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GRAIN SIZE ANALYSIS OF THE SEDIMENTS OF SPURN HEAD, EAST YORKSHIRE, ENGLAND

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Abstract

Grain size statistics can be used to characterize a sediment and may be used to derive some information concerning its origin and depositional processes. Data were collected over two field seasons at regular intervals along the seaward and estuary-facing beaches of a 3.5 km long spit in eastern England. The statistics derived from the sand samples were used to investigate the spatial variability and influence of sediment transport on grain size characteristics. Spurn Head in East Yorkshire was chosen for the study because it has a single identifiable sediment source (the glacial till cliffs of the Holderness Coastline). And has a clear transport direction (to the south). In cliff to spit system, very poorly sorted till is eroded from the cliffs and transported southward by long shore drift to form a mobile narrow sandy beach which terminates in a spit in the mouth of the Humber Estuary. Despite the complexity of the source sediment, and variability in transport mechanisms and energies both spatially and temporally, significant patterns were identified on the long shore direction, which were perpetuated over the two sampling seasons.

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I would like to sincerely thank the Geography Department at Queen Mary and Westfield College, University of London for use of their laboratory equipment, and the Geology Department at the University of Cincinnati for use of their sieve equipment. I would not have completed this project without the encouragement from my wife, and the need to supply updates to my mother oversees. Thank you to Dr. Nicholas Dunning for chairing my review committee and reviewing early drafts of the dissertation, and Dr. Roder and Dr. Lowell for their committee review. Lastly I would like to express my appreciation for being granted the opportunity to study for a Doctorate with financial support from the University of Cincinnati, and Department of Geography.

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1.0 INTRODUCTION

Grain size analysis is the measurement of grain size distribution in samples of sedimentary materials and the subsequent transformation of these measurements into descriptive statistics. These statistics allow direct comparison of one or more sample sites or sedimentary environments. Scholarship in the area of grain size analysis has suggested a link between the depositional environment and the sediment grain size distribution. The degree and sensitivity of this link is debatable, but it may be possible to differentiate different sedimentary environments on the bases of certain distribution characteristics. The key component in this theory is that the grain size distribution is highly influenced by sediment transportation mechanisms. These mechanisms are themselves energy dependent and comprise long shore current transport, swash and backwash motion, wind deflation, and tidal currents. Transportation methods associated with these fluid media include suspension, saltation, and traction.

The purpose of this study it to measure the spatial variability in grain size parameters within a spit environment and to test the theory that a geographic pattern in these parameters can be related to energy inputs and transport mechanisms. In the Spurn Head spit environment (Figure 1) the variable of sediment source has effectively been removed. This is because all the sediment comprising the spit is derived from the eroding glacial till cliffs of Holderness, which are eroding at a rapid rate. With this variable removed, grain size variations may then be related to the physical processes operating in that environment. Furthermore, if zones of high energy activity and high sediment transport rates can be differentiated and mapped using this technique, it may be possible to use it as an additional tool in the prediction of areas of enhanced erosion risk

in this highly dynamic environment. Spurn Head is a feature that is the result of sediment transportation, sorting and deposition and is undergoing frequent alternation and modification. It sits at the distal end of the fastest eroding coastline in Europe and receives large volumes of material derived from the glacial till. This begins as unsorted material (till is one of the most poorly sorted fluid derived deposits in nature) and is reworked by current and wave action. With this in mind, there can be few better places to study the effects of sediment transport on grain size distributions.

Figure 1: Project Vicinity Map, East Yorkshire, England.

Beach sediment size is dominantly influenced by sediment source, wave energy level and the general offshore slope on which the beach is constructed (Komar, 1976). If the source of material does not provide the material that is appropriate for the wave conditions then a persistent beach is unlikely. Beach re-nourishment, such as that commonly conducted on tourist beaches is dependent on selection of the appropriate mix of sediment to ensure maximum duration. Sediment size can vary with position on the

beach. Shore normal sediment size analysis indicates that the coarsest sediments are found at the point of maximum wave energy (breaking point) and decrease both shoreward and landward (Komar, 1976).

Longshore patterns are far more complex and are explored at length along the beaches of Spurn Head in this study. Coastal spits can be thought of as detached beaches, which protrude from the main coastline into deeper waters at estuary mouths or bays (Pethick, 1984). Spits have developed in many parts of the United Kingdom, mainly in areas where the tidal range is less than 3m. Spurn Head is one of the exceptions to this general rule as it has a tidal range in excess of 5m (Ciavola, 1997). Coastal spits are by their nature dynamic features, they are the result of a balance in the flux of sediment in and out. Much like a glacier, where sediment input exceeds output the result is spit growth or increase in beach height and width. Where the sediment "ablation" exceeds accumulation the spit will be narrowed and may be breached. A breach of the spit then prevents sediment moving by longshore drift past the opening, and the ablation processes then dominate and remove the separated distal portion of the spit. Many spits are associated with gravel or sand banks which may be located near the tip or just offshore of the main spit. These act as important sediment sources and sinks (on Spurn Head, there is a gravel area known as the Binks).

Spits generally consist of two parts: (1) a lower level spit platform (2) an upper level sub-aerial spit (Friedman et. al, 1992). Spits lengthen by first extending the submerged platform, then building the exposed part. The platform is fed by longshore currents flowing in the subtidal zone, and in runnels in the intertidal zone at high-tide. This transport occurs whenever the waves approach the shore at an oblique angle. Waves and

tidal currents sweep over the spit platform flattening its profile to a level that is about 1/2 meter below the water surface. Once a spit platform is present, the subaerial portion can grow. The sand to build the upper level may be transported along shore, either in the upper part of the intertidal zone, when vigorous currents in the surf zone erode a beach scarp, or in channels shoreward of a beach berm. If there is plenty of sediment available the spit can grow very rapidly. The spit will typically tend to recurve when it reaches the tip of the spit platform.

Spit beaches are very similar to marine beaches. However, unlike marine beaches, when water spills over the top of a berm crest on a spit beach it tends to flow in a shore parallel (longshore) direction towards the distal portion of the spit, and therefore becomes an important mechanism of longshore sediment transport. Periodically the longshore flow cuts through the berm crest and returns seaward. Therefore, in summary, according to Friedman et al., spit beaches consist of four chief kinds of sediments: (1) beach face sands well laminated with planar layers (2) spit berm top sands, well laminated with nearly horizontal laminae (3) steeply dipping foreset sands of berm spill over areas (4) dark grey silty sands that accumulate in spit bays.

The location of spits at the opening of waterways often gives them significant strategic value. Spurn Head was developed with gun emplacements and was occupied by a garrison in both World Wars. A paved road was built to the tip and a railroad line was laid to bring supplies and munitions to the batteries. Spits positioned across estuary or bay mouths provide protection to the areas within and encourage the development of "low energy" depositional environments such as mud flats and marshes. Increasingly, such wetland environments are being designated as protected reserves. Spurn Head is

protected as a bird sanctuary therefore has significant ecological value. In addition, Spurn Head is the location of the Humber Lifeboat, which provides rapid access to the shipping lanes and coastal waters off the Humber Estuary and the North Sea.

Where a spit (or any coastal feature) is in danger of destruction, its value must be weighed against the need, cost and feasibility of its protection. Any protection strategies should be carefully considered to ensure that ill-conceived protective measures do not result in increased erosion either at the protection site or elsewhere (which is commonly the case). Unfortunately for many residents, the Holderness coastline has the dubious honor of being the fastest eroding coastline in Europe (3). Isolated coastal protection schemes along portions of the coast have invariably failed over time, and have increased erosion down drift of the protection. Protection of one portion of the coast prevents sediment input to the protective beach downdrift, and increases the potential for waves to directly attack the cliffs. As the penultimate sink for the sediments eroded from Holderness, interference with the sediment flow will affect Spurn Head.

Emotions run high among the residents and farmers on the Holderness coast where their homes and livelihoods are at stake. The call for beach defenses increases as more homes and farms are threatened. Unfortunately, the cost of protection invariably outweighs the value of the land being protected. Pethick, a noted geomorphologist, by his own admission made himself “the most unpopular man in East Yorkshire” by suggesting that no new protection schemes be undertaken along the coast. Indeed, some of the protection schemes have themselves caused increased erosion immediately to the south.

2.0 BACKGROUND

2.1 THE HISTORY AND GEOMORPHOLOGY OF SPURN HEAD

Spurn Head in East Yorkshire is a sand and shingle spit jutting 3.5 km into the mouth of the Humber Estuary on the east coast of England (Figure 2). At its northern end, Spurn Head follows the orientation of the Holderness coast in a north-westerly to south-easterly direction, and to the south curves round to point in a south-westerly direction.

Spurn is the result of very rapid erosion of the quaternary-aged glacial deposits of Holderness which overly Cretaceous chalk, which itself outcrops further north at Flamborough Head, defining the northern limit of the sediment source area for Spurn Head. Erosion rates along this stretch of coast were estimated by Valentin (1954) as high as 2.75m yr^{-1}, the highest recorded rate world-wide for the period 1852-1952. This material is transported southward to form Spurn Head. There are several factors responsible for such rapid erosion. The first is that the Holderness plain is a former bay infilled with easily eroded glacial tills. Waves undercutting the cliff produce slumping type landslides and the debris from these is easily swept away by the sea. A paleo-cliff runs from the south side of Flamborough Head to Hessle (on the estuary coast) in the south and the sea is rapidly, in geological terms, cutting back to this pre-glacial shoreline. Deep-sea erosion is occurring as well as cliff line erosion since the deep water has advanced over the sites of former cliff line villages.

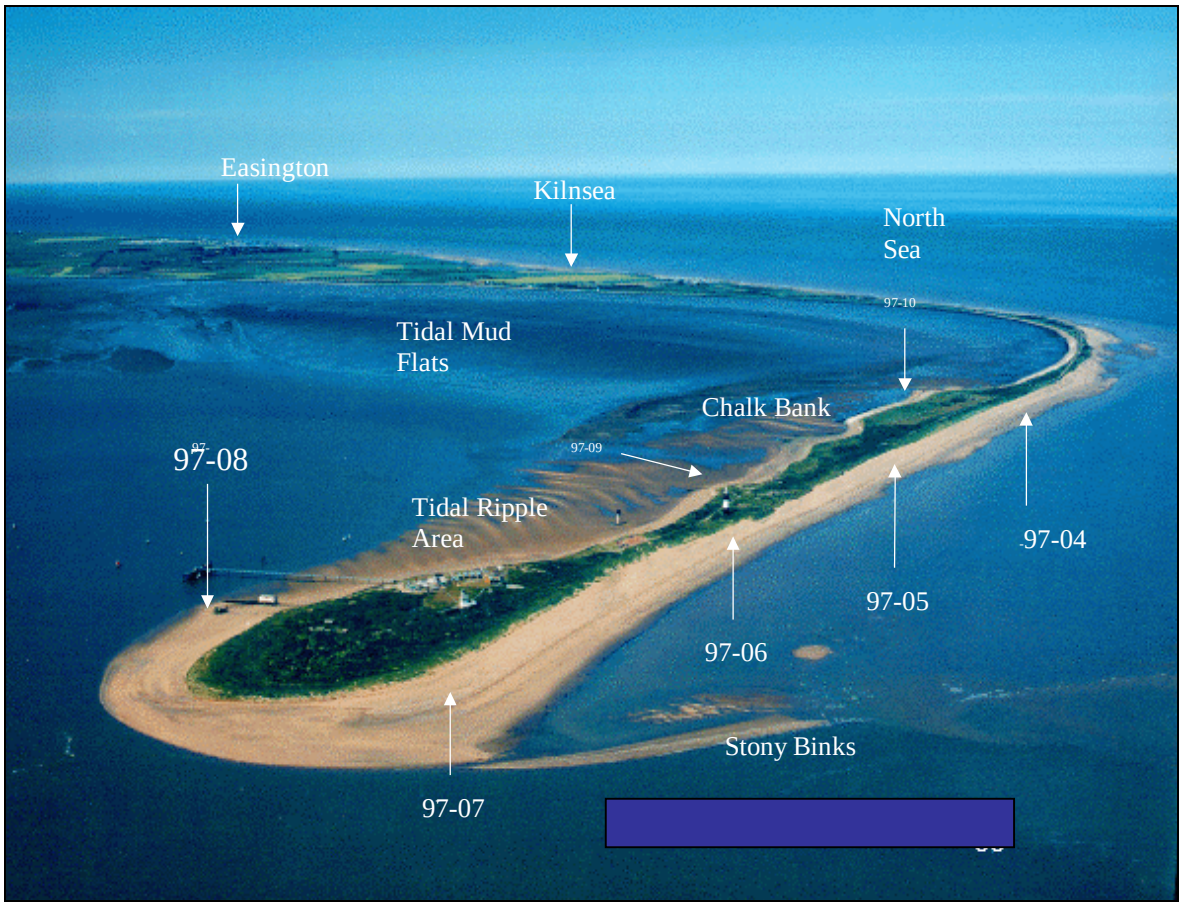


Figure 2: Aerial view of Spurn Head showing the 1997 sample points, and notable geomorphological features. Photograph by R&R Photography, Hull, UK.

The names of Old Ravenser, Port of Ravenser Odd, Hrafnseyrr and Hulton have passed into history, collectively remembered as the lost towns of Holderness. Retreat since Roman times (AD 670) is estimated to be over 2 km (see Figures 3 and 4). The ords may also be described as longshore bars that are aligned slightly offshore which move down the coast as waves. Shoreward of the bar crests they form mid-tide and high-tide channels which allow water from swash and high-tides to flow along the upper portion of the beach southward. Eventually these channels cut through the bars and make their way back to the sea.

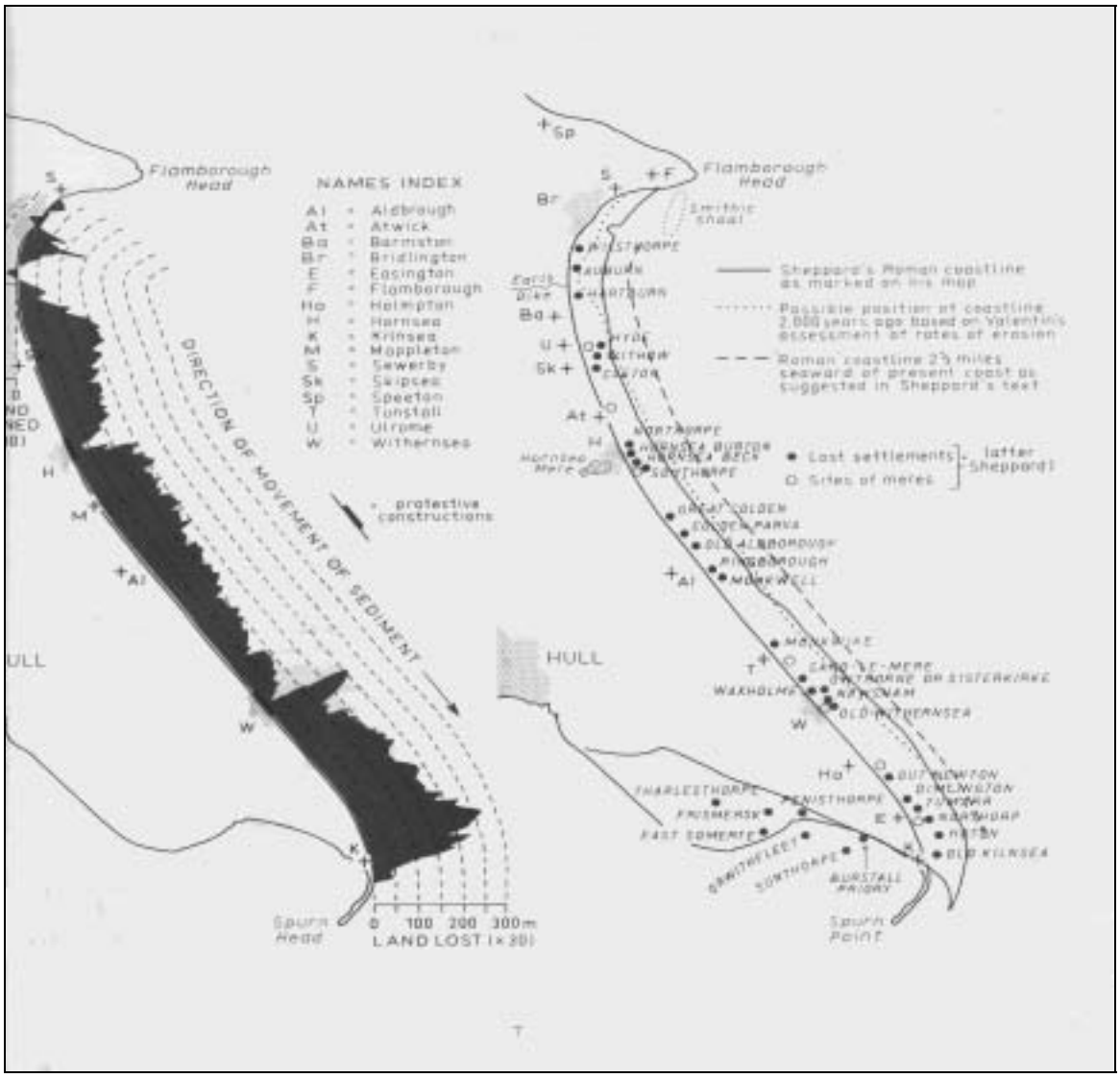


Figure 3: Erosion rates along the Holderness Coast and some of the lost towns (after Neave and Ellis in An Historical Atlas of East Yorkshire, University of Hull Press).

The submarine contours drop off rapidly offshore. In places the 10m submarine contour is only 600m from the beach. The coast is therefore subject to the full force of the waves from the North Sea with little sea bottom attenuation before they reach the cliff line. Flamborough Head prevents transport of materials from the north by the dominant northeasterly waves. The result is that little beach material is transported southward to the beaches of Holderness. The sea attempts to build up an equilibrium gradient by

eroding the soft cliffs behind the beach, to which the strong waves have easy access. Material derived from such rapid erosion along a 55-km front is moved down the coast by longshore drift, and the coarser fraction is deposited in the spit that extends into the Humber Estuary, while the silts and muds are carried offshore. Some of these finer sediments find their way into the Humber Estuary to form expansive tidal mud flats.

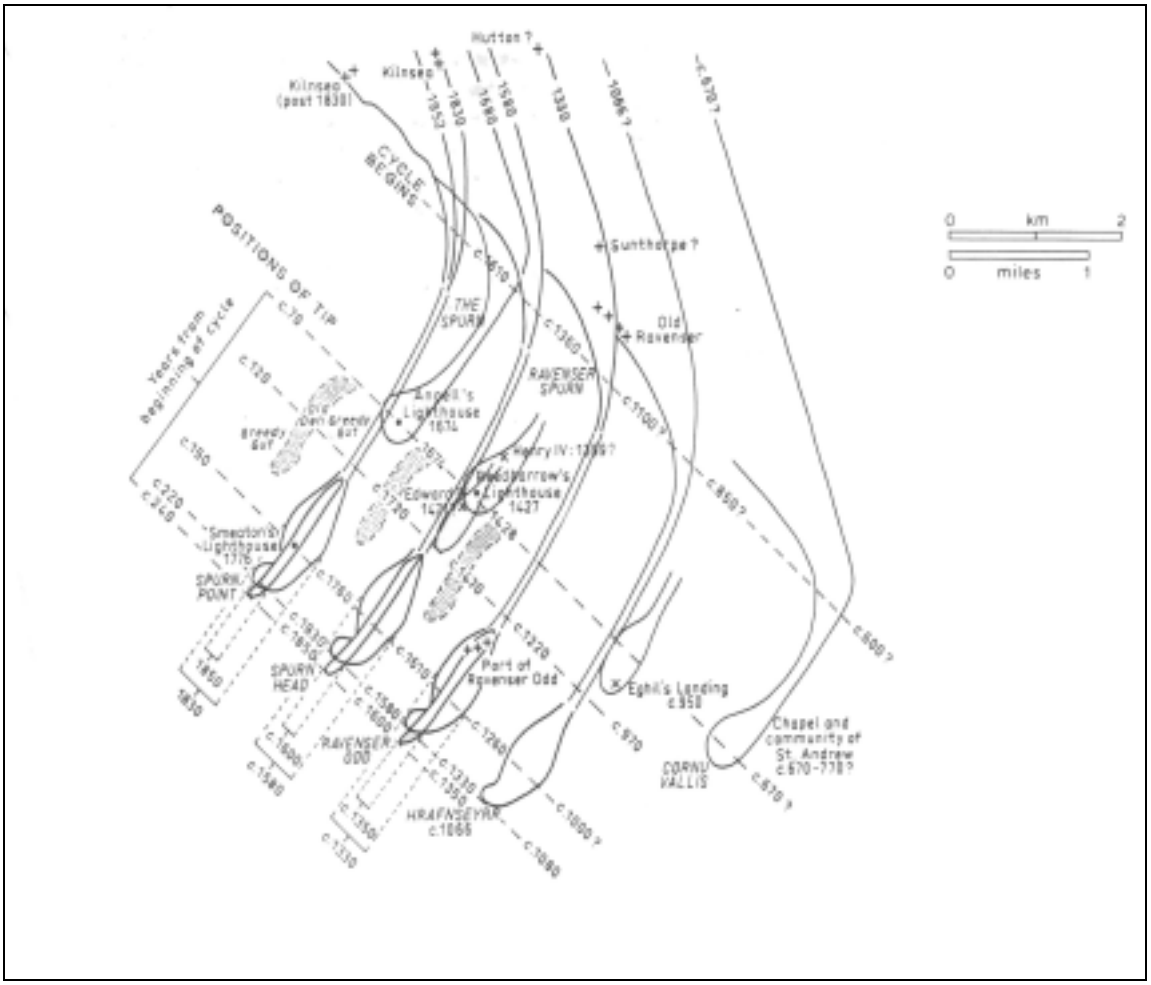


Figure 4: The cyclic construction and destruction of Spurn Head and its predecessors since 670 AD (after De Boer, 1996).

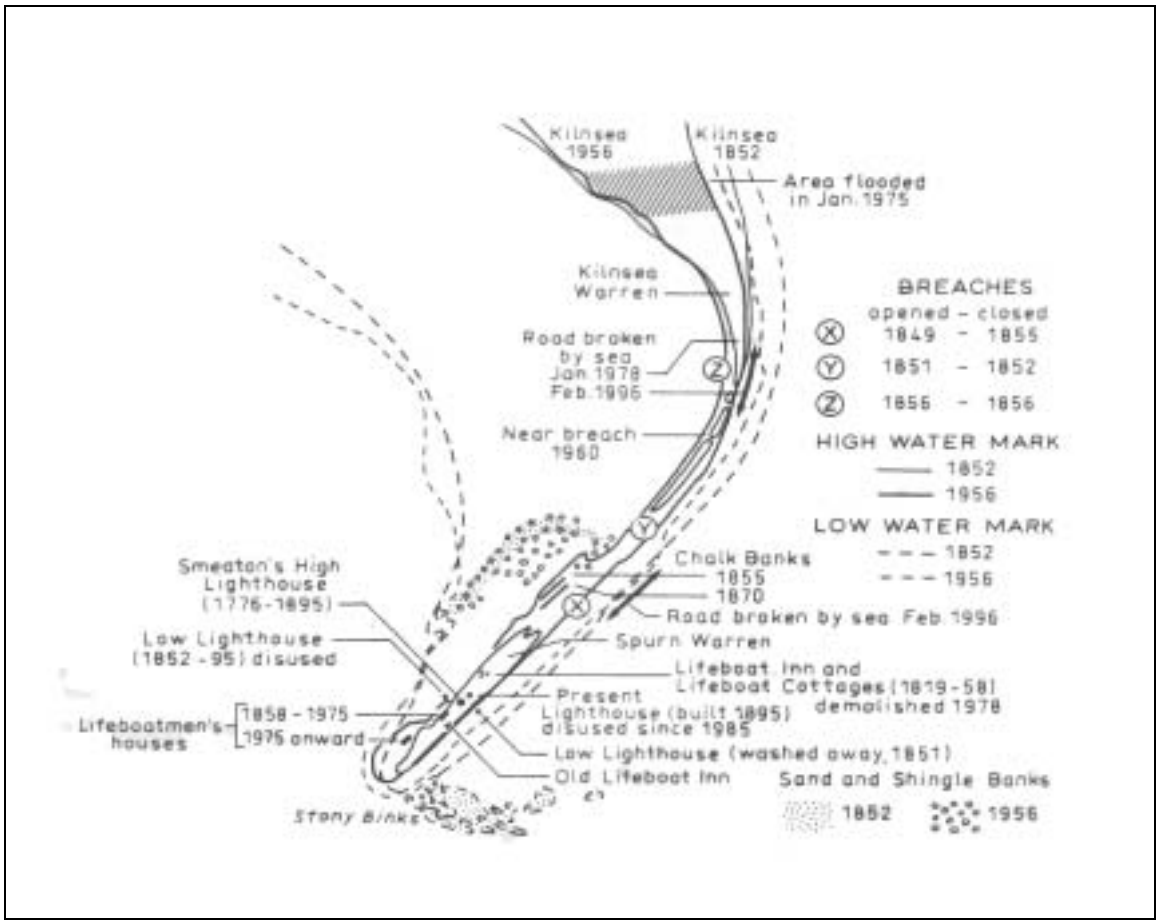


Figure 5: Summary of the recent history of Spurn Head (after De Boer1996).

2.2 Holderness Erosion Processes - The Sediment Source

The problems of erosion along the 55 km Holderness Coastline to the north of Spun Head have been well documented and was recognized by the Royal Commission of 1906-1911 as the most serious around the coast of the British Isles. More recently, erosion mechanisms were studied in detail by Pringle (1985), who recognized the importance of features called “ords” to local erosion rates and processes. Ord is a local term describing low sections of beach, sometimes lacking any appreciable sediment, characteristic of sections of the Holderness Coastline. One such feature was examined by Pringle

between 1977 and 1983 and its rate of progression along the coast and its significance to cliff erosion was assessed. The beaches in this area are backed by glacial till cliffs of variable height and age. Lack of a beach allows even normal high-tides to attack to base of the cliffs inducing slumping and block failures. This is obviously of great concern to the local residents and businesses, particularly British Gas, which operates a receiving terminal 20m from the current cliff edge.

Pringle (1985) recorded wave heights, cliff erosion rates and beach profiles in her six-year study period and arrived at estimations for volume of material eroded per year. She then used this estimate to relate the erosion to a constructional mid-tidal sand bar down drift (south) of the ord. She found that the reduction in beach elevation within an ord of up to 3.9 m enabled even normal high-tides to reach the cliff base and attack it directly. This also exposed a till shore platform, allowing it to be scalloped and lowered by wave and current attack. Volume of material eroded from the cliffs was estimated by Pringle to be 8 times greater when the ord was present compared to when there was a beach present. Furthermore, she demonstrated that 80% of this erosion took place between the months of October and April, when the cliffs were saturated and when northerly storms were more frequent. The most important conclusion from her observations is the quantification of erosion rates associated with the ord features, which progress slowly southward along the entire 55 km length of the Holderness coastline (at about 0.5 km per year). She makes a distinction between previously identified rhythmic beach features (e.g. beach cusps, rip tide embayments etc.) and ords, which do not appear to be the result of a standing wave phenomenon known as edge waves or rip tidal currents. Erosion is accelerated when the cliffs are saturated, which usually occurs in the winter when waves are also at their highest. Under these conditions, cliff failure can occur even

at low-tide, independent of wave attack. Such failures are typically in the form of mudflows, rather than the slumps associated with direct wave impact.

A large range of material size results from the Holderness cliff erosion, yet the presence of coarse material on the beach, which is for the most part narrow, is limited to isolated lenses. Observations by Mason and Hansom (1988) indicate that only 33% of cliff material is compatible with that of the beach, while the total sediment supply to the beach was estimated to be in the order of 4.62×10^5 m^3 per year along the entire Holderness coastline. An overall net movement of 2,800 m^3 of material to the south by longshore drift was calculated. The authors recognize that erosion along the coastline is locally variable, but the form of the coast, which has no embayments or promontories suggests a constant rate along the coast over longer time scales. When a section of coastline was observed to have a high beach, erosion of the backing till cliffs was much reduced, however this reduction in local sediment input was not able to compensate for the continual beach erosion process and longshore sediment transport, and the beach would be lowered. By contrast, a low beach allows the cliffs to be directly attacked, which produces a large source of beach sediment, which builds up a protective beach. In this way each section of beach undergoes periods of accelerated erosion followed a period of protection (similar to the observations made by Pringle in 1985).

