperature)
(ii) passive factors (beach materials, initial profile shape, geology.

Dingler (1981), summed up the situation by stating simply, that, "Beaches change shape because of changes in wave conditions".

BEACH PROFILE MODELS

Any beach profile model must consider the beach as a transient feature in a dynamic system. It must allow beach width, sediment storage and surface configuration to be determined in successive profiles and simulate beach cycles associated with waves, which are in sufficient agreement with actual observations (Sonu and Young, 1970). The majority of beach profile studies attempt to link a number of foreshore parameters within the conceptual framework of the process-response model (Krumbein, 1963). Some laboratory studies have concentrated on the effect of sediment size and shape (e.g. Collins and Chesnutt, 1975; Bagnold, 1940), whilst others have analysed the effect of wave characteristics (especially wave length and steepness) in determining the type of profile, (e.g. Watts, 1951; Rector, 1954). The extent of periodic beach fluctuations is partly dependent on the variability of waves and partly a result of the nature of beach material.

(i) The effect of beach material

Generally, the coarser the material the steeper the beach gradient and the greater mobility of that material. Bagnold (1940), in his model experiments used material that would be equivalent to shingle in nature. Using the ratio R = H/d (where H = wave height, d = diameter of the particle) he obtained profiles that agreed closely with known features of shingle beaches. His model developed a step at wave break point, a common feature on mixed sand and gravel beaches (McLean, 1967). Bagnold (1940) also described how coarse materials are more mobile than finer materials landward of the break point. Noda (1971, 1972) proposed a two-dimensional movable bed scale model to investigate the effects of grain shape and sediment distributions. His scaled models showed that the initial profile could influence the final stable profile shape. Collins and Chesnutt (1975), aimed to refine Noda's "Model Law" (1972) by evaluating the validity of his proposed scale model. They discovered that an apparent instability of profile developed using uniform waves, a uniform grain size and/or smooth, spherical grain shapes. Although they agreed with Noda (1972) that initial beach shape does influence the final profile they indicated that the law failed to reproduce accurately the shape of the offshore and inshore zones or predict shoreline movement.

Gourlay's (1980) laboratory experiments showed significant differences between profiles formed in two different beach materials. Using fine marine sand and crushed coal he showed that the beach profiles formed in sand had an almost constant beach face slope of 12° between still water line and the uprush limit. Profiles formed in the coal were much smoother in shape; profiles formed by low wave heights displayed very steep berms which were built up at the uprush limit with surging breakers. This berm was very high and had a very steep face (55°) above the mean water level.

(ii) The effect of waves and tidal cycles

As early as 1939, Waters postulated that the type of profile was determined by deep water wave steepness, (Ho/Lo). The value of "critical" wave steepness separating steep waves and long, flat waves varies between experiments. Bagnold (1940), and Bruun (1954) gave critical wave steepness a value of 0.025, but Dean (1973), found that it varied with the fall velocity of the sediment (vf), divided by deep water celerity

$$(Co = Lo/T) = \frac{Ho}{Lo} = 0.85 = \frac{vf}{Co}$$

which can be written Ho/vfT = 0.85 (Dalrymple and Thompson, 1976).

King (1972), suggested that these variations depend partly on the size of material, higher values being found with coarser materials.

Beaches are essentially energy sinks that act as a buffer which must dissipate energy without suffering any net change itself (Pethick, 1984). The energy of a wave is proportional to the square of its height and the rate of which energy reaches a beach is related to wave period. Thus, steep waves deliver high energy levels and flat waves low energy inputs, the morphology of the beach being a direct consequence of these energy levels. Beaches also produce morphological features that counteract such energy inputs. Watts (1955, cited in King 1972) examined the effect of slight variations in the wave period on profile development. Results showed that a 10% change had little effect while a 30% change nearly eliminated the formation of bars. Watts (1955), also made a series of tests simulating tidal effects on the beach under steep and flat waves; the greater tidal range was found to increase the amount of material moving.

Gourlay (1980) investigated beach profiles produced by different kinds of breaking waves in two beach materials (fine sand and crushed coal). A variety of wave heights were produced at a constant period in a two dimensional wave basin. Results showed that steep reflective beaches with step-type profiles were developed by low waves on both materials, whilst flat dissipative beaches with offshore bars were developed with the highest waves. Smallest waves produced erosion offshore of the breakpoint and accretion of the beach in the form of a large berm. Intermediate waves produced erosion of the offshore profile with accretion on the beach and further offshore.

Two basic forms of profile morphology have been recognised in nature, and laboratory experiments have been set up in an attempt to replicate their development, modification, destruction and transition under a variety of processes. The two forms are commonly described "summer" and "winter" profiles, their morphology attributed to seasonal differences in weather patterns and consequent wave characteristics. The two terms have become increasingly inadequate to typify general trends in profile behaviour. Gourlay (1980) provided an alternative classification :

(1) step/swell profile - formed when waves are of low steepness and/or material is coarse grained.

(2) bar/storm profile - formed when waves are of high steepness and/or material is fine grained. Storm waves have a higher steepness because of their increased height and shorter period.

Swell and storm profile terms are more accurate because they are not constrained to describe seasonal changes in form. A third generalised profile form can be recognised, that of the 'post-storm" beach face; after a storm event which has resulted in a drastic combing down of the beach, recovery may be rapid before swell conditions resume. This situation is particularly noticeable on beaches where an onshore-offshore exchange of material is the dominant process as opposed to longshore drift. The distinction between swell and storm profile configuration reacts to the concept of the equilibrium beach profile. Tanner (1958) introduced the concept as one of adjustment in the curvature and profile of a beach in such a way that waves impinging on the shore provide precisely the energy required to transport the load of sediments to the beach. Although Kemp (1960), and Gourlay (1980), claim to have produced an equilibrium beach under constant wave conditions in the laboratory, Chesnutt and Galvin (1974) failed to do so (using similar conditions). Zenkovich (1967), recognised that natural waves are far more complex and additional variables (winds, tides and irregular coastal configuration) increase the likelihood that complete equilibrium is rarely achieved in nature. If an equilibrium gradient does exist it is not a static feature, but one which will be continually tending to adjust itself to the changing variables on which it depends. The fact that wavelength is important in determining the equilibrium gradient of a natural beach is significant in explaining the different types of beach profile.

NATURAL BEACHES

Studies of natural beaches have recognised the complex interaction of variables at work in the littoral zone at any point in time. The most important variables are considered to be :

(1) beach material
(2) waves

(1) Effects of beach materials

Bascom (1951), working on Half Moon beach described steep beach gradients with large shingle sized sediment and shallower profiles formed in fine sand grades. Shepard (1963) quoted beach gradients of 15° on shingle beaches with a mean grain size of 16.0mm, whilst gradients of up to 26° have been measured on Chesil Beach (Carr, 1969). Many authors have become increasingly aware of this relationship and suggest that the link between grain size and beach gradient lies in percolation with various sediment sizes, (Zenkovich, 1967). Coarse sediments are influenced by percolation of much of the swash, the backwash is therefore weak and the material is in a state of equilibrium at steep angles. Kemp (1975), examined the effects of removing the backwash from the flow in his model experiments by allowing the swash to spill over the top of the beach, thereby increasing the percolation rate. The effect was to produce a flow pattern on steep beaches which resembled that for flat beaches. King (1972) suggested that percolation will modify the intensity of swash and backwash, producing net sediment regimes in either direction. There have also been a number of attempts to link sediment sorting and grain size to beach gradients as a result of percolation rates. Krumbein and Graybill (1965) showed that poor sorting resulted in less percolation and steeper profiles compared with well sorted sediment the same mean grain size. McLean and Kirk (1968) agreed. Engstrom attempted to link a number of beach foreshore parameters in a process-response framework. Process variables included hindcasted wave statistics and wave characteristics inferred from foreshore morphology, while response variables included the four moments of grain size distribution and foreshore slope. Results suggested that mean grain size affects the foreshore width in an inverse fashion; coarser particle sizes increase percolation and thereby reduce swash volume by producing a narrow foreshore.

Other factors can provide steeper or gentler slopes for any given grain size, including degree of exposure and whether erosion or accretion is taking place. McLean and Kirk (1969) took into account shape, roundness, imbrication, skewness and sorting, (sorting of sediment being of importance on mixed beaches). Inman (1949), Griffiths (1951), Folk and Ward (1957) and Folk (1962), all noted the relationship between mean grain size and sorting. It follows that a characteristic grain size/foreshore slope pattern will exist on mixed beaches in response to grain size and sorting.

(2) Effects due to waves

Early studies by Shepard and La Fond (1940), Bascom (1954), Gorsline (1966) did not obtain satisfactory wave measurements that could determine a critical wave steepness. It showed, however, that an increase in wave height during storm conditions leads to a "storm" profile with an offshore shift of material. Thompson and Harlett (1969) carried out a 60 day field study on selected beach profiles at Del Monte, California; profiles were measured daily and waves continuously. The parameters derived were used to provide a quantitative representative relationship between profile change and average deepwater wave steepness. The most obvious feature of the profile behaviour was the constant change. Changes were not random, but predominent cycles of erosion and accretion in direct response to the arrival of dominant wave trains.

Short (1980), studied beach response to variations in breaker height. His model was based on results from 10 years of daily wave data and 4 years of daily beach response. With the aid of earlier work (1979) he was not only able to identify three broad categories of beach type (low, moderate and high energy beaches) but also to describe a characteristic set of morphological response and dynamic interactions associated with each beach type. The results indicated that breaker wave height, together with period determines the amount of wave energy available to work across the nearshore.

Kemp (1960) confirmed an earlier investigation that breaker height is the dominant wave characteristic acting on shingle beaches. By analysing daily records of wind direction, force, and type, tidal range, low water profiles and sediment characteristics, he showed that the decay of wave velocity subsequent to breaking is similarly related to breaker height or distance. He also confirmed the relationship between maximum crest height and maximum breaker height developed in model studies.

