THE SEDIMENTOLOGY OF ESTUARINE AND COASTAL PLAIN DEPOSITS BETWEEN PENDINE AND WHARLEY POINT, CARMARTHEN BAY

by

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ABSTRACT

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The northern margin of Carmarthen Bay, consisting of the south-facing coastal barrier between Pendine and Ginst Point, and the estuarine complex formed by the River Taf which discharges into the bay between Ginst and Wharley Points, has been described.

Several sedimentary sub-environments have been recognised: dunes, beach, estuarine sand flats, mud flats and saltmarsh; most consideration has been given to the more mobile sandy units.

Attention has been restricted to two aspects of foreshore and estuarine sedimentation: The stability of the respective sand bodies that constitute the coastal barrier and estuarine complex has been studied by means of periodic surveys of transects normal to the foreshore and transverse to the estuary. An attempt has been made to correlate the variations of the profiles with various components of oceanographic and meteorological energy processes. It is shown that, of these, those deriving from oceanic storms in

the south-west are most important in promoting sand transport, moving sand off the foreshore and into the estuary. Other components have local effects, assisting longshore drift on the foreshore and modifying the circulation of both water and sand within the estuary. During the period of study there was a net intrusion of sand from the bay into the estuary.

Secondly, the dynamics of sedimentation have been investigated by means of an intensive examination of the grainsize characteristics of the sediments across the same transects. The sediments have been shown to be mixtures of several components (each with lognormal grainsize distributions) and these are related to distinct modes of sediment transport: surface creep, saltation and suspension. Saltation populations are predominant in beach, estuarine and dune sands: the first two are characterised by two saltation populations, the third by one only. There is little variation of sand texture within the estuary, but a distinctive seaward-fining gradient of the saltation populations across the foreshore of the coastal barrier. Mid-tide level concentrations of a surface creep population are an important feature of parts of the foreshore. It has been argued that tidal currents are the primary agents of sand transport in the estuary, whilst swash and backwash currents, controlled by offshore and foreshore bottom configurations and wave intensities, are most important on the foreshore.

Some attention has been given to the nature of estuarine hydrography using the variations of salinity and current strength measured at various depths over a tidal cycle at several stations. The relationships between estuarine circulation, sand mobility and grainsize characteristics are emphasised.

Finally, the dynamic milieu of the study area has been discussed, and a synthesis of historical and present-day trends attempted.

For Nell and Lawrence

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CHAPTER 1.

THE PHYSIOGRAPHY OF THE AREA, (WITH SOME BRIEF COMMENTS ON FAUNA, FLORA AND SEDIMENTARY STRUCTURES)

1.1 Introduction

Carmarthen Bay covers an area of some 160 square miles, the mouth of the bay from St. Gowan's Head in the west to Worms Head in the east being 30 miles. Several rivers flow into the bay along its northern and north-eastern shores. These are the Taf and Towy from the north, the Gwendraeth system from the north-east, and the Loughor which forms the Burry estuary near Gower.

The bay is largely eroded out of the softer shales of the Millstone Grit and the Coal Measures (Mem. Geological Survey of England and Wales, 1909). The Taf and Towy valleys have been carved into the Old Red Sandstone, which forms the high cliffs that run inland behind Laugharne Burrows from Pendine to Laugharne. From Tenby to Pendine, much of the coastline is formed by cliffs cut in the Coal Measures, the Millstone Grit and Carboniferous Limestone, fronted by narrow, gravelly beaches and rocky inter-tidal platforms. Some wide sandy beaches do also occur, but nowhere on a scale to match the extent of the beach at Pendine running eastwards to Ginst Point (see Fig. 1.0). The beach forms

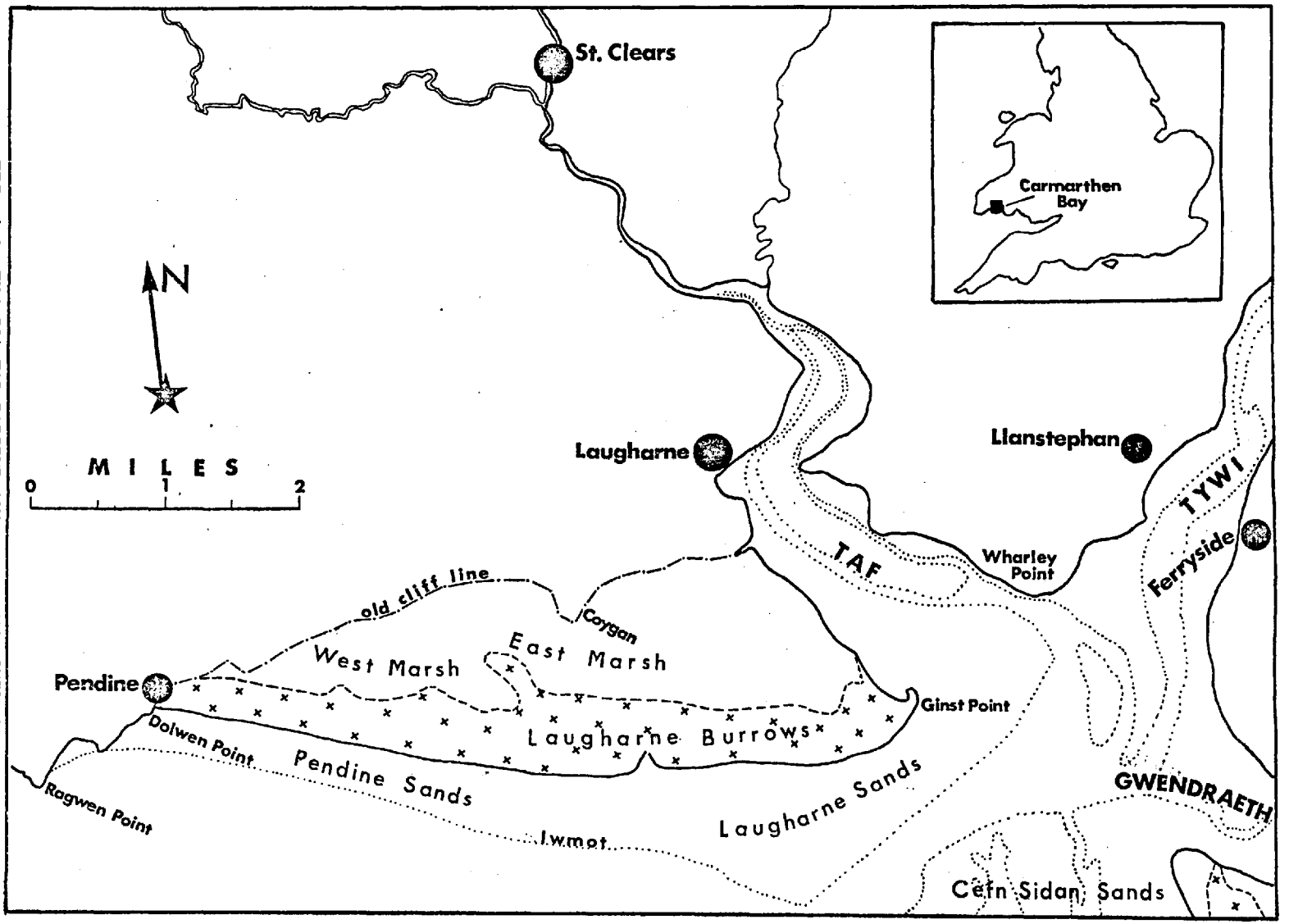


FIG. 1.0: THE COASTAL BARRIER AND ESTUARINE COMPLEX.

the seaward edge of a highly developed coastal barrier, extending over six miles from Gilman Point to Ginst Point and of varying width from 1,500 feet to 4,500 feet or more at low spring tides.

The tidal range in the bay is high, about 26 feet on spring tides and 12 feet on neaps. This produces a wide expanse of intertidal sandy foreshore, so that Pendine Sands and Laugharne Sands are exposed to the action of westerly and south westerly winds which have built up a series of high dune ridges (Laugharne Burrows) behind the beach; these accumulations are matched by similar ones in other bays in South Wales facing west or south-west (described by Steers, 1964). Near Pendine, the highest dunes exceed 50 feet in height.

To the east, an estuarine complex consists of the estuary of the River Taf and its confluence with the rivers Towy and Gwendraeth. Extensive areas of intertidal sandbanks occur in this region; offshore bars are a permanent feature of the eastern bay, off Laugharne Sands and Towyn Burrows. The intertidal sandbank area extends into the Taf estuary, which is some five miles in length, one mile in width at its mouth between Ginst Point and Wharley Point, and tortuous in shape.

A historical survey of the shoreline is not one of the aims of the present study. However, it is prudent to consider a few prominent landmarks in its evolution from both geological and

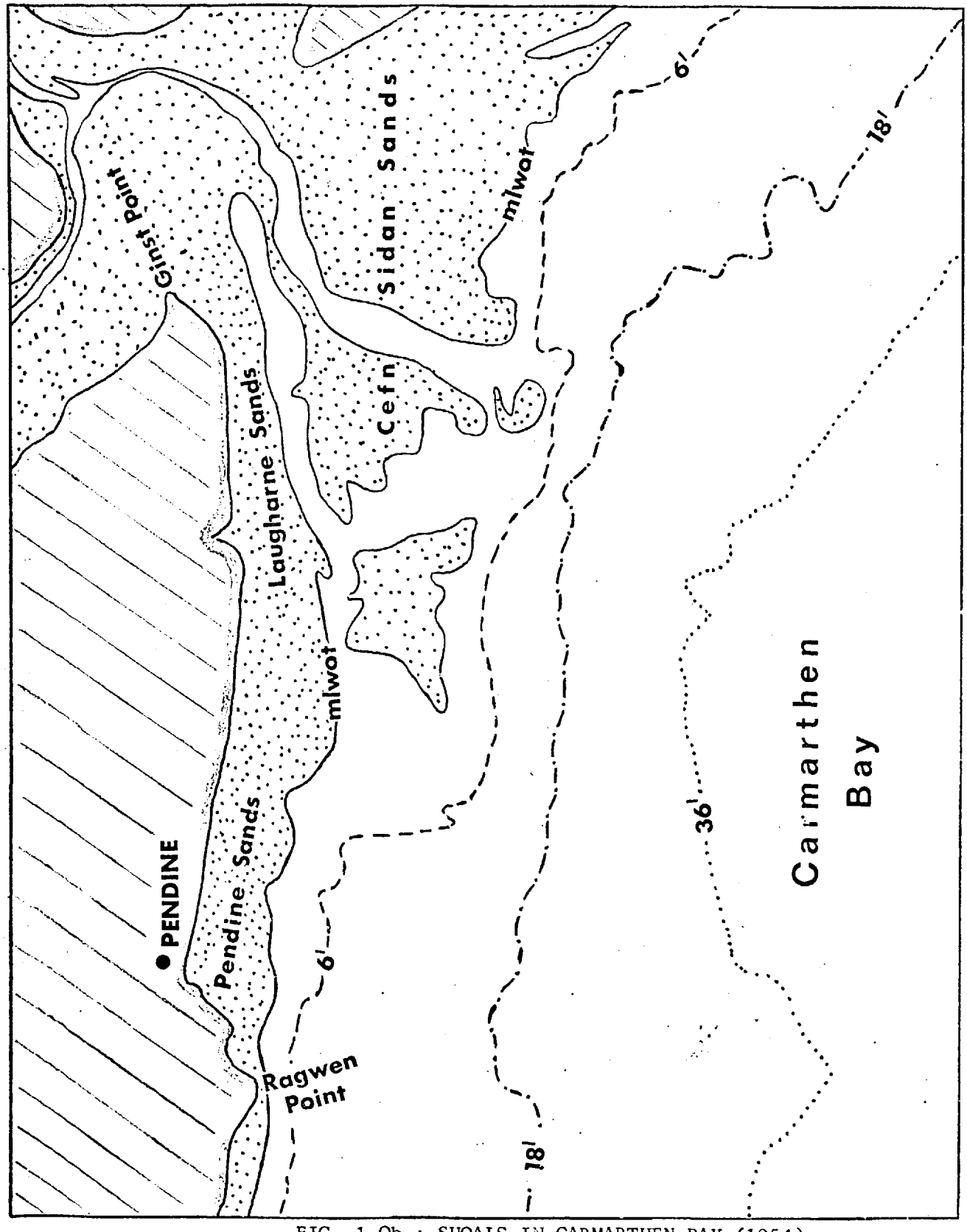


FIG. 1.Ob : SHOALS IN CARMARTHEN BAY (1954).

historical sources since these have some relevance to the study of dynamic sedimentary processes which have shaped, and continue to modify, its nearshore and foreshore geomorphology.

Bowen (1970) has shown that two Pleistocene glaciations occurred in South Wales. Older drift, predominantly fluvioglacial deposits, shows that ice swept east across Pembrokeshire and coastal Glamorganshire from the Irish Sea (Griffiths 1939, 1940), in contact with local Welsh ice pressing southwards; the extensive outcrop of mixed drift on West Gower (George, 1933) may indicate a readvance of Welsh ice subsequent to local deglaciation of the Irish Sea ice sheet (Bowen, 1973). There followed a eustatic 'high' of ocean level during the Ipswichian interglacial, when the raised beach (seen at Marros and Gower) was formed - this occurring at between 0 and 15 metres O.D. (Bowen, 1973). The subsequent, and final, Devensian glaciation (between, perhaps, 30,000 and 18,000 years B.P.) was less extensive than its predecessor; the drift of this advance, deposited by local Welsh ice flowing south, has been shown by Bowen (1970) to have terminated south along a limit extending east from St. Clears to Mumbles Head (roughly corresponding to the limit of the local ice in the preceding glaciation) - therefore just encroaching on the north-eastern and eastern flanks of Carmarthen Bay.

The Pleistocene glaciations undoubtedly created a considerable

accumulation of sediment in the Bristol Channel region. Much, or most, of the bottom sediment of Carmarthen Bay is thus probably of glacial origin.

The bay, as it exists today, was thence formed by the drowning of the lower reaches of several inflowing rivers during the Flandrian marine transgression, following the melting of the world's glaciers after the final glaciation. This reached its high water mark of about 4.5 m. (15 ft.) O.D. about 5,000 years ago; this shoreline lies at the foot of what are now abandoned sea cliffs between Laugharne and Pendine, these having been originally fashioned during the Ipswichian interglacial (Bowen, 1970). The postglacial slope evolution of these cliffs has been studied by Savigear (1953); he suggests that since their slopes become progressively less mature from west to east (i.e. from Pendine to Laugharne), then the cliffs near Pendine must have been abandoned by the sea before the cliffs near Laugharne. If so, then it may be suggested that the coastal barrier (i.e. the dunes and foreshore) probably developed from the west (at Pendine), eastwards to Ginst Point.

After an initially rapid rise of sea level, following the retreat of the final glaciation, the process slowed down considerably, and no major fluctuations (such as the so-called Romano-British transgression) seem to have occurred in historical

times (Hawkins, 1973). However, it is very probable that minor fluctuations have occurred in response to climatic changes and isostatic adjustments. At present, it has been postulated that the land of the South Wales region is sinking (Valentin, 1953) and sea-level slowly rising (Hawkins, 1973).

The glacial sediment of Carmarthen Bay has been largely reworked by Recent processes, both by currents (which reach 2 knots on a flood, 1½ knots on an ebb, see Admiralty Chart 1165, 1954), and, predominantly, by waves, especially those generated by Atlantic storms. The latter have periodically transported much fine grained sediment shoreward to form the coastal barrier and infill the Taf estuary. Historical evidence is somewhat vague as to the timing of this accumulation.

The earliest known human settlement was Palaeolithic and Mesolithic at Coygan, on the high cliffs behind the coastal barrier (Daniel, 1959); this site was occupied as the ice sheets retreated before the barrier came into existence. The barrier must have been well established by the first millenium B.C., since Cantrill (1909) records the finding of Early Iron or Late Celtic period shell mounds on Laugharne Burrows; we may assume that the dunes were then stable enough to afford protection from storms to their human occupiers. Cantrill considered this period of occupation to have lasted from 400 B.C. extending up to the Roman

occupation of the district. However, there is some archaeological evidence (unpublished and, at present, unchecked) to suggest the existence of a Roman harbour below the old cliff-line to the west of Coygan, near Pendine. If this is so then we may conclude one of two possibilities: Either the coastal barrier was, at that time, a true barrier island with a lagoon separating it from the mainland (or a barrier backed by a saltmarsh); or the Taf estuary (or a branch of it) then flowed along the old cliff-line to meet the sea near Pendine. The latter possibility does not seem likely.

More recent evidence (summarised by Steers, 1964) shows that a considerable increase of dune building was recorded during the thirteenth and fourteenth centuries along much of the South Wales coast. It is unknown (by the writer) whether this resulted from a modification of meteorological processes.

Curtis (1880) refers to catastrophic estuary inundations from the sea during the twelfth century, just before the period of increased dune building. These destroyed the village of St. Ishmaels at the mouth of the Towy estuary. Other evidence suggests a further inundation during the early seventeenth century, which also eroded the cliffs near Marros (to the west). Of St. Ishmaels there is now no trace; it seems likely that considerable quantities of sediment must have been transported from the bay to the estuaries at these times so that building foundations may now be covered by sand.

Undoubtedly, the low-lying land behind the Burrows would have been flooded frequently during heavy storms, if not permanently. Nevertheless, some occupation of the dunes is documented during the fourteenth century (Steers, 1964). According to tradition, Laugharne Marsh was reclaimed by a Dutchman in the fifteenth century. Since then, the growth and development of the eastern dunes and marsh must have been considerable, even in the present century, since many an older inhabitant of Laugharne can recall a time when it was virtually impossible to walk the edge of the estuary from Laugharne to Ginst Point, whereas this area is now grazed by cattle. This is undoubtedly related to the growth of the young marsh in the estuary proper, which is discussed below.

Recent adjustments to the dunes near Pendine are also in evidence. Erosion of the dune during the past decade has exposed the remains of a small boat, at beach level, known to have been buried by accumulating sand at the beginning of the present century. Small changes may be recognised from old press photographs taken in the 20's and 30's which suggest that dunes now eroding were then prograding. At present, significant aeolian accumulations are forming in the vicinity of Ginst Point.

Further evidence of a recent shoreward migration of sediment is provided by the estuary, which is at present considerably infilled by sand closely resembling that covering the bay. The

estuary is now virtually impassable to large vessels, although fifty years ago there was a regular traffic of shipping bringing coal to St. Clears from Llanelli.

Therefore, it may be concluded that although the coastal barrier has been in its present position for at least 2,500 years, noteable changes have taken place since then, certainly during the Middle Ages and in modern times. Aerial photographs of the area clearly show the linear and cyclic development of the dune belts which reflect minor fluctuations of either meteorological processes or sea-level. The predominant trend appears to have been one of shoreward accumulation of sand, firstly onto the coastal barrier as a response to wind and wave action during the post-glacial transgression, latterly into the estuary as a response to a continued rise of sea-level.

A physiographic description of the study area is clarified by division into two distinct units - the coastal barrier and the estuarine complex. However this division is merely one of convenience, and is superficial in real terms since, as is shown in Chapters 2 and 4 and Chapters 6 and 7, the area is a dynamic system of complex equilibria and both physiographic units are intimately interrelated.

Before proceeding further, the nature of this investigation, its rationale and purpose, will be briefly outlined. This study forms part of a large-scale investigation of the Recent coastal barrier and estuarine complexes of the northern and eastern coasts of Carmarthen Bay: a comparable coastal barrier complex between the Loughor and Towy estuaries, forming part of the eastern flank of Carmarthen Bay, has been described by Khan (1968); the Towy estuary is now being studied in some detail.

Together, these areas constitute a considerable accumulation of beach, dune and estuarine sand. Historical and contemporary information regarding the evolution of the dune ridges and the infilling of the estuaries suggest that the coastal areas and estuaries are not stable features, and that large quantities of sediment, mostly sand, must be periodically, if not continuously, moved on, off, or along the coastal belts.

In common with most estuaries, that of the Taf has infilled with sediment in geologically recent times. One of the aims of this investigation has been to ascertain whether or not the infilling is still progressing, to attempt to quantify the rate of accumulation, and to determine the source of the sediment.

It is apparent to even a casual observer that sediment transport in the estuary must be closely related to sediment transport on the coastal barrier. For several years prior to the initiation of

this study, and particularly during the winter of 1966-7, it was reported that the dunes behind Pendine Sands were rapidly eroding. It was hoped that periodic surveying of beach and estuary profiles would: firstly, confirm this erosion; secondly, investigate overall volumetric changes of sand on the coastal barrier and in the estuary; thirdly, quantitatively relate sand movements in the estuary with those on the coastal barrier.

Any information on the contemporary rate of sediment accumulation in estuaries, and on the source of this sediment, is of value to those concerned with Quaternary studies; such data are available only for a few estuaries, and quantitative information is rare. Estimates of the rates of estuarine sedimentation are usually long-term calculations based on the known rise of sea level since the retreat of the Pleistocene ice sheets. Estimates based on a medium time span of a year or so are not frequently reported. In this respect, the characteristics of estuarine sedimentation in the Taf might have wider application to other estuaries of similar type.

Such information would be of some practical importance also, since valuable installations behind the dunes are threatened by the encroaching sea, so that some form of coastal protection is perhaps required. However, in so doing, it is important that such protection does not upset any dynamic equilibria controlling sediment transport and sediment accumulation in Carmarthen Bay

as a whole.

To this end, therefore, both the coastal barrier and estuary were regularly surveyed during the period 1968-70. Surveys were limited in number for practical reasons. Unfortunately, neither the estuary nor the beach was always readily accessible; the former because of inclement weather conditions (inflated river discharge during rainy periods, large waves during storms), the latter because of Ministry of Defence control.

Nearshore observations of meteorological and oceanographic conditions at the time of surveying were not made. Such observations would be of limited value since survey times were so widely spaced. Ideally, surveys should be much closer in time, and then continuous measurements of nearshore waves and currents become essential.

Hydrographic measurements were taken in the estuary (see Chapter 3) and these greatly assisted understanding of the processes of estuarine sedimentation (Chapters 4 and 7). Unfortunately, no hydrographic work was possible in Carmarthen Bay. Any operation involving boat application in dangerous shoal waters requires both experienced personnel and adequate funds - neither of which was available. For these reasons, little offshore work could be attempted - obviously an unfortunate restriction in any study of coastal sedimentation.

Furthermore, again because of lack of personnel, funds and equipment, no direct measurements of littoral or estuarine sand transport were made. It is now apparent that such studies require sophisticated equipment, as well as considerable time and effort (Hails, 1974), and were beyond the capabilities of this investigation.

In addition to providing information on contemporary movements of sand, it was intended to consider those sediment characteristics that might have geological significance - i.e. following on the tenets of uniformitarianism, to determine those features of coastal barrier and estuarine sediments that may have diagnostic value in the recognition of comparable ancient sedimentary environments. This aspect of the study concentrated on the textural properties of the sediments, and the trend of their variations in two dimensions. Variations in a third dimension, with depth, were not studied - partly because of the lack of suitably refined coring equipment that would function in the, usually, wet sand of both foreshore and estuary. Nor were variations with time considered, probably an important omission.

The textural properties of the sediments have been studied in some detail with a view to understanding the hydrodynamic processes that control deposition. This approach obviously ties in with the study of sand movements. It is apparent that

the omission of direct measurements of near-bed currents and turbulence is a handicap, since without such data understanding of the processes of foreshore sedimentation is difficult.

Observations of sedimentary structures were limited, primarily because of the problems of preserving them in the water-saturated sands. Probably a study of these structures in detail would add a great deal to a description of foreshore and estuarine sedimentation, at least in qualitative terms.

Finally, it will be noted that an attempt has been made to quantify many of the relationships observed in this study. This has involved a good deal of statistical analysis and produced mixed results. Such an attempt necessarily highlights inadequacies in the planning of individual 'experiments' and restricts the opportunity for speculation (although the author has to admit that there is still a good deal of the latter). However, it is believed that such a semi-quantitative approach is necessary in the study of process/response relationships.

1.2 : The Coastal Barrier

(a) Nearshore and coastal physiography. The coastal barrier consists of a beach and dunes, forming a protective ridge between the sea and the low-lying reclaimed land behind it. The barrier conforms to the definition of Shepard (1952): 'a sand mass which extends along the coast and rises above high-tide level'. Here the definition is extended to include the foreshore above low-tide level.

It is argued in Chapter 6 that the textural characteristics of the foreshore sands are dependent on the nature of offshore bathymetry. Foreshore morphology is similarly a reflection of the dynamics of the nearshore system. For this reason, surveys of the profile of the beach have been conducted across several transects normal to the strandline and these continued below low water mark into the bay. The positions of the transects correspond to those used in the study of temporal variations of beach profiles (see Chapter 2) and are shown in Fig. 1.1.

In the following discussion, the nomenclature adopted is that of King (1972): The 'backshore' - also referred to as the 'uppermost foreshore' - is the zone above the limit of the swash of normal high spring tides; the 'foreshore' is the intertidal zone; the 'offshore' zone extends from the uppermost point always covered by water to a depth at which substantial movement of sand ceases under normal circumstances.

The backshore and foreshore were surveyed in the conventional manner with micropic level and staff. The offshore zone was

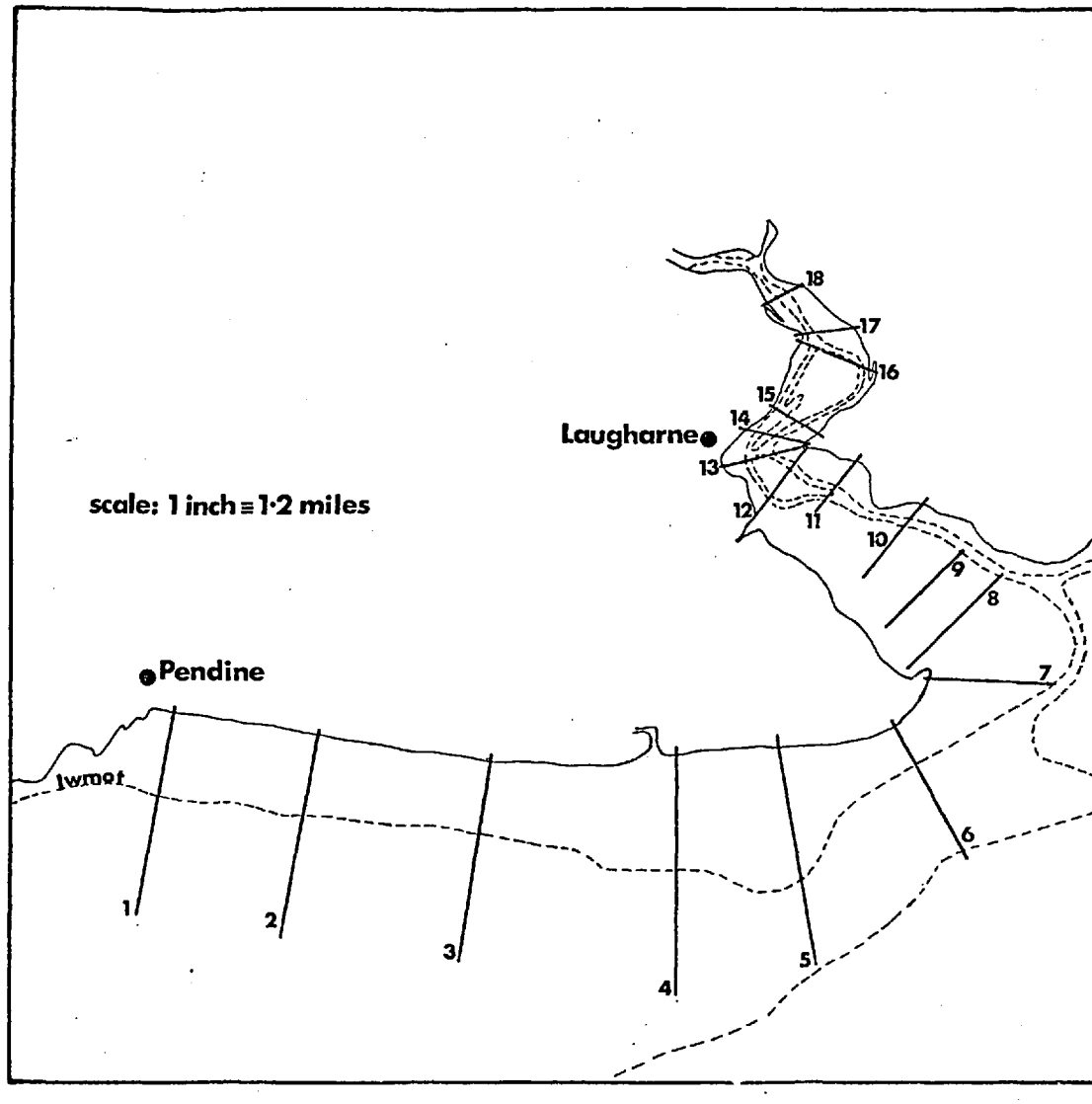


FIG. 1.1 : POSITION OF SURVEYED TRANSECTS.

surveyed by echo sounding along a continuation of each foreshore transect. Unfortunately the vessel used for this purpose was without any direct means of fixing its exact geographical position. To overcome this deficiency, the following procedure was adopted. Two microptic levels, with horizontal circles, were set up 400 feet apart on the uppermost foreshore on either side of the transect. These were used to take bearings on the surveying vessel, at predetermined intervals of 1 minute, as it traversed the offshore transect. Marks were made on the echo trace to coincide with the taking of these bearings. In order to synchronise events on the shore and in the boat, two-way radios were used. Sextant bearings were also taken from the boat on prominent landmarks to complement the land-based bearings. At the completion of a run, as the surveying vessel reached shallow water, a large lead weight was dropped overboard and its position fixed by conventional surveying when exposed at low tide. In this way, the 'dry' and 'wet' profiles were joined accurately. Absolute heights were then ascertained by levelling the profiles into local beach marks.

The resulting profiles are shown in Figs. 1.2a and 1.2b. The heights of mean high water spring tides (MHWS) and mean low water spring tides (MLWS) pertain to Tenby. Slopes, expressed in degrees and minutes, are averaged over varying lengths of the profiles that have roughly uniform gradients (and are written above the appropriate sections in Figs. 1.2a and 1.2b).

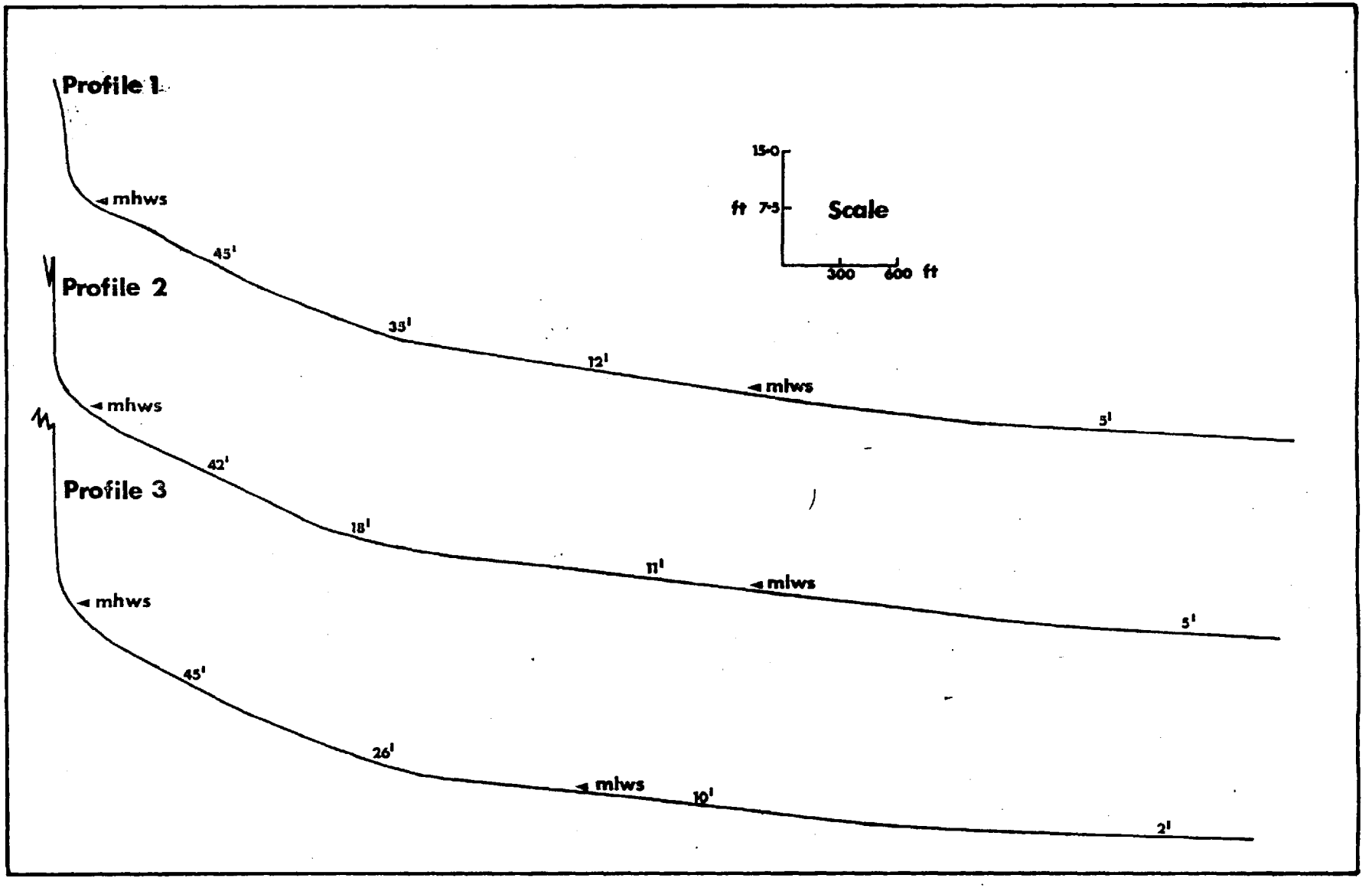


FIG. 1.2a: NEARSHORE BOTTOM PROFILES.

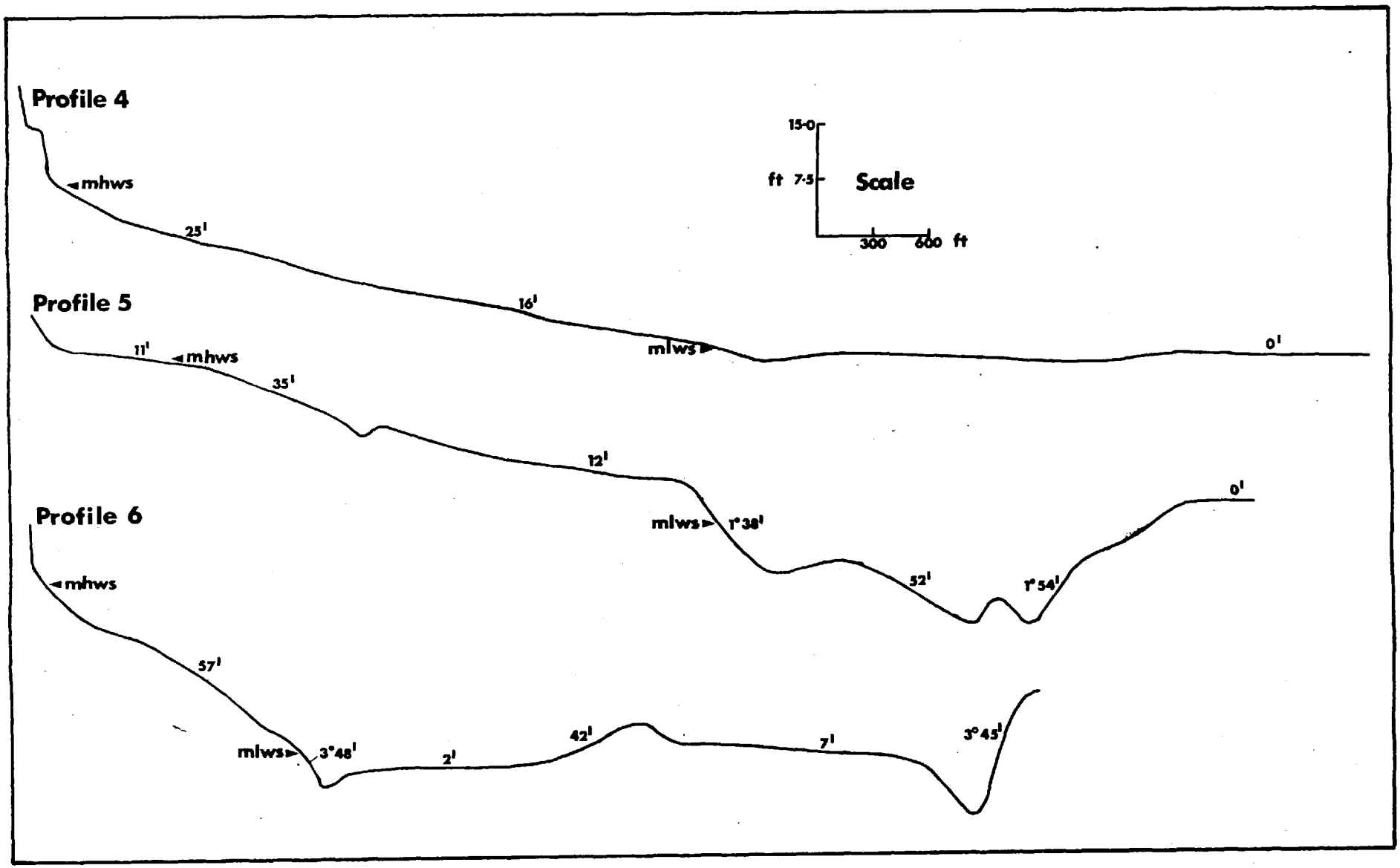


FIG. 1.2b: NEARSHORE BOTTOM PROFILES.

It may be seen from these profiles that the average foreshore/offshore slope is very gentle, less than 1^{o} (except on the upper foreshores of some transects, see below). The greatest slopes are on the upper parts of the foreshore so that the slope of the profiles is generally concave upwards; the reverse is true for transects 5 and 6 which have profiles with small gradients on their upper parts so that their shape tends to be convex upwards.

The foreshore slope decreases eastwards from transect 1 to transect 5 and this is matched by a generally progressive eastwards widening of the foreshore. Profile 6 has a much increased slope and a correspondingly narrower width of foreshore. The transition from transect 5 to transect 6 clearly relates to the altered orientation of the strandline and dune-line between them (Fig. 1.1).

This itself is the result of differences of offshore bathymetry. From transect 1 eastwards, offshore gradients decline until at transect 4 the gradient is nil.

A small bar is developed near MLWS on transect 4 and may be considered as an embryonic ridge and runnel system formed by the still stand of low tides at low water.

It is apparent from the profiles that during low water, much of the north-eastern bay, for over a mile offshore, is virtually emergent. This begins to occur near transect 4 and is more marked

offshore, off the area near transects 5 and 6, where offshore shoals, bars and barriers are well developed. This accumulation of a surfeit of sand in the north-eastern part of the bay is undoubtedly due to the action of waves from the west and south-west (see Chapter 4) which move material towards, and into the estuary. The piling up of sand at this particular location occurs as a response to the interaction of bay and estuarine circulations.

Because of the gentle gradient of the offshore zone, which occurs even off transect 1, it needs relatively small accumulations of sand to build up emergent bars and barriers. Although not surveyed, and not charted on available maps, the offshore shoals appear to occur in longshore, linear ridges, probably corresponding to the break-points of storm waves and normal waves of differing steepnesses. A bar occurs where waves from deep water break, the most persistent bars corresponding to the position of breaking of the most persistent wave type.

These offshore shoals are periodically emergent, but as they are often submergent, they should be termed 'bars'. Although formed by different wave processes, it appears possible that on a coast with a large tidal range and gentle offshore bathymetry, breaker point bars formed by steep waves at high tide may be further prograded by constructive waves, in front of their break-points, at low tide.

These constructive waves may build up a barrier in an attempt to maintain an equilibrium between the bottom gradient and wave steepness. In the shallow waters of Carmarthen Bay, submarine bars may thus develop into barriers.

At present, the estuary exerts a significant influence on offshore bathymetry on transects 5 and 6. Its flushing action maintains a deep and wide channel between the lower foreshore of the established barrier of Laugharne Sands and the offshore shoals. This channel is very wide on transect 6; its shape may well indicate a differentiation of tidal circulation into flood and ebb channels (Cloet, 1954 after Van Veen), since it consists of two deep channels separated by a wide shoal; alternatively the shoal may be a nearshore bar formed at the break-point of waves which have reformed in the deep water of the offshore channel, thus splitting estuarine flow (both flood and ebb) into two streams.

Because of the extent of the estuarine channel, the foreshore of transect 6 is more restricted in width and steeper in slope than at other transects. This is caused by undercutting of the lower foreshore by channel flow, which then enables waves to break higher on the foreshore without first developing a wide surf zone (see Chapter 6).

Transect 5 is transitional between those to the west and

transect 6. Although the channel is deeper on profile 5, it is restricted in width, and further offshore. A persistent ridge and runnel is conspicuous on profile 5. However it does not occur near the still-stand of high or low tides, springs or neaps, as it should according to theory (King, 1972). It appears to coincide with the break-point of large waves (since its migrations relate to the incidence of westerly storms, see Chapter 2), probably during spring tides when least energy is dissipated by large waves on the offshore shoals. Its mode of origin therefore corresponds to a submarine bar and trough (at high water) even though exposed by the ebbing tide.

It is apparent from the foregoing that both bay and estuary exert controlling influences on the development of the coastal barrier as it exists today. In the west, Pendine Sands are moulded by the shoreward translation of waves in shallow water. In the east, Laugharne Sands are moulded by the interaction of a surfeit of offshore sand and the flushing action of the estuary. These factors control not only the slope and width of the barrier beach, but also its orientation, and the orientation of the dependent dunes.

It is apparent that only a small relative fall of mean sea-level would find much of the bay emergent. Offshore shoals would become true barriers separated from the former shoreline by a

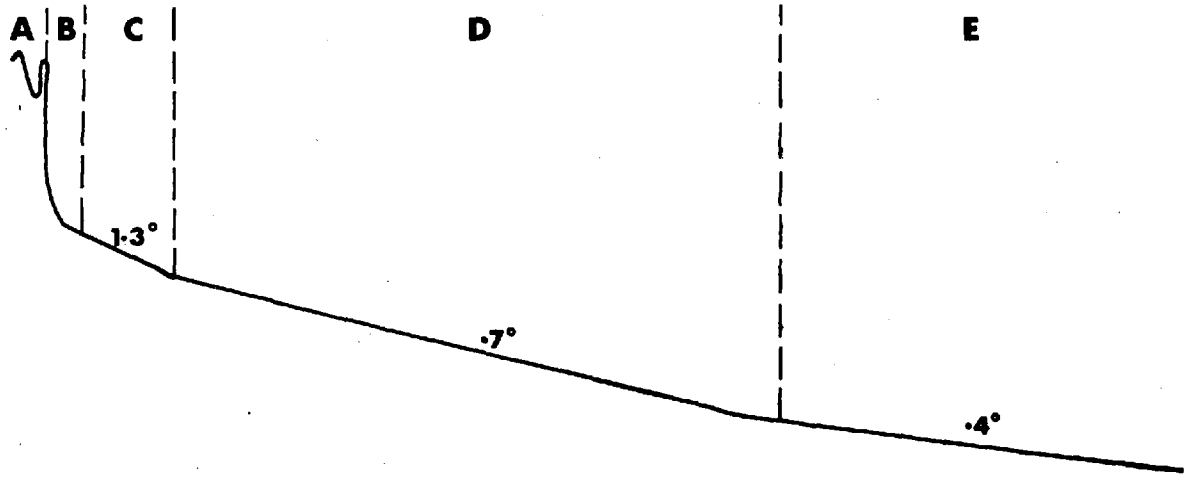
* For discussions of barrier evolution in this context, see Hoyt (1967,1969), Hails and Hoyt (1968) and Pierce and Colquhoun (1970).

wide sandy (initially) lagoon or nascent salt marsh. At present, the land is falling relative to sea-level (up to 1.5 mm/year according to Valentin, 1953), and fresh supplies of sediment may be too small to counteract its effect. However it is possible that the present-day coastal barrier was formed in such a manner, firstly forming an offshore bar, secondly as an emergent barrier. This does not necessitate a falling sea-level, although minor fluctuations undoubtedly have occurred within the post-glacial rise (Per Bruun, 1962). Subsequent to glaciation, the supply of sediment deposited in the bay may have been sufficient for the barrier to have developed ahead of the rising sea-level. Present-day processes however, appear to be concentrating on infilling the estuary rather than building a new coastal barrier.

A less hypothetical view of coastal genesis awaits a study of the nature and structure of the low-lying area behind the dunes, now reclaimed.*

The discussion so far has been concerned with general aspects of the foreshore/nearshore morphology. As described in Chapter 2, backshore/foreshore profiles have been surveyed regularly and in some detail. The following discussion is concerned with the principal characteristics of these profiles.

Average profiles for transects 2, 5, 6 and 7 are shown in greater detail in Figs. 1.3 - 1.6. As described above, although



A: old dune ridges.

B: uppermost foreshore* above MHWST; barchan-like structures common.

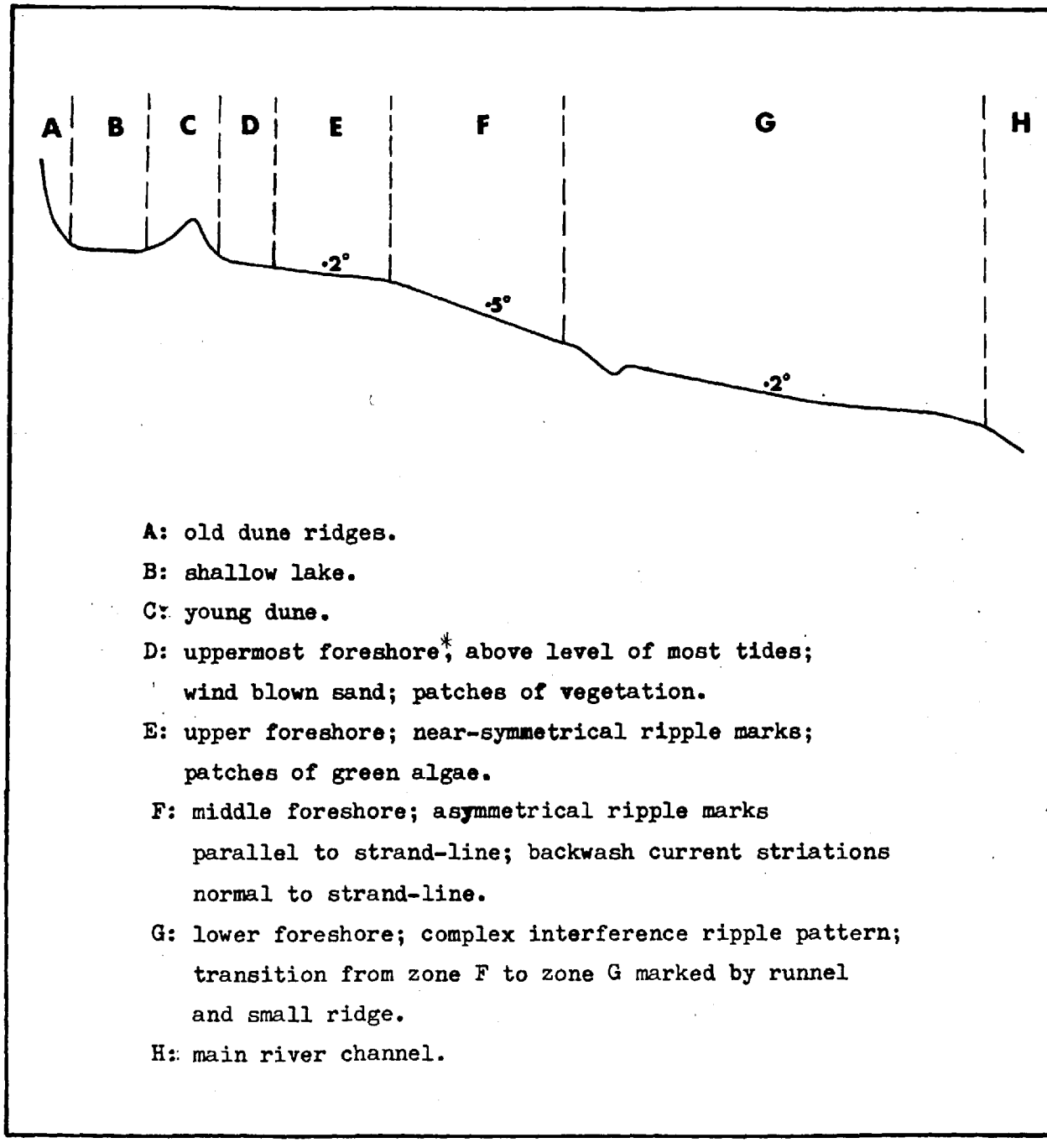
C: upper foreshore; surface generally smooth, but low, long-crested ripple marks sometimes occur; swash/backwash marks common.

D: middle foreshore; surface may be smooth or with long-crested asymmetrical ripple marks; swash/backwash marks common.

E: lower foreshore; surface finely rippled by short crested asymmetrical ripple marks.

FIG. 1.3: SURFACE FEATURES, TRANSECTS 1-4.

* i.e. backshore



A: old dune ridges.

B: shallow lake.

C: young dune.

D: uppermost foreshore*, above level of most tides; wind blown sand; patches of vegetation.

E: upper foreshore; near-symmetrical ripple marks; patches of green algae.

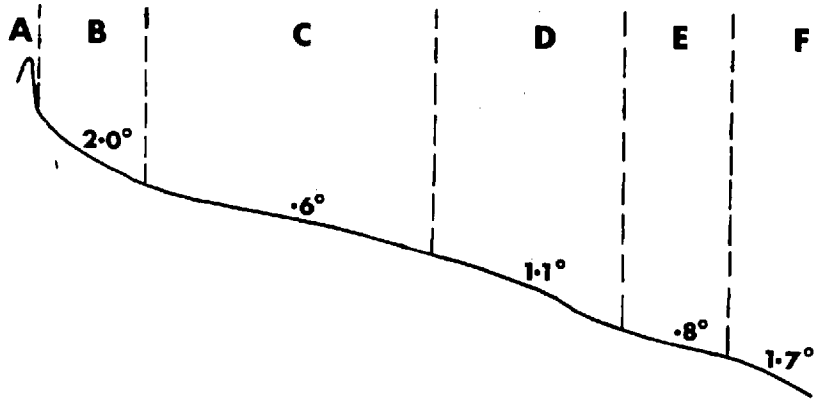
F: middle foreshore; asymmetrical ripple marks parallel to strand-line; backwash current striations normal to strand-line.

G: lower foreshore; complex interference ripple pattern; transition from zone F to zone G marked by runnel and small ridge.

H: main river channel.

FIG. 1.4: SURFACE FEATURES, TRANSECT 5.

* i.e. backshore



A: young dune.

B: uppermost foreshore*, above level of most tides; smooth surface; cavity sand.

C: upper foreshore; smooth surface; swash/ backwash marks common.

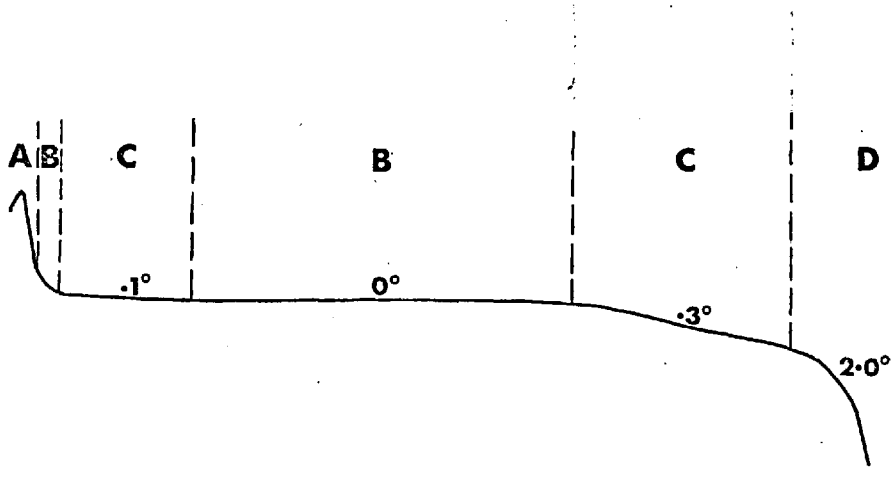
D: middle foreshore; low, long-crested asymmetrical ripple marks parallel to strand-line.

E: lower foreshore; complex interference ripple pattern.

F: main river channel; asymmetrical ripple marks normal to strandline.

FIG. 1.5: SURFACE FEATURES, TRANSECT 6.

* i.e. backshore



A: young dune.

B: aeolian sand flat; at upper limit of high tides; generally smooth surface, some barchan-like structures; cavity sand common; some green algae; shells.

C: foreshore; surface smooth at high levels; short-crested, asymmetrical ripple marks, parallel to strand-line, at low levels.

D: main river channel; surface smooth or with current striations normal to channel; some saturated sand.

FIG. 1.6: SURFACE FEATURES, TRANSECT 7.

* i.e. backshore

foreshore slopes decline from transects 1 - 4, the general profile shape is similar for them all. They can conveniently be subdivided into five zones, defined by distinctive gradients and textural characteristics, (see Chapter 6). These are a dune zone, the uppermost foreshore (above high water mark) the upper, middle and lower foreshores. The first two zones therefore together constitute the backshore. This subdivision also holds for transects 5 and 6, despite their differences, but with the additional feature provided by the steeply sloping main river channel at their seaward extremities.

The profile of transect 7 is quite different from the others. It is characterised by an extensive, level sand flat above the level of many tides and gently washed by the higher spring tides. The textural characteristics of its constituent sand are indistinguishable from those of dune sands. Formed predominantly by aeolian activity, the sand flat has built up rapidly since 1967 and in 1970 was quite extensive in area to the south and west of Ginst Point. Except during stormy weather, the incoming tide flows around the flat rather than across it, and the area is generally submerged for a short period only during high spring tides. Upper foreshore features (cavity sand, barchan-like structures, see below) are usually preserved, the only evidence of submergence being patches of green algae (Enteromorpha sp.).

Below the aeolian sand flat, slopes increase rapidly towards the main river channel.

The dunes of Laugharne Burrows form one of the most extensive accumulations of wind blown sand in South Wales; it forms a near-continuous band from Pendine to Ginst Point and extends inland for about half a mile. From aerial photographs (unfortunately unavailable for publication) it may be seen that the dunes lie in a series of linear ridges parallel to the shoreline. Near Pendine, five or six ridges can be differentiated; they continue for some three and a half miles eastwards, then terminate with a marked change of orientation towards the north-east, where a tongue of dune development extends a mile landwards, dividing the West and East Marshes. Since the landward ridges terminate first, the dune pattern presents a clear record of a progressive progradation of wind blown sand both eastwards and to the south. With the termination of this series of ridges there occurs a small lake fed by a stream (Witchett Pill) which, from old maps, has persisted for a considerable time. A second series of ridges then begins, continuing eastwards to Ginst Point. Both maps and photographs suggest that Witchett Pill separates two quite distinct phases of dune progradation, although this cannot be stated emphatically. However, it is considered significant that the break between the two dune series coincides with a change of

orientation of the dune ridges and the strandline (both of which are related to the Taf channel position, see above) as well as with the rocky promontory of the old cliff line at Coygan. It is not impossible that before the development of the eastern dunes, part of the Taf outfall flowed along the old cliff line as far as Coygan before turning seawards; at that time the coastal barrier may have consisted of the inner ridges near Pendine only.

The linearity of the inner ridges is not always clearly visible because (presumably) of post-depositional modifications (the development of blow-outs, etc.), which have produced a hummocky topography. The outer ridges are clearly linear, but their widths are conspicuously reduced in comparison with the inner ridges. At the western end of the barrier, the outermost ridge presents a near-vertical erosional face to the sea. At the eastern end (from transect 4 eastwards) the outermost established ridge is fronted by a line of new dunes (foredunes), a few feet high, which have accumulated in the past decade or so. On transects 4 and 6, these foredunes are very close to the old dunes, but on transect 5 they are separated from them by a low-lying marshy area containing a few inches of brackish water (see Fig. 1.4); this area is part of the Witchett Pill development. Near Ginst Point the foredunes curl northwards into the estuary. It appears, therefore, that the historical eastwards growth of the

dunes is continuing today (with some interruptions, as on transect 6 -see Chapter 2) with the progradation of a fresh dune ridge from the central barrier eastwards and the growth of a low-lying, but extensive, aeolian sand ridge near Ginst Point.

(b) Surface features; fauna

Ripple marks are conspicuous by their absence over much of the beach surface. This is because, as discussed in Chapter 6, the swash and backwash flows which determine the texture of the surficial sand attain the power of the plane bed regime. With ascending flow enery, very fine and fine sands produce first ripples, then dunes and finally a plane bed with parting lineations (Allen, 1970). When they do occur, the ripple marks have amplitudes generally no greater than 1 cm. and wavelengths up to 30 cm. on the upper foreshore and middle foreshore. On the lower foreshore, antidunes are formed with amplitudes up to 3 cm. but wavelengths of only 6 cm., this shortening probably reflecting the decreased depth of the swash zone on the lower foreshore. These antidunes are formed by the backwash flow, and appear to form only when swash zone depths are diminished.

The antidunes of the lower foreshore are commonly asymmetrical, as are the ripple marks which sometimes form on the upper and middle foreshores, being always orientated parallel to the

strandline and with stoss-sides facing landwards; they are formed by the seaward movement of backwash flow. Off transects 5 and 6, asymmetrical ripple marks often occur normal to the strandline in response to ebb flow in the main river channel.

Symmetrical ripple marks are very uncommon, but can occur where foreshore slopes are negligible as on the upper foreshore of transect 5. They possess shallow troughs and rounded crests and are formed by the oscillatory motion of water retained in thin sheets (or pools) on the foreshore by onshore winds.

Rhomboid ripple marks are not uncommon, being formed by oblique or longshore currents (induced by wind action) superimposed on the onshore/offshore motion of the swash zone.

A complex, interference ripple pattern is formed where the onshore/offshore tidal motion interacts with the longshore motion of the main river channel. This occurs on the lower foreshores of transects 5 and 6.

Unlike ripple marks, swash marks are a common surface feature of the upper and middle foreshores, as well as the lower foreshore. They are always orientated parallel to the strandline, representing successive stages reached by the swash on the ebbing tide. Their positions are marked by concentrations of shelly fragments and coal particles which have been winnowed from the surface sediment by the uprush of the swash and deposited at its landward limit.

Since swash marks may be several feet apart, they must represent the periodic frequency of swash (and therefore wave) energy greater than the norm.

Current striations, or lineations, are common on most of the smooth foreshore but occur predominantly on the middle foreshore of transect 5 and near the main river channel of transect 7 where the foreshore slope is increased. They are always orientated normal to the strandline in the direction of the backwash flow, and appear as small parallel ridges and grooves, centimetres long but only millimetres wide.

Rill marks are sometimes formed on the lower foreshore. They occur only where the underlying water table is high so that a significant effluent zone is produced, and where foreshore slopes are small. Because of the low rate of percolation under these conditions, excess water thrown onto the foreshore by the swash seeks to return seaward via small, very shallow streams.

Above the high water mark, particularly on neap tides, wind action frequently generates small barchan-like structures. They may be up to 3 metres across and half a metre high, moving alongshore. They are also a common feature of the aeolian sand flat near Ginst Point. (cf. Khan, 1968).

In the dunes, ripple marks are always present except on steeply-inclined slopes. Because of lack of vegetation cover,

they occur frequently on the young dunes of the east, but also on blow-outs in the established dunes. These wind-formed ripple marks are asymmetrical, up to 6 cm. in wavelength and less than 1 cm. in amplitude. Shelly material accumulates in their troughs. Their dimensions are in agreement with the observations of Thompson (1937) who has noted that wind-formed ripple marks differ from water-formed ripple marks in their small rates of height to wavelength; however, upper and middle foreshore ripples appear to be anomalous in this respect.

Far more conspicuous on the foreshore surface than these solely physical features are the indications and record of living creatures. Since this is not a zoological investigation, no attempt has been made to complete a rigorous assay of species and numbers. However, the most frequently occurring species have been identified and are recorded here, since their occurrence, both of living animals and shelly debris, is of considerable geological interest.

Because of the intense turbulence of the collision and breaker zones (see Chapter 6), reworking of the upper layers of bottom sediment is complete during each waxing and waning of the tide. Such instability does not provide a suitable habitat for many species of macrofauna. Living animal colonies are therefore rare. Only the sedentary polychaetes have been observed on the exposed

foreshore, and these in restricted numbers. Of these, the most conspicuous is Arenicola sp. which occurs on the wet middle foreshore near Pendine, producing little mounds topped with worm casts. Its distribution is sparse and restricted, and its occurrence sporadic (this presumably being related to its reproductive cycle as well as to meteorological conditions). On the lower foreshore, mainly near low tide level, are several species of tube-forming polychaetes. Lanice conchilega forms a tube almost 12 in. long and $\frac{1}{4}$ in. in diameter, composed of mucus to which coarse sand, mainly shelly fragments, adhere. Another species produces a tube which is smooth in appearance, composed mainly of very fine shelly fragments, and much smaller; this is probably Pygospio elegans. More commonly found lying free on the surface than living within the sediment are the tubes of Pectinaria sp.; although basically sedentary, this worm is also mobile and produces a tusk-like tube, 2-3 in. long, composed of a single layer of fine sand grains.

On very low spring tides, small (young) specimens of Actaeon tornatilis have been observed in large numbers on the surface of the lower foreshore. The sea-urchin Echinocardium cordatum burrows below the surface at the same level. A few of the littoral species listed in Table 1.1 also occur, again below the surface, but they are not common, and can be observed only at the low water mark of extreme spring tides. No investigations of meiofauna have

1. MOLLUSCA

(a) Lamellibranchia

Acanthocardia echinata (S)	Chlamys distorta (S & L)
Chlamys opercularis (S & L)	Cultellus pellicidus (S)
Donax vittatus (S & L)	Dosinia lupinus (S & L)
Ensis ensis (S & L)	Ensis siliqua (S & L)
Gari fervensis (S)	Glycymeris glycymeris (S)
Lutraria lutraria (S & L)	Mactra corallina (S & L)
Mytilus edulis (S & L)	Ostrea edulis (S)
Tellina fabula (S & L)	Tellina tenuis (S & L)
Venus mercenaria (S & L)	Venus striatula (S & L)

(b) Gastropoda

Actaeon tornatilis (S & L)	Buccinum undatum (S & L)
Natica alderi (S & L)	Natica catena (S & L)
Patella vulgata (L)	Turritella communis (S)

(c) Cephalopoda

Sepia officinalis (S)

2. ECHINODERMATA

Echinoidea

Echinocardium cordatum (S & L)

3. ARTHROPODA

Crustacea

Corystes cassivelaunus (S & L) Maia squinado (S & L)

TABLE 1.1 : Sub-littoral (S) and littoral (L) fauna

been attempted; these may well occur in large numbers since they live in the interstitial spaces of the sand, feeding on bacteria adhering to the grains; of these, some forms of Foraminifera are likely to be preserved after burial.

By far the greatest indication of marine life is provided by the enormous concentrations of shells, both complete and fragmented, that occur on the foreshore at all times. Some of these are derived from littoral species, but most from sub-littoral species that must live in large numbers in Carmarthen Bay. Although widely scattered over the whole foreshore, the greatest accumulations occur at the base of the dunes, in low-lying blow-outs within the dunes, and on the aeolian sand flat near Ginst Point. Wind action therefore plays a major role in concentrating them, although initially wave action must bring them onto the foreshore.

The most frequently observed species are listed in Table 1.1 They are mostly molluscs (both bivalves and univalves) that live below low-water level, but some (limpets, mussels) are littoral species that live on the rocky headlands of the bay. Certain species tend to be preferentially selected by winds and waves and accumulate in distinct zones. Thus the common otter shell (Lutraria lutraria) is found in very large numbers at the base of the dunes near the western half of the foreshore. The common

whelk (Buccinum undatum) is very common on the middle foreshore, particularly in the west, as are Tellina fabula and Tellina tenuis. The sea urchin, Echinocardium cordatum, tends to occur most often at mid-tide level on the central part of the foreshore, where the foreshore slope is negligible. The razor shells, Ensis ensis, Ensis siliqua and Cultellus pellicidus tend to be restricted to the eastern foreshore near Ginst Point, and many of the bivalves to the aeolian sand flat in the same area.

Concentrations of some species tend to appear periodically on the foreshore, probably as a result of aspects of their life-cycles. Some species migrate upwards from the sub-littoral to lay their egg masses. The carapaces of thousands of spring spider-crabs (Maia squinado) sometimes accumulate at mid-tide level after the animals have moulted.

Some of the species listed also live, in small numbers, on the exposed lower foreshore, burrowing below the surface; generally however the shells littering the beachface are derived from the bay. If preserved, these would therefore represent a death-assemblage, only the traces of polychaete worms representing an indication of animals living in situ. The discrepancy between environments of origin and accumulation is particularly acute in the case of the oysters (Ostrea edulis) which are most abundant in a dune blow-out near Ginst Point; also necklace shells

(Natica spp.) which are abundant in the dunes, even the high dunes.

The most obvious 'surface features' of the dunes are the various plants and grasses which cover them, binding the accumulated sand and assisting their progradation. The densest growth on the young dunes is of marram grass, Ammophila arenaria, and sand couch, Agropyron junceiforme, the latter generally flourishing below the former, to the upper limits of high spring tides. These species are less conspicuous, or absent, on the older established dunes where dewberry, Rubus ceasus, and bramble, Rubus fruticosus, are dominant. The inland ridges are mostly covered by meadow grass and scrub.

(c) Subsurface structures

The internal structures of beach and dune deposits have been examined using the technique described by Reineck (1961). Metal boxes (about 8 ins. x 10 ins.) were pushed down vertically into the sands and then dug out, undisturbed samples hopefully being retained. These were then slowly dried in a warm atmosphere before being impregnated with lacquer. When this was firmly set, the unimpregnated loose sand behind the lacquered portions was brushed off, leaving the sedimentary structures of the samples exposed in relief, since the lacquer had migrated preferentially along the more permeable structural layers.

Box samples were collected from the western part of Pendine Sands (transects 2 and 3,), the central part (transects 4 and 5) and the eastern part of Laugharne Sands (transect 6). The exact positions of these samples are unimportant and so are not shown. Attempts were made to collect representative samples from various levels of the foreshore but for practical reasons these were not always successful. The technique was found wanting in the very dry deposits of the dunes and in the very wet deposits of the middle and lower foreshore (where a wide effluent zone persists at low water); consequently the great majority of successful lacquered peels originate from the upper foreshore. Samples were always taken in pairs (normal and parallel to the strandline) or in groups of three or four, in order to present a three-dimensional picture of the structures; however, because of the intermittent success of the technique, not all members of the groups were always retrieved.

Photographs of some of the box samples are shown in Plates 1.1 - 1.17. It should be pointed out that the downwarping of laminae at the vertical edges of the samples is due to the method of collection.

The simplest expression of structure encountered on the upper foreshore is illustrated by Plate 1.1, a sample originating from the central portion of the beach and orientated parallel to the

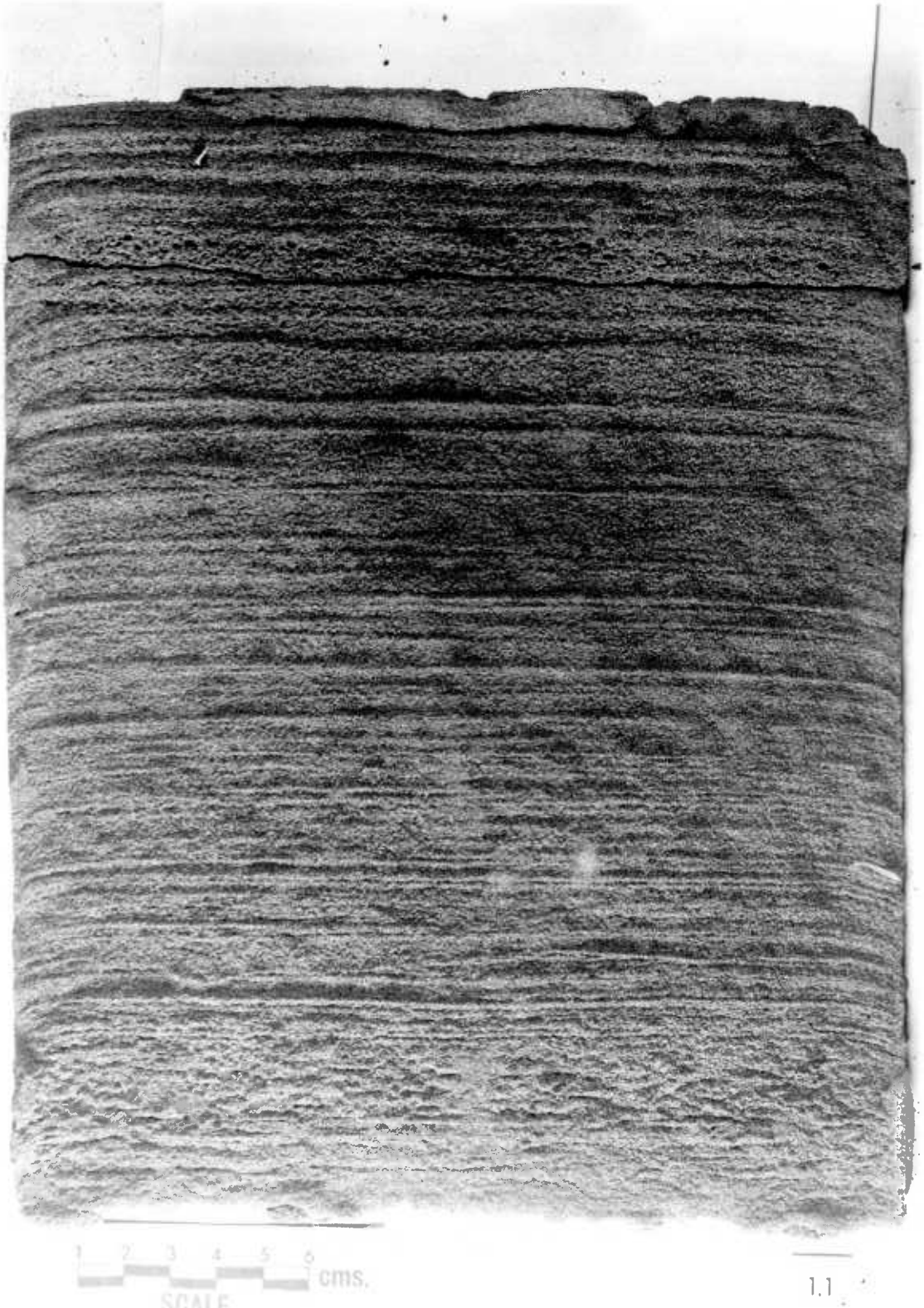


Plate 1.1 : Internal structure of the upper foreshore sands near transect 4. Orientation : parallel to the strandline.

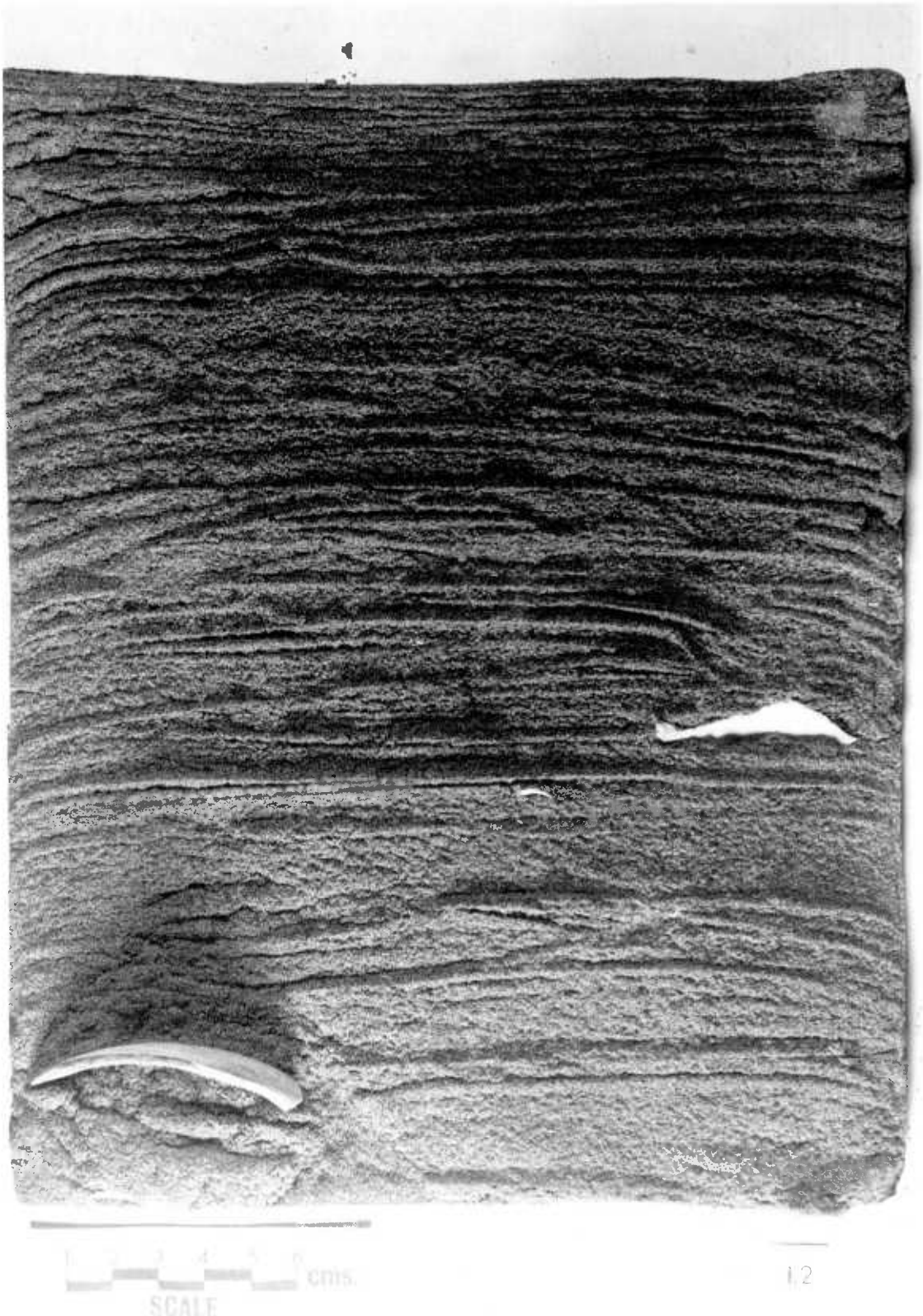


Plate 1.2 : Internal structure of upper foreshore sands, transect 2.
Orientation : normal to the strandline.

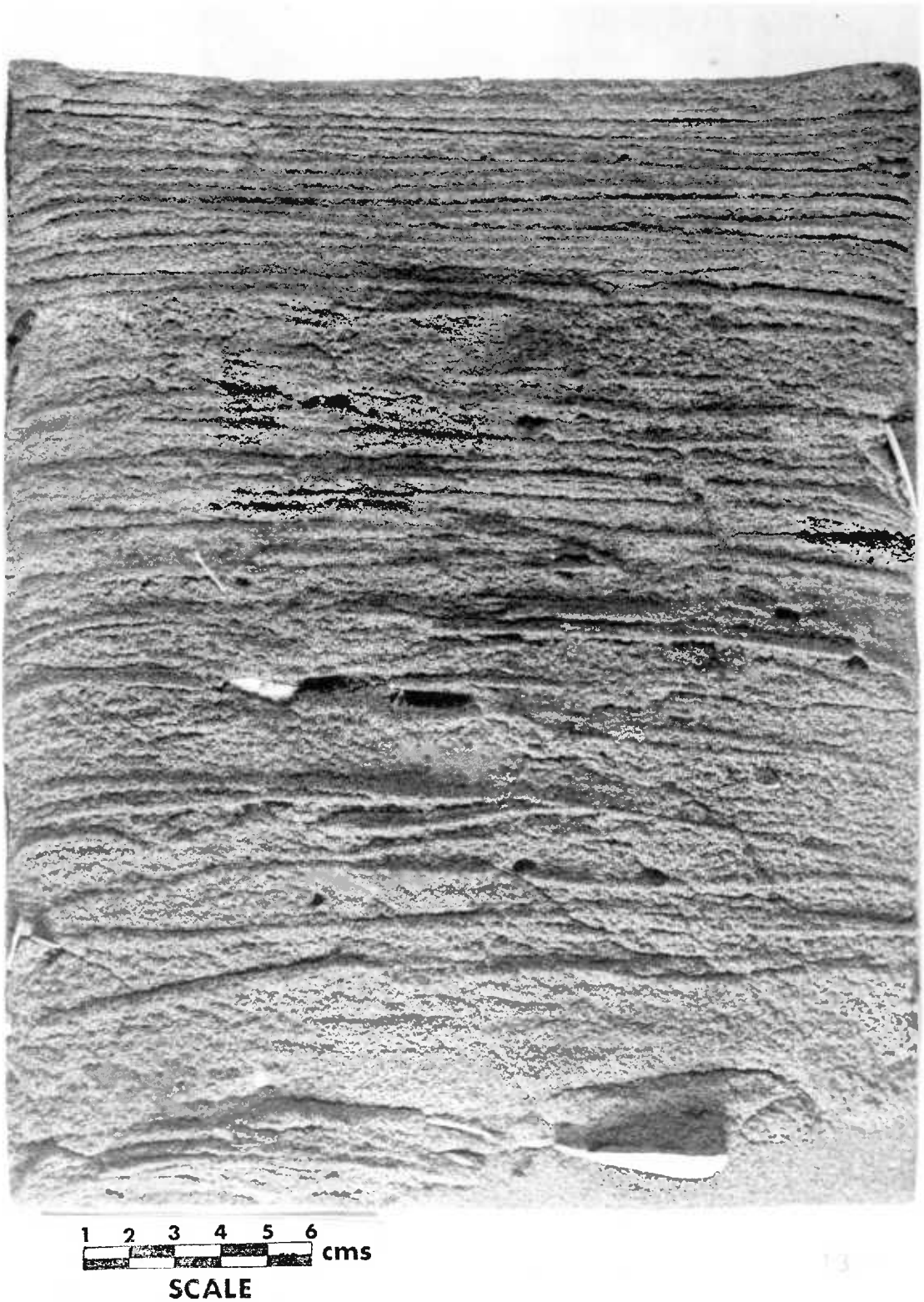


Plate 1.3 : Internal structure of upper foreshore sands, transect 2.
Orientation : normal to the strandline.

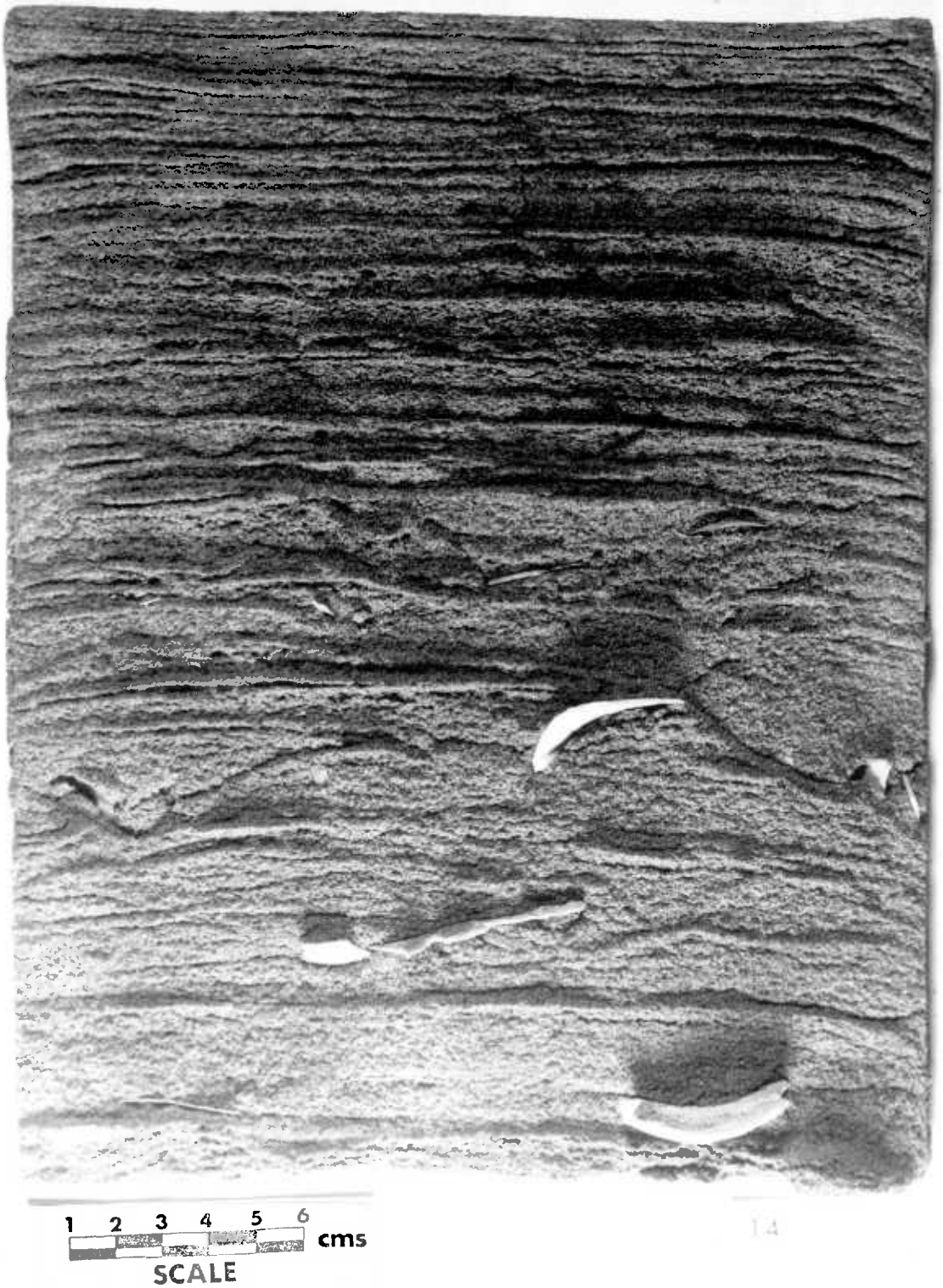


Plate 1.4 : Internal structure of upper foreshore sands, transect 2.
Orientation : parallel to the strandline.



Plate 1.5 : Internal structure of backshore sands, transect 2.
Orientation : normal to the strandline.

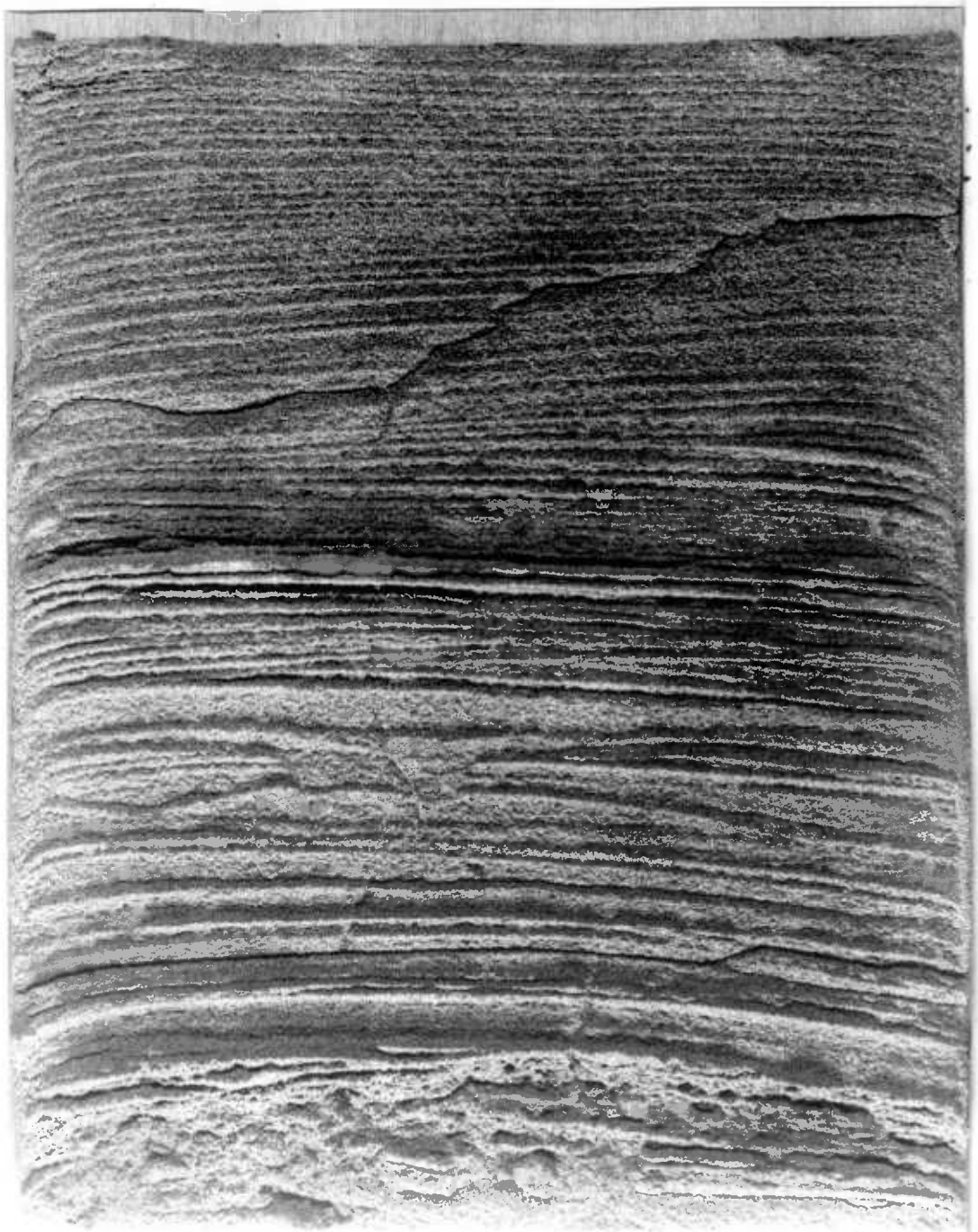


Plate 1.6 : Internal structure of wind- and water-deposited sands, backshore/upper foreshore, transect 3. Orientation : parallel to the strandline.



Plate 1.7 : Internal structure of wind- and water-deposited sands, backshore/upper foreshore, transect 3. Orientation : normal to the strandline.

strandline. The sand is evenly laminated with horizontal partings a few milimetres thick, demonstrating the plane bed regime attained by flow in the swash zone; shelly fragments are absent; a thin layer of cavity sand appears near the surface. Minor erosion surfaces between successive layers of laminae, as a result of successive swash and backwash currents, are just apparent. Cross stratification is absent, but appears in a group of samples from the upper foreshore near Pendine, shown in Plates 1.2, 1.3 and 1.4, the first two orientated normal to the strandline, the third parallel to it. Horizontal lamination still predominates, however. Ripples are uncommon on the upper foreshore, as current velocities must be too great, and water depth too small in the swash zone to allow their development. Cross stratification is therefore a secondary feature, when present, on the upper foreshore. A few large shells are buried in these samples.

Large shells become more abundant in samples taken from the base of the dunes. These are carried shorewards by high spring tides and then concentrated by wind action, often in a minor gully which develops below the dune face. These features are illustrated in Plate 1.5, a sample from Pendine, orientated normal to the strandline. In this case the large fragments are of Lutraria lutraria, the commonest type occurring in this locale.

Features formed by wind action are not uncommon on the backshore. Ephemeral features recalling barchan dunes are sometimes quickly built up, and as speedily destroyed. Two

sections through such a structure are shown in Plates 1.6 and 1.7, the former parallel to, the latter normal to the strandline. The junction between wind laid sand and swash zone water laid sand is clearly defined in both sections. The water laid sand is laminated, but with some erosion surfaces between groups of laminations; these laminations are sloping predominantly just landward, the sample being collected near the high water mark of high spring tides. The wind laid sand is also thinly and evenly laminated, but without erosion surfaces, the deposit having accumulated by means of a consistent current.

Ripple marks are uncommon on the upper foreshore and not often preserved. A rather exceptional case is illustrated in Plates 1.8 and 1.9 (parallel and normal to the strandline, respectively). These samples were taken from the central part of the beach where a creek draining a small marshy lake behind the dunes emerges onto the beach and flows across it. The creek carries some suspended fine grained material (silt), a size grade generally absent from the beach deposits. Coarse and fine laminations are interbedded irregularly. Because of the gentle flow of the creek water, some ripples are developed and preserved. (The amorphous mass of sand near the surfaces of these boxes is artificial).

Horizontally laminated sediments occur with less frequency on the upper foreshore of Laugharne Sands in the east. This is

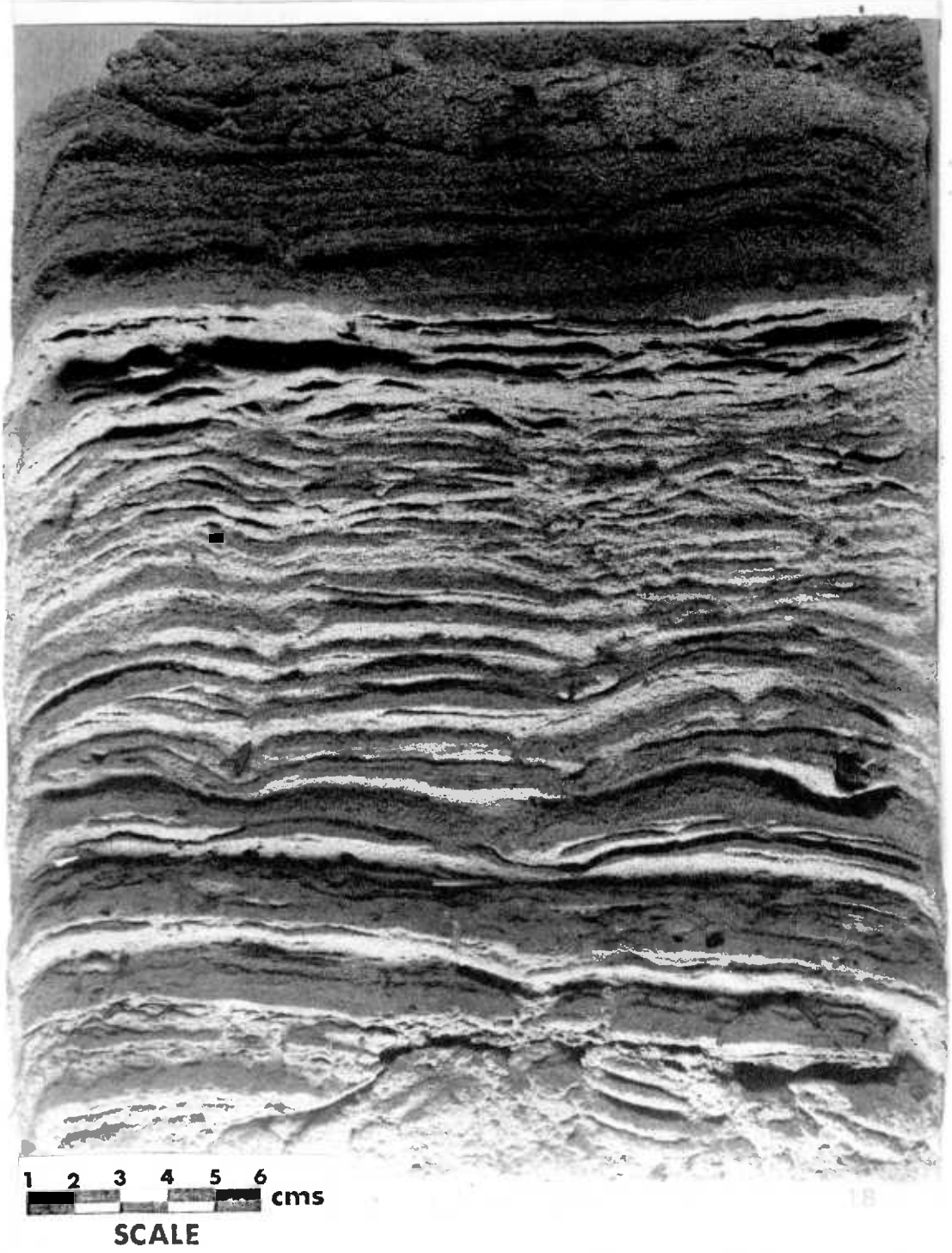


Plate 1.8 : Internal structure of creek-deposited, rippled sands and silts, upper foreshore between transects 4 and 5. Orientation : parallel to the strandline.

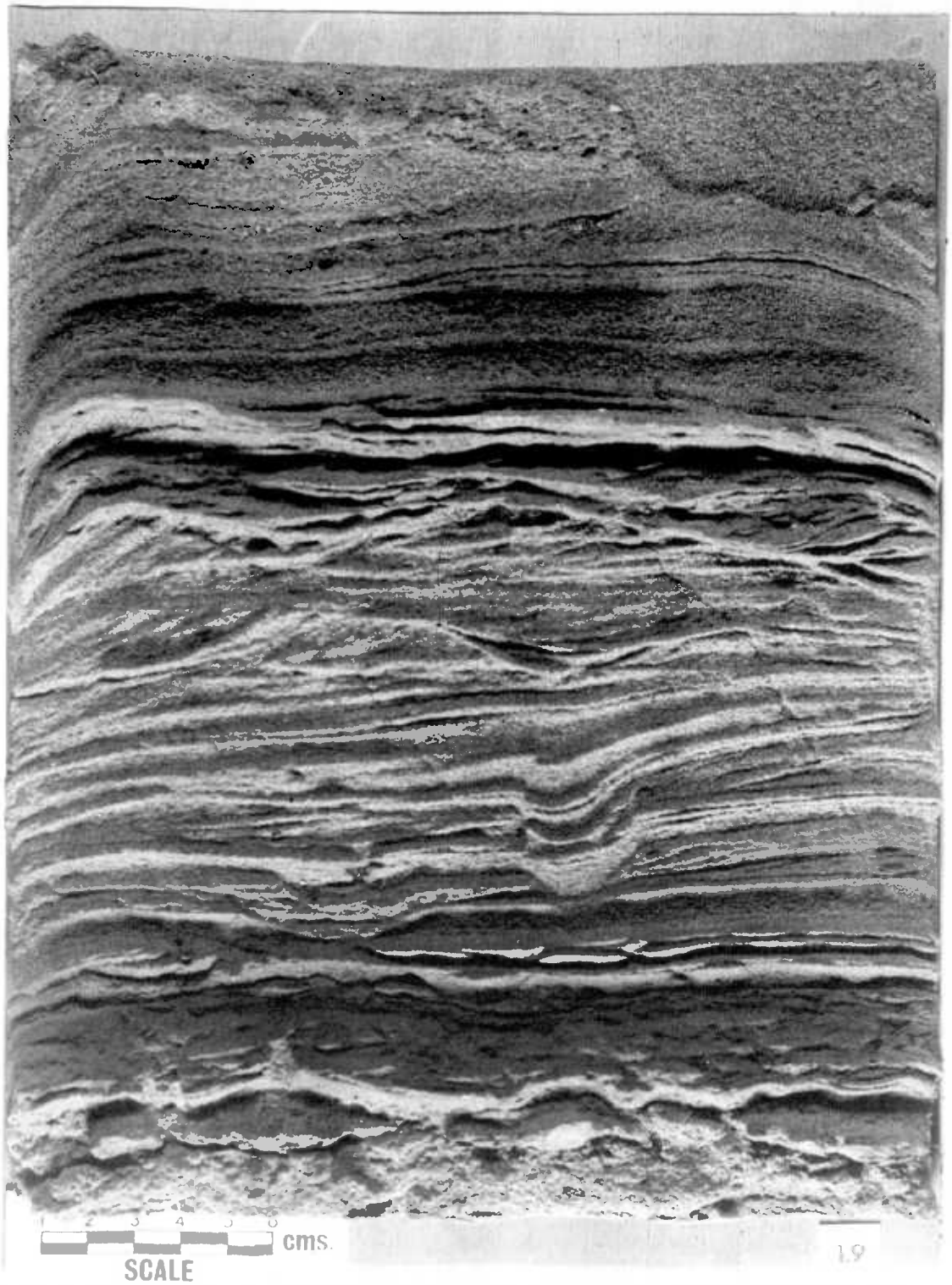


Plate 1.9 : Internal structure of creek-deposited, rippled sands and silts, upper foreshore between transects 4 and 5. Orientation : normal to the strandline.

partly because of the destructive effect of air entrapment cavities, common on the upper foreshore where the beachface is relatively steep. These cavities are formed on a rising tide when a disparity arises between the advancing tidal water and the more slowly rising water table below. The sand of the upper foreshore having partially dried out during the waning of the tide, small pockets of air are retained between the sand grains; as the water table rises this interstitial air is expelled upwards, but its escape is hindered by the surface layer of tidal water, which by saturating the upper layers of sand presents an incoherent, less permeable barrier to the passage of the air. The ensuing build-up of pressure produces cavities in the sand. Their formation can usually be observed on the flooding tide; compressed air, lifting the sand grains upwards and outwards, bubbling upwards from the sand through the shallow water of the swash zone. Cavities are not formed lower down the foreshore where the water table is always sufficiently high to create a wide effluent zone so that the sand is always saturated and incoherent (the hold of capillarity on the sand grains being broken, see Kindle, 1936). They are generally present on those areas of the upper foreshore where the gradient is relatively steep.

Because of their collapsible nature, cavity sands are not easily preserved, but some examples are shown in Plates 1.10 and

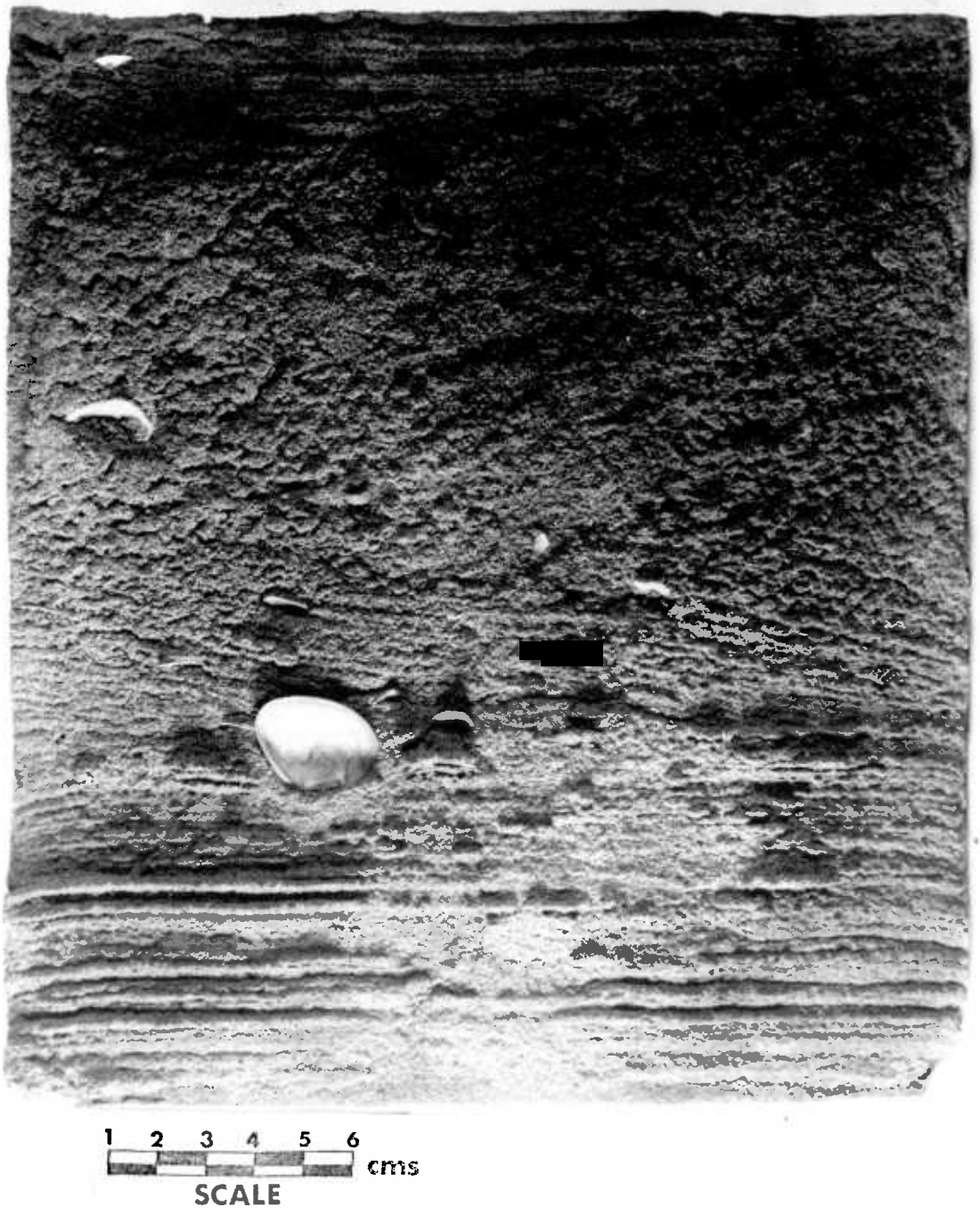


Plate 1.10 : Internal structure of cavity sands, upper foreshore, transect 6. Orientation : parallel to the strandline.

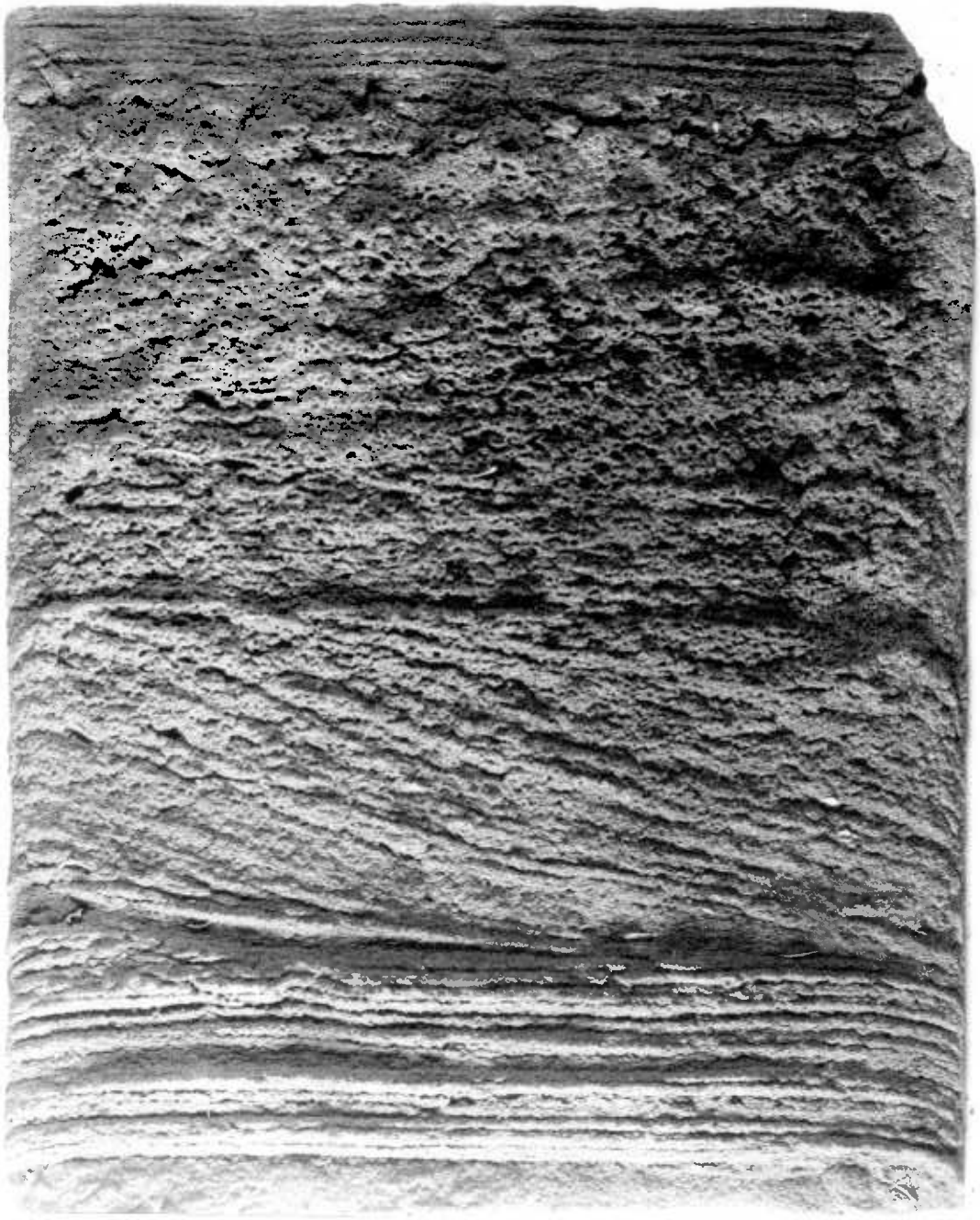


Plate 1.11 : Internal structure of cavity sands, upper foreshore, transect 6. Orientation : normal to the strandline.

1.11 (parallel and normal to the strandline, respectively). Two layers of horizontally laminated and cross laminated sand are separated by a thicker layer of cavity sand; the cavities virtually destroy the original structure, though this is not always complete. It is interesting to note the sequence of sedimentation in the upper parts of these two samples. As discussed in the previous paragraph, air cavities are produced by the flooding tide. The horizontal laminations above the cavity sand must therefore represent the net deposition achieved by the tide subsequent to the early flood. As is shown in Chapter 6, this critical deposition probably occurs in the ebbing swash zone; in this instance, it amounts to only 2 cms. of accumulation, but this is at the least dynamic level of the foreshore - near the high water mark.

These two samples also illustrate a further feature of some upper foreshore sands, particularly in the east - the occurrence of cross-stratification. It will be noted that the cross stratified layer is overlain by the horizontal laminations formed in the swash zone. Hence the cross stratification was formed prior to the laying down of the swash zone deposits. Since cavities are freely developed in much of the cross stratified layer, it can be deduced that the latter must have

been deposited before the onset of the early flood tide - therefore the cross-stratified sands were the product of an earlier tide. Ripples, and the resulting cross-stratification, develop under conditions of tranquil flow (when the Froude number is less than unity). Such flow conditions, as distinct from rapid flow conditions, can develop either in response to a decreased current velocity (with water depth constant) or in deeper water (with current velocity constant) - see Simons and Richardson (1962). The cross-stratification in these samples from the upper foreshore could not have formed in deeper water, and so must represent deposition by a lower current velocity - most probably during calm weather when swash zone velocities would be reduced.

As already described, in the upper foreshore sands of the western beach cross-stratification remains a secondary feature. In these samples from the upper foreshore of the eastern beach, by contrast, the thickness of the cross-stratified layer exceeds the thickness of the horizontally laminated layers. Swash and surf zone velocities are likely to be greater in the east than in the west, as indicated by the significantly greater grainsize of the sand in the east. However, on the eastern beach, the foreshore is reduced in

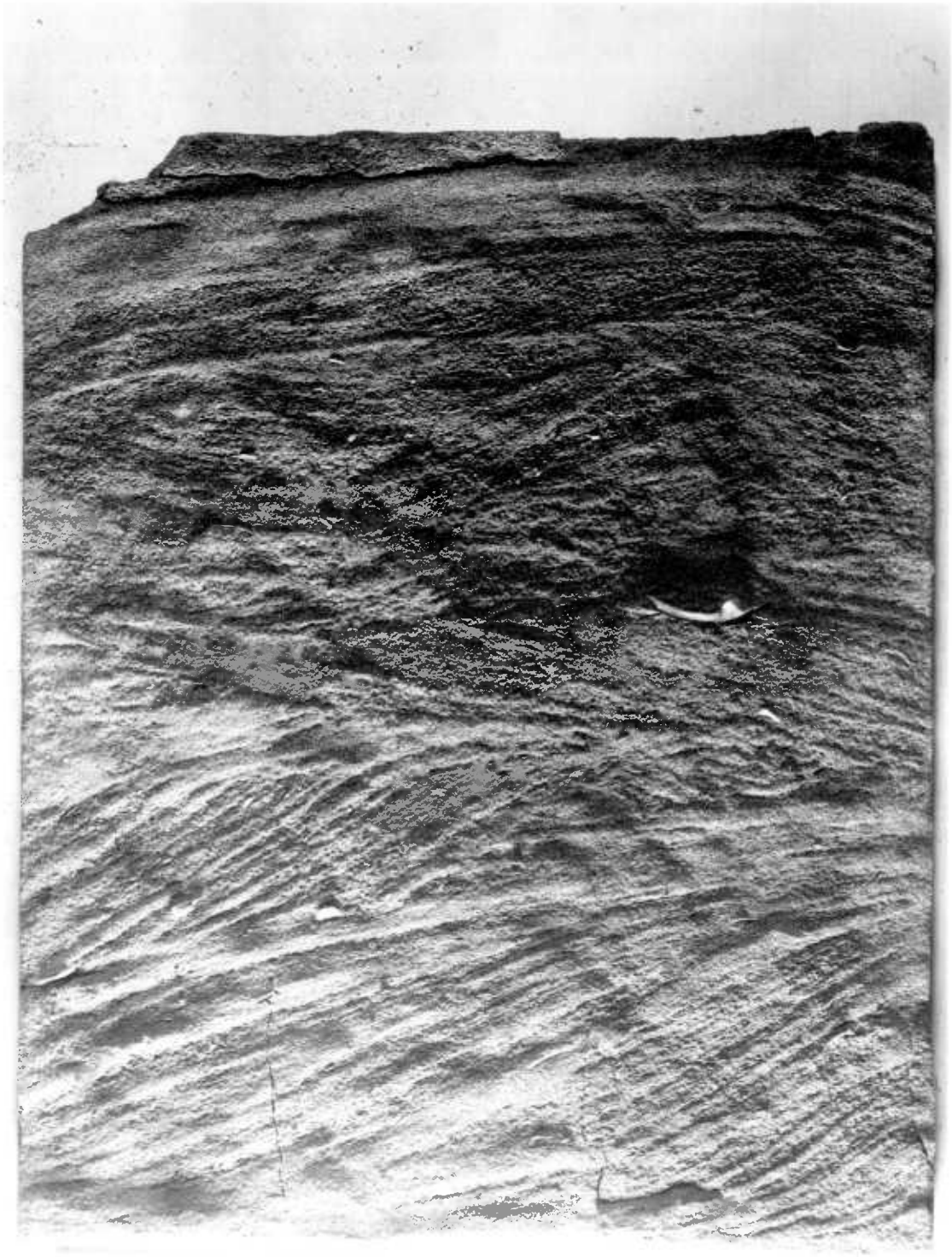


Plate 1.12 : Internal structure of middle foreshore sands, transect 4.
Orientation : parallel to the strandline.

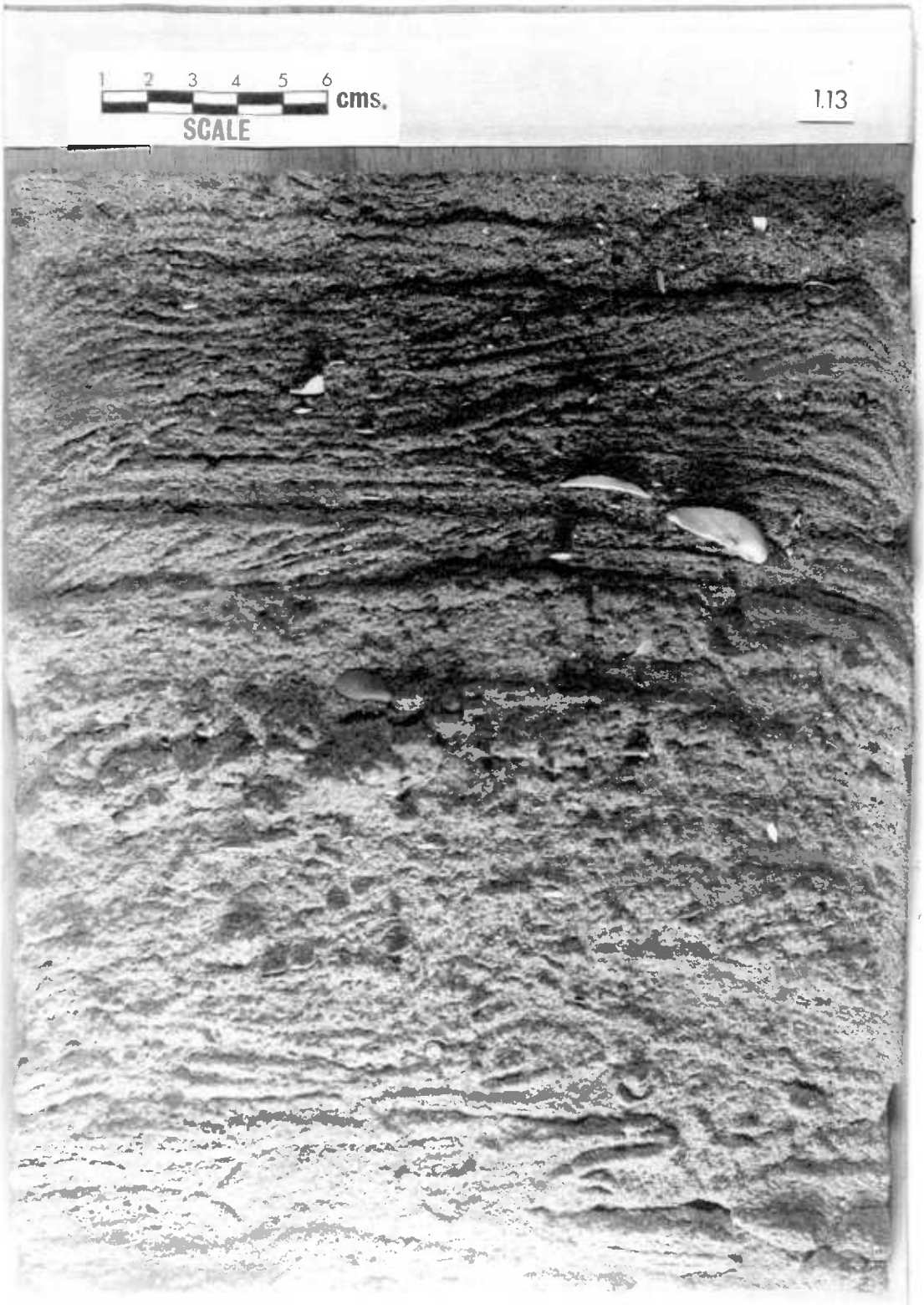


Plate 1.13 : Internal structure of middle foreshore sands, transect 2.
Orientation : normal to the strandline.

width, and has a greater slope; hence, the depth of water in the swash zone is likely to be greater on the eastern beach, so that under suitable weather conditions, bedforms of the lower fluid regime may become stable, so that ripples and cross-stratification are formed. Insufficient box samples were taken to determine whether cross-stratification ever becomes a dominant structure on the upper foreshore of the western beach.

Cross-stratification is more often developed in the sands of the middle foreshore and, in particular, the lower foreshore. As the ebbing tide traverses the foreshore, current velocities in the swash zone decline (see Chapter 6), so that the sand becomes finer grained. Because of a progressive seaward reduction of foreshore slope, water depths in the swash zone also decline as the tide ebbs. Field observations show that this progressive decrease of water depth must be of greater importance than the progressive decrease of current velocity, since standing waves - a feature of upper flow regime - are invariably produced by the backwash. Hence the ripple marks that become common on the surface of the lower foreshore are probably antidunes. The cross-stratification found in box samples from the middle and lower foreshores

may therefore be formed by truncation of antidunes by successive tides. Cross stratification in middle foreshore sands is shown in Plates 1.12 (from the central part of the beach, orientated parallel to the strandline; unfortunately not well preserved) and 1.13 (from the west, near Pendine, orientated normal to the strandline). Cross stratification in lower foreshore sands is shown in Plates 1.14 and 1.15 (from the eastern beach, orientated parallel and normal to the strandline, respectively). As an alternative to antidune genesis, the cross stratification in these samples may have been formed by bedforms of the lower flow regime, in deeper water seaward of the swash zone - the model of foreshore sedimentation put forward in Chapter 6 is concerned with the upper few centimetres of sand. This possibility is also suggested by the occurrence of coarse lithic pebbles and shell fragments in the box samples. It is noteworthy that these particles do not generally appear in the upper parts of the samples - although there is an increase in the frequency of coarse sand-sized shells and lithic grains at mid-tide level (see Chapter 6). The coarse pebbles may represent a lag formed in the collision or breaker zones, or may be brought onto the foreshore during storms. It will be noted that Plates 1,12 and 1.14 show cross-bedding parallel to the shoreline. Tidal currents flowing alongshore probably become important during mid-stages of the flood and ebb. In the east, Taf outflow probably influences the lower foreshore.

Plate 1.15 also shows climbing ripples in its middle section. These ripples, indicative of a surfeit of sand on the bed, appear to be out of phase - probably as a result of high current velocities in shallow water.

Because of the high water table and saturated character of the sand, well preserved box samples were not obtained from the lower foreshore of the western beach. In addition, because of the fineness of the sand in that area, the laminations are thin and not too clearly shown in the box samples. It was noted that structures are there frequently disrupted by burrowing animals (Arenicola sp., Pygospio sp., Lanice sp.). The failure to obtain samples from the western sands is unfortunate because those from the eastern sands may not be truly representative of lower foreshore sands. This is because the lower part of the foreshore in the vicinity of Ginst Point is strongly influenced by the outflow from the Taf. The cross lamination shown in Plates 1.14 and 1.15 may be formed by current action on the flanks of the Taf channel.

The characteristics of the foreshore structures described in the foregoing may not be typical of the environment as a whole at all times. Too few box samples were taken to permit such a complete analysis. In retrospect, it can be seen that this was an unfortunate ommission, since the information derived from an examination of these sedimentary structures would have been an invaluable addition to the textural information described later.

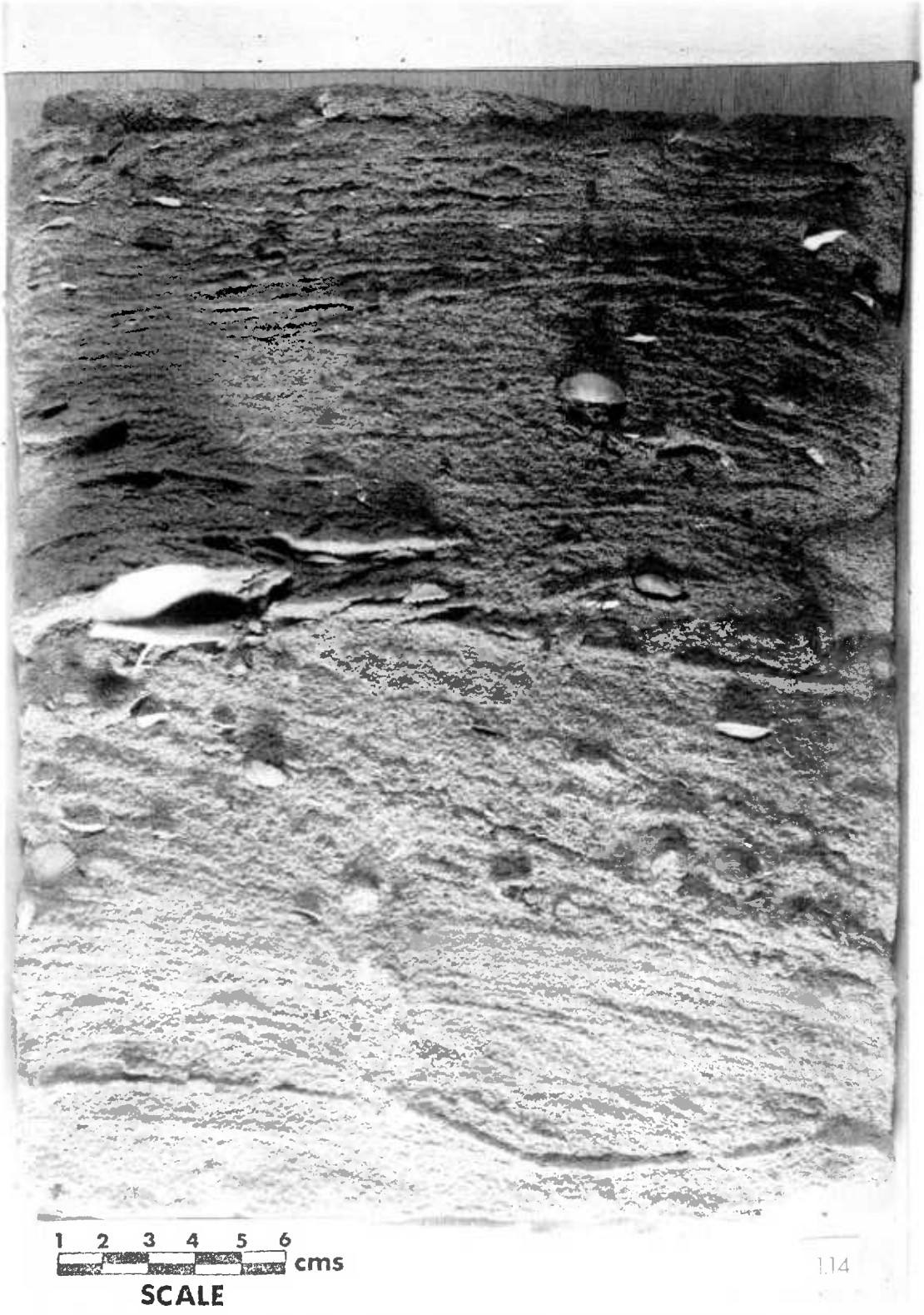


Plate 1.14 : Internal structure of lower foreshore sands, transect 6.
Orientation : parallel to the strandline.



Plate 1.15 : Internal structure of lower foreshore sands, transect 6.
Orientation : normal to the strandline.

laden creek discharges across the foreshore.

Horizontal laminations become rarer in the middle and lower foreshore deposits. There, cross stratification becomes dominant. This may be caused by truncation of antidunes in the swash zone, particularly on the lower foreshore. The cross stratification that occurs below the surface few centimetres of sand may be formed in deeper water, seaward of the swash zone. Certainly, the characteristic feature of these deposits - fairly abundant pebbles and large shell fragments - suggests that some of the sorting and deposition occurs in the collision or breaker zones; or this coarse material is carried shorewards during storms and is then incorporated into the foreshore sands during calmer weather.

In any case, the vertical sequence of structures in the foreshore indicates that the vertical sequence of sedimentary features may not be a simple repitition of the horizontal sequence developed across the foreshore.

Stratification is also the most conspicuous feature of the dune deposits. Dune sands are invariably regularly laminated, with laminae a few millimetres thick; these are steeply inclined (normal to the strandline). Two types of laminae may be observed: foreset laminae occur in the lee of the dunes and are steeply inclined to the horizontal (up to 30°); successive units compose a cross-bedded sequence denoting various stages of dune growth. Accretion laminae occur on the seaward face of the dunes, less



Plate 1.16 : Internal structure of dune sands, transect 3.
Orientation : normal to the strandline.

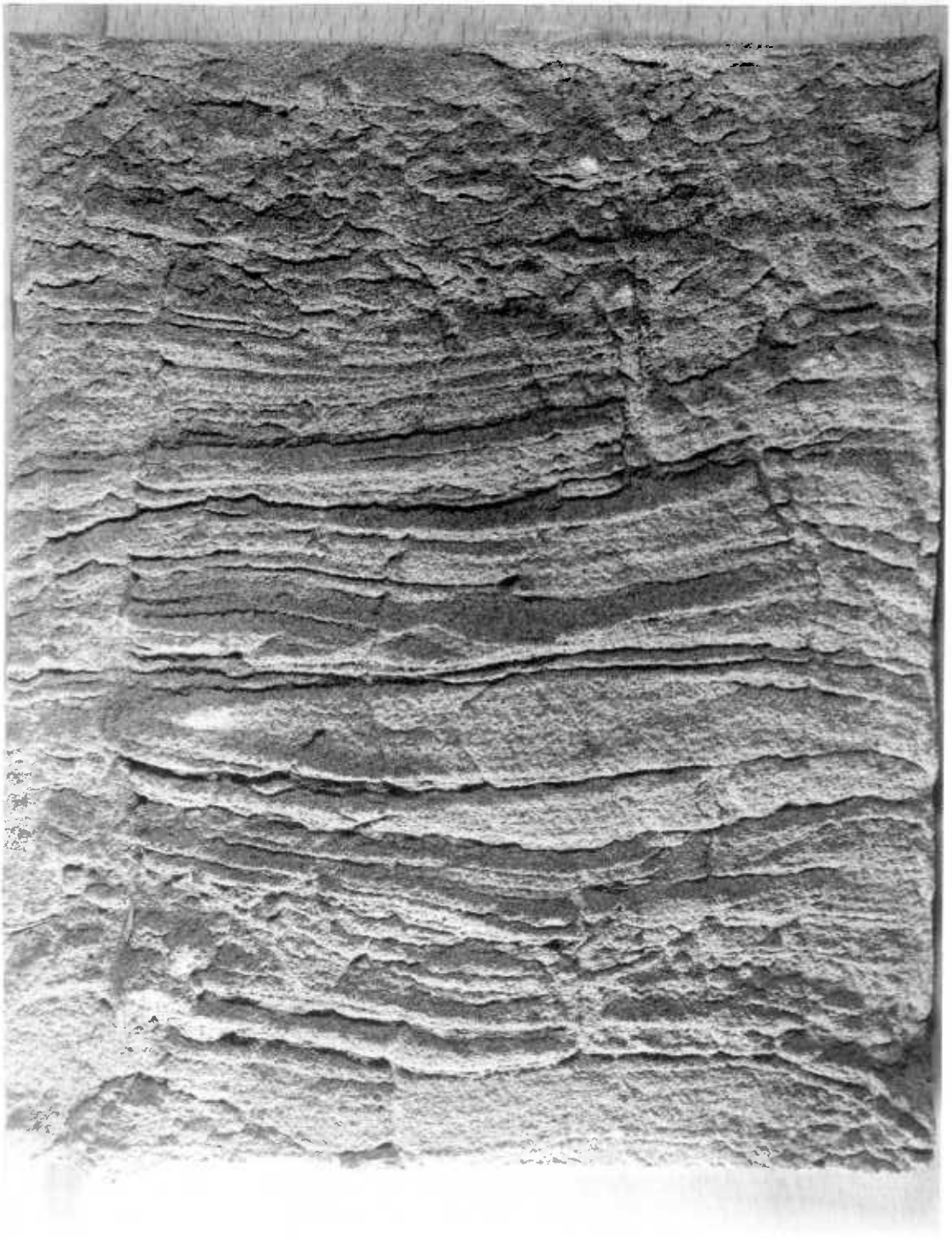


Plate 1.17 : Internal structure of dune sands, transect 3.
Orientation : parallel to the strandline.

steeply inclined to the horizontal (Plate 1.16, normal to the strandline). Parallel to the strandline, dune sections show that the laminae are approximately horizontal, but not always as regular as those of the upper foreshore (see Plate 1.17), reflecting the irregular surface of the dune in contrast to the flat uniformity of the beach. A distinctive feature of most dune sections is created by the long vertical roots of marram grass, although their vertical holes do not destroy stratification.

1.3 : The Estuary.

(a) Physiography; flora. The estuarine complex consists of an outer part composed of a succession of banks and channels shaped by tidal currents and wave action, and an inner part in which the primary features are one, or more, main ebb channels meandering in a sandy bed, and associated flood barbs. Such a form is common to many British estuaries (Robinson, 1960).

The outer part of the estuary, between the outfall of the Taf, Towy and Gwendraeth, has not been the concern of this study. Within the inner part, the estuary proper, several physiographic subenvironments may be defined: The high marsh and low marsh, the mud flats and the open sand flats. These units are differentiated by sediment type, vegetation, and fauna, and relate to tidal cover and currents (see sketch map, Fig. 1.7). Eleven transects were surveyed across the estuary (see Fig. 1.1), and average profiles are shown in Figs. 1.8a and 1.8b.

The salt marsh occupies the highest part of the intertidal

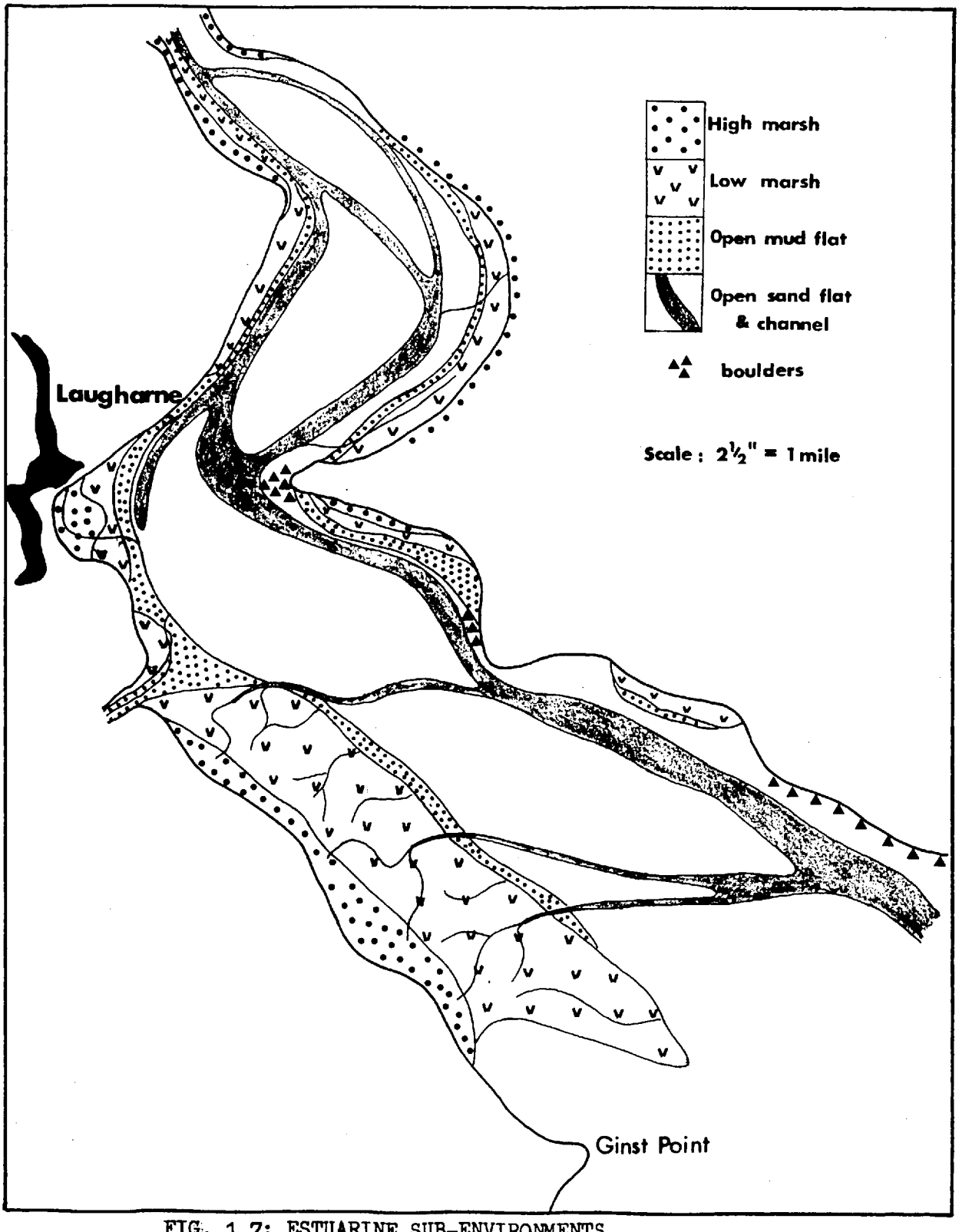


FIG. 1.7: ESTUARINE SUB-ENVIRONMENTS.

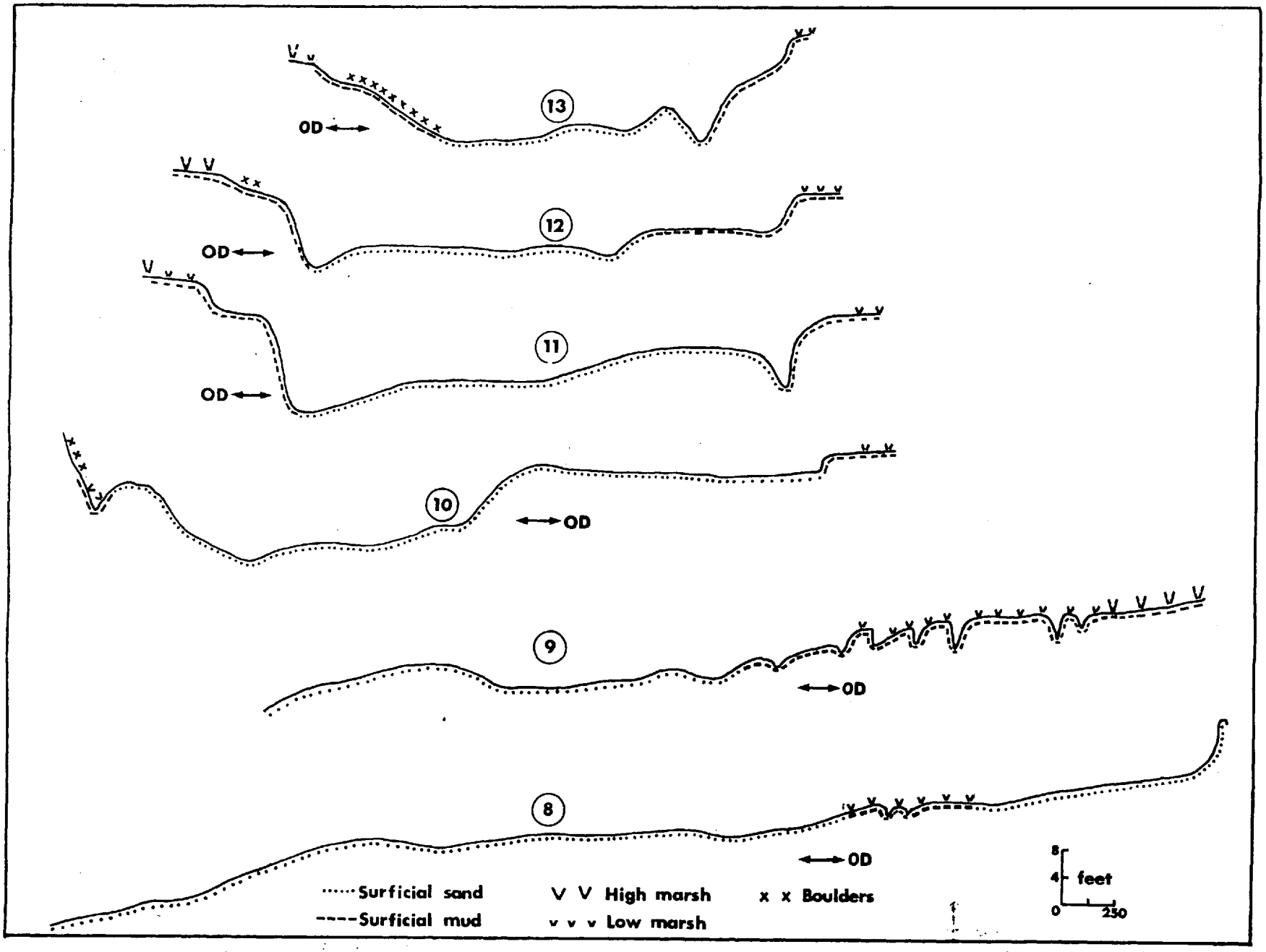


FIG. 1.8a: ESTUARINE TRANSVERSE PROFILES.

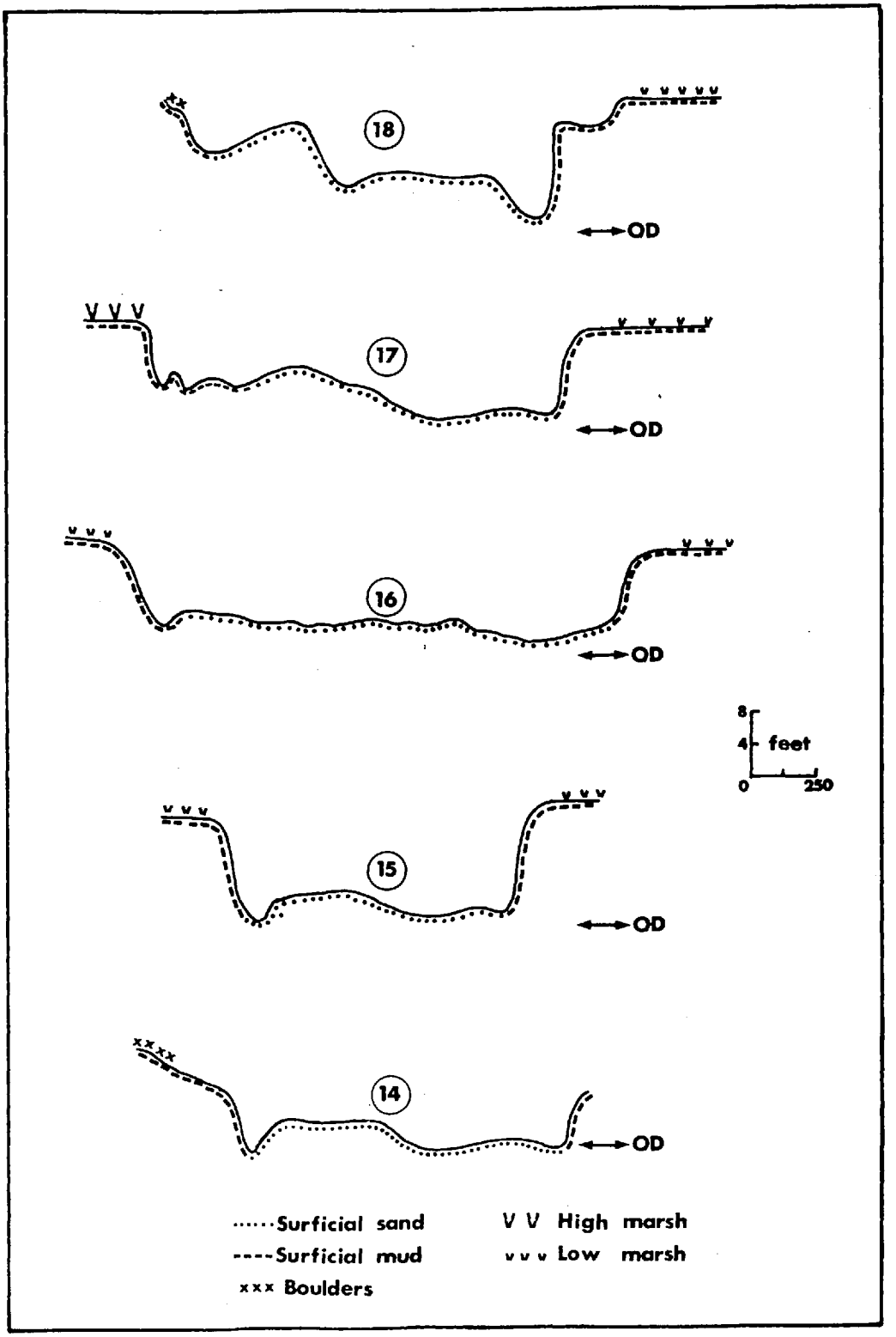


FIG. 1.8b: ESTUARINE TRANSVERSE PROFILES.

zone, occurring on both sides of the estuary in its upper reaches, but predominantly on the right bank in its lower reaches. Apparently, therefore, in the lower estuary the main channel has tended to hug the left bank (which is therefore progressively eroded while the right bank progrades) in response to the growing accumulation of sand off Ginst Point; sediment controls therefore override the effects of the Coriolis force.

The upper part of the salt marsh is the high marsh, not often reached by the surveyed profiles, occurring above the level of all but the highest tides. It is characterised by a definitive flora, dominated by a short sward of Glyceria maritima, Armeria maritima, and Festuca rubra; other types are present, less abundantly, and these include Plantago maritima and Statice limonium. These associations are generally restricted to the lower portions of the high marsh, where there are infrequent inundations by high spring tides. Above the sward, on higher ground, Juncus maritima is dominant.

The lower part of the salt marsh is the low marsh, which is, in places, separated from the high marsh by a low step approximating to the mean level of spring tides; often, however, the demarcation between high and low marsh is not well defined. The low marsh is covered by most tides. In its upper limits, some of the flora of the high marsh are present, but over most of its extent the low

marsh is almost exclusively colonised by Spartina townsendii; this species, rice grass, is not a native one and, according to local information, was introduced by an East Marsh farmer during the 1920's. Its present distribution is a striking testimony to its vigorous growth and spreading habit. Indeed, the growth of the Spartinietum is synonymous with the present growth of the salt marsh, the low marsh being considerably more developed now than it was fifty years ago. Salicornia sp. also grows on the low marsh, but is not widespread. Landward, the low marsh forms a continuous, close-knit feature but at its outer limit it occurs as isolated stands separated by areas of mud flat. The sediment of the low marsh is generally muddy, silt and clay-size particles being effectively trapped by the vegetative cover; in the lower estuary, wind-blown sand from the dunes and aeolian sand flat around Ginst Point is also trapped, so that the sediment of the lower low marsh is predominantly sandy, the marsh passing directly into the open sand flat without an intermediary mud flat.

A distinctive feature of the low marsh is a dendritic drainage pattern of creeks. The creeks may be up to ten feet in depth, twenty feet in width; large creeks are linked by small, meandering creeks. Their borders are usually higher than the surrounding salt marsh, forming natural levees. Some of the creeks show active head water erosion.

The genesis of creeks begins early on in the development of the salt marsh. Young creeks are formed from natural depressions in the original mud flat as marsh drainage becomes progressively concentrated within their confines. Once formed, they are therefore self-perpetuating.

Landward, the creeks degenerate into a series of isolated elongate depressions, or salt pans, in the high marsh. They are characteristically super-saline, drying out periodically with a resulting formation of mud cracks. Some salt pans appear to correspond to original depressions in the mud which have not grown into creeks.

Neither the salt pans nor the creek floors support vegetation. The creek levees however are often colonised by Halimione portulacoides, and this species may extend into the high marsh.

The creeks continue below the salt marsh, traversing the mud flat before discharging into the main channels. The mud flat is most developed at Laugharne, but occurs also elsewhere (see Fig. 1.7). It is defined by the absence of a vegetative cover, although small growths of Enteromorpha sp. are not uncommon. In the lower estuary, the mud flat is very restricted, or absent, and the salt marsh passes directly into the open sand flats.

The open sand flats are the most extensive physiographic unit, consisting of winnowed sand too unstable to support vegetation.

They are exposed periodically by the ebbing tide, but do not generally dry out. At low water, the flats consist of low lying banks separated by a complex pattern of shallow channels. The main channels may be up to four feet deep at this time, but many subsidiary channels are only a few inches deep. Because of the small difference in elevation between many banks and channels the width and orientation of the channels is very variable, depending to a large extent on the magnitude of river discharge. The pattern of channels can change noticiably between tides, and it was observed that the mooring of the survey vessel in a shallow channel off Laugharne resulted in a significantly altered pattern. The major channels are more fixed in position. These have been mapped on six separate occasions and the results are shown in Fig. 1.9. The maps have been constructed partly from the surveyed profiles (see Chapter 4) and partly from approximate compass bearing taken on each occasion. The main flow, generally in the deepest channels, is indicated. Flood barbs are not shown.

Clearly, the position of the main channel in the lower estuary remained the same during the period of study, hugging the northerly bank (not the southerly bank as might be expected). An historical study of channel stability has not been attempted; however, the current Ordnance Survey sheet (1904-1913, partially revised 1948) shows no change from the present.

The most changeable parts of the channel occur on the sharp

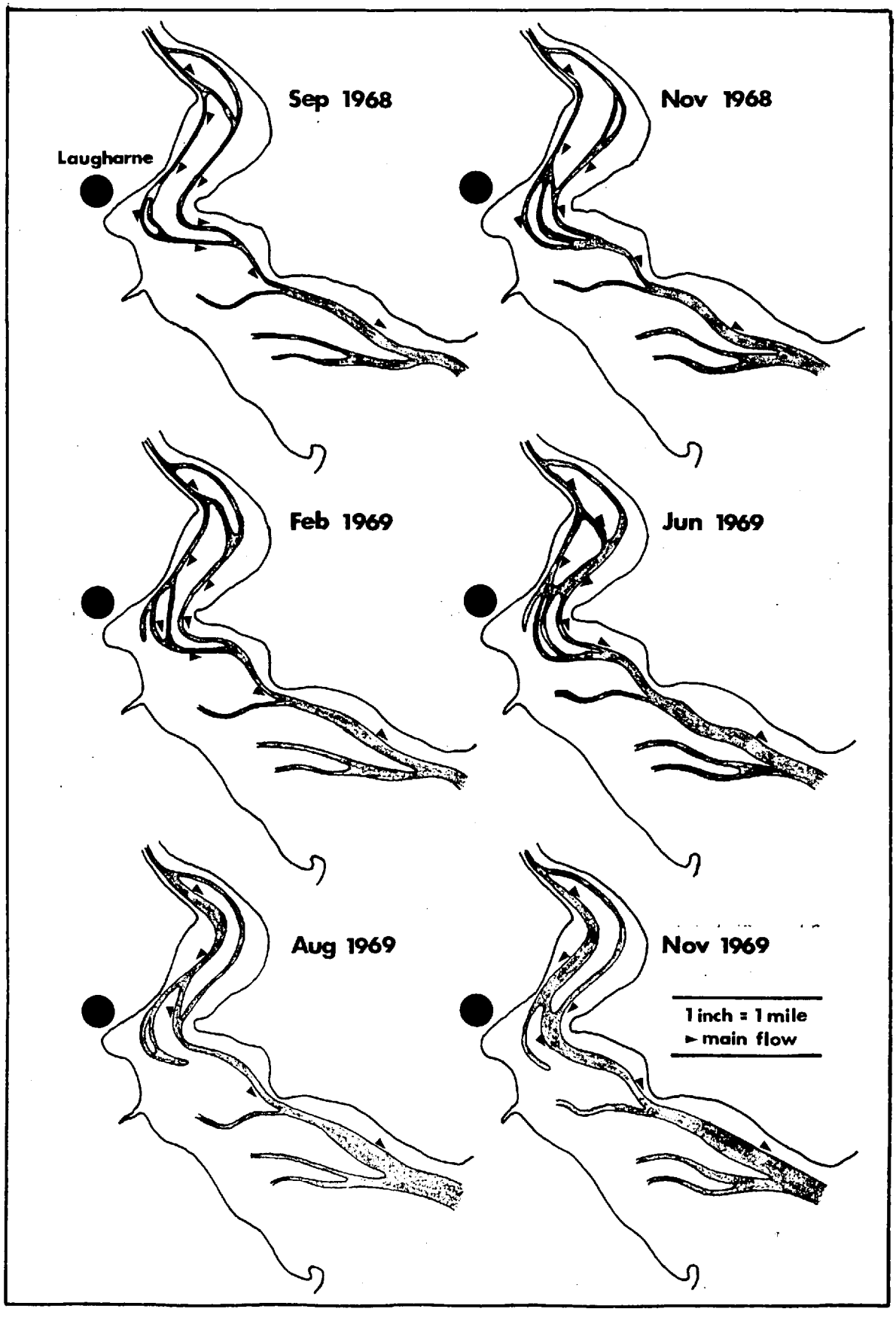


FIG. 1.9: MAIN CHANNEL MIGRATIONS.

bends off, and above, Laugharne. Apparently this must result from straight current streamlines (both ebb and flood) impinging on curved channel sides and banks. In the upper estuary, the present main channel is close to the right bank, though the 1948 map shows it close to the left bank. The remnants of that abandoned channel now form a subsidiary channel.

The only systematic change has developed off Laugharne where the main flow has migrated from the right to the left bank, although at the same time (see Chapter 4) the outer edge of the bend has been locally eroded. It is not known whether this new left bank position in the middle estuary is a new departure in channel morphology, although a right bank position is shown on the 1948 map. Local information suggests that the channel swings from bank to bank with some frequency. Certainly such migrations explain why the salt marsh on either side of the estuary is at a variable height (see Figs. 1.8a and 1.8b).

Fluctuations may well be cyclic, occurring as an inevitable consequence of meander over-extension. However the recent influx of sand, still continuing today (see Chapter 4), coupled with the introduction of Spartina and attendant growth of the salt marsh, must fundamentally modify many aspects of estuarine circulation and assist channel fluctuations.

In addition to these major sub-environments, significant

exposures of boulders, probably glacial moraine, occur on the left bank off Laugharne.

(b) Surface features; fauna

Surface features that are caused solely by physical processes are uncommon in the salt marsh. This is because the action of waves and currents is severely restricted by the height of the marsh surface and the thickness of its vegetation. Ripple marks may occur, however, where vegetation is absent at the outer margin of the marsh and occasionally on the slopes of large creeks. Symmetrical ripple marks are most frequent, formed by the oscillation of water retained in pools after the tide has ebbed. Longitudinal ripple marks, also symmetrical, may form on the convex slopes of large creeks; they are generally orientated sub-parallel to the creeks, and are thought to be caused by tidal eddy currents (cf. Evans, 1960; Khan, 1968). The creek floors are usually smooth, except in the low marsh of the lower estuary, where sand from the open sand flats penetrates up the creeks into the salt marsh; here, asymmetrical ebb-formed ripple marks occur.