Bisat (1948) observed that approximately 38 percent of the glacial material in the eroding cliffs was of sand size. This means that erosion of the cliffs will produce about 4m in thickness of sand, which is clearly not present on either the beach or the immediate offshore region. It appears that this material is removed from the beach and shallow nearshore zone by heavy onshore storms when water surface elevation increases towards

the coast and compensating bottom return currents are sufficiently competent to entrain this material and carry it to deep water. It might therefore be assumed that strong offshore winds would produce a compensatory onshore bottom return current, which would return sediment from the offshore areas to the beach. This does not seem to be happening (Winkelmolen, 1978) largely because of the sheltering effects of the till cliffs themselves and the dominance of tidal currents parallel to the coast over less effective wind driven currents in the deep water environment. It is interesting to note that only an estimated 3 percent of the sand originating from Holderness cliff erosion is incorporated in Spurn Head, the rest is lost to the offshore environment (Valentin, 1954). The fate of the clay and silt sized particles may be explained in the same way, turbulence in the surf zone keeps these sediments in suspension where they are carried both alongshore and offshore. Most of the material is presumably deposited offshore in quieter water, although some is transported around the tip of Spurn and has built-up a large expanse of mud flats on the inside of the spit.

With the sediment source clearly identified it is then possible to examine the history and form of Spurn Head, which is thought by one school of thought to be a progressive feature that grows steadily between periods of catastrophic destruction.

A model for cyclic growth and destruction of Spurn approximately every 250 years was described by De Boer (1974), based upon historical records (Figure 4). De Boer focused on two critical morphological features of Spurn. The first was the relationship of the spit to its tapering root of glacial till. As the seaward edge of the till root retreats south-westwards, the point of the root moves north-westwards twice as fast, effectively lengthening the neck of Spurn, exposing it to the full force of destructive waves. He

reported that erosion seemed to be associated particularly with gales from the north or northwest. Even though these waves are slightly off shore in Holderness they generate the most destructive seas. Because they typically blow in the rear of deep depressions, these winds are accompanied by a storm surge, the degree of which is controlled by the intensity of the cyclonic cell. Under these conditions erosion is maximized at the northeasterly facing section of Spurn (Phillips, 1972). A certain degree of wave refraction around the headland to the north and the shallow nearshore results in oblique waves that can attack the cliffs directly.

According to De Boer's model, the first stage in spit growth is the development of a short, wide feature. As the spit grows longer, material continues to move down the ocean facing coast, but can only move part of the way up the inside of the spit due to the diminishing competence of the tidal currents, lower wave heights, and less frequent winds from the south. The result is a wide tip while the neck tends to thin, as erosion on the ocean side is not matched by deposition on the inside. Tidal charts show the ebb tide channel in the Humber Estuary flows close to the tip of Spurn. Therefore as the spit advances into this channel, currents will act to inhibit the transfer of material round the tip and up the inside of the spit, and limit the advance southward. Further thinning of the neck increases vulnerability to high-energy wave attack, and inevitability, if left to run its course, the neck will be breached. Breaches are usually associated with a coincidence of spring tides, storm surges and powerful waves generated by northwesterly winds. De Boer recognized that once a breach had been initiated, it acted as a new tidal channel with currents in excess of 5 knots recorded, certainly enough to further enlarge the breach. This channel limits movement of sediment by longshore drift southward. The

sediment starved distal portion of the spit becomes effectively an island with a very limited life span. Additional breaches may follow.

Evidence exists for three periods of destruction, 1360, 1620, and 1850. In each cycle different names are associated with the spit; Ravenserodd with the first, Ravenser Spurn with the second, and Spurn Head or Spurn Point with the latest. De Boers cyclic development theory is supported by King (1972) but has more recently been disputed by Pethick (1984). The latest cycle is the best documented and began after a breach in 1620. By 1664 an embryonic spit began to form, which by 1776 had grown to one mile in length. By 1828 the neck has grown so long that it was awash in places during the spring tides. A serious breach followed in 1849 and by 1850 was 300m wide and 4m deep. The breach was filled with chalk blocks in 1851 and a system of groynes was erected which until the spring of 1997 prevented further breaches. Further historical evidence for cyclic spit development was provided by Phillips (1972). Currently the spit is under imminent threat and has been overwashed during spring tide.

Pethick (1984) has suggested that contemporary Spurn is more the result of anthropogenic influence that a natural cycle. Pethick notes that during the eighteenth and nineteenth centuries more than 50,000 tons per year of gravel was removed from the Spurn Head beaches to be used as ballast by whaling and fishing vessels. This meant that the neck, which was formerly dominantly a gravel form, is now mainly comprised of sand, and therefore does not react to strong storms in the same way. The gravel neck would respond to strong storms by "rolling" landward. He further suggests that the tip is a relatively stable feature that has been protected by submarine glacial till ridge, and it has been the neck that has constantly had to re-adjust. If Pethick is correct, Spurn can

only be expected to survive if it is restored to its former state, with the removed gravel replaced.

2.3 Discussion Of Grain Size Analysis Literature

Grain size statistics have been in general use in the sedimentary geology and coastal geomorphology disciplines since the 1930's. Syvitski and Murray (1977) noted that variation in particle size is a fundamental property of sediments and sedimentary rocks which are the result of sediment transport and deposition. The arrangement of particles and their relative abundance within the sediment reveals details of the processes, which operated on the sediment and the depositional environment. Inman (1952) stresses that the purpose of grain size analysis is to aid in correlation between sediment types and their environment. Pethick goes further, and indicates that grain size analysis provides clues to future landform development and of past processes (especially valuable where processes cannot be directly observed).

There have been a large number of publications that have attempted to prove a relationship between grain size frequency distributions and depositional environments (e.g. Friedman, 1977; Middleton, 1976; Mclaren, 1981). To facilitate cross comparison of samples, four statistical measures (known as moments) have been developed and are commonly used; skewness, kurtosis, mean size and sorting (analogous to standard deviation). These are calculated from grain size distribution data, which are usually generated by passing a dry sample through a stack of progressively smaller sieves. The size of the sieve openings determines the size of sediment that is allowed to pass through. That proportion of the sample retained in each sieve is weighed and expressed as a

percentage of the weight of the total sample. Other methods are available but are less commonly used and were not used in this study.

The “moment” was introduced into statistics as an analogy with mechanics. In mechanics, the moment of a force about the point of rotation is computed by multiplying the magnitude of that force and the distance from the force to the point of rotation. In statistics, the force is replaced by the frequency function, and the distance to the point of rotation is replaced by an arbitrary point, usually the mean of the distribution curve. The moment measure is determined by finding the moments of each size class (frequency percent in each size class times the distance of each from the mean), adding them up and dividing the sum by 100. As these represented the entire frequency they were expected to be “environmentally sensitive”.

The mean size serves a simple indication of the force applied to the sediment to move the grains, or a very rough indicator of energy state. Sorting or standard deviation indicates the range of forces that have produced the sediment. A large standard deviation, or poor sorting, indicates that little selection of grains has taken place during transport or deposition. This might be the result of highly variable energy, turbulent conditions, and a lack of constant energy input in any one direction. Good sorting is produced by selective action of wind or water, which transports and deposits only a limited range of grain sizes. A good example is the dune environment where only a limited range of sediment is capable of first being entrained by the wind and then being heavy enough to drop out of suspension. The skewness of a sediment distribution is a good indicator of the history of a sediment. A positive skewness on the phi scale indicates a relative excess of fine grains, usually from the preferred transport and deposition of fine material. A course

skewness may result from winnowing out of fine material, or a high energy storm deposit. These statistics may be used individually or plotted against one another to discriminate sedimentary environments. The effectiveness of scatter plots is mixed, as is the choice of which measures provide the best separation. Scatter plots may be useful in differentiating sedimentary environments, and does have certain applications to palaeo-sedimentology, however they do not provide much information about the energy state and transport direction. With no clear consensus on which statistical moments provide the best environmental discrimination, their application in environmental differentiation has not been generally accepted. It appears that a working knowledge of the type of on which set of parameters is to be used.

Mason and Folk (1958) found that the best means of discriminating beach, dune and aeolian flat environments was to plot skewness against kurtosis. Their reasoning for this success was that environmental factors had their greatest effect on the tails of the distribution. Beach sands were found to form normal size distribution curves, while dune sands were positively skewed. Beach sands were found to be the most poorly sorted, reflecting the high-energy and sediment inputs and oscillatory motions typical of that environment. Martins (1975) also found beach sands to be normally distributed or negatively skewed, and dune sands were positively skewed. Friedman (1971), adding to the consensus, found beach sands to be slightly negatively skewed and dune sands to be positively skewed. Friedman found that a plot of mean size against skewness achieved almost complete separation of beach and dune sands. Shepard and Young (1972), unlike Mason and Folk (1958), found that a plot of skewness against kurtosis was all but useless for differentiating beach and dune sediments. This may have been due to their methodology which did not separate the sediments by 0.25 phi intervals which appears to

be important in showing subtle differences in distributions (Folk, 1972). Therefore, it seems that skewness is a useful diagnostic if it is desirable to separate dune and beach sands.

With skewness firmly established as an important discriminator (negative to normal for beach and positive for dune sands), Friedman (1977), in a bench mark study compared the size frequency distributions for beach and river sands and related these to the different processes operating in these distinct environments. A wide variety of beach samples were collected world-wide along with river samples from 44 rivers throughout the United States. The properties of the beach and river sands were compared in scatter plots. Typically these scatter plots were able to differentiate the two environments fairly well. Mean Cubed Deviation vs Standard Deviation provided good separation, as did skewness vs standard deviation. Friedman did not find the plot of skewness vs kurtosis to be a good discriminator of environments. Friedman's analysis of river sand revealed that it contained a fine tail that originated from the suspended load. By contrast it was found that most beach sands from the swash zone lacked this fine sediment as it was constantly stirred up and carried away. Hence beach sand acted upon by these kinds of motion tend to be symmetrical, negative, or slightly positively skewed. In this back and forth environment, the sediments tend to become well sorted. River sands tend to be less well sorted than beach sands. Friedman proposed that skewness and sorting were the most environmentally sensitive parameters and could be used to discriminate sands of different origins. His theory was received with much skepticism initially by geologists who tended to view the theory as a black box, i.e. that sand put in one end would reveal the source at the other. This, Friedman argues, was never the point of his model. He asserts that there is often more than one solution to a geological problem, and in that

light, particle size analysis plays only a part in environmental discrimination and determination.

None of his early work specifically addresses more closely related sediments, like samples on different positions on the same beach, or a little down drift where longshore processes dominate. Or, for that matter high vs low energy beach environments. The 1970's and 1980's saw a move toward this more specific environmental discrimination. Nordstrom (1977) wanted to compare high and low energy beaches in a spit environment on Sandy Hook, New Jersey. Although the re-curved spit does not have an easily identifiable single source, Nordstrom had some interesting observations. He found that the assumption that mean sediment size was positively correlated to wave energy (i.e. as wave energy increases, so does sediment size) did not hold true for the high and moderate energy beach samples he analysed. In fact, grain size tended to become larger with decreasing energy, however, the high-energy sediments were found to be more poorly sorted (more size classes were present). This variation probably reflects the fact that the volume of sediment influx heavily influences grain size parameters. For example, beaches receiving considerable influx will tend towards poorer sorting than those with a lower influx (Folk, 1975). Nordstrom (1981) revisited Sandy Hook to examined the differences in grain size distribution with shoreline position in the spit environment. He found that the sediments became better sorted and slightly coarser with distance down drift while skewness and kurtosis showed no clear trend. A significant relationship was found between breaker height and sediment size.

To date in the literature the optimum statististical discriminator for beaches and dunes is skewness. With a narrower range of size present in dunes, sorting is also applicable.

When it comes to the more closely related beach versus beach samples there is less clarity with respect to a) what process dominates and b) whether this information can be interpreted from the grain size data.

Grain size analysis of sediments in a longshore bar/trough system in the Great Lakes by Mothersill (1979) indicated that these two environments could be differentiated adequately on the basis of a plot of skewness against kurtosis. Sediments from the bars tended to be unimodal, positively skewed, and better sorted than the trough sediments, which were largely unimodal or bimodal, and tended towards negative skewness. Furthermore, the mean size of the trough samples was greater than the bar samples which led Mothersill to the conclusion that the trough environment was subject to breaking wave action which was able to winnow out the fine sediment fraction, leaving behind the coarse material as a 'lag' deposit.

McCave (1978) studied longshore changes in sedimentary characteristics along the coast of East Anglia, England, and found cells of both downdrift coarsening and fining. One explanation for longshore coarsening is winnowing of the fine material from the beach by continuous wave activity. A common cause of longshore fining is the decreasing competence of the transporting current, either as a result of divergence of tidal currents away from the transport zone, or a decrease in wave driven longshore drift, perhaps the result of orientation change or changing bottom topography. This scenario is a probable cause of deposition of suspended fines. A study of longshore grain size variation by Winkelmolen (1978) on the east coast of England in the Spurn Head area found that there was no clear trend in size with longshore beach position until the eroding cliffs backing the beach had disappeared. From this point on, the trend was for a downdrift coarsening,

consistent with continued winnowing on fines by wave action, without the addition of any more clay and mud material from the eroding cliffs. Similar erosion of till cliffs in Norfolk, just to the south of the River Humber produced a beach sediment which exhibited downdrift coarsening due to the preferential loss of fines to the nearshore environment (Clayton, 1989). There may be seasonal effects which may also cloud the issue of fining and coarsening in the longshore direction.

McLaren (1981) explored the effect of transport on grain size distributions and suggested that mean size, sorting and skewness follow trends that clearly identify the direction of transport and the sedimentary processes of winnowing, selective deposition and total deposition. Using several assumptions his model demonstrated that: sediment in transport must be better sorted, coarser and more negatively skewed than its' source sediment; a lag must be coarser, better sorted and more positively skewed than its source; and that successive deposits must become better sorted and more positively skewed but may be finer or coarser than the source sediment.

Mclaren and Bowles (1985) performed useful quantitative work in the field of longshore trends in grain size statistics. They devised a model for several sediment transport scenarios. When tested in a spit environment the model correctly predicted a downdrift coarsening, improvement in sorting and more positive skewness.

From the large body of literature available, it is clear that there is no perfect model that correctly predicts depositional environments and definitely points to energy environments and drift directions. Skewness and sorting appear to be most widely viewed as environmentally sensitive parameters. Much confusion remains concerning

the relative importance of mean size other than as a gross indicator of energy level. Even there, much care has to be taken when interpreting subtle changes to the size measure.

The advantage of Spurn Head as a field test location for this kind of analysis is the ability to remove sediment source as a critical variable. The results can then focus on the impact of transport and deposition on the grain size distributions.

After the measures to be used have been decided, there are multiple options available for data presentation and analysis. These are explored below.

2.4 Data Presentation Methods

Data presentation methods have been subject to some discussion in the literature. The use of log-probability plots was pioneered by Krumbein (1936) who observed that when the grain size distribution of sediments was plotted in this way it tended to describe a straight line (if it was normally distributed). Subsequent studies have suggested that distinct straight-line segments exist within the overall linear relationship that can be related to transport and depositional processes. Doeglas (1978) recognised that grain size distributions were mixtures of two or more component distributions and these were produced by varying transport conditions. Inman (1949) described the three fundamental sediment transport mechanisms: surface creep (referred to by some authors as traction), saltation, and suspension.

Moss (1972) was one of the first authors to use size and shape of grains to distinguish subpopulations produced by the three modes of transport mentioned previously. He reported that these three populations could appear within the same sample. When data from grain size analysis was plotted on log probability paper the sub populations

produced by the three transport processes manifested themselves as breaks-in-slope on the plot. Each break-in-slope represents the boundary between one process and the next (Fuller, 1971). Visher (1979) provides some insight into the sediment sizes that can be transported by the three transport processes. He studied hydrodynamic literature and reported that authors often reported sediment carried in suspension to range from 0.07-0.1mm but depends on the degree of turbulence of the fluid. This population can easily be recognised on log probability plots. The range of sizes commonly moved by saltation is more difficult to define but sizes of 0.75-1 mm (0.4-0phi) have been observed. The break point between saltation and rolling may be at about 2 phi. Visher (1979) compared three methods of plotting a grain size distribution: a cumulative frequency curve plotted on arithmetic axes, a frequency distribution, and a log-probability plot. The first two curves mentioned are difficult to read and interpret, and change in slope, degree of mixing, truncation points, and other parameters cannot easily be compared or measured. The log probability plot however, normally exhibits two or three straight-line segments, which analysis of over 2,000 samples by various authors showed to occur at similar points, suggesting a meaningful relationship to environmental forces. Visher produced multiple curves for beach, dune and river environments and then came up with what he believed where characteristic curve shapes for each environment. Further still, he found that he was able to classify beach samples into those deposited by beach processes, aeolian processes, wave action, and breaking waves. Beach foreshore sands were found to be highly variable but each had a characteristic dual saltation population, which Visher interpreted to be produced by swash and backwash respectively. This characteristic dual saltation population was found to be unique to beach foreshore sediments. No other consistent characteristics among beach log-probability plots were found. Visher's sample

included 100 dune samples, which were collected from dunes adjacent to beaches. He found that the two saltation populations found in the beach deposits had resolved themselves into a single saltation population, which represented 98 percent of the total sample (on average). The slope of the dune sample curve was steep, indicating excellent sorting. The breakpoint between the coarse traction (rolling) population and the saltation population occurred between 1 and 2 phi in all samples. Samples from the breaking wave zone have a high proportion of their sediment in the coarse traction population and had a truncated saltation population.

Glaister and Nelson (1974) also suggested that these linear segments represented populations deposited by different transport mechanisms. They tested several textural analytical techniques on samples collected from fluvial, coastal and dune environments. They found that the most practical method for identifying different environments was to use log-probability plots of the cumulative grain size frequency. They commented that this method takes into account the entire distribution, particularly the important coarse and fine tails, which some statistical parameters (skewness, kurtosis, sorting) only sample. These findings apply to work with facies identification and it is important to note that when the samples were analysed by these authors, only 0.5 phi intervals were used which is inadequate to reveal all the nuances of the grain size distribution. They explored the characteristic multiple straight-line segments within the grain size distribution recognised by Visher (1979).

According to Glaiser and Nelson's work, in beach samples the saltation population has a steep slope, reflecting excellent sorting. The suspension population was also characterised by a fairly steep slope. The junction between the saltation and suspension

population ("S" Junction) is sharp and there is little if any traction population. The authors thought the steep slope of the suspension population was the most diagnostic feature of a mature beach deposit. They also found that the amount of suspension population increased with distance seaward of the foreshore. The authors urge caution about using this general relationship as many local variations occur in the beach environment but makes logical sense as suspended material is able to settle out. Glaiser and Nelson found no evidence of the dual saltation population that Visher reported in beach face sediments but suggested this might be the result of limited sampling. Glaiser and Nelson (1974) also found that dune samples exhibited a dominant saltation population, with a steep slope suggesting good sorting (as reported by Visher). A trace of traction material was commonly present. A small suspension population with a very low slope was often present.

A dissenting view from Syvitski and Murray (1977) questions the validity of assigning transport mechanisms to the straight-line segments of the probability plots. They suggested that, in reality, most sediment populations are transported by a variety of processes, and the assignment of a portion of the distribution to a single process does not match reality.

A quite distinct school of thought suggests that grain size distributions are better described by a log-hyperbolic distribution than a log normal distribution. The method was described by Barnorff-Nielsen (1977), and further investigated by Hartmann and Christiansen (1992), and Vincent (1986). Hartmann & Christiansen (1992) describe a new method of using grainsize statistics to discriminate sedimentary environments. They recognize that grain size analysis has undergone a reduction in interest due to the lack of

consistency and general inadequacy of results using standard moments. Their aim was to develop a more quantitative solution to the problem. They commented that it has long been assumed that grainsize distributions are basically normally distributed, that is, they fit the gaussian profile, and plot as straight lines on log-probability paper. However, they report there have been many studies performed where the population might be better described by a log-hyperbolic function. The initial work in this area was performed by Bagnold in 1937 when he was searching for the optimal way to represent grain size data during his study of windblown sand samples. He was the first to show that a plot of the percent weight retained in each sieve interval plotted against size class allowed the "dominant diameter" to be seen at a glance. But this still left the important tails of the distribution almost unseen in the same way as the regular histogram of the distribution. Bagnold's next step was to plot the logarithm of the weight in each sieve (N parameter), against the log grainsize. This line of methodology was then largely neglected until the 1970's because most practitioners opted to use moment measures especially those proposed by Folk and Ward (1957) if only so their results could be compared to other authors. In its simplest form the technique plots the grainsize distribution as an inverted V. Parameters derived from this plot are based on the slope of the left and right arms (asymptotes), the angle they form at their apex (analogous to the kurtosis), and the degree of asymmetry between the two asymptotes (skewness). The spread of the asymptotes at their distal ends is used as a measure of sorting.

Vincent (1995) recognized the dominance of the two-parameter log-normal distribution in grain size analysis, but reports that many studies have shown that grain size distributions often do not follow a log-normal distribution. He reports a more satisfactory mass size distribution had been proposed by Bagnold as early as 1937, but

was not formalized as the four parameter log-hyperbolic distribution until Barndorff-Nielsen (1977). Vincent regards the advantages of this technique are (1) greater sensitivity of the parameter estimates in discriminating between samples of closely related origin, and (2) samples relationship with the processes of erosion and deposition. A limitation of the technique is that the technique is unable to accept bimodal distributions.

There is a lack of consensus regarding which grainsize parameters are the "best", in fact, Wyrwoll and Smith (1985) recognise there is a certain difficulty involved in relating sediment size distributions to depositional environments. Wyrwoll and Smith acknowledge that there are grounds for criticism of much of the work in the subject. Nevertheless, the fundamental lack of understanding of sediment transport processes and the availability of empirical data from grainsize analysis is an attractive driving force. From the statistical and graphical methods it seems possible to identify areas where particular sediment sizes are either being removed, or re-introduced to the beach, which reveals valuable information on the types of process operating at that particular location and the source of its sediment. It seems that there is the opportunity in the Spurn Head environment to test the ability of grain size statistics to reveal information about their transport processes.

3.0 METHODOLOGY

3.1 Hypotheses

Several hypotheses are advanced and will be investigated as part of this study.

- It is possible to differentiate between high-energy ocean facing beach, and low to moderate energy river-facing beach through the use of grain size analysis and interpretation of the derived grain size statistics.

- There is an identifiable pattern to the geographic distribution of grain size statistics within the spit environment.

- It will be possible to identify trends in the grain size moments that will mirror the direction of sediment movement to the south on the ocean-facing beach and to the north on the river-facing beach.

- It will be possible to separate the ocean-facing beach into energy zones in the longshore direction based on energy inputs.

- Characteristic log-probability curves can be generated for high energy, low energy and dune samples.

- Differences can be identified between high, mid and low-tide samples.

Investigation of the validity of these hypotheses will reveal important information on the usefulness of grain size derived statistics and analytical techniques in identifying transport processes, and differentiating micro-environments within a complex dynamic sedimentary environment. These are based on the assumption that there is a single sediment source and therefore the variations in the grain size statistics are the result of outside influences. These findings will add to the existing body of literature on the subject, which has thus far not produced a comprehensive study using grain size parameters in such a limited area with a single sediment source. The 'right' solution to the

erosion problem can vary from no action to hard options like sea walls and groynes. Alternative "soft" options proposed include the artificial nourishing of the beach using sand dredged from offshore, creation of artificial low bypass embayments, and in-beach matting and other semi permanent flexible structures. When considering any of these options, it would be wise to use a sediment coarser that that currently remaining on the beach. Simply returning what was off shore back on shore can only lead to further erosion and possible significant socio-economic issues. Sediment size analysis is a crucial precursor to any such endeavour.

3.2 Sample Collection Procedure

3.2.1 Sample Locations

Samples were collected from the study area during two sampling periods, 1990 and 1997. The 1990 samples were collected at the mid-tide level only of the beach at half kilometre intervals beginning at Easington (Figure 6) and working south, round the tip of Spurn and northward along the river-side. A total of 31 samples were collected. These included three dune samples. Kilnsea is the point at which the till cliffs of Holderness finally lower and disappear, and is therefore considered for the purposes of this study to be the beginning of Spurn Head. When reference is made to 1990 samples, these may be assumed to be mid-tide samples. These samples are numbered 1 through 16 for the ocean side samples, 17A thorough 25 for the river-side samples, and 26 through 31 for the dune samples.

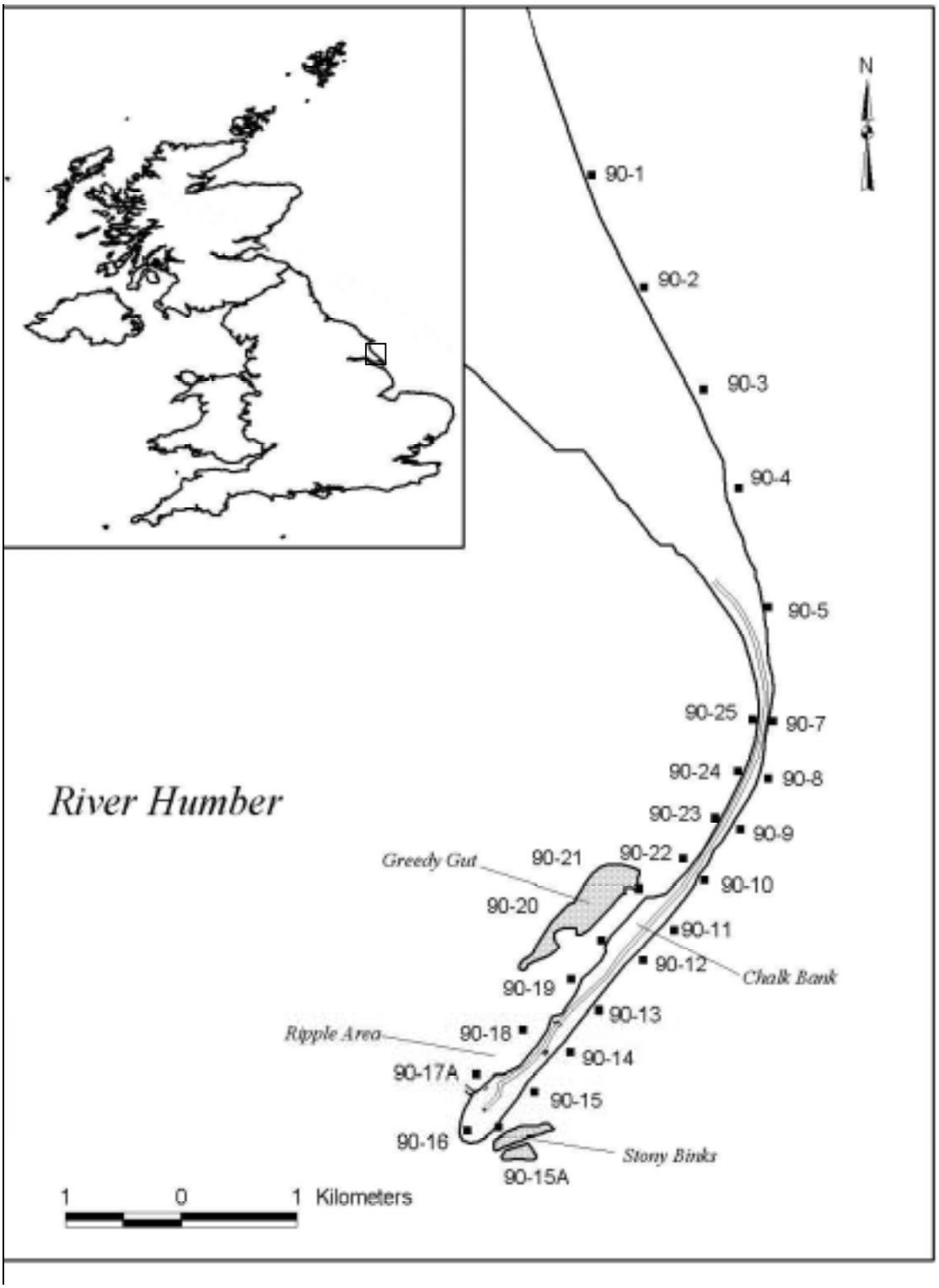


Figure 6: 1990 Sample Locations (mid-tide only)

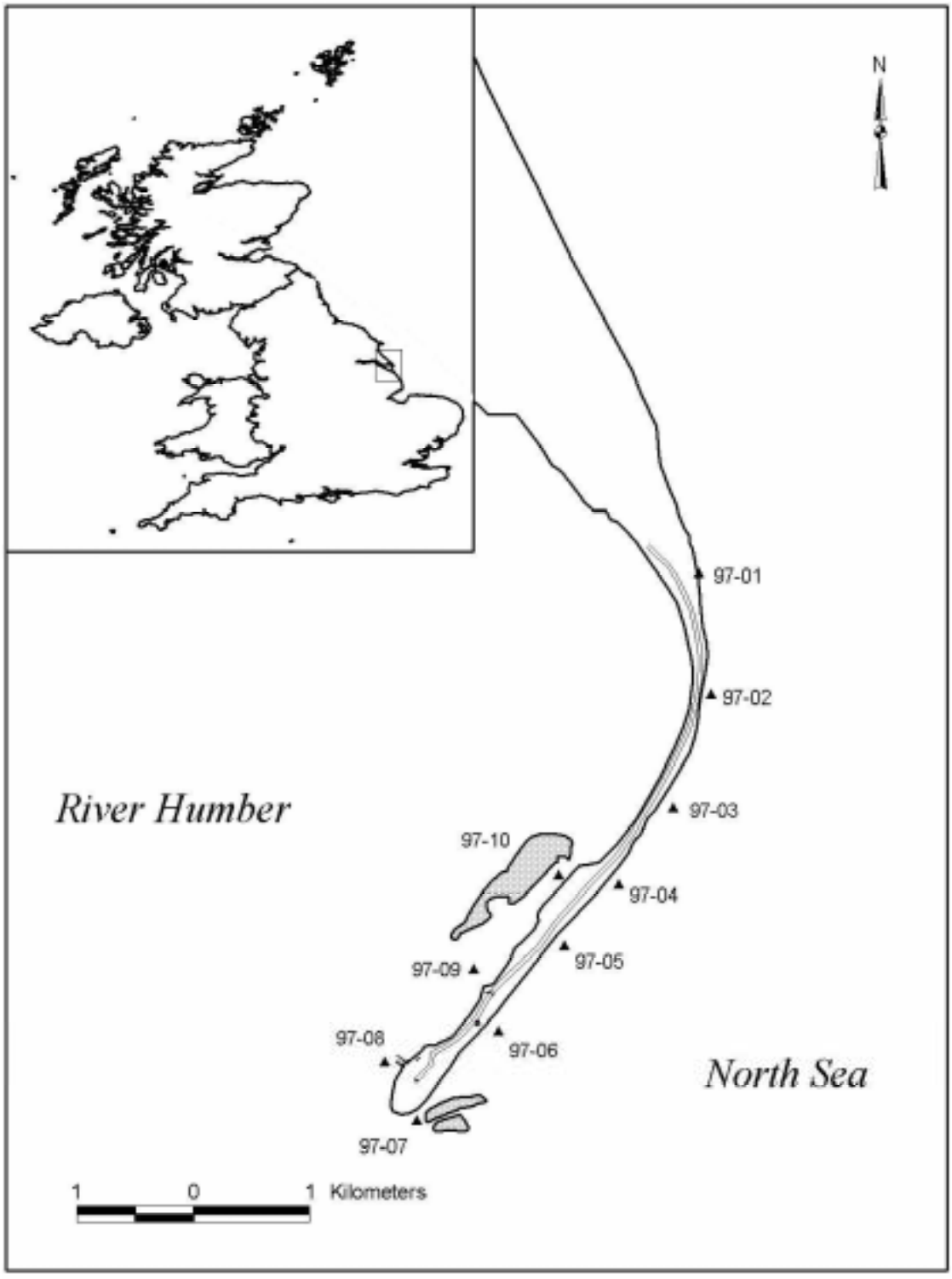


Figure 7: 1997 Sample locations (high, mid and low tide samples collected at each location).