(3) Effects due to tides

Profile alterations corresponding to tidal cycles may be hourly or lunar. Schwartz (1968), made littoral observations on two Nova Scotia beaches in order to delineate the pattern of sedimentation during the tidal cycle while cyclic neap-spring changes were drawn from an earlier Cape Cod study. On tideless shorelines the equilibrium profile developed in the swash-backwash zone would remain stationary were it not for temperature barometric pressure on oceanographic effects which change effective sea level. On tidal shorelines the swash-backwash profile is translated upward and landward by the flood, and downward and seaward by the ebb. Zeigler and Tuttle (1961) measured cut and fill of between 6.0 - 9.0cms on Cape Cod beaches during an average tidal cycle.

Spring tides, having the greatest range, raise and lower sea level at peak flood and lowest ebb tides. Several accounts have been made of spring tide erosion and neap tide deposition on the foreshore (Emery, 1960; Inman, 1960) and a corresponding reversal in the nearshore bottom level (Schwartz, 1966). Onshore storms effectively raise sea level particularly during storm surges and the accompanying higher and steeper waves extend the upper limit of wave action and increase erosion.

Grant (1948) recognised that the position of the water table under the beach surface is an important factor in beach erosion and deposition "... a high water table accelerates beach erosion and conversely, a low water table may result in pronounced aggradation of the foreshore". Emery and Foster (1948) also noted that the water table fluctuated with the tidal cycle but lags behind the tide by 1 to 3 hours. During ebb tide the seaward edge of the water table generally slopes seaward, whilst during flood tide it slopes landward. This occurs in response to the loss of water in the effluent zone during an ebbing tide and a gain of water during a flooding tide. Duncan (1964) indicated that fluctuations in sea level relative to beach water table resulting from semi-diurnal tide cycles produced appreciable effects on sediment distribution when the tide level is high and the beach water table is low, swash deposition and erosion predominate. A relatively high water table results in maximum backwash erosion and deposition. Therefore, as sea level fluctuates above and below the general water table level with the tide, the zone of deposition correspondingly shifts its position within the swash-backwash zone and either increases or decreases the gradient of the beach slope. As the tide rises sediments deposited by previous swashes are redistributed by the encroaching surf.

Heathershaw, Carr, Blackley and Wooldridge (1981) monitored tidal variation in the compaction of beach sediments in Swansea Bay. Two trends were apparent; a temporal variation, the cone index value reaching a maximum just before that part of the beach is covered by the incoming tide, and a spatial variation, with the maximum values of penetration resistance occurring at mid tide level. There was a significant correlation between the cone index and fluctuations in beach level; with increasing distance from the centre of the beach variations in beach levels increase, whereas cone index readings decrease. The trends suggested a tidally induced response of the beach water table and an effect related to the degree of exposure of different sections of the beach to wave activity. Two mechanisms seemed to influence beach elevation and compaction of beach sediments over the tidal cycle; the swash and backwash processes, described by Duncan (1964) and the failure mechanism (Madsen, 1974) which is likely to enhance transport by swash and backwash.

BEACH STAGES AND CYCLES

Due to the rapidity of nearshore morphological change in response to variations in wave energy every beach is characterised by its particular sequential or cyclic behaviour. A number of authors have devised models of systematic beach change for predictive purposes, (Sonu and Young, 1970; Sonu and Van Beek, 1973; Fox and Davis, 1974; Aubrey, Inman and Winant, 1976).

Sonu and Young stated (1970, p.1341), "The process of beach change is stochastic in nature. It is also a Markovian process in the sense that the resulting beach profile is partly a function of the preceding profile". By using stochastic analysis they proposed a model that enabled development of long term equilibrium probabilities from short term observations. Sonu and Van Beek (1971) proposed a model describing beach profile transitions, influenced by characteristic behaviours of migratory shoal and swash bar. They categorised profile configurations into six types, the distinctions resulting from :

(i) whether configuration was curved concave upward, linear or convex upward.
(ii) whether or not a berm was present.
(iii) whether the berm was located at the lower, intermediate or upper elevations of the beach.

Characteristic pathways of profile transition were recognised in a four month beach cycle. Accretion was associated with formation of a berm, or in presence of a berm, with movement farther upward along the beach slope. Erosion was associated with either reduction in size of an existing berm at its elevation, or, in the absence of a berm, lowering of the position of an excessive sedimentary deposit along the beach slope. Attempts to relate beach changes to waves were unsuccessful, it appeared that both erosion and accretion would result from waves of identical height and no significant distinction in wave steepness was recognised between waves associated with erosion and those associated with accretion.

Harrison (1969) attempted to develop quantitative expressions for geometrical changes in a tidal beach. He assumed a two dimensional beach, in equilibrium, and thus with no net transfer of sediment across any boundary. The net change in quantity of foreshore sand was determined for one tidal cycle by using linear correlations between dependent and independent variables, whilst the use of multi-regression analysis highlighted the relation of swash geometry to groundwater table changes. Short's (1979) model predicted three dimensional change in beach-surf zone morphology by considering shape produced by dynamics associated with waves, wave generated currents, interacting with beach gradient and sediment, coupled with pre-existing morphologies. The model was based on the assumption that the beach between the breaker zone and high tide swash responds to variations in breaker height and power. Results indicated 10 beach stages of erosional and accretional sequences in response to all levels of wave energy. Although the model favours sand beaches it can be modified for coarser/finer grained beaches bearing in mind a more reflective/dissipative beach surface. Some studies of beach cycles have been more specific in terms of describing localised cycles related to seasonal changes (Darling, 1965; Aguilar-Tunan and Komar, 1978; Aubrey, Inman and Winant, 1979), or tidal and localised wind wave regimes (Inman and Filloux, 1960). Felder and Fisher (1980) presented a simulation model of seasonal beach changes by describing the formation and destruction of longshore bars in terms of the two basic seasonal configurations - winter and summer profiles. It is this transition from one profile type to another that many of the models try to explain.

According to Sunamura (1975), beach slope helps to modify incoming waves and thus the swash flow must be included in profile discrimination. He recognised a three profile typology (under no tidal variation), based on initial beach slope angle, mean sediment diameter and offshore wave length :

(i) Erosion - development of breakpoint bar - shoreline retreats offshore = bar profile.

(ii) Accretion - development of swash bar - shoreline retreats offshore = step profile.

(iii) Erosion followed by accretion - development of swash and breakpoint bar - shoreline initially retreats and then advances = composite profile.

A negative feedback operates as the initial profile alters with variation in beach slope inducing a change in breaker structure.

Orford (1978) used wave/breaker variation to describe three profile morphological response surfaces :

(i) Step profile (fair weather, post storm swell)
(ii) Bar profile (storm waves)
(iii) Composite profile (severe storm/extreme event)

Certain relationships between breaker type and profile type were noted :

(i) Step and bar profiles were considered diagnostic of distinctive breaker type and wavelength; bar profiles developed as a result of long wave lengths and spilling breakers.
(ii) Composite profile development was shown to require a breaker type conducive to constructional activity at the swash limit (associated with the high water mark) and where a similar combination of breaker height and wave period realises a bar profile at later ebb stages of tidal transition.

Recently, Caldwell (1983) made a number of refinements to Sonu and Van Beek's original model (1971) in order to provide a classification system :

(i) Angular standardisation of profiles in order to erase the problem of variation in height and storage between profiles.

(ii) By making use of hypsographic curves and hypsometric integrals (as used in fluvial geomorphology) a methodology of analysing profiles was used that did not rely on active beach height and width values.

(iii) Only concave and linear macroforms were represented on the study beaches and a ten point category classification system was devised based on those two basic forms.

BEACH PROFILES ON THE S.E. DORSET COAST

METHODOLOGY

The regular study of beach profiles may be important in providing an insight into the amount of sediment that is potentially mobile in that section of the coastal zone over a discrete period of time. Repetition of survey in the long term (>10 years) may help establish sediment budgets and thus determine whether the system is in deficit, aggradation or equilibrium. Carr (1980) noted the potential significance of short term changes; they may detect seasonal changes, tidal changes and extreme events, all of which help to predict degradation/aggradation of beaches under identifiable conditions. Beach volumetric changes cannot be studied in isolation, but must be viewed as part of the integrated system from cliff top to offshore. Wave behaviour in the immediate offshore area is critical to intertidal beach form and change; bathymetry influences, (and is a function of), wave climate and exposure, waves and currents affect longshore drift as well as the onshore-offshore exchange of material. Thus the beach form is the visible balance between processes and responses but is only part of the littoral environment.

The study of beach morphology on five selected beaches on the south east Dorset coast was carried out in order to :

(i) examine the short term erosional and accretional changes between successive surveys.
(ii) attempt to relate those changes to environmental conditions.

Increased knowledge of beach volumetric change is fundamental to the estimation of the sediment balance since the beach is a significant sediment store.

PILOT STUDY

Preliminary field investigations identified a number of beach sections at 100.0m intervals for surveying and sediment sampling, (chapter 7). Each profile site was identified by a temporary bench mark (T.B.M.); particular attention was paid to establishing secondary bench marks in case of damage or loss. During the pilot study attempts were made to survey each profile by quickset level and staff. However, this method proved very time consuming, problematic in inclement weather and high energy swash, and required two operators, so an alternative was sought. That alternative was a slope pantometer, a simple instrument developed by Pitty (1969), for field measurement of hill slopes. Basically, it is a lightweight frame constructed from dexion girders arranged as two uprights 1.5m apart, attached by two crosspieces. One of the uprights has a large scale protractor attached. As the principle of the instrument depends on the uprights being vertical one of the uprights has a spirit level attached. Pitty (1969) described the advantages of the pantometer in comparison with other survey methods (p.719). Briefly they are :

(i) ...the pantometer is easily and firmly steadied.