The mud flat is always free of ripple marks, except at its transition with the open sand flats. Its surface rarely dries out, but when it does, during neap tides in the summer months

when air temperatures are high, mud cracks may develop. Mature mud cracks can develop a reddish coating of iron oxide and hydroxide on the walls of the fissures (cf. Evans, 1965). Less common are mud blisters, small domes less than 5 cm. in diameter and 1 cm. in height, produced by enclosed air or gas; these too have been described by Evans (1960).

In contrast to the higher sub-environments, the open sand flats show a highly rippled surface, a great complex of forms covering most of the surface when viewed at low water. Most frequently occurring are asymmetrical ripple marks, small scale with wavelengths up to 10 cm., amplitudes up to 3 cm., and with short or long crests. At low water, these are always ebb-orientated, although some interference marks can occur. The pattern of ripple marks may be complicated by the development of oscillation troughs along the original crest line of the ripples (cf. Haynes and Dobson 1969). Linguoid ripple marks are sometimes present near the main channel margin, being associated with turbulent water (Allen, 1963).

A distinctive feature of the open sand flats of both the inner estuary and the outer estuary sandbank complex is the spasmodic growth of mega ripples. These are large scale features, with wavelengths exceeding 10 metres and amplitudes up to 50 cm. Those formed within the estuary proper are usually

rather smaller than this (wavelength 6-8 m.) and are restricted to the lower estuary along the margin of the main channel (at the lower ends of transects 8 and 9). They are always ebb-orientated. Their form is rather complex. Scour pits develop at the base of the lee slopes and these are often associated with a ridge that extends over the next stoss. Small asymmetrical ripples are always present on the stoss sides of the mega ripples, their orientation closely following the distribution of the scour pits; small-scale ripples never occur on the lee sides of the mega ripples.

Such large-scale features are now well documented (Cornish, 1901; Van Straaten, 1950, 1953; Cloet, 1954; Khan, 1968; Haynes and Dobson, 1969). Their occurrence and growth is clearly related to hydrodynamic processes, and there is little doubt that they are formed by high velocity currents acting on a mobile bed. The critical formative processes are flow depth and flow velocity. As explained in Chapters 3 and 4, maximum ebb currents occur when tidal flushing nears completion, as flow is contained within a decreasing cross-sectional area. Thus mega-ripples are formed on the margins of the main channels, and perhaps within them too; however as the flow becomes totally contained by the channels, stream power increases to reach the plane bed regime when dunes and ripples are destroyed.

The formation of the mega ripples on the channel margins must cause an increase in sediment transport rate which would tend to increase bed slope; the feedback between bed slope and transport rate would create a mutually accentuating condition (Bagnold,1956; Haynes and Dobson,1969). Because of the influence of gravity, ebb flow must increase downstream and this is reflected by a significant upstream decrease in mega-ripple wavelength, till they die out altogether in the middle estuary. Mega ripples are not a regular feature of the sand flats but occur during some spring tides and during periods of strong upland flow. Their formation must also be to some extent controlled by sand grain size since such large-scale features are most able to form in coarser sand-grade deposits (Allen,1970).

Organic features are common within the estuary. An exception to this is the high marsh upon which macrofauna appears to be extremely limited; this agrees with the findings of Evans (1960) in the Wash salt-marshes. Obviously the paucity of fauna can be ascribed to the long periods of exposure to the dessicating effect of the atmosphere, and to the comparative freshness of the water on the estuary margins (see Chapter 3). The creeks, however, enable some numbers of species to penetrate the high marsh although they are more common on the low marsh.

The low marsh is nearly always waterlogged and is rich in

fauna. The mesogastropods Littorina littorea and Peringia (Hydrobia) ulvae are very common, the former commonly crawling up the Spartina, the latter over the marsh surface. Deposit feeding pelecypods, such as Scrobicularia plana and Mya arenaria are common, Mya truncata being less so. The distinctive surface trails of these, and other marsh living species are shown by Evans, (1965). Amphipods are also common and include Corophium volutator and Corophium arenarium. The polychaete Nereis diversicolor produces abundant rosette patterns on the surface.

Most of these species also invade the mud flat where their surface trails are more clearly visible. Assemblages of the pelecypods, particularly Scrobicularia, are found where the marsh and mud flat are being locally eroded, and large numbers of dead individuals accumulate in the creeks. The shore crab, Carcinus maenas, is also common, but is most readily observed in the creek walls.

Within the marsh and mud flat subenvironments by far the majority of species are found in the lower estuary, many dropping out as the estuary is ascended, so that in the upper estuary the number of species is severely restricted. This distribution is akin to that recorded by Howells (1964) for the adjacent Towy estuary.

The above-described faunal assemblages must not be taken as complete or definitive. Seasonal and long-term fluctuations

may be severe. Some species compete for the same, or similar, ecological niche and the dominance of one may temporarily exclude the others. This is probably the reason for the low frequency of Macoma balthica which occupies a similar environment to Scrobicularia, at present very common. A high density population of the one species excludes the other through the ingestion of its larvae as they settle from the plankton; all other settling larvae are also excluded, and this includes the larvae of the dominant species (Green, 1957). However, Macoma and Scrobicularia are not altogether natural neighbours, the one being a northern, the other a southern species. The extremely cold winter of 1962-3 largely decimated Scrobicularia on British coasts but hardly affected Macoma (Crisp, 1964). At such times therefore we may expect a significant increase in Macoma numbers, and an inevitable decline in Scrobicularia. These two species produce rather different surface trails.

In the lower estuary, on the open sand flats, the edible cockle Cardium edule is extremely abundant, living and dead individuals littering the surface. This species was, until recently, commercially exploited. It also occurs at the transition from mud to sand flats, and dead specimens are swept into, and accumulate in, the creeks. The resulting shell banks, common in the creeks, are often colonised by Mytilus edulis.

Because of the mobility of the open sand flats and channels,

fauna is there restricted. Apart from Cardium, the polychaete Arenicola sp., with its characteristic surface casts, is common in the lower estuary. The isopods Eurydice pulchra and Bathyporeia pilosa also occur in areas where the sand remains waterlogged at low water. Near the estuary mouth, the sand flats are littered with the shells of dead molluscs swept in from the bay, although a few such as Ensis spp., Donax vittatus and Lutraria lutraria are probably derived from a living beach fauna near the low water mark of spring tides. Near Ginst Point therefore, the open sand flats pass into the aeolian sand flat already described.

(c) Subsurface features

Only a few lacquered box samples were collected from the estuary, and are probably not typical in some respects.

Plates 1.18 and 1.19 are of samples taken between the young marsh clumps of transect 8; the former parallel, the latter normal, to that transect. They illustrate the transition between beach sand flats (which occur on the upper part of the transect) and estuarine sand flats (which occur on the lower). The regular, near horizontal laminae, characteristic of the upper foreshore, developed at the base of the samples suggest that swash-type action predominated here before the progradation of the estuarine deposits proper. The estuarine sands show

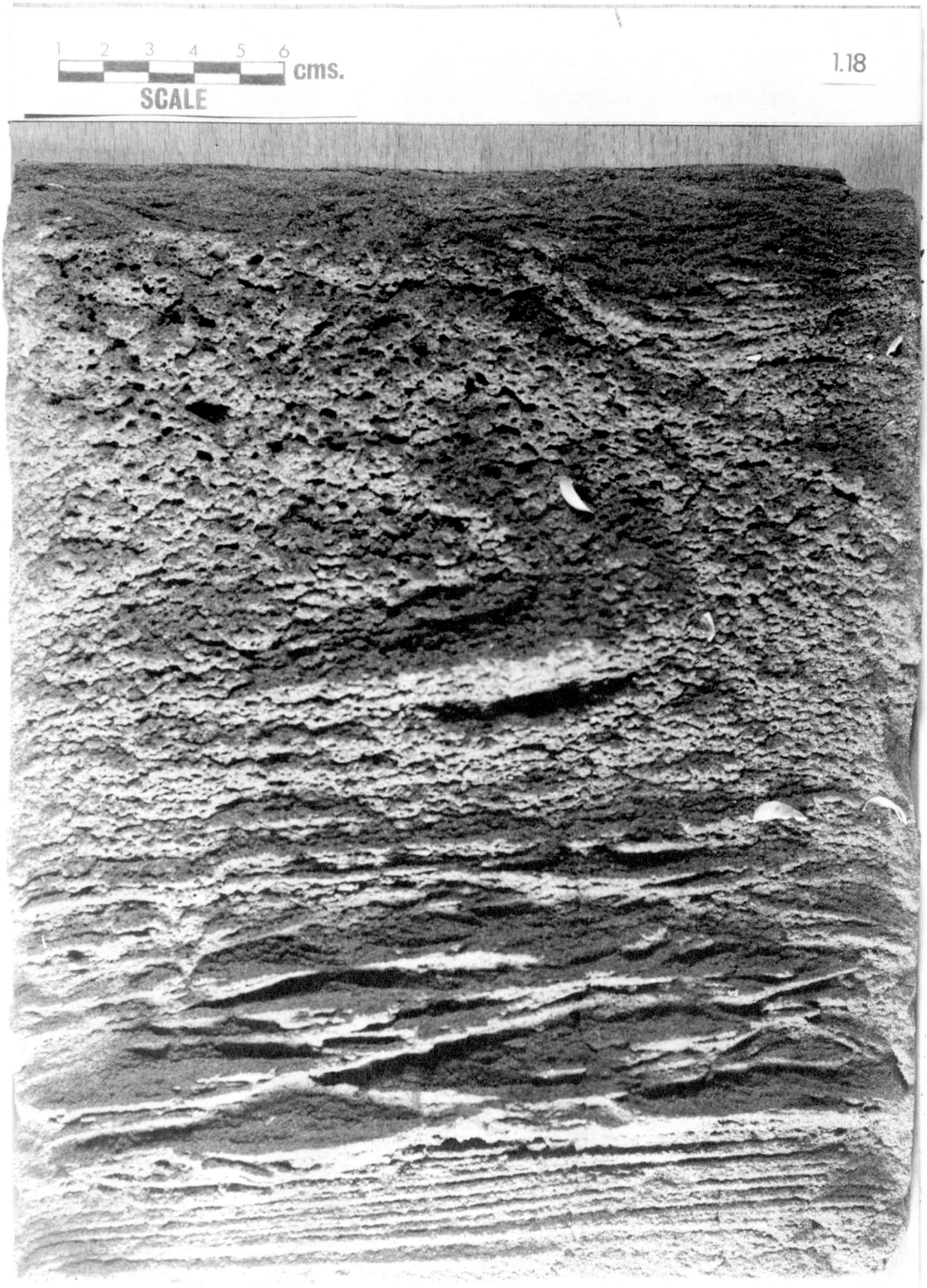


Plate 1.18 : Internal structure of upper foreshore cavity sands/ estuarine sands, transect 8. Orientation : parallel to the main channel.

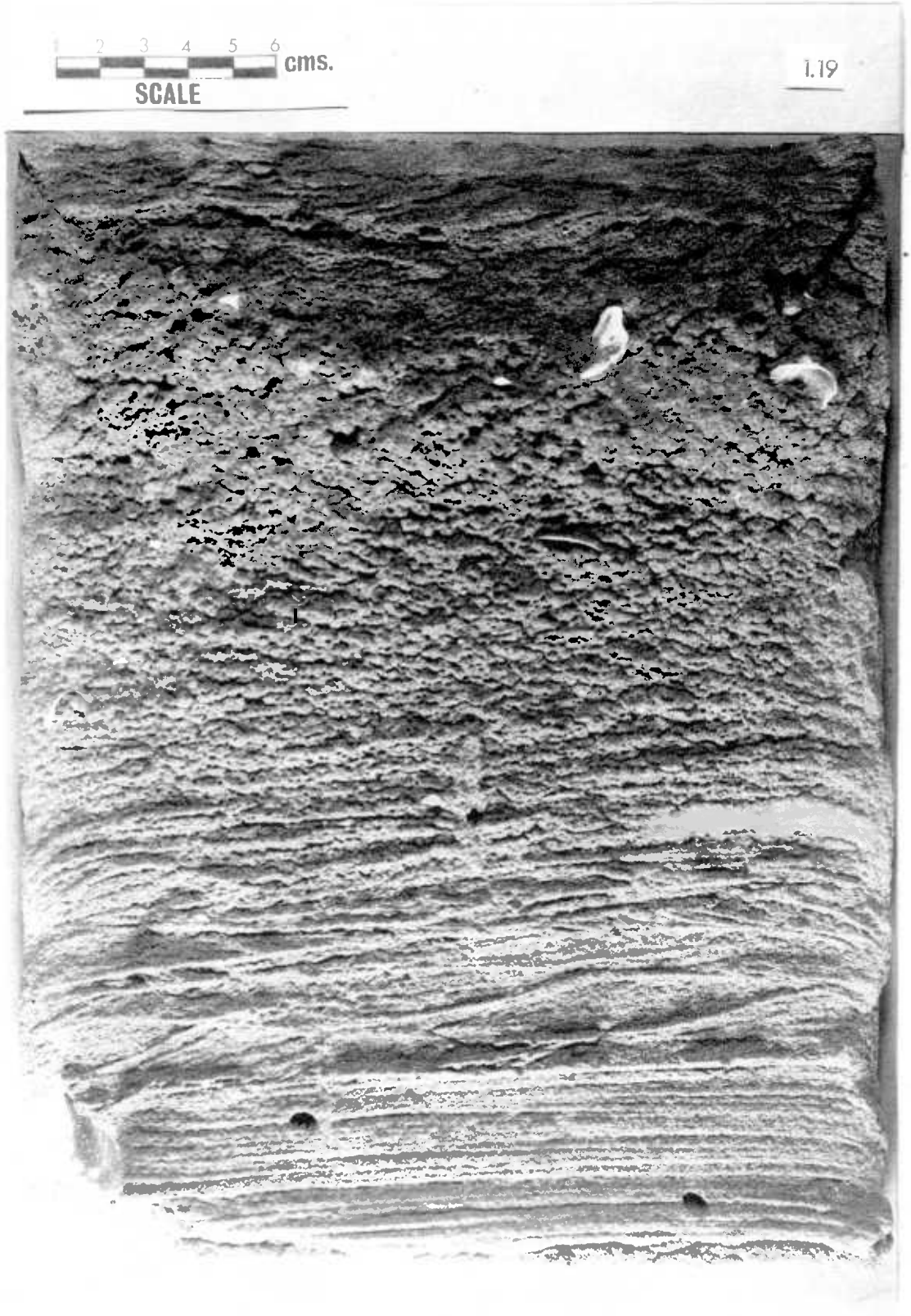


Plate 1.19 : Internal structure of upper foreshore cavity sands/ estuarine sands, transect 8. Orientation : normal to the main channel.

abundant cross laminations due to the fluctuating nature of the depositing currents and the formation of ripples. Cavity sand makes up much of the samples and reflects the very fast rise of the flooding tide (see Chapter 3) which accelerates ahead of the water-table, particularly on the higher shoals. The net accumulation of sand subsequent to the early flood is just two centimetres in these samples, although rather more deposition has been observed in some sections.

Cross-bedding is not uncommon near the centre of the estuary where currents and stream power are at a maximum, although even laminations indicative of the plane bed regime are frequent. Cross-bedding is most developed on the higher shoals, even laminations on the lower shoals; the upper surfaces of sections are always cross-laminated by ripples. An example of a section (longitudinal) through a large, high shoal off Laugharne is shown in Plate 1.20. Cavity sand is restricted to the higher shoals.

Megaripples, periodically developed in the lower estuary, are distinctly cross-bedded, most laminae dipping in the direction of the ebb current at angles up to 30^{o} to the horizontal; erosion surfaces separate successive sets of laminae. These structures appear to merge below with the horizontal laminations generally developed on the estuarine sand flats.



Plate 1.20 : Internal structure of a high shoal of the middle estuary, transect 13. Orientation : parallel to the main channel.

CHAPTER 2.

TEMPORAL VARIATIONS OF THE BEACH PROFILES

2.1 Introduction

It has been generally established by studies in many parts of the world (for summary, see King, 1972)* that beaches are not static features, but continually change their texture, structure and volume, seasonally, annually, or over longer periods of time. These changes are related to varying rates of sediment availability, on-offshore and longshore transport. At any moment in time, the beach may be considered as a sediment body intimately connected with its surrounding environments, and related to them by a series of dynamic equilibria. The beach slope is continually in a state of flux, adjusting itself to constantly changing hydrodynamic controls. This may result in a redistribution of sediment on the beach, overall accretion or overall erosion.

Fluctuations in the volume of sand held on the beach depend on the development and interaction of various meteorological and oceanographic processes, both on the continental shelf and on the shoreface slope. The dominant processes active on the shelf have been described by Swift, et al (1971), and of these, two are of prime importance in the nearshore zone : These are

* See also Clifton et al (1971).

meteorological and tidal processes. The former includes wind drift currents (caused directly by wind stress), wave drift currents (caused, in deep water, by oscillatory wave surge, with a residual motion that is intensified in shallow water) and barometric storm surge (caused by the piling up of water against the coast, during intense storms). In addition, tidal currents, either rotary or rectilinear, also have a residual component.

The cyclic nature of both meteorological and tidal processes suggests that the fluctuations of sediment on the beach should also be cyclic. These cycles will correspond to the semidiurnal and diurnal fluctuations of the tides; the fortnightly cycle of springs and neaps; seasonal variations of wave energy associated with seasonal meteorological variations; an annual tidal rhythm associated with the equinoxes; annual and longer term fluctuations related to long period meteorological trends, and to eustatic and/or tectonic trends. In addition, apparently random fluctuations associated with storms may also be part of a long period cycle (if the time scale under consideration embraces the 'natural cyclic period' of the shelf - see Curray and Moore, 1964).

It is evident that if it is assumed that these postulated fluctuations are indeed real and active, then any study designed to monitor them comprehensively must be prohibitively time

consuming and costly. For economic reasons, the time scale of the described course of study was confined to two years, February 1968 to March 1970. During this period, measurements of beach profiles were made at intervals of approximately three months, mostly during times of spring tides. The three-monthly interval was not always rigidly adhered to for various practical reasons and varied from two to four months.

The study was not intended to provide information on any long-term changes due to climatic or eustatic trends. It was hoped however to monitor seasonal fluctuations (if any) while ignoring short-term daily fluctuations. In fact it was discovered that the latter were often of sufficient magnitude to mask the former, and the results of surveys were dependent on the proximity in time of stormy or vigorous meteorological conditions. It will be shown that storms appear to move sand off the beach. Much of this loss is made good during periods of calm weather. It follows, therefore, that a survey of a beach profile on the day following a summer storm would show a net loss of sand, whilst one a week or more after a winter storm would indicate no such loss. In the absence of further data, it might be concluded that the profile was less stable in summer than in winter. This conclusion would be quite erroneous if, in fact, winter storms were more frequent than summer storms (as is likely to be the case).

* The accuracy of the technique was tested while surveying the estuary profiles (see Chapter 4). There, surveys were made between two fixed poles, and therefore across a constant distance and between constant levels at every survey. Successive surveys thus served to test the accuracy of the technique. In addition, when levelling the reference poles on the dunes into local bench marks, the accuracy of surveying was again checked by traversing closed loops.

Hence the arrangement of surveys adopted in this study has proved to be unsatisfactory. An attempt is made, in the following analysis, to overcome this shortcoming in experimental design. Suggestions on improvements are discussed at the end of the chapter.

2.2 Surveying and Analytical Techniques

The quarterly surveys of Pendine and Laugharne Sands, for the period February 1968 - March 1970, were made using a microptic level and staff. Seven survey transects were set up along the foreshore and at right angles to it (Fig. 2.1); they extended from the dunes to low water mark. Permanent marks, consisting of cemented steel poles, were set up in the dunes, two for each transect so as to provide a line of permanent orientation. Temporary flags were erected on the beach during each survey so as to prevent deviations from the line of the transect. Each transect was surveyed only once, for practical reasons, but the accuracy of the technique is known to be good.* The beach, is controlled by the Ministry of Defence, and is accessible for only short periods, and the beach gradient is such that the lower foreshore is exposed for only short periods near times of low water. These limitations necessitated that each transect be surveyed only once, and

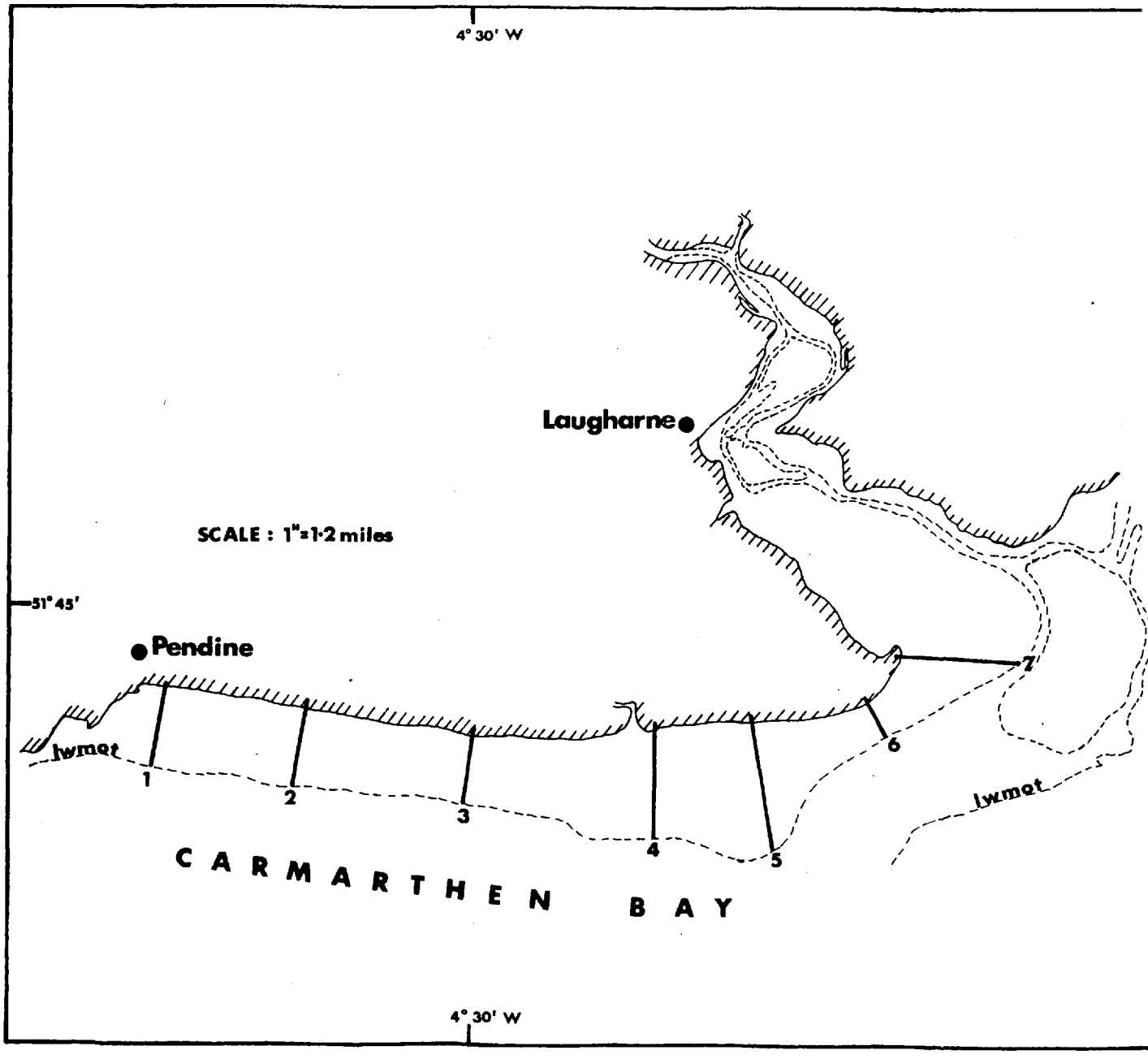


FIG. 2.1 : POSITION OF PROFILES.

that the period required to survey all transects extend over several days (it was generally possible to successfully survey four complete transects in one day). Because of the limitation on freedom of movement on the beach and/or the unpredictability of weather conditions, some surveys were terminated short of the low water mark. As far as possible, all surveys were carried out during spring tide periods.

The profiles from each survey have been constructed with a deliberate vertical exaggeration and successive profiles of each transect superimposed to show the magnitude and distribution of accretion and erosion between surveys. The volumetric changes of sand along each transect have also been examined by measuring, with a planimeter, the area subtended by the profile, using various baselines and a vertical line cutting the dune at its seaward reference pole as the confining boundaries. (Fig. 2.2(b)). The baselines used are the base of the dune (which on some profiles coincides with the high water mark of the highest tides, hwmht), the mean high water mark of spring tides (mhwmst), and four heights which have a rough correspondence to the most marked variation of textural parameters normal to the foreshore (see Chapter 5) - it should be emphasised that since the textural variation of sand across the beach is a continuous one, the division of the beach into distinct units is rather artificial, but is nevertheless useful for the purpose of

subsequent analysis. The area of each unit has been multiplied by unity to give the volume of a prism of sand of unit width. The heights of appropriate tide levels for this exercise have been derived from the tidal information for Whiteford light house, and the height of the permanent reference poles relative to O.D. have been determined by levelling them into local Bench Marks.

The advantages of microptic levelling lie in its accuracy and its provision of a continuous profile that includes local elevations and troughs. However two operators are needed for the method, one for the instrument and one for the staff. It was found that a colleague or assistant was not always available at the required quarterly intervals (so that the periods between surveys range from two to four months). Also, if all local features of the profile are to be surveyed, then the technique is rather slow. For future reference it would be useful to know whether or not it is essential to obtain the complete profile or whether sufficient information could be derived from measurement of a few permanent control points spaced across the foreshore; these could be rods driven into the sand or plates buried below it.

In order to test whether such a procedure could be adopted in future, the variations of profiles between surveys have been studied in another way. The height of each profile above an

arbitrary, but fixed, datum line has been determined at stations 100 ft. apart in a horizontal plane measured relative to the high water mark of the highest tides (hwmht) for each transect (Fig. 2.2(a)). For each profile, these horizontal stations (1, 2, 3, 4 ..... n) have been grouped into threes, each group composing a block (B1, B2, B3 ..... Bn) extending from the base of the dune to near low water. Thus for each transect, both stations and blocks are fixed in space relative to hwmht, and since hwmht is common to all transects, identically notated stations and blocks correspond for all transects. The heights of successive surveys of all profiles have therefore been measured relative to stations fixed in space.

For each station, the measured heights for successive surveys have been subtracted to provide a measurement of cut and fill between surveys, i.e. with season. These measurements give an array of data that can be manipulated statistically. It must be emphasised that this method is entirely a posteriori, and all measurements have been made on the constructed profiles.

In order to interpret the resulting data, use has been made of the analysis of variance in a two-way classification. In this analysis, for each of the seven profiles, the height changes (with season) at successive stations are related spatially for any one season, and the height changes during

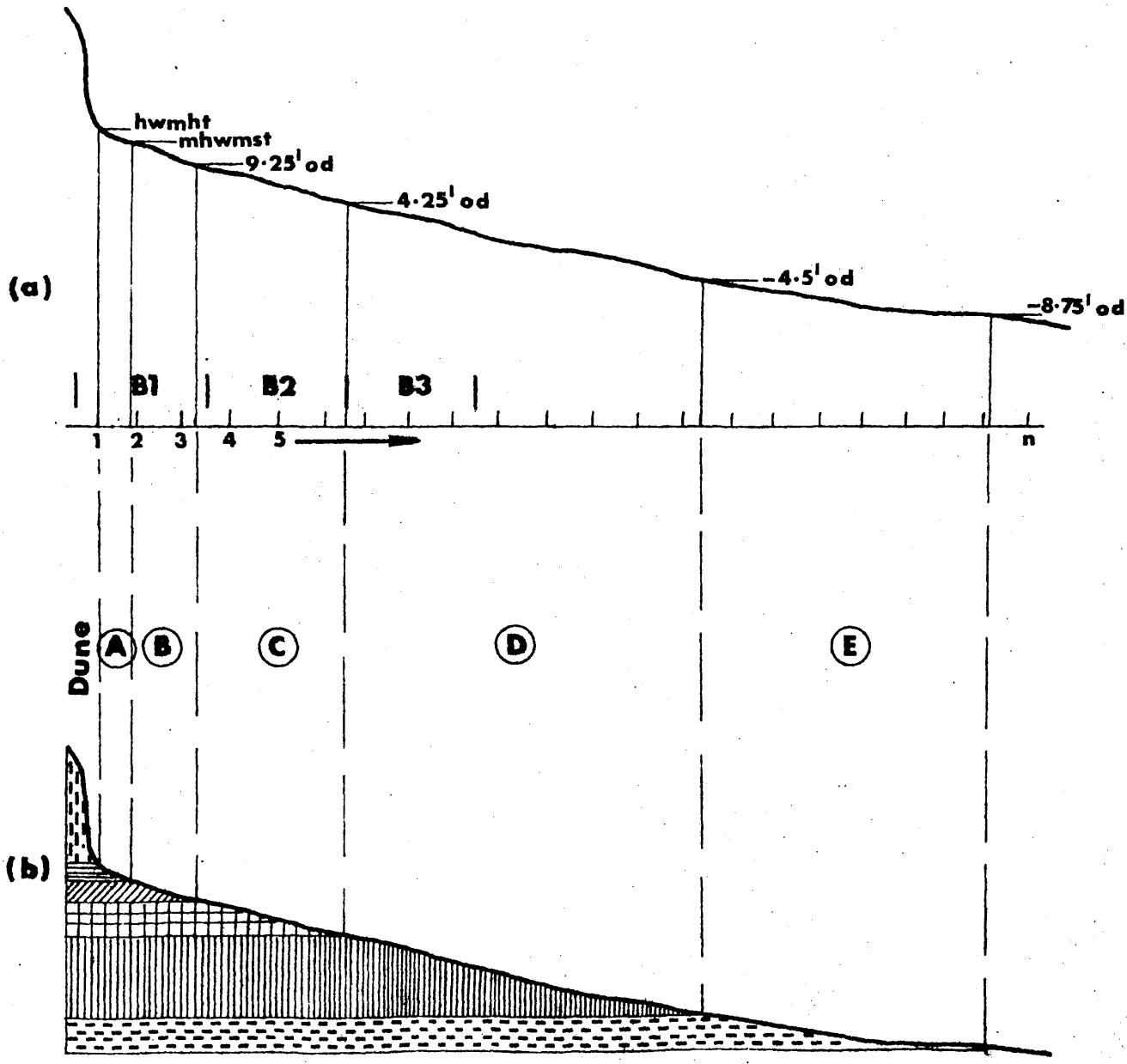


FIG. 2.2 : (a) STATISTICAL & (b) VOLUMETRIC ANALYSIS OF QUARTERLY SURVEYS.

successive seasons are related temporally for any one station. Hence each height change may be related to two factors, a fixed spatial station and a fixed temporal season; these represent the main effects studied by the analysis. This then investigates the existence of differences among class means (main effects), on both bases of classification, and the independence or association among the classifications (interaction). Thus the analysis enables variation (in this case, variation of height change) to be subdivided into two components of variation (in this case, variation with season and with position along the transect). For satisfactory results, it is advantageous if each measurement is replicated. In the field, this could easily be arranged but in such a posteriori procedure as used here, it is obviously impossible. It is to provide replication of measurement that the foreshore stations have been grouped into blocks (B1, B2 etc.), each block being composed of three stations; measurements at stations are then considered as replications within blocks. The anova (i.e. analysis of variance) then tests whether there is any variation among seasons, and among foreshore blocks, over and above the variance within the blocks (i.e. between stations), and also tests the significance of interaction between these main effects. It should be noted that the measurement used in the analysis is itself a measurement of 'variation' (change of height between

surveys) but not variance, and the analysis is therefore a study of the variance of 'variation' associated with season and foreshore position.

The two main effects may be considered as fixed, the one in space the other in time, in which case the design is Model 1, or as random, with regard to space and time, in which case the design is Model 2, or as a combination of both, in which case the design is a mixed model (Sokal and Rohlf, 1969). The significance testing and interpretation are somewhat different for these models. In a Model 1 design, since each effect is measured at a fixed level (i.e. a fixed foreshore block and a fixed season), then the analysis provides a basis for a comparison of mean values at each level i.e. between foreshore blocks (for all seasons) and between seasons (for all foreshore blocks). In a Model 2 design, each effect is measured at a random level, so that the analysis gives the proportion of variation associated with each i.e. with foreshore position and with time. Mixed models are not used here.

It is evident that the change of height at each station between surveys may be considered as either absolute (in which case all changes are positive) or relative (positive rise, negative fall). The importance of this distinction becomes clear when the mean values of each main effect are compared in a Model 1 anova. Obviously if sand is moved from one level of the

foreshore and deposited at another, the mean change is zero in terms of accretion and erosion, but it is a real change nevertheless. Therefore both relative and absolute changes are investigated here. The distinction arises because it is the change of height between surveys, and not the height at each survey, that is used as the raw data of the analysis.

A two-way analysis of variance has been carried out on the data for each of the seven profiles. Another disadvantage of the volumetric method of comparison is that it is impossible for the eye to visualise the superimposition of some 60 profiles in time and space and so to gain an overall impression. Any technique, such as the statistical one, that summarises this information into a few numbers (in this case into seven anova tables) has much to commend it and greatly assists comparisons. The added sophistication of a three-way analysis in which one anova investigates three main effects (two spatial dimensions and one time) and thus summarises the information into one small table, is not possible here because of the variable length of the transects, and the occurrence of incomplete blocks.

A necessary condition for the working of the analysis of variance is that the arrangement of the data array should be orthogonal. In this case however that condition is not upheld

* Such extrapolation is not unreasonable since, particularly on the western profiles, the lowermost foreshores tended to either accrete or erode as homogeneous units, without much difference between adjacent stations.

since some between-survey periods were two months and some four. But since the surveys were intended to reflect seasonal variation, it is assumed (at least in the initial analyses) that each survey was representative of its season and that between-survey changes are indeed representative of orthogonal seasonal changes.

For the reasons outlined earlier, some surveys were terminated short of the low water mark. In order to provide a complete data array for the analysis of variance, the average length of each surveyed profile was adopted as the basis for analysis, and any short profiles extended 100-300 feet by extrapolation.*

The raw data used in the analysis has been transformed to adhere more closely to the assumptions of the analysis of variance. The logarithmic transformation has been used throughout. Since the variates transformed include zeros (no change between surveys), the transformation log (Y + 1), where Y is the value of the variate, is used to avoid the logarithm of zero.

As described above, the Model 1 anova provides a basis for a comparison of means of change at each level of variation. The test used is the Student-Neuman-Keuls multiple range test (Sokal and Rohlf, 1969). Temporal, or spatial, means are

* The inadequacies of the technique are discussed below but may be summarised as ; i) Surveys were not equally spaced in time. ii) True replication of data was not obtained. iii) Interaction between main effects was generally high.

* For obvious reasons, the raw survey data are not reproduced here. If required, these data are of course available from the author.

ranked in order of magnitude and the ranges between them tested using a least significant range (L.S.R.), defined as:

$$\text{L.S.R. (for k groups)} = Q\alpha_{(k,v)} \times S_{\bar{y}}$$

where α = probability at p 0.05, v = degrees of freedom of error mean square, Q = critical studentised range (taken from Snedecor and Cochran, 1967), k = number of means in a group, $S_{\bar{y}}$ = standard error of group mean.

Means may then be incorporated into groups within which there is no significant difference; these homogeneous groups are notated by underlining. Means outside of such groups may be considered as unusual or exceptional.

It must be emphasised that the statistical techniques to be described below are not ideal for the analysis of this data.* The justification for their adoption is felt to be that it would be very helpful to know whether, for future reference, an experiment with similar aims could be more profitably carried out (one observer monitoring beach height at fixed stations) and the data analysed without recourse to graphical methods (which are tedious and not always convenient, particularly if a large number of profiles is available).

A more 'traditional' volumetric analysis of the data follows the statistical one.*

* Obviously, in an analysis which compares mean changes along profiles, there is a distinction between considering overall (or gross) change (i.e. stability, all changes being positive) and relative change (i.e. positive accretion plus negative erosion).

2.3 Statistical Analysis of Stability

Analyses of variance of foreshore change, in which change is considered as absolute,* no distinction being made between accretion and erosion, yield the anova tables shown in Tables 2.1 and 2.2 (all variances are in code). Each analysis has been performed on the between-survey changes for each profile. In order for between-profile comparisons to be meaningful, it is advantageous if the error variance (within blocks variance) is of the same order of magnitude in each analysis. To achieve this, some readjustments to the horizontal distance between stations have been required for profiles 4, 5 and 6. For profile 4, the error variance is about half that for profiles 1-3; by considering alternate foreshore stations only (200 feet apart) grouped in pairs, then the error variance becomes comparable to those for profiles 1-3. For profiles 5 and 6, it is necessary to decrease the between-station distance by half, again grouped into pairs, thereby doubling the number of foreshore stations (50 feet apart). The data shows that the between-station distance could preferably be further reduced along profile 5, but lies between 50 and 100 feet along profile 6, for accurate between-profile comparisons. These adjustments are not necessary for the multiple range tests.

For all anovas, it is apparent that interaction accounts

PROFILE	SOURCE OF VARIATION	df	SS	MS	MODEL 1	MODEL 2		
					F	F	VARIANCE x 10^{-3}	COMPONENT %
	Seasons	7	.1509	.02156	44.51**	14.71**	.957	54.1
	Foreshore blocks	6	.0085	.00141	2.92*	.96ns	.000	0.0
1	Interaction	42	.0616	.00147	3.03**	3.03**	.327	18.5
100 FEET	Error	112	.0543	.00048			.484	27.4
STATIONS	Total	167						
	Seasons	7	.0227	.00324	5.88**	3.33**	.126	14.5
	Foreshore blocks	5	.0106	.00213	3.86**	2.18ns	.048	5.5
2	Interaction	35	.0341	.00097	1.77*	1.77*	.141	16.3
100 FEET	Error	96	.0529	.00055			.550	63.6
STATIONS	Total	143	.1203					
	Seasons	7	.0192	.00275	6.83**	1.87ns	.061	7.3
	Foreshore blocks	6	.0116	.00194	4.81**	1.32ns	.019	2.3
3	Interaction	42	.0617	.00147	3.65**	3.65**	.356	42.4
100 FEET	Error	112	.0451	.00040			.403	48.0
STATIONS	Total	167	.1376					
	Seasons	7	.0134	.00191	8.45**	2.99**	.053	11.8
	Foreshore blocks	7	.0100	.00143	6.33**	2.25**	.033	7.4
4(1)	Interaction	49	.0313	.00064	2.82**	2.82**	.138	30.5
100 FEET	Error	128	.0290	.00023			.227	50.3
STATIONS	Total	191	.0837					
	Seasons	7	.00673	.00096	2.45*	1.58ns	.029	5.5
	Foreshore blocks	5	.00344	.00069	1.75ns	1.13ns	.005	0.9
4(2)	Interaction	35	.0213	.00061	1.55ns	1.55ns	.108	20.3
200 FEET	Error	48	.0188	.00039			.392	73.3
STATIONS	Total	95	.0503					

* = $0.05 > P > 0.01$; ** = $0.01 > P$

TABLE 2.1 : Anovas, absolute change

PROFILE	SOURCE OF VARIATION	df	SS	MS	MODEL 1	MODEL 2		
					F	F	VARIANCE x 10^{-3}	COMPONENT %
5(1) 100 FEET STATIONS	Seasons	6	.2053	.03422	6.41**	4.28**	.874	9.6
	Foreshore blocks	9	.4496	.04995	9.36**	6.25**	1.998	22.0
	Interaction	54	.4314	.00799	1.50*	1.50*	.885	9.7
	Error	140	.7469	.00533			5.335	58.7
	Total	209	1.8332					
5(2) 50 FEET STATIONS	Seasons	6	.4110	.06851	51.27**	8.10**	1.000	13.0
	Foreshore blocks	29	.9755	.03364	25.17**	3.98**	1.798	23.4
	Interaction	174	1.4718	.00846	6.33**	6.33**	3.561	46.2
	Error	210	.2806	.00134			1.340	17.4
	Total	419	3.1389					
6(1) 100 FEET STATIONS	Seasons	5	.0119	.00238	2.58*	1.90 ns	.094	8.1
	Foreshore blocks	3	.00581	.00194	2.10 ns	1.55 ns	.038	3.3
	Interaction	15	.0187	.00125	1.35 ns	1.35 ns	.109	9.4
	Error	48	.0442	.00092			.921	79.2
	Total	71	.0806					
6(2) 50 FEET STATIONS	Seasons	5	.0214	.00429	38.90**	2.94*	.118	12.3
	Foreshore blocks	11	.0234	.00213	19.30**	1.46 ns	.056	5.8
	Interaction	55	.0803	.00146	13.25**	13.25**	.676	70.4
	Error	72	.00794	.00011			.110	11.5
	Total	143						
7 100 FEET STATIONS	Seasons	7	.0952	.01359	23.24**	2.46*	.269	7.5
	Foreshore blocks	9	.2901	.03224	55.10**	5.84**	1.113	30.8
	Interaction	63	.3479	.00552	9.44**	9.44**	1.646	45.5
	Error	160	.0936	.00059			.585	16.2
	Total	239	.8268					

* = $0.05 > P > 0.01$; ** = $0.01 > P$

TABLE 2.2 : Anovas, absolute change

for a large proportion of total variation. This must derive from the fact that the trends of variation along successive surveys of a transect are not the same, so that the effect of one main factor (seasons) is dependent on the level of the other (foreshore blocks). Such a degree of association between main effects must be taken into account in the interpretation of the relative significances of these main effects. In order to compare variations across the foreshore, seasons should be taken individually, or to compare variations among seasons, each foreshore block must be taken one at a time. However, despite these limitations, the analysis provides sufficient information to enable the relative effects of temporal and spatial variation to be further dissected:

The interaction variances (MS) for profiles 1-4 are of a comparable order of magnitude, and so these four profiles may be readily compared with each other. Using Model 2 criteria, profiles 1-3 show a significant component of variation with time; the variance associated with time decreases in magnitude progressively from profile 1 to profile 4; the corresponding variance components also decrease in value, and in proportion of total variance, progressively from profile 1 to profile 4 (see Table 2.1). We may therefore conclude that, during the study period, there was an increase of stability along the

* It is assumed that the observed changes were representative of true seasonal changes. The weaknesses of this assumption are discussed later. Strictly, the data of profile 1 is more variable than the data of profile 4 - this need not necessarily mean that profile 1 was in fact less stable than profile 4 throughout the period of study.

foreshore from profile 1 (least stable) to profile 4 (most stable).* This is, in part, due to the greater width of foreshore at transect 4, so that identical volumetric changes of sand level at transects 1 and 4 produce a smaller mean change on profile 4 than on profile 1. However, transects 1-3 are of similar length and so the stability gradient, increasing from west to east, is a real one.

Between-profile comparisons for profiles 5-7 are less straightforward because of the fluctuating values of the error and interaction variances. The interaction mean squares are greater in value on these three profiles than on the previous four. On the eastern profiles, therefore, there is a diminished tendency for different levels of the foreshore to respond similarly with time. All three profiles show an important component of variation with time, the seasonal variance being greatest for profiles 5 and 7. It is apparent from the anova tables that of the seven profiles, profiles 1, 5 and 7 have the most important temporal components of variation. Thus the least stable profiles are those of the western and eastern extremities of the beach, and of its central portion where the shoreline alters its orientation (see Fig. 2.1).

With a Model 1 anova, all profiles show a significant or highly significant added variance among seasons, most particularly profiles 1, 5 and 7 (care must be taken when comparing

mean squares for profiles 5 and 6). From a Model 1 anova, the analysis may be extended using a range test which incorporates, for each profile, seasonal means into groups within which there is no significant difference ($P < .05$). These groups are shown diagrammatically by underlining. The test is performed on data from the original array for each profile (100 ft. stations); all mean values have here been decoded into feet and represent the mean seasonal change in height of all foreshore stations. Notation is thus: A68, spring 1968; B68, summer 1968; C69, autumn 1969; D69, winter 1969; etc.

(1)	C68	D68	B69	A68	A69	C69	D69	B68
	.13	.13	.17	.17	.19	.24	.35	.78
(2)	D68	B69	A69	D69	C68	C69	B68	A68
	.14	.15	.17	.18	.22	.28	.32	.37
(3)	C68	D68	A68	C69	B69	A69	D69	B68
	.13	.17	.19	.20	.21	.25	.33	.36
(4)	C69	C68	B68	A69	D69	B69	D68	A68
	.10	.13	.13	.13	.15	.15	.23	.25
(5)	B69	A69	A68	C69	B68	C68	D68	
	.18	.28	.35	.43	.53	.63	.88	
(6)	B68	B69	A68	A69	C69	D69		
	.18	.23	.25	.35	.35	.40		
(7)	A69	B69	C68	A68	B68	D68	C69	D69
	.15	.28	.30	.30	.33	.43	.48	.60

It is apparent that the order of means and composition of

groups are not the same for all profiles. This would imply that if there is a seasonal, or cyclic, variation of stability then it cannot apply to the whole foreshore. Each profile may have its own cycle of variation, depending on foreshore morphology and offshore bathymetry and their resultant effect on currents and waves. However, the orders of means for some profiles do have certain common elements. For profiles 1-3, summer 1968 was significantly unstable; for 2 and 4 spring 1968, for 4 and 5 winter 1968, and for 1,3,6 and 7 winter 1969, were significantly unstable. Of all seasons, only spring 1969 for profile 7 was significantly more stable than average. The possible correlation of seasonal variations of beach change to seasonal meteorological changes will be examined subsequently, but it is clear from this analysis that there is no seasonal cycle common to all profiles, or common to 1968 and 1969. Changes in height between surveys have been uniform for all periods with a few exceptions which may be related to unusual meteorological conditions, or to shortcomings in the timing of surveys (this latter possibility is also considered in a subsequent section).

The spatial variation of foreshore change is of varying significance for the seven profiles. Considered as Model 2, the anovas show that this spatial variance component is

significant for profiles 5 and 7 only, reflecting the presence of a variable beach runnel on the former and the variable River Taf channel on the latter. For profiles 1-4 and 6, the variation of change among foreshore blocks is 5% or less of the total variation, compared with 22% and 30% for profiles 5 and 7. Hence beach change across the former profiles is relatively uniform from the base of the dunes to low-water mark. Considered as Model 1, there is a significant or highly significant added effect among foreshore blocks for most profiles, excepting 4 (200 feet stations) and 6. The disparity for some profiles between a Model 1 and Model 2 interpretation is due to the influence of interaction between main effects; the main effect mean squares carry an interaction factor in a Model 2 anova, but not in a Model 1 anova. Using a range test to compare means of change within foreshore blocks provides the following arrangement (means are decoded into feet).

(1)	B2	B1	B5	B4	B3	B6	B7	
	.19	.24	.24	.27	.27	.31	.34	
(2)	B5	B6	B4	B2	B3	B1		
	.15	.17	.22	.26	.27	.30		
(3)	B6	B2	B7	B3	B4	B5	B1	
	.15	.17	.20	.21	.24	.26	.35	
(4)	B2	B5	B3	B7	B4	B6	B1	B8
	.10	.10	.13	.15	.18	.18	.20	.23

(5)	B1	B2	B3	B4	B10	B9	B5	B8	B7	B6
	.20	.20	.20	.25	.28	.35	.40	.75	.90	1.18
(6)	B3	B1	B2	B4						
	.28	.30	.33	.35						
(7)	B1	B6	B5	B3	B4	B2	B7	B8	B9	B10
	.18	.18	.18	.20	.20	.23	.33	.70	.70	.78

Each test has been carried out using data from foreshore stations 100 feet apart. For profiles 1-4 and 6, the differences in change between adjacent blocks are small so that changes may be considered as essentially uniform across the foreshore of each transect. On profile 1, there is a tendency for the lower foreshore to be more unstable than the upper, but on profile 2 there is a tendency for the converse. On profile 3 change is uniform with the upper foreshore the most unstable; on profile 4 both upper and lower foreshores are marginally more unstable than the rest of the foreshore. On profiles 5 and 7, there are two significantly different groups; along the former the blocks corresponding to runnel development are most unstable and along the latter, the lower foreshore near the River Taf channel is most unstable.

These differences across the foreshore at each transect can be examined in greater detail by comparing the means of change at each station. In order, these are:

(1) 2 4 6 3 14 13 5 11 7 9 12 19 18 8 10 16 15
17 20 21 1

(2) 16 14 15 13 6 7 17 11 12 3 18 5 10 9 2 8 4 1

(3) 5 17 18 16 19 20 6 8 9 2 12 4 7 11 13 15 21
10 3 14 1

(4) 4 14 13 5 15 3 6 9 20 12 7 8 21 17 10 19 16
23 18 22 11 1 2 24

(5) 2 4 8 3 5 9 28 6 10 7 1 11 29 12 27 13 14 26
30 25 17 15 24 22 21 20 23 19 18 16

(6) 8 3 7 6 10 4 2 9 5 11 1 12

(7) 15 2 16 3 14 19 6 10 8 17 7 9 11 18 5 1 12 20
4 13 21 22 27 23 26 28 29 24 25 30

For simplicity the numerical values of means are not shown. For profile 6, the stations are 50 feet apart, to increase the sensitivity of the test. A common feature of the arrangements for profiles 1-4 is the occurrence of the mean for station 1, the uppermost station, at or near the head of each series. Hence the foreshore tends to be most unstable at the limits of the highest spring times, where aeolian activity is generally dominant. Otherwise the means across these profiles are essentially homogeneous. As already noted, profile 5 is most variable

in the region of a migrating runnel within the middle foreshore, and profile 7 on the lower foreshore near the river channel. Along profile 6 both the uppermost foreshore (aeolian activity) and the lower (near the river channel) tend to be more variable than the rest of the foreshore.

Thus it may be concluded from this analysis that although the effect of seasonal variation of beach change is closely associated with variation across the foreshore for each transect, particularly for transects 5 and 7, several trends of variation may be recognised. Temporal variations of stability are markedly greater along profiles 1, 5 and 7; however, these variations do not appear to correspond with any common cycle, seasonal or otherwise. Spatial variations of stability, considered among blocks spaced along each profile, are most pronounced for profiles 5 and 7, and these may be related to morphological features of these profiles. For other profiles, mean change has been relatively uniform from the upper to the lower beach, with the exception of those parts of the foreshore (or backshore) which are above the range of most tides, and most exposed to aeolian action; on these parts, mean change is markedly greater.

Between-profile comparisons show that there is a trend of increasing stability from Pendine, in the west, eastwards to

the central part of the beach. At that point, however, the trend is halted, and the eastern part of the beach is generally less stable than its western part; this is because of the development of variable surface features on profile 5, and the influence of the Taf channel on profile 7. It would appear that the eastern part of the beach (Laugharne Sands) is strongly influenced by the estuarine complex and offshore sandbars.

2.4 Statistical Analysis of Accretion and Erosion

Analyses of variance of foreshore change, in which change is considered as relative in terms of accretion and erosion, yield the anova tables shown in Tables 2.3 and 2.4 (variances are given in code). The error variance is of the same order of magnitude for the anovas of profiles 1, 2, 3, 6 and 7, so variances may be directly compared. The error variance for profile 4 is again less than for other profiles, so that the variation of accretion and erosion within foreshore blocks is more homogeneous along this profile than the others. Spreading of the foreshore stations to 200 feet apart does not much alter the error variance. The error variance for profile 5 is significantly greater than for any other profile; however, closer grouping of stations to 50 feet does not aid comparison because of the incidence of a few stations with very large between-

PROFILE	SOURCE OF VARIATION	df	SS	MS	MODEL 1	MODEL 2		
					F	F	VARIANCE x 10^{-3}	COMPONENT %
	Seasons	7	.6071	.08672	74.10**	17.44**	3.893	61.5
	Foreshore blocks	6	.0047	.00078	.67ns	.14ns	.000	0.0
1	Interaction	42	.2088	.00497	4.25**	4.25**	1.267	20.0
100 FEET	Error	112	.1311	.00117			1.170	18.5
STATIONS	Total	167	.9517					
	Seasons	7	.1754	.02506	14.54**	9.43**	1.245	38.0
	Foreshore blocks	5	.0087	.00173	1.01ns	.64ns	.000	0.0
2	Interaction	35	.0928	.00265	1.53ns	1.53ns	.309	9.4
100 FEET	Error	96	.1655	.00172			1.724	52.6
STATIONS	Total	143	.4424					
	Seasons	7	.1288	.01840	13.56**	2.99*	.584	16.5
	Foreshore blocks	6	.0040	.00067	49ns	.10ns	.000	0.0
3	Interaction	42	.2583	.00615	4.53**	4.53**	1.598	45.1
100 FEET	Error	112	.1520	.00136			1.357	38.4
STATIONS	Total	167	.5431					
	Seasons	7	.0820	.01172	22.86**	6.29**	.411	30.0
	Foreshore blocks	7	.0073	.00104	2.02ns	.54ns	.000	0.0
4(1)	Interaction	49	.0910	.00186	3.62**	3.62**	.448	32.6
100 FEET	Error	128	.0656	.00051			.512	37.4
STATIONS	Total	191	.2459					
	Seasons	7	.0495	.00707	10.53**	4.50**	.458	29.0
	Foreshore blocks	5	.0039	.00079	1.17ns	.50ns	.000	0.0
4(2)	Interaction	35	.0550	.00157	2.34**	2.34**	.450	28.5
200 FEET	Error	48	.0322	.00067			1.578	42.5
STATIONS	Total	95	.1406					

* = $0.05 > P > 0.01$; ** = $0.01 > P$

TABLE 2.3 : Anovas, relative change

PROFILE	SOURCE OF VARIATION	df	SS	MS	MODEL 1	MODEL 2		
					F	F	VARIANCE x 10^{-3}	COMPONENT %
	Seasons	6	.5041	.08400	2.54*	1.13ns	.322	0.7
	Foreshore blocks	9	.3651	.04057	1.23ns	.55ns	.000	0.0
5(1)	Interaction	54	4.0141	.07433	2.25**	2.25**	13.772	29.2
100 FEET	Error	140	4.6225	.03302			33.018	70.1
STATIONS	Total	209	9.5058					
	Seasons	6	.0413	.00688	12.60**	1.42ns	.032	1.2
	Foreshore blocks	31	.0442	.00143	2.61**	.29ns	.000	0.0
5(2)	Interaction	186	.9037	.00486	8.90**	8.90**	2.156	78.8
50 FEET	Error	224	.1223	.00055			.546	20.0
STATIONS	Total	447	1.1115					
	Seasons	5	.0564	.01128	6.34**	1.44ns	.287	7.0
	Foreshore blocks	3	.0226	.00753	4.23**	.96ns	.000	0.0
6	Interaction	15	.1176	.00784	4.40**	4.40**	2.020	49.4
100 FEET	Error	48	.0855	.00178			1.780	43.6
STATIONS	Total	71	.2821					
	Seasons	7	.9480	.13543	56.50**	4.35**	3.476	17.5
	Foreshore blocks	9	1.2287	.13652	56.96**	4.38**	4.390	22.1
7	Interaction	63	1.9622	.03115	12.99**	12.99**	9.583	48.3
100 FEET	Error	160	.3835	.00240			2.396	12.1
STATIONS	Total	239	4.5224					

* = $0.05 > P > 0.01$; ** = $0.01 > P$

TABLE 2.4 : Anovas, relative change

survey erosion which necessitated a new coding for the data (thus for anova 5(2) the code is $x = \log (x + 3)$); hence the mean squares of this anova cannot be related to others.

For all anovas, the error variance is greater when foreshore change is considered in relative rather than absolute terms. Hence there is a degree of differentiation into accretion and erosion even within blocks i.e. 300 feet lengths of profile. So relative changes between surveys of adjacent sections of profiles are not necessarily the same in sense and may be contrary. Such fluctuations of cut and fill along profiles must reflect the variable parameters of waves and currents during the flood and ebb of the tides.

Interaction between the main effects is again very significant, the interaction variances also being of greater magnitude when accretion and erosion are differentiated. This would be expected from the nature of interaction and the increased error variance. However, apart from profiles 5 and 6, the proportion of variation attributable to interaction is no greater than before.

This is because the among seasons variance is correspondingly inflated. For most Model 2 anovas, there is a highly significant temporal component of variation. From profile 1 to profile 4, this variance component decreases in magnitude

(though not in proportion, because of interaction), corresponding to a similar gradient in the temporal component of absolute change. The variance component is even smaller for profile 5, but this profile occurs within foreshore blocks and in interaction; these mean squares are not comparable to those in other anovas. Though the error variance is of a comparable order of magnitude for profile 6, most variation also occurs within blocks or as interaction; the temporal variance component is relatively small. For profile 7, with a comparable error variance, the temporal variance component is much increased in magnitude. These results are generally in accord with those of the previous analysis. However this analysis is not particularly suitable for treatment of data from profile 5 in which there is a considerable lack of uniformity in response at different levels of the foreshore at various times.

Nevertheless, this analysis does provide a basis for a comparison of seasonal means which differs in interpretation from the previous one. Considered as Model 1, all profiles have a highly significant among seasons component of variation over and above the parametric variation within blocks, particularly profiles 1 and 7. In order of magnitude, and composed into groups in which there is no significant difference, these are for each profile:

(1)	B68	C69	B69	A69	C68	D68	A68	D69
	-.78	-.22	-.06	.02	.10	.12	.13	.21
(2)	A68	B68	C69	D69	A69	D68	B69	C68
	-.37	-.33	-.28	-.20	-.07	-.01	.15	.17
(3)	B68	A68	D68	C69	C68	B69	D69	A69
	-.33	.05	.05	.08	.10	.10	.13	.20
(4)	A68	C69	B68	C68	A69	B69	D69	D68
	-.23	-.03	-.03	-.03	.03	.05	.10	.20
(5)	B68	C69	A68	C68	B69	A69	D68	
	-.43	-.30	-.25	-.22	-.11	.06	.08	
(6)	A69	C69	D69	A68	B68	B69		
	-.30	-.15	-.10	.05	.10	.18		
(7)	D68	D69	C69	B68	A69	B69	A68	C68
	-.63	-.62	-.45	-.35	.06	.10	.14	.29

It is apparent that, in quantitative terms, all profiles have significant groups of heterogeneous means; these indicate essentially uniform temporal changes. Those means outside of such groups must then be indicative of periods of exceptional variation. Such periods of exceptional net erosion or accretion may be compared with similarly designated exceptional periods of overall instability from the previous analysis. Of these, four seasons were unstable and erosional on one, or more, profiles - spring and summer 1968, winter 1968 and winter 1969; at these times therefore, there was a net loss of sand from some profiles. Only one season, winter 1968, was unstable and

accreting, when there was a net gain of sand on some profiles. Two seasons, autumn and winter 1969, were on some profiles unstable but steady in terms of erosion and accretion; on these, then, sand was moved from one part of the profile and deposited on another. It is evident that a few seasons, common to several profiles, reflect the onset of exceptional variation. But these variations do not appear to be biased towards any particular seasonal cycle. Hence, while significantly large variations do occur at some times of the year, these would appear to be related to randomly occurring periods of abnormal meteorological activity, and not to regular and rhythmic seasonal fluctuations of meteorological activity. Such large variations usually have resulted in a net gain or loss of sand from the profile rather than a redistribution along it.

The spatial variation of accretion and erosion is significant for profiles 5, 6 and 7 only (with 50 feet stations along profile 5). Hence, on these profiles, there is a significant added effect due to foreshore position over and above the variation within blocks. This effect is most pronounced on profile 7. The decoded block means for these profiles are, in order of magnitude:

(5)

B16	B15	B23	B12	B24	B11	B13	B10
-.83	-.43	-.35	-.30	-.25	-.25	-.25	-.25

B9	B30	B25	B26	B27	B14	B31	B32
-.20	-.20	-.18	-.15	-.15	-.15	-.15	-.15

B29	B8	B21	B28	B7	B6	B5	B17
-.15	-.15	-.15	-.13	-.13	-.13	-.10	-.08

B4	B3	B22	B1	B2	B19	B18	B20
-.08	-.08	-.03	-.03	-.03	.03	.03	.13

(6)

B4	B3	B2	B1
-.15	-.13	-.01	.13

(7)

B10	B9	B8	B7	B4	B5	B3	B2
-.85	-.78	-.52	-.19	.00	.02	.03	.05

B1	B6
.05	.06

Mean erosion has been dominant along most of profile 5; only a short section on the middle foreshore has a mean accretion, the result of runnel migration. For the same reason adjacent sections show maximum erosion. Apart from this area of runnel development, the upper foreshore has an overall erosion of smaller magnitude than the lower foreshore. Mean erosion has also been dominant along profile 6, particularly on the lower foreshore, but the upper foreshore has an overall accretion.

The most significant variations of accretion and erosion across the foreshore occur on profile 7. Most of the profile, the upper portion, has been relatively stable with a small mean

accretion. On the lower foreshore, near the transition with the river channel, there has been a substantial mean erosion.

Because of the close spacing of the paired stations along profile 5, there is little point in further differentiating variation along the profile. However, for profiles 6 and 7 the variation can be examined in greater detail by comparing means at successive stations:

(6) 12 9 11 8 10 7 6 5 3 4 2 1

(7) 30 29 28 25 26 27 24 23 22 21 1 20 12

13 11 10 7 6 14 9 8 15 16 5 17 19

18 4 2 3

For simplicity, numerical values are not shown. Along profile 6, the means are not differentiated by the range test except for the lowest station, which shows a maximum mean erosion, reflecting the proximity of the river channel. Similarly along profile 7, those stations near the river channel are characterised by maximum erosion, and those near the upper foreshore by a smaller net accretion. The correspondence between range tests for both blocks and stations demonstrates that the variations mean cut and fill along the profile are relatively uniform; the only exception is the small mean erosion at station 1 of profile 7 compared with a small mean accretion at

adjacent stations, but these differences are not significant.

It may be concluded from this analysis that all profiles have a significant added variation of accretion and erosion associated with season, most particularly profiles 1 and 7 at the western and eastern extremities of the beach. This variation appears to be random rather than regularly seasonal. The variations of accretion and erosion across the foreshore are not significant along profiles 1-4, so these may be considered as responding to change as essentially homogeneous units (although interaction must be taken into account, see below). On profiles 5-7 there is some spatial differentiation, the most significant erosion occurring on the lower foreshore near the River Taf channel for all three, and on the middle foreshore of runnel migration for profile 5. On profiles 6 and 7 there has been some net accretion on the upper foreshore, probably resulting from aeolian action.

Several conclusions can be drawn from the foregoing analyses: The beach can be conveniently divided into two components on the basis of the studied profile changes; a western component (Pendine Sands), comprising profiles 1-4, with a near east-west orientation of the shoreline; an eastern component (Laugharne Sands), comprising profiles 5-7, with a marked change of shoreline orientation, this bending to the north-east to Ginst Point and the mouth of the estuary.

Pendine Sands are linked to a gently sloping, shallow-water offshore zone (see Chapter 1), which is probably stable in its overall configuration. This part of the beach showed, during the study period, a marked trend of increasing stability from west to east. This may be due to wave refraction and eddy effects associated with the headlands at Pendine, or may be related to variations of offshore slope; the bottom gradient normal to the shoreline declines from west to east in this area (see Chapter 1), and so, because of bottom friction, large waves transmit less energy to the foreshore in the east (profile 4) than in the west (profile 1). The western portion of Pendine Sands is thus more susceptible to the effects of storms, and so is less stable, than the eastern portion. The decreasing offshore slope from west to east reflects, perhaps, the effects of wave refraction, and/or a progressive movement of sand from west to east in the offshore zone in response to a possible residual tidal motion or westerly meteorological processes.

The latter processes, in conjunction with estuarine discharge, have produced a marked change of offshore bathymetry in the north-eastern part of Carmarthen Bay. This change is reflected on the foreshore which constitutes Laugharne Sands. Offshore bathymetry is more complex than in the west,

* It should perhaps be pointed out that these conclusions are based on field observations.

consisting of sandbanks and deep-water channels, and is less stable. The Taf channel forms the seaward limit of profiles 5-7; it is the variability of the position of this channel which leads to foreshore instability. This is partly because of undercutting of the lower foreshore, but also because the occurrence of a nearshore deep-water channel periodically enables large waves to break onto the foreshore without first producing a wide surf zone (such waves must first break offshore on the shoals, but they can subsequently reform in the channel).* Variations of foreshore profiles must also reflect a surfeit of sand in the variable offshore zone.

It has been shown that interaction between main effects has been of some importance. Because of this, the above discussion has been concerned with gross variations of profiles, rather than in detail. Important information has been obtained from a few points, generally 100 feet apart, across the transects. The complexities arising from interaction show that for detailed changes to be examined the transects must be surveyed more frequently (in conjunction with wave measurements). By monitoring a few stations along each transect, frequent measurements become practicable, and the important information could be obtained relatively easily. The occurrence of interaction demonstrates that there is little point in detailed

surveying of transects at widely spaced intervals of time, because variations within the profile are almost as important as variations among successive surveys. The importance of interaction is shown pictorially in Figs. 2.8, 2.10, 2.12, 2.14, 2.16, 2.18 and 2.20, in which successive surveys of each transect have been superimposed to indicate zones of accretion and erosion. With the limited data at our disposal, we can only consider the fluctuations in the trend of variation along each profile between surveys as 'random' deviations from a mean. These could become meaningful only if surveys were carried out with some frequency, and with the necessary 'hydrodynamic' control of wave and meteorological observations.

Finally, it must be emphasised that, because of interaction, the analysis of variance is not really suitable for dealing with this data. Nevertheless, some important points have come out of the analysis, some relevent to the present study (and these are pursued in subsequent sections), and some important for future studies.

2.5 Correlation of Profile Variation and Periodic Meteorological Input

From the foregoing analyses it would appear that there are no seasonal changes of beach height which have taken place on

all profiles during the two years of surveying. Between-survey changes are sometimes random in sense but more often constitute runs (i.e. periods) of accretion or erosion that are maintained over three or more successive surveys; of these the extended periods on profiles 3, 4 and 5 are the most developed. However, the sequences of changes measured during the period of study do not describe cycles that can be easily attributed to seasonal variation.

These changes are summarised in Table 2.5(a), where they are categorised into three groups - prevailing, overall and greatest. Prevalent change reflects the predominance of either positive or negative seasonal means; overall change their average magnitudes (all data are in feet). The greatest changes, both relative and absolute, are derived from the range tests on Model 1 anovas. Sequences of changes have also been differentiated into runs of positive or negative means of various lengths, the surplus representing random single means of either sense (there are eight between-survey means for all profiles except profiles 5 and 6 which have seven and six means respectively).

In 1968, a mean erosion occurred along all profiles with the exception of profile 6; similarly in 1969, with the exceptions of profiles 3 and 4. The overall change for both

PROFILE	RUNS	PREVALENT	RELATIVE CHANGE					ABSOLUTE CHANGE			
			OVERALL			GREATEST		OVERALL			GREATEST
			1968	1969	1968-70	A	E	1968	1969	1968-70	
1	1 x 3; 1 x 2	A	-.11	-.01	-.12		B68, C69	.30	.24	.54	B68, D69
2	3 x 2	E	-.14	-.10	-.24		A68, B68	.26	.20	.46	A68
3	1 x 6	A	-.01	+.05	+.04		B68	.21	.25	.46	B68, D69
4	2 x 3	S	-.02	+.04	+.02	D68	A68	.19	.13	.32	A68, D68
5	1 x 3; 2 x 2	E	-.21	-.12	-.33		B68	.60	.30	.90	D68
6	1 x 2	S	+.08	-.09	-.01		A69	.22	.33	.55	D69
7	2 x 2	E	-.14	-.26	-.40		D68, D69	.34	.38	.72	D69
TOTAL	3 x 2	E	-.10	-.08	-.18		B68	.33	.27	.60	B68

A = accretion E = erosion S = stable

TABLE 2.5(a) : Summary of mean changes (ft)

years was therefore a negative one. The greatest relative changes on all profiles were invariably erosional. Hence, on most profiles, the dominant change has been of erosion during the period of study; only profiles 3 and 4 show a small mean accretion. The mean net erosion for the total beach (i.e. all profiles, allowance being made for the different lengths of the transects) was greater for 1968 than 1969, and the first year was accompanied by greater instability than was the second.

The foregoing discussion (and analyses in the preceding section) have been concerned with mean height variations. Since the beach transects vary in length, this may give a misleading picture of the comparative volumetric changes on all seven transects. Accordingly, in Table 2.5(b), overall changes of profiles, in cubic feet, have been computed from the mean overall change (x the number of stations x the distance between stations x 1); these changes then represent, in a statistical rather than absolute manner, the volumetric changes of sand on a unit width of foreshore along each transect. This table also indicates that during 1968 the profiles were some 20% more unstable than during 1969, losing nearly 4,000 cubic feet of sand during the total study period. The comparative instabilities of profiles 5 and 7, and to a lesser degree, profile 1 are clearly shown in this table.

TABLE 2.5(b) : Summary of overall volumetric changes (ft^3)

PROFILE	OVERALL RELATIVE CHANGE			OVERALL ABSOLUTE CHANGE		
	1968	1969	1968-1970	1968	1969	1968-70
1	-231	-21	-254	630	504	1134
2	-252	-18	-270	468	360	828
3	-21	+105	+84	441	525	966
4	-48	+96	+48	456	312	768
5	-630	-360	-990	1800	900	2700
6	+96	-108	-12	264	396	660
7	-420	-780	-1200	1020	1140	2160
TOTAL	-1506	-1248	-3754	5079	4137	9216

The prevailing change was of accretion on two profiles (1 and 3), erosion on three (2, 5 and 7) and stability on two (4 and 6). For the total beach (all profiles) the prevailing change was erosional. Sequences (runs) of accretion and erosion are present but do not readily correlate with temporal rhythms, either seasonal or annual.

There are several possible reasons for an apparent randomness in profile response.

It has been shown that the geometry of the beach sand body is variable, so that the beach environment is a dynamic one, changes of beach level occurring in response to fluctuations of nearshore wave and current parameters, initiated by a changing

* Longshore drift from the west of Pendine Sands cannot occur because of the prominent headland of Ragwen Point - in any case, the beaches immediately to the west are made up predominantly of gravel, not sand.

meteorological input. The temperate climate of the British Isles is obviously a seasonal one, and the beach environment should reflect this. This presupposes that the present day hydrodynamic regime is at an energy level sufficiently high to entrain and transport beach sand. However, since changes do occur, they must be a reflection of shifts in dynamic equilibria between the beach and its environment, unless they result from surveying error.

Profile changes could alternatively indicate a varying sediment input. The only possible sources of sediment are the dunes backing the foreshore, local rivers, and the offshore zone of Carmarthen Bay.* However, any changes brought about by a fresh input of sediment must themselves be controlled by meteorological agents. As the predominant changes have been erosional, fluctuations in sediment input cannot, in any case, be a controlling factor.

A tidal agency can, for the moment, be ignored since eight out of nine surveys were arranged to coincide with spring tides.

It is possible that the period 1968-70 was unusually unsteady, so that normal seasonal variations were effectively masked. This possibility is best examined by recourse to a study of the appropriate meteorological conditions for this period. Unfortunately, no measurements of wave characteristics

* Wave refraction diagrams would obviously be helpful in this context. They have not been attempted because the overall bathymetry of the offshore zone is unknown and unstable. The configuration of shoals and bars shown in Fig. 1.0b (on page 3.1) is taken from the Admiralty Chart and is not representative of the situation during the period of study.

were attempted simultaneously with surveying. Wind and wave data have, however, been obtained from the St. Gowan light-vessel which is anchored some 6 miles off the Pembrokeshire coast, about 25 miles from Pendine. Wind strengths and directions are likely to differ somewhat near the coastline, but these differences are not considered important. Wave parameters recorded in deep water are of course not the same as those for shallow water, but are directly related.*

Vector diagrams for each between-survey period have been prepared for wind speed (Fig. 2.3), deep-water wave height (Fig. 2.4) and deep-water wave period (Fig. 2.5). The differences in numbers of observations (taken at 0600 and 1500 hours GMT) per diagram reflect the varying lengths of the between-survey periods.

The influence of wind on water movements operates through the generation of drift and mass transport currents, longshore and rip currents, and exceptional storm surge currents. The elements of wave properties known to modify beach morphology are wave period and wave steepness (King, 1953). However, it has been shown by Lafond (1939) that wave height itself is a critical factor in determining beach morphology, and so this parameter and wave period have been used in the following analyses. The available data does not warrant the computation

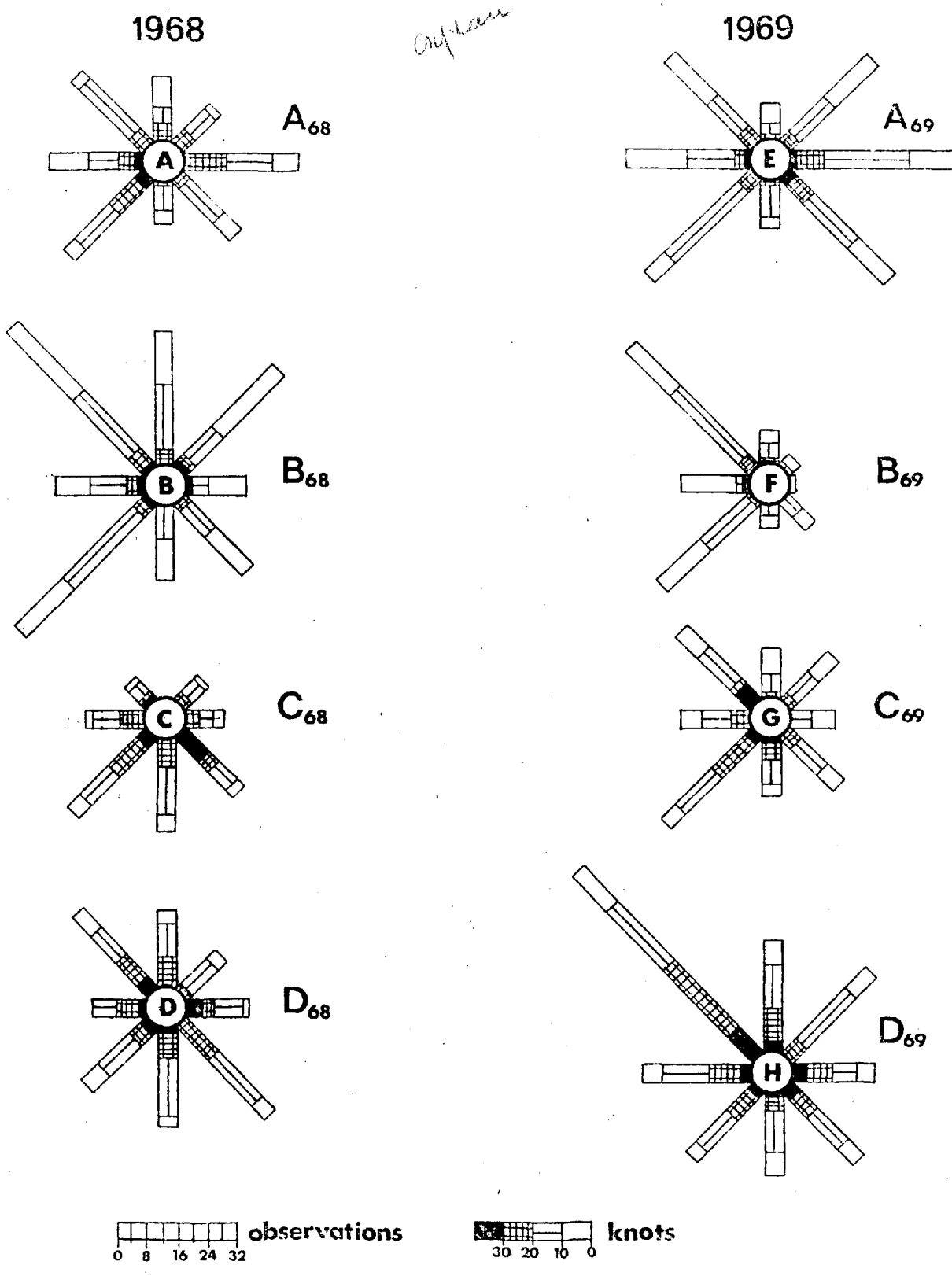


FIG. 2. 3 : WIND VECTORS BETWEEN SURVEYS.

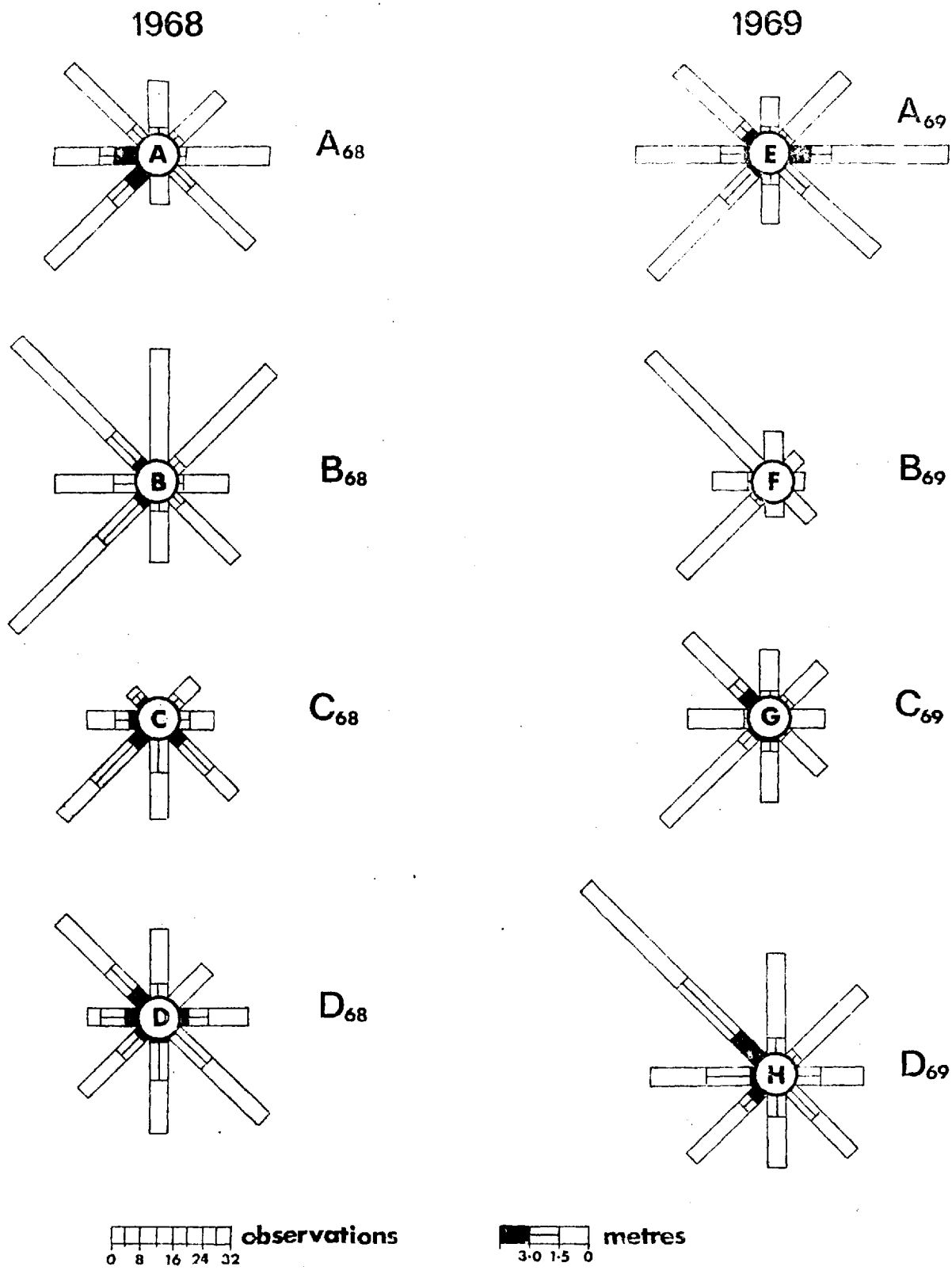


FIG. 2, 4 : WAVE HEIGHT VECTORS BETWEEN SURVEYS.

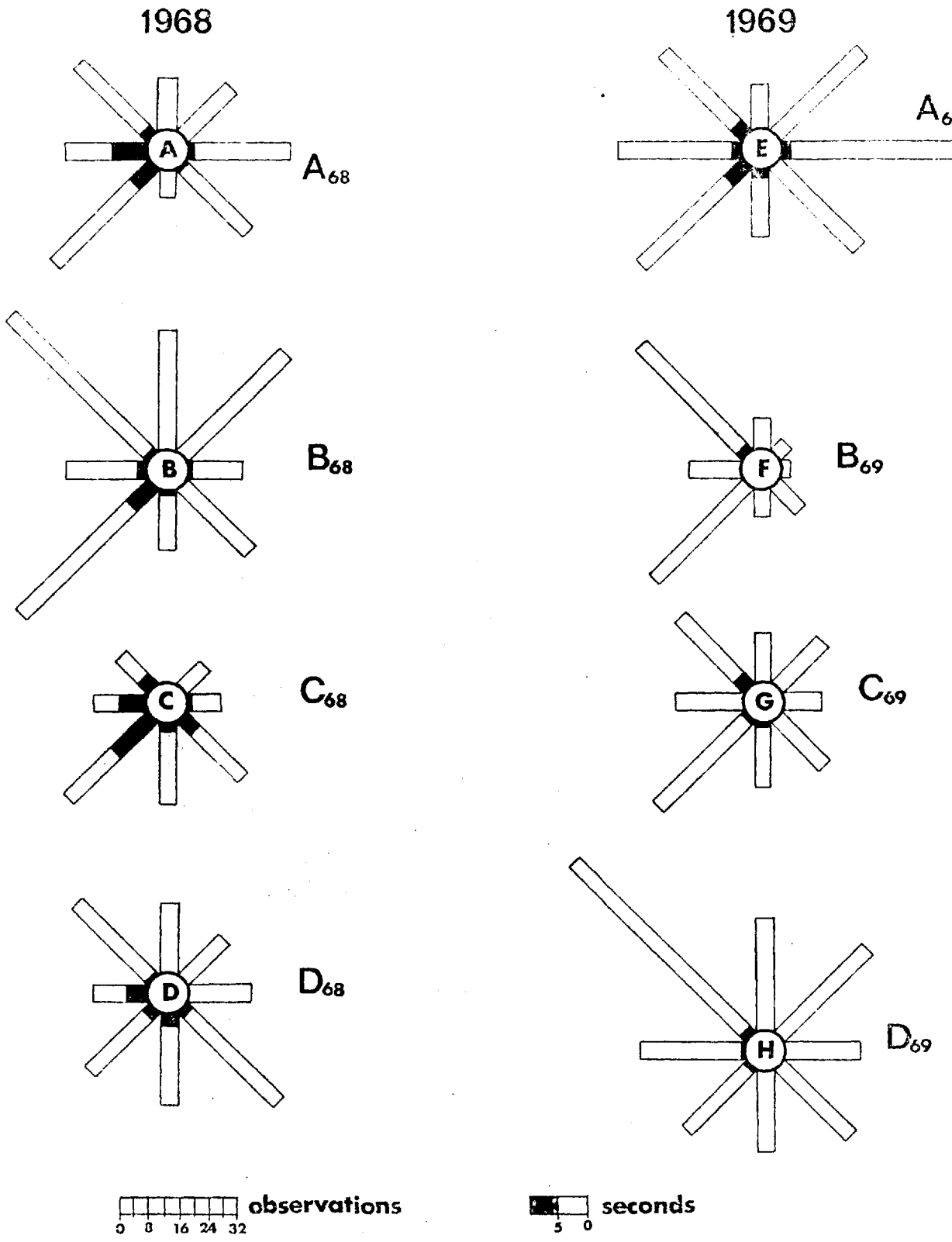


FIG. 2. 5 : WAVE PERIOD VECTORS BETWEEN SURVEYS.

of the wave steepness corresponding to these parameters, since wave periods of 5 seconds and less are undifferentiated in the meteorological records. The wave energy has not been calculated for the same reason.

It is clear that although there is a close correspondence between wind and wave parameters, their distributions are not always the same for equivalent periods of each year. In addition, the differences between summer and winter are not clear-cut, though the strongest winds and largest waves occur more frequently during the former.

Visual comparisons of wind and wave vectors with mean changes along all profiles are not easy. To facilitate the comparison, the wind and wave vectors have been resolved into mutually perpendicular components, north/south and east/west, approximating to components normal and parallel to the shoreline. Several categories of meteorological input have been considered. Winds have been treated as (a) prevailing, (b) dominant, greater than or equal to 20 knots, (c) dominant, greater than or equal to 30 knots; waves as dominant (a) of height greater than or equal to 2 metres, (b) of height greater than or equal to 4 metres, (c) of period greater than or equal to 6 seconds. For each of these six groups have been computed the proportions (of total observations per between-survey period) of each of the

four directional components. The proportions for dominant winds and waves are derived from values that are dominant after resolution into components.

A qualitative study of the relationship of meteorological input to accretion and erosion is not encouraging. For all periods, onshore and westerly components of large waves were more frequent than others; this persistence is obviously not matched by any uniformity of sand movement since both cut and fill occurred on all profiles. Winds were less persistent. The prevailing wind blew with greater frequency from the west than from the east for most periods (7 out of 8) but sometimes onshore, sometimes offshore (5 out of 8 periods experienced a greater frequency of the onshore component). Strong winds (component $\geq$ 20 knots) also came most frequently from the west in 7 out of 8 periods, but offshore components were more frequent than onshore in 5 out of 8 periods. Fig. 2.6 was prepared by plotting the number of observations when cut and fill occurred on each profile against the mean wind direction between surveys. There is no apparent correlation between wind direction and sand movement; but on profile 5, erosion was associated with a greater frequency of the westerly component of prevailing winds and accretion with the easterly. There is obviously no point in preparing similar graphs for large waves.

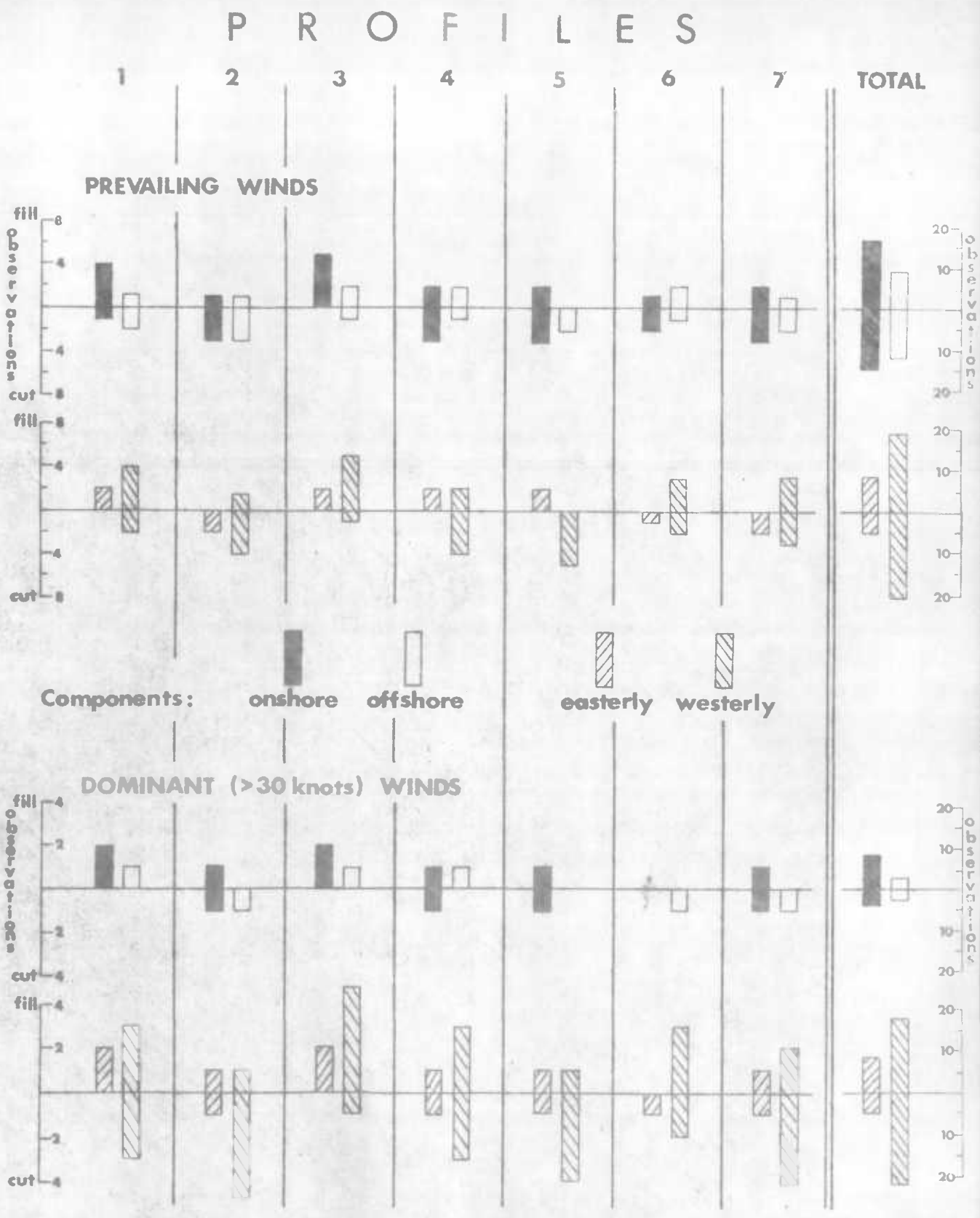


FIG. 2.6 : QUALITATIVE CORRELATION BETWEEN BEACH CHANGES AND METEOROLOGICAL INPUT.

The quantitative degree of association between mean changes of profile heights and proportions of wind and wave components has been examined by means of the product-moment correlation coefficient. For each profile, the mean changes between successive surveys have been correlated with the proportions (of total observation per period) of four vector components of six categories of meteorological input. The resulting correlation coefficients are shown in Tables 2.6 and 2.7, the former applying to absolute change (means from the anovas of analysis 2.3), the latter to relative change (means from the anovas of analysis 2,4) - the relevent means are those summarised in Table 2.5.

(N.B. Onshore and offshore ≡ towards and from the shore, westerly and easterly ≡ from the west and from the east, respectively).

In addition, correlation coefficients have been computed between mean change on each profile and mean River Taf discharge for each period (taken from data provided by the South West Wales River Authority).

Very few of the correlations are significant. Profiles 3, 4, 5, 6 and 7 show some significant associations with wind and wave components, and profile 5 with River Taf discharge, but the paucity of the significant coefficients and the lack

MET. INPUT	% VECTOR COMPONENT	PROFILES							
		1	2	3	4	5	6	7	TOTAL
Prevailing wind	Onshore	-.41	-.16	-.73*	-.29	.58	.00	-.11	-.14
	Offshore	.57	.01	-.76*	.01	-.25	-.19	.45	.43
	Westerly	.00	-.11	-.03	.00	-.70	-.40	-.15	-.49
	Easterly	-.12	.21	.06	.18	.20	.39	-.22	.08
Dominant wind ⩾20 knots	Onshore	-.43	-.15	-.58	-.22	.67	.75	.37	.14
	Offshore	-.13	.61	.11	.19	.64	.51	.75*	.44
	Westerly	-.28	-.37	-.32	.02	.56	.63	-.08	.32
	Easterly	-.52	-.05	-.48	.24	.35	.58	-.11	-.15
Dominant wind ⩾30 knots	Onshore	-.19	-.47	-.23	-.26	.90**	.71	.41	.43
	Offshore	.29	-.24	.58	-.07	.35	.73	.76*	.58
	Westerly	.06	-.01	.32	.26	.46	.52	.86**	.52
	Easterly	-.35	-.14	-.57	-.25	.49	.77	-.10	-.10
Wave height ⩾2 metres	Onshore	-.36	-.14	-.58	-.07	.67	.55	-.48	.05
	Offshore	-.14	-.34	.01	.03	.87*	.70	.67	.55
	Westerly	-.20	-.01	-.23	.24	.74*	.42	.35	.36
	Easterly	-.50	-.38	-.56	-.06	.62	.50	-.20	-.12
Wave height ⩾4 metres	Onshore	-.24	.38	-.15	.91**	.12	-.03	.17	.13
	Offshore	-	-	-	-	-	-	-	-
	Westerly	-.44	.49	-.44	.67	.11	.16	.10	-.01
	Easterly	-.43	-.41	-.59	-.22	.59	.32	-.29	-.18
Wave period ⩾6 seconds	Onshore	-.21	.24	-.60	.06	.60	-.43	-.21	.04
	Offshore	-	-	-	-	-	-	-	-
	Westerly	-.45	.35	-.42	.44	.19	-.25	-.30	-.28
	Easterly	-.26	-.01	-.70	-.07	.35	-.15	-.40	-.21
River flow		-.28	-.44	-.15	.10	.84*	.65	.47	.36
Sample size n =		8	8	8	8	7	6	8	8

* = $0.05 > P > 0.01$; ** = $0.01 > P > 0.001$

TABLE 2.6 : Correlation coefficients for absolute change/percentages of meteorological observations

MET. INPUT	% VECTOR COMPONENT	PROFILES							
		1	2	3	4	5	6	7	TOTAL
Prevailing wind	Onshore	.20	.61	.16	.09	.07	-.15	.34	.42
	Offshore	-.38	-.45	-.40	-.21	.03	.54	-.61	-.51
	Westerly	-.16	.26	.02	-.10	-.18	.67	.36	.21
	Easterly	.24	-.34	.19	-.18	.28	-.75	-.05	-.11
Dominant wind ≥20 knots	Onshore	.39	.34	.37	.17	.07	-.47	-.02	.30
	Offshore	.42	-.05	.24	.57	.46	.02	-.69	.09
	Westerly	.41	-.05	.35	-.03	-.17	-.28	-.17	.10
	Easterly	.68	.20	.48	-.11	.33	-.65	.28	-.48
Dominant wind ≥30 knots	Onshore	.23	.23	.08	.72*	.48	-.59	-.60	.06
	Offshore	.07	-.35	.06	.50	.10	-.49	-.85**	-.37
	Westerly	.33	-.38	.18	.20	-.07	-.05	-.61	-.13
	Easterly	.28	.53	.25	.03	.05	-.82*	.36	-.10
Wave height ≥2 metres	Onshore	.35	.48	.21	.10	.11	-.42	.23	.44
	Offshore	.40	-.05	.18	.59	.46	-.37	-.71*	.02
	Westerly	.47	.07	.18	.08	.16	-.22	-.08	.25
	Easterly	.52	.53	.34	.28	.62	-.77	.17	.54
Wave height ≥4 metres	Onshore	.42	-.44	.13	-.37	-.01	.18	-.01	.06
	Offshore	-	-	-	-	-	-	-	-
	Westerly	.41	-.49	.28	-.51	.03	-.15	.06	.02
	Easterly	.34	.65	.23	.30	.38	-.72	.25	.54
Wave period ≥6 seconds	Onshore	.07	.26	-.06	-.27	-.17	.08	.44	.22
	Offshore	-	-	-	-	-	-	-	-
	Westerly	.33	.21	.21	-.55	-.13	.19	.71*	.44
	Easterly	.20	.49	.11	-.16	.03	-.37	.58	.44
River flow		.57	.20	.30	.56	.56	-.34	-.44	.31
Sample size n =		8	8	8	8	7	6	8	8

* = $0.05 > P > 0.01$; ** = $0.01 > P > 0.001$

TABLE 2.7 : Correlation coefficients for relative change/percentages of meteorological observations

of continuity between adjacent profiles renders their interpretation difficult.

Such an unsatisfactory degree of association between the beach and its environment must be indicative of some shortcoming in the design and/or the methodology of the study. An obvious contender here is the lack of control, or randomness, in the length of the between-survey periods. These were not truly orthogonal, for reasons of practical expediency. Hence, it is possible that a constant rate of change during the period of study could produce variable between-survey changes whose magnitudes were dependent solely on the time intervals between surveys. That this was generally not the case is shown by the absence of significant correlations between either absolute or relative mean changes and the length of between-survey periods. Only profile 3 indicates a significant association (Table 2.8).

	PROFILES							
CHANGE	1	2	3	4	5	6	7	TOTAL
ABSOLUTE	.66	-.42	.85**	-.08	-.04	.19	.01	.52
RELATIVE	-.37	-.63	-.35	.10	-.31	-.46	-.54	-.63

TABLE 2.8

However, others of the coefficients are uncomfortably high, particularly those for total change ($P_{0.05}$ = .71 for n = 8).

In addition, since surveys were not orthogonal with respect to time, corresponding 'seasons' for each year must constitute discrepant periods, and so are not strictly comparable.

Because of these strictures, the correlation analysis has been repeated. In this case, the actual numbers of observations (after resolution) of each vector component, rather than their proportions of the total, have been used for the between-survey periods. Thus, here the discrepancies between the lengths of periods are eliminated, since mean changes along profiles are correlated with the sum of meteorological parameters active between surveys.

It is apparent that many of the coefficients are increased in magnitude, and several more achieve significance (Tables 2.9 and 2.10). Only profile 2 fails to show any degree of association with meteorological input. This would appear to underline the necessity for strict randomness in the design of the surveying programme in order that unbiased comparisons can be made between successive surveys. Otherwise some periods will be preferentially weighted and will not be representative of true seasons. In order therefore to further investigate the temporal variations of the profiles, it is necessary to discover the principal agencies of change and then to study their distribution during the two years of survey.

MET. INPUT	VECTOR COMPONENT	PROFILES							
		1	2	3	4	5	6	7	TOTAL
Prevailing wind	Onshore	.39	-.08	.31	-.38	.58	.13	-.06	.52
	Offshore	.79*	.12	.96***	-.05	-.06	-.02	.38	.65
	Westerly	.73*	.08	.95***	-.06	-.49	-.15	.01	.27
	Easterly	.23	.08	.44	.06	-.01	.34	-.20	.19
Dominant wind ⩾ 20 knots	Onshore	-.33	-.21	-.32	-.21	.71*	.82**	.65	.36
	Offshore	.03	-.31	.31	.15	.67	.55	.78*	.56
	Westerly	-.03	.08	.12	.06	.59	.66	.84**	.52
	Easterly	-.42	-.11	-.15	.30	.14	.62	-.09	-.12
Dominant wind ⩾ 30 knots	Onshore	-.07	-.49	-.03	-.25	.87**	.66	.47	.52
	Offshore	.33	-.26	.66	-.26	.32	.68	.71*	.56
	Westerly	.28	.02	.53	.18	.29	.52	.80*	.54
	Easterly	-.31	-.16	-.43	-.32	.40	.76	-.11	-.05
Wave height ⩾ 2 metres	Onshore	-.34	-.21	-.40	-.03	.80*	.57	.21	.27
	Offshore	.02	-.33	.25	.03	.82*	.66	.76*	.60
	Westerly	.09	-.03	.25	.26	.75*	.44	.53	.58
	Easterly	-.46	-.48	-.36	-.04	.49	.51	-.25	-.11
Wave height ⩾ 4 metres	Onshore	-.23	.32	-.10	.88**	.16	.06	.26	.18
	Offshore	-	-	-	-	-	-	-	-
	Westerly	-.42	.44	-.34	.68	.06	.25	.12	.00
	Easterly	-.46	-.51	-.49	-.23	.51	.32	-.39	-.24
Wave period ⩾ 6 seconds	Onshore	.01	.40	-.43	.13	.71	-.52	-.29	.21
	Offshore	-	-	-	-	-	-	-	-
	Westerly	-.36	.53	-.56	.66	.12	-.22	-.35	-.20
	Easterly	-.19	.00	-.39	-.03	.31	-.12	-.59	-.22
River flow		-.08	-.42	.19	.09	.77*	.65	.55	.46
Sample size n =		8	8	8	8	7	6	8	8

* = $0.05 > P > 0.01$; ** = $0.01 > P > 0.001$; *** = $0.001 > P$

TABLE 2.9 : Correlation coefficients for absolute change/numbers of meteorological observations

MET. INPUT	VECTOR COMPONENT	PROFILES							
		1	2	3	4	5	6	7	TOTAL
Prevailing wind	Onshore	-.27	-.12	-.31	.33	.14	-.53	-.39	-.35
	Offshore	-.46	-.59	-.52	-.19	-.30	-.06	-.65	-.65
	Westerly	-.49	-.46	-.39	-.04	.23	.04	-.31	-.49
	Easterly	-.02	-.45	.02	-.01	.26	-.72	-.25	.30
Dominant wind ≥20 knots	Onshore	.49	.11	.32	.34	.17	-.53	-.13	.08
	Offshore	.39	-.17	.11	.52	.42	-.09	-.74*	-.01
	Westerly	.40	-.34	.18	.01	-.20	-.31	-.51	-.10
	Easterly	.66	-.04	.56	-.04	.51	-.71	.05	.35
Dominant wind ≥30 knots	Onshore	.22	.15	.02	.77*	.50	-.55	-.73*	-.02
	Offshore	.09	-.32	.04	.48	.13	-.44	-.79*	-.31
	Westerly	.25	-.43	.03	.16	-.39	-.10	-.59	-.21
	Easterly	.31	.42	.31	.04	.11	-.81*	.29	.43
Wave height ≥ 2 metres	Onshore	.43	.34	.14	.27	.23	-.48	-.06	.32
	Offshore	.37	-.15	.10	.58	.46	-.35	-.79*	-.08
	Westerly	.39	-.23	.02	.20	.14	-.26	-.43	-.02
	Easterly	.51	.40	.44	.39	.75*	-.75	-.01	.47
Wave height ≥ 4 metres	Onshore	.49	-.42	.10	-.29	.09	.15	-.09	.06
	Offshore	-	-	-	-	-	-	-	-
	Westerly	.47	-.50	.29	-.45	.10	-.24	-.02	-.03
	Easterly	.36	.59	.37	.39	.70	-.72	.15	.49
Wave period ≥6 seconds	Onshore	-.13	.03	-.33	-.32	.24	.09	.32	-.04
	Offshore	-	-	-	-	-	-	-	-
	Westerly	.32	-.09	.10	-.69	-.13	.07	.63	.26
	Easterly	.12	.38	.08	-.16	.16	-.42	.55	.36
River flow		.49	-.01	-.16	.57	.63	-.39	-.62	.11
Sample size n =		8	8	8	8	7	6	8	8

* = 0.05 > P > 0.01;

** = 0.01 > P > 0.001

TABLE 2.10 : Correlation coefficients for relative change/numbers of meteorological observations

From Table 2.9 it may be seen that both profiles 1 and 3 show significant and very highly significant associations between absolute change and prevailing winds, both offshore and westerly components. A significant association does not necessarily imply a causal relationship, but in the case of profile 3 the probability that these relationships are due to chance alone, is less than one in a thousand. Unfortunately there is no meaningful association of prevailing wind components with relative change (Table 2.10). Hence it is highly probable that offshore and westerly prevailing wind components create reduced stability of beach level along profiles 1 and 3, but this does not result in a definitive relative change of mean accretion or erosion.

No further parameters provide meaningful relationships with changes along profiles 1 and 3, and none at all along profile 2.

On profile 4, the onshore component of winds equal to or greater than 30 knots is noticeably associated with accretion; very high waves, also with an onshore component, bear an important relationship with stability, an increased frequency being associated with decreased foreshore stability, but no conclusions can be drawn as to whether this results in accretion or erosion.

The stability of the foreshore of profile 5 shows a meaningful correlation with several parameters. Decreased stability is associated with an increased frequency of dominant onshore winds (both categories), and high onshore waves. In addition, there is a similar relationship with the frequencies of offshore and westerly components of high waves (but not with very high waves). The sole association of relative change with these parameters is one of accretion with an easterly component of high waves. Also foreshore instability closely follows the volume of River Taf discharge (total discharge per period in this analysis, not mean discharge as before); the correlation with absolute change is significant, but not with relative change though the data suggests that an increased river flow may be related to accretion here.

On profile 6, the onshore component of winds equal to or greater than 20 knots is again related to foreshore stability. The easterly component of very strong winds is associated with erosion, but a similar relationship of easterly high waves with erosion is not quite significant.

The most abundant significant correlations are found with profile 7. Decreased stability of the foreshore bears meaningful relationships with offshore and westerly components of strong winds and very strong winds, and with the offshore

component of high waves. These offshore components relate to a mean erosion in each case. In addition, the onshore component of very strong winds similarly relates to a mean erosion. The correlation of relative change to river flow is not quite significant but suggests a negative correlation.

None of the coefficients are significant when the mean changes of all seven profiles are combined, though the correlation of stability (erosion) with prevailing offshore winds nearly achieves significance.

The foregoing relationships are far from complete. Some gaps may be filled by a further correlation analysis in which the resultant onshore and westerly numbers of observations per period of each of the meteorological parameters are considered. The resulting coefficients are shown in Table 2.11.

Fewer of the correlations are now significant, but there are a few important additions. On profile 2 there is a meaningful association of the resultant westerly component of very high waves with mean erosion. On profile 4 there is a similar association of the resultant westerly component of very long waves (swell) with instability and mean erosion. On profile 7 there is a positive relationship between the resultant westerly component of high waves and instability.

For the first time, there is in addition an important

(a)

MET. INPUT	RESULTANT COMPONENT	PROFILES							
		1	2	3	4	5	6	7	TOTAL
Prevalent wind	Onshore	-.66	-.16	-.87**	-.11	.37	.11	-.42	-.46
	Westerly	.35	-.02	.30	-.12	-.36	-.45	.23	.02
Dominant wind ≥ 20 knots	Onshore	-.31	.18	-.64	-.36	.16	-.03	-.33	-.29
	Westerly	.29	.16	.24	-.18	.34	.25	.94***	.64
Dominant wind ≥ 30 knots	Onshore	-.35	-.32	-.58	-.04	.87**	-.61	.08	.09
	Westerly	.33	.14	.60	.27	-.16	.31	.72*	.50
Wave height ≥ 2 metres	Onshore	-.32	-.06	-.59	-.05	.53	.07	-.14	-.01
	Westerly	.38	.28	.47	.30	.44	.23	.74*	.72*
Wave height ≥ 4 metres	Onshore	-.23	.53	-.10	-.29	.16	.06	.26	.18
	Westerly	-.15	.61	-.07	.69	-.17	.12	.28	.11
Wave period ≥ 6 seconds	Onshore	.01	.40	-.43	.13	.70	-.52	-.29	.17
	Westerly	-.34	.63	-.49	.80*	.01	-.21	-.17	-.14

* = $0.05 > P \geq 0.01$; ** = $0.01 > P > 0.001$; *** = $0.001 > P$

(b)

Prevalent wind	Onshore	.36	.57	.41	-.05	.40	-.42	.51	.53
	Westerly	-.38	.10	-.34	.04	-.45	.80	.01	-.06
Dominant wind ≥ 20 knots	Onshore	-.05	.26	.14	-.30	-.20	.37	.47	.11
	Westerly	-.09	-.31	-.24	.10	-.65	.20	-.57	-.39
Dominant wind ≥ 30 knots	Onshore	.16	.42	-.01	.43	.54	.17	-.13	.24
	Westerly	.02	-.59	-.14	.08	-.29	.19	-.63	-.40
Wave height ≥ 2 metres	Onshore	.29	.47	.11	-.01	.01	-.42	.36	.41
	Westerly	.10	-.52	-.25	-.03	-.59	.08	.48	-.31
Wave height ≥ 4 metres	Onshore	.49	-.42	.10	-.29	.10	.15	-.09	.06
	Westerly	.24	-.71*	.08	-.57	-.21	.02	-.09	-.25
Wave period ≥ 6 seconds	Onshore	-.13	.03	-.33	-.02	-.24	.09	.32	-.04
	Westerly	.33	-.27	.08	-.76*	-.22	.20	.51	.16
Sample size n =		8	8	8	8	7	6	8	8

TABLE 2.11 : Correlation coefficients for (a) absolute and (b) relative change/resultant numbers of meteorological observations

relationship involving mean changes for all seven profiles. The resultant westerly component of high waves is significantly associated with total foreshore stability, the foreshore losing stability as the resultant increases.

The significant associations developed from the correlation analyses are summarised below and in Fig. 2.22.

PROFILE	GAIN	COMPONENT	VECTOR	ASSOCIATION
1.	total	offshore	prevailing winds	instability
	total	westerly	prevailing winds	instability
2.	resultant	westerly	very high waves	erosion
3.	total	offshore	prevailing winds	instability
	total	westerly	prevailing winds	instability
4.	total	onshore	very strong winds	accretion
	total	onshore	very high waves	instability
	resultant	westerly	long period waves	instability and erosion
5.	total	onshore	strong winds	instability
			very strong winds	instability
			high waves	instability
	total	offshore	high waves	instability
		westerly	high waves	instability
		easterly	high waves	accretion
	total	River Taf	discharge	instability
6.	total	onshore	strong winds	instability
	total	easterly	very strong winds	erosion
7.	total	onshore	very strong winds	erosion
	total	offshore	strong winds	instability and erosion
			very strong winds	
			high waves	
	resultant and total	westerly	strong winds	instability
			very strong winds	instability
	resultant	westerly	high waves	instability
TOTAL	resultant	westerly	high waves	instability

Westerly components of meteorological input account for associations on all profiles, except profile 6, and for the total. On profiles 2 and 4, the resultant westerly component of very large waves relates to mean erosion of beach level; obviously these waves originate as storm waves of long fetch in the North Atlantic. On most other profiles the westerly components of wind and wave parameters are associated with foreshore instability but not with mean accretion or erosion. On profiles 1 and 3 it is the prevailing wind component, and on most others the dominant wind and wave components that are important.

Easterly components also yield some meaningful associations. On profiles 2 and 4, the resultant easterly component of very large waves relates to a mean accretion of beach level; this may not be the direct converse of the association of resultant westerlies and erosion, because of the effect of wave refraction in shallow water. On profile 6, very strong easterly winds relate to erosion, whilst on profile 5, high easterly waves relate to accretion. As shown in Fig. 2.22, these associations suggest an east to west movement of sand under the influence of easterly meteorological components; however, although these changes along the beach may synchronise in time and sense, they cannot be simply synonymous because of the differences in their relative magnitudes.

* In other words, the association of dominant onshore winds with destructive wave action may be restricted to those beaches whose offshore zones are covered by relatively deep water. Dominant onshore winds may be associated with constructive wave action on beaches whose offshore zones are covered by very shallow water.

Onshore components of meteorological input are important on profiles 4-7, dominant winds and waves relating to instability, but to mean relative change on profiles 4 and 7 only. On profile 4, onshore very strong winds relate to mean accretion, but on profile 7 they relate to erosion. The latter change is most readily acceptable since the association of dominant onshore winds with destructive wave action is well documented (King, 1953 and 1959). The former is not easily explained, but may be a result of incomplete surveying along this profile; because of this the lower foreshore has not been included in any of the foregoing analyses, so that the values for mean change are perhaps not representative of the total profile. However, the correlation may possibly be a real one. Offshore gradients in the area of transect 4 are very low, virtually zero, so that a considerable extent of the offshore bottom is under very shallow water at all times (see Chapter 1). Such offshore bathymetry is probably atypical of those described in other studies of beaches. Onshore winds, and accompanying waves, may in fact cause a shoreward transport from the shoal offshore zone onto the foreshore.*

Offshore components of meteorological input develop meaningful associations with changes on profiles 1, 3, 5 and 7. On the latter, mean erosion is related to offshore dominant wind and

waves. Of course it is unlikely that dominant offshore waves would occur on the shoreline, though detectable offshore from the lightvessel, but they may be developed in the estuary. It would appear that offshore winds, and perhaps waves, most readily affect the speed and nature of river flow which in turn reacts by cutting away the lower foreshore of the profile (it has already been shown that this is the most dynamic section). On profile 5 it is offshore high waves that relate to instability; again these could only be developed within the estuary and hence effect profile 5 through the agency of river flow. However, such offshore waves can be generated only by offshore winds. That these do not correlate with foreshore change on this profile may be because of the discrepancy between foreshore and lightvessel positions.

Offshore prevailing winds are important on profiles 1 and 3, being related to overall instability. The absence of a significant association with relative change implies that other factors are operative that have not been considered. It is most probable that contrary movements of beach material are brought about by different combinations of the prevailing wind with short-term dominant sea conditions. These possibilities are discussed in the following section.

It is odd that there should be such marked discrepancies

between the responses of adjacent profiles. This too is discussed subsequently. However, it is worthwhile to recall that some profiles were more variable than others, so that the amounts of sand being moved differ on the various profiles. If, for example, the mean absolute changes on some profiles are combined to give an overall mean change, then the influence of larger means dominates that of smaller means to such an extent that significant associations with meteorological input are maintained. Thus it may be shown that the most dominant associations are those involving offshore and westerly prevailing wind components for the western half of the beach; and those involving onshore and westerly components of dominant winds and waves as well as River Taf discharge for the central part and eastern half of the beach. These refer to instability, i.e. absolute change. Associations resulting from relative changes are far less pervasive. However, westerly and/or onshore components of dominant winds and waves are related to erosion on profiles 2, 4 and 7; this destructive action is undoubtedly the effect of storm swell on profiles 2 and 4.

It has been stated that the most meaningful results are obtained from a study of absolute changes, without regard as to whether these represent accretion or erosion. This may be because the surveyed profiles are all in a state of equilibrium,

merely adjusting their levels to changing conditions but without net gains or losses of sand. Alternatively it may be because surveys have not extended far enough down the foreshore (since all were terminated at the low water mark) so that the mean relative changes recorded from the profiles are not representative of the true changes, since only part of the mobile zone of the transect was covered. Thus a true mean erosion could conceivably have been recorded as a mean accretion if the major cut occurred in the sub-littoral. This sort of error, in combination with the various permutations of nearshore hydrodynamic and meteorological factors producing it, may have led to spurious estimates of between-survey changes. In other words, the foreshore and offshore zones constitute one dynamic unit, and should not be studied in isolation. For this reason, a study of relative changes of one or the other may not be fruitful. However, a study of absolute change is not so limited, since measurements of change at successive foreshore stations are cumulative. Thus although the foreshore may develop a mean accretion and the offshore zone a mean erosion, measurements of absolute change within both zones may not appreciably differ, and each will be representative of the complete unit.

2.6 Correlation of Profile Variation and Daily Meteorological Input

There is a further possible source of variation of beach level that has yet to be considered. This is the short-cycle variation that occurs from day to day. So far it has been assumed that such fluctuations are of smaller relative magnitude than fluctuations due to long-term and seasonal variation. There is no justification for such an assumption, since a preliminary survey to estimate the relative magnitudes of 'random' variation was not attempted. It is therefore possible that the measured surveys merely reflect this lack of experimental control, each profile representing a random deviation from a seasonal mean. If these deviations are of sufficient magnitude, then any cyclic variation of seasonal means may be effectively masked.

In the absence of daily surveys of transects it is not possible to check this variation. However, it is noteworthy that significant correlations of between-survey relative changes with meteorological input may be obtained if the latter is considered only in terms of those conditions prevailing just twenty four hours prior to surveying. The meteorological data for this analysis was taken from the St. Gowan lightvessel at 0600 hrs. G.M.T. on the day of survey, and at 1500 hrs. G.M.T. the previous day.

Wind speeds have been resolved into components as before. The correlation coefficients are shown in Table 2.12.

	PROFILES							
COMPONENT	1	2	3	4	5	6	7	TOTAL
Onshore	-.26	-.49	-.39	.04	.06	-.85*	.26	-.56
Offshore	.18	.02	.26	-.12	.23	.20	-.50	.20
Westerly	-.74*	-.77*	-.76*	-.47	-.72	.17	.19	-.85**
Easterly	.06	.33	.05	.63	.58	.00	-.02	.17
Sample size n =	8	8	8	8	7	6	8	8

* = $0.05 > P > 0.01$; ** = $0.01 > P > 0.001$

TABLE 2.12 : Correlation coefficients for relative change/ wind speeds 24 hours prior to surveying

The coefficients show an obvious relationship of erosion on profiles 1, 2 and 3 (and strongly suggested on profile 5) with the westerly components of wind speed just prior to surveying. On profile 6, the onshore component has a similar association with erosion. Few profiles were simultaneously surveyed, so that these correlations are independent of each other to some extent. Most interesting of all is the strong relationship between mean erosion of all profiles with the mean westerly wind component (i.e. the mean of all observations, 24 hours before the surveying of each profile, for each period).

It is not suggested that the measured changes along some profiles may be accounted for solely by such short-term meteorological fluctuations. Obviously the beach level is in constant flux between surveys, and measurements are an indication of a cumulative process. Nevertheless this analysis does emphasise the influence of short-term fluctuations of energy input and the resultant fluctuations of profile heights.

It becomes apparent that each survey is going to reflect the relative influences of several cycles of variation, and with the limited data available in this study, a rigorous quantitative analysis cannot be very fruitful. However, several indicators of sources of variation have been uncovered. The subsequent discussion is based on qualitative estimates of variation and its causes.

If it is assumed that a seasonal cycle of variation is operative, with the superimposition of random deviations due to day to day meteorological variations, then it is clear that this cycle will become more apparent the smaller the random deviations. Conversely, if the cycle itself is on a small scale, or is not well developed, then random deviations increase in significance. The relative magnitudes of seasonal and daily variations become of acute importance as the number of surveys is decreased. The situation may arise where surveys are more

indicative of daily than of seasonal variations. This is likely to occur if the time of survey coincides with or shortly follows a particularly large deviation.

In order to investigate such deviations, the wind and wave parameters prevailing during seven days prior to surveying have been examined. Vector diagrams of these are shown in Figs. 2.7(a) and 2.7(b). In the following section, the relationship of pre-survey meteorological conditions to a profile changes are examined in a qualitative way. In order to maintain some degree of objectivity, the attempted correlation has been confined to the 'exceptional' changes of profile height already provided by the range tests of the analyses of variance discussed earlier.

The discussion and analyses of data up to this point have been based on the changes of foreshore height at a few fixed stations on each transect. The following discussion is again based on this data but also involves volumetric variations of whole profiles; this is merely to provide a change of emphasis, since a further use of the fixed station data would be equally suitable; volumetric comparisons do, however, give us a better grasp of the magnitudes of the changes under consideration.

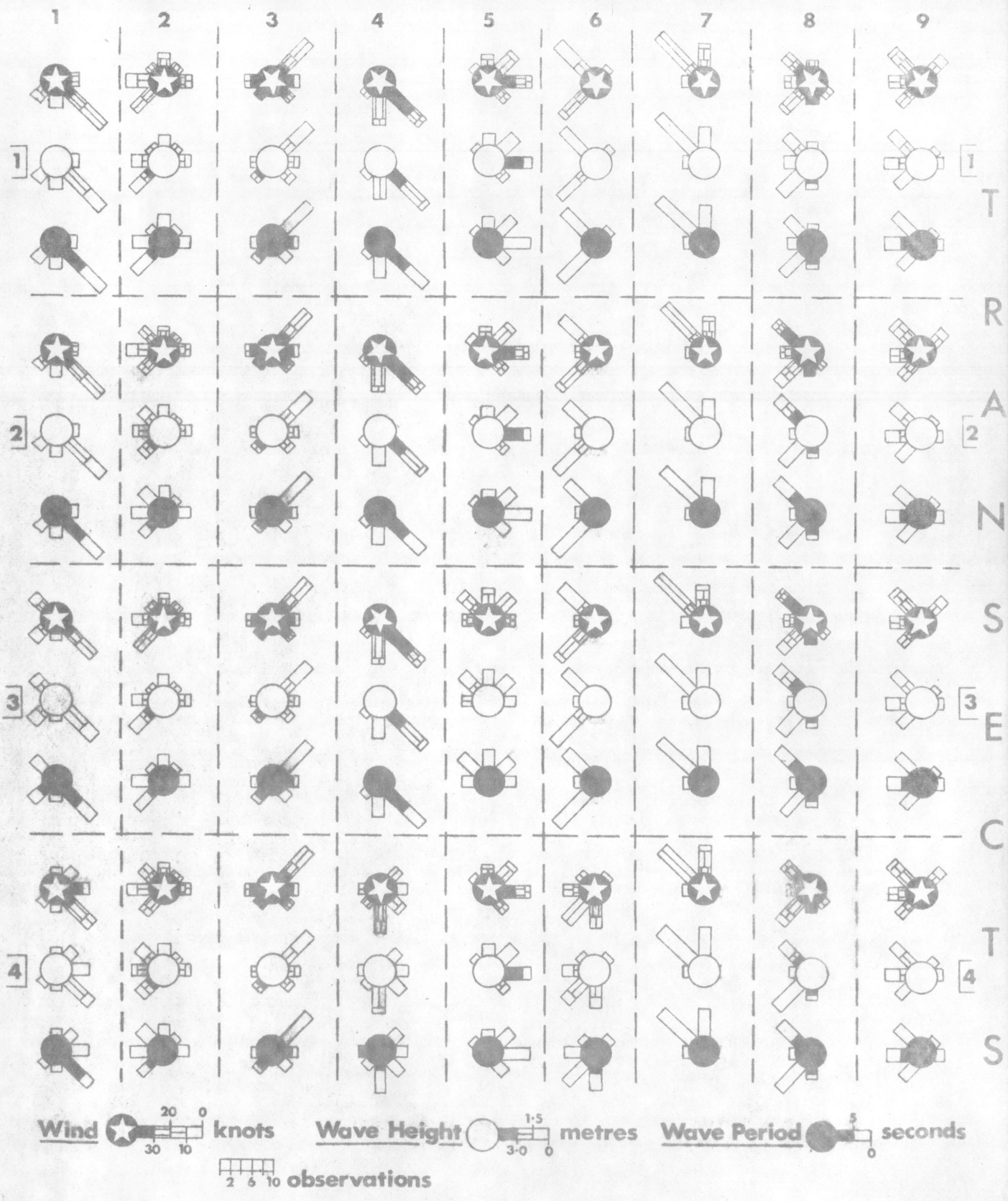


FIG. 2.7a : WIND AND WAVE VECTORS SEVEN DAYS PRIOR TO SURVEYING.

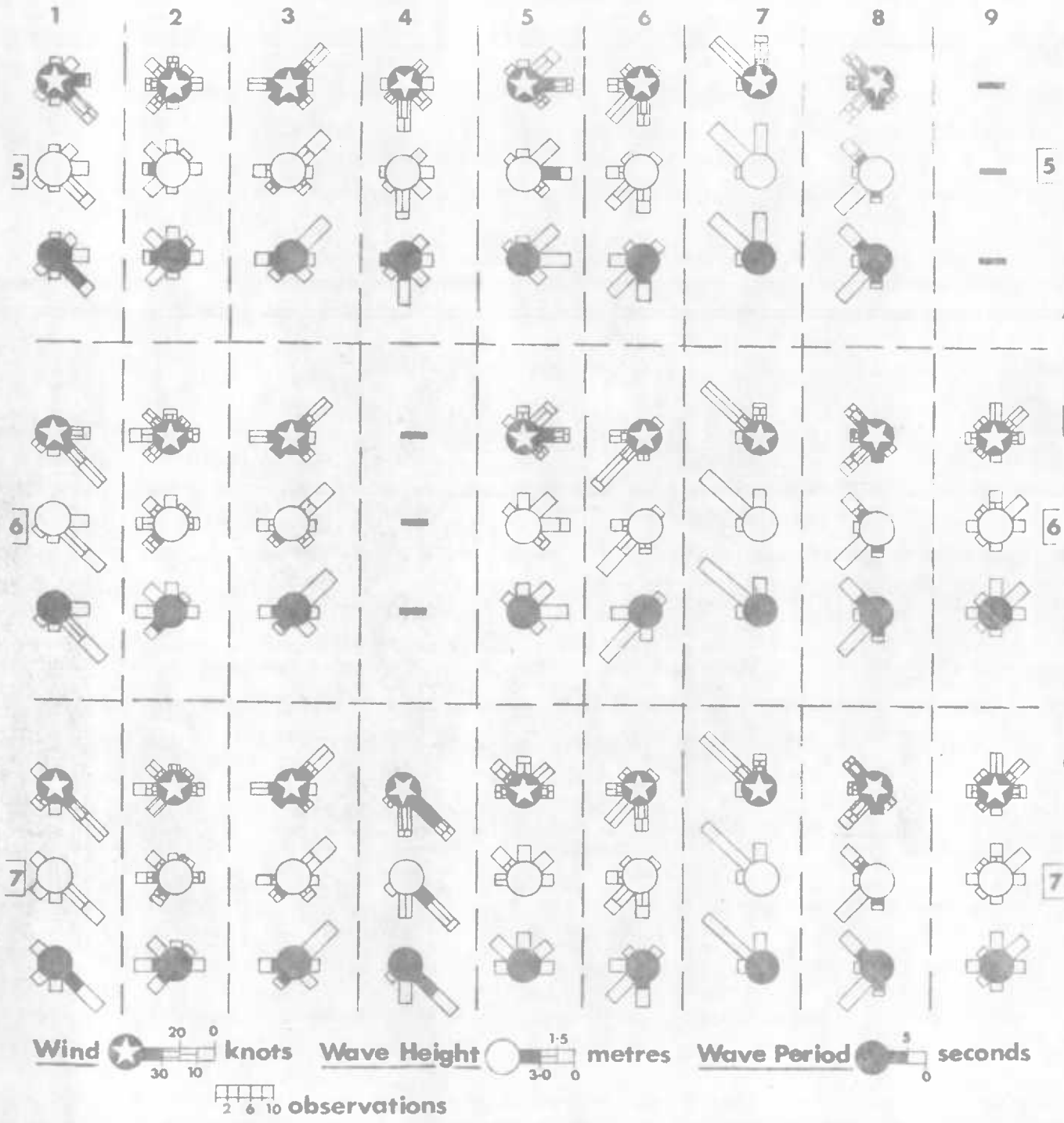


FIG.2.7b : WIND AND WAVE VECTORS SEVEN DAYS PRIOR TO SURVEYING.

2.7 : Volumetric Variations : Importance of Storm Conditions

Volumetric changes of sand along each transect have been examined with reference to various fixed baselines, as previously outlined (see Fig. 2.2(b)). The zones bounded by these baselines have been designated A-E; they approximate to trends of sediment textural variation described in Chapter 5, but can equally be considered as an arbitrary method of subdividing the profiles into convenient portions. No attempt has been made to relate these zones to critical tidal levels e.g. high and low water marks of spring and neap tides, since all or most surveys were carried out during spring tides. The baselines are fixed in a vertical plane and are common to all transects, with the exception of the upper baseline which describes the dune above zone A. This baseline has been chosen as the base of the dune, which of course may not be fixed in time and need not be a height common to all transects and profiles; similarly zone A is a variable entity since its upper limit is set by the same line. For this reason, the dune and zone A are considered separately but also combined into one unit fixed by the unflexible baseline dividing zones A and B.

The statistical techniques used previously have also been extended to an examination of changes between surveys of each

zone. This is done by one-way analyses of variance (fixed Model 1 arrangement) by which the variations of accretion and erosion among between-survey periods are related to variations within such periods, (i.e. variations within zones for each period). The same reference stations, 100 feet apart, are used as a source for raw data, and the same logarithmic transformation of data has been performed. Such an analysis provides two important types of information. Firstly, as a measure of control, it can be seen whether in fact a zone can be legitimately regarded as a homogeneous unit, or whether variation within the zone is so great as to negate the usefulness of comparing temporal variations. Secondly, it furnishes a method of comparing mean values of accretion and erosion for each zone and for each period based on the degree of homogeneity of variation within the zone, using the simple range test as before. The mean changes designated as exceptional for each zone may then be used as a basis for a qualitative correlation of foreshore change with short-term fluctuations of wind and wave input. Thus correlations can be attempted for each zone as well as for the total profile.

To avoid confusion, it should be remembered that the volumetric analyses apply to volumes measured by successive surveys (numbered 1 - 9, February 1968 - March 1970) whilst

the statistical analyses apply to changes of mean height between surveys (between-survey periods 1968_{A-D} and 1969_{E-H}, from 'spring' 1968 to 'winter' 1969).

(a) Surveys of Transect 1

Successive surveys of profile 1 are superimposed in Fig. 2.8. It is apparent that changes between surveys were slight and the overall shape of the profile was constant. The maximum change between surveys involved a volume of sand of 1,028 $ft.^3$ (from a 1 foot width of foreshore along the transect); the greatest fill between surveys was .50 ft., and the greatest cut 1.05 ft.

Volumetric changes (in $ft.^3$) for the total profile and its constituent zones are shown in Table 2.13 and in Fig. 2.9 (the temporal distribution of surveys is, for convenience, shown as orthogonal).

Variation of the dune (the face of which is protected) was small, but was at a maximum during the winter months, decreasing to a minimum during the summer. This cycle may be initiated by a human agency, since the dunes on this profile are accessible to the public and are very popular as a recreational area in the summer season. There is a tendency for the dune to be slightly broken down at this time. However, the rebuilding

	SURVEY								
ZONE	1	2	3	4	5	6	7	8	9
Dune	408	391	401	449	451	404	380	395	413
A	154	171	184	143	101	199	233	244	184
Dune + A	562	562	585	592	552	603	613	639	597
B	714	748	698	714	686	713	716	725	701
C	2510	2535	2273	2388	2420	2448	2445	2406	2471
D	9384	9422	8891	8985	9064	9126	9087	8798	8903
E	7686	7738	7530	7538	7569	7599	7587	(7580)	7820
Total	20,856	21,005	19,977	20,217	20,291	20,489	20,448	(20,148)	20,497

TABLE 2.13 : Volumetric data ($ft.^3$), Transect 1.

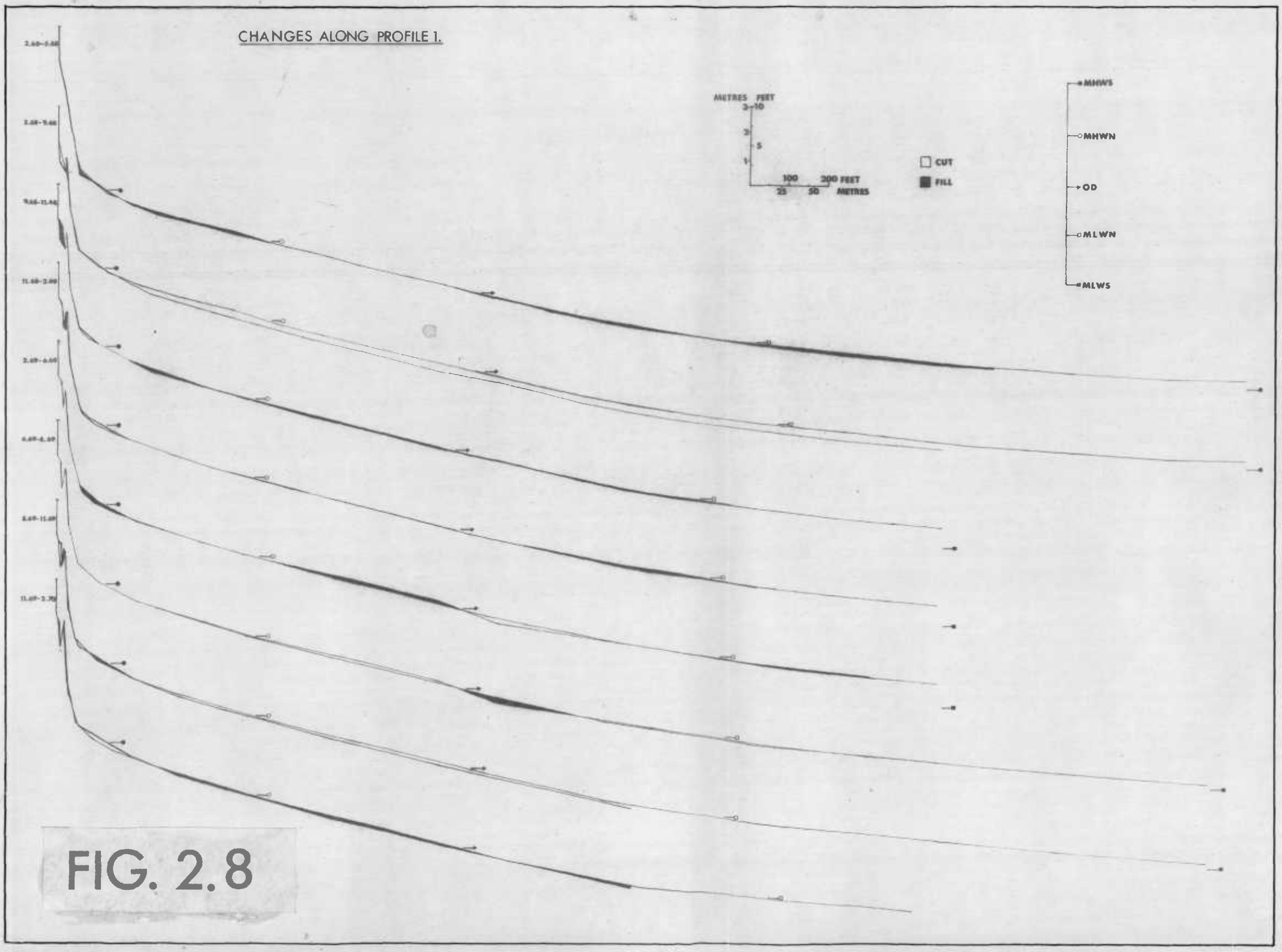

CHANGES ALONG PROFILE 1.
METRES FEET
3 10
2
5
1
100 200 FEET
25 50 METRES
CUT
FILL
MHWS
MHWN
OD
MLWN
MLWS

FIG. 2.8

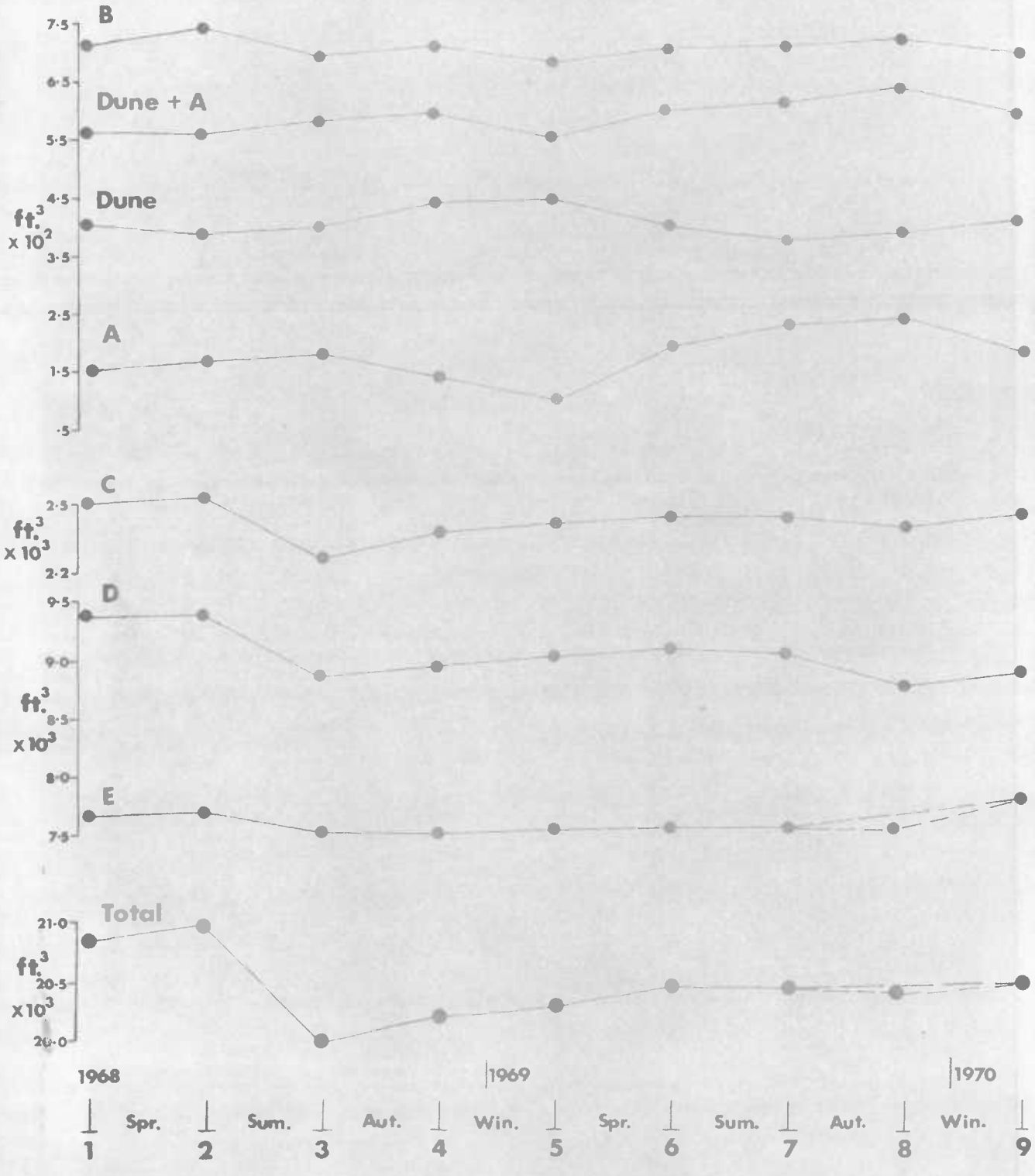


FIG.2. 9 : VOLUMETRIC VARIATION, PROFILE 1.

of the dune in winter cannot be attributed to human intervention.

Zone A, between the base of the dune and MHWST, is of course encroached upon by any increase of the dune. Here, too, there was a predominantly seasonal cycle, the reverse of that in the dune; this is to be expected, since an increased dune produces a decreased zone A, and vice-versa. However, there would appear to be a progressive linear trend superimposed on the seasonal trend, which is independent of the dune. The sequence for 1969-70 was a step up from the sequence of the previous year. Combination of the dune and zone A shows that the seasonal cycles in each are not interdependent entirely, since a seasonal cycle remains. The volume was least during the February/March surveys and greatest during the October/November surveys. In addition, there was an increase of volume during the survey period from 1968 to 1970.

The uppermost portion of the profile is too narrow to be examined by a statistical technique based on stations 100 feet apart. The anovas for the remaining zones are shown in Table 2.14 (data is in code). Zones C, D and E were effectively homogeneous in temporal variation, but there was as much variation of cut and fill within zone B as there was between seasons. It has already been established that the

Zone	Source of Variation	df	SS	MS	F
B	Among periods	7	.0147	.00211	.79ns
	Within periods	8	.0215	.00268	
	Total	15	.0362		
C	Among periods	7	.1322	.01889	52.1**
	Within periods	24	.0087	.00036	
	Total	31	.1409		
D	Among periods	7	.2516	.03594	27.3**
	Within periods	56	.0738	.00132	
	Total	63	.3254		
E	Among periods	5	.2693	.05385	159.0**
	Within periods	30	.0102	.00034	
	Total	35	.2795		

TABLE 2.14 : Anovas, Profile 1.

the lower foreshore tended to be more unstable than the upper on this profile. Change in these zones appears to have been cyclic rather than random, perhaps suggestive of a seasonal variation of accretion in winter and spring, of erosion in summer and autumn. However, there is no reason to suppose that this cycle is not entirely fortuitous, dependent only on daily random deviations from an equilibrium mean.

The mean changes (relative) and their relative importance for each zone (which are sufficiently homogeneous to allow a range test) are (decoded into feet):

C :	B	G	F	E	A	D	H	C
	-.85	-.14	-.07	.02	.08	.11	.16	.17
D :	B	G	F	A	E	D	H	C
	-.83	-.22	-.05	.05	.08	.11	.14	.15
E :	B	F	C	E	D	A		
	-.97	-.06	.04	.14	.15	.24		

Since survey 8 did not reach the lower limits of zone E, periods G and H are excluded from the analysis for that zone.

It is apparent that for zones C, D and E, as well as for the total profile (see section 2.4), period B (B68) resulted in an exceptionally large cut between surveys 2 and 3. Prior to survey 3 (in fact, the day before surveying) exceptional meteorological conditions were recorded by the lightvessel. Fresh gale force winds from the southwest in combination with very large waves of long period were the most likely agents of erosion. At this time, the Tenby coastguard recorded the sea state in Carmarthen Bay as 5-6 (on an arbitrary scale of 0-6). It may be seen from Fig. 2.7(a) that similar meteorological conditions were current prior to survey 2; indeed on some profiles this survey also recorded significant erosion. But on that occasion, though waves were of the same period (6 seconds) they were smaller (3 metres, as compared with 4.5 metres) and most significantly, wind speeds from the southwest quarter were considerably less (a fresh breeze only).

Another possible cause of erosion before survey 3 was the incidence of strong winds and large waves from the east and north-east. However, it is unlikely that waves from the latter quarter could be as well developed off Pendine as off St. Gowan's Head. Also, similar conditions prevailed prior to survey 5 and at that time a mean accretion was recorded on the profile.

Hence, it may be concluded that zones C, D and E are homogeneous units, generally responding in a similar way to changes of dynamic equilibria. Of those changes recorded by nine surveys, the greatest, one of erosion, was probably related to southwesterly gales from the Atlantic. Zone B is a heterogeneous unit, but here too the greatest change may be attributed to southwesterly gales. Zone A (above MHWST) was not similarly affected, appearing to increase in summer and decrease in winter; in the dune the reverse cycle was dominant. Correlations between the volumes of zones are significant for zones C, D and E, but there is a negative correlation between the volumes of zone (A + dune) and zone D. (see Table 2.15). In other words, accretion in the first is associated with erosion in the second, and vice-versa. Overall changes between surveys were slight, but a progressive accretion of zone (A + dune) was matched by a progressive

	Dune	Dune + A	A	B	C	D
A	-.83**	-				
B	-.55	.17	.41			
C	-.19	-.26	-.06	.52		
D	-.16	-.67*	-.32	.47	.73*	
E	-.29	-.11	.12	.34	.72*	.98**

TABLE 2.15 : Correlation, Transect 1.

erosion of zone D. However, the relative volumes of sand involved in each zone show that this is not a simple causal relationship, and the seasonal cycle of zone (A + dune) was not apparent in zone D. However, some (6.3% maximum) of the sand lost progressively from zone D may have been redeposited above MHWST.

Otherwise a seasonal pattern of profile response cannot be established with certainty. The final survey showed an overall volume only 359 ft.^{3} less than the first survey, two years previously.

(b) Surveys of Transect 2.

Successive surveys of profile 2 are superimposed in Fig. 2.10. At any point on the profile, the largest fill between surveys was .40 feet, the largest cut 1.38 feet; the maximum change between surveys across the total profile was 665 ft.^{3} (from a unit foot width of the profile).

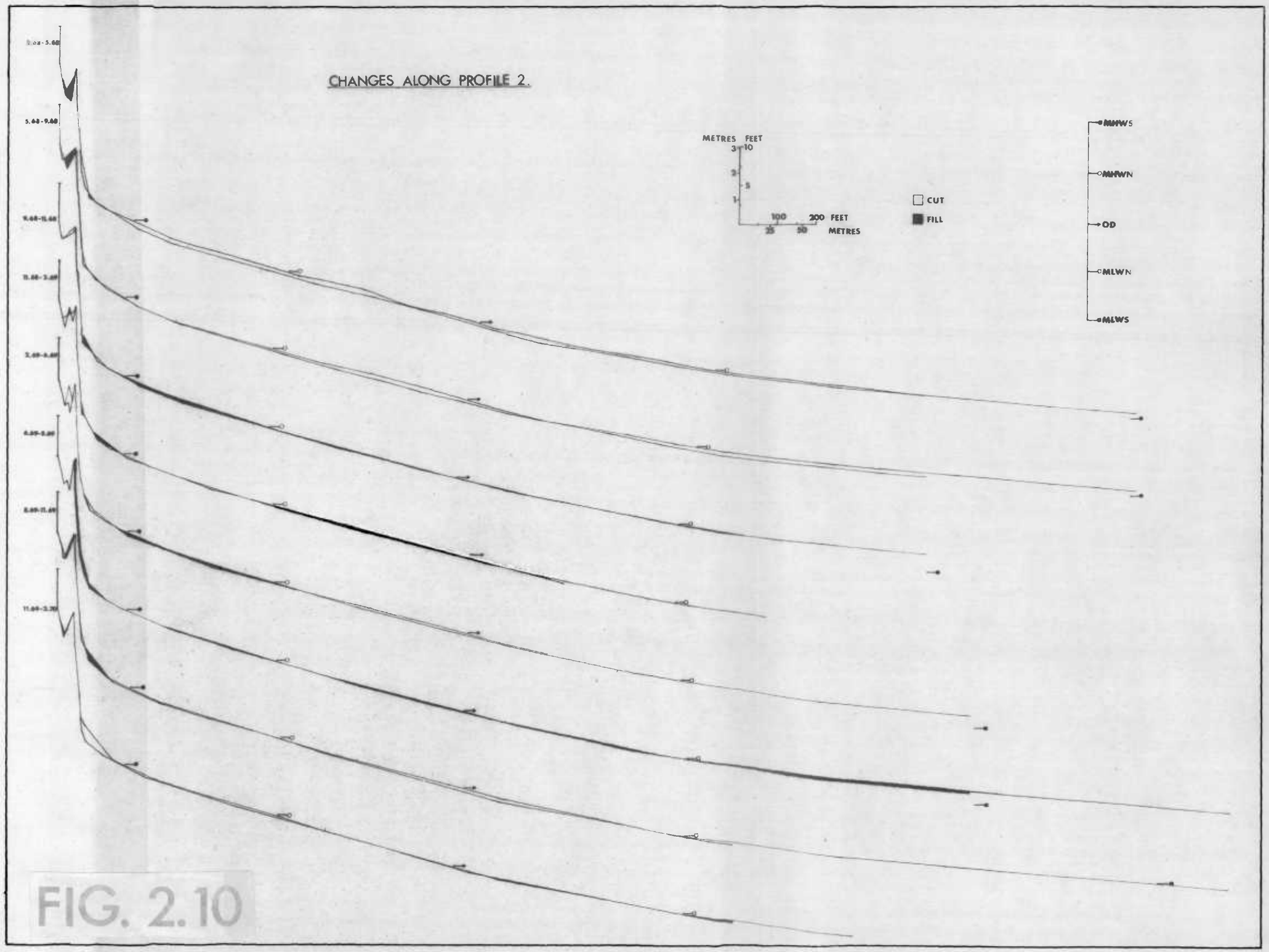

CHANGES ALONG PROFILE 2.
METRES FEET
3
2
1
10
5
100
200 FEET
25
50
METRES
CUT
FILL
MHWS
MHWN
OD
MLWN
MLWS

FIG. 2.10

Volumetric changes, in $ft.^3$, are shown in Table 2.16 and Fig. 2.11.

The volume of the dune decreased during the autumn months of both years and during the spring of the first. This may reflect the action of the highest spring tides of the March and September equinoxes, which become most destructive when supported by stormy conditions and onshore winds. Such conditions did in fact occur at, or near, the September equinoxes of both years and the March equinox of the first. At the March equinox of the second year, gentle offshore and easterly winds prevailed and no assault on the dune occurred. At other times the dune appears to have made good these losses, and maintained an equilibrium volume.

The volume of zone A is dependent on that of the dune, but the trends of variation of each are distinct. That of zone A is not of a seasonal nature, but combination into zone (A + dune) produces a near-seasonal cycle of accretion in summer and erosion in winter, which is akin to that noted for zone A of transect 1.

The anovas for zones B-E are shown in Table 2.17.

	SURVEY								
ZONE	1	2	3	4	5	6	7	8	9
Dune	805	734	808	631	659	783	809	691	808
Dune + A	1111	1128	1224	1080	1120	1043	1142	1150	1051
A	306	394	416	449	461	260	333	459	243
B	880	779	768	823	766	810	819	775	754
C	2728	2626	2554	2616	2571	2608	2653	2600	2521
D	9360	9201	8763	8918	9003	8909	9001	8770	8755
E	7886	7728	7416	7501	[7466]	7304	7558	7461	7534
Total	21,965	21,300	20,725	20,968	[20,938]	20,836	21,173	20,756	20,615

TABLE 2.16 : Volumetric data ($ft.^3$), Transect 2.

