THE RECENT SEDIMENTOLOGY OF THE WEST NORFOLK COAST

Derek South

VOLUME II

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CHAPTER 6

THE TRANSITIONAL AREA

This area is dominated by a wide uniform sand flat backed by a gravel ridge which extends from Hunstanton to Wolferton, a length of seven miles. South of Wolferton a typical Wash association of sub-environments is developed (see Chapter 7 and Evans 1965), while to the north the transitional area passes into the beach-dune-marsh complex of the North Norfolk coast, already discussed. This area may thus be regarded as a transitional one between the exposed coastline and the sheltered embayment. It has two distinctive morphological zones or sub-environments; the gravel ridge on its landward side and the Arenicola sand flat known as Stubborn Sand, which stretches down to low water mark.

I The Gravel Ridge

1. Morphology and Development

The gravel ridge runs in a southerly direction from Hunstanton. It varies in width from about 120 to 400 yards (generally being wider in the south) and rises up to 20 feet above its sharp junction with the Arenicola sand flat to seaward. The seaward face of the ridge normally has a slope of 1 in 10 and there is an abrupt change at its junction with the sand flat. The sediment changes from a gravel or sandy gravel on the ridge face to a fine sand on the sand flat, although gravel may be detected below this sand. At its northern end the ridge abuts against Hunstanton boulder clay and it undoubtedly was originally banked against the Cretaceous deposits at Hunstanton before the human interference at this location. To the south, the reclaimed marshes on its landward side separate it from the Lower Cretaceous and Pleistocene sediments. At the southerly limit the ridge divides into a number of fingers, each of which is surrounded by marsh (fig. 6.1). At one locality



Fig. 6.1 Aerial view of the southern end of the gravel ridge at Wolferton. Fingers of gravel are surrounded by marsh.

within the reclaimed marshes an older gravel ridge may be detected (fig. 6.2).

Throughout most of its length the ridge has been modified for flood protection and on its landward side there is an artificial bank which runs the whole length of the ridge. At Hunstanton the building of a sea wall has either obliterated or obscured the natural features of the ridge, while to the south it has been modified by the extraction of gravel. The Heacham River, which drains the immediate hinterland, once flowed seaward through a gap in the ridge, but this has now been artificially sealed and the water now passes through a culvert.

The termination of the gravel ridge at Wolferton is comparable to that at Gibraltar Point on the Lincolnshire coast. In both areas the coarse sand and gravel, typical of the North Sea coastline, terminate rather suddenly, but whereas on the east side of the Wash, near Wolferton, they reach halfway along the shore of the embayment, on the west, at Gibraltar Point, they hardly extend into the feature. There is no abrupt change across the opposite banks of the Heacham River, on the Norfolk shore, and, although the coarse material does not extend across either the River Steeping at Gibraltar Point, or Wolferton creek, it seems unlikely that either the River Steeping or Wolferton creek is a major factor in the restriction of the longshore transport of coarse material. It is much more likely that the positions of their outfalls are dominated by the littoral drift of coarse material. The cause of this large accumulation of gravel on the east, as compared with that on the west of the Wash, is the relative abundance of supply of coarse material, while a subordinate factor may be the different aspects of the coastlines, being on the opposite sides of the Wash. Evans (1967) suggests that the abundance of gravel on the Norfolk shore may be due to the abundance of Pleistocene gravels on the North Norfolk coast compared with the small amounts of outwash gravel and sand present on the Lincolnshire coast. Also the offshore zone between Sunk Sand and Old Hunstanton has a gravelly bottom. Supply of this gravel to the backbeach and subsequent longshore transport could account for this large gravel feature.



Fig. 6.2 An early gravel ridge surrounded by marsh sediments all of this area now forming part of a reclamation.

It appears to be obvious, both from the configuration of the ridge and also its composition, that longshore transport to the south is the dominant process in its development. Sediment is trapped on the north side of groynes and its southerly transport is also impeded by the sea wall at Hunstanton so that at its southern limit erosion has to be constantly checked. Here an open framework of slag and flint blocks is used to absorb the wave energy, the full impact of the breaking wave being dissipated gradually as water passes between individual blocks. Erosion of the face of the ridge is also dominant on the southern side of Snettisham Scalp, where the ridge has been raised and faced with a framework of slag, chalk blocks and flint. Longshore transport south of the Scalp is limited but the material is not readily replaced, as most sediment from the north is at present retained at this feature (fig. 6.3). Gravel and shell are gradually building southwards so that this feature (the Scalp) is migrating in this direction to produce, eventually, a wider ridge.

At this locality the ridge is composed entirely of shells of Cerastoderma edule with some Mytilus edulis (fig. 6.4, cf. Greensmith and Tucker 1966). These shells are derived from the Stubborn Sand and from the Mytilus beds surrounding the Inner Road just to seaward. The presence of these displaced shells suggests onshore transport at this locality. Thus, although longshore transport of sediment is the most obvious factor, onshore movement of coarse material is also important in the consideration of sediment supply in this region.

The erosion and retreat of Hunstanton cliffs was probably followed by a landward retreat of the gravel ridge. The author has determined the presence of gravel under much of the sand flat at Heacham and it is suggested that this gravel may be a thin lag left capping the boulder clay (see Jackson 1910) after the transgression of the gravel ridge. It may, however, be the result of the redistribution of gravel from the ridge by storms, as this is definitely the origin of some of the gravel spreads seaward of the ridge at Snettisham (local information). Between

Fig. 6.3. Snettisham Scalp.

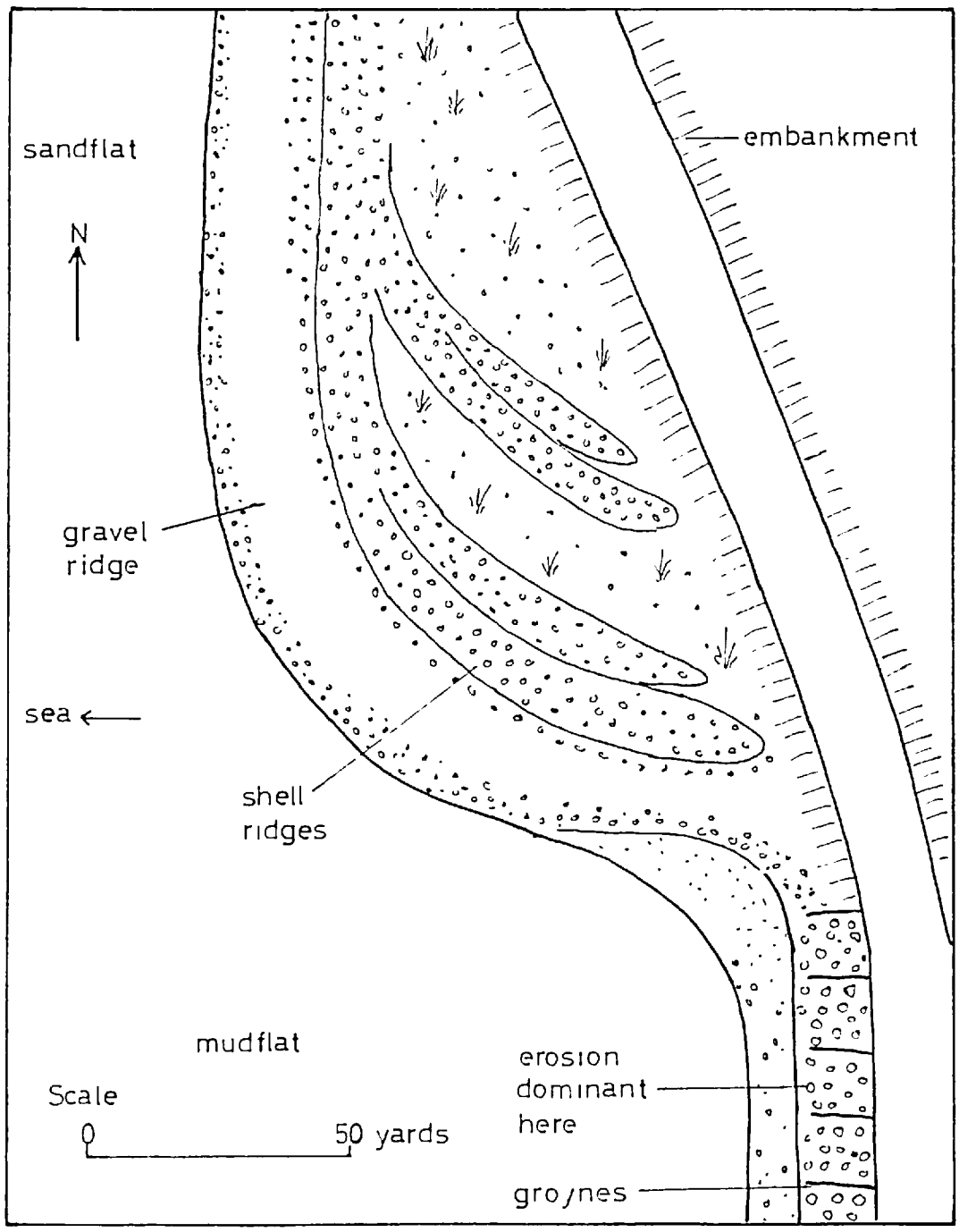




Fig. 6.4 Shell ridges composed entirely of Cerastoderma edule and Mytilus edulis at Snettisham Scalp.

Heacham and Snettisham, where the Heacham River at one time entered the sea, there are gravel lags which are the remains of two promontories on adjacent banks of the old river course.

To produce this landward retreat, accretion of material must take place on the landward slope. Accretion on the seaward face, however, causes a broadening of the ridge by seaward advance of the face. However, short term surveys, carried out during 1966 and 1967, indicate that the seaward face of the ridge is very stable and although minor modifications do take place there is obviously no marked landward movement at present (sheet 6.1). On Profiles 5 and 7 maximum scour occurred near high water mark between October 1967 and January 1968, and in the case of Profile 7 this scour was associated with deposition at the foot of the ridge.

2. The Sediments

a) Grain size

The ridge is composed of gravel or sandy gravel (Folk 1954); however, medium or fine sand may occur as a thin surface film or as lenses on the seaward face or on the crest. Other sand accumulations may be found in the lee of small high water mark swash ridges. Vegetation on the ridge crest aids in trapping wind blown sand, so in some places a thin cover of aeolian sand is formed. However, as the sandflat in this region is permanently saturated, there is very little dry sand available for wind transport, but sand deposited on the seaward face of the ridge dries out at low tide and acts as a limited source area for the aeolian sediment. The saturated nature of the sand flats accounts for the lack of dunes south of Hunstanton, this being in very marked contrast to the barrier development north of Hunstanton, where dunes form an important element on the coast.

A characteristic feature of the seaward face of the ridge is the zonation already described for the beach faces to the north of Hunstanton (cf. Bluck 1967). The sequence found has a coarse gravel base which may be seen occasionally or may be covered by fine sand or silt. This coarse gravel is found beneath

the sand flat in many places. Superimposed on the gravel there is commonly a thin strip of well sorted fine gravel and here there is also an abundance of Cerastoderma edule, this being due to the ease with which these shells are rolled down the beach by the backwash. Above the gravel the sediment is often sandy, although this sand is generally only a thin surface deposit, and passes into a sandy gravel below the surface. Above this zone gravel again becomes predominant and beach cusps may develop, the gravel being sorted into the horns, and the sand into the intervening bays. Gravel is concentrated in the uppermost zone of the seaward face. As with similar developments elsewhere, the lower zones are not so apparent when there is no abrupt change in slope at the foot of the seaward face.

Size analysis of this gravel has not been carried out, although the sandy sediments have been investigated in the northern part of the area, in the region of the sea wall and on the ridge at Snettisham Scalp (table 6.1). These sediments are medium and fine sands with sorting values of 0.35 to 0.40 phi (well sorted) and negative skewness of -0.20 to -0.29. These parameters may be very variable due to the varying abundance of coarser material.

b) Small scale sedimentary structures

Large proportions of limonite fragments are found in the sand fractions of the sediments and very often these are concentrated into laminae on the seaward face, enabling the structures to be readily observed. The smooth beach face is thus shown to possess thin laminae parallel to the surface and dipping seawards. Ripple marks are absent in this zone but beach cusps develop as they do on the backbeach north of Hunstanton. Sand domes and air holes (Emery 1945) are common and rill marks occur where, during low tide, fresh water passes through the ridge and flows onto the sand flat.

c) The sediment composition

The gravel is composed dominantly of flint, with abundant chalk, red chalk, carstone and shell debris. Erratics are common, the main types being similar to those found north

Table 6.1 Grain Size Characteristics of the Sandy Sediments of Gravel Ridge Edge

Sample Number	Mean Diameter	Sorting	Skewness	% Gravel	% Silt & Clay	Locality
18	2.11	0.350	-0.278			outer edge of ridge, Hunstanton
19	1.94	0.419	-0.209	0.090		outer edge of ridge, Hunstanton
22	1.88	0.687	-0.198	4.465		outer edge of ridge, Heacham
25	2.28	0.779	+0.315			)edge of gravel
26	2.07	0.710	+0.146	1.780	0.27	)ridge at junction)with mudflat,)Snettisham

of Hunstanton. The sands investigated near Hunstanton (table 6.2) contain a high proportion of Carstone derived fragments and this decreases in samples to the south. A sample of the thin dune sand between Heacham and Snettisham (sample 36) contained 20% Carstone fragments, this indicating that the dune sand is derived directly from the face of the gravel ridge, which dries out at low tide, rather than from the wet sand flat, which has a much lower percentage of this component.

d) The displaced shell fauna

Although studies of the region over the last few years have revealed that there is a general decrease in the variety of shelly organisms in the sediments of the sheltered Wash embayment as compared with the sediments of the exposed North Norfolk and Lincolnshire coasts (Evans 1967) no quantitative studies of these differences have ever been attempted. The results presented here are the first study of this kind on this coastline.

It is of interest to note here that a similar decrease in variety of shelly organisms has been recorded by van Straaten (1951) in the Wadden Sea sediments when they are compared with the open North Sea coast sediments. The distribution of dead shells on sand flats in the Solway Firth has been discussed by Wilson (1967) but the proportion of displaced forms could not be determined as many of the species also live on the flats. However, van Straaten (1956) has shown that the composition of shell beds in tidal channels gives a reliable picture of the average mollusc fauna of the surrounding area.

A comparison of the dead shell fauna of the backbeach at Holme and the gravel ridge south of Hunstanton shows that there is a distinct change in fauna along the shore. South of Hunstanton, species noted for their abundance on the exposed North Norfolk coast become scarce. These include Spisula solida, Petricola pholadiformis, Zirfaea crispata, Mya sp., Ensis sp., Venerupis pullastra and Nucula sp. (Mya sp. includes Mya arenaria and Mya truncata as these species could not be distinguished in broken fragments. Although the abundance of shell fragments

Table 6.2 Composition of the Sands from the Edge of the Gravel Ridge

Sample No.	Terrigenous	Limonite oolite	Rock Fragment	Mollusc/ Barnacle	Foram	Coal	Bryozoa
18	76.0	20.5		2.5	0.5	0.5	
19	78.0	16.7		5.0	0.3		
22	84.6	8.7		4.0			
25	88.4	2.3		6.0	2.3	1.0	
26	92.0	3.3		3.7	0.3	0.3	0.3
Range	76.0 - 92.0	2.3 - 20.5		2.5 - 6.0	0.0 - 2.3	0.0 - 1.0	0.0 - 0.3
Dune sand 36	77.5	20.5	1.0	1.0			

decreases southwards, Mya arenaria is common in the intertidal flats of the Wash.) The number of species decreases, although the number of individuals in the ridge may remain high. A detailed examination of certain samples was carried out to investigate the main changes which occur.

The sample sites were chosen randomly at positions near profile lines and at various intermediate sites (fig. 6.5). Where a distinct gravel beach face was present the sample was taken approximately half way between the gravel/sand flat boundary and high water mark. At each site a twenty inch square was marked out and the sediment within this was excavated and collected to a depth of approximately $\frac{3}{4}$ inch. This was then transported to the laboratory where the sample was dried before the sand and gravel fractions were separated and the fauna in the gravel determined (table 6.3).

Only some shell fragments were counted, however, and certain criteria were used to determine which fragments should be discarded. Criteria used during counting of the fragments are listed below:-

i) Bivalvia - fragments must possess at least part of the hinge line, or in the case of Mytilus and Modiolus must include part of the umbo.

ii) Gastropoda - fragments must possess at least part of the columella.

iii) Echinodermata - all plates, groups of plates and spines counted.

iv) Annelida - all tubes and fragments of tubes counted.

v) Cirripedia - all plates counted.

The counts of fragments of each species or group in the sample were used to calculate the total number of fragments in the gravel grade of each sample. From these the proportion of each species was calculated as a percentage of the total number of fragments. For each group the percentage variation along

Fig. 6.5. Locality of samples analysed for displaced fauna.

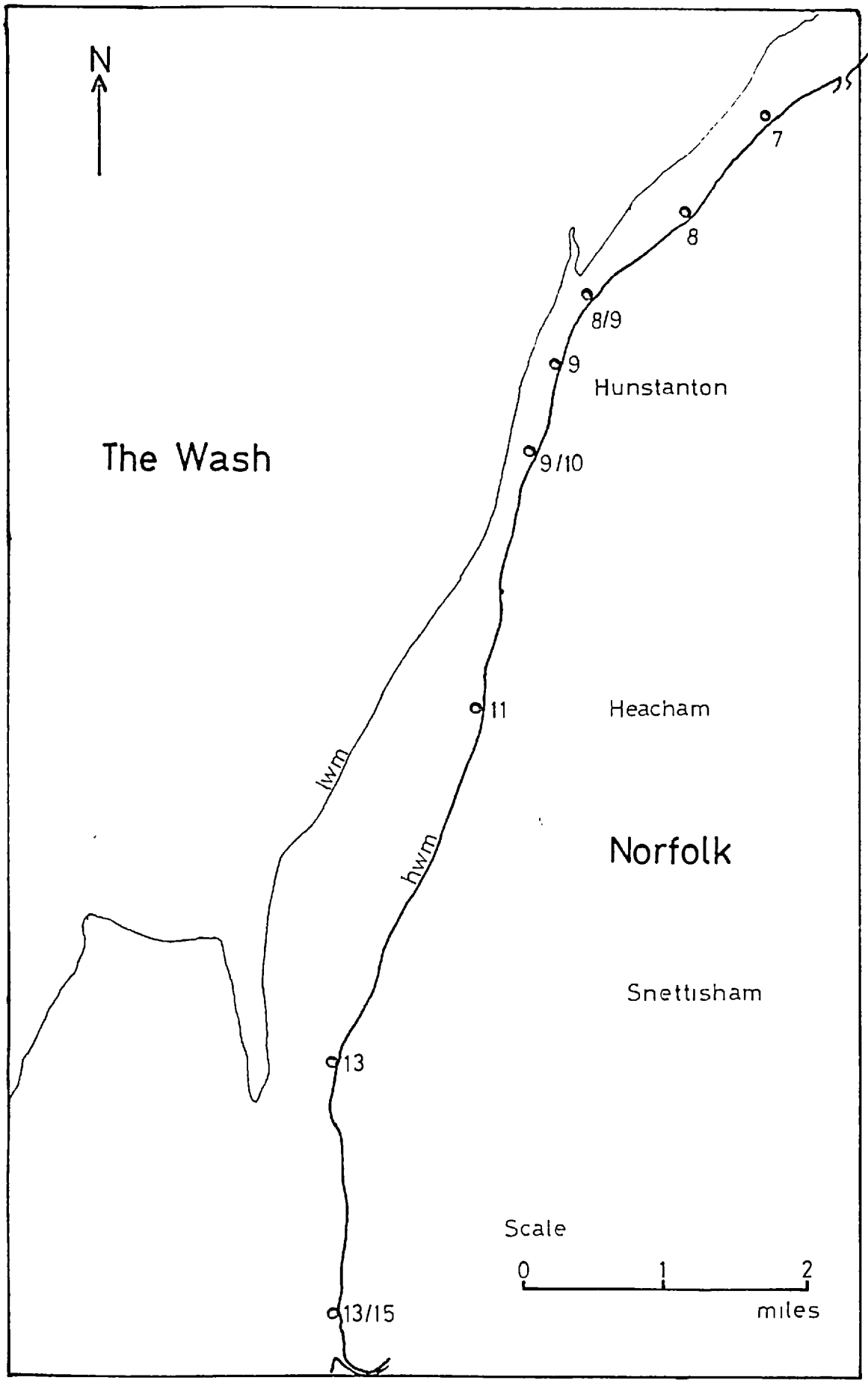


Table 6.3 Results of Counts of Displaced Fauna

Profile		2		3		3/4		4		4/5		6		8		8/9	
		No. of frags.	%	No. of frags.	%	No. of frags.	%	No. of frags.	%	No. of frags.	%	No. of frags.	%	No. of frags.	%	No. of frags.	%
Bivalvia																	
Cardiacea	Cerastoderma edule	11	2.1	9	2.9	22	9.8	71	6.9	47	5.3	27	10.0	110	53.1	130	55.7
Mactracea	Mactra corallina					2	.9										
	Spisula solida	5	.9	8	2.5	3	1.3	11	1.1	3	.3						
Myacea	Mya arenaria / Mya truncata	3	.6	2	.6	4	1.8	6	.6	2	.2	2	.7				
Mytilacea	Mytilus edulis	81	15.2	42	13.3	54	24.1	246	23.7	151	17.0	44	16.4	20	9.7	28	12.0
	Modiolus modiolus	2	.4					1	.1	7	.8						
Nuculacea	Nucula tenuis	107	20.1	7	2.2	7	3.1	3	.3	1	.1						
Ostracea	Ostrea varia	1	.2	3	.9	1	.4	3	.3	1	.1	1	.4				
Pectinacea	Chlamys varians	3	.6	1	.3	1	.4	1	.1	1	.1						
Solenacea	Ensis ensis / Ensis siliqua	4	.8			13	5.8	23	2.2	17	1.9	2	.7	1	.5		
Tellinacea	Macoma balthica	2	.4	2	.6	5	2.2	8	.8	7	.8	2	.7	5	2.4	6	2.6
	Scrobicularia plana	2	.4	7	2.2	8	3.6	3	.3	3	.3	2	.7	1	.5	1	.4
Veneracea	Venerupis pullastra	8	1.5	6	1.9	6	2.7	19	1.8	28	3.2	3	1.1				
Pholadacea	Petricola pholadiformis			1	.3	1	.4	4	.4	2	.2						
	Zirfaea crispata	1	.2	5	1.6			1	.1			1	.4				

Table 6.3 (continued)

Profile	2		3		3/4		4		4/5		6		8		8/9	
	No. of frags.	%	No. of frags.	%	No. of frags.	%	No. of frags.	%	No. of frags.	%	No. of frags.	%	No, of frags.	%	No. of frags.	%
Gastropoda																
Hydrobia sp.			1	.3			2	.2							4	1.7
Littorina littorea			4	1.3	2	.9	24	2.3	21	2.4	28	10.4	29	14.0	34	14.6
Gibbula cineraria	2	.4	1	.3	4	1.8	15	1.4	9	1.0	4	1.5				
Buccinum undatum	1	.2	1	.3	2	.9	7	.7	4	.5	11	4.1				
Nucella lapillus							6	.6								
Littorina littoralis							2	.2								
Echinodermata																
Psammechinus miliaris	12	2.3	5	1.6	2	.9	17	1.6	25	2.8	2	.7				
Echinocardium cordatum			2	.6	1	.4	3	.3	2	.2						
Annelida																
Lanice conchilega							8	.8			2	.7	2	1.0		
Pomatoceros triqueter	9	1.7	2	.6	2	.9	36	3.5	10	1.1	1	.4				
Cirripedia	230	43.2	206	65.4	51	22.8	467	45.1	498	56.1	118	43.9	14	6.8	19	8.2
Unidentified pholads	7	1.3			14	6.3	6	.6	8	.9						
Crab chela							3	.3								
Derived belemnites							1	.1	1	.1						
Terebratula (derived)					2	.9										
Unidentified	42	7.9			17	7.6	39	3.8	40	4.5	19	7.1	25	12.1	11	4.7
Total no. of fragments	533		315		224		1036		888		269		207		233	
Weight of gravel (gms)	1710		684		6030		6120		6480		8370		6750		2205	

the coastline is shown graphically (fig. 6.6). Some variation in fauna must be due to differences in the grain size of the gravel samples collected, but this is nowhere thought to negate the general conclusions obtained.

Certain species, Cerastoderma edule, Mytilus edulis, Cirripedia, Nucula sp., and Littorina littoralis, are present in large percentages. The general results showed:-

i) Cerastoderma edule

This increases from Holme towa ds Hunstanton cliffs, where there is a small peak of 10%. From the southern end of Hunstanton there is a large increase towards Snettisham and the maximum value of 56% occurs in the sediment at the southern end of the ridge.

ii) Mytilus edulis

This attains a maximum of nearly 25% below Hunstanton cliffs and although it decreases in both directions the percentage does not fall below 10%.

iii) Cirripedia

A maximum value of 65% at Old Hunstanton drops off rapidly to less than 10% at Snettisham.

iv) Nucula sp.

This rapidly decreases from 20% at Holme to 0.1% at the southern end of Hunstanton. It does not appear in samples south of this point.

v) Littorina littorea

This is the only really abundant gastropod in the gravel fauna. It increases from 0% at Holme to nearly 15% at the southern end of the gravel ridge. There is a rapid increase between Hunstanton and Heacham.

vi) Other species

Other species, such as Spisula solida, Mya arenaria, Mya truncata, Ensis sp., Venerupis pullastra and Psammechinus miliaris show a decrease towards the south. These species are derived largely from the offshore zone.

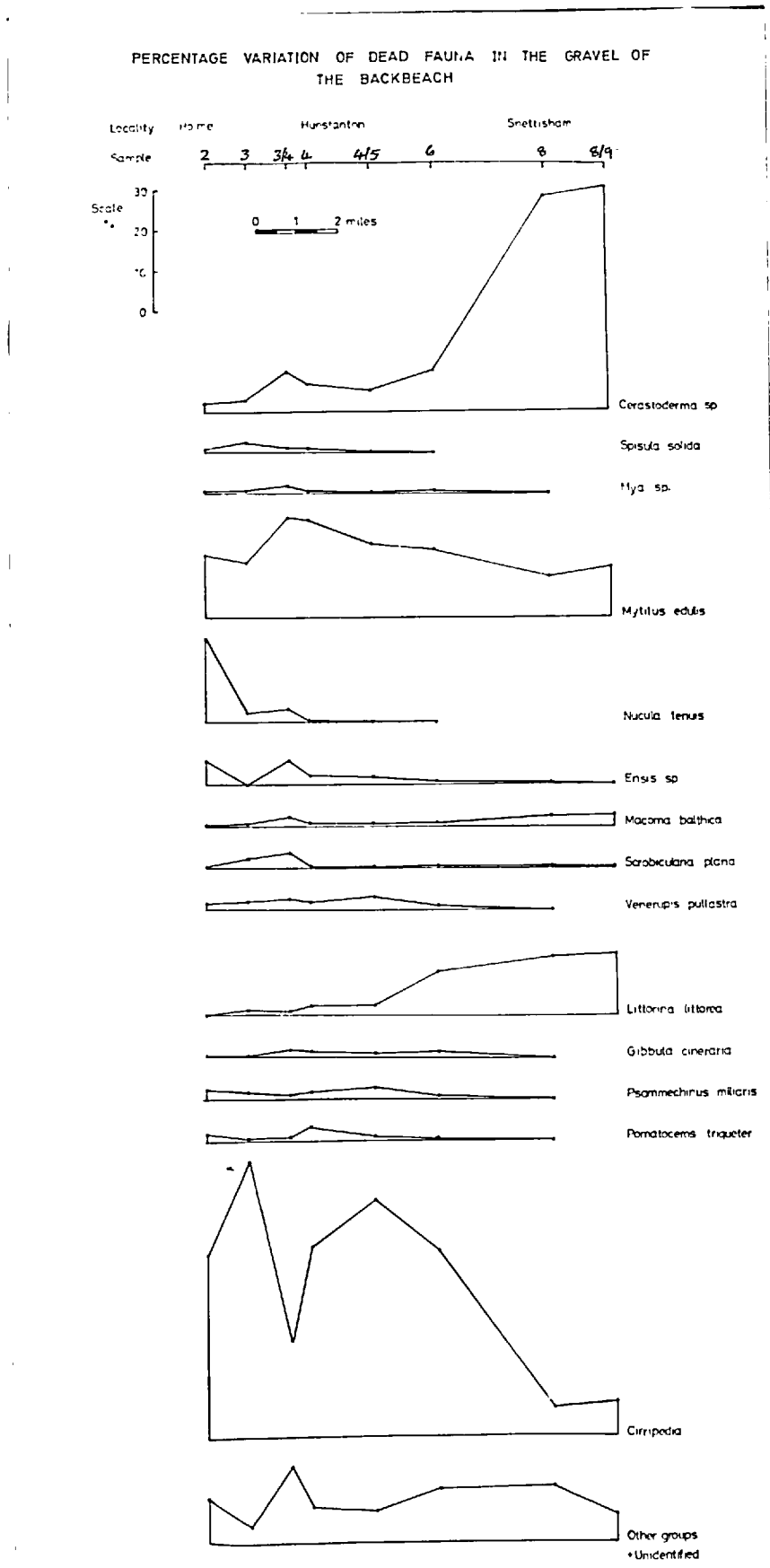

PERCENTAGE VARIATION OF DEAD FAUNA IN THE GRAVEL OF THE BACKBEACH
Locality
Sample
Hunstanton
Snettisham
2
3
3/4
4
4/5
6
8
8/9
Scale %
30
20
10
0
0 1 2 miles
Cerastoderma sp
Spisula solida
Mya sp.
Mytilus edulis
Nucula tenuis
Ensis sp
Macoma balthica
Scrobicularia plana
Venerupis pullastra
Littorina littorea
Gibbula cineraria
Psammechinus miliaris
Pomatoceros triqueter
Cirripedia
Other groups
+Unidentified

Fig. 6.6

This variation in displaced fauna must reflect to some extent the source variation. In this case, the source is the sand flat or forebeach and the offshore zone. Other factors which must affect the distribution of displaced fauna are:

i) the variable rate of onshore movement of various gravel sized shell;

ii) the variable rate of longshore transport of various gravel sized shell along the backbeach;

iii) the rate of destruction of the various groups and species. Fragile components, such as Macoma balthica and echinoids, will be relatively easily broken down, whereas massive shells such as Buccinum undatum will be abraded but not easily broken;

iv) the variation in grain size of the gravel sampled, e.g. small plates of Elminius sp., a cirripedian, are concentrated in very coarse sand and fine gravel of -1.0 to -2.0 phi, whereas fragments of Cerastoderma edule are generally concentrated in coarser grades.

North of Hunstanton, the offshore zone must supply a considerable amount of living shells as many forms found as empty tests on the beach are never seen living within the beach sediments. Occasional live specimens are washed ashore. Separate valves of Nucula sp. are abundant in offshore gravels at Holme, Hunstanton and in the main shipping channel north west of Ferrier Sand. The only intertidal occurrences are, however, north of Hunstanton, this indicating that storms are able to transport the offshore fauna across the relatively narrow exposed beach zone north of Hunstanton, whereas inside the Wash, this material is not transported across the sand flats and on to the gravel ridge. However, the abundance of Cerastoderma edule and Mytilus edulis on the ridge at Snettisham indicates that gravel sized shell on the lower parts of the sand flat are readily transported landwards. The combination of a deep channel with little wave action and strong longshore tidal currents must prevent

the onshore transport of offshore fauna. To the north of Hunstanton, the channel is shallower and tidal currents weaker.

Thus in the Wash the displaced fauna reflects in general the shelly fauna living in the sand flat, whereas north of Hunstanton the fauna is a mixture of forebeach and offshore fauna. In the latter case, Mytilus edulis living on the forebeach dominates the derived fauna of the backbeach.

The absolute abundance of fauna has also been calculated (fig. 6.7 and table 6.4) and the results are shown as the number of fragments in 1,000 grams of gravel. Thus this does not include the sand fraction.

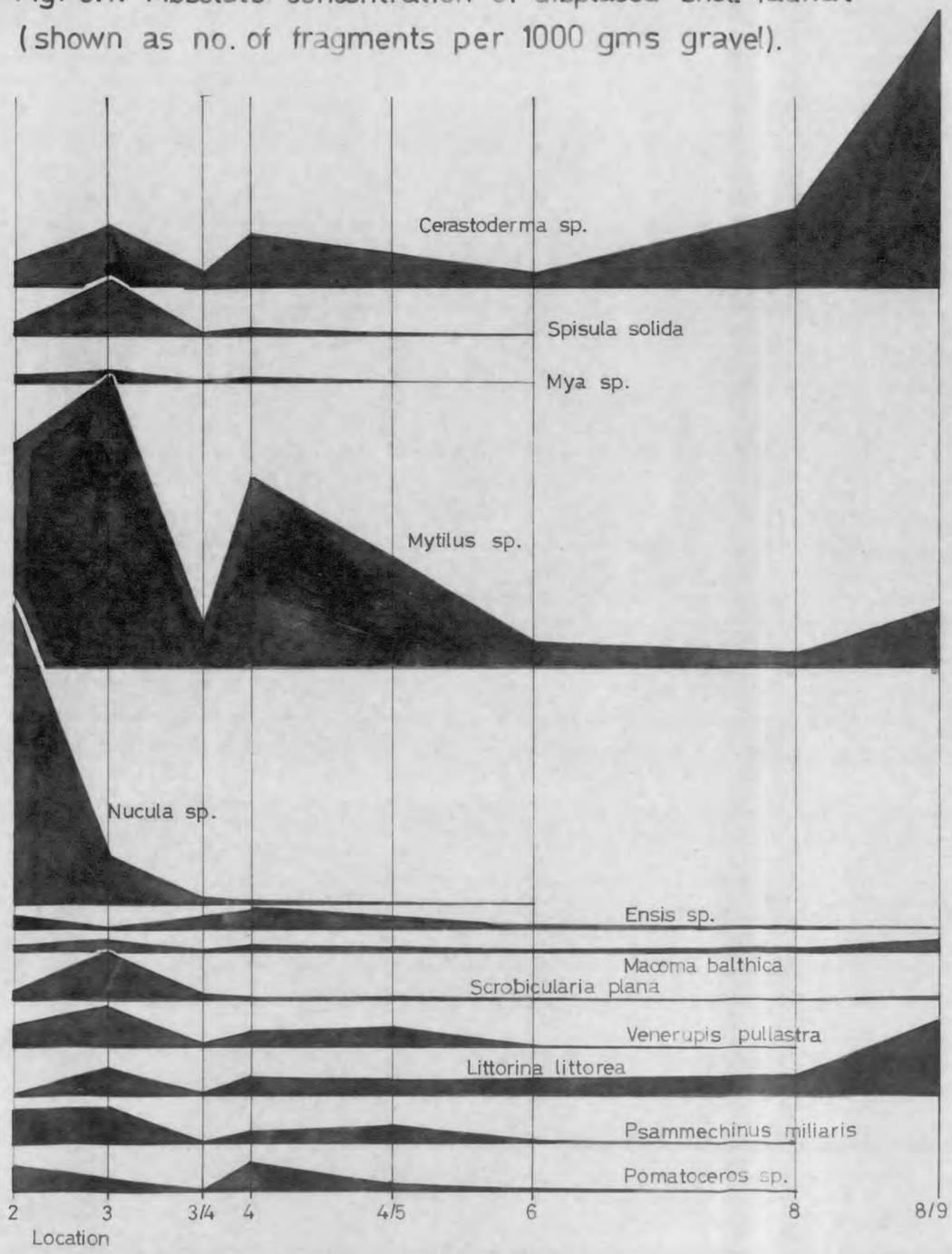
For one sample a count was made for the coarse sand fraction (0.5 - 2.0 mm) and this may be compared with the gravel count (table 6.5). In both fractions cirripedia form the highest percentages. Psammechinus miliaris fragments were very abundant in the very coarse sand but not in the gravel. This is an example of sorting according to size, as the delicate echinoid tests readily break down to single plates of sand size, and there is very little indication of echinoids in the gravel fraction. Hydrobia ulvae is also found in the very coarse sand but is too small to be abundant in the gravel.

e) Shell orientation

At the southern end of the gravel ridge, south of Snettisham Scalp, the seaward face has large numbers of Cerastoderma edule valves with their convex surfaces uppermost and their umbos oriented in preferred directions. Oriented photographs were used to produce rose diagrams of these shell orientations (fig. 6.8).

The umbos are directed mainly into the ebb current (i.e. to the south) which here flows northwards parallel to the ridge. Many umbos also point north, these presumably being oriented by the flood current, while some specimens have umbos pointing up the beach, being oriented by backwash. Very few specimens point down the beach face.

Fig. 6.7. Absolute concentration of displaced shell fauna. (shown as no. of fragments per 1000 gms gravel).