(ii) ...no time spent in deliberations on where to limit a representative length of slope surface or what scale of micro-relief to ignore.

(iii) A pantometer slope angle reading accounts for the distance covered so that separate measurements of ground surface lengths are obtained.

(iv) On steep slopes levelling techniques depend not only on the careful levelling of the instrument but also on the care in setting the staff as near to vertical as can be estimated. The pantometer combines these two operations.

(v) The exercise can be carried out by one surveyor and can generate a lot of data in a short space of time.

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(iv) On steep slopes levelling techniques depend not only on the careful levelling of the instrument but also on the care in setting the staff as near to vertical as can be estimated. The pantometer combines these two operations.
(v) The exercise can be carried out by one surveyor and can generate a lot of data in a short space of time.

Although developed for use on hillslopes, the pantometer has great advantages in beach surveys over more conventional methods. The ease of assembly and carriage is an important factor whilst the breaker/low water zone is as accessible as the operator is able and willing to make it, (Plate 36).

PILOT STUDY RECOMMENDATIONS

1. Reduction of profiles. By recognising "like" profiles the number of sections was reduced to a minimum representative number. Sections became spatially irregular but represented significant variation in form compared to adjacent zones.

2. Each section to be surveyed by slope pantometer from a T.B.M. at the landward end of the beach along a line normal to the coast at the point. Whenever possible sections were surveyed over spring low water; when accessibility restrictions were imposed by the Lulworth Gunnery School at Worbarrow and Mupe surveying was carried out whenever practical. Each T.B.M. to be reduced to Ordnance Datum (Table 31).

3. The main study to be carried out on three levels :

   (i) Daily surveying for a period of one month on Durdle Door beach, in an attempt to identify pathways of transition (very short term), and appraise the value of such an intensive study, and assess the supposition that profile variation due to a changing wave climate, is greater than variation conditioned by tidal cycles.

   (ii) Monthly surveys of all beaches July 1983 - September 1984 (inclusive). Clayton (1977) noted that surveys every 3-4 months were adequate to pick up seasonal shifts but that data runs needed to be >3 years. Monthly surveys were chosen for this study in order to maximise data that would detect general trends of beach behaviour due to seasonal effects, tidal cycle or specific meteorological events.

(iii) Selective surveying of beaches affected by major storm events, or other atypical meteorological events, the success of the exercise dependent upon the prediction of the event and accessibility to the site .

4. Littoral environment observations to be recorded during each survey relating to :

- surf observations (wave period, direction; breaker type, height).
- wind observations (direction and velocity).
- state of tide.
- presence of beach cusps.
- whether photographs were taken.
- whether sediment samples were collected.

PROFILE DATA PREPARATION

Each profile was reproduced to scale without vertical exaggeration. From the literature reviewed it was noted that the selection of the proportion of the profile to be examined is crucial to any attempt of classification due to the difficulty of defining the seaward limit of the beach. The chalk cliffs of Durdle Door and Man O'War beaches provided distinct natural landward boundaries for the beach to pile against. At Ringstead, Mupe and Worbarrow where beaches are backed, for most of their length, by clay cliffs, the landward limit is not always well defined due to slippage and slumping. Boundaries, however, are recognised as being paramount to the calculation of potentially mobile material volumes.

Clayton (1977) described the calculation of material volumes in terms of a geometrically developed beach prism which includes all material (whether true beach sediment or not) within the volume defined by four surfaces - two horizontal planes representing upper and lower limits of wave action, the third a vertical plane parallel to the line of the coast defining the landward limit of the beach system, the fourth being the beach surface. Clayton (1977) in fact defined three ways of measuring a beach prism as well as explaining how they may yield false representations of sediment storage. Orford (1978) used the boundary between the gravel ridge and inter-tidal sand zone to define the seaward prism limit of sediment storage, whilst elevation was measured at the swash limit.

In this study, Clayton's (1977) method A (Figure 40) has been adapted for use in measuring the volume of selected Dorset beach sections, modifications were necessary due to the presence of the underlying chalk platform on Durdle Door beach. The beach prism is defined by an upper horizontal limit (as defined by each T.B.M.) and a lower limit defined by the lower sweep zone (calculated for the term of study). The landward limit was defined as the intersection of the upper prism limit with the beach, the seaward limit at an elevation of -1.0m O.D. (approximating to Chart Datum). Chart Datum was not used as a horizontal lower prism limit because it would not have provided a true representation of the amount of potentially mobile sediment on each section (Figure 40). At Durdle Door for example, the use of a horizontal lower limit would have ignored the presence of a natural lower boundary provided by the chalk platform.

Each (reproduced) section was then divided into upper and lower sections by an arbitrary mid water line extrapolated from the predicted tidal heights (Admiralty Tide Tables, Volume 1, 1983/1984). The area above this line was referred to as upper beach (and included that area above the contemporary high water and/or swash limit), the area below, the lower beach. Profile volumes were measured with an Allbrit planimeter.

PROFILE DATA ANALYSIS

Volumetric values and profile length of each section were used to calculate :

(i) Bruun Index. This index is a measure of beach form, being a function of profile area over the square of profile length. The value is multiplied by two to produce a steepness value (Clayton 1977).

(ii) Mean Depth. This value is derived by dividing cross-sectional area by profile length.
Both parameters, being functions of volume and profile length are restricted by the definition of the lower prism limit on sections where there is no natural lower limit.

(iii) Profile Classification. Classification is based on the three basic macroforms according to the visual smoothed trend (Sonu and Van Beek, 1971; Caldwell, 1983): concave, linear and convex. A number of subdivisions are recognised for each macroform, depending on the absence/presence of berms and the position of the berms on the surface configuration. Table 32 describes the subdivisions used (with abbreviations) and is an adaptation of that devised by Caldwell (1983). In this study, however, composite berm is not used in the same context; the term "remnant" is used to describe the memory of previous berm positions and always refers to the uppermost berm. A falling tide may leave more than one remnant upper berm which are amalgamated and present a "composite remnant upper berm". By using simple abbreviations even complex profile configurations, presenting a number of berms, are easily described. The profile classification was necessary in an attempt to identify patterns or systematic changes in profile morphology.

ONE MONTH SURVEY, JANUARY-FEBRUARY 1983

VOLUMETRIC CHANGE AND BEACH PROFILE CLASSIFICATION

Daily visits were made to Durdle Door beach between 25th January - 22nd February, 1983, in order to survey each of the 9 profiles and record littoral environment conditions. Each section was surveyed by slope pantometer after the first low water (Appendix 2). Table 33 presents the volumetric change of the 9 profiles on selected dates during the one month survey; profile form is tabulated according to its profile classification (Table 34). Beach profile volume was calculated using the modified beach prism method and the parameters of cross sectional area and profile length have been used to calculate the Bruun Index and mean depth (Table 35). A wind rose constructed for the period is presented in Figure 41; the changes in beach volume and form are discussed alongside changing wind and wave climates.

PROFILE 1 : Although the first half of the survey period was dominated by extreme events of cut and fill the amount of erosion and accretion over the whole period was almost equal. Maximum cut occurred between 29/30.1.83 during a storm event; breaking wave heights of 1.5m were assisted by south westerly winds, force 6, and a rising spring tide. An increase in breaking wave height (up to 2.0m within Durdle Cove) under continued storm conditions coincided with maximum fill between 31.1.83/1.2.83, with development of a storm berm and a steep linear foreshore. The remainder of the study period experienced relatively calm conditions; a prevailing offshore wind resulted in a diminishing south west swell and developing easterly seas. Wave trains from the east with wave periods of 5 seconds were expected to affect profile form by initiating littoral drift in a westerly direction, superimposed on changing form due to tidal movements. The sudden change in wave climate and moderation of the wind regime coincided with accretion over the whole profile but particularly along the mid water zone. The reduction in wave height resulted in the storm berm standing above the upper limit of wave action and modification of the foreshore within the tidal range. During the remainder of the study period minor berm development was characteristic of the accreting mid water zone, and despite periods of erosion and accretion the upper and mid berms were maintained. The period 5-10.2.83 was dominated by continuous accretion followed by erosion and cutting back of the storm berm under a rising spring tide. Minimum values of mean depth and Bruun Index were recorded following the storm conditions of 30.1.83, when sediment storage along the profile was at its lowest. Immediate recovery of the profile volume resulted in maximum values of mean depth, Bruun Index and sediment storage. Due to its sheltered position profile 1 was not affected by longshore transport under the prolonged easterly conditions; accretion/erosion sequences affected the whole foreshore simultaneously whilst the swash run up produced by the prolonged low water stand possibly accounted for mid water berm development.

PROFILE 2 : Over the study period profile 2 was in a state of accretion. Sequences of accretion dominated this section during the first half of the study period up until 10.2.83, by which time easterly conditions prevailed. Under the storm conditions at the end of January the profile did not suffer dramatic erosion or accretion and retained its characteristic convex macroform. Maximum fill was recorded between 2/3.2.83 associated with high water berm development under a changing wind and wave climate and residual storm swell. The following period was characterised by modification of the upper berm and mid berm development. The prolonged easterly conditions caused gradual scouring of the inter-tidal zone producing a concave foreshore beneath a well-defined upper berm.

Maximum fill (+22.0m^3)was recorded between 2/3.2.83 (during storm conditions), but maximum Bruun Index and mean depth was recorded on 10.2.83, when sediment storage reached a maximum before the onset of the period of foreshore erosion. The initial period of erosion was the most intense (10/14.2.83), followed by a more gradual cutting back and foreshore shortening. Bruun Index and mean depth values reached a minimum on 22.2.83, the last day of the survey period. The profile retained its convex macroform throughout the survey but towards the end of the period was tending towards linearity, due to the modification of the foreshore.