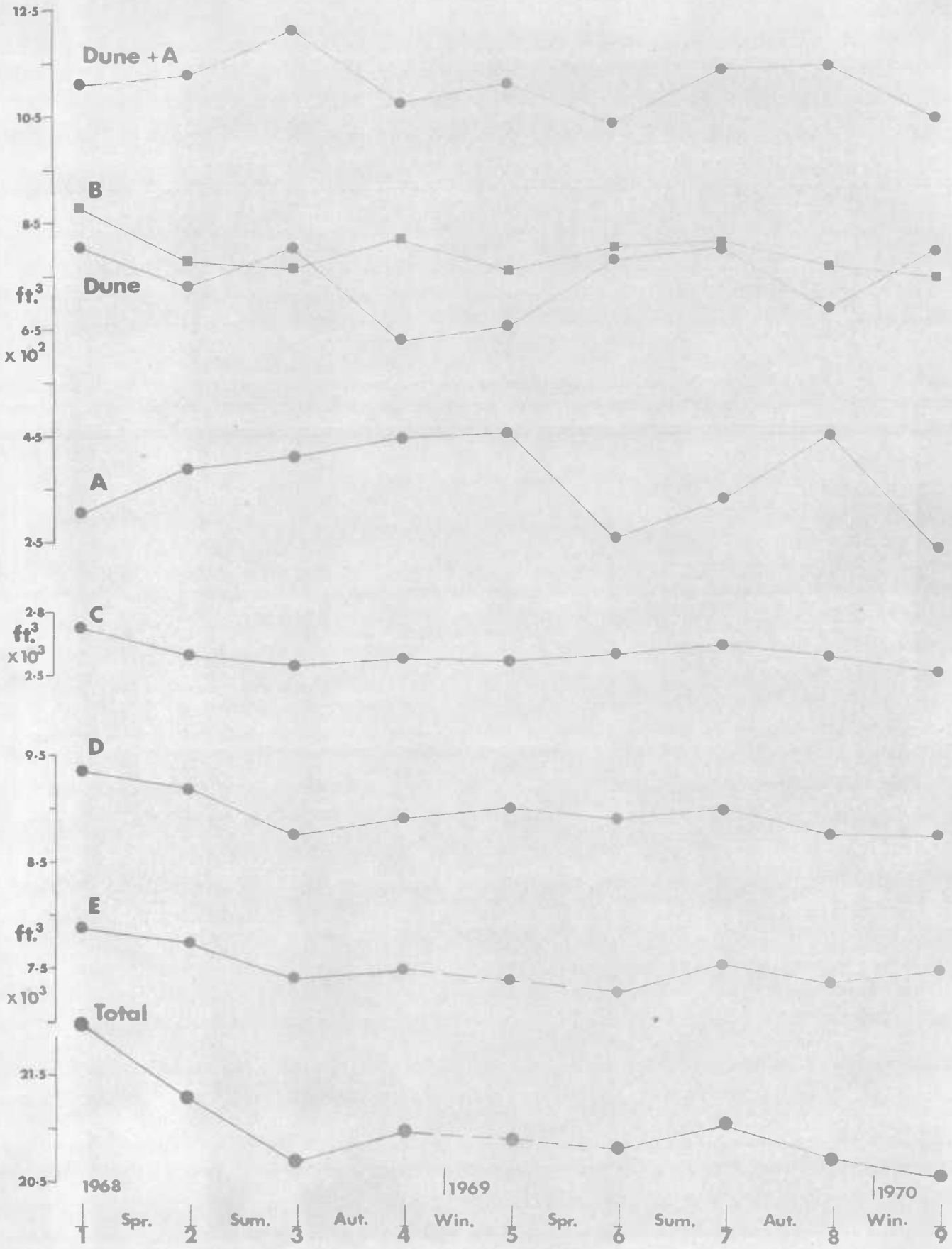


FIG. 2. 11 : VOLUMETRIC VARIATION, PROFILE 2.

Zone	Source of Variation	df	SS	MS	F
B	Among periods	7	.0443	.00633	14.5**
	Within periods	8	.0035	.00044	
	Total	15	.0478		
C	Among periods	7	.0735	.01050	12.8**
	Within periods	24	.0197	.00082	
	Total	31	.0932		
D	Among periods	7	.0948	.01354	17.5**
	Within periods	48	.0372	.00078	
	Total	55	.1320		
E	Among periods	5	.0437	.00874	20.8**
	Within periods	18	.0076	.00042	
	Total	23	.0513		

TABLE 2.17 : Anovas, Profile 2.

All zones below MHWST were effectively homogeneous in temporal variation. Between-survey changes were not seasonally distributed, but within zone B, mean change was least during the summer months. Mean accretion and erosion (in feet) for each zone were:

B :	A	D	G	H	B	F	E	C
	-.56	-.32	-.25	-.13	-.06	.08	.27	.38

C :	A	B	H	G	D	E	F	C
	-.60	-.31	-.19	-.18	-.16	.10	.16	.24

D :	B	G	A	E	H	D	C	F
	-.39	-.37	-.33	-.22	-.01	.12	.17	.19
E :	B	A	G	F	H	C		
	-.45	-.28	-.11	.08	.16	.17		

Since survey 5 did not include all of zone E, the analysis for this zone does not use data for periods D and E.

There is less obvious distinction between exceptional and normal changes on this profile than was the case for profile 1. On the upper foreshore, period A was exceptional, and on the lower, period B. As already noted, southwesterly winds and swell prevailed prior to both surveys 2 and 3, most dominantly before the latter. It is interesting to note that survey 2 of this transect was one of the few surveys conducted on two successive days. Because of lack of time, only the lower foreshore was surveyed on the first day (the same day as profile 1), and the upper foreshore on the following day. The time lag appears to have been sufficient for a few additional hours of southwesterly swell to remove sand from the upper foreshore. Thus for profile 2, erosion of the upper foreshore was increased prior to survey 2, so that erosion was relatively less prior to survey 3.

In spite of these differences, correlations between contemporaneous volumes of zones B-E are highly significant, showing that generally the response of the whole profile has

been a unified one (Table 2.18). The dune and foreshore above MHWST were independent of the rest of the foreshore.

	Dune	Dune + A	A	B	C	D
A	-.77**					
B	.15	-.18	-.24			
C	.11	.00	-.09	.92**		
D	.07	-.08	-.11	.69*	.83**	
E	.18	-.05	-.12	.54	.67*	.82**

TABLE 2.18 : Correlation, Transect 2.

The net change of volume along profile 2 was of erosion, this change occurring below the dune, and amounting to 1347 ft.^{3} of sand per unit width of transect; most of this cut resulted from the southwesterly swells and winds before surveys 2 and 3. However, only two surveys recorded a mean accretion. If these changes are regarded as truly representative of a progressive erosion along this transect, then the mean height of the foreshore would be lowered by some 3 feet in 10 years. But this seems unlikely.

(c) Surveys of Transect 3.

Successive profiles of transect 3 are superimposed in Fig. 2.12. The greatest fill recorded at any point on the transect was .87 ft., and the greatest cut 1.20 ft. The maximum change between surveys was 841 ft.^{3} per unit width of

foreshore. Volumetric data, in $ft.^3$, are shown in Table 2.19 and Fig. 2.13.

The fluctuations of dune volume appear to be random and do not coincide in sense with those of the similar dune of profile 2. Hence, the dune of profile 3 did not respond to the destructive effect of high spring tides at the equinoxes. This may be because the base of the dune is 1 foot higher on profile 3 than on profile 2. The dune has not drastically altered during the study period, but fluctuations were marginally greater here than for the dune of profile 2.

Zone A maintained an overall accretion, with two contrasting cuts recorded by surveys 4 and 9 which do not relate to pre-survey meteorological input. Combination of the volumes of dune and zone A produces a consistent seasonal cycle superimposed on a progressive linear trend of gradual accretion. For both years, the volume was at a maximum in early summer (May/June) and at a minimum in late winter (February/March).

The anovas for zones B-E are shown in Table 2.20.

The temporal variation of cut and fill is not significantly greater than the spatial variation within zone B. The remaining zones are however more homogeneous. Both zones C and D demonstrated a consistent accretion in 1969-70. The volume of zone E was least at surveys 4 and 8 (November of

	SURVEY								
ZONE	1	2	3	4	5	6	7	8	9
Dune	1456	1539	1450	1660	1349	1444	1348	1373	1510
Dune + A	1927	2045	1988	2000	1885	2057	1986	2109	2068
A	471	506	538	340	536	613	638	736	558
B	1015	1030	994	1030	986	1048	1051	1045	1091
C	2785	2830	2744	2776	2751	2825	2863	2879	2999
D	10310	10154	9755	9896	10031	10169	10229	10336	10398
E	8809	8911	8648	8605	8738	8922	9088	8883	9095
Total	24,846	24,970	24,129	24,307	24,391	25,021	25,217	25,252	25,651

TABLE 2.19 : Volumetric data ($ft.^3$), Transect 3.

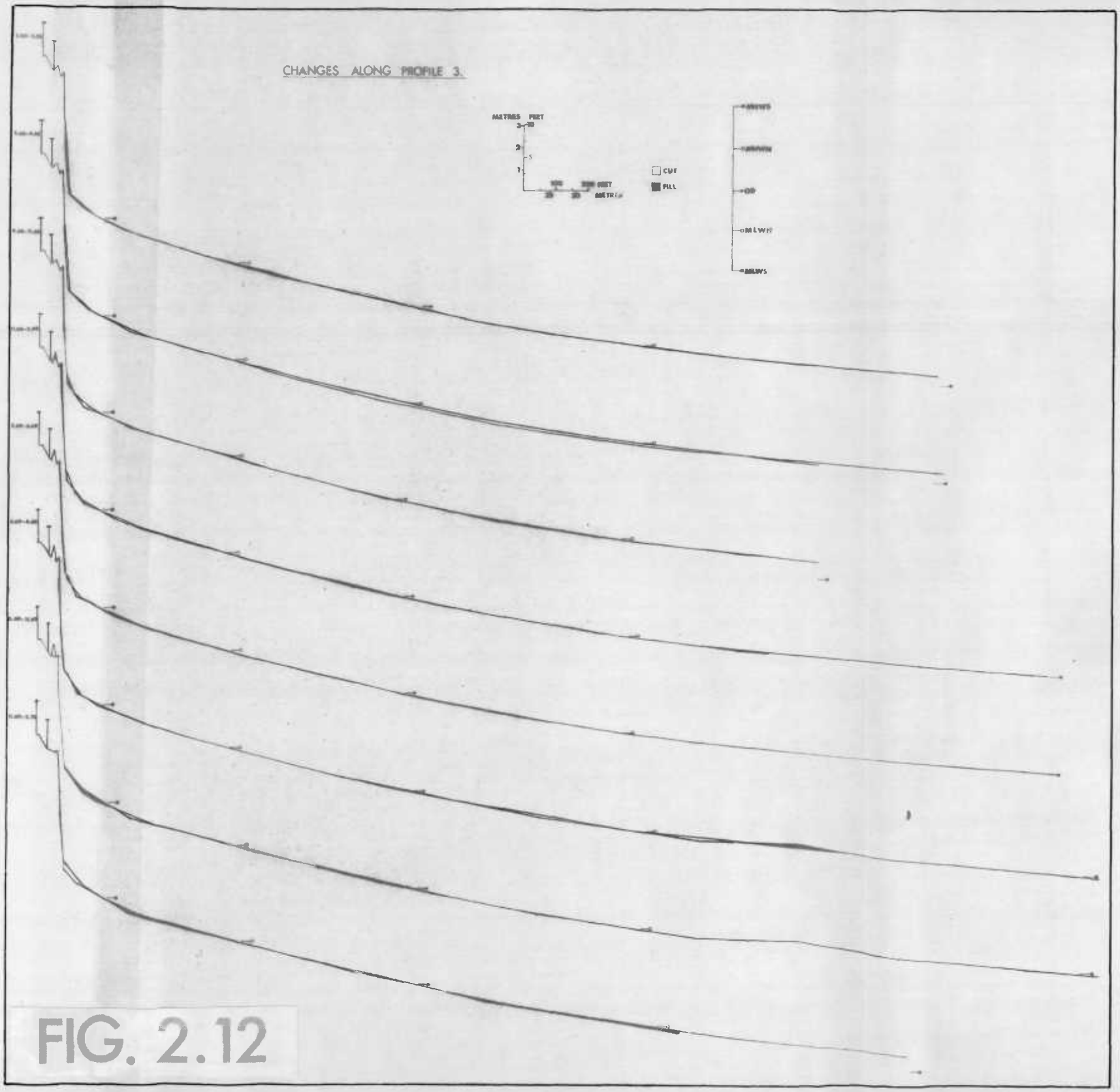


FIG. 2.12

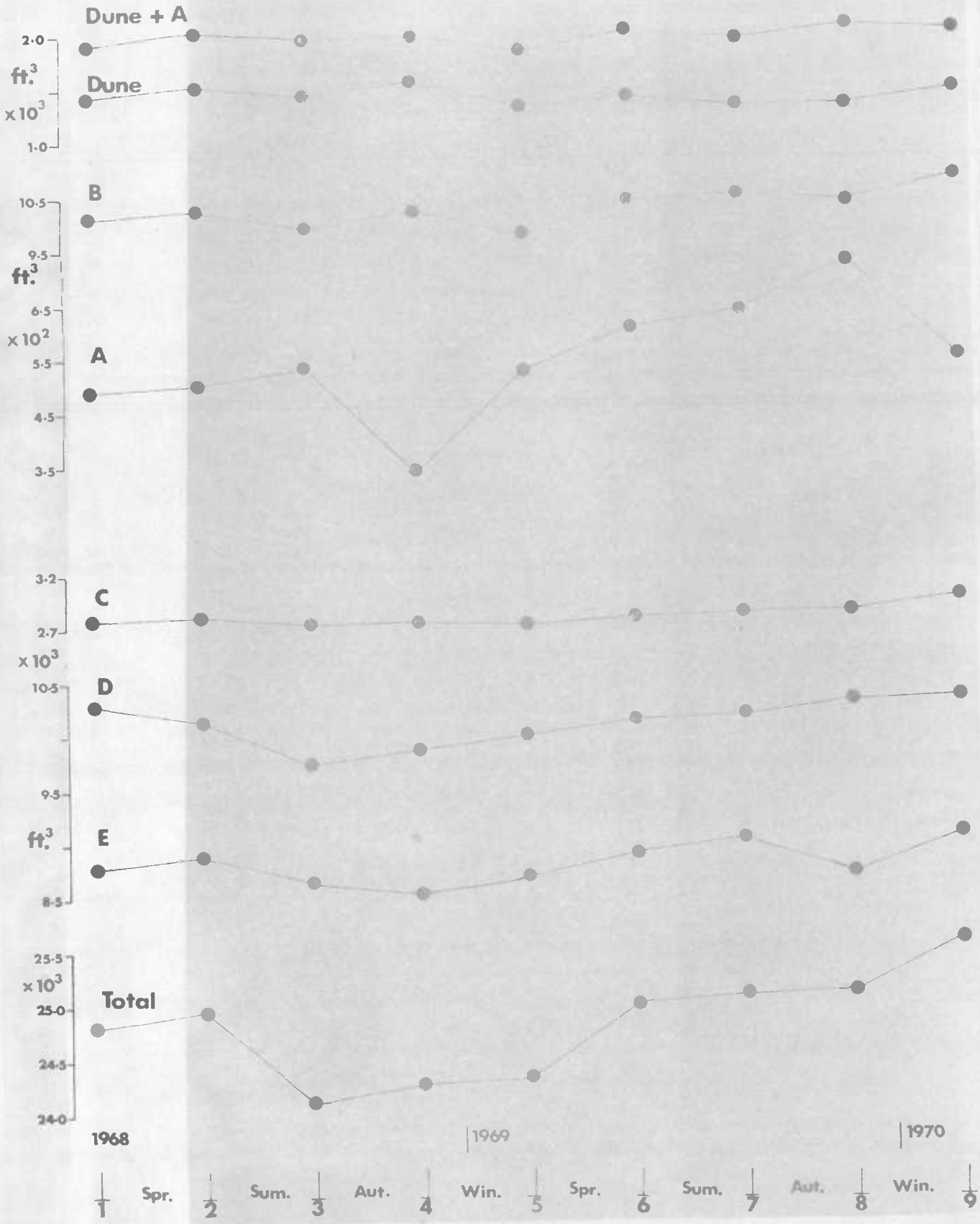


FIG. 2. 13 : VOLUMETRIC VARIATION, PROFILE 3.

Zone	Source of Variation	df	SS	MS	F
B	Among periods	7	.0187	.00268	2.1ns
	Within periods	8	.0103	.00129	
	Total	15	.0290		
C	Among periods	7	.0233	.00332	3.7**
	Within periods	24	.0217	.00090	
	Total	31	.0450		
D	Among periods	7	.0819	.01169	13.0**
	Within periods	48	.0433	.00090	
	Total	55	.1252		
E	Among periods	7	.0580	.00828	26.3**
	Within periods	40	.0126	.00032	
	Total	47	.0706		

TABLE 2.20 : Anovas, Profile 3.

each year) and greatest during May to August; this zone too filled predominantly during 1969-70.

Means of accretion and erosion for the homogeneous zones are:

C :	B	D	C	G	F	A	E	H
	-.18	-.18	.05	.05	.10	.18	.20	.28
D :	B	A	H	F	E	G	D	C
	-.48	.10	.03	.05	.15	.15	.18	.18
E :	B	G	C	A	D	F	E	H
	-.38	-.05	.00	.05	.13	.13	.02	.35

No period can be described as exceptional with regard to zone C. But period B was again characterised by an exceptional

cut in zones D and E, following the southwesterly gales the day before survey 3. Survey 2 was conducted on the same day as the corresponding survey of profile 1, (the day before most of the survey of profile 2) so that period A did not reflect the cut measured on profile 2 and is in accord with the change measured on profile 1.

Zone E also received an exceptional fill during period H, but there is no correlation with meteorological conditions immediately prior to survey 9; these were calm. However, period H was characterised by the greatest frequency of westerly (relative to easterly) high waves ($\geq$ 2 metres) recorded during the study period; very high waves and long period waves from the west were not more frequent at that time. Hence it is probable that westerly waves produced a mean accretion in this zone, but storm waves from the south-west produced a mean erosion by moving sand offshore. It is noteworthy that during period H the total profile was also exceptionally unstable (see section 2.3) following those westerly waves, though the resulting accretion was not exceptional (section 2.4).

As shown in Table 2.21, zones below MHWST were generally alike in temporal fluctuations, maintaining significant correlations. Unlike profiles 1 and 2, the foreshore above

MHWST tended to respond in common with the foreshore below MHWST. With the exception of period B, the dominant change was of accretion, the net gain of sand being common to the total profile. This sand was certainly not derived from the dune and must therefore have been transported from offshore or alongshore. Since the majority of large waves and strong winds are onshore and/or westerly, the obvious source of this material is Carmarthen Bay or the western part of Pendine Sands. The latter is a likely source since a greater net loss was measured on profile 2 (1347 ft.^{3}) than the net gain measured here (751 ft.^{3}) Hence the accretion in zone E attributed to westerly waves may well be indicative of a prolonged littoral drift of sand from profile 2 to profile 3. The net gain is however not very great in comparison with the exceptional loss prior to survey 3 which was in fact about the same (752 ft.^{3}).

	Dune	Dune + A	A	B	C	D
A	-.78*					
B	.17	.37	.30			
C	-.01	.67*	.42	.94**		
D	.10	.37	.48	.68*	.76*	
E	-.34	.42	.58	.78*	.83**	.80**

TABLE 2.21 : Correlation, Transect 3.

(d) Surveys of Transect 4.

Successive surveys of transect 4 are superimposed in Fig. 2.14. The greatest recorded fill at any station was .55 ft. and the greatest cut .70 ft.; the maximum change between surveys was 631 ft.^{3} per unit width of foreshore. Volumetric data in ft.^{3}, are shown in Table 2.22 and Fig. 2.15.

The overall volume of the dune has increased substantially during the study period as the result of an abrupt period of accretion during spring, 1969 (period E, between surveys 5 and 6). There was no unusual meteorological activity immediately prior to survey 6, but in any case 470 ft.^{3} of sand would hardly accumulate in a few days. However, the period between surveys 5 and 6 was the only one in which a greater frequency of winds (both prevailing and dominant) had an easterly rather than a westerly component. The source of this new dune sand was, therefore, the eastern half of Pendine Sands and/or Laugharne Sands. Subsequently, the dune was effectively eroded but still maintained 195 ft.^{3} of sand in March, 1970 in excess of the volume in February, 1968.

Variation of zone A is simply a mirror image of that in the dune. Combination of the two produces a unit that varied in a consistent manner during both years of study. The unit

	SURVEY								
ZONE	1	2	3	4	5	6	7	8	9
Dune	521	504	523	528	471	941	763	679	716
Dune + A	1321	1379	1324	1324	1415	1525	1483	1445	1451
A	800	875	801	796	944	584	720	766	735
B	1721	1660	1703	1711	1749	1783	1764	1754	1734
C	5010	4991	4883	4824	4969	5075	4976	5029	5049
D	17741	17345	17385	17426	17703	17627	17901	17870	18144
E	14504	14291	14540	-	14288	-	14670	-	-
Total	40,297	39,666	39,835	-	40,124	-	40,794	-	-
Total - E	25,793	25,375	25,295	25,285	25,836	26,010	26,124	26,098	26,378

TABLE 2.22 : Volumetric data ($ft.^3$), Transect 4.

CHANGES ALONG PROFILE 4.

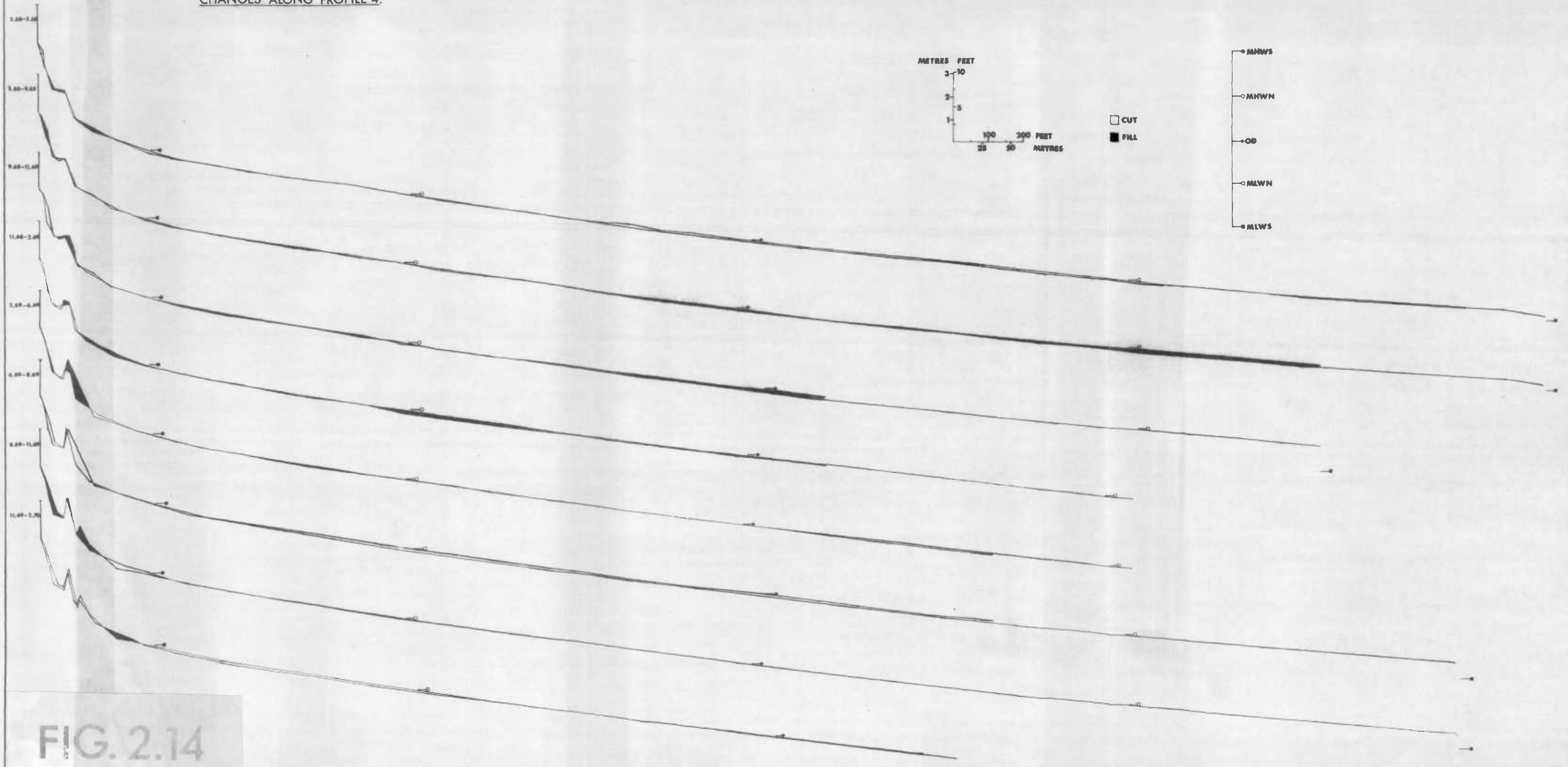


FIG. 2.14

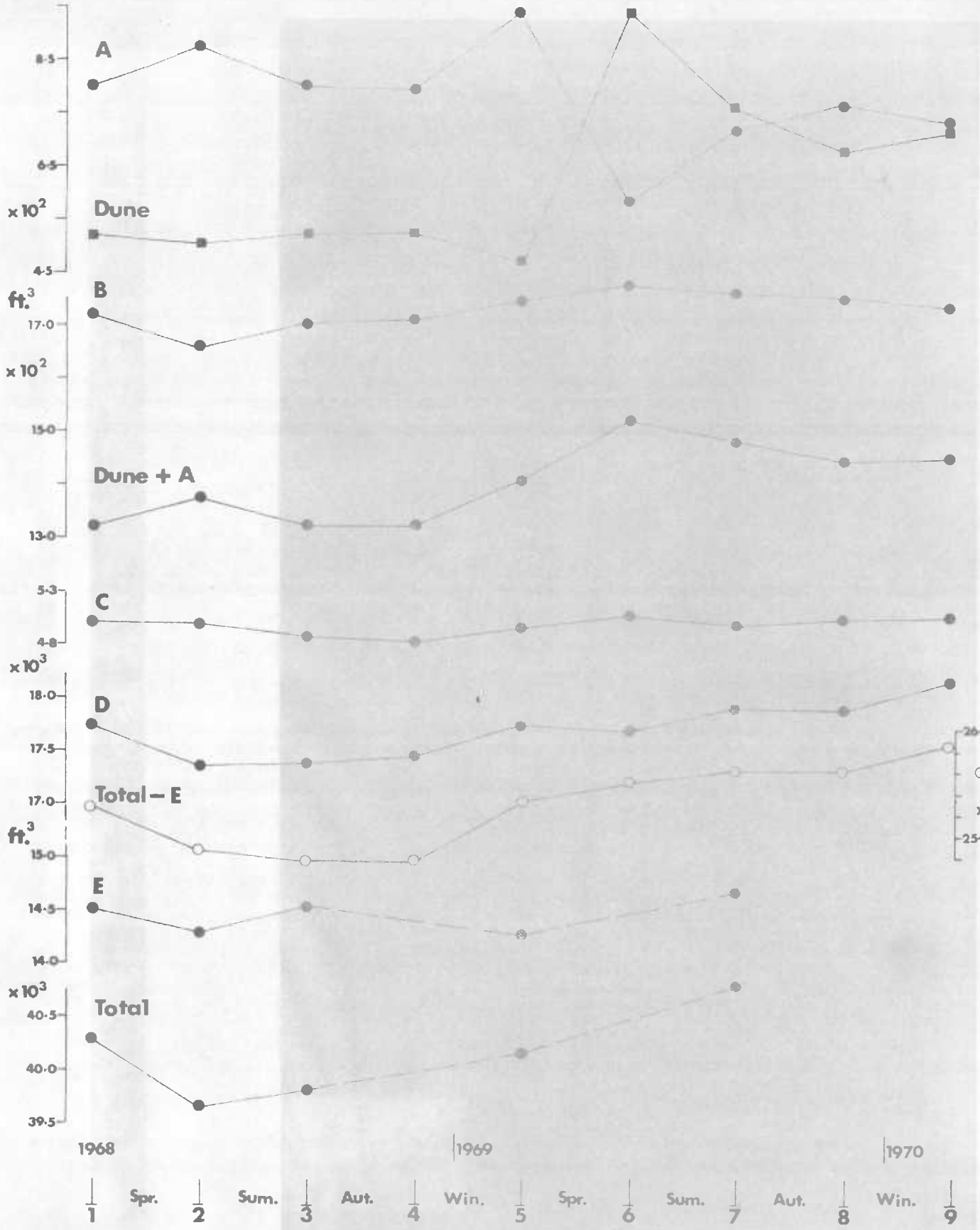


FIG.2.15: VOLUMETRIC VARIATION, PROFILE 4.

was at a maximum in early summer (May/June) and a minimum in early winter (November). This rhythm is similar to that noted on earlier profiles.

The anovas for zone B-D are shown in Table 2.23. Only five out of nine surveys contained the whole of zone E; since the between-survey periods are in no way orthogonal, an analysis of variance has not been attempted for this zone.

Zone	Source of Variation	df	SS	MS	F
B	Among periods	7	.0097	.00138	6.3**
	Within periods	24	.0053	.00022	
	Total	31	.0150		
C	Among periods	7	.0352	.00503	9.7**
	Within periods	40	.0207	.00052	
	Total	47	.0559		
D	Among periods	7	.0709	.01013	20.5**
	Within periods	88	.0434	.00049	
	Total	95	.1143		

TABLE 2.23 : Anovas, Profile 4.

Zones B, C and D were effectively homogeneous in response. The cycle of temporal variation of each (as indicated by surveys) was not seasonal. Accretion was dominant in the surveys of zone B from May 1968 to June 1969, but erosion at other times, so that the net change was negligeable. Fluctuations of zone C were also random and the net change small.

Fluctuations of zone D were much more pronounced, leading to a net accretion. Very little can be deduced from the scanty data for zone E.

Means of relative temporal changes for the homogeneous zones are:

B :	A	H	F	G	D	C	B	E
	-.21	-.09	-.04	.00	.02	.05	.11	.11
C :	B	F	C	A	H	G	E	D
	-.26	-.13	-.11	-.07	.03	.07	.15	.26
D :	A	G	E	B	C	F	H	D
	-.28	-.07	-.03	.02	.05	.18	.19	.22

Only with regard to zone D can any period be considered as exceptional. Survey 3 was conducted on the same day as the corresponding survey of the upper foreshore of profile 2, and, like that portion, recorded a significantly large cut following the additional exposure to swell from the southwest. This cut is also in evidence in zone B, to such an extent that in both zones B and D, the southwesterly gales prior to survey 3 did not effect a larger cut and so period B showed an apparent fill. However, on zone C, these gales were sufficient to further reduce the profile height from its level at survey 2.

The means of total relative change for this profile, excluding zone E, (see section 2.4) show that period D68 (designated D in this section) was characterised by exceptional

accretion. From Fig. 7(a) it is apparent that the week prior to survey 5 was dominated by easterly winds and waves, and it would seem very probable that these conditions were responsible for the mean accretion recorded by that survey.

Table 2.24 shows the correlation coefficients for contemporaneous volumes of zones (including the available data for zone E).

	Dune	Dune + A	A	B	C	D
A	-.92**					
B	.73*	.75*	-.59			
C	.60	.70*	-.42	.45		
D	.45	.55	-.29	.60	.59	
E	.80	.19	-.96**	.55	-.23	.49

TABLE 2.24 : Correlation, Transect 4.

The volumes of zones below MHWST do not correlate significantly. This is perhaps because the foreshore on this profile was more stable than on any other, and between-survey changes were very small so that differences between zones in response to the ebbing tide (presumably the smallest scale fluctuations of all) become relatively important. The foreshore above MHWST tended to respond conversely to the remaining foreshore, most significantly to zone E, but this is probably a reflection of fluctuations in the dune. The dune (or dune + zone A) was significantly in step with the foreshore

of zones B and C. These correlations show that the source of new dune material lay beyond the immediate area of foreshore, as has already been postulated.

The overall change on the total profile was of accretion, particularly from November 1968 onwards, totalling 585 ft.^{3} (excluding zone E, though the incomplete data suggest that inclusion of this zone could perhaps double the net accretion). This is not a large increase by comparison with the erosion that occurred in just a few days prior to survey 3, but if continued would increase the mean height of the foreshore by 1.2 ft. in ten years.

This accretion is perhaps an extension of the longshore drift from the west already discussed in relation to profiles 2 and 3. While profiles 1 and 2 suffered overall erosion during the study period, profiles 3 and 4 showed overall accretion. Do the magnitudes of cut and fill on adjacent profiles relate to each other? We can gain a rough idea of this in volumetric terms by considering the areas of foreshore between transects as trapeziums, thence computing the volumes of sand moved from, or into, each (assuming, of course, that the profiles are representative of the areas they enclose). The area enclosed by transects 3 and 4 has been extended eastwards by 1,000 feet, as far as the beginnings of the near-shore approach of the Taf Channel - half the distance to

transect 5 - this is reasonable since profile 4 is probably representative of this slice of the foreshore. It has been assumed that accretion in zone E was equal to 50% of the accretion on the rest of the profile. With these assumptions, the following volumes have been derived:

BLOCK	1-2	2-3	1-3	3-4
VOLUMETRIC CHANGE ($\times 10^6$ ft.^{3})	-3.92	-1.58	-5.50	+6.33

The balance between the net sand lost between transects 1 and 3 and the net sand gained between transects 3 and 4 is striking, and strongly suggests that a longshore drift from west to east was in fact operative during the study period.

(e) Surveys of Transect 5.

Successive surveys of transect 5 are superimposed in Fig. 2.16. Temporal variation was small over much of the foreshore, but the middle section was highly variable owing to the lateral migrations of a well developed ridge and runnel. Because of this, the mean cut and fill of that section was considerably greater than any encountered on other profiles. The largest fill recorded at any point on the profile was 1.88 ft., and the largest cut 2.17 ft. The lowest foreshore, zone E, was not often completely surveyed along this profile, and so has been ignored in both statistical and volumetric analyses.

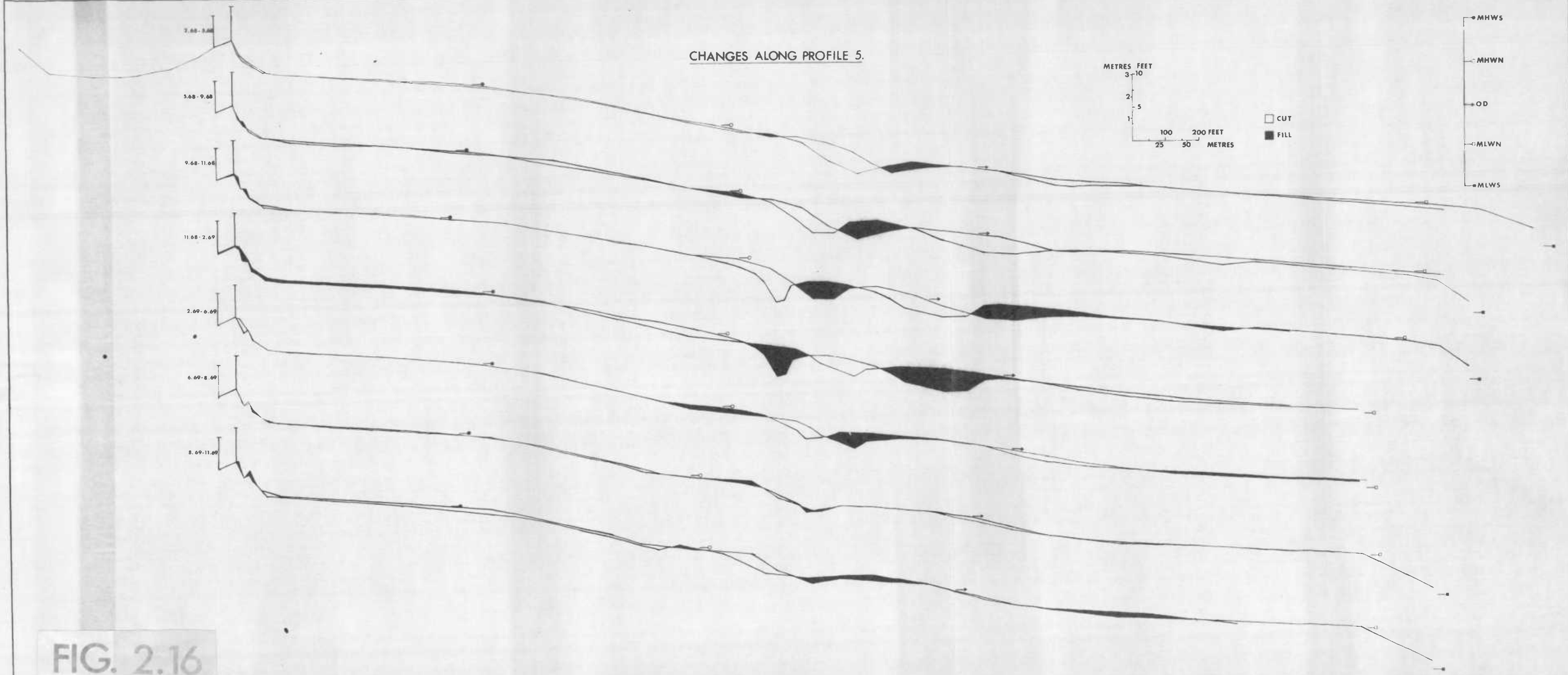

CHANGES ALONG PROFILE 5.
METRES FEET
3 10
2 5
1
100 200 FEET
25 50 METRES
CUT
FILL
MHWS
MHWN
OD
MLWN
MLWS
7.68 - 5.68
5.68 - 9.68
9.68 - 11.68
11.68 - 2.69
2.69 - 6.69
6.69 - 8.69
8.69 - 11.69

FIG. 2.16

Excluding this zone, the maximum change between surveys involved 1,364 ft.^{3} of sand per unit width of profile; data for zone E shows that this would be increased to some 3,000 ft.^{3} for the total length of profile.

Volumetric data, in ft.^{3}, are shown in Table 2.25 and Fig. 2.17.

The volume of the dune increased considerably during the study period, the greatest accretion occurring before surveys 3 and 8 (survey 9 is absent for this profile). Meteorological data does not provide a satisfactory explanation for these increases other than that the greatest relative frequencies of dominant winds from the west were recorded during periods B and G prior to each survey.

On this profile, zone A is much wider than on others, so that sufficient stations are available to allow a statistical analysis of data. Anovas for zones A-D are shown in Table 2.26. Because of the variations of cut and fill within zones C and D, 50 ft. stations have been employed, and because of the magnitudes of changes between surveys, the transformation log (x + 3) has been adopted rather than log (x + 1).

	SURVEY							
ZONE	1	2	3	4	5	6	7	8
Dune	115	93	245	244	244	236	189	263
Dune + A	1316	1228	1050	1034	1357	1299	1232	1122
A	1201	1135	805	790	1113	1063	1043	859
B	3830	3815	3558	3650	3635	3610	3585	3344
C	7506	7441	7381	6908	6930	7000	7015	6753
D	20336	19779	18910	19125	19239	19494	19104	19189
E	16989	-	15843	-	-	-	15541	-
Total -E	32,988	32,263	30,899	30,717	31,161	31,403	30,936	30,408

TABLE 2.25 : Volumetric data ($ft.^3$), Transect 5.

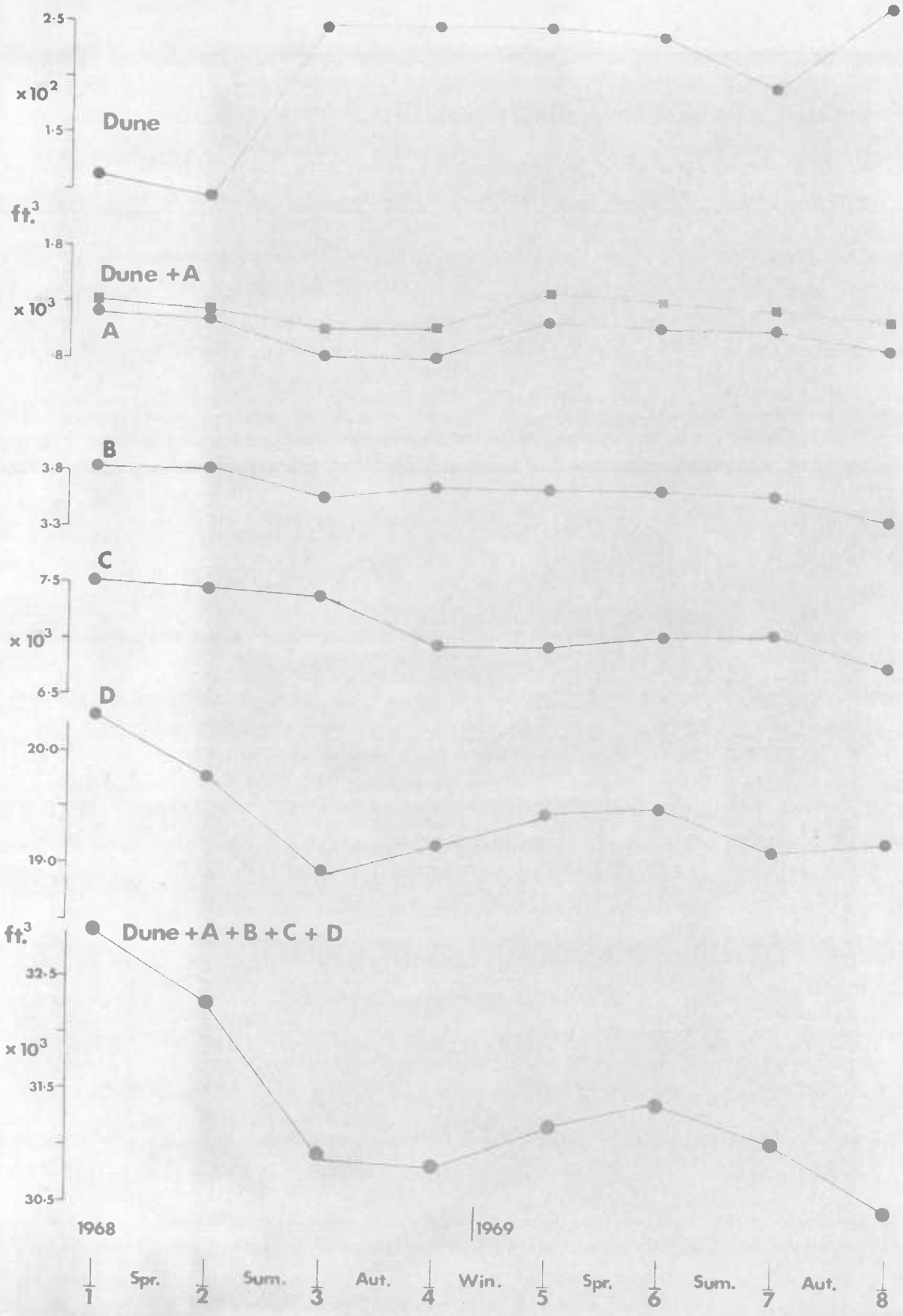


FIG. 2.17: VOLUMETRIC VARIATION, PROFILE 5.

Zone	Source of Variation	df	SS	MS	F
A	Among periods	6	.0825	.01374	21.8**
	Within periods	42	.0263	.00063	
	Total	48	.1088		
B	Among periods	6	.0340	.00566	8.3**
	Within periods	21	.0143	.00068	
	Total	27	.0483		
C	Among periods	6	.0896	.01493	2.37*
	Within periods	77	.4845	.00629	
	Total	83	.5741		
D	Among periods	6	.0439	.00731	2.80*
	Within periods	175	.4575	.00261	
	Total	181	.5014		

TABLE 2.26 : Anovas, Profile 5.

Zones A and B were homogeneous in character, zones C and D less so. None of the zones demonstrated a seasonal cycle of change, but the net change in each was erosion. Means of cut and fill for each period in each zone are:

A :	G	B	A	E	C	F	D
	-.45	-.25	-.09	-.05	-.04	-.02	.38
B :	B	G	A	D	F	E	C
	-.45	-.43	-.13	-.10	-.09	-.08	.08
C :	C	G	B	A	F	D	E
	-1.38	-.57	-.50	-.24	.02	.12	.24
D :	B	A	F	D	G	E	C
	-.52	-.37	-.21	.03	.03	.03	.28

In zones A and B, periods B and G were exceptional. The likely cause for the cut of period B has already been discussed; the cut of period G is most probably related to other meteorological conditions in conjunction with tidal variation. The morning of survey 8 saw a strong gale blowing from the northwest, therefore with offshore and westerly components. That survey was one of the few carried out during a neap tide. Hence at that time a substantial portion of the profile (zones A and B) was exposed and the sand dry, and therefore readily transported. No erosion occurred on the lower foreshore of zone D at that time, since there aeolian entrainment could not occur. Also, no erosion was measured on profiles 1-4 which were surveyed the previous day. It is noteworthy that comparable northwesterly gales were in evidence seven days before these profiles were surveyed at that time, but during higher tides. Any resulting cut on the upper foreshore had been compensated before surveying.

Zones C and D were less homogeneous in response, and no period was strictly exceptional. However, it may be seen that the erosion of period B was important in these zones, but that of period G was maintained only in zone C - in zone D there was a small fill. Thus prior to survey 8 there was a movement of sand off the upper foreshore onto the lower.

In zone C, the cut of period C was the greatest between-survey change. As may be seen from Fig. 2.16, this was part of a progressive shoreward migration of the ridge and runnel that continued throughout the study period, but most particularly during 1968 when their morphology was most developed. The system of ridges and runnels is situated below MHWNT, and cannot therefore be attributed to swash action at tidal still-stand, except during the lowest tides. It is more likely that these features are formed at, or near, the break point of large waves and should perhaps be termed submarine bars and troughs, though it is not clear why they are not destroyed by the ebbing tide, as described, in the case of model experiments, by King (1959).

However, the relationship of submarine, or longshore, bars to storm conditions has been confirmed (Shepard, 1950) and it is significant that long, high storm waves were recorded by the St. Gowan lightvessel with far greater frequency during 1968 than 1969 (Figs. 2.4 and 2.5). It has been shown that there are important associations between instability on this profile and onshore components of strong winds and high waves. These associations refer to overall mean absolute change. Correlation coefficients referring to mean relative change in zones C and D are shown in Table 2.27.

MET. INPUT	ZONE	VECTOR COMPONENTS					
		ONSHORE	OFFSHORE	RESULTANT	WESTERLY	EASTERLY	RESULTANT
PREVALENT	C	-.03	.41	-.45	.46	.40	-.08
WIND	D	.15	-.78*	.92**	-.75*	-.11	-.41
	C + D	.05	.02	.00	.10	.36	-.31
DOMINANT	C	-.52	.45	-.82*	-.46	.10	-.52
WIND	D	.78*	-.06	-.26	.34	.38	-.06
⩾20 KNOTS	C + D	-.22	.43	-.34	-.31	.33	-.56
DOMINANT	C	.20	.34	.08	.08	-.60	.47
WIND	D	.35	-.01	.42	-.53	.74	-.76*
⩾30 KNOTS	C + D	.39	.35	.30	.09	-.25	-.18
WAVE	C	-.56	.31	-.75*	-.14	.14	-.31
HEIGHT	D	.63	.17	.64	-.14	.59	-.45
⩾2 METRES	C + D	-.21	.40	-.44	-.09	.40	-.57
WAVE	C	-.85*	-	-.85*	-.40	-.46	-.27
PERIOD	D	.27	-	.27	.09	.49	-.10
⩾6 SECS.	C + D	-.75*	-	-.75*	-.37	-.22	-.33

TABLE 2.27 : Correlations, Profile 5.

Partly because of interaction between temporal and spatial variations, few correlations referring to mean relative change have previously been significant for this profile. But by considering each zone in isolation, several interesting associations become apparent. Erosion of zone C was related to the onshore component (either total observations or resultant onshore observations) of strong winds, high waves, and long period waves. Accretion in zone D was related to the onshore component of strong winds. Erosion of the combined zones (C + D) was related to the onshore component of long period waves. Thus it appears that dominant onshore vectors of meteorological input were associated with erosion of the nearshore area of the ridge and runnel system; generally some of this eroded material was deposited in the lower area of the system and some elsewhere; with very long period onshore swell, sand was eroded from the total ridge and runnel system.

In addition, the westerly components of prevailing winds (and therefore waves) and of very strong winds (resultant) were associated with erosion of zone D, the lower part of the ridge and runnel system. The resultant onshore prevailing winds were associated with accretion in that zone.

The reasons for the development of the ridge and runnel system parallel to the shoreline on profile 5 only is perhaps

a combination of a wide, gently sloping foreshore and offshore bars which provide a surfeit of sand. Offshore bars do not occur off the western half of the Pendine Sands. The rapid steepening of the bottom slope off profile 5 into the Taf channel provides an area of deep water between foreshore and offshore bars so that large waves can approach close to the foreshore before breaking. It is noteworthy that the shoreward migration of ridges and runnels was matched by a corresponding shoreward erosion of this deep water channel (where surveyed, see Fig. 2.16).

For the separate zones, only zone A experienced an exceptional accretion. This was during period D prior to survey 5. From Fig. 2.7(b) it may be seen that strong easterly winds were operative prior to that survey, and these were probably responsible for the measured fill above MHWST. The same period was also an exceptional one for a mean accretion of the total profile (i.e. zones A-D), as shown in section 2.4. High waves were generated by the strong easterly winds at this time, and as was the case for profile 4, transportation of sand from the east occurred. An exceptional mean fill over the total profile was also measured during period A69 (E in this analysis) as shown in section 2.4. Strong onshore winds and waves prevailed in the days before survey 6, but also before surveys

4 and 8 when no corresponding mean fills occurred. However, for the total period E, between surveys 5 and 6, prevailing winds (and therefore waves) were more frequently from the east than from the west (the only period when this was so) and so an eastern source for the accumulated material seems likely.

It may also be added that high easterly waves have already been shown to have an important association with accretion on this profile; and River Taf discharge with instability. It is significant that those periods of greatest discharge from the estuary (D, E and H) are also those in which large or exceptional accretion was recorded on both profiles 4 and 5 (there is of course no data for period H on profile 5).

Table 2.28 shows the correlation coefficients for contemporaneous volumes of zones (excluding zone E).

	Dune	Dune + A	A	B	C
A	-.71*				
B	-.82*	.42	.66		
C	-.77*	-.14	.42	.74*	
D	-.79*	.58	.77*	.72*	.59

TABLE 2.28 : Correlation, Transect 5.

The beach units generally correlate significantly, and as may be seen from Fig. 2.17, all showed a net erosion during the study period amounting to 2728 ft.^{3} (i.e. excluding the dune and zone E). If continued this erosion would lower the

mean height of the upper and middle foreshores by 4.6 ft. in five years.

It is very significant that the volume of the dune has increased significantly in step with the decrease of the foreshore, but this need not imply a causal relationship. Meteorological data does not provide a satisfactory link between them, but because of the nature of the profile on which a wide expanse of dry sand is often exposed, it can be envisaged that onshore winds could be a suitable agent.

(f) Surveys of Transect 6.

Successive surveys of transect 6 are superimposed in Fig. 2.18. The greatest recorded fill at any station was 1.69 ft. on the upper foreshore, and the greatest cut 3.15 ft. on the lower foreshore, by the Taf channel. Excluding zone E, the greatest between-survey change was 332 ft.^{3} per unit width of foreshore. Survey 4 was missed out on this profile, so that the number of near-orthogonal between-survey periods is reduced to six. Volumetric data in ft.^{3}, are shown in Table 2.29 and Fig. 2.19.

The volume of the dune decreased during the first half of 1968 but then increased substantially between surveys 3 and 5, continuing to increase more gradually till the end of 1969, but then drastically decreasing to less than its original

	SURVEY								
ZONE	1	2	3	4	5	6	7	8	9
Dune	55	55	38	-	68	68	73	70	1
Dune + A	340	319	382	-	268	307	382	311	380
A	285	264	344	-	200	239	309	241	379
B	745	773	856	-	838	761	813	809	853
C	2673	2808	2941	-	2831	2662	2785	2624	2554
D	8713	8566	8619	-	8430	8331	8388	8420	8275
E	6313	5759	5688	-	5655	-	-	-	-
Total	18,784	18,225	18,486	-	18,022	-	-	-	-
Total -E	12,471	12,466	12,798	-	12,367	12,061	12,368	12,164	12,062

TABLE 2.29 : Volumetric data ($ft.^3$), Transect 6.

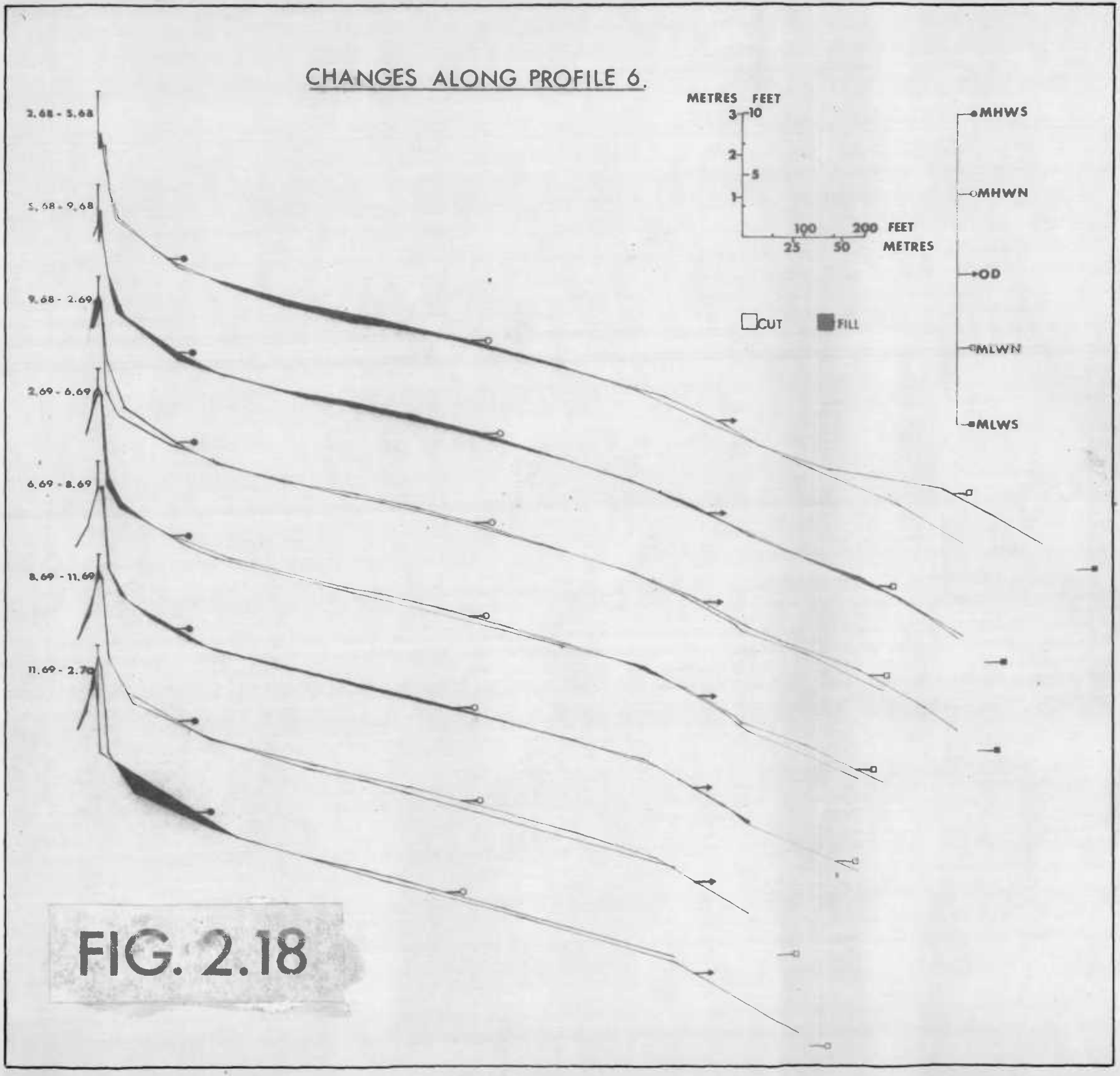

CHANGES ALONG PROFILE 6.
METRES FEET
3
10
2
5
1
100 200 FEET
25 50 METRES
CUT
FILL
MHWS
MHWN
OD
MLWN
MLWS
2.68 - 5.68
5.68 - 9.68
9.68 - 2.69
2.69 - 6.69
6.69 - 8.69
8.69 - 11.69
11.69 - 2.70

FIG. 2.18

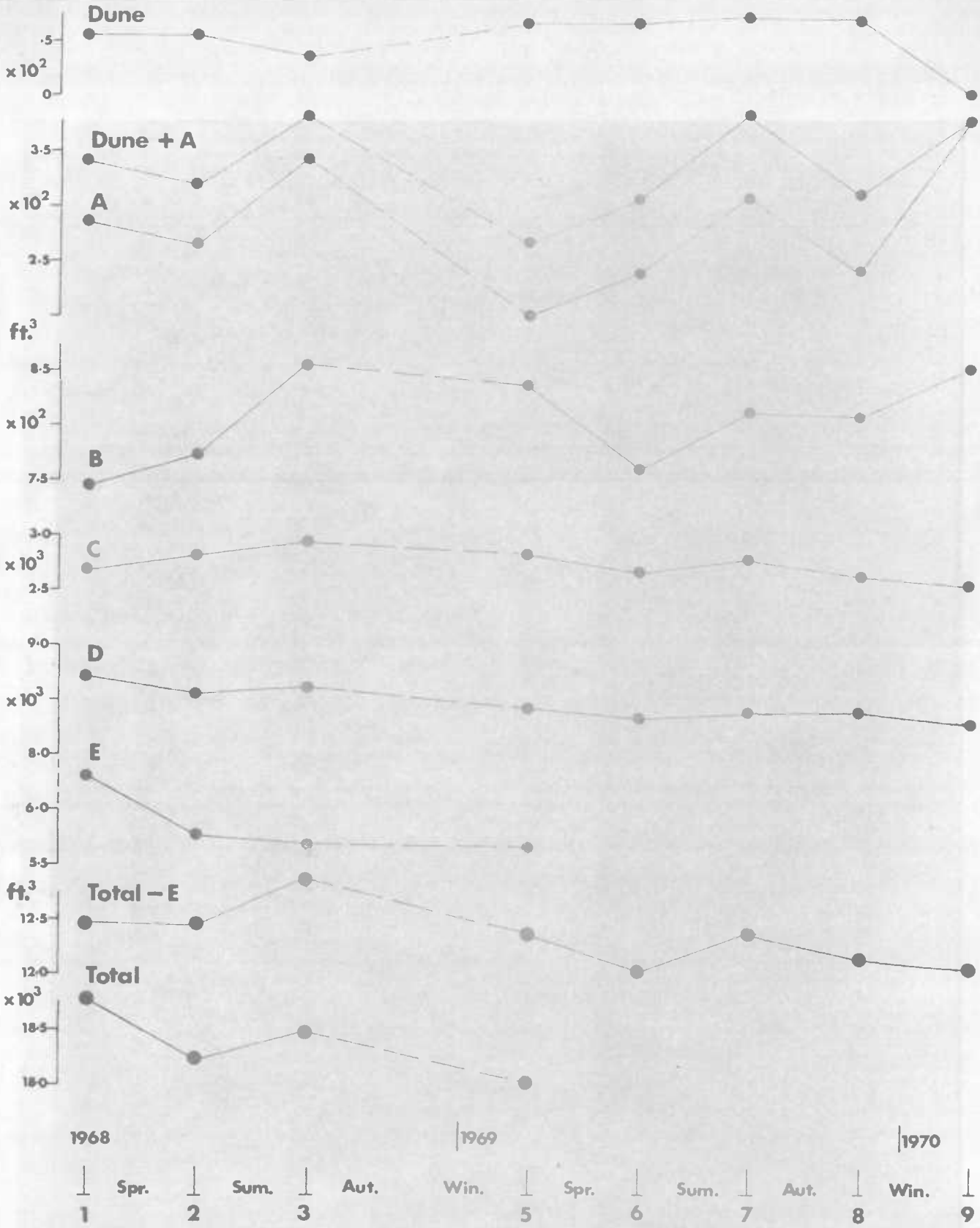


FIG. 2.19 : VOLUMETRIC VARIATION, PROFILE 6.

volume. On the last survey, the marker pole in the dune had been exposed to its concrete foundations and was on the verge of being undermined. This last substantial erosion, in winter 1969-70, may be related to the predominance of offshore components of prevailing and dominant winds at that time (see Fig. 2.3); a second significant cut between surveys 2 and 3 also occurred during a period of predominantly offshore prevailing winds. The equally substantial accretion of the dune between surveys 3 and 5 was probably brought about by a predominance of onshore prevailing and dominant winds during autumn 1969. At other times, when onshore and offshore wind components were more equally balanced, the dune remained stable.

Converse major fluctuations are found for zone A and zone (A + dune). Periods when there was a greater frequency of onshore winds, both prevailing and dominant, as between surveys 3 and 5, show erosion of the upper foreshore as sand was moved inland; periods when there was a greater frequency of offshore winds, as between surveys 2 and 3 and surveys 8-9, show accretion as sand was moved off the land and the dune onto the upper foreshore. The accretion occurring between surveys 5 and 6 was an exception to this pattern; as already pointed out in relation to dune building on profile 4, this was the only period when prevailing and dominant winds blew with greater frequency from

the east. The sand accumulating on the upper foreshore at this time was therefore probably derived from the vicinity of Ginst Point.

Anovas for zones B, C and D are shown in Table 2.30.

Zone	Source of Variation	df	SS	MS	F
B	Among periods	5	.0187	.00374	1.9ns
	Within periods	6	.0116	.00193	
	Total	11	.0303		
C	Among periods	5	.0681	.01363	34.3**
	Within periods	18	.0071	.00040	
	Total	23	.0752		
D	Among periods	5	.0365	.00731	3.1*
	Within periods	24	.0568	.00237	
	Total	29	.0933		

TABLE 2.30 : Anovas, Profile 6.

Variation among constituent stations of zone B are too great for the zone to be treated as a single entity, but zones C and D are effectively homogeneous. For the latter, the means of relative temporal changes are:

C :	E	G	H	F	B	A
	-.39	-.38	-.20	.23	.27	.32
D :	H	E	A	B	G	F
	-.42	-.32	-.13	.09	.05	.12

The means of zone C split into two homogeneous groups, one of accretion, the other of erosion. As can be seen from

Fig. 2.7(b), surveys 6, 8 and 9 were the only ones (other than survey 1 before which of course no between-survey change is known) that were preceded by onshore components of winds and waves; these are the surveys that describe the changes of periods E, G and H, all erosional in zone C. The relation of onshore strong winds to instability of the total profile has already been noted. At other times, accretion occurred in zone C.

No period may be considered as exceptional in relation to zone D. However the means of cut and fill show a highly significant association with River Taf discharge (correlation coefficient = -.89**); a high river flow may therefore result in erosion of this zone.

It is noteworthy that, unlike previous profiles, during period B (i.e. prior to survey 3) all parts of the foreshore, except zone E, experienced an insignificant accretion. The southwesterly gales that were important on the western and central portions of the beach, had no comparable effect on profile 6.

Table 2.31 shows correlation coefficients for contemporaneous volumes of zones (including available data for zone E). None of the associations are significant. This is probably because the interaction between temporal and spatial variations

of change on this profile is maintained among zones, as well as among blocks, since here each zone is barely larger than constituent blocks (because of the steep slope and reduced width of the foreshore). It is therefore more difficult to monitor changes on such a restricted length of profile than on earlier profiles. In addition, the absence of one survey (and therefore two between-survey periods) is a handicap of some magnitude when part of a comparatively short-term study.

	Dune	Dune + A	A	B	C	D
A	-.80*					
B	-.47	.32	.42			
C	.27	.02	-.10	.25		
D	.13	.04	-.03	-.35	.49	
E	.02	.21	.17	-.81	-.87	.78

TABLE 2.31 : Correlation, Transect 6.

(g) Surveys of Transect 7.

Successive surveys of transect 7 are superimposed in Fig. 2.20. The greatest recorded fill at any station was 4.38 ft. and the greatest cut 1.88 ft. both near the lower margin of the profile where it meets the Taf channel. Zone E was not often, and zone D not always, surveyed; but both zones are very narrow here. The greatest change between surveys on the remaining profile was 1501 ft.^{3} per unit width; inclusive of zone D

CHANGES ALONG PROFILE 7.

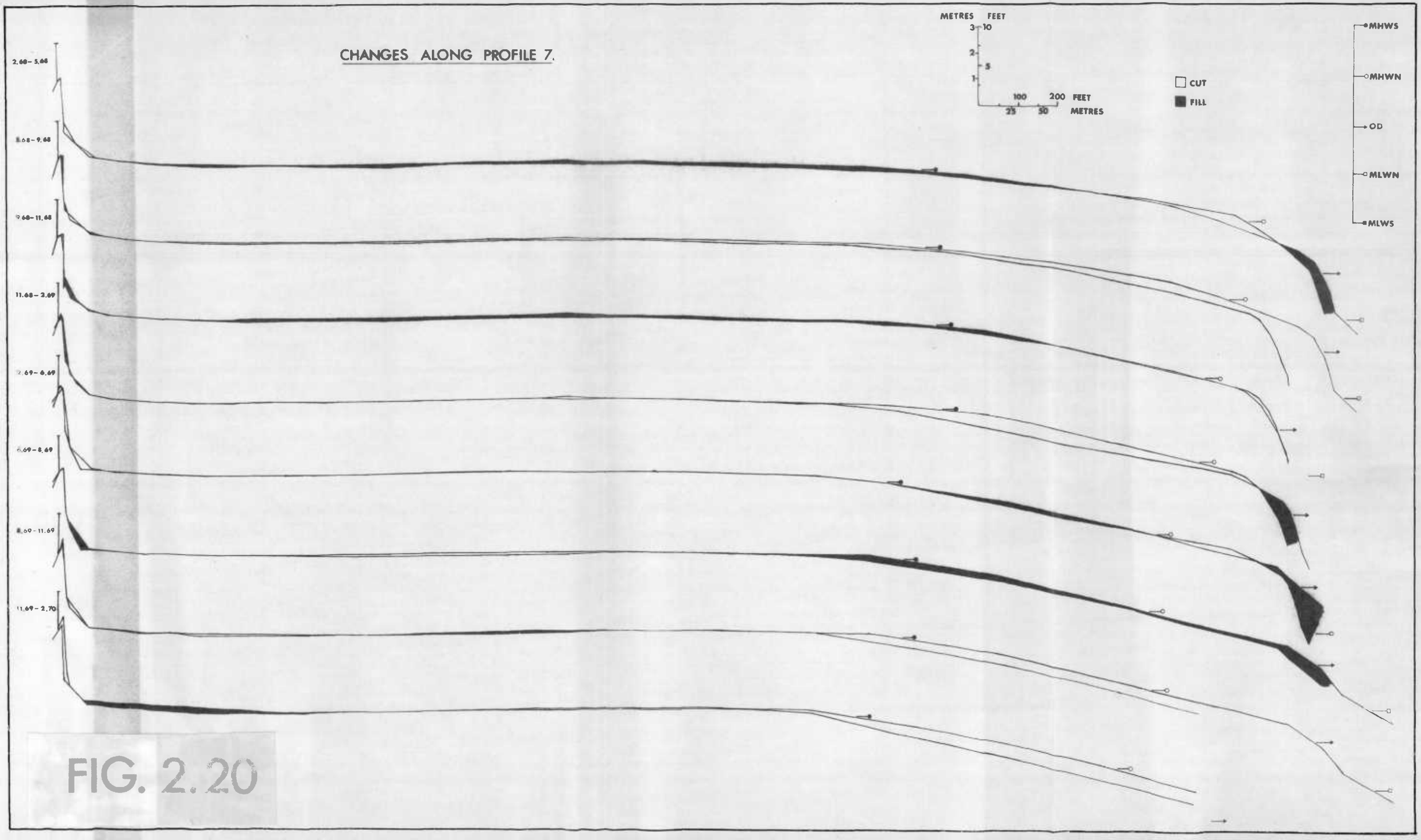


FIG. 2.20

a change of 2,262 ft.^{3} between surveys was measured. Volumetric data are shown in Table 2.32 and Fig. 2.21.

Net change in the dune was nil, but the dune was noticeably larger at survey 5 than at any other time. The agent of accretion prior to this survey is not readily apparent from the meteorological data, but the agent of subsequent erosion is probably the greater frequency of easterly prevailing and dominant winds than westerly winds during period E. It has been noted that at that time accretion occurred on the dune of profile 4 and the upper foreshore of profile 6, and it seems probable that these gains can be linked with the dune erosion of profile 7.

Most of this profile lies above MHWST, and so zone A is here extensive, providing sufficient stations for a statistical analysis. Zones D and E however, are very restricted because of the Taf channel and were not always surveyed; therefore they are not analysed statistically. Anovas for zones A, B and C are shown in Table 2.33. These zones were homogeneous in response to temporal change, but the surveys do not suggest a seasonal cycle of variation. Zone A showed a net accretion, zones B and C a net erosion during the study period. The incomplete data for zone D shows that the zone experienced a prevailing accretion but dominant erosion (particularly during

	SURVEY								
ZONE	1	2	3	4	5	6	7	8	9
Dune	76	85	99	76	145	76	93	105	73
Dune + A	1880	2691	2080	2789	2675	2537	2526	2513	2682
A	1804	2506	1981	2713	2630	2461	2433	2408	2509
B	8146	8251	7960	8086	7428	7510	7794	7441	6986
C	14890	14791	14299	14295	13785	13639	13710	13260	12831
D	27803	28094	27126	27060	27276	27660	27983	-	-
E	-	14820	-	-	14331	-	14973	-	-
Total -E	52,719	53,727	51,465	52,230	51,264	51,346	52,013	-	-

TABLE 2.32 : Volumetric data ($ft.^3$), Transect 7.

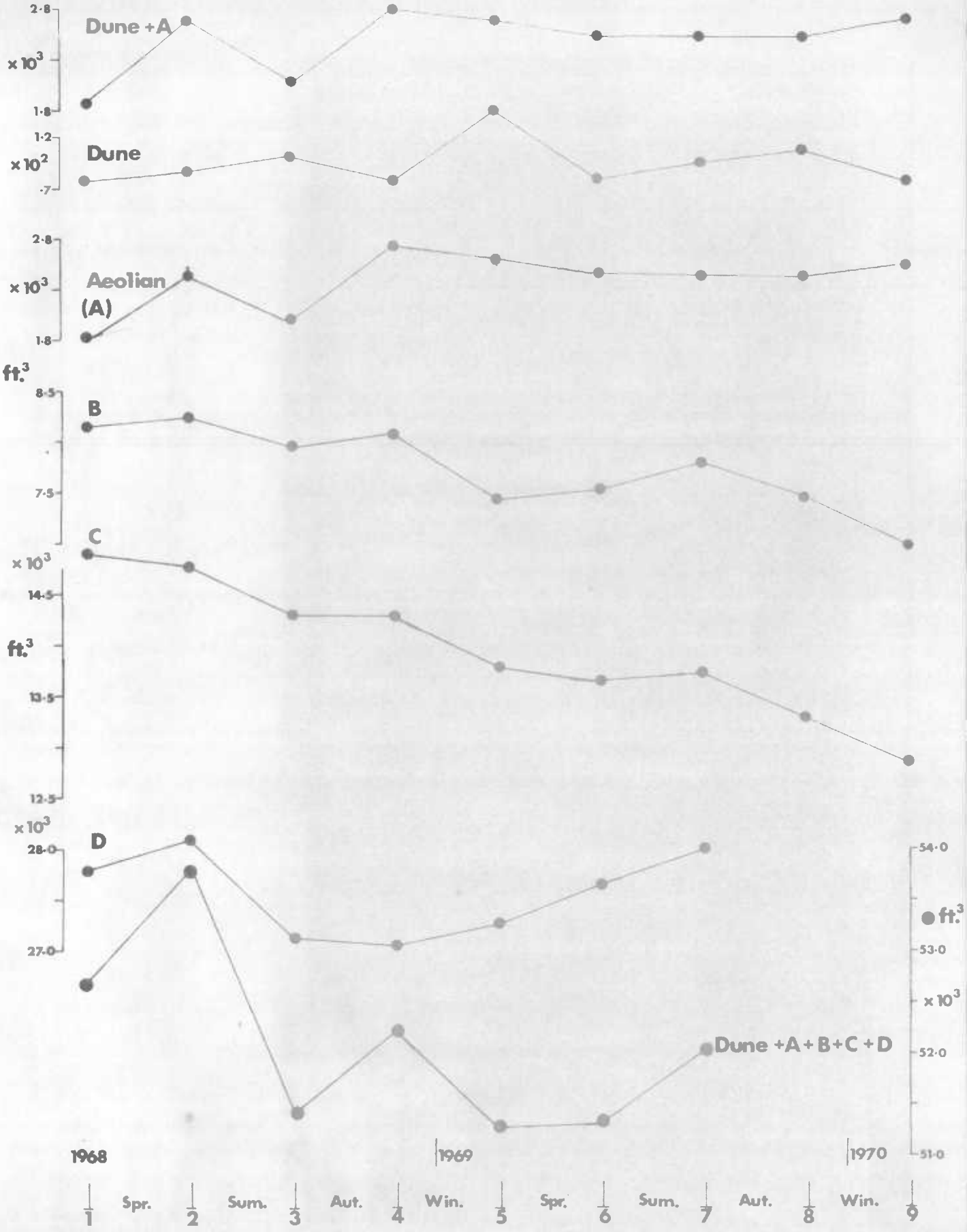


FIG. 2.21 : VOLUMETRIC VARIATION, PROFILE 7.

autumn and winter (1969). Data for zone E is too incomplete to interpret.

Zone	Source of Variation	df	SS	MS	F
A	Among periods	7	.1359	.01941	10.8**
	Within periods	160	.2879	.00180	
	Total	167	.4238		
B	Among periods	7	2.0291	.28987	36.5**
	Within periods	40	.3175	.00794	
	Total	47	2.3466		
C	Among periods	6	.2793	.04655	10.3**
	Within periods	14	.0632	.00451	
	Total	20	.3425		

TABLE 2.33 : Anovas, Profile 7.

Means of relative temporal changes for the homogeneous zones (excluding period H for zone C) are:

A :	B	E	D	F	G	H	A	C
	-.22	-.07	-.05	-.04	-.01	.01	.28	.31
B :	D	H	G	B	E	A	C	F
	-1.67	-1.47	-1.19	-.47	.06	.14	.35	.57
C :	G	D	B	A	E	C	F	
	-1.22	-1.07	-.95	-.68	-.64	.07	.23	

Temporal, relative to spatial, variation of accretion and erosion was very pronounced in these zones. Extensive erosion of zone A followed the southwesterly gale of period B prior to survey 3; undoubtedly the combination of storm and spring tides

enabled waves to substantially reduce the level of this zone (grain-size characteristics of sand from this zone indicate that it is primarily wind-blown and sorted). There is no characteristic of meteorological input common to both periods A and C to account for the exceptional accretion that occurred at those times in zone A. Indeed the accretion of period A cannot be accounted for. But that of period C may be related to the southeasterly gales prior to survey 4 (see Fig. 2.7(b)) which may have moved sand onto the aeolian flat from offshore at times of low water (there is an extensive pattern of sand flats and bars associated with the confluence of the Taf and Towey estuaries to the south-east of Ginst Point and exposed for long periods near low water).

Below MHWST, in zone B, periods D, G and H were of exceptional erosion. The first and last, winters 1968 and 1969, appear to match the very high river flows monitored at that time - correlation is very nearly significant for mean relative change and river flow for all periods ($r_{12} = -.70$; $r_{.05[6]} = .71$) but highly significant ($r_{12} = -.91^{**}$) if period G is ignored. It is therefore legitimate to assume an important relationship between erosion and increased river discharge, supposing that an additional factor was involved in the erosion of period G (when river flow was small). It may be suggested that the erosion

of the lower foreshore from autumn 1969 onwards were the result of a seaward migration of the Taf channel and variation of the offshore configuration of bars and channels, exposing the foreshore to a new element of wave attack and bringing about a readjustment to a more uniform slope over a wider foreshore. In this way some sand previously in zones B, C and D was moved offshore to restore an equilibrium profile. Alternatively the cut of period G may be related to exceptionally heavy seas from the south prior to survey 8 - the association of onshore (i.e. from the south) very strong winds and erosion of the total foreshore has already been noted.

No period may be regarded as exceptional in terms of accretion for zone B, but with the exception of period G, there is a close correspondence between cut and fill and river discharge. The greatest fill occurred when river flow was least (period F).

In zone C, periods C and F were exceptional since each witnessed a mean accretion whilst at all other times there was a mean erosion. Taf flow was low for both periods, but does not correlate significantly for all periods. The only meteorological characteristics of each period that were exceptional were south-easterly gales before survey 4 which may have brought about an apparent mean accretion for period C (this has already been

suggested for a similar fill on the aeolian flat) and the greatest frequency of westerly prevailing winds that occurred during period F (see Fig. 2.3).

The results of an analysis of relative change along the total profile (i.e. in this case zones A, B and C) have already been presented (section 2.4). There it may be seen that both winters 1968 and 1969 were exceptional in producing extensive erosion of the foreshore, and at those times Taf discharge was at a maximum. However, if the incomplete data for zone D is included, then in addition to those periods both period B and period G produced exceptional erosion - these may have been caused by south-westerly and southerly gales respectively prior to surveying. Other associations have already been presented, but these were based on correlations including all periods, not exceptional ones.

Table 2.34 shows correlation coefficients for contemporaneous volumes of zones (excluding zone E). The lower part of survey 9 has been extrapolated for 100 ft. to complete zone C.

	Dune	Dune + A	A	B	C
A	.19				
B	-.21	-.34	-.34		
C	-.13	-.44	-.43	.95***	
D	-.31	-.05	-.35	.63	.19

TABLE 2.34 : Correlation, Transect 7.

Associations between zones are lacking, with the exception of a close relationship between zones B and C. Thus that part of the foreshore below MHWST, but above the abrupt change of slope at the Taf channel, may be considered as an homogeneous unit. The volumes of the dune and of the foreshore above MHWST are largely independent of the volume below MHWST.

The net change in the volume of the total profile was one of erosion, and this is believed to reflect migration of the Taf channel and consequent readjustments of bars and channels in the lower estuary and offshore, as well as the influence of meteorological input.

2.8 Seasonal variations.

It is evident that the course of study outlined above has been unsatisfactory in many ways. Because of the comparative stability of the foreshore, errors in experimental technique have become apparent and must be accounted for; these errors are not those connected with actual measurement (since these have been ignored) but are related to shortcomings in experimental design.

Firstly, it has been shown that the lack of randomness in surveys undermines a basic assumption of the experiment, namely that surveys were representative of seasonal, or periodic,

samples. Correlation of between-survey changes with between-survey meteorological input becomes meaningful only when the comparative durations of between-survey periods are introduced into the analysis. Such correlations are generally not significant if between-survey periods are considered as seasons of equal duration.

Secondly, the nature of the design was not particularly suitable for monitoring seasonal fluctuations. This was owing to the bias inherent in the design. Each survey was a single sample of some population (seasonal) which may, or may not, have been representative of that population. The only estimate of variability obtainable from a series of such single samples is a measure of between-sample variation; if, however, several samples (or surveys) of the seasonal population were taken (on successive days, or even weeks) then a measure of within-sample variation is obtained. Should greater variability exist within samples than between samples, then an estimate of the latter alone may be seriously biased. It would appear that within-sample variation due to daily fluctuations of meteorological input has introduced bias into the present study, so that some between-survey changes have been spuriously boosted and do not represent truly seasonal changes.

The results of bias in the surveying programme can therefore

be important, especially when the duration of the study period is short and if the possible effects of short-term changes are not considered. This can be shown if some of the methodology of Inman and Rusnak (1956), whose experiment was unbiased, is adopted. If in each zone (A-E) of a profile, the mean volume during the study period is calculated, then each survey can be considered as a deviation (plus or minus) from that mean. Then a seasonal (based on survey times) average of deviations from the mean can be calculated. On many profiles, such an analysis leads to the apparent conclusion that the volumes of zones below MHWST were less than the mean during the summer months and greater during the winter. For example, Table 2.35 shows the results of this analysis for profile 3 (data in $ft.^3$).

	Dune	Dune+A	A	B	C	D	E	Total
Feb	-21	-47	-26	-1	+17	+104	+26	+98
May	-48	+44	+12	+7	-1	+20	+62	+131
Aug	-60	-20	+40	-10	-25	-150	+13	-42
Nov	+58	+48	-10	+6	-1	-26	-111	+28
Mean	1459	2007	548	1032	2828	10142	8855	24,865
Sep-Feb	+19	+1	-18	+3	+8	+39	-43	+63
Mar-Aug	-54	+12	+26	-2	-13	-65	+38	+45
Jun-Nov	-1	+14	+15	-2	-13	-88	-49	-7
Dec-May	-35	-2	-7	+3	+8	+62	+44	+115

TABLE 2.35

It is apparent that a consistent differentiation of accretion (> mean) and erosion (< mean) is obtained when the year is divided into two groups, June - November and December - May. However, in this case, the conclusions are false and the results spurious, since they are severely weighted in favour of summer erosion by the exceptional cut recorded by survey 3 in September 1968. If day to day variations are not taken into account, then survey times must be much closer together and the study period extended in order to reduce such biased weighting.

Thirdly, it has been shown that more significant associations of beach changes with meteorological input are apparent when these changes are considered in terms of total instability rather than of mean accretion or erosion. This would imply that the surveys have not been complete and should extend into the sub-littoral in order to gauge the true extent of between-survey change.

Fourthly, it is apparent that there are discrepencies in response between adjacent profiles. Because of the distance between transects, this is perhaps hardly surprising, but practical expediency did not allow for more profiles on closely-spaced transects. The design of the surveying programme has resulted in a very unbalanced monitoring of the foreshore in its three spatial dimensions.

Finally, it has become apparent that because of the small magnitude of beach changes and the nature of the errors outlined above, the results of the study are meaningless unless considered beside meteorological data. No measurements of wind and wave parameters were made at the same time as surveying. Data from the St. Gowan lightvessel has been used, but is obviously less satisfactory than local data obtained from the nearshore zone. It is certainly of some significance in this respect that the modification of wave characteristics from deep water to shallow water is not based on a linear relationship, as was assumed in the correlation analyses; the neglect of the effects of wave refraction may be of even greater consequence.

Three of these shortcomings could be readily overcome in any future study. The profiles must be surveyed more frequently, and at regular intervals, and for a longer period of time, concurrent with estimates of wind vectors and nearshore wave parameters; then a more rigorous correlation analysis of beach changes and meteorological input can be attempted and, more important, the effects of different combinations of wind and wave components, since as was shown by King (1953) these can be significant. Because of the, perhaps, prime importance of the interaction between meteorological processes and the complications arising from feedback mechanisms, the approach attempted in this

study was most unsatisfactory since it ignored both of these factors. A considerably greater density of information would be required before such factors could be investigated.

Unfortunately, without divers, it is probably impossible to extend the surveyed profiles below low-water mark since echo-sounding techniques are of insufficient accuracy to measure the small changes measured by levelling techniques.

As pointed out at the beginning of this chapter, levelling techniques are very accurate but slow in operation, and demand two operators. These factors would certainly hamper the operation of such techniques in an experiment requiring frequent measurements. An alternative, and equally accurate, method would be to set up permanent markers across the foreshore against which beach height could be easily measured by one operator in a short time. It has been shown that good results can be obtained from markers 100 feet apart on most profiles, and 50 feet apart on others. In such an a priori situation, several markers should be set up at each station so as to provide true replication of measurements. Such measurements provide a source of data as accurate as any from levelled profiles, more readily manipulated by statistical and quantitative methods of analysis. The most convenient form of marker at each station is a reference rod such as that adopted by Inman and Rusnak (1956), but such a

method is both aesthetically offensive and dangerous to swimmers. The method devised by Williams (1971) is perhaps the most appropriate, based on the principle of a change in frequency noticed when an oscillator is passed over a metal plate buried in the beach face, thus enabling the precise location of each station to be found.

In spite of the shortcomings in the experimental design and resulting inelegance of the subsequent analysis, it is considered that some meaningful results have been obtained from the study. Quantitative estimates of the relative magnitudes of temporal and spatial variations of periodic change have been attempted for each surveyed transect; it has been shown that the surveys do not delineate any seasonal variation. Qualitative and quantitative correlations between beach changes and meteorological input have been examined in terms both of cumulative meteorological input between surveys and of exceptional meteorological input immediately prior to surveying. Several important associations have been found. These have been summarised in Fig. 2.22. In the light of these, can it be postulated that there was indeed a seasonal cycle of variation that was missed because of bias and lack of randomness in the experimental design?

This possibility can be approached by looking for seasonal cycles of variation within the particular meteorological vectors

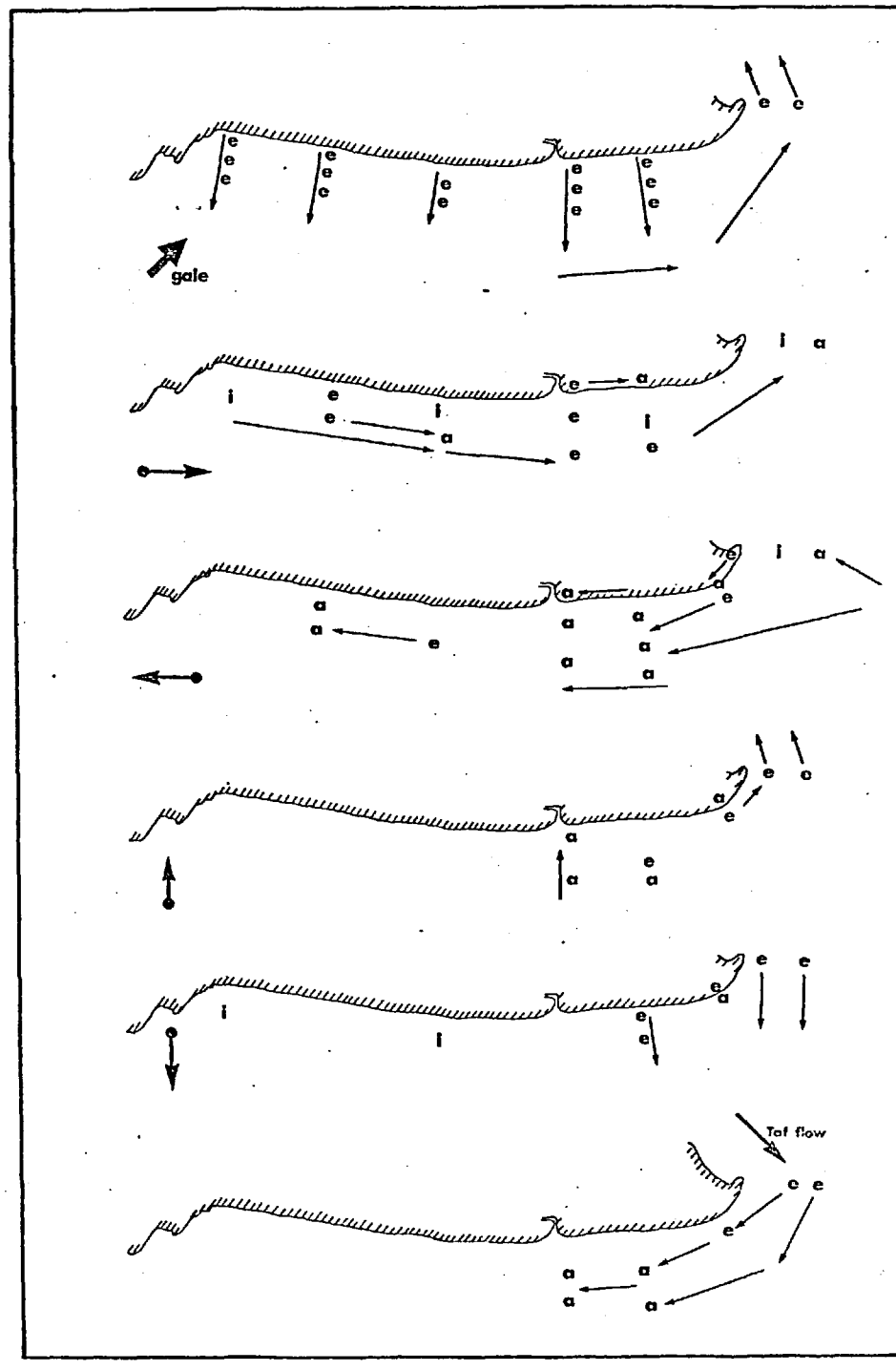


FIG. 2.22: SUMMARY OF PROCESS/RESPONSE RELATIONSHIPS.

a=accretion; e=erosion; i=instability

that have been shown to have important connections with accretion and erosion.

Considering first those components of meteorological input that have been shown to have a quantitative association with beach change : Here seasons are approximately as defined by the vernal and autumnal equinoxes and the summer and winter solstices, and are therefore independent of survey times (previously seasons have been roughly designated with reference to surveys); Jan - Mar (A), Apr - Jun (B), Jul - Sep (C), Oct - Dec (D). Meteorological data has been obtained for the period February 1968 - March 1970, and the mean monthly number of observations of each component (after resolution) derived for each season. These are shown in Table 2.36.

It may be seen that none of the components followed a clear-cut periodic cycle during the study period, but this is understandable since only two possible cycles are under observation. However, the onshore component of very strong winds shows a dominantly seasonal distribution, occurring only during seasons A and D. Hence, it may be postulated that substantial portions of profile 4 (excluding the lowermost foreshore) showed accretion from October - March. Conversely profile 7 showed erosion from October - March. As has already been discussed, the latter cycle is more readily understandable than the former.

PROFILE	METEOROLOGICAL INPUT	NUMBER OF OBSERVATIONS								
		1968				1969				1970
		A	B	C	D	A	B	C	D	A
2 (erosion)	Resultant westerly waves ≥ 4 metres	3	0	1	0	0	0	0	1	0
4 (accretion)	Onshore winds ≥ 30 knots	1	0	0	1	1	0	0	1	0
(erosion)	Resultant westerly waves ≥ 6 seconds	5	0	2	1	0	1	1	1	1
5 (accretion)	Easterly waves ≥ 2 metres	2	0	0	5	6	0	0	2	1
6 (erosion)	Easterly winds ≥ 30 knots	1	0	0	2	2	0	0	1	0
7 (erosion)	Onshore winds ≥ 30 knots	1	0	0	1	1	0	0	1	0
(erosion)	Offshore winds ≥ 20 knots	3	2	2	2	4	1	1	6	3
(erosion)	Offshore winds ≥ 30 knots	0	0	0	0	0	0	0	1	1
(erosion)	Offshore waves ≥ 2 metres	2	1	1	1	2	1	0	3	2

TABLE 2.36 : Monthly mean number of observations per season of meteorological input

The easterly component of high waves occurred most frequently during seasons A and D, as did the easterly component of very strong winds. Hence it may be suggested that from October - March, sand was eroded from profile 6 and deposited on profile 5. During period A, January - March 1968, sand probably accumulated on profiles 2 and 4.

Offshore components of strong winds and high waves show a similar but less well defined distribution. On profile 7 these would produce greatest erosion from October to March, therefore reinforcing the effects of very strong onshore winds. The importance of offshore vectors is undoubtedly due to the orientation of this profile, at right angles to the throat of the estuary (see Fig. 2.1), where waves and winds can be funnelled down the estuary below Laugharne, reinforcing river discharge energy.

In addition, quantitative associations between beach change and meteorological input have been shown for some parts of profiles 5, 6 and 7. The distributions of these significant meteorological components are shown in Table 2.37. None of the significant prevailing wind components showed a seasonal distribution during the period of study. Of the significant dominant components, the onshore component of strong winds showed such a distribution, becoming most important from October to March; at these times it may be predicted that there was increased accretion of zone D of profile 5; this represents the seaward margin of the ridge and runnel system.

River Taf discharge followed a seasonal cycle, with maximum flows occurring in the winter months at times of high rainfall and land run-off. Correspondingly at these times parts of

PROFILE & ZONE	METEOROLOGICAL INPUT	NUMBER OF OBSERVATIONS								
		1968				1969				1970
		A	B	C	D	A	B	C	D	A
5 C (erosion)	Resultant onshore winds ≥ 20 knots	0	-1	-1	5	-1	0	0	-1	0
(erosion)	Resultant onshore waves ≥ 2 metres	2	1	1	10	2	2	0	0	1
(erosion)	Onshore waves ≥ 6 seconds	1	0	1	1	0	0	0	0	0
5 D (erosion)	Offshore prevailing winds	24	24	31	13	26	22	29	27	31
(accretion)	Resultant onshore prevailing winds	2	7	-9	29	-2	4	-5	-1	-10
(erosion)	Westerly prevailing winds	32	33	33	21	22	38	40	34	33
(accretion)	Onshore winds ≥ 20 knots	3	1	1	7	3	1	1	5	3
(erosion)	Resultant westerly winds ≥ 30 knots	2	0	1	-1	-1	0	0	0	3
5 (C+D) (erosion)	Onshore waves ≥ 6 seconds	1	0	1	1	0	0	0	0	0
6 D & 7 B (erosion)	River Taf discharge (in m^3 $sec.^{-1}$)	7.6	5.3	3.0	11.0	10.8	4.4	1.5	7.5	10.8

TABLE 2.37 : Monthly mean number of observations of meteorological input and monthly mean river discharge per season.

profiles 6 and 7 suffered maximum erosion. It has been shown that exceptional accretion occurred on profiles 4 and 5 during periods of increased river flow, which suggests that at such times sand was transported from the eastern edge of the beach and redeposited in the central part. It may be postulated that this movement would be a seasonal one, becoming dominant from October to March.

Based on the significances of a few exceptionally large changes between surveys, some additional elements of meteorological input may be considered. These elements, which have a qualitative correlation with changes on some profiles, are shown in Table 2.38. It can be seen that both easterly components of strong winds and high waves followed a seasonal cycle of frequency during both years of study, increasing in importance from October to March. During these months then, profiles 4 and 5 and part of profile 6 built up in response to movement of sand from the east. This movement was obviously related to that described in the foregoing paragraph, occurring at times of high river discharge. Hence it may be concluded that a combination of wintertime river flow and wintertime dominant easterly meteorological input resulted in movement of sand from profiles 6 and 7 to profiles 4 and 5; above MHWST on profile 6 there was accretion at these times; the movement of sand from profile 7

PROFILE OR ZONE	METEOROLOGICAL INPUT	NUMBER OF OBSERVATIONS								
		1968				1969				1970
		A	B	C	D	A	B	C	D	A
4,5A,6A (accretion)	Easterly winds ⩾ 20 knots	7	1	1	6	7	1	0	4	2
4,5. (accretion)	Easterly waves ⩾ 2 metres	2	0	0	5	6	0	0	2	1
5, 6A (accretion)	Prevailing easterly winds	25	22	19	29	36	17	14	17	20
5 (erosion) 7C(accretion)	Resultant prevailing westerly winds	7	11	14	-11	-14	20	26	17	13
6 A (erosion)	Resultant onshore prevailing winds	2	7	-9	29	-2	4	-5	-1	-10
6 C (erosion)	Onshore winds ⩾ 20 knots	3	1	1	7	3	1	1	5	3
(erosion)	Onshore waves ⩾ 2 metres	4	2	2	10	5	3	0	3	3

TABLE 2.38 : Monthly mean number of observations per season of meteorological input.

was encouraged by increased wintertime offshore winds funnelling down the estuary. A seasonal distribution of easterly prevailing winds was less well developed, but would match the effect of dominant vectors.

Of the other vectors under consideration, only the onshore component of strong winds showed a seasonal cycle of frequency, as has been previously noted. This may have produced a seasonal variation of cut and fill in zone C of profile 6, with maximum erosion in the winter months.

Although there was no clear-cut periodic cycle of resultant westerly prevailing winds, it would appear that these were most important from April to September, at which times erosion would be most pronounced on profile 5 and accretion on the lower part of profile 7.

There was some discrepancy of total input between 1968 and 1969, particularly of dominant components. Offshore and easterly components of dominant vectors were equally common in both years, but onshore and, particularly, westerly components of dominant vectors were more frequent in 1968 than 1969. It is the westerly components that were responsible for the greater instability of the profiles in 1968 than in 1969. This becomes most apparent if we examine the frequency of southwesterly gales during the study period.

It has been shown that the greatest between-survey change

was associated with the proximity of a southwesterly gale, recorded the day before survey 3. This produced exceptional cuts on most profiles, or parts of profiles, with the exception of profile 6 on which there was exceptional overall instability but a small (and unexceptional) fill. Considerations of wave energy and wave fetch would lead us to expect that such gales must indeed provide the greatest energy input to the nearshore zone and foreshore. Of course, it was fortunate that one survey should, by chance, record the response to this boosted energy input. It is feasible that other exceptional changes, caused by other vectors, were not recorded, but it seems unlikely that within the confines of the Bristol Channel or Carmarthen Bay any comparable input could be generated.

The seasonal distribution of strong ($\geq$ 20 knots) and very strong ($\geq$ 30 knots) winds from the south-west quarter are shown in Fig. 2.23. In 1968 there was a coincidence of southwesterly gales with the vernal and autumnal equinoxes, but this was not so in 1969. In both years, southwesterly gales were less frequent from May to August. Gales from this quarter were more frequent in 1968 than in 1969. It can be postulated therefore, that most of the foreshore suffered periods of exceptional erosion, most frequently during the winter months, and more frequently in 1968 than in 1969. Sand removed by this agency

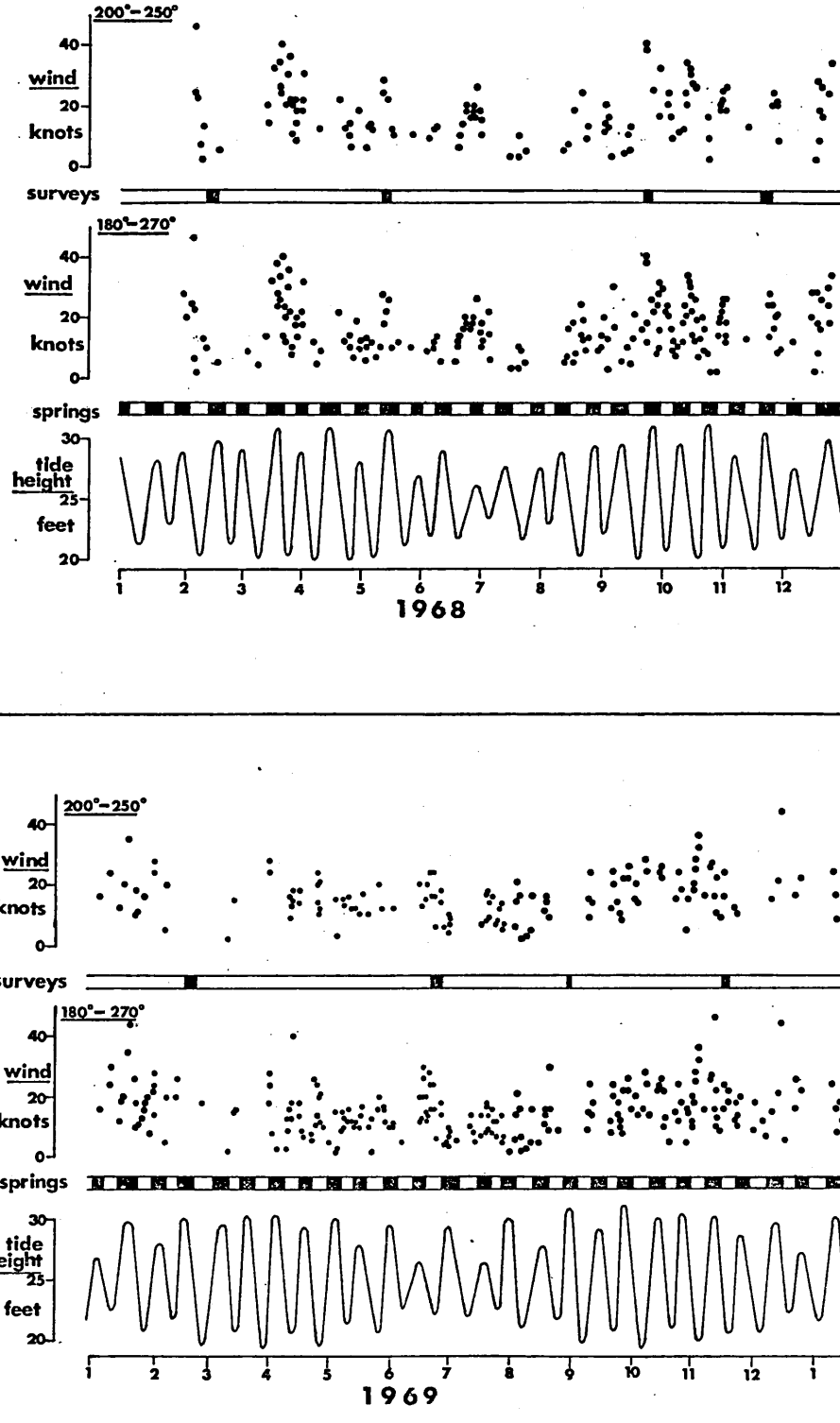


FIG. 2. 23 : DISTRIBUTION OF SOUTHWESTERLY GALES AND COINCIDENCE WITH SPRING TIDES.

must be transported below MLWST, returning to the foreshore with the onset of constructive wave action. However, net erosion exceeded net accretion during the study period, sand being lost to the offshore zone and/or to the estuary (this possibility is discussed in the following chapter).

This study has not considered the variation of foreshore volume between spring and neap tides. It was shown by Lafond (1939) that under normal calm conditions, sand accumulated near and above mean sea level during neap tides and eroded during springs; sand was eroded below mean sea level during neaps and accumulated during springs. These changes occurred on a beach exposed to a small tidal range (c. 6 feet). King (1953) found, on the Durham coast, that the influence of tides (maximum range 14 feet, minimum 7 feet) was small in comparison with the influence of waves, except during long periods of calm weather, when the findings of Lafond were confirmed. In a subsequent study, Lafond and Prasada Rao (1954) confirmed that during spring tides the upper foreshore was eroded and sand deposited on the lower foreshore and offshore. Sand was returned during neap tides. It appears that this is because spring tides produce two zones of long duration wash while neap tides produce only one. Again this study was carried out on a beach responding to a small tidal range. In Carmarthen Bay, the tidal range is considerably

increased, as is the difference between spring and neap tides. However, the same response of beach level to tidal variation may be expected, spread over a wider expanse of foreshore.

It has been shown that erosion of the foreshore must be greatest during the winter months when southwesterly gales are most frequent. This was also observed by Khan (1968) on the neighbouring Pembrey Sands, and previously by Shepard and Lafond (1940) in California. However, on Pendine Sands, it would appear that such a seasonal variation of beach volume is statistical rather than absolute, since the surveys themselves did not record it. In other words, erosion follows in the wake of a south-westerly gale but a compensatory fill is set into motion immediately the storm energy is dissipated. Thus the beach level is more often reduced in winter than in summer, but during calm periods there may be no seasonal difference in volume.

From the foregoing, it may be predicted that the greatest erosion should occur when destructive waves coincide with spring tides. From Fig. 2.23 it may be shown that the coincidence of very strong winds ($\geq$ 30 knots, after resolution, from 200-250^{o}) with spring tides occurred approximately 10 times in 1968 and 9 in 1969, most often between September and April. In 1968 the highest springs, in March, April, September and October, coincided with southwesterly gales, but in 1969 only the high springs of

September and October were coincident with gales. It may be expected therefore that over a long-term study it would be shown that the greatest erosion of the foreshore occurs in winter, most particularly at times of spring tides, and most exceptionally during the vernal and autumnal equinoxes. The most obvious erosion would occur on the upper foreshore; also in the dunes, which are not often reached by waves except during very high tides.

2.9 Summary and conclusions

Most of the foreshore was relatively stable during the period of study - stable, that is, in comparison with some other U.K. beaches such as those on the coasts of Lancashire, Lincolnshire and Durham (see King, 1972). Temporal variations of stability were most pronounced on profiles 1, 5 and 7. Possibly a concentration of wave energy round the headlands of Ragwen, Gilman and Dolwen Points, and associated eddy currents are responsible for the greater instability of profile 1. The foreshore appears to become more stable eastwards, and changes on profile 4 were very small; this may reflect changes of offshore gradients (normal to the shoreline) from west to east. On profile 5, where the orientation of the foreshore is altered, stability decreased due to the influence of the River Taf ebb channel and the development of a mobile ridge and runnel system on the lower foreshore. Profile 7 was again very unstable on its lower section because of the influence of the Taf channel and the generation of waves within the estuary.

Profiles 1-4 generally responded to change as homogeneous units, but on profiles 5-7 much greater variation occurred on the lower foreshores than on the upper. Above the mean high water mark of spring tides, most profiles showed slightly increased instability* due to the effect of aeolian activity and the proximity of the dunes.

The most pronounced changes were due to erosion by south-westerly gales, and these were most frequent in the winter months. At other times, during calm weather conditions, most of the eroded sand was returned to the foreshore. Paradoxically, onshore very strong winds were associated with accretion on profile 4, being most developed in winter, but the sedimentological significance of this association is not understood. The same winds were related to erosion of profile 7, as were offshore components of winds and waves. Thus profile 7 was significantly eroded by strong winds and high waves both from seaward and those funnelled down the throat of the estuary during winter.

Littoral drift was evident from the eastern part of the beach, occurring during the winter months when River Taf discharge was at a peak. Sand was removed from the lower sections of profiles 6 and 7 and some redeposited on profiles 4 and 5 (and perhaps 2). There is good evidence that prevailing westerly

* i.e. instability as shown by vertical variation of beach level.

vectors moved sand from profile 2 to profiles 3 and 4, and from profile 5 (on which there was a net erosion, despite recompense from winter drift from the Taf) to profile 7.

Above mean high water spring tides, profiles 1-4 showed accretion in the summer months and erosion in the winter. This cycle is clearly related to the seasonal distribution of south-westerly gales, and their coincidence with high spring tides.

The dunes of profiles 1-3 were stable during the study period. The dunes of profiles 4-7 showed increased variation, fluctuations being apparently related to alongshore wind vectors on profiles 4, 5 and 7, but onshore/offshore vectors on profile 6. The dune of profile 4 and the upper foreshore (above MHWST) of profile 6 was built up at the same time as the dune of profile 7 was eroded, apparently under the influence of easterly winds. However, the dune of profile 5 appears to have grown in response to westerly winds.

A summary of probable, and possible, seasonal beach changes is shown in Fig. 2.24.

The short duration of the period of study does not allow for prediction of long term trends, the more so since the data and analysis are insufficiently comprehensive to adequately describe the process/response relationships on all of the foreshore.

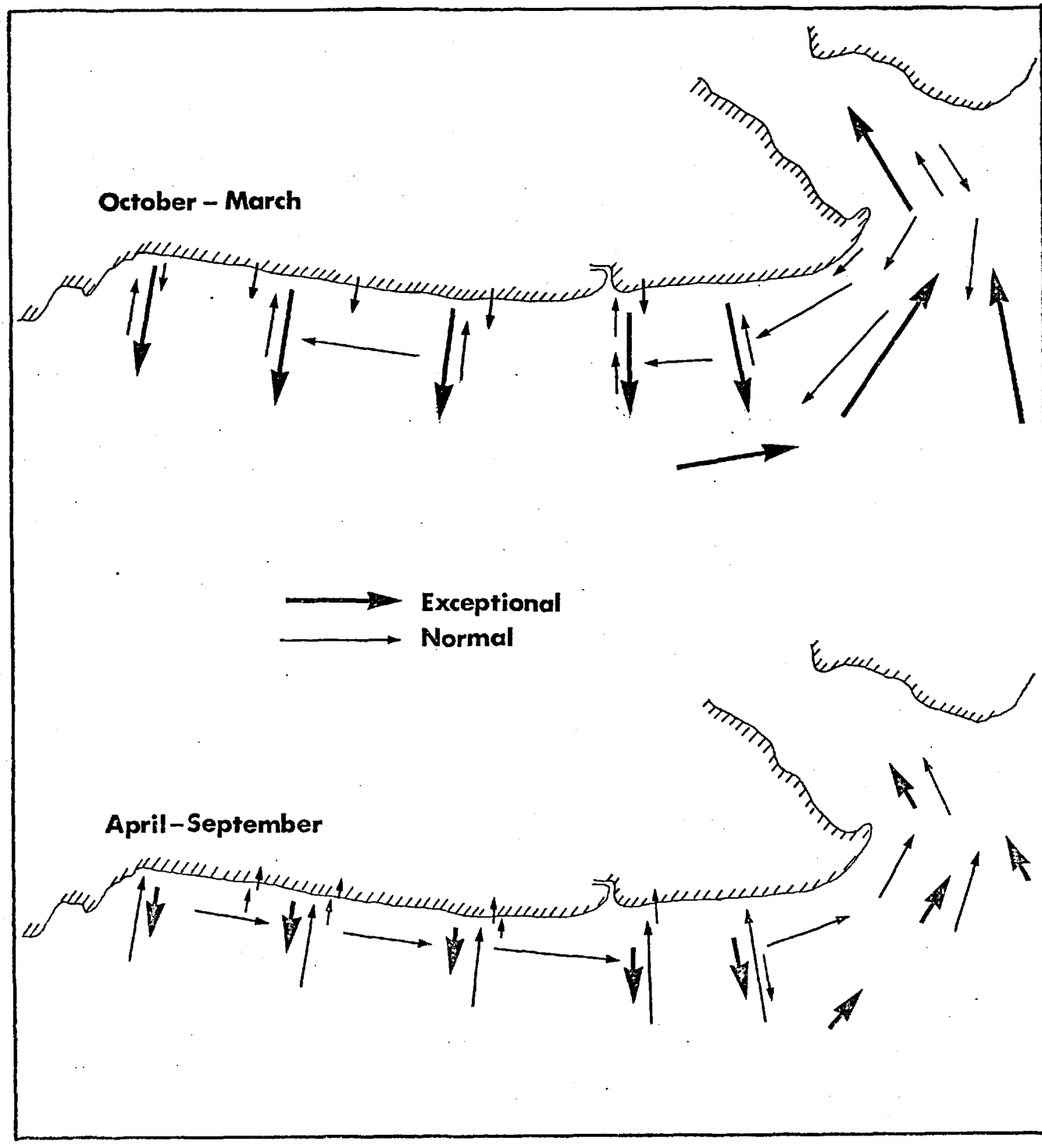


FIG. 2.24: SEASONAL MOVEMENT OF SAND.

CHAPTER 3

ESTUARINE CIRCULATION

3.1 Introduction

Many definitions of the term 'estuary' have been suggested, but in the context of this study, the one proposed by Pritchard (1952) is most apt, since it confines its description to water dynamics and circulation : "An estuary is a semi-enclosed coastal body of water having a free connection with the open sea and containing a measurable quantity of sea salt".

The types of circulation developed in estuaries are determined by several factors. Of these, some are fixed (for any one estuary), while others vary with time. Included in the former oategory are the overall physical dimensions and configuration of the estuary, and the gross characteristics of the ocean tide (i.e. whether diurnal or semidiurnal). In the latter category, we have river discharge, tidal range, tidal height, channel width, and the morphology of shifting channels and shoals, all of which can vary during one tidal cycle and/or over several tidal cycles. As pointed out by Ketchum (1953), estuarine circulation is an extremely variable manifestation of the interaction of these, and other, factors so that no two estuaries are alike and individual estuaries can display a marked seasonal variability.

It has been shown by Pritchard (1955) that some generalisations can be formulated to describe circulation genesis. Of particular importance are the respective influences, and interaction, of tidal currents, river flow, water depth and channel width. These are the dominant factors that together define the character of the integral process variable (estuarine circulation) which in turn determines the activity of the response variable (sediment entrainment, transport and accumulation). At any moment in time, process and response elements constitute a dynamic equilibrium; however, because of a complex feedback situation inherent in such a dynamic system (King, 1970), the equilibrium is itself in perpetual flux.

Many British estuaries display a comparable physical form, dominated by the formation of a mobile main channel meandering in a loose sediment bed and associated with a succession of equally mobile blind channels; this arrangement of a flood-ebb channel system has been described by Robinson (1960). The Taf estuary is of this type.

Clearly, the water circulation within the Taf estuary must fluctuate considerably with time. The coastal part of the lower river is inundated with salt-water twice daily, but all of this salt-water is expelled with the waning of the tidal wave. Hence water depth and channel width are continuous variables. Because

of the asymmetrical tidal wave, tidal currents also vary considerably during each tidal cycle, as well as reversing in direction from flood to ebb. River discharge may also vary during the tidal cycle, depending on local weather conditions, but its relative importance is controlled by a continuously variable and periodic interaction with the tidal wave. There is a regular gradation of tidal dynamics from springs to neaps, as well as a long-term cycle associated with the equinoxes. River discharge follows a seasonal sequence of variation. Superimposed on these processes is the complex feedback induced by sediment response, as unstable shoals and channels are modified by each tide.

Furthermore, an additional factor, a meteorological process element, can have an important influence on estuarine circulation (deduced in Chapter 4). Through the stress exerted on the water surface, wind can produce a net transport of water, and the waves generated will increase the intensity of vertical mixing. Also, temperature changes due to the varying heat budget can also have a significant effect, heating of the surface layer of water tending to reduce vertical mixing (Bowden, 1967).

3.2 Current, Salinity and Temperature Measurements : Methods

Either of two methods may be used for making current measurements : Eulerian methods, in which the flow past a fixed point

is measured; and Lagrangian methods, in which the trajectories of the water are followed. The former technique was adopted for the present study, notwithstanding that it is inevitably a fair weather technique and it may be assumed that some of the most significant water movements occur during stormy weather. The practical difficulties of carrying out boat-based experiments in bad weather constitute a serious, but common, problem in all hydrographic studies.

The monitoring vessel was anchored near the main (ebb) channel and measurements of current, salinity and temperature taken every thirty minutes at depth intervals of two feet between surface and bottom. Instruments used were a rotating element current meter ('Ono') and a salinity temperature bridge ('Electronic Switchgear'); readings were taken to 0.01 metres/second, $0.05^{o}/_{oo}$, and $0.1^{o}C$.

Six stations were occupied during the summers of 1968 and 1969, their positions being indicated in Fig. 3.1. Stations 1, 2 and 5 were monitored for $12\frac{1}{2}$ hours, stations 3, 4 and 6 for 25 hours.

Details of tidal height and river discharge for the appropriate dates are shown in Table 3.1. Data for upland flow has been supplied by the South-West Wales River Authority from its gauge at Clog-y-fran (see Fig. 3.1); data for predicted tidal heights have been calculated from standard port, Milford Haven.

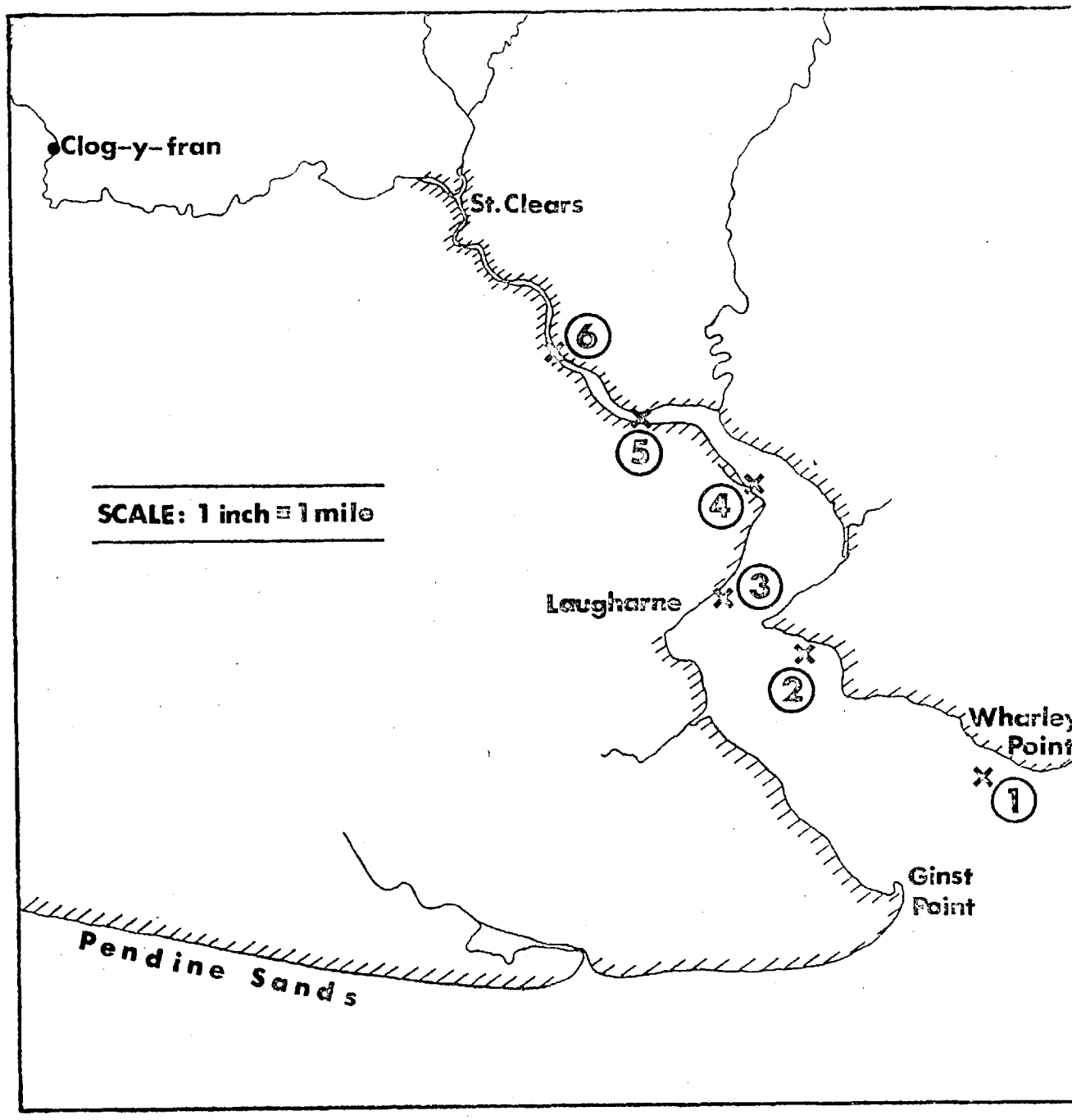


FIG. 3.1 : POSITIONS OF HYDROGRAPHIC STATIONS.

STATION	DATE	DURATION	RIVER FLOW	TIDE HEIGHT
1	5/9/68	12½ hours	2.26 $m.^3 sec.^{-1}$	11.6 ft. O.D.
2	18/6/69	12½ hours	10.50 $m.^3 sec.^{-1}$	8.2 ft. O.D.
3	27-28/8/68	25 hours	1.33-1.31 $m.^3 sec.^{-1}$	13.2,12.2 ft. O.D.
4	30-31/8/68	25 hours	1.25-1.19 $m.^3 sec.^{-1}$	9.1, 7.9 ft. O.D.
5	19/6/69	12½ hours	4.00 $m.^3 sec.^{-1}$	8.6 ft. O.D.
6	2-3/9/68	25 hours	2.15-1.67 $m.^3 sec.^{-1}$	6.4, 6.4 ft. O.D.

TABLE 3.1 : Tide heights and mean river flows for duration of hydrographic monitoring

Extreme spring tides at Tenby reach 14.4 feet O.D., the difference between extreme springs and extreme neaps being 10.4 feet. Mean spring tides reach 12.6 feet O.D. (a range of 24.7 feet), mean neaps 6.2 feet O.D. (a range of 12.1 feet). The tide during observations at station 3 was thus a spring tide, at station 6 a neap. At station 1 the tide was just below mean spring height; at stations 2, 4 and 5 the tides were just above mean neap height.

3.3 Current, Salinity and Temperature Measurements : Observations

Variations with time of surface and bottom measurements of the three parameters, salinity, temperature and current velocity

are plotted in association with tidal height in Figs. 3.2 - 3.7. On the curves for current velocity, positive values indicate ebb flow, negative values flood flow. These curves do not attempt to show the detailed differences of flow direction that sometimes occurred at high tide - these will be considered later.

These variations have several common features : The tidal wave is strongly asymmetric, a spring rise (to 13.2 ft.) being achieved at station 3 in only 3 hours. Flood tide energy is therefore concentrated into a small time interval. Maximum flood currents occurred immediately post low-water in shallow water when strong turbulence ensued. Maximum ebb currents, also with some associated turbulence, occurred near the end of the salt-water flushing time; ebb currents then declined to a minimum, approaching the velocity of the seaward flow of river water.

(It should be noted that the term 'low-water' is used throughout to denote the time of lowest measured salinity within the estuary; this time does not correspond to the time of lowest ebb of the tidal wave in Carmarthen Bay. This is because the tide in the bay is rising for several hours before penetrating the estuary, during which time the only flow in the estuary is the seaward river flow; thus river flow continues a seaward 'ebb' for several hours while the tide is rising in the bay. 'Low-water' therefore refers to the moment before the flooding tide returns seawater to the estuary).

The asymmetry of the tidal wave is related to the pronounced landward shallowing of Carmarthen Bay and the extensive development of offshore bars and shoals. These serve to hold up the waxing tide, thus building up a hydrostatic pressure head which is dissipated very rapidly as the tide floods into the estuary.

High ebb currents are created by the confinement of flow into a decreasing channel cross-section; the 'wet cross-section' through which the ebb tide flushes reaches a minimum immediately prior to the final expulsion of the tidal prism; this occurs some 3 - 4 hours after high water. Hence maximum currents occur shortly before and shortly after effective low tide. This temporal variation is closely akin to that described for Dutch tidal flats and gullies by van Straaten and Kuenen (1957, 1958) and Postma (1961), but differs somewhat, particularly on the flood tide, from that described for the Dovey estuary in Wales by Haynes and Dobson (1969). The contrasts between the Taf and Dovey are undoubtedly due to differences in morphology, the Dovey being wider than the Taf and offering the flooding tide a straight run without impediment from bends in the main channel, but also to differences in offshore bar development and the degree of resultant tidal wave asymmetry.

The curves for salinity also reflect the asymmetry of the tidal wave, with a steep rise in values on the flood and slower

decline on the ebb. The lowest salinities were reached just prior to the flood surge.

The greatest current velocities occurred at the surface, invariably decreasing near the bottom due to friction. For most stations, the maximum deviation of surface and bottom currents occurred on the accelerating ebb tide.

The greatest salinity was measured in the bottom waters, surface waters being 0 - 12 $^{o}/_{oo}$ fresher. This inevitably follows from density differences between river water and seawater, and indicates that, at these times (i.e. during calm weather), mixing of fresh and saltwater was not always complete. Generally, at high water, the surface waters began to ebb before the bottom waters, sometimes even while the final stages of the flood continued in the bottom waters.

In Figs. 3.2 -.3.7, the water column is assumed to be homogeneous with respect to velocity and salinity after expulsion of the tidal prism, since during this period the water was too shallow to allow for more than one depth reading. Water remained slightly saline owing to the late draining of seawater retained by the marshes.

A complete record of temperature variation for station 6 was not obtained owing to instrument failure; for the same reason, there are no temperature data for station 1. Water temperature

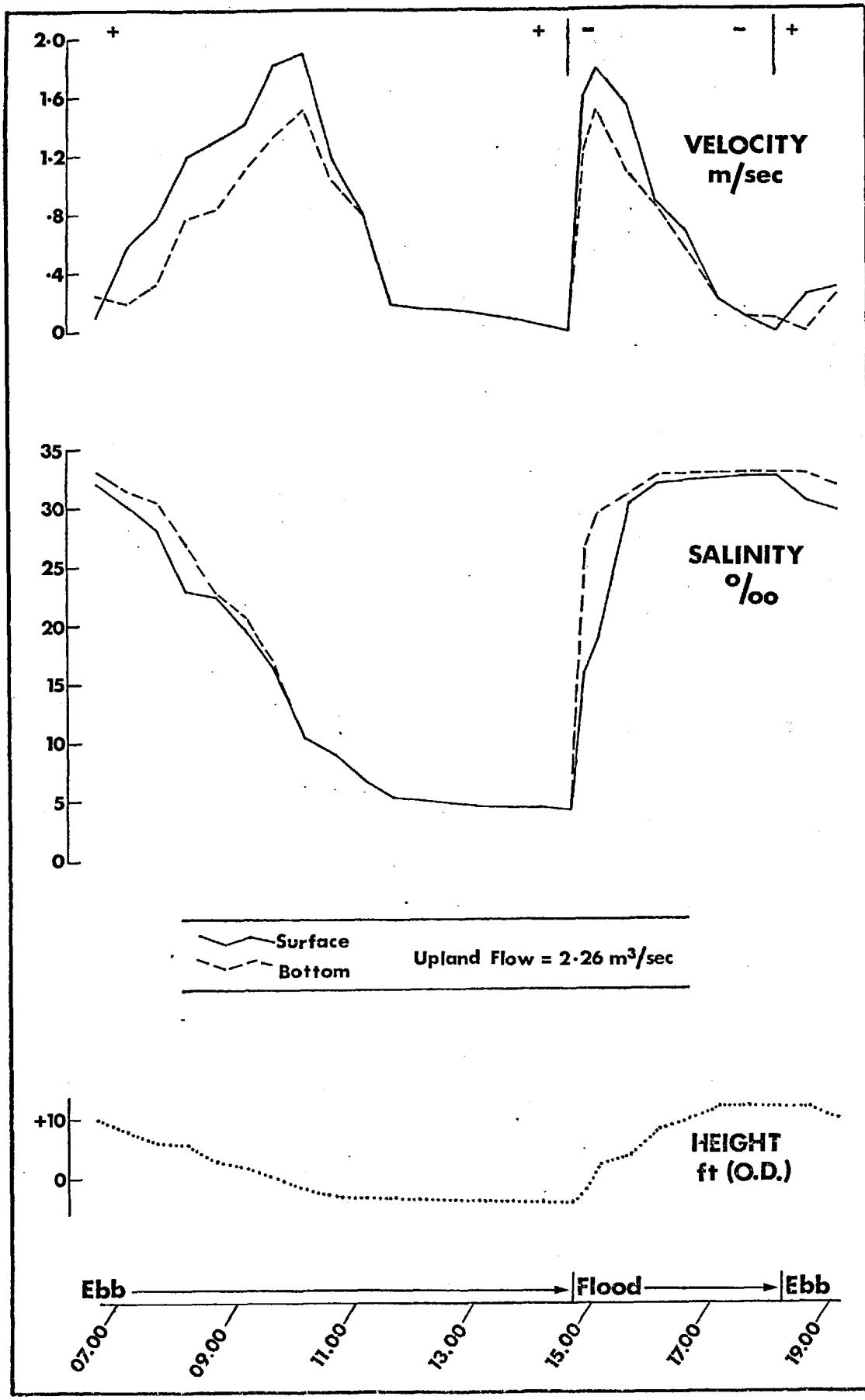


FIG. 3.2: CURRENT & SALINITY, STATION 1.

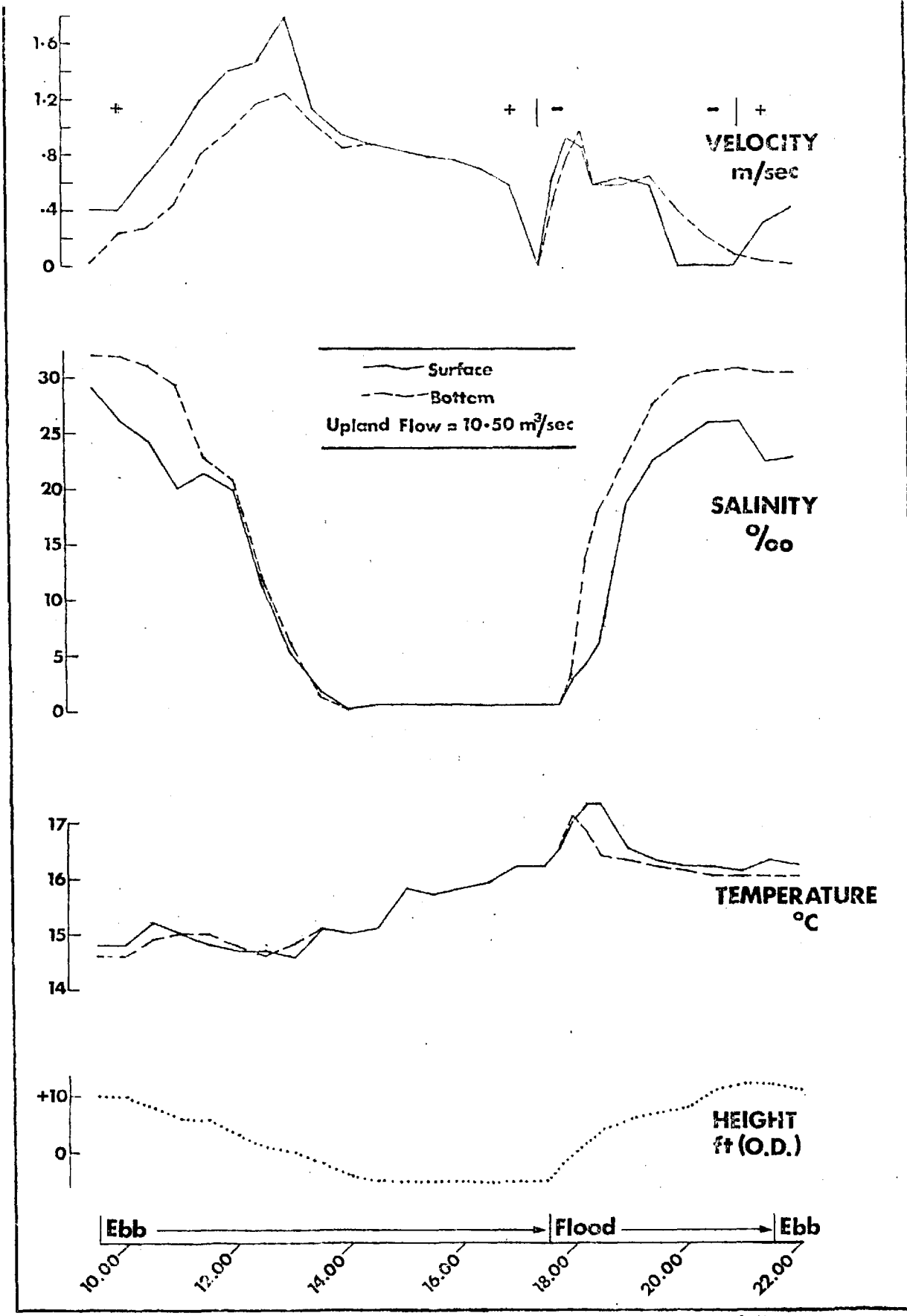


FIG. 3.3 : CURRENT, SALINITY & TEMPERATURE, STATION 2.

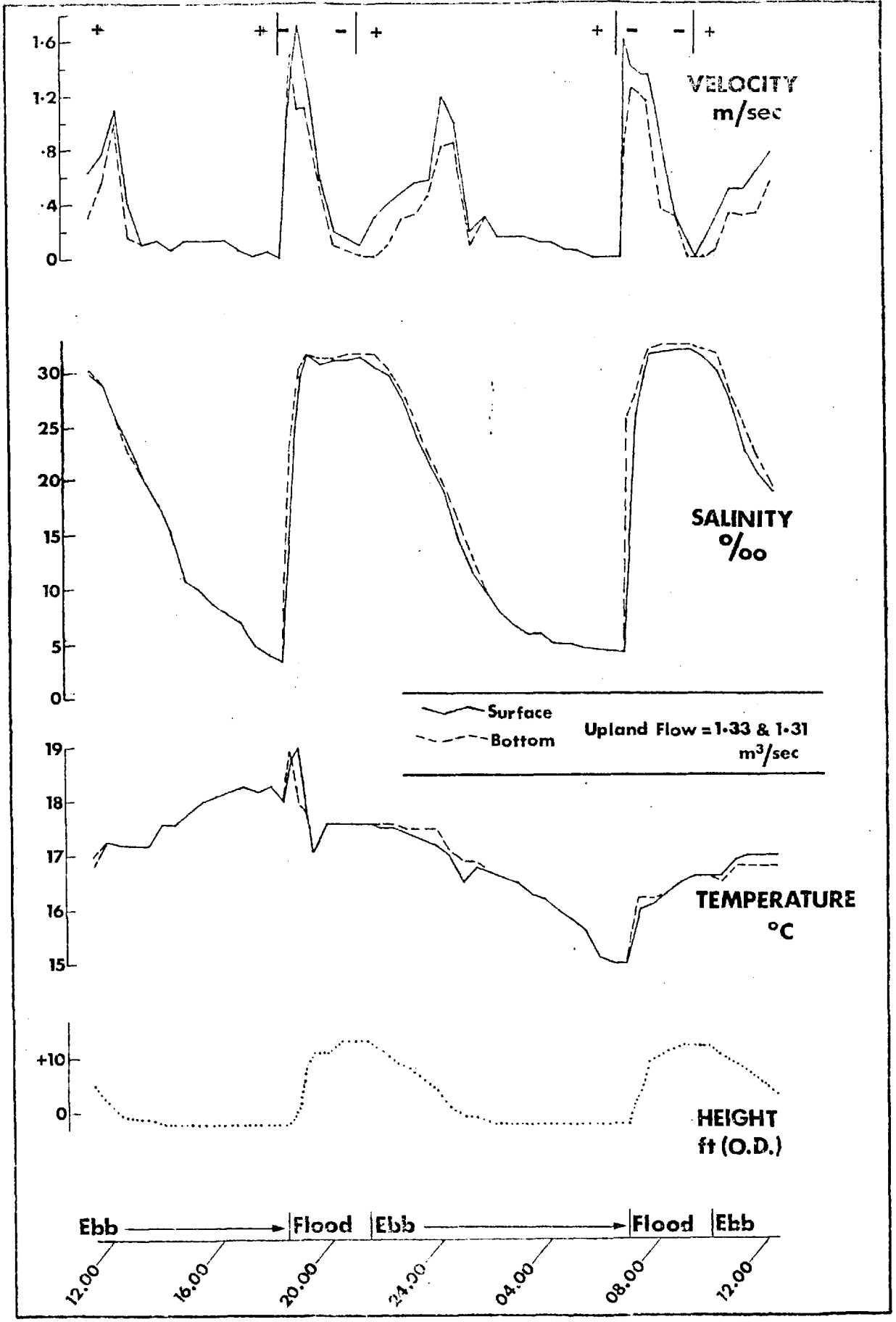


FIG.3.4 : CURRENT, SALINITY & TEMPERATURE. STATION 3.

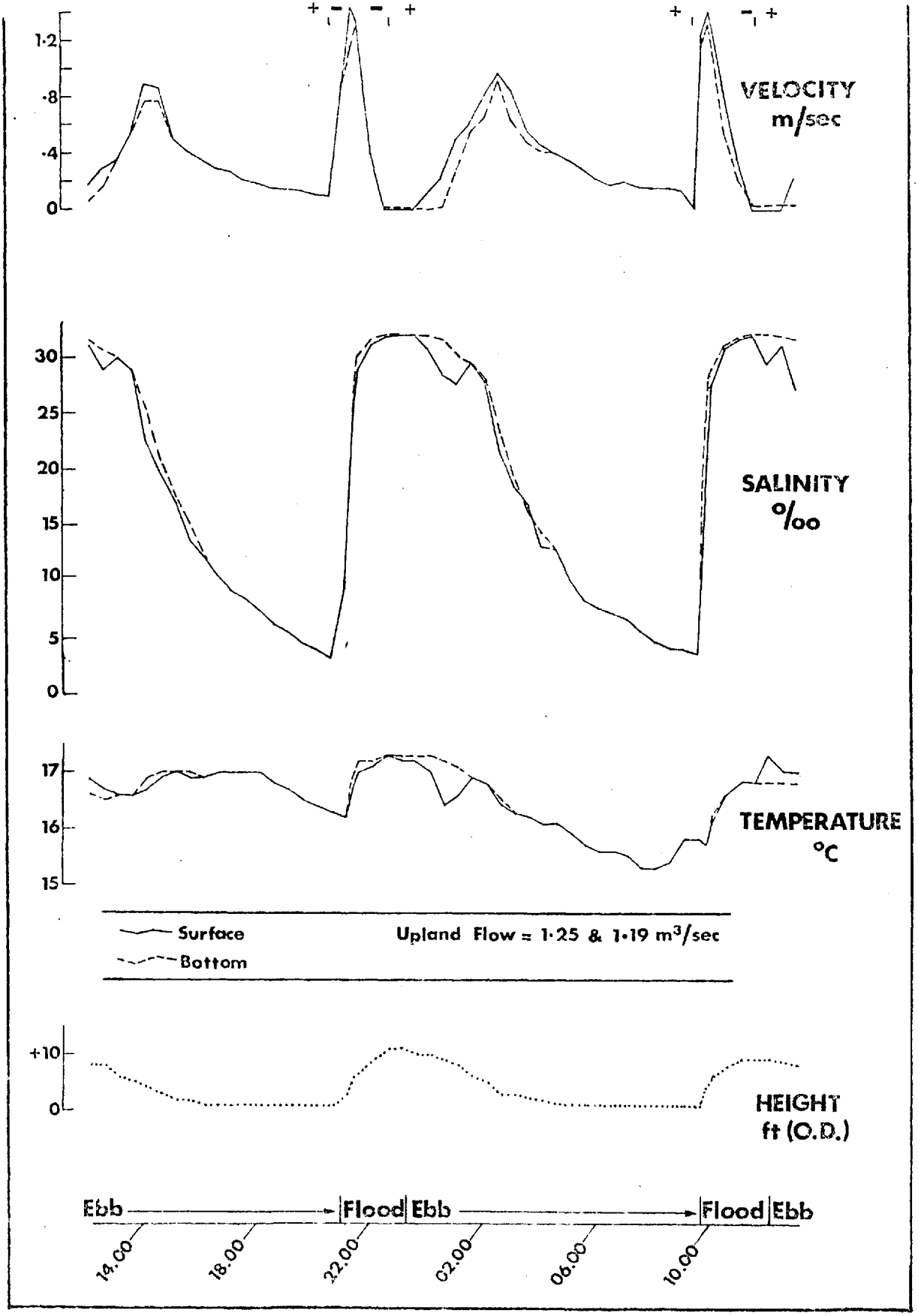


FIG. 3.5: CURRENT, SALINITY & TEMPERATURE, STATION 4.

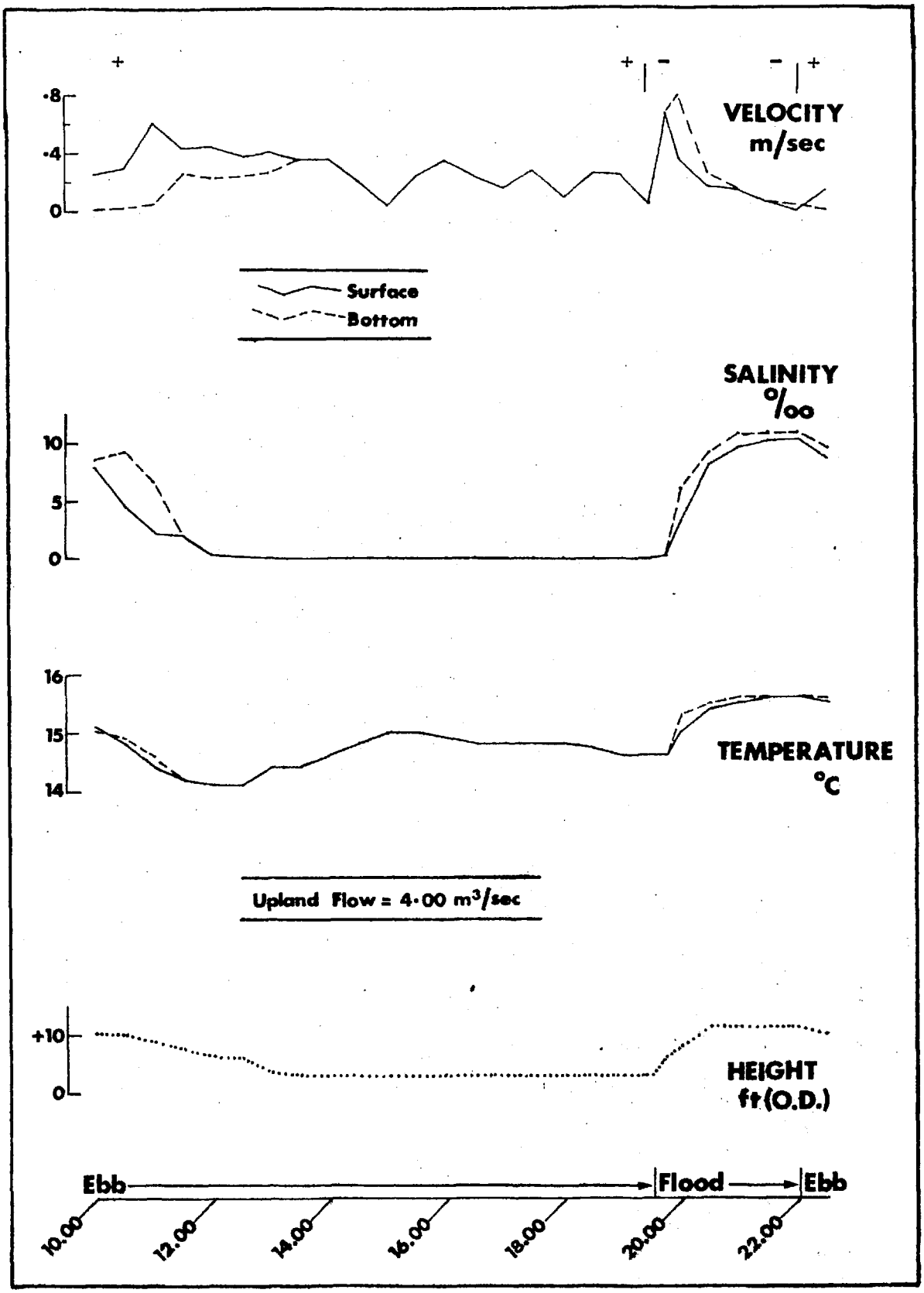


FIG.3.6 : CURRENT, SALINITY & TEMPERATURE, STATION 5.

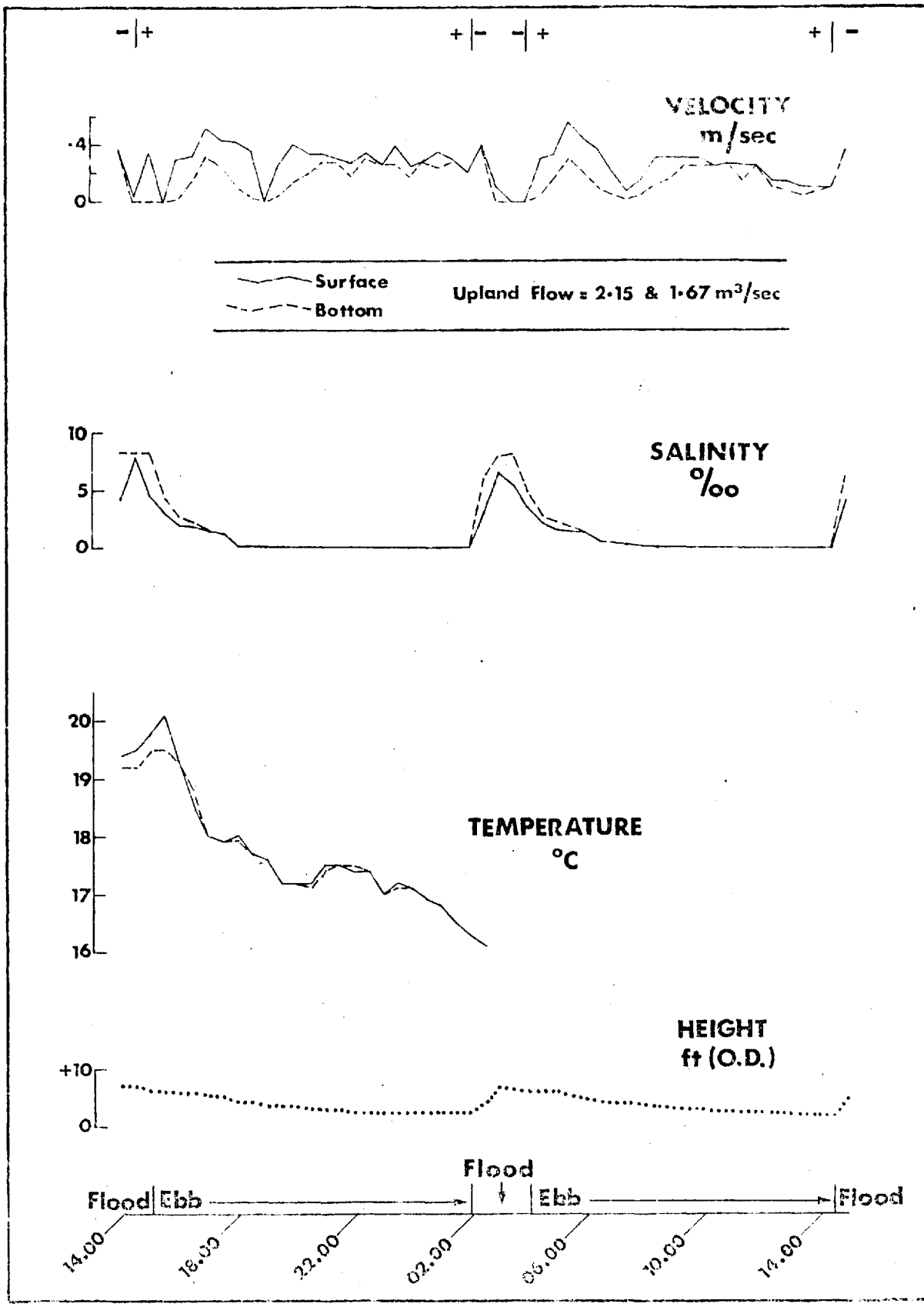


FIG. 3.7 : CURRENT, SALINITY & TEMPERATURE, STATION 6.

closely followed air temperature, reflecting the exposure of the water surface to the sun, rising during the daytime, falling at night. Surface temperatures were generally in excess of bottom temperatures by day, and less than bottom temperatures at night. Temperature tended to increase on the flooding tide, seawater being warmer than river water after direct exposure to the summer sun and contact with heated sandy banks and bars during the early stages of the flood.

There were marked differences in current velocity and salinity patterns for each station. At stations 3, 4 and 5 the maximum flood currents (1.72, 1.45 and .80 metres/second respectively) were greater than the maximum ebb currents (1.20, .98 and .60 metres/second respectively). At stations 2 and 6, the maximum ebb currents were greater than the flood (1.77 > 1.10, .55 > .40 metres/second respectively). At station 1 there was little difference between them (flood 1.79, ebb 1.85 metres/second).

It is likely that generally the flood maximum exceeds the ebb. This was recorded at stations 3, 4 and 5. However, at stations 1 and 2 it was noted that the monitoring vessel was not anchored in the mainstream of the flood surge, but was some 100 - 200 feet to one side of it. At these stations therefore, the flood surge avoided interaction with the main ebb (river) flow and was not realistically recorded. Therefore, the relative

dampening of the flood velocity at stations 1 and 2 is not altogether realistic being due, at least in part, to the particular positioning of the current-measuring instruments. This effect was most pronounced at station 2 because of the inflated river flow at that time (see Table 3.1). Station 6, where the ebb maximum also exceeded that of the flood, was situated near the limit of tidal action for a neap tide, so that river flow was increased in relative dominance, and the flood surge was effectively damped (the channel was here too narrow for the flood to sidestep the ebb).

Salinity maxima at stations 1, 3 and 4 were similar, in the range 31.8 - 33.0 °/oo. No information is available for salinities in Carmarthen Bay, though these are likely to be less than 34 °/oo because of dilution by the Taf, Towy and Gwendraeth rivers. Maximum salinity was reduced to 30.5 °/oo at station 2, because of the effect of an inflated upland flow. Maximum salinities were less than 11 °/oo at station 5 and less than 8 °/oo at station 6, near the landward limit of the neap tide incursion.

Hence it appears probable that the estuarine circulation is longitudinally homogeneous up to station 4, the 32 °/oo isohaline penetrating this distance on medium and high tides, and almost certainly on neap tides as well. Increased river flows are able to markedly depress this degree of marine penetration. The tidal

prism is completely expelled at low water, some remnant salinity being due to slow drainage from the marshes.

3.4 Vertical Salinity Profiles

The foregoing discussion has been concerned only with variations at the surface and bottom. Salinity data for all depths and times are combined in Fig. 3.8. Vertical salinity profiles were drawn for each half-hour of readings. Salinities were then read off for given fractions of the total depth of water, Z/h = 0.05, 0.2, 0.4, 0.6, 0.8 and 0.95 for each half-hour (where Z = depth of measurement, h = total depth). Hence the mean salinity over a tidal period was determined for each value of Z/h. These results are tabulated in Table 3.2.

	Z/h					
STATION	.05	.2	.4	.6	.8	.95
1	19.30	19.65	19.95	20.20	20.35	20.45
2	12.80	13.55	14.70	15.50	15.75	15.90
3	19.00	19.10	19.20	19.30	19.35	19.40
4	18.55	18.75	18.90	19.00	19.10	19.15
5	2.60	2.70	2.75	2.95	3.15	3.25
6	1.10	1.30	1.45	1.60	1.70	1.70

TABLE 3.2 : Mean salinities over a tidal cycle at various depths

From this, and Fig. 3.8, it may be seen that the mean salinity profiles over a tidal cycle were rather similar for stations 1, 3, 4, 5 and 6, when mixing was far advanced. For these stations, the difference between surface and bottom salinities was in the range .40 - 1.15 $^{o}/_{oo}$, being least for station 3 and greatest for station 1. The profiles are essentially linear (product-moment correlation coefficient, salinity : Z/h, ranging from .970 - .989 for n = 6), though the small deviations from linearity suggest that the relationship between salinity and depth is more correctly a logarithmic one.