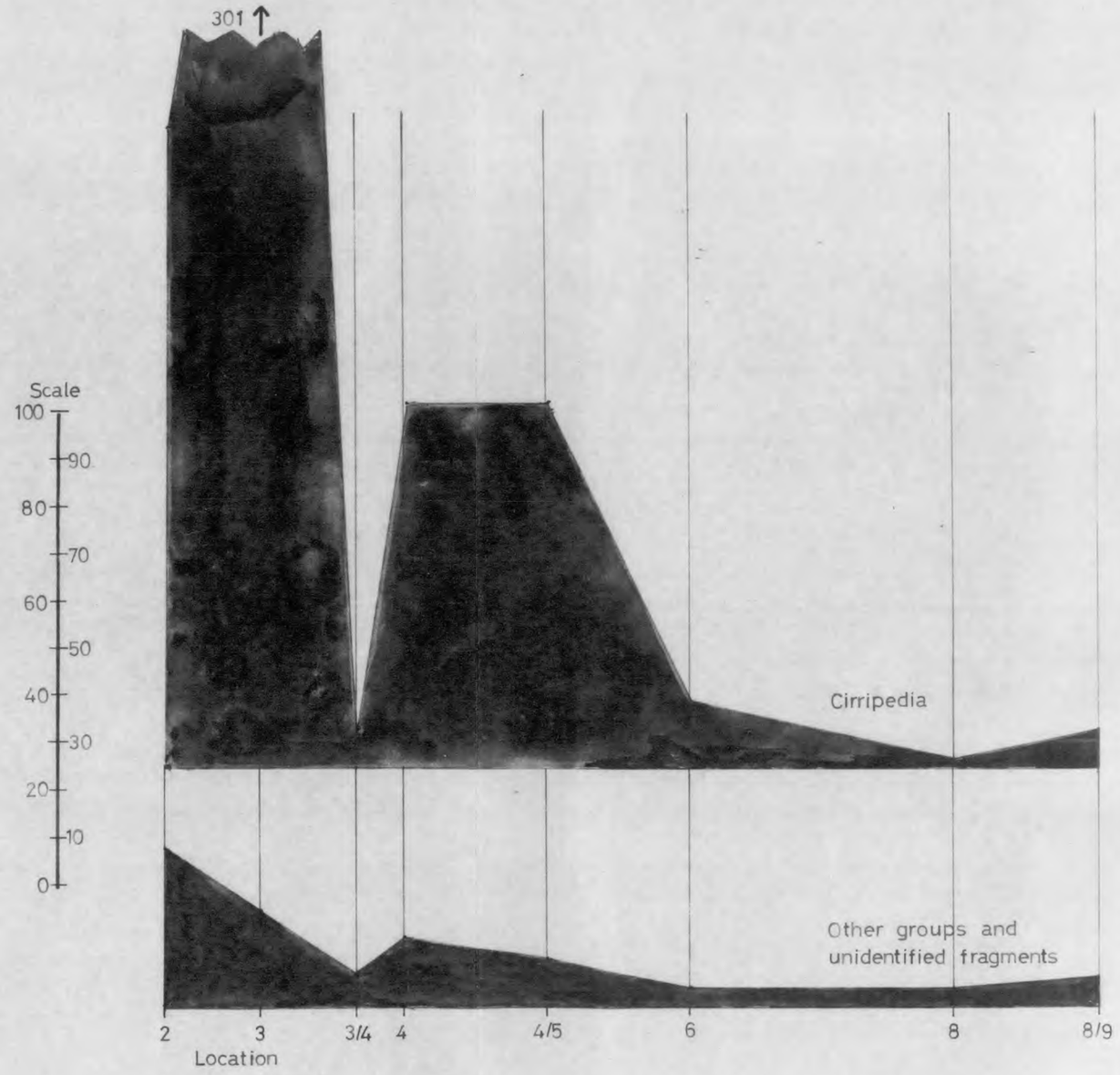


Table 6.4 Displaced Fauna: Number of Fragments per 1,000 grams of Gravel

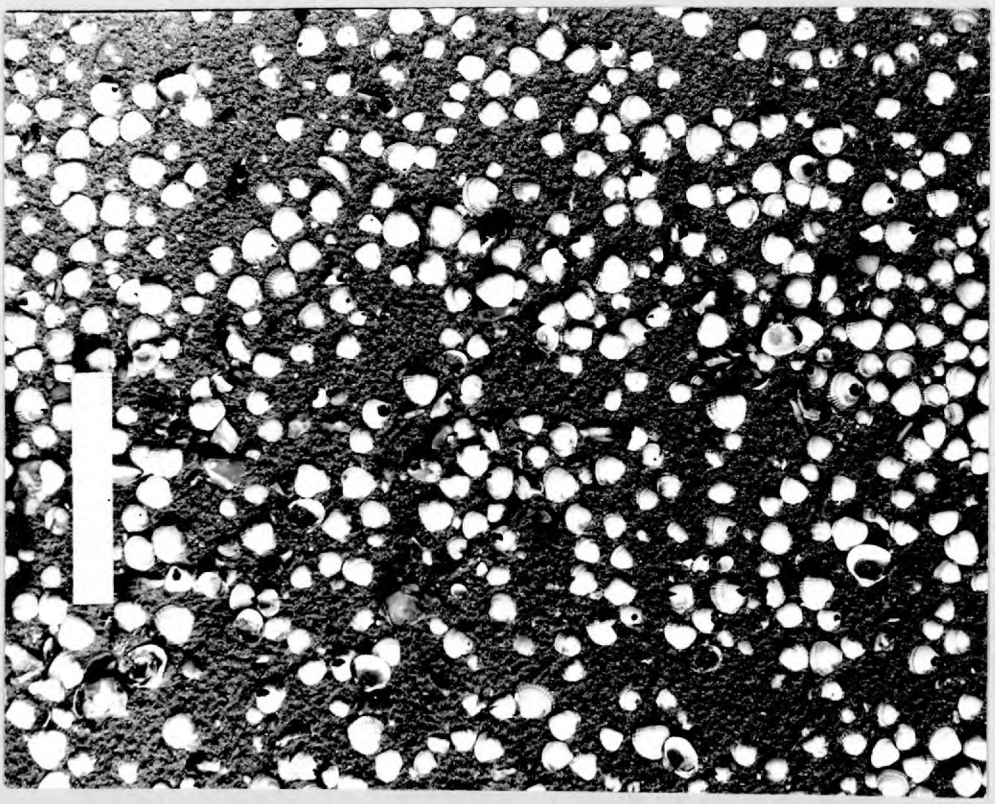
Profile	2	3	3/4	4	4/5	6	8	8/9
Bivalvia								
Cardiacea								
Cerastoderma edule	6.4	13.2	3.6	11.6	7.3	3.2	16.3	59.0
Mactracea								
Mactra corallina			.3					
Spisula solida	2.9	11.7	.5	1.8	.5			
Myacea								
Mya arenaria) Mya truncata)	1.8	2.9	.7	1.0	.3	.2		
Mytilacea								
Mytilus edulis	47.4	61.4	9.0	40.2	23.0	5.3	3.0	12.7
Modiolus modiolus	1.2			.2	1.1			
Nuculacea								
Nucula sp.	62.6	10.2	1.2	.5	.2			
Ostreacea								
Ostrea varia	.6	4.4	.2	.5	.2	.1		
Pectinacea								
Chlamys varians	1.8	1.4	.2	.2	.2			
Solenacea								
Ensis ensis) Ensis siliqua)	2.3		2.2	3.8	2.6	.2	.1	
Tellinacea								
Macoma balthica	1.2	2.9	.8	1.3	1.1	.2	.7	2.7
Scrobicularia plana	1.2	10.2	1.3	.5	.5	.2	.1	.5
Veneracea								
Venerupis pullastra	4.7	8.8	1.0	3.1	4.3	.3		
Pholadacea								
Petricola pholadiformis		1.4	.2	.7	.3			
Zirfaea crispata	.6	7.3		.2		.1		
Gastropodia								
Hydrobia sp.		1.4		.3				1.8
Littorina littorea		5.8	.3	3.9	3.2	3.3	4.3	15.4
Gibbula cineraria	1.2	1.4	.7	2.5	1.4	.5		
Buccinum undatum	.6	1.4	.3	1.1	.6	1.3		
Nucella lapillus				1.0				
Littorina littoralis				.3				
Echinodermata								
Psammechinus miliaris	7.0	7.3	.3	2.8	3.8	.2		
Echinocardium cordatum		2.9	.2	.5	.3			
Annelida								
Lanice conchilega				1.3		.2	.3	
Pomatoceros triqueter	5.3	2.9	.3	5.9	1.5	.1		
Cirripedia	134.5	301.2	8.0	76.3	76.9	14.1	2.0	8.6
Unidentified pholads	4.1		2.3	1.0	1.2			
Crab chela				.5				
Derived belemnites				.2	.2			
Terebratula (derived)			.3					
Unidentified	24.5		2.8	6.4	6.1	2.2	3.7	5.0
Total in 1,000 gms	311.9	460.1	36.7	169.6	137.8	31.7	30.5	105.7

Table 6.5 Comparison of Faunal Counts for Coarse Sand and Gravel

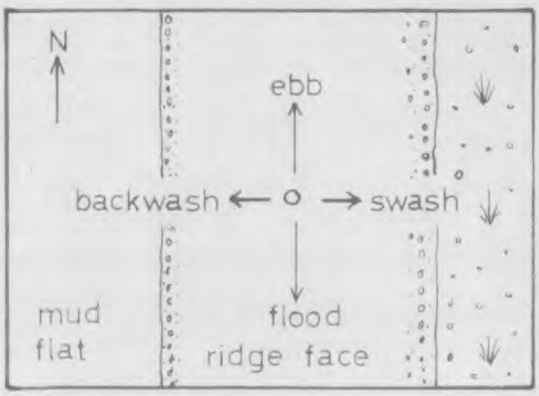
Sample No. 3		Coarse sand 0.5-2.5 mm		Gravel	
		No. of frags.	%	No. of frags.	%
Bivalvia					
Cardiacea	Cerastoderma edule	3	.4	11	2.1
Mactracea	Mactra corallina	-	-	-	-
	Spisula solida	1	.1	5	.9
Myacea	Mya arenaria) Mya truncata)	-	-	2	.6
Mytilacea	Mytilus edulis	14	1.9	42	13.3
	Modiolus modiolus	-	-	-	-
Nuculacea	Nucula sp.	4	.5	7	2.2
Ostreacea	Ostrea varia	3	.4	3	.9
Pectinacea	Chlamys varians	1	.1	1	.3
Solenacea	Ensis ensis) Ensis siliqua)	4	.5	-	-
Tellinacea	Macoma balthica	-	-	2	.6
	Scrobicularia plana	-	-	7	2.2
Veneracea	Venerupis pullastra	2	.3	6	1.9
Pholadacea	Petricola pholadiformis	-	-	1	.3
	Zirfaea crispata	-	-	5	1.6
Gastropoda					
	Hydrobia sp.	10	1.3	1	.3
	Littorina littorea	-	-	4	1.3
	Gibbula cineraria	1	.1	1	.3
	Buccinum undatum	2	.3	1	.3
	Nucella lapillus	-	-	-	-
	Littorina littoralis	-	-	-	-
Echinodermata					
	Psammechinus miliaris	65	8.9	5	1.6
	Echinocardium cordatum	3	.4	2	.6
Annelida					
	Lanice conchilega	-	-	-	-
	Pomatoceros triqueter	1	.1	2	.6
Cirripedia		617	84.4	206	65.4
Total number of fragments		731		315	
Weight of fraction (grams)		161		684	

Fig. 6.8. Orientation of shells on the face of the gravel ridge.

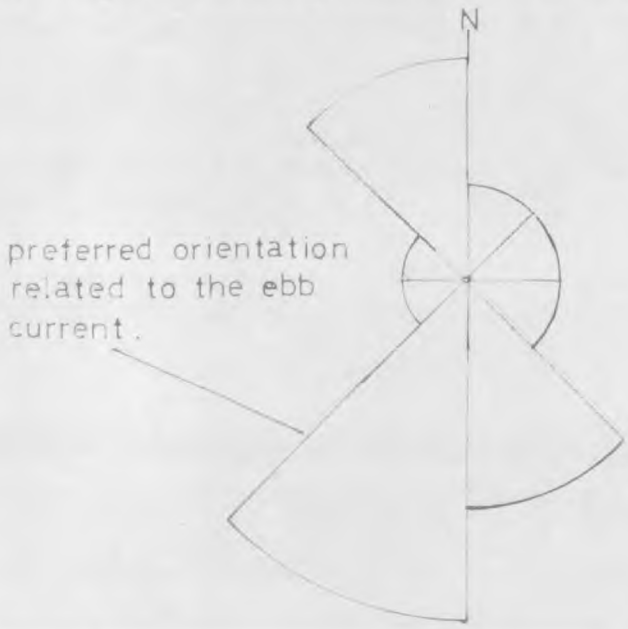
a) Typical concentration of Cerastoderma edule.



b) Locality



c) Rose diagram showing directions towards which umbos point.



Thus the direction of orientation of the majority of individuals is controlled by the ebb, this being the last current which passed over the beach face, while other specimens have retained the orientation imposed by the previous flood. From this data it is shown that the shell fraction of the gravel ridge has been controlled predominantly by tidal currents and wave action is limited by the wide mud flat and sand flat to seaward.

II The Arenicola Sand Flat - Stubborn Sand

1. Morphology

Stubborn Sand extends as a wide, gently sloping and uniform sand flat from Snettisham to Hunstanton. At the northern limit, where it passes into the beaches described earlier, the zone is only 200 to 300 yards wide, but it widens rapidly southwards and reaches a maximum width of approximately one mile in the area seaward of Heacham. In the south, it is restricted by a channel, called the Inner Road, which separates it from Ferrier Sand and the intertidal complex of mud flats and marshes to the south. This sand flat shelves gently seawards. The thickness of the sand body is not known, although in many places gravels are found at depths of only three or four feet beneath the surface and Jackson (1910) has detected the presence of boulder clay beneath the sand at Hunstanton. It is thought that the sand flat is a thin deposit of sand overlying a gravel lag which in turn rests upon boulder clay.

In contrast to the coastline north of Hunstanton, repeated profiling has shown no significant changes in the level of the surface over the last two years (sheet 6.1). Slight fluctuations in the level of the sand flat usually less than six inches are detectable in places but generally no change is shown.

Profile 4 at Hunstanton (discussed in Chapter 4) shows a limited amount of beach change, but Profile 5 is very stable. Thus, although reworking of the sediment may occur, this does not appreciably alter the general topography.

2. The Sediments

a) Grain size characteristics

The sediments of Stubborn Sand are mostly fine sands with mean diameters ranging from 1.86 to 3.03 phi and an average value of 2.59 phi. (table 6.6). They are mostly well sorted with low positive skewness values, but some high positive values of skewness are found. There is no non-skeletal gravel in most samples but gravel sized shell debris is present. Silt and clay are present in varying proportions, being always less than 7%, the average being 1.67%. The silt and clay content is thus higher than that found in the beach sediments to the north, but is lower than that found in the sand flat sediments to the south (e.g. Ferrier Sand). This zone is thus transitional between the two.

Histograms of the grain size distributions of these sediments are shown in figure 6.9. A visual comparison of these with those of the forebeach sediments north of Hunstanton, shows the differences in sorting between the two, the greater wave activity in the latter area leading to better sorted deposits.

i) The mean grain size

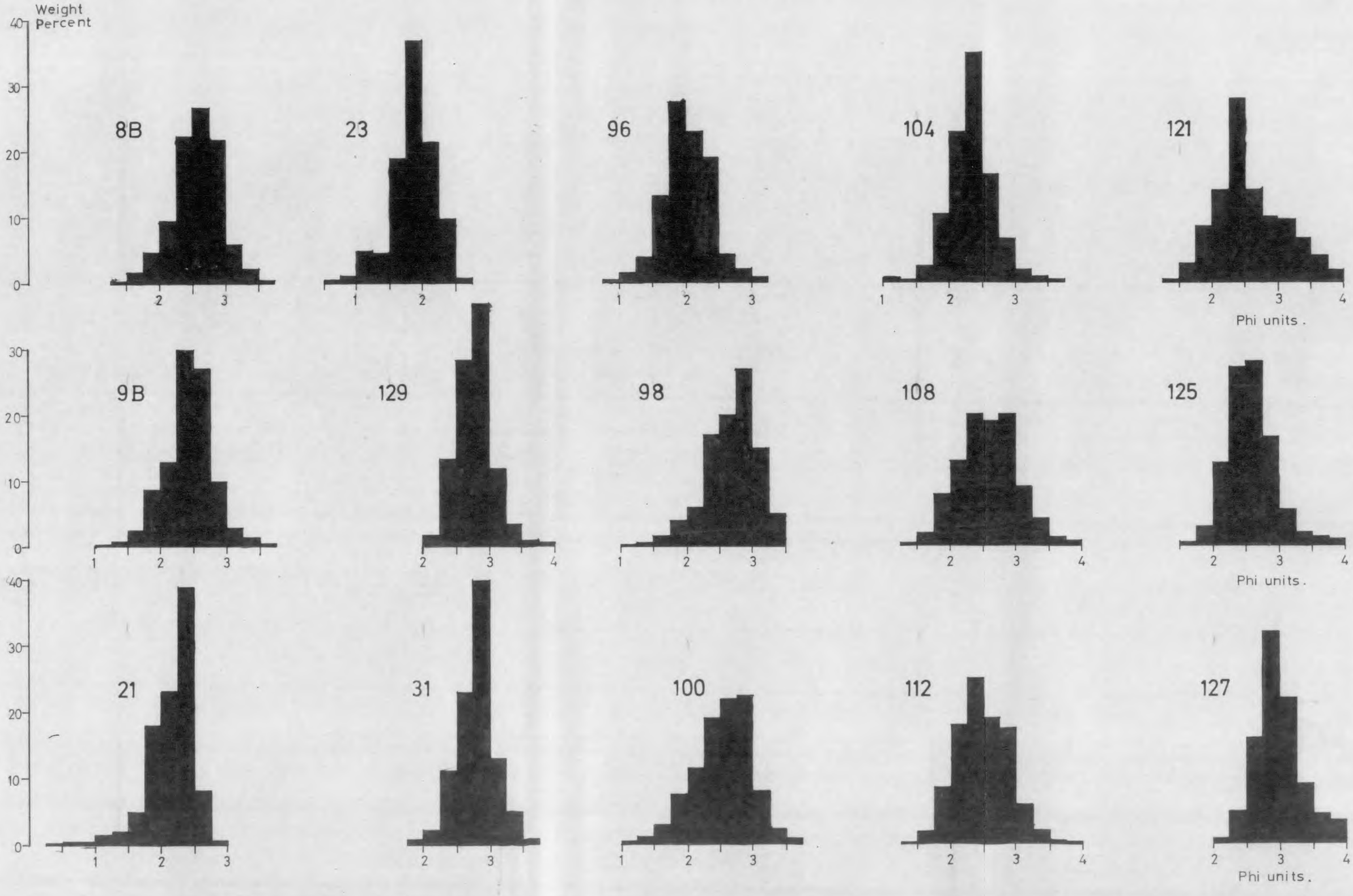
There is generally no persistent trend in mean grain size between high and low water marks. However, on Profile 8 there is a decrease in mean grain size from high to low water mark, i.e. towards the Inner Road. Elsewhere this decrease is not found. At Profile 7 the mean is constant at about 2.5 phi, while to the north, disregarding samples taken near the gravel ridge, there is a slight increase in mean grain size towards low water mark.

The seaward decrease on Profile 8 is probably due to the concentration and deposition of very fine sand, silt and clay caused by the large Mytilus edulis bed at the edge of the Inner Road and because there is a lack of wave activity here, due to the high relief of Ferrier Sand on the west bank of the channel.

Table 6.6 Grain Size Characteristics of Stubborn Sand

Profile	Sample Number	Mean Diameter	Sorting	Skewness	% Gravel	% Silt & Clay
5	121	2.58	0.530	+0.583		1.38
6	96	2.05	0.404	+0.159		2.85
	98	2.71	0.418	-0.149		
	100	2.54	0.438	-0.135		0.65
	104	2.33	0.339	-0.033		0.58
7	108	2.57	0.465	+0.040		1.86
	112	2.49	0.394	+0.050		0.66
	116	2.56	0.357	-0.049	0.05	0.08
8	125	2.57	0.375	+0.140	0.54	1.54
	127	3.03	0.525	+0.392		6.93
	129	2.78	0.288	+0.027		1.73
	131	2.81	0.290	+0.012		1.76
	21	2.17	0.315	-0.389	0.27	not meas.
	23	1.86	0.339	-0.145		"
	31	2.81	0.311	+0.004		2.97
	8B	2.58	0.212	-0.018		1.77
	9B	2.43	0.387	-0.071		2.12
Range	from	1.86	0.212	-0.389	0.00	0.00
	to	3.03	0.530	+0.583	0.54	6.93
Average		2.53	0.376	+0.035	0.03	1.78

Fig. 6.9. Typical Grain Size Distributions of Sediments from Stubborn Sand.



The seaward increase in sediment size on Profile 6 may reflect the proximity to deeper tidal channels floored with coarser sands and gravelly sands.

ii) Sorting (table 6.6)

These sediments are mostly well sorted and in general sorting improves towards low water mark where some samples are very well sorted. Calculated values corroborate the sorting estimated from histograms and show a distinct difference between these sediments and those from the foreshore to the north. A graph of mean grain size vs. sorting (fig. 6.10) shows that the sediments from each of these two sub-environments fall into distinct fields.

iii) Skewness (table 6.6)

The average skewness is +0.036 and the range shows that high positive and negative values occur, although positive values are more common. No trends perpendicular to the coast are detectable but there is a noticeable change parallel to the coast from predominantly negative values in the north to positive values in the south. This assessment does not include samples from the inner edge of the sand flat where anomalies occur. This trend in skewness correlates with the broad trend found throughout the area from Holme to King's Lynn.

b) The composition of the sediments

i) The bulk composition (table 6.7, fig. 6.11)

The sands are composed predominantly of terrigenous material and carstone oolites or fragments of these are always present and make up as much as 11% of the sediments adjacent to the gravel ridge. Elsewhere the content of oolites is small, indicating that the carstone is retained in the zone near high water mark and only a small amount of sediment is able to move towards low water mark. Carstone is more abundant at the upper edge of Stubborn Sand than it is to the north of Hunstanton cliffs, this indicating that longshore movement here is predominantly towards the south.

Mollusc and barnacle fragments are always present in amounts of up to 12%. Generally the higher percentages are found at

Fig. 6.10. Relationships of mean diameter, sorting and skewness for the Arenicola sand flat and the forebeach north of Hunstanton.

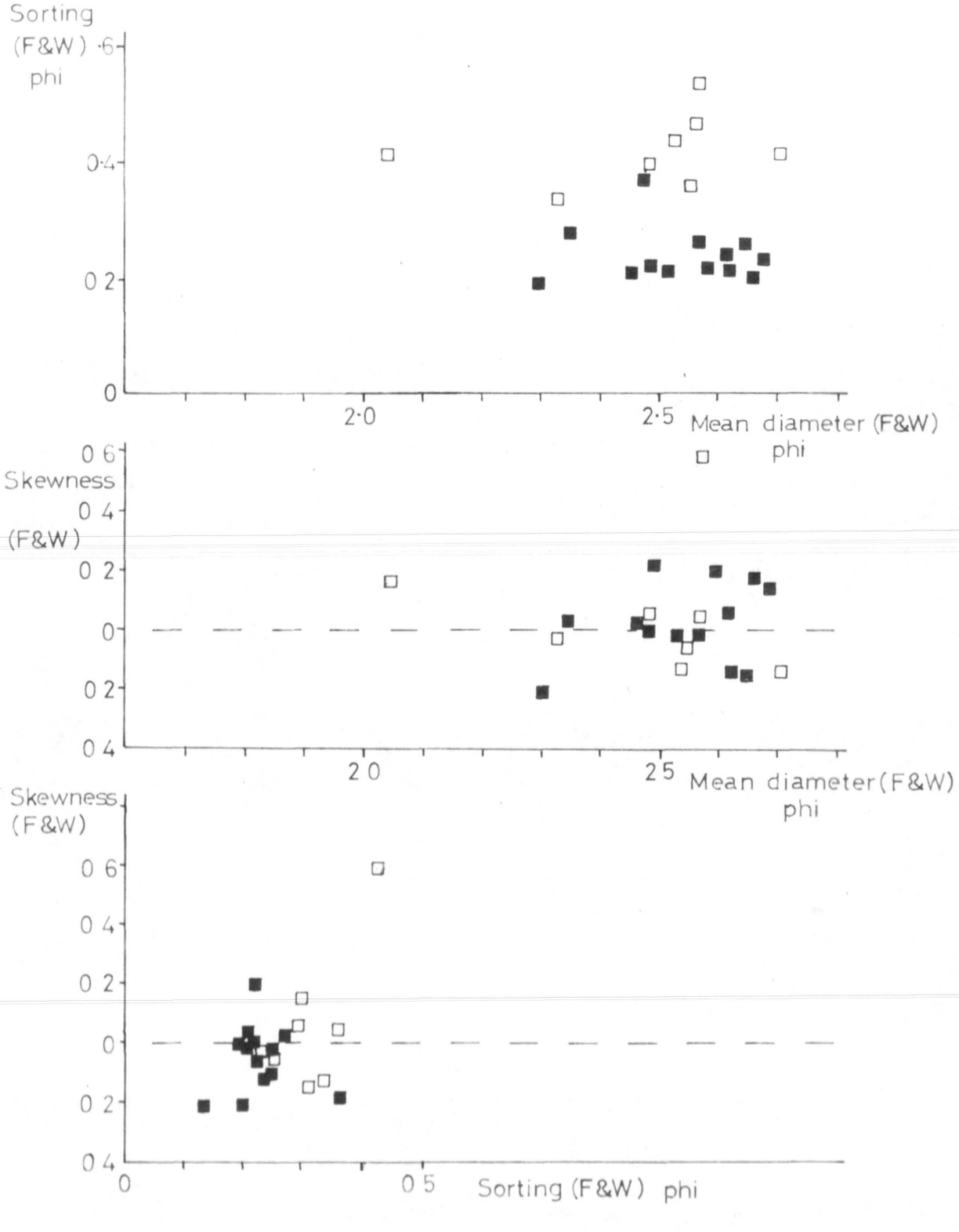
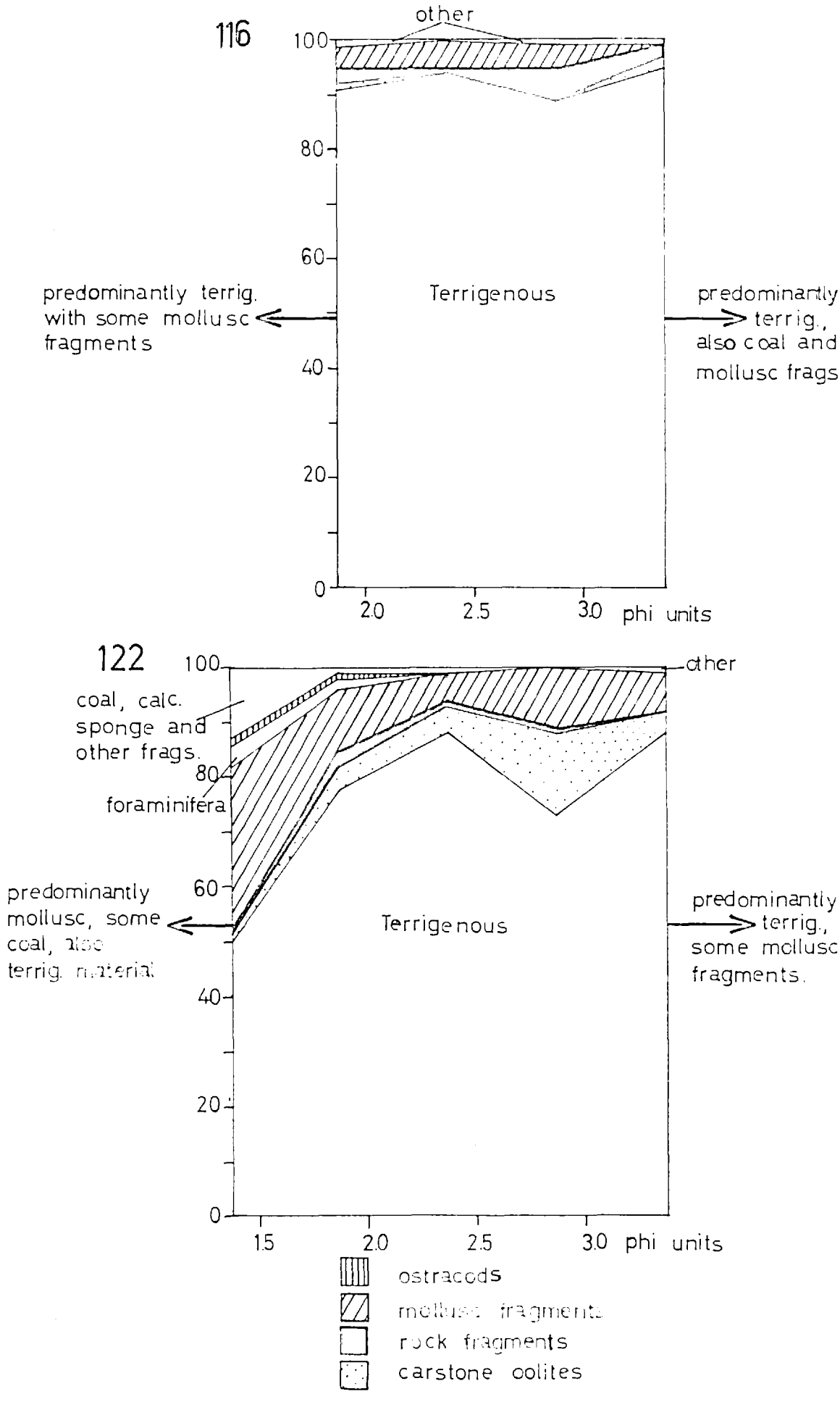


Table 6.7 Composition of Stubborn Sand Sediments

Sample No.	Terri-genous	Limonite oolite	Rock Fragment	Mollusc/ Barnacle	Foram.	Ostracod	Echinoid	Coal	Mica	Bryozoa	Calcareous sponge
8B	94.5	3.0		1.5				0.5	0.5		
9B	97.0	1.7		1.3							
21	73.6	4.7		11.7	7.3		1.0	0.7	0.7	0.3	
23	87.7	11.0		1.3							
96	83.5	6.5	1.0	6.5	0.5			1.5		0.5	
100	92.0	2.0	0.5	4.5	0.5	0.5					
104	93.0	3.5	1.0	2.0				0.5			
108	92.5	3.0	3.0	1.5							
112	93.5	1.5	2.0	3.0							
116	95.5	1.5		3.0							
122	87.5	2.5	0.5	8.5	1.0						
125	89.5	4.5	2.5	3.5							
129	94.0	1.0	0.5	3.5				1.0			
131	94.5	1.0	1.5	1.0				2.0			
G269	80.0	9.5	1.5	9.0							
G272	95.5		1.5	2.5							0.5
G275	95.0	1.0		2.5				1.5			
Range	80.0-95.5	1.0-11.0	0.0-3.0	1.0-11.7	0.0-7.3	0.0-0.5	0.0-1.0	0.0-2.0	0.0-0.7	0.0-0.5	0.0-0.5

Fig. 6.11. Variation of composition with size for samples from Stubborn Sand



the upper edge of the sand flat. This may be due to the breakdown of shell into sand sized particles by wave action on the face of the gravel ridge.

Usually, foraminifera do not exceed 1%, but in one sample (21) from the upper edge of the sand flat, the foraminifera Ammonia becarrii forms 7% of the deposit. Other minor components such as echinoid plates, spines, bryozoa are present in similar amounts to those found in the sediments of the North Norfolk coast.

ii) The composition of graded fractions (fig. 6.11)

The variation of composition with sediment size was investigated for two sediments from this sub-environment.

A sample from low water mark at Heacham (116) had a very uniform composition throughout all the grades analysed. Only minor amounts of carstone were present and molluscan fragments were present in nearly equal proportions in each fraction. Terrigenous components formed 90 to 95% of the sample.

A sample nearer the gravel ridge but further north (122) shows a more variable composition with size. Carstone oolites are more abundant in the finer fractions, whereas molluscan and barnacle fragments become increasingly abundant in the coarser grades. Coal and peat, foraminifera and ostracods are also more abundant in the coarser fractions. These lighter components are concentrated on the upper part of the sand flat.

c) Sedimentary structures

The study of the sedimentary structures of Stubborn Sand was limited to an examination of surface structures and a compilation of the organisms present which are capable of producing bioturbation within the sediment. Only a few samples were taken to investigate the internal sedimentary structure.

i) Ripple marks

The most common forms present on the sand flat are wave formed asymmetric ripples with steep landward faces, crests parallel to the shore and wavelengths of between two and four

inches and heights of one half to one inch. Although this type is normally predominant on the sand flat, during calm conditions rippling may be completely absent or symmetrical ripples may be formed.

At the lower edge of the sand flat, asymmetric ripples, probably produced by the northward flowing ebb current, are abundant (cf. Evans, 1959). They generally have ripple lengths of up to eight inches, crests perpendicular to the coastline and steep slopes facing north. Asymmetric ripples are not commonly seen on higher parts of these flats, but during spring tides they may be present with superimposed symmetric and asymmetric wave formed ripples.

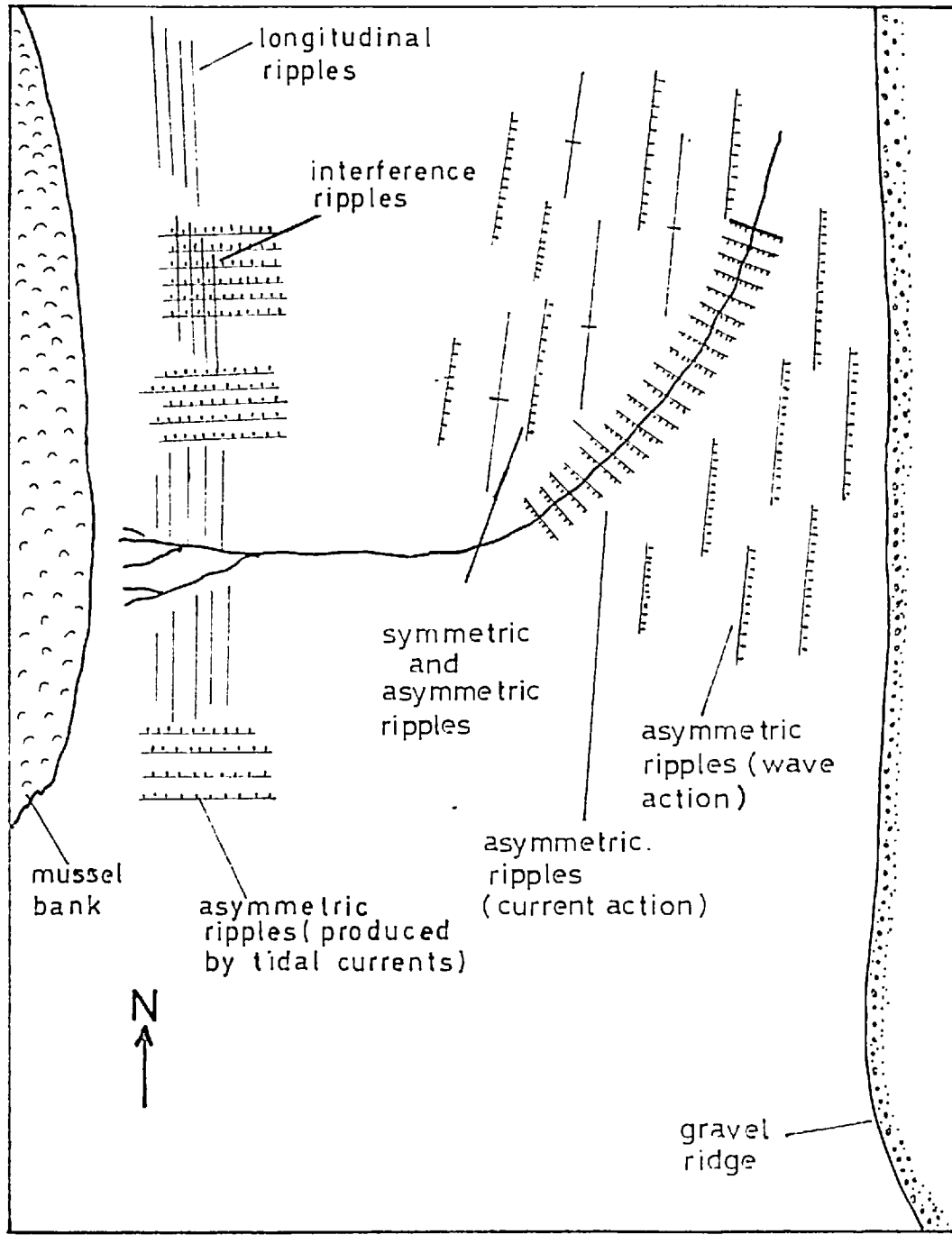
In the vicinity of Cockle Drain, two sets of ripples formed by the ebb current are preserved when there is little wind or wave action (fig. 6.12). The largest and earliest formed face north to north north east indicating currents parallel to Inner Road, while at a late stage of the ebb shallow sheets of water pass off the sand flat parallel to Cockle Drain to produce smaller features which interfere with the earlier forms. These small ripples have larger wavelengths but similar ripple heights (i.e. ripple indices are larger) to the wave formed asymmetric ripples.

Longitudinal ripples (van Straaten 1951) with crests parallel to the channel are a common feature adjacent to the Mytilus banks in the Inner Road, where sediments contain a higher proportion of silt and clay.

ii) The fauna

Kindle (1930) briefly discussed the fauna of Stubborn Sand and remarked on the abundance of Cardium edule (now Cerastoderma edule, see Tebble 1966), Mytilus edulis and Branchiomima vesiculosum (Lanice conchilega). However, since that time the fauna of this sand flat has not been studied until the present writer commenced his work. Here the main elements of the fauna are discussed but the ecology is being investigated in more detail by Croome (unpublished).

Fig. 6.12. The ripple pattern on the intertidal flat near Snettisham.



Stubborn Sand is extensively colonised by the worm, Arenicola marina (fig. 6.13). The casts of this species may be seen over the entire surface from the foot of the gravel ridge to low water mark neap tide. These individuals become most abundant in the central part of the sand flat, whilst towards low water mark they decrease in abundance rapidly.

The worm, Lanice conchilega, becomes important on the lower part of the sand flat and increases in abundance towards low water mark. In only one locality, adjacent to the southern end of Hunstanton sea wall, is it found on the upper part of the sand flat. On Stubborn Sand this worm tends to have an even distribution near low water mark, whereas at Holme it is sometimes found concentrated into clumps (fig. 5.17).

Mytilus edulis has colonised a small area along the east side of the Inner Road near low water mark. As at Hunstanton, this organism has aided the deposition of silt and clay so that a linear bank has been formed along the channel edge. This mollusc is also found associated with some of the gravel spreads on the upper part of the sand flat.

Cerastoderma edule (the common cockle) is very abundant on Stubborn Sand and the highest concentrations are found just above low water mark, where they are collected in bulk by fishermen. Kindle (1930) noted the presence of a 'Cardium' of reduced size in the black sand near Dersingham (presumably seaward of Snettisham Scalp) but no size reduction was detected by the author. Small Mytilus edulis are often found on the surface with groups of Cerastoderma edule attached to the byssal threads.

Macoma balthica is common in these sediments and although it may be found over the whole sand flat it is generally more abundant where there is a higher proportion of silt and clay. Pellets of crushed Macoma fragments (Wilson 1967) produced by birds are common over the entire area.



Fig. 6.13 Stubborn Sand extensively colonised by Arenicola marina. Casts of this species may be seen over the entire surface of this sand flat.

Tellina tenuis is not commonly found living except in the extreme north east of Stubborn Sand, but separate valves may be found on the surface of the sand flat. Wilson (1967) mentions the rare occurrence of this species in the intertidal zone of the Solway Firth.

Littorina littorea is commonly found at the landward edge of the sand flat, especially where small spreads of gravel are present, as between Heacham and Snettisham.

Various barnacles, such as Elminius sp. and Balanus balanoides, occur on these gravels and the individual plates form notable constituents of the sand composition.

Echinocardium cordatum tests are very common on the surface of the sand flat, although no living specimens have been obtained in the zone above low water mark. A grab sample from just below low water mark adjacent to the southern end of Hunstanton brought up one living specimen.

The abundance of infauna throughout Stubborn Sand is due primarily to the lack of sediment disturbance by wave and current action. The black sand noted by Kindle (1930) is extensively developed in this area and is presumably due to the decay of organic matter in an anaerobic environment. Similar, although not so intense, discolorations are found in the Wash sub-environments to the south.

No attempt has been made here to determine the 'crush factor' (van Straaten 1956) for the shells present, although it would appear that very little breakdown of shells occurs prior to deposition on the gravel ridge. Wilson (1967) considers that most of the broken shell fragments on a sand flat are produced by the feeding habits of predators, predominantly birds such as oystercatchers.

iii) Internal structures

The predominant primary structures are normal horizontal lamination, rippled lamination with ripple drift lamination and consequent small scale cross lamination, and small scours

(fig. 6.14). However, the abundance of Arenicola marina results in intensive bioturbation so that many of the primary structures are destroyed. Near the edge of the gravel ridge sands are interlaminated with thin gravels. The sands are rippled or may have steeply dipping cross lamination (fig. 6.15).

Cerastoderma edule and Mytilus edulis are often found in clusters on a bedding plane. These shells often fall into the cone shaped depressions of Arenicola marina and it is thought that this may account for some of the clusters found at depth. However, no concentrated shell layer, as observed by van Straaten (1954) is seen at the base level of normal worm bioturbation.

Burrows of Arenicola marina are common in the box samples (fig. 6.14) and primary horizontal laminae of sediment are turned down around the burrow wall, which is partially cemented. Examples from elsewhere show that laminae from the surrounding sediment are drawn down into the burrow and some of this is used to line the wall (fig. 7.24).

The sediments near low water mark retain very little primary structure. They contain abundant shell debris, normally present as unbroken single valves, and tubes of the worm Lanice conchilega (fig. 6.16).

III Conclusions

Of the two sub-environments in this area the gravel ridge shows the characteristics of the more exposed coastline north of Hunstanton, while Stubborn Sand is very similar to the Arenicola sand flat of the Inner Wash (see Chapter 7). The offshore banks are one of the factors which cause these two sub-environments to occur adjacent to each other. At high water the offshore banks are covered so that wave conditions on the gravel ridge may be vigorous. During lower stages of the tide and at low water, waves may break on the offshore sand banks and dissipate much of their energy before reaching Stubborn Sand. Reworking of the sediment by wave action is thus limited and organisms, being relatively undisturbed, have been able to colonise the sub-environment and produce charac-



Fig. 6.14 Internal structures of Stubborn Sand. Horizontal and rippled laminations, ripple drifting and bioturbation are shown in this sample. (x $\frac{1}{2}$)



Fig. 6.15 Near the inner edge of Stubborn Sand the sands may be interlaminated with thin gravel deposits derived from the gravel ridge. (x $\frac{1}{2}$)



Fig. 6.16 Bioturbated sediment near low water mark, Stubborn Sand. The sediment here shows very little remaining primary structure. Tubes of Lanice conchilega and shells of Cardium edule and Mytilus edulis were abundant. (x $\frac{1}{2}$)

teristic sedimentary structures.

Although this sand flat is described as a transitional area, there is very little change in sediment properties along the area from north to south. The transitions in sediment properties occur in the extreme north at Hunstanton and in the extreme south at Snettisham, where the sand flat merges into a mud flat sub-environment. The area as a whole, however, has been described as transitional as it separates the sub-environments of the exposed north Norfolk coast from those of the sheltered areas of the inner Wash and it also shows some characteristics of both these areas.

CHAPTER 7

THE INNER WASH COASTLINE, SNETTISHAM TO KING'S LYNN

I General

The shoreline from Snettisham Scalp to King's Lynn is about eight miles long and varies from a few hundred yards to three miles in width between high and low water spring tide levels. Its maximum width is developed in the region of the Ferrier Sand (fig. 2.2). To the south, the area is bounded by the Ouse channel and in the north it passes across Wolferton Creek to extend around and partly envelop the gravel ridge which runs south from Hunstanton. The upper intertidal flat zones of mud flat and salt marsh have grown in front of this ridge and in this transition area the normal sequence of zones found between high and low water lines are not arranged in a simple manner as they are in the south. This is due to the presence of the Inner Road, a channel which runs parallel to the shore and which at one time separated the Ferrier Sand from the coast. Thus a traverse here passes into channel sediments and then on to a high sand body (Ferrier Sand) before dropping into Cork Hole, a deeper channel west of Ferrier Sand.

South of this area a more normal succession of zones (i.e. sub-environments) is shown and the sequence from low water to high water levels of lower sand flat, Arenicola sand flat, higher mud flat and salt marsh, with a restricted lower mud flat sub-environment developed in places and a network of creeks which cut across all these zones, is similar to that described by Evans (1965). He has described a number of physiographic zones which were also sub-environments of deposition on the intertidal zone of the Wash between the Witham outfall and Butterwick Low on the Lincolnshire coast. Although he studied only a small intertidal area extending about four miles alongshore, it appears that the zonation established there is typical of much of the coastline of the Wash.

At the southern limit of the study area the sub-environments pinch out and marsh sediments are found adjacent to the channel near King's Lynn.