PROFILE 3 : This section was characterised by its linear macroform and small variations in cut and fill, although for the duration of the study it displayed overall accretion, the increase in sediment almost doubled that of the amount eroded. The profile suffered limited erosion during the storm events but the change in the wind and wave regime coincided with a period of accretion (1/4.2.83), over the whole profile, followed by minimal erosion between mid and low water. Foreshore accretion after 8.2.83 resulted in sequences of minor berm development in the mid water zone. Maximum fill was recorded between 13-14.2.83; infilling around the berms produced a linear macroform with no berms. This period of accretion was succeeded by a period of erosion ($10.0m^3$).

Minimum sediment storage and Bruun Index value was recorded on 25.1.83 with only a thin veneer of sediment (<0.40m) covering the platform below the mid water zone; minimum mean depth coincided with the peak storm activity of 30.1.83. Maximum storage was recorded on 14.2.83, along with a maximum Bruun Index, but maximum mean depth was produced on 18.2.83, following a period of accretion. Thus it can be seen that profile 3 suffered maximum cut and fill under easterly swell and an offshore wind regime.

PROFILE 4 : This section was characterised by a linear macroform but slightly convex foreshore. Variations in cut and fill tended to be small with phases of erosion affecting the whole foreshore whilst accretion was most pronounced around the mid to high water zone. The section suffered little erosion during the storm event but accretion coincided with a post storm change in the wind and wave regime.

Continued accretion resulted in mid water berm development between 5/10.2.83; erosion of the berm followed. Minimum sediment storage was recorded on 25.1.83 and a maximum on 18.2.83.

PROFILE 5 : This section was also characterised by its wedge shaped linear form, displaying minimal berm development. The profile displayed great variations in sediment storage during the survey period but was, in general, an accreting profile during this time. Minimum storage occurred at the beginning of the survey (27.1.83), but was followed by maximum fill (+19.20m^3) during the storm conditions of 27/29.1.83. This accretion was followed immediately by maximum cut (-16.3m^3), during 29/30.1.83, also under storm conditions.

The prolonged period of moderate easterly swell produced sequences of erosion and deposition; periods of erosion tended to affect the whole profile whereas accretion was most pronounced around the mid water zone. Erosion, not accretion, resulted in the development of a mid water berm (10/11.2.83) but the onset of an accretionary phase provided infilling around the berm (14.2.83), maximum storage and Bruun Index values.

PROFILE 6 : Another linear profile showing no berm development during the survey period. Phases of deposition were more numerous than erosion but the latter was more severe and this section was generally in a state of erosion over the study period. The section was not surveyed at the start of the survey period because of a turbulent and long swash run-up. The first survey on 29.1.83 produced a minimum storage value, whilst the minimum Bruun Index and mean depth values were recorded on 30.1.83. The change in the wind and wave regime at the beginning of February 1983 coincided with the beginning of a depositionary phase that prevailed until 15.2.83. It should be noted that between 4/8.2.83 the profile showed no change in form, or volume, suggesting that it was in an equilibrium state with the prevailing wave climate.

Maximum storage Bruun Index and mean depth was achieved between 14/15.2.83 but 41.5m^3 sediment was removed between 16/18.2.83 exposing the underlying chalk platform, suggesting a concentration of wave energy. The platform remained exposed along this section until the end of the study period.

PROFILE 7 : This profile also displayed a linear macroform but occasionally tended towards a concave form whilst undergoing erosion and convexity whilst accreting. Profile form may be influenced by the slightly concave form of the underlying platform. Small variations in sediment storage were dominated by phases of deposition , the section being in a general state of accretion over the study period. Minimum storage values were recorded during the storm event of 29.1.83, but the full effects of storm action were not recorded because surveying was not possible on the early days of the study period because of a dangerously turbulent swash zone. Maximum fill occurred during post storm conditions between 2/3.2.83 (+13.0m^3) but maximum values of Bruun Index and mean depth were recorded on 18.2.83 following the main accretionary phase.

PROFILE 8 : This section displayed dramatic sequences of erosion and accretion during the first half of the survey although it was in a general state of accretion over the study period. Characterised by its linear macroform it displayed only minor berm development during the latter half of the survey. The storm action of 30/3.2.83 coincided with a period of deposition but the section underwent severe erosion between 4/5.2.83 (-19.0m^3) resulting in exposure of the underlying platform. This section of platform remained exposed until 8.2.83 and gained 21.5m^3 of sediment between 8/10.2.83. Accretion dominated the remainder of the survey with deposition favouring the high and low water zones. Maximum storage during the study period was recorded on 22.2.83, whilst maximum Bruun Index and mean depth values were achieved on 3.2.83, following the storm activity.

PROFILE 9 : This section underwent extreme variations of erosion/deposition during the survey period and like its neighbouring profiles maintained its linear form with minimal berm development. Storm conditions removed 18.40m^3 of sediment and resulted in the exposure of the underlying platform between 31.1.83-14.2.83. Exposure occurred under a moderating south west storm swell but was maintained by the easterly wave climate. Maximum cut, minimum Bruun Index and mean depth values were recorded on 30.1.83. Rapid deposition of 29.8m^3 of sediment occurred between 13/14.2.83 and deposition continued until the end of the survey period producing maximum Bruun Index and mean depth values on 16.2.83 and maximum sediment storage on 20.2.83.

DISCUSSION

THE study of 9 beach profiles on Durdle Door beach over a period of one month illustrated the variety of beach form, volume and sediment distributed by one morphologically contained unit under the influence of the same hydrodynamic input. Beach sections did not exhibit similar trends with regard to sequences of erosion and accretion, even neighbouring profiles responded differently to the same wave climate and achieved maximum amounts of cut and fill on different occasions. The wind and wave regime experienced throughout the survey period may be described as "non-normal". South west storm swell with a 10 second wave period and long wavelength with breaking wave heights of up to 2 m is a typical storm event experienced along this section of coastline during the winter months but episodes of large storm waves (with breaking wave heights up to 4.0m) are not infrequent. The largest changes in beach profiles are produced by storm/post-storm wave sequences by means of a direct onshore-offshore exchange of material. Easterly seas, with a 5 second wave period and short wavelength are characteristically short lived conditions (often superimposed upon a prevailing south west swell), that decay rapidly under variable wind directions and a limited fetch. A 3 week period of easterly swell, as experienced during the one-month survey may, therefore, be described as "atypical", or "extreme", particularly during the winter months when onshore winds dominate.

The storm sequence at the beginning of the survey period had the greatest effect on profiles 1, 2 and 5; increasing storm waves resulted in great accretion over the whole beach except for profile 9 which experienced total removal of the "beach" and exposure of the underlaying chalk platform. The initial effects of the sudden change to an easterly wave regime and offshore winds were constructive; beach sections 1 to 7 experienced deposition but profile 8 suffered severe erosion with exposure of the chalk platform, a condition that was maintained along profile 9 (and 8) until the second week of February. The prolonged easterly conditions eventually initiated an erosive period on profiles 1, 2 and 6, that was maintained until the end of the study period; severe erosion along profile 6 resulted in exposure of the platform, whilst profiles 8 and 9 experienced gradual deposition of small amounts of sediment. Calculated rates of erosion and accretion indicated that during the survey period, profiles 3, 4, 5, 7, 8 and 9 were in a state of aggradation. Only profile 6 was in a general state of erosion, whilst profiles 1 and 2 were in equilibrium with erosion/deposition balancing out over the period. Variations in sweep zone volume during the intensive study period reached a maximum of $41.5m^3$ per metre whilst profile lengths only varied by ±10m.

Profiles 3-9 were characterised by their linear macroform and limited berm development. It is worth noting that all the sections have an underlying chalk platform, on average, less than 1.5m below the beach surface. The platform is also linear in form with an average slope of 10^o; a very small change of slope along the mid water zone is discernible, but its effect on beach morphology may be important by inducing a slight tendency for minor berms to develop above the point of inflexion. Conversely, profiles 1 and 2 are characterised by berm development, particularly at the high water mark, and foreshore slopes up to 27°. For the duration of the study period profile 1 displayed a linear form and despite severe storm erosion retained that form, with storm berm development. Being sheltered from the full effect of the easterly swell, berm development in relation to tidal cycles became a significant feature. An upper berm was common and mid water berms probably developed as a consequence of the limit of swash run up over the extended period of double low water. Profile 2, the most exposed and longest section was characteristically convex in form with an upper berm present at all times. The effects of the prolonged easterly swell resulted in foreshore scour producing a concave foreshore beneath a steep high water berm face. Thus it can be inferred that the overall effect of a prolonged easterly wave regime is to initiate littoral drift in a westerly direction as a consequence of waves breaking obliquely to the shoreline. Wave trains from easterly sectors suffer little refraction across Weymouth Bay and despite increased refraction close to the shore waves reach the beach at an oblique angle. On Durdle Door beach profiles 1 and 2 are sheltered from the easterly wave trains and much of their energy is lost by refraction around Durdle Door arch. Despite loss of energy due to refraction, nearshore processes are sufficient to cause gradual "cliffing" along the foreshore face of profile 2 and to transport that sediment westwards with subsequent deposition on profiles 3, 4 and 5. Exposure of the platform at profile 6 suggested that, at that point, there was a concentration of wave energy under the prevailing easterly regime, (a condition that was observed again during January 1985). It appears that profile 6 acted as a parting zone, dividing the beach into 2 transport systems, both controlled by longshore transport in a westerly direction.

Sediment-morphology interactions : In common with other mixed sediment beaches Durdle Door displays moderately steep foreshore slopes and a variety of mean grain sizes. It is well-documented that a relationship exists between foreshore slope and the mean grain size of foreshore sediment, Durdle

Door being no exception. Profiles 1 and 2 produced the coarsest sediments, commonly medium pebble grade with good sorting values; this sediment distribution was able to maintain slopes of 27° and as much as 30°. Further west, profiles 3 to 9 displayed a greater variety of sediment sizes ranging from fine pebbles to medium sand grades. Sorting values were also variable. Linear macroforms were dominant with average foreshore slopes of 10-12° although well sorted gravel grades were able to maintain a slope of 15°. The distribution of sediment was often of a banded nature down the foreshore, with alternate zones of coarse and fine sediments. Often, a distinct change of mean grain size along the mid water mark was associated with a small break of slope in the beach form, which in turn, was considered to be controlled by a similar break of slope in the underlying chalk platform.