The 1997 samples were collected at the low, mid and high-tide levels of the beach beginning at Kilnsea and working south along the length of Spurn and one kilometre intervals. Ten cross-shore transects were sampled yielding 30 samples.

3.2.2 Sampling Procedure

In all cases the same sampling container was used, a metal tin approximately 3 inches by 4 inches and 2 inches deep. This size of container ensured that material was collected from the mobile surface layer of the beach and provided sufficient sediment for sieve analysis. The samples were immediately placed in ziplock bags for transportation to the laboratory. The locations of the 1990 sampling points are shown on Figure 6. The 1997 sample points are shown in Figure 7.

3.3 Laboratory Preparation And Analysis

The samples were dried, disaggregated, and sieved in accordance with recognized standards in a bank of phi scale ($-\log_2$ mm) sieves at a 0.25 phi interval. The weights measured from each sieve were used to generate descriptive statistics. That proportion of the sample retained in each sieve is weighed and expressed as a percentage of the weight of the total sample. This weight data is then plotted as a cumulative frequency curve from which the statistics are generated in the following way:

$$\text{Mean grain size } (\mu) = \frac{(\text{Ø}16 + \text{Ø}50 + \text{Ø}84)}{3}$$

$$\text{Standard deviation } (\sigma) = \frac{\text{Ø84 - Ø16}}{4} + \frac{\text{Ø95 - Ø5}}{6.6}$$

$$\text{Skewness (sk)} = \frac{\text{Ø16 + Ø84 - 2 Ø50}}{2(\text{Ø84 - Ø16})} + \frac{\text{Ø5 + Ø95 - 2 Ø50}}{2(\text{Ø95 - Ø5})}$$

$$\text{Kurtosis (K)} = (\text{Ø95 - Ø5})/2.44(\text{Ø75- Ø25})$$

Samples that contain a large proportion of fine material are considered to have been deposited in a low energy environment, conversely, those that are comprised of a preponderance of coarse sediment and an absence of fines are inferred to be the result of a high energy environment, as the fine material is carried off in suspension. An approximate idea of the relative composition of given sediment can be derived from looking at the grain size distribution histogram. Indeed, an experienced eye can draw much useful information from this visual distribution. However, that is no basis for comparison and analysis of inter-sample relationships. The statistics derived from the distribution allow this analysis.

Previous studies have found that if the grain size distribution of sediments was plotted on log-probability paper it tended to describe a straight line (if it was normally distributed). Subsequent studies have revealed that there appear to be distinct straight-line segments within the overall linear relationship, which can be related to transport and depositional processes. Doeglas (1978) recognised that grain size distributions were mixtures of two or more component distributions and these were produced by variable transport conditions. Inman (1949) described the three fundamental sediment transport

mechanisms: surface creep (referred to by some authors as traction), saltation, and suspension. Moss (1972; 1973) was one of the first authors to use size and shape of grains to distinguish subpopulations produced by the three modes of transport mentioned previously. He reported that these three populations could appear within the same sample. When data from grain size analysis was plotted on log probability paper the sub-populations produced by the three transport processes manifested themselves as breaks-in-slope on the plot. Each break in slope represents the boundary between one process and the next (Fuller, 1971). Although the use of log-probability plots is somewhat controversial, the technique will be applied to the 1990 data set to review it's effectiveness in this type of multi transport environment. For example, when applied to a dune sample, the result should reveal that most of the transport is the result of saltation.

4.0 RESULTS

4.1 Average Histograms

As an initial step in interpretation of the data the samples were grouped by their location on the spit (ocean side versus river side and dune) and for beach position (high, mid and low-tide 1997 only) and averaged. These average distributions were plotted as mean histograms and are presented as Figures 8, 9, and 10.

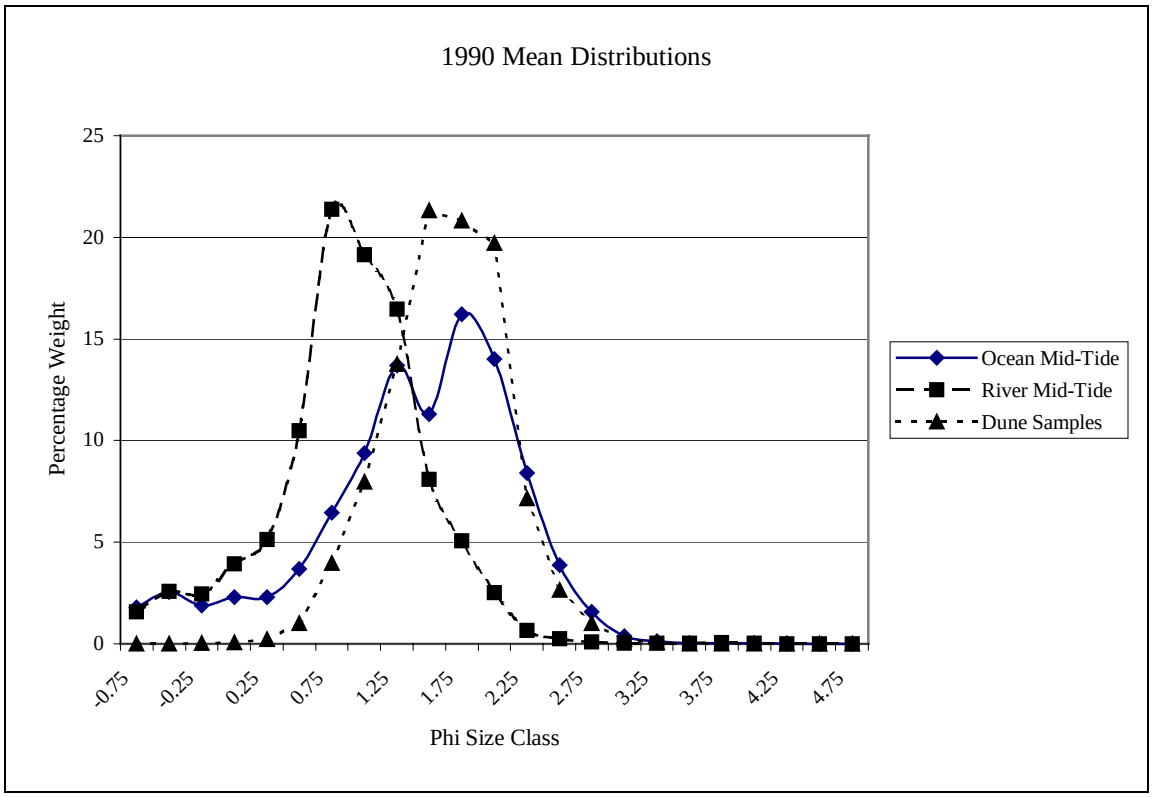


Figure 8: 1990 Mean Histograms, Ocean, River and Dune Samples

The most revealing characteristic of the 1997 samples is the presence of a coarse tail. Although not present in all the samples it is certainly a significant feature of the high, mid and low-tide samples. The most pronounced tail is found in the mid-tide samples,

followed by low-tide. The modal class of the high and low-tide samples in the same at 1.75 phi, although the low-tide sample has slightly more in that class, giving it a more peaky distribution (more leptokurtic). The low-tide sample has a higher proportion of material in the fine sand classes than both the mid and high-tide averages. The modal class of the high-tide sample is 1.5 phi, although there are similar proportions in the 1.75, 1.25, and 1.0 phi classes, making the distribution less leptokurtic than the low-tide samples. Additionally, the high-tide samples have more material in the coarse side if the middle distribution, but a less pronounced coarse tail.

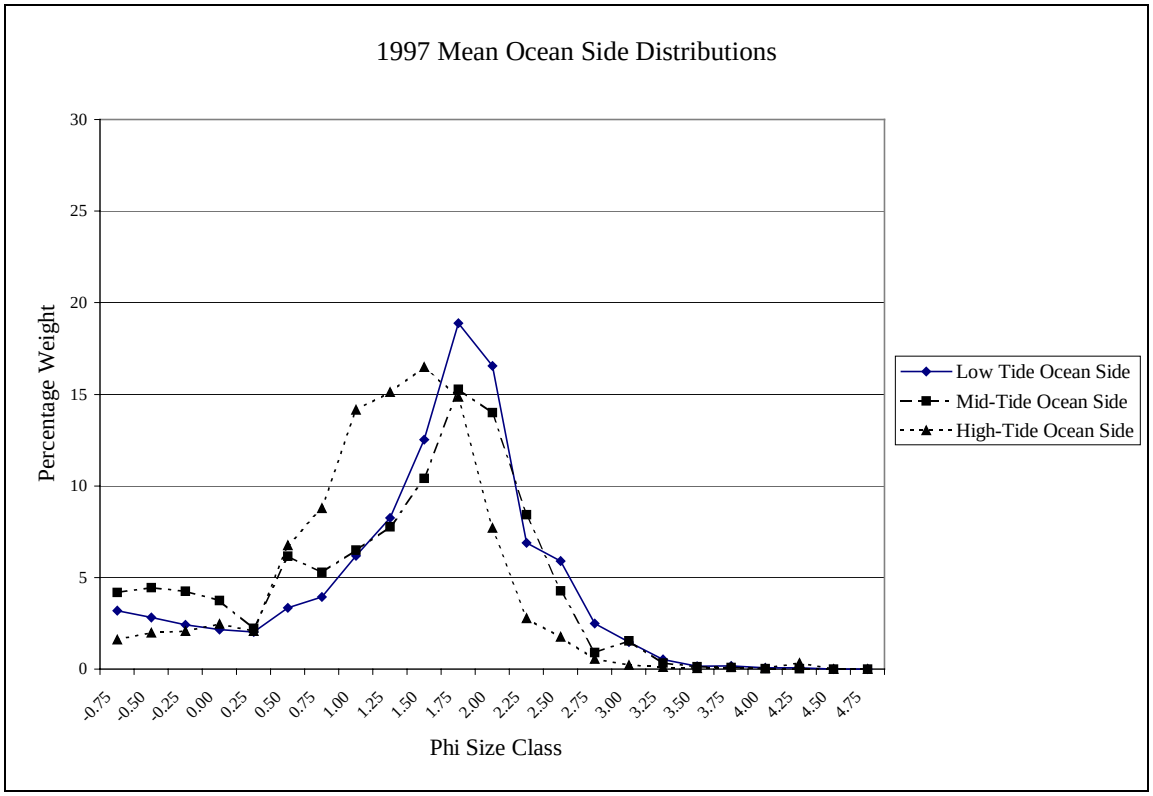


Figure 9: Average ocean side low, mid, and high tide distributions

According to the averaged 1997 data, the river side samples are better sorted, more unimodal and have a slightly coarser modal class. Again the low-tide sediments appear to be the best sorted and most leptokurtic with 1.25 phi as the modal class. The same

modal class is present in the high-tide samples but 1.75 phi has almost the same proportion of material. The high-tide sample has no coarse tail, similar to the high-tide sample on the ocean side. The low-tide sample has a small coarse tail, while the mid-tide sample has the largest.

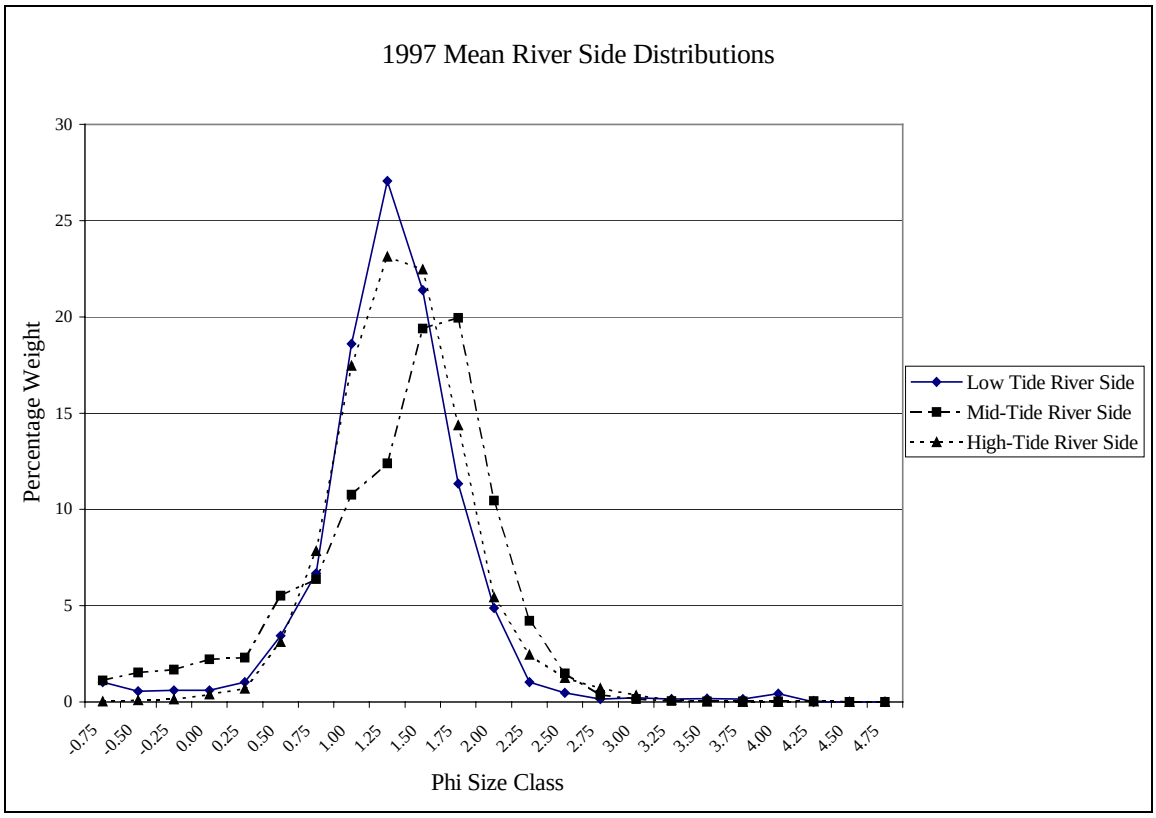


Figure 10: Average river side high, mid and low tide distributions.

Based on the mean distributions, it appears that the high energy, ocean facing beaches are populated by a wider variety or more poorly sorted, platykurtic and perhaps generally finer sediments than the river side beaches. Furthermore, it appears that the low-tide samples are the best sorted, most leptokurtic samples in the shore-normal direction followed by the high-tide samples on the river-side. On the ocean side there is no clear difference between the mid and high-tide samples. The ocean side samples have

significantly more material in the 2.25 phi and greater range than the river samples, perhaps indicating that this material does not make it past the tip of Spurn and does then not make a significant contribution to the river side beaches.

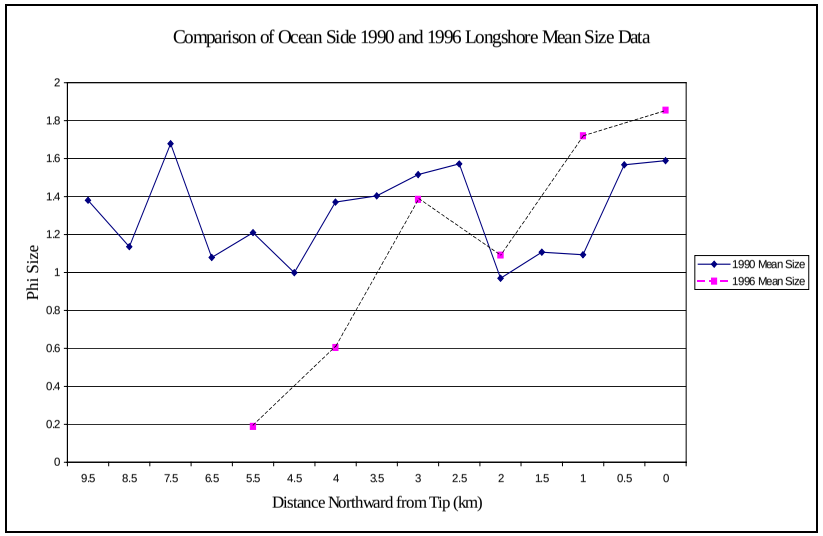
The 1990 samples, collected only at the mid-tide level showed a similar general pattern to the 1997 samples in terms of average distributions. Again the ocean facing beaches were clearly the most poorly sorted and possessed a significant coarse tail. In this data set distributions were also bi-modal with peaks at the 1.75 and 1.25 phi size classes. This is the same general size class that dominated the 1997 data. The river-side samples were again much better sorted than the ocean sediments but were coarser and had a coarse tail. It also appears that a sediment in the size range of 2.25 phi and greater is almost absent from the river facing beaches. The modal class for the river-side samples is 0.75 phi.

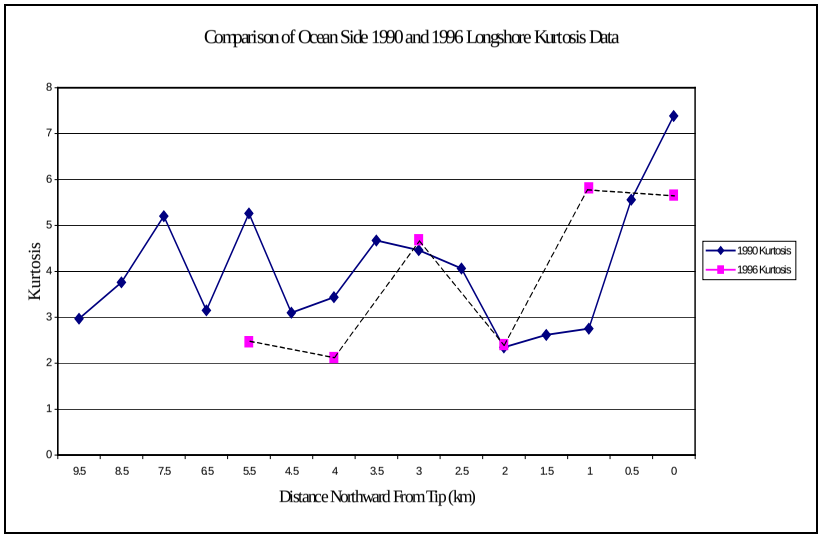
Dune samples collected along with the beach samples in 1990 were also plotted as average histograms. These samples were the best sorted and most leptokurtic of all the sampled environments and lacked any sign of a coarse tail. The modal class for these sediments was 1.75 to 2.0 phi, similar to the ocean facing beaches (perhaps reflecting where their sediment source lies).

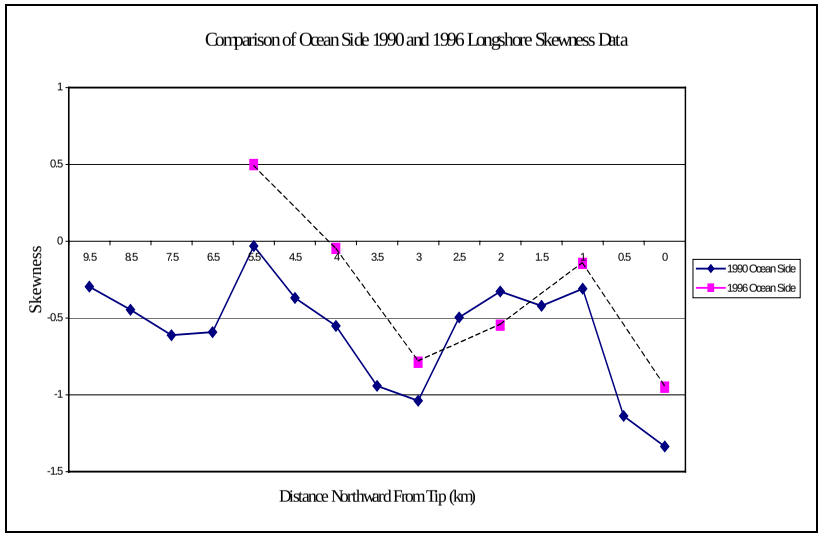
Visual interpretation of the histograms is a valuable tool in sediment description and interpretation but is somewhat subjective and qualitative especially when comparing one sample to another. It does not lend itself well to identifying subtle trends in the data, therefore derived sediment statistics are used when looking for longshore patterns and trends.

4.2 Longshore Trends

Longshore trends in all the derived statistics were plotted and are shown in Figures 11 through 13. A comparison of the mid-tide data for 1990 and 1997 normalized for distance from the tip is shown in Figures 11 and 12. Based on these plots and associated trend lines, together with an examination of the data as they related to previous studies in this subject, it was possible to make some general conclusions. Energy input on the ocean facing beaches must vary in the long shore direction. From its root, Spurn Head makes almost a 90-degree turn, which exposes the neck to the southeast. Strong storms from the north and northeast preferentially attack the northeasterly facing Holderness coast, while at the same time producing ideal conditions for long shore transport along the beaches of the spit. A complicating factor is the spit "platform" which is wider near the tip, and is capped with the Stony Binks adjacent to the southeast corner of the tip. Field observations, beach conditions, aerial photographs and previous studies conducted on the spit all confirm that the ocean tip of Spurn in the area of the binks receives less wave energy input than the beaches further north. What begins to emerge from the grain size data is a picture of multiple sediment inputs and changing beach conditions over short distances. Over short distances the beach profile can change from one with a mid-tide berm and high-tide runnel, to a flat, gently sloping beach with no ripples or bedforms whatsoever. A subsequent observation visit to Spurn revealed a 2-foot thick gravel "drape" where there was previously flat, sandy beach. Therefore, from the outset is appears difficult to have much confidence that there will be a significant trend revealed by the grain size statistics. However, what emerged was quite surprising, especially in its replication in a similar study 6 years earlier.







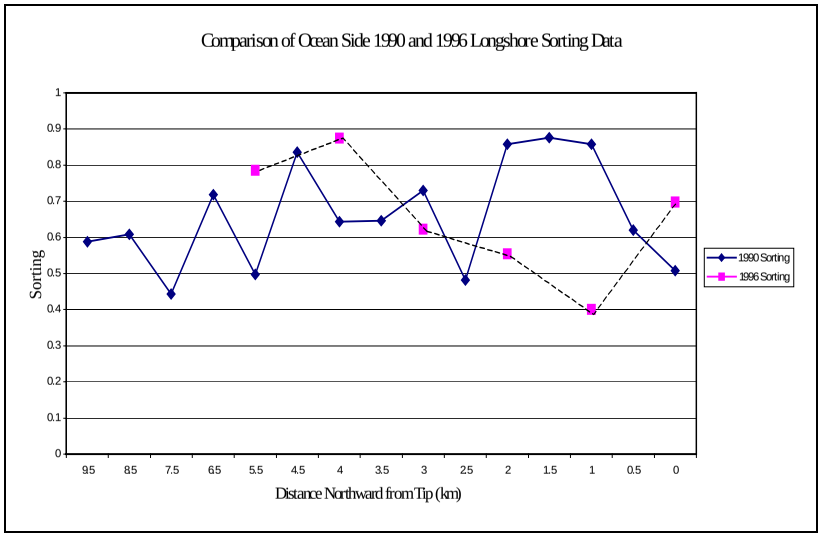
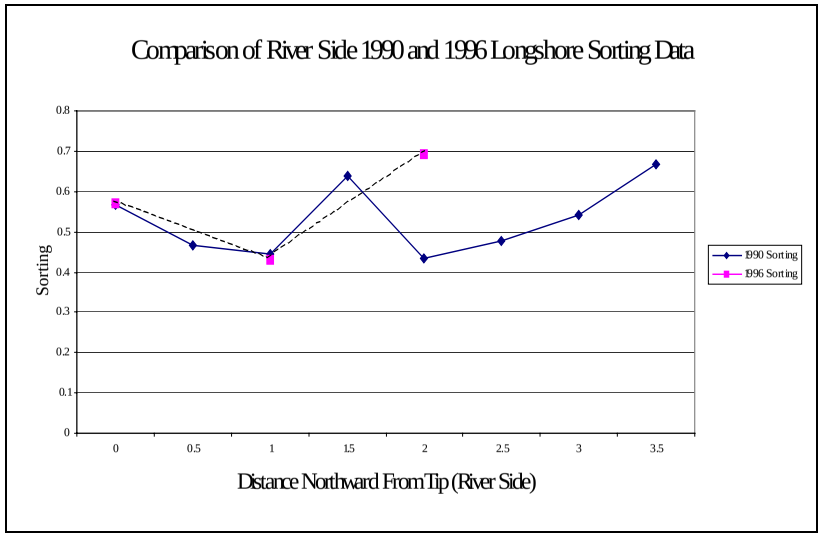
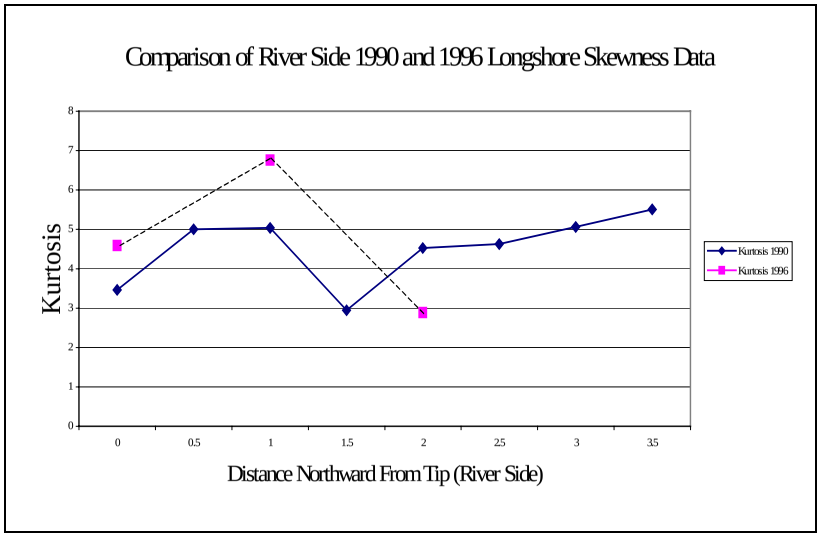


Figure 11: Comparison of 1990 and 1996 Ocean Side, Mid-tide Data.