Detailed traverses were made between the artificial sea wall and low water mark to show the nature of the profile at various points along the coastline and to determine the locality of sediment samples (sheet 3.1). Seaward of the sea wall the marsh top is almost horizontal while the outer marsh has a marked seaward slope. This slope continues but decreases over the higher mud flat. The steeper slope of the outer marsh may be related to the more rapid accretion of sediment where the mud flat is first colonised by plants. Whereas in the south the profile continues with a gentle slope across the Arenicola sand flat before dropping into the Ouse channel, in the north it falls rapidly into the creek complex leading south from the Inner Road and then rises to a wide platform known as Ferrier Sand. The profile then falls away at the edge of the Arenicola sand flat, just as it does in the south.

The various sub-environments of deposition are discussed. In their broader aspects they correlate with those described by Evans (1960) on the opposite shoreline of the Wash. There are, however, a number of important differences and these are discussed later in this section.

1. The Salt Marsh

This forms a continuous sub-environment from Wolferton creek to the banks of the River Great Ouse near King's Lynn. Much of the mature salt marsh has been reclaimed, the dates and areas of reclamations being shown in fig. 2.6. In the past few years two large reclamations of 708 and 316 acres have been made (Great Ouse River Authority); the former was completed in 1965 and the latter in 1966. Seaward of these new embankments, the marsh is immature and only one to two hundred yards in width. Many of the differences between the higher intertidal zone here and that at the Witham outfall may be attributed to these recent reclamations.

Shallow depressions in the outer marsh surface often develop into salt pans when the marsh becomes more mature. Most of the marsh seaward of the training walls is immature as the mature regions have recently been reclaimed. At the southern end of the gravel ridge there is, however, a small area of mature marsh where salt pans are well developed.

The dominant plant living on these marshes is Spartina townsendii (Swann 1965) but other species of this plant are also present. Spartina maritima has become increasingly rare at Wolferton, being confined now to depressions and salt pans in the upper part of the marsh. Here it is associated with Pucinella maritima and Festuca rubra. The spread of Spartina townsendii has lately blocked the channels and has led to the disappearance of Zostera sp. This latter species used to be found on the inner part of the mud flat some distance from the marsh edge. The genus Salicornia sp. is, however, still present in abundance and extends to the seaward limit of marsh vegetation.

Nowhere is the seaward edge of the marsh cliffed as it is at Friskney flats north of the Witham outfall (Evans 1965). These cliffs are found on many intertidal zones along the north Norfolk coast and have also been described on the Essex coastline at Bradwell (Greensmith and Tucker 1966), in the Wadden Sea (van Straaten 1954) and in Jade Bay, Germany (Reineck 1967). The significance of a marsh cliff in the embayment of the Wash is discussed by Kestner (1962). By using aerial photographs and by trenching, he discovered a sequence of various old salt marsh edges. These indicate that before reclamation work started in the seventeenth century, the foreshore of the Wash was not progressively accreting but had reached a state of stability. His work showed that saltings become stabilised when they are one third to half a mile wide with a wider mud flat zone to seaward. Mud flat accretion is balanced by lateral erosion so that a marsh cliff may be formed. Although there is no cliff on the open shoreline today, an earlier cliff has been observed by Kestner at Wolferton and this was re-examined by the author (fig. 7.1). This is now enclosed within the 1965 reclamation. It has a



Fig. 7.1 Salt marsh cliff at Wolferton. Height approximately one foot.



Fig. 7.2 Higher mud flat with a surface of shallow channels and depressions and eroded surface laminae.

height of between nine inches and one foot and its position shows that the old marsh had an irregular outline with small promontories extending seawards. A section through one of these shows that the cliff had a steep almost vertical edge.

The sediments of the earlier, higher cliffed marsh are laminated fine and very fine sands and silts. At the surface the sandy laminae may be up to half an inch thick, while the silts form numerous thin laminae. Some of these are rippled. At a depth of four inches the silt laminae become sparse and very thin. Seaward of the marsh cliff there is much more silt and clay present in the sediment, which is still laminated. Sand laminae may occur up to a thickness of 0.2 inches but generally they are thinner than this. At a depth of 20 inches the sediment may become predominantly sandy with only thin laminae of silt. 260 yards landward of the cliff the sediment is predominantly silty while sands form only very thin laminae, not exceeding 0.1 inches.

Although the sediment in the vicinity of this cliff is sandier than that of the marsh elsewhere, the extremely high sand content in the cliff edge is not shown in the marsh to landward. This cliff is only 600 yards from the termination of the gravel ridge and it is suggested that the coarse sediment of the marsh is associated with the gravel feature. An examination of the gravel ridges of the north Norfolk coast shows that at low water large sand flats are exposed around ridge edges and these flats are often adjacent to marsh sediments which may be cliffed (e.g. Thornham harbour, between Holme and Brancaster). The marsh sediments of this region are thus undergoing some lateral erosion, although accretion of sediment, which is often sandy, occurs on the upper surface. Thus the area near Wolferton creek, at the southern end of the gravel ridge, is analogous to ridge terminations on the north Norfolk coast, although it shows a later stage of development.

2. The Higher Mud Flat

This sub-environment is very much broader than that described by Evans (1960) and here it may reach a width of 1,300 yards. The gradient here varies between 1 in 800 and 1 in 1,400, whilst near the Witham outfall the average gradient is 1 in 461.

The mud flat of the latter area has a very irregular surface with elongate depressions and drainage channels which may have depths of up to one foot. At its outer edge the mud flat may have a cliff several inches high. Inglis and Kestner (1958 B) consider that this irregular surface is typical of well established mud flats and it is not found in front of new training walls. Greensmith and Tucker (1966) described a similar type of relief at Bradwell, Essex, where tongues of silty mud are elongated parallel to the depositional slope and are separated by shallow drainage channels. The development or degradation of these features is dependent on the balance between erosion and deposition. In the well established mud flats of the Wash, erosion and deposition have resulted in the production of this irregular surface.

However, the higher mud flats examined in the present study, generally have a smooth surface although there are occasions when shallow scoured areas exposing eroded laminae are found (fig. 7.2). Drainage channels may develop but these are broad shallow features having depths of less than three inches. Near the outer edge of the mud flat these channelled areas are often sandier and are colonised by Arenicola marina, whereas the intervening ridges have a more silty composition and an abundant fauna of Corophium sp. (fig. 7.3).

There is never a sharp junction at the outer edge of the higher mud flat, but merely a gradual transition onto the Arenicola sand flat. Because of this an inner sand flat, as described by Evans (1960) was not distinguished. In the north, near Snettisham, the higher mud flats gradually merge into the sediments of the Inner Road creek complex but in places small areas of Arenicola sand flat are developed.



Fig. 7.3 Channelled higher mud flat with sandier sediments in the depressions showing casts of Arenicola marina. The ridges are more silty in composition and have an abundant fauna of Corophium sp.

Where creeks cut obliquely across the intertidal zone the sub-environment is occasionally found to change across the creek boundary. On the landward side of the creek the mud flat sediments prograde further towards low water mark, whilst on the seaward side ebb scour removes the finer sediment (fig. 7.4).

Enteromorpha sp. is very common on the mud flat near the Witham outfall, this becoming abundant when the deposition rate is slow. During rapid deposition, as in the study area, the algae do not appear to colonise the zone.

3. The Arenicola Sand Flat

The sub-environment is very extensive here, as it is elsewhere in the Wash, and its maximum width is approximately 1.5 miles. Small areas of Arenicola sand flat are developed between the higher mud flat and creek sub-environments near the Inner Road in the extreme north of the area.

In many places the Arenicola sand flat ends abruptly at the top of a steep slope which passes down into the channel, and is succeeded by a lower sand flat or occasionally a lower mud flat. At the northern limit of the Ferrier Sand, however, the sand flat near low water mark has a very gentle gradient and there is no well defined channel near low water mark. Arenicola marina is found here only occasionally and the sediments appear similar to the sediments found in the lower part of Stubborn Sand, with an infauna dominated by Cerastoderma edule and Lanice conchilega.

4. The Lower Mud Flat

This forms a very restricted sub-environment and only appears along the banks of channels which have a limited tidal flow or have some form of protection from erosion. There appears to be a critical slope factor for the deposition of the lower mud flat. It is found on the west bank of the Inner Road, on the bank of the trained channel of the Ouse near North Wootton

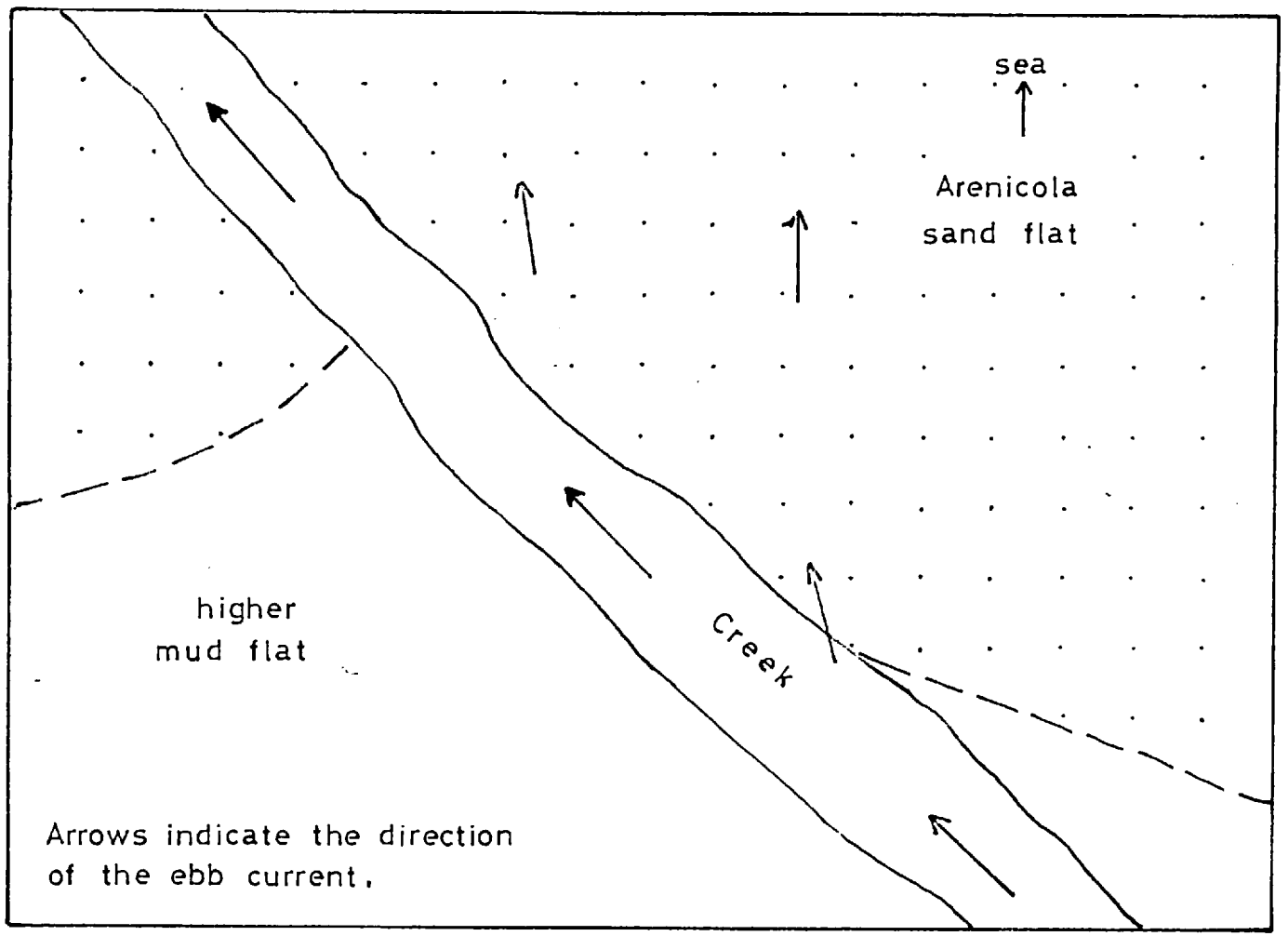


Fig. 7.4 Environment boundary near oblique creeks.

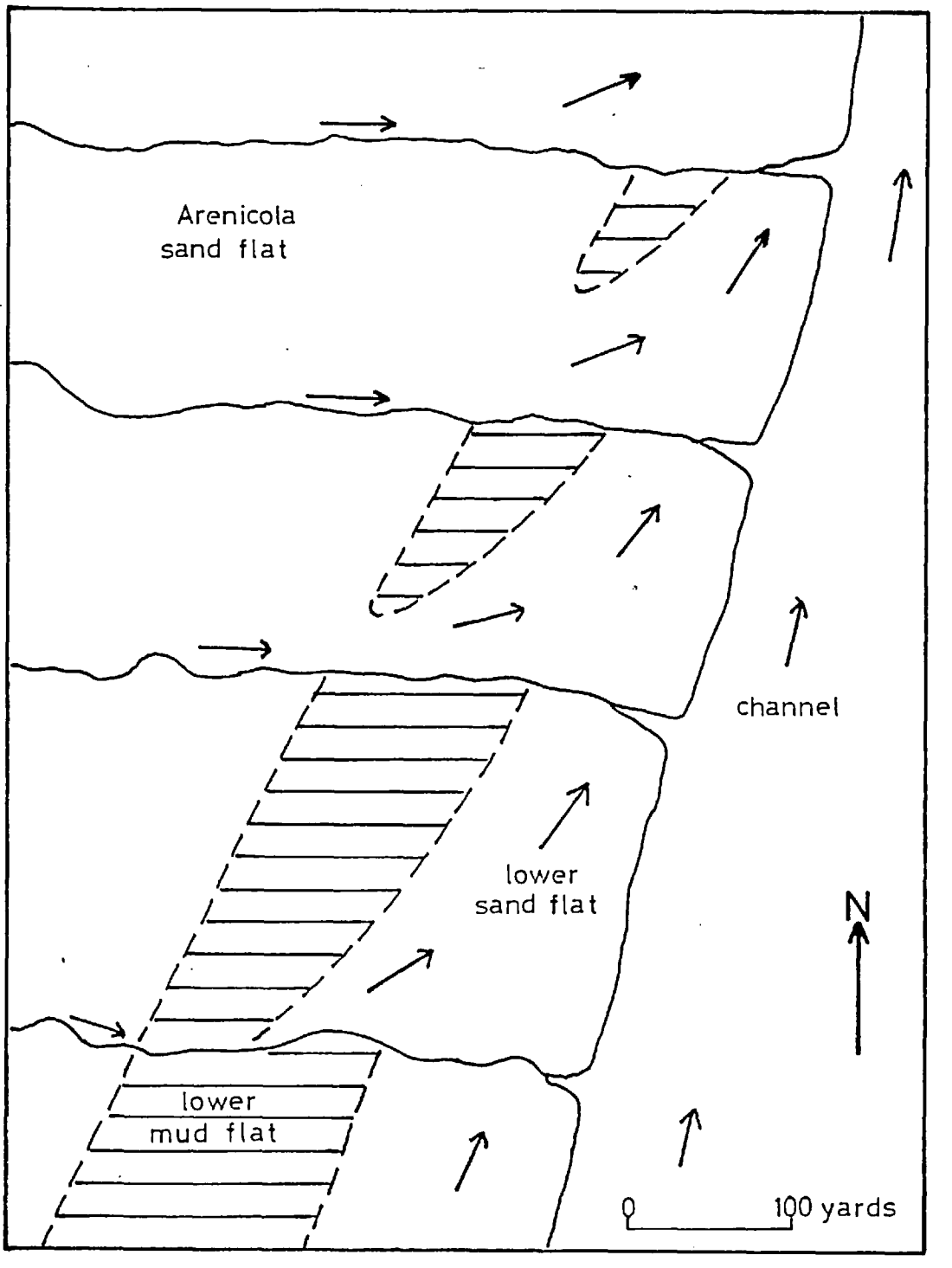
and in the lower regions of creeks near the outer edge of the Arenicola sand flat.

In all three localities the deposition of the lower mud flat sediment takes place on a steeper slope than that of the Arenicola sand flat. However, if there is a very steep slope from the edge of the Arenicola sand flat into the channel, this sub-environment is not present. It is also absent where there is no change in slope towards low water mark. On the opposite shoreline of the Wash the lower mud flat is developed in the area studied by Evans (1960), but to the north the Arenicola sand flat passes seaward into a sand flat at the channel edge with very little change in slope. Where the lower mud flat gradually disappears, it shows its maximum development on the southern side of creeks (fig. 7.5) whilst on the northern side the mud flat does not readily develop due to the constant removal of fine sediment by ebb water from the creek. This is probably due to the influence of the northerly flowing ebb current in the main channel.

The occurrence of lower mud flat in the Inner Road is considered to be analogous to its occurrence near the Witham outfall. In the case of the former it is to some extent related to the presence of a Mytilus edulis bank at the upper limit of the mud flat. This separates it from the Arenicola sand flat of Ferrier Sand.

The lower mud flat in the south, adjacent to the training wall of the Great Ouse has a very recent origin. When this area was first visited, in the early part of 1966, the Arenicola sand flat and higher mud flat were being rapidly eroded and a cliff had been formed at the edge of the channel (fig. 2.9). Since then, however, the channel has been partially trained (the top of the training walls has an approximate height of -1.0 feet O.D.) and erosion of this cliff has ceased. Rapid accretion of sediment took place here so that now the intertidal flat surface slopes gently into the channel. The upper part of this surface is a typical lower mud flat sub-environment, whilst the lower part is equivalent to the lower sand flat of Evans (1960) (fig.7.6).

Fig. 7.5. Restriction of the lower mud flat at Butterwick Low.



Arrows indicate the direction of the ebb current.



Fig. 7.6 Lower mud flat with a smooth surface passing into a rippled lower sand flat near low water mark at North Wootton.

At most localities north of this area the Arenicola sand flat has a steep edge and passes directly into the sands of the channel or lower sand flat. Some zones show patches of more silty sediments but these are not continuous.

5. The Lower Sand Flat

This is also a restricted sub-environment and in many places occupies merely the narrow steep slope bordering the channel. The lower sand flat of the Inner Road has more silt present than is found adjacent to the channel at the western edge of the area. Near the training wall of the Great Ouse, it is similar to the sand flats described by Evans (1960). The lower sand flat may be considered as a channel margin sub-environment and the sediments here are very variable due to the variations in tidal action in the channels.

6. The Creeks and Bordering Areas

A large number of creeks between Wolferton and Ferrier Sand coalesce to form a wide creek belt at the southern limit of Inner Road. South of Ferrier Sand the creeks run east - west, approximately perpendicular to the shoreline, and enter the main tidal channel. Thus drainage of water from the tidal flats is to the north at Wolferton, while south of here drainage is to the west.

The creeks in this region are relatively shallow compared with those near the Witham outfall. In the lower intertidal sub-environments the creeks do not exceed a depth of three feet, whereas in the higher sub-environments they become more incised, reaching depths of about six feet. The shallow creeks of the lower flats are thus able to migrate rapidly (cf. van Straaten 1954) whereas in the marsh, lateral migration is slow. Ebb run-off has less erosive power when the intertidal environment is broad and gradients are low. This must account for the relatively shallow creeks compared with those of the flats near the Witham outfall.

The area to the south of Inner Road can be considered as a wide creek zone, which interrupts the normal succession of intertidal sub-environments. Sediments here are closely comparable to lower mud flat sediments. Throughout the area levees of silty sediment are common, while rippled sandy sediments are present in the floors of the creeks.

In the marsh, the levees are composed of coarser sediment than the marsh and are often colonised by the marsh plant, Halimione portulacoides. On the mud and sand flats the levee and bank laminations vary considerably compared with the tidal flat areas.

Adjacent to the Arenicola sand flat, some levees and banks may have a higher silt content than the surroundings (see van Straaten 1954), the sediment surface may be smooth and the fauna may differ from the sand flat fauna. In the lower parts of creek zones, small areas of mud flat are formed. These interfinger with and occupy low creek areas between the Arenicola sand flat. These areas are found surrounding the creeks immediately south of Ferrier Sand. They occupy a similar position in the vertical succession, as does the lower mud flat. However, these mud flats are directly associated with creek zones and are not found adjacent to the main tidal channel at the edge of Ferrier Sand.

II The Grain Size Distributions of the Sediments

1. The Salt Marsh

Sand-silt-clay ratios plotted on a triangular diagram (after Shepard 1954) show that the marsh sediments sampled contain less than 10% sand, and that silt and clay are present in more or less equal proportions (fig. 7.7). These sediments are clayey silts and silty clays (Shepard 1954). The samples show a very restricted distribution on the triangular diagram. The average percentage of sand is 2.88 and in most samples there is slightly more silt present than clay (table 7.1).

Fig. 7.7. Sand-silt-clay ratios for sediments of the various sub-environments of the intertidal flats.

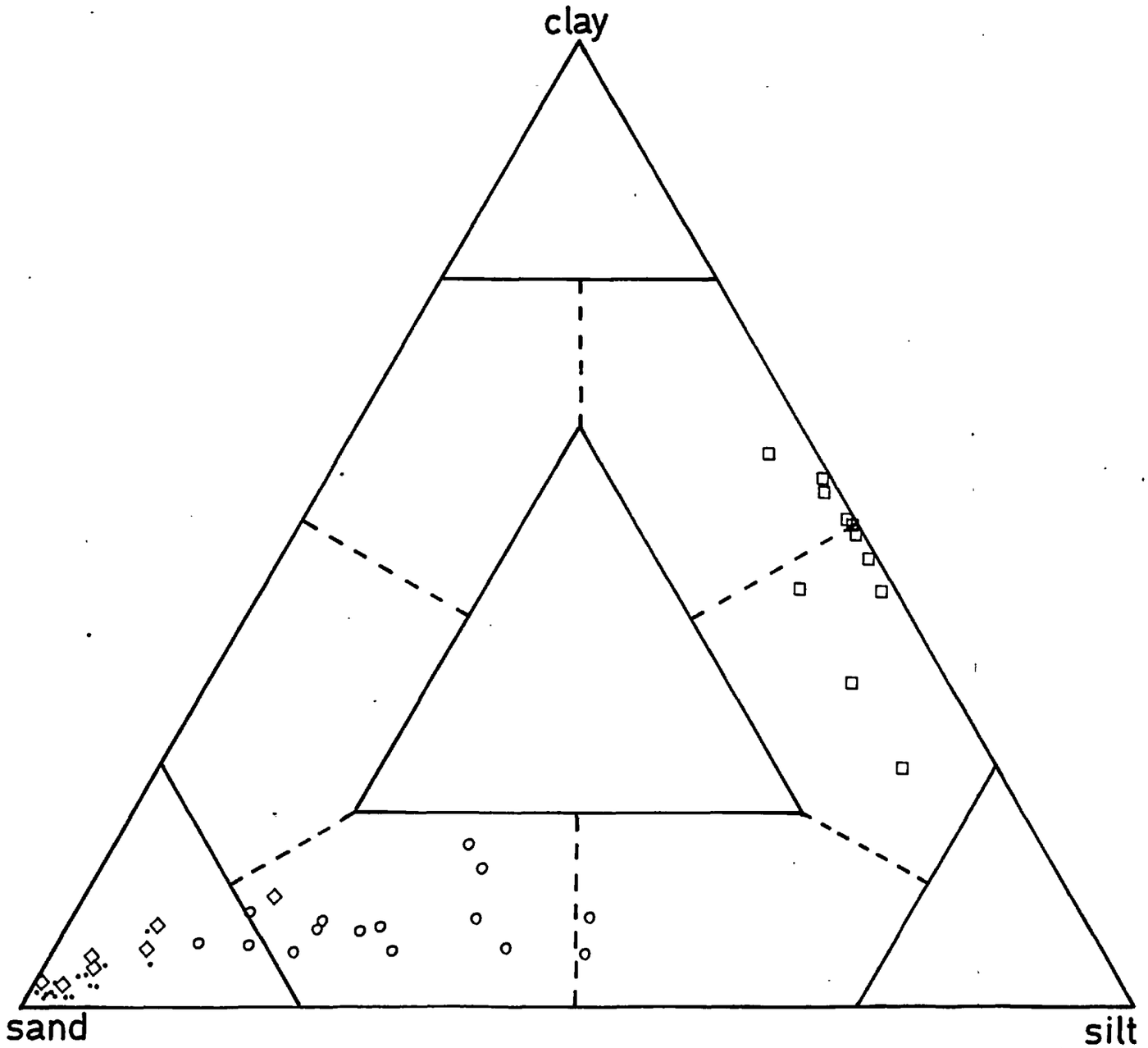


Table 7.1 Grain Size Parameters for Inner Wash Subenvironments

Profile/ Sample Number	Mean Diameter	Sorting	Skewness	% Sand	% Gravel	% Silt	% Clay
Marsh							
9/151	7.87	2.05	-0.045	0.34		49.78	49.88
12/194	7.65	2.12	-0.005	1.15		52.36	46.49
12/199	7.85	2.08	-0.042	0.51		49.85	49.64
12/202	6.33	2.24	+0.552	8.99		66.66	24.35
10/220	7.77	2.12	-0.049	0.46		50.11	49.43
10/223	7.28	2.26	-0.095	1.91		55.01	43.08
11/250	8.16	1.90	-0.115	0.83		44.18	54.99
7B	-	-	-	8.84		58.02	33.14
Higher Mudflat							
9/155	4.18	1.04	+0.490	46.64		47.44	5.92
9/157	4.33	1.43	+0.625	53.44		40.43	6.13
9/160	3.84	1.18	+0.536	72.88		21.21	5.91
12/206	3.31	1.28	+0.668	80.46		12.58	6.96
12/208	5.01	2.47	+0.645	51.54		31.64	16.84
10/226	4.09	1.31	+0.586	63.69		28.28	8.03
10/228	3.94	1.37	+0.190	69.14		22.94	7.92
10/229	4.29	1.56	+0.602	54.70		36.17	9.13
11/254	4.49	1.55	+0.550	44.14		46.34	9.52
11/259	4.00	1.45	+0.908	68.42		22.64	8.94
11/260	3.67	1.34	+0.583	76.71		17.13	6.16
1B	5.11	2.09	+0.632	50.27	1.14	34.31	14.28
6B	4.27	1.39	+0.644	65.40		26.66	7.94
28	3.56	1.68	+0.740	74.75		15.88	9.36
29	3.92	1.15	+0.460	63.84		30.33	5.73
30	3.74	1.28	+0.438	76.14		17.89	5.79
Arenicola Sandflat							
4B	2.80	0.38	+0.167	97.41		1.49	1.09
9/163	3.22	0.50	+0.394	92.05		5.75	2.20
9/166	3.10	0.35	+0.270	95.33	0.04	3.11	1.56
9/168	3.02	0.30	+0.196	97.18		1.29	1.53
9/170	2.80	0.45	-0.030	96.94	0.06	1.20	1.86
9/174	2.93	0.30	+0.092	97.62		1.03	1.35
9/177	2.71	0.32	-0.005	97.66		0.90	1.44
8/185	-	-	-	76.44	17.52	2.88	3.16
8/187	2.86	0.49	+0.269	93.53		3.37	3.10
8/189	2.86	0.47	+0.117	92.40	2.45	2.72	2.43
10/233	3.26	0.85	+0.529	86.07		9.57	4.36
10/235	3.12	0.51	+0.205	92.04	0.09	5.16	2.71
10/237	3.21	0.81	+0.476	90.40	0.07	5.29	4.24
10/239	3.26	1.23	+0.561	84.38	3.00	6.88	5.74
10/242	2.97	0.34	+0.132	95.89	1.14	1.68	1.29
10/245	2.79	0.39	+0.036	97.39		1.11	1.50
11/263	3.07	0.39	+0.177	95.64		3.09	1.27
11/265	2.93	0.36	+0.112	96.84		2.03	1.13

Continued

Table 7.1 (continued)

Profile/ Sample Number	Mean Diameter	Sorting	Skewness	% Sand	% Gravel	% Silt	% Clay
Lower Sandflat and Lower Mudflat							
9/180	2.76	0.46	+0.240	95.56		2.67	1.77
8/181	2.30	0.61	-0.196	97.46	0.27	0.94	1.33
8/183	2.74	0.98	+0.240	90.62	2.01	3.29	4.08
8/191	3.17	1.15	+0.625	85.63	1.12	8.13	5.12
8/193	3.89	1.94	+0.743	71.36		17.84	10.80
11/267	3.20	1.59	+0.681	83.09		8.31	8.60
Musselbed							
8/133	5.07	2.82	+0.010	57.91		21.22	20.88
Crest of Megaripple							
10/247	2.32	0.27	+0.085	99.74		0.26	
Channel Edge							
10/249	2.72	0.26	-0.021	100.00			
11/3B	2.67	-	-	85.82	6.12	4.79	3.27
Creeks and Creek Levees							
196	7.32	2.31	+0.056	4.06		51.45	44.49
222	6.21	2.23	+0.558	10.63		65.05	24.32
224	5.43	2.10	+0.616	31.48		52.49	16.03
251	7.73	2.08	+0.029	1.16		51.89	46.95
159	3.99	0.64	+0.237	56.49		40.12	3.39
204	5.01	2.11	+0.608	43.93		41.74	14.33
243	3.12	1.00	+0.585	91.06		3.91	5.03
244	3.01	0.47	+0.194	94.37		3.41	2.22
2B	5.39	1.96	+0.700	42.96		41.39	15.65

Continued

Table 7.1 (continued) Ranges and Average Values

	Mean	Sorting	Skewness	% Sand	% Gravel	% Silt	% Clay
Marsh							
Range	6.33 to 8.16	1.90 to 2.26	-0.095 to +0.552	0.34 to 8.99		44.18 to 66.66	24.35 to 54.99
Average	7.56	2.11	+0.028	2.88		53.25	43.87
Standard Deviation	0.54	0.11	0.216				
Higher Mudflat							
Range	3.31 to 5.11	1.04 to 2.47	+0.190 to +0.908	44.14 to 80.46		12.58 to 47.44	5.73 to 16.84
Average	4.11	1.47	+0.581	63.35		28.24	8.41
Standard Deviation	0.46	0.36	0.149				
Arenicola Sandflat							
Range	2.80 to 3.26	0.30 to 1.23	-0.030 to +0.529	76.44 to 97.66	0.00 to 17.52	0.90 to 9.57	1.13 to 5.74
Average	3.00	0.50	+0.218	93.08	1.35	3.26	2.32
Standard Deviation	0.27	0.26	0.182				
Lower Sandflat and Lower Mudflat							
Range	2.30 to 5.07	0.26 to 2.82	-0.196 to +0.743	57.91 to 100.00	0.00 to 6.12	0.00 to 21.22	0.00 to 20.88
Average	3.08	0.49	+0.241	86.72	0.95	6.73	5.59
Standard Deviation	0.81	1.30	0.341				
Creeks and Creek Levees							
Range	3.01 to 7.73	0.47 to 2.31	+0.029 to +0.700	1.16 to 94.37		3.41 to 65.05	2.22 to 46.95
Average	5.25	1.66	+0.400	41.80		39.04	19.16
Standard Deviation	1.57	0.68	0.247				

Histograms of the sediment distributions are broad and often polymodal, although the modes are not generally very pronounced (fig. 7.8). Two modes are persistent in the analyses, and these are at 4.75 - 5.00 phi and 5.75 - 6.00 phi. In sample 202, from the outer marsh edge, the coarse mode is very dominant but in other samples there is no obvious relationship to the sample locality.

Mean grain diameter varies from 6.33 to 8.16 phi and the average size is 7.56 phi. The sediments are very poorly sorted (Folk & Ward 1957) and most samples have low negative skewness. Sample 202, from the outer marsh edge, has a high positive skewness and in this respect it compares closely with the sediments of the higher mud flat.

2. The Higher Mud Flat

The sediments of this sub-environment show a wider range of sand-silt-clay proportions than do the marsh sediments, although most samples are included in the silty sand field of the triangular diagram (see fig. 7.7). There appears to be a rapid coarsening of sediment seaward of the marsh edge, as the fields shown for the higher mud flat and salt marsh are widely separated. This is largely due to the effectiveness of vegetation at the marsh edge in trapping silt and clay and in preventing erosion of this finer sediment. The sediments of the higher mud flat described by Evans (1965) are silty sands and sandy silts, the sand-silt-clay ratio having a broader range, so that the composition sometimes approaches the composition of the salt marsh sediments.

Grain size distributions are unimodal, the mode being more dominant than those of the sediments of the salt marsh (fig. 7.9). The modal size is generally between 3.0 and 4.0 phi (very fine sand) although some samples are coarser with a mode in the fine sand grade. All these distributions have large fine tails but the proportions on the coarse side of the mode drop off abruptly. This is reflected in the values of skewness.

Fig. 7.8. Typical Grain Size Distributions of Salt Marsh Sediments.

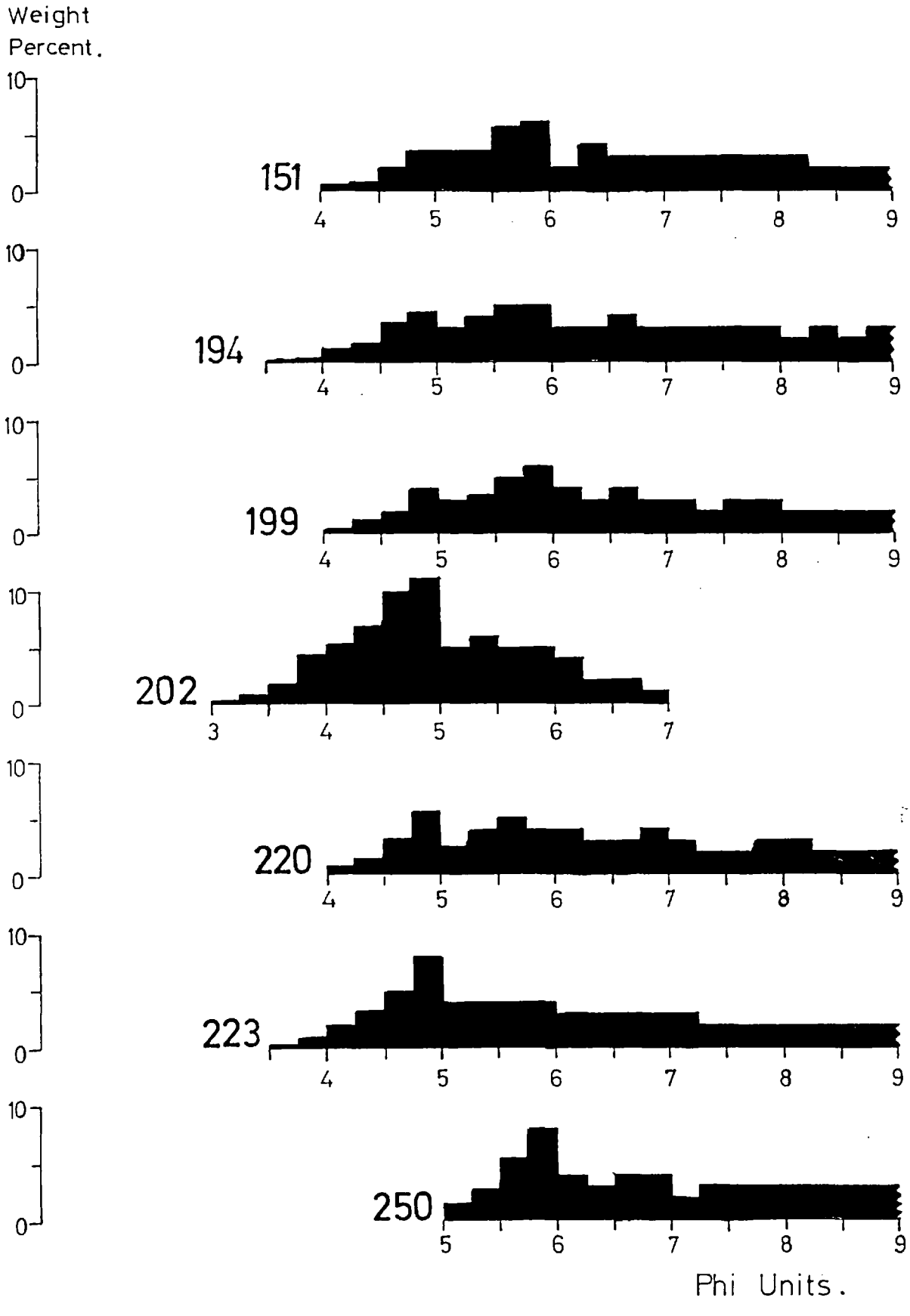
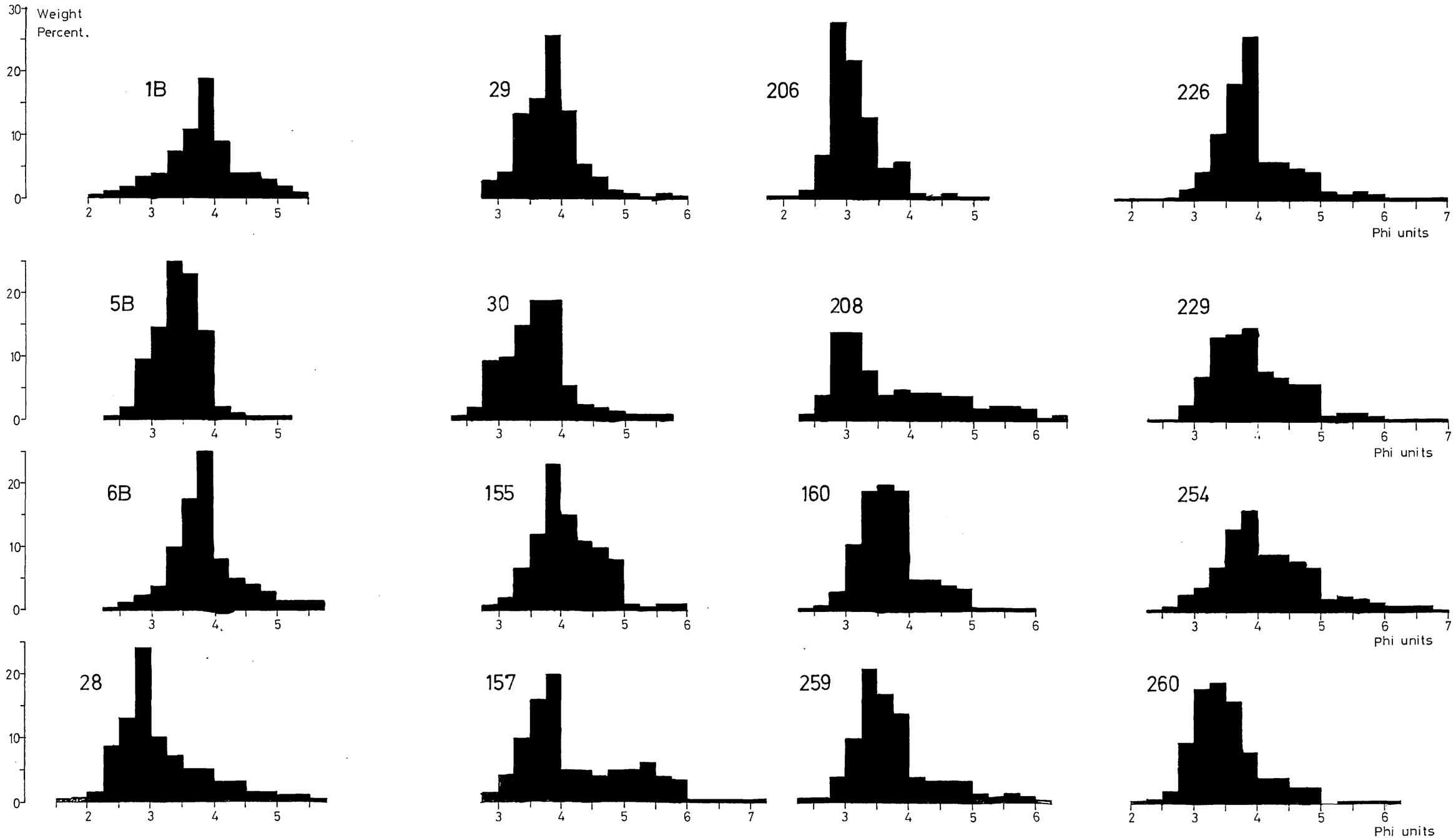


Fig. 7.9 Typical Grain Size Distributions of Sediments of the Higher Mud Flat.



The mean grain diameter ranges from 3.31 to 5.11 phi and the average value is 4.11 phi (table 7.1). The sediments are poorly and very poorly sorted although the average values show that they have a higher degree of sorting than the sediments of the salt marsh. In marked contrast to the salt marsh sediments, the sediments of the higher mud flat have high positive values of skewness. This is due to the large tail of fine sediment which may be seen in the histograms.

3. The Arenicola Sand Flat

The sediments found in this sub-environment are fine and very fine sands with low percentages of silt and clay (fig. 7.7). The silt content varies from 0.90 % to 9.57 %, while there is less clay present, this varying from 1.13 % to 5.74 %. Gravel sized material, normally shell and never lithic or quartz particles, is found as small proportions in some samples.