Eroding profiles tended to produce finer sediment grades with poor sorting whilst accreting profiles produced coarser sediments with better sorting. Sequences of erosion and accretion, particularly on the linear profiles showed even depths of change over the whole profile thus maintaining the linear form; the presence of an underlying chalk platform may be an important controlling factor on the maintenance of linear beach form. Profiles 1 and 2, with characteristic berm development and a tendency to more convex form, displayed changing patterns of erosion and accretion; erosion usually produced an upper berm and a steep concave foreshore, whilst accretion tended to cause infilling of the concave areas or infilling around the berms.

The observations recorded indicate the complexity of the link between beach morphology and nearshore processes. However, the data suggested that a correspondence between grain size and morphology existed but there are many other factors which influence the variety of profile form displayed, including degree of exposure, offshore topography and refraction, sediment availability, sediment size range, the effect of an underlying chalk platform on percolation and the water table, and the effect of initial profile form. These factors (and many other process variables) contribute to the great variation displayed by profile form within a relatively small morphologically contained unit. Prior to the intensive study of profile morphology it had been suggested that south west storm action provided extreme event conditions with regard to the processes at work in the general beach profile model. However, the study revealed the significance of "atypical" conditions; previously, the effects of easterly wave regimes were considered to be negligible due to the rapidity of development and decay. However, the study showed that prolonged exposure to easterly wave regimes resulted in changes that were small in magnitude but of great significance with respect to sediment circulation within a morphologically contained unit powered by the same hydrodynamic energy input. Thus, storm events were no longer considered as extreme events; storm action accounted for dramatic changes in beach volume but the process was a simple onshore/offshore exchange, the material being returned by post storm conditions. Easterly wave regimes were commonly short-lived conditions but if they prevailed for extended periods the effects had a greater impact. Easterly swell initiated longshore drift and exposure of the chalk platform; dramatic changes in beach volume did not occur, there being a redistribution of sediment volume within the beach cell. Such conditions are now considered to be the "extreme events" experienced by beaches along the south east Dorset coast.

STORM EVENT SURVEY

A vigorous depression moving towards Ireland at the beginning of September 1983 forecast south west gale conditions for the English Channel during the period 2 - 4.9.83. The forecast suggested that this was an ideal opportunity to monitor beach morphological change under extreme conditions (following the relatively calm conditions of the summer). Worbarrow beach, being fully exposed to the south west was selected as the primary site of an intensive surveying period, before and after the event. Durdle Door and Man O'War beaches were also surveyed directly before and after the storm event but were not subjected to extended monitoring like Worbarrow.

On 1.9.83 nine profiles were surveyed on Durdle Door, three on Man O'War and four on Worbarrow beach. Gale conditions developed during the 2/3.9.83 with force 6 and 7 winds from the south to westerly quadrant prevailing. Gusts of force 8 were recorded at HMS Osprey, Portland. By the 4th the depression was filling and wind speeds decreasing to force 4/5. Worbarrow beach was surveyed on 4.9.83 despite swash run-up reaching 20.0m and breaker height in excess of 2.5m. Further surveys were carried out on 18.9.83 and 25.9.83 in an attempt to monitor beach recovery; more frequent surveys were impossible due to gunnery range restrictions on acccessibility. At Durdle Door beach only one survey was carried out directly after the storm (5.9.83). Further surveys were not necessary because the storm action did not induce dramatic erosion/deposition on the foreshore. The surveyed sections are reproduced in Appendix 3.

WIND AND WAVE CONDITIONS

Wind conditions for the period 18.8.83 to 1.9.83 are reproduced in the form of a wind rose (Figure 42); the wind rose described prevailing northerly and dominant north easterly winds for the period. The 2 week period prior to the survey of 1.9.83 was one of calm, stable meteorological conditions. The offshore winds had a damping effect on a residual south west swell, observations recorded average breaking wave heights of 0.5m. On 1.9.83 the wind backed from easterly (force 1) to south westerly (force 4), breaking wave height increased to 1.0m after a 12 hour duration of south westerly conditions. Wind speed increased during the 2/3.9.83 (maximum force 7), backing westerly. At the height of the storm, breaking wave height reached an estimated maximum of 4.0m. The observed height correlated well with predicted wave heights extracted from wave prediction curves. With wind speeds of 30 knots, significant wave heights of between 3.4 and 4.1m were predicted (duration 6-24 hours) for an effective fetch greater than 200 nautical miles. On Durdle Door beach, however, observed maximum wave heights were below 2.5m. By 4.9.83 wind speed had decreased to force 5 and backed to southerly. However, with wind speed greater than $10m.sec^{-1}$ over a period greater than 24 hours, breaking wave heights at Worbarrow remained greater than 2.0m, many waves breaking at a height in excess of 2.5m, occasionally as much as 4.0m. These observed wave heights were greater than predicted wave heights (1.6m for a wind speed of $9m.s^{-1}$ and a duration of 24 hours). Between 5.9.83 and 18.9.83 wind conditions returned to a prevailing south westerly regime (Force 1-4), although westerly winds, gusting force 8, affected the area between 15/19.9.83, resulting in breaking wave heights of 1-1.75m. Anticyclonic conditions dominated the rest of the month, accompanied by light winds of variable direction and a long, low south westerly swell. Breaking wave heights recorded at Worbarrow beach were less than 1.0m.

VOLUMETRIC CHANGE

Volumetric changes between successive surveys have been calculated using the method recommended by the pilot study (Table 36). Gross volumetric change over the period 1.9.83 to 25.9.83 showed an erosion value of $-137.1m^3$ and deposition of $86.5m^3$. However, it can be seen that storm and post-storm conditions had a dramatic effect on beach volume; the storm conditions of 2-4.9.83 resulted in severe erosion over the whole beach unit, particularly profiles 2 ($-36.0m^3$) and 3 ($-39.2m^3$). By 18.9.83 a return to more stable, post-storm, meteorological conditions resulted in the volumetric recovery of profiles 2 and 3, to a volume almost identical to that recorded prior to the storm; profile 1 only recovered 36% of its pre-storm volume and profile 4 only 19.5%. Although volumetric recovery was not pronounced on profiles 1 and 4 closer inspection of volumetric change indicated that the lower beach sections experienced deposition and re-established pre-storm volume, whilst upper sections experienced limited accretion.

The survey of 25.9.83 further illustrated changes in sediment distribution over each section relative to the survey of 18.9.83. Profiles 1,2 and 3 suffered erosion, particularly on the upper beach, whilst profile 4 received a small amount of deposition.

BRUUN INDEX AND MEAN DEPTH VALUES (Table 37)

Calculated values of Bruun Index and mean depth indicated that profiles 2 and 3 displayed the highest values prior and post-storm. It should be noted that both profiles produced identical Bruun values on 18.9.83 despite differences in profile volume and length. Maximum mean depths for all profiles were recorded on 1.9.83.

PROFILE CLASSIFICATION (Table 38)

Throughout the study period profiles 1,3 and 4 were characterised by a linear macroform; profile 2 displayed concave profiles immediately after severe erosion on the foreshore at the height of the storm. Prior to the storm berms were present on profiles 2-4, along sections 3 and 4 remnant upper berms marked the last storm event of spring.

Storm action produced storm berms on profiles 1-3, but profile 4 presented a steep, linear, wave ramp; erosion of the low clay cliffs thus extended the beach width. Along sections 2 and 3 the high storm berm (6m. O.D.) prevented erosion of the clay cliffs behind. Beach recovery following the storm was rapid and all but profile 4 regained a similar profile configuration and volumetric prism.

CHANGES IN BEACH PROFILE FORM AND VOLUME, JULY 1983 - SEPTEMBER 1984 (Appendix 4)

1. RINGSTEAD BEACH

Volumetric Change :

Ringstead beach displayed great volumetric variation over the study period, particularly on the upper beach sections, (Table 39). Gross volume, calculated from 6 measured beach sections, indicated a net erosion of -441.50m^3 and a net deposition of +440.10m^3 illustrating that, despite the great variation between monthly surveys, the beach unit as a whole displayed a balance between gains and losses.

Monthly surveys show that the greatest volumetric increase along the upper beach was recorded between 16.1.84 and 10.2.84, whilst greatest cut was recorded between 10.2.84 and 20.3.84. On the lower beach greatest volumetric increase was recorded between 15.8.84 and 24.9.84 with maximum losses between 8.12.83 and 16.1.84.

Individual profile data indicates that section 5 suffered the greatest overall loss of material (-105.0m^3) yet received the greatest overall sediment gain (+95.80m^3) throughout the period. Profiles 2, 5 and 6 displayed a small deficit of material over the period whilst profiles 1, 3 and 4 showed a net increase in sediment storage.

Sequences of erosion and deposition did not conform to King's (1953), correlation between onshore winds and beach "cut", or offshore winds and beach "fill"; on the contrary, offshore winds between 20.3.84 and 13.4.84 coincided with severe erosion of the upper beach whilst prevailing onshore winds from the south west/west accompanied great volumetric increase during the period 1.9.83 to 6.11.83, and 16.1.84 to 10.2.84.