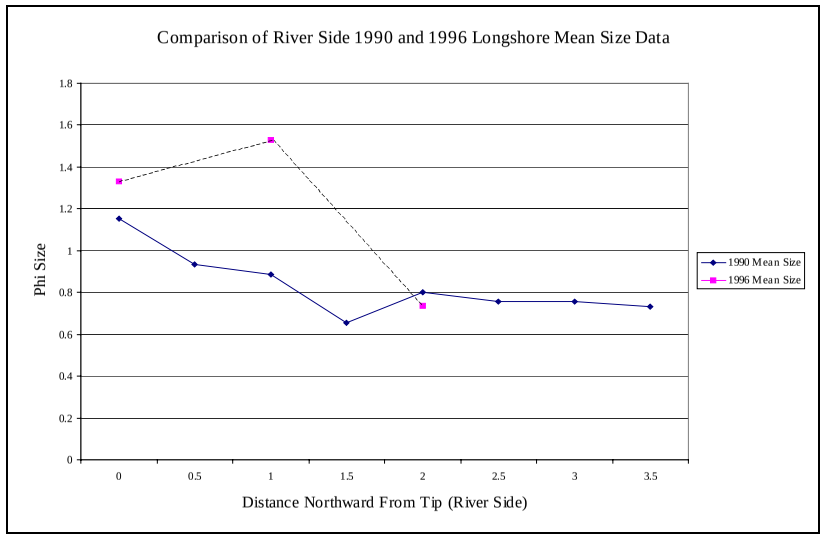
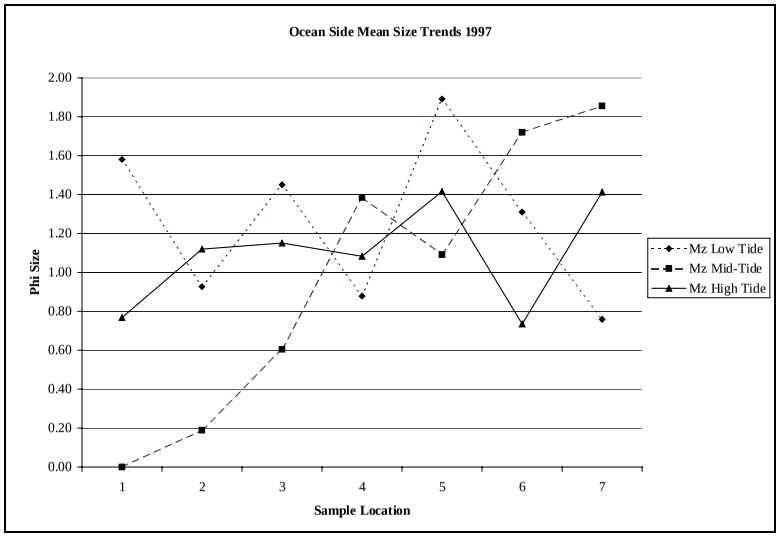
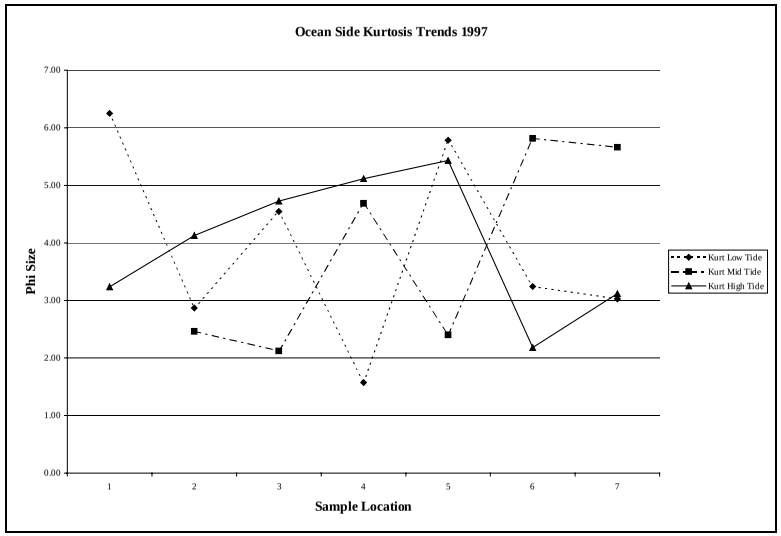
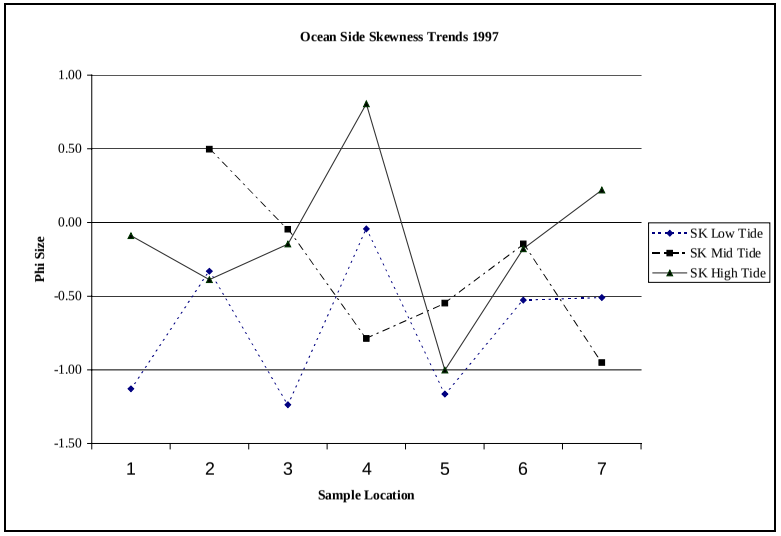


Figure 12: Comparison of 1990 and 1996 River Side, Mid-tide Data.







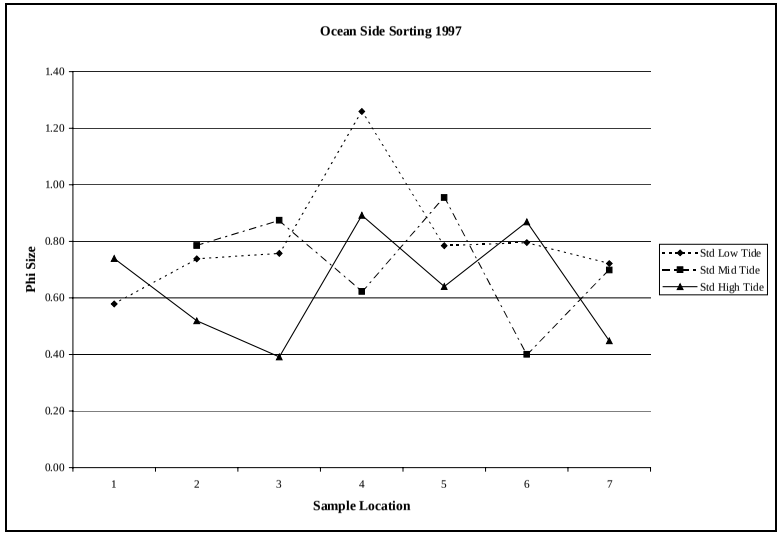


Figure 13: 1997 Ocean side trends, high, mid, and low tide.

4.2.1 Mean Size

(A) **Mean Size Low-tide:** There is no strong trend in this measure on the ocean side beach. Alternate sample locations show alternately higher and lower values. If any trend is present at all it is a very weak coarsening. Worth noting is the fact that the average mean size of the low-tide samples is finer than either the mid or high-tide equivalents. There may be several reasons for this. First, observations in the field indicated that a large amount of fine material is transported down the beach by groundwater seepage. These relatively low velocity currents are able to liberate the fines from the upper and middle beach and deposit them at the low-tide level. In addition, the lower portion of the beaches at Spurn tend to have a shallower profile than the upper beach, again allowing longshore transport and cross shore transported fine material to be deposited. Adding to the variation in size in the longshore direction is the influence of beach topography, shore parallel currents and a longer time under the influence of bi-directional currents in the nearshore environment and swash-backwash effects. As all these vary widely with beach topography, and there is an equal tendency to show variation in the grain size statistics. On the riverside beach, there is an initial increase in size from 1.3 phi at sample site 7 (the tip of Spurn), then the remaining three samples on the riverside beaches show a decreasing trend. This is likely due to decreasing competence of tidal currents as they move up the inside of the spit. In addition, the expansive mud flats on the inside of the spit aid in attenuating the energy of estuary-generated waves. This prevents removal of fine material from the beach by turbulent wave action, and deposition of drapes of coarse material during high-energy storms. Low-tide samples show an opposite fining trend, and

are probably influenced both by fine material brought in by normal tides and river processes, and material transported down the beach by swash and backwash processes.

(B) **Mean Size Mid-tide:** The 1990 ocean side data shows a highly variable series of sediment sizes from sample site 1 located at Easington, to site 5 at Kilnsea which is located at the last exposure of the backing till cliff, and therefore the last clear sediment input from that source. South of site 5 there is an observable fining in the sediment size until site 13, located 1.5 km from the distal end of the spit. At this site there is a significant increase in the size of the sediment, which is also reflected in the next two locations downdrift. These three locations are in an area heavily influenced by tidal currents, as illustrated by the large-scale ripples observed in this area. The remaining two samples on the ocean side (15A and 17) continue the original fining trend. The 1997 longshore trends on the ocean side have a very similar profile to the 1990 trends. The overall trend is one of strong fining towards the tip of Spurn, with a temporary reversal of the trend about 1.5 km north of the tip, again in the area of strong tidal currents and opposite the Binks which may contribute coarse sediment to the beach when winds blow from the east or south. In this case, the reversal occurs at sample site 5. After this reversal, once again like the 1990 data, the original trend is re-established.

Mean Size High-tide: Unlike the low and mid-tide samples, the high-tide samples show a much lower variation and mean size, most are concentrated in the 0.7 to 1.4 phi size range. The dominant trend on the ocean side is one of fining with distance downdrift. This trend is slowed at sample site 4 and is reversed at 5, however sample 6 is the finest of all the sediments are 1.4 phi. The tip sample (7) is the coarsest of all the sediments,

coarser even than the sample at site 1. Possible factors that might affect sediments at the high-tide level are width of the beach (which largely controls the amount of energy reaching the backshore), presence of runnels, presence of shore protection features, dunes and shingle drapes. The high-tide samples were collected from areas which included back shore runnels, eroded road debris, and ripple and scoured areas. Samples 4 and 6 were collected from backshore runnels and reference to their size distribution histograms shows a platykurtic profile typical of sample areas with a large variation of sizes present. High-tide sample areas are dependent on material brought up from the lower portions of the beach by swash action. In winter, when steep plunging breakers are dominant, the beach tends to become wider and flatter as material is moved down the beach by the powerful backwash. Based on the configuration of the shoreline and the nearshore zone, it appears that the most southerly portions of the spit receive less energy than the northern portions, which face east and northeast. It is likely therefore that the less powerful waves at these locations have a tendency to bring up finer particles from the mid shore areas.

On the riverside beaches**,** mean size shows a clear and constant increasing trend in the northerly direction. Observations of large-scale sand waves or mega-ripples in this direction indicate that tidal currents sweep around the southern tip of Spurn and flow up the river side in a northerly direction. The ripples appear to die out around the area of the chalk bank where the breach of 1847 was sealed. From this point northward, the sandy beach narrows to a thin strip on the order of 1 to 5 meters seaward of which is a complex of estuarine mud flats of very low slope. The 1997 mid-tide data show a distinct coarsening of sediment from the tip of the spit northward on the riverside. A possible explanation of the apparent coarsening and by implication high-energy transport towards

the root of the inside of Spurn may lie in the nature of transport processes during storm conditions. It is likely that during normal conditions waves generated in the estuary are not capable of moving sediment on the mid tidal area of the beach, energy will almost certainly be dissipated on the intertidal mud flats before the waves are able to break on the beach itself. However during spring tides, storm waves are of sufficient height and energy as to be able to break on the beach and entrain sediment, preferentially removing fine material and transporting coarser material northward.

Interpretation of Longshore Trends in Mean Size

A decreasing particle size with distance downdrift (on the ocean side) might suggest the classic decreasing competence scenario for sediment transport, common to fluvial sediment transport environments where decreasing gradients with distance from the source area result in slower currents which are unable to support the sediments formerly carried as suspended and bedloads. In this environment it is tempting to suggest that the change in orientation of the spit towards the south results in less high waves and therefore less energy reaching these portions of the spit. This may well be the case, but closer inspection of the size distributions is necessary to confirm this as there are many influences other than wave energy on the Spurn Head beaches. Among these are tidal currents (both flood and ebb tides), longshore wave induced currents and offshore topography. A fining trend can be the result of removal of coarse material, or addition of fines. Inspection of the size distribution histograms for these two years' data suggests that it is the removal of coarse material that is the major influence of the decreasing size with downdrift transport. It is probable that the coarse material eroded from the till cliffs is moved only occasionally by high-energy conditions during storms, whereas the finer

fractions are moved by more common medium energies. The sediments encountered at the root of the spit, resulting from collapse of the till cliffs is poorly sorted, platykurtic and coarsely skewed. The first thing that happens to this sediment suite in the beach environments is the removal offshore of the clay and silt sized fractions. After this, a very coarsely skewed sediment is left behind. Removal of fines can likely be achieved even in low energy conditions. Longshore currents then move the sediment downdrift, but the finer material will tend to move faster in the downdrift direction than the coarse fraction, resulting in the observed fining.

Review of the histograms for the 1990 data reveals that at site 7 there is a high percentage of material in the –1.00 to 0.25 phi size range, as in the 1997 samples. This material is present in very small proportions in samples 8, 9, and 10 located downdrift, but is absent in sample 11. Samples 12, 13, and 15A have large proportions of this size range and are, like sample 5 in the 1997 data, very platykurtic. A small trace of this material is present in the remainder of the downdrift samples, which show a return to the highly peaky, more normal distributions. As was indicated in the introduction to this section, the samples located at 12, 13, and 15A are located in the area somewhat in the lea of the binks. It is probable that material is washed from this area onto the adjacent beaches when wind conditions favor waves from the east or south.

Nordstrom (1981), found no significant trend in the mean size on the ocean side beach when he investigated the spit at Sandy Hook, New Jersey. He did find that sediments became coarser with distance up the inside of the spit. Many studies have suggested that mean size is directly related to wave energy of the local environment. Although as Friedman points out, some authors (e.g. Gorseline (1976), and Engstrom (1974)), have

found this not to be the case in low and moderate energy environments. Friedman considers other factors other than wave height that might influence mean grain size. He identifies tidal currents, which tend to increase in strength towards the tip of a spit, rapidly fluctuating weather conditions, such as those associated with a storm passage, and the frequency of waves breaking on the foreshore (as a result of various factors including offshore topography). Occasional storm wave conditions can have an undue influence on the upper portions of ocean beaches and especially on the normally lower energy riverside beaches. Such waves tend to be steep and of short periods and bring coarse, gravel-sized material up the beach. When more normal conditions prevail, the coarse material may not be removed and will remain as a gravel drape or lag. On beaches with off shore bars and a shallow profile, much of the energy of breaking waves will have been dissipated before the surf reaches the mid and upper portions of the beach. This allows for the accretion of finer particle sizes, particularly at Spurn, where there is a considerable amount of fine material carried in suspension in the nearshore zone. Steeper and narrower beaches will allow breakers to exert more energy on the mid and upper portions of the beach potentially removing a higher proportion of fine material. The downdrift fining along the ocean side beaches is at odds with the results reported by Winkelmolen (1978) who reported coarsening. This may be due to a recent storm event or other weather conditions. Observations during the sample collection for this project, and subsequent photograph field visits indicated that gravel "drapes" can be deposited on an otherwise sandy beach over a single tidal cycle during storm conditions.

4.2.2 Kurtosis

Kurtosis Low-tide: A high kurtosis value is indicative of a more "peaky" distribution, and is often accompanied by a low standard deviation, because by definition if a sample is more peaky, then a higher percentage of the material is occupying fewer size classes which must be closer to the mean size class. On the ocean side in the low-tide samples, there is a weak reduction trend in the kurtosis value, indicating that samples become less peaky with distance downdrift. Minor fluctuations in this parameter are difficult at best to interpret, however major fluctuations from a very peaky to very flat type of distribution is almost certainly a good indicator of a more chaotic sediment deposition regime, i.e. higher energy, or more fluctuations in current direction. Following this logic, one would expect sediments under the influence of both shore-normal and longshore currents to be less peaky than those influenced by constant longshore currents. Reductions in the peakiness can also result from introduction of "tails" of sediment. For instance, a brief storm event, lasting only a few hours is capable of throwing coarse sediment drapes over sediment that has reached equilibrium with the regular prevailing current and wave regimes. A reduction in peakiness downdrift on the ocean side may be the result of introductions of sediment drapes, certainly at sample site 4, the rapid reduction in kurtosis is the result of a coarse tail significant enough to cause the distribution to appear bimodal. On the riverside, sediments become more peaky with distance downdrift, indicating a narrower suite of sediments is present, again probably due to either wind blow sand deposition. On the riverside, low-tide kurtosis shows a strong increase, indicting samples becoming much more peaky with distance northward.

Kurtosis Mid-tide: In the 1997 samples at the mid-tide level, kurtosis show a general improvement with distance downdrift, although there is a strong degree of variation. On the river side beaches, the 1990 mid tidal sediments indicate that Kurtosis initially increases for the first 1 km up the inside of the spit then there is a decrease at 1.5 km which is then followed once again by a steady but consistent increase in kurtosis. The 1997 data show almost the direct opposite trend, that is a clear decrease in the kurtosis value with distance up the inside of Spurn.

Kurtosis High-tide: In the 1997 samples, kurtosis at high-tide shows remarkably little variation from point to point. There is a gradual, but constant increase in peakiness with distance downdrift on the ocean side up to sample point 6, where there is a large decrease in the kurtosis value. Sample point 7 shows a similarly low value. Samples on the riverside show very little trend or variation. A very slight decrease in the kurtosis value is present, although is probably not significant.

4.2.3 Skewness

Skewness Low-tide: Skewness appears to be the most spatially variable of all the grain size parameters in the 1997 sample suite. Low-tide samples on the ocean side show no clear trend from up drift to down drift, but they are collectively more negatively skewed than both the mid-tide and high-tide samples. The more variable nature of this measure at the low-tide level may reflect the greater time under the influence of wave and tidal induced currents. In addition, there is the factor of material being dragged down the beach more in some locations than others, mainly due to spatially variable groundwater seepage rates and volumes. It has been known for sometime that groundwater seepage

from the beach face can have a dramatic effect on the erodibility of the beach mainly due to buoyancy effects on the grains decreasing their collective cohesion. No clear trend is evident in the low-tide samples except for a small decrease in negative skewness around 1997 samples 5, 6 and 7.

Skewness Mid-Tide: Mid-tide samples appear to become generally more negatively skewed towards the tip. Samples 2, 3, and 4 show an almost linear increase in skewness, but this trend is reversed at locations 5 and 6 before a return at more negative skewness at the tip of Spurn (site 7), which has the most negative of all the mid-tide skewness values. The trend towards a negative skewness is indicative of a proportional increase of coarse material relative to the mean size, this may be consistent with the theoretical winnowing out of the sediment at the fine tail of the distribution through the constant wave and current action. If this is the reason for the increasingly negative skewness value overall, then the movement towards a more positive skewness at locations 5 and 6 may be due to either the re-introduction of fine sediment, or the absence of the coarse material. Based on the mean size data, the more plausible reason seams to be a general absence of the coarse material.

Sediments at the mid-tide level seem to exhibit an overall trend towards negative skewness towards the tip of Spurn. Samples 2, 3 and 4 are sequentially more negatively skewed, but at sites 5 and 6 this trend is temporarily reversed. Sample 7, at the tip of Spurn is the mist negative of all the samples. The 1990 data shows a similar overall trend to the 1997 data, i.e. that of a trend towards more negative skewness towards the tip of the spit. Although there are two areas where this trend is reversed. This occurs at 1990 site 5 and 10-13, which corresponds to 1997 sites 1 and 4 and 5. On the river side beach,

mid-tide samples become more positively skewed with distance to the north, indicating a skewness towards the fine fraction of the distribution. This is likely due to the addition of fine sediments from the estuarine muds and clays, as well as windblown sediment from the seaward side and adjacent dunes, which are eroding on the riverside. The combination of a coarsening of the mean size and an increasingly positive skewness is indicative of "Case C" transport according to the McLaren and Bowles (1984) model (see analysis below). According to this model case C is associated with increasing energy of the transport media in the direction of transport. In this situation, this scenario appears unlikely as there is ample evidence that energy actually decreases with distance up the inside of the spit (accumulation of mud and silts forming mud flats, growth of green algae on the chalk cobbles and boulders).

Skewness High-tide: Samples on the ocean side at the high-tide level are generally negatively (coarsely) skewed. Samples 1 to 3 are slightly negatively skewed with no evident trend. Sample 4 is the most positively skewed sample of all indicating a possible influx of fine sediment or absence of a coarse lag. The next sample is the most negatively skewed of all the samples at –1.0 phi. From this sample site to the tip of Spurn, samples are sequentially more positively skewed, perhaps indicating that at this level of the beach there is less propensity for waves at high-tide to push coarse material up the beach and deposit it there as a drape. On the riverside beaches, high-tide skewness shows a very clear trend towards increasingly negative or coarse skewness with distance northward from the tip of Spurn. This is indicative of either a reduction in the proportion of fines, or the addition of a coarse tail to the sediment. Observations of the histograms for these sediments indicate that the reason for this trend is a slight reduction of the finest material, although the histograms are fairly uniform and normally distributed. It is likely

that during transport fine material is lost to the nearshore and low-tide mud flats. Nordstrom (1981) found no trend in the skewness values either in the ocean side or bay side of Sandy Hook. In addition, bivariate plots that included skewness provided no real separation of the two depositional environments.

4.2.4 Sorting

According to McLaren (1985) sorting tends to become better in the direction of regional transport due to the selective transport of sediment by waves. However, as the data presented below illustrates, this can be complicated by the addition of material along the transport path.

Ocean Side Low-tide Sorting: The ocean-facing low-tide samples become more poorly sorted from sample site 1 to 3. At site 4 there is a large increase in the standard deviation, indicating poorer sorting. From this location to the tip, samples become gradually better sorted. The data for the riverside beach samples agree with the pattern discussed by Nordstrom (1981). He found sediments became better sorted with distance down drift on the ocean side beaches and this was carried on round the tip and up the inside of Sandy Hook.

Mid-tide Sorting: The mid-tide samples show considerable variability, but there is an overall improvement in sorting with distance towards the tip of Spurn. The 1990 mid-tide data shown that with the exception of samples 11, 12, and 13, there is a general improvement in the sorting of the sediments with distance downdrift. The three exceptions are the most poorly sorted of all the samples and occupy the same area of the spit which exhibited the poor sorting values in the 1997 mid tidal sample (site 5). The

1990 data shows that at the mid-tide level, river side samples become progressively better sorted for the first 1 km northward from the tip, then at 1.5 km there is a significant decrease in sorting, followed by a return to the pre-peak level and a steady decrease for the remainder of the samples. The peak occurs at the same sample location as decrease in kurtosis, slightly more negative skewness, and the increase in mean size described above. This sample was collected from amongst the chalk debris in the area where the 1849 breach was sealed. This area appears fairly inactive in terms of energy input based on the algae growth on the chalk cobbles and pebbles in the area. Like the 1990 data, the 1997 mid-tide samples show an improvement in sorting from the tip northward for the first 2 km. The next sample at 3 km is much more poorly sorted. This again correlates to the chalk bank area, where, based on aerial photographs, the area of flood tide ripples starts to die out. Nordstrom (1981) reported that at Sandy Hook, sorting improved with distance up the inside of the spit. However, his approach involved multiple samples at the same location rather than a series of equally spaced samples. The Spurn samples between the two sampling runs both show the initial improvement of sorting followed by the rather significant reduction approximately 2 to 3 km up the inside. This is accompanied by an initial trend towards less negative skewness, which reverses at the same sample location in the 1997 data. The 1990 Skewness trend is again towards the positive, but again there is a slight reversal at the same point, although it is less dramatic than the 1997 figure.

High-tide Sorting: Sorting in the 1997 data set shows if anything a slight decreasing trend with distance downdrift. This decrease in the sorting value indicated that samples in this direction are becoming better sorted. The most poorly sorted sample of all occurs at sample location 5, located in the same area where variations in the other parameters

have been identified above. The high-tide samples show an initial improvement in sorting up to sample point 3, then samples become more poorly sorted and highly variable with no distinct trend.

4.2.5 Discussion of Longshore Trends

According to McLaren and Bowles (1984), it should be possible to use this longshore data both to confirm the direction of transport between any two sample sites, and to make some qualitative observations of the energy level of the transport media between the same two sample sites. They identified two possible combinations of mean size, sorting and skewness variation that might result from the transport of sediment in the longshore direction:

Case B: Sediments become finer, more negatively skewed and better sorted in the direction of transport (energy decreasing in direction of transport).

Case C: Sediments become coarser, better sorted, and more positively sorted in the direction of transport (energy increasing in the direction of transport).

The summary tables below indicate how many pairs from both the 1990 and 1997 sample set conform to each of these transport scenarios:

Sample Pair	Mean Size	Skewness	Sorting	Result	Energy
1-2					
2-3	F	-	P	Case B	Decreasing
3-4	F	-	B	Case B	Decreasing
4-5	C	+	P	Case C	Increasing
5-6	F	+	B	No Transport	Indeterminate
6-7	F	-	P	Case B	Decreasing
7-8	C	+	B	Case C	Increasing
8-9	F	+	B	No Transport	Indeterminate
9-10	C	-	P	No Transport	Indeterminate

Table 1: 1997 Mid-tide Longshore Trends, Ocean and River Side

Sample Pair	Mean Size	Skewness	Sorting	Result	Energy
1-2	C	-	P	None	-
2-3	F	-	B	Case B	Decreasing
3-4	C	+	P	Case C	Increasing
4-5	F	+	B	None	-
5-7	C	-	P	None	-
7-8	F	-	B	Case B	Decreasing
8-9	F	-	B	Case B	Decreasing
9-10	F	-	P	Case B	Decreasing
10-11	F	+	B	None	-
11-13	C	+	P	Case C	Increasing
13-14	F	-	-	Case B	Decreasing
14-15	C	+	B	Case C	Increasing
15-15A	F	-	B	Case B	Decreasing
15A-16	F	-	B	Case B	Decreasing
16-17A	C	+	B	Case C	Increasing
17A-18	C	-	P	None	-
18-19	C	+	B	Case C	Increasing
19-20	C	+	P	Case C	Increasing
20-21	F	+	B	None	-
21-22	C	+	P	Case C	Increasing
22-23	C	+	P	Case C	Increasing
23-24	C	+	P	Case C	Increasing

Table 2: 1990 Mid-tide Longshore Trends, Ocean and River Side

The 1990 data pairs show a clear Case B trend in the southward direction, which is indicative of decreasing energy inputs in the downdrift direction. This is reversed around the 11-14 sample site location which shows an increasing energy input. Much the same trend can be seen in the 1997 mid-tide samples where there is a general decrease in the

energy input between samples 1 and 4, followed by a Case C high energy section around sample location 5, which corresponds to the same general location as samples 11-14 in the 1990 data set. Clearly there is some process responsible for the distinctive variations in all the moment parameters seen in this location on the ocean side of the spit.

The identification of this location in both sample sets separated by six years makes the probability of error or transient local processes fairly small. At this location sediments become more poorly sorted, more platykurtic, more coarsely skewed and the mean size is coarser then the updrift samples. It might be the result of focusing of wave energy by bottom topography or the result of rip currents and tidal currents, which flow in the longshore and normal to shore directions in complex patterns towards the southern end of the spit. In addition there is the area of sand and gravel shoals known locally as the Binks lying a few tens of meters offshore from this location, a result of strong ebb tidal currents meeting southerly flowing longshore and flood tide currents. Caviaola reported that the Binks that are just off shore in this vicinity can contribute coarse sand and gravel to the beaches, tip and inside of Spurn when south-westerly winds are blowing. Material may also be swept off the Binks onto the ocean facing beaches during north easterly or easterly storms.

The transport model does not show a correspondingly strong agreement for the river-side beaches between the two sample years. Most of the sample pairs for the 1990 sample set shows increasing energy from the tip northward, which is somewhat surprising given evidence to the contrary, including the presence of low energy mud flats, and algae covered cobbles.

4.2.6 Comparison on 1990 and 1997 Longshore Data

An interesting comparison of longshore trends for the 1990 and 1997 data is possible by plotting the data against distance north of the tip of Spurn. Comparison of the mean size data shows a remarkable degree of agreement. In both cases the ocean side sediments become consistently finer until about 1.5 km north of the tip where there is a marked coarsening of the sediment: from here, again in both cases the sediments get finer towards the tip. Using the same method, the equivalent skewness, kurtosis and sorting values are also remarkably consistent over the 6-year period. This degree of similarity comes as a surprise given the assumed high degree of variation in conditions at the spit, and the collection of the 1990 sample in the summer versus the 1997 samples in the winter.