It may be concluded that under the conditions represented by stations 1, 3, 4, 5 and 6 (including a spring tide, station 3, and a neap tide, station 6), the strong turbulence produced by tides entering the shallow estuary mouth creates a near-homogeneous vertical profile. For this reason, mixing is most complete in the bottom waters, a small degree of stratification remaining in the upper waters. Mixing was most developed on the spring tide at station 3, where intense turbulence was noted, as a result of bed friction and collision of straight stream lines with a curvilinear system of banks and channels off Laugharne. This turbulence-induced mixing is maintained throughout the estuary; on smaller tides, some stratification is developed in the surface and upper waters.

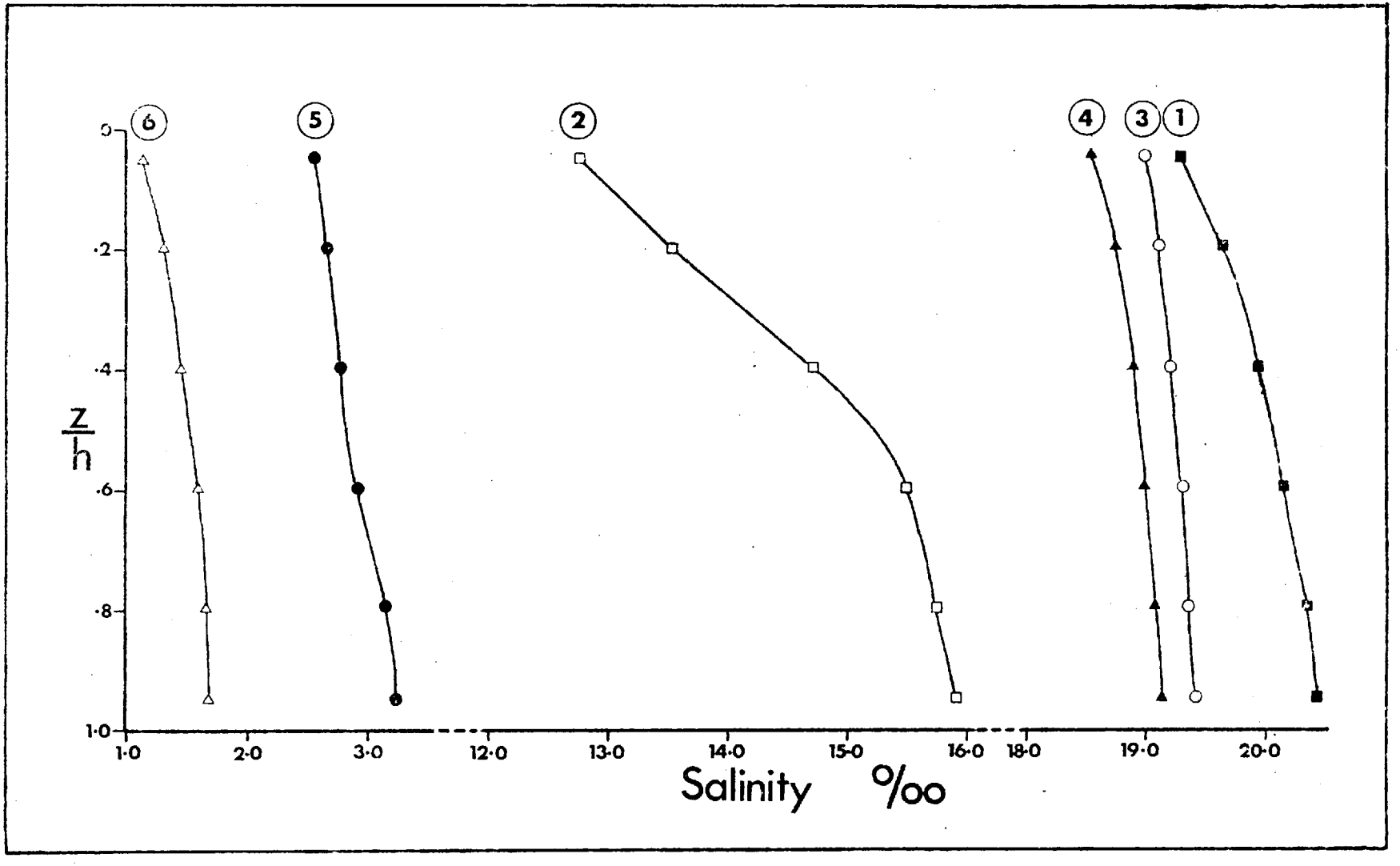


FIG. 3.8 : MEAN VERTICAL SALINITY PROFILES.

The increased stratification measured for station 1 was partly the result of the deeper water encountered there, but mainly because on the early flood tide some differentiation of ebb and flood streams occurred and turbulence was less in evidence at the monitoring station itself, though probably strongly developed towards the middle of the estuary mouth.

Wind appears to have some bearing on the vertical profile. The profile at station 5 showed near homogeneity at both surface and bottom, with some stratification at mid-depth. The breakdown of surface stratification may be attributed to the action of a Force 5 strong breeze from 200^{o} which created local waves sufficient to encourage vertical mixing in the upper layers.

The mean salinity profile demonstrated at station 2 differed appreciably from those at other stations, the vertical variation of mean salinity being considerably greater, 3.10 $^{o}/_{oo}$. Most of this stratification (87%) was confined to the water between the surface and $Z/h = .6$; hence turbulence and vertical mixing were dominant in the lower layers only, due to the effect of bottom friction.

The above salinity observations may be compared with those for other British estuaries. Under most conditions, the maximum vertical stratification recorded in the Dovey is 2 $^{o}/_{oo}$ between top and bottom (Haynes and Dobson, 1969); in the narrows of the Mersey, the mean difference between surface and bottom in early

summer is about 1 °/oo over a tidal cycle (Bowden, 1960), the mean monthly difference being in the range .44 - 3.06 °/oo (Bowden and Sharif El Din, 1966); for the Thames, the difference between surface and bottom over a tidal cycle is 1 °/oo for low river flow, reaching values up to 2 °/oo during the tidal period (Inglis and Allen, 1957).

In an American estuary, that of the James River, Pritchard (1956) observed a mean difference between surface and bottom of 3 °/oo.

Salinity profiles at particular hours after HW are shown in Fig. 3.9 for station 2 (station 3 is included for comparison). Maximum stratification occurred 9 hours after HW (on the early flood, when depth = 9 feet), with a secondary maximum 1 hour after HW (on the early ebb, when depth = 14 feet). The maximum difference between surface and bottom salinities was 11.7 °/oo, most of this being contained in the upper 50 °/o of the water column for the early flood.

From Fig. 3.9 it can be seen that (for station 2) on the early flood, highly saline, well-mixed water was restricted to the lower depths, while low-saline, highly stratified water was present above it. Turbulence was therefore active near the bottom only. On the early ebb, stratification was less marked but more uniformly spread through the water column; bottom

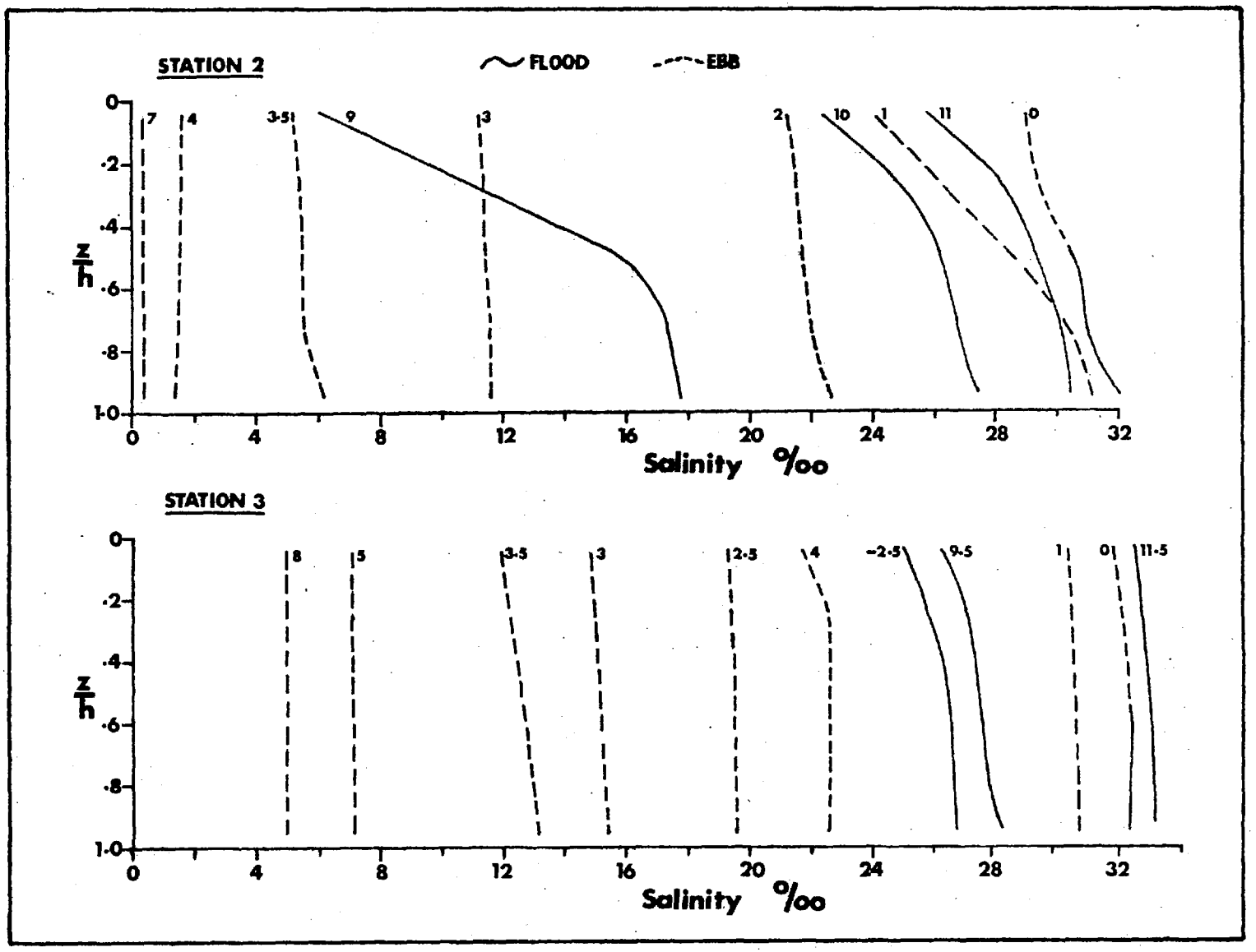


FIG. 3.9 : SALINITY PROFILES, x HOURS AFTER HIGH WATER.

turbulence was thus less developed. At most other times, vertical mixing pervaded most of the water column.

Of the six stations monitored, stations 2 and 3 represent the two extremes of the observed range of vertical mixing. This is shown pictorially in Fig. 3.9X which compares salinity variations at each station.

As shown in Table 3.1, station 2 was occupied at a time when high upland flow coincided with a small tide. Not only did the early flood seek to avoid the mainstream of this high run-off, but strong underthrusting of saline water occurred, low-saline water being dominant in the surface waters. Extreme stratification was maintained for 1 hour only, but re-emerged shortly after slack high water, initiated by strong fresh-water run-off near the surface flowing seaward over the less mobile saline prism.

A similar degree of stratification is noted by Haynes and Dobson (1969) for the Dovey estuary under identical circumstances i.e. the coincidence of high run-off and small tides. The resulting modification of the estuarine circulation illustrates the predictions of the model introduced by Pritchard (1955).

The rate of river discharge is therefore an important factor in determining the characteristics of estuarine circulation. Monthly and seasonal variations of river discharge, as gauged at Clog-y-fran, are shown in Table 3.3.

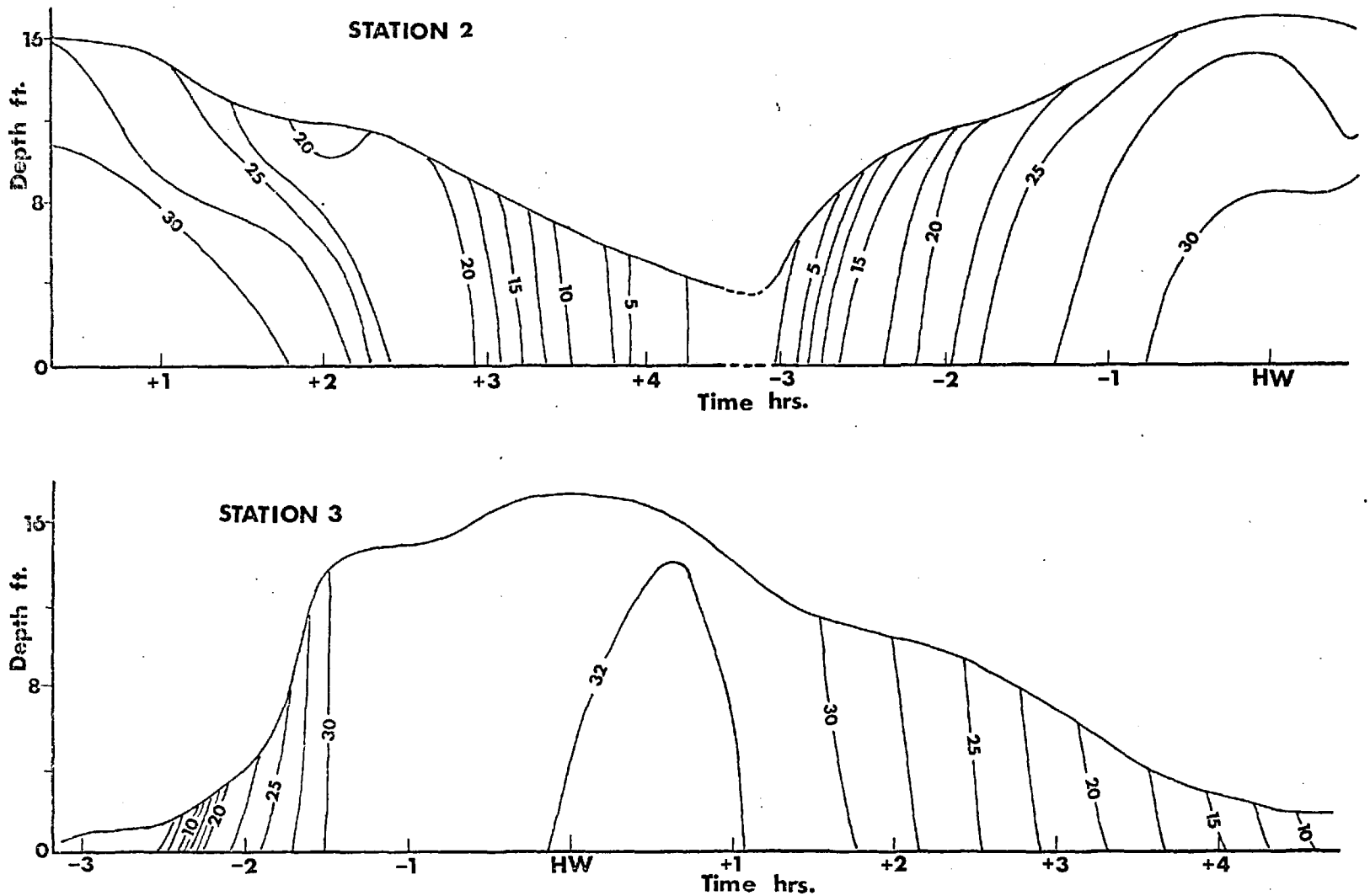


FIG. 3.9X: VARIATION OF SALINITY (‰).

	MONTH	SEASON	CUSECS	M^3/HR.
1968 :	January	Winter 380 cusecs	464	47,300
	February	(38,700 m^3/hr)	204	20,800
	March	Spring 197 cusecs	133	13,500
	April	(20,100 m^3/hr)	198	20,200
	May		260	26,500
	June	Summer 102 cusecs	101	10,300
	July	(10,400 m^3/hr)	144	14,700
	August		61	6,200
	September	Autumn 270 cusecs	110	11,200
	October	(27,400 m^3/hr)	285	29,000
	November		411	41,800
	December	Winter 477 cusecs	471	48,000
1969 :	January	(48,600 m^3/hr)	666	67,900
	February		294	29,900
	March	Spring 165 cusecs	181	18,500
	April	(16,800 m^3/hr)	114	11,600
	May		201	20,400
	June	Summer 93 cusecs	155	15,800
	July	(9,400 m^3/hr)	72	7,300
	August		51	5,200
	September	Autumn 110 cusecs	40	4,100
	October	(11,200 m^3/hr)	38	3,900
	November		252	25,700
	December	Winter 476 cusecs	504	
1970 :	January	(48,500 m^3/hr)	517	
	February		407	

TABLE 3.3 : Mean monthly and seasonal flows at Clog-y-fran

River flows for the duration of observations at most stations were close to the monthly and seasonal means. But at station 2, it was twice the monthly mean. Results at stations 1, 3 - 6 are therefore representative of average conditions for those tides, calm weather and summertime and early autumn. Results at station 2 are exceptional for the time of year.

Upland flow for station 2 was 371 cusecs (10.5 m^3/sec). Monthly mean flows exceed this figure in late autumn and winter only. Maximum stratification is therefore most likely to develop in the winter months (under calm weather conditions). However, station 2 results were observed in June, 1969. Summer rainfall is variable and run-off erratic, so stratification can occur at all seasons, but with greater frequency in the winter months (during calm weather).

However, this tendency must be counterbalanced by the important effect of winds and waves, most frequent in the winter months, which serve to increase vertical mixing. Calm weather occurs most often in summer, and it is therefore probable that maximum stratification will occur most frequently during periods of exceptionally high run-off in summertime, as well as during less frequent periods of calm weather in wintertime. Neap tides are probably an essential element in reducing vertical mixing at these times.

3.5 Vertical Velocity Profiles

Vertical velocity profiles have been constructed for each half hour from the current data; velocities were then read off for given fractions of the total depth of water, Z/h = .05, .2 .4 etc., for each profile. The mean velocity over a tidal cycle was thus determined for each value of Z/h.

	Z/h					
STATION	.05	.2	.4	.6	.8	.95
1	.28	.26	.25	.24	.22	.19
2	.50	.46	.39	.36	.35	.32
3	.10	.09	.06	.06	.05	.02
4	.34	.33	.33	.31	.30	.29
5	.20	.17	.16	.15	.11	.10
6	.26	.24	.22	.20	.17	.15

TABLE 3.4 : Total mean flows, m /sec.

Total mean velocities over a tidal period for each station are shown in Table 3.4. In this, and subsequent, analyses, ebb current velocities are considered as positive, flood as negative. There was a mean flow downstream for all stations and at all depths, indicating the asymmetry of the tidal wave and virtually total ebb flushing. The balance of flow is in favour of the ebb

because of the boost provided by river flow. For this reason, the mean downstream flow is greatest at the surface, decreasing with depth. The depth-mean flows for tidal cycles at stations 1 - 6 were .24, .39, .06, .32, .15 and .21 m /sec respectively; the greatest downstream depth-mean flow occurred at station 2 (small tide, large river flow), the least at station 3 (large tide, small river flow). These values do not represent the mean flow through a complete cross-section of the estuary at each station.

The amplitudes of the tidal currents at each station for various depths are shown in Table 3.5. These values indicate the range between mean ebb and mean flood currents. While the figures

	Z/h					
STATION	.05	.2	.4	.6	.8	.95
1	1.62	1.61	1.61	1.57	1.45	1.34
2	1.22	1.28	1.36	1.36	1.26	1.10
3	1.07	1.05	1.00	.96	.91	.84
4	.87	.87	.92	.93	.87	.82
5	.42	.47	.52	.51	.47	.46
6	.59	.60	.58	.54	.49	.46

TABLE 3.5 : Amplitudes of tidal currents, m /sec.

for mean flows reflect the influence of river flow, those for amplitude of currents reflect the importance of longitudinal position along the estuary section, there being a progression of decreasing amplitude upstream from the estuary mouth. Tidal dominance decreases upstream therefore. Current amplitude is greater at the surface than at the bottom, but at some stations reaches a maximum at mid-depths. The reason for this will become clear below.

The vertical profiles of the mean ebb currents and the mean flood currents for the six stations are shown in Fig. 3.10, from the data of Table 3.6.

The mean ebb flow is a maximum at the surface and decreases with depth. This is because of the combined effects of surface river flow and bed friction. The variation with depth is a linear function (correlation coefficient ranges from -.971 to -.997 for stations 2-6, -.878 for station 1, n = 6).

The mean strength of the ebb currents (at mid-depth) is obviously more dependent on river discharge than tidal height. For this reason ebb currents were strongest at station 2 (high run-off); they were weak on the spring tide of station 3 (low run-off).

The current velocity of the flood tide is generally a maximum at mid-depths. This is the result of both bed friction and salinity stratification. Bed friction decreases the bottom flood

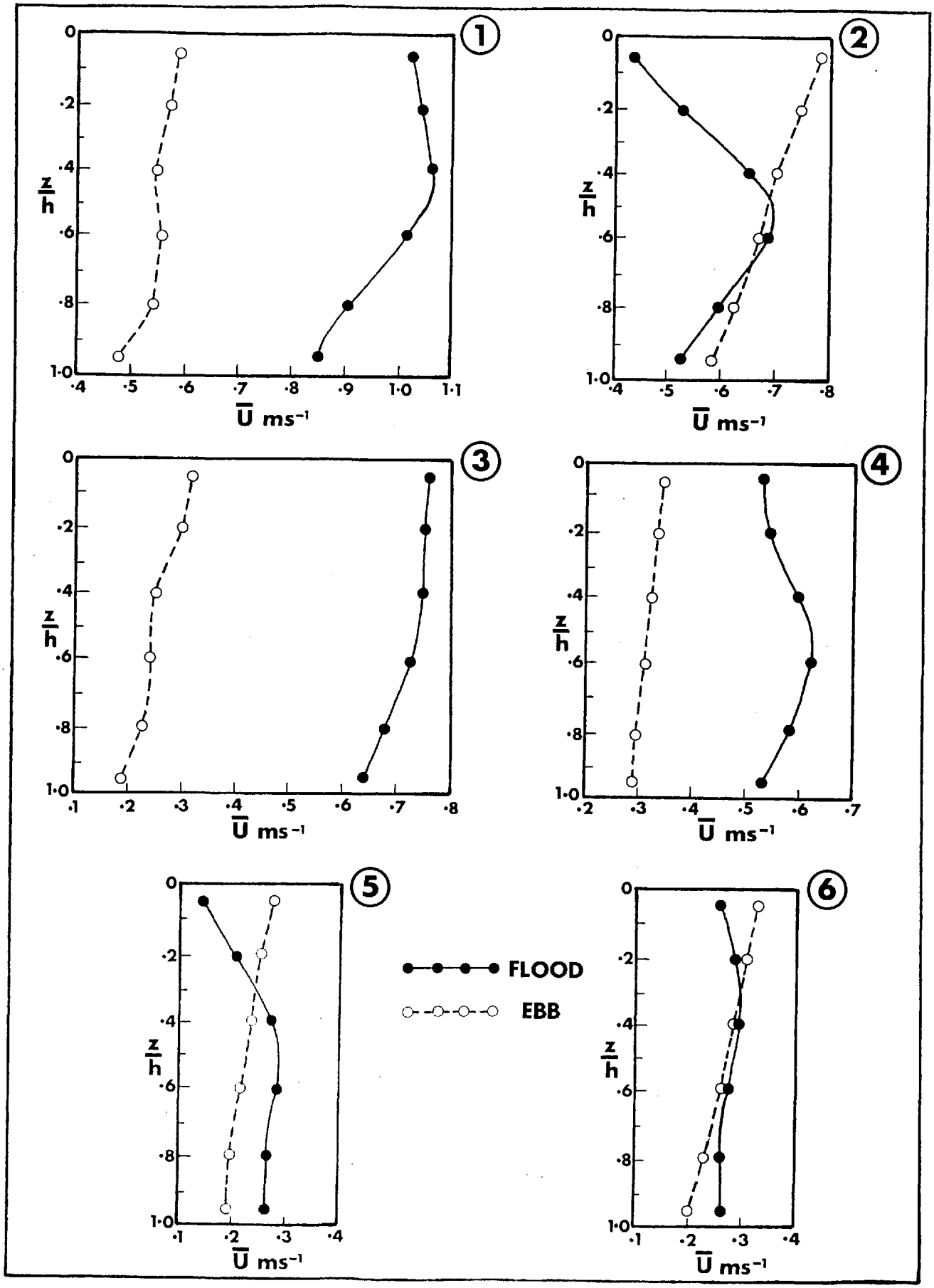


FIG. 5.10: VERTICAL PROFILES OF MEAN FLOW AND FLOOD CURRENTS.

		Z/h					
STATION	CURRENT	.05	.2	.4	.6	.8	.95
(1)	Mean flood	1.03	1.04	1.06	1.01	.91	.86
	Mean ebb	.59	.57	.55	.56	.54	.48
	Differential	-.44	-.47	-.51	-.45	-.37	-.38
(2)	Mean flood	.44	.53	.65	.69	.60	.52
	Mean ebb	.78	.75	.71	.67	.63	.58
	Differential	.34	.22	.06	-.02	.03	.06
(3)	Mean flood	.76	.75	.75	.72	.68	.65
	Mean ebb	.31	.30	.25	.24	.23	.19
	Differential	-.45	-.45	-.50	-.48	-.45	-.46
(4)	Mean flood	.53	.54	.60	.62	.58	.53
	Mean ebb	.34	.33	.32	.31	.29	.29
	Differential	-.19	-.21	-.28	-.31	-.29	-.24
(5)	Mean flood	.14	.21	.28	.29	.27	.27
	Mean ebb	.28	.26	.24	.22	.20	.19
	Differential	.14	.05	-.04	-.07	-.07	-.08
(6)	Mean flood	.26	.29	.30	.28	.26	.26
	Mean ebb	.33	.31	.28	.26	.23	.20
	Differential	.07	.02	-.02	-.02	-.03	-.06

TABLE 3.6 : Mean flood and mean ebb currents over a tidal cycle

currents, and opposition from seaward-biased freshwater flow decreases the surface flood currents. These tendencies were most developed for station 2, to a lesser extent for station 5, when upland flow was greatest. The retardation of bottom flood currents decreases in importance progressively from station 1 to station 6,

and is clearly dependent on total water depth, as well as absolute current velocities. The retardation of surface flood currents was greatest for stations 2 and 5, when tides were small and coincidental with high rates of upland flow, and least for stations 1 and 3, spring tides.

The mean strength of the flood currents (at mid-depth) is dependent on tidal height and longitudinal position along the estuary profile, being greatest on a spring tide at station 1 and least on neap tides at stations 5 and 6. (Fig. 3.10).

Some of these, and other, features of the velocity distributions are shown in Fig. 3.10X. The differences between the distributions at stations 2 and 3 are striking, these being most developed on the flood and early ebb. At station 2 (neap tide, high river flow), flood currents were at a maximum at mid-depth; velocity stratification was strongly maintained at high water, the ebb beginning at the surface while the flood continued on the bottom. These features were muted at station 3. At both stations, on the ebb tide, velocity stratification developed as surface water flowed faster than bottom water; ebb velocities reached a maximum shortly before expulsion of the tidal prism.

It is evident that the relative strengths of the opposing flood and ebb currents were similar at stations 5 and 6. At stations 1, 3 and 4 flood strength was greater than ebb, while at station 2 ebb strength was greater than flood.

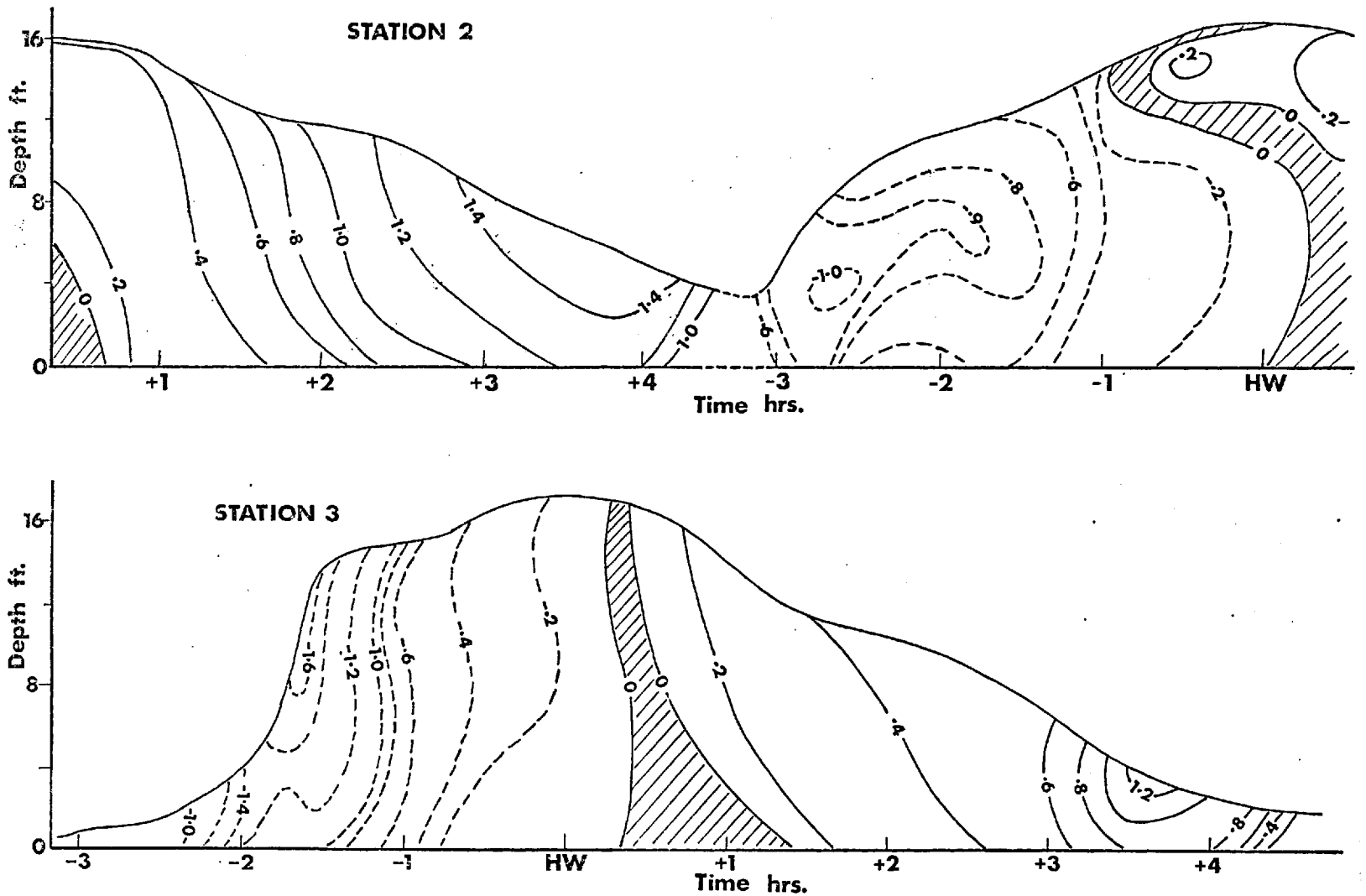


FIG. 3.10X: VARIATION OF LONGITUDINAL VELOCITY (m/sec).

This is more clearly apparent from Fig. 3.11 which shows the vertical profiles of differential flow, or net non-tidal flow, for each set of observations. Positive values indicate down-estuary flow, negative values indicate up-estuary flow. These profiles are similar to those obtained by Bowden (1960, 1963) for the Mersey, and by Pritchard (1967) for the James River. They show that at all times, the greatest relative up-estuary flow occurred at mid-depths, the greatest relative down-estuary flow occurred mostly at the surface but also on the bottom. In absolute terms, the current differential was dominantly upstream at stations 1 and 3 (spring tides, small upland flow), downstream at station 2 (small tide, large upland flow), other stations falling between these extremes.

Of course, it is completely unrealistic to suggest that the non-tidal drift can be upstream in an estuary in which the tidal prism is totally excluded at low tide. The foregoing discussion has been concerned with current variations at individual points in the estuary. Because of the constant flux of channel width during a tidal period, current measurements obtained at any one point are unlikely to be representative of currents throughout the estuary cross-section at that point. For this reason, the non-tidal drift at such a point will not be equivalent to the rate of river discharge. Thus the mean of the depth-mean value of velocity for one tidal cycle at station 3 is -0.45 m.sec^{-1}, while the mean flow corresponding to the river discharge (averaged over the same period,

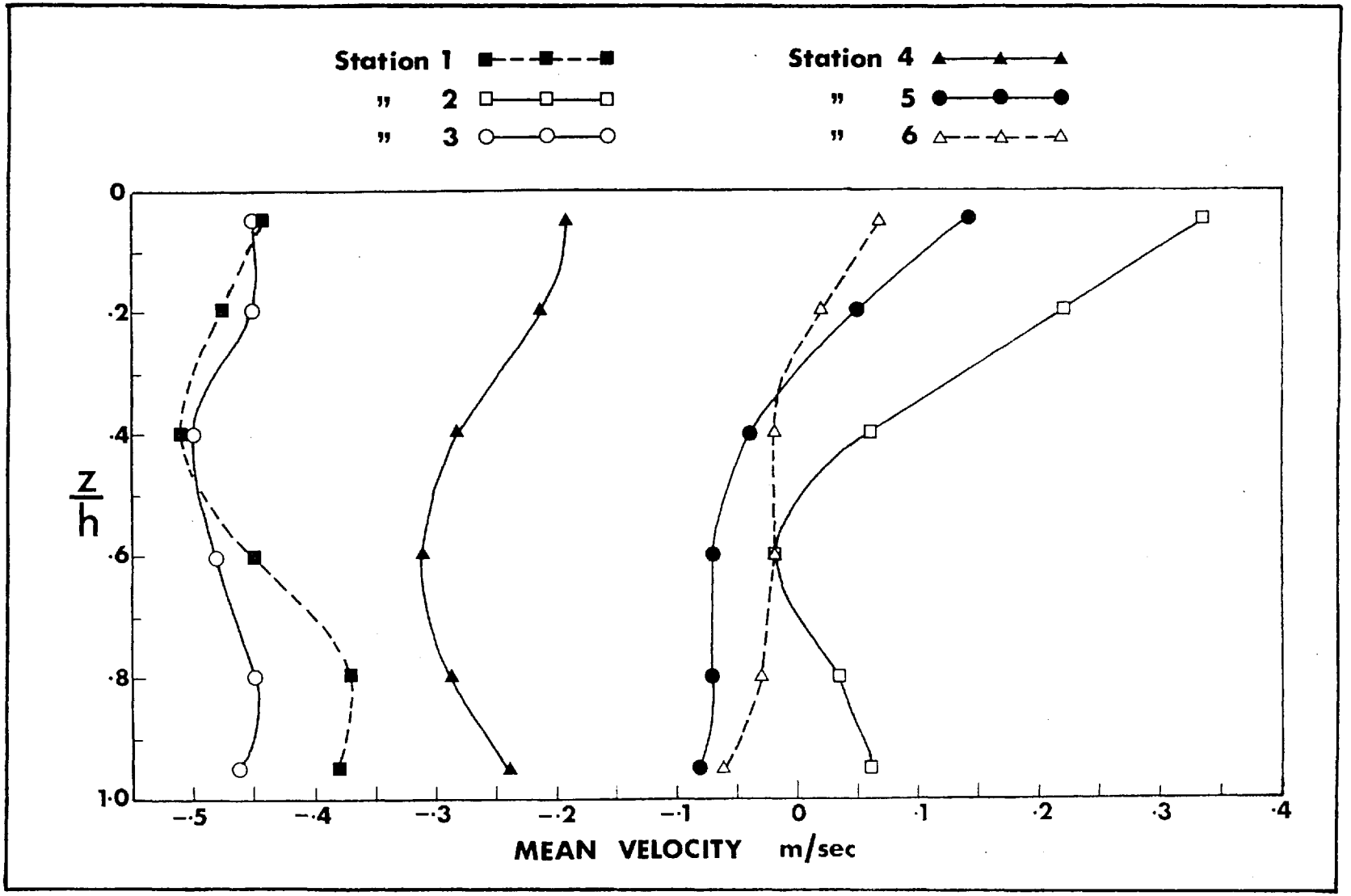


FIG. 3.11 : VERTICAL PROFILES OF NET NON-TIDAL VELOCITIES.

taking the variable cross-sectional area of the estuary at station 3 into account) is +0.002 $m.sec^{-1}$.

3.6 The Influence of Winds and Waves

All hydrological data were collected during calm weather conditions. It has frequently been noted that physical changes of geological importance undoubtedly occur most often during periods of exceptional process instability. This is particularly true of the relationship between the process and response elements involved in any study of marine/estuarine water and sediment movement. The model of estuarine circulation discussed in the foregoing sections must be considered in this light.

Direct observation of stormy conditions was not possible in this study. However, some idea of the influence of strong winds and large waves on the tidal wave may be judged from Fig. 3.12. A pressure gauge (uncalibrated) was set up for several weeks in late summer, 1968 close to the position of station 3. During this period, some gale force winds and storm-induced swell were generated from the west and south-west, and their effect on the shape of the tidal wave was registered by the pressure gauge. Traces of alternate tides from the 19th - 24th September, 1968 are shown in Fig. 3.12, superimposed so that the times of high water coincide on a common vertical axis.

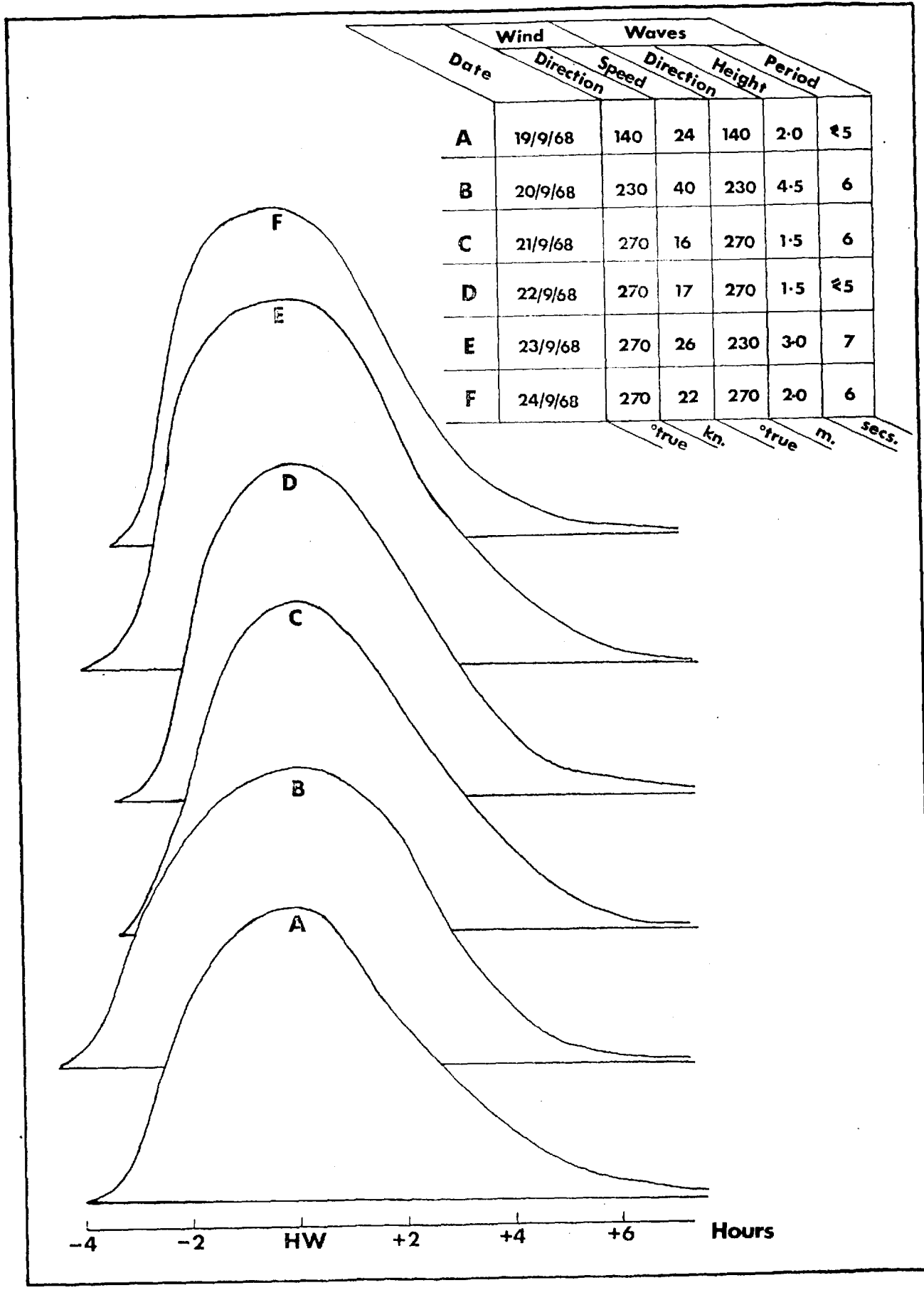


FIG. 3.12 : WIND & WAVE PROCESS MODIFICATION OF TIDAL WAVE.

Tides B and E, coinciding with stormy weather, produced distinctive curves, markedly different from those of calm sea tides (sequence A to F is of rising springs). The flood tides of B and E entered the estuary up to an hour earlier than usual; the period of near slack-water at high tide was extended; the early stages of ebb flushing were retarded.

Hence the effect of stormy conditions from the west and south-west is to prolong the duration of marine domination (and probably marine penetration) during the tidal cycle. This is achieved by processes in the Atlantic Ocean and Carmarthen Bay which induce the tidal wave to build up a pressure head faster than is usual. The combination of faster currents and large waves (of local and oceanic origin) must increase flood turbulence, maintain vertical mixing during the extended slack water period, and prevent early ebb stratification tendencies. Under these circumstances, flood currents must exceed ebb currents, the differential flow being dominantly upstream. Since the power of a stream to move sediment increases markedly with increasing current velocity, tidal 'surges' of this type must be of some significance in promoting sediment displacement from one part of the estuary to another (see discussion in Chapter 4).

3.7 Conclusions and Summary

Emphasis has been laid on the dynamics of the Taf estuarine circulation. It has been shown that there is an intimate relationship between salinity structures, current variation and turbulence, and these have been related to the interacting processes of river and tidal flows.

The results indicate that vertical salinity differences increase with increasing river discharge, during calm weather and neap tides. Vertical eddies and horizontal shearing during spring tides distort and obliterate the vertical density gradient in the bottom waters, extending in some cases to the surface. Wind induced waves obliterate the gradient in the surface waters.

The tidal wave is markedly asymmetrical, as a result of offshore bathymetry. This produces very fast currents and intense turbulence on the early flood tide during spring tides and stormy weather. Flood currents are in excess of ebb currents when big tides coincide with low river flows, locally less than ebb currents when small tides coincide with inflated river flows.

Neither horizontal nor vertical turbulence have been measured in this study. Velocity fluctuations were frequently noted on the early flood tide particularly at station 3, a spring tide, these being due to shearing and eddying phenomena (Bowden, 1962). At this time, some salinity stratification existed, but it is probable that vertical turbulence also must be caused by the

velocity gradient. It has been shown that bottom friction severely modifies the flood tide velocity gradient, so that vertical turbulence must be considerable. Also at this time, on the bend of the river off Laugharne, strong horizontal eddying was a pronounced feature of the water motion. Turbulence generated by the flood surge maintains a high degree of vertical mixing through most of the tidal cycle, except during neap tides, calm weather and high river flows.

Simultaneous lateral and longitudinal variations of salinity were not logged in this study. During spring tides, stormy conditions and low river flows, it may be forecasted that a high degree of lateral and longitudinal mixing occurs as a result of flood-induced turbulence and eddying. During neap tides, calm weather and inflated river flows, it was observed that some lateral differential flow occurs in the lower (NW - SE) estuary on the early flood, reflecting the geostrophic effect; it is very likely that a lateral salinity gradient exists at this time.

It may further be suggested that the circulation characteristics described above indicate that marine penetration by saltwater is also dependent on the relative magnitudes of tidal and river flows, maximum isohalines pushing furthest into the estuary on spring tides in summertime.

The processes controlling estuarine circulation are therefore tidal control of horizontal advection (i.e. salt flux caused by

mean flow), and vertical diffusion (i.e. salt flux caused by short-period eddies) as a result of turbulence induced by bottom friction, eddying, and wind wave surface drag. River flow is important when other process elements are diminished. These elements generally create a high degree of vertical mixing, so that the system might be classified as vertically homogeneous (Cameron and Pritchard, 1963) but more accurately as laterally homogeneous with moderate vertical stratification. As suggested by Bowden (1967) and Pritchard (1967), only very small vertical gradients need occur to provide for a significant vertical shear in the net non-tidal velocity field, and the truly vertically homogeneous estuary probably does not exist. At times, the process variables interact to create a partially stratified type circulation with some lateral variation.

CHAPTER 4.

TEMPORAL VARIATIONS OF THE ESTUARY PROFILES

4.1 Introduction

The movement of suspended sand in front of a beach under the influence of wave and surf action is restricted to a rather narrow strip of water, but the entrapment and accumulation of sediment within an estuary covers a much greater area. The principal agents of sediment transport may be fluvial and/or tidal, which periodically reinforce and oppose one another,* and meteorological, which may be operative within the estuarine circulation system (thereby modifying water circulation and creating waves). and/or outside its dynamic and morphological confines (again modifying circulation through storm surge). These agents are mutually exclusive, though they may sometimes follow parallel trends of seasonal variation, and their continuous interaction creates an ever-changing pattern of water movement and corresponding sediment movement. However, it may be expected that an equilibrium between the bottom, the behaviour of suspended sediment, and water movements, will be established under conditions of constant sea-level.

As has been described in Chapter 1, much of the sediment trapped and deposited within the estuary of the River Taf is undoubtedly of recent origin, entering the estuary during the post-glacial rise of sea-level; Rusnak (1967) has estimated that the rate of accumu-

* thereby creating turbulent interaction.

lation during the past 10,000 - 15,000 years was of the order of 1 - 2 metres per thousand years, the exact figure depending on climatic factors. Local information (Curtis, 1880 and more recent) suggests that the smaller fluctuations of sea-level described by Per Bruun (1962) have produced a cyclic variation of sand accumulation on the dunes above Pendine Sands and probably within the estuary. The tectonic lowering of the coastline of south-west Wales during the present day (Valentin, 1953) means that the estuary is perhaps being inverse-filled (using the terminology of Rusnak, 1967) by sand from Carmarthen Bay, and there is strong historical, though generally undocumented, evidence to suggest, that such a process has been operative during the past fifty years at least.

The present study extended over a period of eighteen months. Obviously such short-term monitoring could not hope to establish any long-term trends of accumulation (because of the extreme temporal variability of the agents of energy input outlined above), unless any progressive trends were of an order of magnitude greater than these short-term variations. The aim of the study was to establish whether a periodic, or seasonal, variation of sediment accumulation occurred, but for practical reasons the results did not directly satisfy this aim, as is described below. As in the interpretation of temporal variations of beach profiles, an attempt has been made to relate changes within the estuary to changes of energy input, whether fluvial, tidal or meteorological, then to

examine the temporal distribution of these elements and postulate whether seasonal variations of sediment accumulation may indeed occur.

4.2
Surveying and Analytical Techniques

The surveying procedures adopted were the same as those described in Chapter 2. Surveying, using a microptic level and staff, was carried out along eleven transects, set up approximately at right angles to the longitudinal cross-section of the estuary (Fig. 4.1). Steel poles, firmly cemented into the high marsh on each bank, were used as permanent reference marks for each transect; in a few instances other features, such as a cliff face and the edge of a building were adopted, but each transect was marked by at least one steel pole, the height of which was determined by levelling into the local bench marks.

It should be noted that for some poles, this latter exercise was not rigorously checked by completing a closed loop and therefore the heights given on subsequent illustrations of profiles are possibly subject to error.

In the case of transects 10 - 18, markers were set up on each bank of the channel, so that all surveys of each transect were between two fixed points and the accuracy of surveying could be tested. In the case of transects 8 and 9, the profile was terminated at the low-water channel since the depth of water and/or

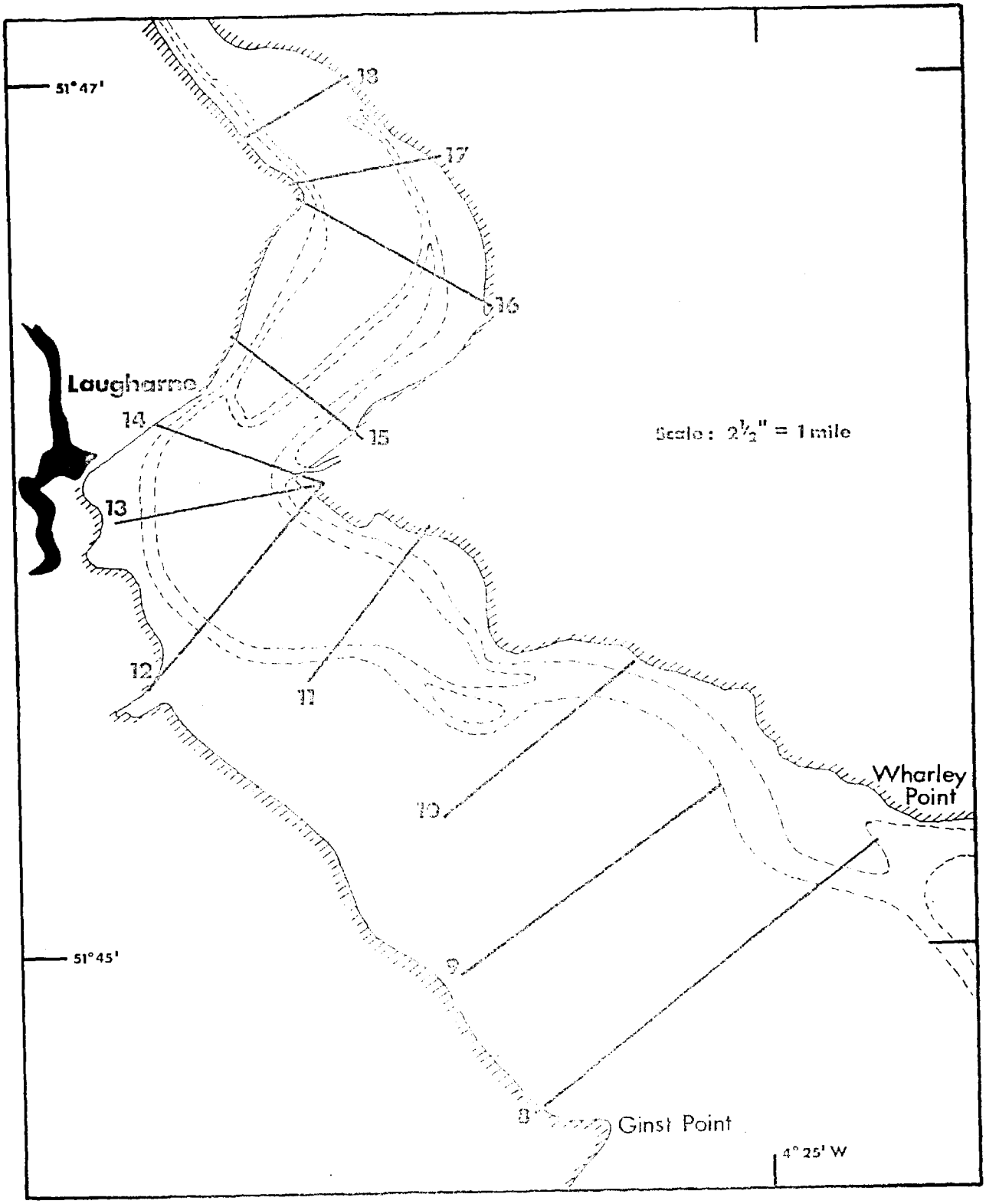


FIG. 4.1: POSITION OF TRANSECTS.

the speed of the current did not allow for safe passage of either equipment or operators; on these two transects, both marker poles were set up on the right bank to establish a line of permanent orientation.

Surveys were carried out at varying intervals during the study period, with an average interval of three months between surveys. Unfortunately, the record of data from these is far from complete. This was partly because of the difficulties of attracting staff operators for a sometimes unpleasant role, but mainly because at times the transects were impassable because of the depth of the low-water channels. The sandbanks are fully exposed for three hours only during a tidal cycle, and lack of time did not always allow for the impedence resulting from the use of a small boat. The most inaccessible profiles (10, 11, 16 - 18) were therefore surveyed irregularly.

The transect lines were established in September 1968 for profiles 10 - 18, but earlier, in February 1968, for profiles 8 and 9. Most surveys were carried out during spring tides, of varying heights, but a few during neaps.

Profiles were constructed from the surveying data with a vertical exaggeration of 20 times the horizontal scale, and successive profiles of each transect superimposed to show zones of accretion and erosion.

The volumetric changes between surveys have been examined in

a similar manner to the one adopted in Chapter 2 for beach profiles. For each profile the volume of sediment per unit cross-section above a fixed datum and between fixed limits on each bank has been determined. The vertical datum corresponds to the lowest point of the profile i.e. the lowest point of the low-water channel (which did not change by more than a few inches on any transect during the study period). This datum may be considered as designating the level of the base of the graded profile of the river (Mackin, 1948) during that period, and is, therefore, at a progressively higher level from transect 8 to transect 18. The lateral limits, fixed for each transect, delineate the zone of mobile sediment, as distinct from the relatively stable zone of consolidated muds and marshland on each bank. Generally the mobile zone included sand only, but on profile 12 a considerable lateral expanse of mud (on sand) was developed near the right bank; in this case, the volume of the mud/sand zone has been considered both as a separate entity and as part of the main sand body in subsequent analyses. In the case of transects 8 and 9, where the profiles did not cross the low-water channel, volumetric estimates are confined to the right bank; however, the right bank accounts for over 85% of the cross-sectional profile here since the main channel sticks close to the cliffs under Wharley Point, so that volumetric estimates derived from the profiles are obviously close to the total volume of the sand body above the graded baseline. On transect 8, marsh

development is patchy and there is almost continuous sand along its whole length; a discontinuous zone of marsh occurs close to the level of mean high water neap tides and this latter has been adopted as a suitable lateral limit for the mobile zone; sand above MHWN is considered as a separate prism of sediment.

Otherwise, the volumes of sediment measured for each profile may be related for all transects, since they indicate the development of accumulation above the graded baseline of the river at low-water (i.e. after the tide has been fully excluded).

Volumes measured in this way obviously provide a quantitative estimate of total change between surveys. In order to examine the distribution of variation across each profile, another procedure has been adopted. The height of the profile above the graded baseline has been measured at stations 50 feet apart, and the temporal variations of heights at each station studied. The analysis of variance technique adopted in Chapter 2 whereby variation of beach profiles was dissected into temporal and spatial components, cannot be applied to these estuary profiles because of the excessive interaction between components. This interaction is well illustrated by superimposing successive profiles of each transect (shown later in the chapter), where it is clear that the trends of variation across any profile were not constant for successive inter-survey periods. In any case, there is no practical application of procedure to justify use of the

technique, since on these profiles, because of the magnitude of cut and fill between surveys, it would be impossible to set up fixed monitoring stations marked by posts or buried plates, as was suggested for studying variation of beach profiles.

4.3 Comparative Variations of Profiles

Successive surveys of each transect have been superimposed to show areas of accretion and erosion; from these it may be observed that inter-survey variations were greater than those measured during contemporaneous periods on the beach profiles. Since it is difficult to view and compare the superimposed profiles of all transects simultaneously, it is advantageous to reduce the information to more readily assimilated forms.

The volumes of mobile sediment above the graded baseline for successive surveys of the eleven transects are shown in Table 4.1.; data is in cubic feet per unit thickness of cross-section.

These volumes have been used to derive the mean, standard deviation and coefficient of variation for each profile. Data is again in cubic feet per unit thickness of cross-section; the coefficient of variation is a proportion, expressed as a percentage. These statistics are shown in Table 4.2.

	SURVEY								
PROFILE	1	2	3	4	5	6	7	8	9
8 (above MHWN)	6,893	6,118	6,154	6,044	6,082	6,019	5,842	-	6.023
8 (below MHWN)	28,919	24,203	28,078	26,128	27,447	29,294	27,875	-	-
9	14,747	16,774	16,773	17,040	17,348	19,258	20,205	-	-
10	-	-	24,768	26,468	-	26,294	29,178	26,252	-
11	-	-	-	15,592	16,104	14,897	14,444	15,353	-
12 (mud/sand)	-	-	5,468	4,958	4,052	4,623	4,444	4,068	3,595
12 (sand)	-	-	6,422	6,350	6,850	6,983	6,954	7,074	7,522
13	-	-	5,408	5,412	5,384	4,978	4,137	4,190	6,199
14	-	-	3,364	3,924	3,272	4,004	3,892	4,675	4,680
15	-	-	2,374	-	3,056	2,652	2,810	2,885	2,349
16	-	-	6,188	7,182	-	6,462	6,654	7,375	-
17	-	-	5,270	5,194	-	5,062	5,000	5,764	-
18	-	-	7,780	-	-	7,278	7,388	7,073	-

TABLE 4.1 : Volumetric data ($ft.^3$)

PROFILE	VOLUMES ft.^{3}			ELEVATIONS ft.	
	MEAN $\bar{X}$	STANDARD DEVIATION σ_V	C.V. %	MEAN STANDARD DEVIATION $\bar{\sigma}_H$	STANDARD ERROR $\sigma_{\bar{\sigma}}$
8 (below MHWN)	27,421	1,753	6.4	.85	.55
9	17,449	1,792	10.3	.93	.46
10	26,592	1,600	6.0	.72	.25
11	15,278	638	4.2	.66	.31
12 (total)	11,409	337	3.0	.95	.52
13	5,101	736	14.4	1.28	.45
14	3,973	558	14.0	.94	.27
15	2,688	285	10.6	.99	.45
16	6,772	496	7.3	.84	.43
17	5,258	303	5.8	.69	.29
18	7,379	298	4.0	.61	.47

TABLE 4.2 : Comparative estimates of variation of mobile sediment volumes and profile elevations.

The standard deviation is an estimate of the amount of variation of sediment volumes, and as such provides some comparable measure for all profiles. However, caution must be exercised in comparison between variance estimates since they are based on unequal sample sizes of surveys taken at (often) different points in time.

It is apparent that greater volumes of sand were added to, and removed from, the lower estuary than the upper. This is hardly surprising since the width of the estuary, and volume of mobile sediment, at profile 8 is some three times that at profile 18. The width of the estuary must be primarily controlled by the underlying geological structure; estuarine hydrodynamics must, to some extent, be influenced by morphology. Profiles 13 and 14 were more variable than would be expected from their position on the longitudinal profile. This must be attributed to increased turbulence generated by fast currents in shallow water interacting with curvilinear patterns of shoals developed on the sharp bend at Laugharne. Such turbulence will be most developed on the early flood (described in Chapter 3), to a lesser degree on the late ebb. This association of sediment instability and horizontal turbulence supports the view of Kestner (1961) that fluctuating, rather than absolute high, current velocities are most capable of promoting sand transport.

The coefficient of variation compares the amount of variation

in populations having different means, being the standard deviation expressed as a percentage of the mean, and answering the question: What were the relative amounts of variation of profiles, independent of the size of the sand bodies defined by their cross-section? By this criterion, profiles 13 and 14 were considerably more variable than any others, profile 12 considerably less so. As will be shown later, the apparent relative stability of profile 12 was due to a balance between erosion on one part and accretion on another.

Above Laugharne, the profiles became progressively more stable (in terms of overall volumetric change). This is, in part, because they were surveyed less regularly than some others. But it will be shown subsequently that this progressive upstream trend of increasing stability is a real one.

Below Laugharne, profiles were more unstable. The low estimates of variance for profile 11 are probably spurious (because of infrequency of surveying), as will become clear later.

The foregoing discussion has been concerned with the variation of total mobile sediment under each profile. The variation of profile elevation at fixed stations along the profiles introduces another aspect of stability, since we may examine the mean variation, in feet, of all such stations (50 feet apart) on each profile. In addition, this approach enables a quantitative estimate to be made of the distribution of variation along each profile. In Table 4.2, the standard deviation of elevation above datum has

been determined for all stations, and the mean standard deviation computed for each profile. Also the standard error of these standard deviations has been computed for each profile, and this provides a comparable estimate of intra-profile variation for all profiles.

The variation of profile elevation was greatest for profile 13 and least for profile 18. Generally, the relative estimates of mean variation are similar to those of total volumetric variation. There is, however, an important difference. Although relatively stable in overall volume, the mean elevations of profile 12 were relatively unstable. This apparent discrepancy indicates that this profile was indeed highly unstable, but the loss of sediment at one point was partly matched by a gain at another point, and vice-versa, so that the overall volume of mobile sediment remained comparatively constant. Since the amount of material eroded was partially matched by the amount deposited, on this profile the estuary may be regarded as having attempted to maintain regime.

The estimates of standard error of variation show that spatial variations of stability were least pronounced for profiles 10, 11, 14 and 17. Thus these profiles were the most homogeneous in their response to changing energy input. The significance of these estimates is examined in more detail below.

4.4 Surveys of Profiles 8 - 11

These profiles cover the outer part of the estuary, its virtually straight lower reaches. As described above, the stability of the profiles appears to increase with increasing distance from the estuary mouth, but this cannot be firmly established (at this stage) because of the infrequency of surveys of profiles 10 and 11. However, more sediment was in relative motion in this part of the estuary than in its upper reaches which does suggest that tidal action may be a prime-mover in sediment transportation and accumulation. The extent of marsh development is important since it limits the width of the mobile zone and concentrates tidal energy within a confined cross-section.

Successive surveys of profile 8 are superimposed in Fig. 4.2, and volumetric changes are shown in Fig. 4.3. For the reasons explained earlier, the profile has been divided into two portions at the level of mean high water neap tides which coincides with the level of patchy marsh development. Above this level, the profile has been comparatively stable, showing a slight overall erosion. Below this level, the profile has been much less stable, with a maximum range of 5,092 cubic feet between surveys 2 and 6. The net change between the first and last surveys was -1,044 cubic feet (which corresponds to a mean reduction of elevation of 0.56 feet) but this cannot be considered significant when compared with the maximum between-survey change of -4,717 cubic feet. Hence no

CHANGES ALONG PROFILE 8.

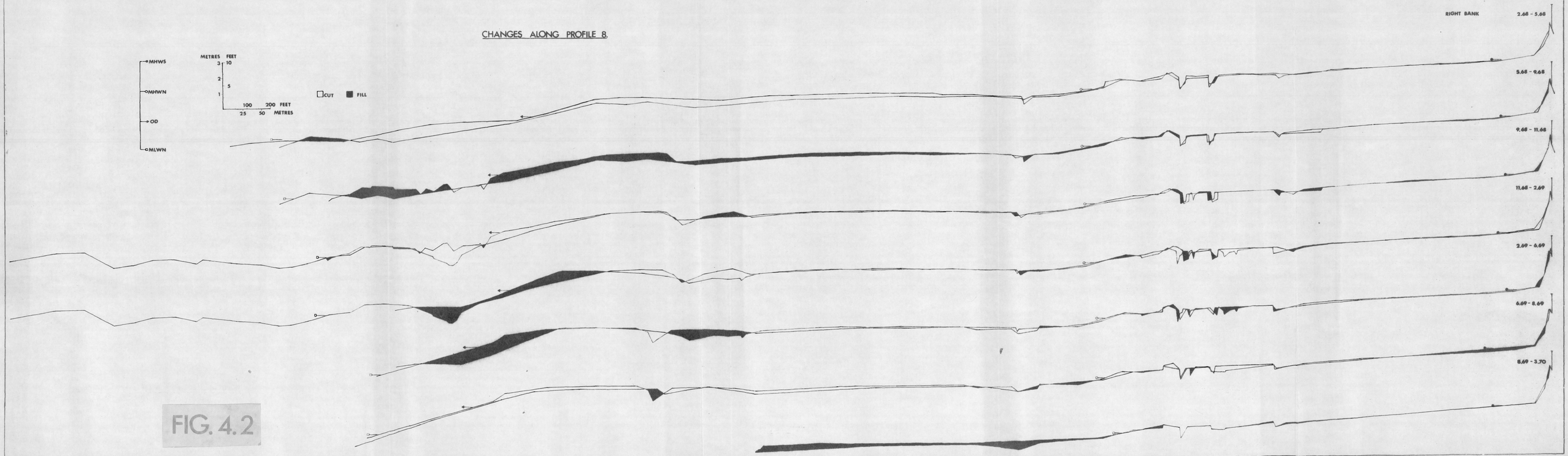


FIG. 4.2

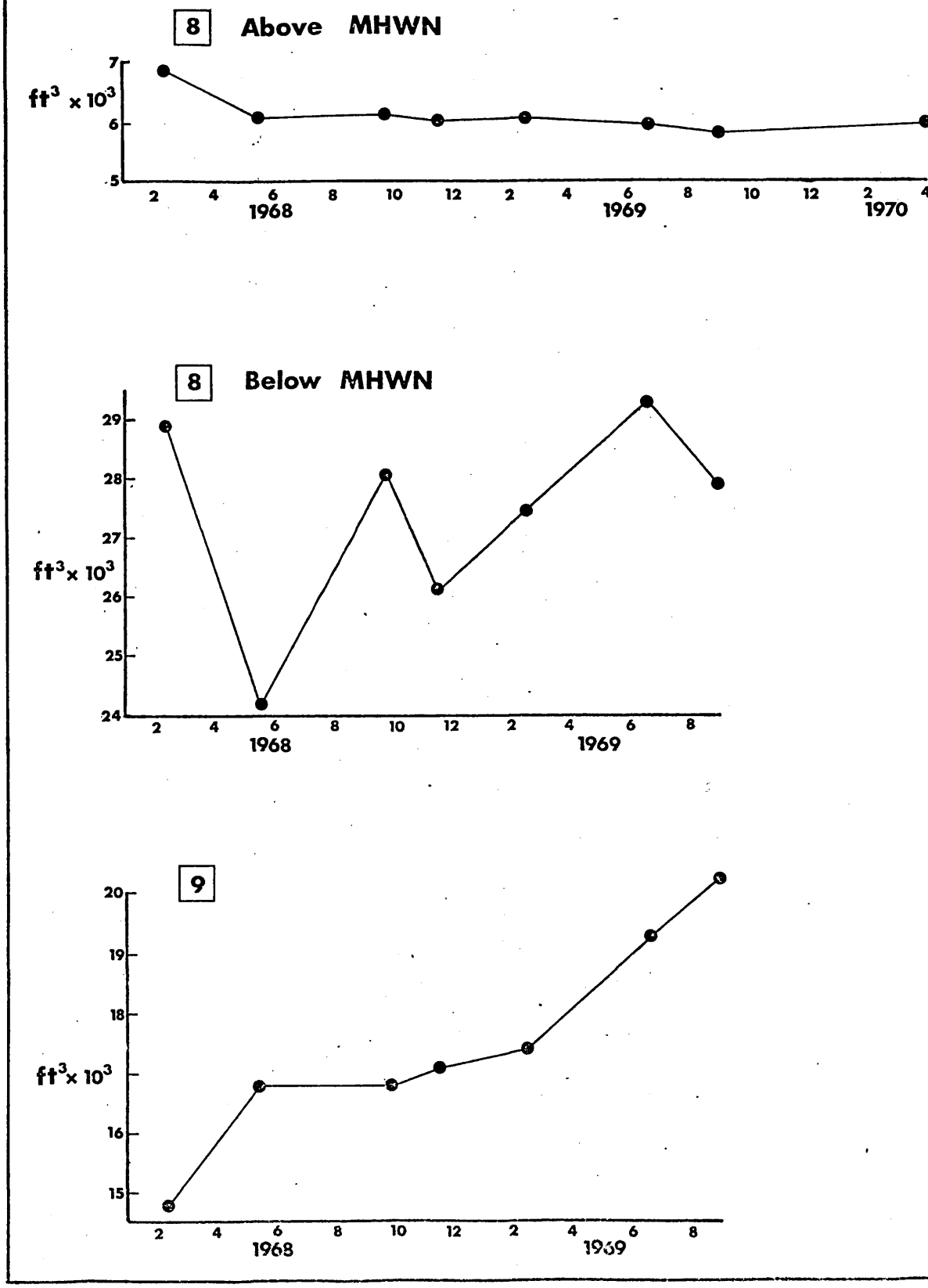


FIG.4.3: VOLUMETRIC VARIATION, PROFILES 8 & 9.

linear trend of accumulation or erosion can be established. This is shown in Table 4.3 which gives the product-moment correlation coefficients for the association between accretion and time (from beginning of study period).

	PROFILE					
	8(upper)	8(lower)	8(total	9	10	11
r_{12}	-.68	.32	.16	.95**	.55	-.57
n	8	7	7	7	5	5

TABLE 4.3 : Correlation coefficients (r_{12}), accretion/time

Intra-profile variation of stability of all profiles was summarised by use of the standard error of standard deviation (Table 4.2). It may be seen that of all profiles, profile 8 was the most heterogeneous in response, some parts of the profile being (relatively) more unstable than others (only the mobile zone below MHWN being considered). This heterogeneity is examined in detail in Table 4.4 and Fig. 4.4, which shows the spatial distribution of temporal variation, as expressed by the standard deviations of elevations above datum. It is felt that this statistic provides a more realistic measure of variation than the sweep zone of King (1959) which is a measure of range and therefore reflects exceptional rather than normal variation. The concept of the sweep zone does not allow comparisons between surveys of all profiles when survey times are not common to them all.

There is a highly significant negative correlation between instability (i.e. temporal variation) and elevation above datum; the profile was most unstable near the main channel, becoming progressively more stable with increasing elevation (and lateral distance) from the channel.

This is not a truly linear relationship, but is more probably a quadratic one, as is evident in Fig. 4.4, the upper (above MHWN) portion of the profile being homogeneous and increased instability occurring close to the main channel.

Successive surveys of profile 9 are superimposed in Fig. 4.5, and volumetric changes are shown in Fig. 4.3. The upper portion of the profile, above MHWN, consists of established marsh traversed by many creeks and was generally not surveyed; all three marker posts were always tied into the survey to fix orientation and elevation. The mobile zone of the profile consistently built up during the study period, the relationship between accretion and time being highly significant (Table 4.3). The net change between the first and last surveys was 5,459 cubic feet, which corresponds to a mean accretion of 1.86 feet.

From Table 4.2, it may be seen that variation on this profile was heterogeneous but less so than on profile 8. This heterogeneity may be expressed as a highly significant linear relationship between stability and elevation above datum (Table 4.4). Again this is more likely to be a quadratic relationship since, as is shown in

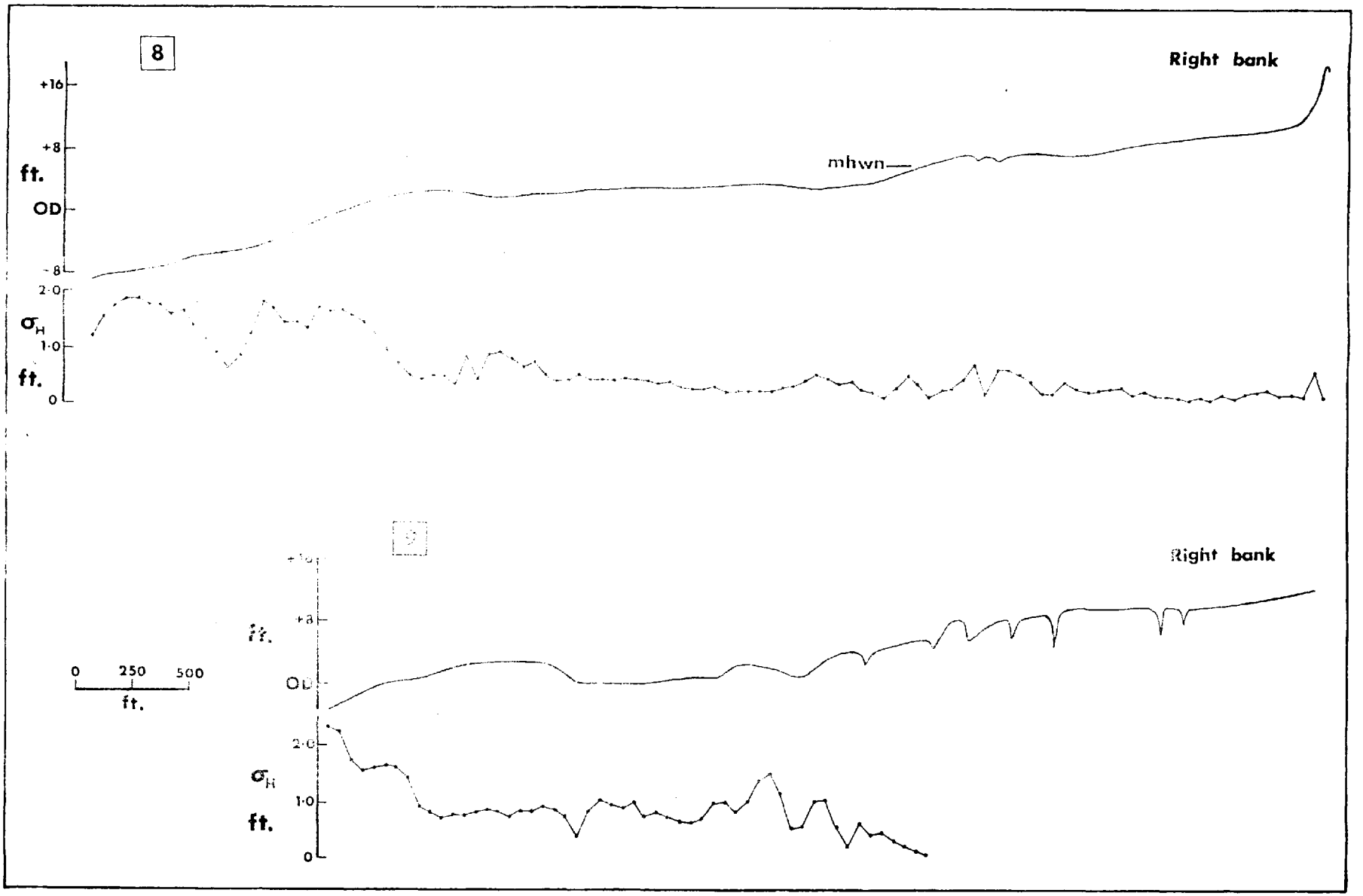


FIG. 4.4: STANDARD DEVIATION OF ELEVATION ABOVE DATUM (σ_H), PROFILES 8 & 9.

FIG. 4.5

CHANGES ALONG PROFILE 9.

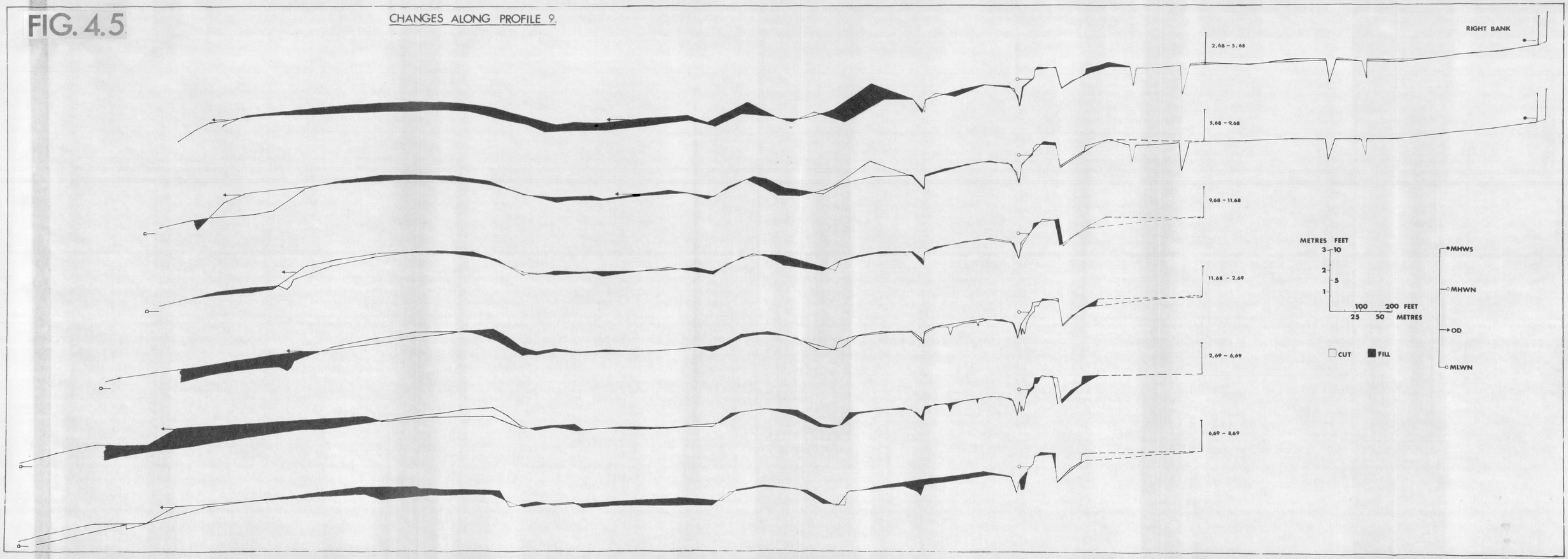


Fig. 4.4 there is a rapid increase of variation as the main channel is approached.

	PROFILE					
	8(upper)	8(lower)	8(total)	9	10	11
r_{12}	-.29	-.82**	-.83**	-.75**	-.25(-.41**)	-.46**
n	40	69	109	54	65 (52)	45

TABLE 4.4 : Correlation coefficients (r_{12}), standard deviation of elevation/mean height of elevation above datum

Successive surveys of profile 10 are superimposed in Fig. 4.6, and volumetric changes are illustrated in Fig. 4.7. Unlike profiles 8 and 9, this transect (and succeeding ones) was surveyed across the main channel. Profile 10 was less variable than either profiles 8 or 9. The maximum range, between surveys 3 and 7, was 4,410 cubic feet, and the net change during the study period was +1,484 cubic feet (which produced a mean accretion of .44 feet); these volumes are not very significant when compared with the maximum between-survey change of 2,926 cubic feet. No linear trend of accretion or erosion with time can be established (see Table 4.3).

It has been shown that profile 10 was apparently comparatively homogeneous in its response to changing energy and sediment input. This is illustrated in Fig. 4.8. The relationship between stability

CHANGES ALONG PROFILE 10.

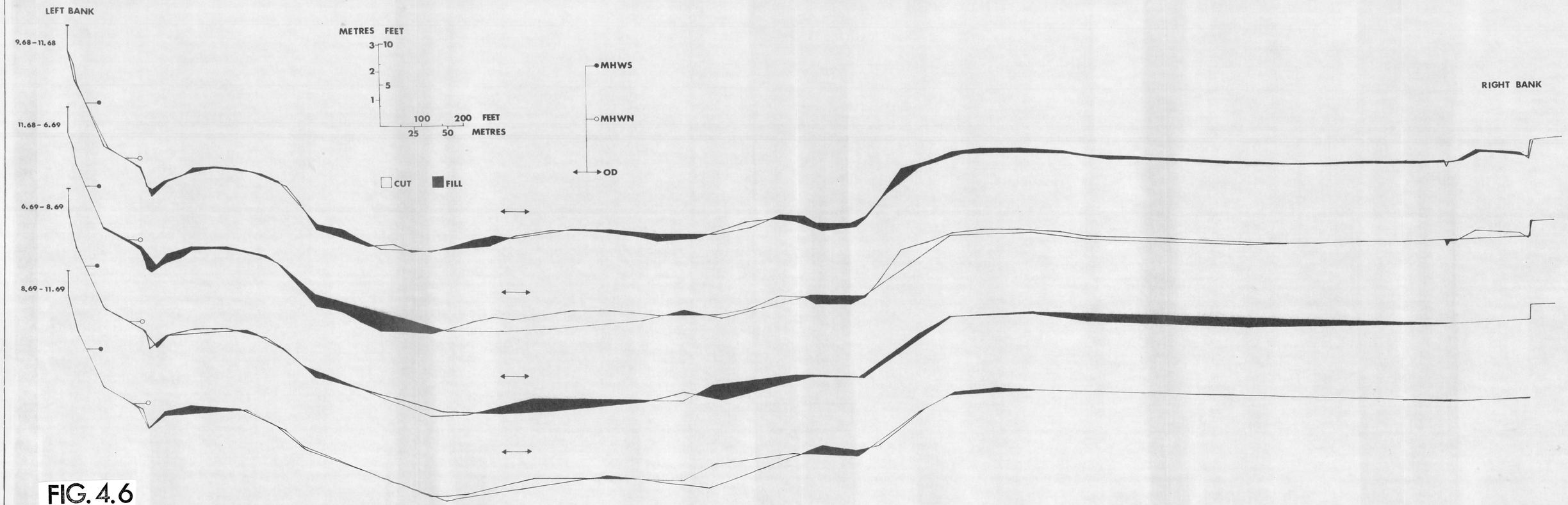


FIG. 4.6

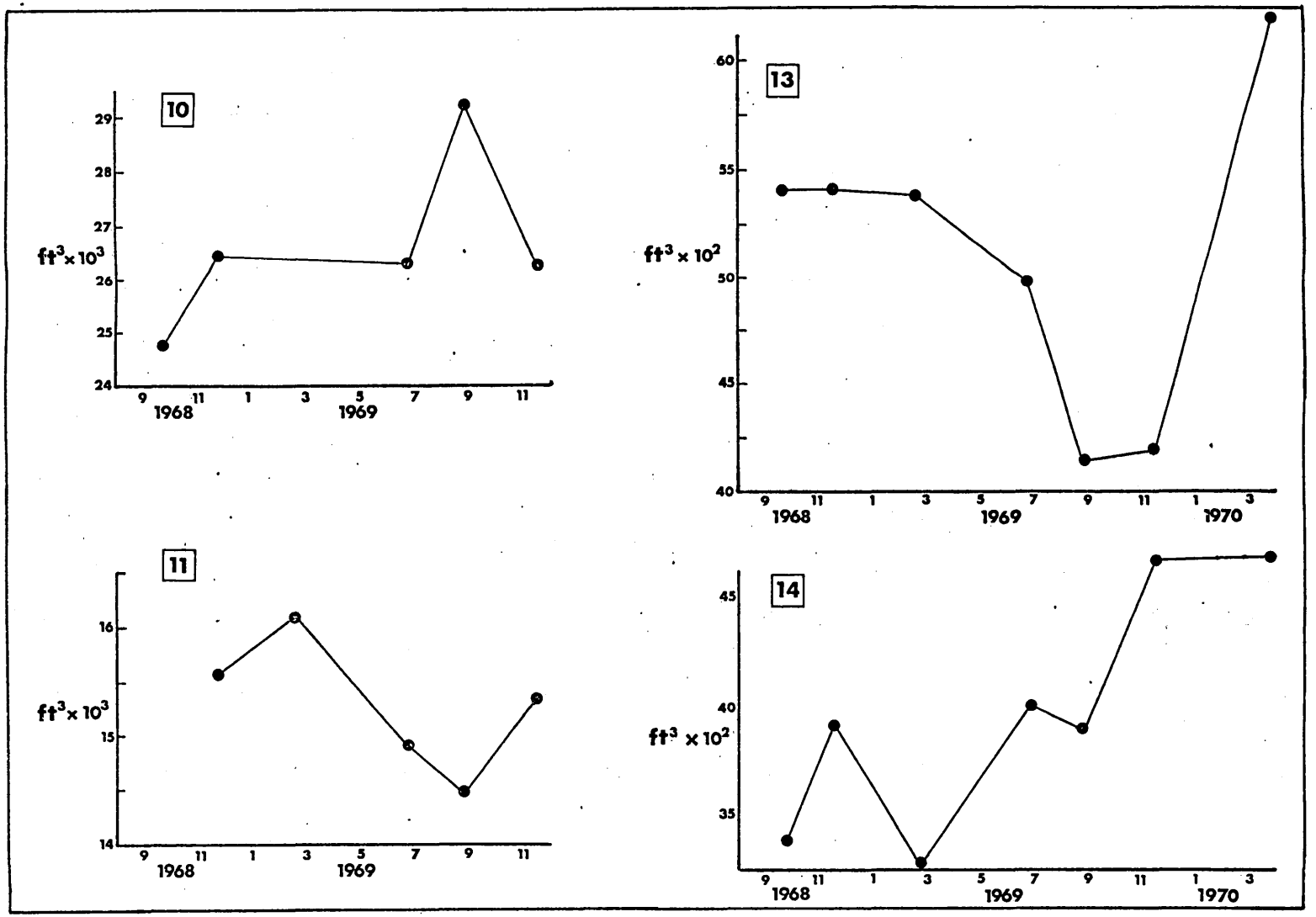


FIG.4. 7: VOLUMETRIC VARIATION, PROFILES 10,11, 13 & 14.

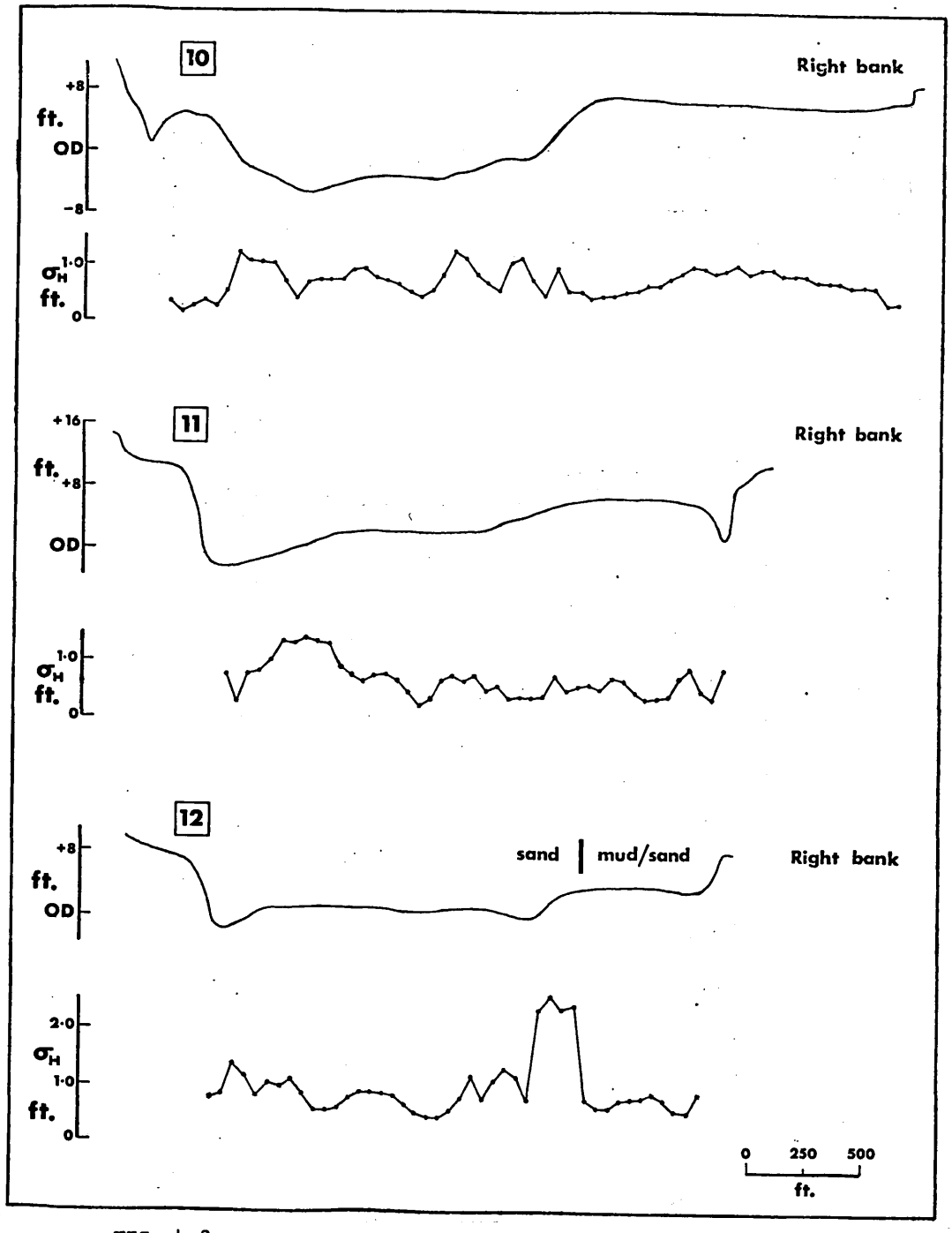


FIG. 4.8: STANDARD DEVIATION OF ELEVATION ABOVE DATUM (σ_H), PROFILES 10 -12.

and elevation above datum is apparently not a linear one. The linear relationships suggested for profiles 8 and 9 did not include the main channel. The main channel on profile 10 is wide and shallow and if it is left out of the analysis, then there is a highly significant linear relationship between stability and mean elevation, as shown in Table 4.4; indeed the relationship remains significant if all but four stations at the deepest part of the channel are included. Hence it is apparent (Fig. 4.8) that most of the profile was relatively stable, but there was a significant increase of variation on both sides of the main channel.

Successive surveys of profile 11 are superimposed in Fig. 4.9, and volumetric changes illustrated in Fig. 4.7. The maximum range between surveys was 1,660 cubic feet (between surveys 5 and 7, see Table 4.1), and the net change during the study period -239 cubic feet; as has been shown this profile was more stable than those downstream. The maximum change between surveys was 1,208 cubic feet, so overall change is hardly significant; as shown in Table 4.3, there was no linear trend of accretion or erosion with time.

Profile 11 was apparently comparatively homogeneous in its spatial distribution of temporal variation. This distribution is illustrated in Fig. 4.8, and, as shown in Table 4.4, there exists a highly significant association between variation and elevation above datum. If the main channel itself is excluded from the

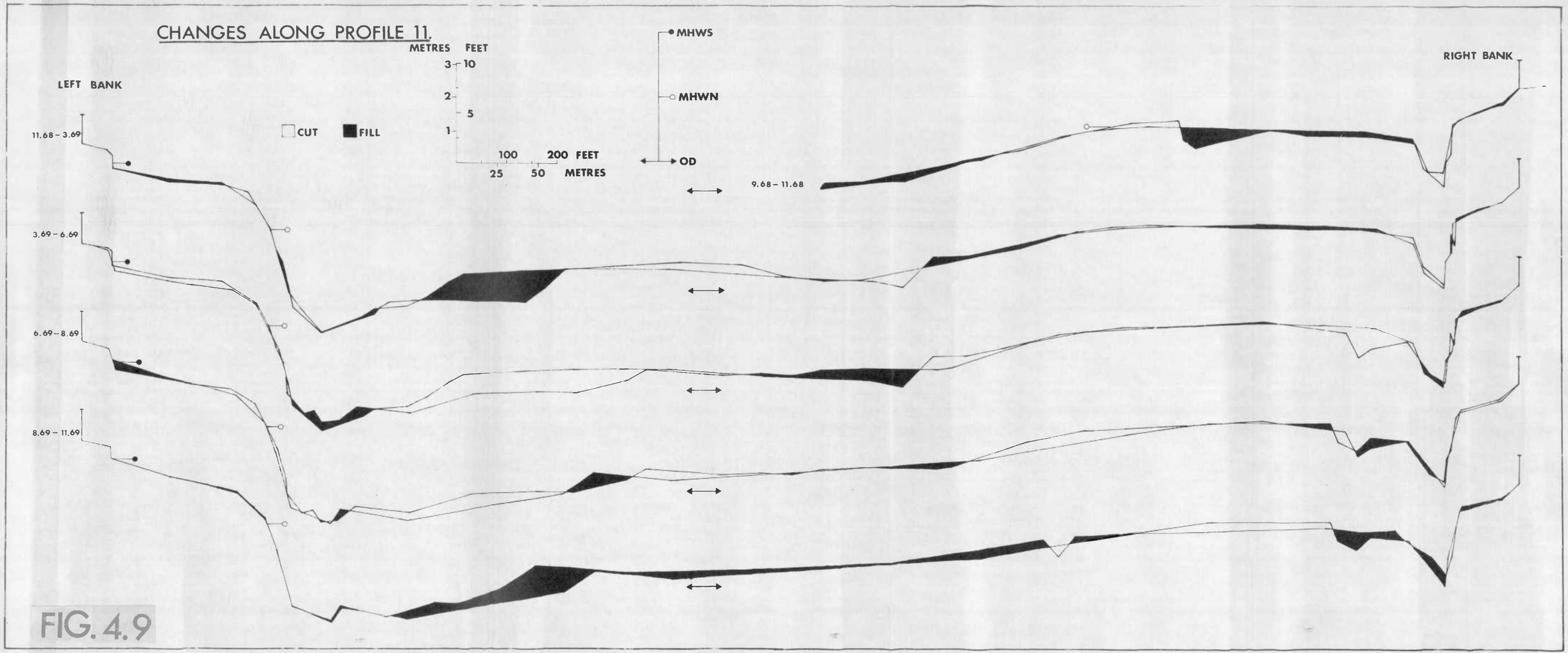

CHANGES ALONG PROFILE 11.
METRES
FEET
3
10
2
5
1
100
200 FEET
25
50
METRES
MHWS
MHWN
OD
CUT
FILL
LEFT BANK
RIGHT BANK
11.68 – 3.69
3.69 – 6.69
6.69 – 8.69
8.69 – 11.69
9.68 – 11.68

FIG. 4.9

analysis (by excluding three stations) then this significance is increased. As before, the reason for this is that the greatest instability occurred on that part of the profile adjacent to the main channel; away from the channel, stability increased.

These four profiles display similar trends of spatial distribution of temporal variation. The position of the main channel did not change during the study period, maintaining its course close to the left bank of the estuary. Although there is no data for the depth of the channel on profiles 8 and 9 the data for profiles 10 and 11 indicates that this was constant also. The most unstable areas of these profiles lay adjacent to the main channel; to the right on profiles 8 and 9 (no data for the left), on both sides on profile 10, and to the right on profile 11 (where the channel was deeply incised against the marsh on the left bank).

The significance of these lateral distributions of stability is discussed in section 4.5.

4.5 Surveys of Profiles 12 - 14

These profiles are grouped together since they define the right angled bend of the estuary at Laugharne, and radiate from a single point on the left bank.

It has been shown that profiles 13 and 14 were extremely variable in total volume of mobile sediment; profile 12 was comparatively stable in total volume but showed a notable re-

distribution of sediment from one part to another.

Successive surveys of profile 12 are superimposed in Fig. 4.10, and volumetric variations are illustrated in Fig. 4.11. On this transect, the mobile zone of sediment was divided into two portions, one consisting of sand, the other of mud deposited on sand (shown in Fig. 4.8).

The maximum range between surveys, between surveys 3 and 5 (Table 4.1), was 988 cubic feet for the total profile, and the net change during the study period was -773 cubic feet. The maximum change between successive surveys was 654 cubic feet. As shown in Table 4.5 there was no linear trend of accretion with time.

However, there was a highly significant trend of accretion with time in the sand zone, and of erosion in the mud/sand zone. These reversed trends resulted in a relative stability of the profile in terms of total volume, but a considerable instability of individual stations along the profile. This heterogeneous distribution of variation is shown in Fig. 4.8. There is no longer a straightforward linear relationship between stability and mean elevation above datum (Table 4.6) for the total profile. However, a negative linear relationship does exist for the sand zone ($r_{12} = -.38^*$, $n = 29$), and for the total profile if the transition area between sand and mud/sand zones is ignored ($r_{12} = -.35^*$, $n = 40$). The transition zone is highly unstable in

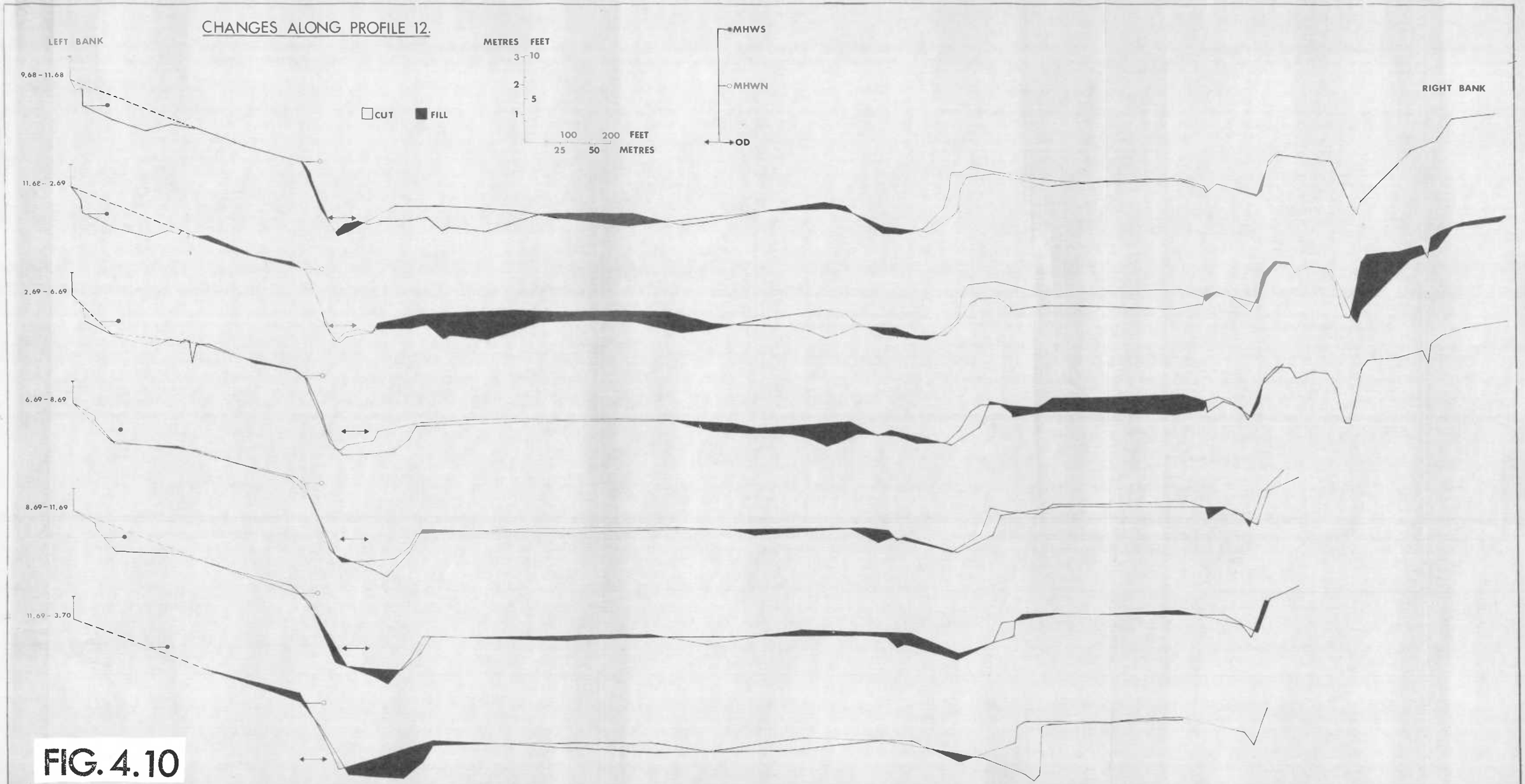

CHANGES ALONG PROFILE 12.
LEFT BANK
RIGHT BANK
METRES FEET
3 10
2
5
1
100 200 FEET
25 50 METRES
CUT
FILL
MHWS
MHWN
OD
9.68 - 11.68
11.68 - 2.69
2.69 - 6.69
6.69 - 8.69
8.69 - 11.69
11.69 - 3.70

FIG. 4.10

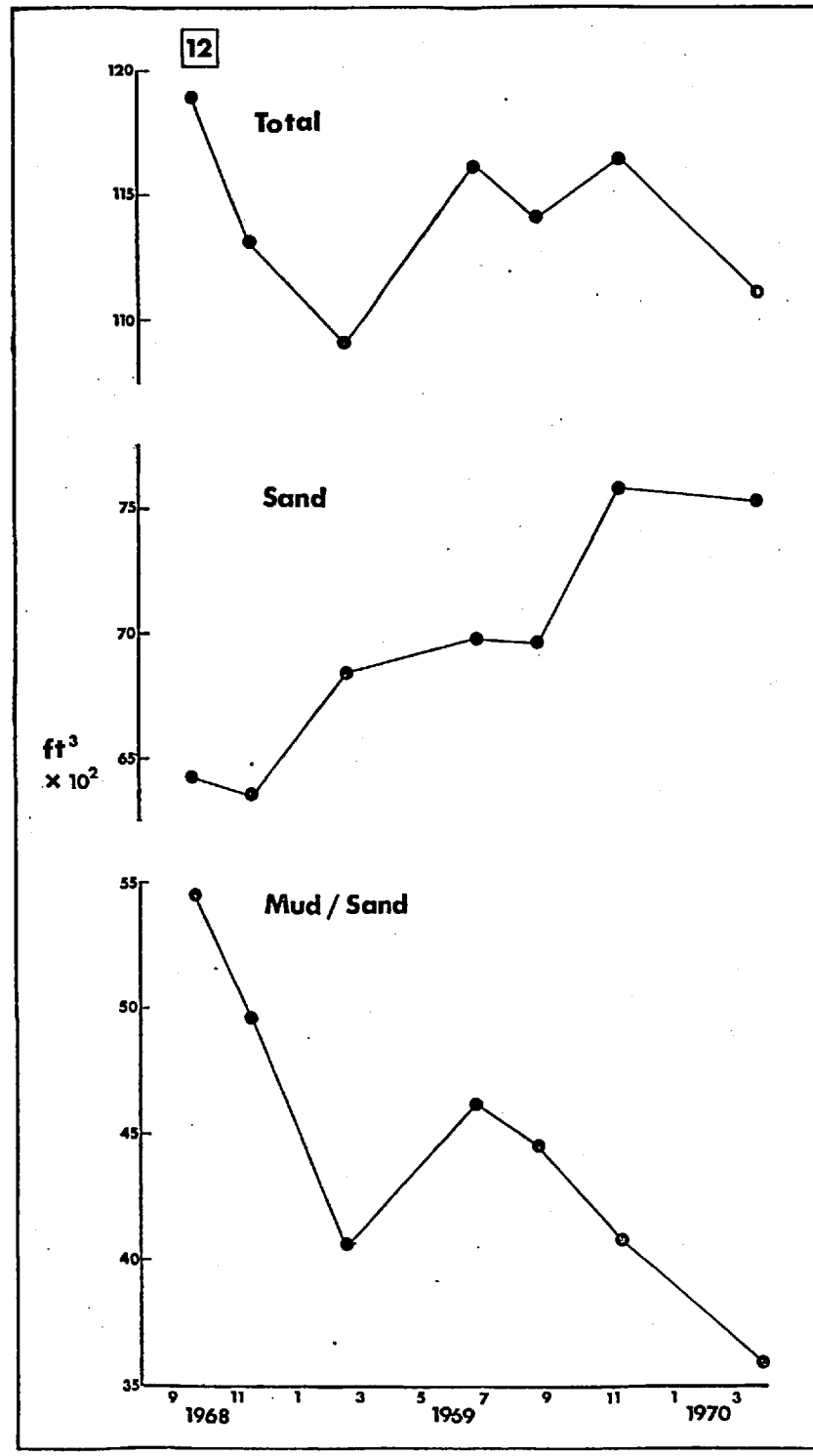


FIG. 4. 11: VOLUMETRIC VARIATION, PROFILE 12.

terms of vertical elevation since the near-vertical inclined slope results in a large vertical change with each small horizontal displacement.

But even by ignoring parts of the profile there remains only a poorly defined spatial trend of stability. This is because, unlike profiles 8 - 11, the main channel is here laterally unstable, and divided into two separate streams; the strongest river flow was developed near the right bank on some surveys, near the left bank on others, and both channels were always present. If we consider the relationship between stability and lateral distance from the closest of the main channels, then a highly significant linear trend re-emerges (Table 4.6). The greatest instability occurred close to the main channels, least variation occurring on the sand flats between them, and on the mud/sand flats of the right bank (see Fig. 4.8).

	PROFILE				
	12(sand)	12(mud/sand)	12(total)	13	14
r_{12}	.95**	-.84*	-.23	-.01	.84*
n	7	7	7	7	7

TABLE 4.5 : Correlation coefficients (r_{12}), accretion/time

The most variable part of the profile was the side of the channel near the right bank, where there was a systematic erosion

(by ebb and/or river flow) during the study period. This is because the energy of flow required to erode deposited material by curved flow is less than that required to scour deposits by straight flow. The flow of streams in channel bends is described by Allen (1970), for both experimental channels and real river channels. The flow of water in a channel bend produces an excess of fluid pressure and large shear stresses on the outer bank and a corresponding deficit over the inner. It was observed that recession of this bank was intermittent rather than continuous, taking place in steps, slumping being a response to increased river flow and to changes of orientation of banks and channels immediately upstream.

However, although the situation in the immediate proximity of the right channel was akin to that of a river meander, the overall stability profile is more complex. Sediment eroded from the right bank was partially compensated by an accumulation of sediment on the inner shallows (see Fig. 4.10), but the movement of material on the left section was obviously controlled by other factors.

Successive surveys of profile 13 are superimposed in Fig. 4.12, and volumetric variations are shown in Fig. 4.7. The maximum range between surveys was 2,063 cubic feet and the greatest between-survey change was 2,009 cubic feet. As already pointed out, this profile was the most unstable in terms of both overall

CHANGES ALONG PROFILE 13.

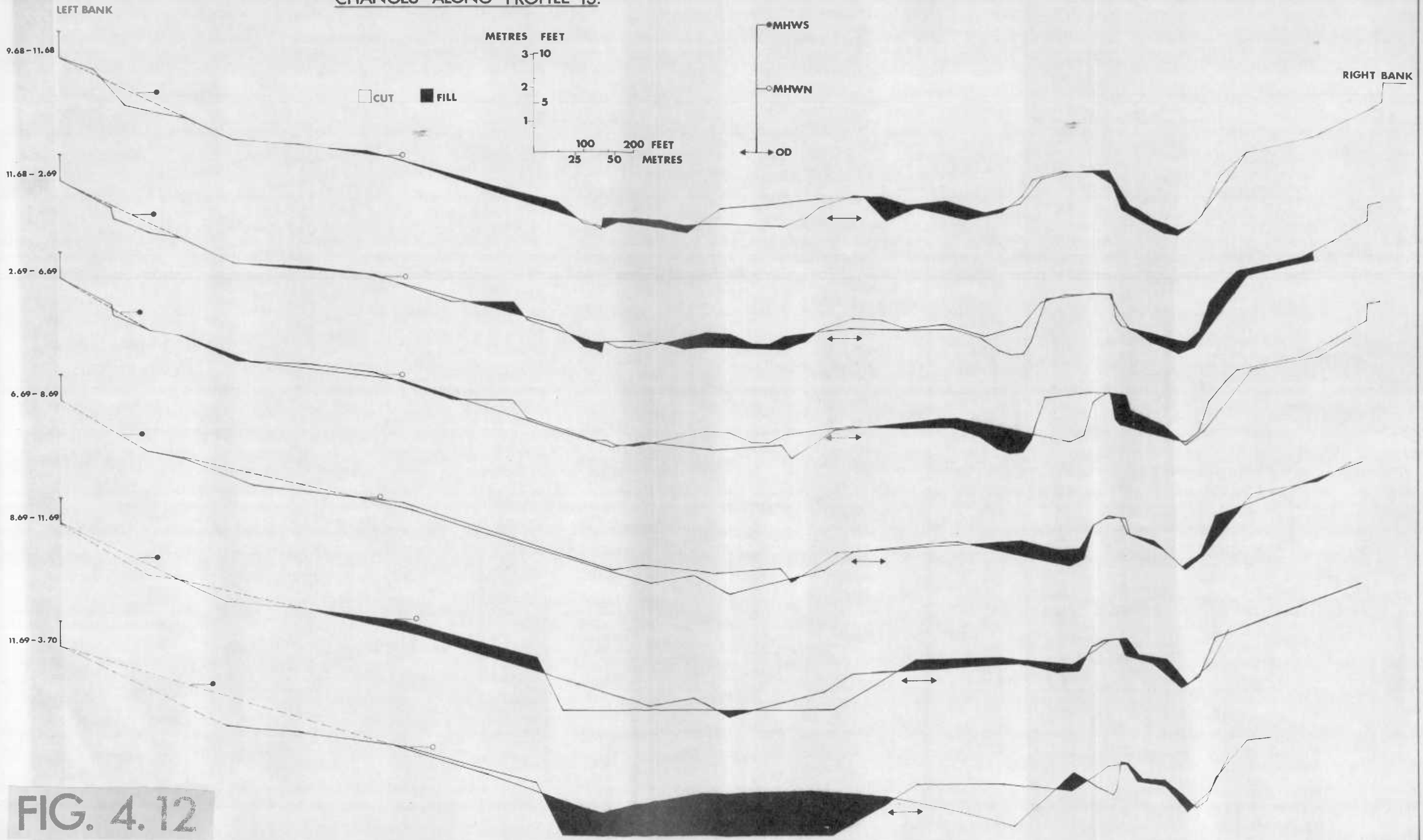


FIG. 4.12

volume and elevations above datum, and variation across the profile was relatively heterogeneous. But the net change of volume during the study period was not exceptional, +792 cubic feet, and there was no linear trend of accumulation with time (Table 4.5).

	PROFILE		
	12	13	14
r_{12}	-.02	-.23	.35
r_{13}	-.56**	-.32(-.56**)	-.62**
n	44	26 (21)	26

TABLE 4.6 : Correlation coefficients, r_{12}, standard deviation/mean height of elevation; r_{13}, standard deviation/distance from main channel(s)

The spatial distribution of stability is shown in Fig. 4.13. There is no linear trend of variation with height above datum (see Table 4.6), nor with lateral distance from the main channels. However, if the channels are ignored, then there is a highly significant negative correlation between variation and lateral distance from the nearest of the two main channels. This situation is the same as the one described for profile 12, and reinforces the results of the analysis of profiles 10 and 11. The channels themselves were relatively stable but the greatest variation occurred close to them, decreasing laterally.

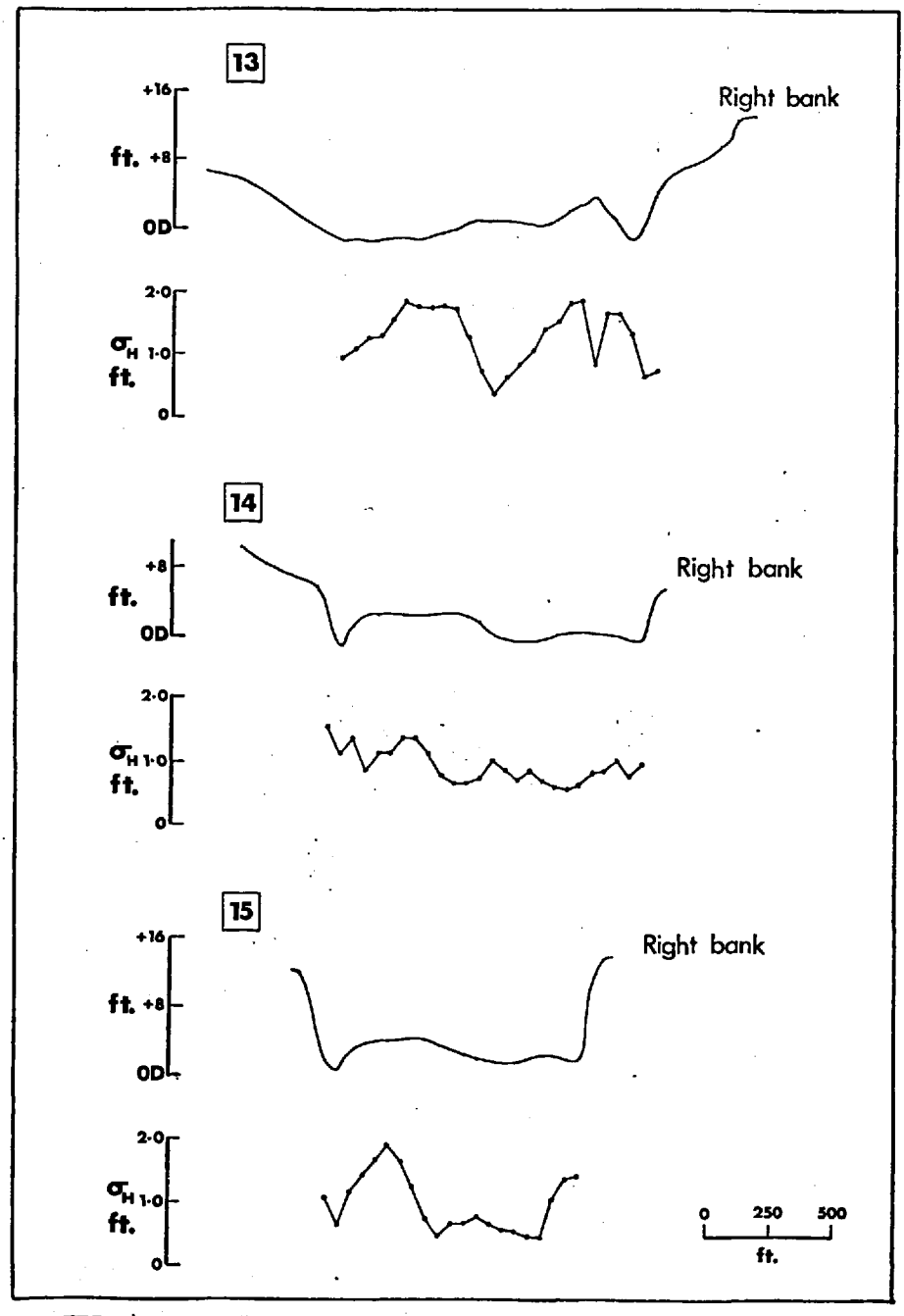


FIG. 4. 13: STANDARD DEVIATION OF ELEVATION ABOVE DATUM, σ_H, PROFILES 13, 14 & 15.

The right bank of the right channel was stable on profile 13 undoubtedly due to the cohesion of the fine grained material of which it is composed. On profile 12, the exposed face of the bank consisted of loose sand, mud being confined to its upper layers.

Successive surveys of profile 14 are superimposed in Fig. 4.14, and volumetric variations shown in Fig. 4.7. The overall trend was one of accretion with time (Table 4.5), the net change amounting to 1,316 cubic feet. The greatest between-survey change was 784 cubic feet. Like profile 13, profile 14 was relatively unstable, but unlike profile 13, the spatial distribution of variation was relatively homogeneous. This distribution is shown in Fig. 4.13. Variation bears no linear relationship to mean height above datum but correlates highly significantly with lateral distance from the left bank channel (Table 4.6). The right bank channel was relatively stable, as were the areas on either side of it. This is because the curvature of the channel is small, so that the pressure gradients set up in a curved channel are here less developed and sediment entrainment needs higher stream velocities.

The early flood tide was generally reluctant to adopt the right bank channel, preferring the shorter route of the left bank channel. The outlet of a developing ebb creek onto the latter also encouraged high ebb currents and increased turbulence from the collision of creek and channel streams, especially near low

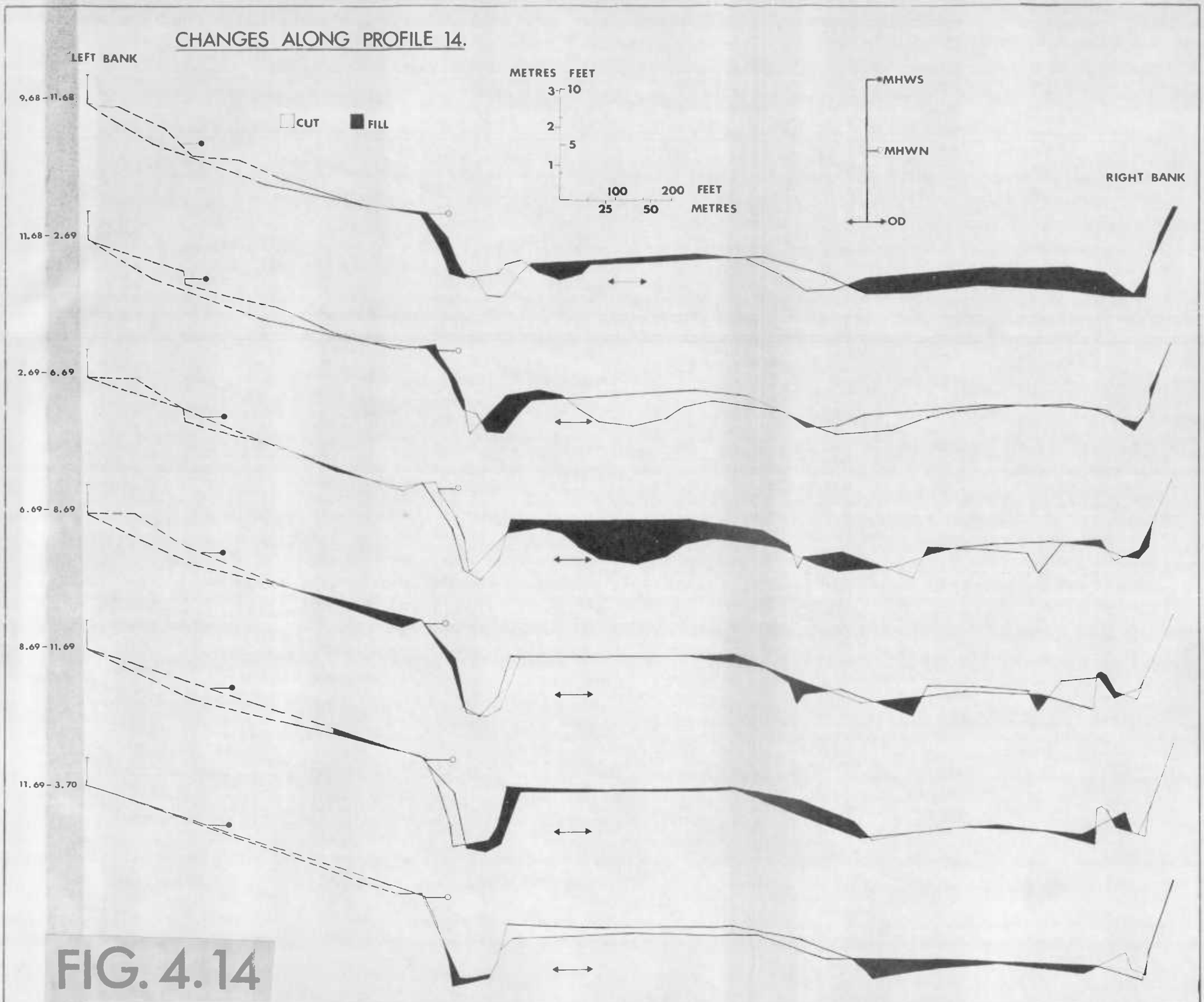

CHANGES ALONG PROFILE 14.
LEFT BANK
RIGHT BANK
METRES FEET
3 10
2
5
1
100 200 FEET
25 50 METRES
CUT
FILL
MHWS
MHWN
OD
9.68 - 11.68
11.68 - 2.69
2.69 - 6.69
6.69 - 8.69
8.69 - 11.69
11.69 - 3.70

FIG. 4.14

water. Thus, although from a consideration of hydraulic gradients of river bends it might be expected that the right bank might be the most unstable, the reverse was in fact the case. This is because the critical times associated with net sediment transport are those near the end of the ebb tide and the beginning of the flood.

The salient features of temporal variation and its spatial distribution are the same for these profiles as for the previous group. The channels themselves tended to be stable, but the sides of the channels, and the proximal sandbanks were highly variable. Away from the channels, or between them, the sandbanks were relatively stable. Variations of the right bank channel were related to the hydraulic gradients set up by river flow at low water. These were most intense on profile 12 where the stream lines most impinged on the side of the channel, composed of easily eroded sand. Variations near the left bank channel of profile 14 are attributed to the interactions of ebb streams in the main channel and in a large, developing creek. The significance of lateral gradients of stability is discussed in section 4.5.

4.6 Surveys of Profiles 15 - 18

These profiles constitute the section of the estuary above Laugharne. Their temporal stability increases upstream from 15 to 18, although because of their varying widths, more sand was

transported between surveys on profile 16 than on the others. The instability found on the bend at Laugharne was not repeated on the reverse bend above Laugharne, presumably because of the loss of momentum of the early flood tide, kinetic energy being dissipated in overcoming bottom friction and potential energy in overcoming gravity.

Successive surveys of profile 15 are shown in Fig. 4.15, and volumetric changes in Fig. 4.16. The maximum range of surveyed volumes was 707 cubic feet, and the greatest between-survey change was 682 cubic feet. Since the net change during the study period was only -25 cubic feet, there was no linear trend of accretion or erosion with time (Table 4.7). The overall change corresponds to a mean cut of 0.31 feet of the mobile zone.

	PROFILES			
	15	16	17	18
r_{12}	-.05	.43	.32	-.95*
n	6	5	5	4

TABLE 4.7 : Correlation coefficients, accretion/time

The spatial distribution of variation is relatively heterogeneous, as shown in Table 4.2. This is shown diagrammatically in Fig. 4.13. There is a significant association between temporal

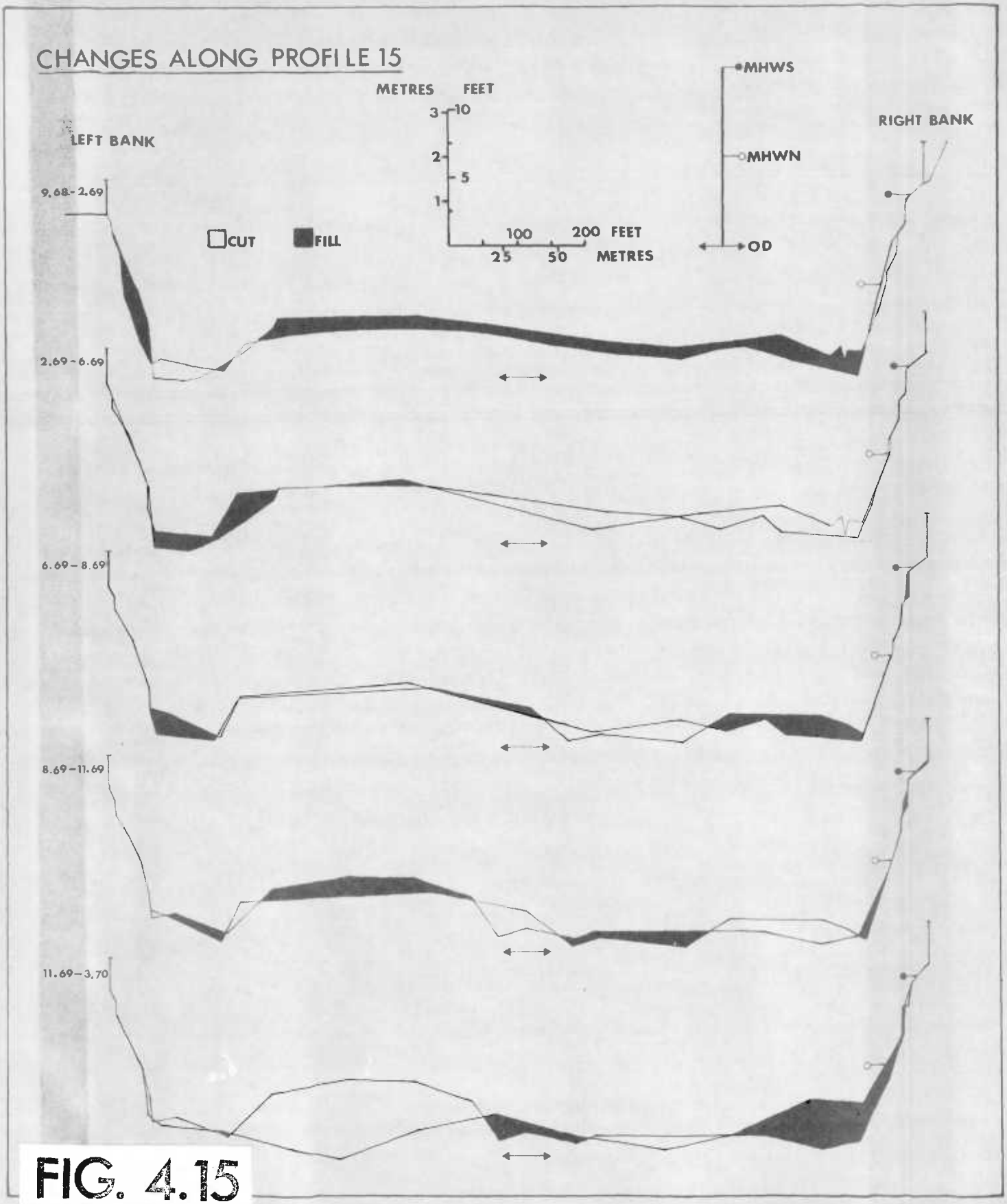

CHANGES ALONG PROFILE 15
METRES
FEET
3
10
2
5
1
100
200 FEET
25
50
METRES
MHWS
MHWN
OD
LEFT BANK
RIGHT BANK
CUT
FILL
9.68-2.69
2.69-6.69
6.69-8.69
8.69-11.69
11.69-3.70

FIG. 4.15

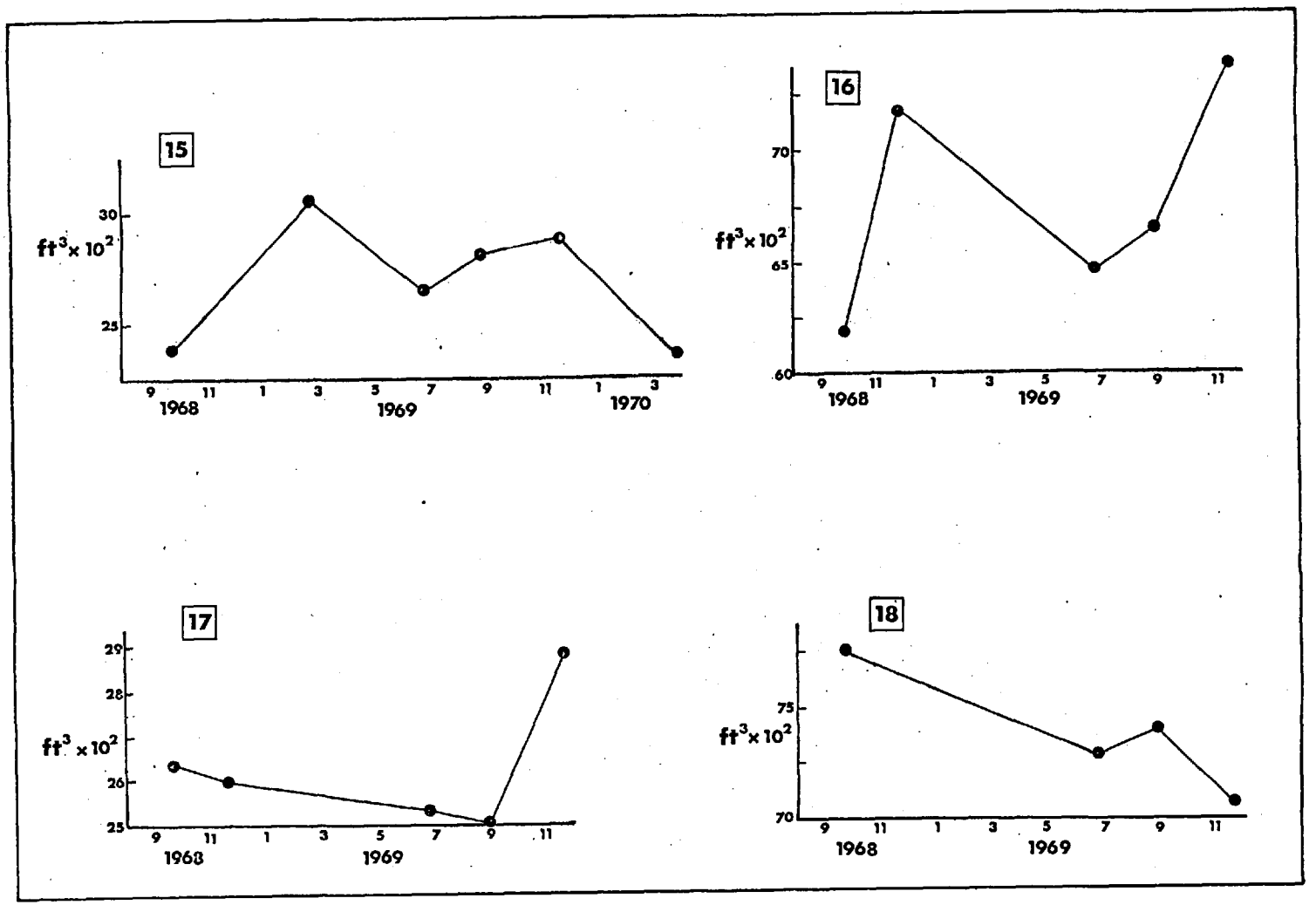


FIG. 4. 16: VOLUMETRIC VARIATION, PROFILES 15 - 18.

stability and mean elevation above datum, but on this profile the relationship is a positive one (Table 4.8). This apparent difference is due to the reduced width and particular morphology of the profile. Two main channels occur, one stable on the left, the other laterally unstable on the right. The channels themselves were vertically stable, but the greatest variation occurred between them i.e. on their proximal banks. The latter make up the highest part of the profile. Hence the trend of spatial variation is essentially the same as for profiles considered above. Of the two channels, the left bank channel, preferentially chosen by the early flood tide, was closest to the most variable zone. However, the situation is rather more complex on this profile, because of the extreme lateral variability of the right main channel which, at times, made up a greater areal proportion of the profile than the sandbanks between channels.

Successive surveys of profile 16 are superimposed in Fig. 4.17 and volumetric variations in Fig. 4.16. There was no linear trend of accretion or erosion (Table 4.7). The maximum range between surveys was 1,188 cubic feet, which was also the net change during the study period, amounting to a mean accretion of 0.73 feet. However, the greatest between-survey change was almost as large, amounting to 994 cubic feet.

The spatial distribution of variation was heterogeneous, as shown in Fig. 4.18. The main channel was always close to the

CHANGES ALONG PROFILE 16.

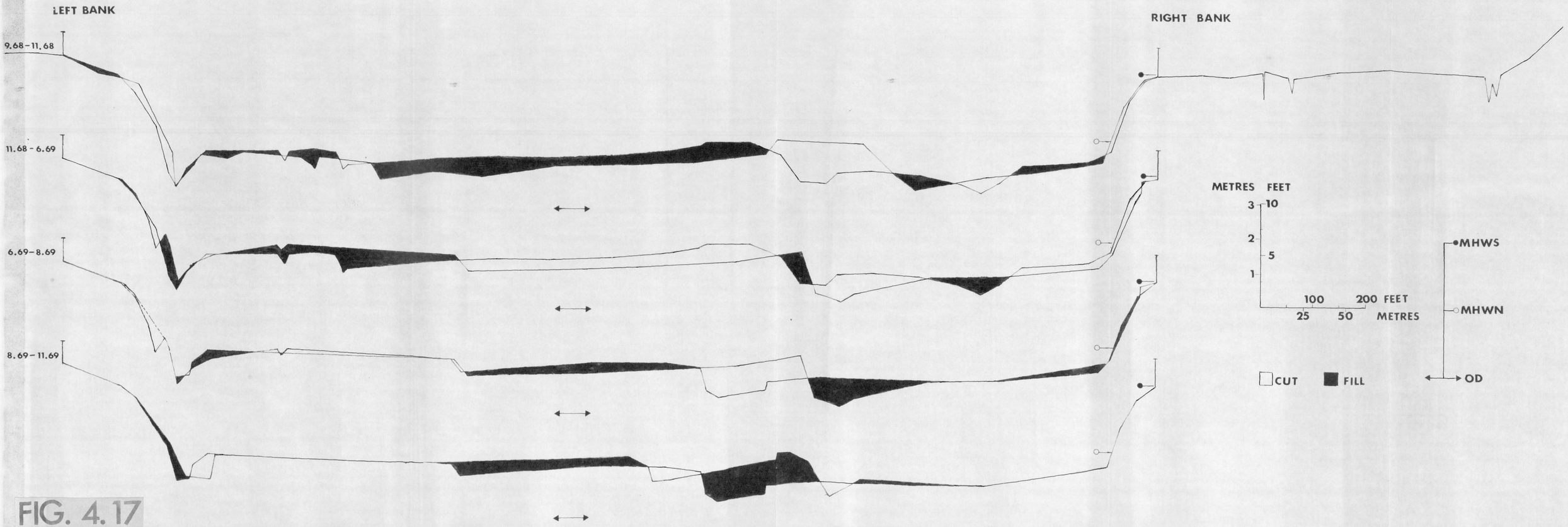


FIG. 4.17

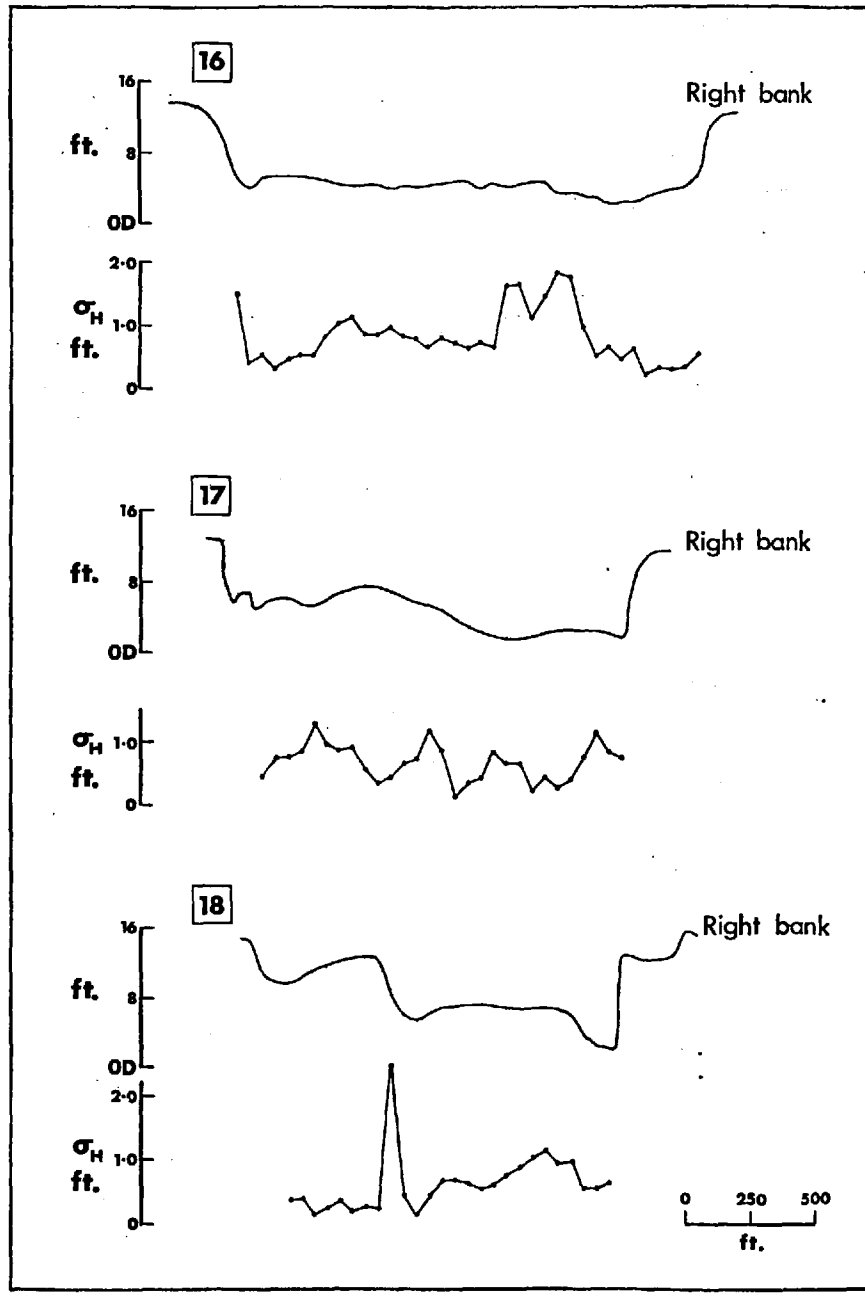


FIG 4. 18: STANDARD DEVIATION OF ELEVATION ABOVE DATUM (σ_H), PROFILES 16,17 & 18.

right bank, but was generally wide and mostly shallow. There is no relationship between stability and mean height above datum, but a highly significant negative correlation between stability and lateral distance from the main channel zone (distances being measured from the limits of the zone, not from the deepest part of the channel). The correlation coefficients are shown in Table 4.8. As before, greatest instability was associated with the sandbanks to one side of the channel, stability increasing away from it; the main channel zone was stable in vertical elevation.

	Profile			
	15	16	17	18
r_{12}	.52*	.00	.24 (.31)	-.23 (-.61**)
r_{13}	.37	(-.61**)	.20 (.42*)	-.33 (-.86**)
n	21	37 (29)	29 (22)	26 (22)

TABLE 4.8 : Correlation coefficients for standard deviation/mean elevation (r_{12}), and standard deviation/distance from main channels (r_{13})

Successive surveys of profile 17 are shown in Fig. 4.19. Surveying of this transect was interrupted by the loss of the marker pole on the right bank; a new pole was set up in a slightly different, but more stable, position. Hence the orientation of the line changed somewhat, and in Fig. 4.19 the two orientations are

CHANGES ALONG PROFILES 17A AND 17B.

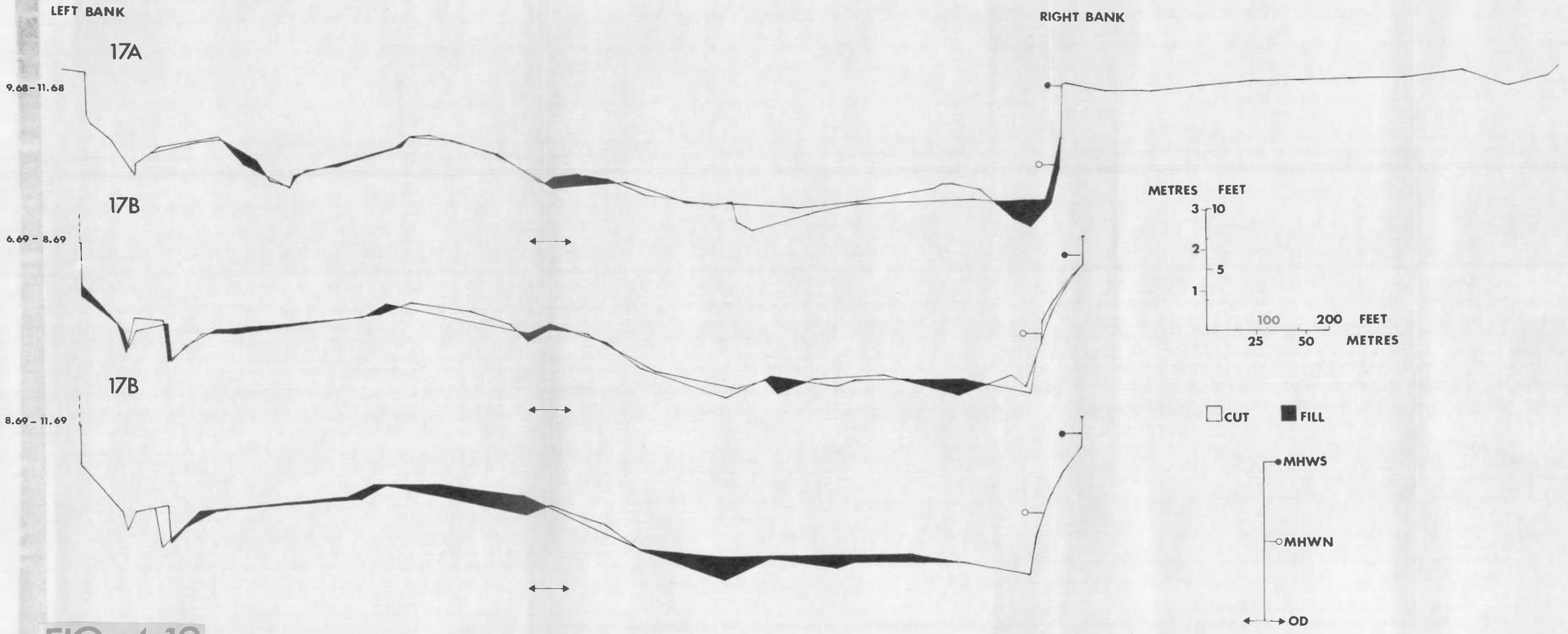


FIG. 4.19

designated A and B. However, the differences between 17A and 17B orientation were small, and for the purposes of subsequent analyses they are ignored. Volumetric changes on profile 17 are shown in Fig. 4.16. The maximum range between surveys, and the greatest change between successive ones, was 764 cubic feet. The net change was +494 cubic feet, a mean accretion of 0.48 feet. The trend of variation with time was not a linear one (Table 4.7).

The profile was relatively homogeneous in its response to change, and the spatial distribution of variation is shown in Fig. 4.18. There is no linear relationship between variation and mean elevation, but there is a just significant positive association of variation with distance from the main channel, when the channel itself (very wide here) is ignored. The reasons for this are not the same as those for a similar relationship on profile 15; on profile 17 the relationship is not due to the restricted width of the estuary, but really is connected with critical processes that must be markedly different from those on other profiles. Thus there is a tendency for the shoals to be most variable, and not the channel boundaries. This suggests that winds and waves, rather than currents, were the most effective causes of sediment displacement on this profile.

Successive surveys of profile 18 are superimposed in Fig. 4.20, and volumetric changes are shown in Fig. 4.16. This was the most stable of all profiles, in part because it was surveyed

CHANGES ALONG PROFILE 18.

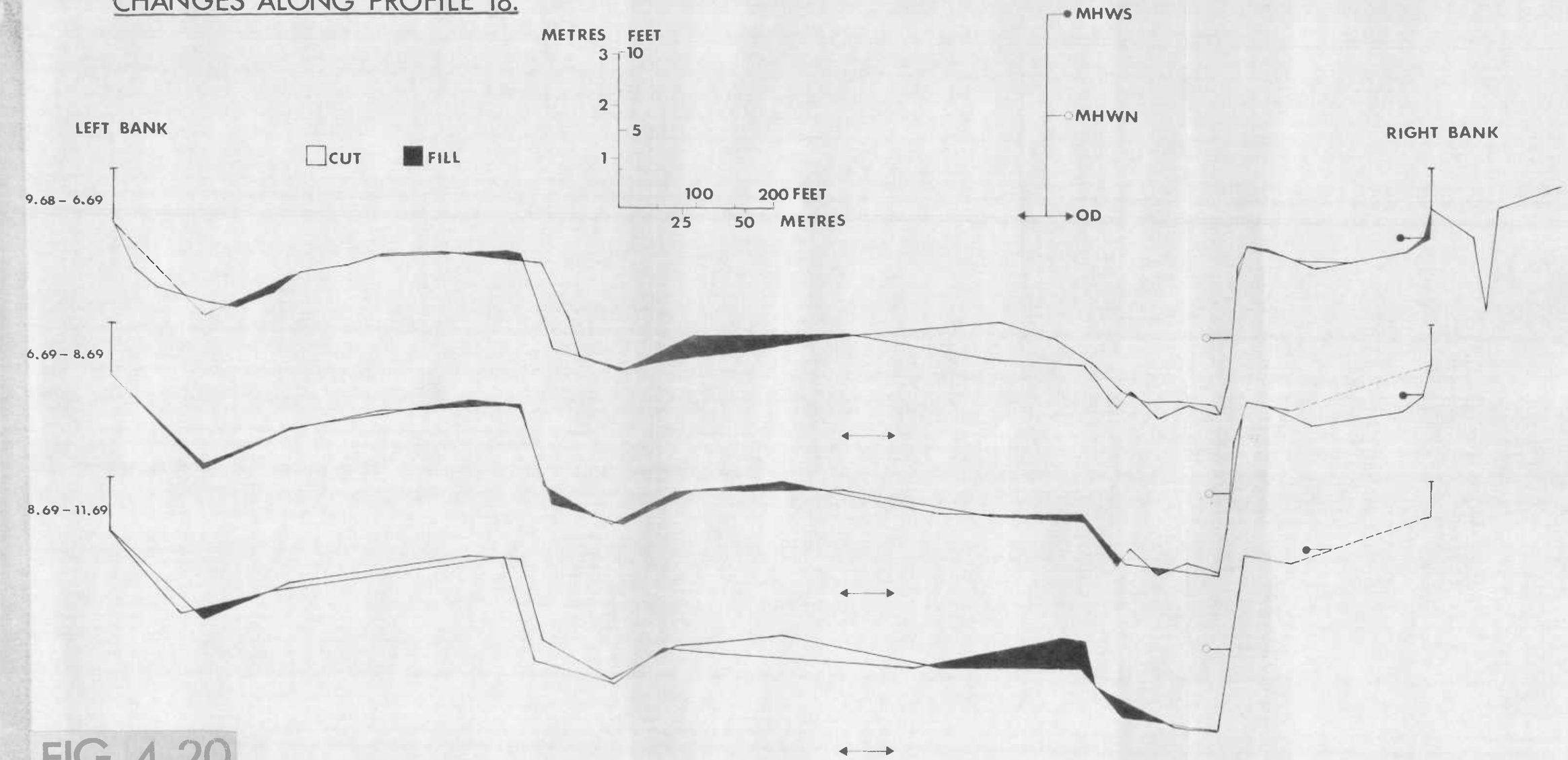


FIG. 4.20

least often. The maximum range between surveys, and the overall change, was -.708 cubic feet, a mean erosion of -0.67 feet. This may be considered as a linear trend of erosion with time (Table 4.7). The greatest between-survey change was 503 cubic feet, but this represents an erosion over some nine months.

The spatial distribution of variation was a heterogeneous one, but as may be seen in Fig. 4.18, this was due to the variability of one part of the profile where, because of the steep slope, a small lateral displacement produced a large vertical change. There is no linear association of variation with either elevation or distance from the channel if the variance for the station on the steep slope is included. Obviously some bias is introduced by unweighted inclusion of this point, since this part of the profile is not truly more variable than the remainder (see Fig. 4.20). Excluding both this station, and those in the main channel itself (which is here both narrow and deep), there are highly significant negative associations of variation with elevation above datum and distance from the channel (Table 4.8). Hence the distribution of variation was the same here as on most other profiles, though the degree of variation was less.

Profiles 15, 16 and 18 therefore demonstrated similar response characteristics to downstream profiles. Variation was greatest on the proximal channel areas, the channels themselves being comparatively stable in depth. Profile 15 was unusual because of its

restricted width so that the proximal channel areas make up its central, and highest, portion.

The lateral distribution of sediment stability described for most profiles indicates that the proximal channel areas experience the fastest fluid currents and/or turbulence. This may occur on both flood and ebb tides, during the early stages of the former and the final stages of the latter (see Chapter 3). The low-water ebb flow is confined to its main channel. The early flood tide avoids this opposing flow, preferring a course to one side of it, generating fast currents and intense turbulence. Maximum currents on the ebb occur during its later phases when some shoals have emerged, reducing the wet cross-section of the stream (van Straaten and Kuenen, 1958), thus concentrating ebb flow energy. In this way, maximum currents occur shortly before, and shortly after, low tide (Postma, 1961). At these times, the shoalest water occurs over the proximal channel areas and turbulence is most developed; sediment transport (i.e. relative transport between flood and ebb components) is therefore greatly increased.

Hence tidal currents, rather than river flow, must be the principal agents of transport, as was concluded for the Thames, Medway and Taw-Torridge by Prentice et al (1968). Waves become an important factor on profile 17 since the shoals are here most unstable. It may seem odd that this occurs in the upper estuary, but it should be remembered that this part of the estuary is

rather exposed to winds from the south-west (since the coastal barrier is comparatively low-lying).

4.7 The Significance of Process Variables

The foregoing has been a discussion of the results of monitoring the variation of sediment response in the estuary; little mention has so far been made of the processes that cause sediment transport and displacement. The connection between net variation of sediment accumulation and turbulence associated with tidal motion has been discussed, as well as local effects of river flow. The following is an attempt to quantify the relationship between process and response variables (using the terminology of Krumbein, 1964).

As pointed out by Ippen (1966), estuarine sediment transportation is controlled by time-dependent currents which vary with the fluctuations and interactions of tidal motion, river flow, density currents, and transverse currents. In addition, wind stresses and wave action may assume importance under temporary conditions and may contribute materially to the estuarine circulation. Depending on the relative magnitude of these forces, the state of mixing produced may vary within a wide spectrum, and circulation characteristics are constantly in flux (Pritchard, 1955). For these reasons, no equilibrium can exist from day to day, though in the long-term some sort of equilibrium, or regime, is usually

established between bed-load, suspended sediment and water movement (Postma, 1967).

The problems involved in a quantitative study of process-response variable relationships in which experimental control is inadequate have been discussed in Chapter 2. In the present exercise, there are additional problems resulting from the incompleteness of the data and the even shorter duration of the study. These are likely to exaggerate the inevitable bias that results from lack of randomness in surveying times and absence of information on day to day variations.

Obviously only continuous monitoring of many hydrographic stations could hope to accurately define the spectrum of circulation patterns experienced by the estuary. Nothing so ambitious has been attempted here. Instead the forces operative within the estuarine system will be examined individually and their relationship with sediment variation established. In this way, the process elements are considered as sources of energy from <u>without</u>; the resulting complexities of circulation <u>within</u> the estuary (which are directly responsible for sediment transport) cannot be easily forecast; this is because, in common with most geomorphological systems, the interaction between process elements may be complex and understood only after the application of cross-spectral analyses (King and Mather, 1972), which demands a density of information not available in this study; also the estuarine

system is one in which feedback from response to process variables is likely to be important (King, 1970).