Profile Classification :

Table 40 indicates the great variety of form displayed by each profile over the study period; all profiles (with the exception of 2 and 5) displayed all 3 macroforms. The central profiles, 2 to 5, tended to be linear in form, with upper berm development, particularly on profiles 2, 4 and 5; it was noted that profiles 2-4 showed no high water berm on the survey of 8.12.83 although each section displayed different typology. Profile 6, at the eastern end of the beach and marking the junction between the beach and boulder field, displayed all 3 profile forms but tended to be concave during the autumn and spring, and linear throughout the summer months. Profile 1, marking the westward extent of the beach did not show any seasonal trend for profile form, but, like profile 6 presented upper berms on all surveys. Alongshore variation in profile form indicated that linear forms were most common and often dominated the central, most exposed section of the beach; only profile 6 displayed any preferred seasonal form. It should be noted that changes in profile form revolved around the linear macroform, on few occasions was there any direct change from concave to convex macroform (or vice versa) and such changes were restricted to the winter period.

Bruun Index and Mean Depth (Table 41) :

Alongshore variations illustrate that section 3 maintained the highest average steepness values during the period May-August 1984. Profile 6 also maintained high steepness values whilst profile 5, immediately to the west, displayed the least average steepness values between February and July 1984. Other profiles tended to record greater variability. Results for 8.9.83 reflect the extensive drawdown of material from the entire beach experienced during the severe storm even that preceded that survey. By the following survey of 8.10.83 much of the sediment had been returned above low water thereby increasing steepness.

Mean depth values described a similar trend, with central beach sections 2-4 recording the greatest mean depth, although on several occasions profile 2 produced least mean depth. The results suggested that no seasonal trends existed; spatially, central profiles stored the most sediment whilst end profiles showed a slight tendency toward an inverse relationship. On several occasions high values of mean depth (and increased sediment storage) were reflected by smaller mean depth values on profile 1 (and vice versa).

2. DURDLE DOOR

Volumetric Change :

Of all the beach units surveyed Durdle Door displayed the greatest volumetric variation. Over the study period total volumetric "cut" (all 9 profiles) amounted to $-617.92m^3$, whilst total "fill" amounted to $+604.78m^3$. Table 42 illustrates the variations of cut and fill on both upper and lower beach sections between successive surveys. The data indicates that the greatest recorded amount of cut on the lower beach took place between the surveys of 17.2.84 and 21.3.84 ($-22.7m^3$) under prevalent north easterly winds force 3-4, backing easterly 48 hours prior to the survey. Greatest fill on the lower beach was recorded between the surveys of 19.1.84 and 17.2.84 ($+21.85m^3$). Prior to the survey of 17.2.84 the prevailing wind direction was north easterly/easterly, force 2-4, following a prolonged period of westerly conditions, force 3-8 (28.2.84 - 8.2.84). On the upper beach maximum cut occurred between 8.5.84 - 7.6.84 under northerly winds although 7 days prior to the survey, wind direction was highly variable force 3-4. Greatest fill ($+110.25m^3$) between 21.3.84 and 13.4.84 also coincided with offshore (northerly) winds.

Trends of volumetric change of individual profiles indicated profiles 1, 4, 5 and 6 gained sediment, whilst profiles 2, 3, 7, 8 and 9 displayed a negative imbalance. The data suggests that there is little material exchange between adjacent profiles, that is, longshore drift cannot be considered the dominant process, that process being a direct onshore/offshore exchange of sediment.

Profile Classification :

The morphological classification of beach profiles on Durdle Door is illustrated in Table 43. The results do not suggest any cyclical trend between profile macroform over time. Alongshore variation in profile was pronounced, especially with regard to berm position. Sections were characterised by one profile type, its variation expressed by berm development and position. Profile 1, for example, displayed convex form on all but 2 survey dates, (7.12.83, linear; 13.4.84, concave). Berm development was associated with high water mark, with secondary, minor berm development around the low water mark. Observations implied that tidal fluctuations were responsible for a migrating high water berm, whilst wind and wave action was considered to be the primary influence upon the smoother profile morphology.

The most exposed beach sections (3-9) described a marked tendency towards linear or concave form, whilst the sheltered sections, 1 and 2, showed an increased portion of convex profiles. Profiles 5 to 9 described a common tendency towards no berm development between October 1983 and February 1984, despite great variation in profile form.

Bruun Index and Mean Depth (Table 44) :

The data indicates great variability of beach slope and mean depth, both spatially and temporally. Profile 1 displayed the steepest average beach slope between October

1983 and March 1984 (although a maximum steepness was recorded in May 1984). Close inspection of the data reveals a general hierarchy of beach steepness, the end profiles (1, 2, 8 and 9) displayed the steepest slope, whilst values decreased towards profile 5 from both ends. The beach unit as a whole recorded the steepest beach face on 8.5.84 and 25.7.84.

Mean depth values highlighted the scant veneer of sediment along the western section of the beach, particularly during the winter period when mean depth was often as little as 0.20m and large areas of the chalk platform lay exposed.

3. MAN O'WAR

Volumetric Change :

Man O'War beach displayed less variability in sediment storage than the more exposed beaches to the east and west. Gross volumetric change indicated a net erosion of $-157.4m^3$ and net accretion of $+147.4m^3$. In contrast to Durdle Door beach where maximum volumetric variability occurred on the upper beach sections, on Man O'War beach the lower beach sections tended to be more active. Table 45 shows that maximum volumetric erosion on both upper and lower beach sections occurred between 11.7.83 and 17.8.83 ($-60.0m^3$), and coincided with prevailing offshore (northerly) winds. Maximum deposition on the upper beach took place between 19.1.84 and 17.2.84 ($+24.0m^3$) under westerly winds and a dominant south west swell whilst on the lower beach maximum fill occurred between 1.9.83 and 7.10.83 ($+13.70m^3$). The positive imbalance of sediment during this period was a consequence of a severe storm event during 3 - 5.9.84. During this storm the beach suffered severe erosion over the whole beach face, the material being moved offshore. Following the storm, a return to more constructive conditions resulted in a net accretion of material.

Profile Classification (Table 46) :

Profile morphology on Man O'War beach suggests that a seasonal cycle of change exists. All 3 profiles displayed a tendency towards concavity during the winter period and linearity during the summer months (April-August). Upper berms were common features of sections 1 and 2; profile 1 displayed both a remnant upper berm and a contemporary upper berm during the period April-June 1984. Profile 2 also tended to display more than one berm on each survey, particularly between April-August 1984; an upper berm development was consistent during the period but lower down the beach face the profile form was dominated by either a mid or lower berm. Mid and low water berms were not found to co-exist on any of the survey dates. Profile 3 displayed the greatest diversity of berm position. During the winter period the profile displayed either no berm or only one berm at a preferred position on the foreshore. Upper berms were restricted to the period May-August 1984; a lower berm was also common of this period. The August survey produced a profile form with berm development at all 3 recognised positions.

Bruun Index and Mean Depth (Table 47) :

Alongbeach variations in Bruun Index values indicated that profile 3, towards the eastern end of the bay, frequently displayed the steepest beach slope during the winter months, whilst profile 2 displayed the average steepest slopes during the summer period. Profile 1 always produced the least average steepness values. No marked seasonal trends emerged for either beach steepness or mean depth. Mean depths ran from maximum to minimum, east to west, i.e. 3 being deepest and 1 the shallowest.

4. MUPE

Volumetric Change (Table 48) :

Gross volumetric change on Mupe beach indicated that beach erosion and accretion almost balanced over the whole study period. Total erosion recorded was $-138.8m^3$ with total accretion $+126.6m^3$. Maximum erosion on the upper beach occurred between 19.2.84 and 24.3.84 ($-30.0m^3$) whilst maximum accretion was recorded between 27.11.83 and 31.12.83 ($+28.6m^3$). Maximum erosion was associated with prevailing north easterlies and dominant north westerlies, whilst maximum accretion coincided with westerly winds and a south westerly swell. On the lower beach the range of erosion and accretion on the lower beach was recorded between 18.8.83 and 1.9.84, with maximum accretion between 27.11.83 and 31.12.83. Both events were associated with offshore winds (northerly). However, no seasonal trend of erosion or accretion was apparent. On upper beach sections the extremes occurred during the winter months whilst on the lower beach maximum accretion occurred during the winter and maximum erosion during Autumn 1983 (prior to a major storm event).

Profile Classification (Table 49) :

In keeping with the other beach units, one type of form tended to characterise each beach section. Profile 1, at the western end of the beach and marking the junction between the beach and the extensive boulder field towards Mupe Ledges, displayed a linear form throughout the survey period with no berm development. Profile 2 tended to be convex in form, particularly during the summer months, and displayed an upper berm on every survey date. Profile 3 tended to be marginally more linear than convex in form, and like profile 2 displayed a high water berm on all surveys.

Bruun Index and Mean Depth (Table 50) :

Profile 2 produced the highest average values of beach steepness and mean depth values from September 1983 through to June 1984. Results indicate that the highest Bruun value for profile 1 was recorded during July 1984, for profile 2 during February 1984 and for profile 3 during July 1983. All 3 profiles displayed lowest steepness values during December 1983, which coincided with the greatest amount of beach fill on the upper sections. Greatest mean depths and highest Bruun values were achieved during February 1984, and coincided with deposition on both upper and lower beach sections.

5. WORBARROW

Volumetric Change (Table 51) :

Contrary to Ringstead, Durdle Door, Man O'War and Mupe beaches, Worbarrow profile data suggested a tendency for seasonal phases of erosion and deposition on the upper beach. However, gross volumetric change indicated that by the end of the study period the beach unit had shown a balance between total erosion (-282.10m^3) and total deposition (+260.40m^3). Maximum erosion on the upper beach took place during the winter period, November 1983 - January 1984; between 8.10.83 and 27.11.83 erosion reached a maximum of -81.40m^3. Accretion on the upper beach dominated the period April-September 1984, although maximum sediment gain was recorded between September-October 1983 (+50.70m^3) following the major storm event during early September.