4.3 Shore Normal Observations

Thus far, the analysis has concentrated on longshore patterns and relationships. However, the collection of the 1997 data at the approximate high, mid and low-tide levels of the beach allows observation of the variation in grain sizes in the shore normal direction. The shore normal plain is subject to variation due to the distribution of processes acting on the portions of the beach. The mid-tide area is likely to be subject to the action of breaking waves for the maximum time. Low-tide areas are covered by water for the maximum time, while the high-tide areas are left high and dry for the maximum time. Mid-tidal areas undergo two cycles of breaking wave action, during both the rising and falling tide. Given this assumption, these samples can be thought of as best examples of material most heavily influenced by breaking wave action. The same train of thought

then assumes that the low-tide samples are most likely to be influenced by nearshore and tidal currents, while the high-tide samples are likely to be composed of swash deposited material, storm deposits (usually coarse sand or gravel “drapes”) and wind deflated material. This simple model of the beach foreshore is complicated by the addition of longshore bars and troughs, backshore runnels and rip current swales. All combine to produce an immensely complex environment in which a suite of sometimes complementary, but often opposing processes are at work.

4.3.1 Shore Normal Mean Size

On average, low-tide samples appear to be finer than both the mid and high-tide samples, although the pattern is certainly not conclusive. On the ocean side all the low-tide samples are at least coarser than the high-tide samples with the exception of sites 5 and 6, which occur in the central zone identified earlier in this paper. In samples 2, 3, and 5 the mid-tide sample is the coarsest, where as in 4, 6 and 7, the mid-tide sample is the finest of the three. The concept of variation in grainsize down the beach has been explored extensively by many authors, and has been related to beach steepness, angle of wave approach and on/offshore winds. The most important factor in determining the relative percentage of grain sizes in the shore-normal direction is flow asymmetry. In general on low gradient beaches, swash is of sufficient strength to move both coarse and fine particles up the beach face, however, the backwash may have sufficient strength to move only the fine material back down the face. A consequence of this is the redistribution of coarse material to the upper portion of the beach and finer material to the lower portion. The degree of asymmetry in this swash-backwash can also depend on the sorting of the beach material. Well-sorted sediments will have more pore space than those composed

of many different sizes, i.e. poorly sorted. Pore space allows rapid percolation of backwash, diminishing its power and velocity. A consequence of this theory therefore would be that as sorting increases in a longshore direction, the material on the upper portion of the beach will become coarser relative to the sediments lower down the beach.

4.3.2 Shore Normal Sorting

In terms of sorting, six out of the nine sample locations (with a mid-tide sample collected) indicate that the mid-tide samples are generally the most poorly sorted, which reflects the tendency of these areas to be subject to relatively more wave action than either the high or low samples. In sample sites 4 and 6, the mid-tide sample is by far the best sorted. These two samples do tend to skew the means calculated for these measures therefore the mean sorting for the mid-tide level was not considered for discussion. Sorting can be influenced by either sediment inputs or highly variable transport mechanisms. For example, in a backshore tidal runnel, the dominant transport mechanism is the current generated during the retreating tide. This allows the sediment in the runnel to approach equilibrium with the transport media. The mid-tidal environment is generally subject to two cycles of breaking waves, swash and backwash action and nearshore currents. Therefore there is both a normal to shore and a shore parallel component to processes operation in the middle region of the beach. The best-sorted sediments are generally the high-tide samples. The difference between the sorting values for the high and low-tide samples is actually quite small compared with that for the mid-tide samples. The high-tide samples are subject to wind deflation action and a very limited amount of swash action.

4.3.3 Shore Normal Skewness

Skewness in the shore normal direction shows greater variability and less consistency than the moments previously discussed. Generally, the low-tide samples are more likely to be more negatively skewed than the mid or high-tide samples. This may be due to recent low energy conditions bringing fine material up the beach, while leaving the coarser material on the lower portions as a lag deposit. This seems to be true for the ocean side and river-side beaches, although on the river side beaches, the mid-tide sample is the most negatively skewed.

4.3.4 Shore Normal Kurtosis

Observation of the individual kurtosis values for the ocean side beaches reveal that the low-tide samples range from approximately 1.5 to 6.25, mid tidal samples range from 2.0 to 5.9, and high-tide samples range from 2.25 to 5.5. There is no obvious relationship in these data beyond the fact that the high-tide samples have a lower variation in the data than either the mid or low-tide samples. If the average for all the high mid and low-tide samples are used, then it appears that the highest kurtosis values occur at the low-tide level and decrease towards high-tide. This is also reflected if the river-side beaches are taken separately. High kurtosis values (a leptokurtic distribution) are indicative of a fairly narrow range of sediment, or can be heavily influenced by a dominant size class.

4.3.5 Summary of Shore Normal Observations

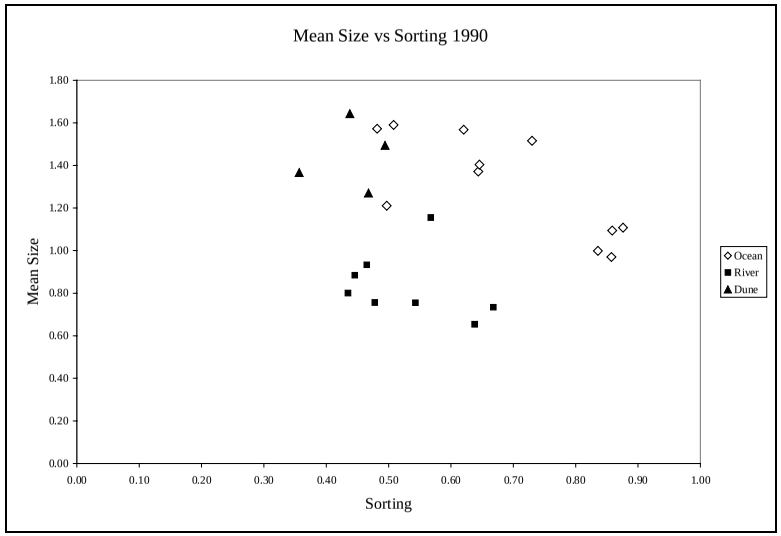
According to the means for the data, samples become coarser with position shoreward, they become better sorted in the same direction, less negatively skewed, and more

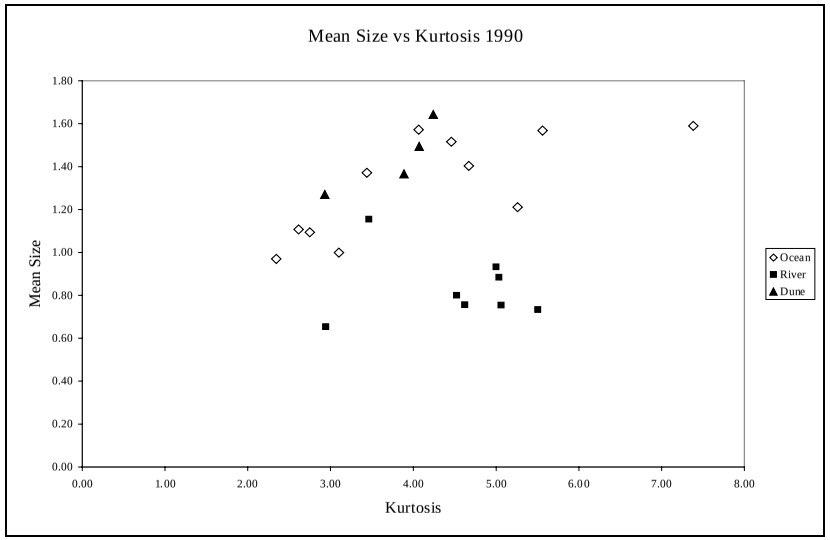
platykurtic (less peaky). The poorer sorting at the lower tide levels is not surprising based on the throughput of sediment in these locations, both from wave induced longshore currents, and the powerful tidal currents that sweep sediment alongshore, particularly close to the tip. The coarsening of the sediments towards the high-tide level indicated by the means is heavily influenced by two extreme data points, which hide the most common pattern that is for a fining of the sediments at the high-tide level. This is most likely due to the preferential movement of fine material up the beach by swash action. An additional factor to consider on at least the high-tide samples is the influence of wind deflation. During sampling in the 1990 season, several dune samples were collected in order to characterize the size of sediment typically removed from the beach by wind action. The most dominant size range removed was the 1.75 to 2.00 phi range. This did not appear to have a great effect on the data.

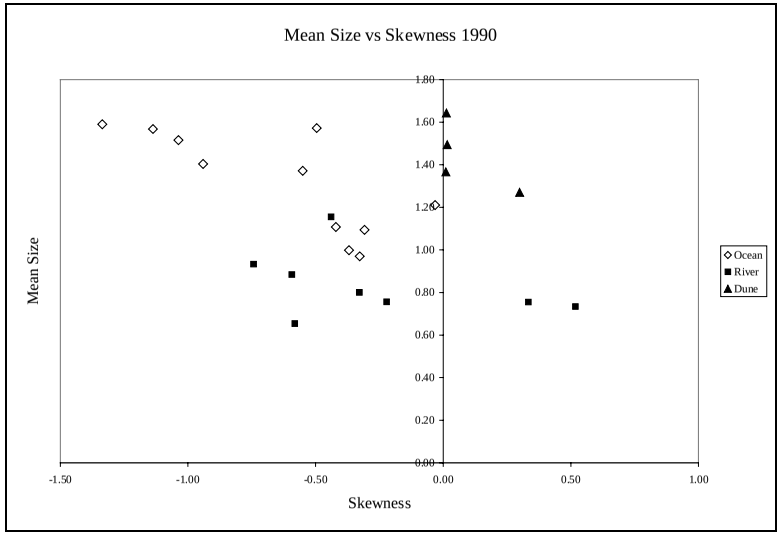
4.4 Inter Parameter Plots

Inter parameter plots have been used extensively by many authors in an attempt to visually separate samples from distinct depositional environments. Although there has been some success, the consensus in the literature now seems to be that the relative usefulness of this technique is limited to site-specific projects. The days of the “black box” approach to using grain size data as a tool for paleo-environmental interpretation seem to be waning. However, they still serve to provide a useful role as a visual indicator of the data collected from the various subenvironments. Clustering of data points in a small area of the plot as distinct from another set of points, indicates a pattern or a unique signature as a causal factors, pointing to areas worthy of further investigation.

Inter parameter plots for the 1990 data are shown on Figure 14 and the 1997 data are shown on Figure 15.







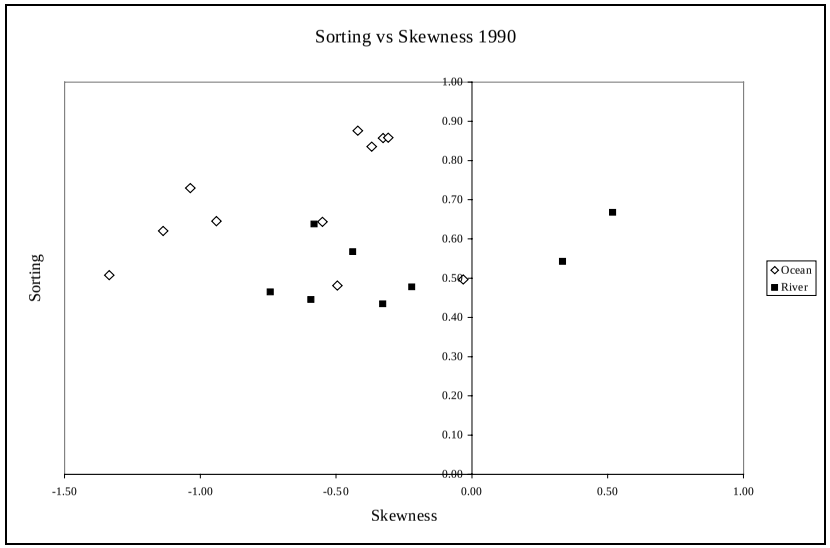
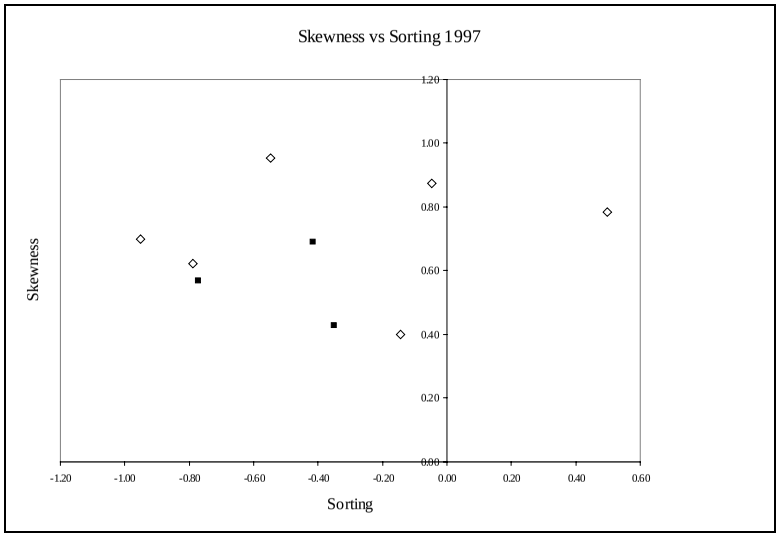
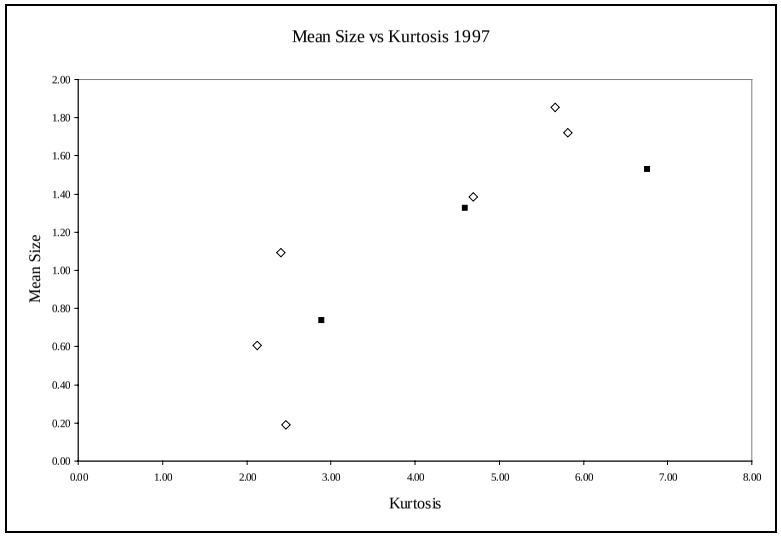
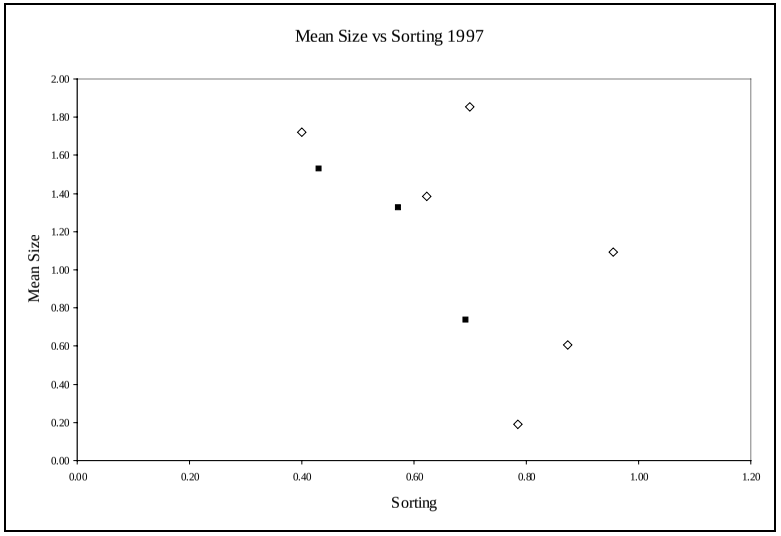


Figure 14: 1990 Inter-parameter plots.







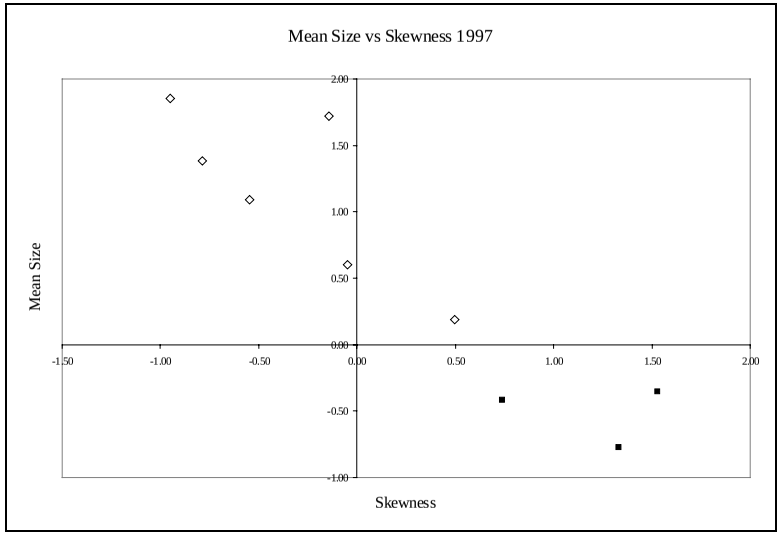
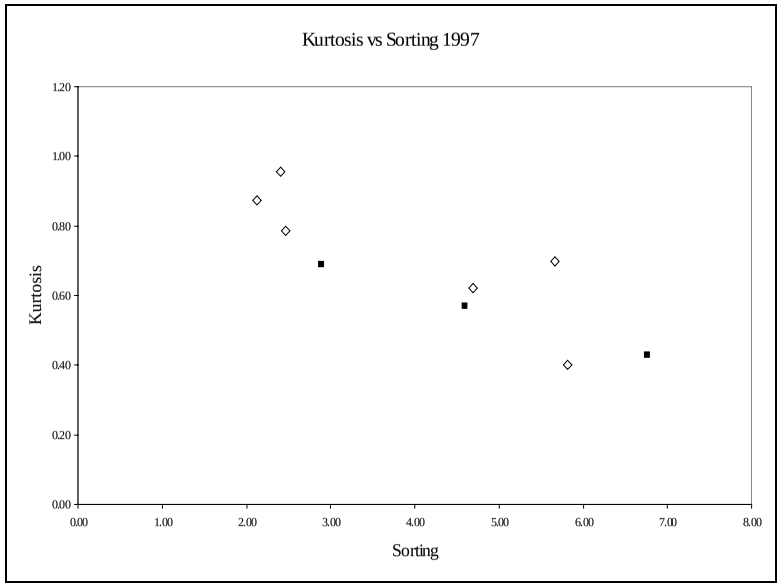


Figure 15: 1997 Inter-parameter plots (1 of 2).



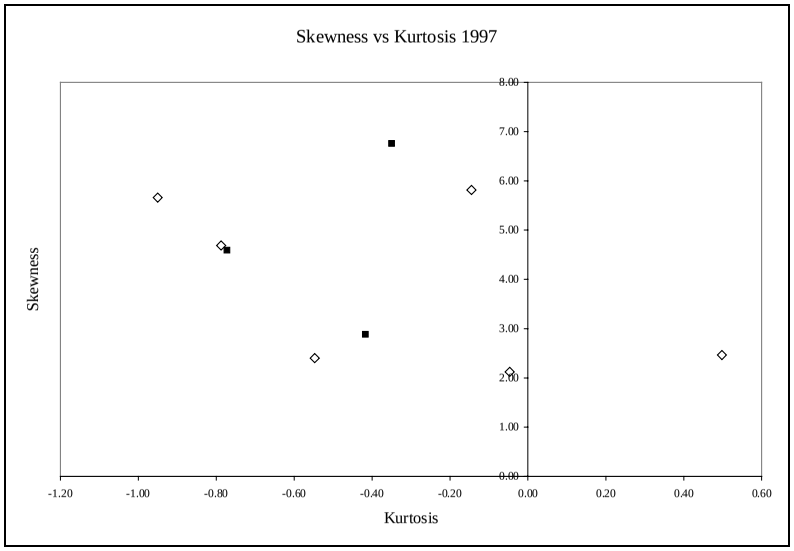


Figure 15: 1997 Inter-parameter plots (2 of 2).

4.4.1 Mean Size vs Kurtosis

These two moments provide moderately good separation of the ocean beach and river beach environments. Ocean sand appears as a finer cluster with a lower kurtosis. Six out to the eight river side samples are clustered in a relatively small area on the plot. The tow outliers have a significantly lower kurtosis. The ocean beach samples are scattered through a wider range of sizes and kurtosis values, and do not therefore form a tight pattern on the plot. There is no separation between the ocean beach and dune samples, but there is fairly good separation between the river sand and dune samples, perhaps indicating there is a closer relationship between the dune and ocean beach sediments. Observations in the field indicated that there was a high volume of sand blowing from the wide ocean beaches at the tip of Spurn onto the dunes. The 1997 samples (which do not have dune samples) show no identifiable clustering or separation between the two beach environments.

4.4.2 Skewness vs Kurtosis

These two moments show no separation between ocean and river beach sediments. Most of the samples are negatively skewed. The beach sands do separate well from the dune sands that form a distinguishable cluster in the center of the plot. The 1997 samples also fail to provide discrimination of the two beach environments.

4.4.3 Mean Size vs Sorting

Mean size and sorting provide good separation between the ocean and river-side beach samples. The ocean side samples are more poorly sorted and generally finer than the

river beach sands. The dune samples are better sorted than the ocean beach samples, but about as well sorted as the river beach samples. The dune samples also have a similar mean size to the beach samples but are coarser than the river sands. The 1997 samples also reflect the same pattern, although there are fewer data points. Nordstrom (1981) also reported that sorting and mean size did an effective job of separating ocean and bay side sands, although his approach used fewer locations but took multiple samples over successive time intervals, and was therefore temporal rather than spatial in nature.

4.4.4 Mean Size vs Skewness

These two parameters perform a moderately effective separation of all three environments with the 1990 data. The river-side sediments are generally coarser and slightly less negatively skewed than the ocean side sediments. There is a small cluster of four samples within the ocean beach environment that are distinct from the remainder of the ocean samples and are located close to the center of the plot. These are 1990 sample points 7, 13, 14, and 15. The dune sands are also effectively separated and are distinctive based on being generally finer and less negatively to positively skewed than the beach samples. The 1997 data separate river side and ocean side samples even more effectively than the 1990 data. The same pattern is evident, that is the ocean samples are more negatively skewed and finer.

4.4.5 Skewness vs. Sorting

These two parameters do not effectively discriminate the tow beach environments. It is possible to see that the river-side samples are generally more poorly sorted and slightly

more negatively skewed than the river samples. The separation is not sufficient for positive discrimination.

4.4.6 Summary of Inter Parameter Plots

Friedman (1977) found that a bivariate plot of sorting and skewness was the most effective in discriminating beach and river sands, and not surprisingly, these do not adequately discriminate high and low energy beach sediments. Mason and Folk (1958) found that Skewness and Kurtosis provided the best means of discriminating beach, dune and aeolian flat environments. In this environment, these tow parameters fail to discriminate the high and low energy beach environments, but do provide a good separation from beach and dune sands. Martins (1975) also made the same observation regarding the separation of beach and dune sands. All these authors reported beach sands to be either normally distributed or negatively skewed, the latter being the most common. Dune sands are typically reported as being normally or slightly positively skewed. There results from this study agree with these generalisations. Friedman (1971) also found that mean size against skewness successfully separated beach and dune sands, as was the case in this study.

Nordstrom (1977) found that skewness was not useful in distinguishing environments especially between high and moderate energy beaches. He found kurtosis values to be generally higher on the moderate energy beach, while a plot of mean size against sorting provided the greatest degree of separation. In this study, river beach sands (the moderate energy environment) were also more leptokurtic as Nordstrom reported. In this case also the combination of mean size and sorting provide good separation of the two beach

environments as did mean size and skewness. This data then provides further evidence that at least to some degree, the grain size distribution of sediments from the same source and in proximal locations can be shown to be environmentally sensitive. The question that follows then is that are these plots useful to the scientist studying palaeo sediments? Clearly the answer is yes, as long as they are used in conjunction with other pieces of evidence.

4.4.7 Statistical Tests of the Discrimination Between the River and Ocean Beaches

Because of the larger number of data samples particularly on the river side beaches, the 1990 data set was used to test statistical significance of the differences observed between the ocean beach and river beach sediments.

(i) Mean Size

The average value for mean size on the ocean facing beach sediments is 1.31 phi, while for the river facing beach is it 0.83 phi. Therefore, it appears that the sediments on the ocean facing beach are finer than those of the river beach. To determine whether the difference is significant, a t-test was performed on the two samples.

H_0: There is no significance between the two sample means
H_1: There is a significant difference between the two sample means

Degrees of freedom = 17
Confidence level = 0.05
Test Statistic = 4.87
Critical Value for t = 2.10

The test statistic is greater than the critical value for t, therefore the null hypothesis is rejected. The two sample means are significantly different. Although a significant difference in the mean size has been established between the two beach environments, there is still some disagreement among the authors as to the reason for this difference. It would be convenient to be able to assign the difference in size to energy conditions alone, however, as Folk, 1958 and Nordstrom 1977 and 1981 pointed out, there appears to be an inverse relationship between sediment size and wave energy when one might reasonable expect the opposite to be true. Again, at Spurn Head, where the energy input on the ocean facing beach is clearly greater than at the river facing beach, there is an inverse relationship. As a consequence, it appears that mean size alone is not a reliable indicator of energy conditions. To answer the vexing question of mean size decreasing with increasing energy input, Nordstrom hypothesised that the river facing beaches were not nourished by the finer sediments from the source material as was the case with the ocean facing beaches. This may be true in the Spurn Head environment also, as the finer material is clearly held in the nearshore zone and as it is stirred up from the beach by wave action, and may not be carried round the tip and up the inside of Spurn. It has also been suggested by several authors that beaches on the inside of spits may be influenced by occasional steep storm wave conditions which dump coarse sand and gravel material on the upper portions of the beach, which normal low energy conditions are unable to remove, resulting in a coarser sediment. These two hypotheses can be tested to some extent by comparing the average size distribution histograms for ocean beach and river beach sediments. These reveal a striking difference between the two environments. The ocean beach sediments have their modal value in the 1.75 phi range, while the river sediments peak around 0.5 phi. Although the ocean beach sediments have a coarse tail, it

is not nearly so significant as the relative absence of material in the 2.00 to 2.75 phi range from the river sediments that is present in the ocean beach sediments. This suggests that this material is not transported round the tip of Spurn onto the river beaches rather it is probably diverted to the off shore area around the tip of Spurn by the strong tidal currents.

(ii) Sorting

The average sorting on the ocean side beach was 0.69, and 0.53 on the river side beach. Therefore, the ocean side beaches appear to be more poorly sorted than the river side beaches. To test the significance of the better sorting on the ocean facing beach a t-test was performed on the sorting data.

H_0: There is no significance between the two (1990) sample means
H_1: There is a significant difference between the two sample means

Degrees of freedom	= 17
Confidence level	= 0.05
Test Statistic	= 2.57
Critical Value for t	= 1.74

Therefore the null hypothesis is rejected and there is a significant difference between the two sample means. From this data, it can be concluded that the high-energy beaches are more poorly sorted than the river facing beaches. The 1997 data, although there were a limited number of samples also indicate that the river-side samples are generally better sorted than the ocean-side samples. Better sorting would be expected in areas where the input of sediment is relatively low, and the conditions are relatively stable. The high

mobility of the beach sediments coupled with the high sediment influx from the eroding cliffs updrift contributes to the poorer sorting on the ocean side beach. Folk (1975) was one of the first authors to observe this same difference and attribute it to relative sediment mobility.

(iii) Skewness

The average skewness on the ocean beach was –0.63 and –0.26 on the river-side beach according to the 1990 data, and –0.39 on the ocean beach, and –0.58 on the river facing beach in the 1997 data. Clearly there is a disparity in the two sampling sets. To assess the significance of the difference in the two sample means in the 1990 data a t-test was performed.

H_0: There is no significance between the two (1990) sample means
H_1: There is a significant difference between the two sample means

Degrees of freedom = 14
Confidence level = 0.05
Test Statistic = -1.85
Critical Value for t = 1.76

Therefore there is no significant difference between the two samples. Although skewness is a useful descriptive statistic, and is invaluable in tracing sediment transport, its usefulness in environmental discrimination has been recognized as being rather poor by several authors (e.g. Nordstrom, 1977). Furthermore, it is a bi-directional statistic, and as such results either side of zero can cancel each other out.