The process variables under consideration are river discharge, tidal flow and meteorological input. River discharge data has been provided by the South-West Wales River Authority from its station at Clog-y-Fran; tidal flow data has been taken from the Admiralty Tide Tables; and meteorological data from the St. Gowan Lightvessel.

Before discussing the quantitative association of process and response elements, it is useful to look at the qualitative aspects of the problem. In Table 4.9, between-survey volumetric changes are classed as either accretion (A) or erosion (E). Between-survey periods are notated A - H.

	PROFILE										
	8	9	10	11	12	13	14	15	16	17	18
A	E	A									
B	A	E									
C	E	A	A		E	A	A	[A]	A	E	
D	A	A	[E]	A	E	E	E		[E]	[E]	[E]
E	A	A		E	A	E	A	E			
F	E	A	A	E	E	E	E	A	A	E	A
G			E	A	A	A	A	A	A	A	E
H					E	A	A	E			

TABLE 4.9 : Net between-survey changes

It is evident that there was little continuity of response even between adjacent profiles. This illustrates the complexity of process/response interaction and emphasises the limitations of any method of analysis that considers each process element in isolation. It also suggests that better experimental control would have resulted from closer spacing of transects.

However, examination of the profile response during each period shows that in only one, period G, was there any degree of unanimity, when seven adjacent profiles (11 - 17) experienced accretion. This period, autumn 1969, was distinguished by a very low river discharge (in fact, 120 cusecs, the lowest for any between-survey period during the study period) coupled with a high incidence of onshore and westerly strong winds. At this time, the flushing energy of the river flow was at a minimum and the energy of landward tidal flow therefore relatively increased. In this situation, the estuarine circulation system would be both vertically and laterally homogeneous (Pritchard, 1955), as a result of rapid vertical diffusion engendered by high turbulence. Sand from the outer estuary could therefore more easily penetrate the inner estuary, movement occurring on the early flood tide. Whether such an upstream sand movement represents an overall gain of accumulated sand is considered below.

(a) The Influence of River Discharge

In Table 4.10 are shown the product-moment correlation coefficients for the association of sediment variation and river discharge. Sediment variation is treated as either net accretion or net erosion of the mobile sediment zone between surveys. River discharge has been considered in several ways. Firstly, as total discharge between surveys, so as to test the cumulative effect of river flow; secondly, as maximum recorded discharge on any day during each between-survey period, so as to test the effect of exceptional conditions. Also an attempt has been made to test the importance of short-term effects, both the day before, and the week before surveying. This has been done very crudely by taking the discharge prior to surveying (the day before, and the total during the week before), then using the differences between them for successive surveys as a basis for correlation with the corresponding between-survey sediment changes. Of course, although a similar procedure provided useful results in the study of process/response associations for beach profiles, it is not suggested that changes can be attributed solely to events just prior to surveying, when surveys are several months apart. Evidently, if river flow is an important process element, then a combination of all four aspects of variation, with appropriate weighting, is most likely to achieve significant results.

		TAF DISCHARGE			
PROFILE	n	Cumulative	Greatest	Day before	Week before
8(upper)	7	.50	.43	-.32	-.21
8(lower)	6	.30	.06	-.21	-.40
8(total)	6	.30	.08	-.26	-.41
9	6	-.17	-.41	.38	.59
10	4	-.77	-.34	-.71	-.92
11	4	.05	.37	.38	.52
12(sand)	6	-.11	-.05	.79	.67
12(mud/sand)	6	-.37	-.60	.03	-.13
12(total)	6	-.43	-.61	.50	.28
13	6	.75	.68	.00	.22
14	6	-.55	-.39	.54	.45
15	5	.10	.04	.32	.20
16	4	-.81	-.30	.49	.33
17	4	-.49	-.40	.76	.77
18	3	-.73	-.89	-.73	-.81

TABLE 4.10 : Correlation coefficients, river discharge/sediment variation

None of the associations of Table 4.10 are significant. This is hardly surprising. It was shown in Chapter 3 that the estuary is dominated by tidal motion, and so it is unlikely that river flow, considered in isolation, is of prime importance in sediment entrainment and transport. River discharge dominance, as well as river dominant sediment sources, prevails in estuaries with low tidal ranges such as the mouth of the Mississippi (Meade, 1969).

This does not mean that river flow does not influence sedimentation. It has been noted in the preceding sections that river flow does have a local effect on some profiles, although this may be due to the properties of the late ebb flow rather than river flow itself; since both streams occupy the same channels near low water it is impossible to differentiate them. As has been shown in Chapter 3, and by Postma (1961), maximum ebb currents may develop near low water when the stream is confined to a restricted channel. Reinforcement by river flow at this time would result in maximum currents and sediment entrainment.

Also the combination of low river discharge and high tidal input does have an important influence on net sediment transport and accumulation, as described above. Although not tested here, it is likely that the combination of local wind waves and high river discharge results in a resuspension and flushing out of sediments during the late ebb tide (Anderson, 1970).

Furthermore, another deficiency of the analysis must be pointed out. The correlation analysis assumes that all relationships are linear. Such an assumption is probably not valid for the association of sediment variation and river discharge. As pointed out by Allen (1970), for rivers in semi-arid areas, the mean flow velocity increases as the 0.34 power of the discharge, and the sediment transport rate is proportional to the cube of the mean flow velocity. In addition, the mean fluid velocity increases

with growing distance from the bed and walls of the channel, and the vertical position of the velocity maximum is dependent on the relative orders of the channel depth and width.

(b) The Influence of Tidal Flow

In Table 4.11 are shown the product-moment correlation coefficients for the association of net sediment variation and tidal height. A continuous record of tidal current velocities is not available, but since current velocity is dependent on the size of the tide (actually the logarithm of velocity $\propto$ tide height, see Haynes and Dobson, 1969), figures for tide height have been substituted for current values. This data has been treated in a similar manner to river flow data. The total cumulative tide heights between surveys is of course partly an indication of the time interval between surveys, since the spring/neap tidal cycle is short in comparison.

A few associations of tidal input and sediment variation are significant, but it is a mute point how much weight can be given to them when so sparsely distributed, particularly when the crudity of the analysis is taken into account. The three significant relationships pertain to tidal input close to the time of surveying, and suggest that big tides are associated with erosion of the mobile zone of profile 8 and accretion of sand on profiles 12 and 18. Thus spring tides are more likely to initiate sediment transport and move sediment up the estuary than are neaps.

		TIDAL INPUT		
PROFILE	n	Cumulative	Day before	Week before
8(upper)	7	.44	-.60	-.44
8(lower)	6	.64	-.81*	-.22
8(total)	6	.60	-.77	-.30
9	6	.17	.10	.59
10	4	-.50	.90	.44
11	4	-.46	.12	.66
12(sand)	6	.05	-.01	.87*
12(mud/sand)	6	.35	-.67	-.33
12(total)	6	.38	-.71	.17
13	6	.55	.06	-.05
14	6	.00	-.43	.04
15	5	-.02	-.21	.45
16	4	-.90	.33	.77
17	4	-.24	-.45	-.18
18	3	-.80	.95	1.00**

TABLE 4.11 : Correlation coefficients, tidal height/sediment variation

This follows from the increased turbulence associated with the flood of a spring tide (see Chapter 3) which is most likely to create instability of the proximal channel zones. Such a relationship between strong currents and fine-grained matter is reported by Postma (1967), but the additional factor of severe turbulence makes the relationship equally applicable to coarser-grained matter. The importance of such an association will

become clearer below when winds and waves are taken into account.

(c) The Influence of Meteorological Input

Components of wind and wave parameters are considered here in the same way as in Chapter 2. The inevitable discrepancies between deep water and shallow water wave properties are probably even more pronounced within the complicated estuary configuration than on the foreshore of Pendine Sands. Similar discrepancies must exist between maritime and coastline wind vectors. In addition, there is the added complication that meteorological input may be an important process variable operative from both within and beyond the confines of the estuary, while itself being modified by the relief and morphology of the estuary.

Produce-moment correlation coefficients for associations between components of wind and wave vectors and sediment variation are shown in Tables 4.12 - 14. The terms onshore and offshore mean from the south and from the north respectively, but infer up-estuary and down-estuary when considered within the estuary itself.

A considerable number of associations are important, notwithstanding the small number of observations. These may be summarised as below (the information should be read across the page for each profile); they are shown pictorially in Fig. 4.21:

		PROFILE				
VECTOR	COMPONENT	8(upper)	8(low)	8(total)	9	10
Prevailing wind	Onshore	.79*	.67	.81*	-.34	-.47
	Offshore	.69	.48	.66	-.14	-.45
	Resultant On.	-.35	-.17	-.32	-.03	-.12
	Easterly	.43	.29	.40	.44	-.53
	Westerly	.57	.45	.54	.13	-.30
	Resultant West.	-.01	.24	-.01	-.36	.64
Dominant wind ⩾ 20 knots	Onshore	.46	-.01	.05	-.40	-.69
	Offshore	.42	.12	.12	-.20	-.51
	Resultant On.	-.01	-.10	-.09	-.19	-.19
	Easterly	-.01	-.20	-.21	.63	-.42
	Westerly	.35	-.14	-.15	-.16	-.95*
	Resultant West.	.41	.09	.09	-.81*	-.44
Dominant wind ⩾ 30 knots	Onshore	.44	.27	.28	-.31	-.51
	Offshore	.61	.89*	.88*	-.21	-.77
	Resultant On.	-.19	-.10	-.09	-.26	-.29
	Easterly	.35	.04	-.23	-.02	-.25
	Westerly	.31	-.12	-.15	.06	-.85
	Resultant West.	.14	-.02	-.05	.04	-.21
Dominant waves ⩾ 2 metres	Onshore	.26	-.18	-.16	-.31	-.19
	Offshore	.50	.31	.30	-.30	-.55
	Resultant On.	-.02	-.33	-.31	-.26	.04
	Easterly	.22	.16	.17	.21	-.27
	Westerly	.33	.12	.11	-.20	-.41
	Resultant West.	.24	.00	-.02	-.36	-.70
Dominant waves ⩾ 4 metres	Onshore	-.57	-.59	-.61	.44	-.38
	Offshore	-	-	-	-	-
	Resultant On.	-.57	-.59	-.61	.44	-.38
	Easterly	.17	.20	.22	.20	-.23
	Westerly	-.40	-.58	-.60	.60	-.83
	Resultant West.	-.40	-.59	-.62	.40	-.83
Dominant waves ⩾ 6 seconds	Onshore	-.18	.04	.03	-.29	-.43
	Offshore	-	-	-	-	-
	Resultant On.	-.18	.04	.03	-.29	-.43
	Easterly	-.08	-.02	.00	-.07	-.05
	Westerly	-.67	-.75	-.75	.36	-.16
	Resultant West.	-.75*	-.82*	-.84*	.43	-.29
	n =	7	6	6	6	4

TABLE 4.12 : Correlation coefficients, meteorological input/sediment variation

		PROFILE				
VECTOR	COMPONENT	11	12(sand)	12(sand/mud)	12(total)	13
Prevailing wind	Onshore	-.11	.22	.05	.19	.21
	Offshore	-.55	-.03	.08	.06	.69
	Resultant On.	.12	.12	-.06	.02	-.55
	Easterly	-.48	.08	.54	.57	.25
	Westerly	-.91	-.29	.58	.39	.33
	Resultant West.	.13	-.30	-.19	-.36	-.04
Dominant wind ≥20 knots	Onshore	.79	.38	-.68	-.44	.70
	Offshore	.58	-.02	-.50	-.49	.81*
	Resultant On.	.13	.31	.01	.29	-.43
	Easterly	-.43	-.17	.28	.17	.41
	Westerly	.84	.22	-.47	-.33	.90*
	Resultant West.	.95*	.32	-.63	-.42	.62
Dominant wind ≥30 knots	Onshore	.43	.44	-.61	-.33	.35
	Offshore	.27	-.01	-.09	-.10	.91*
	Resultant On.	.40	.45	-.53	-.25	-.37
	Easterly	-.43	-.54	.18	-.15	.38
	Westerly	.95*	-.15	-.30	-.39	.96**
	Resultant West.	.81	.16	-.38	-.27	.67
Dominant waves ≥2 metres	Onshore	.32	-.06	-.55	-.58	.32
	Offshore	.43	.07	-.47	-.42	.78
	Resultant On.	.18	-.10	-.35	-.35	-.10
	Easterly	-.49	-.14	.25	.16	.10
	Westerly	.22	-.16	-.41	-.48	.84*
	Resultant West.	.89	-.10	-.59	-.64	.95**
Dominant waves ≥4 metres	Onshore	.40	.10	-.59	-.52	.68
	Offshore	-	-	-	-	-
	Resultant On.	.40	.10	-.59	-.52	.68
	Easterly	-.71	-.18	.53	.41	-.33
	Westerly	.57	.61*	-.25	.24	.32
	Resultant West.	.97*	.68	-.56	-.14	.46
Dominant waves ≥6 seconds	Onshore	.27	.38	-.35	-.11	-.27
	Offshore	-	-	-	-	-
	Resultant On.	.27	.38	-.35	-.11	-.27
	Easterly	-.63	-.28	.19	.01	-.26
	Westerly	-.07	-.16	-.12	-.22	-.21
	Resultant West.	.55*	.00	-.30	-.42	-.11
	n =	4	6	6	6	6

TABLE 4.13 : Correlation coefficients, meteorological input/sediment variation

		PROFILE				
VECTOR	COMPONENT	14	15	16	17	18
Prevailing wind	Onshore	.08	.59	-.78	-.35	-.79
	Offshore	-.26	-.50	-.95*	-.15	-.75
	Resultant On.	.28	.88*	.11	-.38	-.83
	Easterly	.25	-.16	-.82	-.26	-.83
	Westerly	.03	.01	-.99*	-.33	-.66
	Resultant West.	-.26	.21	.30	.08	1.00*
Dominant wind ⩾20 knots	Onshore	.10	.49	-.40	.05	-.94
	Offshore	-.70	.07	-.95*	-.22	-.81
	Resultant On.	.81*	.67	.74	.37	-.99
	Easterly	.32	.09	-.66	-.40	-.81
	Westerly	-.02	.25	-.24	.42	.74
	Resultant West.	.25	.08	.63	.95*	.01
Dominant wind ⩾30 knots	Onshore	-.64	.55	-.79	-.29	-.83
	Offshore	-.14	-.57	-.74	.11	-.98
	Resultant On.	-.53	.88*	-.73	-.53	-.74
	Easterly	.44	.50	-.01	-.33	-.84
	Westerly	-.25	-.38	-.65	.27	-.98
	Resultant West.	-.51	-.67	-.34	.47	.74
Dominant waves ⩾2 metres	Onshore	-.20	.61	-.22	-.47	-.80
	Offshore	-.57	.13	-.81	-.24	-.86
	Resultant On.	.11	.78	.13	-.46	-.78
	Easterly	.01	.48	-.70	-.55	-.74
	Westerly	-.31	-.01	-.60	-.41	-.81
	Resultant West.	-.36	-.13	-.25	.02	-.92
Dominant waves ⩾4 metres	Onshore	-.74	.15	-.90	-.40	-.74
	Offshore	-	-	-	-	-
	Resultant On.	-.74	.15	-.90	-.40	-.74
	Easterly	.38	.79	-.62	-.58	-.74
	Westerly	.00	.39	-.62	.21	-.98
	Resultant West.	-.27	-.77	-.11	.85	-.22
Dominant waves ⩾6 seconds	Onshore	.11	.77	.30	-.30	-.83
	Offshore	-	-	-	-	-
	Resultant On.	.11	.77	.30	-.30	-.83
	Easterly	.33	.56	-.25	-.61	-.74
	Westerly	.29	.76	-.46	-.48	-.78
	Resultant West.	.16	.88*	-.68	-.60	-.83
	n =	6	5	4	4	3

TABLE 4.14 : Correlation coefficients, meteorological input/sediment variation

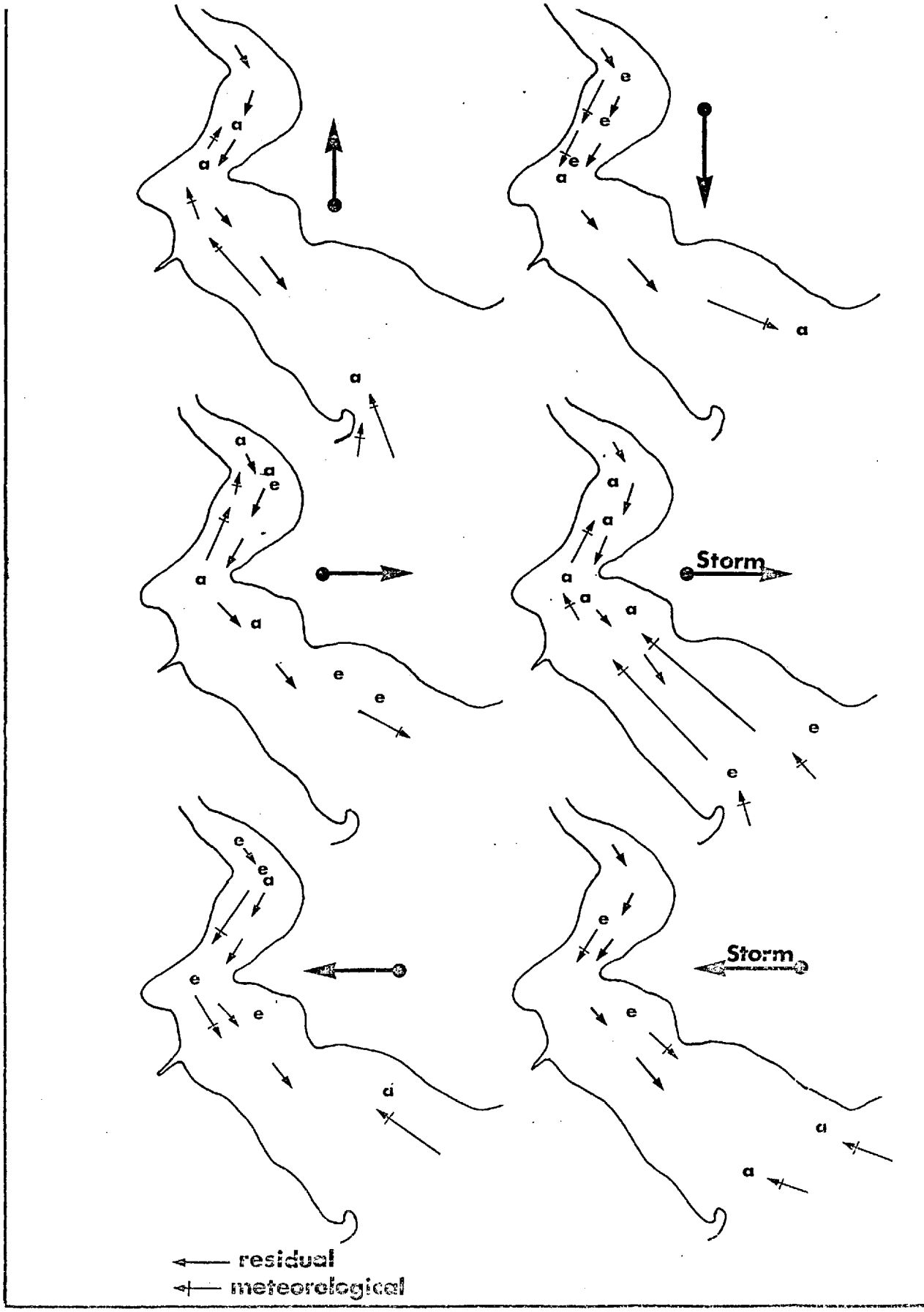


FIG. 4.21: PROCESS/RESPONSE RELATIONSHIPS.

a=accretion; e=erosion.

PROFILE	GAIN	COMPONENT	VECTOR	ASSOCIATION
8(upper)	total	onshore	prevailing winds	accretion
	resultant	westerly	long period waves	erosion
8(lower)	total	offshore	very strong winds	accretion
	resultant	westerly	long period waves	erosion
8(total)	total	onshore	prevailing winds	accretion
	total	offshore	very strong winds	accretion
	resultant	westerly	long period waves	erosion
9	resultant	westerly	strong winds	erosion
10	total	westerly	strong winds	erosion
11	resultant	westerly	strong winds	accretion
	total	westerly	very strong winds	accretion
	resultant	westerly	very high waves	accretion
	resultant	westerly	long period waves	accretion
12(sand)	total	westerly	very high waves	accretion
12(mud/sand), 12(total):	no significant associations			
13	total	offshore	strong winds	accretion
			very strong winds	accretion
	total	westerly	strong winds	accretion
			very strong winds	accretion
			high waves	accretion
	resultant	westerly	high waves	accretion
14	resultant	onshore	strong winds	accretion
15	resultant	offshore	prevailing winds	erosion
			very strong winds	erosion
	resultant	westerly	long period waves	accretion

PROFILE	GAIN	COMPONENT	VECTOR	ASSOCIATION
16	total	offshore	prevailing winds	erosion
			strong winds	erosion
	total	westerly	prevailing winds	erosion
17	resultant	westerly	strong winds	accretion
18	resultant	westerly	prevailing winds	accretion

There is a distinct trend of process/response association from the lower to the upper estuary. The resultant number of observations of westerly long period waves was related to erosion of profile 8 but to accretion on profiles 11 and 15; the total and/or the resultant number of observations of westerly high and/or very high waves were related to accretion on profiles 11, 12(sand zone) and 13; the total and/or resultant number of observations of westerly strong and/or very strong winds were related to erosion of profiles 9 (in this case, since the predominant trend was of progressive accretion, the association may be regarded as one with decreased accretion, or erosion relative to the overall trend) and 10, accretion on profiles 11, 13 and 17. Thus it is clear that westerly components of wind and wave input were associated with a net movement of sand from the lower estuary (profiles 8 - 10) to the middle estuary (profiles 11 - 13, 15) and probably to the upper estuary (profiles 17 and 18) as well, this trend being least developed in the summer months when the relative frequency of westerlies is low. Whether such an upstream

accumulation can be accomplished solely by processes generated within the estuary is discussed below.

In the absence of dominant westerly vectors, or in some cases in association with dominant easterly vectors, there was accretion in the outer estuary and erosion in the middle and upper estuaries. The significance of this trend is also discussed below.

There is a further trend of process/response association from the upper to the lower estuary. Offshore strong and very strong wind components are the critical process elements here, being related to erosion of profiles 16, 15 and 14, to accretion on profiles 13 and 8. Conversely, the resultant onshore components of the same vectors were related to accretion on profiles 14 and 15. This latter effect may be the result of decreased erosion of accumulated sand by a wind-retarded ebb flow, so that the net tidal sand movement is one of accretion by the flood tide. The process source may then be within and/or without the estuary. However, offshore winds must be active within the estuary, providing a boost to the ebb flow, and thereby producing a net erosion in parts of the upper and middle estuaries. Local wind waves undoubtedly aid this process by resuspending sand particles, thus enabling ebb currents to more readily transport them (Anderson, 1970). Flushing is not complete however, and sand is deposited on parts of the middle and lower estuaries, where high

cliffs on the northern shore of the estuary afford some protection from offshore winds.

Prevailing winds appear to have been less widespread in promoting net sediment movement than dominant winds. The total and resultant number of observations of offshore prevailing wind components were related to erosion of profiles 16 and 15 respectively. This association probably reflects the combination of local wind waves, resuspension of sand particles, and ebb flushing, as postulated above.

The total and resultant number of observations of westerly prevailing winds were related to erosion of profile 16 and accretion on profile 18. These are presumably related to each other, reflecting the effect of westerly winds within the estuary itself, which serve to provide a net sand movement upstream. In the section above Laugharne, westerly winds can be effective along its longitudinal profile; they occur with least frequency during the summer months.

Onshore prevailing winds were also associated with accretion on profile 8; these too were least frequent during the summer months. This may have been the result of incursion of wind blown sand from the dune and aeolian sand flat near profile 7 (described in Chapter 2), or of wave-driven sand from the same area and from offshore.

Little significance can be attributed to apparently linear

trends of accretion on profiles 9 and 14, and of erosion on profile 18, because there is no available information on short-term changes. Also no direct conclusions can be drawn from these results on seasonal trends of variation, since surveys were not equally spaced in time. However, as linear correlations between sediment variation and meteorological input have been established, seasonal variations of sediment accumulation can be studied indirectly by an examination of seasonal meteorological variation.

It has been shown that westerly components of meteorological input were associated with erosion of sand from the lower estuary and with accumulation of sand in the middle and upper estuary. Easterly components often were associated with converse trends. It is necessary to consider the quantities of sand involved in these movements, so as to ascertain whether there was a net movement of sand into or out of the estuary, or whether there was a simple redistribution of sand within the estuary.

Since significant linear correlations of sand variation with westerly vectors have been established for most profiles, it is possible to use linear regression equations to predict the probable monthly variations of sand volume, given the appropriate information on the frequency of the critical meteorological vectors, even for those months that were not effectively monitored by surveying. There is no logical certainty that such predictions based on induction will lead to the truth, and in the absence of

further data, no way of testing them. But it may be intuitively deduced that if the process/response relationship was true for some of the study period, then it should hold for all of it (i.e. February 1968 - March 1970). In this way, a complete record of sediment variation may be obtained for all profiles.

Linear regression equations for this purpose follow from the significant correlation analyses. Since these seek to describe the functional relationship between two variables, both of which are uncontrolled, they cannot be obtained by conventional least squares methods. Hence they have been obtained using Bartlett's three-group method (Sokal and Rohlf, 1969); the equations are shown in Table 4.15. Actually they are very similar to those that would be obtained by conventional methods. In these, x = the number of observations per between-survey period of the westerly component of the meteorological vector, y = the change in volume of the mobile sediment zone during the same period. Volumes are in cubic feet.

It may be seen that when the absolute, or relative, frequency of westerly vectors is zero (x = 0), there is a residual accretion on profiles 8 - 10 and a residual erosion on profiles 11, 12, 13, 15 and 17. The magnitudes of these residuals relate to the averages for between-survey periods (about three months). They obviously depend on factors other than direct westerly/easterly meteorological processes. Some probable factors have been shown

in the correlation analyses. It seems likely that factors due to interaction of process elements account for much of this residual trend of response variation.

PROFILE	GAIN	VECTOR	LINEAR REGRESSION
8 (total)	resultant	long period waves	y = 4725 - 1325x
9	resultant	strong winds	y = 1185 - 184x
10	total	strong winds	y = 3024 - 146x
11	total	very strong winds	y = -2176 + 1058x
	resultant	strong winds	y = - 309 + 76x
	resultant	very high waves	y = - 589 + 529x
	resultant	long period waves	y = -5351 + 2117x
12(sand)	total	very high waves	y = - 265 + 245x
13	total	strong winds	y = -1023 + 77x
	total	very strong winds	y = - 779 + 276x
	total	high waves	y = - 894 + 62x
	resultant	high waves	y = - 630 + 79x
15	resultant	long period waves	y = - 911 + 283x
17	resultant	strong winds	y = - 14 + 39x

TABLE 4.15 : Linear regressions of changes of sand volume on frequency of meteorological vectors (westerly components)

The equations have been used to predict between-survey changes for each profile, based on meteorological records from the St. Gowan Lightvessel. Results are shown in Table 4.16, in cubic feet.

	PROFILES							
PERIOD	8	9	10	11	12	13	15	17
A	-7200	818	696	4545	1205	377	1636	65
B	2075	- 650	1278	-70	-265	149	-345	377
C	-1901	1002	1133	691	-20	-42	221	26
D	750	-100	696	630	470	309	-62	182
E	2075	3571	2006	-1124	225	-432	-345	-443
F	2075	818	2733	-746	-265	-689	-345	65
G	750	-1935	-177	989	470	81	-62	650
H	2075	-1751	-1341	2428	225	1581	-345	611

TABLE 4.16 : Predicted volumetric changes (in $ft.^3$) of mobile sand associated with westerly meteorological vectors for successive between-survey periods

No attempt has been made to reconcile these volumes with those actually measured, nor has use been made of confidence limits for the regression lines. A problem arises when several equations are available for one profile, whether to take the mean change offered by all equations or to take the greatest change. For the data of Table 4.16, the former alternative has been adopted, variations due to several vectors being considered as estimates of the same variation.

Transects were not equally spaced, and so some weighted

compensation must be sought to allow for an estimate of total estuarine volumetric changes. This is done in Table 4.17, where volumetric variations for successive periods have been computed for the zones between transects. The sediment change in each zone has been roughly calculated by taking the mean change on the two boundary profiles and multiplying this by the distance between them; in effect, each zone has been viewed as a trapezium. For convenience of presentation, the data of Table 4.17 is expressed as cubic metres x 10^3.

These volumes include the residual components mentioned above. It would appear that there is a resultant increase of mobile sand within the estuary during the study period, amounting to some 1,397,000 cubic metres, an average of 1,800 cubic metres each day. The amount of accretion varies for successive periods, partly because of their varying lengths; but the rate of daily accretion also varies from 100 cubic metres to 4,300 cubic metres so that there is an extreme temporal variation of accretion during the study period. Periods of erosion occur, particularly in the middle estuary, but only zone 10 - 11 shows consistent accretion.

The influence of westerly vectors over and above the residual changes is shown in Table 4.18. These volumes are derived from the x terms of the linear regression equations, ignoring the constant y-intercept term, and so are dependent only on the regression coefficients. Apparently, the overall effect of westerly

	ZONES								
PERIOD	8-9	9-10	10-11	11-12	12-13	13-15	15-17	TOTAL	PER DAY
A	-191.4	45.4	235.8	129.4	23.7	60.4	89.3	392.6	4.3
B	42.7	18.9	54.4	-7.5	-1.8	-5.9	1.7	102.4	.8
C	-26.9	64.0	82.0	16.1	-.9	5.4	13.0	152.7	2.6
D	19.5	17.9	59.7	24.8	11.7	7.4	6.3	147.3	1.6
E	169.3	167.2	39.7	-20.2	-3.1	-23.3	-41.4	288.2	2.3
F	86.8	106.5	89.4	-22.8	-14.3	-31.0	-14.7	199.9	3.1
G	-35.6	-63.3	36.5	32.8	8.3	.6	30.9	10.2	.1
H	9.7	-92.8	48.9	59.7	27.1	37.1	13.9	103.6	.8
						GRAND TOTAL		1396.9	1.8

TABLE 4.17 : Predicted resultant volumetric changes (in $m.^3 \times 10^3$) of mobile sand within the estuary associated with westerly meteorological vectors

	ZONES								
PERIOD	8-9	9-10	10-11	11-12	12-13	13-15	15-17	TOTAL	PER DAY
A	-368.7	-80.9	194.5	182.7	40.2	112.6	137.8	218.2	2.4
B	-134.6	-107.4	13.0	45.8	14.7	46.4	50.2	-71.9	-.6
C	-204.3	-62.3	40.7	68.5	15.6	57.6	61.5	-22.7	-.4
D	-157.8	-108.4	18.4	78.0	28.2	59.7	54.8	-27.1	-.3
E	-7.9	40.9	-1.6	33.2	13.4	28.9	7.2	114.1	.9
F	-90.5	-19.8	48.1	30.6	2.2	21.3	33.8	25.7	.4
G	-212.8	-189.6	-4.8	86.2	24.6	52.8	79.4	-164.2	-2.1
H	-167.6	-219.0	7.6	113.0	43.6	89.3	62.5	-70.6	-.6
						GRAND TOTAL		1.5	.002

TABLE 4.18 : Predicted changes of volume ($m.^3 \times 10^{-3}$) of mobile sand within the estuary directly attributable to westerly meteorological vectors (conservative estimate)

vectors is minimal, being associated with an increase of sand of only 1,500 cubic metres during the whole study period, which if spread uniformly through the period amounts to 2 cubic metres per day. For the purposes of this analysis, such a figure must be analogous to zero. However, the increase is not a constant one; during period A the average rate per day is +2,400 cubic metres whilst during period G the rate is an erosion of -2,100 cubic metres. Because of the discrepent survey times, no seasonal significance can be attributed to this data.

Hence it must be concluded that westerly components of winds and waves were associated with erosion of sand in the lower estuary, accretion in the middle and upper estuaries, sometimes associated with a small overall accretion, sometimes a small overall erosion, the resultant effect during two years amounting to a negligible accretion. There was in addition a residual trend of accretion in the lower estuary and of erosion in the middle and upper estuaries, accretion being greater than erosion so that there was a significant gain of mobile sediment during the study period.

This is probably a conservative estimate. As pointed out earlier, some profiles provide several regression equations. The conservative estimate is based on the mean of several possible estimates for such profiles. These estimates are similar for any one profile, with the exception of those relating to very high and long period waves (i.e. storm swell) on profile 11, which

forecast greatly inflated amounts of accretion during stormy weather. Taking these maximum estimates, then a very different picture of sand accumulation is obtained. The predicted changes of sand volumes using maximum estimates for profiles 11 and 13 are shown in Table 4.19 (the intermediate data for each profile is omitted). In this case, there is an overall sand accumulation of 1,900,000 cubic metres for the study period, a daily accretion of 2,400 cubic metres. This is considerably more than the residual accretion (Table 4.17). Such a possibility must be rejected as unlikely for two reasons. Firstly, the predicted fill would necessitate a mean rise of 6 feet in the vicinity of profile 11 for period A; such a considerable change was neither observed by the writer nor reported by local people. Secondly, surveys of profile 11 were few in number, monitoring a period of relatively storm-free seas. The predictions take in period A, which was exceptionally stormy and probably not subject to the laws governing calmer periods from which the prediction equation was obtained. It may be seen from Table 4.15 that the equation referring to long period waves for profile 11 is of a numerically higher order of magnitude than the others for the same profile, and must therefore be treated with caution.

However, without additional data it is impossible to positively decide between conservative and maximum estimates.

	ZONES								
PERIOD	8-9	9-10	10-11	11-12	12-13	13-15	15-17	TOTAL	PER DAY
A	-368.9	-80.9	745.1	458.2	41.0	114.3	89.3	998.1	11.0
B	-134.6	-107.4	156.1	117.4	16.3	49.6	1.7	99.1	.8
C	-204.2	-62.3	329.6	218.5	11.9	50.5	12.9	356.9	6.1
D	-157.8	-108.4	109.5	123.7	33.2	69.8	6.3	76.3	.9
E	-7.9	41.1	72.2	33.2	6.2	14.6	-41.4	118.0	1.0
F	-90.5	-19.8	104.9	59.5	2.3	21.6	-14.7	63.3	1.0
G	-212.8	-189.6	70.2	86.2	30.4	64.2	30.9	-120.5	-1.5
H	-167.6	-219.0	276.6	247.7	52.9	103.6	13.9	308.1	2.4
						GRAND TOTAL		1899.3	2.4

TABLE 4.19 : Predicted changes of volume ($m.^3 \times 10^3$) of mobile sand within the estuary directly attributable to westerly meteorological vectors (maximum estimate)

The prediction equations do provide a further dissection of the study period into months, if it is assumed that the regression coefficient (i.e. the amount of volumetric change per meteorological observation) remains constant, which seems very likely if the results of the correlation analyses are accepted. In Table 4.20 are shown the predicted monthly variations (February, 1968 to March, 1970) of sand volume (in $m.^3 \times 10^3$) directly attributable to westerly vectors (i.e. the residual variation is ignored). These are conservative estimates. As already explained, because of the nature of the correlation coefficients, these are also to some extent attributable to easterly vectors.

The total volumetric increase is slightly greater than that noted in Table 4.18 because the time period is slightly extended (since the whole of February, 1968 and March, 1970 are included).

For comparative purposes, the mean monthly residual change is shown for each zone, assuming that this was at a constant rate throughout between-survey periods. Monthly changes 200% greater than the monthly residual are underlined if that residual is negative, marked * if the residual is positive. Monthly changes 200% less than the monthly residual are underlined if that residual is positive, marked * if it is negative. In this way exceptional changes, in which the residual trend is either strongly reversed or strongly reinforced are distinguished from the others.

Clearly, the pattern of change is different for some months

	ZONES									
MONTH	8-9	9-10	10-11	11-12	12-13	13-15	15-17	8-10	10-17	TOTAL
2/1968	15.3	41.9	13.5	22.1	5.8	12.7	-5.6	57.2	48.4	105.6
3	-384.0	-122.8	186.7*	163.5	33.6	98.3	143.4	-506.8	625.4	118.6
4	0	-4.4	-6.6	0	1.9	3.8	0	-4.4	-.9	-5.3
5	-39.8	-8.8	11.1	20.4	5.0	11.1	14.9	-48.6	62.5	13.9
6	-11.0	-19.8	-11.4	.9	2.2	4.3	4.1	-30.8	.1	-30.7
7	-11.0	-19.8	-11.4	.9	1.7	3.3	4.1	-30.8	-1.4	-32.2
8	-50.8	-19.8	30.3	27.2	8.8	18.7	18.9	-70.6	103.9	33.3
9	-237.2	-82.2	89.3*	82.9	14.7	64.4	88.6	-319.4	339.9	20.5
10	-90.5	-32.8	16.6	24.7	6.4	29.7	33.8	-123.3	111.2	-12.1
11	118.0	34.2	-66.1	-29.8	-.9	-27.2	-58.9*	152.2	-182.9*	-30.7
12	-96.0	-47.1	16.1	30.9	4.8	26.6	35.9	-143.1	114.3	-28.8
1/1969	-67.3	-58.1	23.7	40.3	11.9	24.9	25.1	-125.4	125.9	.5
2	-11.0	-32.8	-48.9	-8.1	2.9	5.8	4.1	-43.8	-44.2	-88.0
3	105.8	61.7	-46.5	-20.0	-1.6	-11.8	-39.4	167.5	-119.3*	48.2
4	-135.7	-29.5	66.2*	48.5	9.3	36.7	50.7	-165.2	211.4	46.2
5	16.5	16.5	-2.6	-1.3	.5	1.1	-6.2	33.0	-8.5	24.5
6	5.5	5.5	-.9	-.4	1.1	2.1	-2.1	11.0	-.2	10.8
7	-79.5	0	47.6*	23.8	0	16.9	29.7	-79.5	118.0	38.5
8	-11.0	-19.8	.5	6.8	2.2	4.3	4.1	-30.8	17.9	-12.9
9	-16.5	-29.6	-17.1	1.3	.9	1.8	6.2	-46.1	-6.9	-53.0
10	-11.0	-19.8	-11.4	.9	1.1	2.2	4.1	-30.8	-3.1	-33.9
11	-179.8	-130.4	29.6	83.7	22.4	48.2	67.1	-310.2	251.0	-59.2
12	22.0	8.9	-5.2	12.8	7.0	7.4	-8.2	30.9	13.8	44.7
1/1970	-28.8	6.7	33.4	25.5	5.3	11.6	10.8	-22.1	86.6	64.5
2	-104.6	-191.9	-19.6	55.7	25.4	50.7	38.9	-296.5	151.1	-145.4
3	-61.8	-52.6	5.2	25.5	8.3	25.1	23.1	-114.4	87.2	-27.2
TOTAL	-1344.2	-746.6	322.1	638.7	180.7	472.7	487.2	-2090.8	2101.4	10.6
MONTHLY CHANGE	-51.7	-28.7	12.4	24.6	7.0	18.2	18.7	-80.4	80.8	.4
MONTHLY STABILITY	73.5	42.2	31.5	29.2	7.1	21.2	23.0			
MONTHLY RESIDUAL	54.6	38.9	12.7	-16.4	-5.1	-16.1	-14.9	93.4	-39.8	53.6

TABLE 4.20 : Predicted monthly volumetric changes ($m^3 \times 10^3$) of mobile sand directly attributable to westerly components of meteorological input (see text for explanation)

(May to August) than for others. In the summer months, changes associated with westerly vectors are not exceptionally different from residual changes. The distribution of variation is in opposition to the residual, since westerlies are associated with erosion of the lower estuary and accretion on the middle and upper estuaries, but of insufficient magnitude to reverse the residual trend. Overall changes of volume throughout the estuary due to westerly vectors are small, sometimes accretion sometimes erosion.

During the rest of the year, when the frequency of westerly vectors increases, changes associated with westerlies are often in marked contrast to the residuals. This is most apparent in March, September, October, and December, 1968; January, April, and November, 1969; February, and March, 1970. At such times, westerly vectors were dominant (the frequency of south-westerly gales during the study period is shown in Fig. 2.23). There is an exceptionally large erosion of the lower estuary and corresponding accretion elsewhere at these times. However, the total variation throughout the estuary does not follow the same trend for all such months.

Westerly strong winds and high waves, indicative of local weather, undoubtedly effect the nature of the tidal wave to some extent. The flood-tide, from the south-west, is given an added forward energy component by following winds and waves (allowing

for refraction in shallow water), so that early-flood velocity and turbulence is increased. This enables the young flood to transport sand from the lower estuary upstream where it is deposited as the current slackens. This deposited sand is less readily resuspended by the subsequent ebb flow because current speeds are reduced by interaction with the opposing westerly winds, though locally formed wind waves may help to overcome this. However, above Laugharne less sand is removed by the ebb than was deposited by the flood. Below Laugharne, particularly in the outer estuary, ebb flushing is reinforced by the following westerly winds which are here able to blow along the estuary because of the low relief of both dunes and marsh (see map in Fig. 1.0); resuspension is also aided by wave formation. The result is that the lower estuary loses more material than it normally gains.

At these times then, there is an exceptional fill upstream and an exceptional cut downstream. This differentiation is very apparent in Table 4.20, particularly for November, 1969 and February, 1970. The downstream loss greatly exceeds the upstream gain, so that there is an overall erosion, even though considerable quantities of sand have been moved into the middle and upper estuaries. This overall erosion also exceeds the overall residual accretion. At other times, the distribution of cut and fill within the estuary is similar, but the overall erosion is not apparent. Thus in October 1968, January and April 1969, there is

a similar (though less extreme) redistribution of sand within the estuary, but the overall change is not exceptional relative to the residual. The difference is due to the smaller frequency of very strong westerlies which are necessary to cause the inflated ebb flushing noted above.

Hence it may be concluded that westerly winds and waves, formed by local weather, move sediment into the inner estuary from the estuary mouth by modifying the nature of the tidal flood and ebb pattern. This process generally involves a redistribution of sediment without any net gains or losses. Very strong westerly winds produce a similar redistribution but also effect a net loss from the estuary by increasing erosion in its lower reaches.

Westerly storm waves occurred with much the greatest frequency in March, 1968. These are large energy waves produced by Atlantic storms. Their energy is great since wave energy increases with the square of both deep-water height and period, so that their mass-transport boost to the flood tide is correspondingly greater. Flood-induced turbulence is then at its most developed in the estuary, so that movement of sand from the outer to the inner estuary is increased. Swell then continues to sweep into the estuary during the flood and most of the ebb as well. Ebb flushing is therefore reduced throughout the estuary, being confined to the latter stages of the ebb when tidal height is sufficiently low to bar the storm swell entry into the estuary.

The overall change is one of considerable accretion.

Hence westerly storm swell also moves sand into the inner estuary but in increased quantities.

On occassions, the easterly component of meteorological input was dominant relative to the westerly component (February, and November, 1968; March, May, and December, 1969). At these times the residual trend of accretion in the lower estuary is reinforced, since ebb flushing is diminished by the opposing wind. In February, 1968 the reduction of ebb flushing is sufficiently widespread to produce a large net accretion throughout most of the estuary; there are similar, but smaller, gains throughout most of the estuary in May and December, 1969. November, 1968 and March, 1969 present apparent discrepancies, exceptional erosion occurring in the upper estuary at the same time as dominant accretion in the lower. The latter may be explained by reduced ebb flushing. The former may be due to increased ebb flushing by following easterly winds but it is difficult to visualise how easterlies can do this because of the high relief of the left bank of the inner estuary. Also there is no such erosion during other months of dominant easterlies. However, these two months were distinguished from all others by a dominance of easterly very high and long period waves (in addition to easterly winds). These cannot be generated within the estuary but must modify the tidal wave in the bay, by reducing the forward impetus of the flood (from the south-west).

Hence less sand is carried into the inner estuary, and ebb flushing is relatively predominant.

To summarise : There was a predominant trend of accretion in the estuary, primarily in its lower reaches, independent of westerly meteorological influences. At the same time there was a tendency for the inner estuary to suffer erosion, this being of smaller magnitude than overall accretion. Westerly and easterly meteorological variables effectively altered the pattern of accumulation; westerly winds and waves (of local origin) promoting erosion of the lower estuary and accretion of the upper; easterly winds and waves (of local origin) reinforcing the residual accretion in the lower estuary, extending it to the middle and upper estuaries. Hence local westerly winds and waves reverse the predominant overall residual accretion; local easterly winds and waves reinforce it.

Storm waves from the west also reverse the residual distribution within the estuary, but in addition greatly increase the overall residual accretion. Storm waves from the east tend to encourage the residual erosion of the inner estuary.

The foregoing analysis has considered the relationship of sediment movement and westerly/easterly components of meteorological processes. A considerable amount of variation of sediment volumes is not explained by this association - there are residual

variations independent of these components, variations that occur in their absence.

It has been shown that other components of meteorological processes have important relationships with sediment variation in some parts of the estuary. These can now be included in the analysis.

In Table 4.21 are shown the additional model 2 regression equations used for this purpose. These also follow from the correlation analysis and have been obtained by the method described above.

PROFILE	GAIN	COMPONENT	VECTOR	MODEL 2 REGRESSION
8(total)	total	onshore	prevailing winds	y = -13804+225x
	total	offshore	very strong winds	y = -3662+663x
13	total	offshore	strong winds	y = -476+ 70x
	total	offshore	very strong winds	y = -593+725x
14	resultant	onshore	strong winds	y = 178+ 50x
15	resultant	offshore	prevailing winds	y = -55- 5x
	resultant	offshore	very strong winds	y = -94-148x
16	total	westerly	prevailing winds	y = 1695- 18x
	total	offshore	prevailing winds	y = 1228- 18x
	total	offshore	strong winds	y = 1083-101x
18	resultant	westerly	prevailing winds	y = -501+ 10x

TABLE 4.21 : Linear regressions of volumetric variation on frequency of meteorological vectors

By means of the appropriate regression equations, the changes of volume of mobile sediment associated with all meteorological process have been determined, and the related volumetric changes of the zones between profiles computed as before. The results are shown in Table 4.22; the changes relate to the variable x factor in the regression equations i.e. they relate to changes over and above the residual variation. For comparative purposes, these residuals are displayed separately.

The analysis indicates that a total accumulation of 816,800 cubic metres of mobile sand may be accounted for by association with meteorological process vectors. An additional residual of 336,000 cubic metres, also of accumulated sand, cannot be accounted for. The total gain of sand volume during the study period is 1,152,800 cubic metres, somewhat less than the volume estimated using only westerly process/response and residuals (see Table 4.17). Since the amount of information used in this analysis is greater than used previously, we may assume that this estimate is more acceptable than the previous one. It is noteworthy that 71% of total postulated sand variation in the estuary may be associated directly with meteorological process variables.

The magnitude and sense of this variation have been fluctuating periodically, notwithstanding the variable lengths of the between-survey periods. The overall change during the study period attributable to meteorological process has been one of

ZONES	PERIODS								TOTAL	TOTAL RESIDUAL	NET
	A	B	C	D	E	F	G	H			
8-9	-22.3	86.9	67.7	83.5	211.6	48.0	-5.5	37.8	507.7	-734.4	-226.7
9-10	-81.1	-107.7	-62.4	-108.7	41.1	-19.8	-190.1	-219.6	-748.3	1009.6	261.3
10-11	194.1	12.8	40.4	18.4	-1.8	48.0	-5.3	6.9	313.5	330.4	643.9
11-12	182.7	45.8	68.4	78.1	33.1	30.6	86.2	113.0	637.9	-426.4	211.5
12-13	30.5	10.3	8.3	26.0	14.0	2.1	20.6	38.3	150.1	-120.0	30.1
13-14	8.5	11.0	11.4	16.4	5.2	4.4	15.6	37.7	110.2	-66.4	43.8
14-15	16.2	3.5	17.3	10.1	2.0	5.9	12.5	11.7	-178.2	259.2	81.0
15-16	-.3	-40.2	4.4	-23.2	-24.4	-22.6	-18.5	-53.4	79.2	-24.8	54.4
16-17	-14.9	-17.5	-6.1	-16.0	-26.3	-14.1	-3.5	-21.5	-119.9	190.4	70.5
17-18	3.1	15.2	2.9	5.8	-12.6	14.4	17.7	18.1	64.6	-81.6	-17.0
TOTAL	316.5	20.1	152.3	90.4	241.9	96.9	-70.3	-31.0	816.8		1152.8
RESIDUAL	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	336.0	

TABLE 4.22 : Predicted periodic volumetric changes ($m^3 \times 10^3$) of mobile sand associated with all meteorological process vectors

accumulation, predominantly in the areas between transects 8 - 9, 10 - 14, 15 - 16, and 17 - 18. This trend of accumulation results from the relative frequencies of the wind and wave components summarised at the beginning of this sub-section.

It has been shown that the overall effect of westerly meteorological process of total accumulation in the estuary is comparatively small (taking the study period as a whole). The rate of accumulation is greatly increased when all meteorological components are considered. This is due primarily to the effect of onshore prevailing winds on profile 8 where they are associated with accretion. The trend is strongest on the upper, stable part of the profile. Therefore, although stable in terms of continuous cut and fill, this area does in fact produce much of the sand that subsequently accumulates in the middle and upper estuaries via predominantly westerly components of meteorological input.

Onshore prevailing winds are associated with sediment variation on profile 8 only. They may encourage deposition of ebb-transported material by reducing ebb-flow energy. But it seems most likely that they sustain a progressive movement of sand from immediately offshore into the estuary, perhaps by means of small wind waves and/or direct wind action on exposed sandbanks and beach. This accumulation is most pronounced on the profile above the mean high tide mark of neap tides, and must therefore be dependent to some extent on the frequency of spring tides, so

that wind-wave action is important during spring tides and wind action during neap tides.

The significance of the residual variation is considered in the following section.

The foregoing discussion has concentrated on sediment movements within the confines of the estuary. However, it is nonsense to assume that the estuarine dynamic process/response system is terminated by transects 8 and 18. Obviously there must be a considerable movement of sand between the estuary and the complex of sandbanks off its mouth, and it has been shown that much of the sand accumulating in the estuary is derived from that area. But this need not imply a marine source for the accumulating sand. Most responses of sand to meteorological processes have been explained qualitatively in terms of response to changing estuarine circulation patterns by means of tidal wave modification. These responses could apply equally well to a positive-filling or a negative-filling sediment sink. It is felt that the balance of evidence is in favour of the second mechanism (in terms of profile variations); but it is impossible to verify this in the absence of data on bed-load and suspended-load transport by the river.

Finally, by means of the regression equations, it is possible to fill in missing data, so that the comparative study of profile stability attempted in section 4.2 can be more rigorously managed. For this purpose, the total variation of each profile per inter-

survey period has been computed using both actual and predicted data, no distinction being made between cut and fill. This variation (in cubic feet) is then divided by the mean volume of the profile, providing a comparable figure of stability/volume for each profile. Results are shown in Table 4.23; the conclusions drawn in section 4.2 are seen to be correct.

	PROFILES										
	8 (low)	9	10	11	12 (sand)	13	14	15	16	17	18
S_1	2716	1144	1457	1352	361	508	407	318	426	323	316
S_2	.10	.07	.06	.09	.05	.10	.10	.12	.07	.06	.05

TABLE 4.23 : Comparative profile stability

S_1 = mean stability (cu.ft.) between surveys

S_2 = mean stability/mean volume

4.8 Summary and Conclusions

Evidence collected at periodic intervals during the study period shows that there was an overall accumulation of sediment within the estuary; this sediment was predominantly sand.

Meteorological process variables accounted for much of the sediment variation. Onshore prevailing winds were associated with sand accumulation at the estuary mouth, probably deriving this material from immediately offshore. Westerly strong winds and

waves were then able to achieve a landward movement of this deposited material, therefore periodically filling the inner estuary. Westerly storm waves were the most important agent of this movement.

Within the estuary, westerly and easterly meteorological components brought about significant redistributions of sediment between the inner and outer estuaries by modifying estuarine circulation. Westerlies encouraged accretion in the middle and upper estuaries, erosion in the lower. Easterlies encouraged a converse redistribution. Westerly winds and waves of local origin were associated with a resultant loss of sediment gain. Again easterlies were generally associated with converse resultant changes.

The primary source of sand variation must be the daily incursion of a large volume of tidal water. This involves high current velocities and intense turbulence on both the early flood tide and the late ebb tide, so that the most unstable areas were those close to the main channels, though the channels themselves were relatively stable (in vertical range).

The mouth of the estuary was less stable than the upper reaches partly because more sediment is available for transport, but also because tidal influence, particularly flood energy, diminishes upstream. There was a temporary decrease of stability at Laugharne because of increased turbulence created by collision

of fluid streamlines with curvilinear shoals and banks.

It is probable that spring tides, through an increased flood tide surge, brought about a net landward movement of sediment, ebb tides having a reverse tendency.

River flow is not a major process variable, when considered in isolation, but caused local instability where the main ebb channel was curved, as off Laugharne. Its effect was to reinforce ebb flow, becoming most important at low water. Locally, flushing from marsh creeks played a similar minor role.

Principally, however, flushing of sand downstream is achieved by the returning tidal flow, encouraged by local wind waves generated by winds from the north in the upper estuary, from the west in the lower.

Process variables have been considered in isolation. Some evidence suggests that interaction of process and response variables is an important factor that has not been considered. River flow became important when examined in conjunction with other factors. The most areally consistent accumulation of sand occurred when low river discharges coincided with high frequencies of westerly and onshore winds and waves. However, the exact quantitative contribution of river flow to sediment movements within the estuary is unknown. Nevertheless, it must be emphasised that interaction of several process variables is likely to be of great importance; the failure of this experiment to investigate such

interaction must mean that a vital aspect of sand transport and accumulation has been ignored, so that the results and conclusions presented here represent, perhaps, only a part of the complete dynamic milieu of estuarine sedimentation.

A significant proportion of variation has not been accounted for. From Table 4.22 it may be seen that there was an 'unexplained' residual accretion during the study period, amounting to 336,000 cubic metres. This may be a real variation, compounded by combinations of process variables that have not been examined; or a progressive infilling from the sea (or from the land) that occurred without assistance from meteorological processes but was due entirely to normal tidal incursion (the correlation analysis for this variable being particularly arbitrary and unsatisfactory).

However, because of the lack of 'sampling' design and control in the surveying programme, it may be that this apparent accumulation reflects error variation. It has been assumed in the analysis that all variation represents between-survey and between-profile variations; no estimate has been made of among-survey and among-profile error variations. Because of the method of surveying between fixed markers, error among surveys can safely be ignored. But error among profiles is unknown. This means that the profile measurements probably include some bias. It has been assumed that if profile 8 experienced erosion, and profile 9 erosion, then the zone between them also must experience erosion.

This may be quite wrong, and it is feasible that the contrary is correct. In other words, it is a mistake to assume that samples are representative of a population without prior knowledge of within-sample variation.

The authority with which the above conclusions can be argued is therefore dependent on the confidence that can be placed on the method of data collection. It has not been ascertained whether the transects were sufficiently closely spaced to outweigh bias introduced by local variations. The determination of statistically significant associations of profile variation with meteorological process variables suggests that the surveys were usefully representative of some of the trends active in the estuary. For this reason most conclusions are based on results obtained via statistical postulates; all conclusions are based on trends that are statistical rather than absolute. It must however be admitted that the fact that statistical associations of profile variation with even westerly process variables (the most consistent component of meteorological input) are with differing elements (winds, waves or swell) of those processes is puzzling and detracts from the value that can be placed on these results. However, a considerable proportion of variation has been 'explained'; this amounts to 71% of the statistical variation, and to 55% of the survey variation (using actual data with predictions based on regressions to fill in missing values).

It is therefore probable that the 'unexplained' variation, the residual, represents error variation due to bias inherent in the surveying programme.

Two years is a short period from which to extrapolate long term changes. The results obtained do allow for an estimate of mean annual accumulation within the estuary during the study period. The total volumetric accumulation may be divided by the total area of the mobile zone for the whole estuary, and for each zone between transects. This is shown in Table 4.24. These results stem from the predicted data of Table 4.22. Variations are divided into 'explained' (i.e. associated with total meteorological process input) and 'unexplained' (i.e. residual) components.

	ZONES					
ANNUAL VARIATION	8-9	9-10	10-11	11-12	12-13	13-14
EXPLAINED	.30	-.61	.18	1.09	.52	.51
UNEXPLAINED	-.43	.82	.19	-.73	-.41	-.31

	ZONES				
ANNUAL VARIATION	14-15	15-16	16-17	17-18	TOTAL
EXPLAINED	-.61	.12	.29	.19	.110
UNEXPLAINED	.89	-.04	.46	-.24	.045

TABLE 4.24 : Mean annual relative changes of mean elevations (in metres)

There was therefore a postulated mean annual accumulation of .110 metres within the estuary during the study period due to the influence of meteorological processes; there was an additional accumulation of .045 metres/year that remains unexplained and may reflect a real change or experimental error.

These estimates are some two orders of magnitude greater than Rusnak's (1967) estimates for accumulation in modern estuaries. However, his estimates are averaged over the total period since the Pleistocene. It is known (see Chapter 1) that a significant infilling of the estuary has occurred since the Middle Ages, particularly within the past century, of sufficient magnitude to curtail the activity of trading vessels. It is also very probable that minor sea-level fluctuations during the past millenium have caused some reversals and accelerations of the infilling process. Hence it is hardly surprising that the results monitored over a short period are incompatible with predictions based on a time-scale of geological proportion. However, it must be recognised that because of the shortcomings of the method of data collection, the postulated accumulations stated above may be very wide of the mark. It is very probable that these results will need to be greatly modified if, and when, the problems of interaction and feedback are properly studied. Until then, however, the results suggested by this experiment do provide us with an interesting, if surprising, hypothesis of rapid sand accumulation in the estuary.

Of course, these postulated results were not recorded directly by the surveys (which did, however, show a general trend of accretion, see Table 4.1), but were deduced by statistical methods. In this way, it is hoped that the bias inherent in the design of the experiment has been, to some extent, overcome. It seems probable that, even with a much denser array of data, some such approach will be necessary, since it is practically impossible to monitor the whole estuary for a prolonged period.

Finally, it is interesting to attempt a synthesis of beach and estuary profile results and conclusions. Unfortunately, as explained in Chapter 2, sampling bias renders the beach profile data highly unsuitable for such a task. Predictions based on statistical trends cannot be attempted, since significant correlations between meteorological processes and volumetric responses (in terms of accretion and erosion) have been established for some profiles, but not all, and without much consistency, so that it is evident that these are representative of a few response trends only. Survey data is highly biased since it is inclusive of short-term temporal variation and among-transect variation.

Limited by these dictates, it is perhaps permissible to compare beach and estuary variations in terms of order of magnitude only.

In Table 4.25 are shown estimates of periodic variations of zones between beach profiles (using biased actual data). These

have been computed by treating zones as trapeziums. In this way, the volume of sand lost by the total foreshore during the study period (contemporaneous with the estuary study period, most survey times coinciding) is estimated at 0.46×10^6 cubic metres. Because of bias this is probably a low estimate. This figure compares with an 'explained' accumulation due to meteorological processes of 0.82×10^6 cubic metres in the estuary. It is thought to be of striking significance that these two estimates should be of the same order of magnitude (although, of course, it may be purely fortuitous).

	ZONES						
PERIODS	1-2	2-3	3-4	4-5	5-6	6-7	TOTAL
A	-34.8	-44.6	-26.5	-60.0	-43.8	42.6	-167.1
B	-108.2	-116.8	-82.9	-75.8	-61.9	-55.7	-501.3
C	32.6	34.5	15.1	-18.8	[-14.4]	[-41.0]	[129.8]
D	3.0	4.5	57.1	57.2			
E	6.5	43.5	72.3	23.8	-1.6	-31.9	112.6
F	20.0	44.0	30.9	-13.9	-6.4	34.2	108.8
G	-51.8	-31.5	-2.2	-31.9	-45.1	-53.5	-216.0
H	17.4	21.3	61.1	[20.0]		-48.1	71.7
					GRAND TOTAL		-461.5

TABLE 4.25 : Volumetric changes for the total foreshore (profiles 1 - 7) from survey data ($m.^3 \times 10^3$).

It is tempting to relate the two estimates. They do suggest support for the intuitive notion that beach and estuary are part of a continuous dynamic equilibrium. Historical evidence for cyclic changes in both beach (and related dunes) and estuary must be noted. Westerly storm swell is instrumental in erosion of the beach, accumulation in the estuary. With the present-day rise of sea-level (Valentin, 1955), such meteorological processes may be critical in creating a new equilibrium dynamic by a progressive adjustment of the status quo. Movement off the beach, and movement into the estuary then occurs at the greatest rate during the period September - April, a smaller, but reversed, movement becoming dominant at other times. The greatest influx of sediment also probably occurs during spring tides.

V. 2
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THE SEDIMENTOLOGY OF ESTUARINE AND COASTAL PLAIN DEPOSITS BETWEEN PENDINE AND WHARLEY POINT, CARMARTHEN BAY

by

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A thesis submitted to the University of London
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CHAPTER 5.

SEDIMENT SAMPLING AND ANALYSIS : A DISCUSSION OF THE INTERPRETATION OF GRAIN-SIZE DISTRIBUTIONS

5.1 Sampling Procedure

Most geological studies are hampered by severe sampling restrictions. The geologist has no control over the natural occurrence of outcrops, though he does generally have complete freedom in sampling any one outcrop. However, in the case of a present-day environment of sedimentation, since all or most of the environment is readily accessible, samples can be collected without restriction, with a measure of statistical randomness, since the geologist has control of the upper level of sampling as well as the lower. Hence, using the terminology of Cochran, Mosteller and Tukey (1954), inferences can be generally made from sample to sampled population and from sampled population to target population.

Any sampling procedure which includes the selection of a single sample will yield only a single mean value, which may or may not be representative of the sampled population. It is necessary, therefore, to obtain a series of samples, according to some pre-arranged plan. If unrestricted random sampling is the goal, then it is better to choose a plan which is symmetrical but not

related to any imagined gradient in the population, rather than one designed to fit a particular environmental pattern (several of which are suggested in Krumbein and Pettijohn, 1938), since the latter is likely to induce bias into the sampling by the very process of fitting it to the environment. On the other hand, alternative arrangements may be more efficient and equally precise if it can be shown that the programme is improved by reducing variability without introducing bias.

No such rigorous plan was adopted here. The goal or goals of any experiment will modify the choice of arrangement, and the degree of randomness. In the present study of beach sands, the variability of certain properties has been investigated in two directions (see Fig. 5.1), normal and parallel to the strandline. Further, it was assumed, a priori, that variability parallel to the strandline, i.e. along the beach, would be less than that normal to the strandline. A small-scale preliminary survey supported this assumption; whether or not results bear this out will be discussed later, but it is immediately apparent that while the closely-spaced samples normal to the beach will throw light on both local and 'regional' variation, the widely-spaced samples parallel to the beach can do neither, unless assumptions are made beforehand. In retrospect, it is evident that the sampling plan was arranged with the mistaken notion that widely-spaced samples bring out the regional variation unbiased by any local variation;

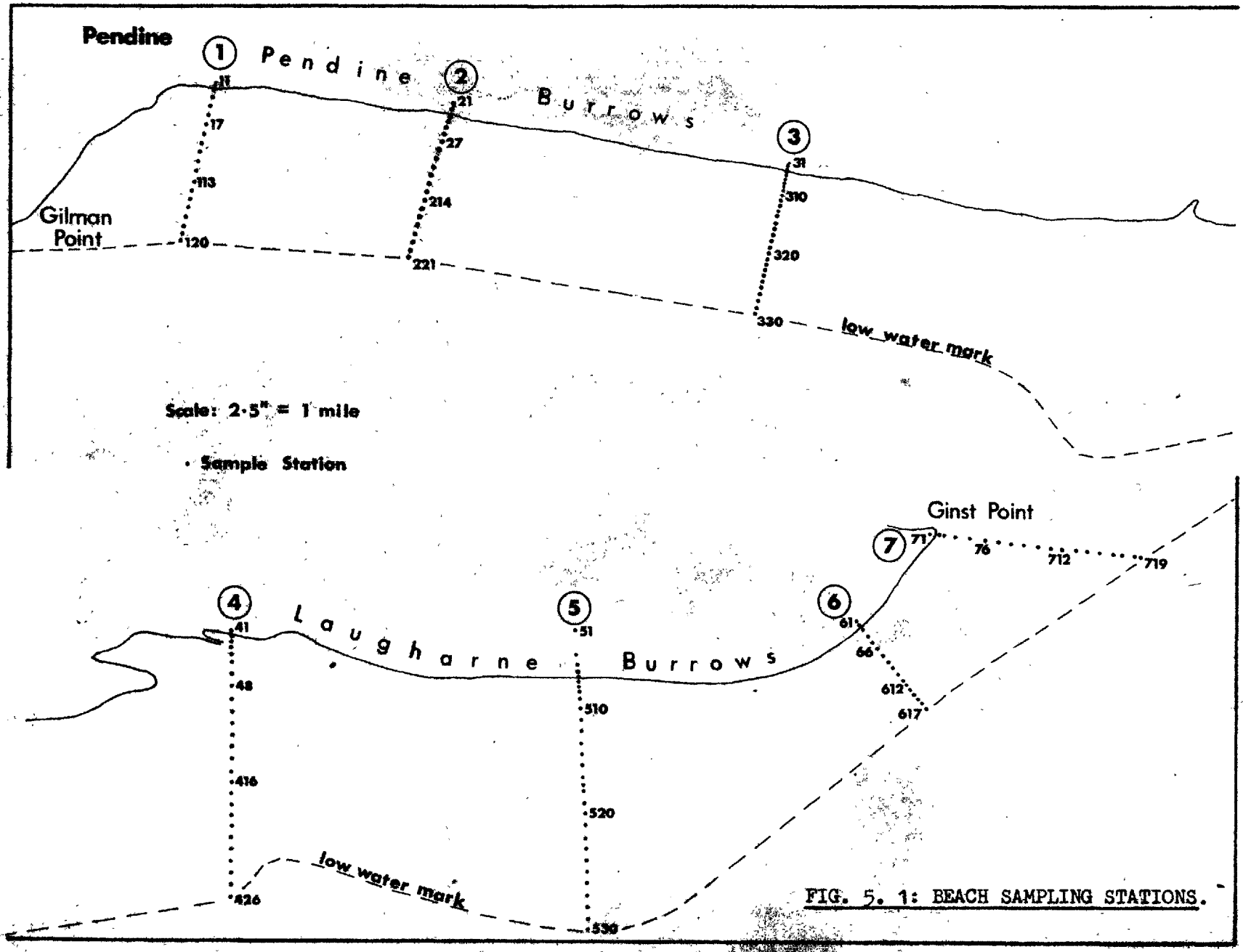


FIG. 5. 1: BEACH SAMPLING STATIONS.

this is obviously not so.

It was not originally intended that samples normal to the strandline be equally spaced along each transect; samples were to be collected subjectively at points of interest, e.g. changes of slope, ripple pattern etc. However, since the beach slope is rather uniform and the beach surface generally featureless, in practice the samples were collected at equally-spaced stations, the distance between each station being measured by pacing, equal to 130 - 150 ft. Along transect 3, the stations are twice as closely-spaced in places, to pick out greater detail. However, the sampling stations normal to the strandline are essentially equidistant apart. The transects are themselves not equally spaced, but were set up for convenience and accessibility (certain areas of the beach being permanently closed to the public). In spite of these factors, the sampling plan retains a semblance of arrangement, albeit not random (see Fig. 5.1), similar to the stratified random sampling recommended by Krumbein (1953). However, since it has not been quantitatively ascertained whether or not the arrangement introduces bias, as explained above, the plan can be regarded as statistically semi-rigorous at best. The optimum arrangement is probably a strictly random one based on a square grid; however, this would involve an enormous number of samples and would undoubtedly be very inefficient in terms of time and result. The most practical and efficient approach, and

equally precise, would be a preliminary experiment to establish the maximum sampling distance parallel to the strandline that could be adopted without introducing bias, and to base a grid on this. The same procedure would strictly be needed for samples normal to the strandline, but because the total distance along each transect is comparatively small, there is no great harm in collecting a greater number of samples than needed.

In common with many geological populations, beach and dune sediments are characteristically layered, each layer with its particular population, mean and variance. In stratified vertical sampling design, it is attempted to sample within the layers and then by appropriate weighting to obtain an estimate of the population mean and variance and a knowledge of within-and between-layer variation (Krumbein, 1960). In channel sampling design, the sampling is arranged to cross the layers; each channel should be a random sample of the population, and yield unbiased, consistent estimators of the population characteristics; precision of estimation can be improved by increasing the number of channel samples. However, since the rate of sedimentation and intensity of stratification will vary from one part of the beach to another, a channel sample may not be the most efficient or meaningful in layered deposits, and data interpretation becomes difficult. In order to take stratified samples, it then becomes necessary to define and distinguish a unit layer of sediment. The definition

has been laid down as 'that thickness of sediment deposited under essentially constant physical conditions', called a 'sedimentation unit' by Otto (1938) and a 'phase' by Apfel (1938). But recognition, selection and sampling of a unit presents difficulties since it must, by definition, be very small. Furthermore, choice of an homogeneous unit presupposes that variability can be estimated before sampling, so that in many cases the sampling unit would need to be a single grain (Griffiths, 1967). Nevertheless, very often sediment laminae can be distinguished by abrupt changes in grain size, mineralogy and colour, though these need not correspond to elemental sedimentation units, which might be much smaller.

Since the goals of the study were altered after sampling, the original sampling design used here does not best suit these intentions. Thus channel samples were taken at each sampling station and then an attempt made to interpret them as stratified samples, a compromise approach necessarily fraught with difficulties, and emphasising the need for careful defining of experimental goals before the experiment is begun, and arranging of a sampling design best suited to these goals. The samples have also been treated as originally intended, as channel samples taken from a standard thickness (1 inch) of sediment; since the environments of sedimentation under consideration are comparatively homogeneous, it may be assumed that such samples yield unbiased estimators of a comparable, if undefined, population. The relation of these

estimators to those of the stratified layers is considered in Chapters 6 and 7.

No absolute estimate of sampling error has been made in the present study. Krumbein (1934) found that the probable error of sampling beach sands varies from 0.75% to 4.51%, but could be reduced by taking composite samples, a composite of four closely spaced samples reducing the error of a single random sample by half. This procedure was adopted here, four separate samples, in close but random proximity, being taken round each sampling station and combined into one composite sample for analysis. A comparative estimate of sampling error and analytical error relative to between-sample station variation is considered in a later section; it will be shown that sampling and analytical errors are not significant. Hence it is considered that the samples taken for analysis give a precise and unbiased estimate of the sampled population, but because of the sampling arrangement, it seems likely that only biased estimates of the target population can be inferred from the sampled population (parallel to the strandline).

Composite channel samples were also taken of the dune and estuarine sediments in the same way as the beach sediments. Very few dune samples have been studied, and their distribution was purely subjective (see Fig. 5.1), being taken at points of interest along the landward extensions of beach transects. The estuary sampling arrangement is also subjective (Fig. 5.2a) both in the

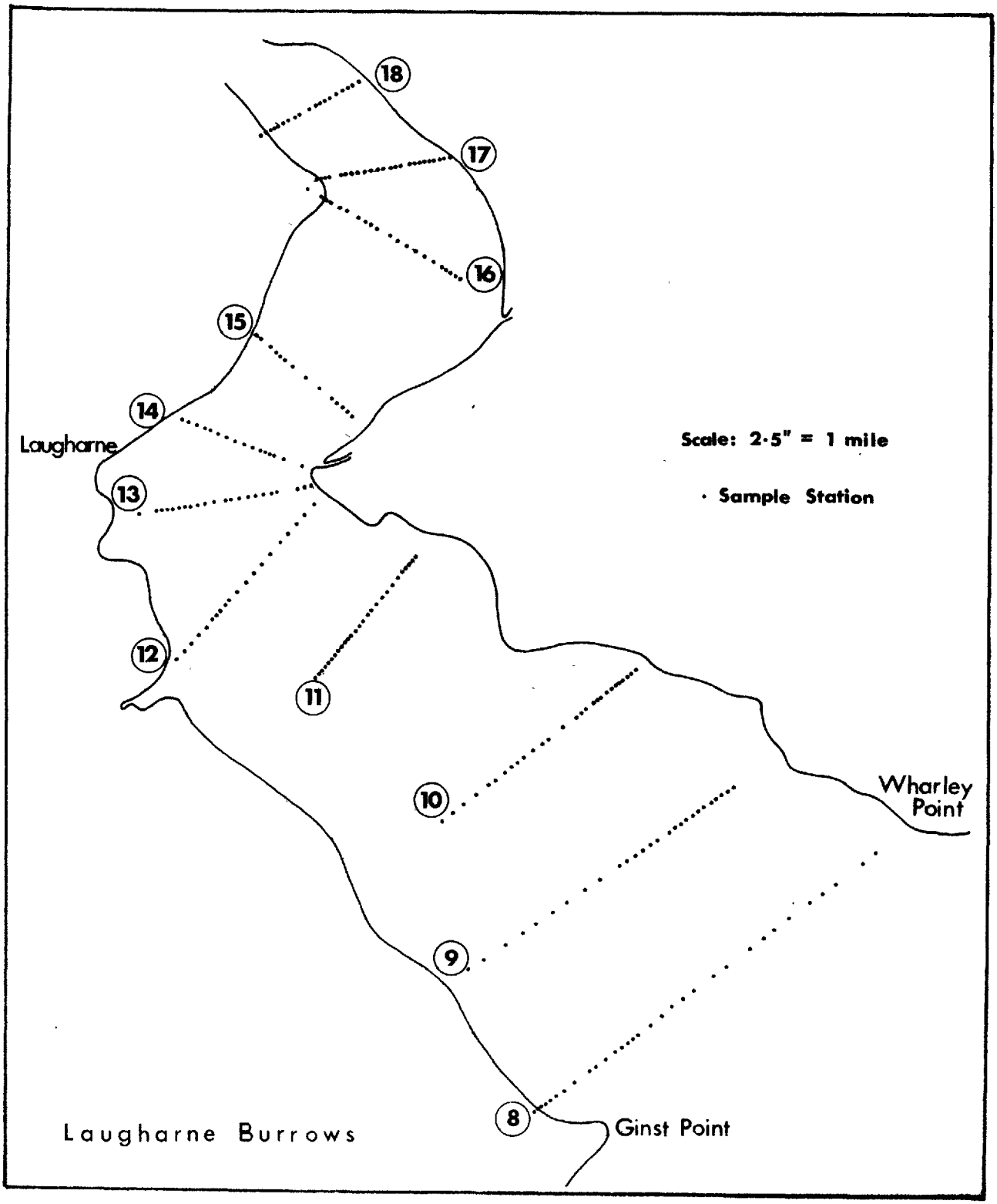


FIG. 5.2a: ESTUARY SAMPLING STATIONS.

positions of the transects and in the sampling stations along the transects; stations were determined by changes in slope and changes in surface features. Hence for these sediments, as above, quite valid estimates of the sampled population characteristics can be made, but inferences from sampled to target population will be biased, even more so than for the beach sediments. A few river samples and shallow-water samples from Carmarthen Bay were also taken (Fig. 5.2b). These were single spot samples, the former taken with a Van Veen grab, the latter with a Dietz-Lafond snapper grab. They are not composite samples*, so that no deductions can be made from sample to sampled population or to the target population.

5.2 Sample Preparation

The absence of silt and clay-sized sediment in the beach samples greatly facilitated their treatment for analysis. Salt was thoroughly washed from each sample with distilled water prior to drying; this virtually eliminated the problem of aggregates. Gravel, of which there was very little, was removed from the bulk sample by sieving, and the sand residue split into suitable aliquots for size analysis using a simple rotary-type splitter.

The size of split suitable for size analysis by sieving falls somewhere between an upper limit beyond which individual screens become choked so that some grains fail to make contact with the

* i.e. they are not composites of four closely spaced subsamples.

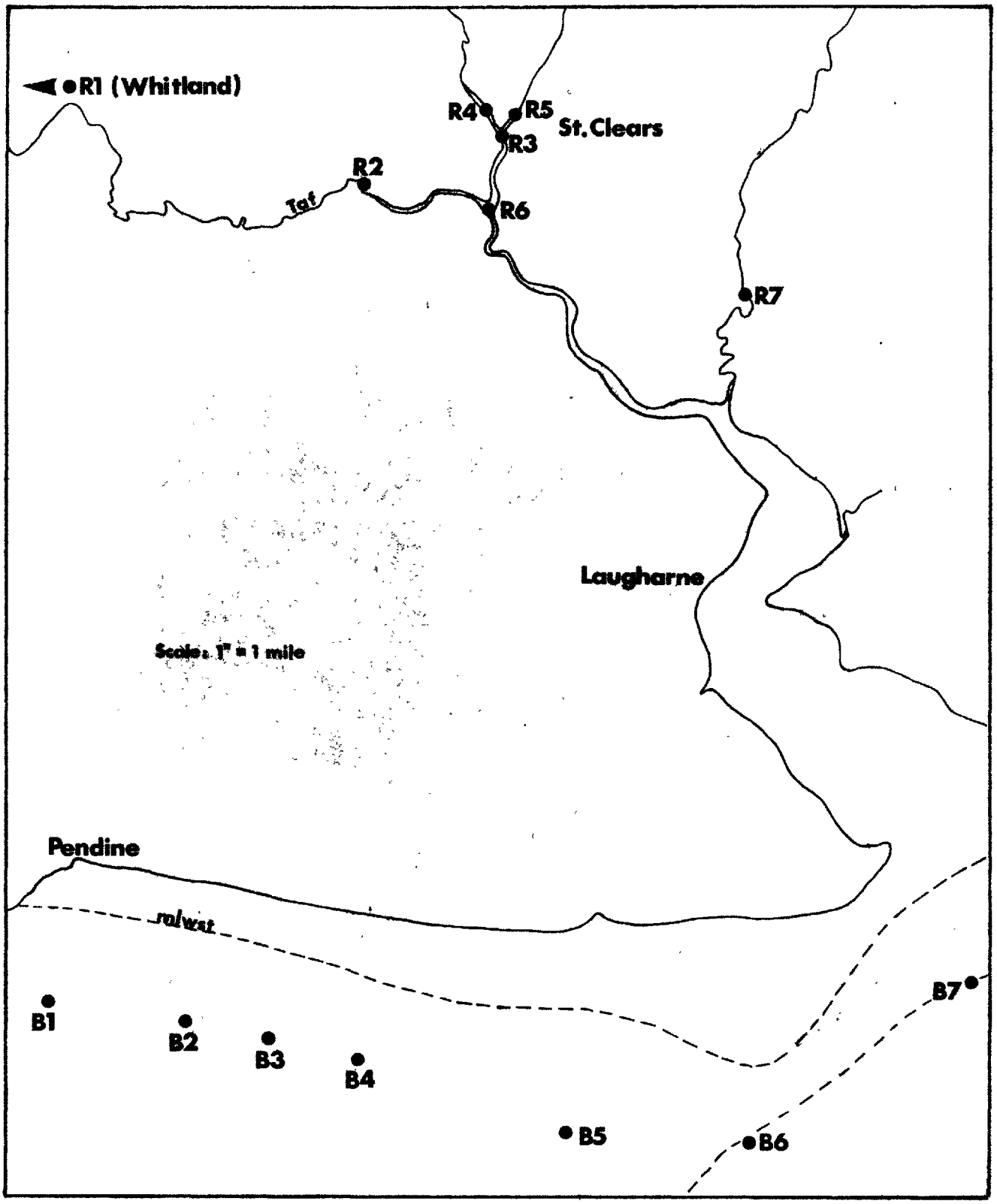


FIG. 5.2b: RIVER AND BAY SAMPLE STATIONS.

mesh, and a lower limit below which the split is no longer representative of the bulk sample. Griffiths (1967) recommends 100 to 150 g. for the average sedimentary sample; Rogers (1959) recommends 30 to 50 g. for most sands, 100 to 200 g. for coarse material. Obviously the degree of sorting of the sediment will determine the proportion of grains falling on each screen, so that relatively large samples can be accommodated if their sorting is poor, but the sample size will need to be reduced if sorting is good. Mason and Folk (1958) report that with well-sorted sands, samples weighing 50 - 60 g. gave a phi diameter consistently 0.05 phi units coarser than when replicate samples of 30 - 35 g. were used. Preliminary examination of the beach sediments in this study showed that a sample size of 25 - 35 g. gave the most consistent results; hence the total sieved sample weight was maintained between these limits, and the splitting procedure arranged so as to give splits of this weight. Although widely used as a measurement of grain size, lack of standardisation in the procedure of the sieving technique would seem to reduce its usefulness for comparative purposes, especially in measures of skewness and kurtosis, very sensitive parameters which are greatly affected by changes in the tails of the grain-size distribution. For meaningful distinctions of depositional environments by size analysis, Rogers (1965) has estimated that phi skewness (Sk_I in the system of Folk and Ward, 1957) should be measured to an accuracy of $\pm$ 0.1 ϕ units, phi mean to $\pm$ 0.1 ϕ units,

and phi standard deviation to $\pm$ 0.2 ϕ units. Obviously this stringent degree of precision cannot be achieved if the sieve analysis does not reproduce the size distribution of the sediment because the sample size is either too large or too small.

Sandy estuarine samples were washed and split in the same manner as the beach samples. Those samples containing material finer than 62.5 microns were first washed through a 240 sieve, and the sandy residue split as usual. If silt and clay-sized material was present in appreciable quantities, the sample was first wet split to a manageable fraction, then the fine material washed out with salt water. The sandy residue was rewashed in fresh and distilled water, dried and split if necessary; the fine material was allowed to settle out in a large, shallow container (the time for complete settlement being just a few hours because of flocculation in the salt water); the salt water could then be easily poured off and the fine material rewashed several times in distilled water in a centrifuge. It was found that the use of salt water (sea water) for wet sieving greatly reduced the time of sample preparation since the very quick settlement of flocculated particles meant that the inevitably large quantity of water associated with wet sieving could be poured off immediately; this eliminated the usually endless task of concentrating a large volume of muddy water by centrifuging.

After several washings in distilled water, a peptiser was

added to the sample. Several peptisers, sodium carbonate, sodium oxalate, ammonium hydroxide and sodium hexametaphosphate (Calgon) were tried and their relative dispersive efficiencies compared; for these sediments the latter, sodium hexametaphosphate (3.06 gm. litre^{-1}) gave the best results and was used in this concentration throughout. The sediment sample was added to about 200 ml. of peptiser solution and strongly agitated on a mechanical shaker for several hours, then topped up to 1 litre and placed in a constant temperature tank ready for pipette analysis. The material in the cylinder was allowed to stand a day, then efficiency of dispersion was gauged by checking for Brownian movement under a high powered microscope.

5.3 Sample Analysis

The grain-size distributions of the sand-sized fractions were studied by means of the technique of sieving. Although many experimental errors enter into this procedure, most of these are easily removed by careful analysis, but some difficulties are inherent in the technique and cannot be overcome. Sieving involves linear measurements which can be considered as only approximations to the true grain size (which is the volume); whether or not a grain passes a particular screen seems to be dependent on its intermediate diameter, though the diameters of grains on any screen show a considerable range in intermediate diameters

(Rittenhouse, 1943). In addition, the size measurement obtained includes variation in three interdependent interacting variables, the grain mineralogy, size and shape, since $P = f(m,s,sh)$ (Griffiths, 1967), which cannot be evaluated independently to arrive at a correction factor. Hence, size of oddly-shaped (micas, shelly material) higher density (heavy minerals) and higher porosity (skeletal fragments) grains is not truly recorded in hydraulic terms, so that distributions represented are somewhat artificial in the case of polycomponent mixtures, though yielding meaningful comparisons when the analytical technique is suitably standardised. Nevertheless, sieving has considerable advantages over alternative techniques.

Settling methods also give an indirect measurement of size but are very rapid in use; advantages are that such methods measure a more realistic hydraulic size value for polycomponent mixtures and the speed of operation allows for replication of measurements, so improving statistical control. However, errors within the technique lead to valueless estimates of skewness and kurtosis (Folk, 1962).

Another technique, that of grain counting in thin-section has considerable advantages for measurement of cemented grains since disaggregation is unnecessary, but is tedious and slow in operation and inaccurate for estimation of skewness and kurtosis (Friedman, 1962a), probably because of the small number of grains counted.

A further technique, that of measurement in loose grains, summarised by Griffiths (1967) holds promising possibilities in that it concentrates on grains of uniform mineralogy, usually quartz but, because of the small number of grains counted, obviously involves renewed difficulties of sampling.

Hence, for the present, sieving would seem to be the most useful technique for size analysis, despite its errors.

Samples, after splitting, were sieved in the conventional manner, described by Krumbein and Pettijohn (1938) and Folk (1968). Each sample was run through two stacks of 8 inch British Standard sieves, at nominally quarter phi intervals, which recalibrated had the following apertures: 2.05 mm. (-1.03 Ø units), 1.65 mm. (-0.73 Ø units), 1.37 mm. (-0.47 Ø units), 1.19 mm. (-0.25 Ø units), 1.00 mm. (0.00 Ø units), 0.85 mm. (0.24 Ø units), 0.74 mm. (o.48 Ø units), 0.62 mm. (0.72 Ø units), 0.50 mm. (1.01 Ø units), 0.41 mm. (1.32 Ø units), 0.36 mm. (1.49 Ø units), 0.30 mm. (1.74 Ø units), 0.26 mm. (1.98 Ø units), 0.216 mm. (2.22 Ø units), 0.177 mm. (2.50 Ø units), 0.150 mm. (2.74 Ø units), 0.124 mm. (3.02 Ø units), 0.108 mm. (3.21 Ø units), 0.094 mm. (3.42 Ø units), 0.079 mm. (3.67 Ø units), 0.062 mm. (4.02 Ø units). Each fraction was weighed to 0.001 g.

Shaking was performed by an Endecott mechanical shaker, which includes a jarring vertical action as well as horizontal, demonstrated by Swineford and Swineford (1946) as the most efficient.

The shaking interval is based on a compromise aimed at avoiding excessive wear of sieve mesh, disintegration of less durable grains and wedging of grains between the sieve openings (which decreases efficiency of screening) on the one hand, and completeness of separation, which follows the law of diminishing returns, on the other. In his investigation of the accuracy of sieving analysis, Mizutani (1963) considered a sieving time of 35 minutes sufficient to give accurate results, but he used very large sample sizes of 80 - 200 g.; most workers, using sample sizes of less than 50 g., have adopted a sieving time of 15 minutes as standard procedure (Folk, 1968). A few preliminary runs showed that this gave consistent results when the same sample was re-run several times, and so throughout this investigation, the sieving time has been kept constant at 15 minutes.

After weighing, each sieve fraction was examined under a binocular microscope and the percentage of aggregates estimated and deducted. As long as the pre-sieving procedure outlined above was adhered to, aggregates were virtually non-existent. However, if for any reason a sample was oven-dried before de-salting, then aggregates became significantly abundant, even though the sample was washed several times after drying (in such samples, which were dried and then split before washing, the splitting error also increased, see below). Accordingly, early on in the investigation, the pre-sieving procedure outlined above was fixed and adhered to.

Several workers, notably Folk (Folk and Ward, 1957) have emphasised the importance of deducting aggregates from the coarser sieve fractions since they can noticeably affect the coarse tail of the distribution. But it is surely equally important to add the individual grains of the aggregates to the size fractions from which they were originally derived, which would probably in turn affect the fine tail; though this would involve practical difficulties. Aggregates, as used here, refers to clusters of grains held together by a weak cement or salt, which may reflect their condition at the place of deposition and/or the technique of sample preparation. In addition there are 'aggregates' which may not be affected by laboratory procedure; these include worm tubes and grains trapped within shell fragments and organisms. It is a mute point whether such aggregates should be removed from, or included in, the analysis, a problem which did not arise in the present study, though common enough in studies of sub-marine sediments.

Inevitably, during sieving, some material is lost, either by escaping as dust or by sticking to the screens. In calculating size distributions, no assumptions have been made concerning the lost material, but the recovered material has been reconsidered as 100% of the sediment. Throughout, sieving loss does not exceed 0.3 - 0.6%, and it is considered by the writer that it would be prohibitively time consuming to reduce this error further.

The silt and clay-sized sediment, after separation from the

sand followed by dispersion as described, was analysed by means of the pipette sedimentation technique. Many of the disadvantages relating to sieve analysis apply also to this technique, though it is probable that the analysis by sedimentation gives a truer picture of the hydrodynamic size relationships. However, it is impossible to derive the size distribution of a fine grained grained sediment as it exists at the place of deposition because of the fluctuating property of flocculation; the distribution of floccule sizes changes as soon as the sediment is sampled. Furthermore, it is very difficult to achieve perfect dispersion of the individual grains for analysis. Thus the size measurement rarely, if ever, reflects the size of the particles as originally deposited or as they exist in the sample before treatment. The analysis has been rigorously standardised during this study to ensure that, in spite of these limitations, the results may be applied to compare the grain sizes of different samples, though as with sieving, the sizes measured are reflections of complex interactions between mineralogy, size and shape. The principles and limitations of pipette analysis are fully treated in Krumbein and Pettijohn, (1938); the practical details of application as used here follow the suggestions of Folk (1968).

Because coarse particles create turbulence during settling, only grains smaller than 62.5 microns have been analysed by sedimentation. The smallest size measured was 0.98 microns, since

below this size it is probable that settling velocity is greatly affected by the flaky shapes of the particles, degree of dispersion and electrical charges on the particles. The analysis was carried out at 32°C in a constant temperature tank; settling times were computed using Stokes' Law. Aliquots of 20 ml. drawn from the settling cylinders (1 litre) were dehydrated for 24 hours at 200°C, then cooled in a dessicator before weighing.*

5.4 Sampling and Analytical Errors

The estimation of errors inherent in grain size analysis has been considered by Krumbein (1934), Griffiths (1953), and Folk (1955); accordingly it was deemed unnecessary to quantify the errors here, since the procedures adopted for sampling and analysis are the same as tested by these writers. It is generally agreed that the highest reproducibility is obtained by the same operator using a standardised procedure and the same apparatus; mean size is probably reproducible to 0.05 phi units and standard deviation to within 0.05 phi units for sands. Different investigators using a standard method but different apparatus should achieve a mean size reproducible to within 0.1 - 0.2 phi units and standard deviations to within 0.1 - 0.2 phi units (Rogers, 1965).

However, an acceptable degree of precision does not necessarily imply a corresponding degree of accuracy. Bias introduced at any stage of the analysis must be recognised, and, as far as possible,

corrected. The amount of error that can be tolerated is obviously dependent on the precision and accuracy of the technique, but is determined by the purpose of the experiment. Hence if a gravel is to be compared with a fine sand, a larger error is acceptable than if two fine sands are to be compared. The error, or variation, introduced by analytical technique must be considered in the light of the variation among samples. If the variation within the technique is greater than that among samples, the analysis is useless and any interpretation meaningless.

There are many sources of error in grain-size analysis, but the following items were specifically cited by Krumbein (1934):

1. Sampling variation, a function of
   (a) Homogeneity of the sediment.
   (b) Locality of the collected samples.
   (c) Type of sample (e.g. one phase, composite).
2. Laboratory variation, a function of
   (a) Subsampling variation (e.g. sample splitting).
   (b) Sieving error.
   (c) Drawing of curves, computation etc.

The type of sample collected, a composite channel sample, has been discussed above. Certain a priori assumptions were made on the probable magnitude of variation within such a sample based on the recommendation of Krumbein (1934). However, the variation among the four samples making up the one composite sample has been

compared with the variation amongst subsamples (splits) and the variation added by the sieving process; these sampling and laboratory errors have been related to the amount of variation between successive sampling points. This is achieved using a multivariate analysis of variance based on a model introduced by Krumbein and Tukey (1956) for use in another context. The design may be considered as a two-way factorial in which one factor represents a nested grouping of sampling, splitting and sieving effects, and the other represents percentage proportions (by weight) of successive sieve fractions (see Table 5.1).

Three adjacent beach sampling positions were chosen such that the textures of this group of samples showed the greatest homogeneity of any comparable group of samples collected in the main sediment survey (this analysis being performed after that survey); in other words, these samples were chosen because they constituted a group with the least among-sample variation. As at all sampling positions, four samples were collected from each, but were not amalgamated; each of the four samples was subdivided into six splits, and each of three randomly chosen splits sieved three times.

Sieving was done in the normal way, with screens at one quarter phi intervals. Since a computer was not available, in order to minimise the quantity of computation successive screen weights were lumped together, then converted to percentages, for the size

ranges less than 2.0 ∅ units, 2.0 - 2.5 ∅ units, 2.5 - 3.0 ∅ units, 3.0 - 3.5 ∅ units, greater than 3.5 ∅ units (with the appropriate modifications due to the screen recalibrations described above). This procedure thus involved a loss of information, but not of precision, and included all grain sizes.

The design, shown in Table 5.1, therefore included 3 sampling positions, 4 samples per position, 3 splits per sample, 3 sievings per split (hence totalling 108 separate sievings) with 5 size classes per replication.

The computations were set up to partition the total sum of squares into nine portions, one of which was attributable to size constituents, one to each nested level of sampling and treatment, and one to each interaction : The raw percentage data was first transformed by the arc sine square root transformation; this comes close to making equal scale changes of equal geological importance, making the change from 50 to 55 percent much less important than a change from 5 to 10 percent, but still more important than a change from 5 to 6 percent (Krumbein and Tukey, 1956). This is particularly valuable for treatment of the present data in which the tails of the distribution are of paramount importance. The data here represents all of the distribution, and the analysis is perhaps more useful than one considering merely variation among medians or even means or higher moments (see below).

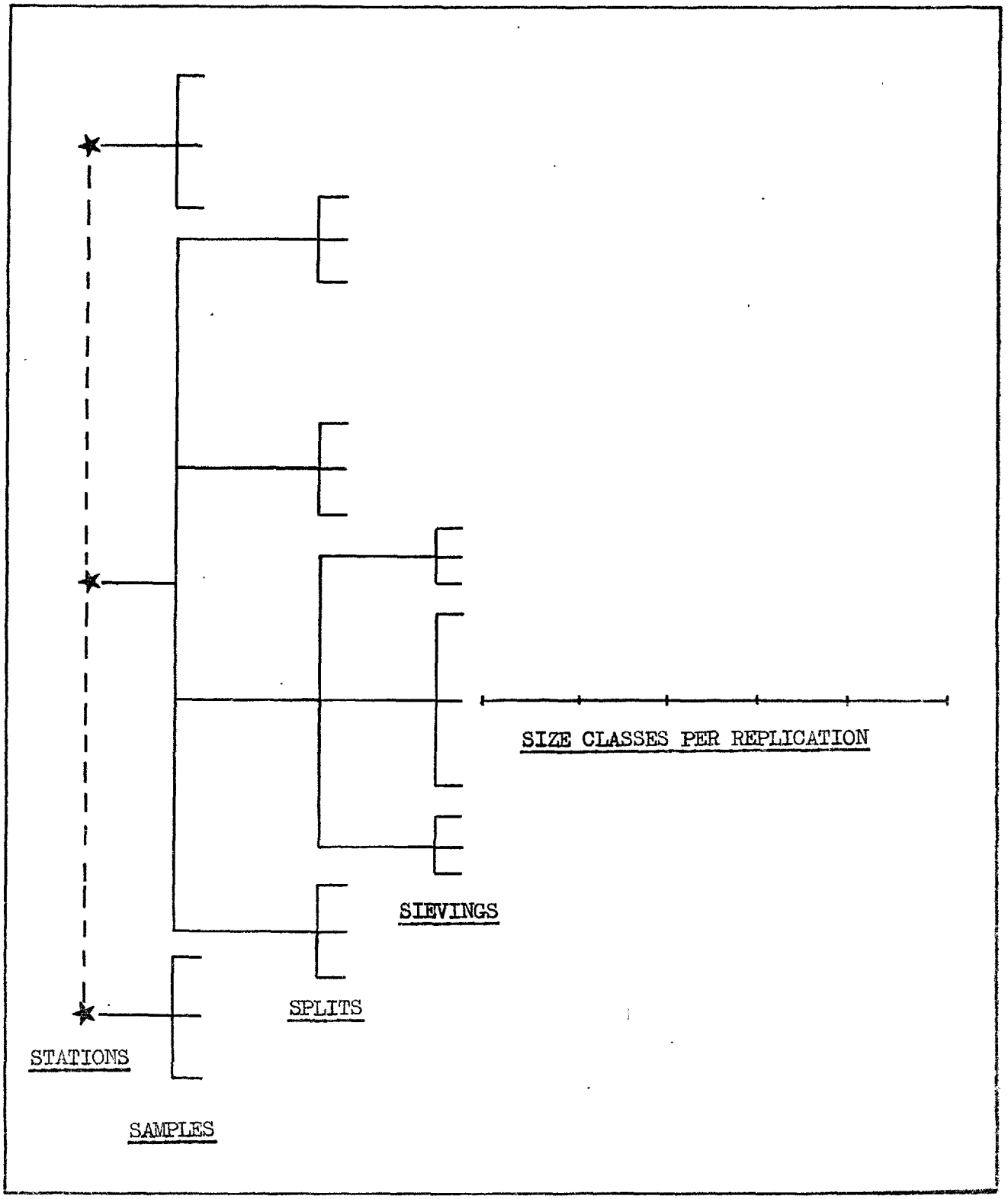


TABLE 5.1: DESIGN OF MULTIVARIATE ANALYSIS.

The completed analysis of variance is shown in Table 5.2. The F tests indicate a significantly greater variation between sampling stations than among the group of samples at each station; there is further a significantly greater variation between samples than among subsplits of those samples. There is no significantly greater variation between splits than among successive sievings of each split.

Source	Sum of Squares	d.f.	Mean Square	F
Between stations	109.34	2	(54.670)	
Between samples within stations	.77	9	(.086)	
Between splits within samples	.61	24	(.025)	
Between sievings within splits	1.76	72	(.024)	
Between screens	150,786.07	4	(37,696.518)	
Stations x screens interaction	6,522.27	8	815.284	2079.81***
Samples x screens interaction	14.12	36	.392	5.09**
Splits x screens interaction	7.36	96	.077	.21ns
Sievings x screens interaction	106.71	288	.371	
Total	157,549.01	539		

* = $0.05 > P > 0.01$ ** = $0.01 > P > 0.001$ *** = $P < 0.001$

TABLE 5.2 : Analysis of Variance of Sampling and Analytical Errors

Thus it is apparent that sampling and experimental error (for these three sampling stations) is significantly less than the variation between stations. Each sample of the four taken at each station is a random sample at that station; the analysis shows that the variation among random samples is significantly less than that between stations, and as has been stated above, combining of four random samples into one composite reduces sampling error even further, approximately by half. Hence when interpreting the variation between sampling stations, the contribution of a sampling error can be ignored. Combining of samples does not affect the magnitude of laboratory errors, but these have been shown to be significantly less than random sampling error anyway, and so significantly less than composite sampling error. Surprisingly, splitting does not introduce any significant added variation to the variation due to sieving; of the analytical procedures, sieving contributes most variation (error). It should be pointed out that preliminary, but not tested, data suggests that splitting becomes an important source of error when carried out on samples that have not been previously desalted.

An alternative model for such an analysis of errors is one used by Kelley and McManus (1970). This is a univariate design involving a similarly nested arrangement but using graphically determined parameters rather than weight percentages falling on successive screens; a separate analysis is performed for each

factor, such as mean, skewness etc. If one assumes that these parameters have a geologically meaningful correspondence to the grain-size distribution, then this approach is of course useful. However, in the present case, no such assumptions have been made, since one of the aims of the study has been to test to what extent, if any, such parameters can be applied to the interpretation of these sediments. So the raw percentages of screen weights have been used here. Of course it is assumed that these percentages have a meaningful correspondence to the grain-size distribution, i.e. it is assumed that a meaningful measurement of size is obtained by sieving. As has been pointed out above this is a tenuous assumption for complex polycomponent mixtures, though these sediments are more homogeneous than most, being predominantly quartz. Unfortunately, at present, there is no simple improvement on this assumption. Furthermore, it is assumed that the conclusions based on comparison of just three sampling stations can be applied to all other stations, a somewhat extreme extrapolation. However, this test was a posteriori and applied to three samples known to be more uniform in size characteristics than any other set of adjacent samples from the foreshore. Thus since the between-sampling station variation for these three samples is a minimum, the analytical variation achieves greater comparative importance for these three than for any others.

Sediments in which the silt and clay-sized fractions are

predominant make up a small proportion of the sediments studied, and so no comparable investigation of errors due to sampling, splitting, dispersion and analysis by pipette sedimentation has been attempted.

5.5 Graphical Expression of Data

The weights of the screen fractions were cumulated and percentages computed as usual, using a 'splitting factor' (Folk, 1968) to incorporate any gravel fractions; the data from pipette analyses were incorporated where appropriate.

Cumulative percentages were then plotted against phi diameter on arithmetic probability paper. Folk (1955) has shown that a substantial part of the total analytical error is in the drawing of curves, if an arithmetic ordinate is employed. However, this error becomes negligible for curves drawn with a probability ordinate since interpolation between data points is less subjective and reflects the sample characteristics rather than the skill of the draughtsman. Accordingly, all curve parameters can be read to the nearest 0.01 ϕ units.

The log transformation introduced by Krumbein (1938) in which $d = 2^{-\phi}$ ($\log d = -\phi \log 2$) has been used throughout, partly because of its advantages in statistical treatment but also because the log-normal law seems more suited to sediment size-distributions than the arithmetic-normal (see discussion below).

Data points have been joined with a curved line, no attempt being made to smooth out the graph. Since the use of cumulative curves involves a tacit acceptance that the distribution under consideration is a continuous one (Krumbein, 1934) the practice of joining data points with straight lines seems somewhat unfortunate, although of course a continuous scale remains a conceptual ideal rather than a practical achievement since any scale must be discrete at some finite level of subdivision. At the same time, inflexion points can often be more easily recognised on curves for which data points have been joined with straight lines.

Histograms are not used here, since their shapes vary with the grade scale used (Krumbein, 1934) and imply discrete series in the sharp breaks between classes. Nevertheless, histograms do have considerable advantages for pictorial comparisons between sediment distributions, advantages shared by frequency curves. The frequency curve in effect represents a smoothed histogram and is independent of the grade scale; also it is more suitable for the description of continuous distributions. However, it was found that frequency curves failed to show the small differences between adjacent samples that became apparent in the subsequent graphical dissection of the cumulative probability curves (see below); for these reasons, neither histograms nor frequency curves are used here.

5.6 The Normal Size-Distribution

It is well known that the grain-size distribution is generally approximately either Gaussian or lognormal, though the geological reasons for, and implications of, this phenomenon are hardly understood. Since the grain-size distribution of a sediment is dependent on a number of interrelated influences it is remarkable that many sediments should have generally similar size-distributions approaching or achieving normality. It seems feasible that one or two factors imprint normality on the size-distributions and other, less dominant, factors produce minor alterations, adding to or subtracting from the original design. If sand is assumed to be the product of multiple abrasion, then as shown by Epstein (1947), removal of random increments from material of finite size will produce an asymptotically lognormal particulate distribution, though such an interpretation has been questioned by Middleton (1962). It is persuasively argued by Rogers, Kreuger and Krog (1963) that a lognormal distribution will be produced by such a breakage mechanism if the size of abraded material is appreciably affected by the abrasion process and if the abraded material is included in the final distribution measurement. On the other hand, if a grain being abraded is essentially of infinite size by comparison with the chips being produced, if the sizes of chips are random and if the remnant source material is excluded from the final size distribution measurement, then the chips should have a

Gaussian distribution. This distinction between a lognormal and a Gaussian function is important in the light of the observation that while the size distribution of a typical sand is approximately lognormal (Krumbein, 1938), the size distributions of many silts and fine sands are approximately Gaussian (Doeglas, 1946). This accords with the experiments on quartz sand abrasion by Kuenen (1959) which show that abrasion of particles below 2mm. is minimal, and supports the view that sand and silt are derived from a common source but by different mechanisms. Furthermore, Krumbein and Tisdel (1940) have shown that naturally weathered materials follow a Rosin-Rammler size distribution, a distribution that should result from ideal single-stage crushing of a homogeneous material (Bennett, 1936). This has led to the interesting proposition that sediments can be divided into three populations on the basis of their size range (Rogers and Schubert, 1963); coarse materials (Rosin-Rammler), sand (lognormal) and silt (Gaussian).

These considerations would seem to lead to the conclusion that the property of normality in the size distributions of sands and silts is in itself not an indicator of the process of deposition and cannot be used to differentiate between environments of deposition.

It has been shown (Aitchison and Brown, 1957) that lognormal distributions can be interpreted as resulting from the action of a random combination of processes. Thus the presence of a lognormal

distribution in a sediment is an indication of the absence of non-random combinations of geological processes, perhaps the result of random abrasion followed by transportation and deposition in a medium having random current fluctuations.

However, in apparent contradiction to the foregoing, it has frequently been reported that natural sediment size distributions are not truly normal, but merely approximate to normality. This might suggest that the abrasion hypothesis is incorrect, or that further factors are superimposed on the abrasion process; such factors would be related to transportation and deposition, i.e. to sorting. Hence non-normal sediment distributions may be the result of non-random progressive sorting processes overriding the results of abrasion. Obviously sorting cannot in any way affect the size distribution of all sedimentary material from any one source, if that material is considered in its entirety, since sorting does not produce grains but merely moves them around differentially. However, the essential property of sorting is that it is selective, moving some grains in preference to others, so that there is little point in considering sedimentary material as an homogeneous unit from source to final deposition. While sorting may be random in relation to the whole of the sedimentary material (since 'randomness' is not synonymous with 'lack of control'), it will, by definition, be selective and non-random at any one point in space and time. At the moment of deposition, grains are

not in equilibrium with the transporting medium. Hence a normal distribution of grains in suspension can retain its normality only so long as all of the grains are deposited; this will generally mean that, for the grains to remain in equilibrium with the transporting medium, this must come to rest. In most cases, however, since flow will not cease, all of the grains will not be deposited and the normal distribution will be lost. Part, or all, of these deposited grains can be subsequently resuspended, mixing with already suspended grains with which they have had no previous relation. Thus with continuing truncation and mixing of grain size distributions, at any one point of deposition the sediment may be expected to show a size distribution differing considerably from the original lognormal one. Hence the form of size distribution, whether lognormal or not, derived from the source by abrasion mechanisms, is certain to be greatly modified during transport and deposition, and would seem unlikely to retain any indication of that distribution. If the total grain population is considered as an entity from source to deposition i.e. if the abrasion mechanism is considered to operate within a closed system, then the final population might be a lognormal derivative of the original. But since the effect of progressive sorting is to remove some grains and add others from perhaps another source or dynamic regime, then it is difficult to predict what form the final population might take. One parent lognormal distribution cannot produce a number

of lognormal offspring without at the same time producing a residue of a very strange distribution, since lognormal distributions are not simply additive (Aitchison and Brown, 1957). Therefore at this point, the conclusion must be that most grain size distributions should not be lognormal at all.

However, most of them somehow do retain their normal or log-normal character to a greater or lesser degree. This can only be so if the process of sorting itself is 'normal-selective', in spite of the apparent contradiction that a non-random and selective process can produce a distribution considered to be the result of random, non-selective processes.

The importance of sorting on grain size distributions was first recognised by Doeglas (1946) who suggested that those distributions which deviated from normality were in fact bimodal or trimodal mixtures of two or more populations, each produced by a particular transport condition. Tanner, in a succession of papers (1958, 1959, 1964) has subsequently shown that the three subpopulations designated by Doeglas can be obtained by suitable manipulation of normal distributions, and that most sediment size distributions are in fact composed of mixed and truncated normal subpopulations. Fuller (1961, 1962) has also distinguished three subpopulations, and ascribed them to entrainment by the three forms of fluid transport described by Inman (1949) i.e. surface creep, saltation and suspension. In a similar manner, Spencer (1963) has suggested

that all clastic sediments are mixtures of three or less lognormally distributed populations, and that sorting is a measure of the mixing of these populations, conclusions deriving from the classic paper of Folk and Ward (1957). Using the same data as Spencer, by means of factor analysis, Klovan (1966) found the degree of mixing of the subpopulations to be environment-sensitive.

Of fundamental importance to the understanding of sorting in clastic sediments are the two papers of Moss (1962, 1963) in which the close interdependence of surface creep, saltation and suspension in any sediment is rigorously examined. These terms refer to dynamic regimes rather than to grain populations, and the same grain can move into more than one regime under certain conditions, this depending on its relationship to the rest of the grain population. Nevertheless, within limits, a particular range of grain sizes is associated with each regime (gravel, coarse sand/surface creep, medium and fine sand/saltation, silt and clay sized/suspension) and it is the grain size population which controls the behaviour of any single grain. It might be tentatively suggested that within the limits of each regime, the sorting process can be considered as quite random; grains moving within the saltation population do so in a random manner, some joining and others leaving in a continuous process of selection. The population is subject to a random combination of processes even though it may remain stable and the distribution of grain sizes be constant.

If the dynamic equilibrium is examined at any one moment, as at sampling or when the transporting current ceases abruptly, then a randomly-produced lognormal distribution will be encountered. Also since any one population will tend to move throughout its transporting history as a dynamic unit e.g. in saltation (even though individual grains may be added or removed), then the mechanism of abrasion will be able to operate within a 'closed' system during that time. It is noteworthy that crushing produces gravel which moves by surface creep, abrasion produces sand moving by saltation, and chipping produces silt and clay moving in suspension; this is very much an oversimplification and not always true, but the interrelationships of abrasion/grain size/transporting mechanism are too striking to be ignored.

Unfortunately, at present, the generation of grain size distributions can be considered by deduction only, since experimental evidence is conspicuously lacking. The genetic property of lognormality can be understood mathematically in terms of abrasive processes, but it is very difficult to simulate these processes in the laboratory. The nature of laminar and turbulent flow can be adequately described by Stokes' Law and the Impact Law, but the transition region of saltation is not readily understood. And there is no uniform method of size analysis which covers the complete spectrum of grain sizes and it seems likely that apparent differences in the types of size distributions in different size

ranges may, in part, reflect the differences in analytical technique, (e.g. the transition from a lognormal to a Gaussian size function in the region of 62.5 microns may be a reflection of the transition from sieve to pipette analysis (Griffiths, 1967)).

In addition to the processes considered so far, other factors may of course affect the size distribution of a clastic sediment. A mathematical explanation of the generally Gaussian distribution of major elements and lognormal distribution of minor elements in rocks has been given by Jizba (1959), though this is unlikely to be reflected in the grain-size distributions of most sediments. Also the addition of biological particles, such as shells and worm tubes, after deposition of the sediment, will modify and mask the original size distribution.

Hence, the grain size distribution of a clastic sediment may be determined by the following factors, modified from Maiklem (1968):

(A) An inherited size distribution dependent on:

1) Distribution of elements and minerals in the source rock.
2) Grain-size distribution of individual minerals in the source rock.
3) Mechanism of size reduction, whether by crushing, abrasion, chipping or chemical disintegration.
4) Relative hardness of each mineral type.

(B) Hydraulic modification dependent on:

1) Method of transportation, whether by surface creep, saltation or suspension.

2) Hydraulic properties of each mineral type, a property of its shape, angularity, density and size.

3) Duration of transport.

4) Competency and capacity of the transporting agency.

5) Rate of supply of material.

6) Mode of deposition.

7) Mixing of populations.

8) Truncation and recycling of populations.

9) Post depositional modifications.

(C) A superimposed modification dependent on:

1) Method of sampling.

2) Method of analysis.

An immature sediment will tend to have an inherited grain-size distribution giving information of its source, whereas a mature sediment will have a modified grain-size distribution, indicating more about the environment of deposition than source, though at what stage an inherited distribution becomes modified by environment to a recognisable degree is difficult to predict. The grain-size distributions of the sediments in this study will be considered as reflections of environment of deposition and not of source, for reasons discussed in Chapter 6. Since the sediments

to be considered are almost entirely medium and fine sands, only lognormal distributions are investigated, though with very well sorted fine sands both lognormal and Gaussian functions seem equally applicable.

5.7

Graphical Dissection of Heterogeneous Distributions

The rationale of treating skewed frequency and cumulative distributions as mixtures of several subpopulations stems from Doeglas (1946) and Folk and Ward (1957); the latter showed that the oft-quoted measures of skewness and kurtosis are sensitive indicators of interaction between these subpopulations.

Numerical methods for the dissection of heterogeneous distributions are available, usually complex and time-consuming, though a simple technique is described by Tanner (1959). The technique used here is graphical and is fully described by Harding (1949), with extensions by Cassie (1950, 1954): each normal curve is fitted by means of its exposed flank, i.e. the part which does not overlap with its neighbour, thus exposing the flank of the next curve, so that the process may be repeated. The selection of points of inflexion on the original cumulative frequency curve is partly subjective, though it is usually possible to place them with some certainty.

Since the technique has not been described in the literature, a brief summary of the steps involved are reproduced here (after

Cassie, 1963). The steps are shown with reference to Table 5.3 and Fig. 5.3:

(1) Compute the cumulative percentage frequencies, p_c, of successive grainsize grades.

(2) Plot p_c on a probability scale against X_ϕ, the class marks of the size grades.

(3) Select points of inflexion by eye; these occur at the percentage frequencies P_{c1}, P_{c2}, P_{c3} (0.5%, 17.5%. 99.8% in this example).

(4) Compute the percentage frequencies, P_1, P_2 and P_3, of the subpopulations, where $P_1 = P_{c1}$, $P_2 = P_{c2} - P_{c1}$, $P_3 = P_{c3} - P_{c2}$ (here $P_1 = 0.5\%$, $P_2 = 17.5\%$, $P_3 = 81.8\%$).

(5) Compute the cumulative percentage frequencies, q_{c1}, of subpopulation 1, where $q_{c1} = p_c \times 100/P_1$.

(6) Fit, by eye, a straight line to the points q_{c1}. The last two points deviate strongly from linearity. This may simply be due to overlap with the next subpopulation. However, after dissecting many curves, it was found that much the best 'fit' is obtained if it assumed that this deviation is due to truncation of the first subpopulation at its fine end - this also makes sense when the hydrodynamic significance of the subpopulations is considered (see following Chapters). Therefore extend straight line to form a curve through these points.

(7) From this curve, estimate and enter Q_{c1}, the 'expected' values of the cumulative frequencies of subpopulation 1.

(8) Recompute these frequencies to give p_{c1}, the expected cumulative frequencies of the parent population that can be attributed to subpopulation 1, where $p_{c1} = Q_{c1} \times P_1/100$.

(9) Compute p_{c-1}, the cumulative frequencies of the parent population after the expected frequencies due to subpopulation 1 have been removed; thus $p_{c-1} = p_c - p_{c1}$. The first few values of p_{c-1} are small and can be ignored.

(10) Compute and plot q_{c2}, the cumulative percentage frequency of the second group (here called subpopulation2A), where $q_{c2} = (p_{c-1} \times 100)/P_2$.

(11) Fit, by eye, a straight line to the points q_{c2}. The last of the plotted points lies off the fitted line, and this is most simply due to mixing between subpopulations 2A and 2B (the latter forms the third group); in this case, there is no need to consider truncation of 2A as the simpler explanation of mixing gives a good fit. This implies, firstly, that the fitting of the third group may be commenced below the point of inflexion, and secondly, that a correction must be made to the first points of the third group.

(12) Accordingly, estimate and enter Q_{c2}, the expected values from the fitted line of the cumulative frequencies of subpopulation 2A.

(13) Compute p_{c2}, the expected cumulative frequencies of the parent population that may be attributed to 2A; $p_{c2} = Q_{c2} \times P_2/100$.

(14) Compute p_{c-2}, the cumulative frequencies of the parent population after subpopulations 1 and 2A have been removed; $p_{c-2} = p_c - (p_{c1} + p_{c2})$. The first few values of p_{c-2} are small and can be ignored. It may be seen that, in this example, overlap between 2A and 2B occurs up to 3.42 ϕ units.

(15) Compute q_{c3}, Q_{c3}, p_{c3} ..... p_{c-4}, following the above steps. The results are shown in Table 5.3.

(16) Finally compute p, the expected values of p_c. These then can be plotted to form the fitted curve (Fig. 5.3). The deviations between observed and expected values $(p - p_c)$ can be calculated; these should be small.

A typical curve for a beach sand is shown in Fig. 5.3, with its dissected components. Components 2A and 2B make up most of the parent population; their means are very close together relative to the spacing of the data points (screen interval) which makes for added difficulty in their separation. In many cases only trial-and-error methods are successful, but the writer has found that the method becomes less time-consuming with practice. The form of mixtures of lognormal distributions has been described, in part, by Tanner (1964) and Irani (1959), and various combinations of components with different means, standard deviations, truncation points, and proportions have been examined by the writer.

		P_{c1}=0.5		P_1=0.5	P_{c2}=18.0		P_2=17.5		P_{c3}=99.8		P_3=81.8		P_4=0.2					
X_ϕ	P_c	q_{c1}	Q_{c1}	P_{c1}	P_{c-1}	q_{c2}	Q_{c2}	P_{c2}	P_{c-2}	q_{c3}	Q_{c3}	P_{c3}	P_{c-3}	q_{c4}	Q_{c4}	P_{c4}	P_{c-4}	P	P - P_c
0.00	.158	31.6	28.5	.143	(.015)													.143	-.015
0.24	.176	35.2	36.8	.189	(-.013)													.189	.013
0.48	.226	45.2	46.0	.230	(-.004)													.230	.004
0.72	.271	54.2	54.8	.274	(-.003)													.274	.003
1.01	.325	65.0	65.6	.328	(-.003)													.328	.003
1.32	.408	81.6	81.6	.408	(.000)													.408	.000
1.49	.483	96.6	96.0	.480	(.003)													.480	-.003
1.74	.73			.500	.23	1.31	1.31	.23	(.00)									.73	.00
1.98	2.33				1.83	10.46	10.20	1.79	(.04)									2.29	-.04
2.22	6.32				5.82	33.14	33.00	5.78	(.04)									6.28	-.04
2.50	15.52				15.02	85.82	64.00	11.20	3.82	4.67	5.00	4.09	(-.27)					15.79	.27
2.74	39.48				38.98		87.48	15.31	23.67	28.92	31.50	25.78	(-2.11)					41.59	2.11
3.02	82.19				81.69		97.60	17.08	64.61	78.95	77.20	63.18	(1.43)					80.76	-1.43
3.21	96.37				95.87		99.60	17.43	78.44	95.85	95.90	78.48	(.04)					96.41	.04
3.42	99.35				98.85		99.94	17.49	81.36	99.42	99.55	81.45	(-.09)					99.44	.09
3.67	99.913				99.413			17.50	81.913			81.80	.113	56.5	56.5	.113	.000	99.913	.00
4.02	99.965				99.465				81.965				.165	82.5	82.5	.165	.000	99.965	.00

TABLE 5.3 : Work sheet for plotting of subpopulations

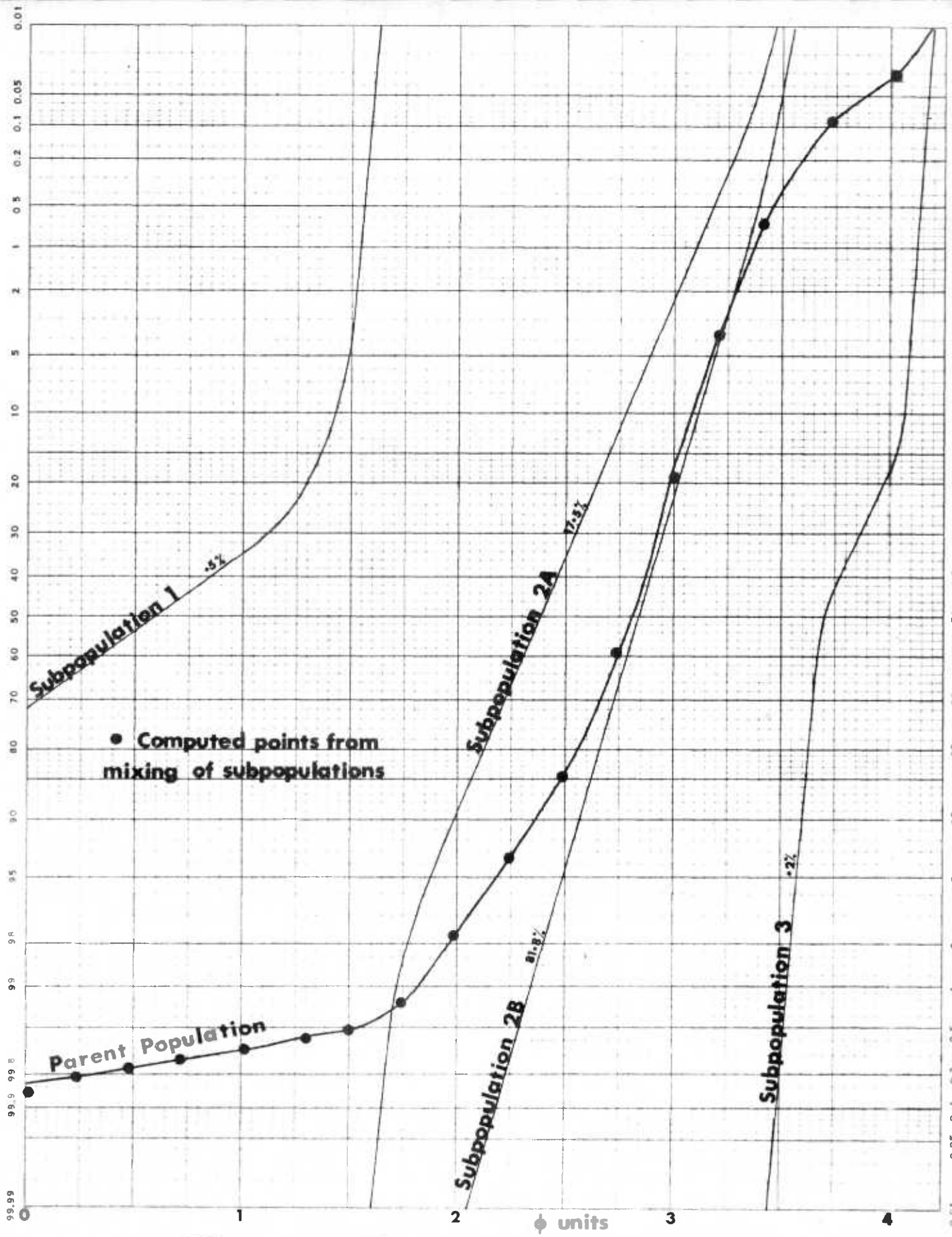


FIG. 5.3 : PARENT POPULATION, SUBPOPULATIONS AND FITTED CURVE.

As shown in Fig. 5.3, population 1 has a mean widely separated from that of population 2A, and so the point of inflexion between them can be readily distinguished. It is evident that in all the samples studied, the fine end of population 1 is truncated; also in most samples, the coarse end of population 2A is truncated. Population 3 is present in very small proportions and is represented generally by two data points only; it is shown here as truncated at both ends of its distribution though in the case of its coarse truncation point this may or may not be so. But because of its small total proportion, the presence or absence of this truncation has no effect on the fitting of the curve.

Since the cumulative curves have been plotted on a probability scale, the accuracy of placing each point of inflexion varies, depending on its position on the scale. For most of the distributions, it is considered that the point of inflexion between populations 1 and 2B can be placed to within 1%, between populations 2A and 2B to within 1 - 5%, and between populations 2B and 3 to within 0.1%.

While it is true that any one heterogeneous distribution may be dissected in a number of different ways, the simplest solution that produces a close fit has been accepted here. In some, even most, cases it is probable that more than four components are present, but because of the closeness of their means these could be dissected with very little accuracy. Population 1 is very

rarely exactly lognormal and one or more additional inflexion points are usually evident, but these are considered to indicate mineralogical components within the main subpopulation since this consists of quartz, lithic fragments and much shelly material.

For this reason, the standard deviation of population 1 is somewhat meaningless and so has not been determined; for all samples it is of the order of 1.5 phi units. The mean size too will be affected by the mixing within the population but is recorded so as to indicate the dynamic process controlling the growth of the population.

By contrast, populations 2A and 2B are composed predominantly of quartz, and approach very closely to lognormality. Population 3 has too few data points for the form of its distribution to manifest itself. Because of the nature of the sampling technique, it is highly improbable that a sample consists of only four components, but because of the closeness of fit to the original distribution achieved by these components it is probable that each component (in particular 2A and 2B) represents a mixutre of populations with near-identical means and near-identical variances.

5.8 Determination of Statistical Parameters

Many attempts to interpret environments of deposition from grain size characteristics have adopted the statistical meaures of moments, eliminating the use of cumulative frequency curves

(Friedman 1962a,b; Griffiths, 1961); others have made use of graphically determined parameters. Such attempts have had mixed success. It would be interesting therefore to examine the variation of these statistical parameters in the light of the sub-population interaction within the parent population.

The parameters may be determined either mathematically using the method of moments (Krumbein and Pettijohn, 1938) or graphically by reading selected percentiles off the cumulative curves. The latter method was used here since it is much quicker and nearly as accurate. Various graphic measures have been proposed (Trask, 1930; Krumbein, 1938; Otto, 1939; Inman, 1952) but those proposed by Folk and Ward (1957) appear to be the most useful and have been used here.

Mean size, M_Z, is determined by the formula

$$M_Z = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

As a measure of sorting, the Inclusive Graphic Standard Deviation is determined by the formula:

$$\sigma_I = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

Inclusive Graphic Skewness is determined by

$$Sk_I = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$$

Kurtosis, or peakedness, of the distribution is determined by

$$K_G = \frac{\emptyset 95 - \emptyset 5}{2.44(\emptyset 75 - \emptyset 25)}$$

Using this equation, normal curves have $K_G = 1.00$ and the distribution of K_G for natural sediments is itself non-normal. Hence, following Folk and Ward, the distribution has been approximately normalised using the transformation

$$K_G^{\,1} = \frac{K_G}{(K_G + 1)}$$

Normal curves then have $K_G^{\,1} = 0.50$.

CHAPTER 6.

BEACH AND DUNE SEDIMENT TEXTURES

6.1 Introduction

Before considering the hydrodynamic significance of the dissected subpopulations in the light of the theory discussed in the previous chapter, it is worthwhile summarising some relevent aspects of nearshore circulation processes and sediment transport and deposition.

The most-used terminology of nearshore current/wave systems was established by Shepard and Inman (1950), who recognised four major subdivisions of a continuous and open dynamic system. These are a zone of shoaling waves, a breaker zone, a surf zone and a swash zone. Schiffman (1965) has added a collision or transition zone to this classification, being the area of intense turbulence formed by backwash and surf collision.

Beaches vary considerably in their characteristics because of variations of aspect and exposure to oceanic conditions, variations of foreshore/inshore slope and variations of tidal range. Because of these factors, the degree of development of some dynamic zones is also highly variable. This applies particularly to the surf zone which may or may not occur depending on the magnitudes of foreshore slope and tidal range (Ingle, 1966).

* As pointed out above, the nearshore zones are here described according to the definitions used by Shepard and Inman (1950), Schiffman (1965) and Ingle (1966).

There is some disagreement as to which dynamic zone plays the dominant role in establishing the foreshore textural gradient (which is itself highly variable, being a seaward fining one on some beaches, seaward-coarsening on others; some examples are given by King, 1972). Model experiments tend to suggest that swash zone transport is the dominant aspect (Saville, 1950) but, as pointed out by Ingle (1966), this may be because scale effects ordinarily do not allow a substantial surf zone to be created in the laboratory. Duncan (1964), however, has studied the considerable influence of swash zone processes in bringing about sand accumulation and erosion; Otvos (1965) and Williams (1971) have emphasised the roles of both swash zone and surf zone processes in creating dual sedimentation units, particularly at mid-tide levels. In these studies, foreshore/inshore slope was considerably greater (up to 10 times) than the slope at Pendine, and tidal range considerably less, or even negligible.

Samples from the foreshore were collected at low tide, so the textural distribution that they present must be related to sorting processes on the ebbing, rather than the flooding, tide. If we consider the variations of nearshore hydrodynamics and sediment transport on an ebbing tide, then the following conclusions may be suggested (taking the nearshore zones and associated hydrodynamic processes in turn):*

(a) Tidal Currents

It has been suggested (Swift, 1970) that the reverse (seaward coarsening) textural gradient of many broad intertidal zones extends out to a nearshore maximum in tidal current velocities (induced by continental shelf shoaling and/or tidal resonance associated with a variable coastline configuration). Such a mechanism necessitates that the textural gradient is established when tidal currents are at a maximum, the lower velocities of the early and late stages of tidal flow being unable to readjust this gradient. Evans (1965) has shown that the reverse textural gradient of the intertidal flats of the enclosed embayment of the Wash can be attributed to the decreasing velocity of the tidal currents as they move onshore; the reduction in the capacity and competency of the tidal flow is presumably a response to bottom friction and water depth.

However, if we consider the effect of tidal currents at a uniform depth on an ebbing tide (and seaward of the breaker zone), then there may be a tendency for a somewhat different sediment pattern to emerge. In a normal tidal environment currents reach a peak mid-way through each flood or ebb phase (Roy, 1967, discusses exceptions to this generalisation). That both competency and capacity of currents are increased by comparatively small increases in velocity is well documented. Thus we may expect that at mid-tide level, there may be increased transport of larger

grains, though the vectors will have a greater component alongshore than normal to the strandline.

The dominance of such a tidal current control of sediment response demands that wave action be a subordinate or negligible process.

(b) Zone of Shoaling Waves

Sorting processes active in the zone of shoaling waves (i.e. seaward of the breaker zone) may be assumed to comply with the arrangement forecast by Cornaglia's (1898) null point theory (Ippen and Eagleson, 1955; Miller and Zeigler, 1958, 1959).

According to Cornaglia, since wave crest velocity is greater than trough velocity in shallow water, there will be a resultant force acting upon sediment particles, tending to move them in the direction of crest movement; the distance moved by the particles will be proportional to the differential of crest and trough velocities. This differential becomes negligible in deeper water, but there, gravity becomes relatively important in moving the particles seaward. At a critical point, all of these forces are equal for any one particular grainsize; this is the null point, where the net motion of a particle of that size is zero (along a line normal to the wave direction). Seaward of this point the net movement is seaward; landward of this point the movement is landward. Particles larger than the critical size move seaward; those finer move in the direction of the crests.

It has been shown by Miller and Zeigler (1958) that, in fact, gravity may not play an important role in establishing the postulated null points. This is illustrated in Fig. 6.0(a). In this example it was assumed by Miller and Zeigler that there are five arbitrary grain-size classes numbered 1 to 5. Thus if beach slope, wave length and height are constant, there will be five null points normal to the shoreface, the finest being seaward, the coarsest nearest land. If the bottom material is initially unsorted, then as the waves begin to transport it, grains finer than a particular null value will move shoreward, accelerating to a maximum velocity just seaward of the breaker point; just shoreward of the breaker point, the velocity of the sediment will drop to zero.

Thus the mean size of the bottom sediment should increase regularly towards the shore; sorting should improve shorewards. Shoreward of the largest null point, where the net sediment velocity drops to zero, the accumulated mass of sediment in transport will be abruptly deposited, so that the sorting at this point should be poor.

Some of the non-equilibrium sediment will be carried further shoreward into the swash zone, and of this some will be returned in the backwash. Other than gravity (which can probably be ignored when the bottom slope is very small), there is no mechanism that allows sediment to return seaward from the breaker zone except at mid-depth (Miller and Zeigler, 1964). This material, in

suspension, will tend to be fine-grained, except during storm periods, and in deeper water will begin to settle out and rejoin the bottom traction carpet; it can then be resorted and moved shorewards according to the null-point hypothesis.

Thus although the null-point model tends to imply a static situation once equilibrium is achieved, in fact there will be a constant movement of sediment at all times, because of the mid-depth seaward drift. Hence the equilibrium is a dynamic one, producing a steady state system. Changes in this equilibrium must also occur at all times in response to changes of wave energy. This will be most apparent during storms when both shoreward and seaward transport must increase, and relatively coarse grains can join the mid-depth drift because of increased turbulence; these grains can then be moved shorewards again during calmer weather.

The effect of the tide on this model must now be considered. The tidal effect was also considered in the study of Miller and Zeigler (1958) : Results were rather inconclusive since, at times, the sediment distribution in the shoaling waves zone conformed to the null-point model but, at others, the actual distribution appeared to be the reverse of that predicted. These inconsistencies may have been caused by factors that were not included in the conceptual model, such as irregular offshore bathymetry.

However, assuming ideally uniform offshore bathymetry and uniform long-term meteorological conditions, the sediment

distribution predicted by the model should be maintained on a rising tide, the seaward fining sequence being progressively transposed shorewards. As the tide rises, any position on the bottom represents progressively smaller null points as the water above it deepens. Thus, for example, the 3 mm. null point will become a 2 mm. null point; this means that all grains finer than 2 mm. are moved shorewards from that point. However, grains finer than 3 mm. are not present in the bed, having been previously moved shoreward. This implies that in fact there should be a discrepancy between the status of the null-point (2 mm.) and the actual grains in the bed (none finer than 3 mm.). This does not in fact appear to happen (Miller and Zeigler, 1958), presumably because of the constant supply of grains, via the seaward mid-depth flow, gravity settling, and shoreward displacement by wave motion. These grains, some of which will be finer than 3 mm., will then be moving shorewards past the position of the new 2 mm. null-point, and some will achieve equilibrium at this position. Because of the constant circulation of sediment, the seaward-fining textural gradient of the shoaling waves zone can be maintained throughout the tidal cycle in this way. Whether or not it can be maintained continuously will depend on the quantitative nature of the sediment circulation pattern, which must be able to supply the requisite grains for equilibrium to be satisfied. In any case, there is likely to be a time lag between the null-point distribution and the establishment of the corresponding textural distribution.

In this study, we are primarily concerned with the textural distribution on the exposed foreshore after the tide has ebbed. If it is assumed, for the moment, that this distribution is the result of deposition in the zone of shoaling waves only (i.e. ignoring the possibility of surf and swash zone deposition), then it is clear that the observed distribution, normal to the strandline, should not describe any trend at all. This is because each part of the foreshore profile will be subjected to an identical progression of sorting processes associated with constantly decreasing water depths. Hence, using the example shown in Fig. 6.0(a), each part of the foreshore profile will represent, in turn, the positions of the 1.0, 2.0, 3.0 and 4.0 mm. null points.

The model of nearshore sorting processes outlined above is applicable only if wave energy remains uniform throughout the tidal cycle. Should this condition be unfulfilled, then the model must be modified. A change of wave energy can occur as a result of changing weather conditions or because of complications of bottom slope. The former is likely at all times and adds a further factor to the continual re-adjustment of the postulated dynamic equilibrium. The latter occurs when the bottom profile does not describe a simple, uniform slope; such a complication arises on most beaches.

On a coastline in which the bottom profile slopes abruptly

into deep water, it is evident that the effect of bottom friction on wave energy will be least at low tide. Off Pendine Sands, however, as shown by the offshore profiles recorded in Chapter 1, the offshore bottom gradient gradually decreases into the bay. In this case, waves will experience the maximum effect of bottom friction, and maximum wave refraction, during low tide when the offshore water depth is at a minimum; for the present, we will consider only the simple bathymetry of the western portion of the study area.

Hence on a rising tide, the wave energy at *any* point in the zone of shoaling waves will progressively increase; conversely, on a falling tide, the wave energy at that point will decrease (the point being considered as fixed relative to the position of the breaker point). This variation of energy will also, of course, be transmitted to the breaker and swash zones.

Such a variation can easily be verified in the field, since on beaches with concave-upwards bottom profiles, waves are higher at high tide than at low tide (as long as meteorological factors do not change).

We must now consider the effect of this wave energy variation on the null-point hypothesis. The position of each null-point is no longer fixed according to water depth; thus the 3 mm. null-point, for example, must occur in deeper water at high stages of the tide than at low stages. This implies that for any given

water depth the corresponding null-point grain size will progressively decrease as the tide ebbs, assuming the ideal conditions of uniform long-term meteorological energy (Fig. 6.0(b)). This can be verified from the curves given by Miller and Zeigler (1958) that describe the relationship between still water depth, grain diameter and wave energy for Cornaglia's null-points.

Therefore, during the tidal cycle, the textural gradient of the bottom sediment, established according to the predicted placing of the null-points, will vary in magnitude, though not in sense. A seaward-fining gradient should occur at all times, but the sediment in the shoreward area of the zone of shoaling waves will be coarser at high tide than at low tide, becoming progressively coarser as the tide rises, finer as it falls; the textural gradient will ensure that sediment texture throughout the zone will change accordingly.

A further result of this tidal variation will be a compensating adjustment of nearshore bottom slope, since the coarser sediment at high tide will produce a steeper equilibrium slope than will the finer sediment at low tide (see Fig. 6.0(b)).

The variation of wave energy will also effect the size of the non-equilibrium sediment supplied to the breaker zone during the tidal cycle. Thus this sediment will be coarser at high water than at low water. This variation of grainsizes available for onshore movement is considered in the following sections.

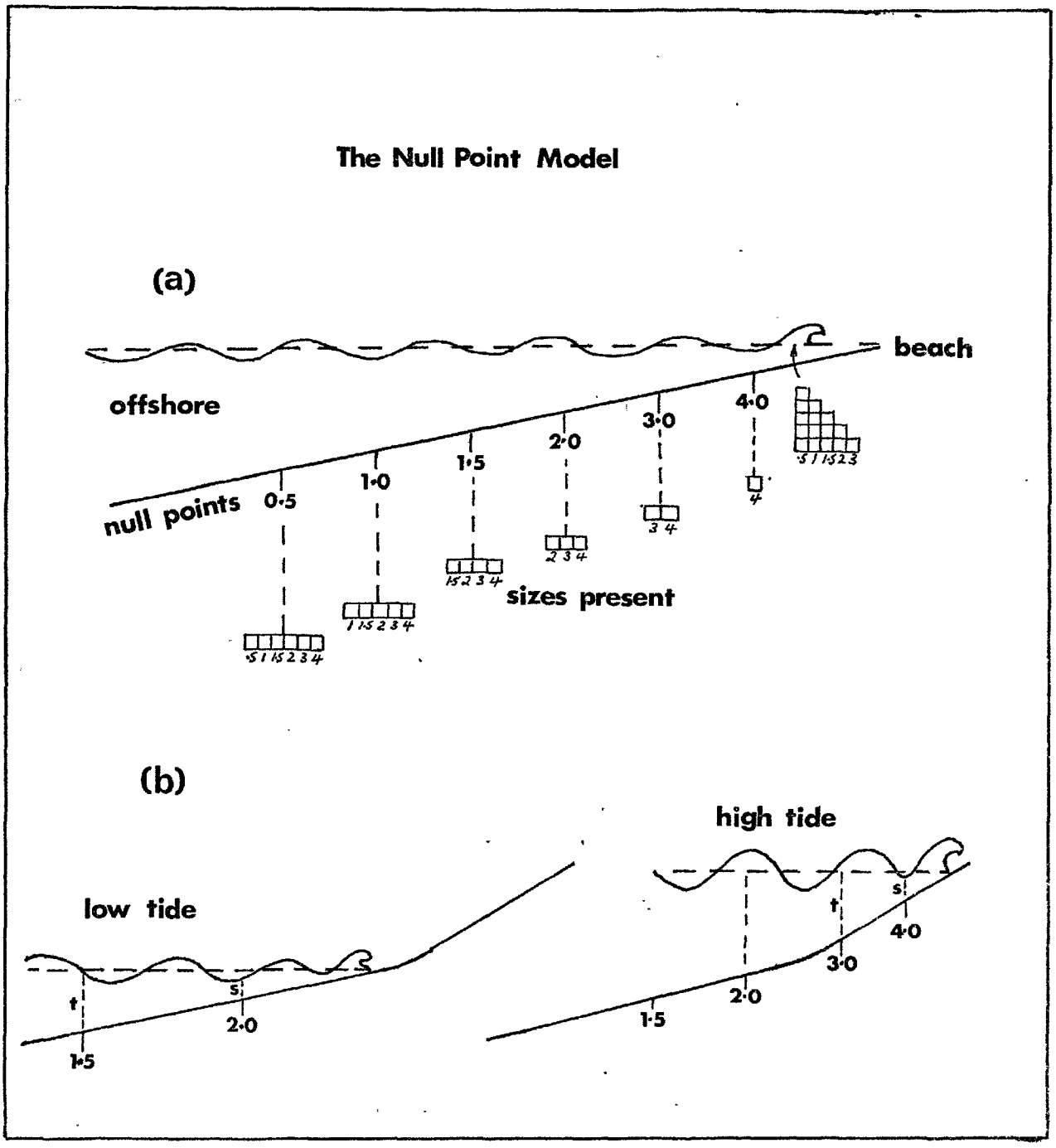


FIG. 6.0: (a) THE NULL POINT DISTRIBUTION.

(b) THE EFFECT OF VARYING WAVE ENERGY.

But if we consider that the exposed foreshore sediment is sorted and deposited within the zone of shoaling waves, then it is apparent that, in this case, a seaward-fining textural gradient (and a corresponding seaward-decreasing bottom slope) will result. Because of the decreasing nearshore wave energy on the ebbing tide, the magnitude of the most shoreward null point will also decrease. If we ignore the effects of breaker surf and swash zone sorting and/or deposition, then the exposed foreshore sediment texture will be determined by the passage of the final, most shoreward null-point (assuming that the depth of disturbance at this point equals or exceeds the depth of sampling). Hence, according to the predictions of the null-point model, there should be a seaward-fining textural gradient on the exposed foreshore.

This prediction really depends upon an efficient circulation of sediment, moving onshore on the sea-bed, and offshore from the breaker zone at mid-depths, so that the grainsizes corresponding to the competence of the wave-induced currents are always available to satisfy the postulated equilibrium. This may not be so. As pointed out by Roy (1967), the maximum sand transporting energy available to the low tide wave regime may control the maximum grainsize of the sediment introduced from offshore, even during higher stages of the tide, and this limitation could therefore effectively dampen the proposed influence of the seaward-decreasing wave energy during the ebb. A textural gradient may not then be

developed. However, since a distinctive textural gradient does exist across the foreshore (see below), this limitation does not appear to be operative here.

On the eastern half of the foreshore, Laugharne Sands, the null-point model is hardly applicable in a straightforward way because of the complex offshore bathymetry (cf. Miller and Zeigler, 1964).

(c) Breaker Zone

The point below the breaker is where much wave energy is dissipated, in turbulence and in disturbing sediment, representing a maximum in the energy profile of the nearshore system (Inman and Nasu, 1956). The movement of sediment from both sides towards the breaker zone is well attested by tracer studies (Ingle, 1966) and direct measurements of the velocity vector (Shepard and Inman, 1951; Schiffman, 1965). There is a higher concentration of suspended sediment, mostly sand, in the zone than in any other part of the nearshore system, the bottom sediment being coarse and poorly sorted, composing a highly winnowed lag concentrate (Miller and Zeigler, 1958, 1959).

As the tide ebbs and wave energy decreases (see previous section), this concentrate may be expected to become progressively finer, since the non-equilibrium grains supplied by the zone of shoaling waves will become finer, but will always be poorly sorted.

(d) Surf Zone

Work by Schiffman (1965) and Ingle (1966) suggests that the surf zone represents a surface of transportation between two bounding high energy zones (the collision and breaker zones). The primary water motion is probably an oscillatory one, and grains below a critical settling velocity trace this motion. The onshore fluid motion of the wave of translation in the surf bore may not extend to the sand surface, Shepard and Inman (1950, 1951) and Schiffman (1965) noting that bottom currents are predominantly, if intermittently, offshore. Grains smaller than the critical equilibrium size probably move offshore in suspension under most conditions (Inman, 1963), but some must move onshore into the collision zone. Grains larger than the critical equilibrium size move in sheet flow (indicative of high-velocity fluid flow, Inman, 1963) towards the breaker zone and/or the collision zone. Therefore, for a given wave regime, the net transport, normal to the shoreline, of certain grains within a critical size range will be zero, these composing most of the bottom traction carpet (Inman, 1949); finer grains have a net seaward motion in suspension; coarser grains have a motion sometimes onshore, sometimes offshore on the bottom (under normal conditions), offshore in suspension (under storm conditions).

Grains within certain critical size ranges will exist in overlapping zones of oscillating equilibrium (Ingle, 1966), and

these constitute the material most susceptible to longshore transport (Bagnold, 1963).

On Pendine Sands, a surf zone is present at all stages of the tide, but is most extensive during the lower phases of the tide on the gentle gradients of the lower foreshore. Hence near high tide, the energy input to the zone (from the mass transport of the breaker) is contained within a smaller cross-section of water, and width of foreshore; hence shear stresses on the sand-fluid interface are greater near high tide than near low tide; accordingly, the mean grain size of the equilibrium traction carpet at any one point in the surf zone must be greater near high tide than at an equivalentpoint near low tide (see Fig. 6.0(c)).

On a rising tide, the equilibrium grain size range must progressively increase in mean size, in accordance with the landward increase of surf zone bottom shear. Conversely, on a falling tide, the equilibrium grain size range must progressively decrease in mean grainsize. Grains ejected from the bottom traction carpet and moved shoreward (under average wave regime) become progressively larger in size on a rising tide, smaller on a falling tide. Suspended grains can be ignored for the present, since most of these eventually become concentrated in the breaker zone.

Through this mechanism, a seaward fining textural gradient can be expected on the exposed foreshore (this applies to the equilibrium resident population; rejected grains moving into the

collision and swash zones are considered below).

(e) Collision and Swash Zones

The collision zone is characterised by high turbulence, an energy maximum at its seaward edge and a low-energy null-point at its shoreward edge (Schiffman, 1965). Its development depends entirely on the interaction of surf and swash zones.

Swash zone flow, like surf zone flow, is dominated by sheet flow since both swash and backwash currents may attain the power of the plane bed regime (Allen, 1970).

Swash velocity is to some extent affected by local foreshore slope, but to a greater extent by overall slope of the foreshore/inshore profile, breaker zone position and proximity, and surf zone development. With increasing bottom slope, the cross-sectional area of water in the swash zone is decreased, so that water depth and swash velocity are increased (Ingle, 1966); see Fig. 6.0(d). Backwash velocity must also increase (other factors being equal). Although initiated by gravity, backwash velocity is not particularly dependent on local foreshore slope (Ingle, 1966).

An important factor governing swash zone velocities is the position of the underlying water table relative to sea level (Duncan, 1964). Swash zone currents attain greater velocities if not impaired by percolation of the water sheet into the underlying sand. For this reason, swash processes and sediment responses are rather different on rising and falling tides.

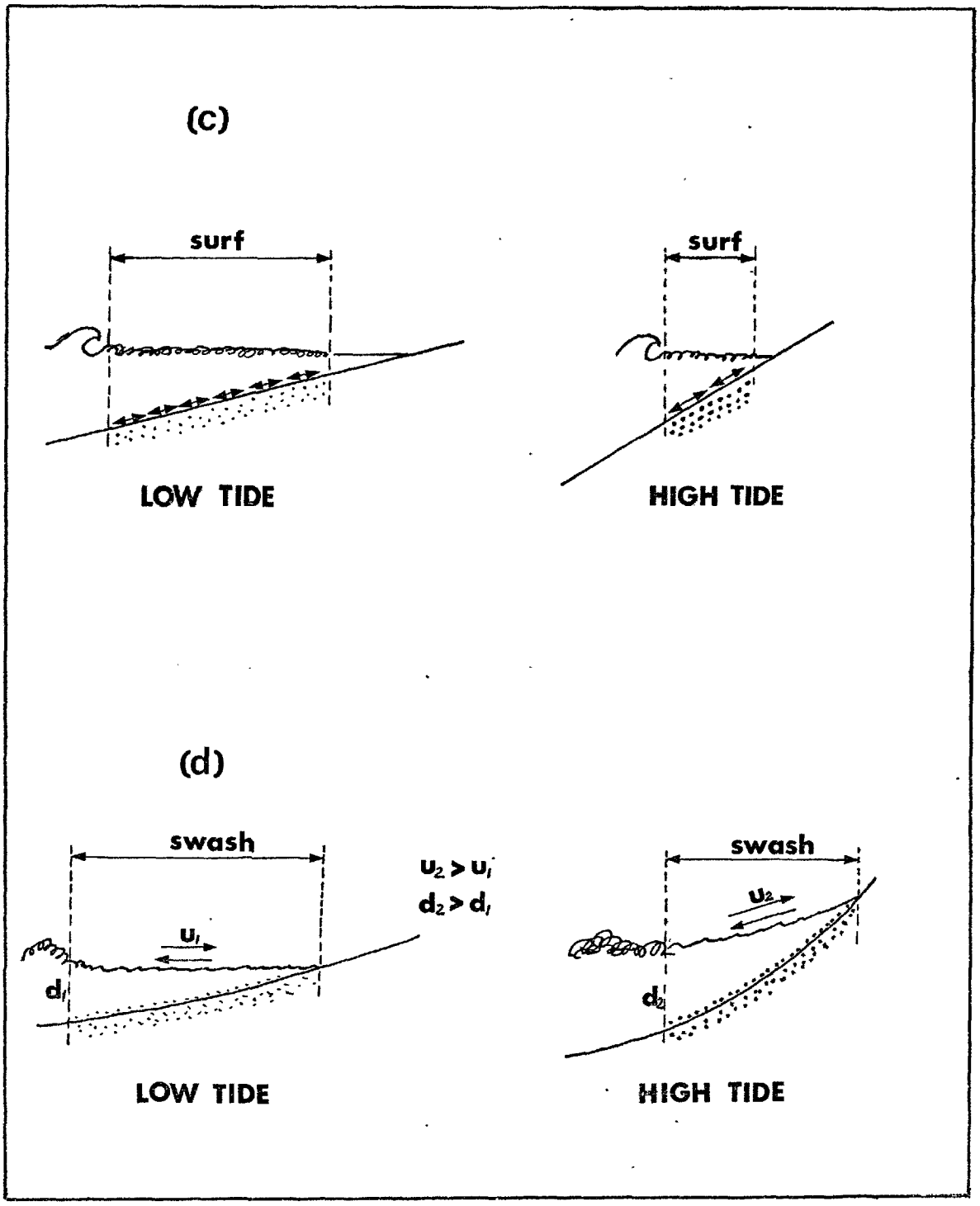


FIG. 6.0: (c) TIDAL VARIATION IN THE SURF ZONE.