Volumetric change on the lower beach sections of Worbarrow beach ranged between -13.30m^3 and +13.4m^3. Maximum accretion on the lower beach occurred between the surveys of 10.8.84 and 29.9.84 (+13.40m^3) with maximum erosion between 8.10.83 and 27.11.83, (-13.30m^3). Maximum erosion on both the lower and upper beach sections was produced under prevailing easterly but dominant westerly winds, whilst maximum accretion coincided with prevailing and dominant westerly winds (September-October 1983 for the upper beach; August-September 1984 for the lower beach).

Profile Classification (Table 52) :

All sections displayed variety in their macroforms, although each section was dominated by one form. Profile 1 was characterised by a concave form, particularly between the period February-July 1984. The autumn/early winter period (August-November 1983) produced convex profile form. Concave forms tended to display upper berms whereas convex forms tended to exhibit no berm development. Profile 2, the most exposed profile, exhibited marginally more concave macroforms than linear forms. Concave forms with upper berms (often displayed as composite upper berms) dominated the period September 1983 to April 1984, whilst linear forms (also with upper and often remnant upper berms) dominated the remainder of the survey dates. Profile 3 displayed greater variability, all 3 macroforms being represented. A remnant upper berm was recorded on all survey dates; standing almost 5.45m above O.D. the berm was a storm feature, affected only by the severest storm waves (>4.[illegible]m breaking wave height) such as experienced during September 1983. A slight seasonal trend emerged; linear forms were presented during the autumn (September-November 1983) and early summer (April-June 1984), whilst concave forms dominated the winter period (December 1983 - March 1984). Convex forms appeared to be a function of summer conditions (July 1983; July-September 1984). Profile 4, the westernmost section was characterised by linear form throughout most of the study period. Convex form was displayed during July 1983 and July, August 1984, all with upper berms developed. Only the survey of December 1983 produced a concave form with a contemporary upper berm and a remnant upper berm.

The classification of profile form on Worbarrow beach indicate that concave and linear macroforms are most common during the winter period with convex forms characteristic of the summer and autumn periods.

Bruun Index and Mean Depth (Table 53) :

Calculated values signify that profiles 3 and 4 displayed the highest average steepness values more frequently than profiles 1 and 2. All profiles exhibited high values of steepness between July and November 1983, the highest values recorded on the October 1983 survey. Slopes were more gentle during the period from December 1983 through to the summer months of 1984, before increasing again through the autumn (1984). Mean depths, being related to steepness values, exhibited a similar trend. Profiles 3 and 4 produced the highest mean depths, profile 1 (the shallowest) and profile 2 produced moderate values of mean depth.

CONCLUSIONS

The nature of the investigated enclosed bays meant that the supply of beach material was very localised, from cliff and platform erosion. Longshore transport was restricted to south east wave regimes and limited by fixed cell boundaries; onshore/offshore exchange of material was the major process of sediment transport. 25 beach sections from 5 selected beaches were investigated by monthly surveys and analysed in terms of changes in the beach sediment prism, beach surface configuration, mean depth and average steepness (Bruun Index). Attempts were made to relate profile configuration and sediment storage to changes caused by storms, longshore transport, tides and coastal winds. It was generally accepted that profile configuration was a stochastic function of past profiles and the intensity of energy dissipation of breaking waves.

Meteorological records indicated that onshore winds dominated the summer and winter period with more variable wind conditions during the autumn and spring. The majority of monthly surveys were carried out over a three day period and although each beach unit experienced the same potential energy input and wave regime there was marked variation of beach morphology between beaches. Morphological variation also existed within beaches, adjacent profiles often displayed quite different surface configurations even though they were in the same erosive/depositional sequence. The monthly surveys did not reveal any characteristic pathways of transition. Despite morphological variation it was apparent that each beach section was characterised by one type of macroform with regard to tidal cycles and constructive/ destrictive sequences.

Volumetric changes were calculated between monthly surveys and values of maximum erosion and deposition were derived from the results. The results highlighted the discrete nature of each beach unit; phases of deposition and erosion were not systematic between beaches although affected by the same wave regime and tidal conditions. Neither was erosion or deposition linked to seasonal differences in marine conditions; maximum cut and full occurred during the winter period with the exception of Durdle Door and Man O'War beaches where maximum erosion was recorded between May-June 1984 and July-August 1983, respectively. At Durdle Door beach, maximum deposition was recorded between March-April 1984, whilst at Man O'War January-February 1984 produced maximum deposition value. On Ringstead, Mupe and Worbarrow maximum cut and fill values were recorded during the winter between the months of October 1983 and March 1984. Sequences of erosion and deposition described no convenient relationship with periods of offshore/onshore winds, as described in many previous beach studies. On the contrary, maximum erosion along Durdle Door, Mupe and Ringstead beaches occurred under prevailing offshore winds whilst at Ringstead, Man O'War, Mupe and Worbarrow onshore winds coincided with maximum deposition of beach material. Only Man O'War and

Worbarrow beach suffered maximum erosion under onshore winds. Such behaviour is possibly related to the dominant effect of the south west swell component; only under prolonged periods of south easterly seas will the effects of a decaying south west swell be cancelled out. Thus a south westerly wave regime will be dominant under offshore winds. During the calmer, more stable marine conditions of the summer months the presence of the offshore Portland reef may have a greater effect on incoming waves. Seasonally reduced levels of wave energy may be further attenuated by the reef so that energy is concentrated along various sections of each beach thereby producing variable conditions of erosion/deposition within each beach unit.

Variation in beach volume (per metre width) was greatest along those sections fully exposed to the south west, particularly the eastern sections of Durdle Door and Worbarrow beach. Mupe and Man O'War beaches were more responsive to south easterly wave climates; Mupe beach, the most exposed to the south east, suffered maximum erosion under such conditions, whilst Man O'War experienced maximum accretion.

Profile configuration showed a greater tendency for multiple berm development (all beaches) during the summer period. Berm development and position was a reflection of limited tidal variations; the variation in spring tidal heights tended to produce multiple berms around the high water mark whilst mid to low water berms were a consequence of reduced wave action and the more pronounced effects of tidal cycles resulted in a redistribution of sediment and modification of berm shape rather than cycles of erosion or deposition. During the summer, berms tended to be more rounded in form; in winter a concave foreshore extended to a single, steep (30^o) berm at high water. During the summer, berms were present on the narrow, fine grained sections of Durdle Door but the early autumn storms caused a return to a more characteristic steep, linear ramp, allowing waves to reach the cliff base.

The results suggest that all the beaches are in a state of equilibrium with south westerly wind and wave regimes. Mupe and Man O'War beaches, orientated to the south east are little affected by the dominant south westerly component due to the shelter and refraction of incoming wave trains afforded by the offshore Portland reef and ledges. The effects of severe south west storm events produce a simple onshore/offshore exchange of material; the removal of sediment from the most exposed sections may appear severe but beach recovery is also rapid and the section regains the volume lost and an almost identical profile configuration, (e.g. Worbarrow, September 1983). Similar exchanges, but of smaller magnitude, were observed on the more sheltered bays to the west. In contrast, prolonged south easterly wave regimes have a more pronounced effect on both beach volume and configuration, particularly Durdle Door. Locally generated south east waves are usually short lived due to the limited fetch but under atypical conditions they may prevail for up to three weeks. The oblique angle at which such waves reach the shore initiates longshore drift. The monitoring of such an event suggested that its effects on profile form and volume are more significant than severe storm events. It was assumed that severe south west storms produced the "extreme event" of beach behaviour but it became apparent that atypical conditions of prolonged and dominant south easterly waves produce "extreme event" behaviour. Therefore, "normal" changes in beach configuration are a response to changing marine conditions (within the westerly quadrant), exposure, tidal cycles and the feedback effects of beach slope on wave steepness.

CHAPTER 9

SUMMARY AND CONCLUSIONS

The study aimed to further the investigation into the morphological characteristics, processes and sediments of five compartmentalised, mixed gravel and shingle bayhead beaches on the south east Dorset coast. A conceptual framework of process-response was adopted to which observations were referred; the model considered energy inputs, sediment transport and coastal morphology, under conditions of limited sediment supply and an inferred closed cell environment. Theoretical considerations and extensive and intensive fieldwork have helped to :

(i) gain a better understanding of the overall sediment system within Weymouth Bay and selected embayments on its northern shore.

(ii) gain a better understanding of the relationship between cliff, beach, platform and nearshore processes and to describe that relationship in the context of the conceptual model of a self-contained unit.

(iii) begin to quantify the variables of the model with the ultimate aim of producing a realistic sediment budget.

(iv) verify the hypothesis that each bayhead sediment cell is morphologically contained, yet all are powered by the same hydrographic system.

The findings of the study are summarised under a number of headings that represent the key elements of compartmentalised sediment circulation.

MORPHOLOGICAL AND SEDIMENTOLOGICAL CHARACTERISTICS OF WEYMOUTH BAY

The bathymetry of the Weymouth Bay plateau is controlled by its geology, bounded by land to the north and west and by St Alban's Ledge to the south and east (Admiralty Chart 2610). Major changes of relief are presented by contemporary sediment forms (Adamant Shoal, Shambles Bank) to the south of the bay whilst the geologically distinct features of the Lulworth Banks and the submerged Portland stone reef dominate the northern coastal zone;minor rock outcrops such as the Purbeck Anticline act as additional sediment traps near the shoreline. A number of independent surveys have revealed that surficial sediments within the bay consist of a relatively thin veneer of rippled sand and shell material. Tidal currents are strongest to the south east of Portland Bill (where they are responsible for the Adamant Shoal and Shambles Bank), but are only capable of transporting gravel sized material at spring tides when they reach a maximum 1.7kts; close inshore and within the study bays, current velocity is negligible. As the whole of the Weymouth plateau is shallow enough to be affected by wave action it is assumed to be the dominant force of sediment movement. A side-scan sonar survey, by the author, was carried out to map sedimentology and morphology along a line approximating to the 10 m bathymetric contour, bed forms being used to infer sediment mobility. Sand ribbons, orientated at right angles to the prevailing south west swell dominated the coastal zone whilst flat bed sands marked areas where wave action was more moderate (e.g. shoreward of high vertical face of Portland reef in Worbarrow bay). Due to the weak currents in the bays the morphology of the offshore reef acts as a significant impediment to sediment movement into/out of the nearshore system.