(iv) **Kurtosis**

The average kurtosis on the ocean side beach was 4.15 and on the rover beach was 4.52, indicating that the river-side beaches are more leptokurtic (peaky) than the ocean

beaches. The 1997 data indicated that the ocean side average was again 4.15 and the river average was 4.81. To test the apparent difference between these data, a t-test was performed (on the 19909 data).

H_0: There is no significance between the two (1990) sample means
H_1: There is a significant difference between the two sample means

Degrees of freedom = 16
Confidence level = 0.05
Test Statistic = -0.67
Critical Value for t = 1.75

Therefore the null hypothesis is accepted and there is no significant difference between the two sample means.

4.4.8 Summary of Environmental Discrimination

Based on the analysis performed on the Spurn Head beach and dune sediments, it appears to be possible to discriminate between the sediments deposited on the ocean facing beaches and those on the river side of the spit based on their grain size distribution. Significant differences were found in their sorting and mean size. The sediments on the ocean facing beach are finer, but more poorly sorted than those on the river side of the spit. Based on observations made from the previous work done in the area, much of it unpublished, it is clear that the ocean-facing beach receives higher energy inputs than the river/estuary facing side. The result of this higher energy input is to decrease the sorting of the ocean beach sediments, even though they are finer. The ocean facing beaches experience high energy both in terms of breaking waves and wave induced currents and tidal currents which act both directly on the beach and slightly offshore facilitating the movement of suspended sediments quickly down the length of the coast.

Considering the nature of the parent material, much of which is clay and silt, very little, if any, of this material remains on the spit. Some muds and clays are deposited on the estuarine mud flats on the inside of Spurn, but is not immediately apparent how much of this is fluvially derived and how much can be attributed to deposition from flood tide currents.

Although mean size and sorting were the most significantly different in terms of sample means, they were not necessarily the most useful discriminators in terms of interparameter plots. The most useful of these bivariate relationships was the mean size vs skewness and mean size vs sorting (in the 1990 data set especially).

4.5 Log-Probability Plots

A log-probability plot of every sample from 1990, 1997 and some isolated samples collected in 1995 were prepared. A summary of observations made from these plots is presented in the following table.

Sample Number	Traction Population	Saltation Population	Suspension Population	Description of Sample Site
97-LT1	Poor '(5%)	94.60%	0.40%	Flat, Sandy beach
97-HT1	Medium			Among erosion debris
97-LT2	Poor (5%)	Well (93.5%) - Bi	Very Poor	
97-MT2	Medium (55%)	Medium-Poor (44.97%) - Bi	Poor	Erosion Debris
97-HT2	Poor (4%)	Medium-Well (94%) Bi	Poor	Sandy backed by dunes
97-LT3				Sandy with water Seepage
97-MT3				Fine gravel and occasional cobbles
97-HT3				Flat beach backed by riprap
97-LT4	Well (32%)	Poor (58%) - Strong Bi	Medium	Flat/Sandy
97-MT4	Poor (6%)	Well (93.5%) Uni	Poor	Berm Crest
97-HT4	Well (11%)	Well (83%)	Poor	Runnel
97-LT5	Poor (10%)	Well (86%) - Weak Bi	Well (3.5%)	Scallops and Ripples
97-MT5	Poor-medium (44%)	Well (54.5%) Bi	Well (1.5%) Truncated	Smooth Beach
97-HT5	Poor (7%)	Well (92.9%) - Uni	Poor (0.1%)	Smooth Beach
97-LT6	Well (5%)	Medium-Well (94%) Bi	Poor (1%)	Flat Beach seaward of berm
97-MT6	Poor (0.25%)	Well-Very Well (99.25) - Bi	Poor (0.5%)	Landward Side of berm
97-HT6	Well (28%)	Well (71.7%) Bi	Poor-Medium 0.3%	Runnel with ripples
97-LT7	Medium (34%)	Well (65%)	Poor (1%)	Scallops, no ripples
97-MT7	Medium-poor (10%)	Well (83%)	V Well (10%)	Flat Sandy Beach
97-HT7	Medium (0.06%)	Well (90.3%)	Poor (0.1%)	Wide flat sandy beach
97-LT8	Medium-Poor (3%)	Well (97%) Weak Bi	None Present	Scallops, no ripples
97-MT8	Medium (10%)	Well (89.8%) Bi	Poor (0.2%)	Flat Beach
97-HT8	Medium/Well (5%)	Well-Medium(94.75%) Bi	Poor (0.25%)	Flat Beach
97-LT9	No Sample	No Sample	No Sample	No Sample
97-MT9	Medium-Poor (3%)	Well (97%) Weak Bi	Poor (0.5%)	Bi-Directional Ripples
97-HT9	Medium-Well (1.5%)	Well (98.5%) Weak bi	None Present	Wide flat sandy beach

Sample Number	Traction Population	Saltation Population	Suspension Population	Description of Sample Site
97-LT10	Poor (10%)	Well ((82%) - Uni	Poor (4%)	Shallow gradient with some tidal sand waves and scattered mud drapes. Little or no chalk cobbles on the lower beach.
97-MT10	Medium (55%)	Well (98%) - Bi	Poor (0.5%)	Sandy with numerous chalk cobbles
97-HT10	Medium-Well (1%)	Medium (44.5%) - Bi	Well (0.5%)	Medium gradient upper beach comprised of sand, with low dunes to the rear.

Table 3: Summary of data observed from the 1997 sample log-probability plots.

4.5.1 Discussion of Log-Probability Plots

The work cited earlier in this study related to log-probability plots has been applied to many different environments from around the world. Less attention has been given to the usefulness of these techniques within a specific environment such as Spurn. In general, log-probability plots have proved to be a very useful aid to grain size distribution discrimination and interpretation. Sediments from specific environments display certain identifiable characteristics when plotted in this way. Their usefulness in two specific areas was tested in this study. First, their ability to reveal clues about the process of deposition responsible for the sediment sample was examined. Second they were examined for their ability to help in environmental discrimination of the sample. For clarity, this examination concentrated on the 1997 sample set (which included mid, low and high-tide samples), although reference to the 1990 samples is made for comparison. The mean plots for high, mid and low-tide 1997 samples are presented in Figure 16. Means for beach, dune and river beach samples are plotted on Figure 17. Plots for all samples are presented in Appendix A.

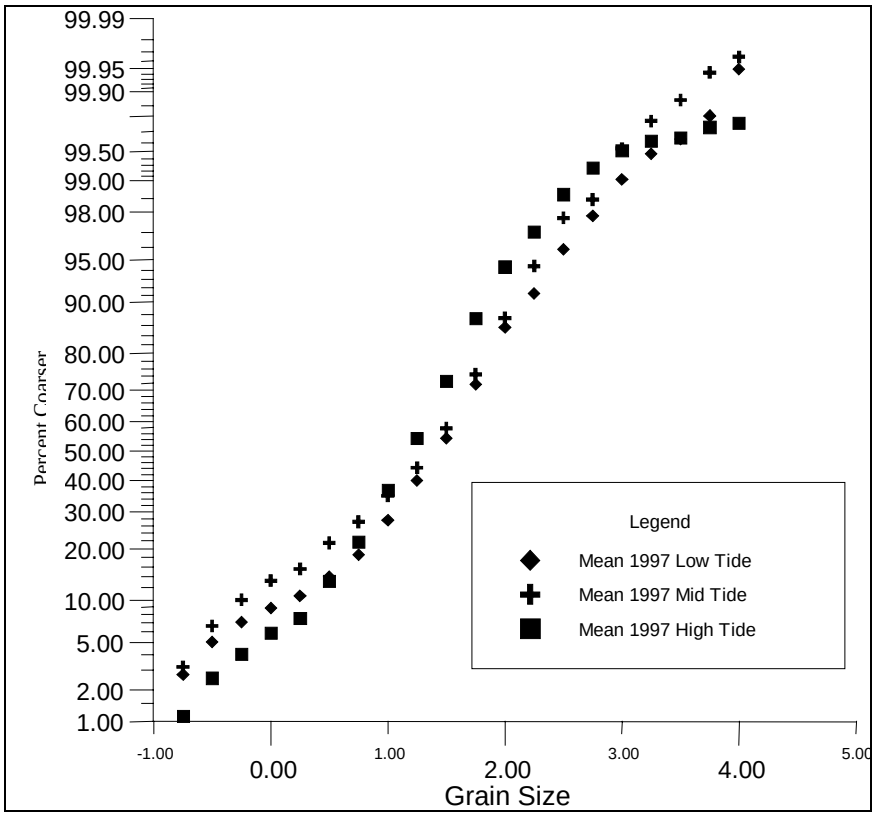


Figure 16: Average log-probability plots for1997 high, mid and low-tide samples

Collectively, the Spurn Head samples have a characteristic elongated reverse "Z" shape with three distinct straight-line segments. These are interpreted to be the traction (or bedload) population at the coarse end of the size distribution, saltation population (in the center of the distribution, and suspension load (at the fine end of the distribution). Each of these populations can reveal something of the sediment transport process at that particular location. Analysis of these sediment distributions in conjunction with the other data presented here suggests that the ocean facing beach is a very complex sedimentary environment which is separated into zones within which different processes dominate depending on the weather conditions, tidal, and wave state. The relative percentages of

the distribution of each sample in each transport population along with a qualitative comment on the sorting of that population is provided in Table 3 above.

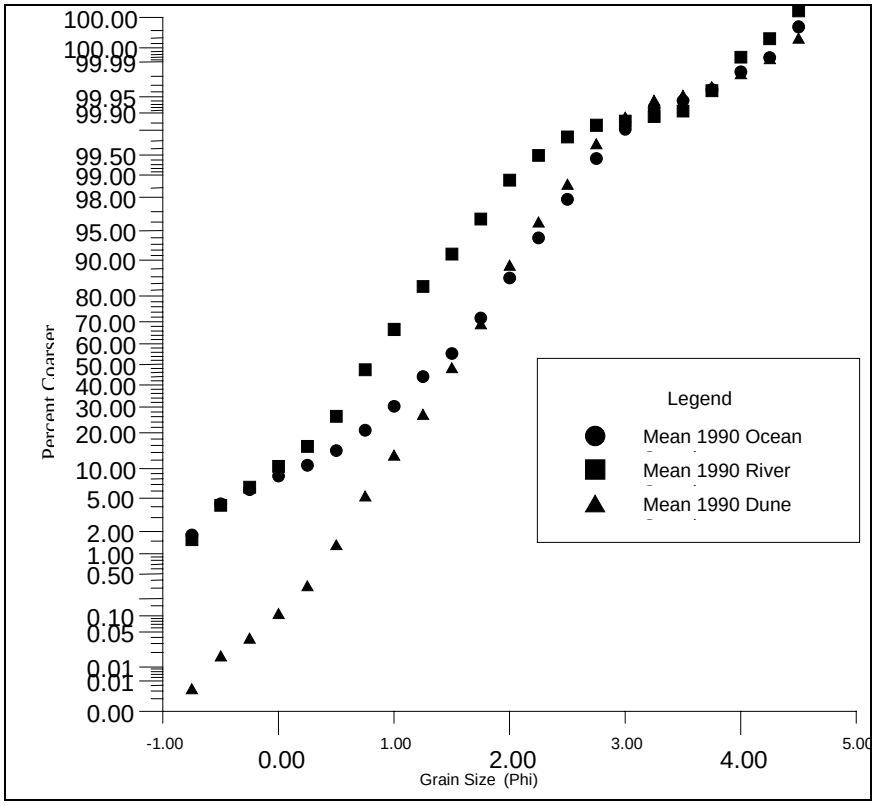


Figure 17: Average Log-probability plots for 1990 ocean, river and dune samples.

Typically the traction population is poorly sorted especially compared to the relatively well sorted saltation population. The only exception to this is the mid-tide sample at 97-2, which has an a-typical shaped curve. Other less obvious exceptions occur at sites 97-6 low and high-tide. Intuitively, traction populations are expected to become better sorted with time and distance in the direction of transport in the presence of a uniform current. This type of environment is not present in the breaker zone where the swash and backwash processes dominate. Following from this, samples with a well-sorted traction population are interpreted to be more heavily influenced by currents that wave action. A

relatively unscientific observation of two samples was made to test this general hypothesis. Sample 97-6 was collected from a high-tide runnel with bedforms that suggested a unidirectional current (similar features were observed in operation during subsequent visits to the site). The log-probability plot of this sample revealed a fairly well sorted traction population, almost undistinguishable from the saltation population.

Strong currents therefore are expected to produce a well-sorted traction population, well sorted saltation population, and negligible (if present at all) suspension population. A review of Visher's 1979 paper reveals that fluvial samples show just this type of curve.

For the fist time in this analysis there is some potential method that at least suggests the type of process that acted most recently upon the sediments rather than just grouping samples into distinct population. Observed differences between the ocean side samples and those collected from the river side, especially those collected from the large tidal ripples lend some support to the working hypothesis. The ripple-based samples possess a well-sorted coarse fraction, suggestive of a strong unidirectional current. Additional samples that has well sorted traction populations included samples 17 A, 18, and 19 from the 1990 sample set. Again these are some of the most current dominated samples sites in the entire area.

A poorly sorted traction population was interpreted to indicate highly variable, relatively high-energy transport conditions, the more variable, the less well sorted. Such a poorly sorted traction population is the more common situation on the Spurn beaches and is considered in this study to be diagnostic of a dominant transport by wave action. Assuming this is true, Visher thought it was possible to identify separate swash and backwash populations within the saltation population. Swash and backwash motions

were observed during sample collection and subsequent visits made to the site. His rationale for this difference within the saltation population was that a different laminae were laid down by the swash and backwash as they typically do not possess the same energy.

The characteristic good sorting of the saltation population is the result of constant reworking by wave action. The Spurn data confirms that most saltation populations are indeed well sorted. Poor sorting may be expected where there is less intense reworking of this sediment population.

The dune samples collected from near the tip of Spurn in 1990 as expected had a dominant saltation population, and are included in this analysis as a control as their saltation population is of a uniform slope. Most of the ocean samples exhibit a bi-directional element in the saltation population, one that is almost absent in both the river-side and dune samples. It may be that the slope of the saltation curve toward the coarse side of the break in slope represents the surging swash, while the fine end may represent the less energetic backwash.

It might be more useful to look at the average log-probability plots for each environments in the same way as was done for the histograms. After review of these figures, some general comments are possible. According to the 1990 data, the ocean and river beaches have a similar coarse (traction) population, with that of the ocean beach being marginally more poorly sorted than the river-side. The most outstanding difference between the two beach curves, is the saltation population which is more poorly sorted on the ocean side than the river site. The dune samples lack the coarse traction population of the beach samples and have a much better sorted saltation population. According to the 1997 data,

there are minor differences only in the averages for high, mid and low-tide beaches. The mid and low-tide beaches generally have slightly more coarse material then the high-tide beaches. The high-tide beach is has the best sorted saltation population of the three sample means but is largely missing sediment 3 phi and finer. When comparing ocean and beach data, it appears that the ocean beaches again have a larger proportion of material in the coarse tail of the distribution, but a more poorly sorted saltation population.

5.0 CONCLUSIONS

At the beginning of the study, several hypotheses were posed:

- It is possible to differentiate between high-energy ocean facing beach, and low to moderate energy river-facing beach through the use of grain size analysis and interpretation of the derived grain size statistics.
- Differences can be identified between high, mid and low-tide samples.
- It will be possible to identify trends in the grain size moments that will mirror the direction of sediment movement to the south on the ocean-facing beach and to the north on the river-facing beach.
- It will be possible to separate the ocean-facing beach into energy zones in the longshore direction based on energy inputs.
- Characteristic log-probability curves can be generated for high energy, low energy and dune samples.

It does appear possible to differentiate between the ocean facing and river facing beaches using the grain size distribution and derived statistics. It was found that the ocean facing beaches are significantly finer and more poorly sorted than the river facing beaches, although no significant difference was found between the environments in terms of kurtosis and skewness. These fundamental differences can also be seen in the mean distributions for the samples. The mean ocean distribution is less "peaky", has a finer modal class, and a coarse tail. The river samples are typically more "peaky", have a finer

modal class and equivalent coarse tail. The two environments could also be distinguished through the use of scatter plots. A plot of mean size and sorting provide good separation of the two beach environments as did mean size and skewness. These data then provides further evidence that, at least to some degree, the grain size distribution of sediments from the same source and in proximal locations can be shown to be environmentally sensitive. The reason the mean size and sorting appear to be the most successful discriminatory parameters seems to be rooted in the fact that conditions at the tip of Spurn are such that only a narrow range of material is able to be transported to the river side beaches.

In the shore normal plain, there were identifiable differences between the low, mid and high-tide samples. The low-tide samples were generally the best sorted, with a fine tail on the ocean side. The mid-tide samples had a tendency to bimodality and were the most poorly sorted of the three environments. There does not appear to be a significant difference in mean side between the low and mid-tide samples. The high-tide samples were generally coarser on the ocean side, but finer on the river side. This is likely a reflection of the different beach profiles present on either side of the spit. Ocean facing beaches were often observed to have berms with shoreward runnels at either the mid-tide or high-tide levels. No berms or runnels were present on the river beaches. The low-tide samples are likely better sorted because they spend the most time under the influence of wave and current action. Although not as clear cut as the differences between river side and ocean side beaches, it does appear that position on the beach profile does impact the grain size distribution of the sample, and some differences can be seen, notably sorting.

Longshore trends in the data were observed. For mean size, the 1990 ocean side data shows a highly variable series of sediment sizes from sample sites 1 located a Easington, to site 5 at Kilnsea which is located at the last exposure of the backing till cliff, and therefore the last clear sediment input from that source. South of site 5 there was an observable fining in the sediment size until site 13, located 1.5 km from the distal end of the spit. At this site there is a significant increase in the size of the sediment, which is also reflected in the two next locations downdrift. The remaining two samples on the ocean side (15A and 17) continue the original fining trend. The 1997 long shore trends on the ocean side have a very similar profile to the 1990 trends. The overall trend is one of strong fining towards the tip of Spurn, with a temporary reversal of the trend about 1.5 km north of the tip. After this reversal, once again like the 1990 data, the original trend is re-established.

In the 1997 samples at the mid-tide level, kurtosis shows a general improvement with distance downdrift, although there is a strong degree of variation. On the river side beaches, the 1990 mid tidal sediments indicate that kurtosis initially increases for the first 1 km up the inside of the spit then there is a decrease at 1.5 km which is them followed once again by a steady but consistent increase in kurtosis. The 1997 data show almost the direct opposite trend, that is a clear decrease in the kurtosis value with distance up the inside of Spurn.

Sediments at the mid-tide level seem to exhibit an overall trend towards negative (coarse) skewness towards the tip of Spurn. Samples 2, 3 and 4 are sequentially more negatively skewed, but at sites 5 and 6 this trend is temporarily reversed. Sample 7, at the tip of Spurn is the most negative of all the samples. The 1990 data shows a similar overall

trend to the 1997 data, i.e. that of a trend towards more negative skewness towards the tip of the spit. Although there are two areas where this trend is reversed. This occurs at 1990 site 5 and 10-13, which corresponds to 1997 sites 1 and 4 and 5. On the river side beach, mid-tide samples become more positively skewed with distance to the north, indicating a skewness towards the fine fraction of the distribution.

The mid-tide samples show considerable variability, but there is an overall improvement in sorting with distance towards the tip of Spurn. The 1990 mid-tide data shows that with the exception of samples 11, 12, and 13, there is a general improvement in the sorting of the sediments with distance downdrift. The three exceptions are the most poorly sorted of all the samples and occupy the same area of the spit which exhibited the poor sorting values in the 1997 mid tidal sample (site 5). The 1990 data shows that at the mid-tide level, river side samples become progressively better sorted for the first 1 km northward from the tip, then at 1.5 km there is a significant decrease in sorting, followed by a return to the pre peak level and a steady decrease for the remainder of the samples. The peak occurs at the same sample location as decrease in kurtosis, slightly more negative skewness, and the increase in mean size described above. This sample was collected from amongst the chalk debris in the area where the 1849 breach was sealed. This area appears fairly inactive in terms of energy input based on the algae growth on the chalk cobbles and pebbles in the area. Like the 1990 data, the 1997 mid-tide samples show an improvement in sorting from the tip northward for the first 2 km. The next sample at 3 km is much more poorly sorted. This again correlates to the chalk bank area, where, based on aerial photographs, the area of flood tide ripples starts to die out.

An interesting comparison of longshore trends for the 1990 and 1997 data is possible by plotting the data against distance north of the tip of Spurn. Comparison of the mean size data shows a remarkable degree of agreement. In both cases the ocean side sediments become consistently finer until about 1.5 km north of the tip where there is a marked coarsening of the sediment, from here, again in both cases the sediments get finer towards the tip. Using the same method, the equivalent skewness, kurtosis and sorting values are also remarkably consistent over the 6-year period. This degree of similarity comes as a surprise given the assumed high degree of variation in conditions at the spit, and the collection of the 1990 samples in the summer versus the 1997 samples in the winter.

In summary, it was possible to identify, and to some extent interpret the changes in sediment statistics along the length of Spurn. Although data from the northern portion of the coast is limited, no real trends were evident until the sediment source had been eliminated. After the backing till cliffs disappeared, the sediments generally became finer, more negatively skewed and better sorted with distance downdrift. These general trends made it possible to identify areas where significantly different processes were operating. An area 1.5 km north of the tip appeared to be heavily influenced by medium to coarse material washed onto the beaches from the Binks area.

An interesting test performed on the longshore data was application of the McLaren model. The 1990 data pairs show a clear Case B trend in the southward direction, which is indicative of decreasing energy inputs in the downdrift direction. This is reversed around the 11-14 sample site location which shows an increasing energy input. Much the same trend can be seen in the 1997 mid-tide samples where there is a general decrease in

the energy input between samples 1 and 4, followed by a Case C high energy section around sample location 5, which corresponds to the same general location as samples 11-14 in the 1990 data set. The model also identifies the area around the Binks as one where a different set of processes are operating.

While being a valuable additional tool in identifying processes at work on the beaches of Spurn, the log-probability plots did not produce the hoped for characteristic curves for river, ocean and dune environments.

5.1 Limitations Of Sediment Sampling Strategy

Certain compromises must be made whenever sampling a complex environment. Spurn Head and its associated sediment source beaches of Holderness present a highly dynamic environment with enormous sediment fluxes operating over multiple temporal scales. Both the 1990 and 1996 sampling efforts represent conditions on that particular day during that particular season (winter in both cases). Analysis of the data from 1996 indicated that there was often a wider difference in grain size distributions between low, mid and high-tide samples than consecutive longshore samples. It would, therefore, be desirable to increase the density of samples to assess the magnitude of short-distance variations compared to longer distance trends. Furthermore, collection of a suite of samples from each sampling location would help ease concerns over sieving and other analysis based sources of error.

Observations during sample collection indicated that, in addition to wave dominated swash and backwash beaches, longshore runnels were often present at the mid-tide or high-tide level. This allowed water and sediment to be transported rapidly alongshore,

effectively bypassing the "traditional" mode of longshore transport by oblique swash and backwash motions. A sampling program designed to include these micro-environments would reveal more information about the characteristics of these smaller scale environments compared to the larger, regional scale variations.

The magnitude of diurnal variation at each sample site is unknown. Collection of samples after each tidal cycle over a week would provide some valuable information on these short temporal cycles. The effect of storm events could be observed if samples were collected following such events. Seasonal variations could be interpreted from monthly data collected over the course of a year.

All of these alternatives would add greatly to an understanding of the complex mechanisms that operate at Spurn over a multitude of temporal and geographic scales. However, the number of samples collected would present a logistical challenge during analysis. Sieving is a labor intensive process. Modern methods such as laser counting may make this a more feasible approach for future researchers.

5.2 Related Research And Applications Of Grain Size Analysis

Although there are limitations to the usefulness of grain size statistics for absolute determination of depositional environments, it is encouraging that even in such a dynamic environment as Spurn Head, it is possible to identify regional trends through environmentally sensitive statistics. The ability to potentially identify transport direction has important implications for palaeo-sedimentology and more contemporary coastal management issues.

Coastal management is one of society's growing problem areas, with more people living adjacent to coastal zones and the possibility of sea level rise and increased exposure to storm and associated surges. The coastal manager has many important decisions to make. In addition to preservation and safety issues, viable, attractive beaches are an economic resource that must be protected to preserve the viability of tourist resorts. Increasingly, hard engineering options are seen to be inappropriate solutions to beach erosion due to the difficulties in predicting unintended consequences (e.g. down drift erosion, scouring around sea wall structures, and disruption of natural sediment movement patterns). Grain size analysis research has been integral in identification of problems associated with hard options, and the development of less intrusive "softer" options. For the softer options to be successful, the character of beach sediments must be understood, along with the local processes and the response of those sediments to the processes. For instance, nourishment of a beach with material brought from the nearshore environment may be of an incompatible grain size for successful establishment of the equilibrium beach. Too fine and the material will be quickly removed; too coarse and the material may alter the natural beach profile from gently sloping dissipating beach to a steep, reflective beach, which may induce scour in the near shore and movement of beach material down slope and off the beach.

Increasingly dunes are recognized as a vital part of the beach system. Understanding sediment exchange between the beach and the dunes has been made possible through the analysis of the beach and dune sediments. Therefore, when the beach is nourished it is possible to ensure that sufficient sediment in the appropriate size class is available to replenish and support the desired beach-dune system (as long as the natural conditions are also present).

Understanding the movement of sediment size classes is also valuable in the environmental contamination field. If the typical size class of a known contaminant is known, then given knowledge of the sediment transport characteristics of the particular area, it might be possible to predict the transport pathway and ultimate sink for the contaminant.

Identification of palaeo environments relies on the combination of many disciplines. One of the tools now available, and increasingly so as the data pool increases, is statistical interpretation of the grain size analysis. Although clearly not a stand-alone landform and process determination tool, grain size analysis has demonstrated that it is possible to make some observations concerning transport methods and energy states. These include high and low energy environments, uni-directional versus bi-directional movement, and traction, saltation and suspension transport. Typically it is not possible to base these conclusions on one parameter, rather a suite of parameters along with visual analysis of log-probability plots and distribution curves is needed.

Lastly, each study conducted in the area of grain size analysis adds to the world-wide pool of data from an increasingly wide variety of environments. The more that is known from contemporary environments, the more refined our coastal management can become and the better our interpretation of the palaeo environment might be.

At Spurn Head, while some of the grain size patterns and processes can be related, it would take a more comprehensive study to solidify relationships between processes and the deposits, which, in addition to the suggestions above, might include sediment traps, wave measuring devices and current meters. The variety of environments at Spurn provides an invaluable laboratory in which to study these relationships.