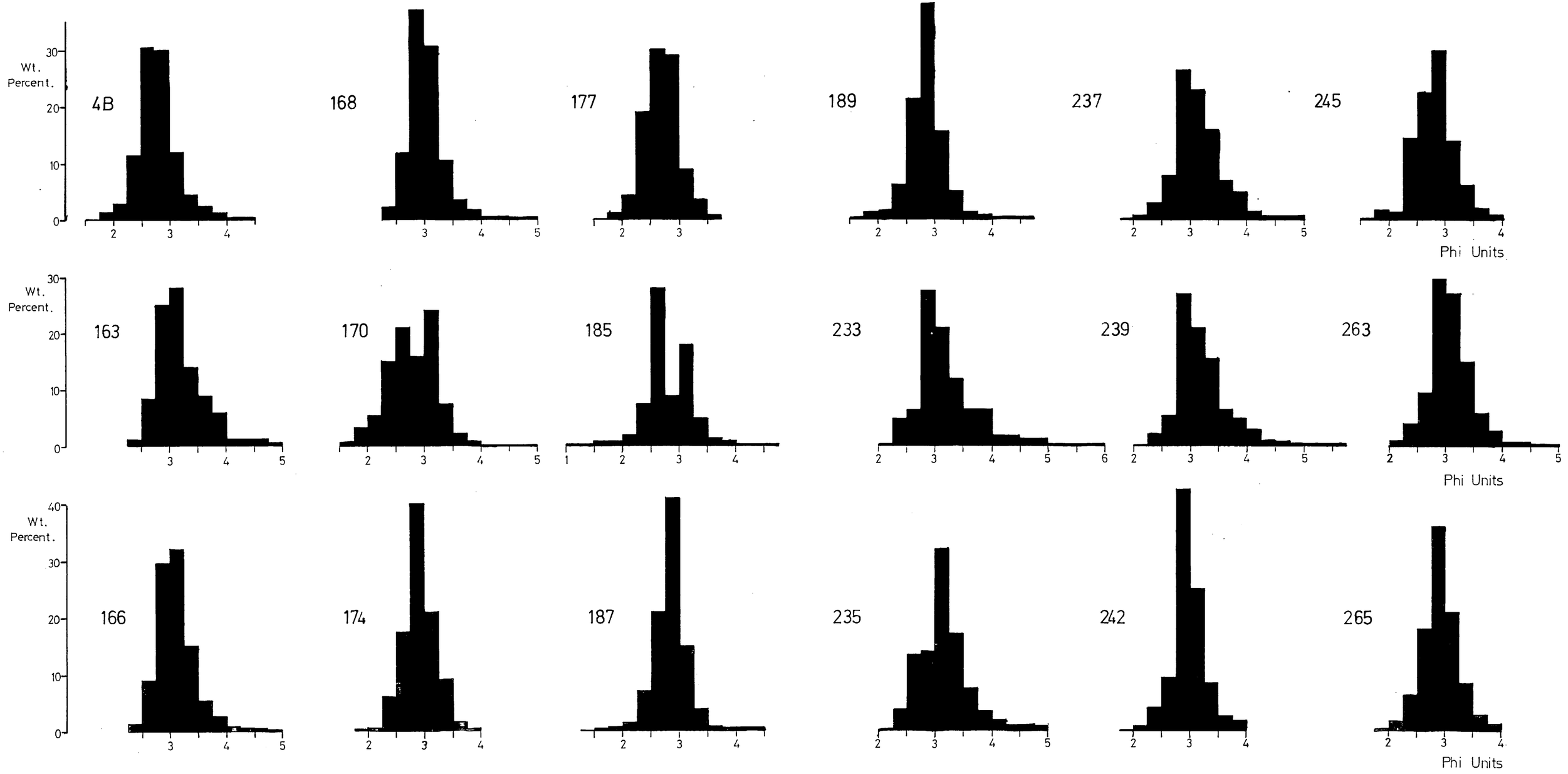
Histograms of these sediments show that the distributions are usually unimodal, although two samples have bimodal distributions (fig. 7.10). The most common modal size is 2.75 - 3.00 phi, while modes of 2.50 - 2.75 phi and 3.00 - 3.25 phi are also found

The average mean diameter is 3.00 phi and the range is more restricted than that for the sediments of the higher sub-environments (see table 7.1).

The degree of sorting of the sediments is highly variable and the distributions range from poorly sorted (1.225 phi) to very well sorted (0.298 phi). The average value and standard deviation of the sorting show, however, that the sediments are generally well sorted. The extreme value of 1.225 phi was obtained from a small mud flat zone within the Arenicola sand flat. Apart from this the sediments show a more limited range and a distinctly higher degree of sorting than the sediments of the higher mud flats.

Skewness varies from -0.030 to +0.529 but most samples have low positive values, the average being +0.218. The higher positive values were obtained from samples having higher percen-

Fig. 7.10 Typical Grain Size Distributions of Sediments from the Arenicola Sand Flat.



tages of silt and clay. These sediments are characteristic of the inner edge of the sand flat adjacent to its junction with the higher mud flats.

4. The Lower Sand Flat and the Lower Mud Flat

The sediments of the two lower sub-environments are sands and silty sands and the content of silt and clay is very variable (table 7.1). The silt content ranges from 0.0 % in the clean sands of the sand flat to nearly 20.0 % in the mud flat sediments. The sediments of the Mytilus reef contain over 20 % of silt. The sediments contain similar proportions of clay.

A plot of the sand-silt-clay proportions shows that these sediments cannot be clearly differentiated from the sediments of the Arenicola sand flat (fig. 7.7). The grain size distributions are unimodal, and the modal size generally lies between 2.5 phi and 3.0 phi (fig. 7.11). The average mean grain diameter is 3.08 phi and is almost exactly the same as the value for the sediments of the Arenicola sand flat. However, the sediments of these lower sub-environments show a wider range of grain size and this reflects the variable nature of the frequency distributions of the sediments.

The sorting also shows a wide spread, from very well sorted to very poorly sorted (0.26 to 2.82 phi) although the average value is in the well sorted category. Skewness results range from low negative to high positive values but most of the sediments are positively skewed.

5. The Creeks and Bordering Areas

There is an increase in mean grain diameter from high to low water mark; the sediments near high water mark are clayey silts, while seawards they pass into silty sands and sands (fig. 7.12).

The sediments of the creek floors and levees are characteristically coarser than the sediments of the adjacent higher

Fig. 7.11. Typical Grain Size Distributions of the Sediments of the Lower Sand Flat and Lower Mud Flat.

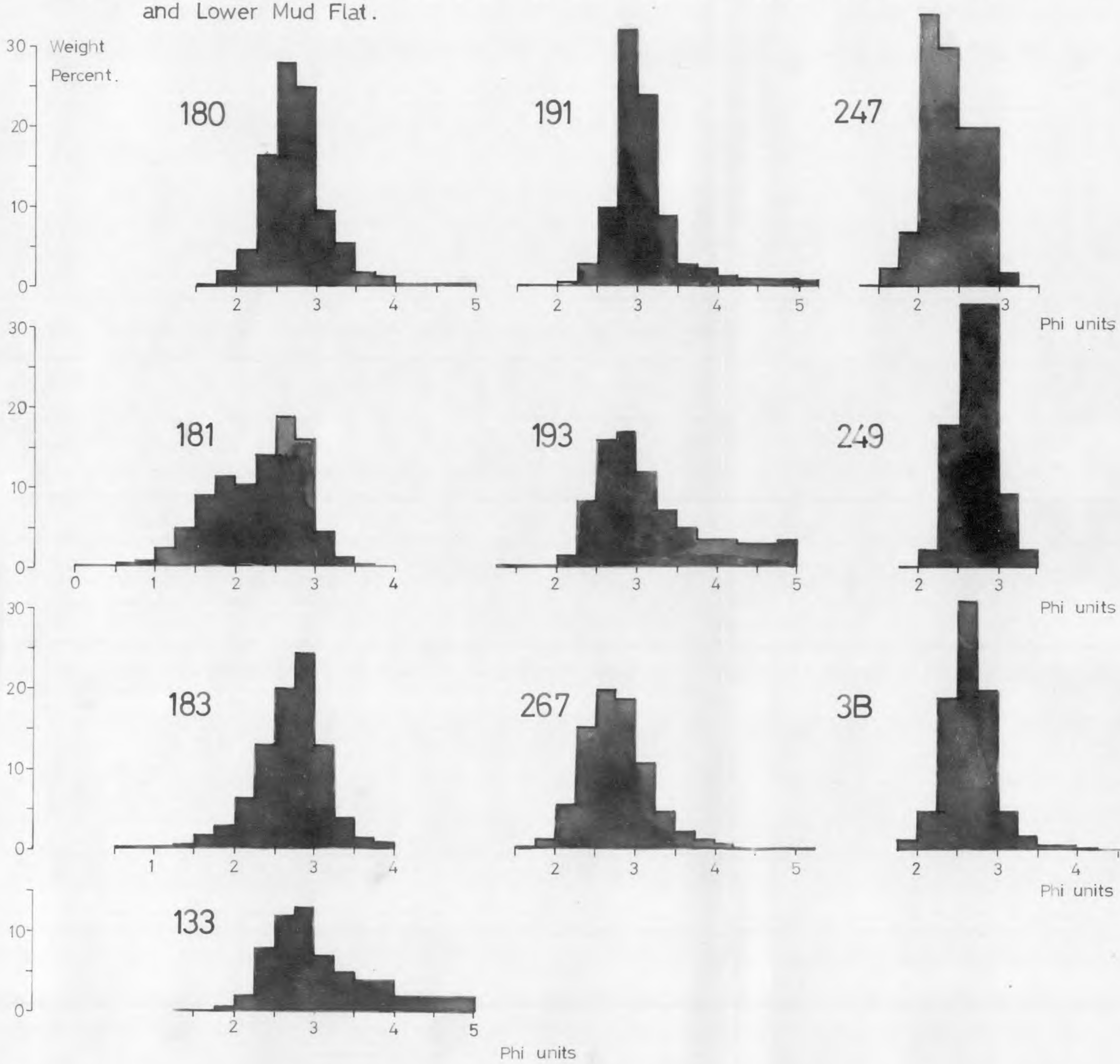
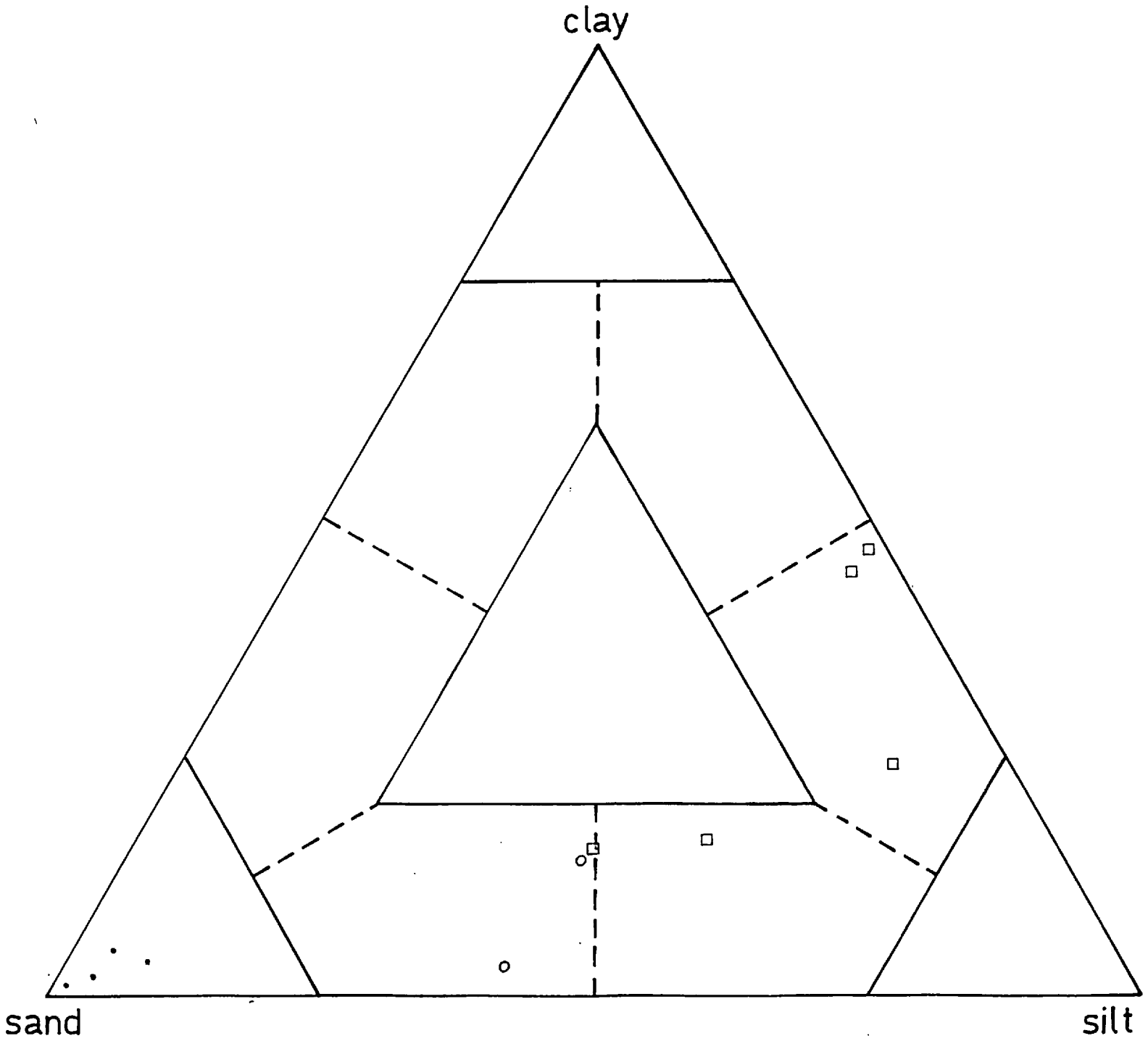


Fig. 7.12. Sand silt clay ratios for sediments of the creeks and bordering areas.



tidal flats. This is not, however, shown for the sediments adjacent to the Arenicola sand flat.

Sediments adjacent to the marsh are polymodal, while nearer the Arenicola sand flat the sediments are unimodal (fig. 7.13). In this respect they are similar to the sediments of the adjacent sub-environments. Modal sizes for the marsh creeks compare with the modal sizes of the marsh sediment distributions, but in some samples a coarser mode, between 3.75 and 4.00 phi, is present. This mode is also the dominant mode shown by creek samples adjacent to the higher mud flat.

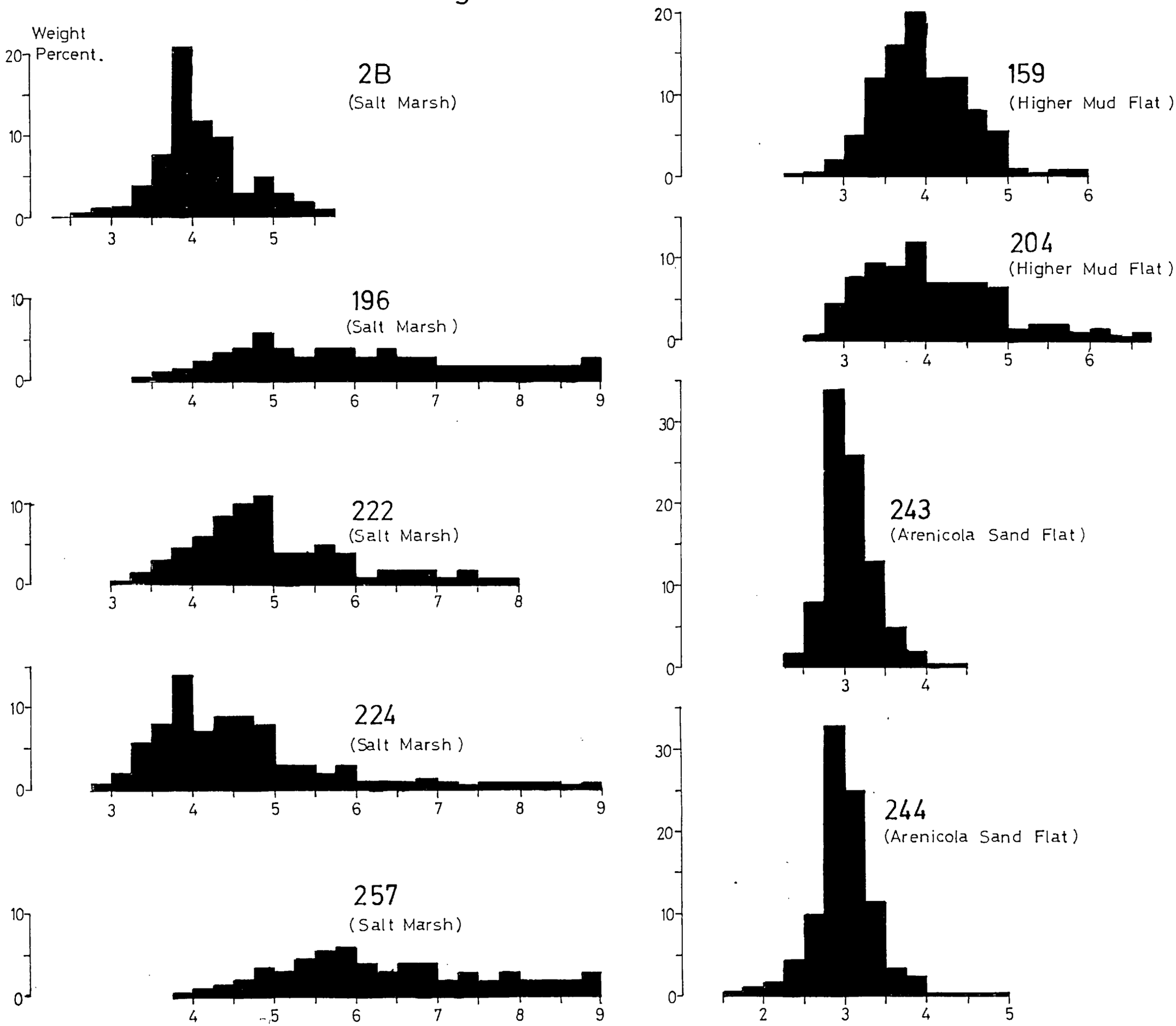
The modal size of creek sediments adjacent to the Arenicola sand flat is 2.75 - 3.00 phi. This is also the commonest modal size for Arenicola sand flat sediments. Values for sorting and skewness of these sediments are also very similar to those of the adjacent sub-environment.

Sorting and skewness parameters have wide ranges although the results are similar to the values for the adjacent sub-environments. The sediments near high water mark are very poorly sorted, while seawards the sorting improves. All skewness results are positive. In this respect the marsh creek sediments differ from the marsh sediments, where negative skewness is more common.

6. Conclusions

This sequence of sub-environments, from low to high water marks, shows a gradual decrease in the mean grain diameter of the sediments. Some exceptions to this do occur due mainly to the proximity of creeks and restricted tidal channels. Evans (1960) has shown this to be true for the tidal flats near the Witham outfall and it would appear that this also applies to the remaining shoreline of the Wash. The fine and very fine sands and silty sands of the lower sub-environments pass up into the sandy silts, clayey silts and silty clays of the upper sub-environments (see Shepard 1954 for terminology).

Fig. 7.13. Typical Grain Size Distributions of Sediments of the Creeks and Bordering Areas.



Horizontal scales in phi units.

Evans (1965) notes that the sediments north of the area which he studied are much sandier and there is less mud present. This is true for this area between Wolferton and King's Lynn. The higher mud flats here are noticeably sandy (mostly silty sands) and the range of mean diameter is 3.31 to 5.11 phi. At the inner edge of this sub-environment, however, there is a rapid decrease in the sand content. The median diameter which Evans measured ranged from 4.00 to 6.75 phi.

A consistently high degree of sorting is shown by the sediments of the Arenicola sand flat of both this area and that studied by Evans (1965). Some of the sediments of the lower sand flat have high degrees of sorting (e.g. sample 247 from the crest of a megaripple (table 7.1) and 249 from a steep channel edge) but other sediments of this sub-environment show lower values.

The high degree of sorting of the Arenicola sand flat sediments reflects the extensive reworking by waves and organisms which takes place in this sub-environment.

The high degree of sorting seen in some of the lower sand flat sediments is due to reworking by longshore tidal currents. The poorly sorted sediments in the lower sub-environments are the result either of rapid sedimentation (as in the small lower mud flat in the south, in the lower mud flats near the Witham outfall and where Mytilus sp. aids the deposition of fine sediment) or of deposition in an area which is not subject to strong tidal current action and wave action, e.g. low areas fingering into the Arenicola sand flat south of the Ferrier Sand. These are sheltered from longshore tidal currents by the surrounding sand flats and they are too deep at slack water high tide for effective wave action. Evans (1965) has shown that the sediments of all the sub-environments are positively skewed, although he did not obtain results for marsh sediments. A similar skewness was generally found in the sediments of the study area. The skewness of marsh sediments was determined by extrapolation of the cumulative curve. As the frequency distribution of the clay fraction of each sample has not been determined and as a large

percentage of clay is present, the significance of these results may be questionable and it seems that they are of little value. The low results of skewness, both positive and negative, merely aid in distinguishing these sediments from those of the higher mud flat.

Apart from the marsh, the sediment distributions of the Arenicola sand flat have lower skewness values than those of the other sub-environments, showing that they have only small tails of fine sediment and are almost symmetrical. Similarly, some sediments of the lower sand flat show these features (samples 181, 247 and 249) and there is a considerable overlap of skewness results.

The higher mud flat sediments have higher positive values of skewness because of the large tail of silt and clay which is present.

Thus the reworking of the Arenicola sand flat sediments results in the production of a well sorted sediment with low positive skewness. The higher mud flat is not reworked to the same extent and thus silt and clay accumulate here to form the fine tail.

III The Composition of the Sediments

The coarse fraction composition of these sediments was investigated using a similar procedure to that used for the sediments from the areas already discussed. The coarse fraction was first examined in bulk (table 7.2) and for some samples graded splits were examined. The feldspar content of a limited number of samples was determined and it was found to range between 6.5% and 16.0%. These sediments should therefore be classified as subarkoses (Folk 1954). These results compare closely with those of Evans (1965).

1. The Salt Marsh

The terrigenous component of the salt marsh ranges between 21% and 62%. Coal, mica and rock fragments form a large propor-

Table 7.2 Results of Total Coarse Fraction Determinations

Sample	Terrigenous	Glauconite colite	Rock Fragments	Mollusc/ Barnacle	Foramin-ifera	Plants	Ostracods	Echinoids	Coal	Mica	Bryo-zoa	Calc. spines	Dia-toms
Marsh													
151	30.0		27.5	6.5	6.5	24.0	0.5	1.0				0.5	0.5
194	53.5	0.5	26.5	4.0	6.0	9.0	0.5						
199	56.0		14.0	6.0	4.0	18.0	1.0	1.0				0.5	
220	42.5	0.5	18.5	5.0	7.5	20.0	3.5	0.5					2.5
223	62.0		19.5	9.0	5.0	very	3.5	0.5				0.5	
250	21.0		62.0	6.0	5.0	abund.	4.0	2.0					
Range	21.0 to	0.0 to	14.0 to	4.0 to	4.0 to	9.0+	0.5 to	0.0 to				0.0 to	0.0 to
	62.0	0.5	62.0	9.0	7.5		4.0	2.0				0.5	2.5
Average	44.36	0.17	28.0	6.08	5.67	-	2.17	0.83				0.25	0.50
Higher MF													
154	73.5	2.0	0.5	11.0	5.5	1.5	0.5		2.0	2.5		1.0	
155	93.5		00.5	7.0	0.5	0.5		0.5		0.5			
157	88.0	0.5	1.5	6.0	2.0		0.5		0.5	0.5		0.5	
160	89.0	0.7	0.3	5.7	1.7		0.7	0.7					
206	92.0		1.0	5.0	0.5				0.5	1.0			
210	80.0		1.0	10.5	1.5	0.5	0.5	0.5	0.5	0.5			
212	84.0		2.0	7.0	0.5		1.0	0.5	3.5	0.5	0.5	0.5	
226	91.0		0.5	7.5	0.5				0.5				
228	87.0	0.5	2.0	8.5	1.0			0.5		0.5			
229	87.0	0.5	0.5	7.0	0.5	1.0		1.0	1.5	1.0			
254	83.5	0.5	1.5	7.5	1.0	0.5		1.0	1.0	2.5		1.0	
256	80.5		1.0	11.0	1.5	0.5			4.0	1.0		0.5	
259	84.5	0.5	1.0	8.5	1.5			1.0	1.5	0.5	1.0		
260	79.5	1.0	0.5	11.5	2.0	1.0	0.5	1.0	2.5				
Range	73.5 to	0.0 to	0.5 to	5.7 to	0.5 to	0.0 to	0.0 to	0.0 to	0 to	0 to	0 to	0 to	
	92.0	2.0	2.0	11.5	5.5	1.5	1.0	1.0	4.0	2.5	1.0	1.0	
Average	85.00	0.44	0.99	8.12	1.44	0.39	0.26	0.48	1.60	0.78	0.10	0.25	
Arenicola SF													
166	93.0	3.0	1.0	1.5	5.0								
170	92.0	2.0	0.5	4.0			0.5		0.5	0.5			
174	95.5	0.5	1.0	2.0					1.0				
187	90.0	0.5	0.5	6.5	1.0			0.5	0.5	0.5			
233	92.0	1.5		3.5	2.0				0.5	0.5			
235	90.0		1.5	1.5	0.5		0.5		0.5	0.5			
239	92.5	2.0	0.5	3.5	1.0			0.5	0.5	0.5			
245	90.0	1.5	2.0	5.0	1.0				0.5				
263	93.0	1.5		4.0	0.5				0.5	0.5			
Range	90.0 to	0.0 to	0.0 to	1.5 to	0.0 to		0.0 to	0.0 to	0.5 to	0 to			
	95.5	3.0	2.0	6.5	5.0		0.5	0.5	1.0	0.5			
Average	92.00	1.39	0.78	3.50	1.22		0.11	0.11	0.50	0.33			
Lower SF & MF													
180	93.0	0.5	1.5	4.0	0.5		0.5						
181	89.0	2.5	1.5	5.5					1.5				
193	88.0	0.5		7.0	1.5	0.5			2.0				
249	93.0	2.0	2.0	3.0									
267	92.5	2.0	1.0	2.5	1.0	0.5			0.5				
Range	88.0 to	0.5 to	0.0 to	2.5 to	0.0 to	0.0 to	0.0 to		0.0 to				
	93.0	2.5	2.0	7.0	1.5	0.5	0.5		2.0				
Average	91.10	1.50	0.83	4.40	0.60	0.20	0.10		0.80				
Creeks, etc.													
159	85.0	0.5	1.0	5.5	2.0		0.5	1.0	2.5	1.5		0.5	
196	64.0	0.5	9.5	6.0	3.0	14.0	3.0	0.5				0.5	
222	79.5		4.5	4.0	2.0	5.0	3.5	1.0				0.5	
224	81.5	2.0	1.0	4.5	5.5	0.5			2.5	1.5			
243	93.7	1.0	0.7	3.7	0.3			0.3	0.3				
244	85.5	0.5	2.0	8.0		0.5	0.5	0.5	1.5	0.5	0.5		
251	45.0		11.0	7.0	6.0	v.abund.	3.0		28.0				
Range	45.0 to	0.0 to	0.7 to	3.7 to	0.0 to	-	0.0 to	0.0 to	0 to	0 to	0 to	0 to	
	93.7	2.0	11.0	8.0	6.0		3.5	1.0	28.0	1.5	0.5	0.5	
Average	76.31	0.64	4.40	5.53	2.68	2.86	1.50	0.47	5.0	0.5	0.07	0.21	

Note For marsh sediments, % coal is included with the rock fragments.

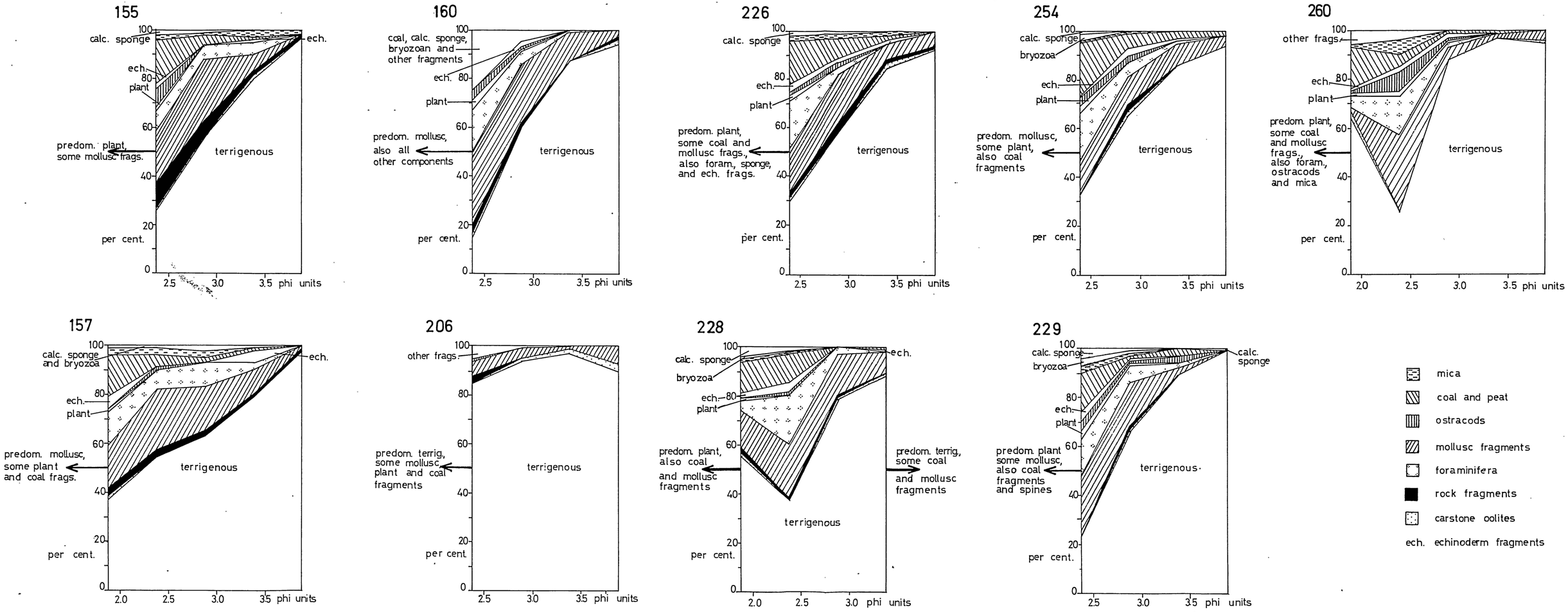
tion of the sediment (14 to 62%, the greater part of this being coal), while plant fragments are also exceedingly abundant. Some samples were treated in order to remove the plant fragments and hence the actual proportion here is not known. Carstone oolites are present in very small proportions, whilst molluscan and barnacle fragments, foraminifera, ostracod, diatoms and echinoid fragments and aggregates of iron hydroxide are abundant. Bryozoa and spheres (described by Evans (1965)) are also found but only in trace quantities. The sediments of the salt marsh were not split into size fractions in order to determine the variation of composition with size.

2. The Higher Mud Flat

The terrigenous component here has a more limited range and forms the major proportion of the sediment. Coal and rock fragments form less than 5% of the total. Carstone oolites are present in minor amounts. Plant fragments are present in only minor proportions, showing that there is a very rapid decrease in plant remains seaward of the marsh edge. Molluscan and barnacle fragments and echinoid spines and plates are present in similar proportions to those found in the salt marsh but there are fewer foraminifera and ostracods in the sediments of the higher mud flat.

The finest grade (3.75 - 4.00 phi) of the coarse fraction contains very high proportions (generally over 90%) of the terrigenous component, whilst the other 10% is predominantly molluscan and barnacle fragments (fig. 7.14). In the coarser grades there are larger quantities of these and other components, foraminifera being reasonably abundant. The proportion of minor components increases towards the coarser end of the distribution. Here coal and peat become apparent and these increase in abundance very rapidly to reach proportions of 12 to 20% at 2.25 to 2.50 phi. At this size interval the terrigenous component normally forms only 20 to 30% of the sediment.

Fig. 7.14. Variation of composition with size for higher mud flat sediments



3. The Arenicola Sand Flat

The sediments of the Arenicola sand flat contain between 90 and 95% of terrigenous components. The most abundant of the minor constituents are the molluscan and barnacle fragments and the average value of these is 3.5%. Carstone oolites are present in proportions of up to 3%, whilst coal is present as less than 1%. Foraminifera are generally present and usually form at least 1% of the deposit, whilst ostracods and echinoid fragments are more rare.

The terrigenous component thus forms a higher proportion of the sediment than it does in the higher sub-environments. Carstone oolites are slightly more common in the sediments of the sand flat, whilst coal is much less abundant. Molluscan fragments, foraminifera, ostracods, bryozoa and echinoids are all less abundant.

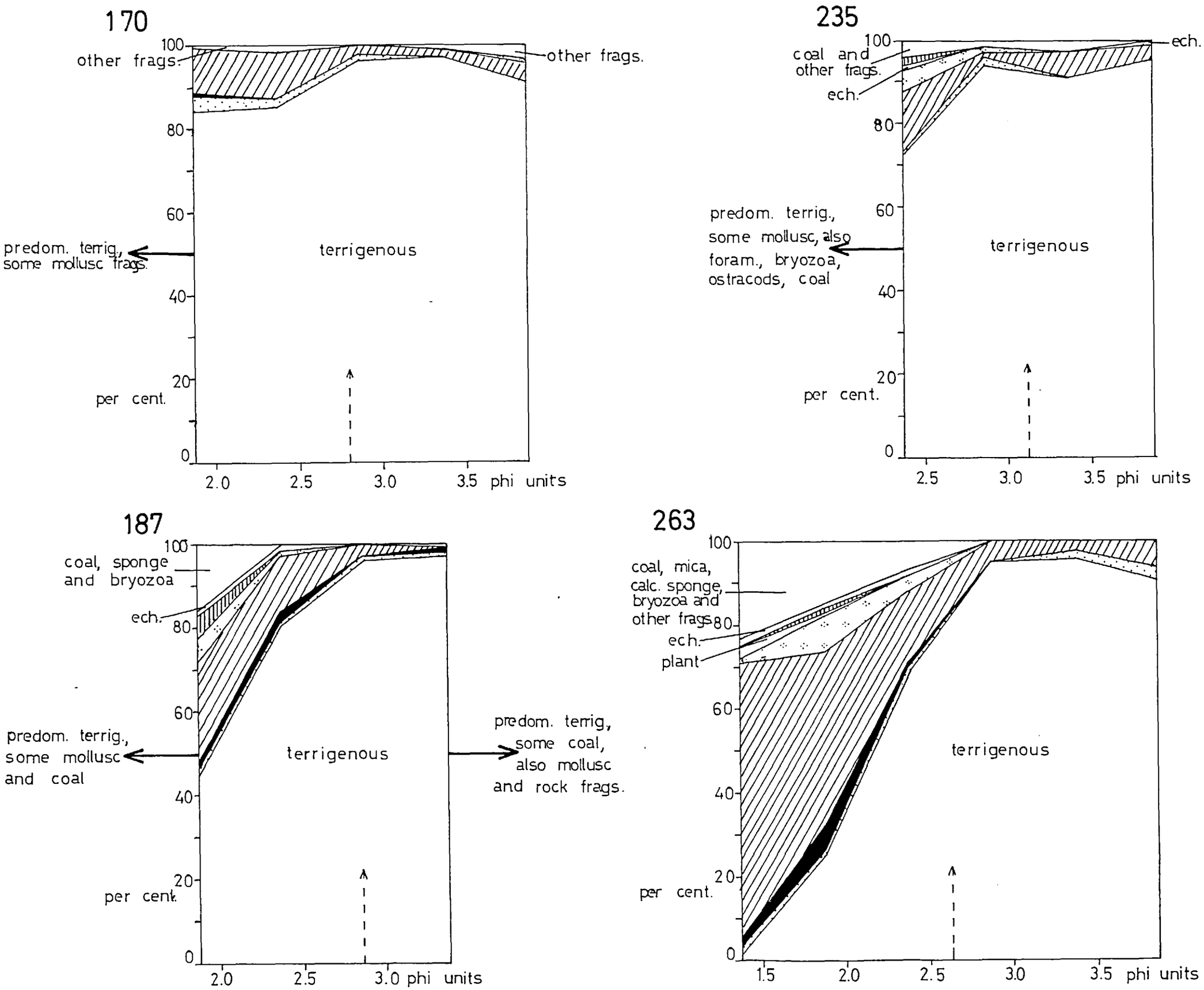
The finer fractions of these sediments also contain very high proportions of the terrigenous components and molluscan and barnacle fragments form the predominant minor component of this size (fig. 7.15). There is a marked increase with size in the proportion of the molluscan and barnacle fragments and in one sample these form over 65% of the 1.25 to 1.50 phi fraction. There is also an increase in the proportion of the other minor components although coal and peat do not form such a large proportion here. Other minor constituents include foraminifera, ostracods, echinoid fragments, bryozoa, mica and calcareous sponge fragments.

4. The Lower Sand Flat and Lower Mud Flat

The sediments of these sub-environments have compositions which are closely similar to those of the Arenicola sand flat. The terrigenous component again forms approximately 90% of the deposit, the remaining 10% being composed of the minor constituents as described for the Arenicola sand flat.

The minor components in the sediments of these sub-environments do not show the same rapid increase in proportion toward the

Fig. 7.15. Variation of composition with size for Arenicola sand flat sediments



coarser fractions, as is found in the graded compositions of the sediments of the higher mud flat and the Arenicola sand flat. In the sediments of the Arenicola sand flat the increase in proportion of the minor components is first shown by the 2.25 to 2.50 phi fraction, whereas in these sub-environments this increase is shown in the coarser fractions, the 1.25 to 1.50 phi and 1.75 to 2.00 phi groups (fig. 7.16). This shows that in the sub-environments near the channel edge the coarser fractions of the sediment have higher proportions of the terrigenous component. The coarse tail in the sediments of the lowest sub-environments has a higher proportion of the terrigenous component, whilst the coarse tail in the sediments of the Arenicola sand flat has a higher proportions of minor components, predominantly molluscan and barnacle fragments. The most abundant of the minor components in the lowest sub-environments is the molluscan and barnacle group, while Carstone oolites, rock fragments, coal and organic fragments are also present.

5. The Creeks and Bordering Areas

These sediments are also variable in composition, this being related to the composition of the adjacent tidal flat sediment. Thus marsh creek sediments have high proportions of coal and rock fragments and of foraminifera, plant fragments and ostracods. The sand flat creeks have fewer of these components.

The creek and creek associated sediments appear to have similar graded compositions to the sediments of the sub-environments which the creeks traverse. The increase in minor components in the creeks adjacent to the sand flat occurs at 2.25 to 2.50 phi, whereas in the creeks adjacent to the higher sub-environments this increase occurs in a finer fraction. Foraminifera, ostracods, bryozoa, calcareous sponges, coal and peat are all abundant in the coarser fractions and the graphs show very similar variations in composition to those of the higher mud flat (fig. 7.17).