The lack of coarse grade material within Weymouth Bay means that there is little appropriate material to nourish the predominantly (>99%) silica beaches. Contemporary rates of erosion of flint bearing chalk are not sufficient to have created the beaches and their development is linked to that of Chesil beach, the flint being derived from the widespread erosion of Channel chalk during fluctuating sea levels and are, therefore, considered to be relict features of the Flandrian transgression. Within the study bays the morphology and sedimentology was investigated by scuba divers and grab sampling. The beaches were found to extend no further than 30 m beyond low water; the beach toe was most clearly defined along the most exposed sections of each bay, where pebble grades predominate. Where sand/granule grades dominated the littoral zone the seaward edge of the beach was more diffuse, with no distinct break of slope or textural change (western sections of Durdle Door and Worbarrow beaches). In the more sheltered bays of Man O'War and Mupe the coarsest pebble grades were found offshore; the seaward edge of the beach was marked by a distinct break of slope and seaward of that point pebbles displayed encrustations and animal borings, suggesting limited mobility. Such textural differences within the bays suggest that the littoral and offshore systems are almost discrete. The side-scan survey and offshore sampling programme also noted the extent of the boulder fields at White Nothe, Mupe, Cow Corner (Worbarrow) and Worbarrow Tout. The boulder fields at White Nothe and Cow Corner mark actively eroding chalk cliffs and their development prevents leakage of the sediment cell and provides protection to the beaches (by wave attenuation). The boulder fields tend to encourage weed growth, particularly during the summer months, preventing active sediment mobility. During the winter, storm waves destroy the kelp fields and kelp rafting is an active process. The amount of material added to the littoral zone by this process is difficult to quantify.

Wave action is the dominant force of sediment movement within Weymouth Bay and its embayments, south west swell with an effective fetch >2000kms being the dominant and prevalent regime. Storm waves with breaking wave heights up to 2.5m are typical of winter storms; breaking wave heights of 4.0m are considered extreme events along this coastline.Such conditions are capable of removing up to 50 m^3 (per metre width) during one tidal cycle, but beach recovery can be almost as rapid under a return to fair weather swell. Prolonged exposure to locally generated south east seas is atypical; south east seas tend to be very short lived (average 3 days), rapid in development and decay, and commonly superimposed upon a remnant south west swell, thereby producing a bimodal wave train. This study has noted that locally generated south east seas have a more significant effect on beach morphology than south west swell because it initiates a westward littoral drift, (Plates 37 and 38).

BEACH SEDIMENTOLOGY

Standard sampling procedure produced a large amount of data to illustrate the scale of variation in sediment size within and between beaches. Graphically derived measures indicated that along beach variations were more significant than variations between beaches; downbeach variations were of secondary importance. It was apparent that sampling procedure and laboratory analysis influenced and biased results towards coarse fractions, sieving was chosen as standard laboratory procedure because of the difficulty of individual measurement of coarse sand grades. Beach sampling, followed the common procedure of random selection from surface lamina of a one metre square, despite the possibility that the surface lamina may have been made up of particles rejected by the traction carpet; composite sampling was not a practical alternative.

Results indicated that the most exposed profiles on each beach displayed the coarsest grades, downbeach uniformity of mean grain size and the best sorting values. Bimodal samples tended to be found along the mid to low water zone, possibly a consequence of the double wave trains; bimodality increased along Durdle Door under changing wave regimes.

Intensive sampling along Durdle Door beach revealed a weak tendency for three small interdependent sediment cells to develop under stable south westerly swell; the cells being centred upon Durdle Cove, Scratchy Bottom and Swyre Head to Bat's Head. Fluctuations in mean grain size were not a result of littoral drift but related to localised increases in wave energy due to exposure and offshore bathymetry. Locally generated south east seas produced a two cell arrangement; littoral drift produced a spit like feature from Durdle Door to Scratchy Bottom, terminated in front of Swyre Head by exposure of the chalk platform, this section being most exposed to the south east conditions. A secondary cell stretched from Swyre Head to Bat's Head, but exists only as a thin veneer of fine sediment over the underlying platform, (Plate 39).

Mupe and Man O'War beaches presented the coarsest sediment distributions but the condition of the offshore sediments suggested little mobility or exchange of sediment between the littoral zone and offshore; measured volumetric changes between monthly surveys enhance the limited mobility assumption. Worbarrow and Ringstead beaches displayed coarse sediments along the most exposed sections towards the centre of each beach. Similar observations to Arkell (1947), with regard to the sediment distribution on Worbarrow beach have been noted on both Worbarrow and Ringstead beaches; this study implies that the distributions are a consequence of bimodal wave trains or frequently changing wave regimes. Although the coarsest grades are found to the centre of the beach, large pebbles apparently travel back to the extremities of the beach; south west swell does not initiate longshore drift and south east seas are not capable of moving the largest pebbles, so the movement must be due to complex interactions under bimodal conditions, causing selective transport and particle rejection.

BEACH MORPHOLOGY

All the study beaches presented narrow, steep, reflective profiles. Beach widths were commonly 20-40m with the highest elevations associated with storm berms (approximately 6 m O.D.). Storm berms were best developed at Worbarrow beach where the eastern sections were fully exposed to the south west. Surveyed profiles were subjected to a simple macroform classification to describe general beach configuration (after Sonu and Van Beek, 1972; Caldwell, 1983), but no quantitative standardisation was attempted. It became apparent that each section was characterised by a particular profile type, adjacent profiles commonly displayed quite different macroforms. Intensive surveying of nine beach sections on Durdle Door beach did not reveal any distinct cycle of development due to the atypical wave regime under which the survey was carried out. Even monthly surveys failed to describe any cyclical morphological development with only a weak tendency towards seasonal adjustments (a more convex form around high water during the summer period).

Beach volumetric change, steepness and mean depth values were calculated using a standardised beach prism (after Clayton, 1977). Volumetric calculations revealed that all the study beaches have a neutral sediment budget at the scale of 12-14 months, sequences of maximum erosion/accretion were not seasonal.

Two typical beach morphologies were recognised during the study,(Figure 43a, b). Beaches developed upon chalk platforms in front of high, hard chalk cliffs (Durdle Door) tended to be very planar, narrow (15-30m.), steep (10^{o}), shallow (mean depths <1m.), with restricted berm development. These sections were characterised by linear macroforms, a reflection of the form of the underlying platform. Profiles in front of clay cliffs tended to be larger (40m.) with high berm developments and steep, concave foreshores (up to 30^{o}). These sections presented the greatest morphological variation, coarsest sediments and best sorting. The macroform was commonly dominated by a remnant storm berm (up to 6m. O.D.), only modified by the highest storm waves. Multiple berm developments at high, mid and low water marks were common.

CLIFFS AND PLATFORMS

Chalk cliff and platform morphology was investigated in an attempt to establish its role in the sediment budget and sediment transport. Due to structural differences in the south east Dorset chalk coast a variety of profile form was displayed. Three profile configurations were observed (as recognised by May, 1964). Erosion was active on all cliff forms. At Durdle Door marine and subaerial erosion was continuous throughout the year, the magnitude of the erosion tended to be seasonal. During winter months frost action and marine spray micro-erosion was most active, whilst during the summer, dessication of the chalk surface predominated. It is worth noting that frost action and dessication produced similar quantities of eroded material, the fine material being easily washed away. Even large boulders have a limited residence time in the littoral zone. Observations of a fall at Swyre Head noted the limited real input of material into the beach systems, almost all the material being lost to the offshore zone, the smaller fragments and fines being washed away, the boulders removed by storm waves. At White Nothe and Worbarrow erosion of the chalk has extended the boulder fields and increased protection of the cliff base; subaerial erosion has since become more important than marine erosion.

Exposure of the chalk platform at Durdle Door occurred under storm activity (south west) or prolonged south easterly seas. The platform surface is planar, steep (10°) and narrow (15m.). The clean substrate surface aids active sediment transport of the thin sediment cover. Mean depths less than 1m. suggest that attrition of the platform and flint ridges is an active process but the amounts of material added to the sediment budget occur virtually undetected.

Studies by Hutchinson (1984) also noted this process and based on his findings it may be inferred, that, along Durdle Door beach, greater amounts of flint are added to the beach from erosion of the platform than from cliff erosion.

Notch development at the cliff/platform junction is most marked at sites where the platform is narrow with the cliff base <2m. O.D. The great variety in profile form and junction height appears to be related to geology and local variations in marine conditions. Although most of the junctions are within the tidal range, the 5.6m variation of junction height produces no relationship between exposure and tidal height.

The main objectives of the study have been fulfilled by developing the basic conceptual beach model in conjunction with the simple cell of sediment transport. Fixed boundaries and the presence of an offshore reef, compartmentalised bays and provided natural boundaries to impede sediment circulation and prevent leakage. Examination of the textural differences between the littoral zone and offshore zone reveal discrete systems of circulation; beach movement is limited to an area not much more than 30 m below low water; even during severe storms, when beach erosion is extreme, the sediment is stored immediately offshore, readily available for onshore movement under fair weather swell. The morphology and distribution of the Portland stone reef is capable of restricting movement into or out of each cell and protects the beaches by wave attenuation. The sediment distribution, wave regime and weak tidal currents verify the closed cell hypothesis; each embayment is an exclusive unit of sediment describing temporal and spatial variations. The key elements of the closed cell model of sediment circulation, as derived from the study of south east Dorset beaches are diagrammatically represented in Figure 44.

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