(d) TIDAL VARIATION IN THE SWASH ZONE.

According to Grant (1948), there is a gradual diminution of velocity as the surf bore is transformed into swash and flows up the shoreface. Swash flow changes from turbulent to laminar towards the termination of shoreward motion and sediment, carried by turbulence, is rapidly deposited. The backwash then begins under the influence of gravity, accelerates so that flow changes from laminar to turbulent and sediment is resuspended and transported seaward. Backwash velocity probably reaches a peak and then retards due to the entrained sediment load (Miller and Zeigler, 1958), before being abruptly checked and halted in the collision zone on meeting the next opposing surf bore.

The textural gradient of swash zone sorted and deposited sediment left by an ebbing tide may therefore be expected to match that of surf zone sorting processes; a seaward fining gradient; it is also probable that overall foreshore slope and tidal phase are the dominant process parameters in establishing this gradient, though the former is determined by the tidal variation of nearshore wave energy discussed above.

Because of the influence of the water table, there will be a tendency for backwash deposition to predominate over swash deposition on the lower foreshore, but for swash deposition to predominate on the upper foreshore (Duncan, 1964).

On the uppermost foreshore swash zone deposition occurs at tidal still-stand, so that the textural gradient must be a landward

fining one, according to the model proposed and tested by Miller and Zeigler (1958).

6.2 The Hydrodynamic Significance of the Dissected Grainsize Subpopulations, Transect 1.

Four major subdivisions of the composite population have been recognised and isolated for many beach samples, as described in Chapter 5. Of these, one is coarse and moderately to poorly sorted, two are fine and very well sorted, one is very fine and moderately well sorted (using the class limits of standard deviation nomenclature proposed by Friedman, 1962). The standard deviation of the first population, and the mean size and standard deviation of the fourth population, have not generally been determined with any accuracy since these populations make up a very small proportion of the total composite population for most samples.

These populations have been designated 1, 2A, 2B and 3 respectively. Their relationship to hydrodynamic processes will be discussed in detail with reference to the spatial variation of their proportions and properties across the foreshore at transect 1. This data is shown in Table 6.1 and Fig. 6.1.

The possibility that the beach sediments retain inherited characteristics, either physical or mineralogical, from the source rock cannot be eliminated, since the link between source and deposition must be a continuous one. But that the textural character-

Sample	% Co_3	% heavies	Proportions %				Textural Parameters Ø units				
			1	2		3	2				
							M_2			σ_2	
11D	9.9	2.3	1.5	97.9		.6	2.60			.25	
12D		1.7	.8	98.5		.7	2.65			.25	
			1	2A	2B	3	1	2A		2B	
							M_1	M_{2A}	σ_{2A}	M_{2B}	σ_{2B}
13*		9.8	.4	0	94.5	5.1				2.56	.23
14	11.9	1.2	.1	2.8	97.3	.5		2.03	.18	2.56	.24
15		1.0	.2	4.0	95.3	.5		2.00	.18	2.56	.26
16		1.5	1.0	3.0	95.5	.5	1.41	1.90	.23	2.50	.28
17	13.6	2.2	2.0	8.0	89.6	.4	1.05	1.95	.18	2.57	.28
18		.8	4.5	14.0	81.4	.1	.75	2.06	.24	2.73	.30
19		.9	8.0	27.0	64.8	.2	.45	2.40	.27	2.92	.25
110	19.2	.8	9.0	37.0	53.6	.4	.35	2.58	.30	3.02	.24
111		1.6	18.0	33.0	48.6	.4	.10	2.55	.25	3.00	.21
112		3.2	27.0	25.0	52.0	1.0	-.60	2.53	.26	3.03	.20
113	19.3	2.2	14.0	15.0	70.0	1.0	-.85	2.72	.26	3.13	.19
114		1.7	.7	9.3	89.0	1.0	.60	2.76	.27	3.18	.21
115		2.5	.9	8.6	89.5	1.0	.85	2.73	.30	3.13	.21
116	16.2	2.4	.7	9.3	89.0	1.0	.22	2.70	.26	3.15	.18
117		2.9	.7	7.0	91.0	1.3	1.25	2.67	.23	3.15	.18
118		2.9	.6	6.4	92.0	1.0		2.69	.28	3.19	.19
119	16.1	1.9	.4	5.6	92.0	2.0		2.65	.22	3.17	.17
120		2.0	.5	3.5	94.0	2.0		2.60	.23	3.20	.18

TABLE 6.1 : Subpopulation proportions and textures, transect 1.

D = dune sample * = HW mark

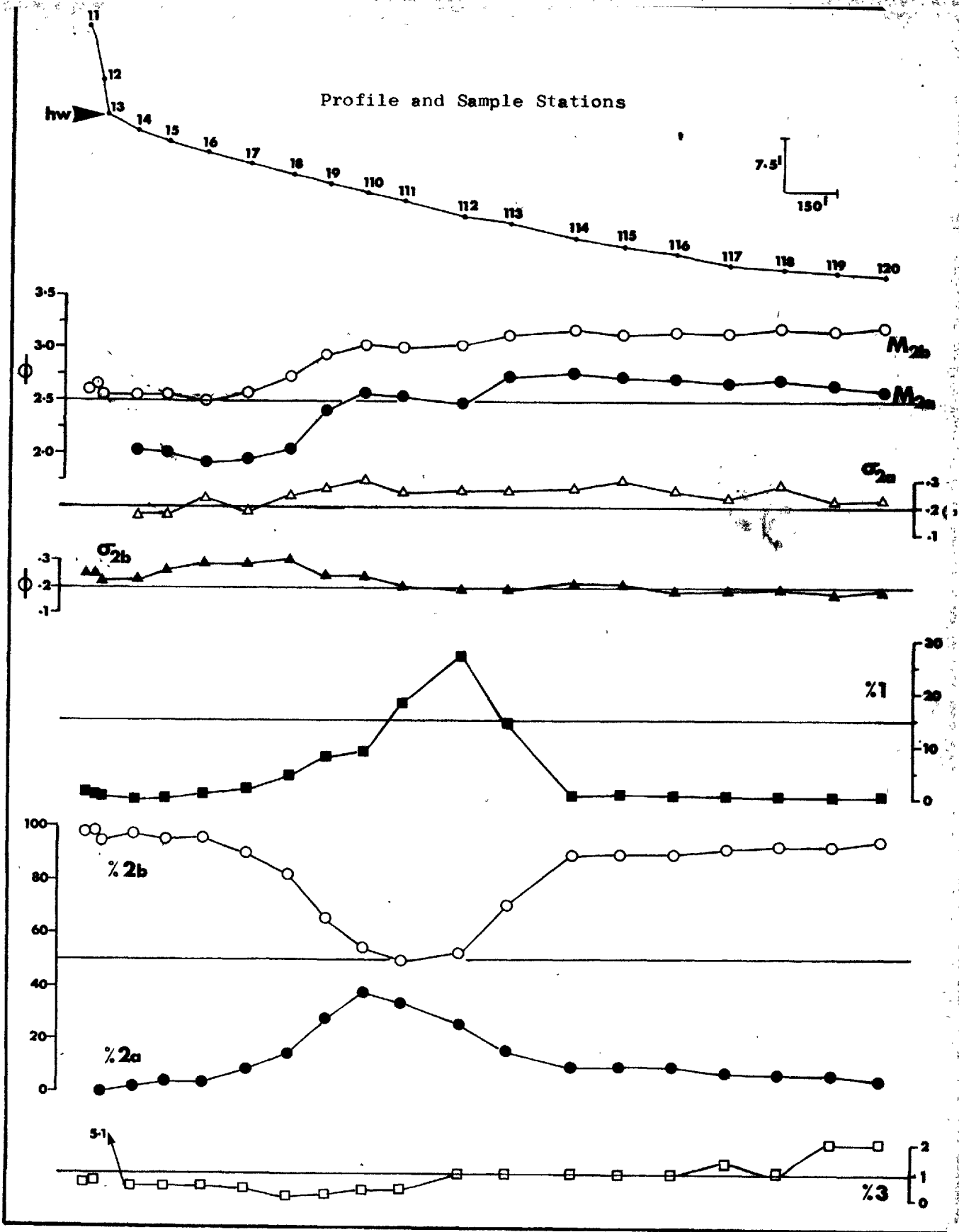


FIG. 6.1: SUBPOPULATION TEXTURES AND PROPORTIONS, TRANSECT 1.

istics are, in large measure, independent of source inheritance is shown by their considerable variation normal to the foreshore.

The mechanism of in situ grain abrasion cannot explain such rapid changes across the foreshore because of the very small distances involved (Kuenen, 1959). Nor can long term abrasion of a source rock population account for the spatial variation of texture.

Post-depositional modifications cannot exist, since sampling was carried out immediately after assumed deposition.

The composite parent population represents the results of mixing, truncation and possible recycling of primary subpopulations, and the method of sampling has superimposed its own modification, but the technique of graphical dissection serves to reverse these responses to provide the original, unmixed subpopulations. There is little doubt that these subpopulations are the sediment sorting responses to nearshore hydrodynamic processes.

From Table 6.1 and Fig. 6.1 it may be noted that subpopulations 2A and 2B are both very well sorted. Both have properties in common with the population A of Moss (1962, 1963) which forms the bulk of sandy deposits. This population, in his study, is built by a selective process that allows some saltatory particles to be retained on the bed but rejects the rest, so that it has a small size range grading from small, well rounded particles to somewhat larger, less rounded particles.

Population 1 is moderately to poorly sorted, always coarser than either saltation population and generally in subordinate proportion to them. This subpopulation corresponds to Moss's population C, comprising those grains of large size and/or angularity that are transported by sliding or rolling (i.e. by surface creep) over the saltating traction carpet, and which come to rest when the current can no longer move them against the friction offered by the bed.

Population 3 is well sorted to moderately well sorted (only a few samples contained sufficient of these grains for their standard deviation to be estimated), always finer than either saltation population and usually making up a negligible proportion of the total composite population. It corresponds to Moss's population B, comprising small grains that pass directly from saltation or suspension into positions between the grains of population A.

Certain limitations imposed by the graphical approach to the composite parent population should be emphasised. The dissected curve shown in Fig. 5.3 shows a clear-cut dependence on the four subpopulations. Some samples did not present such an easy interpretation. The section of the main curve imposed by population 2A is not always straight, but describes a long curve between the straight sections offered by populations 1 and 2B. An alternative, but usually less accurate, fit can be obtained by ignoring population 2A and attributing the long curve to considerable overlap and

mixing of populations 1 and 2B (such was the manner of sampling, that this is very feasible). This suggests that population 2A may, in some samples, be non-existent, representing a spurious manifestation of lack of experimental control. This alternative suggestion becomes viable only when the proportions of populations 2A and 1 fall below 10% and 1% respectively. However, for the sake of fidelity to the analytical technique and of continuity of interpretation, this alternative has been rejected, since it can be tested only by a further investigation using rigorous sampling methods. It is felt that the results of the analysis, to be outlined below, amply support this decision.

Near the uppermost foreshore, the logarithmic cumulative curves of many of the beach samples become virtually straight. It has been assumed that these represent single, unmixed populations, although they can be simulated by mixing two truncated subpopulations of very close mean size and variance in equal or subequal proportions. As pointed out in Chapter 5, the simplest interpretation has been chosen in these, and comparable, situations.

It is now possible to consider where in the nearshore environment the response characteristics of these subpopulations are established and by which hydrodynamic processes. Five distinct wave-controlled zones have been described and their characteristics proposed in the previous section. On an ebbing tide, the order in which these dynamic zones pass over any point on the foreshore is

: 1. Zone of shoaling waves 2. Breaker zone 3. Surf zone 4. Collision zone 5. Swash zone (a swash current is the final positive flow as regards sediment deposition, since swash deposition occurs shorewards of backwash deposition).

(a) Subpopulations 2A and 2B

Populations 2A and 2B show closely correlated textural gradients across the foreshore (Fig. 6.1), which suggests that they have closely related dynamic controls. From station 16 seawards, the gradient is a seaward fining one. This rules out tidal currents as critical process elements as the gradient is diammetrically opposite to that proposed for a current-induced response. Since both populations are always very well sorted (both coarser and finer grains being excluded from the saltating carpets), neither can represent lag deposits of the breaker zone. Also since the breaker zone does represent an energy maxima in the nearshore zone, its passage probably obliterates the effect of the previously operative zone of shoaling waves, so the latter zone cannot be responsible for establishing the textural gradient (Fig. 6.X, page 451).

This leaves the swash, collision and surf zones. Of these, the swash and collision zones are, at times, zones of active deposition; the collision zone is also one of active erosion, in parts, as well as intense vertical mixing and maximum depth of disturbance; the surf zone is one of transportation and sorting.

Because of the successive dynamic zones that pass over any

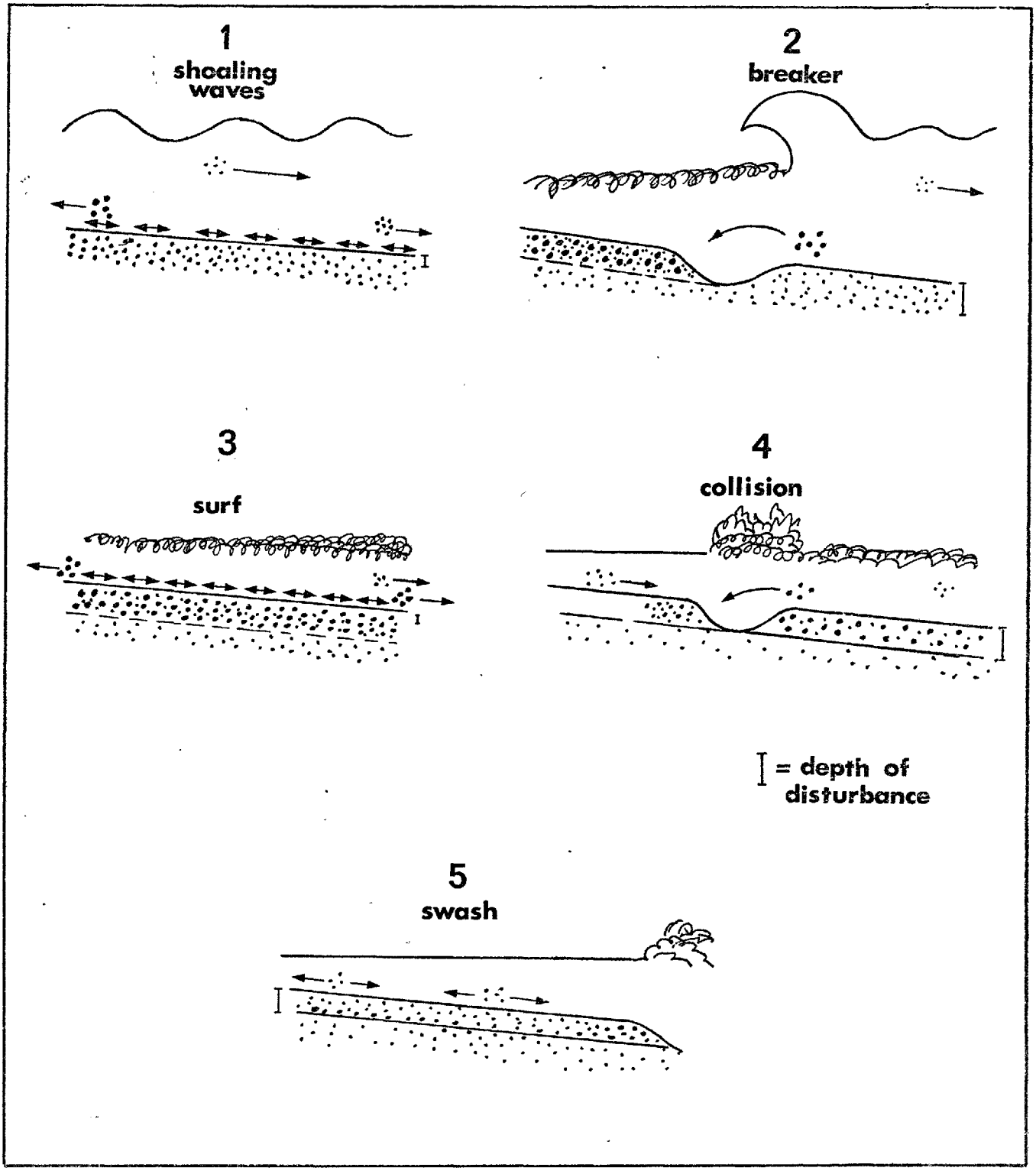


FIG. 6.X: IDEALISED SEDIMENTATION SEQUENCE DURING EBB.

point on the foreshore during the ebb phase, the energy relationships between the bottom sediment (i.e. traction carpet) and its dynamic environment must be always changing; we may consider that a complex series of dynamic equilibria are in constant flux. The situation is radically different from those studied by many investigators (e.g. Inman, 1949; Ingle, 1966) in which tidal range was small and the flux of process/response equilibria correspondingly so (for a given wave regime).

Although the breaker zone has been eliminated as a dominant process element in establishing the exposed textural gradient, it is nevertheless, with the collision zone, the point of maximum energy in the nearshore environment and must exert a profound influence on sediment responses. The depth of disturbance in the breaker zone is considerably greater than in the surf zone, the mobile bed layer in the latter being no greater than a few grain diameters in thickness (Einstein, 1948). The breaker zone has progressively traversed the foreshore, but textural evidence of its passage has been eradicated by a subsequent response to another dominant process. Because of the depth of sampling, and since populations 2A and 2B singly compose up to 37% and 95% of the total sample respectively, the superimposed textural change subsequent to breaker activity cannot have taken place in the surf zone, because of the restricted depth of sheet flow in that zone (even at the coarsest population 2A mean size, station 16, the depth of the

mobile bed layer in the surf zone may be of the order of only 0.12 inches, this estimate being based on the data of Ingle, 1966).

Only in the collision and/or swash zones can the depth of disturbance be of sufficient magnitude to eradicate any textural evidence of the passing breaker, since the depth of the mobile traction carpet must be at least as great as the depth of sampling (see Fig. 6.X). For nearby Rhossili beach, King (1951) found that the depth of disturbance of sand by waves is as great under the 'swash' of the waves in only a few feet of water as under the breaker or in deeper water. Under normal conditions, this depth of disturbance is about 1 or 2 inches, or less. Hence it may be concluded that sorting and deposition of grains within the collision and/or swash zones has determined the distribution of the two saltation subpopulations.

Both Otvos (1965) and Williams (1971) record rather greater depths of disturbance, but this is undoubtedly due to differences in bottom configuration and resulting surf zone development. Both writers consider surf zone or breaker zone deposition to be important at mid-tide level, but it appears from their descriptions that the surf zone was virtually non-existent in their studies, so that the breaker zone and collision zone were synonymous. Furthermore, from the textural information given by Williams, it is apparent that his 'surf' zone deposit is a surface creep population, akin

to subpopulation 1 in this study, and so will be discussed in the following subsection.

The incidence of two saltation populations, of close mean size and comparable standard deviation, each truncating the other, has been reported and discussed by Visher (1969), and is considered by that writer to be an integral feature of foreshore sands. The reason for this may be related to opposing swash and backwash currents, each of which forms distinct saltation populations which remain as separate laminae. Alternatively, the two populations may reflect mixing of grains of separate provenance, or reflect the separate shape of particles of different size, or indicate populations of distinct specific gravity.

The latter alternatives may be mutually dependent. Evidence for this hypothesis is provided by Fig. 6.2A & B. These curves show the relationships between the proportion, by weight, of carbonate and the proportions, by weight, of populations 2A and 2B. The data is actually based on samples from transect 3, since there was a greater sampling density on that transect, but the relationships are similar for transect 1 samples. The proportion of carbonate was obtained crudely by determining the weight percentage of insoluble matter after digestion in dilute (10%) hydrochloric acid.

Subpopulation 2A proportions are closely related to carbonate proportions, an increase of one correlating with an increase of the other. An inverse relationship holds between carbonate and

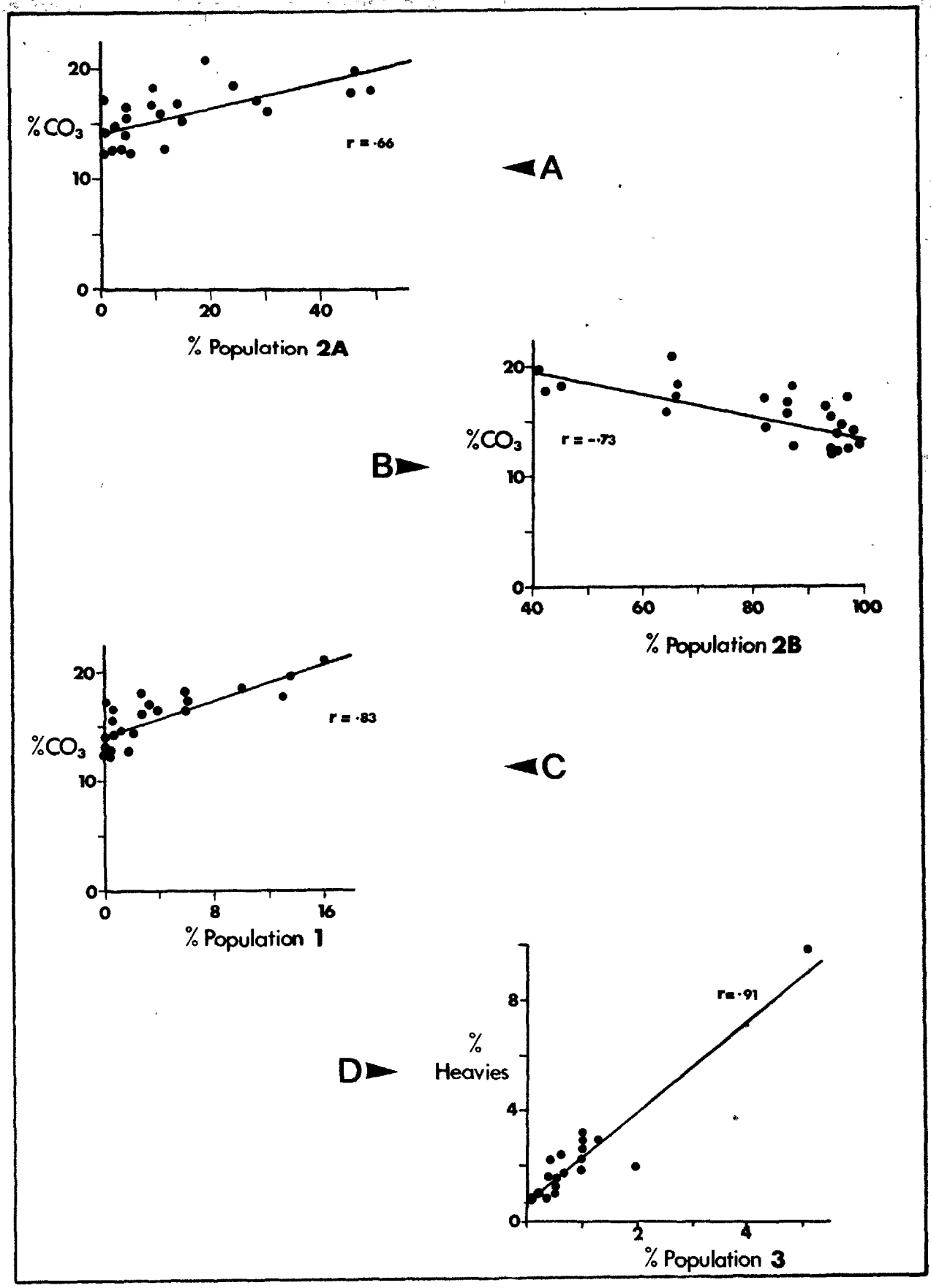


FIG. 6.2: TEXTURE/MINERALOGY ASSOCIATIONS.

subpopulation 2B proportions. Clearly, subpopulation 2A contains a dominant carbonate fraction, whereas subpopulation 2B does not. The carbonate fraction is almost exclusively shell particles. Population 2A is not wholly carbonate, since it is present, in much reduced proportions, in leached samples.

Both populations 2A and 2B coarsen landwards to station 16 (Fig. 6.1), in step with the progressive landward increases of swash flow and collision zone turbulence, both of which are accompanied by increased bottom shear stresses in the boundary layer.

Below station 16, the standard deviation of the dominant population 2B decreases seawards; this cannot indicate an increase of swash zone/collision zone bottom shear, since this is contrary to the conclusion of the previous paragraph, but must result from a slower rate of sedimentation on the lower foreshore than on the upper (i.e. fewer grains are provided by the surf zone).

The standard deviation of subpopulation 2A tends to increase at mid-tide level, and since its mean grain size shows no corresponding trend, the rate of sedimentation of the deposit must be increased at this level.

The amount of the saltation population is dependent partly on the rate of deposition and partly on the stability of the moving traction carpet (Visher, 1969); these conditions may be interdependent. The proportion of population 2A increases substantially at mid-tide level, corresponding to a change in foreshore/inshore

slope. This means that on the middle foreshore, either the rate of deposition of population 2A increases, or the stability of its traction carpet increases, or both. The first possibility has already been suggested by the variation of its standard deviation.

Such an increase of sedimentation at mid-tide level may be due to a combination of several factors. Shelly fragments, because of their shape, density or slightly coarser size, are moved landward in the surf zone since they are rejected by the overlapping equilibrium traction carpets that constitute the bottom sediment of the surf zone; some fragments will also move seawards into the breaker zone, the direction being dictated by their point of departure. At this stage, transport of many fragments may be by surface creep, because of their shape and density, as well as by saltation, but because of their low concentration they are not only rejected by the traction carpet but are also unable to form a saltating traction carpet of their own. The rate and degree of shoreward transport is dependent on the nature of the surf zone bottom and the magnitude of bottom shear stresses. The surf zone bottom becomes progressively finer as the tide ebbs (see section 6.1), so that non-equilibrium particles are more easily moved over a smooth bottom near low water than over a rough bottom near high water. Surf zone bottom shear stresses become progressively smaller as the tide ebbs, so that the same particles are moved more readily near high than near low water. Combination of these contrary trends may

result in the greatest concentration of coarse, subequant grains occurring in the collision and swash zones at mid-tide level.

These particles, which may be slightly coarser, less rounded, and of lower specific gravity than the dominant population 2B traction carpet, may them be able to build a secondary saltating traction carpet because of their increased abundance (Moss, 1963), so that their rate of sedimentation also increases.

Tidal currents may also play a part if a peak in velocity is achieved halfway-through the ebb; the coarser, subequant grains of subpopulation 2A may be moved into the breaker zone in greater concentrations at this time, and deposited there as a lag concentrate.

If the hypothesis outlined above is correct, then we may conclude that the two saltating populations 2A and 2B represent traction carpets differentiation by size, shape and density, constituting organic (predominantly) and detrital (predominantly) populations respectively. Below station 16, their textural gradients are parallel, closely related to foreshore slope, and determined by the variation of swash and collision zone velocities and turbulence on an ebbing tide. Their standard deviations and overall proportions are determined by respective rates of deposition. The detrital population 2B rate of sedimentation depends upon the supply of suitable grains from the surf zone and collision zone, this decreasing as bottom shear stresses in these zones decline as the tide ebbs. The organic population 2A rate of sedimentation is

similarly dependent, but also on the ability of its subequant grains to move over the bed of the surf zone; interaction of trends may bring about an increase of sedimentation near mid-tide.

The hypothesis suggests that population 2B will be deposited in the swash zone (as the swash uprush retards) and in the collision zone (as the backwash retards and halts on contact with the surf). Population 2A will tend to concentrate in the collision zone.

Above station 16, the mean grain size of both saltation populations progressively decreases (Fig. 6.1). This reversal of trend is actually more exaggerated on some other transects (see section 6.3). On this uppermost part of the foreshore, the textural gradient is one of seaward coarsening from the high water mark of the previous tide at station 13 to the point of tidal still stand of the collision zone a little below station 16; this is in accordance with the model of swash zone deposition presented by Miller and Zeigler (1958). From station 16 shorewards, the swash current progressively drops its load, the grains entrained in the traction carpet having a size range of progressively fining mean size. This is reflected by the shoreward fining of the means of both saltation populations.

The standard deviation of both subpopulations decreases shorewards from station 16 to the high water mark, as a result of progressive sorting (Russell, 1939) in the direction of the predominant flow, which here is probably the swash.

The proportion of subpopulation 2A (organic) is very small, and dies out altogether at the high water mark. This is because greater bottom shear stresses are required to form and maintain this population than the detrital population, and as turbulent flow becomes laminar it is the small quantities of the organic population which are preferentially deposited in the seaward portion of the swash zone.

An alternative mechanism to account for two foreshore-deposited saltation populations is one of dual sedimentation by swash and backwash currents. The swash deposit is laid down as swash flow is modified from turbulent to laminar flow. The backwash deposit is formed mainly when backwash strikes surf, in the landward section of the collision zone, but some dumping of sand probably occurs before this if the material carried in suspension and traction is sufficient to decrease the backwash current.

It must be assumed that population 2A represents backwash deposition, and population 2B swash deposition. Contemporaneous deposits of swash and backwash flow must be relatively coarse and relatively fine respectively, since swash velocity will invariably exceed backwash velocity. But at any one vertical section, a backwash deposit must be below a swash deposit, since the former is associated with the collision zone, the latter with the swash zone, and on an ebbing tide the collision zone will pass the section before the swash zone. In addition, the backwash population will

tend to be the coarser since swash, collision and surf zones experience decreasing flow velocities and bottom shear as the tide ebbs.

If this is the case, then swash deposition must account for up to 95% of the total sample. This need not represent a net accumulation since parts of the collision zone undergo erosion and it is this eroded material that provides most of the swash-laid deposit. Thus at any point of the foreshore there may be erosion (turbulent collision zone), deposition (backwash deposit), deposition (swash deposit) with little overall change.

The variation of population 2A and 2B textures across the foreshore may be explained by the same processes as proposed above for the first hypotheses. Both swash and backwash population mean grain sizes increase shorewards to station 16 as a result of an increase of bottom shear stresses in both collision and swash zones. Population 2B has a shoreward increasing standard deviation as the supply of grains from the collision zone to the swash uprush is greater on the upper than on the lower foreshore.

On the middle foreshore, the swash deposit (2B) is reduced as the backwash deposit (2A) is increased. This may be because on an ebbing tide, at this level, backwash volume increases relative to swash volume, due to addition of water from the effluent zone (Grant, 1948; Duncan, 1964); the effluent zone is that zone of the foreshore at or below the low tide height of the water table.

This prolongs the time of the backwash flow so that much more of the swash laid material is picked up and redeposited by the backwash.

At all times, population 2B is in excess of population 2A. This appears to contradict the opinion of King (1959) who asserts that when the backwash velocity is sufficient to move sediment, the bottom sediment will be predominantly affected by the backwash owing to the longer duration of the backwash flow. The increase in backwash deposition at mid-tide level does not agree with the experience of Duncan (1964) who found backwash deposition to be greatest on the lower saturated foreshore (where the effluent zone exerts most influence on swash zone dynamics).

This apparent discrepency may indicate that the proposed mechanism is in error. Or it may be a reflection of the very gentle foreshore/inshore slope at Pendine Sands. Previous studies, by American sedimentologists, have dealt with foreshores with very much steeper foreshore gradients : 2^{o} - 8^{o} (Ingle, 1966), 3^{o} (Duncan, 1964), 4^{o} - 9^{o} (Otvos, 1965), 4^{o} - 12^{o} (Williams, 1971), 6^{o} - 13^{o} (Miller and Zeigler, 1958). On all of these beaches, it may be supposed that gravity assists the backwash flow, notwithstanding that Ingle (1966) found a very weak correlation only between backwash current and local foreshore slope. At Pendine, below station 16, the foreshore slope is less than 1^{o}, and on the lower foreshore less than $\frac{1}{2}^{o}$. It is possible that on the whole

profile, backwash development is slow because of these gentle gradients. On the lower foreshore, swash dominance persists in spite of the assistance given to the backwash by the extensive effluent zone.

Above station 16, the mean grain sizes of both populations decreases, as, at tidal still-stand, swash and backwash currents decrease landward. Sorting of both deposits improves towards high water, again in accordance with the swash zone model of Miller and Zeigler (1958). Backwash deposition decreases shorewards and is absent at the high water mark. However, it is no longer clear why the backwash deposit (2A) should be coarser than the swash deposit (2B) since at this level deposition of both populations must be virtually contemporaneous.

The problem can be solved by an amalgamation of both proposed hypotheses. The backwash deposit need not be assumed to be truly coarser than the swash deposit, if in fact it is composed of shelly and light mineral material. Because of their mineralogical differences, backwash and swash populations from any one sample may be hydrodynamically equivalent, although of different absolute grain sizes.

Subpopulations 2A and 2B together make up 71 - 95% of the sampled surficial sediment of transect 1. Their response characteristics therefore give us a good idea of the dominant process variables which establish the low water textural gradient.

The concept that these subpopulations are the deposited traction carpets of distinct organic (and light mineral) and detrital (with some light minerals) constituents, differentiated also (or perhaps primarily) by roundness characteristics, can be successfully applied to the observed textural distribution. A further concept, which attempts to distinguish swash and backwash deposited grains, can be successfully applied to the total transect only when combined with the mineralogic concept.

Both hypotheses remain empirical, in the absence of observations of the appropriate hydraulic mechanisms.

(b) Subpopulation 1.

The proportion of population 1 material follows a similar trend across the foreshore to that of population 2A (Fig. 6.1, Table 6.1), so that it is likely to accumulate in response to similar processes. However, its mean grain size is also at a maximum on the middle foreshore (Table 6.1). Its standard deviation (not shown) varies in parallel with the mean, with a maximum at station 111 (1.60 ϕ units) diminishing to 0.80 ϕ units at station 17 and to 0.90 ϕ units at station 114.

The population contains a highly significant proportion of shelly fragments, its concentration in the composite sample being correlated with carbonate concentration (Fig. 6.2C). Other constituents are lithic fragments.

Population 1 is therefore a surface creep deposit composed primarily of shelly fragments (transported predominantly by sliding) but with some rounded lithic grains (transported by rolling).

The coarseness of the population indicates sorting in a high energy environment, such as occurs in the breaker and collision zones. Its textural distribution does not match the energy variations proposed for an ebbing breaker zone (section 6.1), so deposition probably takes place in the collision zone. Comparable coarse lag deposits are reported by Miller and Zeigler (1958) and Schiffman (1965).

Most of the grains constituting population 1 are fragmented particles of mollusc shells, of coarse and very coarse sand size. Fragmentation will occur in both the breaker and collision zones. Whole shells, shelly fragments, and lithic grains are moved shorewards in the surf zone, constituting a coarse, alien population of surface creep particles rejected by the overlapping traction carpets of the surf zone. As explained for subpopulation 2A particles, there will be two opposing trends of grain concentration, one shoreward, the other seaward, which may combine to create peak concentrations at mid-tide level. Superimposed on these is the effect of gravity, which attempts to prevent shoreward and promote seaward movement of the rolling and sliding grains, particularly on the steeper gradients of the upper foreshore.

Combination of these processes would serve to encourage the

greatest concentration of surface creep particles on the middle foreshore, where the foreshore/inshore slope demonstrates an abrupt change from $\frac{1}{2}^{o}$ to 1^{o} (at stations 112 and 113).

Maximum tidal current velocities occurring halfway through the ebb phase may also promote increased transport of coarse grains by increasing shear stresses in the surf zone. Moved shoreward, these would therefore accumulate at the mid-tide position of the collision zone.

Some grains would attempt to penetrate the swash zone. On the lower foreshore, swash energy is too low to transport the grains shorewards from the collision zone. On the upper foreshore the swash zone bottom deposits are too coarse to facilitate shorewards rolling and sliding, particularly against the increasing opposition of gravity. The optimum level, where both factors in combination form the least obstacle to swash transport of these grains, is perhaps the middle foreshore. However, at this level, backwash flow volume relative to swash volume (see previous subsection) is relatively high, and so swash deposited grains are readily rolled seawards by the backwash to form a concentrated accumulation in the collision zone.

The increased proportion of the coarse saltation population 2A at mid-tide level may also encourage accumulation of rolling and sliding grains (population 1) by increasing the roughness of the bottom and creating a 'traction clog' (Moss, 1963). Particles that

are poorly rounded or of low specific gravity are rejected by the saltating population 2B grains, but can become predominant and concentrated through relative immobility (and increased supply) as they are built into a secondary saltating population 2A. The coarseness of the latter encourages the halting of rolling and sliding individuals; when the concentration of these large grains exceeds a critical value, many more are forced to jam on the surface to form a closely packed population 1 accumulation.

Combination of these various dynamic and textural processes brings about a concentration of coarse, poorly sorted surface creep grains, which accumulate in the collision zone, on the middle foreshore.

Because of the complex feedback mechanisms inherent in such a dynamic system, it is difficult to confidently assert whether a particular variable is a process or response variable. For this reason, it is difficult to isolate the process element in the relationship between foreshore slope, hydrodynamic energy and sediment texture. However, the close interdependence of these variables is clearly evident (see also Krumbein, 1944; Bascom, 1951).

(c) Subpopulation 3.

The proportion of the suspension/saltation population 3 is small along most of the transect (Fig. 6.1), increasing on the lower foreshore and at the high water mark. This follows from the

high energy associated with the surf, collision and swash zones. Suspended grains are highly concentrated in the breaker and thrown forward into the surface water of the surf zone to be carried up the beach by the swash. Most of them are resuspended by the backwash to the surf zone where they are transported seaward by an intermittent bottom current (Schiffman, 1965) and a net seaward drift (Inman, 1963) to rejoin the breaker. Some of these begin the cycle anew but the very finest are finally released from the breaker on its seaward side where they enter a net drift at mid-depth (Miller and Zeigler, 1964) to be transported seaward.

Most of the suspension population will therefore be removed from the beach environment; the last remaining are likely to be its densest members (Moss, 1963). This is confirmed by Fig. 6.2D, which shows the relationship between % population 3 and % (by weight) heavy minerals for transect 1 samples. Heavy minerals were separated by a conventional settling method (Krumbein and Pettijohn, 1938) using tetrabromoethane (specific gravity 2.97).

The proportion of population 3 increases near low water because swash and backwash flow velocities are reduced, and laminar flow maintained over a wider expanse of the foreshore.

The proportion is negligible on the upper foreshore for the opposite reasons, except at station 13, the high water mark of the previous tide (the percentage of heavy minerals is here 9.8% by weight). This may represent deposition from the uprush of the

highest swash flow over relatively dry sand and/or deposition by wind (since the beach at this level is dry most of the time, except during high spring tides).

(d) The Dune

The dune has been sampled at stations 11 and 12 (Fig. 6.1). In both samples, only one saltation population is present, which distinguishes them from most of the beach samples. This population comprises 98% of the total sample.

The importance of saltation in wind transport of sand has long been emphasised (Bagnold, 1941), and the relationship between them may be a genetic one (Visher, 1969).

Wind processes are generally incompetent to move coarse grains by surface creep, which accounts for the small percentage of material in population 1.

Additional material, contained in the suspension population 3, makes up a very low proportion of the total, generally lower than that present in the beach samples.

6.3 Variations of Subpopulation Properties, Transects 2-7.

The significance and variation of subpopulation proportions and textures along transect 1 have been discussed in some detail in the preceding section. It has been shown that there is an intimate relationship between the surficial sand texture and the foreshore/

inshore slope. For convenience, the foreshore may be divided into four zones, although three of these compose a continuous gradation from low water to high water marks. These zones are: The lower foreshore, gently sloping, in which a wide surf zone is characteristic, the sediment being dominated by a very well sorted, fine grained saltation population 2B, indicative of a (relatively) low energy depositional interface. The middle foreshore, marking an abrupt change in slope, in which the surf zone is more restricted, an additional mineralogic component, mainly shelly with some lithic, being admixed with the detrital saltation population; much of this component is selected by a second saltation population 2B while the coarser, predominantly shelly, fraction composes a surface creep population 1. The upper foreshore, relatively steeply sloping, in which the surf zone is least developed so that the breaker and swash zones are closest together, the sediment again being dominated by a well-sorted, medium-grained saltation population 2B, the shelly component being absent, deposition occurring in a high-energy swash zone near, and at, the still-stand of high water. The dune, physically distinct from the beach, but composed of a single saltation population which is not readily distinguishable from the population 2B of the upper foreshore. The three foreshore zones have been separated, for descriptive convenience only, and cannot easily be physically separated from each other in the way that they can be distinguished from the dune. It is not suggested that the foreshore

can easily be divided into three distinct morphological or textural zones; in fact the zones merge imperceptibly into each other.

Representative grain-size distributions from the three beach zones of transect 1 are shown in Fig. 6.3 (for graphical convenience, the coarse continuations of the coarse tails are not shown). As already described in Chapters 1 and 2, the profiles of the western beach are essentially similar in shape, though variable in length, whilst those of the eastern beach differ in shape and length, both from the western profiles and from each other. Sediment textures reflect these similarities and differences, representative grain-size distributions being shown in Figs. 6.4 - 6.9. Transects 2-6 bear the four zone definition, but there are radical changes on transect 7.

Subpopulation properties and textures for the samples of transects 2-7 are shown in Tables 6.2 - 6.7 (which also include results of carbonate determinations) from which Figs. 6.10 - 6.15 are derived.

All dune samples are characterised by a single saltation population. This is perhaps surprising if the manner of sampling is taken into account. Each sample must contain several sedimentation units, but these are not separated by the method of graphical dissection, and so must have mean grain size and sorting coefficients that are very close together. Although separated by real time intervals, of unknown length, and presumably deposited by winds of differing velocities, several units make up a homogeneous composite.

This is because wind currents have a lower competence than water currents, and are unidirectional (onshore for purposes of deposition). The dune deposits represent grain populations that are transported when a critical wind speed is exceeded, and deposited when wind speeds fall below a second critical magnitude. Grains reach the high dunes only when wind speeds are large, the requisite critical speeds being large also; successive laminae therefore do not differ in texture, since they represent a response to all wind speeds above the critical entrainment magnitude (for the grain sizes available for transport).

Many samples from the uppermost (above HW) foreshore also contain only one saltation population. These may be attributed to undirectional swash currents of very high spring tides or to aeolian action on deposits which are dry for most of the time.

The latter possibility is clarified on transect 3, where several samples were taken between the base of the dunes and high water mark. The single saltation populations here may be formed by the swash action of previous very high tides, but are most likely to be formed by longshore winds. At the time of sampling, many small barchan-like structures were present and samples were taken on, and between, these. They had disappeared by the following day. Significant proportions of population 3 grains (heavy minerals) occur here, since unidirectional winds must be able to incorporate suspended grains into the traction zone at the depositional interface. Initially, these grains must be brought

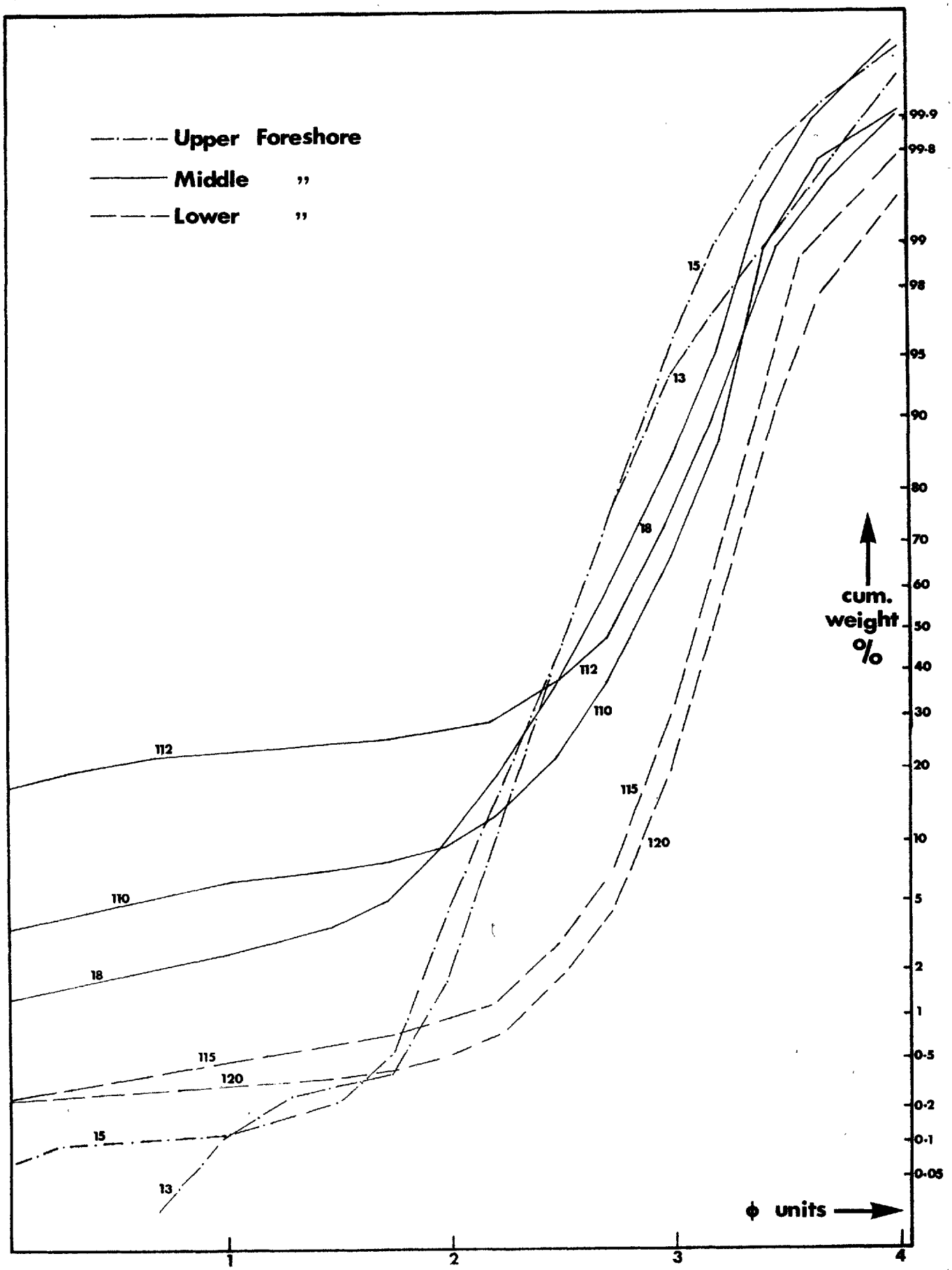


FIG.6.3: GRAINSIZE DISTRIBUTIONS, TRANSECT 1.

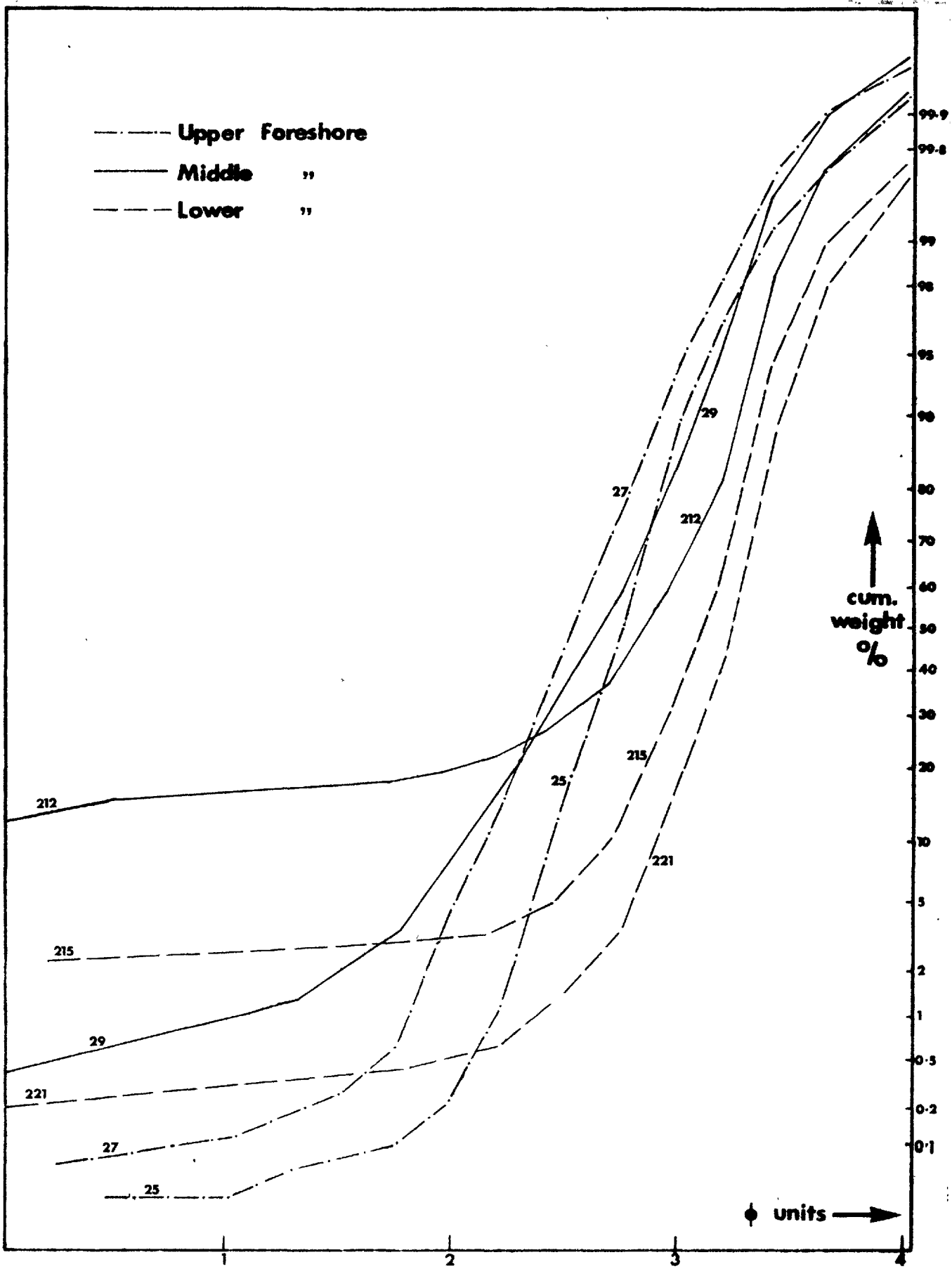


FIG.6.4: GRAINSIZE DISTRIBUTIONS, TRANSECT 2.

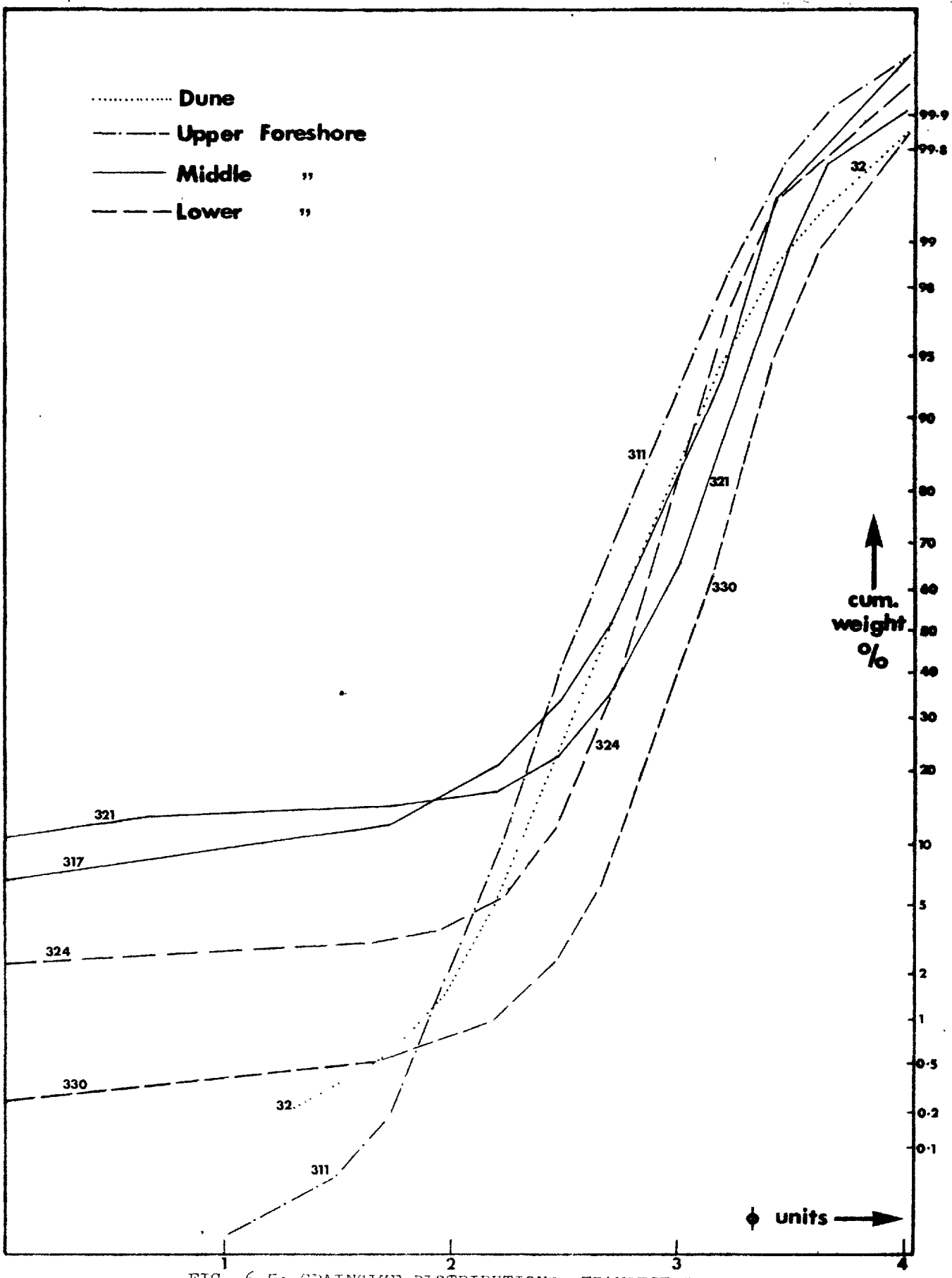


FIG. 6.5: GRAINSIZE DISTRIBUTIONS, TRANSECT 3.

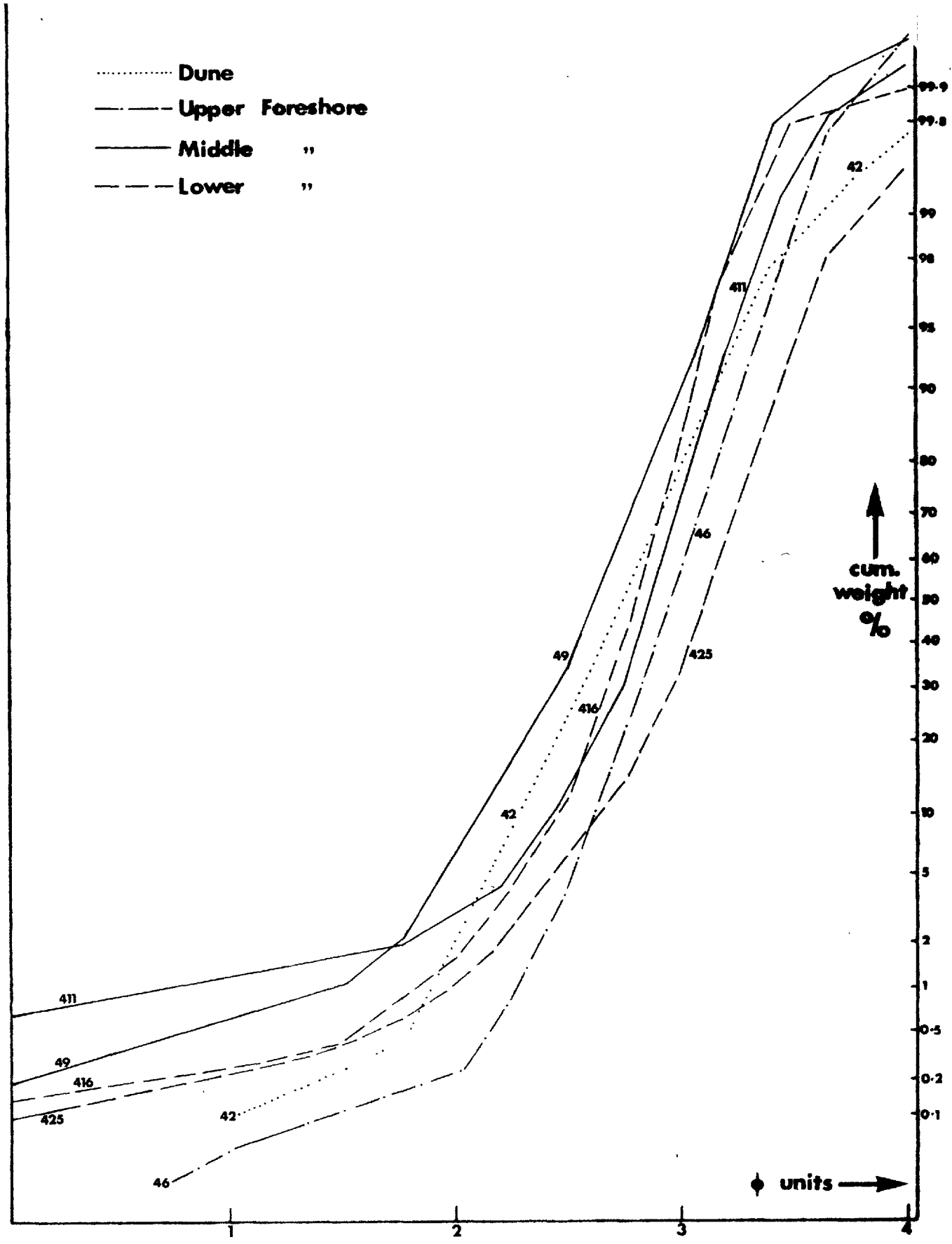


FIG. 6.6: GRAINSIZE DISTRIBUTIONS, TRANSECT 4.

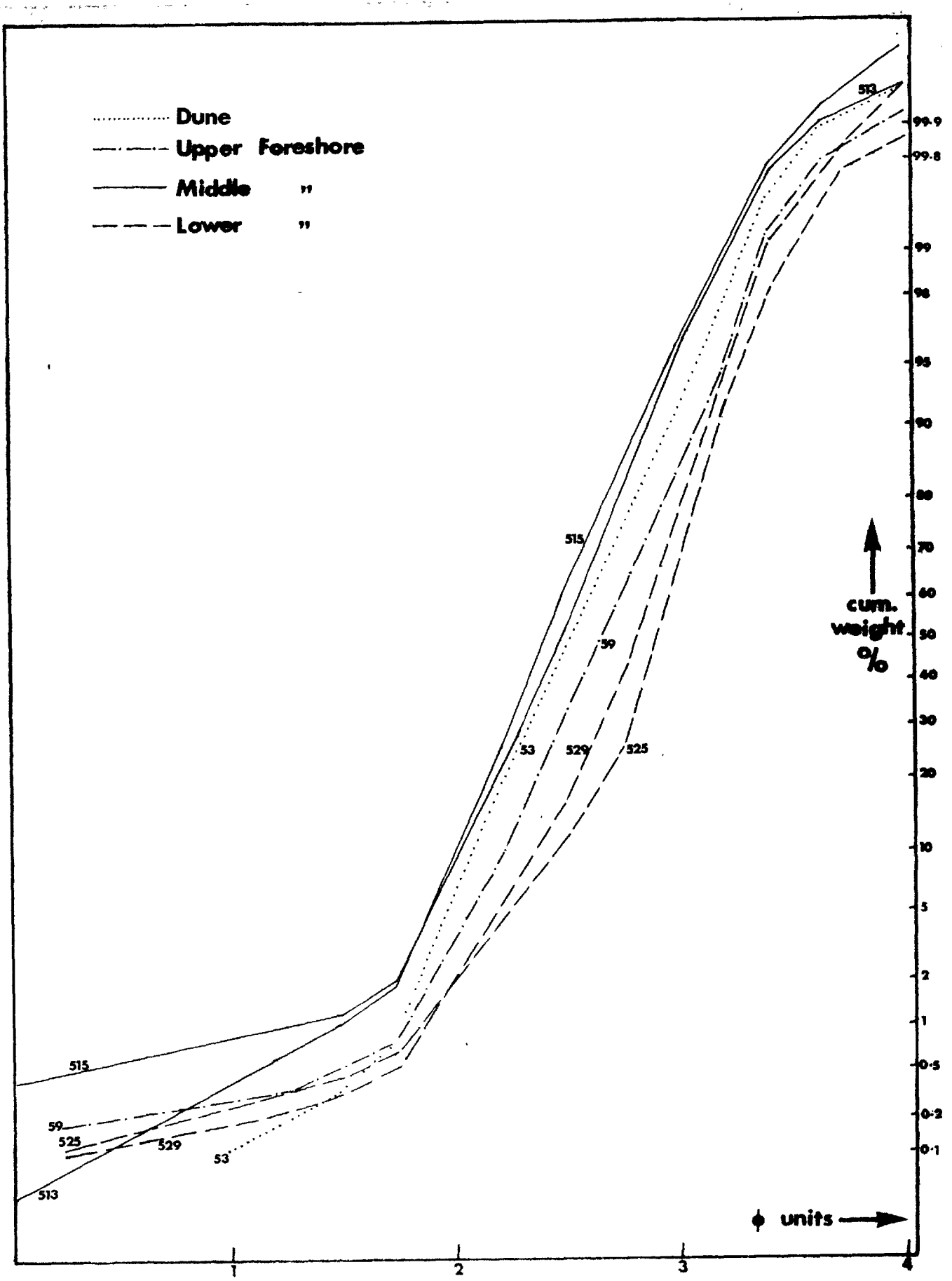


FIG. 6.7: GRAINSIZE DISTRIBUTIONS, TRANSECT 5.

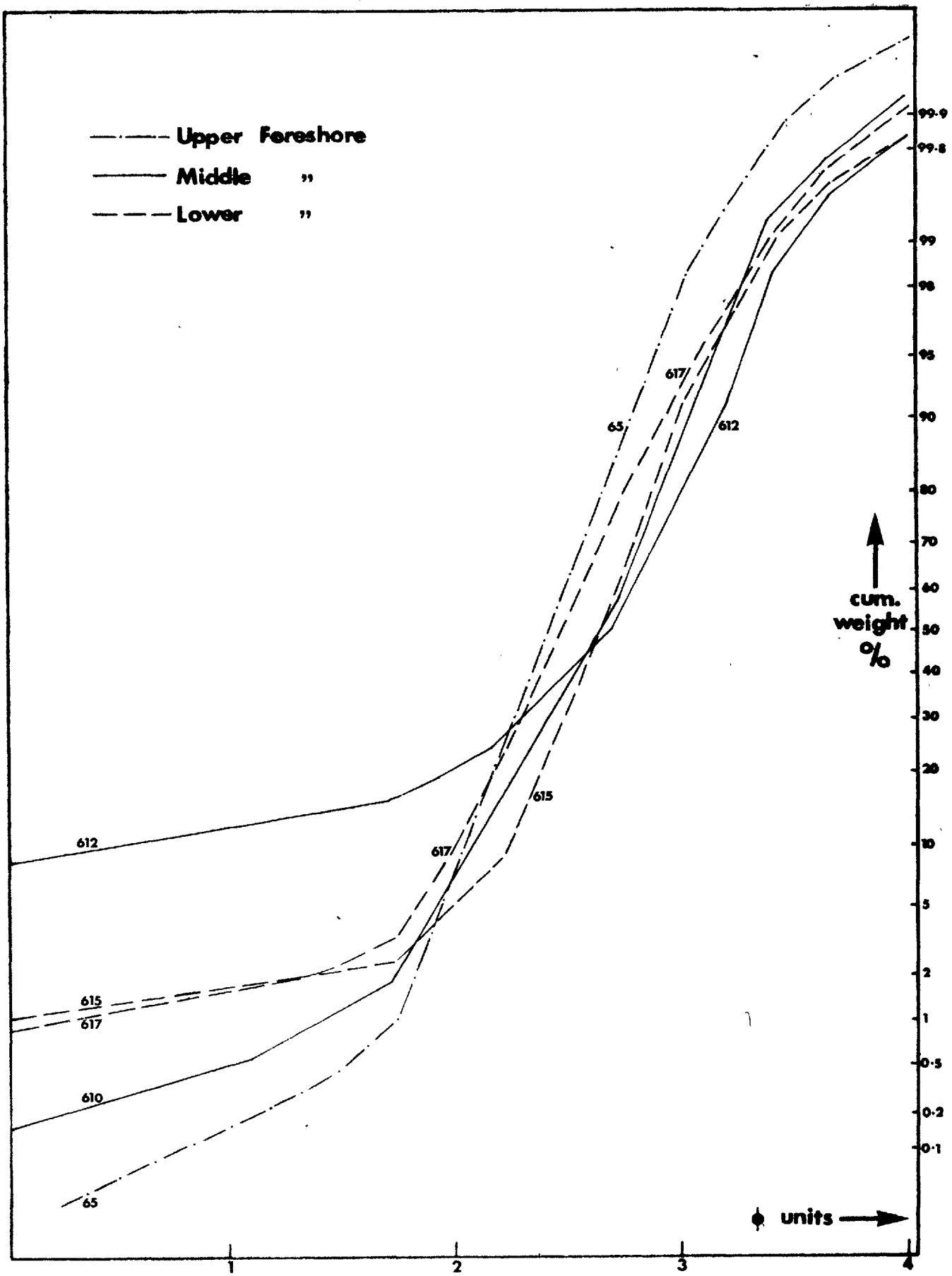


FIG. 6.8: GRAINSIZE DISTRIBUTIONS, TRANSECT 6.

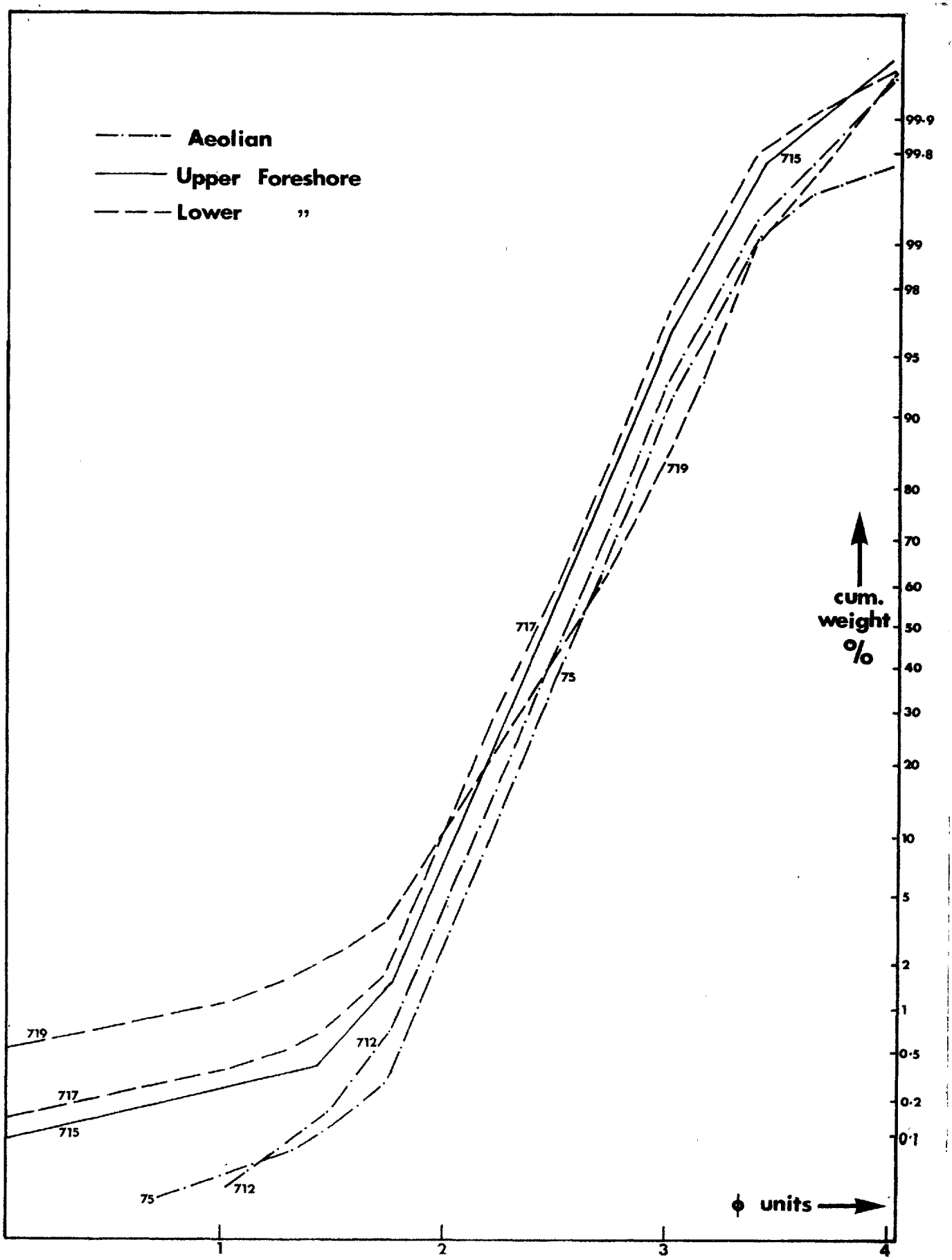


FIG. 6.9: GRAINSIZE DISTRIBUTIONS, TRANSECT 7.

Sample	% Co_3	Proportions %				Textural Parameters ø units				
		1			3	2				
						M_2		o_2		
21 D	10.6	5.0		94.0	1.0	2.71		.25		
22 D		.5		99.0	.5	2.67		.25		
23 D		.3		99.4	.3	2.72		.24		
		1	2A	2B	3	1	2A		2B	
						M_1	M_{2A}	o_{2A}	M_{2B}	o_{2B}
24	12.3	.2	0	98.8	1.0				2.70	.28
25*		.2	0	98.8	1.0				2.73	.22
26		.1	8.4	91.0	.5		2.30	.22	2.62	.23
27	11.5	.7	9.3	89.7	.3		2.08	.21	2.56	.29
28		2.7	30.3	66.8	.2	1.80	2.19	.27	2.79	.27
29		3.6	35.4	60.9	.1	2.10	2.30	.27	2.84	.27
210	15.3	4.0	38.0	57.7	.3	.64	2.42	.30	3.02	.21
211		14.0	37.0	48.8	.2	.37	2.53	.35	3.05	.19
212		19.0	23.0	57.6	.4	-.55	2.53	.32	3.08	.21
213	18.4	12.0	15.0	72.7	.3	-.75	2.62	.23	3.11	.18
214		14.0	20.0	65.5	.5	-1.10	2.77	.19	3.16	.16
215		3.7	16.3	79.1	.9	-.55	2.81	.23	3.19	.17
216	15.0	.9	9.1	89.5	.5	.21	2.73	.22	3.17	.18
217		2.5	13.5	83.0	1.0	.70	2.81	.19	3.22	.16
218		1.8	6.5	90.7	1.0	.97	2.76	.23	3.20	.18
219	14.9	.8	6.7	91.5	1.0	1.47	2.77	.24	3.23	.18
220		1.2	9.8	87.4	1.6		2.84	.23	3.23	.19
221		.7	7.3	90.2	1.8		2.80	.24	3.24	.19

TABLE 6.2 : Subpopulation proportions and textures, transect 2.

D = dune samples * = HW mark

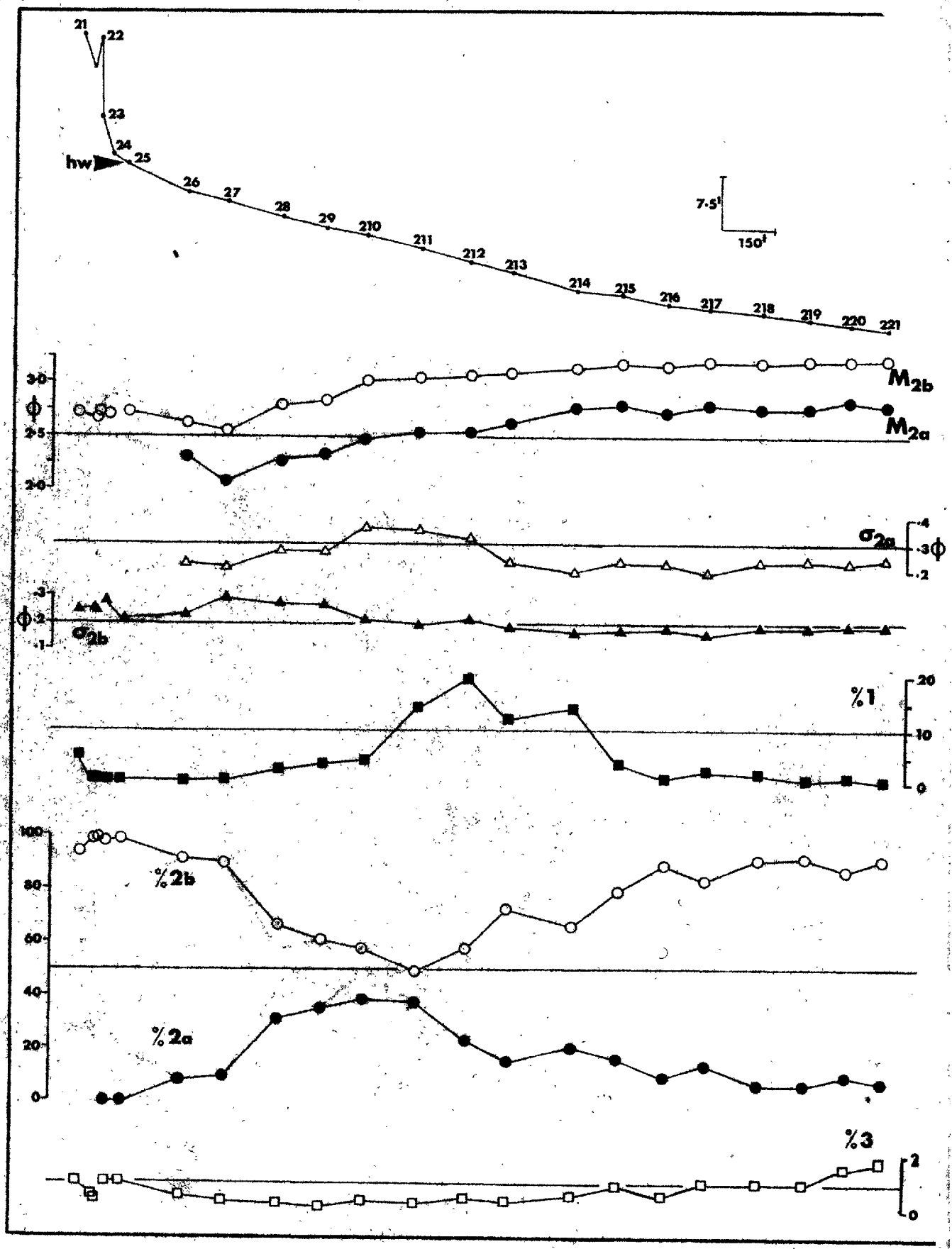


FIG. 6.10: SUBPOPULATION TEXTURES AND PROPORTIONS, TRANSECT 2.

Sample	% Co_3	Proportion %				Textural Parameters ø units				
		1	2		3	2				
						M_2			σ_2	
31 D	10.3	1.4	98.0		.6	2.67			.33	
32 D	10.3	.6	98.0		1.4	2.71			.30	
33 D	13.1	.2	99.6		.2	2.74			.28	
		1	2A	2B	3	1	2A		2B	
						M_1	M_{2A}	σ_{2A}	M_{2B}	σ_{2B}
34	13.6	.1	0	99.0	.9				2.74	.28
35 A	12.3	.1	0	95.4	4.5				2.70	.24
36 A	17.3	.1	0	96.7	3.2				2.67	.22
37	12.5	0	0	97.1	2.9				2.68	.24
38	13.1	.1	0	98.9	1.0				2.68	.24
39*	12.5	.1	3.1	94.0	2.8		2.24	.27	2.62	.25
310	14.0	0	4.2	95.3	.5		2.20	.24	2.70	.28
311	12.5	.1	2.0	96.9	1.0		2.20	.25	2.57	.25
312	12.2	.4	5.2	94.3	.1		2.13	.25	2.52	.30
313	12.8	1.8	11.2	86.9	.1	1.10	1.98	.25	2.48	.30
314	14.6	2.0	15.5	82.4	.1	.82	1.98	.33	2.47	.35
315	16.1	6.0	30.0	63.9	.1	.69	2.16	.26	2.74	.25
316	18.3	6.0	45.0	49.8	.2	.68	2.44	.33	2.90	.22
317	17.8	13.0	45.0	41.6	.4	-.20	2.53	.35	2.90	.22
318	17.4	6.0	28.0	65.7	.3	-.10	2.54	.35	2.90	.24
319	19.7	13.5	45.5	40.7	.3	.05	2.57	.33	3.06	.20
320	18.6	10.0	24.0	65.5	.5	-.22	2.50	.30	3.04	.20
321	21.1	16.0	19.0	64.7	.3	-.53	2.57	.20	3.04	.22
322	16.7	4.0	9.0	86.4	.6	-.92	2.63	.30	3.04	.23
323	18.3	2.8	9.4	86.8	1.0	-.63	2.60	.30	3.08	.20
324	17.0	3.2	13.8	82.3	.7	-.53	2.74	.27	3.10	.19
325	16.0	2.8	11.0	85.5	.7	-.13	2.65	.27	3.10	.21
326	14.8	.9	2.7	95.9	.5	.13	2.59	.35	3.08	.25
327	14.4	.4	1.0	97.8	.8		2.45	.28	3.12	.24
328	15.4	.6	4.6	93.7	1.1		2.73	.37	3.12	.23
329	15.3	.6	4.2	93.9	1.3		2.70	.37	3.12	.23
330	16.3	.6	4.4	93.4	1.6		2.75	.37	3.14	.24

TABLE 6.3 : Subpopulation proportions and textures, transect 3.

D = dune sample * = HW mark A = aeolian sample

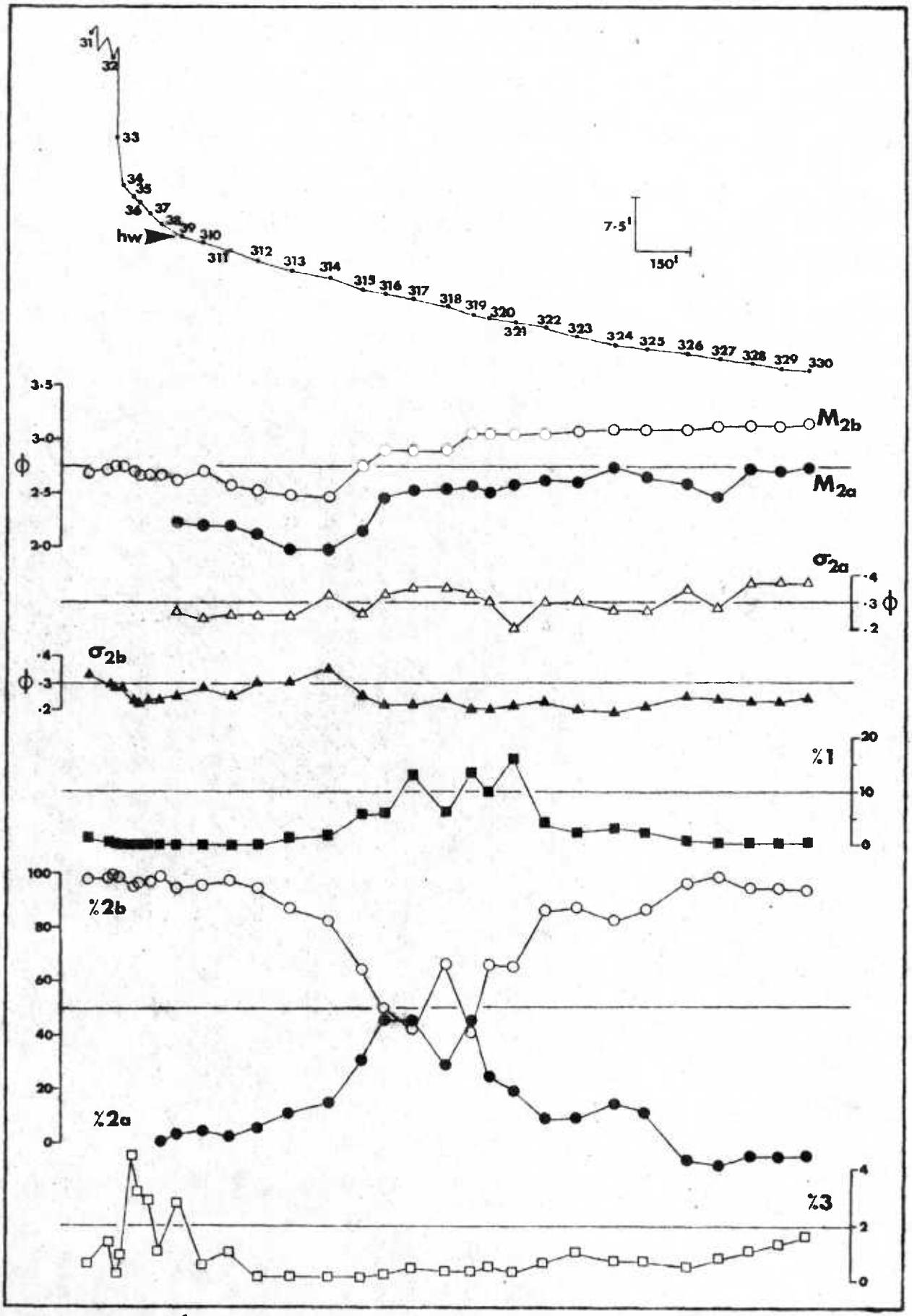


FIG. 6.11: SUBPOPULATION TEXTURES AND PROPORTIONS, TRANSECT 3.

Sample	% Co_3	Proportions %				Textural Parameters ∅ units			
		1	2		3	2			
						M_2		σ_2	
41 D	12.0	.2	97.8		2.0	2.68		.27	
42 D		.8	98.7		.5	2.73		.31	
43 D		.4	99.2		.4	2.70		.29	
		1	2A	2B	3	2A		2B	
						M_{2A}	σ_{2A}	M_{2B}	σ_{2B}
44	13.2	0	0	90.0	10.0			2.70	.23
45*		.1	1.2	98.6	.2	2.15	.24	2.88	.23
46		.2	2.8	96.9	.1	2.14	.20	2.72	.24
47	12.6	.4	6.0	93.5	.1	2.13	.25	2.65	.26
48		.9	14.6	84.4	.1	2.13	.18	2.71	.25
49		1.2	32.8	65.9	.1	2.30	.31	2.77	.23
410	15.9	2.0	34.0	63.9	.1	2.44	.31	2.88	.21
411		2.0	16.5	81.4	.1	2.60	.35	2.89	.21
412		1.2	11.8	86.9	.1	2.62	.28	3.00	.19
413	16.0	.7	16.3	82.8	.2	2.66	.28	3.02	.18
414		.5	9.5	89.8	.2	2.66	.34	3.06	.23
415		1.0	17.0	81.9	.1	2.69	.23	3.08	.20
416	18.5	.5	16.0	83.4	.6	2.80	.39	3.07	.20
417		.3	14.2	85.0	.5	2.75	.40	3.11	.18
418		.5	9.5	89.8	.2	2.56	.35	3.13	.18
419	22.2	.5	13.5	85.5	.5	2.53	.24	3.10	.20
420		.7	20.3	78.6	.4	2.74	.34	3.15	.20
421		.5	20.0	79.2	.3	2.62	.28	3.15	.20
422	26.1	.6	26.4	72.7	.3	2.82	.38	3.23	.22
423		.3	25.7	73.0	1.0	2.75	.34	3.20	.18
424		.3	22.0	76.8	.9	2.88	.42	3.23	.23
425	25.1	.5	17.0	81.5	1.0	2.61	.30	3.19	.20
426		.4	27.1	71.0	1.0	2.82	.33	3.28	.16

TABLE 6.4 : Subpopulation proportions and textures, transect 4.

D = dune sample * = HW mark

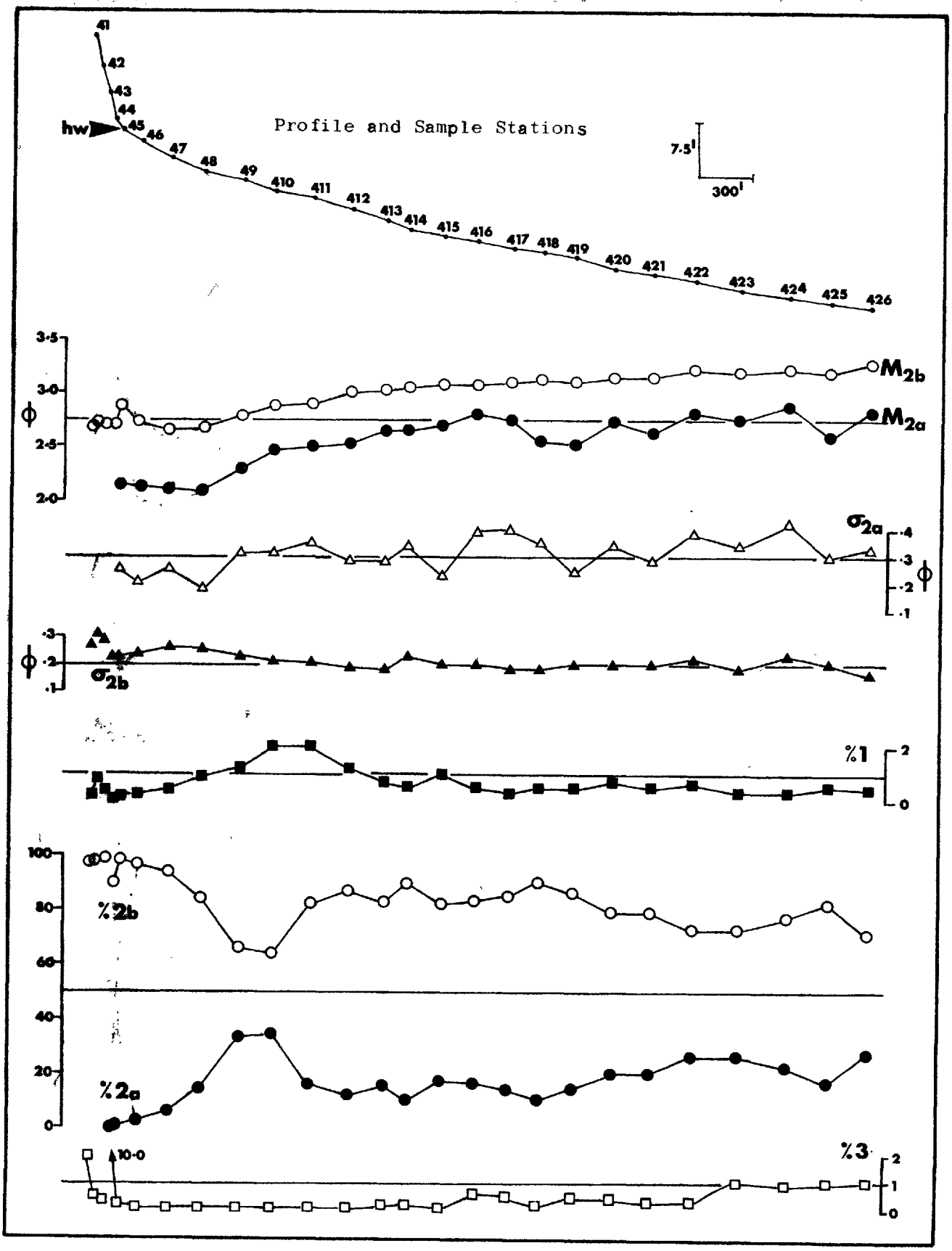


FIG. 6.12: SUBPOPULATION TEXTURES AND PROPORTIONS, TRANSECT 4.

Sample	% Co_3	Proportions %				Textural Parameters ø units			
		1	2		3	2			
						M_2		σ_2	
51 D	8.3	2.0	97.6		.4	2.56		.36	
52		0	8.0	91.4	.6	1.95	.30	2.86	.27
53 D		.7	99.2		.1	2.57		.33	
54 D	9.5	.5	99.4		.1	2.67		.31	
55 D		.5	99.4		.1	2.60		.33	
		1	2A	2B	3	2A		2B	
						M_{2A}	σ_{2A}	M_{2B}	σ_{2B}
56		.2	4.0	95.6	.1	2.15	.18	2.79	.28
57	11.0	.4	.5	98.7	.2	2.15	.19	2.69	.30
58		.5	2.0	97.3	.2	2.16	.18	2.65	.35
59*		.8	2.2	96.7	.2	2.15	.18	2.69	.30
510	13.0	.4	3.6	95.8	.2	2.15	.16	2.85	.24
511		1.6	8.4	89.6	.4	2.19	.18	2.66	.25
512		1.8	28.2	69.9	.1	2.18	.21	2.65	.25
513	8.8	1.9	59.1	38.9	.1	2.33	.26	2.61	.29
514		2.4	45.6	51.9	.1	2.28	.22	2.70	.23
515		2.2	52.5	47.4	.1	2.30	.27	2.65	.25
516	10.5	1.9	34.1	63.9	.1	2.24	.19	2.80	.18
517		1.7	20.3	77.8	.2	2.15	.17	2.65	.20
518		.9	12.1	86.8	.2	2.19	.17	2.73	.25
519	9.6	.9	13.6	86.4	.1	2.13	.22	2.64	.22
520		.6	7.0	92.2	.2	2.28	.25	2.80	.21
521		1.0	7.5	91.0	.5	2.27	.27	2.80	.19
522	11.4	.7	10.3	87.5	1.5	2.29	.30	2.81	.23
523		.9	8.1	90.6	.4	2.27	.25	2.87	.22
524		.8	12.2	86.6	.4	2.35	.32	2.87	.23
525	13.1	.5	18.5	80.6	.4	2.51	.35	2.96	.19
526		.4	17.6	81.8	.2	2.48	.33	2.95	.20
527		.5	12.5	86.7	.3	2.42	.32	2.91	.20
528	10.3	.5	17.5	81.8	.2	2.38	.30	2.85	.21
529		.4	24.6	74.6	.4	2.48	.32	2.90	.20
530		.5	14.5	84.9	.1	2.53	.30	2.95	.21

TABLE 6.5 : Subpopulation proportions and textures, transect 5.

D = dune sample * = HW mark

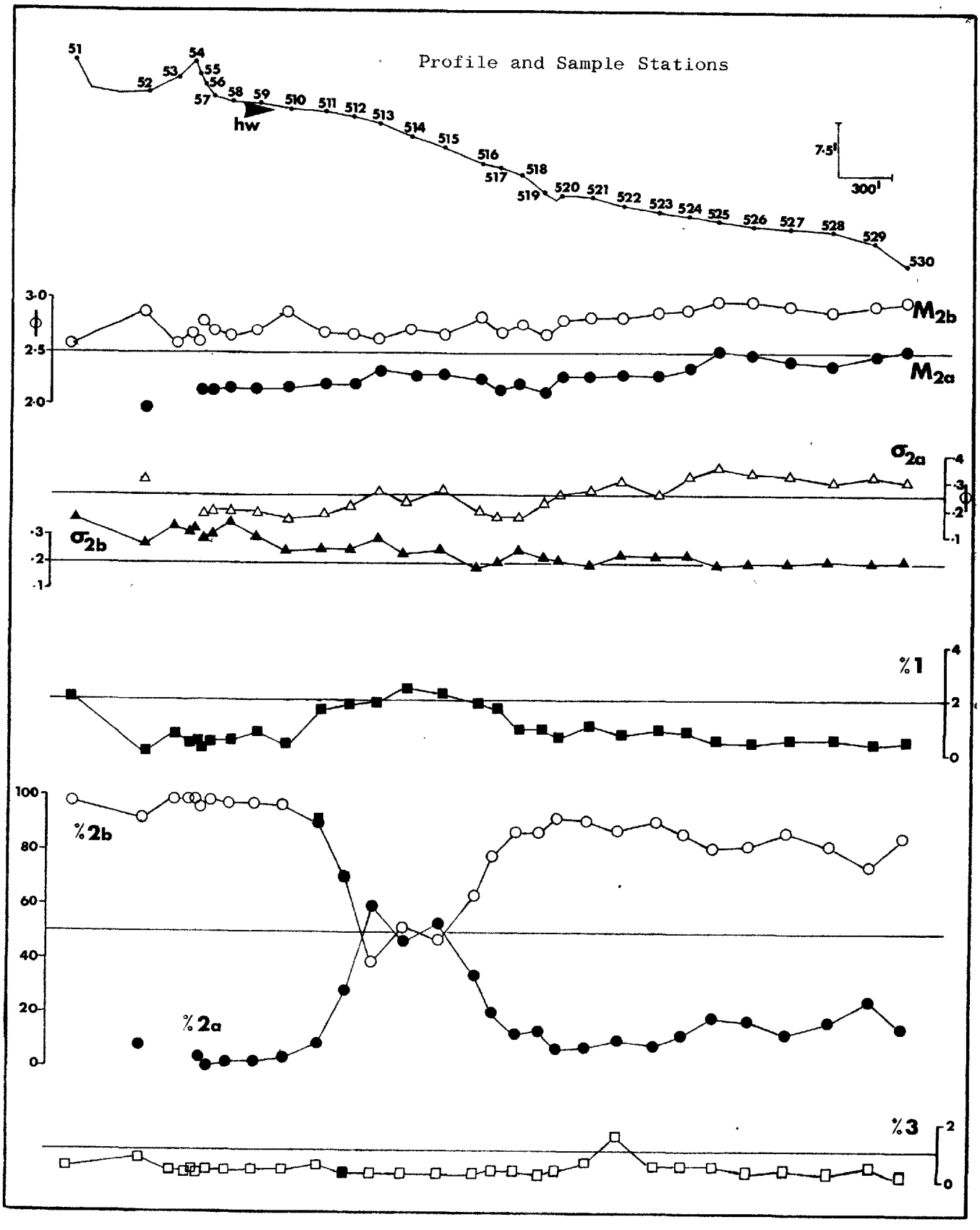


FIG. 6.13: SUBPOPULATION TEXTURES AND PROPORTIONS, TRANSECT 5.

Sample	% carb-onate	Proportions %				Textural Parameters ø units			
		1	2		3	M_2		σ_2	
61 D	7.1	.2	99.7		.1	2.59		.26	
62 D		.2	99.7		.1	2.60		.30	
		1	2A	2B	3	2A		2B	
						M_{2A}	σ_{2A}	M_{2B}	σ_{2B}
63	3.8	.3	0	90.0	9.7			2.40	.25
64		.3	0	99.5	.2			2.45	.30
65*		.5	0	99.3	.2			2.40	.29
66	9.4	.3	0	99.4	.3			2.44	.28
67		.5	5.0	94.2	.3	2.10	.25	2.50	.27
68		.5	16.0	83.3	.2	2.09	.18	2.63	.25
69	9.4	1.0	17.0	81.7	.3	2.11	.20	2.65	.24
610		1.0	42.0	56.8	.2	2.36	.31	2.79	.26
611		4.0	48.0	47.8	.2	2.35	.33	2.82	.26
612	20.0	20.0	36.0	43.4	.6	2.47	.28	2.97	.23
613		5.0	58.0	36.0	1.0	2.55	.28	2.77	.30
614		4.0	64.0	31.6	.4	2.58	.27	2.81	.28
615	13.2	4.0	11.0	83.0	2.0	2.25	.26	2.69	.22
616		4.0	12.0	82.0	2.0	2.19	.22	2.68	.21
617		3.0	12.0	83.0	2.0	2.12	.27	2.50	.29

TABLE 6.6 : Subpopulation proportions and textures, transect 6.

D = dune sand * = HW mark

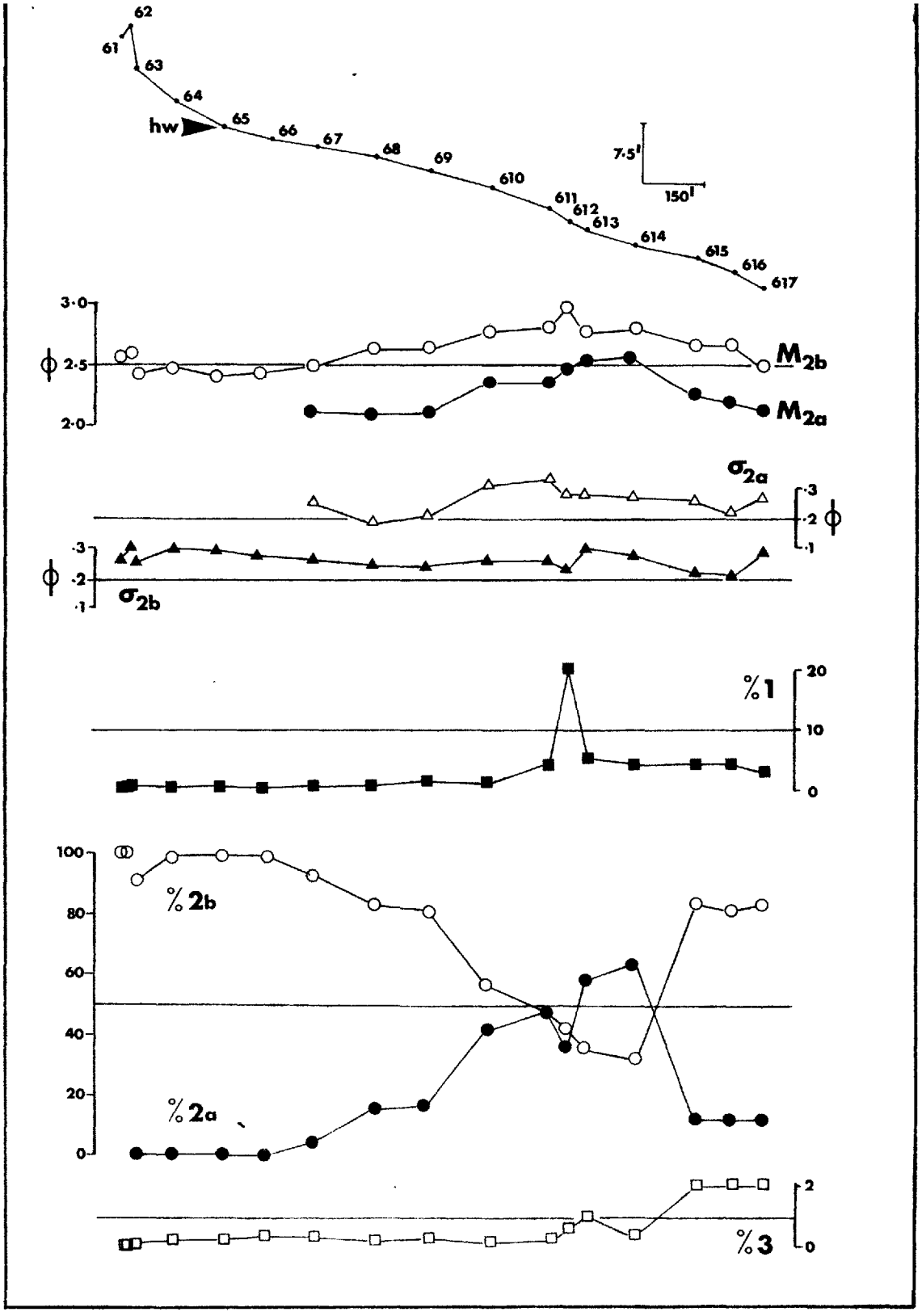


FIG. 6.14: SUBPOPULATION TEXTURES AND PROPORTIONS, TRANSECT 6.

Sample	% carb-onate	Proportions %				Textural Parameters ø units			
		1	2		3	2			
						M_2		σ_2	
71 D	8.2	.1	99.8		.1	2.63		.27	
72 A	10.9	.1	99.8		.1	2.57		.27	
73 A	11.0	.2	99.1		.7	2.64		.30	
74 A	8.1	.2	99.8		1.0	2.58		.31	
75 A	9.8	.2	98.6		1.2	2.60		.30	
76 A	10.1	.3	98.9		.8	2.61		.29	
77 A	11.5	.2	99.2		.6	2.63		.31	
78 A	11.7	.5	99.0		.5	2.63		.32	
79 A	12.0	.1	99.4		.5	2.63		.30	
710 A	12.6	.2	98.8		1.0	2.65		.31	
711 A	11.9	.2	99.4		.4	2.57		.31	
712 A	12.5	.1	99.3		.6	2.56		.32	
		1	2A	2B	3	2A		2B	
						M_{2A}	σ_{2A}	M_{2B}	σ_{2B}
713	9.8	.6	0	99.2	.2			2.45	.32
714	12.0	.6	0	98.8	.6			2.45	.31
715*	11.2	.4	0	99.1	.5			2.45	.31
716	10.3	.6	22.4	76.5	.5	2.10	.18	2.63	.25
717	11.4	.6	19.4	79.7	.3	2.13	.25	2.48	.28
718	12.0	.7	31.3	66.0	2.0	2.50	.32	2.90	.25
719	9.8	1.6	13.4	84.0	1.0	2.08	.32	2.67	.34

TABLE 6.7 : Subpopulation proportions and textures, transect 7.

D = dune sample A = aeolian sample

* = HW mark

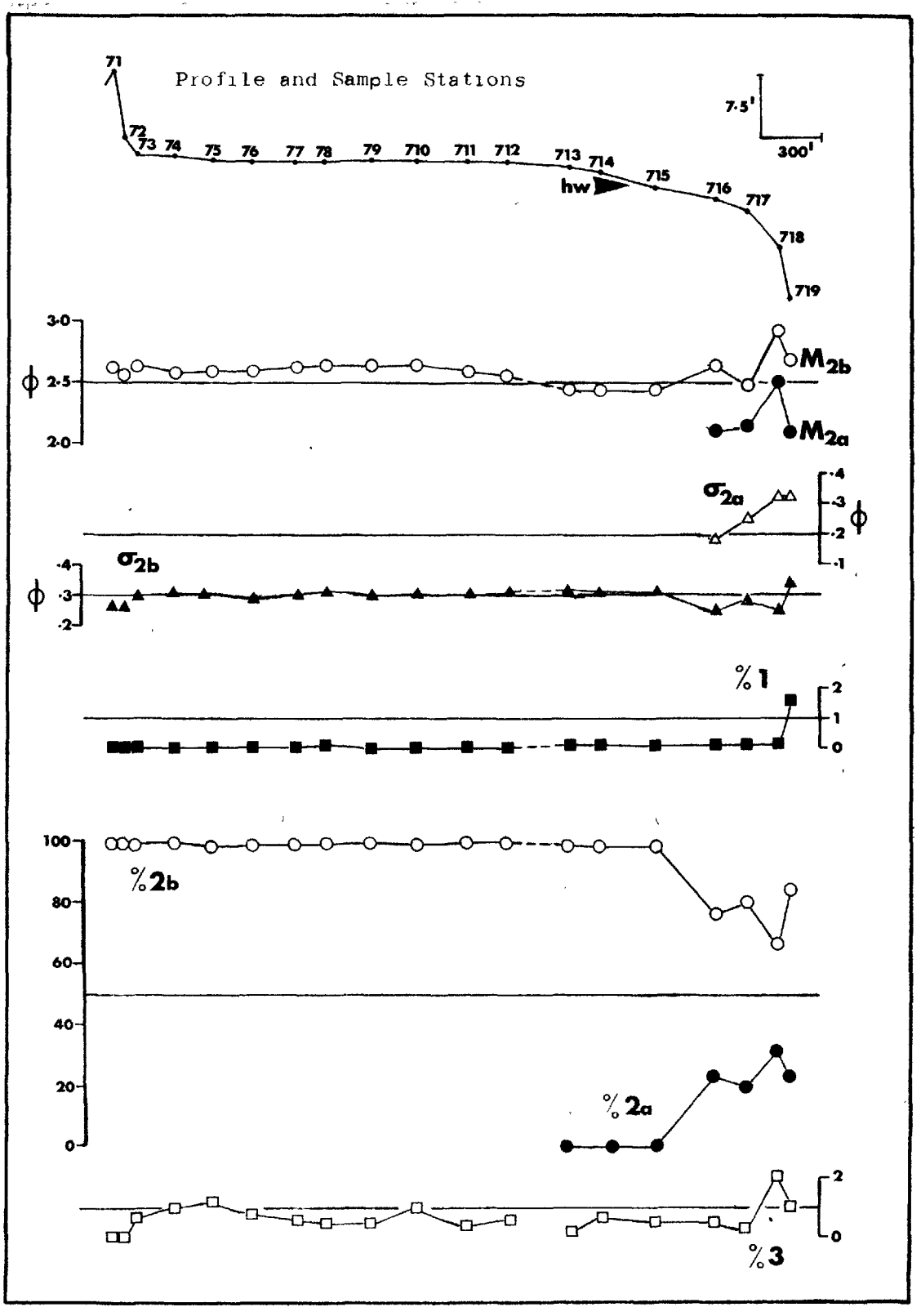


FIG. 6.15: SUBPOPULATION TEXTURES AND PROPORTIONS, TRANSECT 7.

onto the upper foreshore by very high swashes (dune sands generally do not contain this suspended population).

Transect 5 is distinguished from the others by the development of a runnel, and associated ridge, parallel to the shoreline. These features serve to demarcate the middle and lower foreshores, since it is here that some change in foreshore/inshore slope occurs. However, the differentiation of middle and lower foreshore is damped on transects 4 and 5 because of the restrained slopes of most of their profiles.

Sample 52 was taken from the edge of a small, shallow (6 inches) lake behind the seaward line of young dunes. The coarser saltation population is of organic origin, the finer (which may be deposited from wind suspension) is detrital.

Several samples from the uppermost foreshore of transect 6 were taken from cavity sands above high water mark (which was not distinctly visible, cavity sand also occurring below it). These probably are aeolian deposits, since the steep foreshore slope and dry, highly permeable, cavity sand combine to reduce the effect of upper swash zone action.

Transect 7 traverses a profile that is quite distinct from the others. Most of it is above the level of many tides, including springs, and owes its formation to aeolian action (see Chapter 1). This is reflected by the nature of sediment textures, only one saltation population being present. Even on high spring tides, the sea reaches stations 74 - 76 by encircling the aeolian flat from

north and (partly) south, stations 77 - 713 remaining uncovered or being partially covered by 'dead' water. Hence marine action proper is restricted to periods of intensified meteorological input and high sea states.

6.4 Quantitative Analysis of Longshore Variations

It has been shown that the variations of textural characteristics along successive transects have much in common. In order to establish the extent of uniformity, or otherwise, between transects, it is necessary to quantify some of the relationships suggested qualitatively in the previous sections.

To this end, it is advantageous if these relationships can be simplified to conform to a workable model that facilitates statistical manipulation. For present purposes, linear functions offer the most straightforward approach.

In Tables 6.8 and 6.9 are shown the product-moment correlation coefficients for the association of textural response variables with some of the static 'process' variables that are easily measured - height (relative to MHWS), distance (horizontal from the point of intersection of MHWS with the foreshore surface) and slope (local). For this analysis, both sets of variables are considered as random.

The response variables fall into two broad categories - the purely textural variables which approximate significantly to linear correlation with the process variables, and the proportion variables

TRANSECT	VARIABLES	HEIGHT	DISTANCE	SLOPE
1	M_{2A}	.80**	.76**	-.63**
(n=17)	M_{2B}	.92**	.89**	-.80**
	σ_{2A}	.37	.29	-.37
	σ_{2B}	-.81**	-.81**	.54*
	% 1	-.09	-.16	.22
	% 2A	-.40	-.44	.31
	% 2B	.31	.36	-.04
	% 3	.81**	.86**	-.57*
2	M_{2A}	.94**	.91**	-.73**
(n=16)	M_{2B}	.94**	.90**	-.76**
	σ_{2A}	-.30	-.32	.33
	σ_{2B}	-.80**	-.73**	.51*
	% 1	-.06	-.18	.30
	% 2A	-.50	-.54*	.45
	% 2B	.41	.49	-.46
	% 3	.77**	.85**	-.73**
3	M_{2A}	.74**	.76**	-.51*
(n=23)	M_{2B}	.87**	.86**	-.64**
	σ_{2A}	.57**	.58**	-.59**
	σ_{2B}	-.47*	-.45*	.24
	% 1	.07	.01	-.20
	% 2A	-.18	-.23	.01
	% 2B	.12	.18	.04
	% 3	.05	.13	.28

TABLE 6.8 : Correlation coefficients, textural response variables/static process variables, transects 1-3

* = .05 > P > .01; ** = .01 > P

TRANSECT	VARIABLES	HEIGHT	DISTANCE	SLOPE
4 (n=20)	M_{2A}	.78**	.74**	-.78**
	M_{2B}	.95**	.91**	-.87**
	σ_{2A}	.47*	.45*	-.47**
	σ_{2B}	-.56**	-.53*	.63**
	% 1	-.58**	-.58**	.26
	% 2A	.19	.06	-.37
	% 2B	-.19	-.22	.35
	% 3	.81**	.84**	-.57**
5 (n=19)	M_{2A}	.67**	.77**	-.25
	M_{2B}	.86**	.87**	-.27
	σ_{2A}	.66**	.72**	-.32
	σ_{2B}	-.59**	-.54*	.17
	% 1	-.90**	-.85**	.07
	% 2A	-.67**	-.54*	.05
	% 2B	.69**	.56*	-.03
	% 3	.26	.20	-.33
6 (n=13)	M_{2A}	.02	.00	.31
	M_{2B}	.02	.09	.06
	σ_{2A}	.01	.01	.23
	σ_{2B}	-.02	-.10	.32
	% 1	.33	.36	.33
	% 2A	-.44	-.48	.18
	% 2B	-.12	-.15	-.50
	% 3	.84**	.81**	.41
7 (n=15)	M_{2A}	-.65**	-.80**	-.57*
	M_{2B}	.43	.19	.26
	σ_{2A}	-.08	-.41	.17
	σ_{2B}	-.15	-.41	.28
	% 1	.89**	.64**	.92**
	% 2A	-.76**	-.85**	-.56*
	% 2B	.51	-.73**	-.20
	% 3	.43	.54	.30

TABLE 6.9 : Correlation coefficients, textural response variables/static process variables, transects 4-7

which generally do not (percentage population 3 is an exception to this on four transects).

The correlation coefficient relating to slope is generally lower in magnitude than those relating to height or distance. By using a partial correlation coefficient, we may hold the latter two variables constant and examine the relationship between response variable and slope only. For transect 1 samples, the relationships between subpopulation 2A and 2B mean grain sizes (M_{2A} and M_{2B}) and slope are no longer significant ($r_{MS.HD}$ = 0.39 and 0.19 respectively). This supports the view of Ingle (1966) that overall foreshore/inshore slope (i.e. height and distance, or shape of the profile) is more important in fixing swash zone characteristics than is local slope. It may further be shown that, of the two remaining process variables, height is significant when distance is held constant, whereas distance is not significant when height is held constant. Thus for subsequent analyses, the height of a station relative to a fixed point will be used in preference to the other two static variables.

The textural variables' relationship to this static variable can be best studied by linear regression analysis. Such is not suitable in the case of the proportion variables. For these, the analysis of variance provides a suitable vehicle for comparisons between transects.

As explained in Chapter 2, when the same analysis of variance was adopted for between-profile beach stability comparisons, a

serious limitation to the method is imposed when interaction between main effects becomes important. In this case, where we are considering transects and foreshore heights as main effects, then interaction between them becomes significant if the trends of variation of the response variable with foreshore height are not the same for all transects. Thus a study of interaction gives us a quantitative estimate of the degree of uniformity of trends on successive transects.

To provide the necessary framework for the analysis, one or more replicates per sample are required. These are not directly available. By dividing the profile into blocks (of height 2 feet), two values of the required parameter were obtained at fixed positions within each block (generally directly, but sometimes by extrapolation between two adjacent samples), these then being treated as replicates. An equal number of blocks was thereby obtained on all transects, since the vertical elevation of high water mark above low water mark was approximately the same for most transects.

All heights were measured relative to the high water mark of the tide prior to sampling. This datum therefore varies a little between transects. Subpopulation proportions (%) have been transformed into arcsines, to normalise their distribution; anova tables are thus coded.

The completed anovas are shown in Table 6.10. For the purpose of these, and subsequent, analyses a fixed-effect Model 1 type is assumed.

For all four subpopulation proportions, there are highly significant variations with foreshore height and transect position over and above the parametric variances of the items (i.e. within block variance). Interaction is well developed in all cases, so that the trends of variation with height of these response elements are not uniform for all transects.

In order to examine the interaction in greater detail, the analyses have been repeated in six steps, by considering adjacent transects in pairs. The resulting anovas are shown in Tables 6.11-6.14. It is apparent that interaction is not equally developed between all pairs of transects. This information is conveniently summarised below; transects between which interaction is <u>not</u> significant are joined by a line (the trends of variation are therefore the same along those transects that are joined in this way).

SUBPOPULATION (1)	1	2	3	4	5	6	7	1% P
SUBPOPULATION (2A)	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	5	6	7	1% P
SUBPOPULATION (2B)	<u>1</u>	<u>2</u>	<u>3</u>	4	5	6	7	5% P
SUBPOPULATION (3)	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	6	7	1% P

With the exception of population 1 proportions, there is a significant measure of homogeneity of trends of variation across those transects which monitor the western half of the foreshore. It may be seen from Tables 6.11 - 6.14 that, even when significant, the interaction mean square is small for pairs 1-5 (again with the exception of population 1) and considerably larger for pairs 5-7.

RESPONSE VARIABLE	SOURCE OF VARIATION	df	SS	MS	F
1	Foreshore heights	9	2074.58	230.51	79.31**
	Transects	6	1222.53	203.76	70.11**
	Interaction	54	2462.18	45.60	15.69**
	Error	70	203.44	2.91	
	Total	139	5962.73		
2A	Foreshore heights	9	10173.11	1130.35	76.86**
	Transects	6	1188.06	198.01	13.46**
	Interaction	54	7937.19	146.98	9.99**
	Error	70	1029.50	14.71	
	Total	139	20327.86		
2B	Foreshore heights	9	12119.48	1346.61	90.60**
	Transects	6	1202.76	200.46	13.48**
	Interaction	54	9407.46	174.21	11.72**
	Error	70	1040.37	14.86	
	Total	139	23770.07		
3	Foreshore heights	9	135.23	15.03	25.81**
	Transects	6	155.07	25.85	44.40**
	Interaction	54	99.00	1.83	3.15**
	Error	70	40.75	.58	
	Total	139	430.05		

TABLE 6.10 : Anovas, subpopulation proportions

TRANSECTS	SOURCE OF VARIATION	df	SS	MS	F
1 & 2	Foreshore heights	9	2516.59	279.62	44.87**
	Transects	1	1.84	1.84	.30ns
	Interaction	9	229.54	25.50	4.09**
	Error	20	124.63	6.23	
	Total	39	2872.59		
2 & 3	Foreshore heights	9	1467.15	163.02	20.04**
	Transects	1	97.41	97.41	11.98**
	Interaction	9	398.78	44.31	5.45**
	Error	20	162.62	8.13	
	Total	39	2125.95		
3 & 4	Foreshore heights	9	607.97	67.55	20.86**
	Transects	1	175.31	175.31	54.14**
	Interaction	9	288.90	32.10	9.91**
	Error	20	64.77	3.24	
	Total	39	1136.95		
4 & 5	Foreshore heights	9	101.87	11.32	27.89**
	Transects	1	23.46	23.46	57.80**
	Interaction	9	19.43	2.16	5.32**
	Error	20	8.12	.41	
	Total	39	152.88		
5 & 6	Foreshore heights	9	337.74	37.53	63.49**
	Transects	1	87.56	87.56	148.13**
	Interaction	9	516.32	57.37	97.06**
	Error	20	11.82	.59	
	Total	39	953.44		
6 & 7	Foreshore heights	9	492.43	54.72	90.86**
	Transects	1	188.27	188.27	312.65**
	Interaction	9	336.01	37.34	62.00**
	Error	20	12.04	.60	
	Total	39	1028.76		

TABLE 6.11 : Anovas for paired transects, subpopulation 1 proportions

TRANSECTS	SOURCE OF VARIATION	df	SS	MS	F
1 & 2	Foreshore heights	9	2798.28	310.92	38.67**
	Transects	1	282.01	282.01	35.07**
	Interaction	9	153.84	17.09	2.12ns
	Error	20	160.82	8.04	
	Total	39	3394.95		
2 & 3	Foreshore heights	9	3215.49	357.28	21.54**
	Transects	1	360.48	360.48	21.74**
	Interaction	9	294.58	32.73	1.97ns
	Error	20	331.71	16.59	
	Total	39	4202.26		
3 & 4	Foreshore heights	9	2204.56	244.95	6.86**
	Transects	1	75.65	75.65	2.12ns
	Interaction	9	719.59	79.95	2.24ns
	Error	20	714.13	35.71	
	Total	39	3713.93		
4 & 5	Foreshore heights	9	3124.56	347.17	17.53**
	Transects	1	361.62	361.62	18.26**
	Interaction	9	818.15	90.91	4.59**
	Error	20	396.00	19.80	
	Total	39	4700.33		
5 & 6	Foreshore heights	9	4552.35	505.82	31.73**
	Transects	1	.28	.28	.02ns
	Interaction	9	5246.39	582.93	36.56**
	Error	20	318.86	15.94	
	Total	39	10117.88		
6 & 7	Foreshore heights	9	7522.53	835.84	68.75**
	Transects	1	138.83	138.83	11.42**
	Interaction	9	1517.92	168.66	13.87**
	Error	20	243.14	12.16	
	Total	39	9422.42		

TABLE 6.12 : Anovas for paired transects, subpopulation 2A proportions

TRANSECTS	SOURCE OF VARIATION	df	SS	MS	F
1 & 2	Foreshore heights	9	5037.64	559.74	30.42**
	Transects	1	152.18	152.18	8.27**
	Interaction	9	225.56	25.06	1.36ns
	Error	20	367.95	18.40	
	Total	39	5783.33		
2 & 3	Foreshore heights	9	4283.66	475.96	19.04**
	Transects	1	356.95	356.95	14.28**
	Interaction	9	685.80	76.20	3.05*
	Error	20	499.93	25.00	
	Total	39	5826.24		
3 & 4	Foreshore heights	9	3268.77	363.20	20.41**
	Transects	1	14.65	14.65	.82ns
	Interaction	9	894.05	99.34	5.58**
	Error	20	355.97	17.80	
	Total	39	4533.45		
4 & 5	Foreshore heights	9	3172.42	352.49	19.46**
	Transects	1	399.30	399.30	22.04**
	Interaction	9	818.31	90.92	5.02**
	Error	20	362.29	18.11	
	Total	39	4752.32		
5 & 6	Foreshore heights	9	4166.11	462.90	29.32**
	Transects	1	39.09	39.09	2.48ns
	Interaction	9	5934.82	659.42	41.76**
	Error	20	315.80	15.79	
	Total	39	10455.82		
6 & 7	Foreshore heights	9	7622.93	846.99	194.98**
	Transects	1	324.16	324.16	74.62**
	Interaction	9	1649.28	183.25	42.19**
	Error	20	86.88	4.34	
	Total	39	9683.25		

TABLE 6.13 : Anovas for paired transects, subpopulation 2B proportions

TRANSECTS	SOURCE OF VARIATION	df	SS	MS	F
1 & 2	Foreshore heights	9	39.73	4.41	12.72**
	Transects	1	9.30	9.30	26.80**
	Interaction	9	7.03	.78	2.25ns
	Error	20	6.94	.35	
	Total	39	63.00		
2 & 3	Foreshore heights	9	71.55	7.95	5.11**
	Transects	1	6.40	6.40	4.12ns
	Interaction	9	11.78	1.31	.84ns
	Error	20	31.09	1.55	
	Total	39	120.82		
3 & 4	Foreshore heights	9	54.68	6.08	4.30**
	Transects	1	35.80	35.80	25.31**
	Interaction	9	19.72	2.19	1.55ns
	Error	20	28.29	1.41	
	Total	39	138.49		
4 & 5	Foreshore heights	9	14.00	1.56	5.23**
	Transects	1	.26	.26	.87ns
	Interaction	9	2.77	.31	1.03ns
	Error	20	5.94	.30	
	Total	39	22.97		
5 & 6	Foreshore heights	9	44.36	4.93	18.77**
	Transects	1	16.87	16.87	64.27**
	Interaction	9	21.07	2.34	8.92**
	Error	20	5.25	.26	
	Total	39	87.55		
6 & 7	Foreshore heights	9	69.34	7.70	95.09**
	Transects	1	32.69	32.69	403.46**
	Interaction	9	35.82	3.98	49.12**
	Error	20	1.62	.08	
	Total	39	139.47		

TABLE 6.14 : Anovas for paired transects, subpopulation 3 proportions

This is partly because the parametric variance of items is very small on transects 6 and 7, which follows from the fact that the actual number of samples per unit length of transect (below HW) was small on these transects, the resulting uniformity of proportions within blocks being due to necessary extrapolation between sample stations. However, the relative mean squares show that there is a real difference between transects 1-4 and transects 5-7, the former group being statistically homogeneous in response, but the latter differing significantly from them and from each other (in terms of trends of variation of subpopulation 2A, 2B and 3 proportions). Transect 5 represents a transition between the two groups.

This division is clearly related to strandline morphology and orientation, and to offshore bathymetry (see Chapter 1); these 'static' processes exert a profound influence on nearshore hydrodynamics.

Subpopulation 1 proportions are distributed in a different way on each transect, although as shown in Figs. 6.1 - 6.8 the pattern of distribution is essentially the same for transects 1-5. Hence the trends of distribution are similar with respect to foreshore height but out of phase with each other. This may indicate that this parameter is very sensitive to variations of offshore bathymetry and foreshore/inshore slope (both of which change progressively from west to east, see Chapter 1). Alternatively, the variation may reflect the nature of sampling, which was done on

different days, and the response of the parameter to changes of wave and tidal regimes.

The above analysis has been concerned with foreshore heights relative to the high water marks of the tides prior to sampling. The analysis has been repeated using a fixed datum common to all transects (MHWS), and the interaction between adjacent pairs examined at the same probability levels as before:

SUBPOPULATION (1)	1	2	3	4	5	6	7	1% P
SUBPOPULATION (2A)	1 2		3	4	5	6	7	1% P
SUBPOPULATION (2B)	1 2 3			4	5	6	7	5% P
SUBPOPULATION (3)	1 2 3			4 5		6	7	1% P

The tendency for interaction to disappear between the western transects remains, but clearly interaction is more widespread now than previously. Thus the trends of variation across successive transects are more compatable when related to the high water mark of the previous tides than when related to an average height of spring tides. This supports the assumption that process/response equilibria are in constant flux, adjusting to progressively cyclic tidal regimes. The relative responses to spring and neap regimes are however unknown, and it may be that the latter are able to modify the response to the former only slightly.

Because of the nature of interaction of main effects, a comparison of means is of limited statistical value but has some interpretative justification. The mean proportions of subpopulations on each transect (below HW mark) are shown in Table 6.15.

SUBPOPULATION	TRANSECT						
	1	2	3	4	5	6	7
1	4.8	4.4	2.4	.7	1.3	2.6	.8
2A	12.9	19.7	12.7	14.3	21.7	22.1	16.2
2B	81.7	75.5	84.4	84.8	76.8	74.9	82.0
3	.6*	.4	.5	.2	.2	.4	1.0

TABLE 6.15 : Mean proportions of subpopulations
(*this does not include the value for sample 13)

Using the Student-Neumann-Keuls test, these mean values may be divided into the following statistically homogeneous groups (.05 P .01):

% (1) 4 7 5 3 6 2 1

% (2A) 3 1 4 7 2 5 6

% (2B) 6 2 5 1 7 3 4

% (3) 4 5 2 6 3 1 7

There is some gradation of subpopulation 1 proportions from west to east, particularly from transects 1-4. This eastward diminishing gradient on the western half of the foreshore is similar to that already noted for foreshore stability (Chapter 2). Since transects were not sampled in order, this gradient cannot be related to changing tidal regimes, but must reflect a real diminution of bottom shear stresses in the collision zone and surf zone from transect 1 to transect 4. The eastward decreasing offshore and foreshore slopes on the western half of the beach produce an

eastward decreasing wave energy and an eastward increasing surf zone width respectively, both of which serve to restrain the shoreward movement of surface creep grains.

On transects 5 and 6, surface creep particles make up only a moderate proportion of the total populations, although the nature of offshore bathymetry with deep water close inshore must increase nearshore wave energy. On transect 5 the surf zone is well developed, but on transect 6 it is restricted in width. Steep offshore gradients may enhance the effect of gravity and so prevent shoreward movement of the sliding and rolling particles. However, on these transects, the proportion of subpopulation 2A grains is significantly greater than on most other transects. Hence it appears that the increased wave energy is able to pulverise the shelly fragments to form the less coarse and more concentrated saltating subordinate traction carpet of subpopulation 2A. Movement of coarse grains by surface creep must also be hindered by the greater coarseness of the resulting bottom sediment.

The out-of-order position of transect 2 subpopulation proportions can only be attributed to unsettled sea states prior to sampling (a moderate gale from 140° with waves 3 metres high, period 6 seconds, reported by the St. Gowan lightvessel). The greater wave energy and volume at that time would be transmitted through the nearshore system to produce more swash and, if percolation is unchanged, more backwash. Thus the coarser saltation population increases because swash zone shear stresses and velocities increase,

and/or the influence of backwash deposition increases.

The distribution of the mean proportions of subpopulation 3 may reflect differences of foreshore slope, but seems to be related to tidal regime. The highest spring tides occurred prior to sampling of transects 4 and 5; at this time, sea states were very calm. Thus it is likely that the increased current velocities of the spring tide were sufficient to outweigh the tendency of fine-grain deposition during calm weather.

The analysis of variance may also be used to examine the variations of subpopulation textures (mean size and standard deviation) with foreshore height and transect position. The framework for the analysis is as before. However, data has not been transformed since it is already in logarithmic units (ø units).

The completed anovas for the mean size and standard deviation of subpopulations 2A and 2B are shown in Table 6.16. For all four parameters, there are highly significant variations with foreshore height and transect position over and above the parametric within-block variance. Interaction between the main effects is also highly significant.

That the trends of variation of textures are not uniform across all transects has already been determined by the correlation analysis (Tables 6.8 and 6.9). On transects 1-5, there are important associations between textures and foreshore height that can be usefully described by linear functions. This is not so for transects 6 and 7.

RESPONSE VARIABLE	SOURCE OF VARIATION	df	SS	MS	F
M_{2A}	Foreshore heights	9	4.246	.4718	105.37**
	Transects	6	1.169	.1949	43.53**
	Interaction	54	2.441	.0452	10.10**
	Error	70	.313	.0045	
	Total	139	8.169		
M_{2B}	Foreshore heights	9	3.561	.3956	136.17**
	Transects	6	1.220	.2033	69.96**
	Interaction	54	1.263	.0234	8.05**
	Error	70	.203	.0029	
	Total	139	6.247		
σ_{2A}	Foreshore heights	9	.1576	.0175	13.02**
	Transects	6	.0401	.0067	4.96**
	Interaction	54	.2098	.0039	2.89**
	Error	70	.0942	.0014	
	Total	139	.5017		
σ_{2B}	Foreshore heights	9	.0653	.00726	34.20**
	Transects	6	.0727	.01212	57.15**
	Interaction	54	.0699	.00130	6.10**
	Error	70	.0149	.00021	
	Total	139	.2228		

TABLE 6.16 : Anovas, subpopulation textures

Interaction between main effects can therefore be usefully studied by means of linear regressions. However, it is worthwhile to compare the mean values of the textural parameters for each transect, which are shown in Table 6.17.

PARAMETER	TRANSECT						
	1	2	3	4	5	6	7
$\overline{M_{2A}}$	2.37	2.44	2.41	2.48	2.29	2.26	2.22
$\overline{M_{2B}}$	2.89	2.93	2.86	2.91	2.77	2.69	2.69
$\overline{\sigma_{2A}}$	.24	.25	.29	.29	.24	.26	.26
$\overline{\sigma_{2B}}$	.23	.22	.25	.22	.22	.26	.28

TABLE 6.17 : Mean textures of subpopulations 2A and 2B, Ø units

Split into homogeneous groups, in order of magnitude these means may be arranged thus ($.05 > P > .01$):

M_{2A}	7	6	5	1	3	2	4
M_{2B}	7	6	5	3	1	4	2
σ_{2A}	5	1	2	6	7	3	4
σ_{2B}	4	5	2	1	3	6	7

The magnitudes of the mean sizes of the two saltation populations divide very clearly into two distinct groups. A near homogeneous group composing transects 1-4, and another composing transects 5-7, though transect 5 appears to be transitional between them. This division obviously relates very closely to

strandline orientation and offshore bathymetry. The latter factor is probably crucial since deep water immediately offshore (caused by Taf flushing) enables deep water waves to maintain considerable energy nearshore on transects 5-7 (after reforming shoreward of the offshore shoals in the bay, see offshore profiles, Chapter 1). The resulting increase of swash zone/collision zone bottom shear stresses is reflected by the coarsening of the bottom sediment on the eastern half of the beach. The longshore textural gradient is not, of course, necessarily indicative of a net east to west longshore drift.

The distributions of $\overline{\sigma_{2A}}$ and $\overline{\sigma_{2B}}$ do not show such well defined groupings. This may be, in part, because these parameters are probably most subject to error during graphical dissection. However, it is noteworthy that the best sorted population 2B traction carpets occur on transects 4 and 5 (very high spring tides) and transect 2 (moderate gale offshore) when swash zone velocities would be at a maximum. The comparatively poor sorting of this population on transects 6 and 7 is not indicative of smaller swash zone velocities (see above) but of a faster rate of sedimentation (the tidal cycle being restricted to a much reduced foreshore width on these transects). The mean values of σ_{2A} are generally homogeneous, only those of transects 3 and 4 being significantly greater than the others. This is perhaps due to the high proportion of dominant population 2B grains on these two transects, which does not permit

an efficient selective process for the subordinate traction carpet of shelly particles.

Significant linear regression equations can be generated for most textural parameters on foreshore heights along transects 1-5. These are shown in Table 6.18, where y = textural element (in ϕ units) and x = foreshore height relative to HW (in feet). Some non-significant regressions are also included for the purpose of comparison.

	TEXTURAL PARAMETERS			
TRAN-SECTS	M_{2A}	M_{2B}	σ_{2A}	σ_{2B}
1	y=2.04 + .033x	y=2.56 + .032x	y=.22 + .0018x^{i}	y=.27 - .0046x
2	y=2.12 + .033x	y=2.60 + .031x	y=.28 - .0023x^{i}	y=.27 - .0048x
3	y=2.02 + .037x	y=2.46 + .038x	y=.25 + .0047x	y=.30 - .0051x
4	y=2.23 + .023x	y=2.71 + .021x	y=.24 + .0046x	y=.23 - .0014x
5	y=2.17 + .011x	y=2.66 + .011x	y=.20 + .0048x	y=.25 - .0025x

TABLE 6.18 : Linear regression equations for textural response/ static process variable association. ^{i} not significant

These relationships may now be compared, for each textural parameter, in order to quantitatively determine the degree of homogeneity of trends along these transects. The most convenient approach is to compare the residual variances first, then the slopes and lastly the elevations of the regression lines, using the methods of Snedecor and Cochran (1967). Some of these comparisons are shown in Tables 6.19 - 6.22.

The residual variances are of least interest and have been

compared by means of a simple, but inefficient, F_{max}-test (Sokal and Rohlf, 1969). This suggests that for present purposes, the residual variances are generally homogeneous (at $0.01 > P$).

The results of the comparison of slopes are summarised below, homogeneous slopes being joined by a straight line.

M_{2A}	5	4	1	2	3	5% P
M_{2B}	5	4	2	1	3	1% P
σ_{2A}	2	1	4	3	5	5% P
σ_{2B}	4	5	1	2	3	5% P

Clearly, the slopes are homogeneous for the relationships along transects 1-3 or 1-4, transects 4 and/or 5 tending to differ from the others. The slope of the association between o_{2A} and height on transect 2 is negative, where it is positive on other transects. However, this is not a significant association, so no conclusions can be drawn. But the discrepancy may be due to the stormy conditions prior to sampling on that transect.

The significance of these differences is that on transects 4 and (especially) 5, the rate of change of M_{2A} and M_{2B} with unit change of vertical height is less than on transects 1-3. This is related to the greater widths and restrained slopes of the foreshore at transects 4 and 5, which permit a comparatively wide surf zone to be maintained throughout the tidal cycle, even on the upper foreshore. For this reason, there is a diminished transition from surf zone dominance to breaker zone dominance during the higher

	SOURCE OF VARIATION	DEVIATIONS FROM REGRESSION			
		df	SS	MS	F
(A)	Within transect 1	15	.5090	.0339	
	Within transect 2	14	.0920	.0066	
	Within transect 3	20	.4024	.0201	F_{max}= 5.50*
	Within transect 4	20	.7251	.0363	
	Within transect 5	19	.1833	.0096	
	$F_{4(1,3)5}$= 3.78*; $F_{1(3,5)2}$= 5.14*; $F_{4(1)3}$= 1.81ns; $F_{1(3)5}$= 3.53ns; $F_{3(5)2}$= 3.05ns				
(B)	Among slopes 1-5	4	.3875	.0969	4.47**
	Residual within	88	1.9118	.0217	
	Among slopes 1-4	3	.1083	.0361	1.44ns
	Residual within	69	1.7285	.0251	
	Among slopes 2-5	3	.3320	.1107	5.76**
	Residual within	73	1.4028	.0192	
	Among slopes 3-5	2	.2627	.1314	5.92**
	Residual within	59	1.3108	.0222	
	Among slopes 4-5	1	.0880	.0880	3.78ns
	Residual within	39	.9084	.0233	
(C)	Among adjusted means 1-5	4	.7007	.1752	7.01**
	Pooled within	92	2.2993	.0250	
	Among adjusted means 1-4	3	.0426	.0142	.55ns
	Pooled within	72	1.8548	.0258	
	Among adjusted means 4-5	1	.5274	.5274	21.17**
	Pooled within	40	.9965	.0249	

TABLE 6.19 : Comparisons of regressions M_{2A}/height

A : residual variances; B : slopes; C : elevations

	SOURCE OF VARIATION	DEVIATIONS FROM REGRESSION			
		df	SS	MS	F
(A)	Within transect 1	15	.1454	.0097	
	Within transect 2	14	.0821	.0059	
	Within transect 3	20	.2563	.0128	F_{max}= 2.17ns
	Within transect 4	20	.1891	.0095	
	Within transect 5	19	.1413	.0074	
(B)	Among slopes 1-5	4	.3813	.0953	10.25**
	Residual within	88	.8142	.0093	
	Among slopes 1-4	3	.1420	.0473	4.83*
	Residual within	69	.6729	.0098	
	Among slopes 2-5	3	.3354	.1118	12.15**
	Residual within	73	.6688	.0092	
	Among slopes 1-3	2	.0199	.0100	1.01ns
	Residual within	49	.4838	.0099	
	Among slopes 2-4	2	.1327	.0664	6.77**
	Residual within	54	.5275	.0098	
	Among slopes 3-5	2	.2852	.1426	14.40**
	Residual within	59	.5867	.0099	
	Among slopes 3-4	1	.1227	.1227	11.05**
	Residual within	40	.4455	.0111	
	Among slopes 4-5	1	.0619	.0619	7.28*
	Residual within	39	.3304	.0085	
(C)	Among adjusted means 1-5	4	.5445	.1361	10.47**
	Pooled within	92	1.1955	.0130	
	Among adjusted means 1-4	3	.0396	.0132	1.17ns
	Pooled within	72	.8149	.0113	
	Among adjusted means 4-5	1	.3901	.3901	39.77**
	Pooled within	40	.3923	.0098	

TABLE 6.20 : Comparisons of regressions M_{2B}/height

A : residual variances; B : slopes; C : elevations

	SOURCE OF VARIATION	DEVIATIONS FROM REGRESSION			
		df	SS	MS	F
(A)	Within transect 1	15	.01751	.001167	F_{max}= 2.52ns
	Within transect 2	14	.03650	.002607	
	Within transect 3	20	.03671	.001836	
	Within transect 4	20	.05875	.002937	
	Within transect 5	19	.04513	.002375	
(B)	Among slopes 1,3-5	3	.00530	.001767	.83ns
	Residual within	74	.15810	.002136	
(C)	Among adjusted means 1-5	4	.0637	.01593	6.56**
	Pooled within	92	.2236	.00243	
	Among adjusted means 1-4	3	.0584	.01947	8.02**
	Pooled within	72	.1748	.002427	
	Among adjusted means 2-5	3	.04870	.01623	6.03**
	Pooled within	76	.2044	.002690	
	Among adjusted means 1,2,5	2	.00244	.00122	.51ns
	Pooled within	50	.1195	.00239	
	Among adjusted means 1-3	2	.0376	.0188	8.94**
	Pooled within	51	.1072	.00210	
	Among adjusted means 2-4	2	.0369	.01846	6.60**
	Pooled within	56	.1566	.00280	
	Among adjusted means 3-5	2	.0371	.01855	8.05**
	Pooled within	61	.1406	.00231	
	Among adjusted means 1,3,4	2	.0372	.01860	9.02**
	Pooled within	57	.1175	.00206	
	Among adjusted means 3-4	1	.0010	.00101	.43ns
	Pooled within	41	.0955	.00234	

TABLE 6.21 : Comparisons of regressions σ_{2A}/height

A : residual variances; B : slopes; C : elevations

	SOURCE OF VARIATION	DEVIATIONS FROM REGRESSION			
		df	SS	MS	F
(A)	Within transect 1	15	.00913	.00061	
	Within transect 2	14	.00901	.00064	
	Within transect 3	20	.01431	.00072	F_{max} = 1.57ns
	Within transect 4	20	.01109	.00055	
	Within transect 5	19	.00873	.00046	
(B)	Among slopes 1-5	4	.01036	.00259	4.39**
	Residual within	88	.05227	.00059	
	Among slopes 1-4	3	.00958	.00319	5.07**
	Residual within	69	.04354	.00063	
	Among slopes 2-5	3	.00868	.00289	4.90**
	Residual within	73	.04314	.00059	
	Among slopes 1-3	2	.00009	.000045	.07ns
	Residual within	49	.03245	.00066	
	Among slopes 2-4	2	.00835	.00418	6.52**
	Residual within	54	.03441	.00064	
	Among slopes 3-5	2	.00586	.00293	5.05**
	Residual within	59	.03413	.00058	
	Among slopes 3-4	1	.00584	.00584	9.27**
	Residual within	40	.02539	.00063	
	Among slopes 4-5	1	.00059	.00059	1.16ns
	Residual within	39	.01982	.00051	
(C)	Among adjusted means 1-5	4	.01607	.00402	5.91**
	Pooled within	92	.06263	.00068	
	Among adjusted means 1,2,4,5	3	.00229	.00076	1.17ns
	Pooled within	71	.04585	.00065	
	Among adjusted means 2-3	1	.01497	.01497	22.34**
	Pooled within	35	.02334	.00067	

TABLE 6.22 : Comparisons of regressions, σ_{2B}/height

A : residual variances; B : slopes; C : elevations

stages of the tidal cycle, and correspondingly less of an increase of swash zone depths and velocities. In the same way, the rate of change of σ_{2B} with foreshore height is significantly less on transects 4 and 5 than on 1-3.

The results of the comparison of elevations are summarised below, in a similar manner:

M_{2A}	1	2	3	4	5	5% P
M_{2B}	1	2	3	4	5	5% P
σ_{2A}	1	2	5	3	4	5% P
σ_{2B}	1	2	4	5	3	5% P

This comparison assumes that the regression lines are parallel and that variances are homogeneous, and has limited value when, as here, the lines are not all parallel. Accordingly, the elevations are not listed in order of magnitude. However, the analysis does reinforce the weight of evidence in favour of considering transects 1-4 as homogeneous in terms of variations of saltation population mean sizes. The groupings of σ_{2A} and σ_{2B} elevations are less obvious. The former is similar to that presented by the comparison of means (see above). The latter indicates that σ_{2B} elevation on transect 3 differs significantly from the others, although why this should be so is not clear.

As pointed out in Chapter 5, no estimate of longshore textural variance was attempted prior to sampling. For this reason, transects 1-7 cannot be used to determine true between-transect variation because we have no idea of sampling error variation.

However, from the foregoing, it is clear that, in most respects, the textural properties and their variations across transects 1-4 are very similar, many being statistically homogeneous. Hence, with some justification, it may be concluded that no important lateral textural differences occur on that part of the foreshore monitored by transects 1-4. The only exception to this homogeneity is represented by the distribution of subpopulation 1, which decreases in proportion from transect 1 to transect 4.

Transects 5-7 show marked differences in sediment textures, which can be related to the character of shoreline morphology and offshore bathymetry.

Finally, it is of interest to comment on the nature of the variation of textural parameters (of subpopulations) normal to the strandline. As shown in the previous section, the variations of M_{2A} and M_{2B} are qualitatively similar across those transects that are not influenced by complicated offshore bathymetry. For the purposes of statistical comparison between transects, these variations have been approximated to linear relationships between texture and foreshore height. The true relationships are, however, not linear, nor quadratic, but 'parabolic'. In the case of, for example, the variation of M_{2A} with height on transects 1-4, the trend of variation describes a curve with notable assymmetry. This trend may be gauged from Figs. 6.1, and 6.10 - 6.12.

To quantify this trend, linear functions have been ascertained for the two asymptotes of the parabolic curve (considered to be of

the form $x^2 + Axy + By^2 + Cx + Dy + E = 0$). Using the method of Geary, Lowry and Hayden (1945), the equation of the curve has been determined from those of the asymptotes. For the relationship of M_{2A} (in ϕ units) and foreshore height (in feet relative to high water marks), the curve is:

$$x^2 - 21.6\,xy - 450.0\,y^2 + 43.0\,x + 2045.9\,y - 2317.7 = 0$$

where x = foreshore height and y = mean grain size, subpopulation 2A.

Similar equations may be obtained, with varying degrees of precision, for the other major textural coefficients. The trends of variation of subpopulation proportions appear to be quadratic in most cases.

6.5 Variations and Significance of Mean Grainsize, Sorting, Skewness and Kurtosis Parameters; a Comparison of Beach and Dune Sands

In recent years there has been a spate of information on the 'environmental' significance of grain-size data. By far the greatest effort has been made on the meaning and usefulness of those statistical measures (mean, standard deviation, skewness, kurtosis) derived from normal distributions which condense the information provided by a grain-size cumulative curve into a few, easily handled, numbers. Attempts have been made to relate these statistical measures to environments of deposition, principally

with a view to applying such criteria to the recognition of ancient environments. Unfortunately, results have had mixed success, and often contradictory views have been expressed as to their significance. Reviews of these results are given by Folk (1966) and Friedman (1967).

Unfortunately, at present, no theoretical relationship can be upheld to demonstrate the exact relationship between particle/fluid dynamics and grain-size parameters, although intuitively one feels that it must exist. It may be that whilst these parameters are indeed accurate and sensitive indicators of sediment response, the amount of information summarised by each may be too great for their meaning to be easily grasped.

It has been shown by Folk and Ward (1957) that mixing of two or more separate populations imposes its own variation on parameter properties, although this in itself may be environment-sensitive. In the present study, the four statistical parameters adopted must summarise a grain-size distribution created by the mixing of three or four separate subpopulations, each with variable properties. The character of the parent curve is determined by the interaction of twelve separate variables - subpopulation proportion (x 4), mean grain-size (x 4) and standard deviation (x 4). Can such a complex interplay be usefully described by these statistical parameters?

The variations of parameters across each transect are shown in Tables 6.23 - 6.29, the data being expressed graphically in Figs. 6.16 - 6.22.

Sample	Mean M_Z Ø units	Standard Deviation σ_I Ø units	Skewness Sk_I	Kurtosis K_G	K_G'
11	2.57	.27	-.021	1.18	.54
12	2.65	.26	-.059	1.14	.53
13	2.55	.28	+.075	1.05	.51
14	2.54	.26	-.109	1.02	.50
15	2.52	.29	-.062	1.02	.50
16	2.51	.32	-.002	1.07	.52
17	2.49	.36	-.078	1.10	.52
18	2.60	.43	-.144	1.10	.52
19	2.70	.57	-.410	1.73	.63
110	2.79	.61	-.419	2.11	.68
111	2.41	.87	-.610	2.19	.69
112	1.92	1.49	-.761	1.23	.55
113	2.94	.84	-.608	4.23	.81
114	3.12	.23	-.203	1.16	.54
115	3.10	.24	-.117	1.08	.52
116	3.11	.23	-.199	1.16	.54
117	3.12	.22	-.143	1.13	.53
118	3.16	.22	-.214	1.01	.50
119	3.16	.22	-.106	1.17	.54
120	3.16	.22	-.143	1.14	.53

TABLE 6.23 : Variation in Statistical Parameters of Bulk Sample Populations, Transect 1.

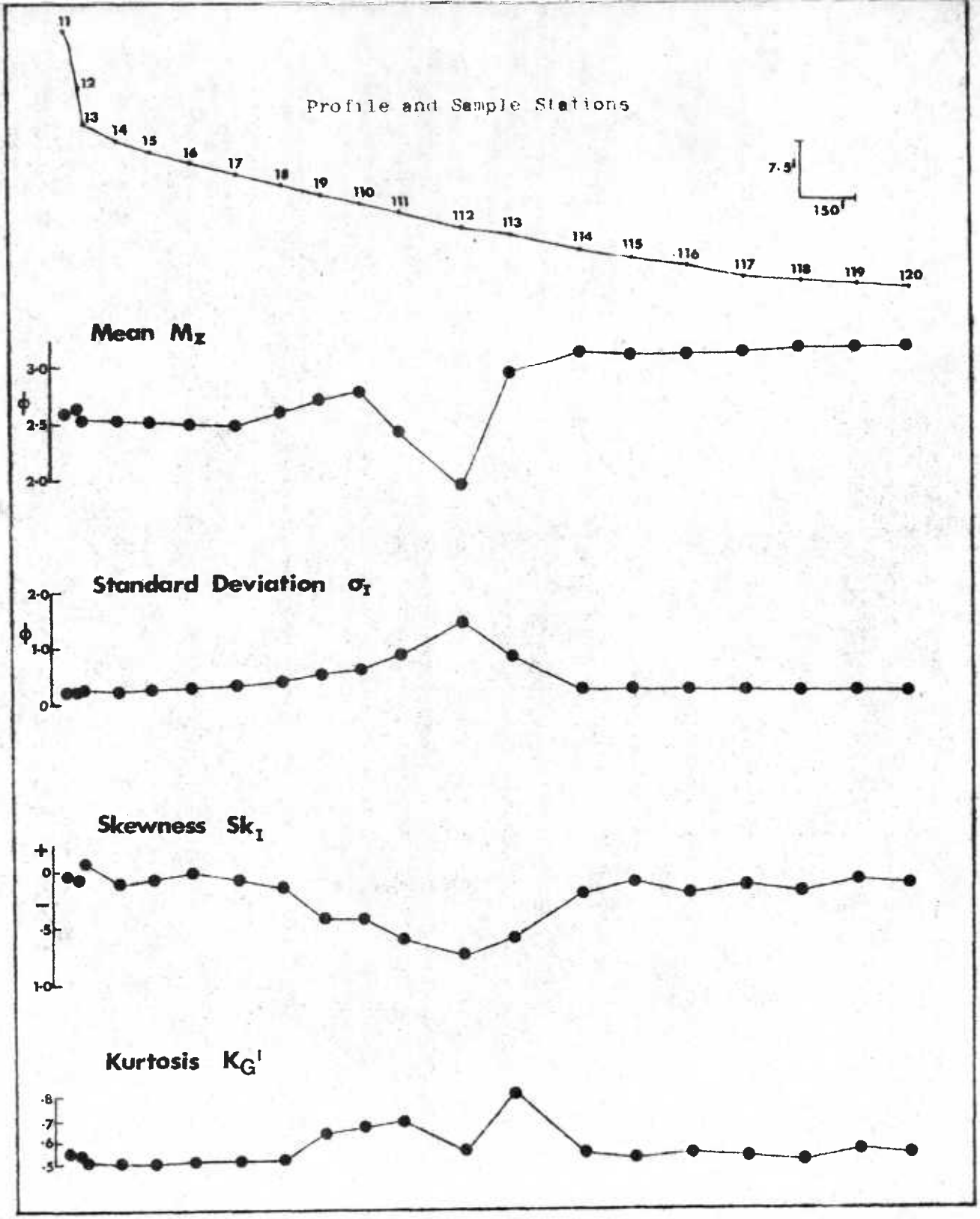


FIG. 6.16: GRAPHICAL STATISTICS, TRANSECT 1.