Fig. 7.16. Variation of composition with size for lower sand flat and lower mud flat sediments

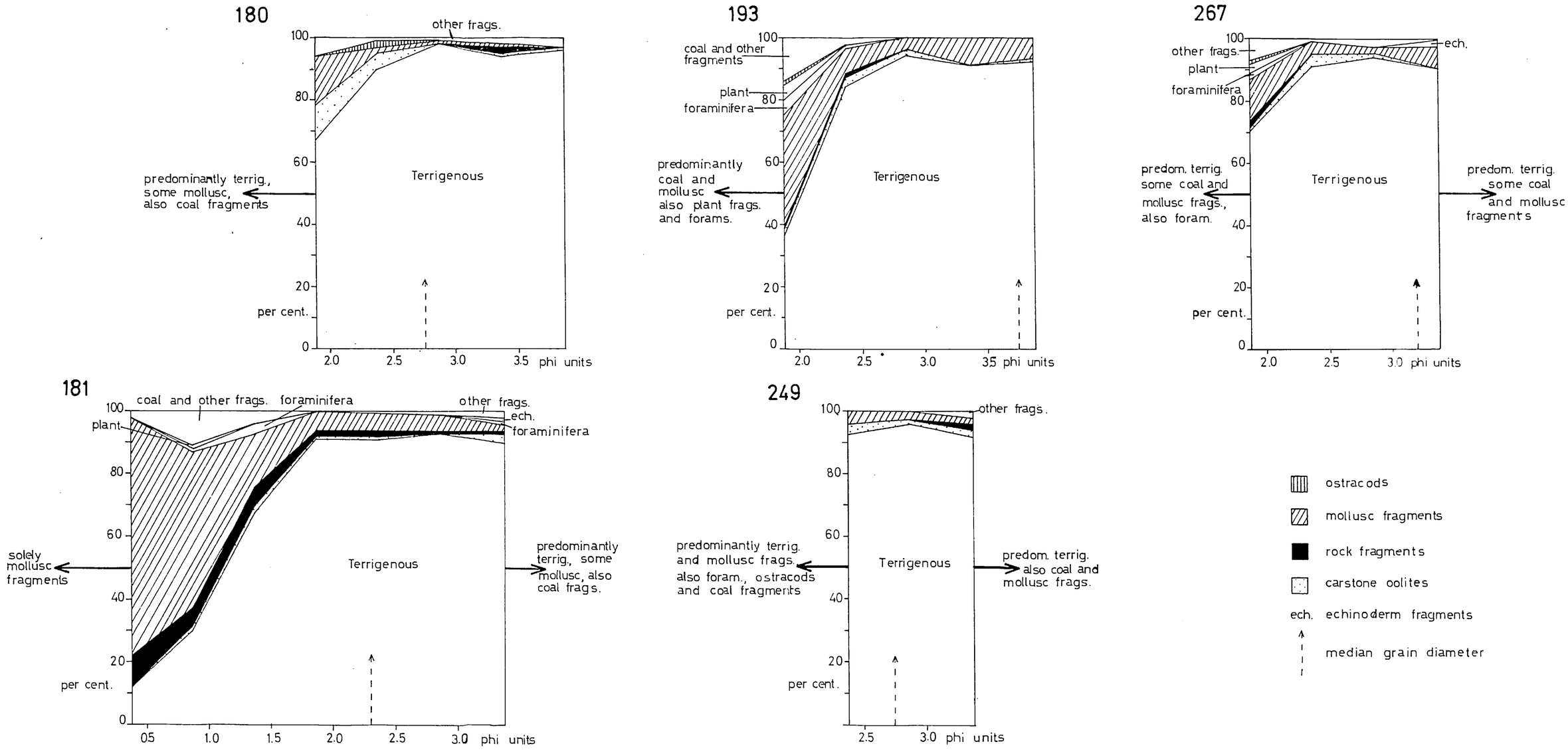
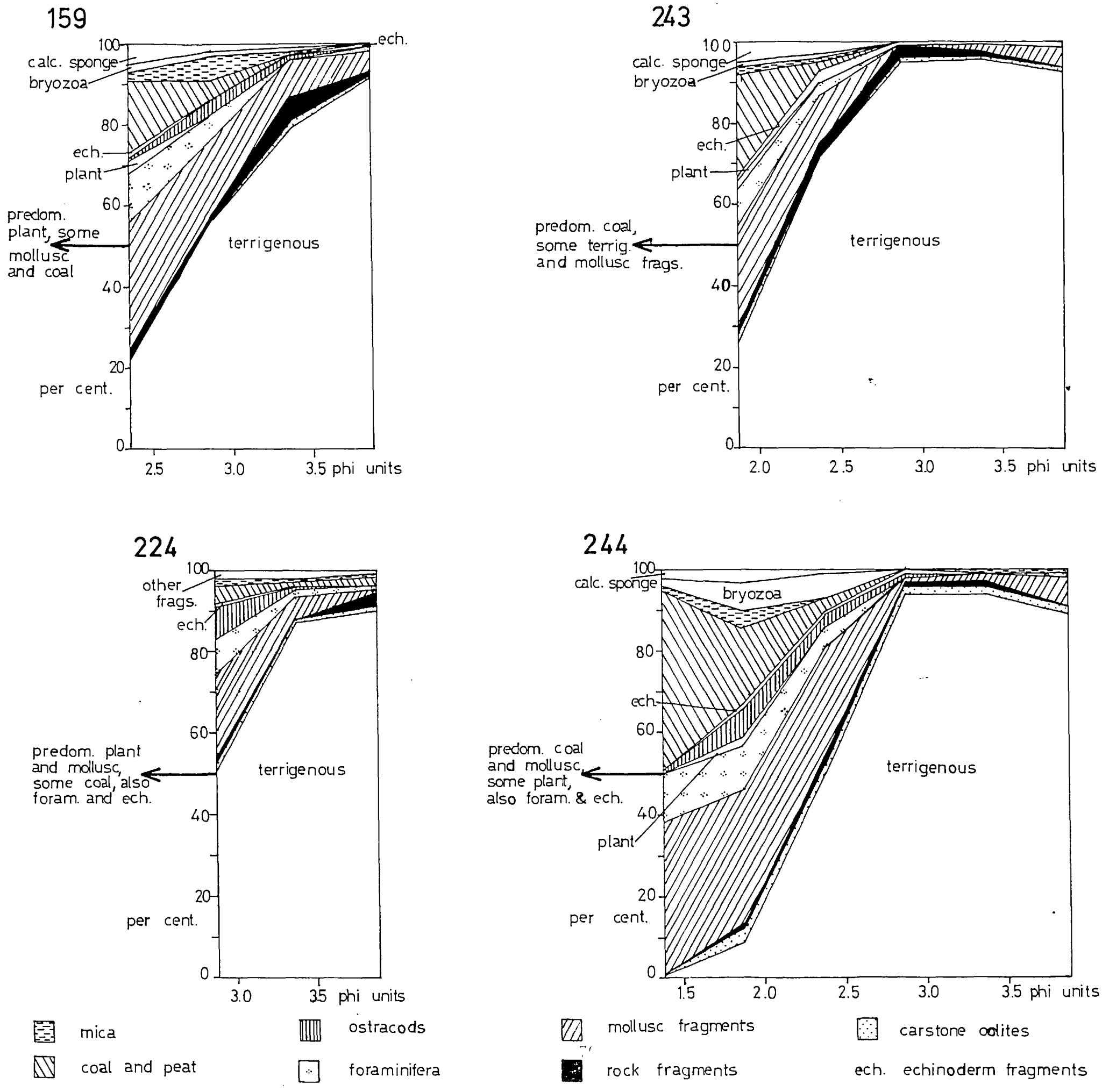


Fig. 7.17. Variation of composition with size for sediments from creeks and bordering areas



6. Conclusions

The compositions of the total coarse fractions of the sediments of the upper three sub-environments show easily recognisable differences. Plant fragments are only abundant in the marsh as they are formed *in situ*. Very few plant fragments are transported seawards on to the higher mud flat and none are found on the *Arenicola* sand flat. The light fragments of coal, foraminifera, ostracods, molluscan fragments and echinoid spines are readily transported landwards. There is thus an increase in proportion of these components from the outer tidal flats landwards and they are concentrated in the sediments of the upper sub-environments. Foraminifera are most readily transported to the marsh due to the very buoyant nature of their tests. Thus they are concentrated in the marsh (4.0 to 7.5%) and are appreciably less abundant in the sediments of the higher mud flat (0.5 to 5.5%), the concentrations here being similar to those of the *Arenicola* sand flat. This trend is also shown by the ostracods and diatoms. The concentration of molluscan and barnacle fragments is similar for the marsh and the higher mud flat and, within these two sub-environments, no landward increase in concentration has been determined for this component.

The very high proportion of the terrigenous component in the *Arenicola* sand flat (average 92%) is due to the reworking and winnowing to which it is subjected. There is thus a crude correlation between the proportion of these components in the sub-environments and the sorting of the sediments, both of these factors being dependent on the same physical process.

No significant differences may be detected between the composition of the *Arenicola* sand flat and the lower sub-environments.

The graphs of composition vs. size for higher mud flat sediments show that there is generally a very marked change in composition between 2.5 and 3.5 phi, with a very marked increase in the proportion of the minor components as the sediment size

increases. This trend is also shown by the coarser sediments of the Arenicola sand flat although it is not as marked as those of the higher mud flat.

Generally, there are few significant differences between the size vs. composition graphs for sediments from the sub-environments.

IV The Sedimentary Structures

1. The Salt Marsh

The sediments of the salt marsh are finely laminated and there is very little disturbance by organic activity. Very few burrowing organisms inhabit this zone and crabs are probably the most effective in disrupting the primary structures.

Plant roots are abundant in the marsh sediment. In the outer marsh Spartina sp. is often found in depressions of the surface. It is thought that these depressions are formed by scour around the plant roots. Where the plant cover is thicker the vegetation aids in the accretion of sediment. The amount of erosion or accretion around these stems probably depends on the relative amount of movement at the base of the plant. If this is small the stem does not break up the sediment and aid its erosion.

Unlike the salt pans described in Holme marsh, the salt pans of this area show very little evidence of disturbance of the sediment by organic activity. However, at Wolferton, some burrows of crabs may be seen in the salt pan edges and occasionally casts of Arenicola marina are found in salt pan floors. This is in marked contrast to the salt pans of the north Norfolk coast marshes (see Joysey in discussion of Evans 1965) and of Gibraltar Point (see Evans' reply), where Arenicola marina is very abundant. In the outer marsh the shallow depressions readily dry out during neap tides. Here burrows of Scrobicularia plana, Macoma balthica and Nereis diversicolor are occasionally found (fig. 7.18). Littorina littorea and Hydrobia ulvae are present in abundance



Fig. 7.18 A shallow depression in the outer marsh which has been colonised by Nereis diversicolor.



Fig. 7.19 Thin lamina of silt, overlying sand and gravel adjacent to the gravel ridge at Wolferton.

on certain parts of the outer marsh. Generally, therefore, the marshes are areas showing little evidence of animal activity except for the pans, as pointed out by Evans in his reply to Joysey (Evans 1965).

2. The Higher Mud Flat

a) Stratification

The sediments of the higher mud flat are laminated sands and silts. Generally they are thinly laminated and nearly always the primary structures are disrupted and even obliterated by burrowing organisms. Occasionally, thicker laminae of sand are found. Although the cores show only horizontal laminae, creek bank sections show that cross stratified deposits are common here, as was shown on the opposite shoreline of the Wash (Evans, 1960). The angle of dip of these cross strata is variable but may reach very steep angles (over 60 degrees) depending on the original inclination of the creek bank on which the sediments were deposited. The process of creek migration and deposition has been adequately described by van Straaten (1954), Evans (1960) and Davies (1962).

b) Ripple Marks

Ripple marks are commonly found on some areas of the higher mud flat, although these are neither as abundant or as large as those formed on the Arenicola sand flat.

Longitudinal ripple marks, parallel to the direction of the ebb current are found in areas adjacent to creeks. They are common on the mud flat seaward of the gravel ridge and the crests are generally north-south, parallel to the gravel ridge. Here the ebb current flows north into Inner Road. In places, longitudinal ripples may interfere with normal asymmetric ripples, but the latter are only found when there are high proportions of sand in the surface sediment. Asymmetric ebb current ripples are found in the elongate depressions of the outer higher mud flats.

c) Erosional features

The large scale morphology of this sub-environment and the balance between erosion and deposition has been discussed in a previous section, where the sub-environment was compared with the morphology elsewhere within the Wash.

Although erosion is only of minor importance in the mud flat studied, small scour marks are common features here. Adjacent to the gravel ridge, thin laminae of silt overlie sand and gravel (fig. 7.19) and these are frequently eroded to produce mud pellets. Here, also, small channels in the mud flat may contain deposits of gravel which have been transported seawards from the gravel ridge (fig. 7.20).

When the channels and depressions contain shallow sheets of water, erosion of the edges of these may occur, especially if the water is disturbed by wind. Wavelets erode the leeward edges of the depressions so that low cliffs may be formed. These low cliffs, which have heights of only 1 or 2 inches, face into the direction of the wind.

d) Mud cracks

Mud cracks are a very common feature of the higher mud flat. During neap tides the water does not completely cover the mud flat at high water, hence the sediment surface dries and often produces mud flakes and cracks. Concentrations of iron hydroxides are found lining the walls of these cracks and the migration of creeks often causes the erosion of the sediment surface so that the sediment within the crack, normally partially cemented, stands as a thin vertical sheet. These sheets consist of three layers, the outer two being cemented by iron hydroxides and the inner consisting of loose sand which has washed in between the linings of the crack.

Mud blisters, described by Evans (1960) and Davies (1962) are also observed here.

e) Organic structures

The sediments of the higher mud flat are intensely bioturbated as there is a large infauna in this sub-environment.

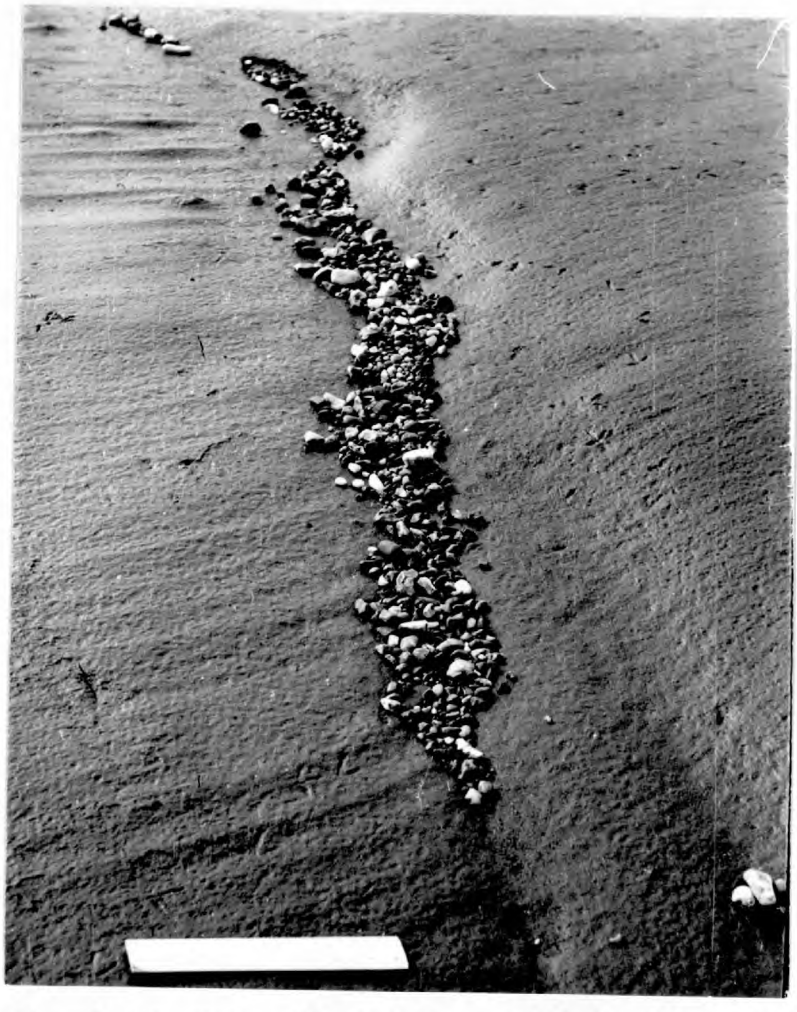


Fig. 7.20 Channelled higher mud flat with coarse pebbles in the bed. Longitudinal ripple marks pass across and are deflected by the shallow channel.

Counts of the absolute concentrations at various localities have been made by Croome (unpublished). The box samples and cores from this sub-environment show that the primary laminae are disrupted and in some cases completely obliterated by bioturbation due to Corophium volutator (fig. 7.21). Evans (1960) distinguishes an inner sand flat between the higher mud flat and the Arenicola sand flat. Corophium volutator was found to be most abundant in this zone. However, in this study area Corophium volutator is abundant throughout much of the higher mud flat. Birds feeding on high concentrations of this organism may be seen to break up the sediment at the surface into small fragments of pebble size.

Scrobicularia plana is also found on some parts of the higher mud flat, together with Macoma balthica and Hydrobia ulvae. Mounds of Macoma balthica shell fragments regurgitated by birds are distributed widely over most parts of the tidal flat (see Wilson 1967). Mya arenaria is occasionally found in the mud flat seaward of Snettisham Scalp and nearby large numbers of shells in life position are being exposed by lateral erosion in Wolferton creek (fig. 7.22). Mya arenaria burrows deep into the sediment (twelve inches or more) and is able to retreat rapidly down into its burrow (see Reineck 1967) when the sediment surface is eroded. Fig. 7.23 shows a coarsely laminated mud flat sediment with a burrow of Mya arenaria. The laminated sediment is drawn down around the burrow wall.

In the southern part of the higher mud flat erosion of the surface layers of sediment has washed out numerous tubes of Pygospio sp. and these are now present in the depressions on the mud flat.

In areas where the mud flat surface has a low relief (three or four inches) of shallow channels and ridges, the surface sediment varies slightly in relation to the relief. The channels have higher sand contents than the ridges as run off removes some silt and clay. Towards the outer edge of the mud flat the channels are colonised by Arenicola marina and sometimes Cerastoderma edule, whilst the intervening ridges have an entirely



Fig. 7.21 Lamination of sand and silt of the higher mud flat distorted by burrows of Corophium volutator. (x $\frac{1}{2}$)



Fig. 7.22 Shells of Mya arenaria in an upright growth position, exposed in the floor of Wolferton creek.



Fig. 7.23 Coarsely laminated higher mud flat sediment burrowed by Mya arenaria. (x $\frac{1}{2}$)

different fauna, dominated by Corophium volutator, Nereis diversicolor and Hydrobia ulvae, with occasionally Nephthys sp. Thus the type of bioturbation must vary laterally. As these small channels are not deeply incised they are able to migrate and change position rapidly so that the sediment suffers bioturbation by the typical higher mud flat fauna and by the fauna of the sandier sub-environments. This process is particularly marked in the mud flat region south of the Inner Road where there are some large areas of this type.

The alga Enteromorpha sp, so well developed on the higher mud flat described by Evans (1960), plays only a minor role in the mud flat development of the study area. Evans (1960) describes how the alga binds the sediment together and hinders erosion of the surface. As the higher mud flat of this area is accreting more rapidly the alga has not been able to colonise the surface layers. Zostera sp., described from depressions of the higher mud flat by Evans, was not found between Wolferton and King's Lynn. Swann (1965) noted the disappearance of Zostera sp. from this coastline and attributes it to the spread of Spartina townsendii.

3. The Arenicola Sand Flat

a) Stratification

The Arenicola sand flat of this inner Wash area is closely similar to the Arenicola sand flat between Snettisham and Hunstanton. The sediments are coarsely laminated, although in many cases the lamination is not apparent due to bioturbation. The laminae contain very little silt except at the upper and lower limits of the sub-environment and adjacent to creeks, where silty sediments are interbedded with the sands.

Reworking of these sediments by wave action is common and this prevents the accumulation here of fine sediment which is carried towards the higher mud flat sub-environment.

b) Ripple Marks

Ripple marks are found throughout this sub-environment. As on Stubborn Sand they are normally asymmetric with crests parallel to the coastline (cf. Evans, 1965). Amplitudes and wavelengths of these ripples are similar to those from the area previously described. Symmetrical ripples having the same orientation and of similar size are occasionally found.

At the outer limit of this sub-environment the ripples may be oblique or perpendicular to the shoreline and the adjacent tidal channel. This is presumably due to the increasing influence of the longshore tidal currents.

A traverse from the upper to the lower limits of the sub-environments often shows that ripples have steep slopes facing landwards at first, then may become symmetrical and finally have steep slopes facing seawards or at an oblique angle to the coastline. The ripples described by Evans at the outer edge of the Arenicola sand flat, have crests parallel to the coastline. However, in this study area, due to the limited extent of the lower sub-environments, the outer edge of the Arenicola sand flat is often very close to the tidal channel. Hence, this has a greater influence on the ripple pattern of the outer edge of the sub-environment.

Adjacent to creeks the orientation of ripple crests is often influenced by local water movement. Here, interference ripples are occasionally observed.

In general, ripple marks are modified at low tide by water passing out of the ripple troughs. They may also be completely obliterated during heavy rainstorms or when high winds drive thin sheets of water over the tidal flats.

c) Fauna and Bioturbation

Abundant casts of the worm Arenicola marina cover the sediment surface of this sub-environment and the activity of this worm is responsible for the large amount of bioturbation found here. The burrows (fig. 7.24) are generally sand filled, but where silty laminae are present these show that the sediment



Fig. 7.24 Coarsely laminated sand and silty sand of the Arenicola sand flat. A clearly defined burrow of Arenicola marina truncates the laminae. (x $\frac{1}{2}$)

is drawn down and lines the burrow walls. The burrows may have a diameter of up to half an inch. Sediment is drawn down into the burrow from the surface and here cone shaped depressions are formed. The burrows attain a depth of approximately one foot. Where the worm is particularly abundant the numerous mounds of faecal pellets interfere with the ripple patterns. At the norther edge of Ferrier Sand, Arenicola marina decreases in abundance, being replaced by the worm Lanice conchilega.

Cerastoderma edule is abundant on the Arenicola sand flat. This species lives within the top inch of sediment and disturbs the primary lamination by its movements. As on Stubborn Sand, the surface is often scattered with groups of Cerastoderma edule which are attached to the byssal threads of Mytilus edulis.

A single valve of Ensis siliqua has been found on the lower part of this sand flat, although no living specimens have been observed. Ensis sp. valves have not been found in the Wash south of this point, although they are present in abundance on the coastline to the north.

The sediment of this lower region generally has a slightly higher content of silt. This may be associated with the proximity of the Mytilus bed on the eastern side of Ferrier Sand, adjacent to the Inner Road. This separates the Arenicola sand flat from the lower mud flat which has developed here.

4. The Lower Mud and Sand Flats

A small area of lower mud flat (having a higher content of silt than the Arenicola sand flat) is present between the Inner Road tidal channel and the Ferrier Sand. This is not generally rippled although, occasionally, longitudinal ripple marks of very low amplitude and with long straight crests are present. The crests of these ripples are parallel to the axis of Inner Road (cf. Evans 1965). These are similar to those found on the opposite bank of Inner Road at the edge of Stubborn Sand. The mud flat surface may be cut by small shallow run off channels or rill marks.

In some parts of the Inner Road this mud flat passes into a lower sand flat. This also has a higher silt and clay content than the lower sand flat elsewhere and this is due probably to the restricted nature of the Inner Road compared with the main tidal channel west of Ferrier Sand. This sand flat is commonly rippled, the crests being short and cuspate and oriented perpendicular to the tidal channel. No megaripples are developed here.

In both these sub-environments there is very little fauna and no evidence of bioturbation (see figs. 7.25 and 7.26). Some areas have been colonised by Lanice conchilega, though these are generally confined to the lower parts of the Arenicola sand flat where there is no development of these lower sub-environments.

At the edge of the main tidal channel between Ferrier Sand and King's Lynn, the lower mud flat shows a very limited development. In general, there is a steep edge to the channel and this often shows the effect of tidal scour. Arenicola marina is not found along this steep slope, but Lanice conchilega is present in places. As at Holme, this worm has an uneven distribution and is often present in groups. The worm tubes are often seen to project well above the sediment and these aid in preventing erosion. Ridges of sediment perpendicular to the channel and having a form similar to transverse megaripples may be observed with Lanice tubes projecting from the ridge crests.

Where there is a more gentle slope into the channel a wider, lower sand flat sub-environment is developed. Here, large transverse megaripples may develop. Crests are generally straight and amplitudes may reach twelve inches. The sediment forming these features is sand and there is negligible silt present. The sands may be slightly coarser than those of the Arenicola sand flat. The steep slopes of these ripples normally face south, although sometimes they have a more symmetrical form. This would indicate that they are formed dominantly by the flood current although modified by the ebb. The troughs of these megaripples are generally filled with silt and clay deposited during the last stages of the tide. Where megaripples are not developed, asymmetric cusp shaped ripples are generally formed, these crests also being transverse to the channel axis.



Fig. 7.25 Finely laminated sands and silty sands of the lower mud flat. No evidence of bioturbation is shown here. (x $\frac{1}{2}$)



Fig. 7.26 Predominantly sandy sediment of the lower sand flat. Laminae of silt are present and there is a general absence of bioturbation. (x $\frac{1}{2}$)

Mud clasts are common throughout the lower sand flat sediments. These are derived from the small areas of lower mud flat and from the muddy creek zones where they enter the tidal channel. Scour of parts of the higher mud flat produces blocks which are rounded off to produce mud pebbles. These often form mud pebble conglomerates which are found interbedded with the clean sands of the lower sand flat (fig. 7.27). The sediments of the lower sand flat are often coarsely laminated sands and silts (see fig. 7.26) and box samples show the evidence of scour (fig. 7.28).

5. The Creeks and Bordering Areas

Sedimentation in the creeks and their adjacent areas differs widely from low to high water mark as this sub-environment cuts across others. The creek floor sediments, if present, are generally coarsely laminated, may be rippled and show evidence of scour. The shallow creeks cutting the Arenicola sand flat are often eroding and do not have a characteristic deposit on their bed. Lateral erosion and deposition in tidal creeks of the Wash has been described by Evans (1965) and the dip of the cross stratification produced by the meandering of the creeks is perpendicular to the direction in which the creeks drain.

Slumps are not so common in these creeks and they are generally confined to the upper part of the sub-environment, where the creeks are more incised, than they are in the lower areas. Slumping is on a small scale compared with that found near the Witham outfall. The slumping of cohesive sediment breaks it into blocks which are eroded to form mud pebble conglomerates. Layers of these and of shell gravels are found in creek floors and these are eventually covered by the cross-stratified sediments of laterally prograding creek banks. Cross section in creek banks show the presence of numerous infilled channels.

Crab burrows are very extensive in the creek banks of the marshes (fig. 7.29) and in some channels, deposits of crab faecal pellets line the floors (fig. 7.30).

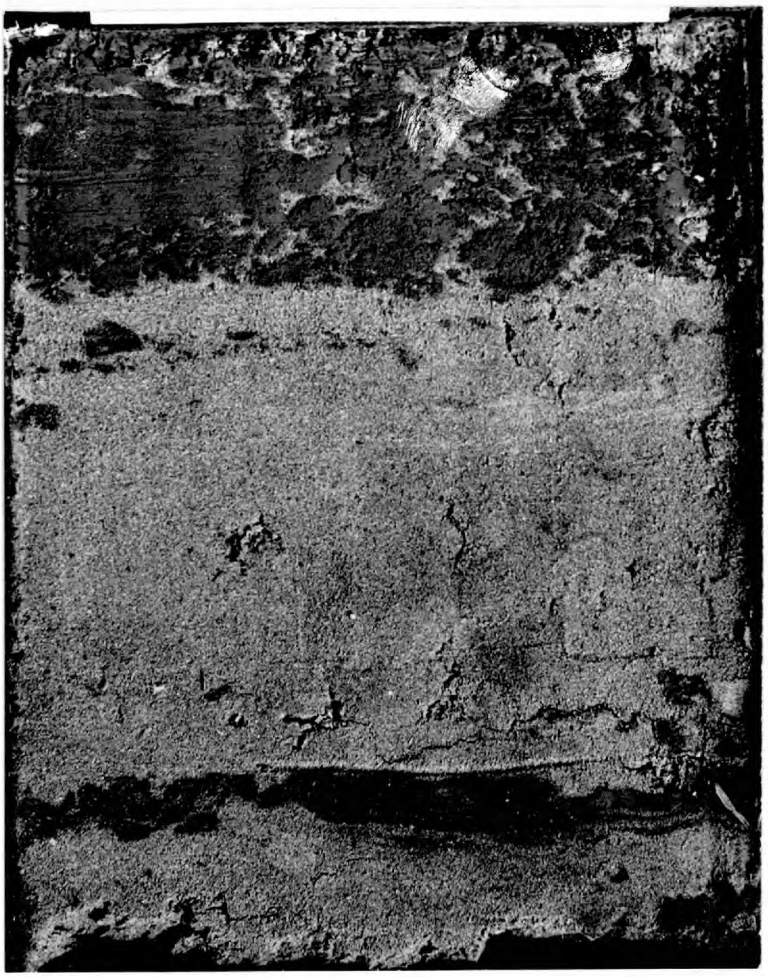


Fig. 7.27 A mud pebble conglomerate in sandy sediments of the lower sand flat. The mud pebbles are derived from the rapid erosion of the higher mud flat in the North Wootton region, where the *Arenicola* sand flat is absent. (x $\frac{1}{2}$)



Fig. 7.28 Sediments of the lower sand flat, showing scoured surfaces, mud flake deposits and rippled sandy and silty laminae. (x $\frac{1}{2}$)

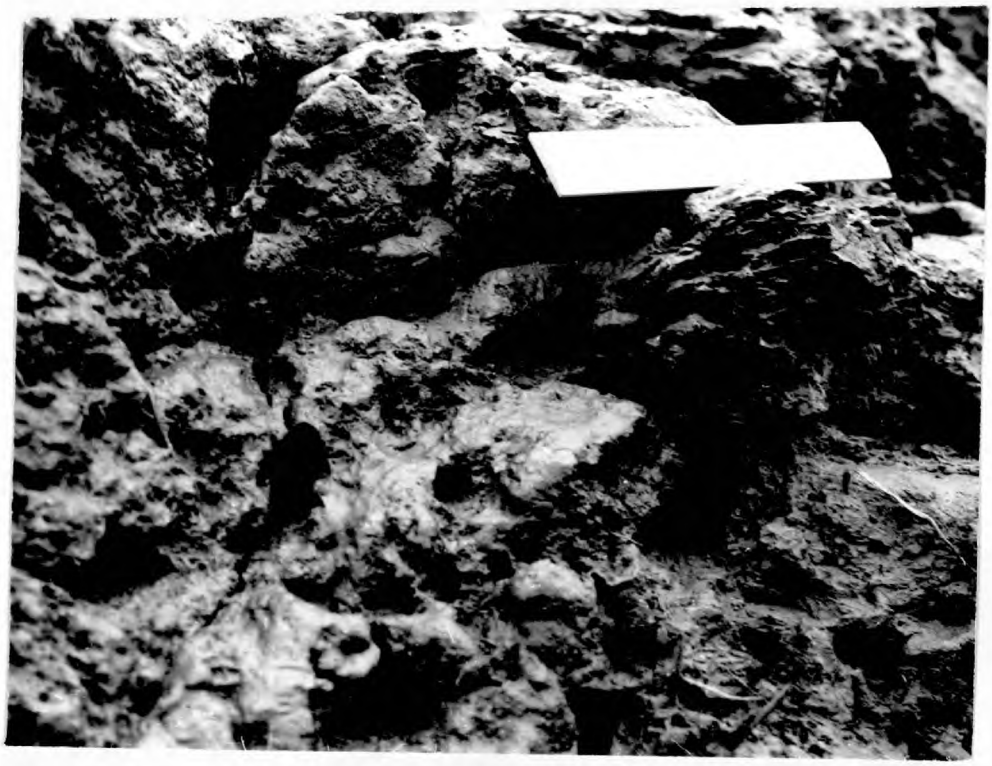


Fig. 7.29 Crab burrows in the wall of a creek within the salt marsh.



Fig. 7.30 Crab faecal pellets in the floor of a creek.

In the creeks of the outer marsh, valves of Scrobicularia plana are seen in the creek floors and these organisms live in the creek banks and adjacent areas. Mya arenaria is abundant in some areas of the higher mud flat adjacent to creeks. The migration of Wolferton creek has exposed the valves of this species in their life position (fig. 7.22). Corophium volutator is present in abundance in some creek walls and their burrows are often at right angles to the surface slope. In some creeks this species is found to extend well seawards of its normal position.

The mud flat areas surrounding creeks south of Ferrier Sand have high concentrations of young Cerastoderma edule. Whether or not these migrate to the adjacent Arenicola sand flat at a later stage of growth is not known.

Mytilus edulis reefs are present in the Inner Road at the lower limit of the creek zones. These have caused the accretion of large quantities of silt and clay by the production of and deposition of faecal pellets. This organism is probably responsible for much of the silt and clay deposition in the lower regions of this creek zone. On the tidal flat adjacent to one of these creeks, groups of this organism are arranged in a linear pattern, elongated parallel to the creeks and the main directions of tidal currents (fig. 7.31) (cf. van Straaten 1953B).

6. Conclusions

Examination of the intertidal flats between Snettisham and King's Lynn has shown that the sequence of deposits may be grouped into a number of sub-environments of deposition which closely correlate with those identified by Evans (1965) on the opposite shoreline of the Wash near Boston. These sub-environments may readily be distinguished in the field by their surface characteristics. The sequence of deposits found on the tidal flats of the Wadden Sea has been discussed by van Straaten (1954) and it may be seen that these sediments show a closely analogous succession of sedimentary structures. Van Straaten distinguishes



Fig. 7.31 Linear pattern of Mytilus edulis shells parallel to an adjacent creek and the normal direction of ebb and flood.

four zones:

a) a thick series of channel bottom deposits with current bedding and current ripples, overlain by

b) low flat deposits with laminated structures,

c) high flat deposits with burrowing structures, and

d) a cover of finely laminated marsh deposits.

A detailed comparison of the intertidal flats near Boston and those of this study area shows that there are a number of important distinguishing features, and these have been pointed out in the description. These differences are largely a result of:

a) the recent construction of training walls (see Inglis and Kestner 1958B);

b) the coalescence of Ferrier Sand with the shoreline;

c) the construction of training banks along the estuary of the Great Ouse north of King's Lynn.

Thus the intertidal flats near Boston form a well established series of sub-environments which are parallel to the coastline, whereas, in the area studied, these sub-environments are to some extent immature.

CHAPTER 8

THE OFFSHORE AREA

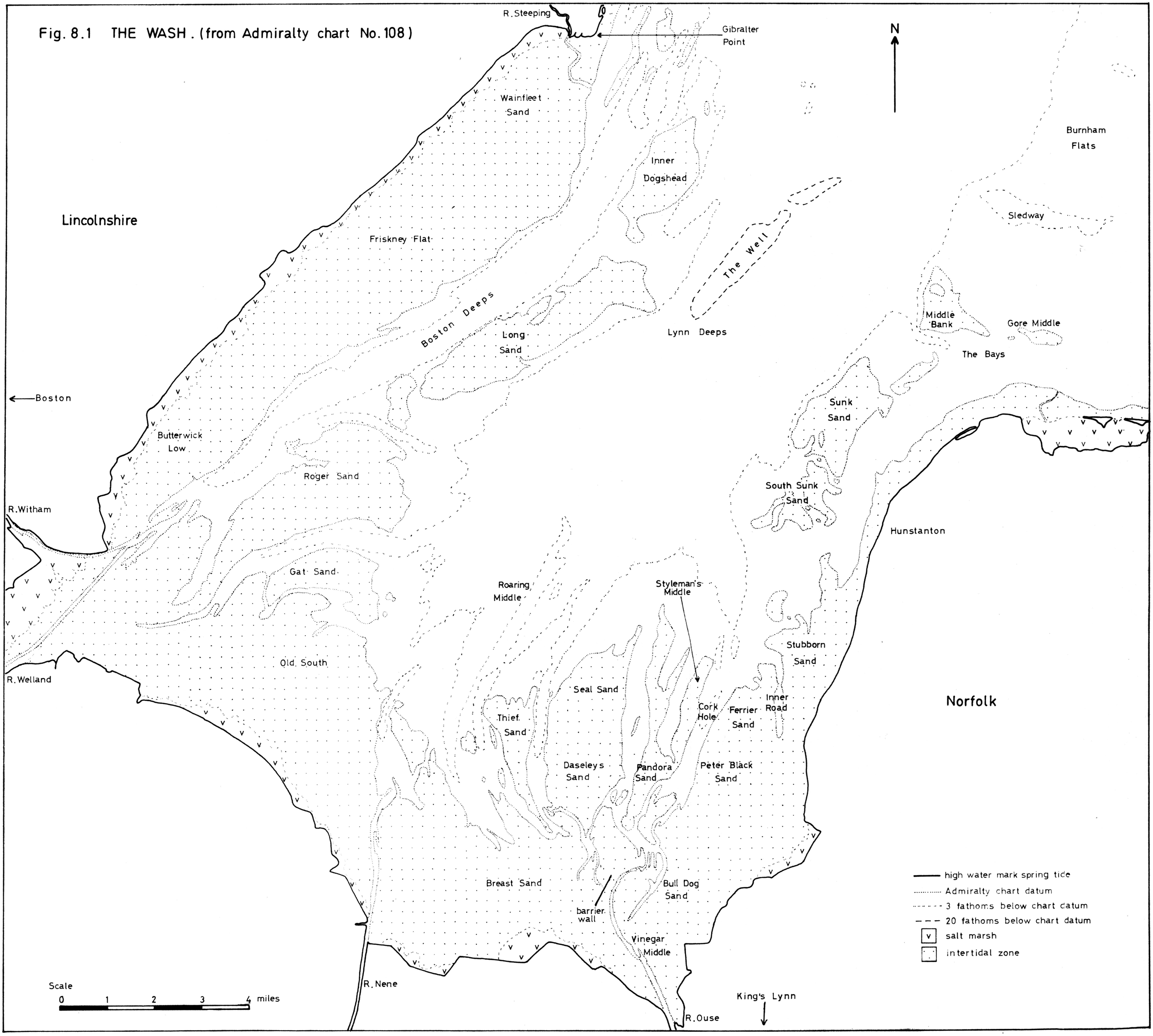
I Introduction (fig. 8.1)

The embayment of the Wash has a more or less constant width of about sixteen miles and extends in a south south westerly direction for approximately the same distance. Around its shoreline and adjacent to the coastal intertidal flats, numerous sand banks are exposed during low water. Many of these are elongate features parallel to the axis of the Wash. A limited area of the Wash and its environs, immediately adjacent to the Norfolk shore, was examined during this study as it was considered that the offshore environment is closely related to the intertidal and supratidal complex.

Very little work has so far been carried out on the sedimentology of the offshore areas adjacent to the Lincolnshire and Norfolk coasts. Skertchley (1877) reviewed the available data on the bottom sediments of the Wash. He showed that the floor of the Wash is composed chiefly of fine and coarse sand and shingle and that the sand banks which rise above low water mark are composed of fine sand and gravel. Skertchley noted the abundance of fragments of peat, mainly on the Lincolnshire coast, which he considered to be derived from offshore deposits. The Admiralty Survey, 1948 - 1956, indicates briefly the distribution of sand and gravel on the floor of the Wash and also details the nature of tidal currents at various locations. Using this tidal data, Roy (1967) has predicted the patterns of residual sediment movement in the area. Tidal current measurements made during this present study in the vicinity of Sunk Sand, have shown residual current directions which support some of Roy's predictions (see later).

In recent years, areas of the North Sea adjacent to the Wash have been examined. The general configuration of the sea

Fig. 8.1 THE WASH. (from Admiralty chart No. 108)



bed and the patterns of sediment movement have been described by Stride (1963) and Houbolt (1968). Houbolt has investigated the internal and surface sedimentary structures of linear submarine sand bodies in the area to the north of the Norfolk coast. Some sediment movement studies have been carried out on the nearshore sediments adjacent to Scolt Head Island (Steers, ed., 1964) and during these studies an onshore movement was detected. Studies of the east coast of East Anglia by Robinson (1966) showed a relationship between the offshore environment and shoreline evolution. Robinson's work showed that the influence of tidal streams extends to the coastline where, combined with wave action, favourable conditions for sedimentation are occasionally created. The Ness features, such as at Winterton, Caister, Benacre and Thorpeness, are formed by such conditions.

Approximately sixty sediment samples were collected from the offshore area between Cork Hole and The Bays, using a Lafond and Dietz (1948) grab (see sample locality map, sheet 3.1). Some sampling was attempted with a small van Veen grab but this was normally swept sideways by the tidal currents and gave very poor recoveries. Most samples were obtained from the channels and sand bank edges, while only a few samples were obtained from the offshore sand banks due to their inaccessibility.

A limited number of tidal current measurements were carried out in the offshore area and in the intertidal zone. These results are compared and related to Admiralty current measurements in the area. An investigation of sediment movement, using fluorescent sand, was initiated during this study and these results are related to tidal currents in the lower intertidal zone.

II The Offshore Morphology (fig. 8.1)

The middle of the Wash is a deep elongate basin with a distinct seaward lip. The basin, known as Lynn Deeps, reaches a maximum depth of 162 feet below Admiralty datum but shoals rapidly towards the Lincolnshire and Norfolk coasts (see Skertchley 1877).

The present channel to King's Lynn enters Lynn Deeps in the area north of Ferrier Sand. Between this point and King's Lynn the channel is narrow and shallow, except for the basin known as Cork Hole.

Between Ferrier Sand and Holme a shallow channel, which almost dries out in places during low water spring tides, separates the sand banks known as South Sunk Sand, Sunk Sand and Middle Bank, from the shore. At its north eastern end this channel widens into an area called The Bays. The sand banks are separated from each other by shallow channels which trend from south east to north west, where they pass into Lynn Deeps. On this north west side the sand banks have steep edges and drop rapidly into Lynn Deeps.

III The Sediments

1. Grain Size Characteristics

A detailed grain size analysis was not carried out for most of these samples, which were described according to Folk's classification (1954) (fig. 3.4). The sediments range from sandy muds to gravels whilst they are predominantly fine sands (fig. 8.2).

In The Bays and the channel seaward of Old Hunstanton, gravelly sediments are common and at one locality near the south eastern side of Sunk Sand the channel is floored by flint cobbles. Generally, however, the sediments have high sand contents and occasionally silt and clay are also present. The proportions of gravel in the sediments of this channel decrease south of the area adjacent to Hunstanton cliffs and the shallow channel between Sunk Sand and the shore is floored by fine sand with less than 10% silt and clay. Detailed grain size analysis of one sample (325) from this area showed the presence of a well sorted, fine sand (table 8.1) with a bimodal frequency distribution (fig. 8.3). Further south, adjacent to Stubborn Sand, fine sand is still the dominant sediment type, although some sediments have higher proportions of silt and clay and are

Fig. 8.2. Sediment Grain Size - Offshore Area.