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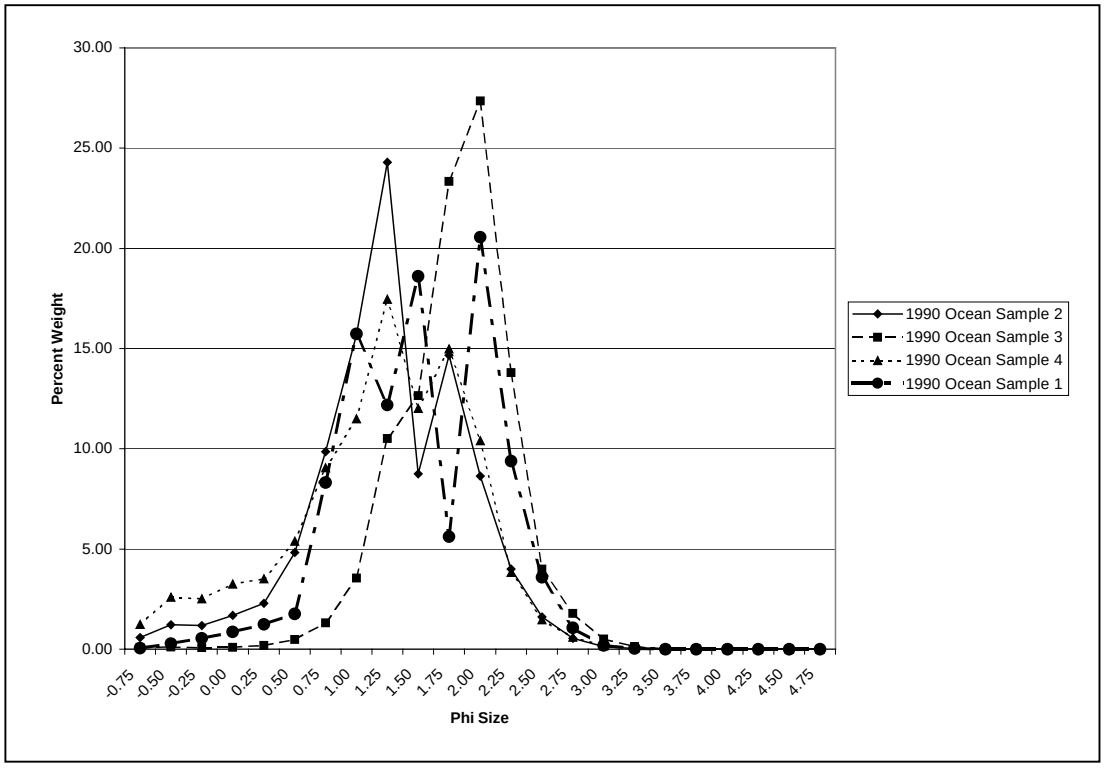
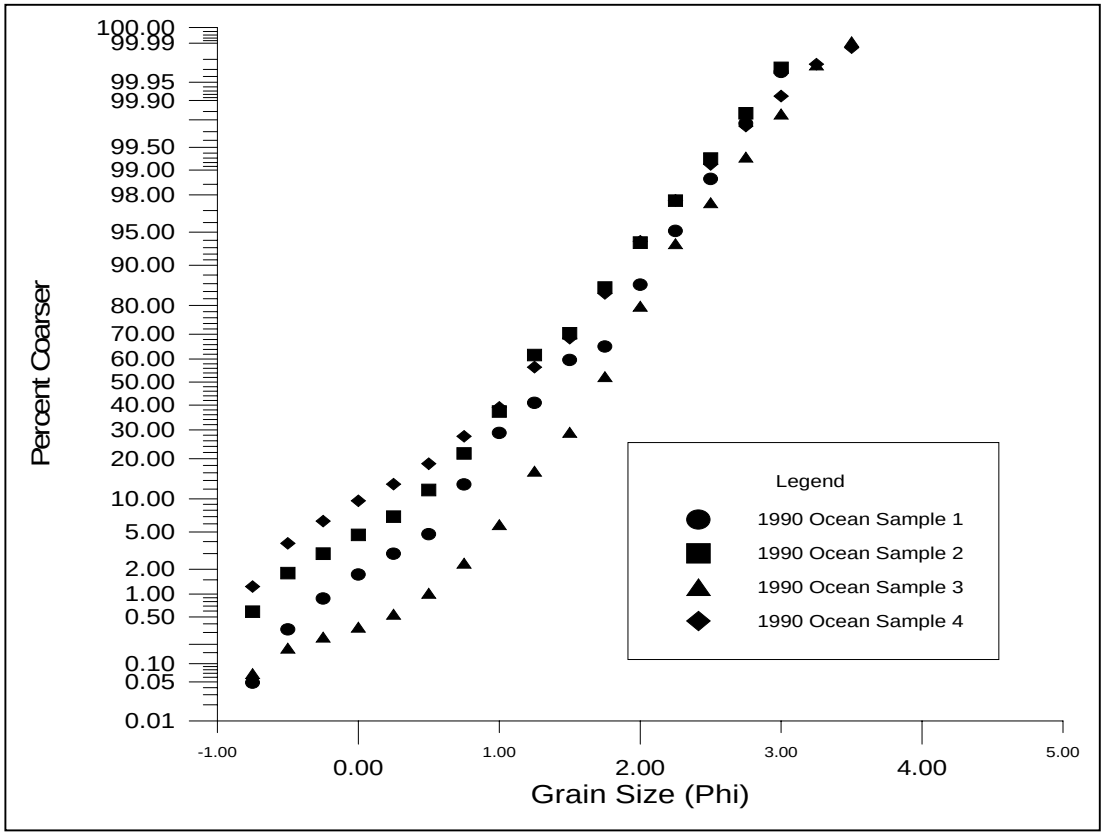
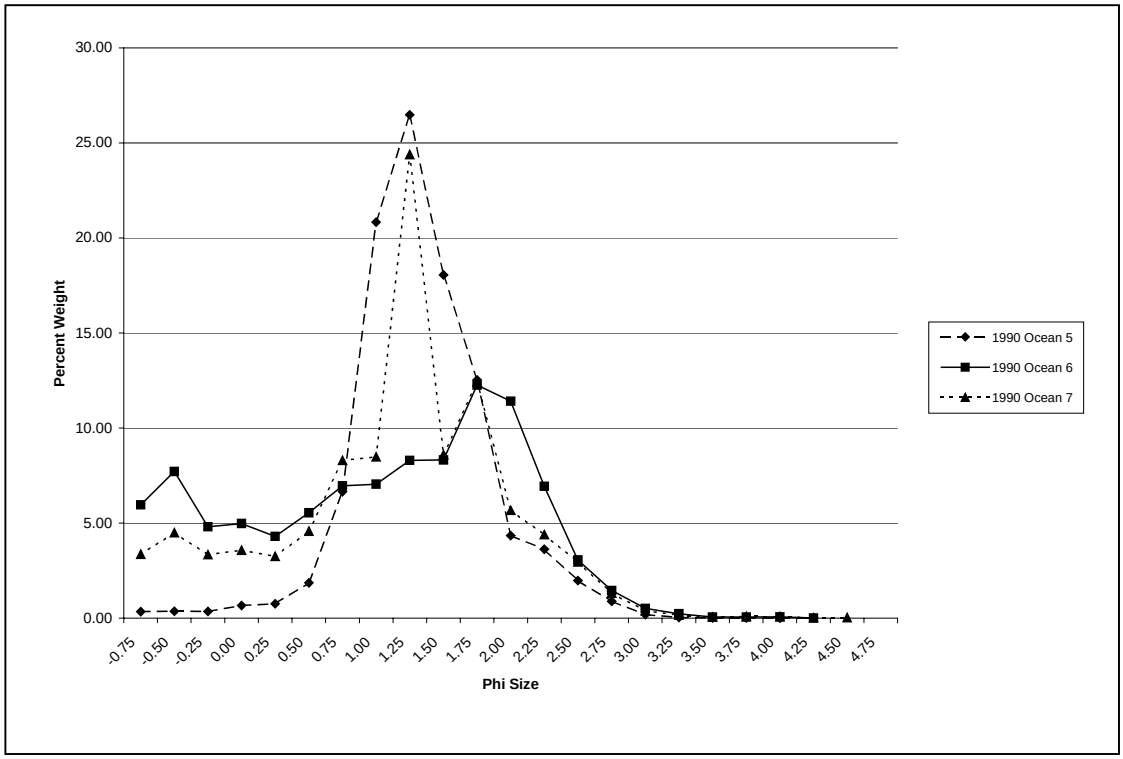
APPENDIX A

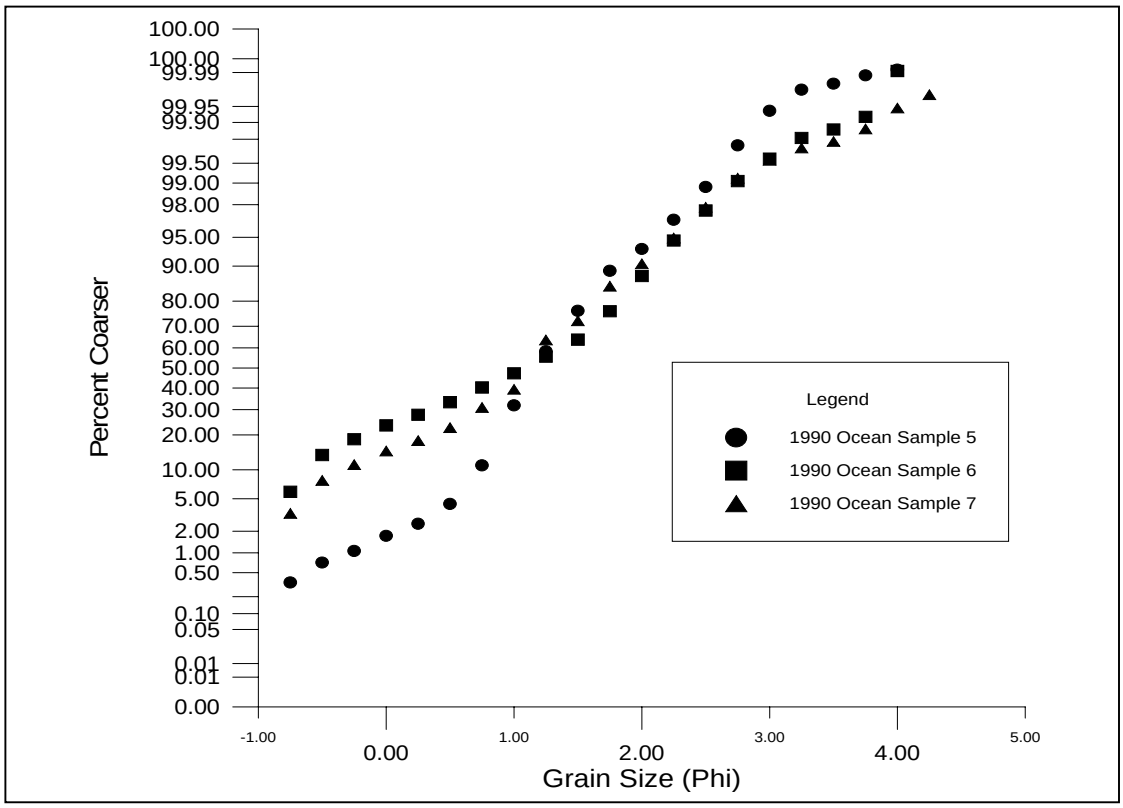
HISTOGRAMS AND LOG-PROBABILITY PLOTS FOR ALL 1990 AND 1997 SAMPLES



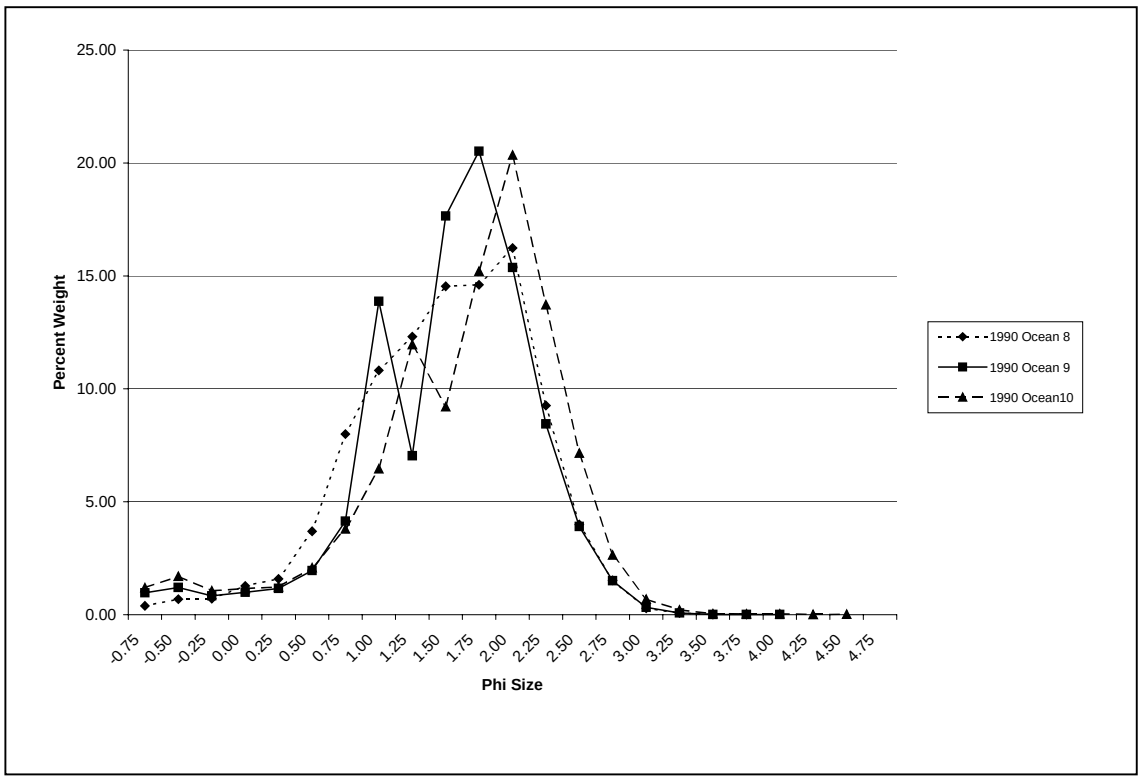


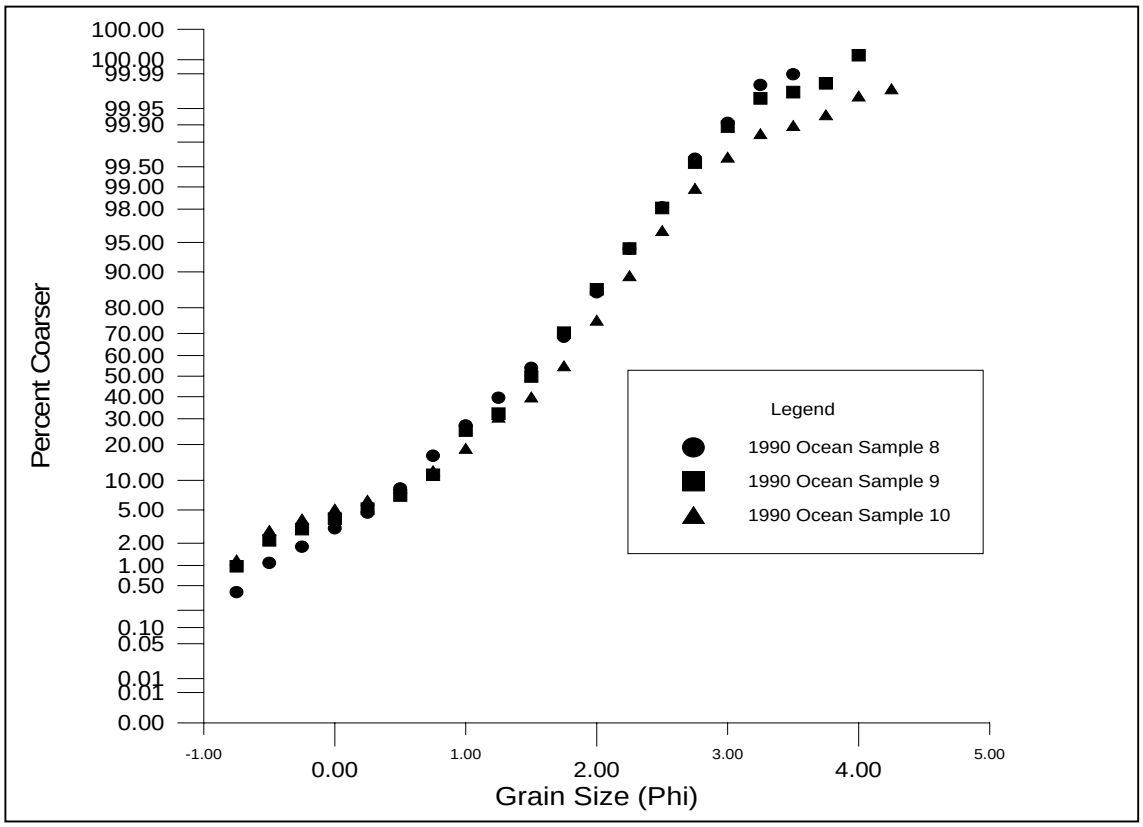
Appendix A-1: Grain size distribution and log-probability plots for 1990 ocean side samples 1 through 4.



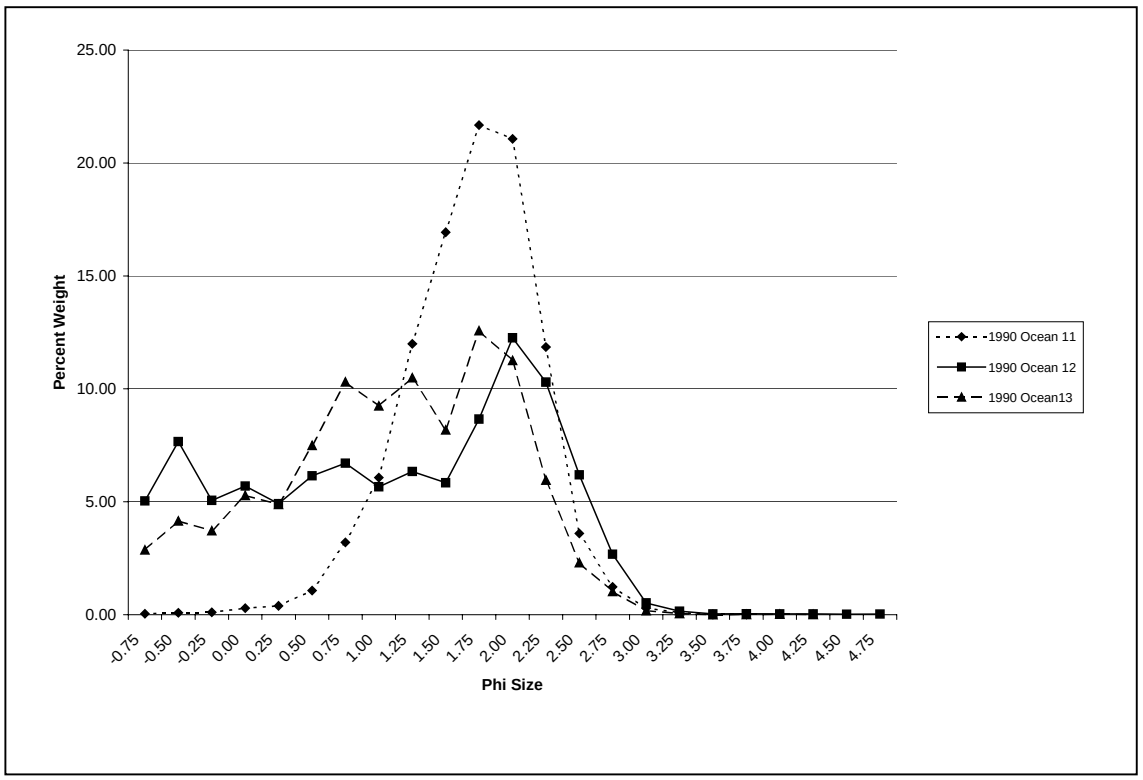


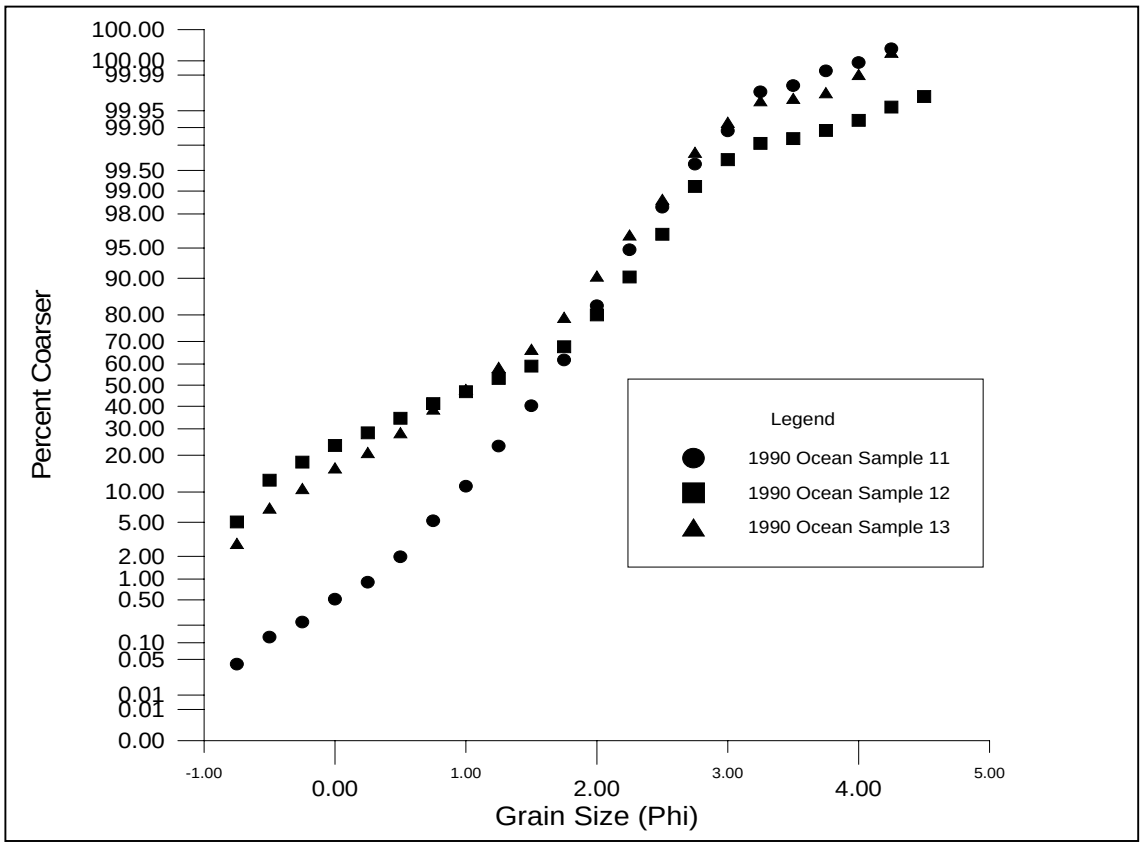
Appendix A-2: Grain size distribution and log-probability plots for 1990 ocean side samples 5 through 7



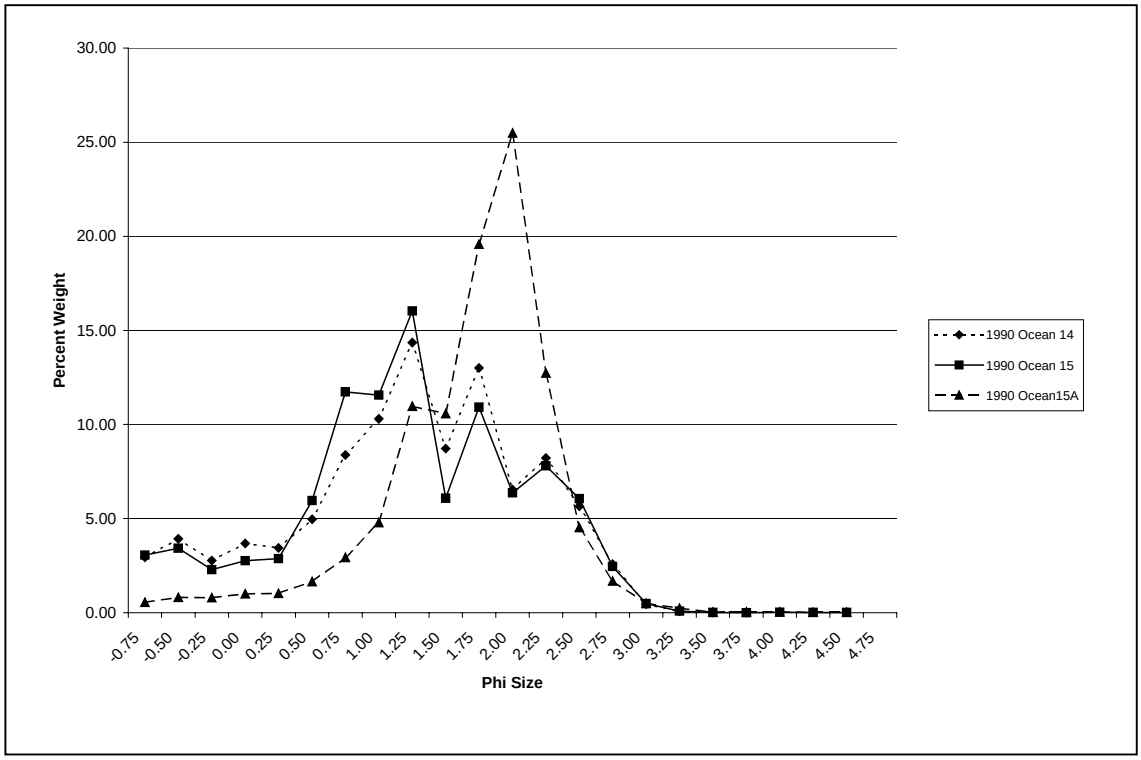


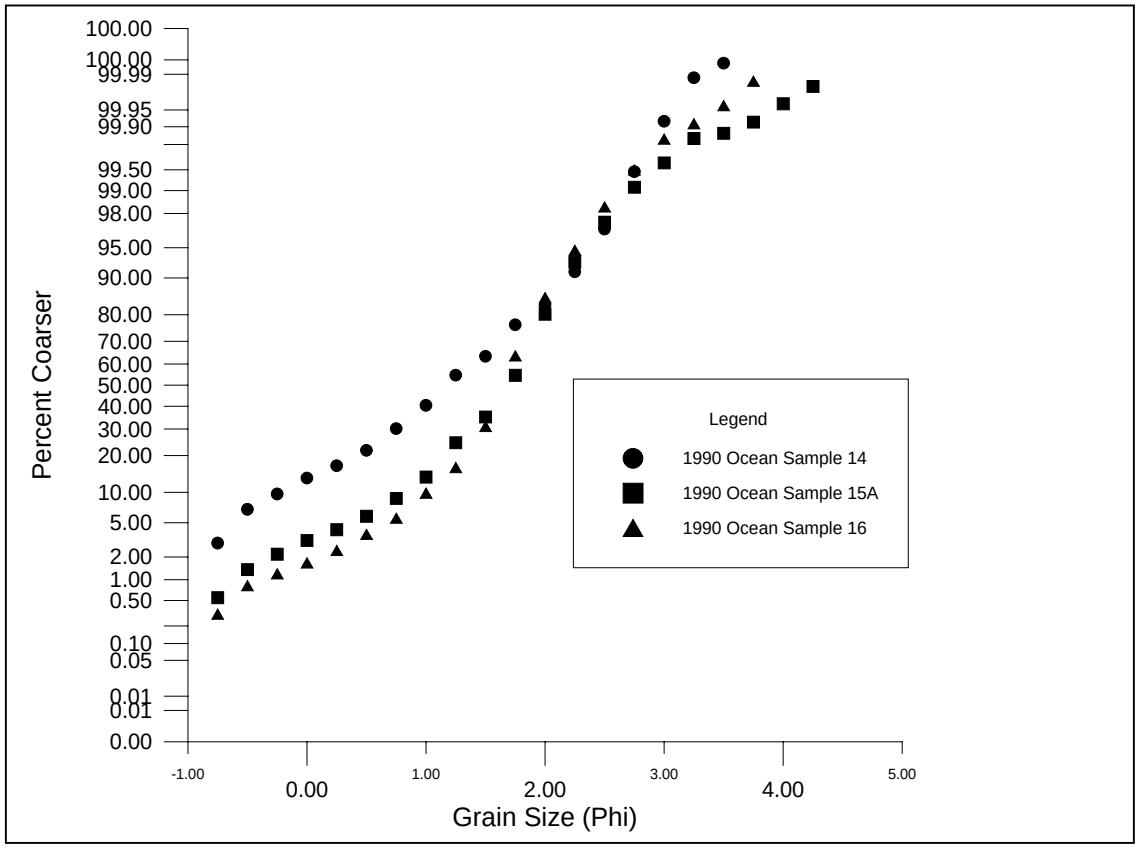
Appendix A-3: Grain size distribution and log-probability plots for 1990 ocean side samples 8 through 10



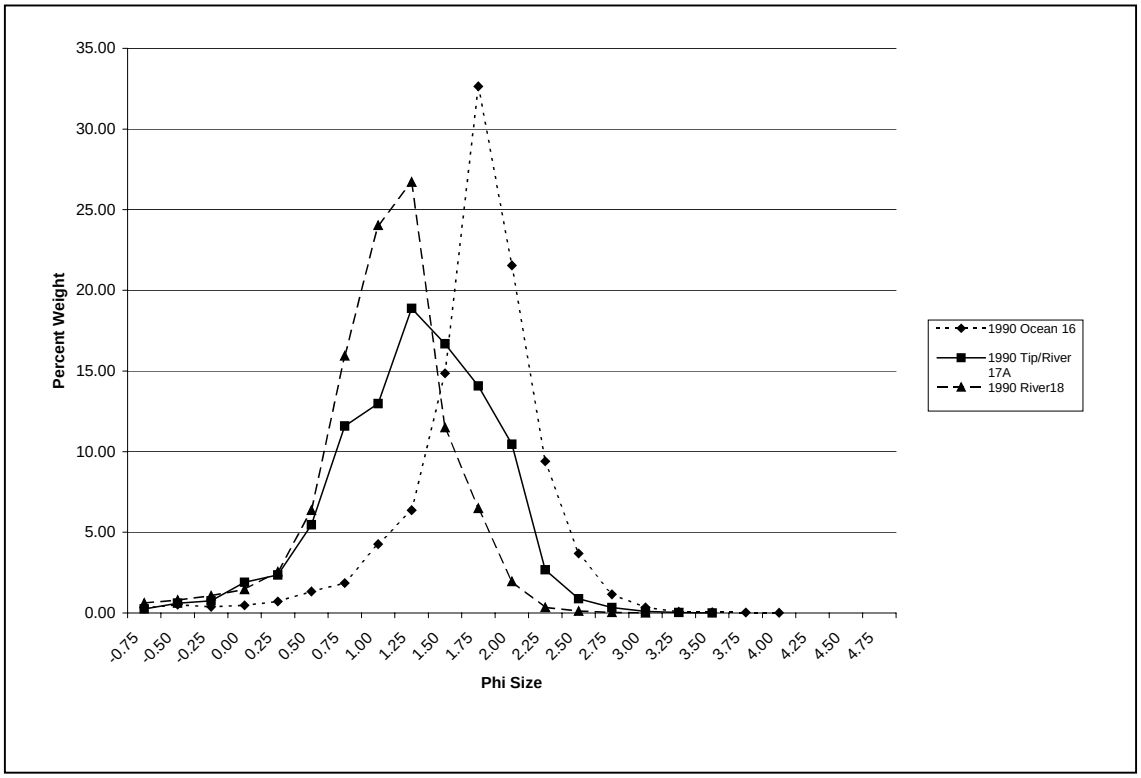


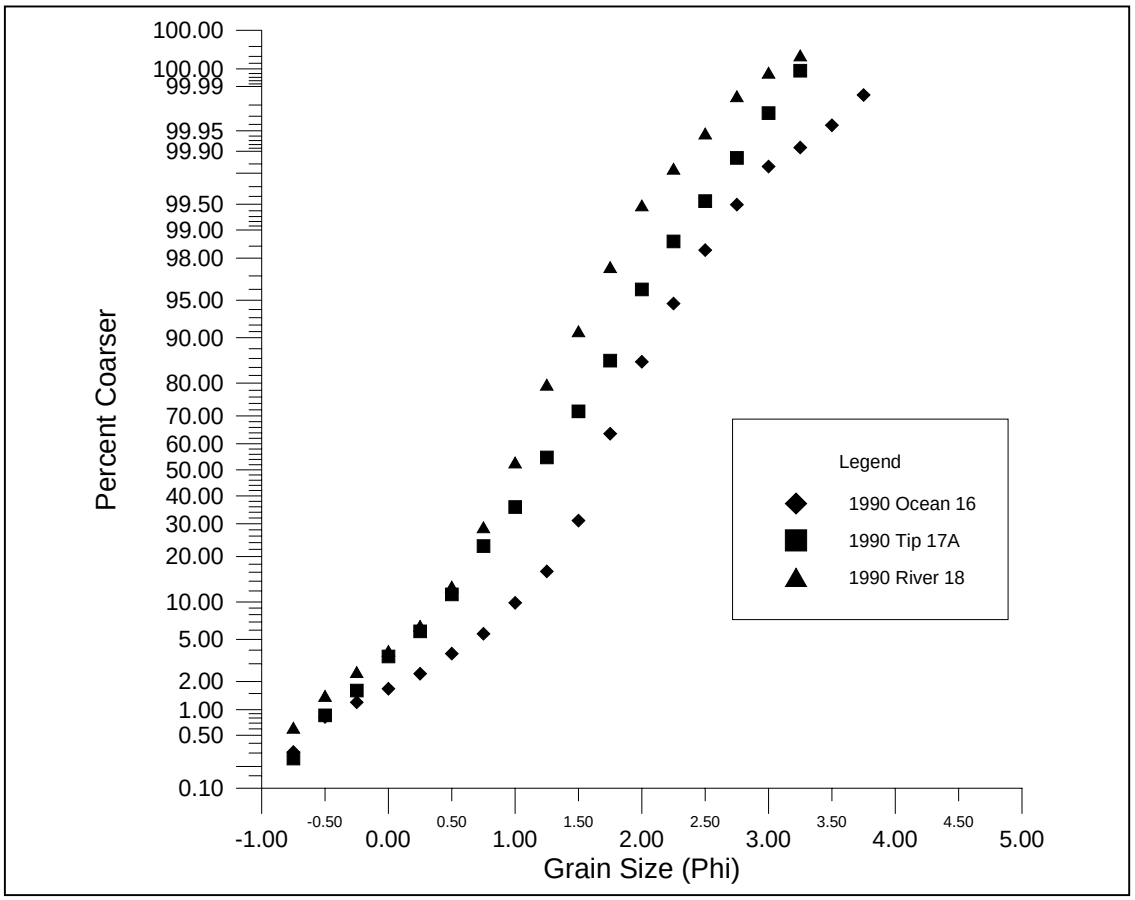
Appendix A-4: Grain size distribution and log-probability plots for 1990 ocean side samples 11 through 13.