Sample	Mean M_z ø units	Standard Deviation σ_I ø units	Skewness Sk_I	Kurtosis K_G	K_G'
21	2.67	.31	-.141	1.16	.54
22	2.67	.29	-.010	1.02	.50
23	2.71	.26	-.010	1.04	.51
24	2.71	.28	-.006	1.01	.50
25	2.73	.23	-.056	1.07	.52
26	2.55	.27	+.039	.92	.48
27	2.51	.30	+.025	1.10	.52
28	2.59	.39	-.141	.99	.50
29	2.61	.41	-.177	.95	.49
210	2.74	.44	-.267	1.00	.50
211	2.64	.81	-.577	1.87	.65
212	2.22	1.31	-.756	2.25	.69
213	2.90	.79	-.661	3.84	.79
214	2.95	.92	-.692	4.62	.82
215	3.10	.27	-.286	1.15	.53
216	3.12	.22	-.115	1.08	.52
217	3.14	.22	-.237	1.40	.58
218	3.15	.22	-.174	1.11	.53
219	3.20	.21	-.213	1.12	.53
220	3.19	.23	-.143	1.13	.53
221	3.19	.22	-.184	1.11	.53

TABLE 6.24 : Variation in Statistical Parameters of Bulk Sample Populations, Transect 2.

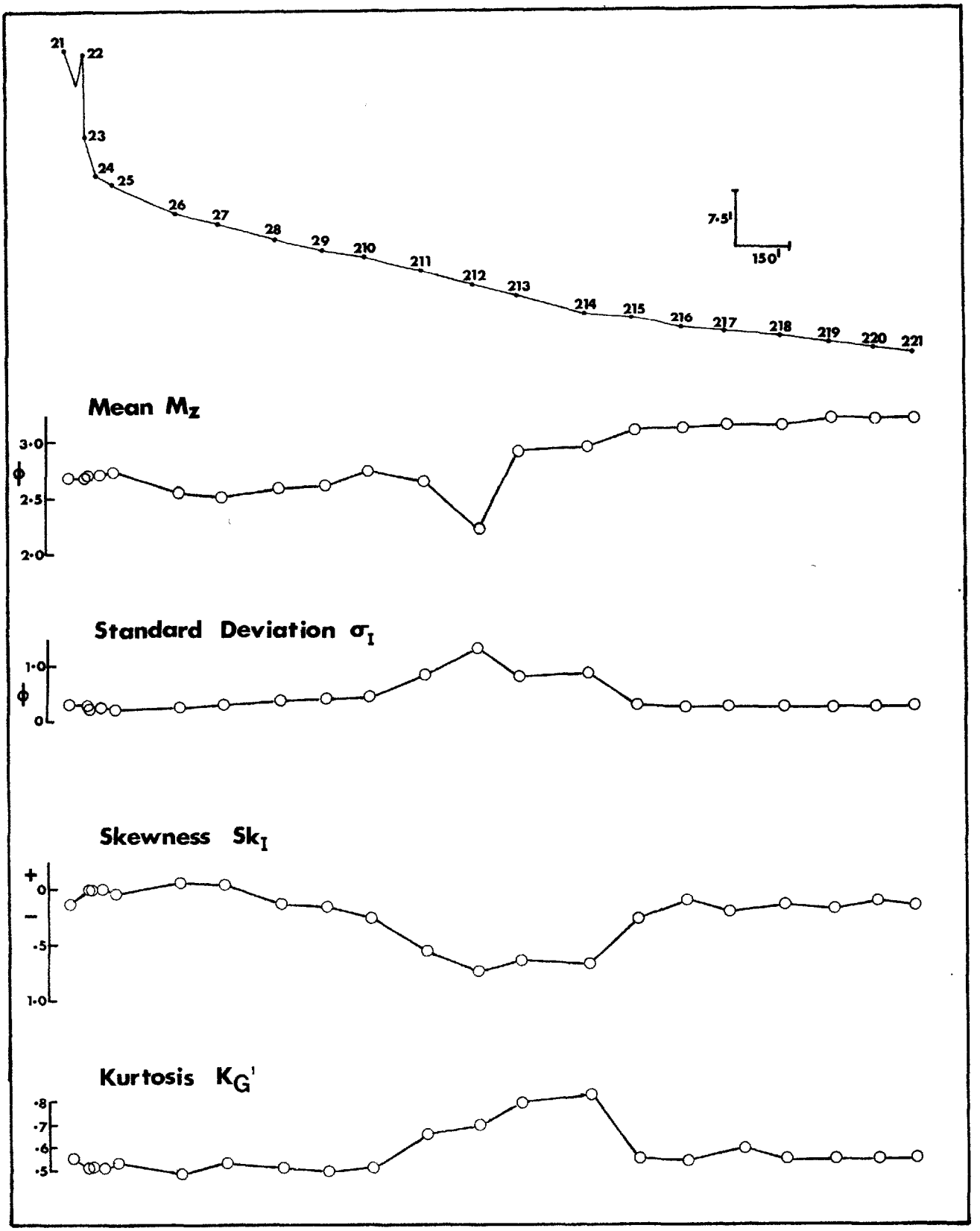


FIG. 6.17: GRAPHICAL STATISTICS, TRANSECT 2.

Sample	Mean M_z ∅ units	Standard Deviation σ_I ∅ units	Skewness Sk_I	Kurtosis K_G	K_G'
31	2.67	.34	-.043	1.04	.51
32	2.70	.31	+.018	1.00	.50
33	2.73	.28	+.041	.95	.49
34	2.74	.28	+.049	.99	.50
35	2.72	.28	+.068	1.00	.50
36	2.69	.25	+.127	1.06	.51
37	2.68	.25	+.080	.98	.49
38	2.67	.25	+.034	.96	.49
39	2.61	.28	+.080	1.04	.51
310	2.67	.28	+.074	.96	.49
311	2.56	.29	+.067	1.04	.51
312	2.50	.33	+.009	.96	.49
313	2.43	.37	-.049	.98	.49
314	2.36	.41	-.025	1.10	.52
315	2.50	.46	-.266	1.24	.55
316	2.61	.46	-.293	1.28	.56
317	2.57	.86	-.531	2.67	.73
318	2.76	.48	-.392	1.71	.63
319	2.64	.81	-.514	2.17	.68
320	2.81	.75	-.552	2.61	.72
321	2.69	.93	-.610	3.23	.76
322	2.99	.30	-.280	1.28	.56
323	3.01	.30	-.254	1.21	.55
324	3.03	.27	-.214	1.22	.55
325	3.06	.25	-.127	1.07	.52
326	3.05	.25	-.057	1.08	.52
327	3.10	.21	-.021	1.00	.50
328	3.09	.23	-.079	1.01	.50
329	3.09	.23	-.083	1.06	.51
330	3.11	.24	-.103	1.05	.51

TABLE 6.25 : Variation in Statistical Parameters of Parent Populations, Transect 3.

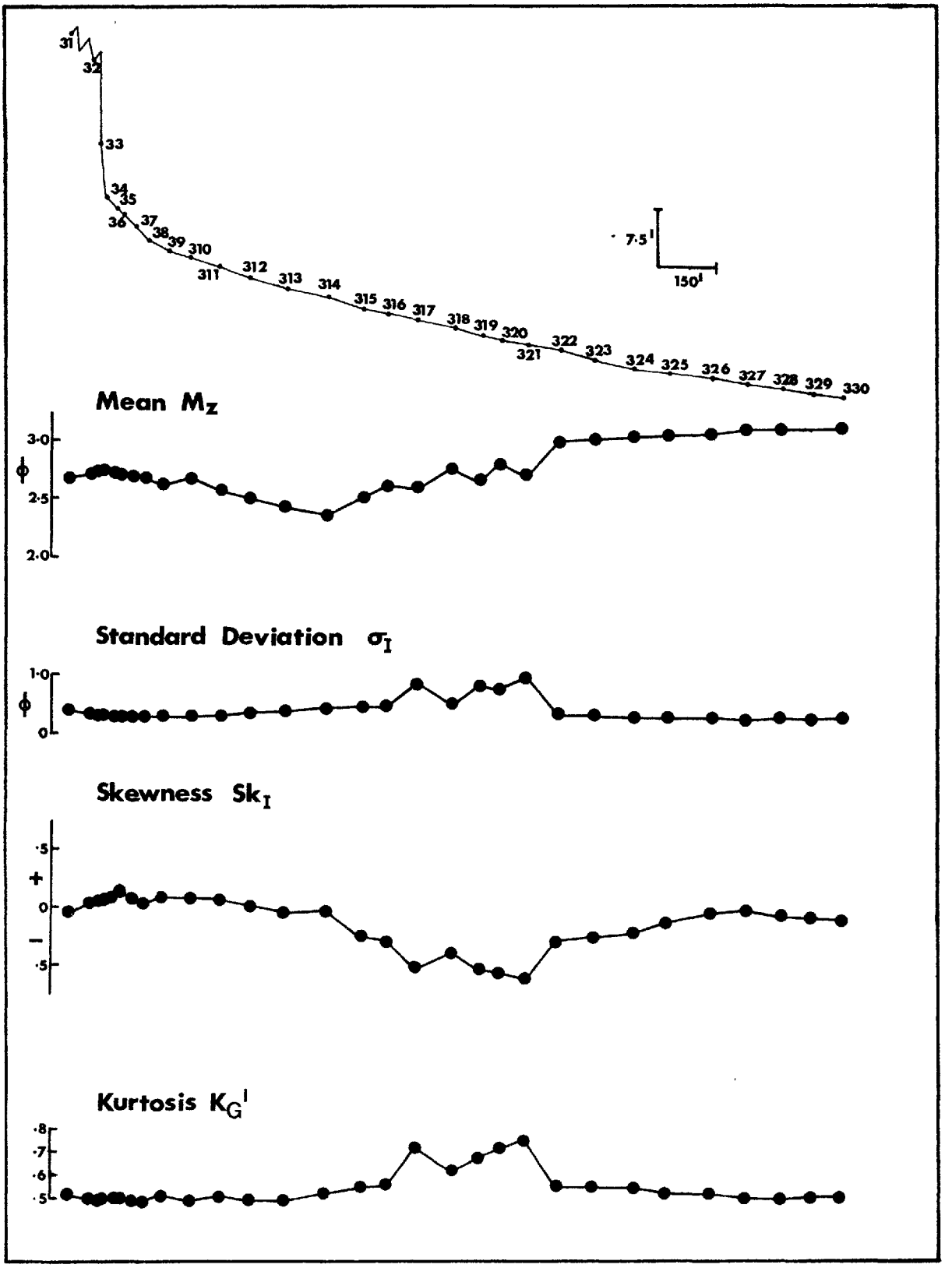


FIG. 6.18: GRAPHICAL STATISTICS, TRANSECT 3.

Sample	Mean Size M_z ø units	Standard Deviation σ_I ø units	Skewness Sk_I	Kurtosis K_G	K_G'
41	2.67	.29	-.017	.91	.48
42	2.74	.34	-.061	1.01	.50
43	2.69	.29	-.080	.99	.50
44	2.74	.34	+.154	1.14	.53
45	2.89	.25	-.120	1.06	.51
46	2.68	.25	-.032	.98	.49
47	2.59	.30	-.132	.96	.49
48	2.59	.33	-.126	1.04	.51
49	2.58	.34	-.114	1.08	.52
410	2.72	.35	-.220	1.21	.55
411	2.83	.28	-.197	1.17	.54
412	2.95	.24	-.163	1.08	.52
413	2.96	.25	-.083	1.08	.52
414	3.01	.24	-.175	1.05	.51
415	3.01	.24	-.056	1.10	.52
416	3.02	.25	-.172	1.08	.52
417	3.06	.25	-.160	1.10	.52
418	3.07	.26	-.271	1.15	.53
419	3.04	.26	-.152	1.11	.53
420	3.07	.28	-.230	1.06	.51
421	3.06	.29	-.245	1.09	.52
422	3.11	.29	-.311	1.24	.55
423	3.09	.30	-.292	1.20	.55
424	3.14	.29	-.263	1.34	.57
425	3.08	.31	-.169	1.24	.55
426	3.15	.30	-.333	1.17	.54

TABLE 6.26 : Variation in Statistical Parameters of Bulk Sample Populations, Transect 4.

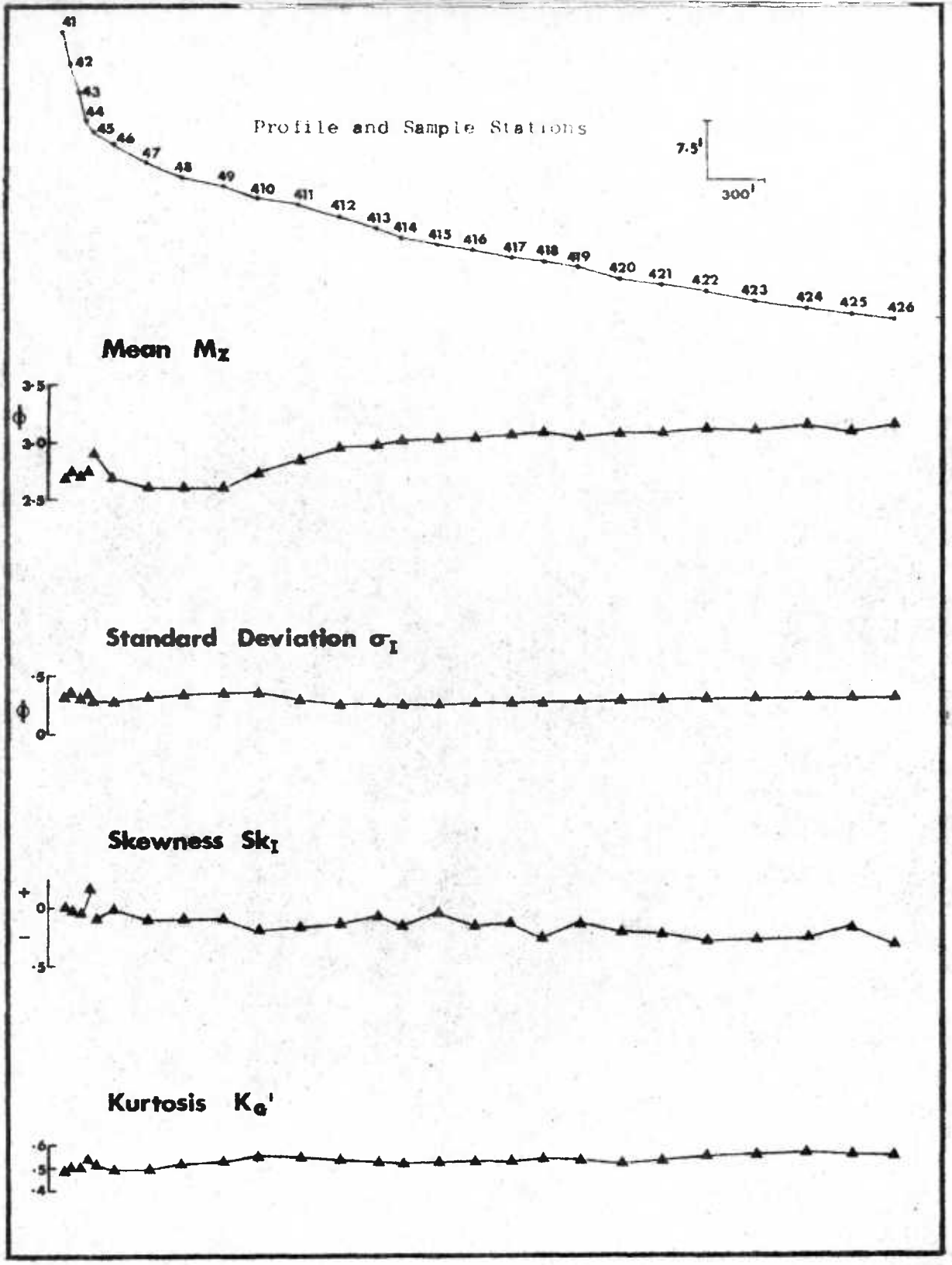


FIG. 6.19: GRAPHICAL STATISTICS, TRANSECT 4.

Sample	Mean Size M_z ø units	Standard Deviation σ_I ø units	Skewness Sk_I	Kurtosis K_G	Kurtosis K_G'
51	2.55	.38	-.030	.96	.49
52	2.80	.34	-.221	1.22	.55
53	2.55	.36	-.011	.94	.48
54	2.68	.31	-.036	1.14	.53
55	2.60	.34	±.000	.94	.48
56	2.81	.30	-.148	.96	.49
57	2.66	.35	±.000	.97	.49
58	2.63	.34	-.025	1.02	.50
59	2.65	.35	-.010	.95	.49
510	2.81	.28	-.083	1.02	.50
511	2.60	.30	-.038	1.00	.50
512	2.46	.31	-.031	1.04	.51
513	2.42	.32	+.045	1.04	.51
514	2.48	.34	-.120	1.09	.52
515	2.45	.33	-.072	1.04	.51
516	2.58	.35	-.143	.92	.48
517	2.52	.32	-.066	1.00	.50
518	2.66	.29	-.033	1.17	.54
519	2.56	.30	-.037	1.16	.54
520	2.76	.24	-.098	1.16	.54
521	2.76	.24	-.154	1.19	.54
522	2.77	.27	-.098	1.23	.55
523	2.81	.27	-.131	1.32	.57
524	2.82	.28	-.174	1.25	.56
525	2.87	.28	-.142	1.38	.58
526	2.85	.28	-.199	1.26	.56
527	2.84	.27	-.173	1.12	.53
528	2.77	.28	-.215	1.12	.53
529	2.79	.30	-.150	1.07	.52
530	2.90	.25	-.137	1.11	.53

TABLE 6.27 : Variation in Statistical Parameters of Bulk Sample Populations, Transect 5.

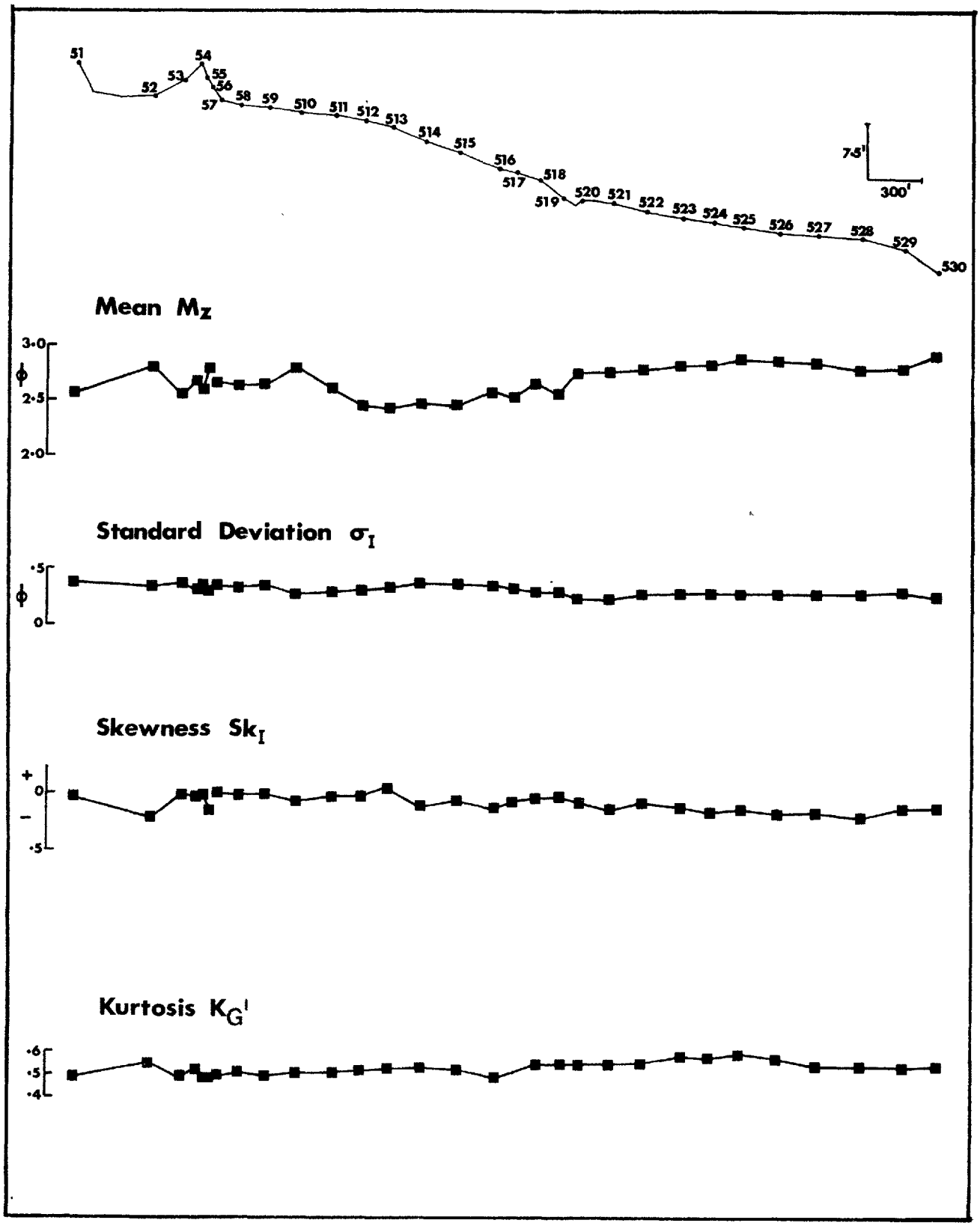


FIG. 6.20: GRAPHICAL STATISTICS, TRANSECT 5.

Sample	Mean Size M_z Ø units	Standard Deviation σ_I Ø units	Skewness Sk_I	Kurtosis K_G	K_G'
61	2.58	.29	+.018	1.00	.50
62	2.60	.30	-.008	.98	.49
63	2.43	.28	+.066	1.01	.50
64	2.44	.30	+.014	1.19	.54
65	2.40	.28	-.023	1.00	.50
66	2.44	.29	-.033	1.00	.50
67	2.49	.30	-.057	1.00	.50
68	2.53	.32	-.085	.94	.48
69	2.56	.33	-.118	.98	.49
610	2.63	.36	-.278	.98	.49
611	2.56	.40	-.160	1.00	.50
612	2.32	1.08	-.628	1.23	.55
613	2.62	.36	-.115	1.30	.57
614	2.65	.32	-.137	1.09	.52
615	2.63	.31	-.107	1.13	.53
616	2.60	.31	-.111	1.15	.53
617	2.46	.35	-.008	1.11	.53

TABLE 6.28 : Statistical Parameters of Parent Sample Populations along Transect 6.

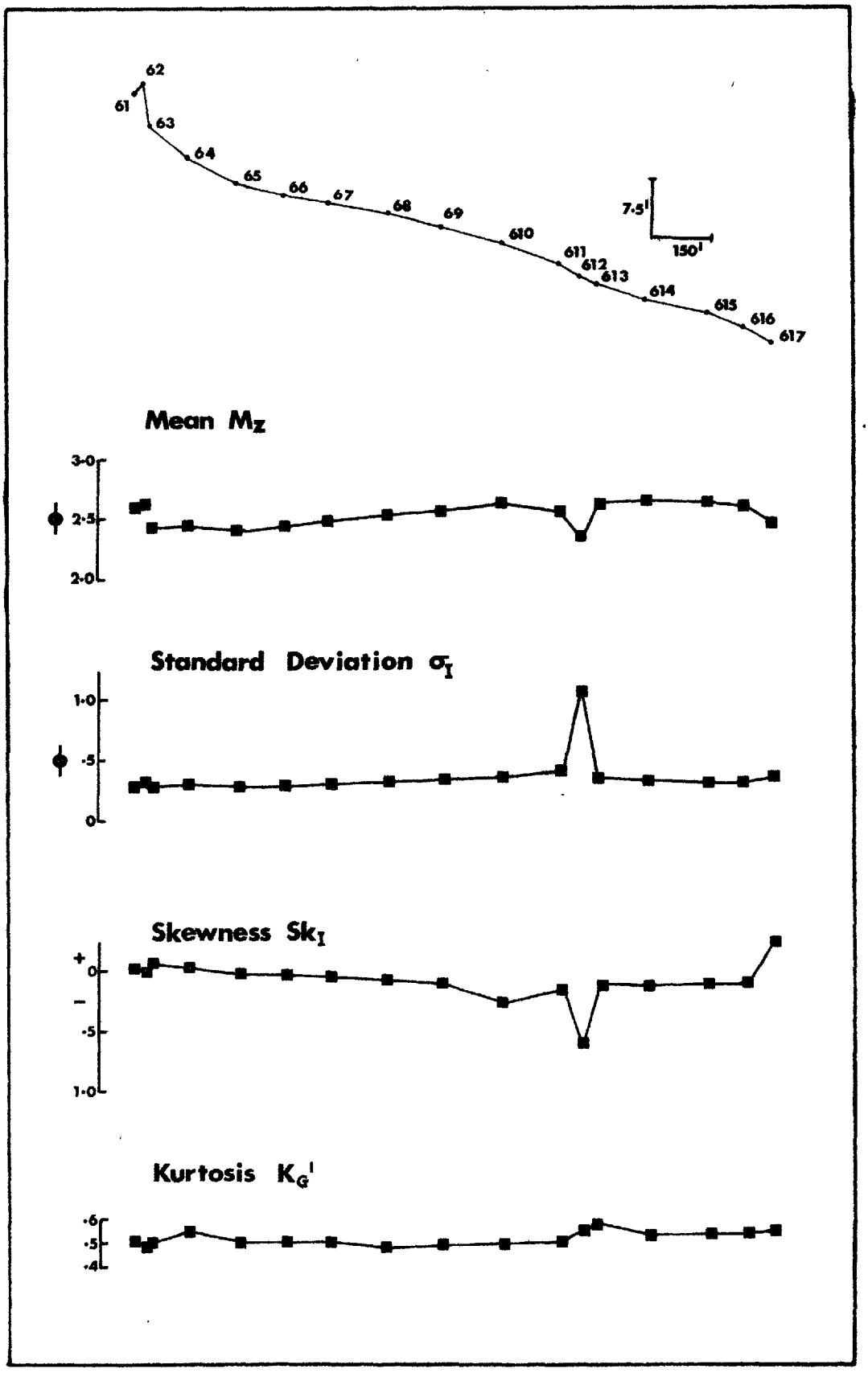


FIG. 6.21: GRAPHICAL STATISTICS, TRANSECT 6.

Sample	Mean Size M_z ø units	Standard Deviation σ_I ø units	Skewness Sk_I	Kurtosis K_G	K_G'
71	2.63	.29	-.042	.95	.49
72	2.56	.29	-.038	.96	.49
73	2.63	.31	+.036	.95	.49
74	2.60	.31	±.000	1.01	.50
75	2.60	.31	-.017	1.01	.50
76	2.59	.32	-.024	.97	.49
77	2.63	.31	+.038	1.08	.52
78	2.63	.33	-.080	.99	.50
79	2.63	.30	-.012	1.08	.52
710	2.66	.33	-.074	.97	.49
711	2.57	.32	+.020	1.00	.50
712	2.54	.30	-.068	1.01	.50
713	2.45	.32	-.028	.94	.48
714	2.45	.31	-.018	.95	.49
715	2.45	.31	-.013	1.01	.50
716	2.48	.32	-.067	.89	.47
717	2.42	.32	-.017	.84	.46
718	2.78	.34	-.111	1.10	.52
719	2.58	.42	-.083	.97	.49

TABLE 6.29 : Statistical Parameters of Parent Populations along Transect 7.

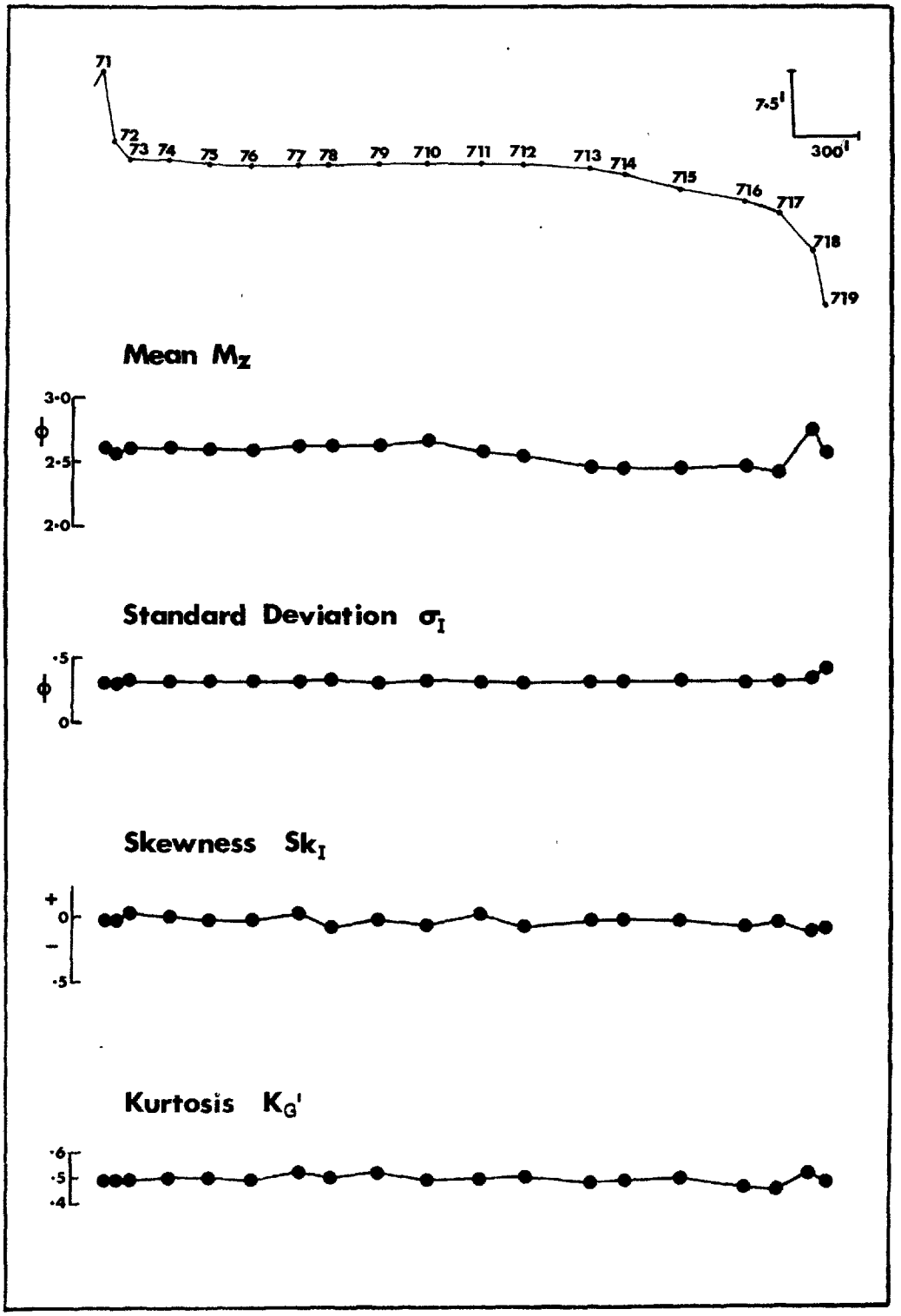


FIG. 6.22: GRAPHICAL STATISTICS, TRANSECT 7.

It is evident that the across-foreshore variations are similar for most transects, and significantly reflect the known variations of subpopulation properties. Their statistical variations (in their degree of linearity) with foreshore heights are shown in Table 6.30 in terms of the product-moment correlation coefficient.

The mean grain size M_z retains an approximately linear relationship with foreshore height, showing a progressively seaward-fining gradient. In this, the parameter reflects the trends of variation of subpopulations 2A and 2B mean grain sizes. But at mid-tide level, the gradient is markedly reversed over a short section of the foreshore, due to admixture of the coarse surface creep population. This reversal is most extreme on transect 1, becoming progressively less apparent eastwards, and absent on transects 4 and 5. Hence the trend of variation of M_z is closely dependent on the trends present in the variables M_{2A}, M_{2B} and % 1.

	GRAPHICAL PARAMETERS			
TRANSECT	M_z	σ_I	Sk_I	K_G'
1	.72**	-.16	-.08	.02
2	.84**	-.18	-.24	.17
3	.83**	-.10	-.27	.10
4	.92**	-.18	-.64**	.58**
5	.93**	-.68**	-.72**	.54*
6	.35	.12	-.09	.66*
7	.02	.79**	-.49	-.19

TABLE 6.30 : Correlation coefficients, graphical parameters/foreshore height

On transects 6 and 7, the relationship between M_z and foreshore height does not approximate to linearity because of the influence of the Taf ebb channel on both, and the aeolian sand flat on the latter.

The interaction of subpopulations on the middle foreshore also serves to remove linearity from the relationship of σ_I with foreshore height. This is most apparent on transects 1, 2, 3 and 6 where the proportions of subpopulation 1 are relatively high. Generally the sand of the upper foreshore has a higher σ_I than that of the lower foreshore, reflecting the trend present in the standard deviation of the dominant subpopulation 2B. At mid-tide level, where subpopulation 1 appears, σ_I increases drastically. Thus at high and low-tide levels, σ_I indicates very well sorted sands, at mid-tide level moderately to poorly sorted sands (using the descriptors of Folk and Ward, 1957).

On transect 5, where subpopulation 1 is not well represented, the trend of variation of σ_I with foreshore height is a linear one, sand becoming progressively better sorted from upper to lower foreshores. On transect 7, there is little variation of σ_I across the aeolian sand flat, but an abrupt deterioration of sorting as the Taf channel is approached.

On transect 4, where subpopulation 1 proportions are low, sorting does not improve on the lower foreshore because of an increased admixture of subpopulation 2A to the dominant 2B.

Thus, generally, the trends of variation of σ_I across the foreshore are dependent on the variations of σ_{2B}, % 1 and % 2A.

Values of inclusive graphic skewness are generally negative for most samples from the beach. It has been proposed by Mason and Folk (1958) and Friedman (1961) that this is due to winnowing of fine grained material from the high energy nearshore system, so that the frequency distributions of such sands lack the tail at the fine end of the curve. This is partly true here since those few samples that exhibit positive skewness occur at, or near, high-water mark where heavy minerals of the suspension population 3 are present in increased proportions. But for most samples, negative skewness is imparted by admixtures of subpopulation 2A or 1 to the dominant subpopulation 2B which give the resulting frequency curves tails at their coarse ends. Thus negative skewness pervades even the lower foreshore where subpopulation 1 is reduced in proportion, but is most developed on the middle foreshores of transects 1, 2, 3 and 6 where subpopulation 1 proportions are at a maximum.

Therefore the major variations which affect Sk_I are % 1 and % 2A, and to a lesser extent % 3. Because these variables are themselves generally distributed across the foreshore in a manner that does not approximate to linearity, Sk_I does not correlate significantly with foreshore height (Table 6.30), except on transects 4 and 5 where there is a trend of increasing negative skewness seawards. This cannot be attributed to greater winnowing of fine grained sediment because on transect 4 there is also a trend

of increasing % 3 seawards (Table 6.9), but is in fact due to the influence of % 2A. On transect 4 there is a significant linear trend of increasing % 2A seawards, which gives the frequency curves a progressively more significant coarse tail, and greater negative skew. On transect 5 the situation is more complex since here too there are linear trends of seaward decreasing % 1 and % 2A (Table 6.9) but seaward-increasing negative skewness. This arises because on the middle/upper foreshore, subpopulation 2A becomes temporarily dominant so that the mode of the parent distribution is shifted to the left and subpopulation 2B becomes a long positive 'tail', sufficient to impart slight positive skew at station 513. Such a cycle of transition of negative to positive skewness as the coarser mode becomes dominant has been demonstrated by Folk and Ward (1957).

It is noteworthy that only 3 out of 18 dune samples show positive skewness, and even these are best regarded as symmetrical. Indeed almost all dune and aeolian samples are symmetrical, with a slight negative skew that is probably insignificant. This, of course, is because they consist almost exclusively of a single, normal saltation population with very little contamination by surface creep or suspension populations (excepting sample 21 which has a coarse tail of shelly material). These results contradict the findings of Mason and Folk (1958) and Friedman (1961) who found predominantly positively-skewed wind-formed sands, presumably because of the occurrence of interstitial fine grained material. This discrepancy may be due to a lack of a suspension population at source (for the

dunes and aeolian flats this must be the foreshore) so that no grains finer than 62 microns are available for wind-blown accumulation.

Values of K_G' are generally in the range meso to leptokurtic on the upper and lower foreshores, but becoming very or extremely leptokurtic on the middle foreshores of transects 1-3 due to admixture of increasing population 1 proportions. Increasing values of K_G' occur as sorting in the tails of the distribution deteriorates relative to that in its centre; increasing proportions of both subpopulations 1 and 2A are able to achieve this.

Because of the influence of subpopulation 2A, upper foreshore samples tend to have lower kurtosis than lower foreshore samples. This is most apparent when the influence of subpopulation 1 is negligible, as on transects 4 and 5 where there is then a linear trend of seaward-increasing kurtosis (Table 6.30).

No sample has sufficiently low kurtosis to be termed platykurtic. Most dune and aeolian samples are mesokurtic (symmetrical) for obvious reasons, but some are just leptokurtic because of small admixtures of coarse, shelly material.

It is apparent from the foregoing that there is a clear correspondence between parent population parameters and subpopulation parameters. Some of the grosser connections have been outlined. However, it is unlikely that the full information provided by the subpopulation analysis could ever be gleaned from an analysis of the parent parameters, except in broad outline.

Nevertheless, because of their mathematical elegance, the appeal of these parameters is strong. It is worthwhile to continue the investigation in order to determine whether or not they have any value as criteria of sedimentary processes on the foreshore.

As demonstrated by Folk and Ward (1957), the sedimentological significance of the four size parameters becomes more apparent when their interrelationships are examined by means of scatter diagrams. All six, two-variable scatter plots are shown in Fig. 6.23 for the samples of transect 2; the trend of variation from dune and upper foreshore to lower foreshore is indicated for each combination.

These trends are rather complex. As shown by plot A, minima of best sorting occur on the upper and lower foreshores where subpopulation 2A is dominant; maxima correspond to the middle foreshore where mixing of subpopulations is most developed.

Plot B illustrates the relationship of mean grain size and graphic skewness. The dunes and uppermost foreshore are near symmetrical. On the middle foreshore, the sands become coarser and very negatively skewed as subpopulation 1 grains are added. On the lower foreshore, skewness is reduced as subpopulation 2B regains dominance, and mean grain size M_z decreases in step with M_{2B}.

The plot of K_g' against M_z is essentially similar. Minima of mesokurtosis occur where subpopulation 2B is dominant on the upper and lower foreshores. Increasing quantities of coarser population 1 and 2A grains produces a frequency curve with poor sorting in the coarse tail but retaining a well-sorted centre; hence extreme

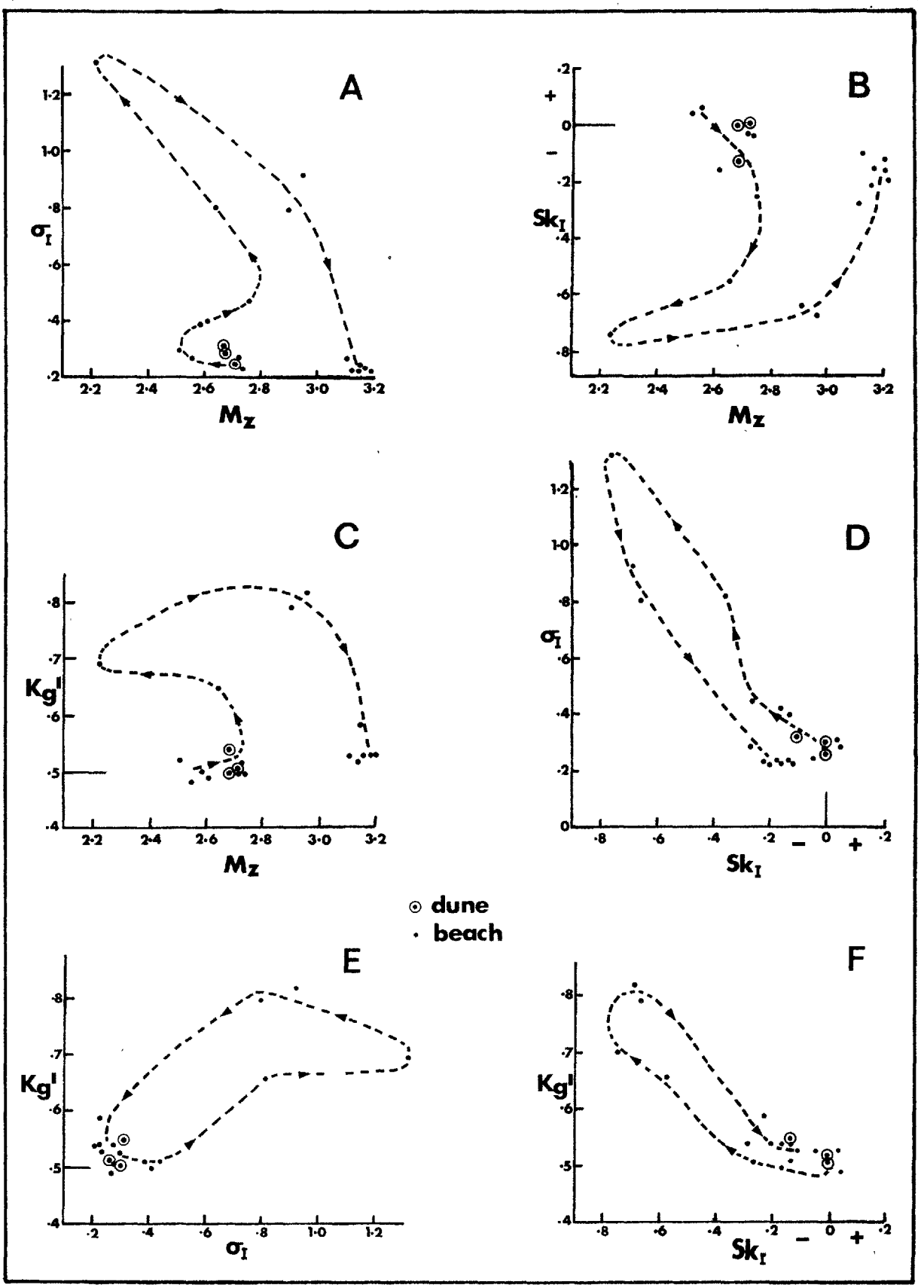


FIG. 6.23: SEQUENCES OF VARIATION, TWO-VARIABLE SCATTER PLOTS, TRANSECT 2.

leptokurtosis develops. However the mean grain size is not affected. But increasing quantities of coarser grains not only coarsens the mean grain size, but depresses the leptokurtosis slightly as the two modes approach subdominance.

The plot of standard deviation against skewness follows a flattened elliptical pattern (plot D). The most extreme skewness coincides with the maximum of poor sorting since both are caused by admixture of subpopulations at mid-tide level. There is very little distinction between upper and lower foreshore samples on this, and subsequent, plots since M_z is not represented.

Plot E is essentially similar although maximum kurtosis and standard deviation do not exactly coincide because, as noted above, leptokurtosis is slightly reduced as the two major components approach subequality (and this is when σ_I is at a maximum).

The relationship across the foreshore between skewness and kurtosis is shown in Plot F. As shown above, both of these parameters depend on the proportions of the two major modes present (i.e. coarse and fine). The relationships are more subtle than this however, and although not developed here, it may be shown that both parameters are affected by the relative magnitudes of the means and standard deviations of the constituent subpopulations. But in broad outline, the scatter plot trend across the foreshore when these parameters are in combination can be viewed in terms of the interaction of subpopulation proportions. Starting with the near-normal samples of the dune and upper foreshore the trace rises to the left

of the plot as the middle foreshore is approached. For the reason given above, maximum leptokurtosis is reached before maximum negative skewness. The trace then returns to a point close to its starting position but displaced slightly since lower foreshore samples have kurtosis and negative skewness values that are both a little greater than those of upper foreshore samples (owing to the increased admixing of subpopulation 2A at the lower level).

The scatter plots of Fig. 6.23 have been interpreted in terms of the known sequence of events across the face of the foreshore. It is doubtful whether a very detailed account of foreshore texture could be obtained from the scatter plots without the foresight granted by the subpopulation analysis of previous sections. To check this, a colleague was given the blank scatter plots and asked for his comments on the significance of the two-variable relationships. At first, he recognised possible linear relationships between the variables for plots D, E and F. When pressed, he admitted the feasibility of an asymmetric polynomial for plot A, symmetrical sine curves for plots B and C, exponential decay laws for plots D and F, and an asymptotic regression for plot E. These are, of course, subjective choices. However, they are worth comparing with the corresponding plots given by Folk and Ward (1957) for bimodal river sediments.

The assumed relationships are shown in Fig. 6.24 and they do indeed bear comparison with those of Folk and Ward. However, some of the similarities are misleading. For example, plot A is similar

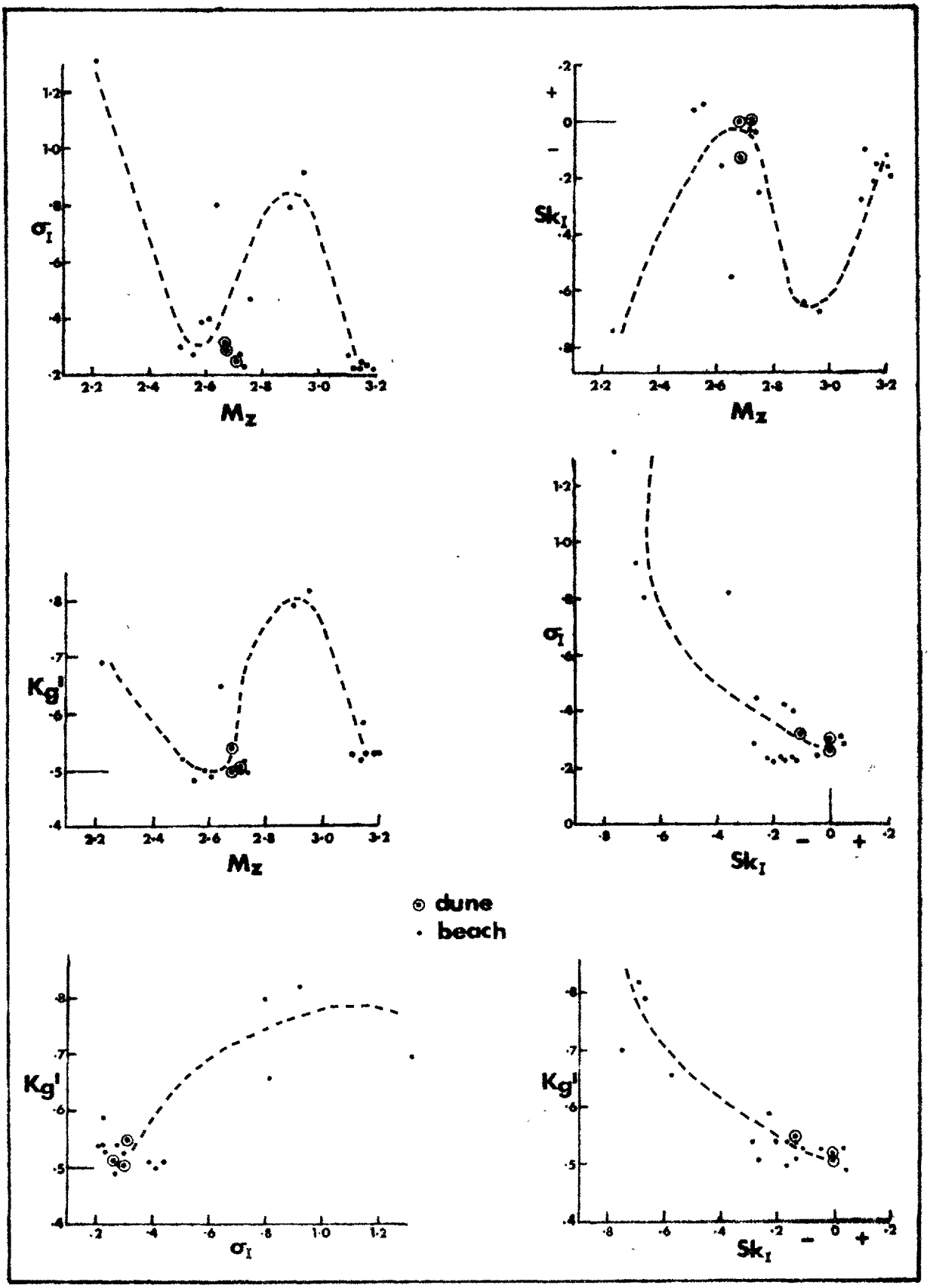


FIG. 6.24 : TWO-VARIABLE SCATTER PLOTS, TRANSECT 2.
(FOR EXPLANATION, SEE TEXT).

to the corresponding one of Folk and Ward. But the points of sorting minima at 2.6 and 3.2 Ø units do not represent the modal diameters of two distinct populations, but in fact represent the modal diameters of the same population (2B) from two distinct sub-environments of deposition (the upper and lower foreshores respectively). The same differentiation between sub-environments occurs in plots B and C where again the two primary modes represent the same population.

Plot D is similar to an arc of the circular relationship between σ_I and Sk_I found by Folk and Ward; plot E represents a segment of the inverted double V of the relationship between σ_I and K_G'. Unfortunately, neither curve clarifies the distinction between upper and lower foreshores since samples from these sub-environments cluster together and are not easily differentiated. This is also the case for plot F.

Hence if we take the plots of the river samples of Folk and Ward as our model, then the scatter plots of M_z with σ_I, Sk_I and K_G' might produce misleading conclusions (if we were sampling an ancient deposit in which there was no known differentiation of sub-environments) and plots of σ_I with Sk_I and K_G', and of Sk_I with K_G', would involve a loss of important information.

This is perhaps clarified by an alternative approach in which the relationships deduced by Folk and Ward are superimposed on the present scatter plots; these are shown in Fig. 6.25. Clearly the plots represent only small sections of the continuous relationships

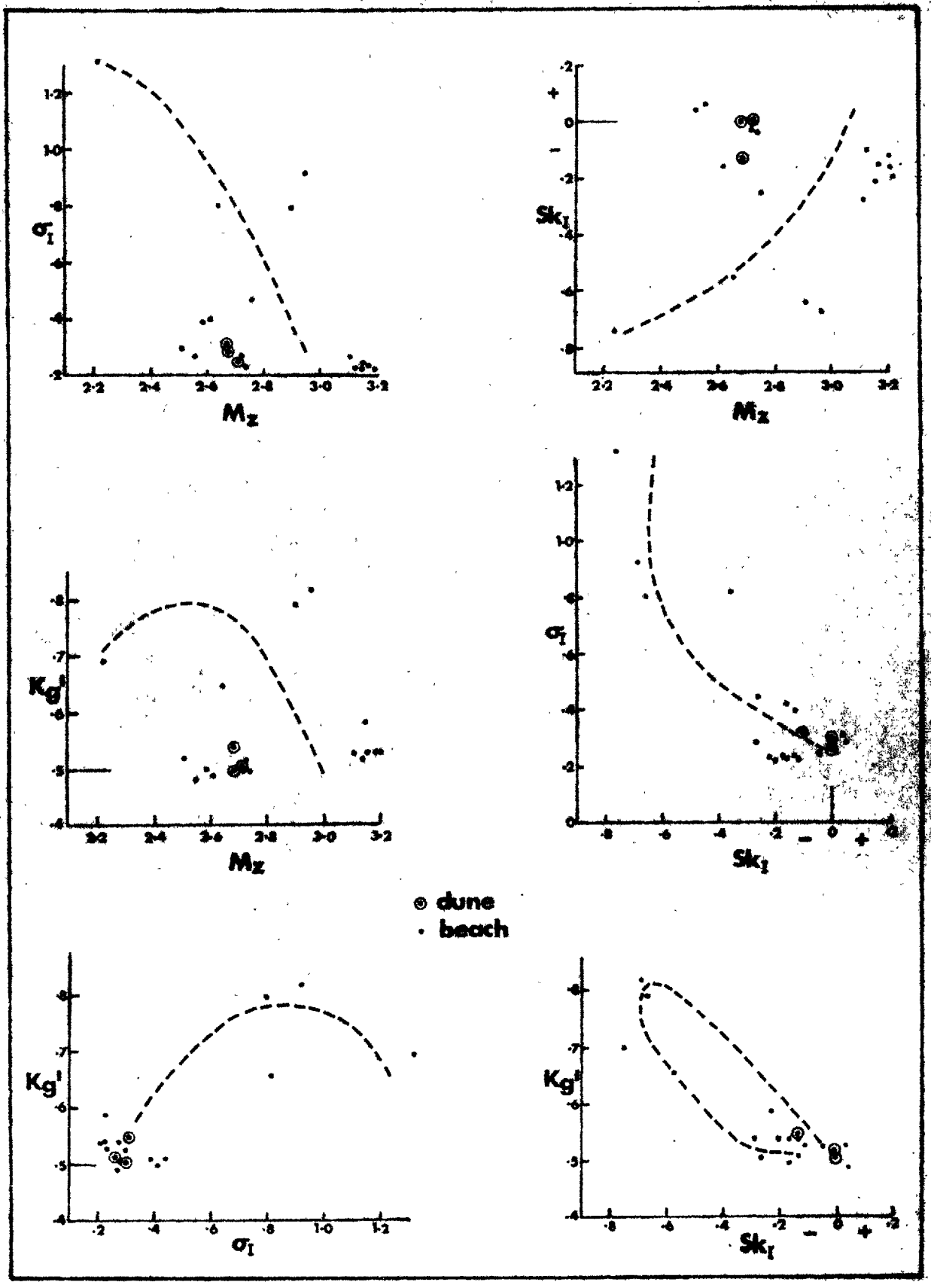


FIG. 6.25: TWO-VARIABLE SCATTER PLOTS, TRANSECT 2.

that exist for the complete spectrum of mixing that occurs in a bimodal sediment. While these relationships are of course true ones (Folk and Ward, 1957) there is a considerable deviation of points from the theoretical curves. This is because the curves apply to the mixing of two modes of constant grain size. Such is not the case here since it has been shown that the mean grain sizes of the subpopulations change drastically across the foreshore. The curves apply also to the mixing of two populations of constant standard deviation. Again this is not the case here. Finally, the curves relate to bimodal sediments whereas many of the sediments under study are considered to be essentially trimodal.

The scatter plots become more complex when samples from other transects are introduced; the deviations from the theoretical curves become considerable. This is understandable since these new samples come from slightly different subenvironments and the curves relating to them are in slightly displaced positions on the plots. The important point is that the interpretation of the resulting plots, without suitable foreknowledge, becomes very confusing.

It may be concluded therefore that all four statistical parameters are highly sensitive to the environment of deposition but their interpretation is too complex for them to be readily useful as diagnostic of ancient subenvironments (i.e. within subenvironments of a foreshore).

However, this does not preclude their application to gross

differentiation of major environments. It is in this area that their significance has been most tested.

Again, scatter plots of one parameter against another have been most used, although Sahu (1964) and Sevon (1966) used discriminant functions and Klovan (1966) factor analysis. Successes have been fragmentary and generally fail to have more than local application. We are here concerned with beach and dune sands only. Mason and Folk (1958) and Friedman (1961) concluded that scatter plots successfully differentiate between beach and dune sands; Shepard and Young (1961), Sevon (1966), Moiola and Weiser (1968) and Solohub and Klovan (1970) reached converse conclusions.

Some scatter plots are shown in Figs. 6.26 - 6.29, for random samples from all transects (the numbered prefixes on some points refer to the transects from which the samples were taken). The plot of σ_I against M_z separates dune sands from most beach sands of the middle and lower foreshores but the separation of dune sands and beach sands from the upper foreshore is less complete. It should be noted that the boundary lines drawn on the scatter plots to separate the subenvironments are not intended to be discriminant functions but merely serve to assist the eye.

The plot of M_z against Sk_I successfully differentiates the beach subenvironments and the dune environment for most samples. Dune sands are generally near-symmetrical, tending to slight negative skew whereas middle and lower foreshore sands are negatively to extremely negatively skewed. Upper foreshore sands are also

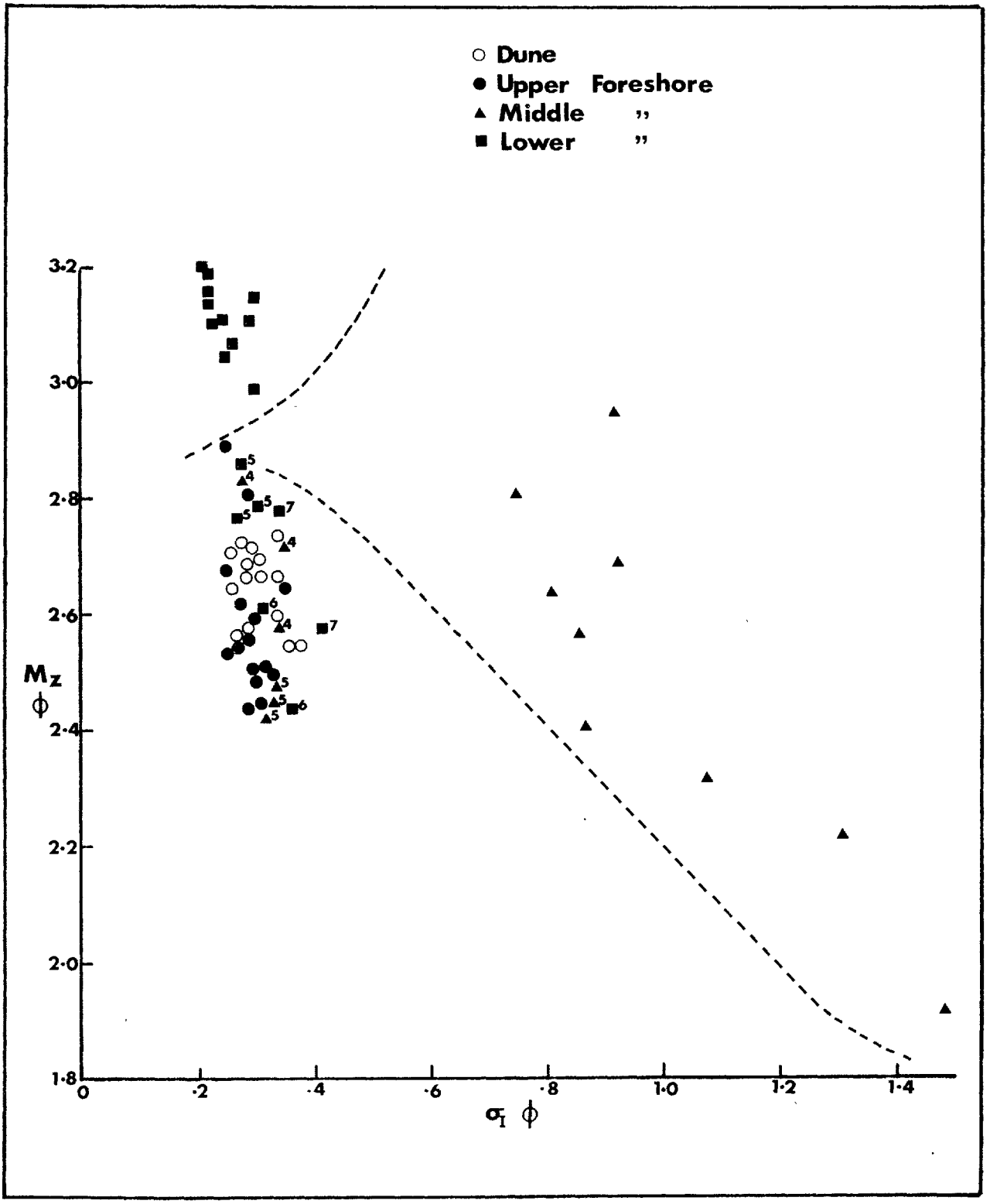


FIG. 6.26: PLOTS OF GRAPHICAL STATISTICS OF BEACH AND COASTAL DUNE SANDS.

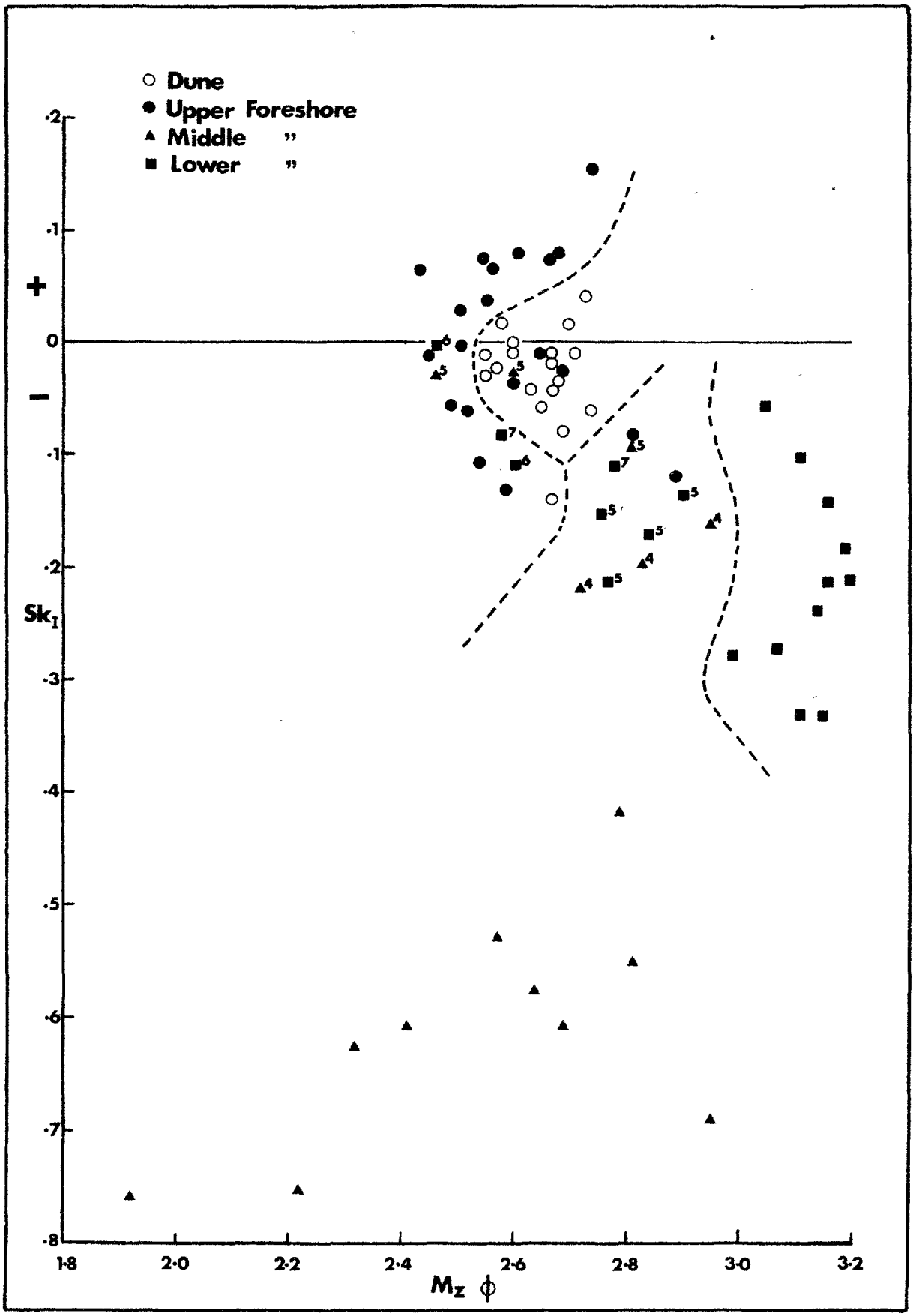


FIG. 6.27: PLOTS OF GRAPHICAL STATISTICS OF BEACH AND COASTAL DUNE SANDS.

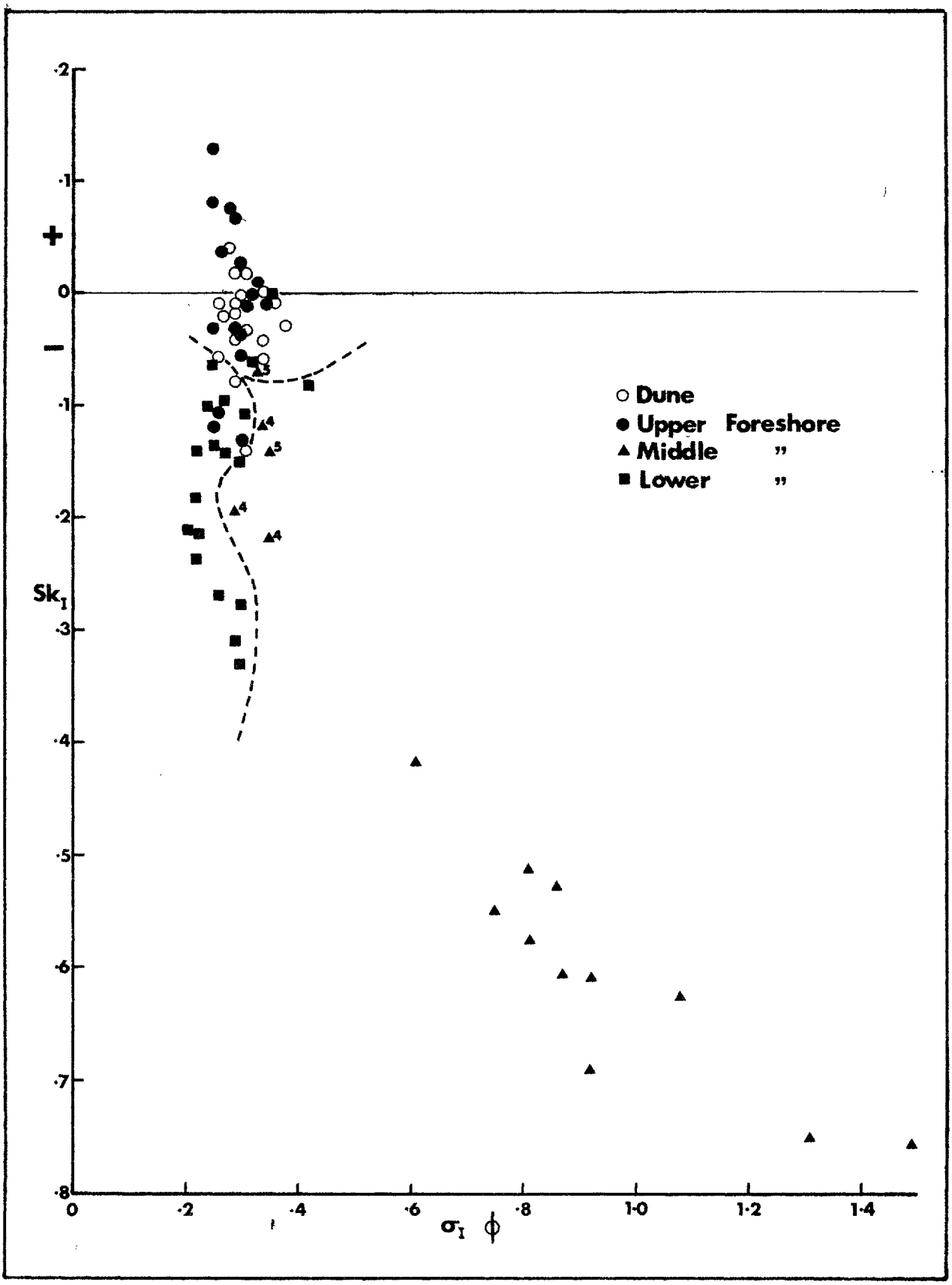


FIG. 6.28: PLOTS OF GRAPHICAL STATISTICS OF BEACH AND DUNE SANDS.

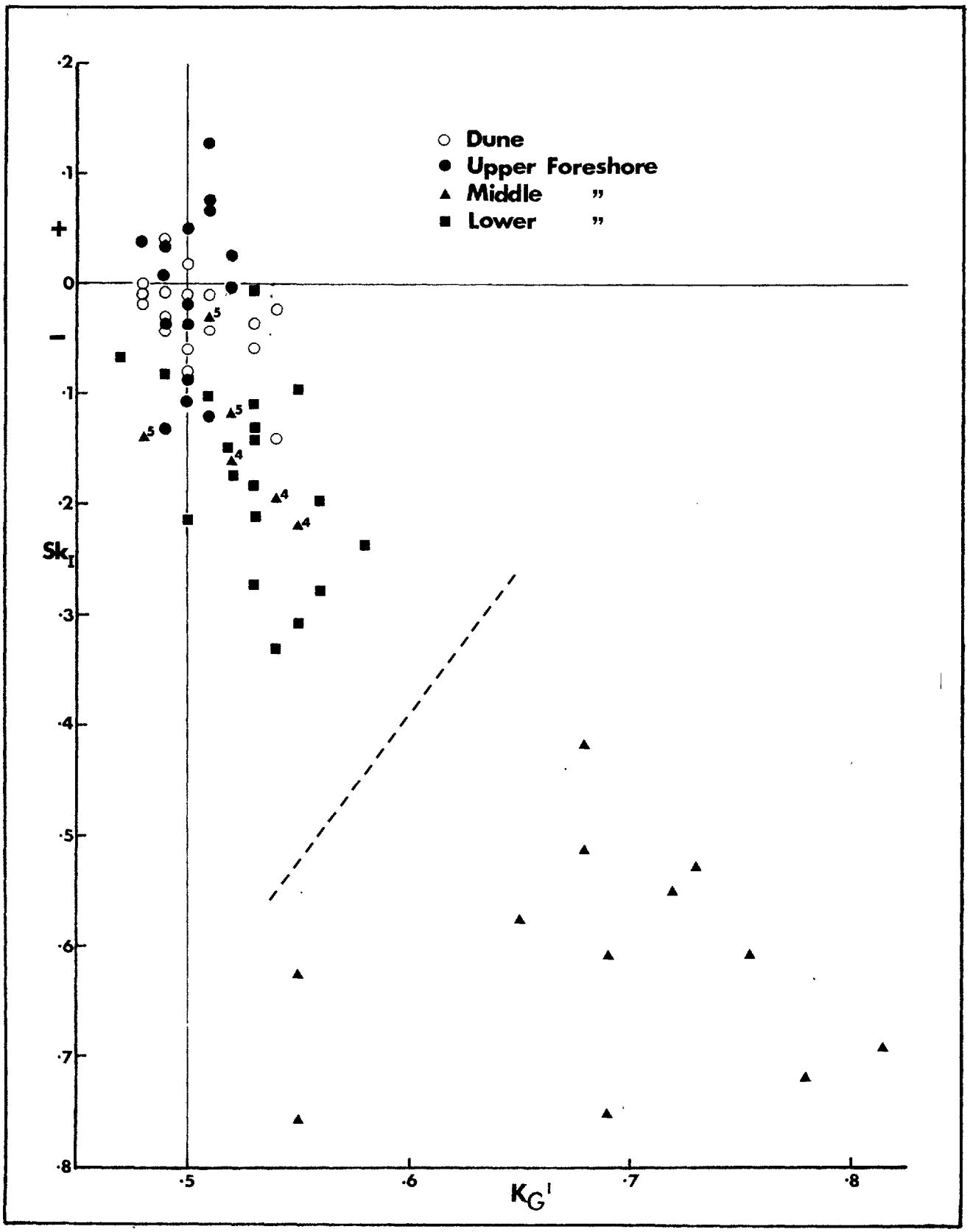


FIG. 6.29: PLOTS OF GRAPHICAL STATISTICS OF BEACH AND COASTAL DUNE SANDS.

near symmetrical, but some are just positively skewed, others just negative; however, they are generally rather coarser than the dune sands.

The plot of σ_I against Sk_I is again able to separate middle and lower foreshore sands from the dune sands, but there is a confusing overlap of upper foreshore and dune sands. It is interesting to compare this plot with an identical one given by Hails and Hoyt (1969) for beach and coastal dune sands of the Georgia coastal plain. The differences outweigh any similarities, emphasising that the universal application of significant results pertaining to any one geographical area can produce misleading results.

The plot of Sk_I against K_G' is even less productive, although regarded by Mason and Folk (1968) and Martins (1965) as able to separate beach and dune sands. Here only samples from the middle foreshore display any degree of separation from the dune samples.

Passega (1957) proposed that the fine and coarse fractions of sediments often act independently of each other and hence should be treated separately. This view finds strong agreement in the present study. However, the resulting CM diagram proposed by Passega, and shown in Fig. 6.30, is conspicuously unsuccessful in differentiating between dune sands and upper foreshore sands. The beach sands, taken as a whole, do illustrate some features noted by both Passega and Solohub and Klovan (1970) in comparable CM diagrams. But the technique does not appear to hold much promise for diagnosis of unknown environments of deposition.

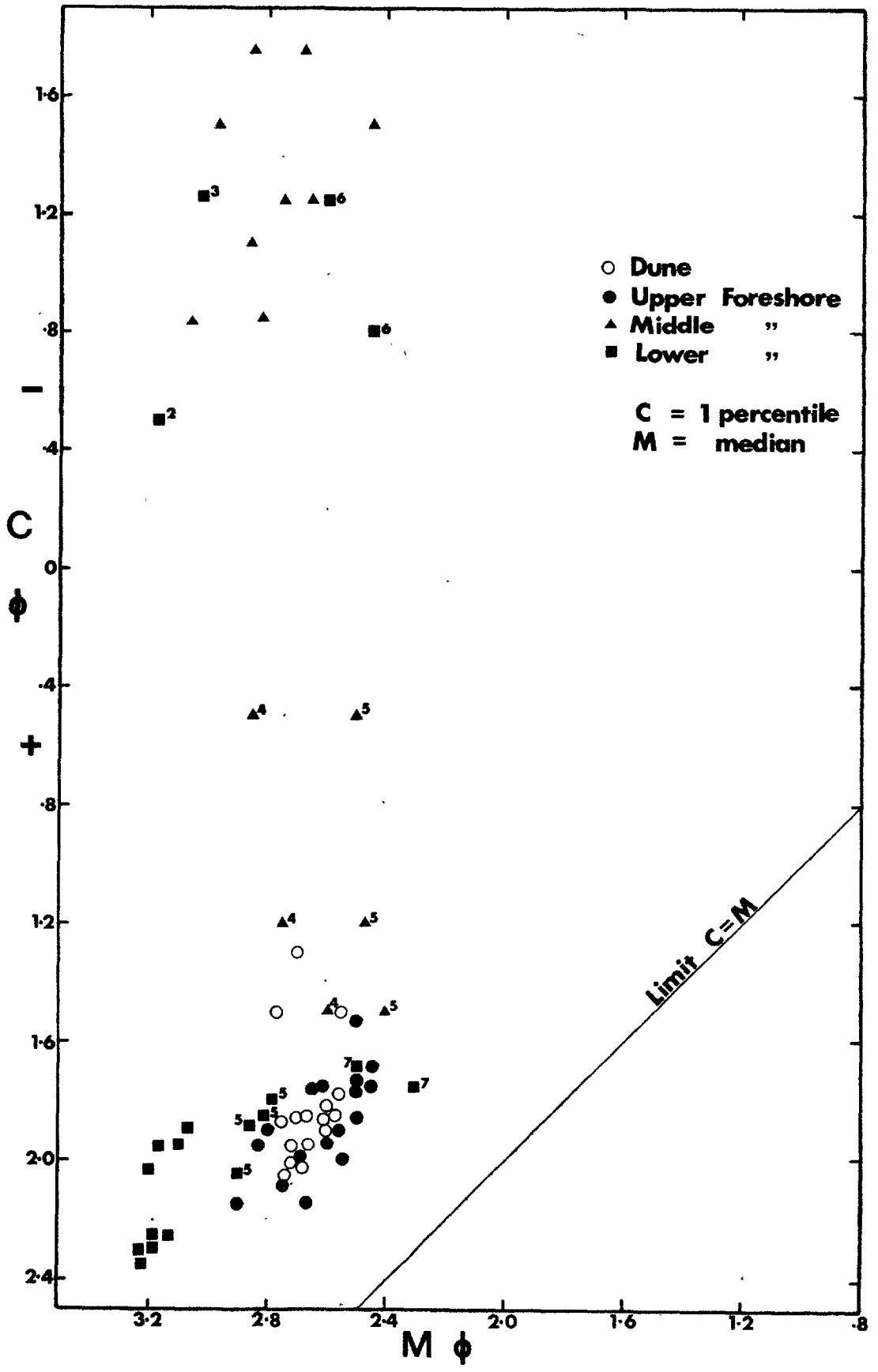


FIG. 6.30: CM PLOTS FOR BEACH AND DUNE SANDS.

Indeed it is a mute point whether any of the scatter plots would serve a useful purpose if all samples had been represented by an identical symbol. This would become a serious limitation if the number of samples was increased so that the complete spectrum of foreshore samples, including transitions between subenvironments, was plotted.

The only useful diagnostic feature of these plots is probably the uniformity of the dune sands in comparison with the wide variation of the beach sands. However, if only upper foreshore beach sands were available, then by this criterion these would be classified as dune sands.

It must also be emphasised that these plots probably have no significance for any other geographical area. If plotted on the supposedly diagnostic diagrams proposed by other workers for other areas, totally spurious conclusions would be reached. Even within the study area, there is a notable discrepancy in the plots between samples from the western half and those from the eastern half. This arises because the so-called middle foreshore is less developed on some transects than on others and also because there is a longshore variation of grain size. The incursions of samples from one subenvironment into the field of another is demonstrated on the scatter plots (the prefixes attached to these samples refer to their transect number).

As pointed out by Solohub and Klovan (1970), although depositional environments may be physiographically distinct, the

dynamic processes of sediment entrainment and accumulation operating within them may be identical. This is illustrated by the comparison of dunes and aeolian flats (although not shown on the plots, the samples of the transect 7 aeolian sand flat appear to be indistinguishable, texturally, from the dune samples).

Conversely, physiographically homogeneous subenvironments may display radically differing textural features. This is illustrated by the heterogeneity of the foreshore textures studied here, the surface features of the beach often providing no clue to such compositional variation.

6.6 Summary and Conclusions

It has been shown that the beach sediment of Pendine and Laugharne Sands are composed of three or four major components, and the dune sands of three or less components. Of these, one or two saltation components are predominant. At mid-tide level, on the western sands, significant proportions of a surface creep component occur. Near high and low water marks small proportions of a suspension component are infiltrated into the principal saltation components.

At present, the true significance in terms of dynamic responses of these principal components is not altogether clear, though several possible explanations have been proposed. The two saltation subpopulations of the beach sands may result from dual sedimentation by swash and backwash currents, or they may represent preferential

sorting within the swash zone of rounded detrital grains and angular organic grains. Both mechanisms may be in operation. The textural properties of both components must however be determined within the swash and collision zones.

The surface creep population is composed of predominantly shelly fragments with some lithic grains, these particles being too coarse and/or angular and in too small a concentration to be incorporated into a saltation population.

Suspension grains, composing a small proportion of the total surficial sediment, are predominantly heavy minerals settling out in increased proportions at the high water mark of the previous tides, but also on a widespread area of the lower foreshore near low-tide still-stand.

The distribution of sediment on the beach transects results from the action of the previous falling tide. There is an intimate association of sediment texture and foreshore slope, both of which are dependent on offshore bathymetry. Wave action, rather than current action, is the most important process element in defining these relationships.

The major saltation populations become progressively coarser in texture from lower to upper foreshore. This is related to the concave-upwards shape of the beach profile which permits increased swash zone velocities at higher stages of the tide. Wave energy, as transmitted to the breaker, does not directly establish the textural gradient of the saltation populations, although it may

contribute a significant effect on the eastern sands. This effect is due to the formation of offshore bars in the eastern sector; only near high water may the water depth be sufficiently great to allow waves to clear the shoals without substantial loss of energy. Thus waves may contribute an increased amount of energy to the upper foreshore than to the lower.

The occurrence of the coarse saltation population on the middle foreshore is matched by a corresponding increase in the coarser of the two saltation populations. This may be associated with local peaks of tidal current speeds halfway through the ebb phase of the tide. However, it seems also likely that it results from the superimposition of the effects of two conflicting trends. Coarse grains are moved into the nearshore zone most readily near low water where the bottom sediment is finer grained and therefore smooth. But surf zone bottom shear stresses must be greater at high than low tide, so that by this criterion coarse grains are most readily transported near high water. The resultant response to these trends may encourage a maximum concentration of coarse grains near mid-tide level.

Gravity must also be important, the surface creep population being concentrated at a marked break in slope between middle and lower foreshore. On the eastern sands, the coarse surface creep grains are generally absent, either because offshore slopes are too steep to allow for their shoreward displacement, or because they are incorporated into the coarser saltation population.

It has been demonstrated quantitatively that in major respects the western sands are texturally homogeneous along the strandline. Only the surface creep population shows a lateral trend of variation, and this can be attributed to the nature of offshore gradients. Nearshore gradients (on this western sector) are greatest at the westernmost transect so that nearshore wave action is correspondingly greater there, this being reflected by the increased proportions of the coarser grains.

On the eastern sands, although the coarse surface creep population is absent, the two saltation populations are significantly coarser than on the western sands. This is due to the presence of deep water close inshore formed by the main channel of the Taf, so that nearshore wave energy is increased.

Dune sands are in most aspects very similar to upper foreshore sands. The former are created by unidirectional wind action, the latter by unidirectional swash action at high tide still-stand. The distinguishing feature of both these sediments is the presence of one saltation population only. Very small proportions of surface creep and suspension grains are also present. Near high water mark, however, there is a dramatic increase of the suspension population, dumped by the ultimate swash current of the previous tide.

It must be emphasised that since it has been demonstrated that the exposed sediment textural gradients are created by the ebbing tide, the relevance of this study to the science of ancient sediments must be qualified by a consideration of further processes.

It is very probable that the high water pattern of sedimentation is essentially similar to the low water one (approaching that proposed by the null point theory) in terms of the predominant saltation populations.

As discussed by Curray (1964), the preservation of nearshore and littoral deposits depends upon the relative rates of transgression/regression and deposition/erosion. Whether or not the observed foreshore textural gradient would be preserved in the stratigraphic column would depend on the rate of sediment supply relative to the rate of changing sea level, and also on the thickness of the underlying beach deposits. Unless the beach deposits are of some thickness, they are likely to be preserved only if there is an abundant supply of sediment. Where a high influx of sediment is accompanied by a regression of the shoreline (which may itself be caused by the high rate of sedimentation), then the beach can prograde seawards; an upwards coarsening textural gradient of the saltation populations will result. High sediment influx accompanied by a relative rise of sea-level will produce a transgressive sequence; this will result in an upwards fining textural gradient.

It has been shown that the use of graphical parameters of composite sand populations is of limited value in deciphering differences between physiographic environments (at least as regards the beach and coastal dunes). Inspection and dissection of cumulative probability curves seems to hold most promise for an

understanding of the dynamic processes responsible for their generation. The present study has demonstrated this to some extent. However, future studies should perhaps concentrate attention on the properties of the grain-size distributions of single sedimentation units both normal and parallel to the strandline, and also in depth. The recognition and sampling of discrete sedimentation units however presents considerable difficulties, as explained in the previous chapter.

CHAPTER 7.

ESTUARINE SEDIMENT TEXTURES

7.1 Introduction

The processes of sedimentation in estuaries have received comparatively little attention from geologists, who have concentrated on littoral and deltaic elements of the nearshore environment, and as a result they are not yet understood in detail. Published studies on estuarine sedimentation tend to be somewhat fragmentary because there is at present little sense of continuity between them. This is partly because of the limited number of publications, but primarily it reflects the diversity inherent in their subject matter, the processes of sedimentation being themselves so variable so that no two estuaries are apparently alike.

Of the published work, rather more attention has been devoted to the deposits of the fine-grained rather than to the coarser-grained deposits (Postma, 1967), probably because of the major contribution of geologists in the Netherlands, working on muddy intertidal flats and estuaries (van Straaten and Kuenen, 1957, 1958; Müller, 1964), in France (Francis-Boeuff, 1947; Milon, 1935; Guilcher, 1958) and in the U.S.A. (Scruton, 1958; Nelson, 1960). Relatively few studies are concerned with sandy deposits (Terwindt et al, 1963). In Britain, information is rather scant, notable exceptions being the studies of Prentice et al (1968) in

the Thames, Medway and Taw-Torridge, Sheldon (1968) in the Crouch, Haynes and Dobson (1969) in the Dovey and Evans (1965) in the Wash (not strictly an estuarine environment, but with many pertinent similarities).

The present study may hopefully be considered a useful contribution to our knowledge of British estuaries; however, its results and conclusions can at present be considered as applicable to the Taf estuary only, and any universal implications may be minimal.

The differences already apparent between estuarine systems are obviously due to the variability and interaction of the various process parameters from one estuary to the next. These include the shape of the estuary, the strength of the tidal currents and river flow, the intensity of wind-generated waves, the accessibility of intruding oceanic swell, and the amounts and character of sediments available for transport and deposition. Some of these parameters have been considered in Chapters 3 and 4 and their relationships to estuarine circulation and sediment accumulation discussed. In this chapter, the textural properties of the sediments, particularly the sands, are examined in the light of those relationships.

7.2 The Significance of the Dissected Subpopulations

Four major subdivisions of the composite parent populations have been recognised for most of the estuarine samples, as explained in Chapter 5. Of these, one is coarse and poorly sorted

(a surface creep population), two are fine and well to very well sorted (saltation population) and the fourth is very fine and poorly to extremely poorly sorted (a suspension population), using the nomenclature for sorting of Friedman (1962). The surface creep population is always subsidiary, rarely exceeding 5% of the total. The suspension population makes up less than 2% of the open sand flats, but becomes a dominant constituent of the mud flats and saltmarsh. The finer grained saltation population is the major constituent of the sand flats, composing more than 80% of the total. The other saltation population has a coarser mean grain size and larger standard deviation than, and is always subordinate to, the finer-grained one.

Because of the striking similarity of the subpopulations from both the beach and the estuary, there can be no doubt that we are dealing with the populations 1, 2A, 2B and 3 that were recognised in the beach environment.

As with some of the beach samples, population 2A is often present as a minor constituent, and in some estuarine samples it has not been detected. In the case of the saltmarsh samples in which this sometimes occurs, its absence is undoubtedly a real one since the major saltation population 2B is also absent. In the case of the sand flat samples, in which it is almost always present, its occasional absence is probably apparent only, the graphical dissecting procedure having failed to isolate it from the ever-present major saltation population.

In contrast to all of the beach samples and estuarine sand flat samples, those from the mud flat and saltmarsh contain a significant proportion of the suspension population 3. As a result of its laboratory separation and analysis, its hydrodynamic interpretation is not a straightforward one. This is because the distribution of individual particles measured in the laboratory is not the same as the distribution of original aggregates in nature. Because of the unstable character of flocculation, this original distribution cannot be ascertained. Any connection between the textural properties of the 'laboratory' suspension population and the hydrodynamic processes that formed the original suspension deposit must be a tortuous one. Hence any interpretation of the texture/energy of deposition relationship will remain qualitative and comparative.

After graphical dissection, the population 3 of these muddy sediments generally describes a lognormal distribution, but gently truncated at its coarse end. The incidence of such a truncation means that it is impossible to directly read off the subpopulation parameters (M_3, σ_3) from the graph (i.e. by using the 16, 50 and 84 percentiles, where $M_3 = \phi\ 50$ and $\sigma_3 = (\phi\ 50 - \phi\ 16)$ or $(\phi\ 84 - \phi\ 50)$). The formulae for the graphical determination of grain-size parameters given by Folk and Ward (1957) have therefore been used for this purpose, since the subpopulation is not a lognormal one. The resulting parameters therefore refer to the actual truncated population, and not to any hypothetical lognormal

population adjusted to remove the effect of truncation. Also, since the pipette sedimentation analysis terminated at 10 ∅ units, it has been necessary to extrapolate the curve in some instances in the manner described by Folk (1968).

7.3 Variations of Subpopulations within the Estuary

Variations of subpopulation parameters are shown in Tables 7.1 - 7.11 and Figs. 7.1 - 7.11. As described in Chapter 5, sampling in the estuary was entirely subjective, and confined to eleven transects across it. Most samples were collected from the open sand flats, the most unstable and dynamic sedimentary environment, but a few were also taken from the mud flats and saltmarsh. Decisions on sampling locations were made on the grounds of a notable change of bed slope, surface features or shelly concentrate. Because of the current strength and/or water depth it was not always possible to collect a sample from the main channel on each transect.

After graphical dissection, the lateral variations of the various subpopulation parameters are continuous along the transects, but it is more convenient to discuss these within the broad sedimentary confines of sand flat, mud flat and saltmarsh.

(a) The Open Sand Flats

In all sand flat samples, subpopulation 2B is dominant, making up over 80% of the total. Its variation and distribution is

Sample	Proportions %				Silt: Clay	Textural Parameters Ø units					
	1	2A	2B	3		2A		2B		3	
						M_{2A}	σ_{2A}	M_{2B}	σ_{2B}	M_3	σ_3
81	.4	0	99.4	.2				2.60	.30		
82	.2	0	99.4	.4				2.68	.29		
83	.2	0	99.7	.1				2.65	.30		
84	1.1	0	97.5	1.4				2.75	.35		
85	.6	0	99.1	.3				2.65	.34		
86	.4	0	99.1	.5				2.66	.33		
87	.5	0	98.9	.6				2.62	.30		
88	.6	6.0	93.0	.4		2.17	.33	2.73	.28		
89	.6	5.5	93.6	.3		2.16	.32	2.74	.27		
810	.8	0	97.6	1.6				2.53	.29		
811	.8	0	97.7	1.5				2.54	.29		
812	1.1	0	43.4	55.5	1.81			2.65	.30	7.30	3.22
813	1.2	0	97.6	1.2				2.38	.29		
814	0	1.3	77.2	21.5	2.05	2.10	.30	2.70	.30	6.03	2.87
815	.8	5.8	91.5	1.9		2.23	.45	2.68	.29		
816	.9	6.3	91.0	1.8		2.24	.47	2.67	.28		
817	.8	6.0	91.3	1.9		2.25	.46	2.68	.27		
818	.6	3.4	60.3	35.7	1.63	2.25	.22	2.87	.23	6.38	2.91
819	2.8	4.7	56.5	43.5	4.97	2.10	.25	2.79	.25	5.78	2.72
820	3.5	7.1	62.4	27.0	4.21	2.45	.25	3.00	.22	5.54	1.92
821	6.0	17.5	75.0	1.5		2.35	.50	2.54	.35		
822	6.1	18.9	73.5	1.5		2.36	.53	7.53	.34		
823	3.0	17.0	79.5	.5		2.37	.54	2.60	.36		
824	1.3	2.5	95.8	.4		2.30	.42	2.46	.39		
825	1.7	23.3	74.5	.5		2.33	.32	2.53	.32		
826	.4	2.4	96.9	.3		2.32	.35	2.74	.28		
827	1.0	0	98.9	.1				2.52	.33		
828	.4	5.3	93.8	.5		2.25	.36	2.72	.32		
829	1.6	15.4	82.8	.2		2.30	.35	2.72	.28		
830	.1	0	99.8	.1				2.63	.29		
831	1.0	17.0	81.4	.6		2.25	.34	2.77	.28		
832	.2	2.8	96.9	.1		2.25	.31	2.73	.28		

TABLE 7.1 : Subpopulation Proportions and Textures, Transect 8.

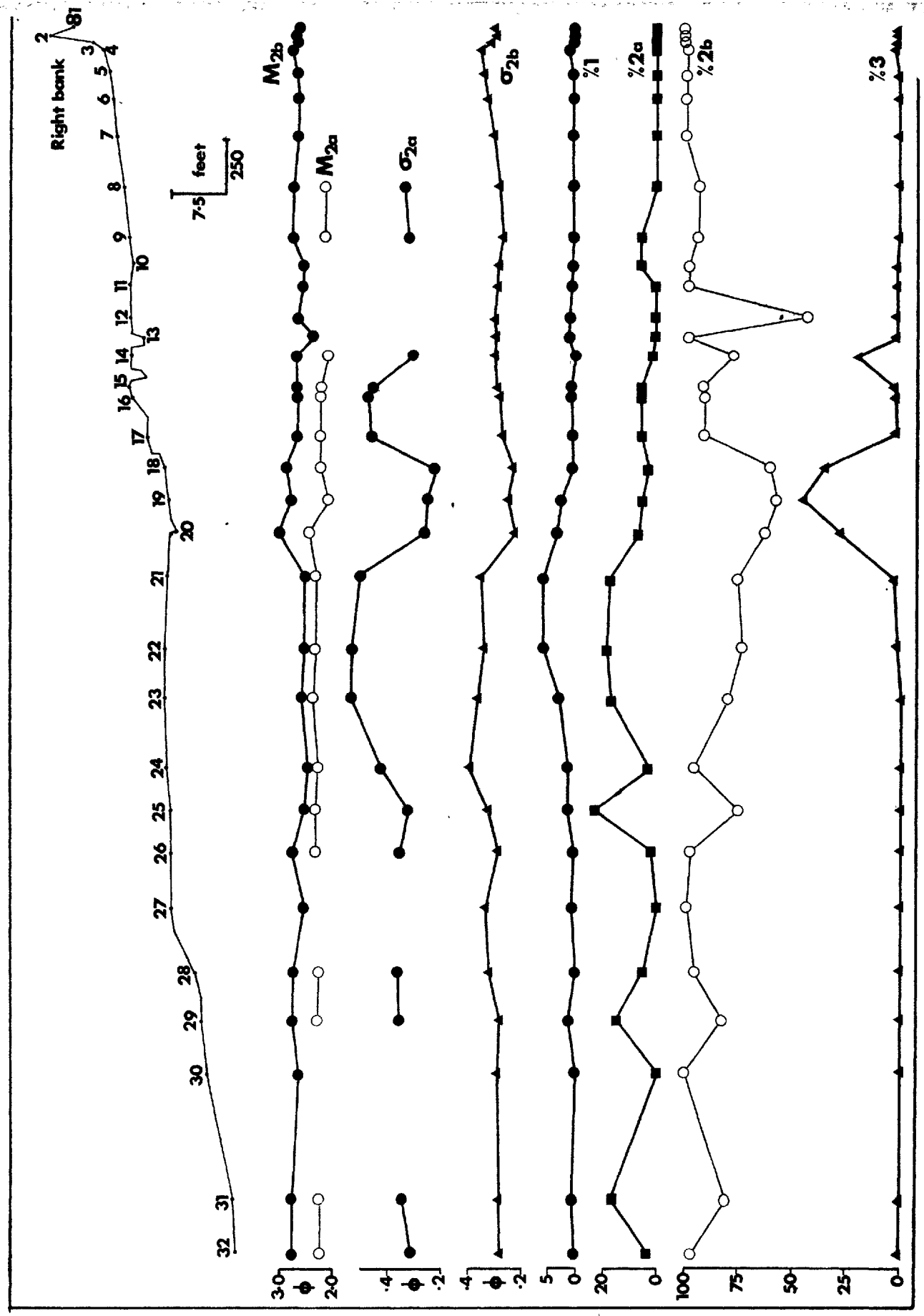


FIG. 7.1: SUBPOPULATION TEXTURES AND PROPORTIONS, TRANSECT 8.

Sample	Proportions %				Silt: Clay	Textural Parameters ∅ units					
	1	2A	2B	3		2A		2B		3	
						M_{2A}	σ_{2A}	M_{2B}	σ_{2B}	M_3	σ_3
91	0	0	0	100.0	1.05					8.77	2.55
92	0	0	0	100.0	1.37					7.92	2.33
93	0	0	0	100.0	1.58					7.53	2.41
94	1.4	13.6	52.0	33.0	1.51	2.44	.32	3.35	.30	7.03	3.04
95	0	.5	4.5	95.0	2.40	2.57	.40	3.49	.27	6.75	2.19
96	0	.4	20.6	79.0	2.87	2.48	.40	3.41	.35	6.20	2.49
97	.5	2.3	71.2	26.0	3.08	2.70	.41	3.25	.25	6.63	3.24
98	.3	6.5	55.2	38.0	4.87	2.75	.35	3.23	.25	5.44	2.00
99	.4	1.6	73.8	24.2	2.28	2.27	.42	3.07	.26	6.86	2.99
910	2.0	6.0	82.0	10.0		2.61	.33	3.10	.22	3.75	
911	3.5	8.0	79.5	8.0		2.69	.32	3.07	.22	3.60	
912	2.0	14.5	75.5	8.0		2.56	.33	3.07	.25	3.65	
913	3.1	8.9	80.1	7.9		2.55	.24	3.12	.21	3.67	
914	3.3	8.7	80.0	8.0		2.54	.23	3.12	.20	3.67	
915	3.2	8.5	80.2	8.1		2.54	.23	3.13	.21	3.67	
916	3.0	7.8	80.9	8.3		2.53	.24	3.13	.20	3.68	
917	.6	3.4	94.0	2.0		2.25	.33	2.88	.24		
918	.9	3.5	91.8	3.8		2.25	.32	2.81	.23		
919	1.0	3.4	91.5	4.1		2.25	.32	2.80	.23		
920	.6	3.1	94.4	1.9		2.26	.28	2.81	.24		
921	.5	3.3	94.4	1.8		2.25	.28	2.83	.24		
922	.5	4.0	93.8	1.7		2.21	.26	2.80	.24		
923	.4	4.0	94.0	1.6		2.20	.25	2.80	.24		
924	.4	4.1	94.0	1.5		2.20	.26	2.81	.24		
925	.4	5.1	93.5	1.0		2.24	.27	2.84	.25		
926	.4	5.2	93.5	.9		2.25	.27	2.84	.25		
927	.5	10.5	87.7	1.3		2.32	.27	2.79	.24		

TABLE 7.2 : Subpopulation Proportions and Textures, Transect 9.

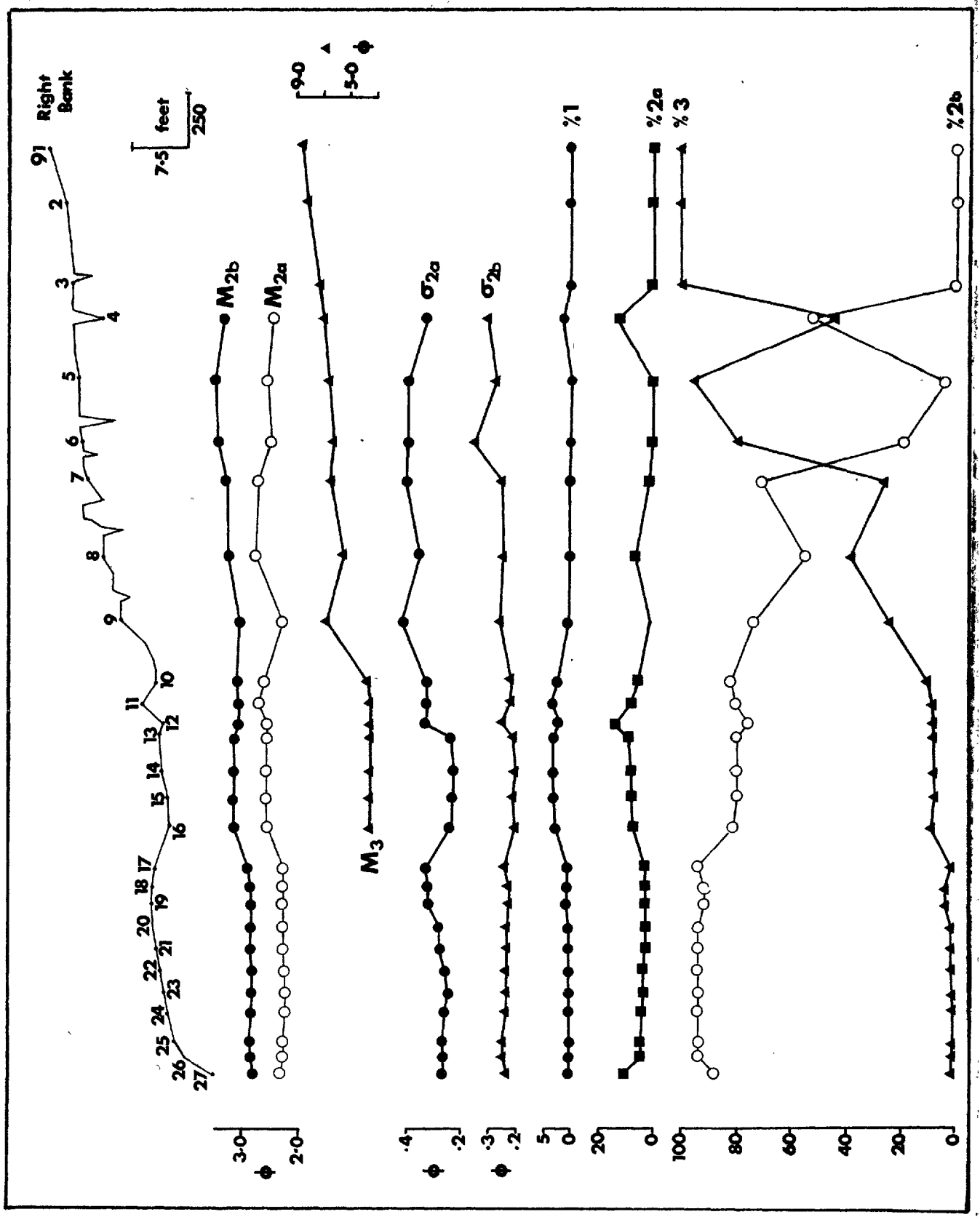


FIG. 7.2: SUBPOPULATION TEXTURES AND PROPORTIONS, TRANSECT 9.

Sample	Proportions %				Silt: Clay	Textural Parameters ø units					
	1	2A	2B	3		2A		2B		3	
						M_{2A}	σ_{2A}	M_{2B}	σ_{2B}	M_3	σ_3
101	17.0	0	81.0	2.0				2.66	.54		
102	2.2	0	34.3	63.5	2.19			3.33	.27	6.79	3.02
103	2.2	0	45.1	54.9	2.59			3.28	.25	6.55	2.86
104	.8	4.0	76.2	19.0	2.30	2.51	.25	3.17	.21	5.25	2.68
105	.6	4.4	76.2	18.8	2.29	2.54	.26	3.16	.20	5.21	2.67
106	1.8	6.6	86.7	4.9		2.60	.27	3.26	.22		
107	1.8	6.7	87.0	4.5		2.60	.27	3.27	.23		
108	2.0	24.0	72.5	1.5		2.50	.27	2.98	.24		
109	3.0	10.0	86.1	.9		2.20	.23	2.85	.24		
1010	2.7	23.3	73.7	.3		2.43	.34	2.85	.27		
1011	4.8	13.2	81.5	.5		2.42	.28	2.95	.25		
1012	.2	3.6	95.5	.7		2.21	.28	2.88	.24		
1013	.2	4.1	95.3	.4		2.20	.28	2.87	.25		
1014	.2	4.3	95.2	.3		2.18	.29	2.83	.26		
1015	.7	10.2	87.9	1.2		2.30	.30	2.87	.25		
1016	.5	5.0	94.1	.4		2.20	.33	2.77	.26		
1017	.5	4.8	94.2	.5		2.20	.31	2.77	.26		
1018	.5	3.8	95.0	.7		2.25	.31	2.97	.25		
1019	1.0	12.0	86.3	.7		2.20	.30	2.88	.27		
1020	.3	3.0	96.2	.5		2.20	.30	2.88	.24		
1021	.3	3.7	95.7	.3		2.25	.35	2.85	.26		
1022	.3	3.8	95.5	.4		2.26	.34	2.87	.26		
1023	.4	3.6	95.1	.9		2.28	.33	2.90	.25		
1024	1.4	6.4	75.2	17.0	1.66	2.67	.27	3.14	.24	6.22	3.07
1025	1.0	5.5	62.8	30.7	1.94	2.72	.27	3.17	.20	5.99	2.92
1026	3.5	4.7	52.2	39.6	2.78	2.89	.27	3.24	.24	5.68	2.25
1027	.6	3.4	43.4	52.6	2.74	2.60	.27	3.32	.24	5.91	2.63
1028	.5	3.5	26.0	70.0	2.03	2.60	.27	3.30	.21	7.43	3.35

TABLE 7.3 : Subpopulation Proportions and Textures, Transect 10.

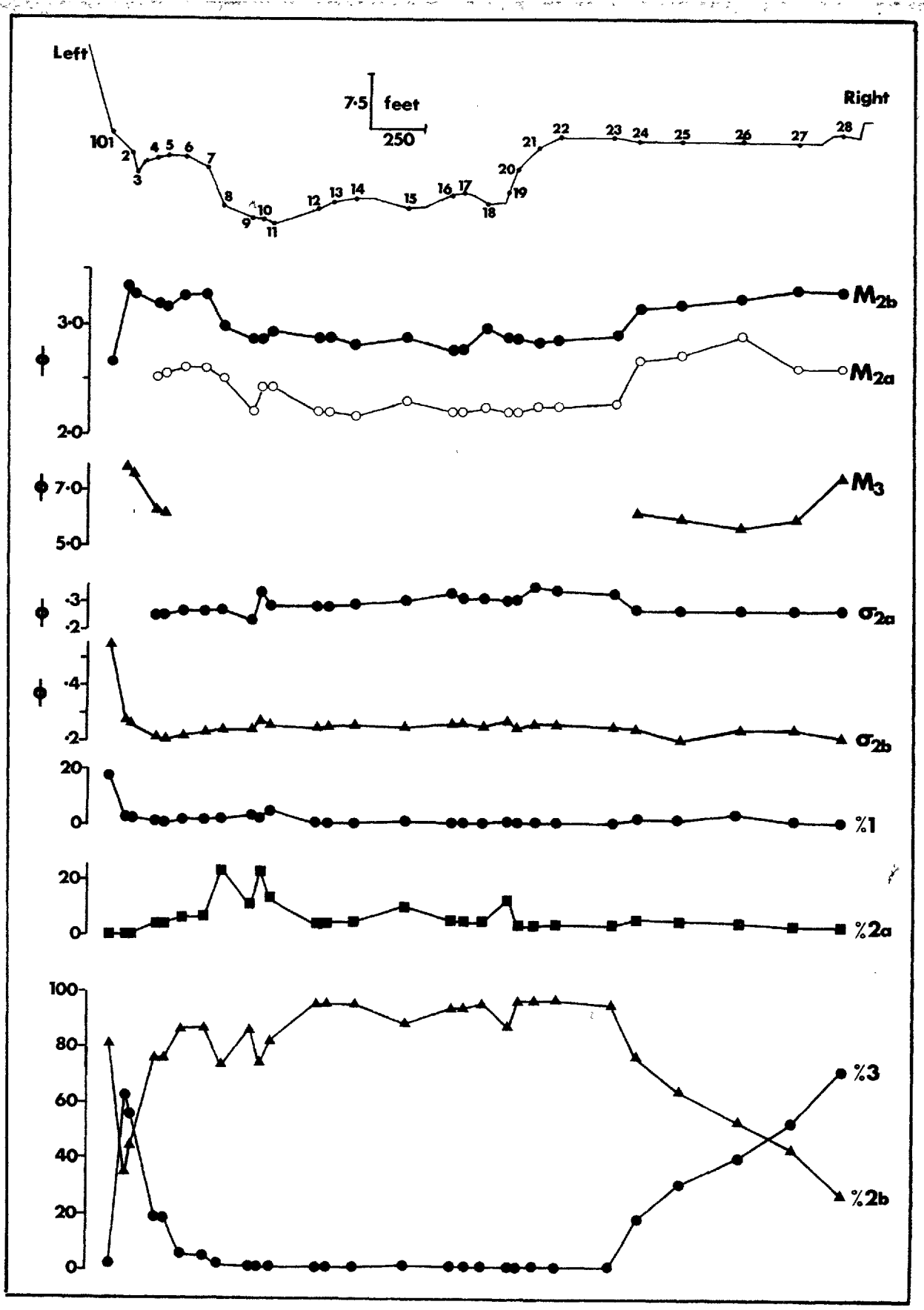


FIG. 7.3: SUBPOPULATION TEXTURES AND PROPORTIONS, TRANSECT 10.

Sample	% CO_3	Proportions %				Silt: Clay	Textural Parameters ø units					
		1	2A	2B	3		2A		2B		3	
							M_{2A}	σ_{2A}	M_{2B}	σ_{2B}	M_3	σ_3
111		1.0	5.8	57.1	36.1	2.50	2.70	.22	3.19	.18	5.40	2.10
112		1.3	6.5	57.2	35.0	2.54	2.72	.23	3.18	.18	5.32	2.02
113		1.2	5.9	58.1	34.8	2.56	2.70	.23	3.18	.19	5.30	2.04
114	17.8	.6	4.2	94.9	.3		2.35	.37	2.97	.25		
115		0	.8	98.6	.6				3.00	.23		
116	12.9	0	.7	98.8	.5				3.01	.23		
117		0	1.3	86.8	11.9		2.26	.41	3.00	.20		
118		0	1.4	86.3	12.3		2.27	.43	3.00	.20		
119		.5	2.5	91.1	5.9		2.24	.30	2.95	.24		
1110	17.4	.5	2.7	91.0	5.8		2.23	.27	2.94	.24		
1111		.6	2.9	91.6	4.9		2.23	.27	2.93	.24		
1112		3.0	9.7	86.6	.7		2.15	.25	2.75	.25		
1113	14.4	.5	2.9	95.9	.7		2.28	.27	2.93	.25		
1114		.4	2.9	95.1	1.6		2.53	.35	3.08	.24		
1115	12.8	.4	2.8	95.1	1.7		2.54	.36	3.09	.24		
1116		1.7	9.0	87.9	1.4		2.50	.36	2.95	.23		
1117		1.8	9.2	87.7	1.3		2.50	.37	2.94	.23		
1118		.7	8.6	90.2	.5		2.27	.33	2.87	.25		
1119	13.2	.6	8.4	90.6	.4		2.26	.32	2.85	.25		
1120		1.8	10.0	87.5	.7		2.32	.30	2.85	.26		
1121		.5	3.0	95.0	1.5		2.25	.29	2.83	.25		
1122		.6	4.2	93.4	1.8		2.24	.25	2.80	.24		
1123		.5	4.0	94.0	1.5		2.21	.26	2.81	.25		
1124		.3	5.2	93.5	1.0		2.25	.27	2.83	.24		
1125		.4	5.5	93.2	.9		2.26	.28	2.83	.25		
1126		.5	10.5	87.7	1.3		2.32	.27	2.79	.24		
1127		4.8	13.3	81.4	.5		2.32	.28	2.86	.25		

TABLE 7.4 : Subpopulation Proportions and Textures, Transect 11.

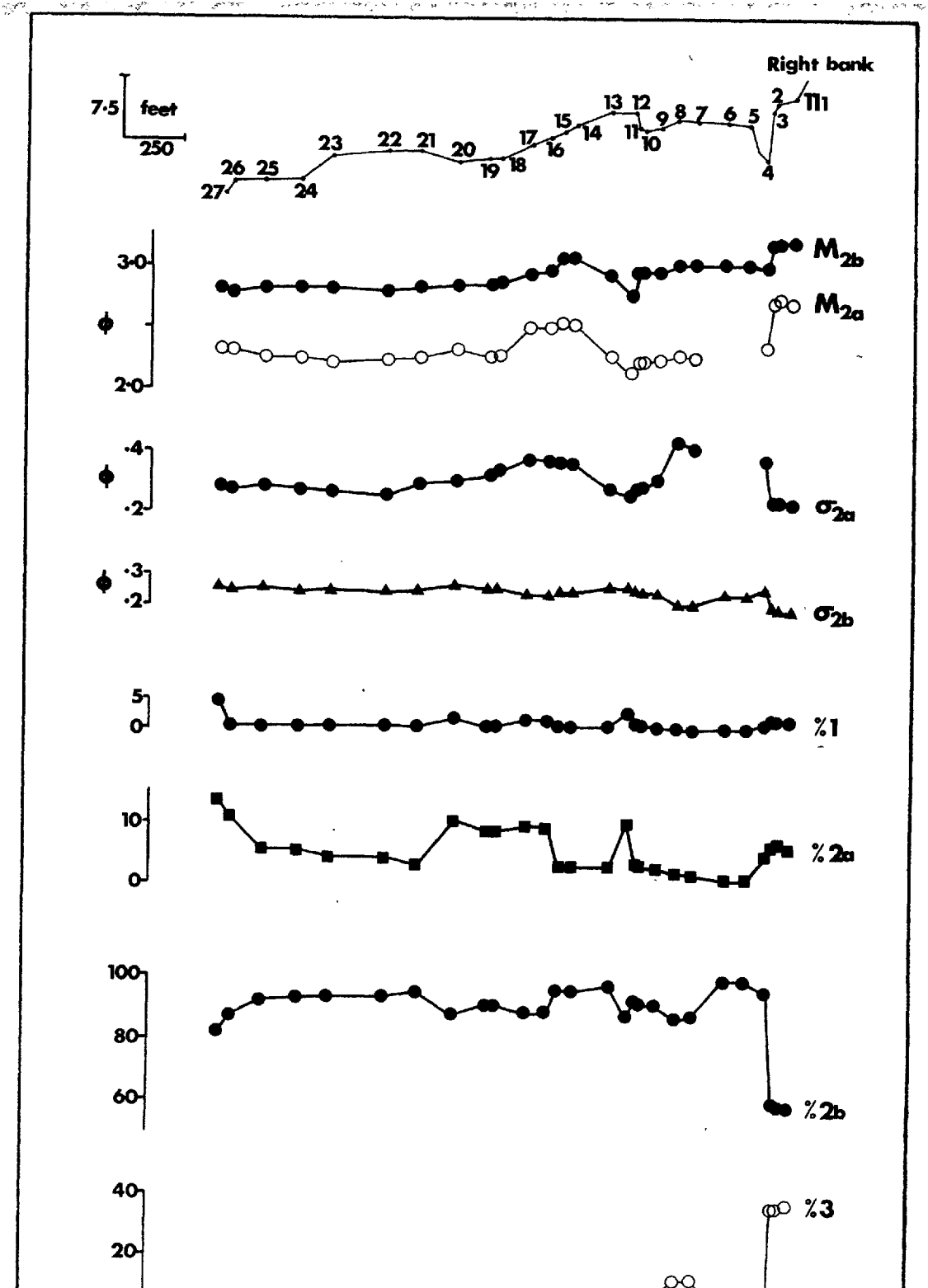


FIG. 7.4: SUBPOPULATION TEXTURES AND PROPORTIONS, TRANSECT 11.

Sample	% Carb	Proportions %				Silt: Clay	Textural Parameters ∅ units					
		1	2A	2B	3		2A		2B		3	
							M_{2A}	σ_{2A}	M_{2B}	σ_{2B}	M_3	σ_3
121		.7	3.5	63.8	32.0	2.32	2.65	.20	3.17	.20	5.61	2.57
122	17.5	1.6	8.4	89.2	.8		2.35	.37	3.00	.25		
123		1.8	6.0	91.0	1.2		2.29	.27	3.00	.27		
124	13.5	.7	4.8	93.8	.7		2.25	.32	2.95	.27		
125	11.8	.8	4.2	94.5	.5		2.27	.31	2.94	.25		
126	12.6	.6	3.7	95.4	.3		2.24	.30	2.91	.24		
127	15.7	.3	3.0	96.2	.5		2.30	.32	2.95	.24		
128	25.4	6.0	0	93.7	.3				2.92	.26		
129		5.8	1.3	92.5	.4		2.41	.35	2.92	.25		
1210	19.5	.4	6.6	92.5	.5		2.42	.38	2.92	.24		
1211	10.4	.1	2.0	97.2	.7		2.35	.29	2.94	.22		
1212	12.4	.8	0	98.5	.7				3.06	.22		
1213	19.5	2.5	0	97.0	.5				2.91	.27		
1214	24.0	1.0	5.6	91.4	2.0		2.33	.40	3.08	.24		
1215		4.0	9.0	51.0	36.0	3.09	2.60	.27	3.14	.20	5.58	2.47
1216	28.8	3.1	4.8	63.6	28.5	2.60	2.66	.24	3.23	.25	5.66	2.25
1217		3.2	5.0	63.8	28.0	2.56	2.67	.23	3.25	.25	5.67	2.23
1218		3.3	4.9	62.3	29.5	2.50	2.67	.24	3.25	.25	5.69	2.30
1219		3.6	5.0	29.5	63.5	2.29	2.65	.20	3.25	.25	6.63	2.92
1220		3.5	4.5	27.0	65.0	2.28	2.63	.20	3.26	.24	6.65	2.90

TABLE 7.5 : Subpopulation Proportions and Textures, Transect 12.

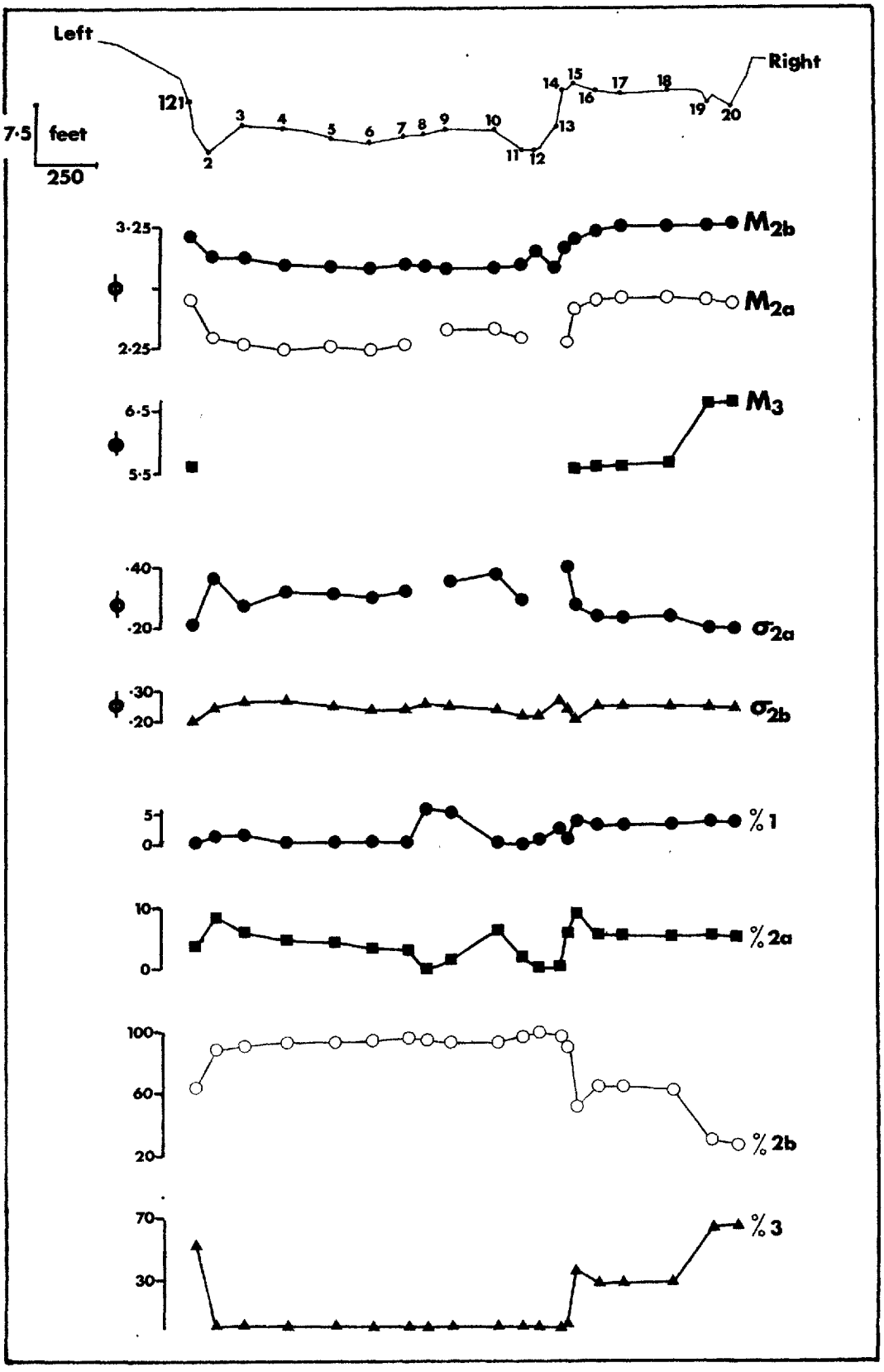


FIG. 7.5: SUBPOPULATION TEXTURES AND PROPORTIONS, TRANSECT 12.

Sample	% Carb	Proportions %				Silt: Clay	Textural Parameters ø units					
		1	2A	2B	3		2A		2B		3	
							M_{2A}	σ_{2A}	M_{2B}	σ_{2B}	M_3	σ_3
131	29.9	7.9	10.5	53.1	28.5	1.90	2.65	.21	3.24	.24	7.20	3.50
132		1.6	2.5	67.9	28.0	2.40	2.57	.20	3.20	.20	5.55	2.60
133		2.8	7.2	58.5	31.5	1.88	2.75	.20	3.20	.20	5.90	2.88
134		2.5	7.0	89.7	.8		2.30	.40	2.95	.27		
135	14.0	1.2	7.3	91.2	.3		2.25	.38	2.90	.26		
136	14.7	.4	3.8	95.3	.5		2.20	.38	2.93	.24		
137	10.7	.2	1.6	97.7	.3		2.20	.38	2.90	.24		
138	10.4	.6	5.0	94.1	.3		2.15	.38	2.84	.24		
139	9.1	.1	2.7	97.1	.1		2.25	.28	2.80	.26		
1310	12.0	.8	0	98.7	.5				2.92	.23		
1311	12.0	.4	1.9	97.3	.4		2.31	.33	2.95	.23		
1312	11.8	.4	1.4	97.8	.4		2.44	.33	3.03	.23		
1313	14.2	.3	2.5	96.8	.4		2.25	.30	2.95	.23		
1314	14.7	.4	2.0	96.9	.7		2.30	.32	2.90	.25		
1315	12.9	.7	0	98.3	1.0				2.95	.24		
1316	21.5	.3	7.0	90.7	2.0		2.26	.40	2.90	.26		
1317	19.4	2.3	0	95.7	2.0				3.05	.25		
1318	25.1	2.9	0	93.6	3.5				3.05	.26		
1319	10.0	.3	2.2	97.2	.3		2.20	.26	2.94	.25		
1320		3.0	7.0	88.9	.1		2.17	.45	2.76	.33		
1321	23.8	0	5.9	68.1	26.0	18.80	2.35	.45	3.22	.25	4.80	2.01
1322		.5	4.1	40.4	59.0	4.05	2.75	.30	3.25	.19	5.97	3.02

TABLE 7.6 : Subpopulation Proportions and Textures, Transect 13.

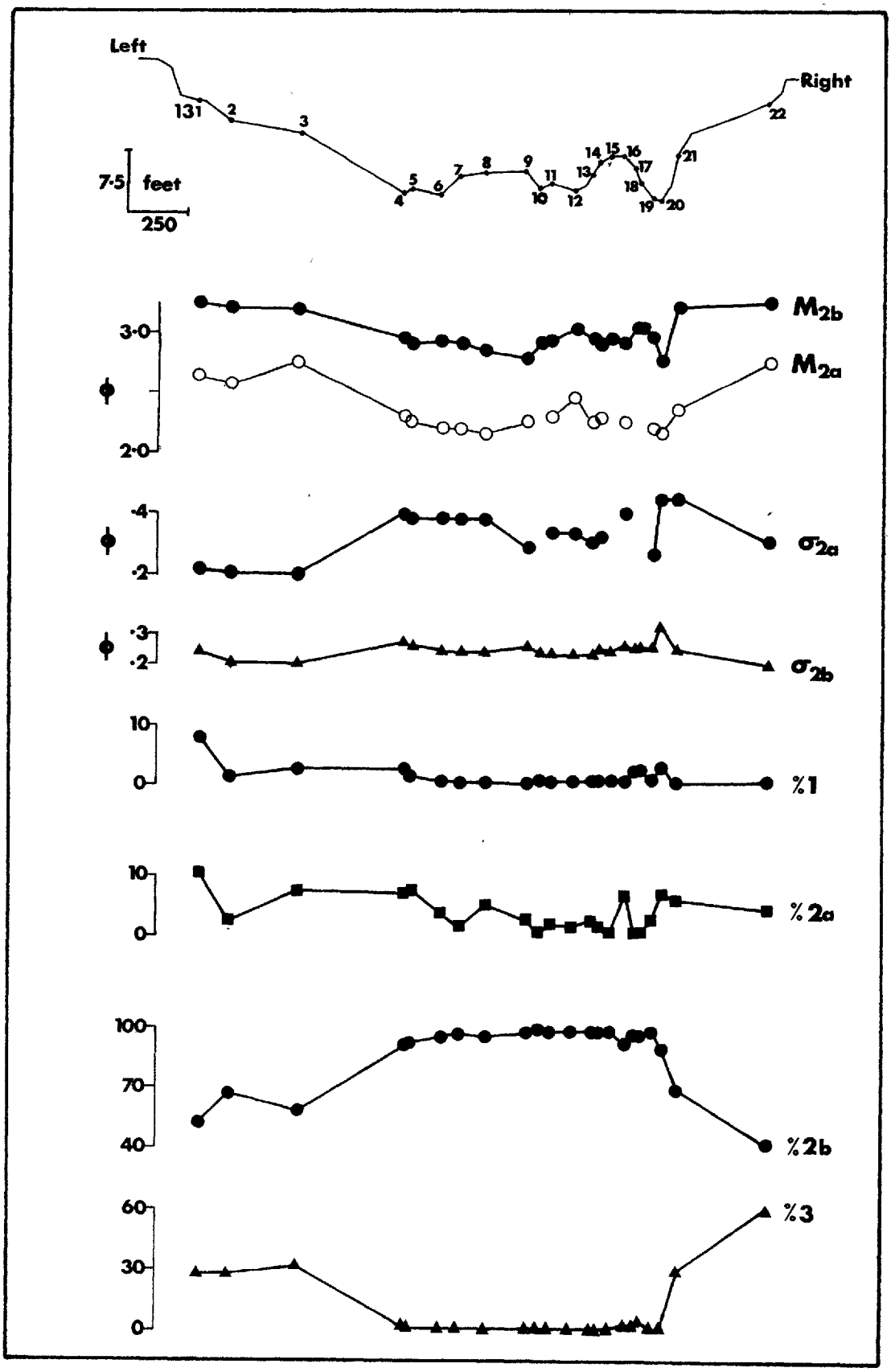


FIG. 7.6: SUBPOPULATION TEXTURES AND PROPORTIONS, TRANSECT 13.

Sample	% Co_3	Proportions %				Silt: Clay	Textural Parameters ø units					
		1	2A	2B	3		2A		2B		3	
							M_{2A}	σ_{2A}	M_{2B}	σ_{2B}	M_3	σ_3
141	32.0	8.0	11.0	53.5	27.5	1.93	2.65	.25	3.25	.25	7.16	3.54
142	23.9	4.2	6.8	71.3	17.7	1.32	2.65	.28	3.17	.20	6.16	2.77
143		3.0	18.6	76.0	2.4		2.56	.24	3.07	.21		
144	14.0	2.9	19.1	75.7	2.3		2.55	.23	3.07	.22		
145		.7	5.1	93.7	.5		2.26	.30	2.93	.25		
146	13.2	.6	4.9	94.1	.4		2.27	.31	2.91	.25		
147	18.1	.4	5.6	93.5	.5		2.37	.33	2.94	.25		
148		.7	5.8	92.8	.7		2.30	.40	2.95	.26		
149	26.3	1.6	11.9	85.9	.6		2.37	.45	3.00	.28		
1410	13.8	1.2	4.6	93.9	.3		2.35	.35	2.95	.25		
1411	11.7	.3	3.0	96.4	.3		2.21	.28	2.91	.26		
1412		.6	4.1	94.7	.6		2.35	.29	2.95	.25		
1413	15.0	.6	4.3	94.6	.5		2.37	.30	2.96	.25		
1414		.2	3.5	95.0	1.3		2.26	.37	3.00	.25		
1415	19.4	.1	3.7	94.6	1.6		2.25	.38	3.00	.26		
1416		.1	3.9	94.6	1.4		2.23	.38	3.00	.26		

TABLE 7.7 : Subpopulation Proportions and Textures, Transect 14.

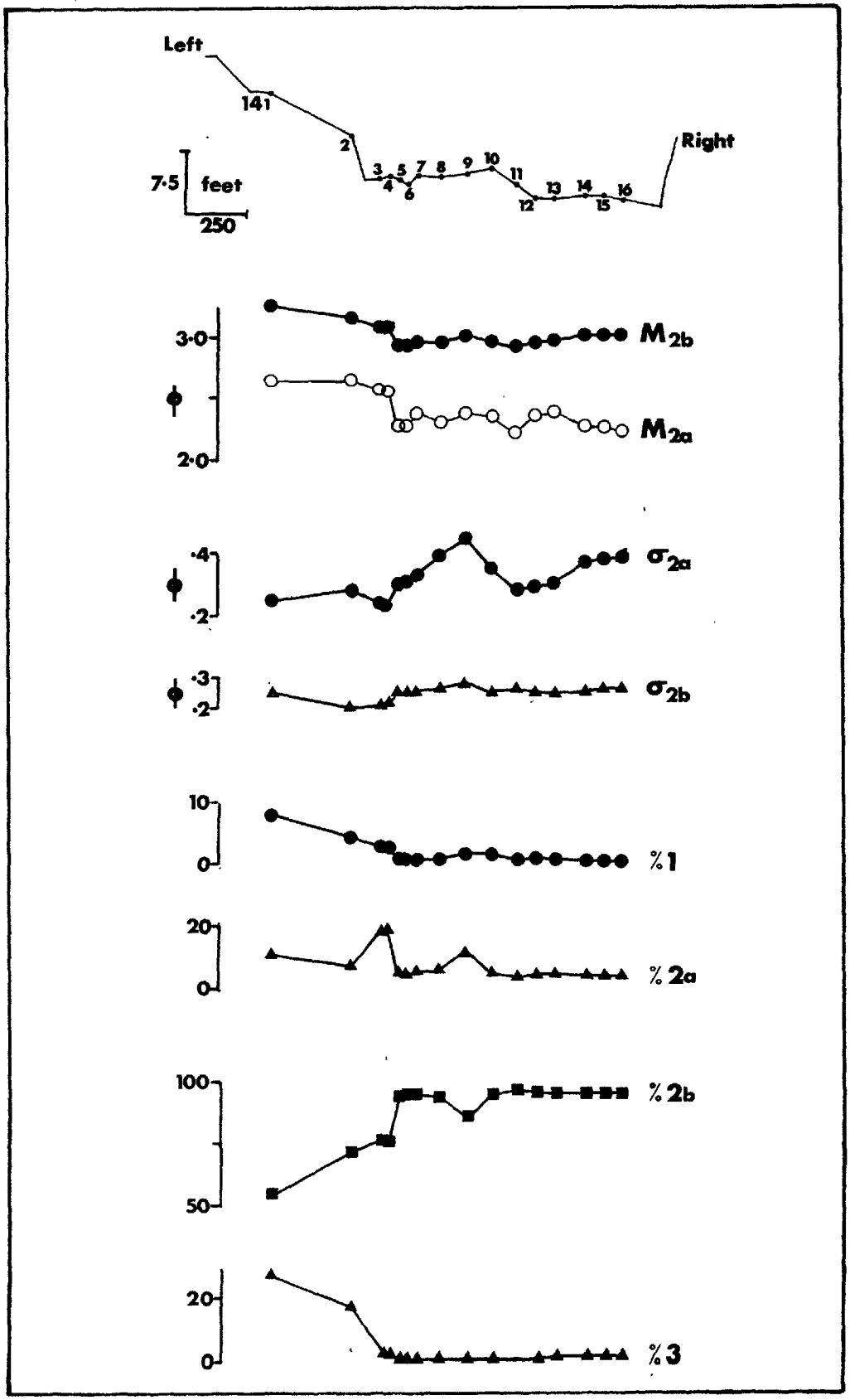


FIG. 7.7: SUBPOPULATION TEXTURES AND PROPORTIONS, TRANSECT 14.

Sample	% Co_3	Proportions %				Silt: Clay	Textural Parameters Ø units					
		1	2A	2B	3		2A		2B		3	
							M_{2A}	σ_{2A}	M_{2B}	σ_{2B}	M_3	σ_3
151		2.6	0	9.6	87.8	2.29			3.35	.23	6.77	2.51
152		0	.9	32.9	66.2	3.97	2.62	.34	3.28	.22	5.52	2.08
153		6.0	0	93.6	.4				2.76	.30		
154	10.4	.2	4.6	95.0	.2		2.38	.33	2.94	.25		
155	10.9	.2	2.6	96.8	.4		2.50	.34	2.98	.24		
156	12.6	.4	10.8	88.4	.4		2.70	.39	2.95	.25		
157		.4	3.0	96.1	.5		2.17	.25	2.90	.25		
158		.8	6.2	92.4	.6		2.36	.31	2.89	.27		
159	17.2	.9	6.3	92.4	.4		2.28	.35	2.95	.27		
1510	17.2	.6	7.4	91.7	.3		2.35	.44	2.94	.26		
1511	16.4	3.0	0	96.2	.8				3.00	.25		
1512	13.0	1.2	6.8	91.6	.4		2.30	.33	2.94	.26		
1513		.8	3.0	45.7	50.5	1.83	2.59	.31	3.28	.23	6.76	2.88
1514		.8	3.2	42.5	53.5	1.78	2.60	.30	3.28	.22	6.86	2.93

TABLE 7.8 : Subpopulation Proportions and Textures, Transect 15.

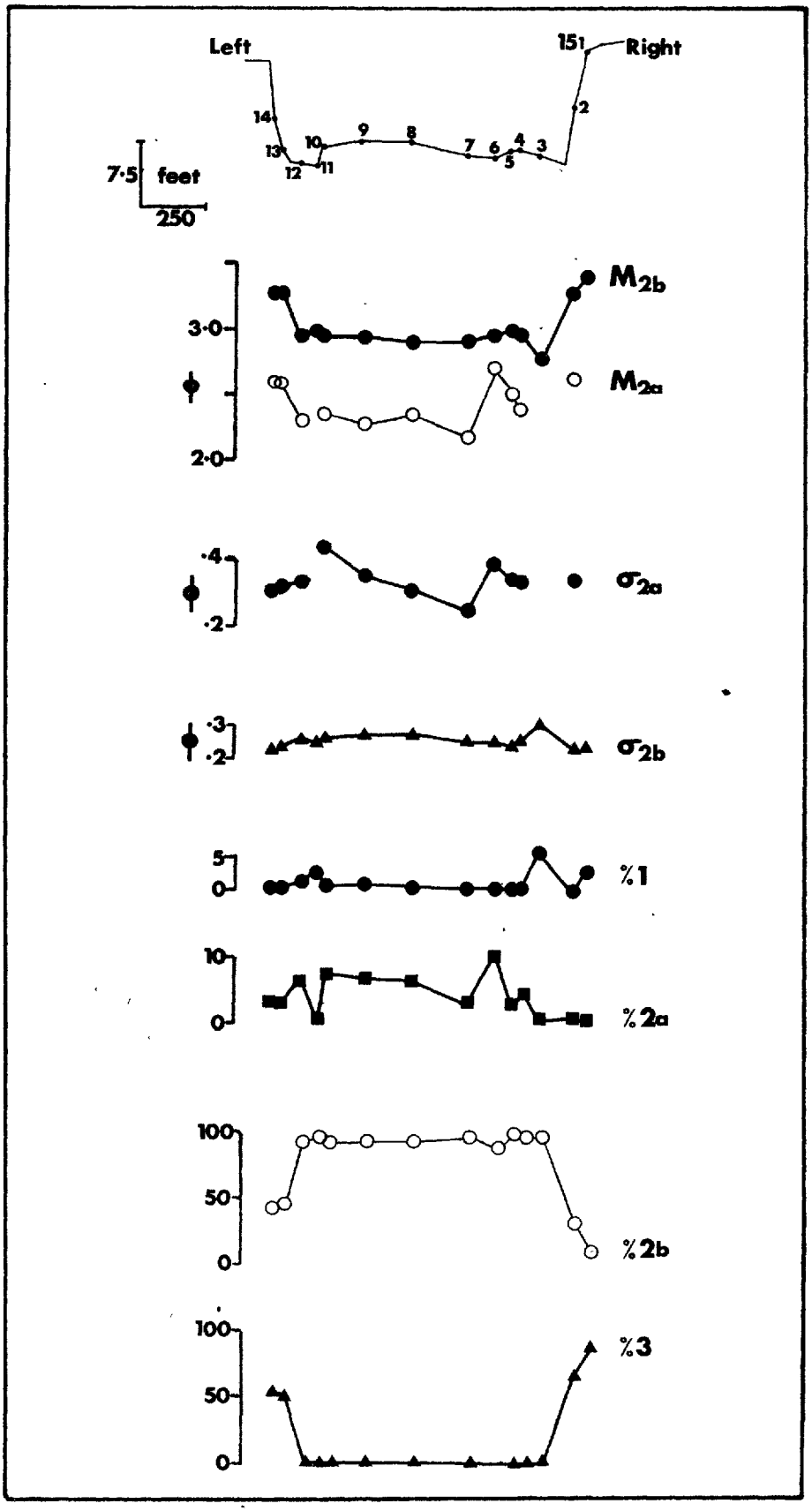


FIG. 7.8: SUBPOPULATION TEXTURES AND PROPORTIONS, TRANSECT 15.

Sample	% Co_3	Proportions %				Silt: Clay	Textural Parameters ø units					
							2A		2B		3	
		1	2A	2B	3		M_{2A}	σ_{2A}	M_{2B}	σ_{2B}	M_3	σ_3
161		2.0	7.4	62.1	28.5	1.81	2.60	.28	3.20	.20	6.98	3.78
162	24.5	1.4	0	90.6	8.0				3.20	.23		
163		1.3	2.1	88.8	7.8		2.68	.31	3.21	.23		
164	21.6	4.0	7.0	86.0	3.0		2.70	.33	3.10	.22		
165	15.2	3.8	30.2	65.6	.4		2.23	.33	2.71	.27		
166	10.1	.2	2.4	96.4	1.0		2.26	.29	2.96	.25		
167	10.8	.5	2.0	96.7	.8		2.38	.23	2.95	.23		
168	12.7	.3	4.0	95.1	.6		2.35	.30	2.96	.25		
169	19.9	.6	10.4	88.5	.5		2.35	.37	2.97	.23		
1610	28.7	2.2	12.6	82.5	2.7		2.52	.28	3.12	.22		
1611	32.1	3.8	17.4	69.1	9.7		2.63	.32	3.18	.23		
1612	19.4	1.8	8.2	86.3	3.7		2.60	.35	3.10	.26		
1613	14.4	2.0	6.2	90.0	1.8		2.59	.35	3.10	.23		
1614	16.8	.8	4.2	92.4	2.6		2.33	.36	3.05	.25		
1615	12.6	1.0	4.0	94.4	.6		2.31	.32	3.01	.25		
1616		1.0	5.5	91.0	2.5		2.48	.31	3.12	.23		
1617	20.4	1.0	5.8	91.4	2.8		2.50	.30	3.12	.23		
1618	26.6	0	9.0	83.4	7.6		2.54	.40	3.18	.22		
1619		1.7	4.5	45.2	48.6	.72	2.55	.30	3.32	.23	7.65	3.65
1620		1.8	4.2	43.5	50.5	.74	2.55	.28	3.34	.23	7.89	3.68

TABLE 7.9 : Subpopulation Proportions and Textures, Transect 16.

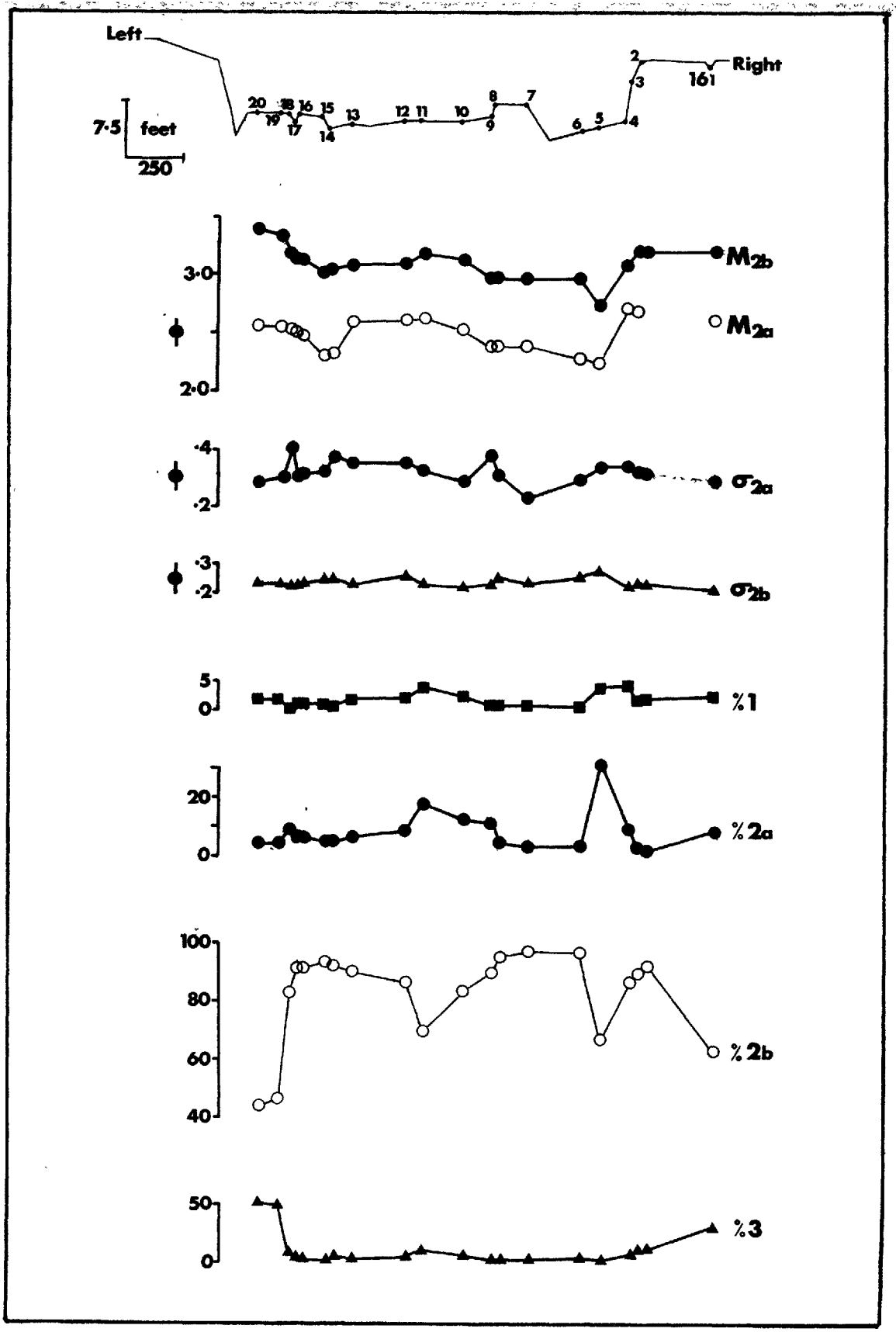


FIG. 7.9: SUBPOPULATION TEXTURES AND PROPORTIONS, TRANSECT 16.

Sample	% Co_3	Proportions %				Silt: Clay	Textural Parameters ø units					
		1	2A	2B	3		2A		2B		3	
							M_{2A}	σ_{2A}	M_{2B}	σ_{2B}	M_3	σ_3
171		0	4.8	49.2	46.0	2.08	3.10	.55	3.61	.25	7.49	2.76
172		.7	7.8	65.5	26.0	1.98	2.85	.36	3.17	.22	6.12	2.89
173	17.5	1.8	0	97.3	.9				2.98	.26		
174	14.5	.7	2.6	96.2	.5		2.29	.34	3.00	.25		
175		.8	0	98.5	.7				2.90	.26		
176	14.3	.7	5.3	93.8	.2		2.40	.35	2.93	.24		
177		1.2	0	98.3	.5				3.00	.24		
178	16.2	2.4	8.6	88.2	.8		2.50	.25	2.99	.23		
179	15.6	.6	6.4	92.0	1.0		2.52	.42	3.04	.27		
1710	14.6	1.4	10.6	87.0	1.0		2.46	.33	2.94	.25		
1711	14.6	.7	10.0	88.3	1.0		2.41	.37	2.96	.27		
1712	19.4	.7	10.0	88.1	1.2		2.59	.43	3.04	.25		
1713		.7	9.5	88.8	1.0		2.60	.42	3.03	.25		
1714		3.6	0	95.2	1.2				3.02	.25		
1715	18.3	4.4	0	94.2	1.4				3.02	.26		
1716		3.9	1.3	93.8	1.0		2.60	.40	3.01	.26		
1717		3.6	1.4	93.5	1.5		2.61	.39	3.02	.24		
1718	28.8	.3	6.7	83.0	10.0		2.61	.38	3.22	.23		
1719		.4	5.8	83.5	10.3		2.60	.39	3.23	.23		
1720	20.1	.5	5.3	90.4	3.8		2.37	.46	3.06	.25		
1721		.5	5.0	91.0	3.5		2.38	.45	3.05	.24		
1722	21.7	1.0	3.8	76.2	19.0		2.77	.32	3.20	.20		
1723		.1	2.0	72.4	25.5		2.57	.41	3.17	.18		
1724		0	3.8	56.7	39.5	2.48	2.60	.44	3.29	.22	6.27	2.60
1725		0	4.5	49.5	46.0	2.49	2.62	.50	3.30	.23	6.37	2.64

TABLE 7.10 : Subpopulation Proportions and Textures, Transect 17.

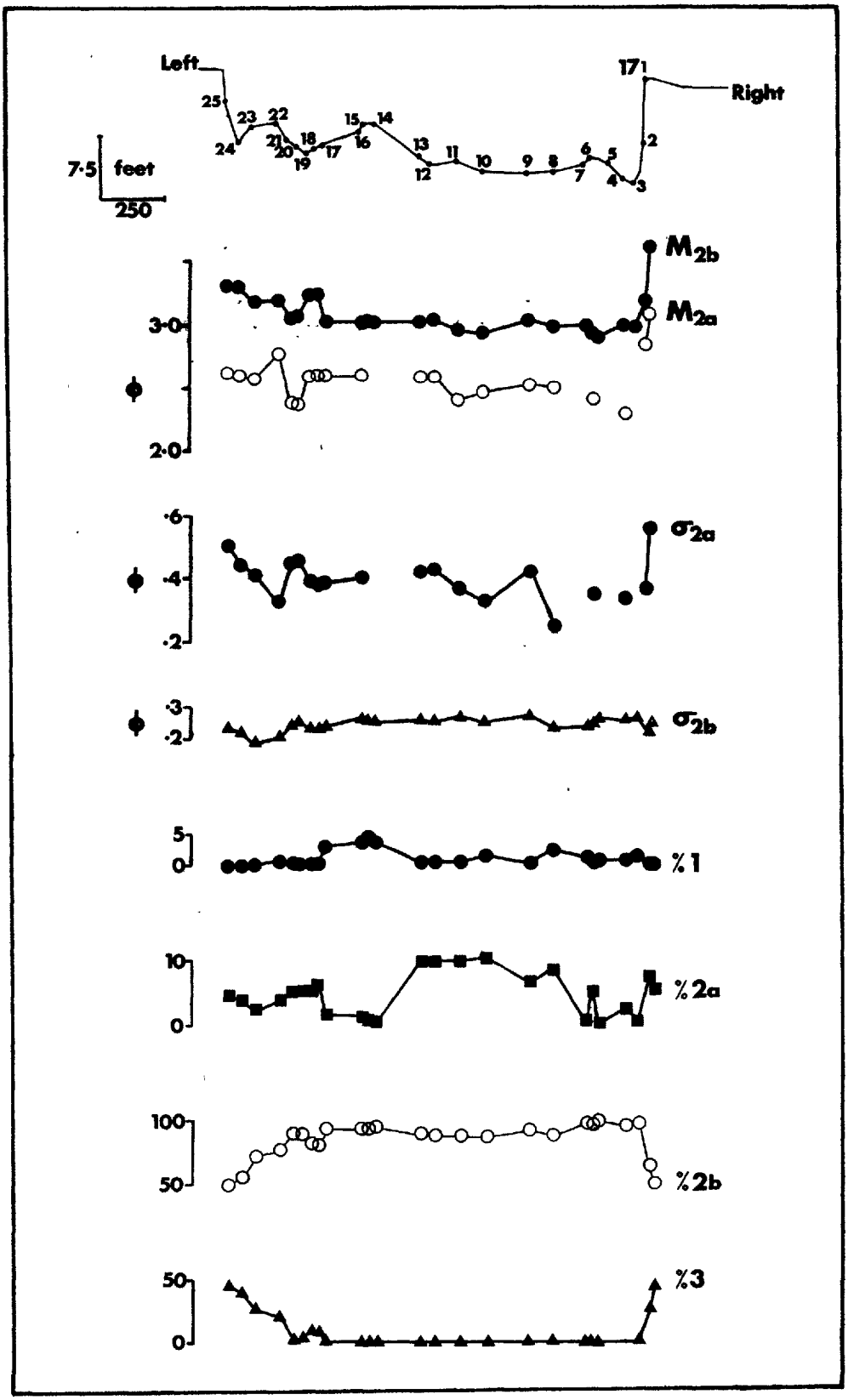


FIG. 7.10: SUBPOPULATION TEXTURES AND PROPORTIONS, TRANSECT 17.