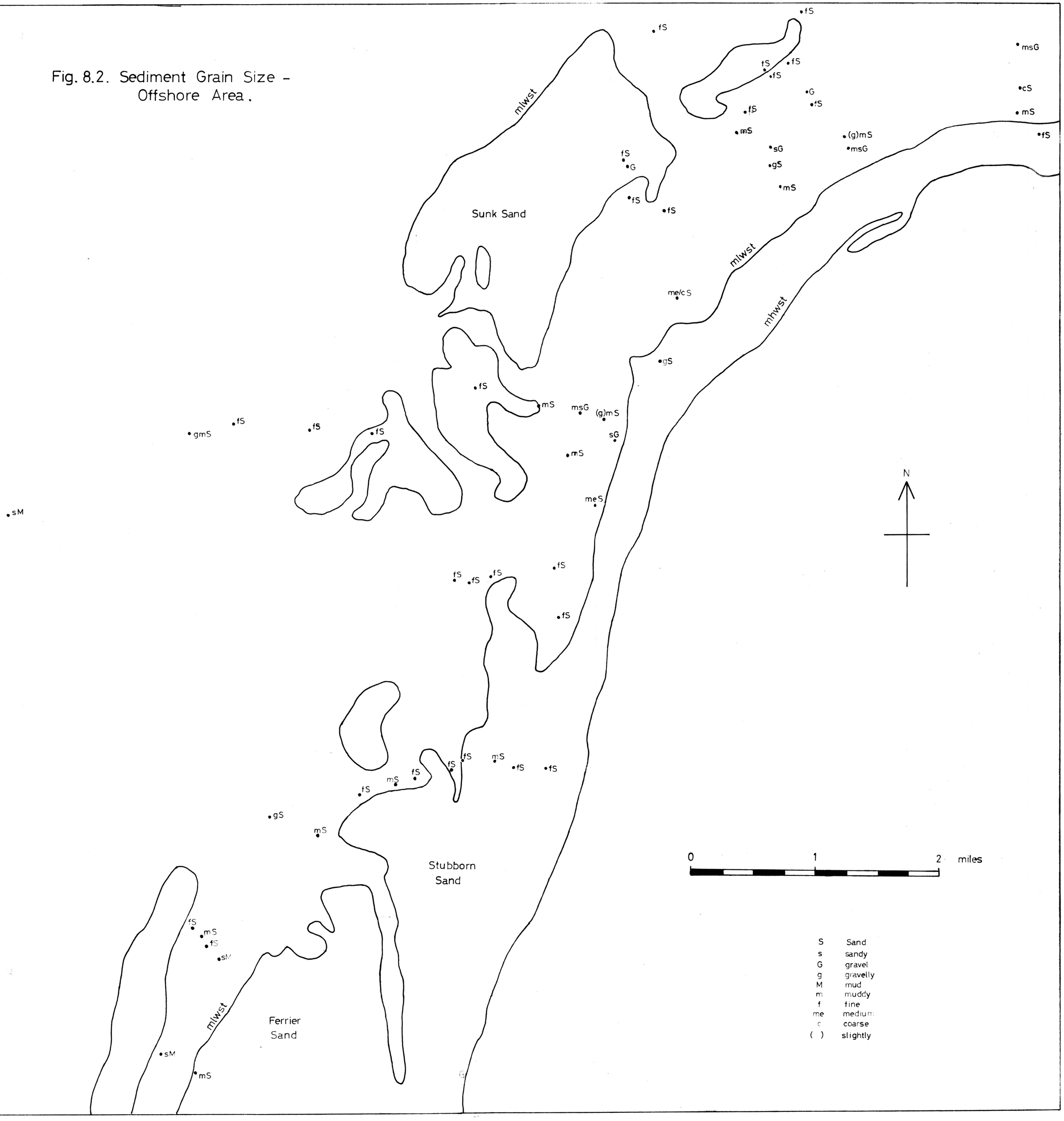


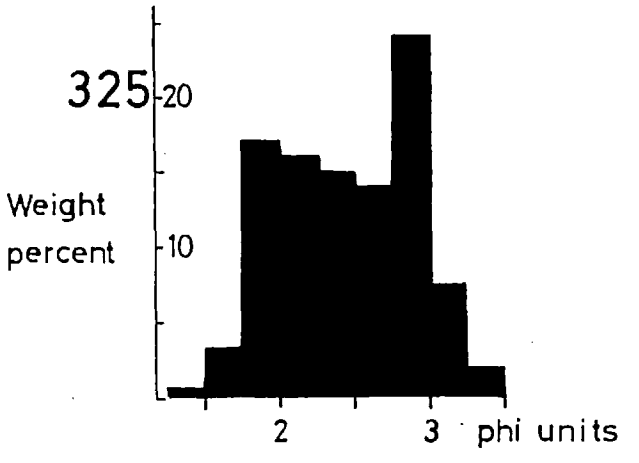
Table 8.1 Grain Size Characteristics of an Offshore Sediment (sample 325)

Mean Diameter	Sorting	Skewness
2.44	0.46	-0.053

Table 8.2 Grain Size Characteristics of Channel Sediments, King's Lynn

Sample	Median Diameter	Mean Diameter	Sorting	Skewness
B 3	2.87	2.84	0.249	-0.138
B 6	2.98	3.00	0.255	+0.049
B11	3.00	3.01	0.226	-0.001

Fig. 8.3. Grain size distribution of an offshore sample.



described as muddy sands. The proportion of silt and clay increases in some sediments on the floor of Cork Hole, where sandy muds are also present. The elongate depression in the channel floor here may aid in the deposition of fine grained sediment.

Gravel is present in the channel floor north of Cork Hole, while in the deeper channel to the west of South Sunk Sand two samples indicate the presence of sandy mud and gravelly muddy sand. As the sand bank is approached, the sediment becomes a fine sand.

The few samples collected from the sand banks are all well sorted fine sands and very little gravel, silt or clay is present. Thus, in contrast to the channels, the sediments of the sand banks show very little variation.

The sediments on the top of the sand banks are constantly being reworked by wave action and by tidal currents. Silt and clay would not normally be deposited in these areas but even if deposited, they would be rapidly removed. These sand banks, composed of well sorted sandy sediments, are a result of the redistribution of glacially derived sediment on the floor of the North Sea, whilst the gravelly sediments of the channels are predominantly lag deposits. A similar sediment pattern has been described by Houbolt (1968) for other areas of the North Sea. Although gravelly sediment is abundant around the margins of the banks, it appears that very little is carried up the steep slopes to the tops of banks. Kidson and Carr (1956) have shown, however, that pebbles on the sea bed in this vicinity may be moved by wave and tidal current action. Thus if conditions on the sea bed are occasionally vigorous enough to move pebbles, then the finer components of the sediment may be readily transported.

During radioactive tracer tests off Scolt Head Island, a landward transport of gravel was detected (Steers, ed., 1964). In this present study, the forebeach at Holme has often been scattered with small pebbles after storms, while pebbles attached

to sponges were frequently seen on the intertidal zone. The offshore gravel, lying immediately seaward of the shoreline, must act as a limited, but more or less constant, source of supply to the beach sediments.

Three samples were collected from the bed of the Great Ouse, in the vicinity of King's Lynn, using a van Veen grab. These sediments are fine and very fine sands, with negligible silt and clay (less than 0.10%) (fig. 8.4). Mean diameter values range from 2.84 to 3.01 phi and the sediments are very well sorted and have low positive and negative values of skewness (table 8.2). Their closest counterparts in the intertidal zone are found in some of the megarippled sands of the lower sand flat, whilst they have a higher degree of sorting and less silt and clay than most intertidal flat sediments. These features are due to the strong tidal currents in this artificial channel. Silt and clay are deposited on the banks of the channel where tidal action is less vigorous.

2. The Sediment Composition

The composition of the twenty five samples from the offshore zone was investigated. These were washed to remove the silt and clay and the sand and gravel fractions were then separated. The compositions of the sand fractions were determined by point counting and estimations of composition were made for the gravel fractions.

a) The sand fractions (table 8.3)

The terrigenous minerals form the bulk of these sediments (72.0 - 96.5%), as they do in the sediments of the intertidal sub-environments, whilst rock fragments are present in small proportions, not exceeding 3%. Coal is present in nearly all samples although it does not exceed 1.5%.

Carstone oolites and fragments were identified in most samples, the highest percentages being found immediately seaward of Hunstanton (4%). In the channel north of this the proportion decreases gradually, although even in the area seaward of Gore

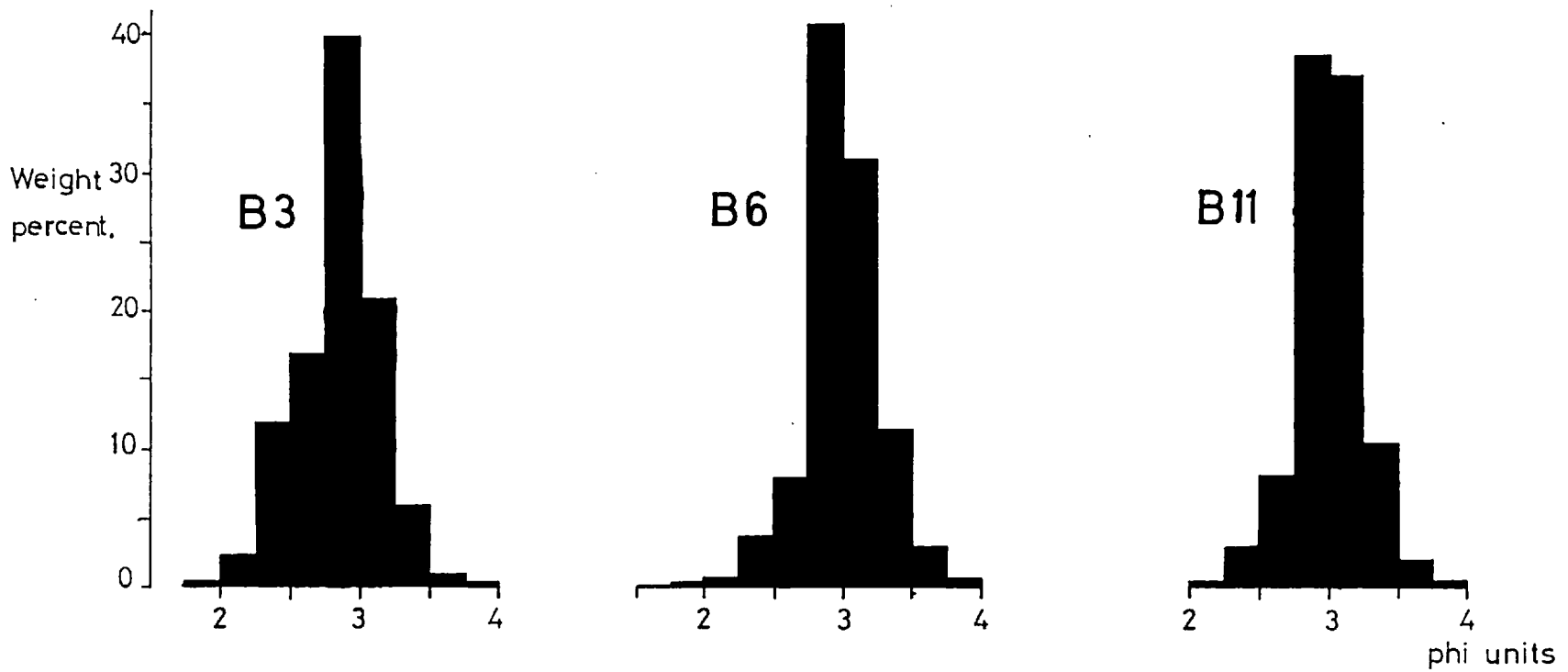


Fig. 8.4. Grain size distributions of sediments from the Great Ouse, King's Lynn.

Table 8.3 The Composition of Offshore Sediments (Sand Fraction)

Sample	Terrigenous	Limonite oolite	Rock Fragments	Mollusc/ Barnacle	Forami-nifera	Plants	Ostracods	Echinoids	Coal	Bryozoa	Spines
B3	96.0	0.5	1.0	1.5	0.5				0.5		
300	87.5	4.0	1.0	5.0	1.0	0.5			0.5		0.5
304	87.5	1.5	2.5	7.0			0.5		1.0		
305	77.0	2.0	2.5	12.0	2.0			2.5	1.5		1.0
307	72.0	3.0	1.5	22.0	0.5			0.5	0.5		
308	92.0	1.0		3.0	1.0			1.5	1.5		
310	90.0	1.0	1.0	6.0	1.0				1.0		
312	87.0	2.0	1.0	8.5	0.5				1.0		
314	90.5	3.0	0.5	5.0				0.5		0.5	
315	86.0	1.5	1.0	4.5	6.0				1.0		
317	90.5	0.5		7.0	1.5				0.5		
321	86.0	4.0	1.0	5.5	1.0	0.5		0.5	1.5		
325	91.0	2.0	1.0	4.5	1.0				0.5		
326	92.5	1.5	1.5	3.5	1.0						
334	92.5	2.0	1.0	4.5							
337	87.5	1.5	1.0	9.0	0.5				0.5		
341	84.5	2.5	1.5	10.0				0.5			1.0
343	92.5	2.5	0.5	3.5					0.5		0.5
345	91.0	1.5	2.0	4.5					1.0		
346	85.5	0.5	3.0	7.5	1.0			0.5	1.0	0.5	0.5
349	87.0	4.0	2.0	5.5	0.5				1.0		
352	89.0		2.0	6.0				1.0	1.5		0.5
411	96.5		1.0	2.5							
412	90.0	2.0	1.5	5.5					1.0		
414	96.0	1.0		3.0							

Point, proportions ranged up to 3%. South of Hunstanton the percentage drops rapidly to 1.5%, this being in marked contrast to the high values in the sediments of the intertidal zone at the edge of the gravel ridge (near high water mark). Seaward of Stubborn Sand values of between 1.5 and 2.0% are common, while in Cork Hole the percentage is low and variable. The sand bank sediments generally contain between 1 and 2% of Carstone oolites and fragments.

The proportion of molluscan and barnacle fragments is generally higher than in the sediments of the intertidal zone and in one sample (from the channel adjacent to the Mytilus reef north of Hunstanton cliffs) this proportion reached 22%. In the area seaward of Hunstanton and Holme, the highest percentages occur along the channel axis, these decreasing both towards the shoreline and towards the offshore sand banks. Seaward of Stubborn Sand, the percentage increases to reach 10% in the area north of Cork Hole. Graded fractions of a sample (325) from the offshore area immediately adjacent to Stubborn Sand show an increase in the proportion of coal, peat, and mollusc and barnacle fragments in the 1.25 - 1.50 phi fraction (fig. 8.5). Carstone oolites and fragments are most abundant between 2.0 and 2.5 phi. This sample is very similar to the sediments of the adjacent shoreline.

Foraminifera are present in most sediments although they are noticeably absent from the sediments of the offshore sand banks. Other minor components include ostracods, plant fragments, echinoid fragments, mica, bryozoa, calcareous sponge fragments and diatoms.

The sediments in the bed of the Great Ouse at King's Lynn (sample B3) is composed almost entirely of terrigenous minerals (96%), the remainder consisting predominantly of molluscan fragments. An analysis of graded fractions (fig. 8.6) shows that there is very little variation with size and no consistent trend in variation.

b) The gravel fractions

In most samples shell fragments form a large proportion of the gravel fraction. The terrigenous component is predominantly

Fig. 8.5. Variation of composition with size, sample 325, offshore sediment

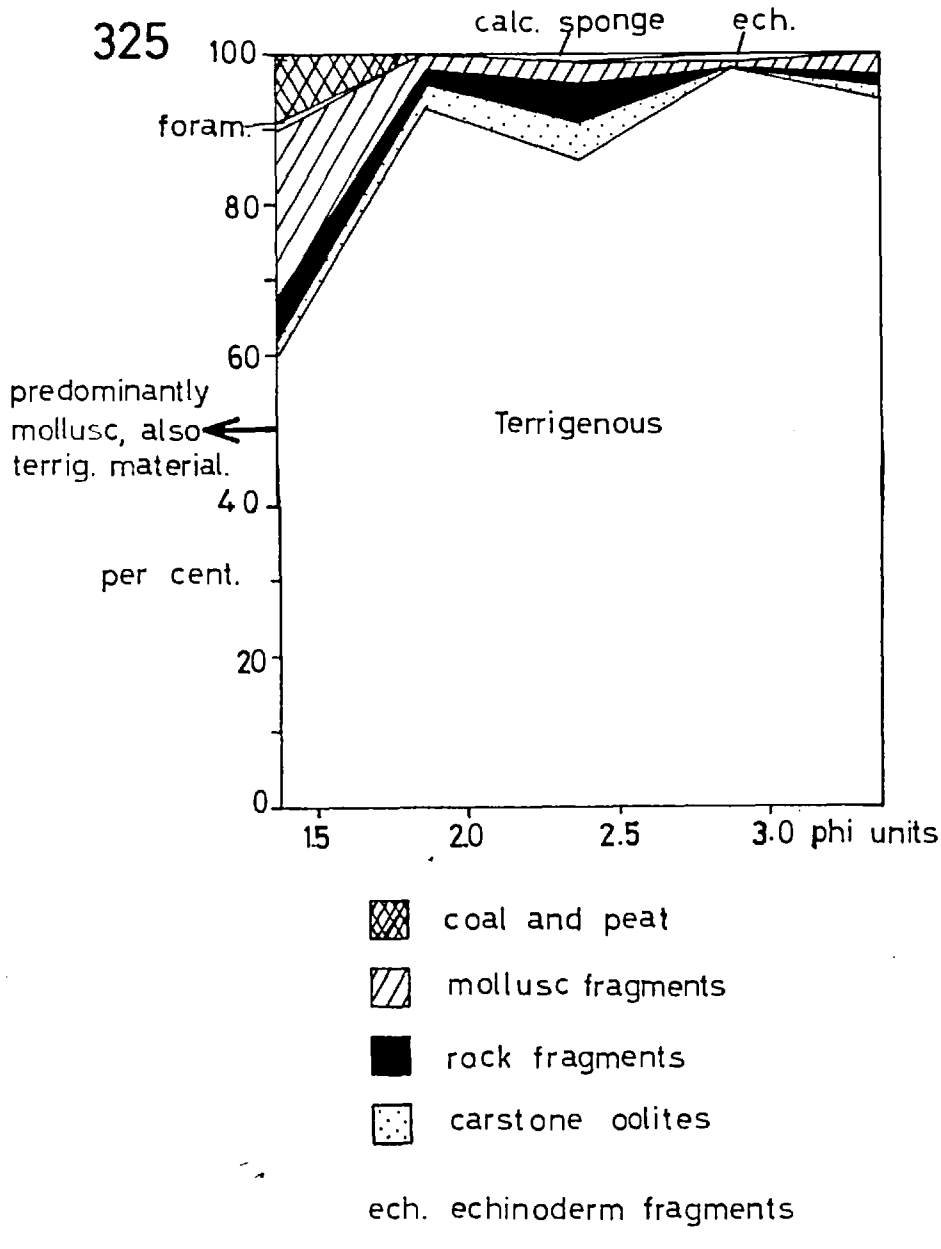
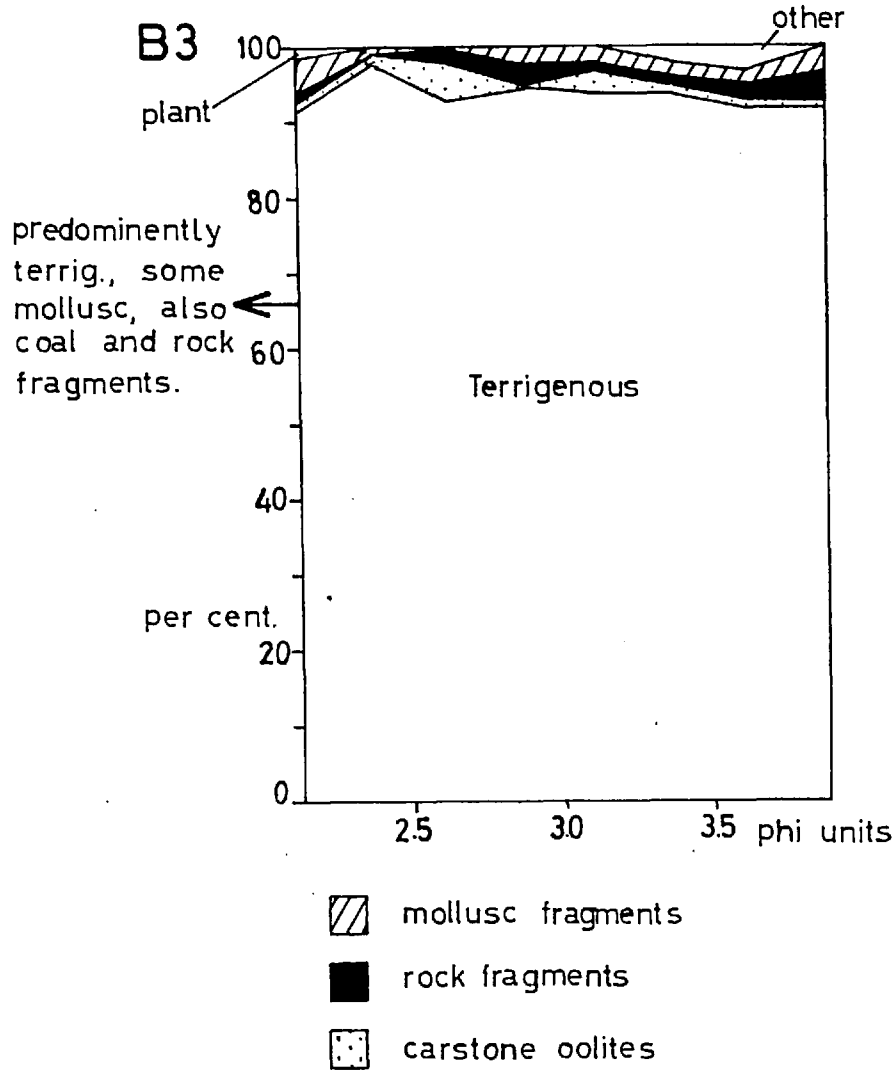


Fig.8.6. Variation of composition with size, sample B3 from the River Ouse



flint, much of this being encrusted with bryozoa. The shell component is largely composed of fragments of Cerastoderma edule, many of these being from immature forms.

Fragments of Mytilus sp. are abundant, especially in the area north of Hunstanton. Here, fragments of Petricola pholadiformis, Nucula sp., Gibbula sp., Tellina sp., Venerupis pullastra, echinoids, cirripedia and calcareous and grain cemented worm tubes are also common, and in this region the displaced shell fauna of the backbeach reflects the varied nature of the offshore fauna.

Fewer species are present south of Hunstanton. Valves of young Cerastoderma sp. are very abundant and may form the entire gravel fraction, but Tellina tenuis is often present here.

Gravel from the deeper and more distant channel north of Cork Hole is composed of terrigenous and shell fragments in equal proportions. Nucula sp. valves are abundant here, with some fragments of Chlamys sp. and Mya sp. Although Nucula sp. is abundant in this channel, it is not transported to the adjacent intertidal zone (i.e. the Snettisham Scalp area).

IV Tidal Current Measurements

1. Introduction

An examination of tidal currents was considered to be an important factor in the study of the offshore zone as sediment movement must be related to these currents to some extent. A general discussion of the pattern of tidal currents in the Wash is followed by some details of Admiralty current measurements and an outline of Roy's (1967) suggestions concerning residual sediment transport in the vicinity of Sunk Sand. Tidal current measurements carried out by the author in both the offshore and intertidal zones are then described together with a study of sediment movement in the intertidal zone, detected by a fluorescent sand tracer.

2. Patterns of Tidal Movement in the Wash

The pattern of surface water circulation in the Wash is shown by Admiralty chart no. 108. Five hours before high water at Immingham (on the Lincolnshire coast north of the Wash) the flood current starts to flow through Lynn Deeps into the Wash, although at this time the current at King's Lynn and at Boston is still ebbing. At Brancaster, on the north Norfolk coast, water is flowing westwards while between Hunstanton and Sunk Sand the direction is towards the south west. An hour later the flood current reaches Boston, while soon after this it reaches King's Lynn.

This condition remains unchanged until just before high water at Immingham, when the inshore current adjacent to Hunstanton (i.e. between Hunstanton and Sunk Sand) begins to flow towards the north east. West of Sunk Sand, however, water is still flowing into the Wash, although soon after, the current here also reverses.

Six hours after high water at Immingham, although the ebb is still continuing in the centre of the Wash, the current has reversed in the area adjacent to Hunstanton. Thus the nearshore tidal currents at Hunstanton precede those in the centre of the Wash by an hour.

The Admiralty current station (I) between Hunstanton and Sunk Sand (fig. 8.7) indicates a residual effect to the north (i.e. ebb current velocities are greater than flood current velocities) (fig. 8.8). In Lynn Well, at station H, there is a residual towards the south, in the flood direction. Roy (1967) concluded that there is probably an anti-clockwise direction of residual currents (and hence residual sediment transport) around Sunk Sand and South Sunk Sand. By a comparison of Admiralty charts for successive years, Roy has also shown that sediment is steadily accreting on the southern side of Sunk Sand, so that the bank is extending towards the south. The tidal current measurements of this study were located around Sunk Sand in order to determine in more detail the current pattern in the area.

Fig.8.7. The location of tidal current stations.

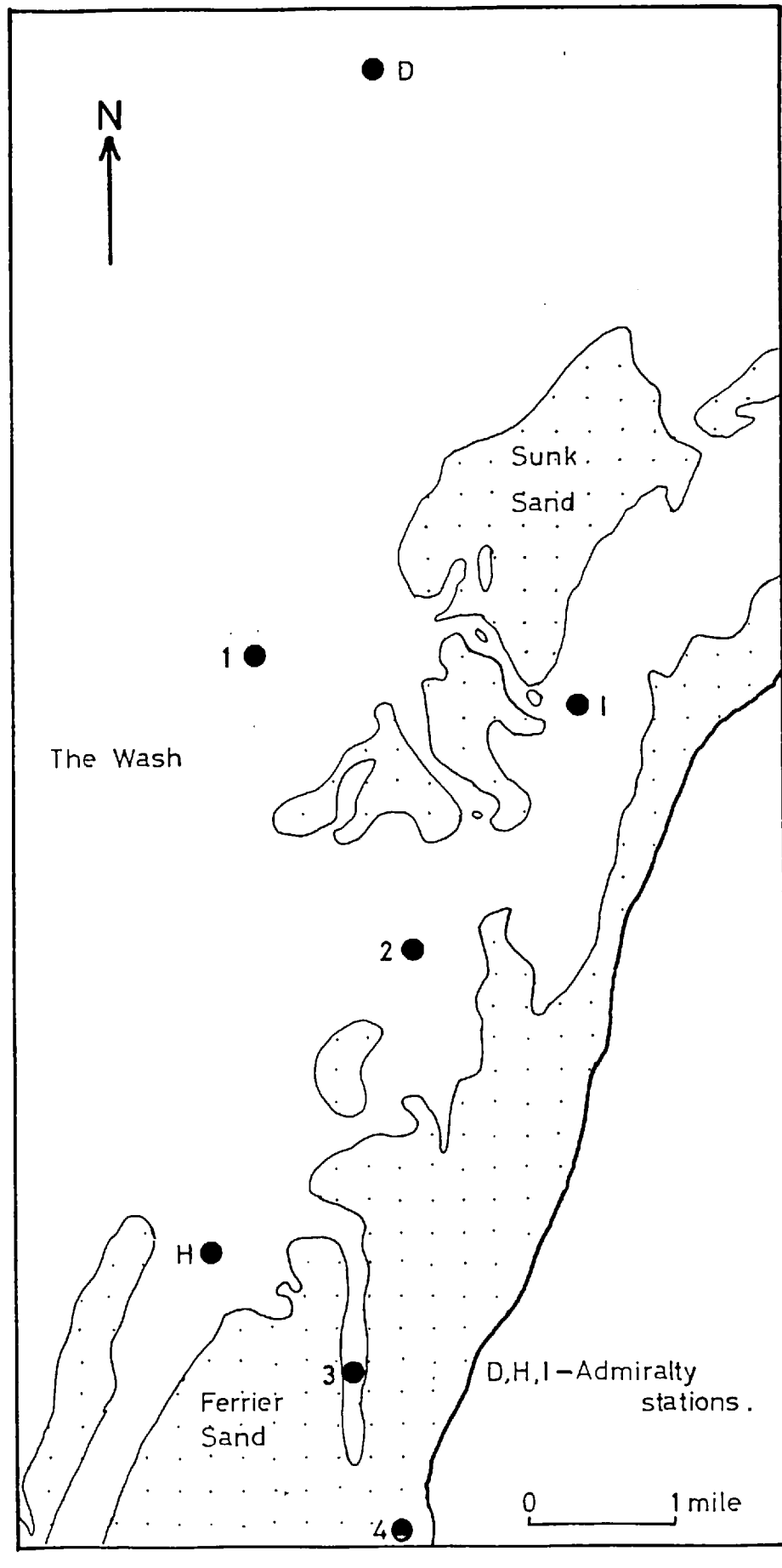
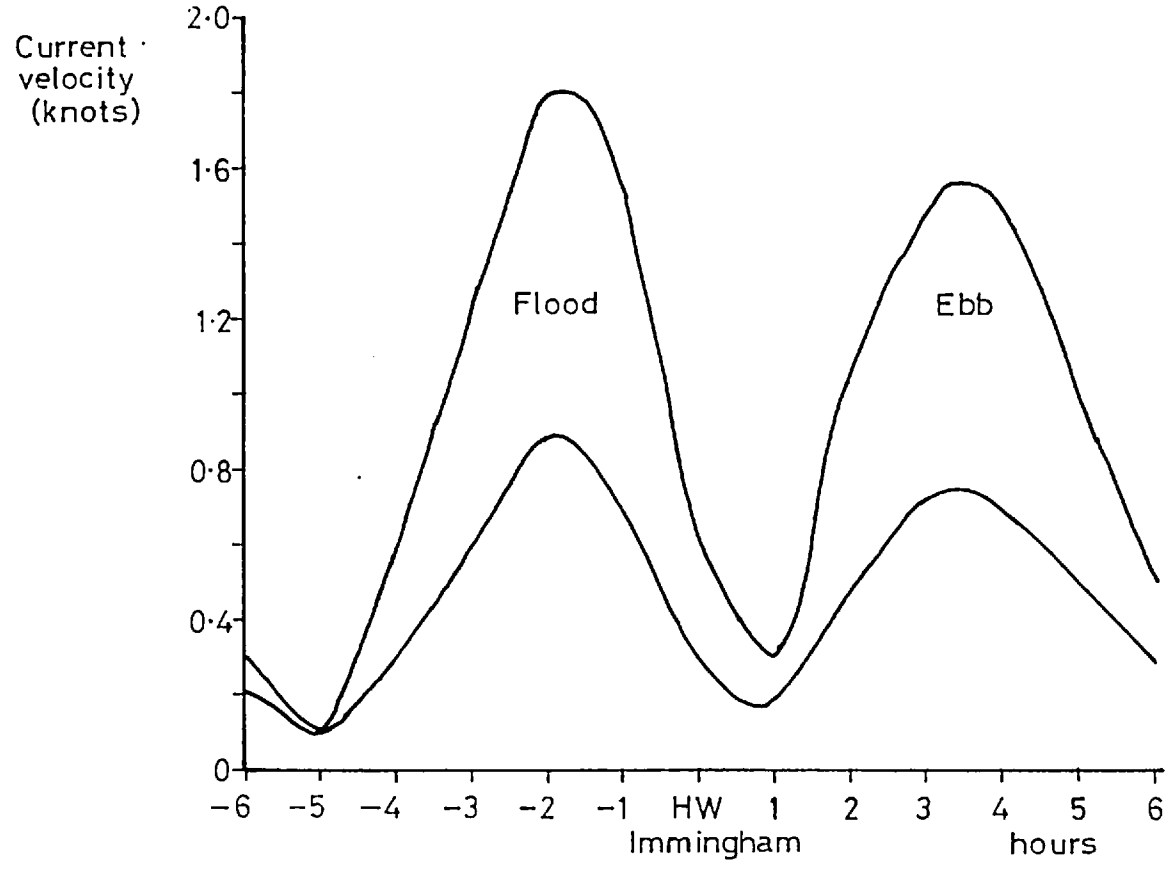
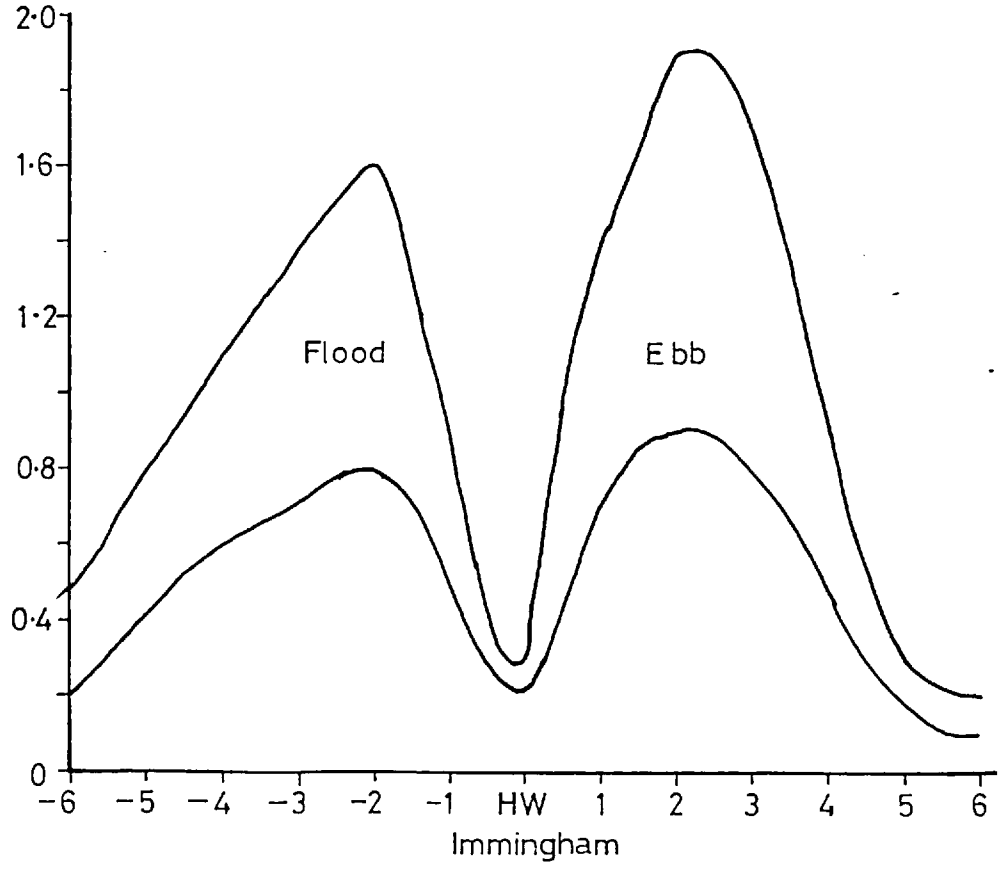


Fig. 8.8. Current velocities at Admiralty current stations near Sunk Sand and Ferrier Sand.

H) Cork Hole



I) East of Sunk Sand



3. Offshore Tidal Current Measurements

These measurements were made at two locations in the offshore zone (stations 1 and 2, fig. 8.7).

a) Station 1, Sunk buoy (figs. 8.9, 8.10)

Current roses, indicating both velocity and direction for surface and bottom currents, show a relatively simple pattern of ebb and flood. The maximum ebb current velocity at the sea bed was 0.6 metres per second, whilst the maximum velocity of the succeeding flood current reached 1.0 metres per second. At the surface the maximum velocities were 1.0 and 1.25 metres per second respectively.

As these measurements were made during the period following the highest spring tides and before the true neap tides, the maximum velocities of each tide would be expected to decrease through this cycle. But in this case the flood velocity is much greater than the preceding ebb velocity, indicating that there is a strong residual current in the flood direction, i.e. towards the south west.

As would be expected, bottom velocities were slightly lower than those at the surface. During both ebb and flood there was very little change in current direction, the current in each case flowing parallel to the edge of the sand bank.

b) Station 2, South Sunk Sand (figs. 8.9, 8.11)

The tidal currents in the region south of South Sunk Sand show a very complicated pattern, although the rate of change of water depth between high and low water remains very constant (fig. 8.12).

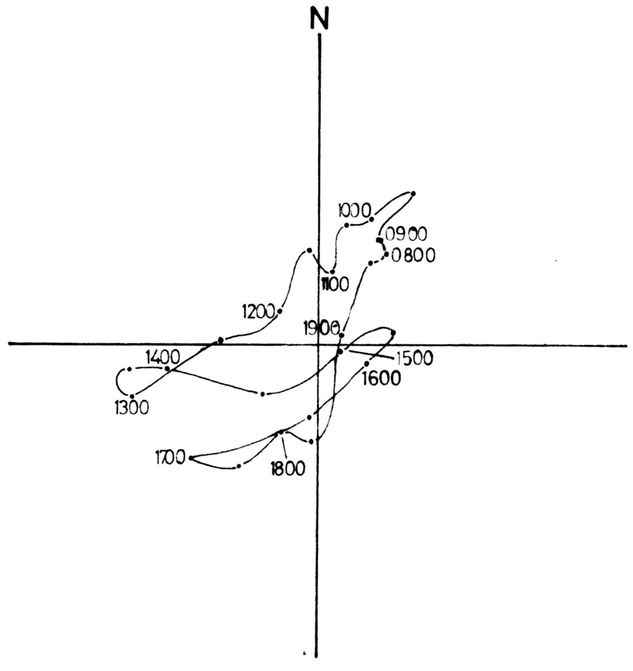
In one tidal cycle the surface current velocity shows three major maxima, the highest of these (0.68 metres per second) appearing just after high water when the current is flowing towards north north east. This velocity gradually decreases but increases again to reach a maximum of 0.48 metres per second at one hour before low water. During this time the current gradually changes direction until it is flowing towards the west.

Fig. 8.9 CURRENT VELOCITY AND DIRECTION AT STATIONS NEAR SUNK SAND.

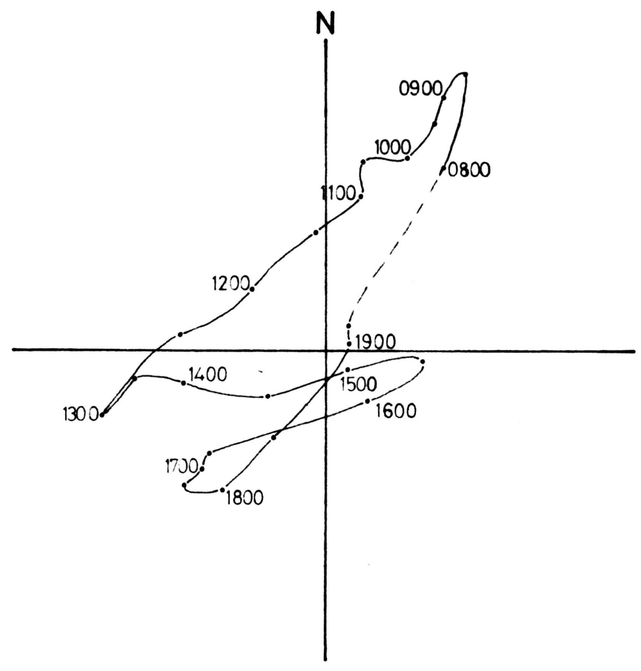
STATION 2

South of South Sunk Sand
measured 11/5/67.

BOTTOM

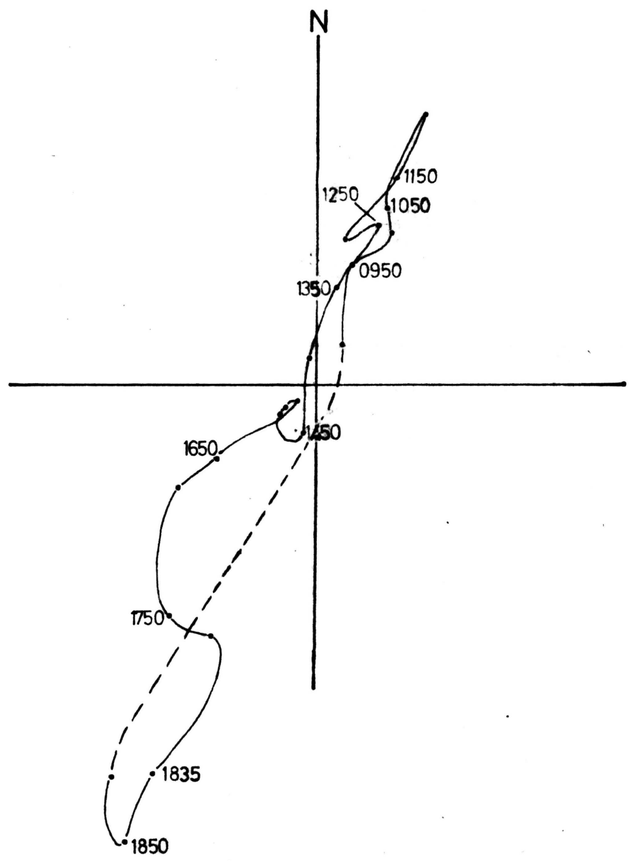


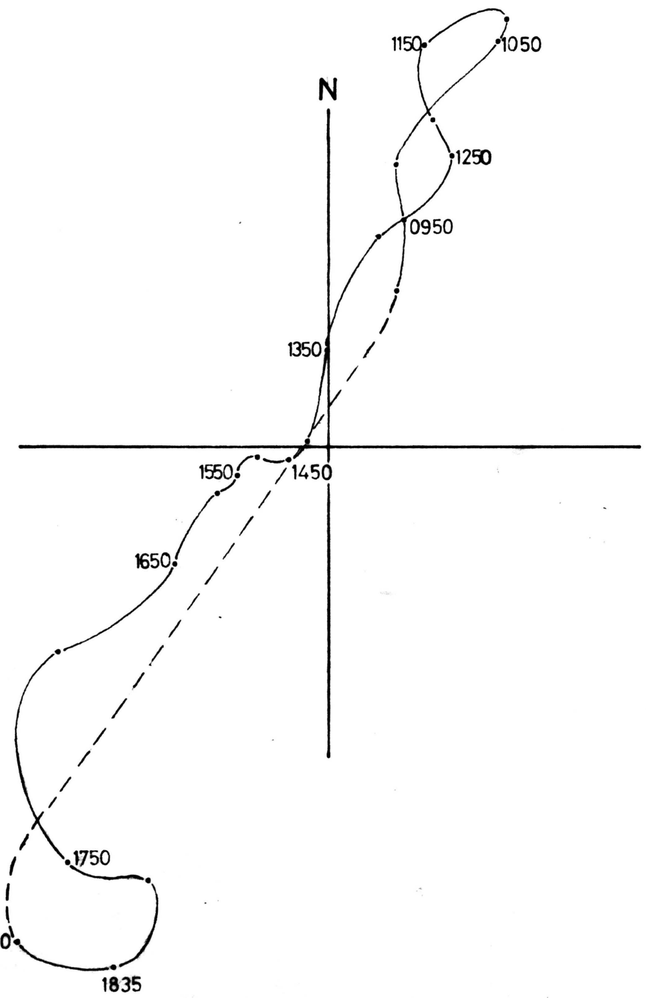
SURFACE



STATION 1

at Sunk buoy
measured 23/8/67.