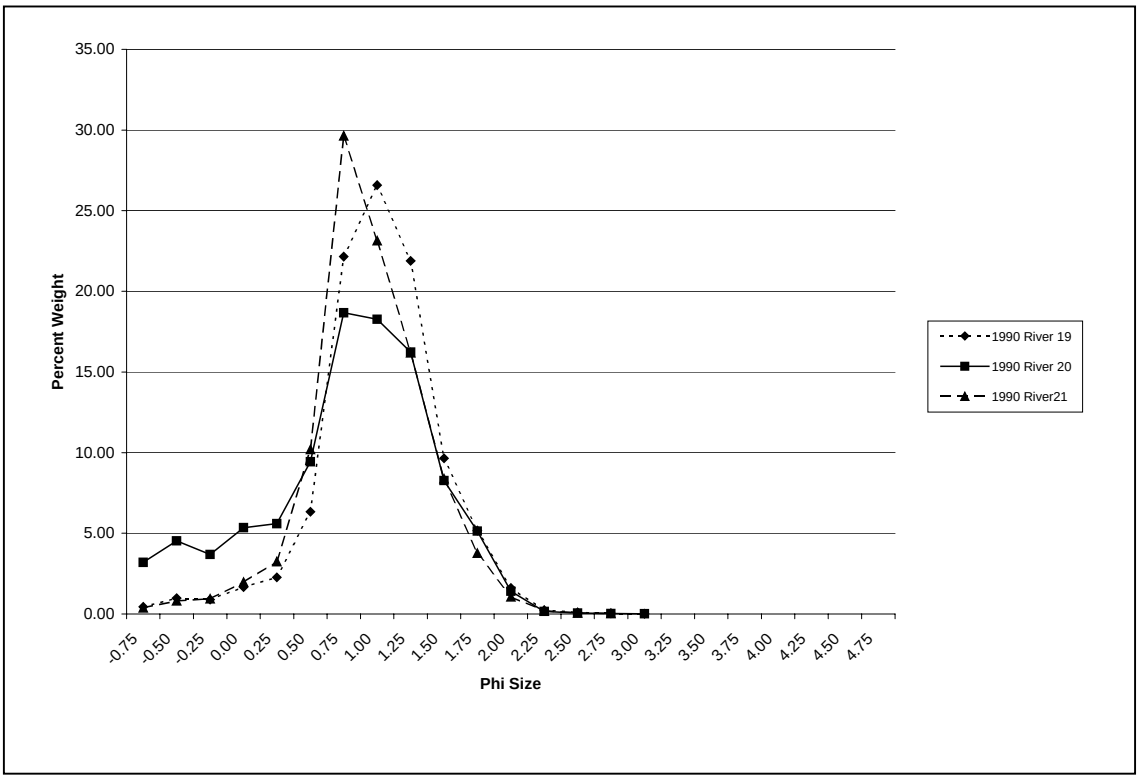


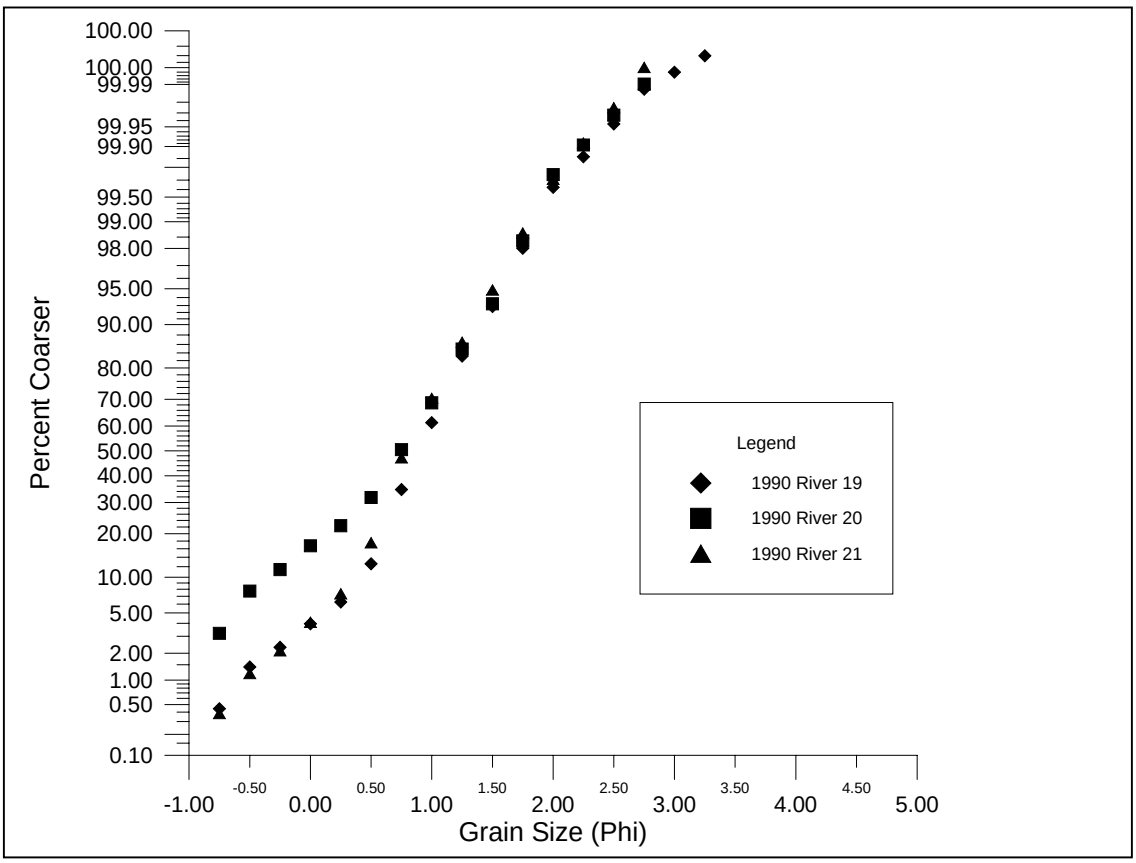
Appendix A-5: Grain size distribution and log-probability plots for 1990 ocean side samples 14 through 16.



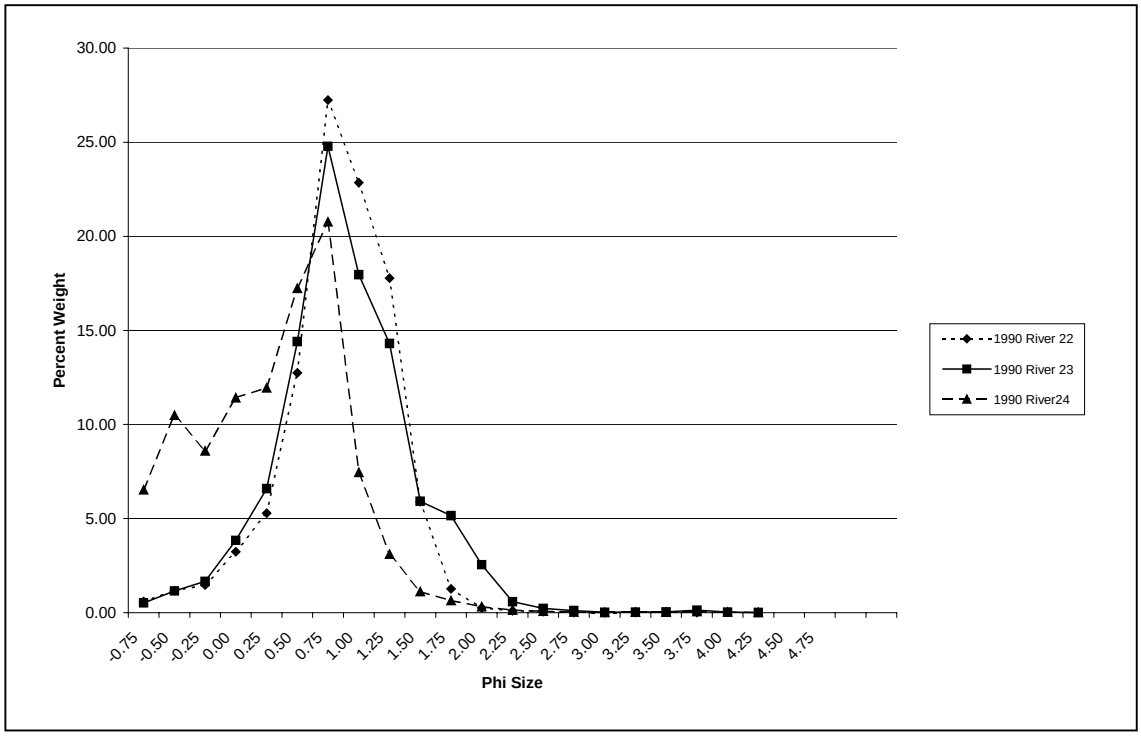


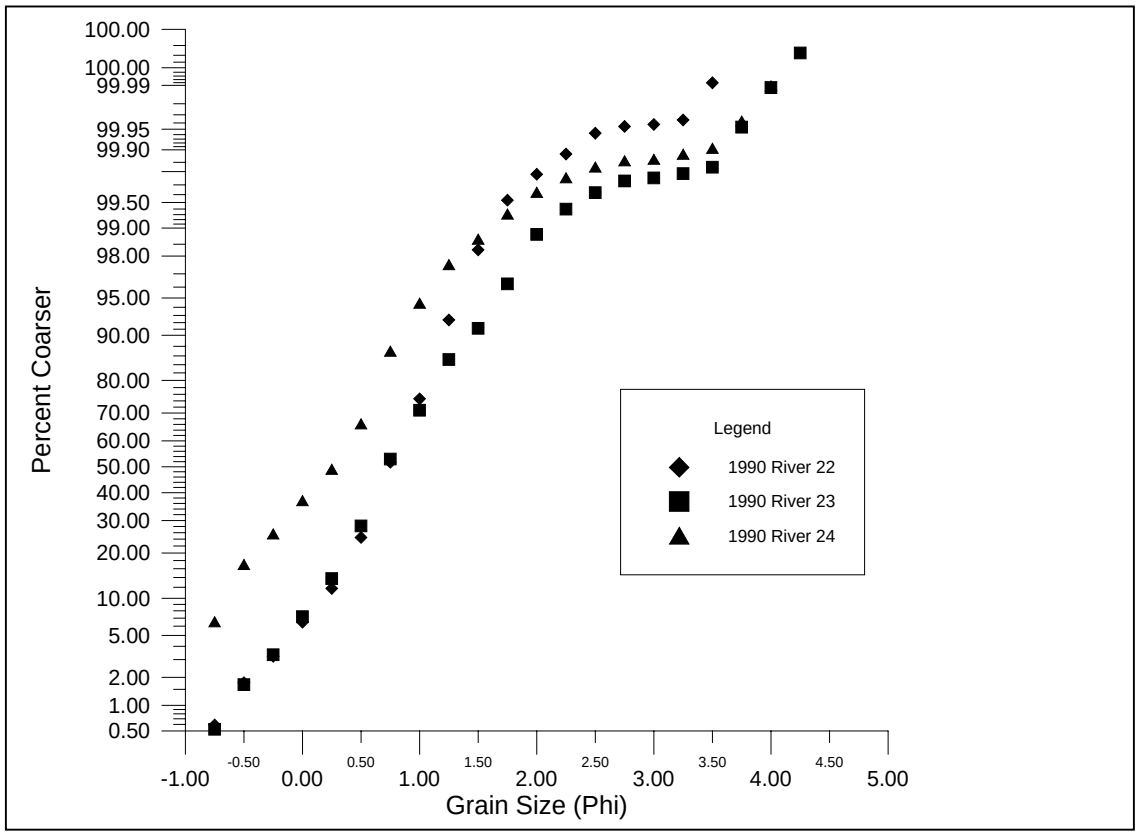
Appendix A-6: Grain size distribution and log-probability plots for 1990 tip samples 16 through 18



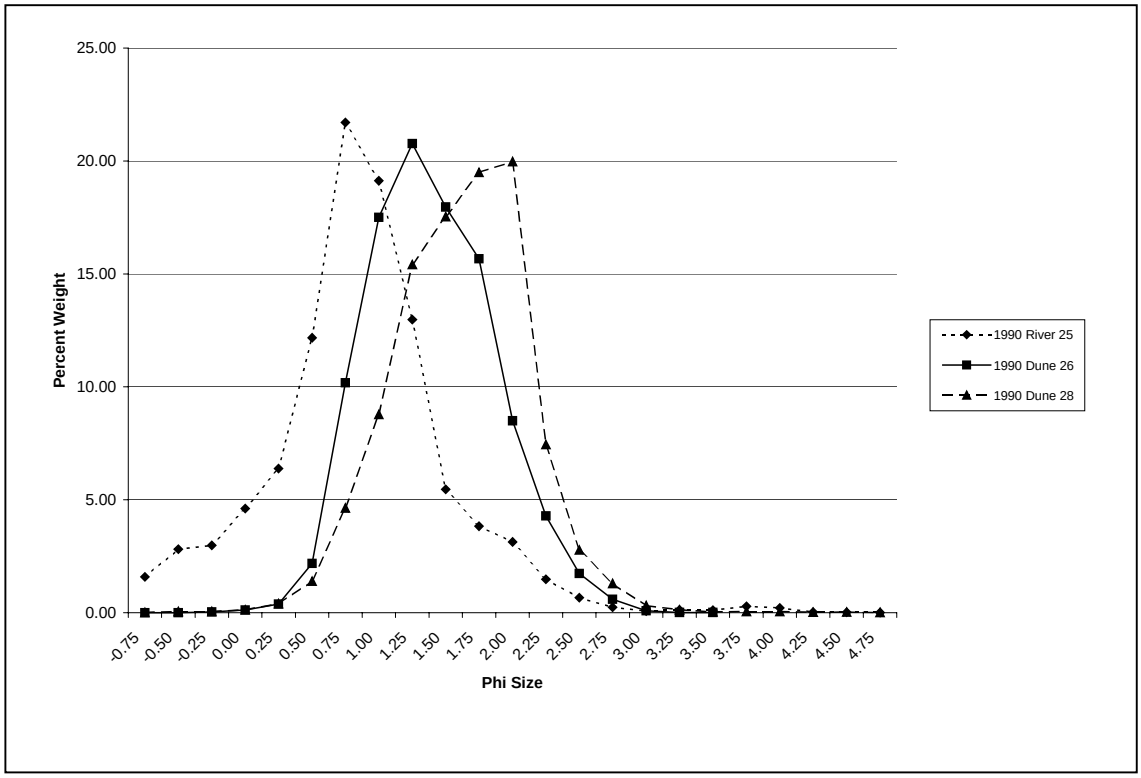


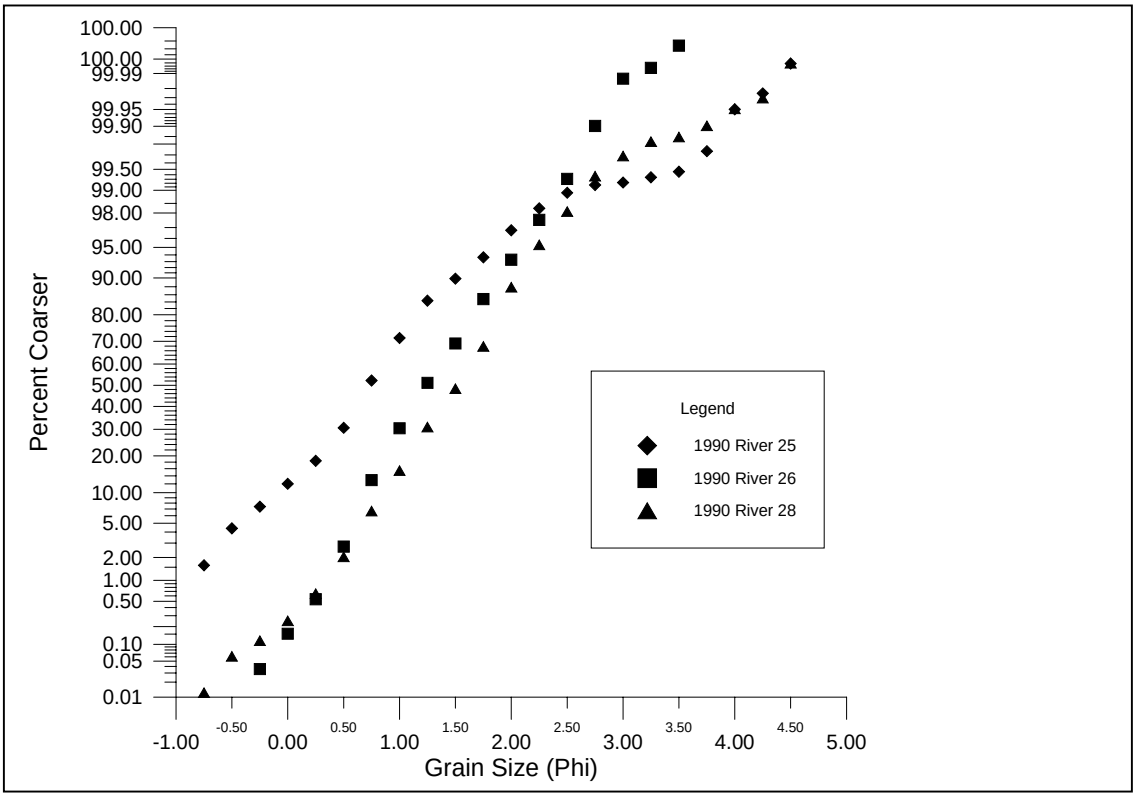
Appendix A-7: Grain size distribution and log-probability plots for 1990 river side samples 19 through 21.



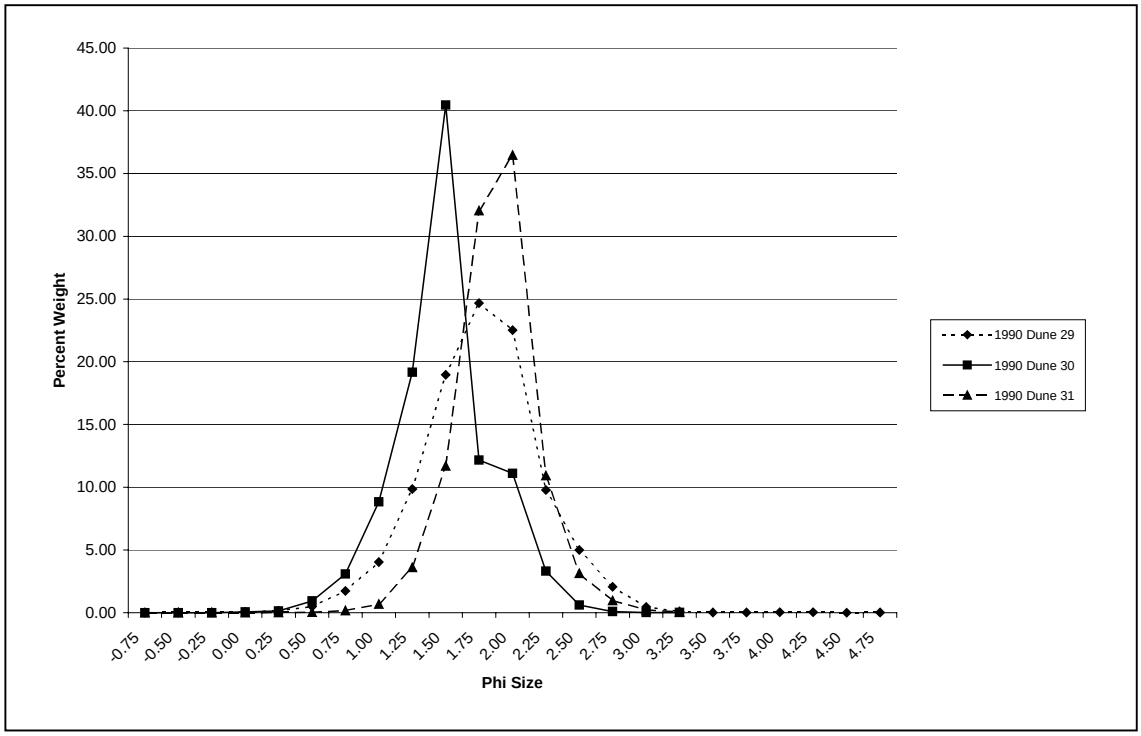


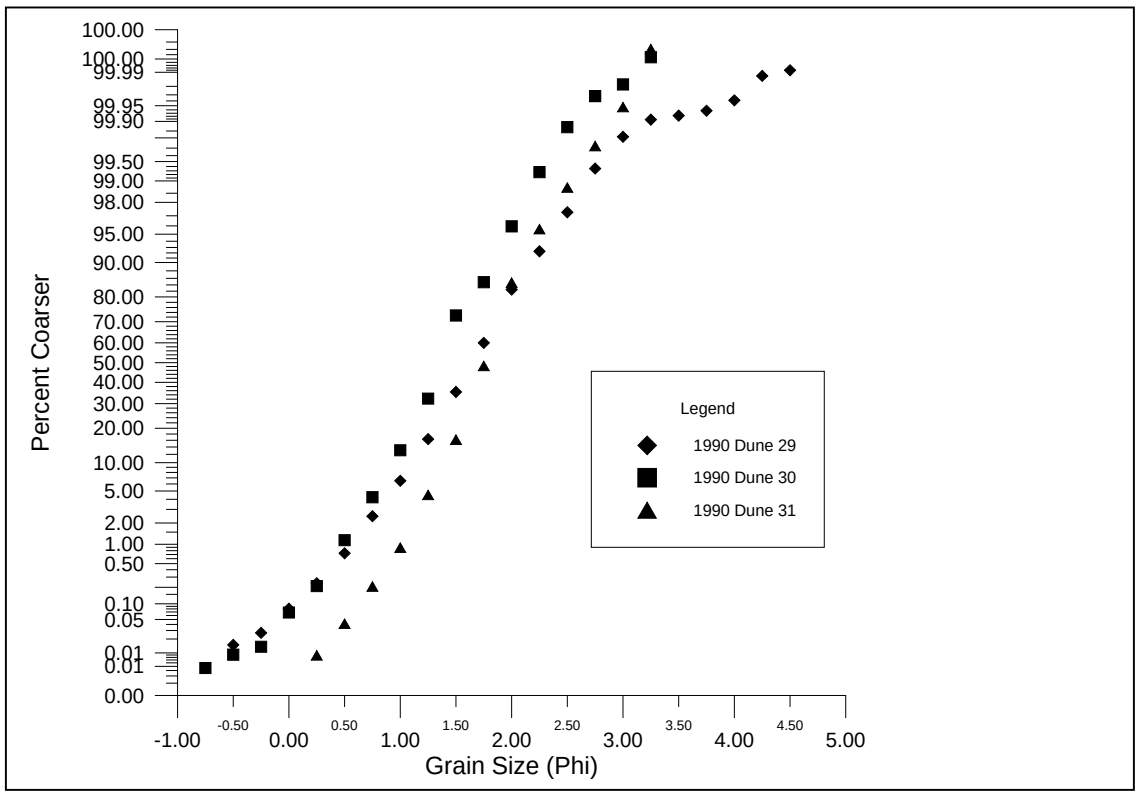
Appendix A-8: Grain size distribution and log-probability plots for 1990 river side samples 22 through 24.





Appendix A-9: Grain size distribution and log-probability plots for 1990 river side samples 25 through 28.





Appendix A-10: Grain size distribution and log-probability plots for 1990 dune samples 29 through 31.

APPENDIX B

SELECTED SAMPLE SITE PHOTOGRAPHS

Photograph B-1: View of sample profile 97-03

Photograph B-2: Two views of profile 97-04. Picture right shows mid-tide runnel.

Photograph B-3: View of sample profile 97-05, shows three distinct sedimentary zones.

Photograph B-4: View southward from sample profile 97-6 showing high tide runnel

Photograph B-5: Wide, smooth sand beach at sample profile 97-07 at tip.

Photograph B-6: View ocean ward along flood tide runnel at the tip (1997).

Photograph B-7: View of flood tide runnel from opposite direction (1997).

Photograph B-8: Gravel dominated tip beach observed 1995, compare to gently sloping sandy tip in Photograph B-6.

Photograph B-9: Soft, scalloped sand at sample profile 8, low tide area.

Photograph B-10: View shoreward from river site mega-ripple area.

Photograph B-11: View towards ripples from chalk bank area (river site).

Photograph B-12: Typical low beach or “ord” showing exposed till platform.

Photograph B-13: Rotational slips in the Holderness till cliffs.

Photograph B-14: Till balls that result from reworking of slumped cliff debris. Exposed till platform and low tide sand bar are visible.

Photograph B-15: Former gun emplacement at Kilnsea.

Photograph B-16: Erosion of a coastal road on Holderness Coast 1995.

Photograph B-17: Same coastal road in 1998