Measurements were made at half hour intervals and each point represents both velocity and direction, measured from the centre.

Velocity Scale.
10 cms ≡ 1.0 metres/sec.

Fig.8.10. Current Velocity and Direction, Station 1, Sunk buoy.

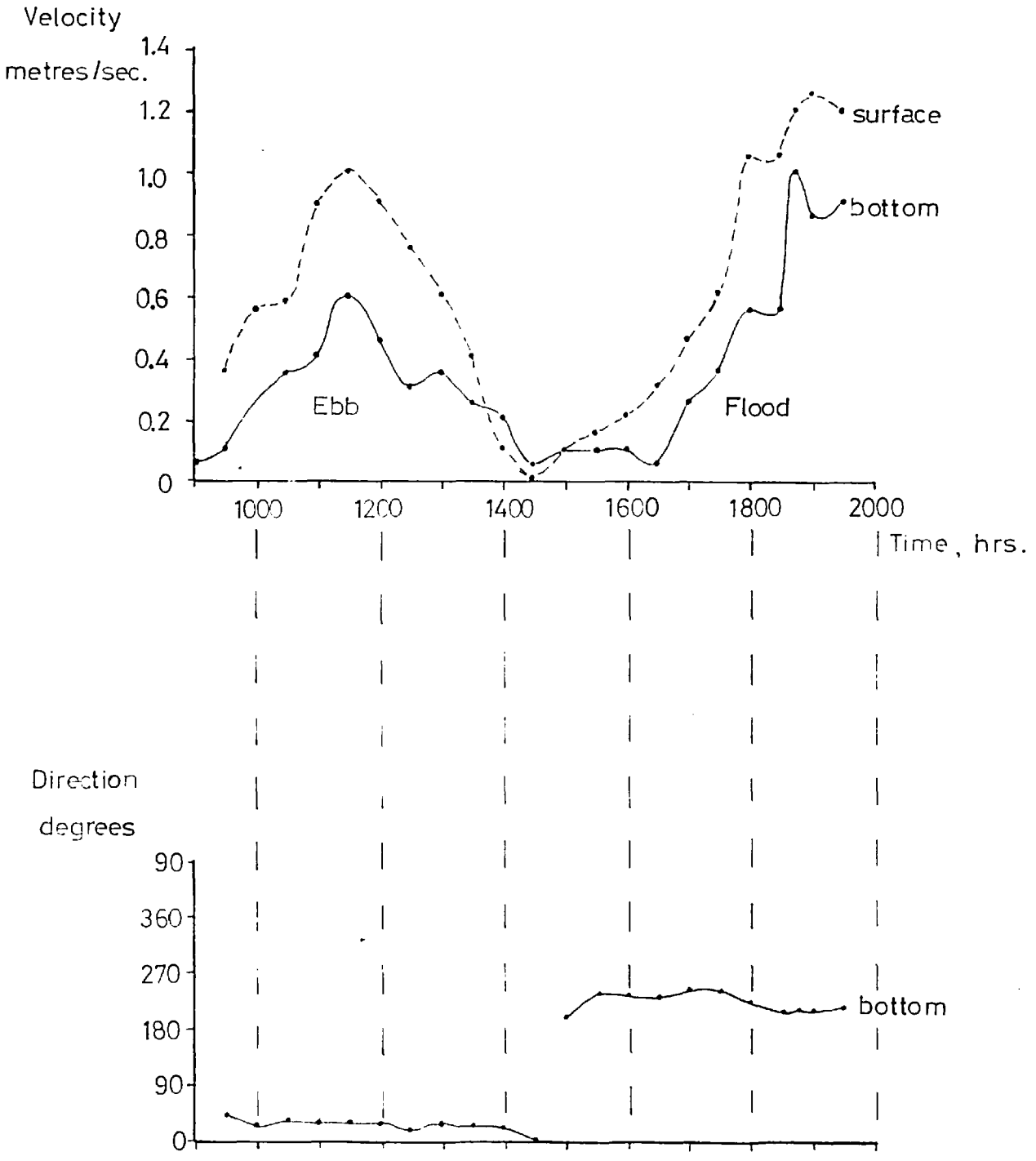


Fig.8.11. Current Velocity and Direction , Station 2, South Sunk Sand.

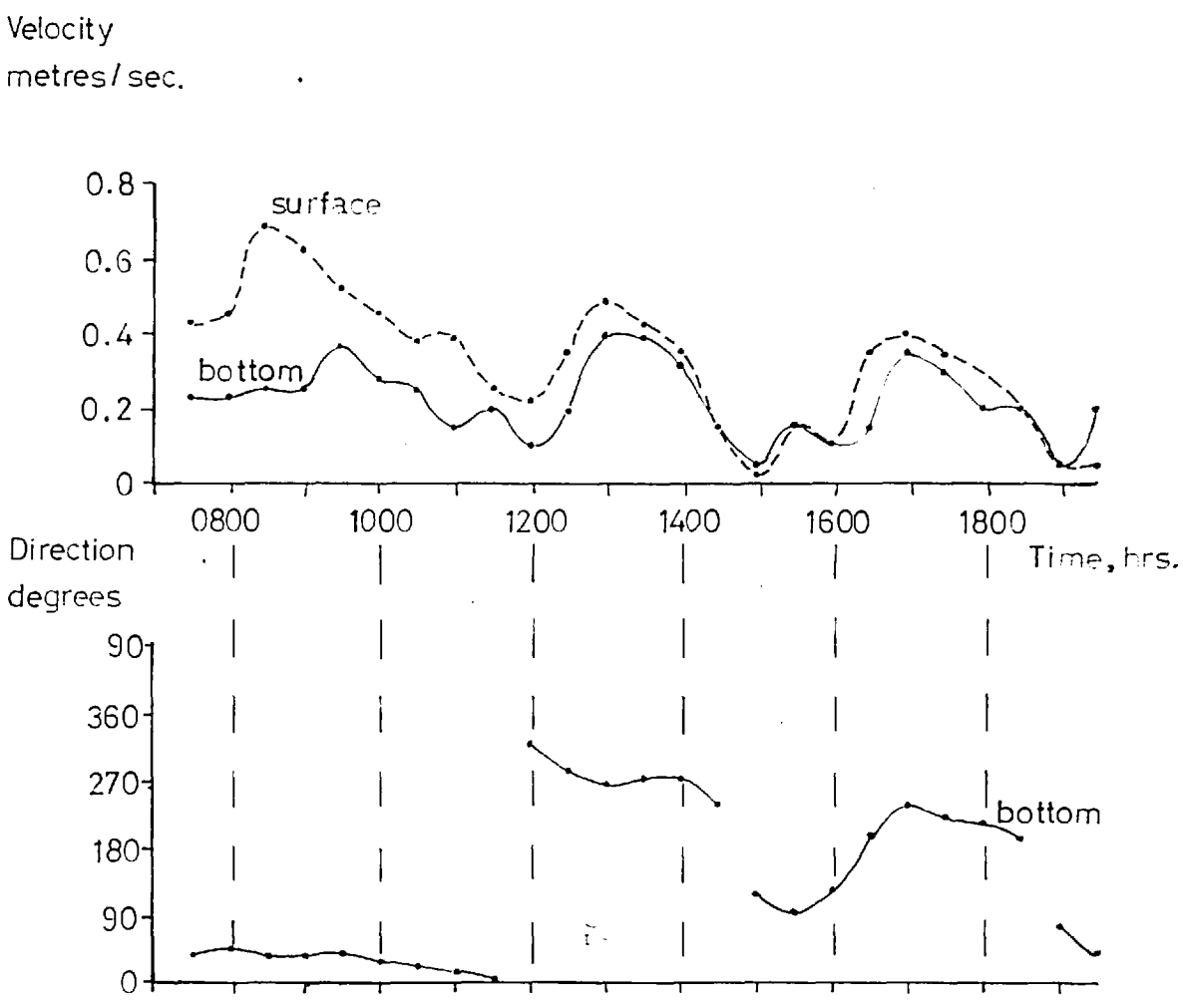
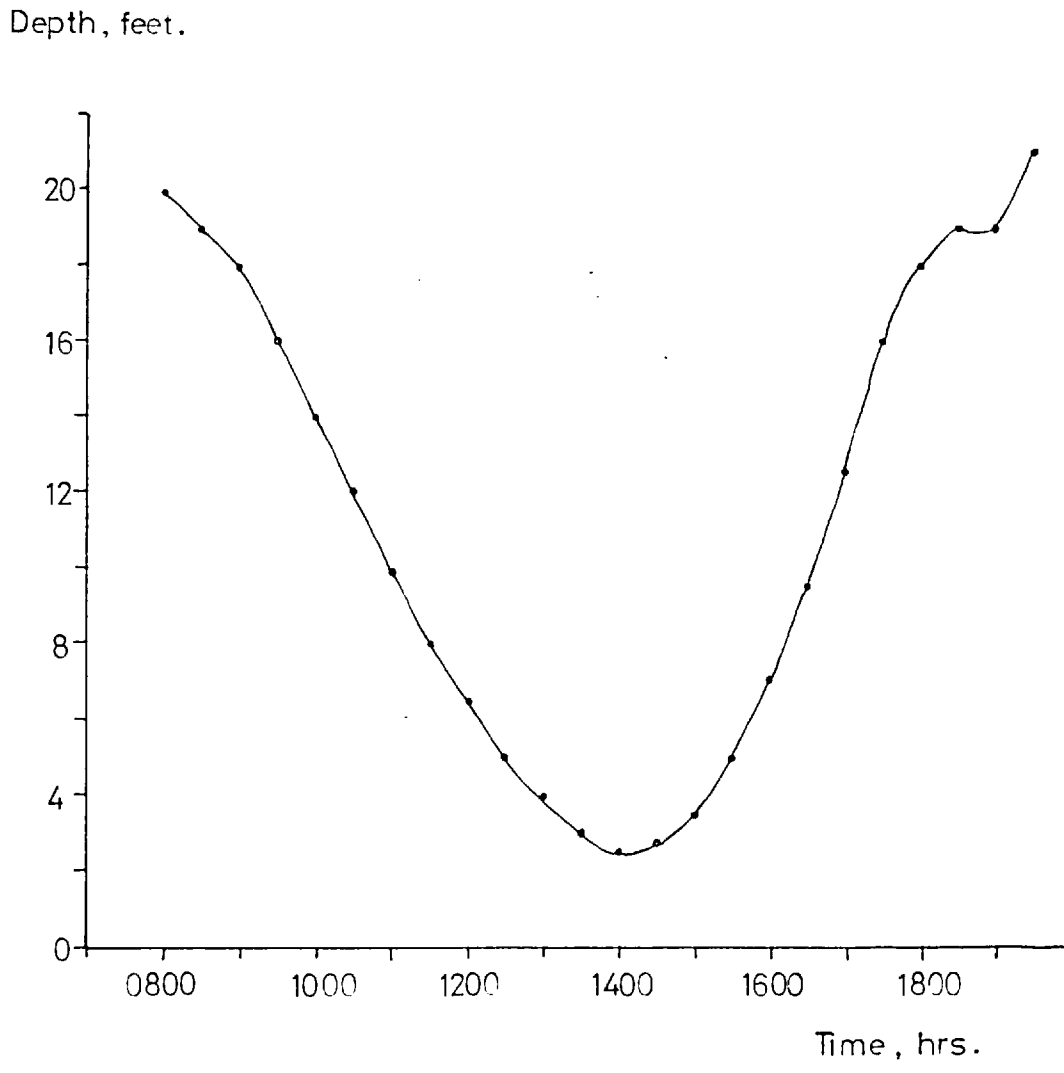


Fig.8.12. Rate of change of depth at Station 2, South Sunk Sand.



It retains this direction until soon after low water when there is a rapid reversal and the current flows east to south east for a short period of about an hour. The current again reverses and flows towards the south west, reaching a maximum velocity of 0.4 metres per second. This velocity decreases to almost zero at high water.

A similar current pattern is shown at the sea bed, although the three dominant maximum velocities all range between 0.35 and 0.40 metres per second.

This complicated current pattern may be explained by the time differences for the flood and ebb currents on either side of Sunk Sand. During the ebb, water first passes towards Hunstanton, but just before low water it changes direction and passes westwards around the southern side of South Sunk Sand. This may be related to the early flood current flowing south from Hunstanton. The later flood current passing south on the west of Sunk Sand then produces an easterly flowing current at Station 2 for a short period only, while the dominant south or south south west current prevails here after this.

o) Conclusions

These offshore tidal current measurements confirm the presence of a strong anti-clockwise residual current around Sunk Sand, although no measurements were made at the northern limit of the bank. Ebb current megaripples observed on the east bank of Sunk Sand also indicate that the ebb current (i.e. flowing north) is dominant here.

It is suggested that sediment is transported south along the western edge of Sunk Sand and then moves east to accrete on the southern side of the sand body. This pattern of movement is predominantly due to the residual tidal currents and explains the growth of the southern limit of Sunk Sand.

4. Tidal Current Measurements and Sediment Movement Tests on the Intertidal Zone

Tidal current measurements were carried out in the Inner Road and in Wolferton creek (stations 3 and 4). In Inner Road, measurements were continued from one high tide to the next, although the channel was dry for approximately two hours. In Wolferton creek, however, measurements were made only a few hours before and after one high tide.

a) Station 3, Inner Road, Snettisham (fig. 8.13)

Here, a long, slow ebb current is contrasted with a high velocity flood current of short duration. This station was situated to one side of the creek axis. When the station dried out, water continued to drain off the tidal flats and along the central part of the creek until the flood current started to flow. These measurements were made during a spring tide and a maximum flood velocity of 0.50 metres per second was recorded on the channel bed.

b) Station 4, Wolferton creek (fig. 8.14)

These records show that tidal currents may reach fairly high velocities in the creeks of the intertidal zone. The final ebb velocity reached 0.42 metres per second, although higher values would be recorded during spring tides. Although the dominance of the flood current is shown in the Inner Road, this is not found at station 4 in Wolferton creek, which is a tributary to Inner Road. Higher velocities of both flood and ebb currents were recorded during the periods when the adjacent intertidal flats were covered with water.

c) Sediment movement tests

The results of a sediment tracer experiment carried out at the north end of Ferrier Sand (fig. 3.2) are discussed. Samples were collected twenty-four hours after the fluorescent sand was dropped at the injection site and the analysed samples indicated a distribution pattern as shown in figure 8.15. The distribution indicates that during this period the sediment was transported predominantly by the tidal currents, although affected to a slight

Fig. 8.13. Current Velocity and Direction, Station 3, Inner Road, Snettisham.

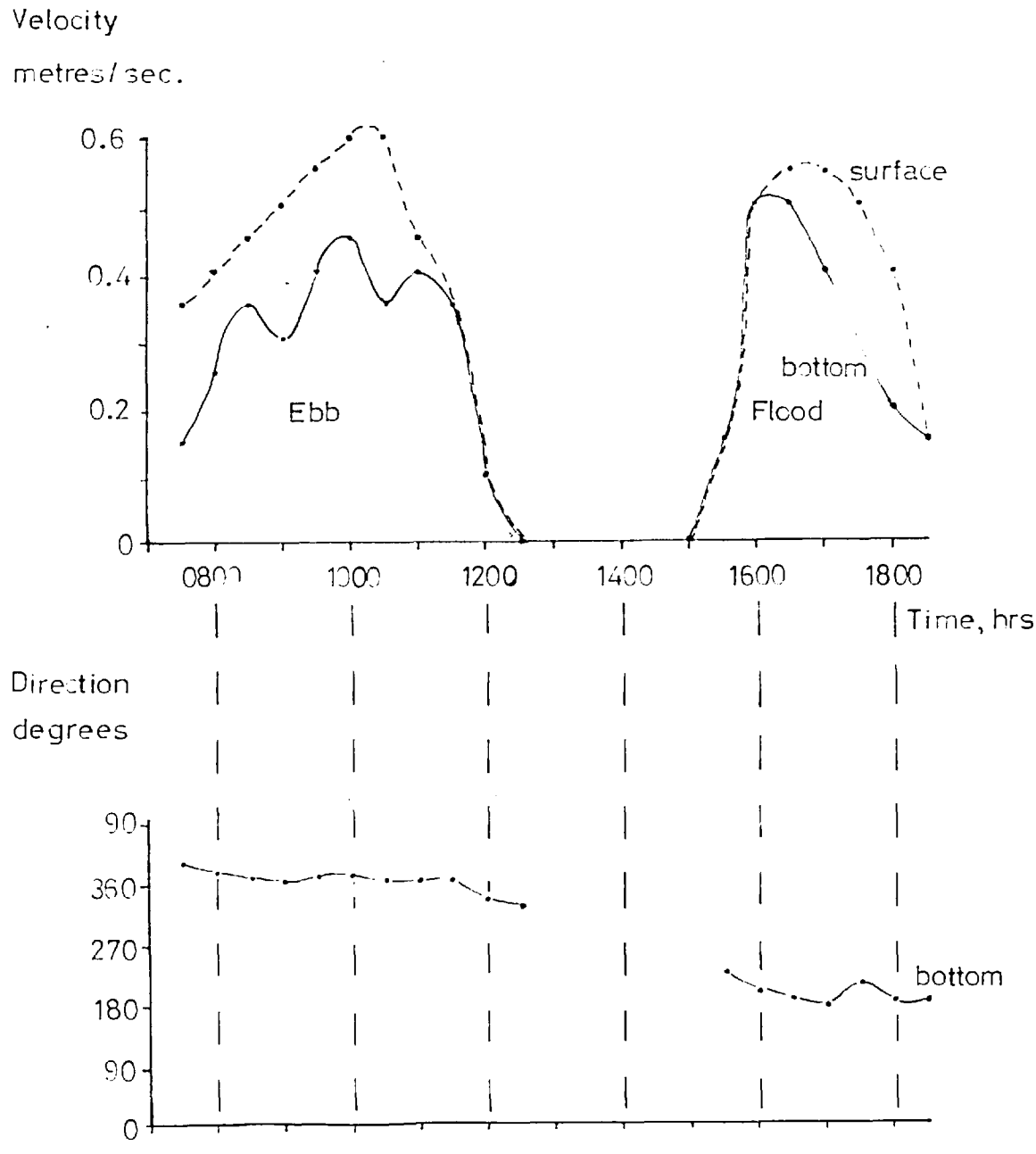


Fig. 8.14. Current Velocity and Direction, Station 4, Wolferton creek.

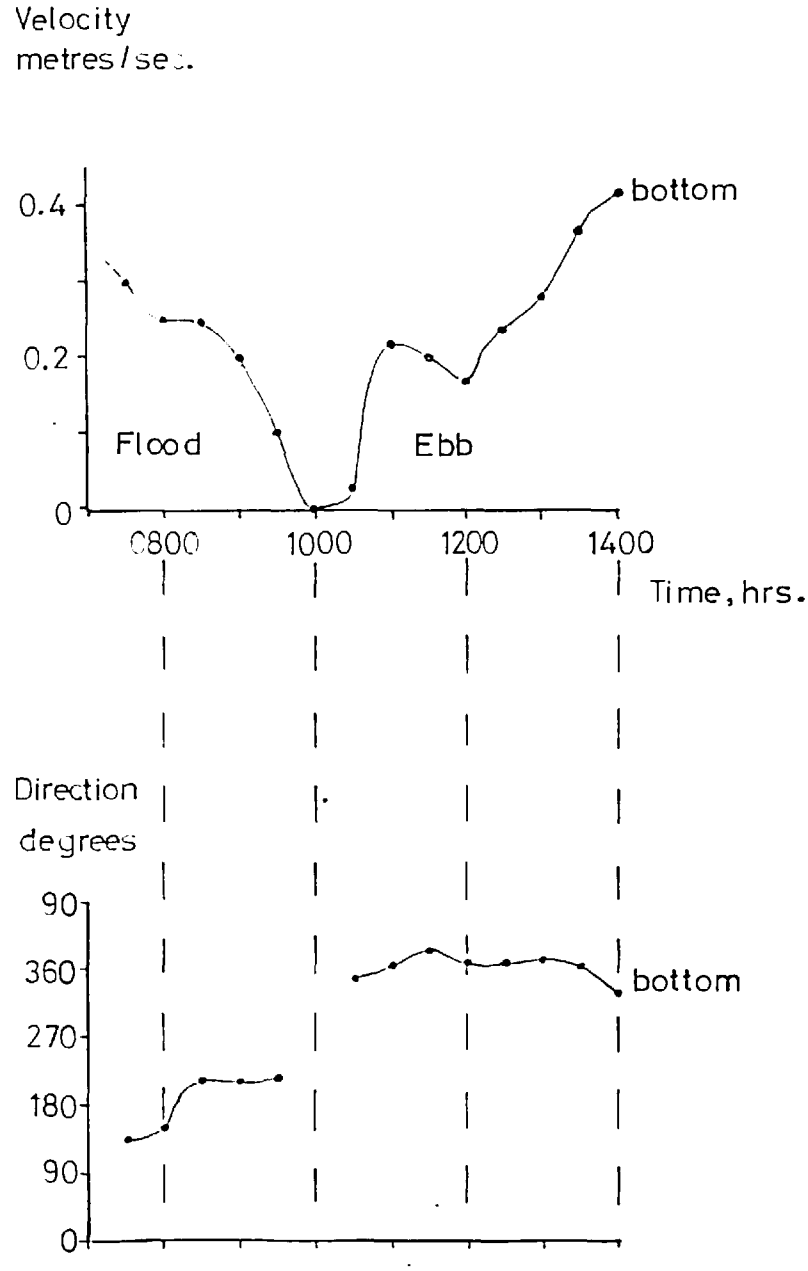
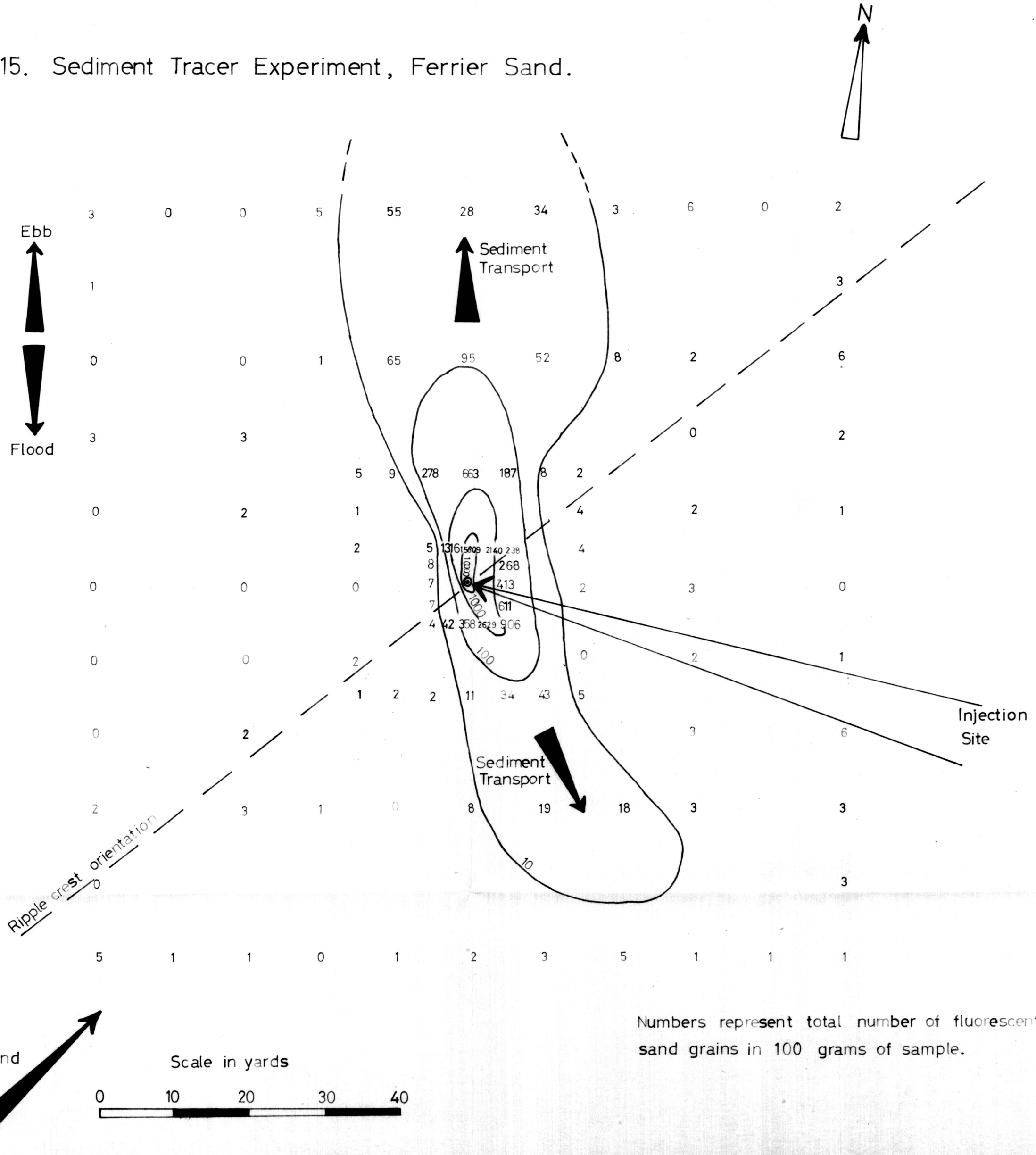


Fig. 8.15. Sediment Tracer Experiment, Ferrier Sand.



extent by wind action. Due to the limited time available, further analyses could not be carried out. It was hoped, however, to carry out tests simultaneously at three or four sites on the intertidal zone, in order to investigate the relative movement of sediment throughout the area.

CHAPTER 9

CONCLUSIONS

This study was designed to further the work of Evans (1960) and Davies (1962) carried out in the Wash region. Similar methods and techniques to theirs were used in this study to define in detail the characteristics of the region as a whole. In addition, different research techniques were also used to extend these investigations (Chapter 3). These latter techniques included beach profile measurements, which accurately recorded the changes which occurred in the beach zone (Chapter 4), a quantitative study of the displaced shell fauna of parts of the upper intertidal zone (Chapter 6), and a brief offshore survey which examined offshore sediments and tidal conditions (Chapter 8). A detailed examination of test sieves was carried out prior to the investigation of the grain size properties of the sediments (Chapter 3), and a fluorescent tracer technique, designed to investigate sediment movement in intertidal zones, was tested (Chapters 3 and 8).

In this chapter a brief outline of the physical processes affecting the region is followed by a summary of its morphology and sedimentology. The stratigraphic significance of these deposits and the relevance to ancient sequences are examined. Further sections discuss the source of the sediments of the Wash and the possible future development of the area.

I. A Summary of Physical Processes throughout the Region

Considering the region as a whole it can be seen that there are variations in the physical processes affecting the coastal zone and these variations occur in directions both along and across the shoreline. The changing nature and extent of wave, wind and tidal action throughout the region are discussed and related to the morphology and sedimentology of the sub-environments.

1. Wave Action

Wave action is most pronounced in the north of the region where the coastline has only limited shelter from the offshore sand banks (Chapter 4). Wave action gradually decreases towards King's Lynn; waves breaking against the coastline to the south have only a limited fetch and therefore cannot develop as they do in the north of the region. Pronounced breaking waves are commonly observed north of Hunstanton, generally most marked in the backbeach sub-environment and at high water they are also frequently developed along the gravel ridge south of Hunstanton.

2. Tidal Action

Tidal current action is present throughout the region and is not as variable as wave action. Longshore tidal currents may be strongly developed in the offshore zone and these affect the intertidal zone at various stages between high and low water (Chapter 8). Tidal action in the intertidal zone is concentrated in creeks and runnels.

3. Wind Action (see Appendix)

Wind speeds at any particular moment in time may be considered to be the same throughout the area. Wind action alone is responsible for the transport of loose, dry sediment and this is generally only found in the northern area, either in the dune belt or in the gravel and sand ridges and berms.

II. Variation in Coastal Morphology and Sediment Properties

The area divides itself naturally into four distinct regions and these have been described separately in the text. This division was based originally on the more obvious features of the coastal morphology, although during the investigation it has become apparent that these sections also differ in many other respects which were not at first obvious.

The northern area - the barrier coastline of north Norfolk - and the transitional area may both be considered as barrier coastlines, whereas the southern area of the inner Wash is a

sheltered embayment. The transitional area shows characteristics of both the sheltered embayment and the well developed barrier coastline to the north.

The variations in the major features of the area are summarised in figures 9.1 and 9.2, which also show the variations in physical processes in the region.

1. Coastal Morphology

a) Relationship of sub-environments

Four separate sub-environments are recognised in the northern area and these may be related to those of the transitional area.

The forebeach of the northern area and the Stubborn Sand Arenicola sand flat of the transitional area exhibit many similar features, while the backbeach, well developed in the north, is represented by the gravel ridge in the transitional area. Dunes, also well developed north of Hunstanton, are not found in the transitional area, although some thin accumulations of wind blown sand are found on the crest of the gravel ridge. Holme salt marsh has its counterpart in the transitional area, although the marshes here have been reclaimed.

The southern area shows a different suite of sub-environments and these are typical of the inner part of the Wash (Evans 1965). Distinctions between the study area and previously described areas have been pointed out in Chapter 7. The sub-environments common to both this area and the barrier coastline are the salt marsh and the Arenicola sand flat.

In the transitional area, the zone near high water mark, i.e. the gravel ridge, exhibits the characteristics of an exposed coast, while the lower zone, i.e. the Arenicola sand flat, exhibits characteristics more typical of a sheltered intertidal region. Within the transitional area there is very little variation and changes are found at its northern and southern limits, where it merges into the other areas.

Fig. 9.1 Longshore trends of intertidal zones

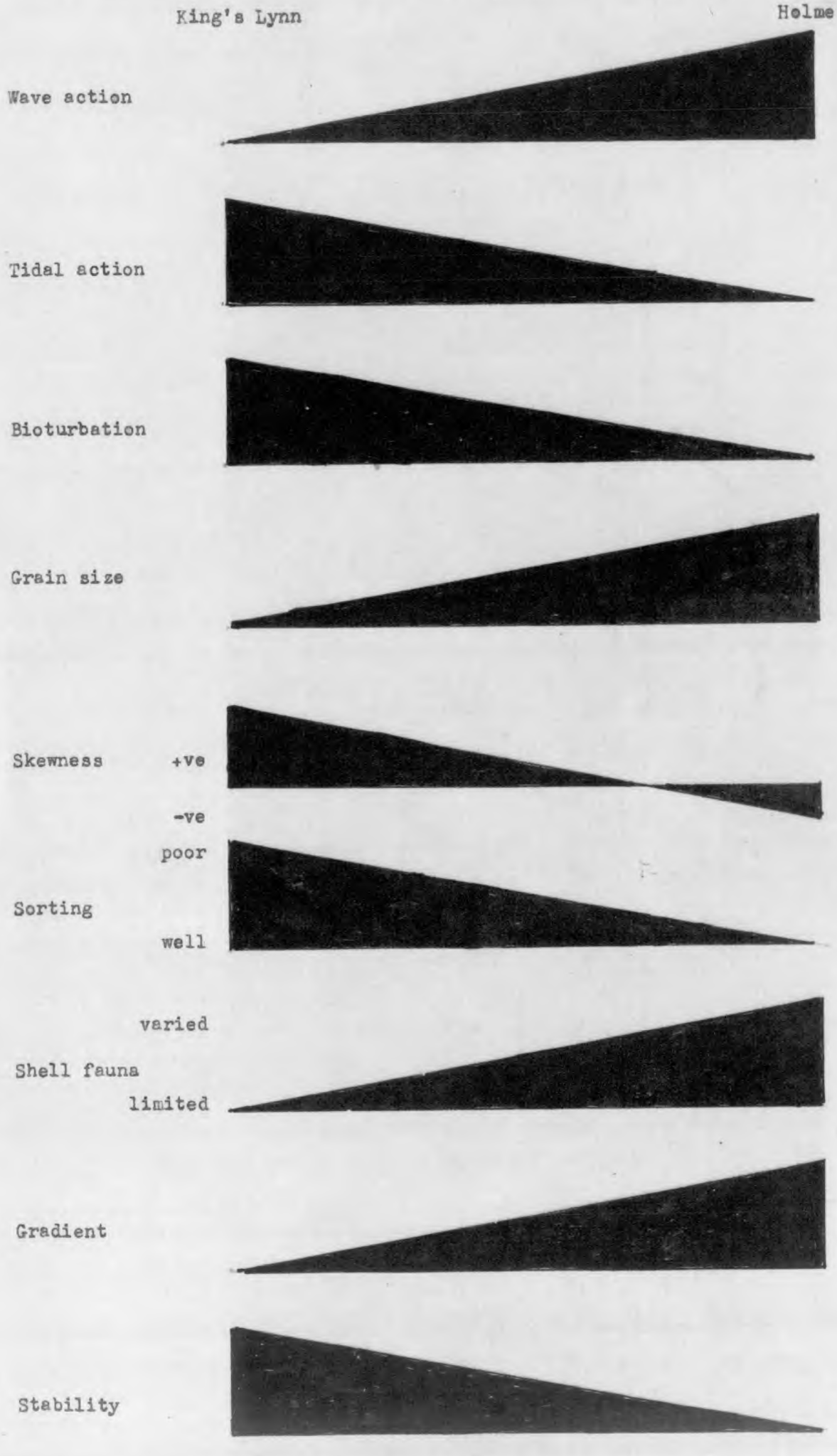
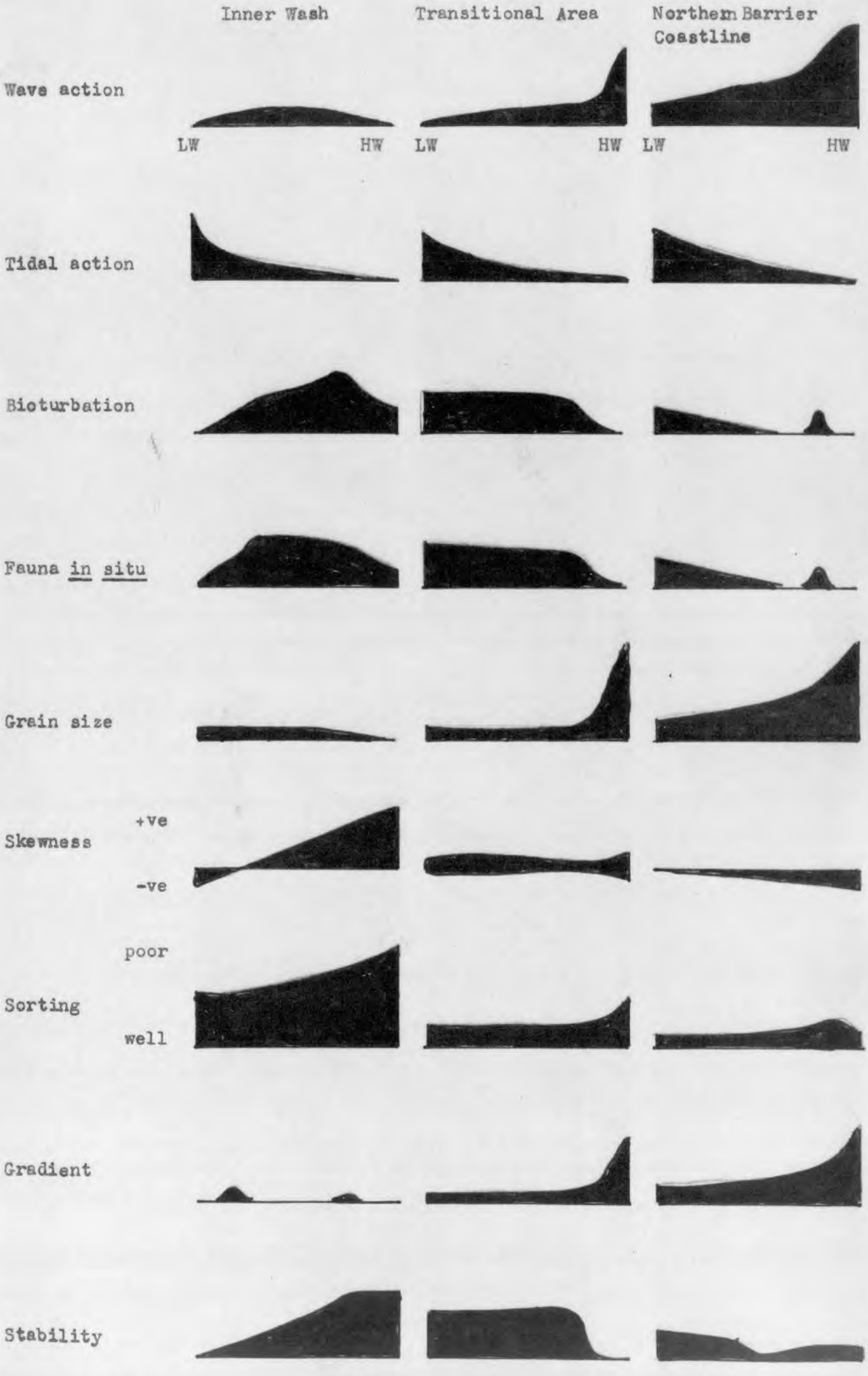


Fig. 9.2 Trends perpendicular to the Coastline, Intertidal Zones



b) Gradient of the intertidal zone (cf. Chapters 4 and 6)

A comparison of profiles across the shoreline indicates the differences in gradient, the barrier beaches generally being steeper. In the area studied, the barrier beach zones show low gradients towards low water mark and these compare closely with the gradients of the intertidal flats to the south. The low gradients of these intertidal zones is also indicated by their large widths.

c) Profile variation (Chapters 4 and 6)

Profile variation is common on the barrier coast beaches north of Hunstanton, as these are often exposed to severe wave conditions which may cause rapid erosion or accretion of sediment on various parts of the profile (Chapter 4).

A comparison of profile changes for the northern and transitional areas shows that the transitional area is relatively stable and not subject to such dramatic variations. Generally, the sand flat of the transitional area shows gradual accretion of sediment (Chapter 6).

No measurements were made to indicate profile changes in the southern area. However, it has been shown that for a similar intertidal zone slow accretion of sediment takes place over the whole area (Inglis and Kestner 1958B).

Profile variation north of Hunstanton has been studied in detail. In particular the development of beach ridges was examined and it was shown that these features undergo seasonal changes. Generally, they become more prominent in summer and are cut down in winter, when their landward migration is most rapid. It was shown that large volumes of material are removed and redeposited on the beach over a short period and that the most unstable region of the beach is the beach face. During the period of this study (October 1965 to January 1968) the beach gained sediment, the volume accreted being largest at Gore Point and becoming less towards Hunstanton. The profile studies showed that accretion is dominant on the beach face and the berm, while it is very limited on the forebeach. A 'ridge and runnel' beach topography, as is

found in this area, is considered to originate from the formation of swash ridges at the limits of wave action at stationary states of the tide.

2. Sediment Properties (Chapters 5 to 8)

The overall trends in sediment properties throughout the area are summarised and variations both perpendicular and parallel to the shoreline are indicated. These trends are related to the physical factors previously summarised.

a) Sediment grain size

i) Mean grain diameter

The trend in mean grain diameter of the sediments of the intertidal flats of the Wash, contrasts with that of the sediments of the barrier coastlines. In the Wash, south of Snettisham, there is a seaward increase in grain size, whereas on the barrier coastline there is a seaward decrease. This trend of grain diameter has been shown for other areas in the Wash (Evans, 1965) and in the Wadden Sea (van Straaten 1961, van Straaten and Kuenen 1957). It may readily be explained by the pattern of decreasing current velocity across the intertidal zone and by the settling lag and scour lag effects described by van Straaten and Kuenen (1957).

The reverse trend on the beaches north of Hunstanton reflects the variation in wave energy on the shore zone (King 1959, Davies 1962). Material of all sizes moves landwards but the backwash carries only the finer sediment seawards, this producing a concentration of coarser sediment towards high water mark.

On Stubborn Sand, at Heacham, there is little variation in the mean diameter of the sediment. High values, however, are present in the sediment of the gravel ridge and in this respect the intertidal zone is comparable to that north of Hunstanton.

South of Snettisham, clayey silts of the marsh pass seaward into very fine and fine sands, while north of Hunstanton, medium sand, with some gravel, passes seaward into fine sand. A lobe of

fine sediment is associated with the creeks around Inner Road, while a smaller lobe near Heacham may possibly be associated with the old outfall of the Heacham River.

ii) Sorting

The pattern of sorting is not immediately obvious. In most areas sorting improves seawards but in the area around Inner Road, the pattern is more complex and sediments near low water mark are poorly sorted. Considerable variation in sorting is also found north of Hunstanton.

In the intertidal flat environment of the inner Wash, the seaward increase in the degree of sorting is predominantly due to wave action which reworks the sediment. This wave action is most effective on the Arenicola sand flat and sediments here show superior sorting to those of the other sub-environments. In the lower sub-environments tidal action is responsible for sediment sorting but generally this is not as efficient as wave action. At slack water fine sediment is deposited and this is not always removed but may become interlaminated with subsequent deposits of sandy sediment. The sediments of the lower sub-environments are not subjected to such prolonged wave action as is the Arenicola sand flat.

To the north, the sediments of the forebeach are better sorted than the sediments of the other sub-environments of the barrier coastline. Coarse material is rare here as the limited proportion derived from offshore is eventually transported landwards to be deposited on the backbeach, while silt and clay are generally not deposited here, due to the constant wave action. Backbeach sediments are not so well sorted due to the mixture of coarse sediment, while dune sediments show an intermediate sorting, between that of the forebeach and the backbeach. The sorting of the dune sediments reflects to some extent the sorting of the source area, which in this case is the backbeach.

iii) Skewness

In general, sediments in the south are normally positively skewed, while to the north they are negatively skewed.

There is also a general trend towards symmetrical distributions or to low negative values from high to low water mark.

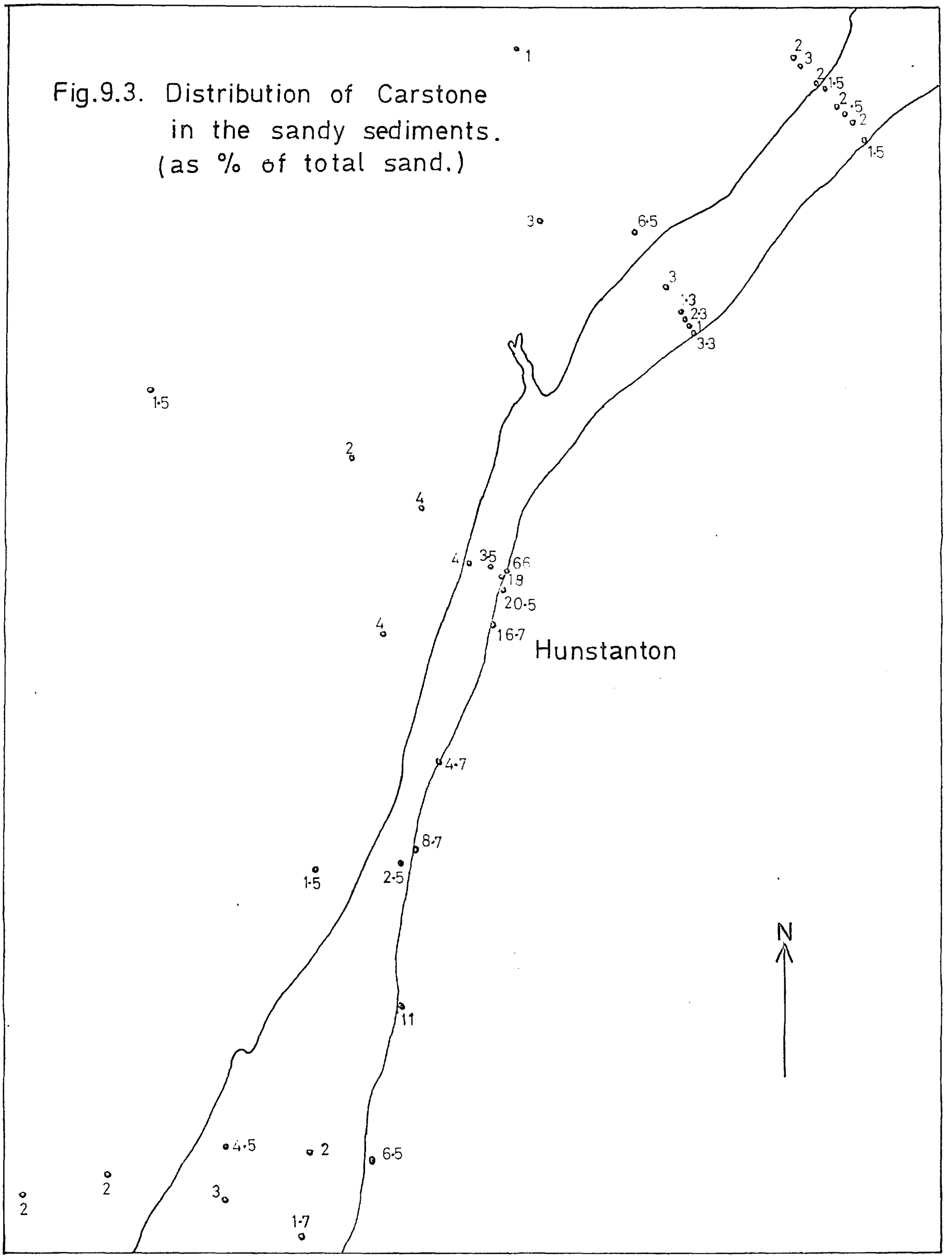
The positive skewness of the intertidal flat sediments is due to the presence of a tail of fine sediment, whereas the negative character of the barrier sediments is a reflection of the tail of coarse sediment present. This contrast indicates clearly the difference in physical processes affecting the coastline. The tail of fine sediment in the inner Wash sediments is due to the lack of winnowing of the sediment by wave and tidal currents. The tail of coarse sediment, generally present in the barrier sediments, may be considered due to coarse material being transported into the environment during periods of strong wave action. Subsequently this coarse material remains in the environment.

b) Sediment composition

The main variations in the coarse fraction composition are found in the inner Wash area, where higher proportions of generally minor components are found in the sediments of the upper sub-environments. The marsh sediments of the barrier coastline also show high proportions of these minor components. The sandy sediments, predominantly terrigenous, show little significant variation in composition, except in a few cases. Determinations of feldspar content indicate that the sediments are subarkoses.

The Carstone oolites and fragments, derived predominantly from the Hunstanton cliffs, are easily recognizable in the sandy fractions and form a useful tracer for sediment movement. They are, however, very soft and their resistance to wave action is considered to be limited. The concentration of these fragments in the sediments surrounding Hunstanton shows that in the high water mark zone, transport is predominantly to the south, although some transport does occur in the opposite direction (fig. 9.3). At low water mark and in the channel, sediment moves predominantly towards the north. These opposing directions of movement are due to the relative effectiveness of wave action and tidal current action. At high water mark, wave action predominates and although

Fig.9.3. Distribution of Carstone in the sandy sediments. (as % of total sand.)



this may move sediment in either direction alongshore, due to the differences in fetch of the waves, the preferred direction of transport must be towards the south. In the channel and in the lower intertidal zone, tidal currents are more effective in the transport of sediment. The northerly residual current is responsible for sediment transport in this direction.

It is also interesting to note that although this component may reach proportions of over 60% in the backbeach sediment immediately adjacent to the Carstone cliffs at Hunstanton, very little sediment is transported seawards and the sediment at low water mark contains only 4% of this component. For this reason, the proportions seen in the sediments of the offshore zone and of the lower sub-environments are very limited compared with those of the backbeach and gravel ridge sediments.

The distribution of molluscan and barnacle fragments shows an increase from low to high water mark in the inner Wash area, whilst on the barrier coastline the reverse trend is found, with high percentages in the offshore area. The abundance of shell fragments in the offshore area in the north must be due to the proximity of an abundant source, while the concentration in the upper intertidal flats in the south is due to the preferential landward transport of these relatively light fragments by waves and currents. This distribution is also discussed in the following section on fauna.

c) Sedimentary structures

Sedimentary structures were studied in detail by visual examination of the exposed sediment surface and by box and core sampling.

Considerable variation in types of sedimentary structures occurs throughout the area and box samples have been used to illustrate in cross section the nature of the sediments from the various sub-environments.

The sediments of the sub-environments, seen in cross section, are generally distinguishable by their sedimentary structure and approximate grain size. The sedimentary structure of the offshore deposits was not investigated due to problems of sampling.

i) The barrier coastline of north Norfolk (Chapter 5)

The sub-environments of the barrier coastline north of Hunstanton generally showed distinctive characteristics in cross section, although the backbeach showed a wide range of sedimentary structures and some of the examples could equally be representative of the forebeach.

The major characteristics of the sub-environments are summarised:-

1. The forebeach - rippled laminae, normally dipping gently seawards, commonly bioturbated, very little coarse sediment.
2. The backbeach - high and low angle cross stratification (high angle stratification generally dips landwards), coarsely laminated, sometimes rippled, coarse sediment present, generally very little bioturbation although some lenses of bioturbated sediment.
3. The dunes - may have high angle cross stratification, dipping both landwards and seawards, finely laminated, root structures, no bioturbation, usually no coarse sediment.

Cores from Holme marsh contained finely laminated clayey silts and silty clays interbedded with medium to fine grained clean sands. The sands are deposited on the marsh during breakthroughs of the adjacent barrier. Similar horizons of sand could not be identified in the marshes of the Wash, there being no adjacent source of sand.

ii) The transitional area (Chapter 6)

Only a limited number of box samples was collected in this area and these were taken from Stubborn Sand.

Characteristic sedimentary structures include horizontal lamination, rippled lamination and small scale cross lamination. Many of the primary structures are destroyed by intensive bioturbation caused by Arenicola marina and Cerastoderma edule.

iii) The inner Wash coastline (Chapter 7)

Distinctive internal sedimentary structures are present in the dominant sub-environments of this area and the characteristics of each compare closely with those illustrated by Evans (1965). The major characteristics are:

1. The salt marsh - finely laminated silts and clays with very little disturbance due to organic activity. Root structures are abundant.
2. The higher mud flat - finely laminated sands and silts, where the primary laminations are disrupted and even obliterated by organic activity. Occasionally thicker laminae of sand are present. Creek bank sections indicate that cross stratified deposits are common in this sub-environment.
3. The Arenicola sand flat - the sediments are coarsely laminated although in many sections this is not apparent due to bioturbation. Thin laminae of silt may be present at the upper and lower limits of the sub-environment. Burrows of Arenicola marina are common.
4. The lower mud and sand flats - well defined undulating and discontinuous coarse laminae of silts and sands characterise these sub-environments. There is a noticeable lack of bioturbation compared with the higher sub-environments. Mud pebble gravels are common in the lower sand flat. The lower sand flat shows evidence of sediment scouring and contains thicker and more abundant laminae of sand than does the lower mud flat.

d) Fauna

A brief survey of both the in situ fauna and the displaced fauna has been carried out during this project.

i) In situ fauna

North of Hunstanton an in situ fauna is present in the forebeach sediments and in the runnels of the backbeach

(Chapter 5). The dominant species here is Arenicola marina, while towards low water mark Lanice conchilega, Tellina tenuis, Macoma balthica, Mytilus edulis, Petricola pholadiformis and Cerastoderma edule also occur. In the backbeach runnels a more limited fauna is developed, consisting predominantly of Cerastoderma edule, Macoma balthica, and Hydrobia ulvae.

The creeks of Holme marsh also contain a limited fauna consisting notably of Arenicola marina, Scrobicularia plana, Macoma balthica, Hydrobia ulvae and Littorina littorea.

Stubborn Sand, in the transitional area (Chapter 6), supports a similar fauna to the forebeach sub-environment north of Hunstanton, although here the species are generally present in greater abundance. This is considered to be due to the more sheltered nature of Stubborn Sand.

The fauna of the sub-environments of the Wash are described by Evans (1960) in his work on the intertidal flats near Boston. This study demonstrates that the faunal zonation established there is typical of the inner Wash coastline as a whole (Chapter 7).

ii) Displaced fauna (Chapter 6)

An examination of the displaced shell fauna of the backbeach north of Hunstanton and the gravel ridge of the transitional area was undertaken in order to establish accurately the distribution and variation in abundance of displaced species.

It was shown that in the Wash (i.e. the transitional area) the displaced fauna of the gravel ridge reflect the shelly fauna living in the intertidal sand flat (Stubborn Sand). North of Hunstanton the fauna are a mixture of forebeach and offshore fauna. This distinction may be related to a variation in the offshore fauna from one part of the coastline to the other but it is also considered to be due, in part, to the more sheltered nature of the transitional area, where offshore shell fauna have less likelihood of being transported to the gravel ridge.

Mollusc and barnacle fragments were counted in the analysis of the coarse (i.e. sand) fraction. North of Hunstanton, these

form up to 10% of the coarse fraction near low water mark, but decrease in abundance towards high water mark. Davies (1962) found that the backbeach sediments at Gibraltar Point contained higher concentrations of shell than did the sediments from other sub-environments. It is considered that the high shell concentrations of the forebeach north of Hunstanton are due to the adjacent reef which provides an ample source of shell material. Displaced foraminifera are present in the sediments although they never exceed 2% of the coarse fraction.

The sediments of the upper limit of Stubborn Sand contain higher proportions of mollusc and barnacle fragments than elsewhere on the sand flat. These results are comparable to those of Davies and contrast with the results immediately north of Hunstanton. The higher values are probably due to the concentration of shell fragments by wave action and the relative ease with which they are broken down to sand sized particles.

In the intertidal area of the inner Wash a similar increase in mollusc and barnacle fragments and in foraminifera occurs towards high water mark.

In the sediments of the offshore area the proportion of mollusc and barnacle fragments is higher than in the sediments of the intertidal areas, and this is considered to be related to an abundant adjacent source of shelly organisms.

III The Comparison of Recent and Ancient Sequences: Stratigraphic Significance

1. Problems

One of the main aims in the study of Recent sediments is to determine characteristics which may be used to explain the depositional relationships and sedimentary history of earlier deposits. The difficulties encountered in the comparison of Recent and ancient sequences have been discussed by Doeglas (1959).

Perhaps the major difficulty is that, in studies of Recent sedimentation, thin surface layers over large areas are examined, whereas in ancient sequences, vertical sections of restricted lateral extent are described. Other difficulties arise due to the time correlation of ancient sequences and the separation of sediments of different transgressions and regressions. Doeglas suggests that methods of investigation of Recent and ancient sequences should be standardized and that in research work on Recent sediments undisturbed samples should be collected from borings through the sequence. Potter (1967) claims that the main problem in producing an environmental interpretation of a sand body lies in the lack of systematic and quantitative data on petrology, texture, sedimentary structures and internal organisation of the sand body. In the past, the detailed analysis of a thin succession has not been considered important in the investigation of a thick sand body, which may be the result of a large number of regressions and transgressions. Thus it appears that there is here a problem of scale; the Recent environment investigated indicates the distribution and relationship of sediments at one period of time, whilst in an ancient sand body, a large number of cycles may be represented.

2. Relationship of the Deposits in Cross Section

Complete sections through the Recent deposits were not available for this study and the sections described are therefore, to some extent, hypothetical, being derived from an interpretation of surface information and from a limited number of relatively shallow pits and auger holes, which penetrated only a small part of the succession.

Progradation of the barrier sand body is occurring at Holme and also along the coastline immediately to the east, although this progradation is not found along the whole length of the north Norfolk barrier coast. A section through a part of this barrier would be expected to show the sequence of deposits indicated in table 9.1. Hoyt and Weimer (1963) illustrate a similar sequence in the Recent and Pleistocene sediments of Sapelo Island.

Table 9.1 Summary of Characteristics of Barrier Sediments

Sub-environment	Sediment type	Mean Diam.	Sorting	Skewness	Composition	Sedimentary Structures	Fauna and Bioturbation
Dune	medium sand	limited	well sorted	low, normally negative	very little change in composition throughout decreasing ↑ Mollusc content up to 10%	laminated // to surface results in horizontal and steep dips	no bioturbation plant root structures
Backbeach	fine/medium sand sandy gravel gravelly sand gravel	wide range	well or moderately well sorted	symmetrical and negative		landward dipping cross stratified beds with horizontally bedded rippled sediments	rare lenses of intense bioturbation nil elsewhere
Forebeach	fine sand	limited	very well sorted	symmetrical or low positive & negative		rippled horizontal or slightly seaward dipping laminae	limited bioturbation by Arenicola sp. Lanice sp. abundant towards base
Offshore	sands and gravels	wide range	poorly sorted (esti-mated)	negative (esti-mated)		structures not investigated	intense bioturbation by Lanice sp.

In the transitional area some progradation of the gravel ridge has occurred at Snettisham Scalp, and here a broad gravel ridge has been produced. On the landward side of this ridge other elongate gravel features are also present, surrounded by marsh sediment. A cross section perpendicular to the gravel ridges would show lenses of gravel passing laterally into marsh sediments which overlie intertidal sand flat deposits.

The sediments of the inner Wash area are considered to show a similar stratigraphic relationship to that described by Evans (1965), with some notable differences. The inner sand flat deposits of Evans are not clearly defined in this area and the lower mud flat deposits do not form a continuous belt. Evans (1965) shows that the lower mud flat deposits pass northwards into a sandy equivalent.

Evidence from boreholes in the vicinity of King's Lynn indicates that early Holocene deposits probably underlie the intertidal flat sequence, although the upper surface of these deposits is likely to have been cut into by later channels.

IV The Source of the Sediments

In the last century, Skertchley (1877) concluded that the sediments of the Wash are being derived from the sea rather than from the rivers which enter the region. This conclusion was also reached by Evans (1960) and Davies (1962), who investigated the Lincolnshire shoreline and by Kestner (1963) who has carried out an investigation of the suspended silt around the Wash margins. Kestner agreed that sediment derived from the rivers is negligible but does not rule out the possibility that the material at present in suspension and accreting around the margin could originally have been derived from the rivers. He considers the immediate source for suspended material to be the marginal areas where high concentrations are present. These values decrease rapidly in a seaward direction.

Van Straaten and Kuenen (1957) have discussed the accumulation of fine sediment in the Wadden Sea and have shown how this material

is derived from the North Sea and concentrated in the Wadden Sea. It is considered that a similar process must operate in the Wash. The fine sediment which is present in the marshes of the north Norfolk coast must be derived from the sea, as here there are only a few small rivers and most marshes have no connection with them.

The gravelly sediments both in the area south of Hunstanton and on the north Norfolk coast are mainly derived from offshore and it is apparent that both onshore and alongshore sediment movement is responsible for the emplace of gravel in the backbeach and in the gravel ridge. Onshore movement of gravel has been shown by Kidson, Carr and Smith (1958) and by the author (Chapter 5), whilst longshore movement is seen to produce spits and other related features. The immediate source of the gravel north of Hunstanton is obviously the offshore area called The Bays. Gravel is only rarely present in the offshore zone south of Hunstanton and has not been observed on the sandflat surface. Here longshore transport is considered to be the most effective agent in sediment supply to this gravel ridge and most of the coarse sediment has probably been previously transported to high water mark either at Hunstanton or farther north.

The sands and gravels of the offshore area are probably reworked glacial deposits on the floor of the North Sea. Other sources which must contribute material to the Wash area include the eroding part of the Yorkshire, Lincolnshire and Norfolk coasts. The cliffs at Hunstanton must provide considerable quantities of sediment, some of which is recognised in the Recent deposits.

V The Future Development of the Area

The future development of the area depends ultimately on the relationship between the rates of sedimentation and erosion and the relative movements of land or sea level (Willis 1961). Wide barriers of a prograding nature are seen on certain parts of the Norfolk coast (e.g. at Holkham and at Stiffkey) whereas,

elsewhere, there are narrow barriers moving landwards across intertidal sediments (e.g. at Scolt Head Island and at Blakeney). If the landward advance of the barriers continues, then it may result in the complete destruction of the marsh sediments behind so that eventually the beach face lies adjacent to the high ground. If sufficient sediment is introduced to these barriers then progradation may prevent this transgression.

In the Netherlands, coastal accretion of barrier sediments has been followed by a period of continual coastal erosion. Kruit (1963) considers that the coastal retreat is related to a dwindling supply of marine sand from the North Sea floor. The narrow barriers of the Norfolk coast may be an indication of the restricted supply of sediment to this region. There is certainly no major progradation due to an abundant supply.

The inner Wash area should continue to prograde rapidly, especially if this progradation is aided by the construction of training walls. It is difficult to judge whether this accretion will continue until the Wash is completely infilled but if this happens it may result in the formation of a barrier coastline similar to that developed around the Wadden Sea. The rapid accretion during the last 150 years around Sunk Sand, at the mouth of the Wash, and around its counterpart on the opposite side, the Inner Dogshead Sand, may be the first indication of such a barrier.

The construction of an artificial barrage across the Wash would considerably alter the pattern of accretion which has been taking place. No further sediment would be brought into the area and, hence, progradation of the sedimentary sequence would cease. Furthermore a barrage would cause a confluence of the tidal streams which flow along the Norfolk and Lincolnshire coasts and this might result in a zone of accretion between Skegness and Hunstanton. The restriction of sediment transport into the Wash might also result in a more rapid progradation of the barrier coastline north of Hunstanton.

Further work in this area could be related to the proposals for a barrage across the Wash. Sediment movement experiments, using fluorescent sand tracers, a technique which was experimented with in this work, should prove a very interesting and valuable study.

Another possible topic for research would be the examination of the sediments in the regions immediately behind the coast. A series of core holes which penetrate the complete sequence of intertidal and subtidal deposits should indicate the extent of these, their nature, and their relationships with the underlying deposits.

A P P E N D I X

WIND DATA

Wind observations have been made at Lynn Well lightship by the Great Ouse Catchment Board and the main results of these have been noted by Steers (1936).

1. The prevailing wind throughout the year is south west, except during the second quarter, when it is east.

2. The prevailing strength of the wind is 3, i.e. a gentle breeze, 12 m.p.h.

3. Strong gales, usually from the west north west, occur about twice a year, at any season.

Roy (1967) has used wind data from Manby and Gorleston meteorological stations to produce frequency diagrams for various wind speed categories (fig. A.1). As these were prepared from data for a short period only, the wind distributions are not representative of a yearly average distribution.

The author obtained hourly wind records from the meteorological station at Gorleston and these were used to plot wind roses, consisting of twelve directional sectors, for various wind speed categories. These were chosen in order to coincide with Beaufort's scale of wind force and also so that the results could be compared with those of Roy (1967). The data were plotted for periods between beach surveys (see Chapter 4) so that wind roses could be compared with beach changes.

Figure A.2 shows the dominant wind speeds and directions during the first survey period, i.e. October 1965 to January 1966. In the lowest speed category (7 to 10 knots) westerly winds predominated. Winds of 11 to 16 knots were dominantly west and south west, but there was also an east and south east component. Higher wind speeds were generally from the east and south east, although winds from the south west and south were

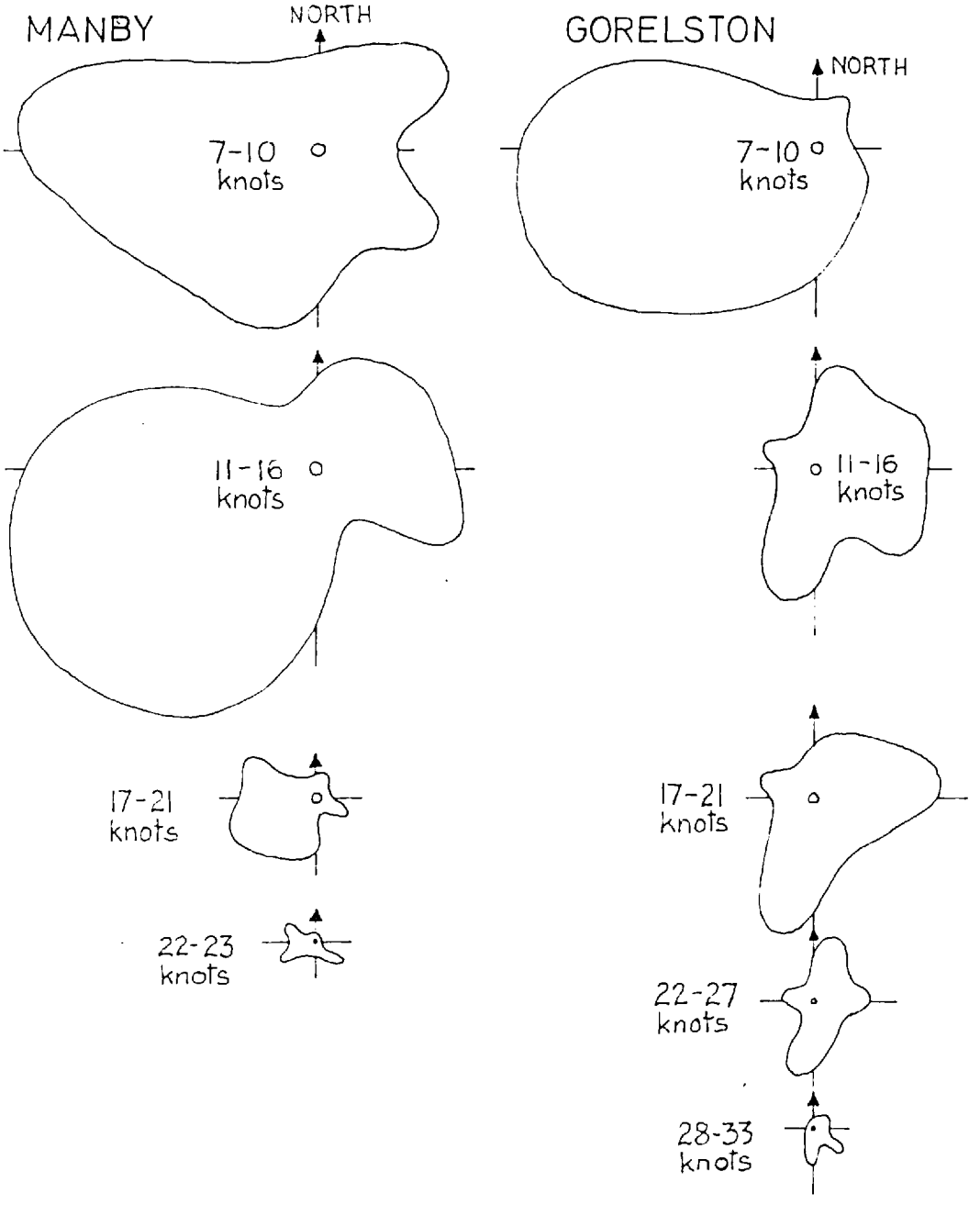
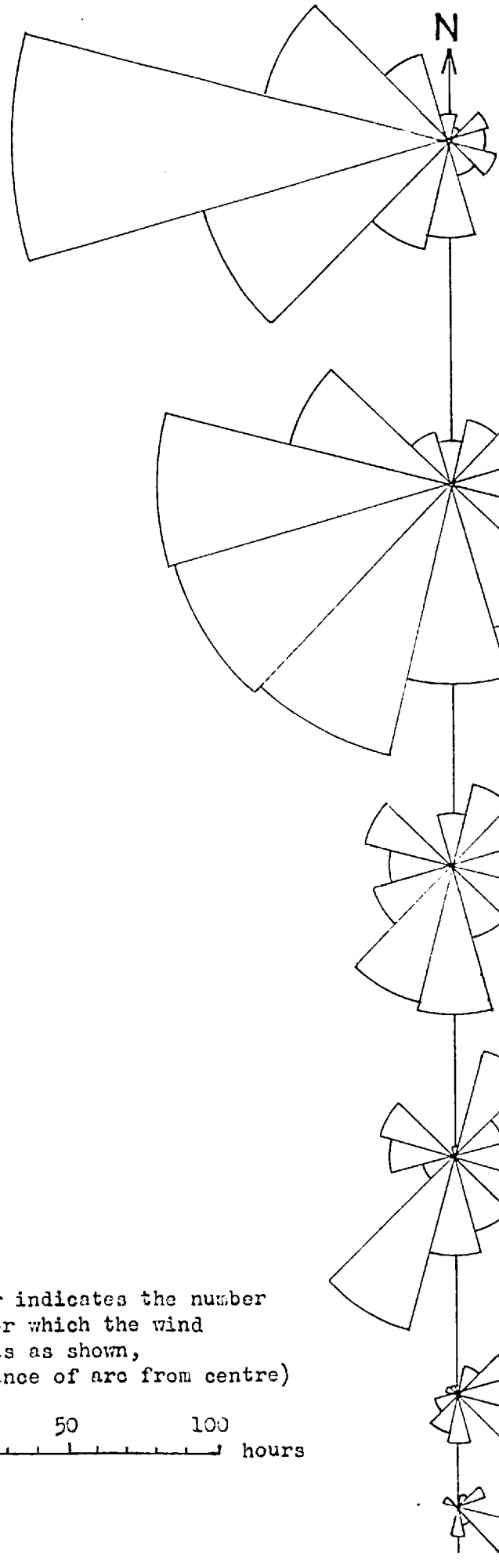


Fig. A.1 Frequency diagrams based on wind speed categories for the meteorological stations of Manby and Gorleston (from Roy 1967).

Fig. A 2 WIND ROSES

22 October, 1965 - 19 January, 1966



common. Gale force winds were predominantly east south east.

Wind roses were also constructed for the same period of the following year (fig. A.3). These compare favourably with those already shown and it is seen that the prevailing wind strengths were again west and south west, while higher wind speeds were predominantly from the south and north east.

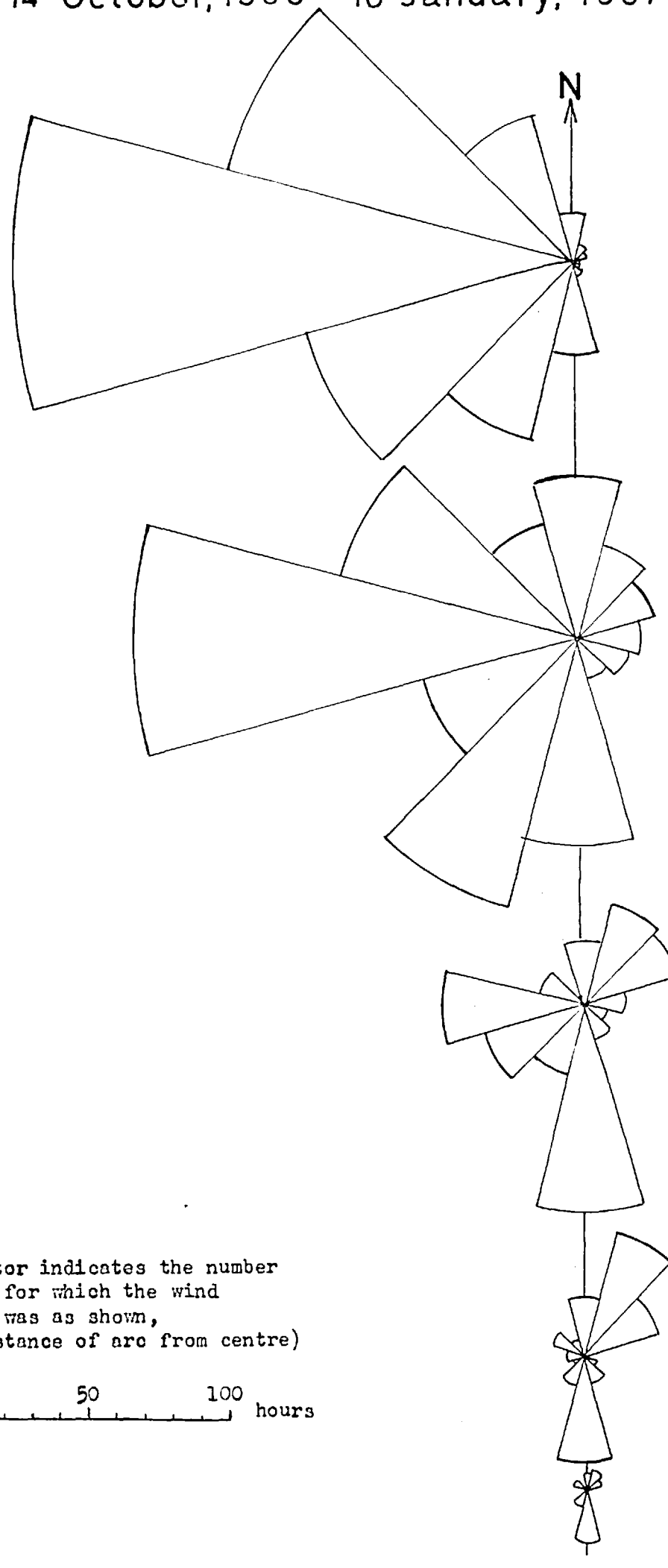
Rose diagrams for the period between the April and July surveys in 1966 indicate that the lowest speed category winds were from the south west and north east, with south west winds most frequent (fig. A.4). The low velocity north east wind is not seen in either of the October to January diagrams. Winds of 11 to 16 knots were mainly south east or north, while winds of higher velocities were dominantly from the north east.

Comparison of the rose diagrams for wind strengths of 22 to 27 knots indicates the lack of wind of this strength between April and July. In fact, the highest wind velocities recorded during this period never exceeded 35 knots.

Although these results show the general pattern of wind behaviour in the area, no direct relationship to the beach profile changes has been determined. Any correlation would be rather speculative, as short-term surveys during periods of high winds have shown that considerable quantities of material may be eroded or deposited very rapidly (see Chapter 4). The change in a beach profile over three months must be due to the effect of the combination of wind, wave and tidal conditions which prevailed during that period. It was found that the resultant profile could not be readily related to all the physical processes affecting the beach. In order to determine the cause of specific changes in the profile, it has been shown that surveys should be repeated after much shorter intervals, during which all the processes affecting the beach should be recorded.

Fig. A 3 WIND ROSES

14 October, 1966 - 10 January, 1967

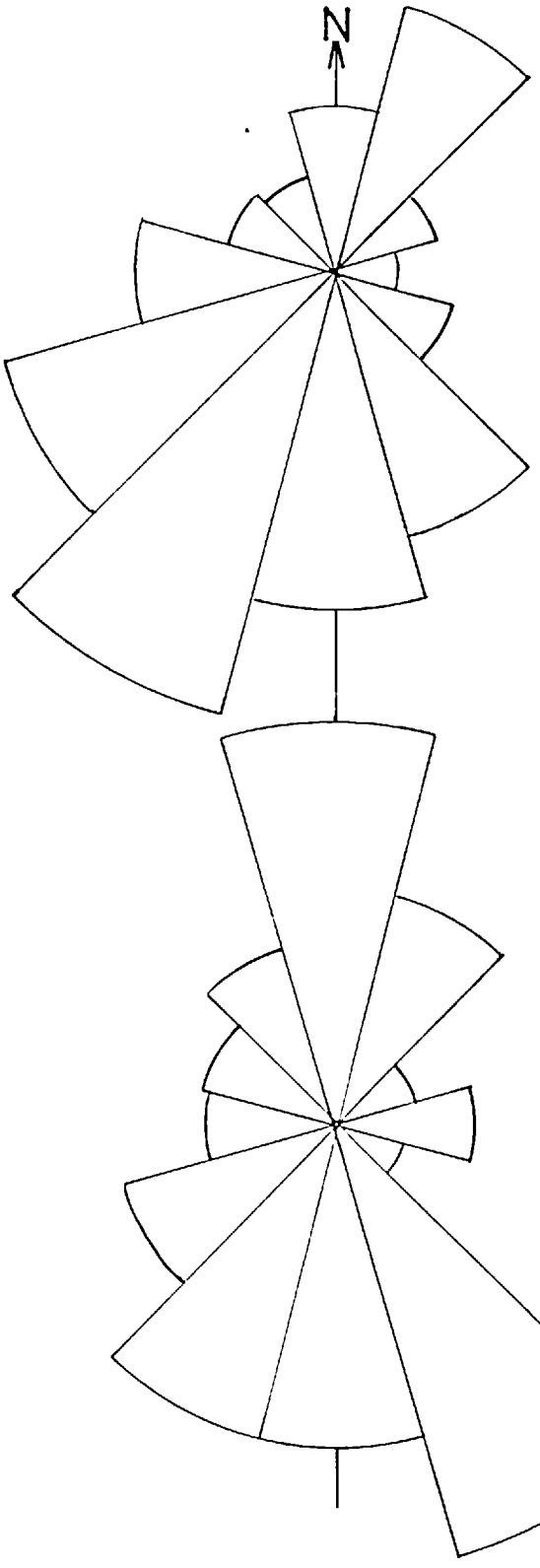


Each sector indicates the number of hours for which the wind category was as shown, (i.e. distance of arc from centre)

Scale 0 50 100 hours

Fig. A 4 WIND ROSES

5 April, 1966-6 July, 1966



WIND SPEED
(knots)

7-10

11-16

17-21

22-27

Each sector indicates the number of hours for which the wind category was as shown, (i.e. distance of arc from centre)

Scale 0 50 100 hours

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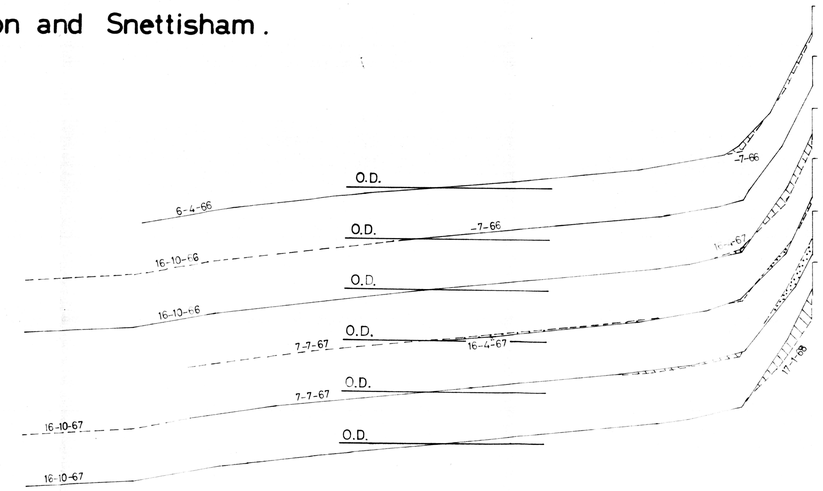
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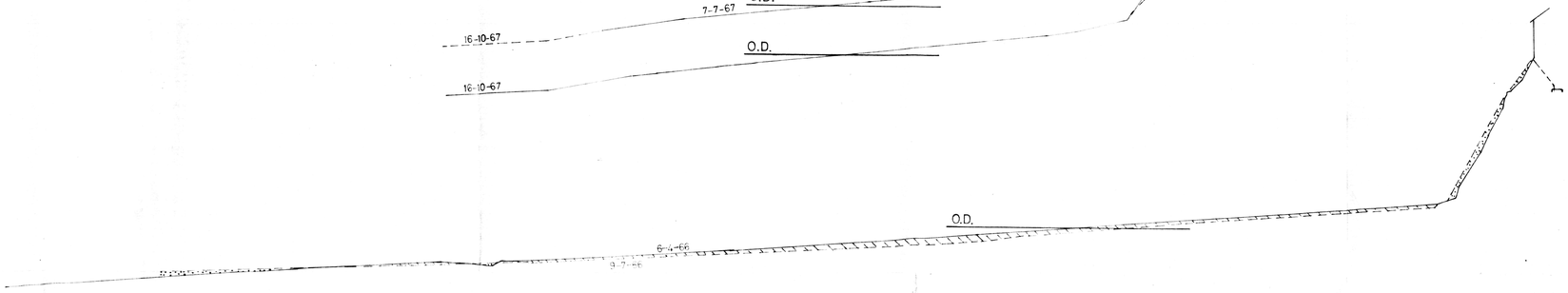
Sheet 6.1 Profile changes between Hunstanton and Snettisham.

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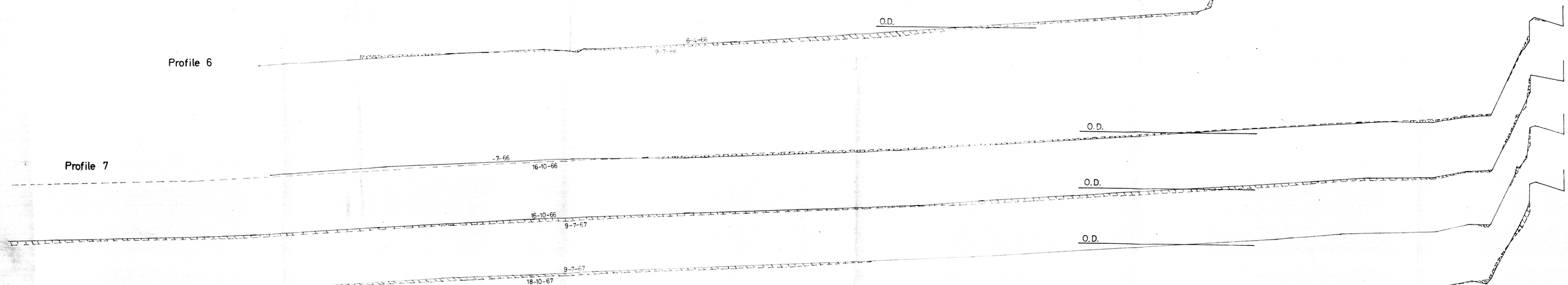
Profile 5



Profile 6



Profile 7



Profile 8