Sample	% Co_3	Proportions %				Silt: Clay	Textural Parameters ø units					
		1	2A	2B	3		2A		2B		3	
							M_{2A}	σ_{2A}	M_{2B}	σ_{2B}	M_3	σ_3
181		0	3.8	36.7	59.5	3.29	2.58	.55	3.20	.20	5.58	2.14
182	14.5	1.6	8.4	89.4	.6		2.53	.30	3.04	.25		
183		1.5	7.5	90.2	.8		2.52	.30	3.04	.26		
184		0	3.8	78.0	18.2		2.44	.46	3.12	.24		
185	19.1	.2	1.8	97.2	.8		2.38	.30	2.98	.25		
186		.3	2.3	96.8	.6		2.37	.29	2.97	.25		
187	19.8	.6	11.0	84.6	3.8		2.60	.35	3.06	.25		
188		.4	3.5	94.7	1.4		2.50	.35	3.01	.26		
189	13.1	.3	3.0	95.5	1.2		2.49	.34	3.00	.27		
1810		1.6	12.4	85.3	.7		2.60	.25	3.08	.23		
1811	16.3	.7	4.3	94.1	.9		2.42	.37	2.98	.24		
1812	11.4	.1	2.0	97.0	.9		2.33	.30	2.90	.27		
1813	14.5	.4	7.6	91.0	1.0		2.57	.28	3.07	.23		
1814	10.4	.2	2.6	96.8	.4		2.40	.33	2.93	.25		
1815	11.2	.3	1.5	97.5	.7		2.35	.25	2.97	.25		
1816	20.3	2.6	10.4	86.4	.6		2.40	.25	3.03	.22		
1817	11.6	.1	1.0	98.4	.5		2.40	.37	3.05	.23		
1818		0	2.0	40.0	58.0	3.61	2.52	.40	3.28	.23	5.89	2.30
1819		0	2.3	37.2	60.5	3.61	2.55	.45	3.30	.23	5.92	2.26

TABLE 7.11 : Subpopulation Proportions and Textures, Transect 18.

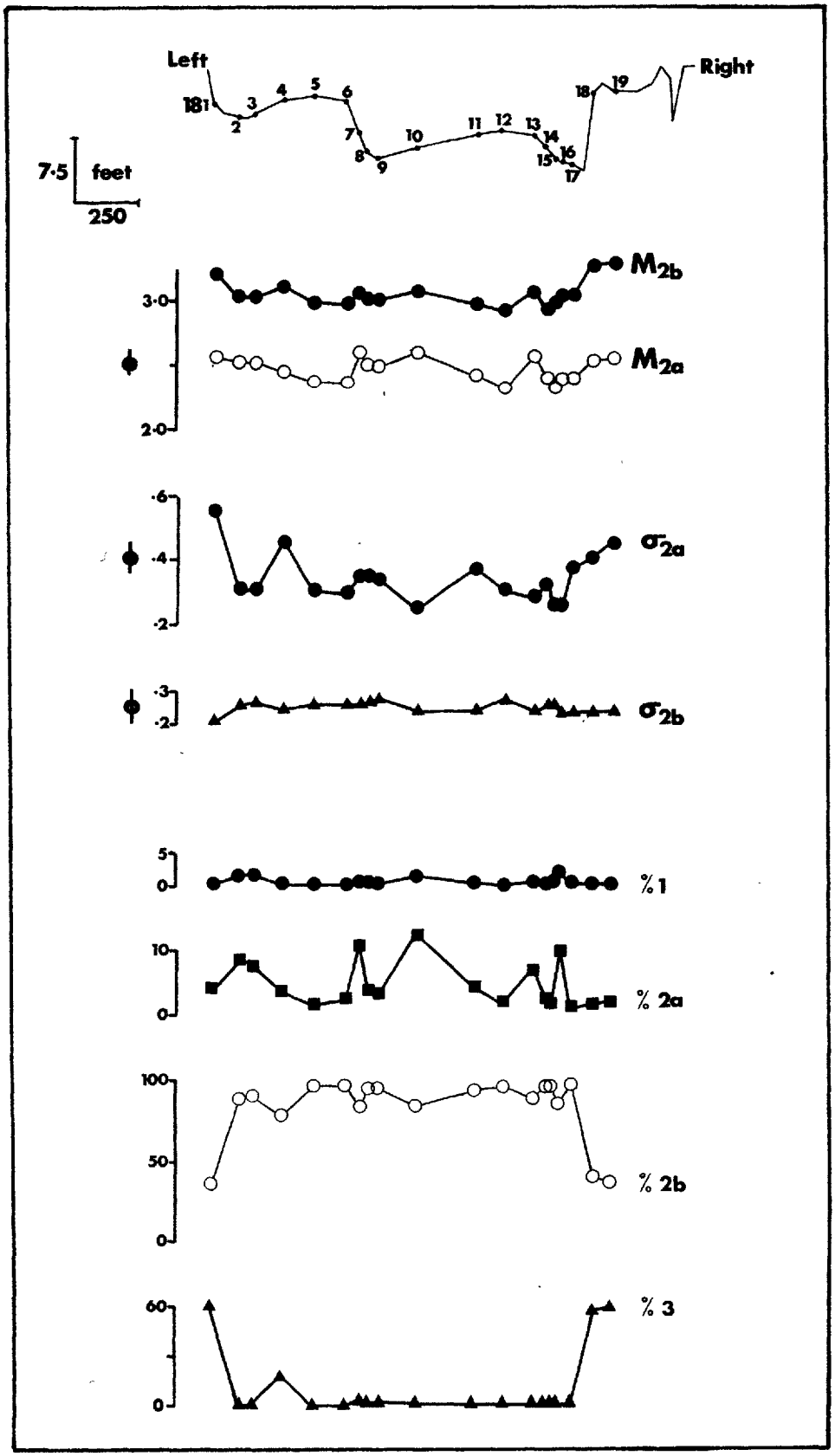


FIG. 7.11: SUBPOPULATION TEXTURES AND PROPORTIONS, TRANSECT 18.

therefore likely to be a crucial reflection of the processes of sedimentation in the estuary.

The most striking feature of its textural properties lies in their uniformity across each of the transects. The mean range of its mean grain size, M_{2B}, across all transects is only 0.30 ϕ units. There is no great differentiation between its magnitudes on shoals and in shallow channels. The main channel was not sampled on transects 8, 9 and 14, but on most others the maximum mean grain size M_{2B} occurs not in the channel but on the exposed areas immediately adjacent to it. On transect 13, the maximum grain size does occur in the main channel and on transect 11 in a subsidiary ebb channel. Allowing for the temporal migration of channels, there is thus a close correspondence between zones of maximum temporal instability (in terms of vertical variation, see Chapter 4) and zones of maximum mean grain size of the dominant sand population on most transects. Since the former is known to result from the generation of maximum currents and turbulence on the early flood and late ebb tides, the latter can be attributed to similar processes. Evidently, the variation of M_{2B} across the transects is current controlled. The range of M_{2B} is small, and even at its coarsest is well within the transporting capabilities of currents throughout most of the tidal cycle (using the graph given by Hjulstrom, 1939). Thus bed movement must occur throughout the tidal cycle. The restricted range of M_{2B} is then source controlled, there being no coarse sediment available to compare with

the maximum competency of the currents. However, the capacity of the currents is not restricted and results in the development of channels as the current speed increases.

Wave action is in evidence on some transects (10, 11, 13 and 18) where there is a tendency for a coarsening of the mean grain size M_{2B} on the higher shoals. This indicates the action of local wind waves whose activity is most influential near high water when there is a continuous body of sea water in the estuary available for wave transmission.

The range of σ_{2B}, the standard deviation of the dominant saltation population is equally restricted. With very few exceptions it falls between 0.20 and 0.30 $\emptyset$ units, so that the population may be classified as very well sorted (Friedman, 1962). This degree of sorting is characteristic of particles that move in the saltation load and are deposited by the 'kind seeks kind' action described by Kuenen (1966), but in this instance the upper (coarse) limit of the size range appears to be also source controlled. The small variation of σ_{2B} that does occur shows some correlation with the variation of M_{2B}; samples with coarser mean grain sizes tend to show larger standard deviations. This may reflect the turbulent character of the currents on the early flood and late ebb, deteriorating sorting being associated with fluctuating currents (Folk, 1968). However, since the range of σ_{2B} is so small, this correlation may not be a real one.

Sand transport undoubtedly occurs on both flood and ebb tides,

and the depth of disturbance is at least as great as the depth of sampling. This is known from an abortive attempt to determine the movement of sand during a tidal cycle using sand grains (of appropriate size) tagged with fluorescent dye. This proved unsuccessful because most of the tracer sand was distributed too widely by the tidal influx and outflow to be practically monitored. However, it was noted that after one tidal cycle, much of the dyed sand was buried an inch or more below the surface. It is unknown how much the respective flood and ebb currents contributed to this depth of disturbance. However, since almost all ripple marks exposed at low tide are ebb-orientated, the surface layers of sand owe their deposition to the ebb stream, and the effect of flood entrainment and deposition is not directly apparent at low water. The textural variation of population 2B may be attributed to ebb currents.

Subordinate to the major saltation population is a second saltation population 2A. Its distribution does not present a uniform picture. Generally, maximum concentrations occur in, or close to, the main channel (transects 10, 11, 12, 16, 18) or in subsidiary ebb channels (11, 14, 15, 17) but on other transects it appears to be randomly distributed. As described in Chapter 6, this population is composed dominantly of marine shell fragments when it occurs on the foreshore, and this is also the case in the estuary. The distribution of its mean grain size (see below) suggests that it is hydrodynamically equivalent to the major population 2B, at least in terms of the fluid energy/hydraulic equivalence relationship.

Its concentration in, and near, the main and subsidiary ebb channels reflects the effect of concentration of water into these as the tide ebbs. Concentration of the main flow, with increasing current velocities, leads to a greater surface concentration of the coarser, angular shelly fragments which are then available in sufficient quantities to build a secondary saltation population. This will occur wherever the tidal flow is differentiated into streams. The apparently random concentrations of the populations away from the channels are probably created in this way during the ebb phase, the current streams being directed by bed features above the sampling point.

In general, the distribution of the population mean grain size, M_{2A}, is rather similar to that of M_{2B}, but fluctuates a little more (its mean range across transects is 0.36 ϕ units). Its coarsest values are found in the main channel (transects 13 and 17), in or close to subsidiary ebb channels (transects 11, 14, 16 and 17) or in zones adjacent to the main channel (transects 9, 10, 11, 12, 15, 16). This distribution is also obviously current controlled. On transect 18, coarse values occur on shoals, indicative of wave action near high water.

In a few instances (transects 13 and 15, to a certain extent 10), relatively fine grained occurrences of the population occur in local depressions. These correspond to isolated, shallow back-waters that have developed during the ebb, the quiescent conditions away from the main stream ensuring a selection process in favour

of finer grains. Subsequently, the action of wind ripples on these ponds creates symmetrical ripple marks and conceivably encourages the formation of the discreet population 2A.

The range of values of σ_{2A}, the standard deviation of population 2A, is small, the population being usually well sorted or very well sorted, but its variation is fluctuating and apparently random. This may be because this parameter is very sensitive to variations of sedimentation rate which may be in part controlled by the bed morphology above the point of sampling. More probably, it is because its magnitude cannot be determined with much accuracy when the population is present only in small concentrations and the mean grain sizes of populations 2A and 2B are close together. Thus the variation of σ_{2A} may simply reflect analytical error.

Subpopulation 1, formed by rolling and sliding of predominantly coarser shelly fragments of marine origin, is present in minor proportions, and varies little across the transects. Slight concentrations may be recognised in, or near, the main channel on some transects (10, 11, 13, 15, 16, 18) resulting from the strong currents of the late ebb (and perhaps early flood). On transect 17, a local increase occurs on a shoal, formed by wave action. The grains never occur in concentrations sufficiently large to create the 'traction clogs' (Moss, 1962, 1963) that are diagnostic of the middle level of the beach.

It is noteworthy, that although the truly organic (shelly) population 1 and 2A occur in diminished proportions within the

estuary than on the foreshore, there is no corresponding reduction in overall carbonate content (see Tables 7.1 - 7.11). Obviously, more carbonate must be incorporated into the detrital population 2B here. This must occur because the shelly material is more broken up into finer grains by the time it is transported into the estuary from the bay and/or beach.

Subpopulation 3 also occurs, but in concentrations of less than 3% (except near the mud flats), and so is not an important component of the sand flats. This is inevitable in a high energy environment of fast, fluctuating currents. The suspension population cannot be deposited where sand is being actively moved, and any deposition that occurs at high slack water cannot survive the ebb flow. Suspended grains must be either flushed out of the estuary altogether, or diverted onto the low energy saltmarsh. The intense turbulence over the sand flats does not allow for the creation of quasi-continuous mud deposition described by McCave (1970) for offshore accumulations.

Longitudinal variations of the subpopulation parameters cannot be examined satisfactorily from the sample array of the present study because of its subjective basis, so that adjacent transects cannot be compared meaningfully. Contour maps of parameter distributions cannot be constructed on the basis of eleven subjectively chosen transects. The parameter variations on the transects are intimately associated with the positions of main and subordinate ebb channels, an association that is likely to be

widespread over the entire area of the sand flats, so that subpopulation distributions cannot be postulated without an accurate plot of banks and channels.

However, this deficiency is unlikely to be of great importance. This follows from the uniformity of the sediment that composes the sand flats, so that longitudinal variations, are of minor importance. This can be shown by comparing mean values of the parameters on successive transects. The shortcomings of such an approach using a subjective sampling array are too obvious to need further discussion. These shortcomings are most critical for the textural parameters that provided criteria for sampling choice, namely the proportions of the surface creep and suspension populations. They are least critical for those properties that are virtually unconnected with sampling choice - M_{2A}, M_{2B} etc. Proportion averages are also strongly biased by the length of transects which in turn affects the energy distribution across the transects. Average values per transect of subpopulation properties are shown in Table 7.12.

It may be seen that longitudinal trends emerge for the first two parameters only. The mean grain sizes of both saltation populations show a progressive upstream fining. That of saltation 2B shows the larger range (of the order of 0.4 ϕ units), twice that of saltation 2A (0.2 ϕ units), although that of the dominant saltation population is less variable laterally (see above). The longitudinal variation of these two significant parameters is

PARAMETER	TRANSECT 8	9	10	11	12	13	14	15	16	17	18
M_{2A} Ø	2.28	2.32	2.30	2.31	2.35	2.25	2.34	2.38	2.47	2.50	2.47
M_{2B} Ø	2.63	2.90	2.92	2.92	2.96	2.92	2.97	2.93	3.04	3.03	3.02
σ_{2A} Ø	.40	.27	.30	.31	.33	.35	.33	.34	.32	.38	.32
σ_{2B} Ø	.31	.23	.25	.24	.25	.25	.25	.26	.24	.24	.25
% 1	1.3	1.3	1.2	.9	1.7	1.0	.9	1.4	1.5	1.4	.7
% 2A	5.6	5.6	7.4	5.2	3.5	3.0	7.0	4.8	7.7	4.5	5.2
% 3	.8	3.6	1.1	2.5	.7	.8	1.0	.4	3.0	2.2	2.0

TABLE 7.12 : Mean values of subpopulation parameters

shown in Fig. 7.12. It has been shown that the progressive landward fining of silt and clay-sized particles over tidal flats is the result of their transportive history, with particular reference to settling lag and scour lag (Postma, 1954; van Straaten and Kuenen, 1957, 1958). However, lag effects are of no importance for grains larger than 100 microns or 3.20 Ø units (Postma, 1967), and so their operation on the sands of the open sand flats is unlikely to be a crucial contribution. Rather the mean energy level at the site of deposition is the primary factor producing such a textural trend, and this must follow from an upstream diminution of the mean flood and/or ebb currents (see Chapter 3).

There are no visible trends in the sorting coefficients of the two saltation populations which, allowing for bias, probably indicates that the rate of deposition of the sand does not alter from the lower to the upper estuary. The proportion parameters

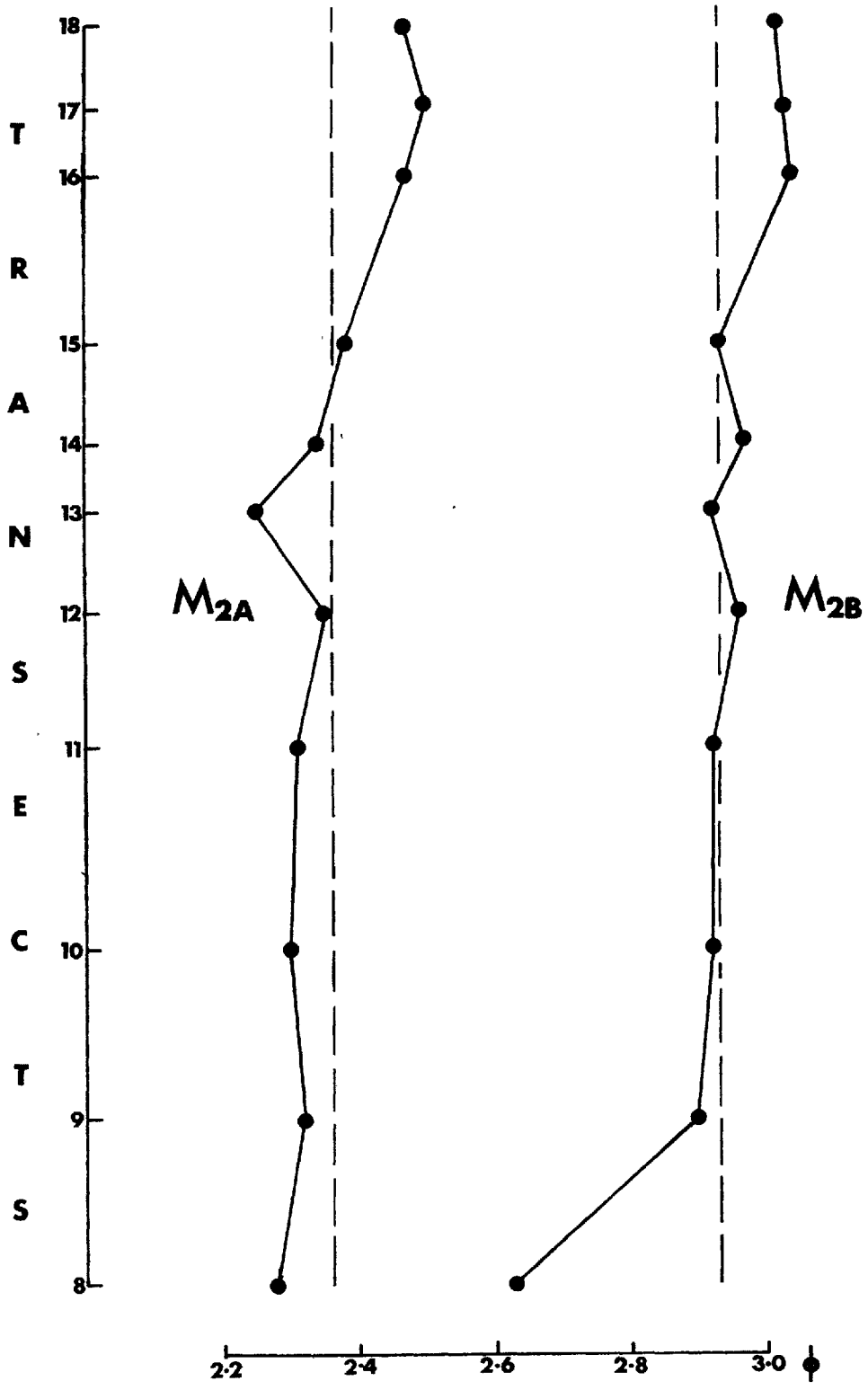


FIG. 7.12: LONGITUDINAL TEXTURAL VARIATION.

are randomly distributed among transects; this may indicate some degree of homogeneity or more probably reflect the sampling bias. A final limitation on such a comparison is that since sampling could not be completed in one day, the dynamics of sedimentation themselves were not stable during the sampling period, and to this extent between-transect variations were even less controlled.

It should be noted that the upper part of transect 8, although composed of clean, well sorted sands shows important differences from the deposits of the open sand flats elsewhere. As can be seen from Fig. 7.1, these sands are composed of one saltation population only, and are indistinguishable from the dune sands at the head of the transect. This association is the same as that which was found on the uppermost foreshore/dune of the beach, where it was attributed to the absence of a backwash current and/or shortage of the shelly material at the top of the foreshore. In this case these factors may be operative; or the sand deposited at the top of transect 8 may be transported by aeolian action off Ginst Point and the aeolian sand flat of transect 7.

Because of the limitations imposed by the subjective sampling design, a controlled statistical analysis of textural distribution is not possible. Fortunately, the general homogeneity of the sands diminishes this drawback. The uniformity of the sand textures throughout the estuary is the most distinctive feature of the sand flats. In this the estuarine sands differ noticeably from the beach sands. However, the four subpopulations are common to both

facies and demonstrate the continuum of sediments from Pendine to Laugharne. Five typical cumulative probability plots of sediments from the estuarine sand flats are shown in Fig. 7.13, which may be compared with plots of beach sands in Figs. 6.3 - 6.9.

In conclusion therefore, it is apparent that the pattern of sedimentation over the open sand flats and channels is very uniform. The sediment is nearly everywhere composed of a dominant, very well sorted, fine grained quartzose sand saltation population; a second, subordinate saltation population, well sorted, a little coarser than the primary population, but principally organic in composition, forms a significant but minor admixture to the sediment. Surface creep and suspension admixtures are generally insignificant.

The samples collected in this study were representative of an almost exclusively current controlled deposit. Sand entrainment and transport is initiated at the start of the tidal incursion by fast currents and intense horizontal and vertical turbulence in shallow water. This initial phase is confined to the relatively straight flood channels which tend to avoid the meandering ebb channel. As the water level rises, the flats are submerged, though the differentiation of flood and ebb streams may continue for some time, particularly when a high river run-off coincides with a neap tide. In this way, blind flood barbs may be formed and these trace the straight path of the main flood stream across the banks. Because of the fine grain sizes of the saltation

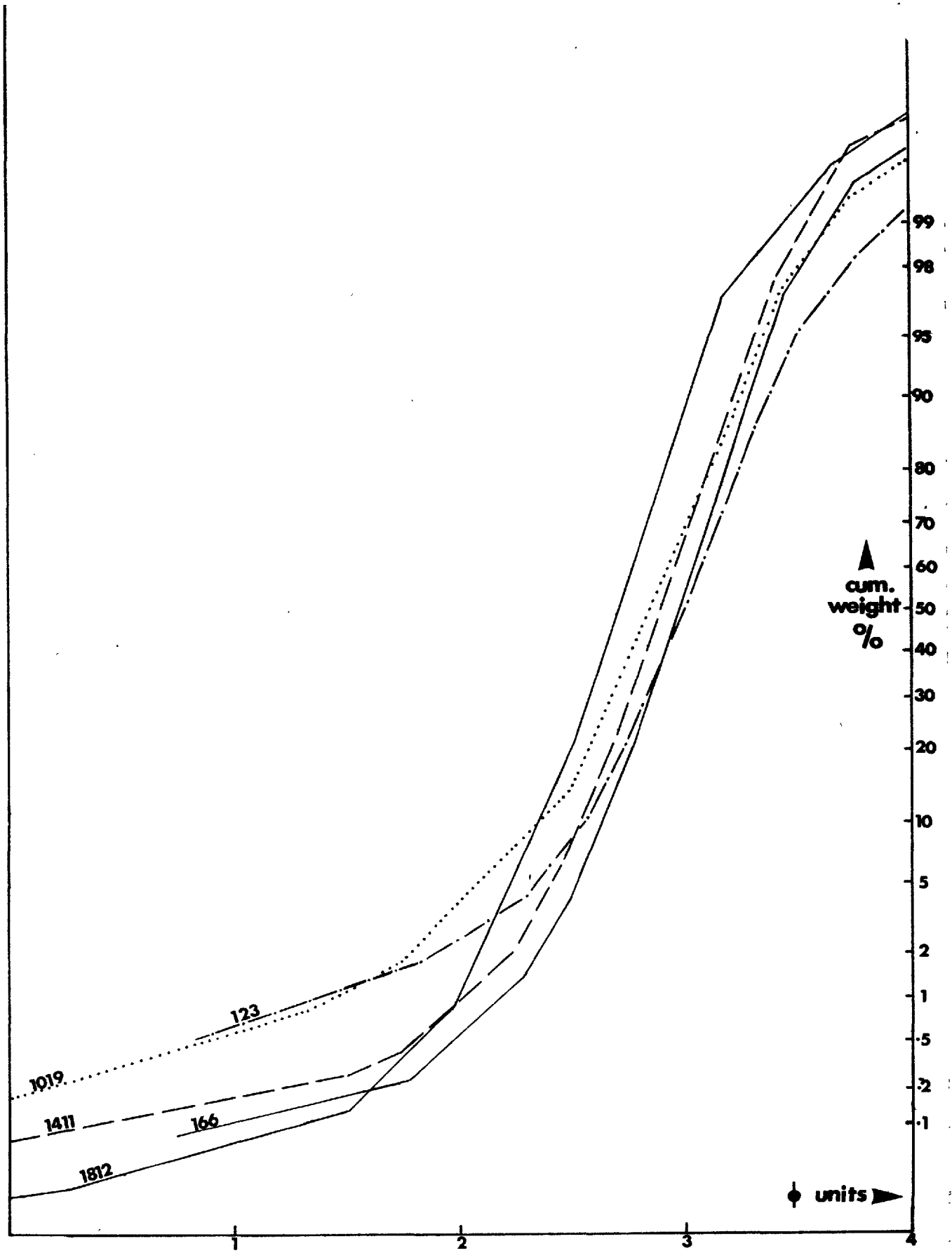


FIG. 7.13: GRAINSIZE DISTRIBUTIONS, ESTUARINE SAND FLATS.

populations, the bottom saltating sand layer is in motion for most of the period of tidal incursion (except for a period of one and a half hours on either side of high water on a spring tide, using the current data of Chapter 3, and from Hjulstrom, 1939). The ebb flow begins with currents too small to cause sand entrainment. Since the flood currents themselves cause the creation of channels, some ebb stream differentiation begins immediately; this is because the ebb begins before the flood is halted, the opposing streams being necessarily separated. However, even in an imaginary tidal area free from initial depth differences, some differentiation of parallel stream trajectories will occasionally occur (van Bendegom, 1950; Postma, 1967). This would be inevitable in an estuary with sharp bends. Depth differences will therefore be created by the inherent character of the ebb stream and by its avoidance of the remnant flood stream. The ebb currents in the channels will then increase at a greater rate than those on the shoals; a corresponding differential rate of sediment transport will develop. Because the tidal body is totally flushed from the estuary, the water level is constantly falling as the tide ebbs, and the current velocity is increasing. This results in a constantly changing energy distribution and channel/shoal development. The final distribution of sand textures reflects this. While the shoals remain submerged, sand transport continues across them as well as in the channel - the grain size of the bottom sediment is below the competency of the currents - though the greatest amount

of transport occurs in the channel. Transport ceases only near the moment of emergence. Flow continues in the main channel, and as the width of the stream is restricted, current speeds and turbulence increase. It is only at this stage that any differentiation of grain size between channel and shoals can occur. In the shallower water to one side of the main channel, turbulence assists the fast currents to create a rather coarser saltating traction carpet; the sand here may also be a remnant from the very fast, highly turbulent currents that traverse the proximal channel zone on the early flood. In the final stage, near completion of tidal flushing, the flow is entirely restricted to the channel and the current velocity is diminished so that the bottom deposit derived from the saltating carpet becomes finer-grained in most instances. During any one tidal period, assuming no change in meteorological conditions, tidal dominance extends over a longer period in the outer estuary than in the inner, and current velocities are greater. Consequently, the saltation texture coarsens downstream.

The differences of mean grain sizes of the sand populations within the estuary are therefore minimal and this must reflect the nature of estuarine circulation, described in Chapter 3 as essentially laterally homogeneous (with some vertical stratification). The primary control in this respect however must be the availability of sediment of a limited grain size range. Sand enters the estuary from Carmarthen Bay (see below), carried landward by the high energy flow of the early flood tide (assisted forcibly

at times by meteorological and oceanic influences, see Chapter 4). The very coarse sand (and even granules) that could be moved by this flow is not available in the bay (although present in the higher reaches of the river itself) and so cannot be present. Because the sand size is so fine-grained relative to the competency of the currents (on the ebb as well as the flood) the differentiation of the tidal stream to form shoals and channels depends on a delicate interplay of variable parameters such as tidal height, river flow, oceanic surge, meteorological activity, so that the emergent pattern of major and minor ebb channels is in constant flux and can (and often does) change from one tidal incursion to the next. If a greater textural variety of sediment were available, then the textural distribution of material, once established, could exert a strong feedback control of the tidal stream development, and instil some measure of channel stability. The instability of the banks and channels within the estuary owes its maintenance to the absence of such a control.

The dominance of current control over wave control of the sand flats appears to be a persistent feature of estuarine sedimentation (Prentice et al, 1968; Terwindt et al, 1963). This is in strong contrast to the reverse order of importance of waves and currents encountered on Dutch intertidal flats (Postma, 1957) but in accord with the processes over the flats of the Wash embayment (Evans, 1965). Nevertheless, as demonstrated in Chapter 4, wave action from winds greatly assists the transportive capacity

of the tidal currents by boosting the tidal input from Carmarthen Bay and by generating local wind wave turbulence within the estuary. Since the distribution of sand textures is strictly limited by provenance, such action is unlikely to modify the basic pattern of sedimentation (a few, isolated samples taken at a later date from the sand flats confirms this) but will affect local variations by modifying (coarsening) the textures of the shoals.

(b) The Mud Flats and Saltmarsh

Relatively few mud flat and saltmarsh samples were studied, and so no detailed discussion of textural trends is possible. The most distinctive, diagnostic feature of these sediments is the significant or dominant proportion of the fine grained suspension population 3 which they all contain. Its presence is due partly to the infrequency of wave action, and is assisted by flocculation in brackish water, and compaction of the deposited material which inhibits and retards resuspension.

As described above, the use of peptisers in the deflocculation of the silt and clay fraction of the sediments renders any hydrodynamic interpretation of the results rather arbitrary in an absolute sense, but useful for comparative purposes.

Of all the samples from these categories, only those of transects 8 and 9, and one from transect 16, are from the saltmarsh, the others being from the open mud flats. This latter group will be considered first.

The passage from sand flats to mud flats is rapid but not

abrupt, and so the mud flat samples show a variable proportion of subpopulation 3 as the transition is crossed. For most of the samples this varies from 17% to 77%; although some with smaller proportions do occur these may be considered as deriving from either the sand flat or the mud flat. The mean grain size, M_3, of the suspension population is also variable depending on its position, varying from 4.8 Ø units (coarse silt) to 7.9 Ø units (very fine silt). The standard deviation, σ_3, is large, varying from 2.01 - 3.78 Ø units which according to Friedman (1962) encompasses a range from very poorly sorted to extremely poorly sorted. However, as explained by Spencer (1963), standard deviation is a measure of dispersion and not sorting in the genetic sense of the term. Genetically, the suspension population is, by definition, well sorted since it has been effectively separated into a discreet, distinctive population in the same way as the well-dispersed saltation populations. The silt : clay size ratio of the mud flat also varies from 0.72 to 18.80, again depending on sample position and proximity of the sand flats.

Sample stations were sufficiently frequent on transects 10, 12 and 13 to allow for an examination of lateral variations of the suspension population parameters (Figs. 7.3, 7.5 and 7.6). Obviously the proportion of the population contained by the parent deposit increases towards the saltmarsh, away from the sand flats. This is because the capacity of the tidal currents to maintain a suspension load diminishes towards high water so that more material

is deposited at progressively higher levels. Similarly, the mean grain size of the population decreases away from the sand flats as the competency of the currents diminishes. The increased accumulation of finer grained suspension population is also directly related to the lack of turbulence at high levels. The standard deviation generally increases as more clay-sized material is added towards the estuary margins; more silt may also be added however so that the silt : clay ratio may even increase slightly in the same direction (transect 10).

The proportion of sand contained in the mud flats varies inversely with the proportion of mud. The sand is predominantly composed of subpopulation 2B grains, occurring in proportions varying from 17% to 76%, its mean grain size, M_{2B}, varying from 3.14 - 3.35 Ø units, and its standard deviation from 0.18 - 0.27 Ø units. This population is therefore conspicuously finer grained here than on the sand flats, becoming progressively finer away from the sand flats, the transition between sand and mud flats being in this respect a continuous one. This saltation population is undoubtedly water-laid and not derived from the dunes since it is finer grained than any of the dune saltation populations, and does form a continuous trend upwards from the estuarine sand flats.

The subordinate saltation population 2A also occurs on the mud flats, but in minor proportions of less than 6 - 7%. It appears to diminish away from the sand flats. Its mean grain size, M_{2A}, varies from 2.51 - 2.89 Ø units, again noticeably

finer grained than when encountered on the sand flats. Its standard deviation ranges from 0.20 - 0.45 ∅ units, as on the sand flats. This subpopulation never achieves significant proportions in the mud flat environment (except probably in the creeks, see below) because the concentration of water into channels does not occur as on the sand flats, and the organic and subequant grains are insufficiently abundant to form a discreet saltating carpet. The diminished current velocities must also inhibit its growth. Rather higher proportions of a subordinate saltation population occur on the left bank at transects 13 and 14, but this is composed of predominantly lithic grains associated with an exposed glacial moraine.

Finally, the surface creep population is generally very minor in importance, hardly exceeding 4% and often absent altogether. This results from the low energy environment of the mud flats which effectively prevents the intrusion of rolling and sliding grains. A few exceptions occur on the left bank at transects 10, 13 and 14 where the mud flat is developed over a partially exposed moraine, which contributes coarse lithic particles to the sediment population. However, this contribution is not extensive and of no importance to sedimentation in the estuary.

Longitudinal variations of the various subpopulations cannot be ascertained with any confidence because of the paucity of samples. Certainly, with respect to M_3, there is no obvious longitudinal trend in variation, although allowing for differences

in relative sampling positions on the transects, some such trend might be discernible. It would appear however that this parameter is more affected by gross estuarine morphology rather than actual longitudinal position, showing high values (small grain size) where the mud flat has developed some distance away from the main ebb channel (for example, on the left bank of transect 16). Because of the complex morphology of the estuary and the nature of its circulation pattern, intrusion of mud particles by settling lag and scour lag (Postma, 1954; van Straaten and Kuenen, 1957, 1958) is unlikely to be as simply developed as in tidal flat areas. Rather, the nature of the suspension population is determined by in situ energy levels, which in turn are determined by the proximity of the main channel.

The saltmarsh has been sampled mostly on transects 8 and 9. Of these, the samples of transect 8 are from the young, unstable low marsh that has developed in recent years; those of transect 9 are predominantly from the stable low marsh that has developed in the past fifty years. Only the uppermost samples of transect 9 are from the lower high marsh.

The unstable marsh of transect 8 shows intermediate amounts of the suspension population 3, varying from 22 - 56%. Its development was uncertain during the study period, sometimes prograding, sometimes swamped by interdigital sand flats. At the time of sampling, the marsh clumps were separated by incursive sandy areas. It can be seen from Table 7.1 and Fig. 7.1 that as

on the mud flats, the suspension population becomes progressively finer grained (5.5 - 7.3 ∅ units), with increased dispersion, away from the sand flats. Because of the intermediate nature of this marsh, sandy population 2B remains the dominant sediment component but it is significantly finer grained than when forming the sand flats on either side of the marsh. This demonstrates the important dynamic influence of the Spartinietum which reduces the energy level sufficiently to encourage accumulation of muddy deposits (at higher levels on the transect, where there is no vegetation, energy levels are sufficient to maintain an open sand flat). The standard deviation of the saltation population 2B is also slightly depressed in the marsh compared with the sand flat as a result of a slower rate of deposition in the former.

As on the mud flats, saltation population 2A is present in minor quantities and the surface creep population 1 is virtually absent, except where living colonies of the edible cockle Cardium provide coarse shelly fragments.

The stable marsh of transect 9 contains rather larger proportions of the suspension population 3, from 24 - 95% on the low marsh, and 100% on the high marsh. Generally there is a progressive fining of its mean grain size towards the estuary margin, from 5.4 ∅ units (coarse silt) to 8.8 ∅ units (clay-size). Its standard deviation is variable within the range 2.0 - 3.2 ∅ units, apparently because of a simultaneous fining of the silt mode and addition of clay-size grains. Only on the high marsh does the

proportion of clay-size material equal that of the silt. This is understandable since the high marsh is covered only by the highest spring tides at their maximum level. Compaction between such tides would prevent resuspension of the deposit.

As before, because of the cover of vegetation, the mean grain size of the saltation population 2B is finer than on the sand flats but here this is also because of the height of the marsh above the level of the sand flats. The population is not present on the high marsh. Populations 2A and 1 form minor constituents only, and are also absent from the high marsh.

Two samples illustrate the situation of the marsh creeks. Both (transect 9 and transect 16, Figs. 7.2 and 7.9) show reduced proportions of the suspension population and increased proportions of the three other subpopulations. This is due to the landward incursion of sand from the sand flats and to the increased concentrations of organic matter eroded from the marsh and washed in from the mud flats. These are the only samples in which population 1 (and presumably population 2A) consisted of shelly fragments of estuarine animals rather than of marine animals. A similar situation is encountered in the creeks of the mud flats, but the concentrations of population 1 are less.

It would appear that there is no sharp division between the sediments of the mud flats and saltmarsh. The latter represents the development of the former under the more quiescent conditions of the estuary margins, and this is reflected by the increased

occurrence of clay-size components and silt components, a shrinking of the silt : clay ratio and a decrease of the saltation and suspension mean grain sizes. These trends are encouraged by the growth of vegetation on the marsh which also imparts some degree of stability.

Cumulative probability curves of mud flat and saltmarsh samples are shown in Fig. 7.14. There is no genetic difference between them except for the curves of samples from the high marsh (91, 93) which are composed entirely of the suspension population. However, the progressive trends described above are apparent. Allowing for differences of scale, the marsh samples match the proposed T curves of Doeglas (1946), showing the progressive displacement of the mean size to the right as the samples move towards the inner margins of the estuary.

7.4 Comparison with Fluviatile and Sub-littoral Sediment Textures : Source of Estuarine Sediment

The present study has concentrated on the sediments of the estuary and little work has been attempted on the sediments of the river above St. Clears or those of Carmarthen Bay. For comparative purposes, a few samples of fluviatile and sub-littoral sediments have been collected as described in Chapter 5 and their textures examined in the usual manner.

The physical and dynamic continuity between estuary and bay is obvious and its importance has been demonstrated earlier. The

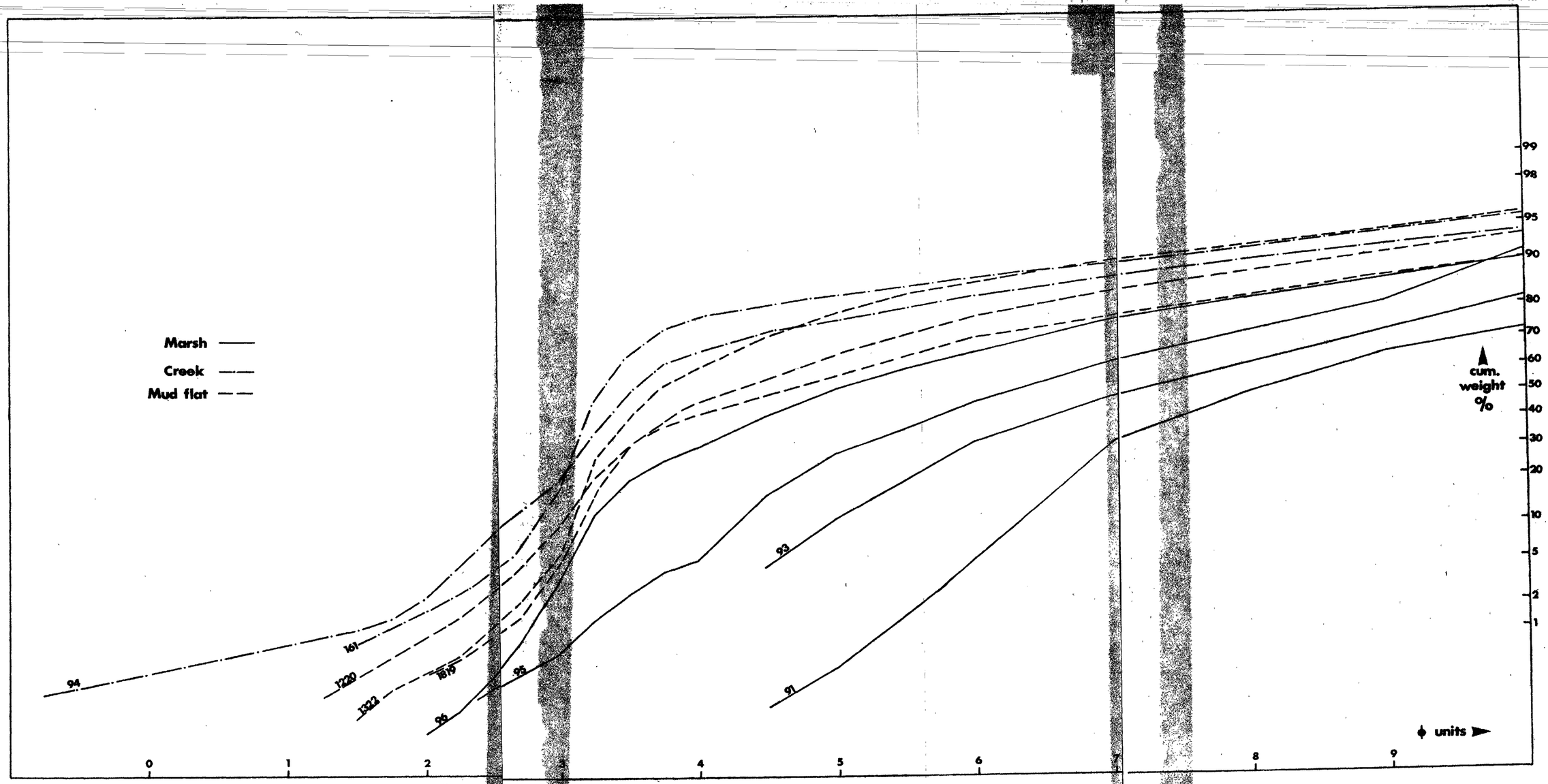


FIG. 7.14: GRAINSIZE DISTRIBUTIONS, MUDFLATS AND SALTMARSH.

similarities of estuarine and bay sands emphasises this. But the similarities of beach and bay sands are even more striking. Textural statistics of subpopulations of bay sands are shown in Table 7.13, cumulative probability curves of parent populations in Fig. 7.15.

Sample	Proportion %				Textural Parameters ø units			
	1	2A	2B	3	2A		2B	
					M_{2A}	σ_{2A}	M_{2B}	σ_{2B}
B1	1.8	14.2	76.5	7.5	2.85	.29	3.29	.19
B2	4.8	19.2	71.0	5.0	2.87	.27	3.22	.18
B3	.8	11.2	82.0	6.0	2.92	.28	3.28	.18
B4	4.7	15.3	75.4	4.6	2.88	.30	3.15	.21
B5	.5	10.0	89.4	.1	2.28	.31	2.54	.30
B6	.4	10.5	89.0	.1	2.27	.32	2.55	.31
B7	.3	13.7	85.9	.1	2.30	.30	2.68	.25

TABLE 7.13 : Sub-littoral subpopulation parameters

All samples show a predominance of the saltation population 2B, in common with dune, beach and estuarine sands. Population 2A is also present in proportions of 10 - 19% which places these samples mid-way between the majority of beach sands (high concentrations) and estuarine sands (low concentrations) in this respect. This is consistent with the distribution of nearshore dynamics. As explained in the previous chapter, subpopulation 2A is largely composed of fragmented carbonate grains derived from the shells of neritic bottom-dwelling organisms. These grains are moved

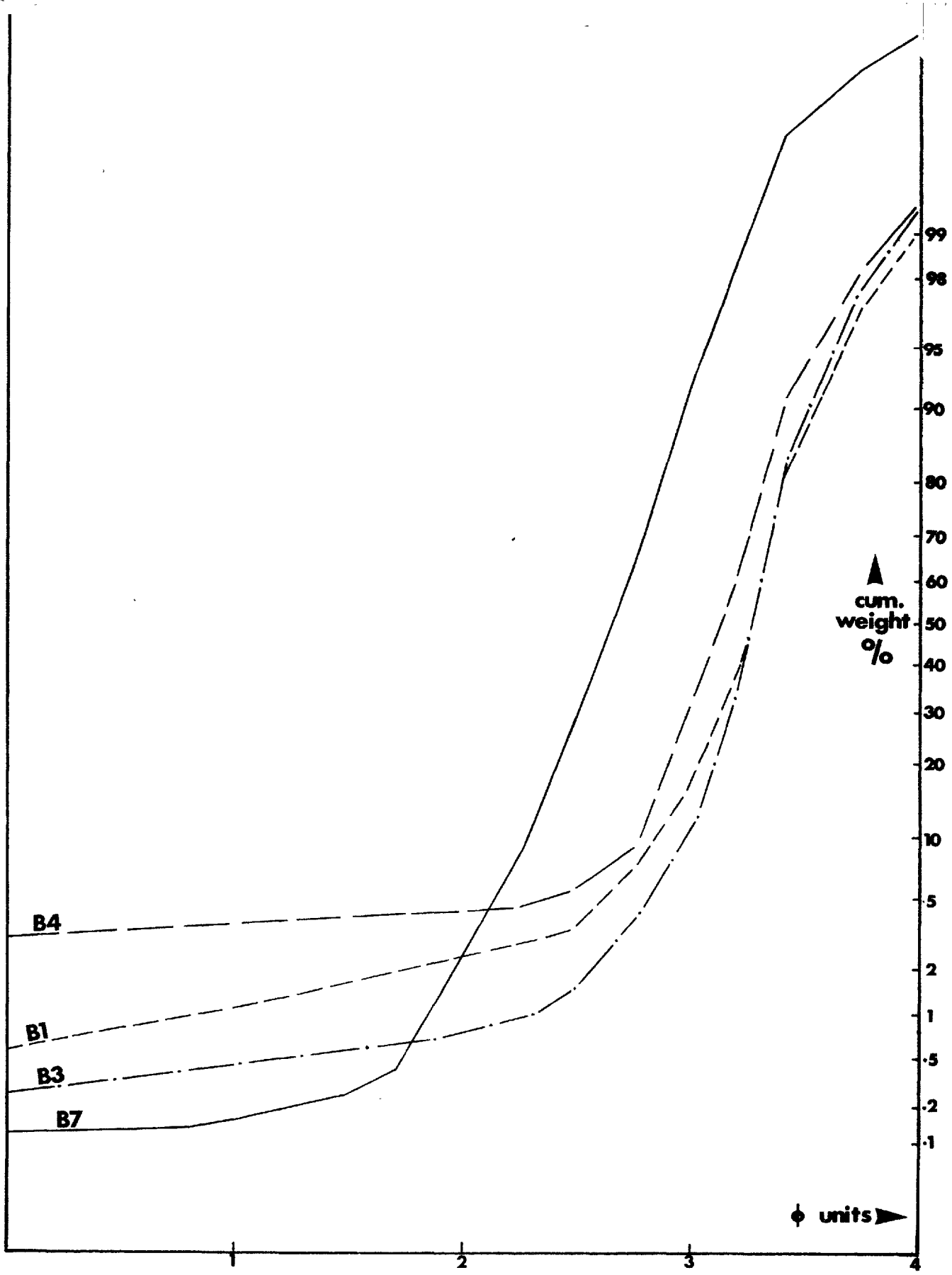


FIG. 7.15: GRAINSIZE DISTRIBUTIONS, SUBLITTORAL SANDS.

shorewards by wave action by either saltation or surface creep, where the intense and selective sorting processes of the shoreface enable them to form a discreet saltation population, particularly concentrated near mid-tide level. Landward transport of the grains into the estuary also occurs, but there the sorting processes produce an intermittent saltation population, widely dispersed but thinly distributed. At their point of origin, within the bay, the grains are present in sufficient quantities to produce a significantly developed saltation population whose stability is encouraged by the uniformly reversing currents and persistent wave activity (this latter probably being the chief agency).

Subpopulation 1, almost entirely organic in content, is deposited in minor quantities, as on the lower exposed foreshore and estuarine sand flats. The coarser, surface creep particles of this deposit are widespread throughout the marine, littoral and estuarine environments, composed of the larger shelly fragments of the marine benthos. Only on the middle foreshore are these grains selectively concentrated into deposits akin to traction clogs.

The bay samples were collected at points close to the seaward extremities of the sub-littoral profiles plotted in Figs. 1.2a and 1.2b (Chapter 1). Thus samples B1 - B4 are from depths of six feet below mean low water springs, whereas B5 - B7 are from up to three feet above mean low water springs. This difference is immediately apparent from the development of a suspension population in some of the first group compared with its absence in the

second. Evidently this reflects the disruptive action of breaking waves on the exposed bars in the eastern bay, which by keeping the depositional interface agitated maintain fine-grained material in suspension. Small amounts of the suspended grains are deposited on the submerged bottom in the west; these are probably re-suspended in winter (sampling took place in summertime).

There is a corresponding contrast between the two groups in the magnitudes of M_{2A} and M_{2B}. In the first group, both saltation populations are a little finer than when deposited on the foreshore; hence the seaward-fining textural gradient is continued seaward from the beach (although its slope is conspicuously reduced). In the second group, the reverse occurs, both populations being coarser than their immediate foreshore counterparts (but about the same on transect 6, sample B7). Thus the offshore bars are subjected to greater wave energy than is the foreshore, as would be expected. The standard deviations of both populations is also rather larger on the bars than on the lower foreshore, signifying that a greater rate of deposition is associated with the higher energy environment of the bars, and illustrating the developed selectivity of the swash/backwash currents on the foreshore.

The seven samples discussed above do not provide much information on sedimentation within the bay. Neither their isolated positions nor the manner of their collection allow for any projections of their characteristics onto the bay sediment as a whole.

However, their close similarities in terms of surface creep, saltation and suspension populations both with each other, and with the beach and estuarine sand flat samples is striking and important. They illustrate further the unbroken textural continuity of the nearshore, littoral and estuarine environments. Since populations 1 and 2A are largely derived from material whose only source is Carmarthen Bay, such a continuity argues favourably for a marine source of the estuarine sands.

The river sediment samples do not provide any such uniformity or continuity. But this must be largely the result of uncontrolled sampling. Some of the samples were taken from very shallow water (less than an inch) using a trowel, others from deeper water using a Van Veen grab. Inevitably, all samples contain a complex mixture of subpopulations which defies any attempt at graphical dissection.

As pointed out by Doeglas (1946), the transported material in rivers consists of three main components - bottom deposits of local origin, fine grades from far upstream, and middle sizes of material less far upstream. However, this assumes an equilibrium situation under uniform flow conditions. The true situation fluctuates widely over a period of time because of the extreme fluctuations of river run-off so that both the supply of sediment and the current capacity and competency at any point are highly variable. The manner of sampling ensures that many such fluctuations are recorded in the grain-size distributions which are accordingly complex.

However, an attempt has been made to deal with these samples and the results (tentative) are shown in Table 7.14. In most samples, the coarse surface creep population is dominant and, in contrast to all samples analysed previously, is not always truncated at its fine end. Its mean grain size is in the range -3.9 to -.30 Ø units (pebbles) and is moderately sorted (or dispersed). The grains composing this population are of varied lithology, and can be transported only when the river is in spate, predominantly during the winter months.

One or more saltation populations are present. Together these may outweigh the surface creep population but individually they are generally subservient to it. The several populations probably represent the manner of sampling, each corresponding to an average (perhaps seasonal) current energy. However, since there are some similarities between the component parameters of several samples, they may represent saltation carpets built up of grains of particular shapes as well as sizes. The mean grain sizes of the saltation populations are variable as are their standard deviations. The latter suggest that some of these so-called saltation components may in fact be subsidiary surface creep components. Their mean grain sizes range from -1.21 to 3.20 Ø units (granules to very fine sand) and their standard deviations from 0.24 to 1.20 Ø units (very well to moderately sorted, the latter possibly being a surface creep population). Generally their standard deviations are of the order 0.50 to

0.70 Ø units, moderately-well sorted, and are in this respect equivalent to the fluviatile saltation populations of Visher (1969) who considered this property to be typical of river sediments.

The suspension population is barely present in most samples. Some (R2, R4, R5, R7) were collected in the summer months when the river level was low, the supply of fine grained material small, and most of the fine grained deposit winnowed out. However, with the exception of sample R6, the winter-collected samples (R1, R3) were also deficient in suspension population even though they were collected when the supply of suspension loads from upstream was presumably high. Of the analysed populations, all showed lognormal distributions truncated at the coarse end, with mean grain sizes varying from 3.20 to 7.07 Ø units. Since these distributions were lognormal, they probably are representative samples of the total suspended load.

Sample R6 is quite distinctive since it is composed almost entirely of the suspension population. This sample was collected from below St. Clears (Fig. 5.3) near the upper limit of the tidal saline intrusion. It is there that flocculation of the grains that compose the suspended load first occurs and, in the absence of wave action, accumulation of the deposited flocs can take place.

The river sediment therefore is quite different in texture from the estuarine sediment (some cumulative probability curves are shown in Fig. 7.16); in contrast to the bay sediment which is

Sample	Proportions %					Textural Parameters Ø units									
	1	2A	2B	2C	3	1		2A		2B		2C		3	
						M	σ	M	σ	M	σ	M	σ	M	σ
R1	47.0	0	52.1	0	.9	-3.70	1.30			.32	1.20			6.38	2.82
R2	58.0	34.0	0	7.0	1.0	-3.50	1.25	-.97	.80			2.55	.73	3.70	2.54
R3	87.0	10.8	0	0	2.2	-3.88	1.18	-.50	.62					3.21	2.77
R4	62.0	23.0	14.0	0	1.0	-3.75	1.30	-1.21	.73	1.40	.64			3.20	2.51
R5	0	10.0	80.0	10.0	0			-.62	.38	.86	.50	1.98	.80		
R6	0	0	.5	13.5	86.0					2.15	.55	3.20	.24	7.07	2.99
R7	21.0	27.0	39.2	12.6	.2	-3.00	1.30	-.90	.70	.56	.45	2.03	.73		

TABLE 7.14 : Fluviatile subpopulation parameters

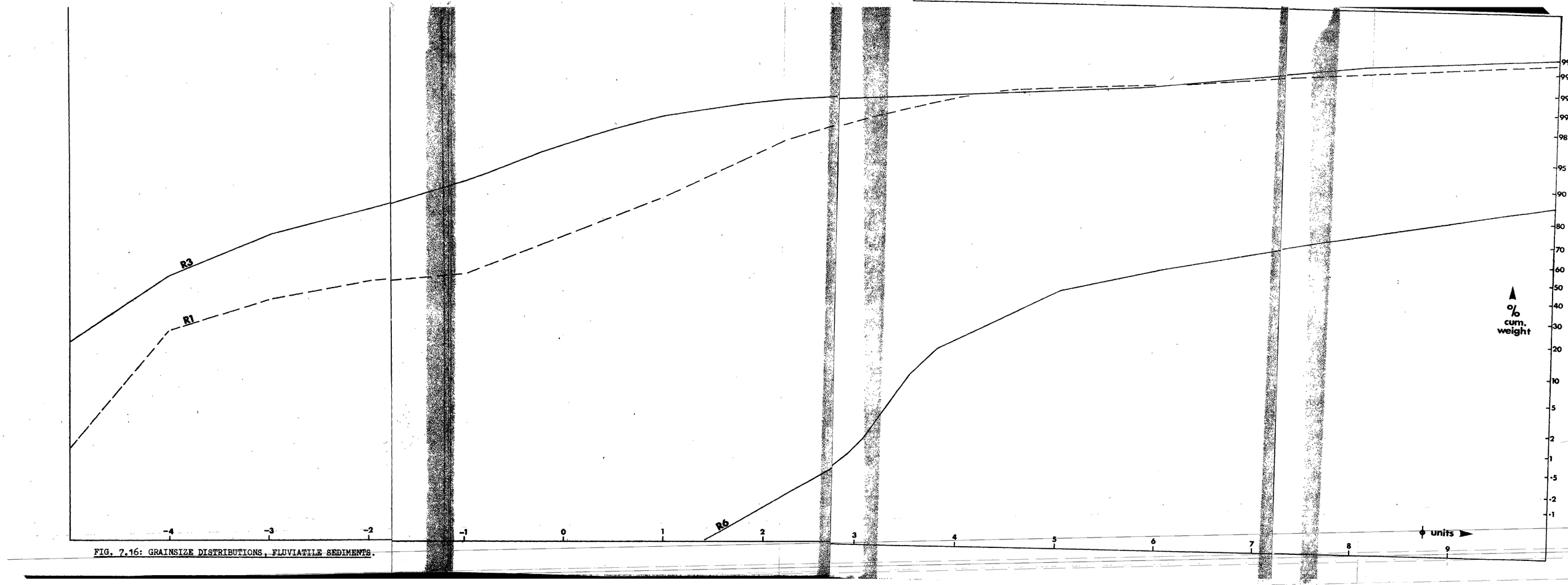


FIG. 7.16: GRAINSIZE DISTRIBUTIONS, FLUVIATILE SEDIMENTS.

very similar. However, since it has been shown that these textures are controlled by the dynamics of transport and deposition, the textural properties of the respective sediments may not perhaps tell us much about the source of the estuarine sediments, whether fluviatile or neritic.

Fortunately, the mineralogical differences between fluviatile and sub-littoral sands are striking, the former being made up entirely of lithic fragments, the latter predominantly of quartz and feldspar, shell fragments, minor proportions of lithic fragments and glauconite. The estuarine sands are virtually identical to the sub-littoral sands in this respect. No quantitative comparison of environments by mineralogy has been attempted in the present study, but it may in fact be shown from textural evidence alone that the rivers cannot be contributing a significant quantity of sand to the estuary.

The important points to consider are that : 1) The estuary is being actively filled by sand at the present time and 2) this sand is of remarkably uniform texture, fine grained and very well sorted.

There can be no debate as to the source of the grains of subpopulations 1 and 2A since these are predominantly organic and can be derived only from Carmarthen Bay. The major subpopulation 2B is uniform and restricted in size range, 82% of all values of its mean grain size falling in the range 2.7 - 3.1 ϕ units (for all sand flat samples, see Fig. 7.36). Since the estuary is

being infilled, grains within this small size range must be present at the sand source, either in the rivers or in the bay. In Table 7.15 are shown the percentages, by weight, of such grains in the collected fluviatile and sublittoral samples.

	SIZE RANGE Ø units			
SAMPLE	2.71 - 2.80	2.81 - 2.90	2.91 - 3.00	3.01 - 3.10
R1	.3	.2	.3	.2
R2	.3	.2	.3	.3
R3	.01	.01	.02	.03
R4	.3	.3	.3	.3
R5	.2	.2	.1	.1
R6	.1	.2	.3	.6
R7	.4	.3	.3	.2
B1	2.5	3.5	5.0	9.0
B2	3.0	6.0	7.8	14.5
B3	1.8	3.0	3.8	10.4
B4	4.1	9.1	11.0	15.0
B5	12.0	9.5	5.5	3.8
B6	12.0	9.3	5.7	3.7
B7	14.0	13.0	7.8	3.7

TABLE 7.15 : Frequencies of some fine sand grades in fluviatile and sublittoral samples

The difference between the two groups of samples is striking. The critical grain sizes are virtually absent from the river samples but make up 20 - 39% of the bay samples. If these samples are representative of their sedimentary environments, then we can

affirm that the size grades now infilling the estuary are present in appreciable quantities only in the bay (and, of course, on the beach) and not in the rivers. It may be objected that the critical size grades are not present in the river sediment because they are transported by suspension and deposited only in the estuary, their source being up-river of the sampling points. However, this view cannot be upheld in the light of the distribution of subpopulations within the sediments. In all cases (except sample R3), these grains are part of the finest saltation population; grains finer than these compose the suspension population. Hence grains of the size range under consideration form part of the saltating carpet when undergoing fluviatile transport and (under the conditions represented by the samples) do not move by suspension.

In the absence of first-hand quantitative evidence of fluviatile and tidal sand transport, no definite assertion can be made as to the immediate source of the estuarine sand. Nevertheless, the above evidence is considered sufficiently persuasive to argue for a Carmarthen Bay source.

The fine grained material that has been deposited on the saltmarsh may have either a seaward or landward source, or both. River suspended material is deposited via flocculation within the estuary but not generally in the rivers (above the limit of salt intrusion). Bay suspended material is maintained in suspension by wave action and settles only in the low energy environment of the estuary margins, although some is deposited in the western part of the bay.

7.5 Variations of Graphical Textural Parameters

As before, graphical grainsize parameters have been computed for estuarine sediments using the formulae of Folk and Ward (1957). These are shown in Tables 7.16 - 7.26 and their relationship to sampling positions in Figs. 7.17 - 7.27. These variations are essentially similar across all transects.

The mean grain size, M_z, shows a marked contrast between the sand flats and margins (mud flats, saltmarsh) but little variation within the sand flats themselves. Within the latter, its range is from 2.45 - 3.05 ϕ units (for most samples), up to 3.15 ϕ units where local intrusions of muddy sediments occur. The value of M_z is largely determined by the mean grainsize of subpopulation 2B, but also by the concentrations of subpopulations 1 and 2A where these become significant. Thus its coarsest values tend to occur in, and close to, the main channel (as a result of current action) and on the tops of some shoals (wave action).

Similarly, the graphic standard deviation, σ_I, shows inflated values on the mud flats and saltmarsh, partly because of mixing of subpopulations 2A, 2B and 3 but also because subpopulation 3 itself has a large dispersion. On the estuary margins, the parameter varies from 1 - 4 ϕ units (poorly to extremely poorly sorted), the worst 'sorting' occurring farthest from the mobile sand zone. Within the sand flats, its range is very limited owing to the dominance of the uniform population 2B, extending from 0.20 - 0.44 ϕ units (very well or well sorted), but increasing slightly

Sample	Mean M_Z ø units	Standard Deviation σ_I ø units	Skewness Sk_I	Kurtosis K_G	K_G'
81	2.62	.30	-.068	.96	.49
82	2.69	.30	-.068	1.07	.52
83	2.66	.30	-.028	1.05	.51
84	2.76	.35	-.049	1.01	.50
85	2.67	.34	-.046	1.00	.50
86	2.69	.33	-.040	1.02	.50
87	2.63	.31	-.039	1.02	.50
88	2.69	.32	-.052	.99	.50
89	2.70	.31	-.050	1.00	.50
810	2.54	.31	-.044	1.13	.53
811	2.55	.31	-.042	1.12	.53
812	5.59	3.84	+.774	.91	.48
813	2.36	.33	-.034	1.06	.51
814	3.09	1.26	+.656	3.42	.77
815	2.68	.33	-.053	1.03	.51
816	2.67	.32	-.052	1.03	.51
817	2.68	.32	-.053	1.03	.51
818	3.99	2.05	+.795	1.40	.58
819	3.32	1.27	+.559	2.11	.68
820	3.46	1.27	+.636	3.11	.76
821	2.49	.62	-.281	2.05	.67
822	2.48	.61	-.272	2.05	.67
823	2.56	.44	-.053	1.15	.53
824	2.45	.43	+.101	.97	.49
825	2.68	.38	-.144	1.00	.50
826	2.72	.28	-.100	.94	.48
827	2.52	.31	-.043	1.09	.52
828	2.70	.31	-.025	.99	.50
829	2.65	.35	-.140	1.04	.51
830	2.61	.30	-.047	.95	.49
831	2.66	.37	+.003	.98	.49
832	2.72	.30	-.034	1.00	.50

TABLE 7.16 : Variations of Composite Textural Parameters, Transect 8.

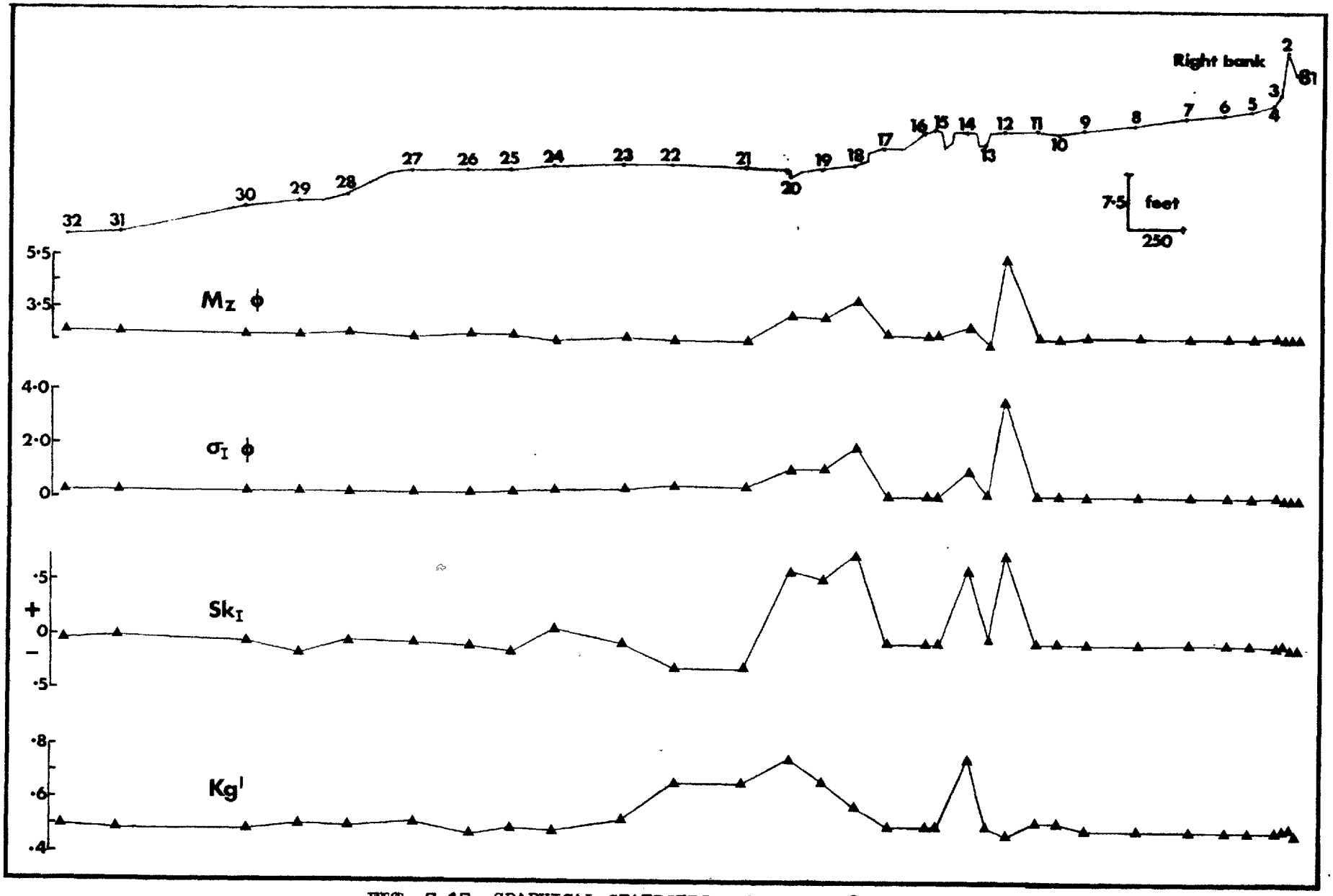


FIG. 7.17: GRAPHICAL STATISTICS, TRANSECT 8.

Sample	Mean M_Z Ø units	Standard Deviation σ_I Ø units	Skewness Sk_I	Kurtosis K_G	K_G'
91	8.76	2.53	+.461	.93	.48
92	7.95	2.35	+.339	.92	.48
93	7.53	2.40	+.322	.89	.89
94	4.15	2.10	+.653	2.07	.67
95	6.63	2.16	+.301	.90	.47
96	5.53	2.58	+.496	1.11	.53
97	4.02	1.31	+.711	3.91	.80
98	5.23	1.38	+.689	1.81	.64
99	3.75	1.55	+.756	3.61	.78
910	3.11	.35	+.036	1.22	.55
911	3.06	.32	-.085	1.25	.56
912	3.04	.38	-.142	1.23	.55
913	3.11	.35	-.127	1.36	.58
914	3.11	.35	-.126	1.35	.58
915	3.12	.36	-.128	1.36	.58
916	3.13	.35	-.126	1.35	.58
917	2.85	.29	+.118	1.02	.50
918	2.79	.26	+.140	1.03	.51
919	2.78	.26	+.145	1.03	.51
920	2.81	.28	-.068	1.04	.51
921	2.83	.28	-.066	1.04	.51
922	2.78	.28	-.051	1.03	.51
923	2.78	.28	-.045	1.03	.51
924	2.79	.28	-.043	1.03	.51
925	2.82	.29	-.045	1.03	.51
926	2.82	.29	-.047	1.03	.51
927	2.77	.28	-.051	.99	.50

TABLE 7.17 : Variations of Composite Textural Parameters, Transect 9.

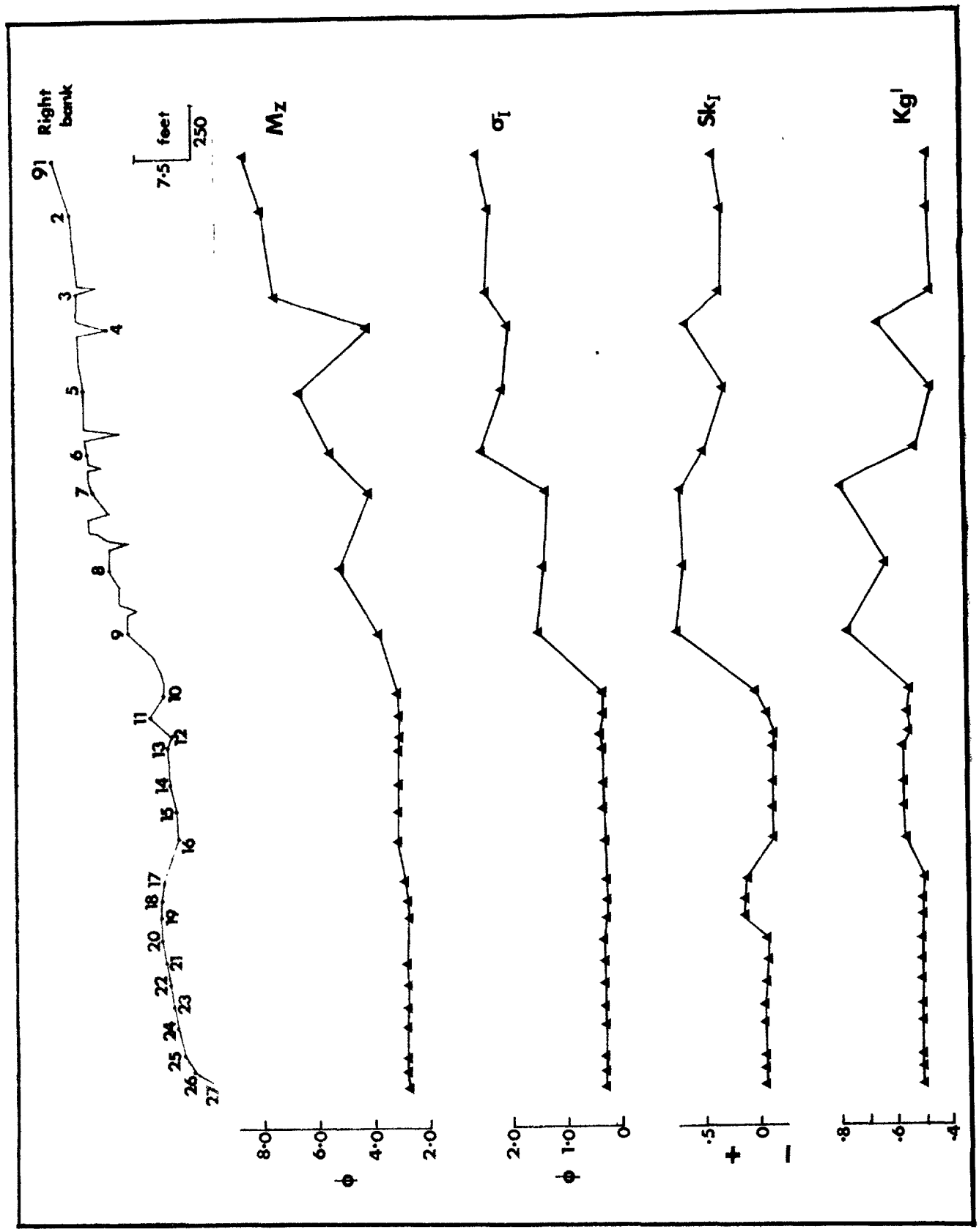


FIG. 7.18: GRAPHICAL STATISTICS, TRANSECT 9.

Sample	Mean M_z ø units	Standard Deviation σ_I ø units	Skewness Sk_I	Kurtosis K_G	K_G'
101	2.32	1.19	-.394	1.89	.65
102	5.38	2.99	+.650	1.37	.58
103	4.63	2.27	+.685	1.71	.63
104	3.28	.65	+.521	3.08	.75
105	3.27	.63	+.503	3.10	.76
106	2.98	.28	+.025	1.19	.54
107	2.99	.29	+.023	1.19	.54
108	2.83	.39	-.260	1.39	.58
109	2.76	.36	-.131	1.12	.53
1010	2.76	.36	-.200	1.10	.52
1011	2.83	.39	-.185	1.28	.56
1012	2.87	.27	-.022	1.02	.50
1013	2.86	.28	-.025	1.02	.50
1014	2.82	.27	-.032	1.08	.52
1015	2.81	.32	-.113	1.05	.51
1016	2.76	.29	-.030	1.04	.51
1017	2.76	.29	-.031	1.04	.51
1018	2.95	.28	-.125	1.06	.51
1019	2.83	.37	-.097	1.25	.56
1020	2.86	.27	-.025	1.01	.50
1021	2.84	.30	+.005	1.09	.52
1022	2.86	.30	+.009	1.09	.52
1023	2.89	.29	+.011	1.09	.52
1024	3.24	.97	+.510	4.27	.81
1025	3.61	1.41	+.745	3.97	.80
1026	3.97	1.59	+.709	2.46	.71
1027	4.47	2.00	+.708	1.91	.66
1028	5.65	2.83	+.548	1.01	.50

TABLE 7.18: Variations of Composite Textural Parameters, Transect 10.

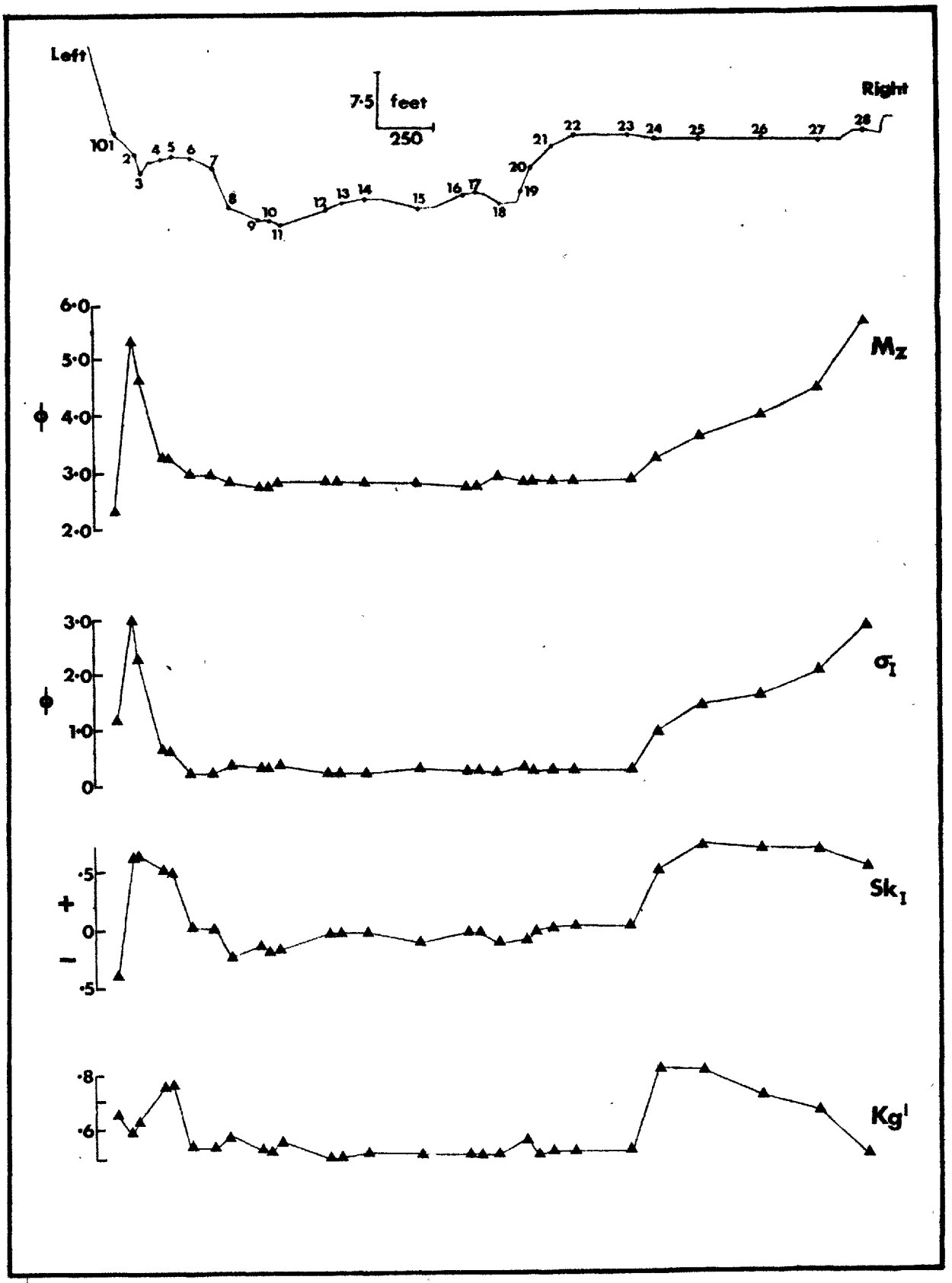


FIG. 7.19: GRAPHICAL STATISTICS, TRANSECT 10.

Sample	Mean M_z Ø units	Standard Deviation σ_I Ø units	Skewness Sk_I	Kurtosis K_G	K_G'
111	3.64	1.41	+.720	4.01	.80
112	3.62	1.39	+.716	3.96	.80
113	3.60	1.37	+.705	3.95	.80
114	2.96	.26	-.103	1.08	.52
115	3.00	.21	+.075	1.05	.51
116	3.01	.21	+.079	1.06	.51
117	3.10	.50	+.375	2.47	.71
118	3.10	.50	+.383	2.49	.71
119	3.01	.22	+.050	1.50	.60
1110	3.00	.23	+.051	1.49	.60
1111	2.99	.23	+.051	1.50	.60
1112	2.68	.35	-.052	1.14	.53
1113	2.91	.27	-.041	1.08	.52
1114	2.85	.27	-.025	1.12	.53
1115	2.86	.27	-.026	1.13	.53
1116	2.89	.27	-.045	1.15	.53
1117	2.88	.27	-.046	1.15	.53
1118	2.83	.29	-.018	1.05	.51
1119	2.81	.29	-.017	1.04	.51
1120	2.81	.33	-.174	1.16	.54
1121	2.83	.28	-.067	1.04	.51
1122	2.78	.28	-.046	1.03	.51
1123	2.78	.28	-.041	1.03	.51
1124	2.82	.29	-.048	1.03	.51
1125	2.82	.29	-.050	1.03	.51
1126	2.77	.28	-.051	.99	.50
1127	2.75	.36	-.185	1.25	.56

TABLE 7.19 : Variations of Composite Textural Parameters, Transect 11.

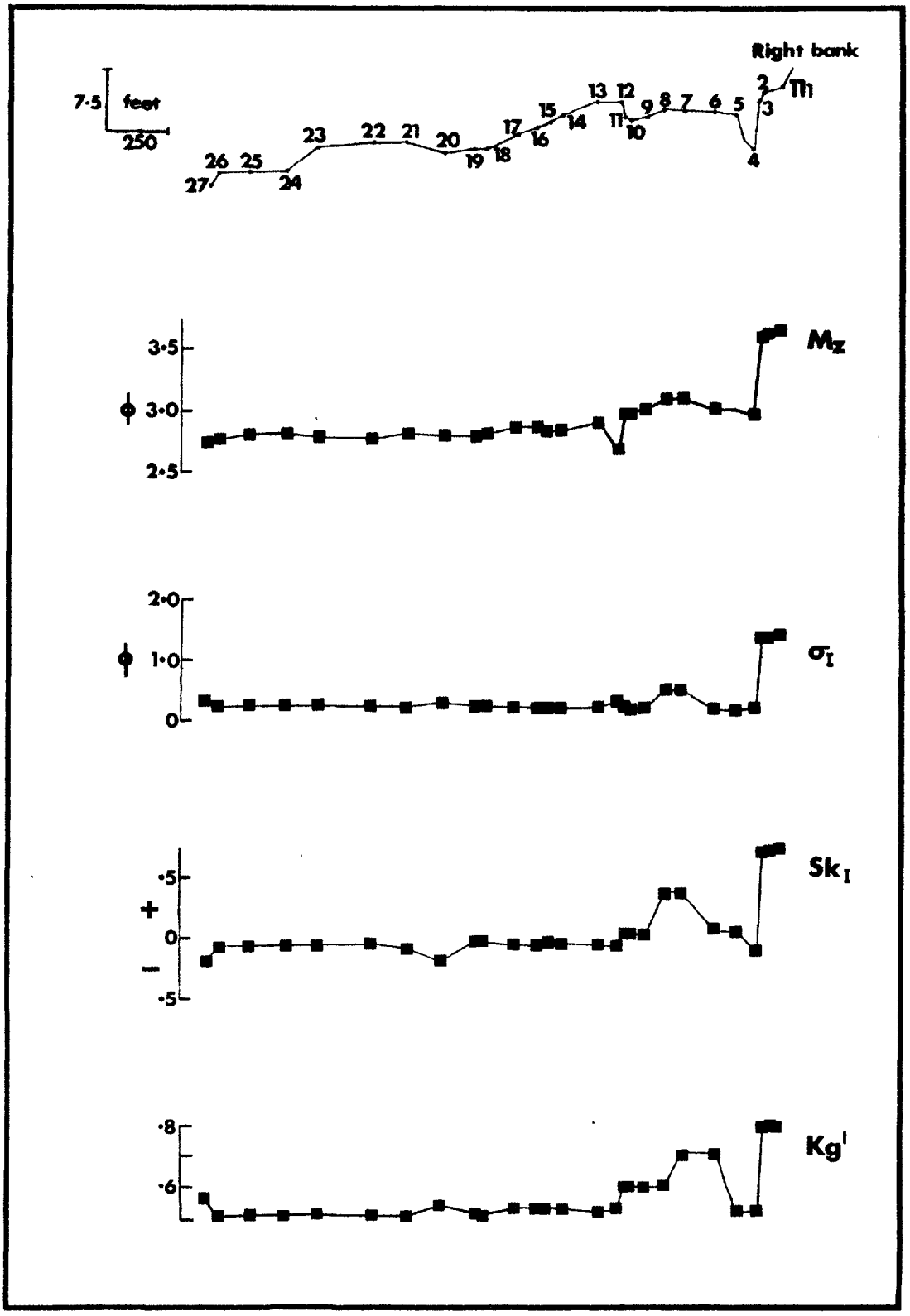


FIG. 7. 20: GRAPHICAL STATISTICS, TRANSECT 11.

Sample	Mean M_z Ø units	Standard Deviation σ_I Ø units	Skewness Sk_I	Kurtosis K_G	K_G'
121	3.58	1.30	+.718	3.51	.78
122	2.94	.33	-.162	1.20	.55
123	2.95	.34	-.128	1.16	.54
124	2.92	.30	-.095	1.13	.53
125	2.92	.29	-.117	1.17	.54
126	2.90	.27	-.059	1.13	.53
127	2.92	.26	+.040	1.19	.54
128	2.88	.33	-.283	1.46	.59
129	2.88	.33	-.285	1.45	.59
1210	2.89	.26	-.127	1.12	.53
1211	2.93	.23	-.065	1.08	.52
1212	3.06	.21	+.012	1.05	.51
1213	2.90	.30	-.089	1.11	.53
1214	3.06	.31	-.099	1.25	.56
1215	3.59	1.45	+.612	2.60	.72
1216	3.58	1.18	+.630	3.31	.77
1217	3.59	1.17	+.642	3.34	.77
1218	3.59	1.18	+.640	3.30	.77
1219	5.28	2.70	+.556	1.22	.55
1220	5.29	2.70	+.550	1.23	.55

TABLE 7.20 : Variations of Composite Textural Parameters, Transect 12.

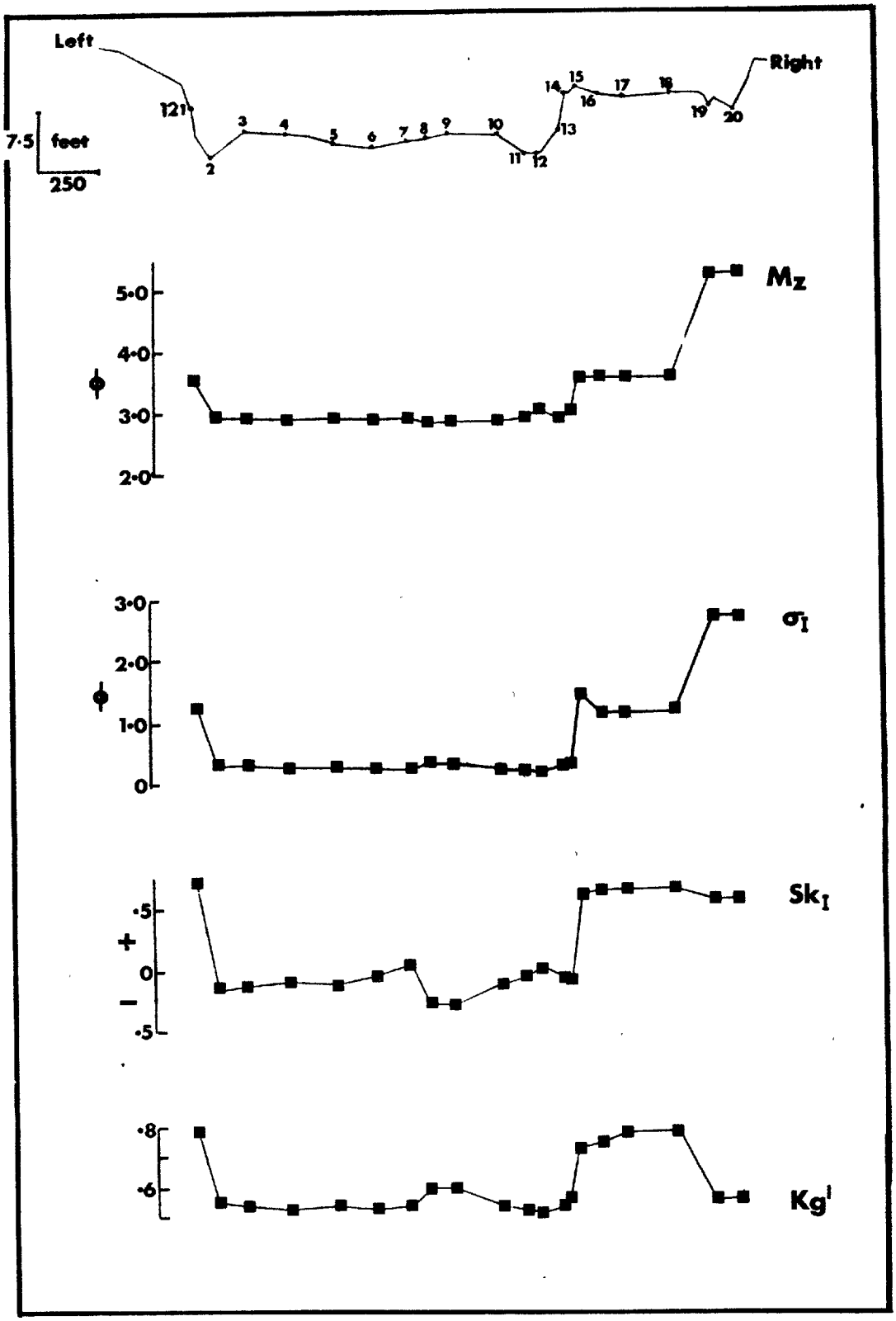


FIG. 7.21: GRAPHICAL STATISTICS, TRANSECT 12.

Sample	Mean M_z Ø units	Standard Deviation σ_I Ø units	Skewness Sk_I	Kurtosis K_G	K_G'
131	3.65	1.75	+.531	3.58	.78
132	3.52	1.16	+.658	3.68	.79
133	3.74	1.60	+.764	3.66	.79
134	2.90	.35	-.110	1.36	.58
135	2.84	.28	-.172	1.16	.54
136	2.92	.26	-.165	1.07	.52
137	2.91	.24	-.042	1.04	.51
138	2.80	.28	-.135	1.04	.51
139	2.77	.28	+.009	1.00	.50
1310	2.91	.24	+.002	1.01	.50
1311	2.94	.24	-.103	1.02	.50
1312	2.96	.24	-.024	1.05	.51
1313	2.92	.25	-.049	1.05	.51
1314	2.88	.26	+.004	1.01	.50
1315	2.93	.25	+.016	1.03	.51
1316	2.89	.31	-.086	1.23	.55
1317	3.05	.25	-.090	1.07	.52
1318	3.08	.36	-.136	1.80	.64
1319	2.91	.32	-.145	1.54	.61
1320	2.78	.39	-.180	1.12	.53
1321	3.55	.88	+.568	1.82	.65
1322	4.10	1.70	+.688	2.11	.68

TABLE 7.21 : Variations of Composite Textural Parameters, Transect 13.

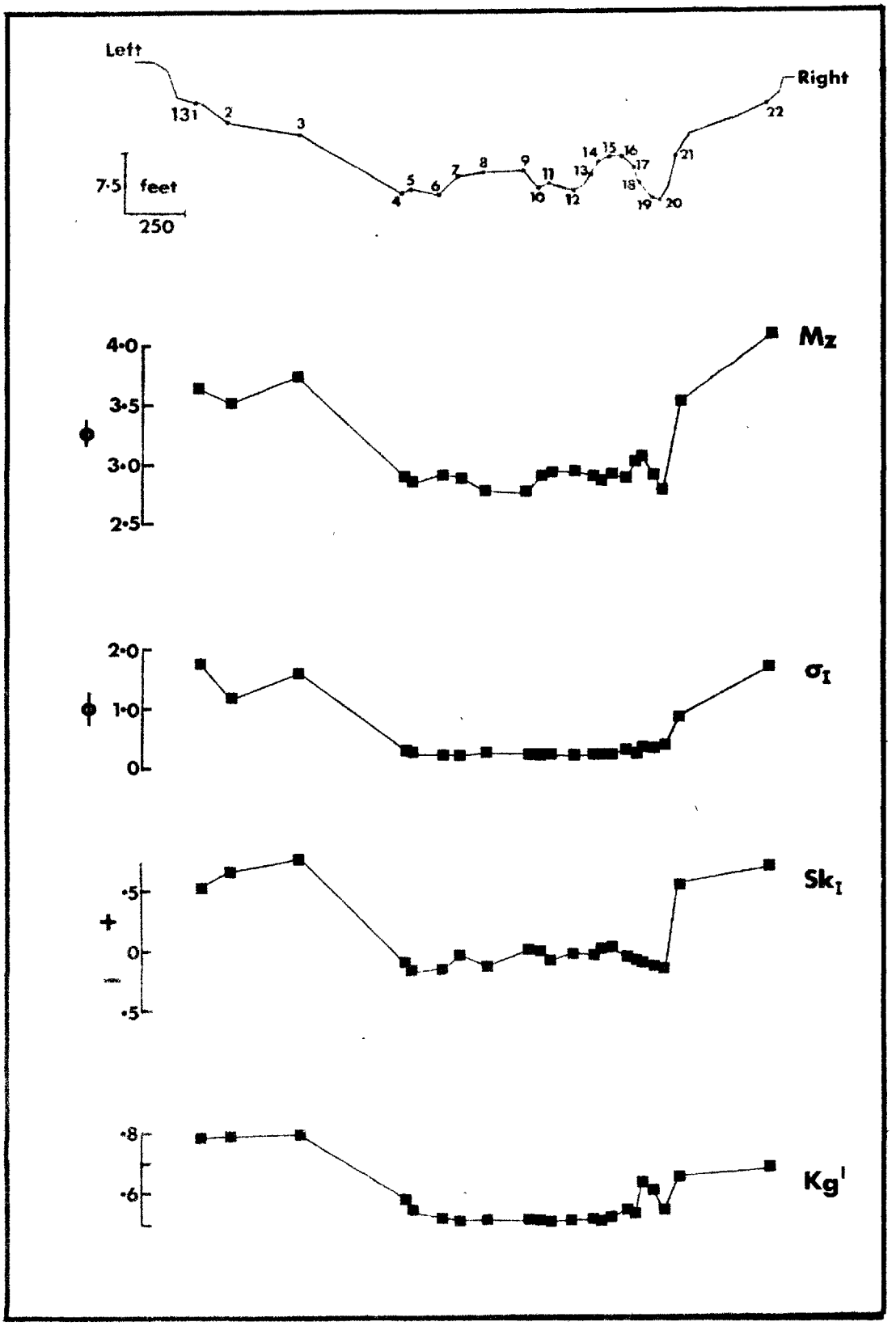


FIG. 7.22: GRAPHICAL STATISTICS, TRANSECT 13.

Sample	Mean M_Z ø units	Standard Deviation σ_I ø units	Skewness Sk_I	Kurtosis K_G	K_G'
141	3.62	1.78	+.509	3.58	.78
142	3.24	1.04	+.450	4.96	.83
143	2.95	.34	-.230	1.20	.55
144	2.95	.35	-.225	1.20	.55
145	2.91	.27	-.110	1.11	.53
146	2.89	.27	-.103	1.11	.53
147	2.91	.28	-.095	1.12	.53
148	2.92	.29	-.092	1.09	.52
149	2.92	.36	-.233	1.24	.55
1410	2.92	.29	-.114	1.14	.53
1411	2.89	.27	-.057	1.10	.52
1412	2.94	.29	-.068	1.10	.52
1413	2.95	.29	-.064	1.10	.52
1414	2.99	.27	-.051	1.15	.53
1415	2.99	.28	-.045	1.17	.54
1416	2.98	.28	-.050	1.16	.54

TABLE 7.22 : Variations of Composite Textural Parameters, Transect 14.

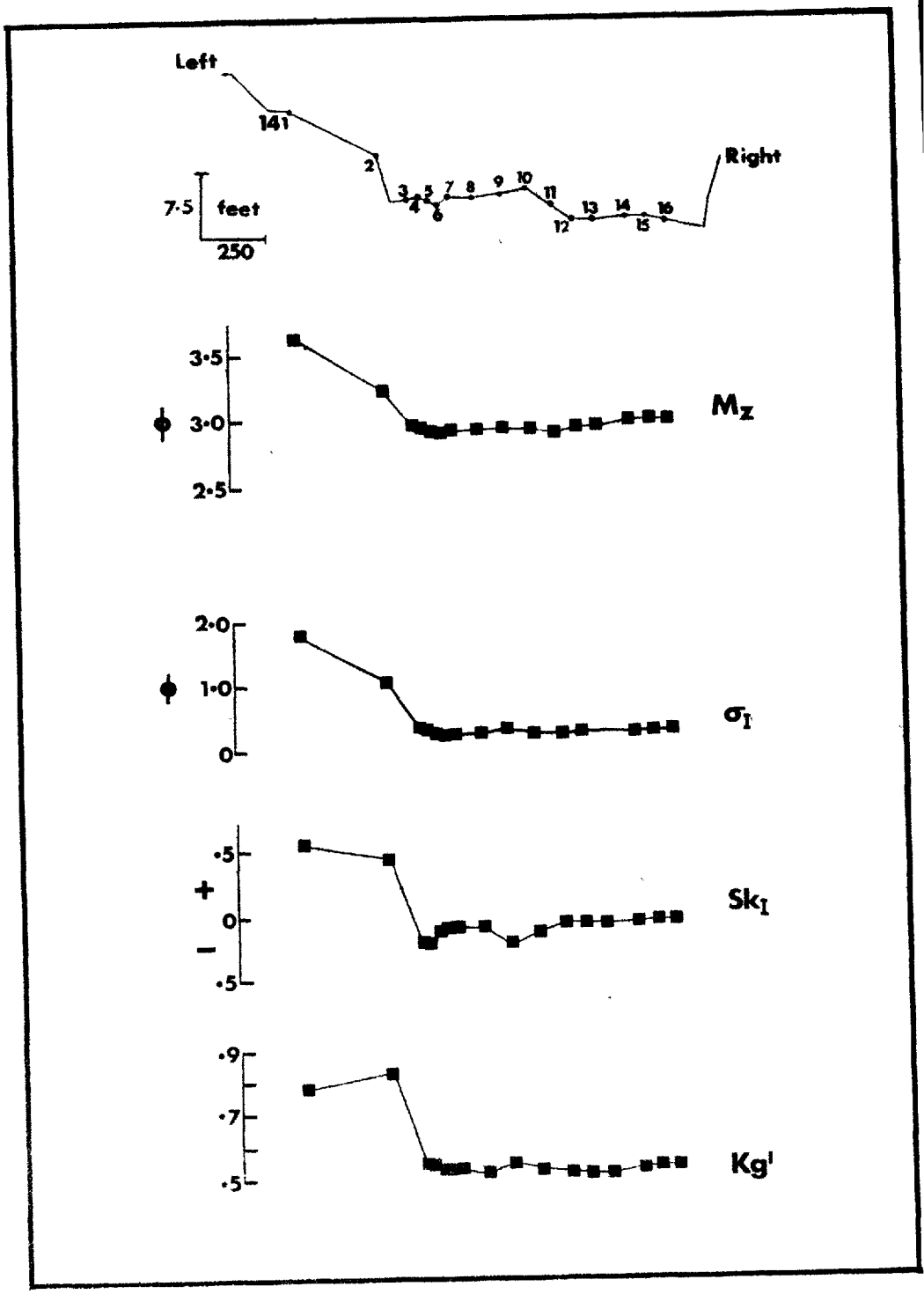


FIG. 7.23: GRAPHICAL STATISTICS, TRANSECT 14.

Sample	Mean M_z ∅ units	Standard Deviation σ_I ∅ units	Skewness Sk_I	Kurtosis K_G	K_G'
151	6.37	3.04	+.430	1.22	.55
152	4.65	1.79	+.620	1.33	.57
153	2.73	.38	-.285	1.41	.59
154	2.92	.26	-.096	1.01	.50
155	2.98	.25	-.089	.99	.50
156	2.89	.32	-.100	1.47	.60
157	2.89	.29	-.063	1.05	.51
158	2.85	.33	-.060	1.08	.52
159	2.93	.29	-.159	1.04	.51
1510	2.93	.30	-.114	1.10	.52
1511	3.00	.25	-.062	1.10	.52
1512	2.87	.31	-.095	1.29	.56
1513	5.00	2.48	+.693	1.11	.53
1514	5.02	2.53	+.777	1.11	.53

TABLE 7.23 : Variations of Composite Textural Parameters, Transect 15.

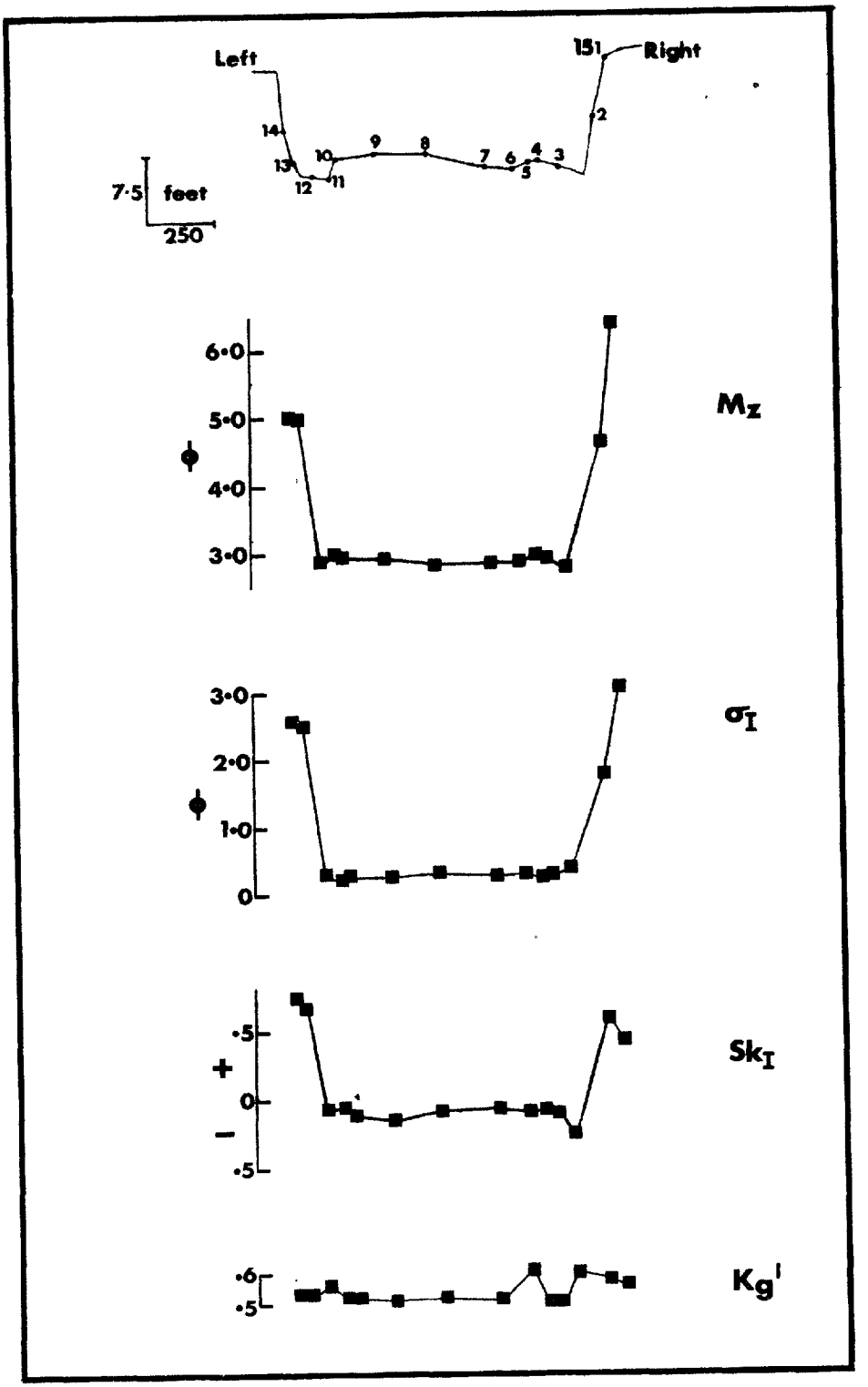


FIG. 7.24: GRAPHICAL STATISTICS, TRANSECT 15.

Sample	Mean M_z Ø units	Standard Deviation σ_I Ø units	Skewness Sk_I	Kurtosis K_G	K_G'
161	3.66	1.52	+.728	4.07	.80
162	3.23	.36	+.275	1.83	.65
163	3.24	.36	+.268	1.80	.64
164	3.04	.30	-.116	1.40	.58
165	2.59	.44	-.276	1.17	.54
166	2.95	.26	-.055	1.01	.50
167	2.94	.24	-.045	1.02	.50
168	2.94	.25	-.072	1.00	.50
169	2.92	.30	-.231	1.20	.55
1610	3.05	.32	-.190	1.27	.56
1611	3.11	.48	-.058	1.69	.63
1612	3.06	.31	-.103	1.26	.56
1613	3.06	.28	-.068	1.23	.55
1614	3.03	.30	+.019	1.18	.54
1615	2.99	.27	-.103	1.16	.54
1616	3.09	.28	-.080	1.19	.54
1617	3.09	.28	-.083	1.19	.54
1618	3.20	.41	+.205	1.78	.64
1619	6.42	4.01	+.838	.84	.46
1620	6.67	4.13	+.852	.79	.44

TABLE 7.24 : Variations of Composite Textural Parameters, Transect 16.

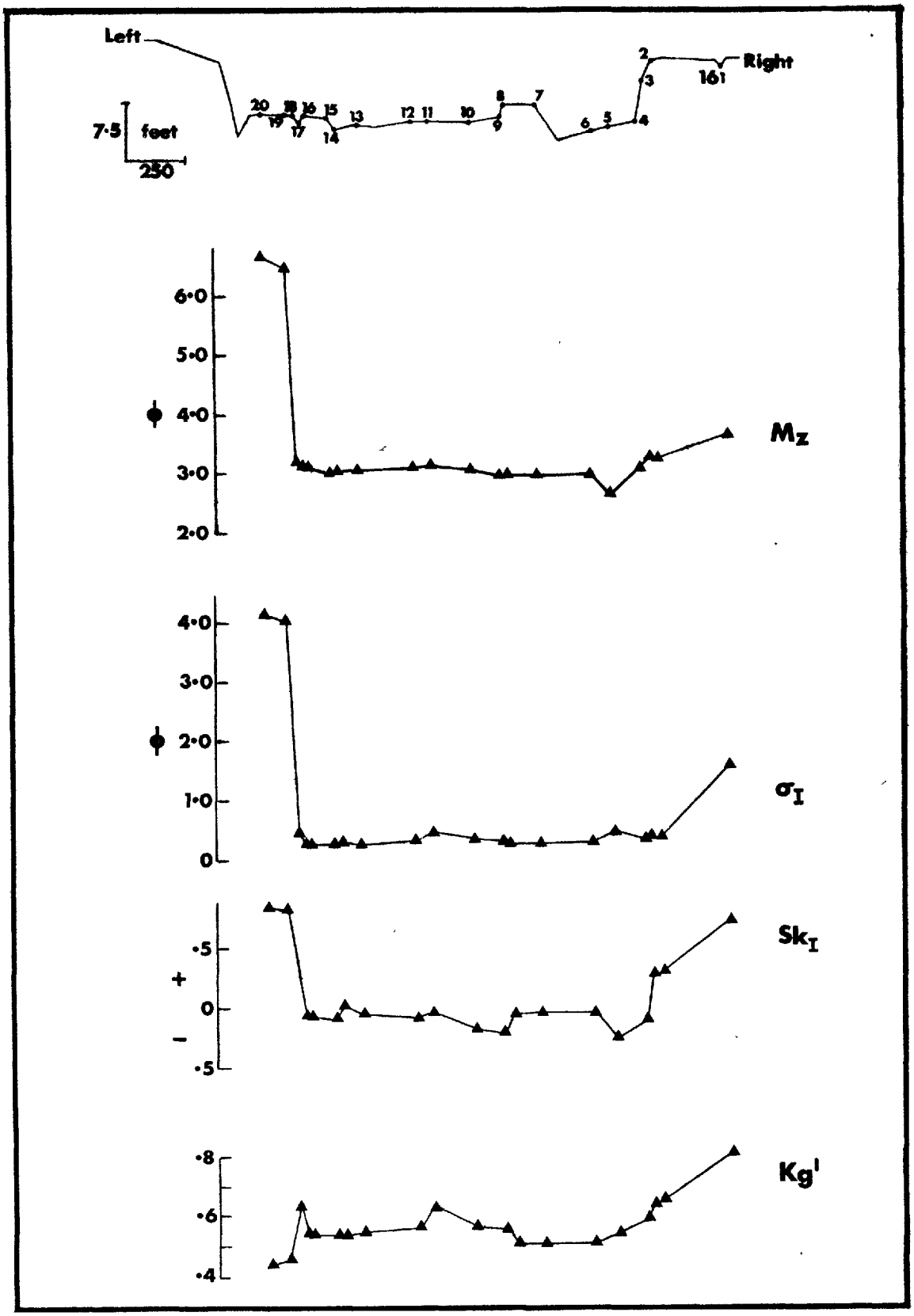


FIG. 7.25: GRAPHICAL STATISTICS, TRANSECT 16.

Sample	Mean M_Z Ø units	Standard Deviation σ_I Ø units	Skewness Sk_I	Kurtosis K_G	K_G'
171	4.72	2.19	+.750	1.28	.56
172	3.50	1.26	+.717	4.36	.36
173	3.00	.26	-.119	1.08	.52
174	3.00	.25	-.113	1.07	.52
175	2.93	.26	-.043	1.08	.52
176	2.91	.26	-.111	1.17	.54
177	3.00	.24	-.098	1.10	.52
178	2.94	.29	-.127	1.17	.54
179	3.01	.28	-.177	1.05	.51
1710	2.89	.28	-.239	1.22	.55
1711	2.91	.32	-.160	1.13	.53
1712	3.01	.29	-.211	1.12	.53
1713	3.00	.29	-.221	1.12	.53
1714	2.99	.29	-.143	1.12	.53
1715	2.99	.30	-.139	1.12	.53
1716	2.98	.29	-.140	1.12	.53
1717	2.99	.28	-.135	1.12	.53
1718	3.24	.40	+.185	1.75	.64
1719	3.25	.40	+.180	1.74	.64
1720	3.06	.31	-.036	1.21	.55
1721	3.05	.30	-.025	1.20	.55
1722	3.32	.46	+.380	1.81	.64
1723	3.36	.46	+.577	1.84	.65
1724	4.60	2.11	+.580	1.66	.62
1725	4.65	2.12	+.577	1.65	.62

TABLE 7.25 : Variations of Composite Textural Parameters, Transect 17.

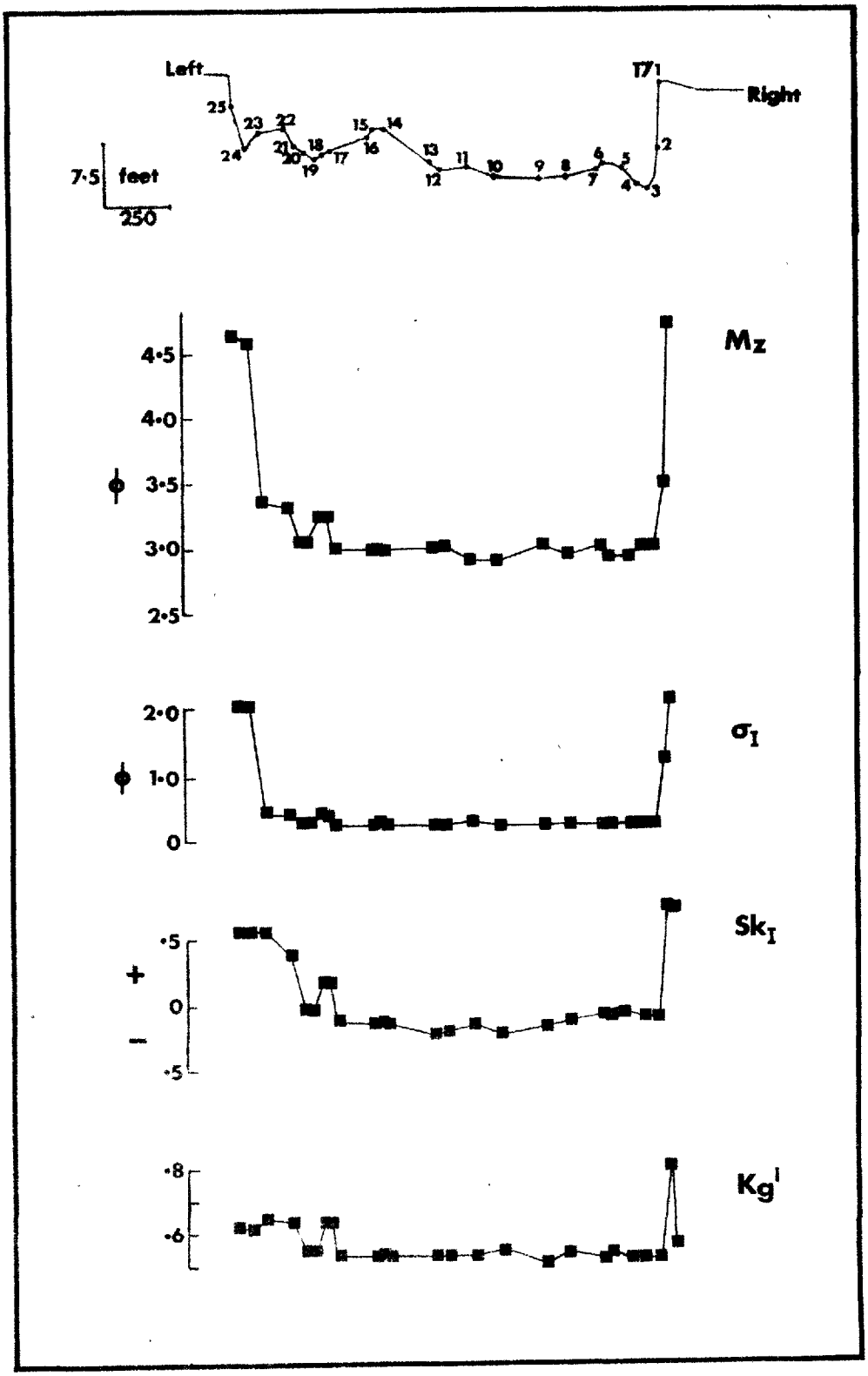


FIG. 7.26: GRAPHICAL STATISTICS, TRANSECT 17.

Sample	Mean M_z ø units	Standard Deviation σ_I ø units	Skewness Sk_I	Kurtosis K_G	K_G'
181	4.46	1.96	+.694	1.66	.62
182	2.95	.32	-.149	1.13	.53
183	2.95	.33	-.154	1.13	.53
184	3.05	.82	+.564	3.18	.76
185	2.99	.25	+.039	1.07	.52
186	2.98	.25	+.051	1.07	.52
187	3.06	.29	+.037	1.18	.54
188	3.01	.29	-.052	1.07	.52
189	3.00	.27	-.043	1.07	.52
1810	3.01	.30	-.135	1.20	.55
1811	2.97	.27	-.031	1.18	.54
1812	2.93	.27	-.003	1.15	.53
1813	3.03	.26	-.042	1.08	.52
1814	2.93	.26	-.011	1.12	.53
1815	2.97	.25	+.063	1.16	.54
1816	2.97	.31	-.133	1.18	.54
1817	3.05	.23	-.002	.92	.48
1818	4.53	1.89	+.431	1.41	.59
1819	4.57	1.96	+.462	1.42	.59

TABLE 7.26 : Variations of Composite Textural Parameters, Transect 18.

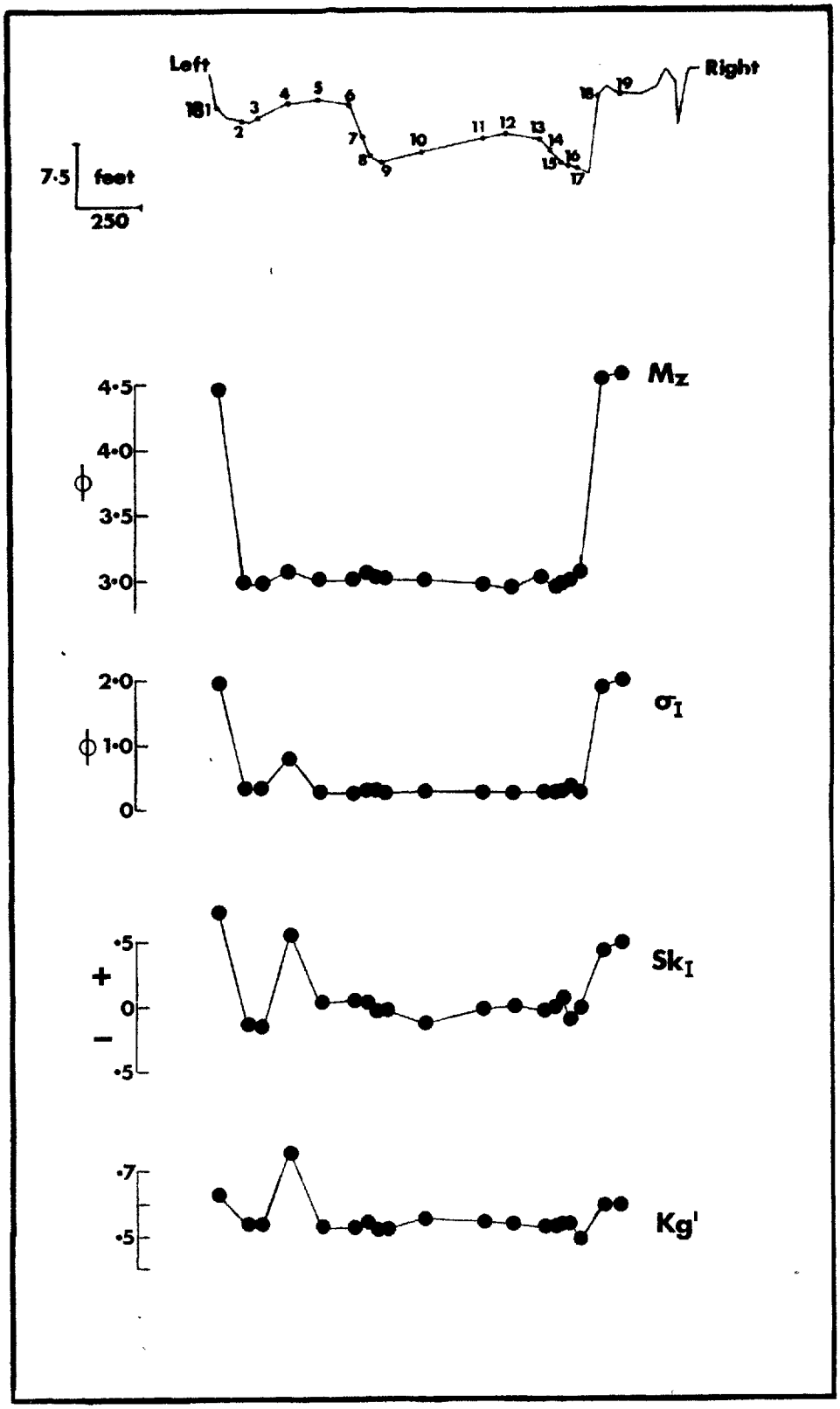


FIG. 7.27: GRAPHICAL STATISTICS, TRANSECT 18.

with local muddy sediment incursions. Fluctuations within this range are determined by the variations of subpopulation 2A frequency. Values at the lower end of the range occur where this frequency is small, or nil; values at the higher end where it is large. The frequency of the surface creep population has a comparable effect. Because of this, the worst 'sorting' (i.e. greatest mixing) generally occurs near the main channel; however this is not always the case.

Inclusive graphic skewness, Sk_I, contrasts the frequency of the suspension population 3 in the sands and muds of the sand flats and saltmarsh respectively. Across the latter, the sediment distributions have a strong positive skew (> 0.30) owing to the dominance of the suspension population. Across the sand flats, where population 3 is absent, the sediment distributions are either symmetrical or negatively-skewed. The symmetrical distributions reflect the near dominance of the lognormal population 2B. The negatively-skewed distributions result from admixtures of populations 1 and 2A which produce a coarse tail. In most cases, the main channel sands are therefore negatively skewed, but this is not always so, so that it cannot be categorically stated that there is a definitive skewness preference from channels to banks (cf. Duane, 1964). This is because, as described in a previous section, the ebb circulation pattern is rather subtle in creating preferred streams which probably vary somewhat during the ebb phase, as a result of which the low-water differentiation of

low banks and shallow channels is a very ephemeral one and not necessarily representative of a fixed current differentiation. For this reason, since the main current flows have undoubtedly switched course during the tidal phase (both ebb and flood), the concentrations of population 1 and 2A grains away from the main channel indicate either remnant flood barbs or, more often, ebb 'channels' operative during some period of the ebb phase but later abandoned in preference to the main channel. Their distribution is rather confused because of the very slight difference only between banks and channels (other than the main channel) in elevation. Hence negatively skewed sands, by way of their shelly coarse tails, indicate zones where, at some stage of the tidal phase, the flow has been concentrated and a slight accumulation of angular grains has ensued.

As pointed out in the discussion on the skewness of beach sands, the negatively skewed sediments owe this property not to the winnowing out of fine suspension material (which should produce a normal, unskewed, saltation population) but to the mixing of the primary saltation population with a secondary, coarser saltation population, and a tertiary, even coarser, surface creep population. It is the absence of positive skewness on the sand flats, and not the presence of negative skewness, which is the result of direct winnowing in an area of extreme turbulence. Here, negative skewness is primarily the result of Carmarthen Bay control. Duane

(1964) considers that skewness is significant after -0.1 and +0.1, by which criterion almost all these sand flat sediments are negatively skewed. If, however, we take account of the near symmetrical sediments as well, then a significant proportion are just positively-skewed. This generally occurs near the outer margins of the sand flats, at the transition to the mud flats, as a result of increased deposition of the suspension population, but is also found intermittently on the more exposed areas of the sand flats, where the coarse tail is absent and only a small infiltration of suspended grains is required to impart a slight positive skew. This slight negative/positive association can therefore be attributed to small energy fluctuations imposed by the complex morphology of the estuary and the variations of both tidal and meteorological influences during the tidal phase.

As pointed out above, the muddy sediments of the mud flats and saltmarsh are highly positively skewed. This results from the admixture of a suspension population with one or more saltation populations which produces a grain size distribution having a long fine tail. Towards the estuary margins, as the proportion of the saltation grains declines, the sediments become less highly-skewed. But even when the suspension population occurs in isolation, as on the high marsh (transect 9, Fig. 7.18), a high degree of positive skewness is retained. This follows from the coarse truncation of the suspension population which is therefore deficient in grains

at the coarse end of its size distribution and so is not lognormal.

Kurtosis also points the contrast between the open sand flats on the one hand, and the mud flats and saltmarsh on the other. The distinction between them, on the basis of this parameter alone, is however not clear-cut. The sand flat sediments are invariably mesokurtic (i.e. near-normal, Folk and Ward, 1957), because composed of one lognormal population with only small coarser admixtures; where populations 1 and 2A occur in increased proportions, the sands become slightly leptokurtic. The mud flats and saltmarsh have sediments that are very, or extremely, leptokurtic - addition of the suspension population ensures that the central areas of their size distributions are relatively better sorted (i.e. dispersed) than are the tails. However, on the high marsh, low marsh, or even mud flat, wherever the suspension becomes truly dominant or exclusive, then the sediments revert to normality and become mesokurtic; in these cases, the parameter apparently ignores the effects of coarse saltation tails or truncation points, but this is because the sorting (dispersion) in the central areas and tails of the size distributions become equalised. Hardly any of the sediments are platykurtic. As shown by Folk and Ward (1957), this property should occur when two populations occur in subequal proportions so that the sorting in the tails of the distribution is good relative to the sorting in its centre. Certainly, mixing of subpopulations 2B and 3 in subequal proportions occurs throughout

the mud flats and saltmarsh. However, because the sorting (i.e. dispersion) of population 3 is intrinsically poor, and since this population forms the fine tail of such mixtures, a platykurtic situation is hardly ever achieved.

Within the saltmarsh, creek sediments are characterised by higher kurtosis (and more positive skewness) than the adjacent sediments. This is not because of a greater frequency of the suspension population but, paradoxically, because of a greater frequency of the coarser populations 1 and 2A. These coarse admixtures convert the size distribution to one with a well-sorted centre and a long fine tail, in contrast to the marsh sediments which have size distributions that are, in effect, so dominated by the fine tail that it becomes the centre of the distribution.

Graphical parameters of the sublittoral and fluviatile samples are shown in Table 7.27. The former are all very well sorted, fine sands. Because of the admixture of population 2A, they are slightly negatively skewed, but those with admixtures of population 1 are negatively skewed to a greater degree. These coarse admixtures therefore outweigh the effects of the fine admixtures ($>5\%$ in the western samples) of population 3. The suspension population is however important in determining kurtosis; samples with both coarse and fine tails are very leptokurtic, those (on the offshore bars) with coarse tails alone are mesokurtic.

The fluviatile samples are quite distinctive. Most are

Sample	Mean M_z ∅ units	Standard Deviation σ_I ∅ units	Skewness Sk_I	Kurtosis K_G	K_G'
R1	-1.33	2.29	-.203	.58	.40
R2	-1.62	1.97	+.189	.80	.44
R3	-3.42	1.53	+.285	.78	.44
R4	-1.75	1.98	+.267	.69	.41
R5	.83	.73	-.094	1.14	.53
R6	6.51	3.17	+.492	1.10	.53
R7	-.19	1.57	-.266	1.40	.58
B1	3.23	.27	-.146	1.48	.60
B2	3.13	.29	-.263	1.50	.60
B3	3.24	.22	-.083	1.62	.62
B4	3.10	.31	-.235	1.52	.60
B5	2.54	.32	-.051	1.01	.50
B6	2.55	.32	-.045	1.01	.50
B7	2.64	.27	-.093	1.05	.51

TABLE 7.27 : Variations of Composite Textural Parameters, Fluviatile and Sublittoral Samples

considerably coarser than any of the foreshore and estuarine sediments because of their large surface creep constituent. For the same reason, they are moderately to very poorly sorted. The one sample without a surface creep population is also very poorly sorted because of the dominant suspension admixture. Where the gravel (surface creep) population is of moderate significance, the size distributions are negatively skewed, but where it becomes dominant the size distributions are positively skewed (cf. Folk

and Ward, 1957). The sample with a large suspension population is also very positively skewed. Some samples are platykurtic (and therefore unique in the sequence of sediments studied here) as the surface creep and saltation populations are present in subequal amounts, some leptokurtic where the saltation populations in summation exceed the surface creep population. The very muddy sample is mesokurtic since the suspension population (truncated lognormal) composes most of the sample. Obviously, kurtosis and skewness values are generally complementary but sometimes apparently contradictory; this is because they are measuring rather different properties of the size distribution. The fluctuations of skewness and kurtosis probably reflect the uncontrolled manner of sampling, but they are also indicative of the comparative heterogeneity of the fluviatile sediments.

All four graphical parameters are predictably sensitive to environment, but their interpretation is meaningful only when they are considered in the light of mixing of subpopulations 1, 2A, 2B and 3. Without this requisite subpopulation data, their value must be restricted. For this reason, their use would appear to be rather superfluous, although they are commended by their economical description of an otherwise dense collection of information. Also their use appears to the writer to be often a sophisticated (or pretentious) technique for stating the obvious; it is unnecessary to derive skewness and kurtosis values in order to distinguish clean sands from muddy sands.

7.6 Comparison of Sedimentary Environments

As pointed out in Chapter 6, the graphical parameters hopefully come into their own when used to bring together a considerable amount of textural data from sediments with various depositional histories. Claims have been made for their ability to distinguish sedimentary environments, though such claims are rarely upheld by subsequent studies. In the previous chapter, it was shown that scatter plots of pairs of parameters conspicuously fail to distinguish the dune and beach sands. It cannot be denied that such plots will successfully distinguish mud flat, saltmarsh or (most) fluviatile sediments (in this study) from dune, beach, sublittoral or estuarine sand flat sediments. However, since even the layman can distinguish these groups (by observing mud or gravel contents), the use of scatter plots must be out of proportion to their declared aim. Hence it is useful, in this study, to compare only the quartzose sands by such means. Accordingly, a random selection of estuarine sand flat samples and all of the sublittoral samples have been taken to provide additional points on the scatter plots described in the previous chapter. The results are shown in Figs. 7.28 - 7.31. In all cases, the degree of overlap between the individual groups of data is too great to allow for a meaningful, even empirical, separation. Generally, the data of each sub-environment plots in a restricted field on each diagram, but these fields are too close together to be separated - they would be

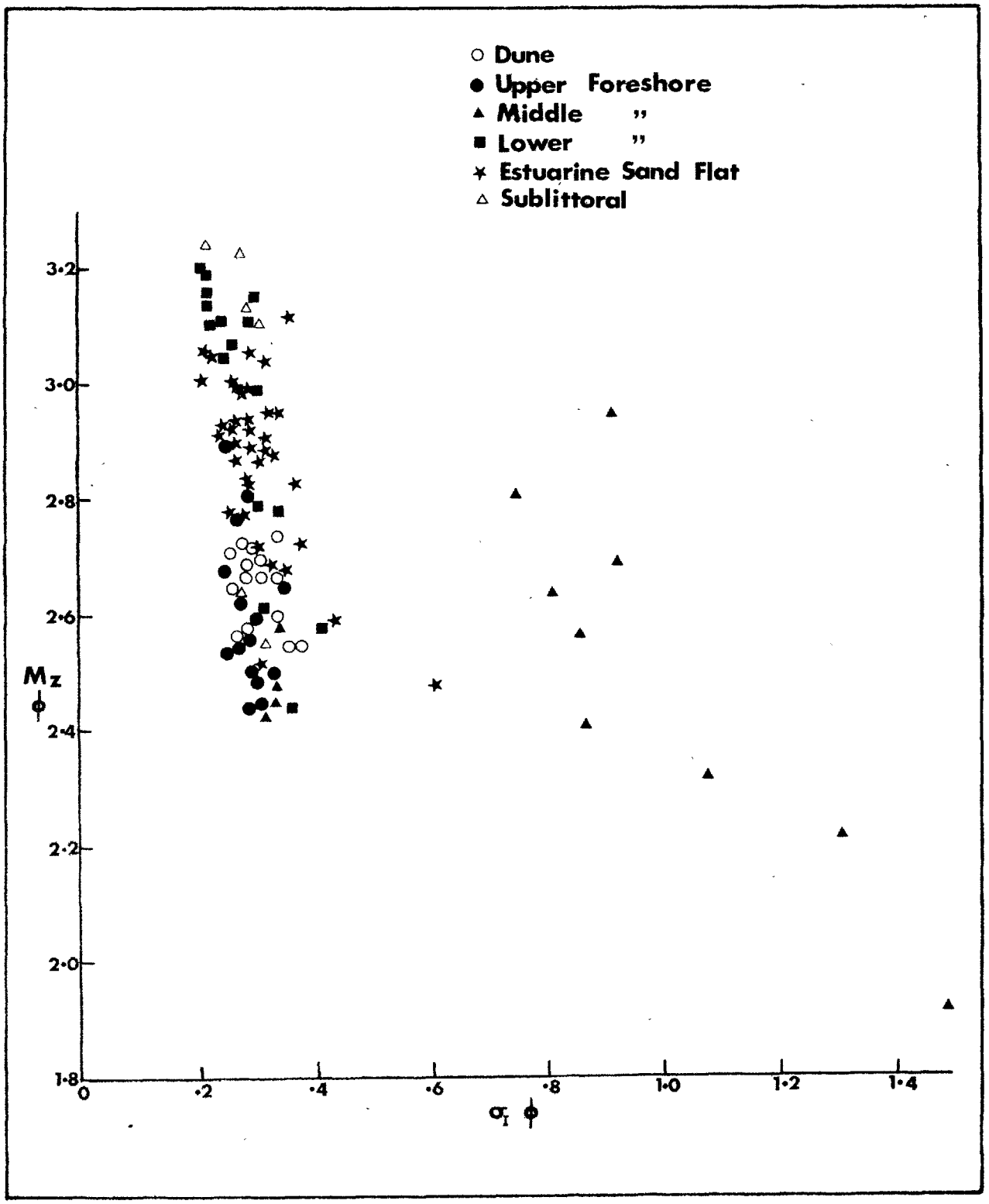


FIG.7.28: COMPARISON OF SUB-ENVIRONMENT GRAPHICAL STATISTICS.

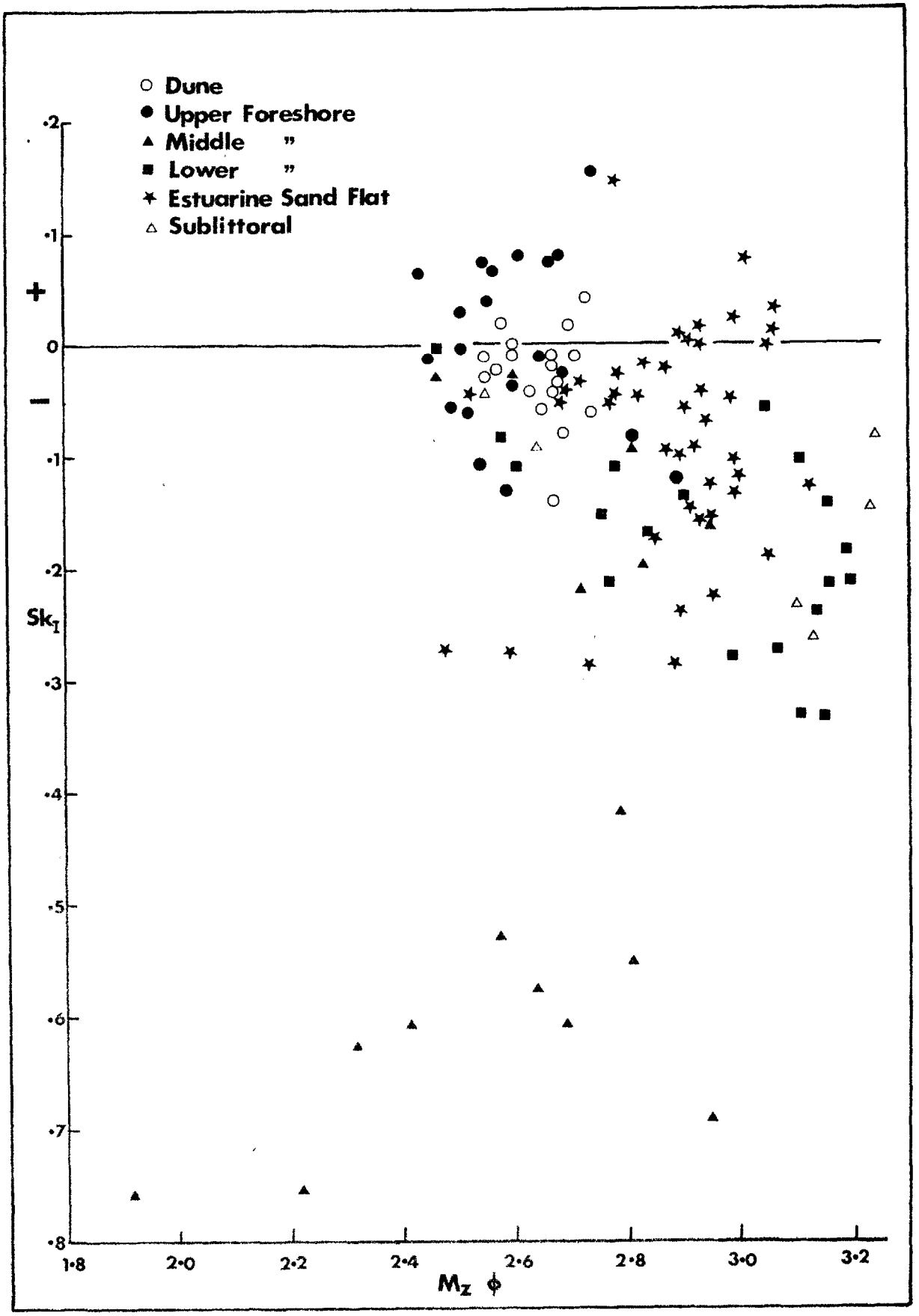


FIG. 7.29: COMPARISON OF SUB-ENVIRONMENT GRAPHICAL STATISTICS.

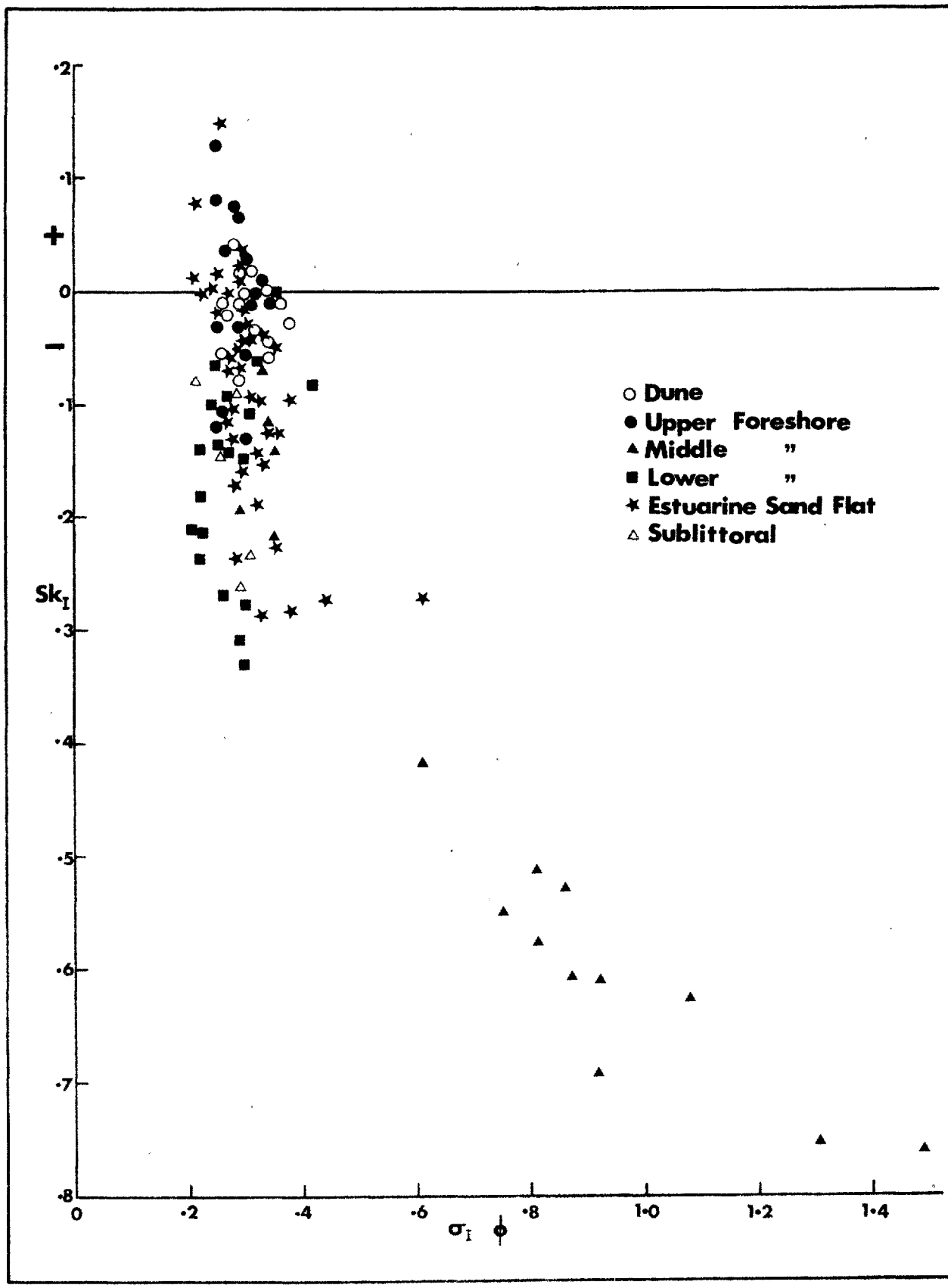


FIG. 7.30: COMPARISON OF SUB-ENVIRONMENT GRAPHICAL STATISTICS.

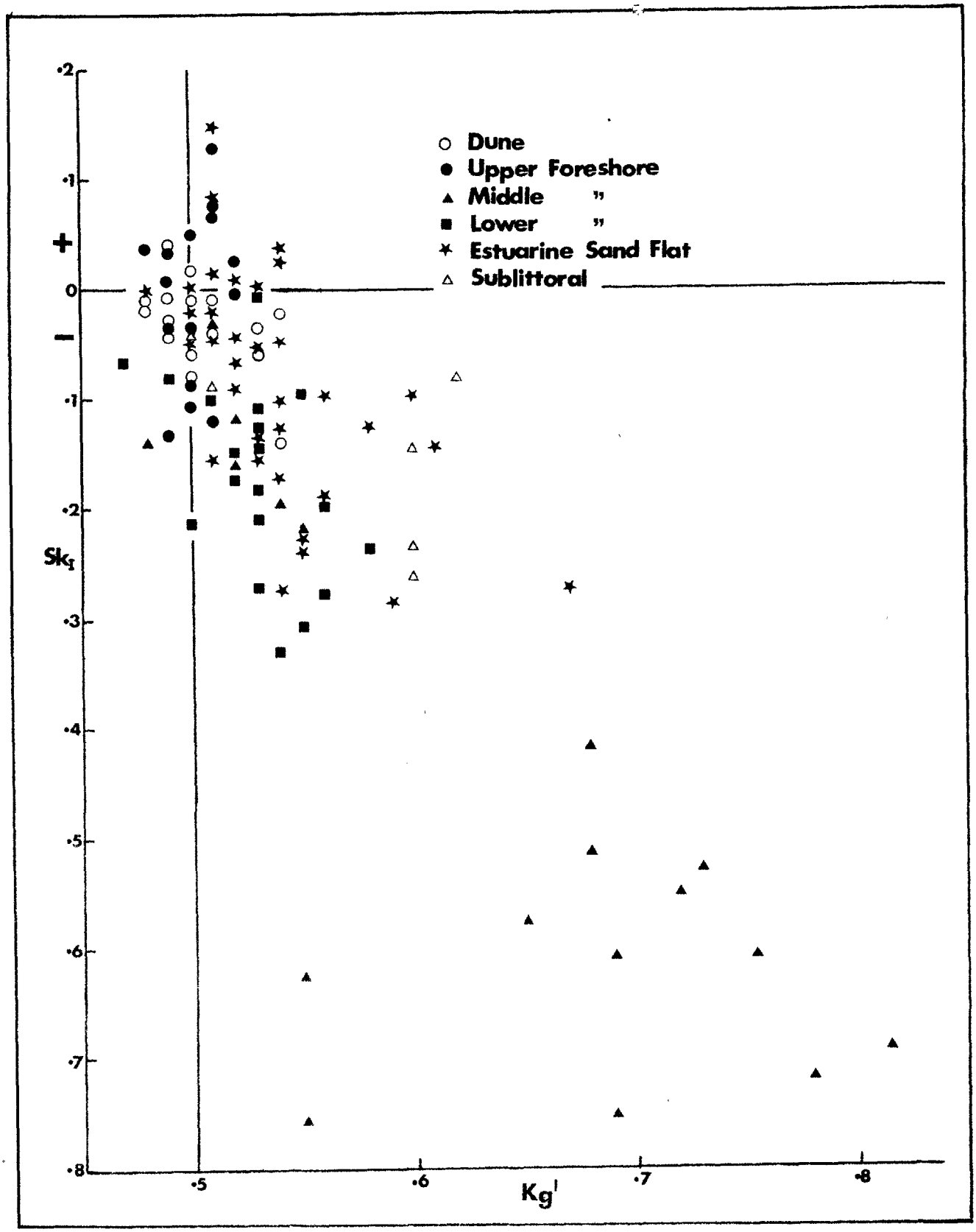


FIG. 7. 31: COMPARISON OF SUB-ENVIRONMENT GRAPHICAL STATISTICS.

indistinguishable if not labelled by distinctive symbols. In all four diagrams, only the sands of the middle foreshore are in any way separate from the others (because of the traction clogs of the surface creep population) and then only in the western half of Pendine Sands. The CM plot of Fig. 7.32 is even less useful for this purpose.

Thus, according to these plots, there is no great difference between the wind-laid dune sands, swash/backwash-laid beach sands and current-laid estuarine sands; the sublittoral sands are also inseparable from these. The beach sands differ only in their greater heterogeneity so that they plot over a wider area of the diagrams. It should be noted however, that both dune and sublittoral samples were few in number, and their properties may not represent the full extent of their true field variation.

An alternative form of comparison is via frequency histograms using all the sample data, rather than a few random selections. This is only valid if the various sets of data have been collected in an identical manner, i.e. objectively. Clearly sublittoral and dune sand data has to be rejected on this basis. So should the estuarine data for a truly objective comparison. However, because of the number of estuarine samples collected and their textural uniformity, it is considered that they may be included in such a comparison. Beach sands and estuarine sands only have therefore been compared.

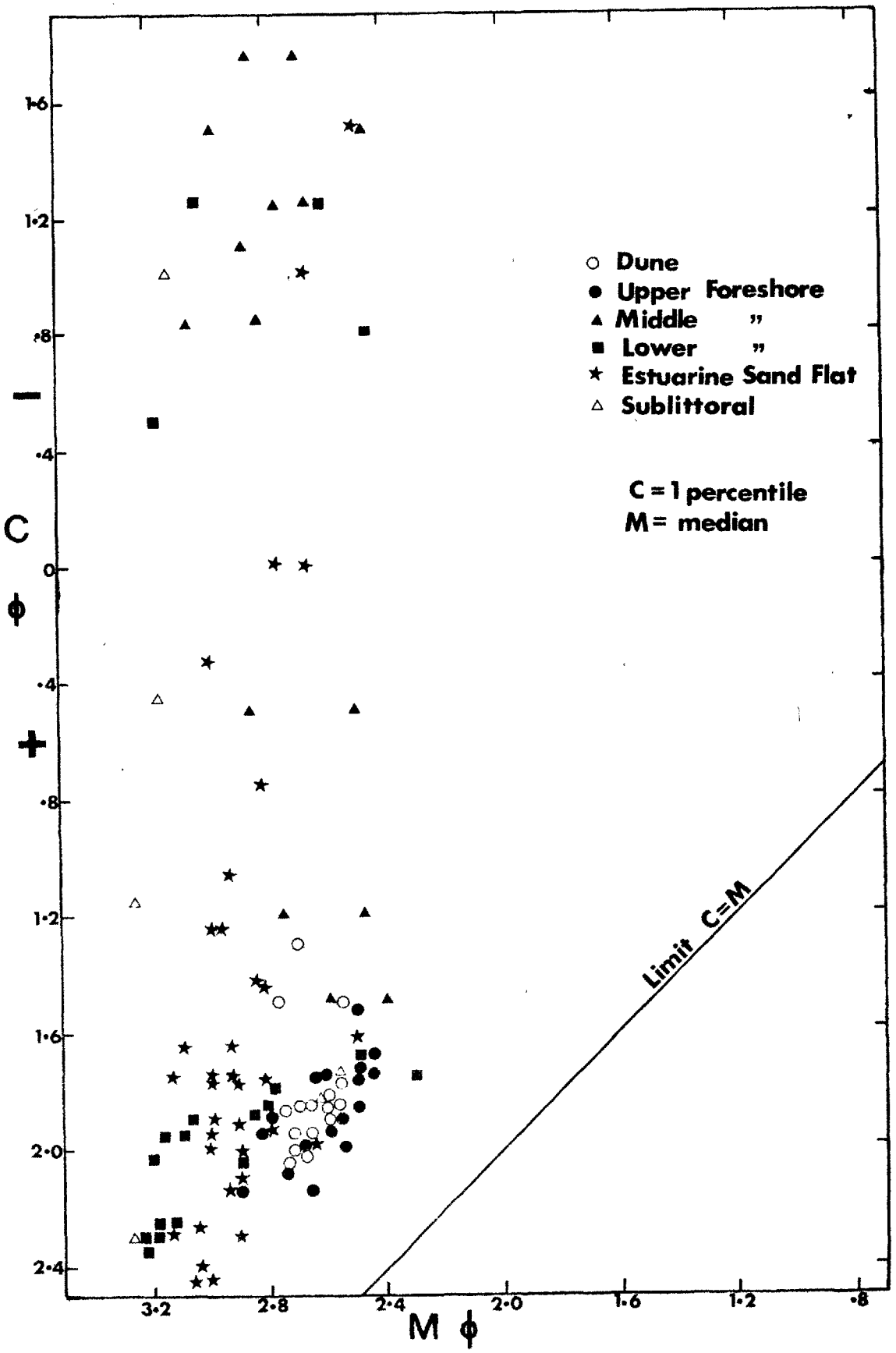


FIG. 7.32: COMPARISON OF SUB-ENVIRONMENTS BY CM PLOTS.

Starting with the subpopulation parameters, frequency histograms based on appropriate class intervals have been constructed. The frequencies of the suspension population (minor, and probably very changeable from day to day) and the saltation population 2B (variable, but only in response to variations of % 1 and % 2A) have not been considered.

The frequency modes of the proportions of population 1 are the same for both subenvironments (Fig. 7.33). The distribution is however noticeably skewed to a greater extent for the beach sands, because of the increased occurrence of the population at mid-tide level. This is even more apparent in the histograms of population 2A frequencies (Fig. 7.34). These differences have already been commented upon, and are the result of the intrusion of less-rounded (predominantly organic) grains into an otherwise detrital sediment. Such a comparison would not be available in the absence of the shelly grains which are themselves dependent on an abundant nearshore benthic fauna. But mid-tide concentrations of shelly grains should occur whenever the foreshore is fronted by a shallow, sandy bay.

The frequency distributions of the two saltation population mean grain sizes are distinctive for both environments (Figs. 7.35, 7.36). The comparative homogeneity of the estuarine sands is striking. The abrupt cut-offs at the fine ends of the diagrams are artificial, reflecting the termination of the beach sampling

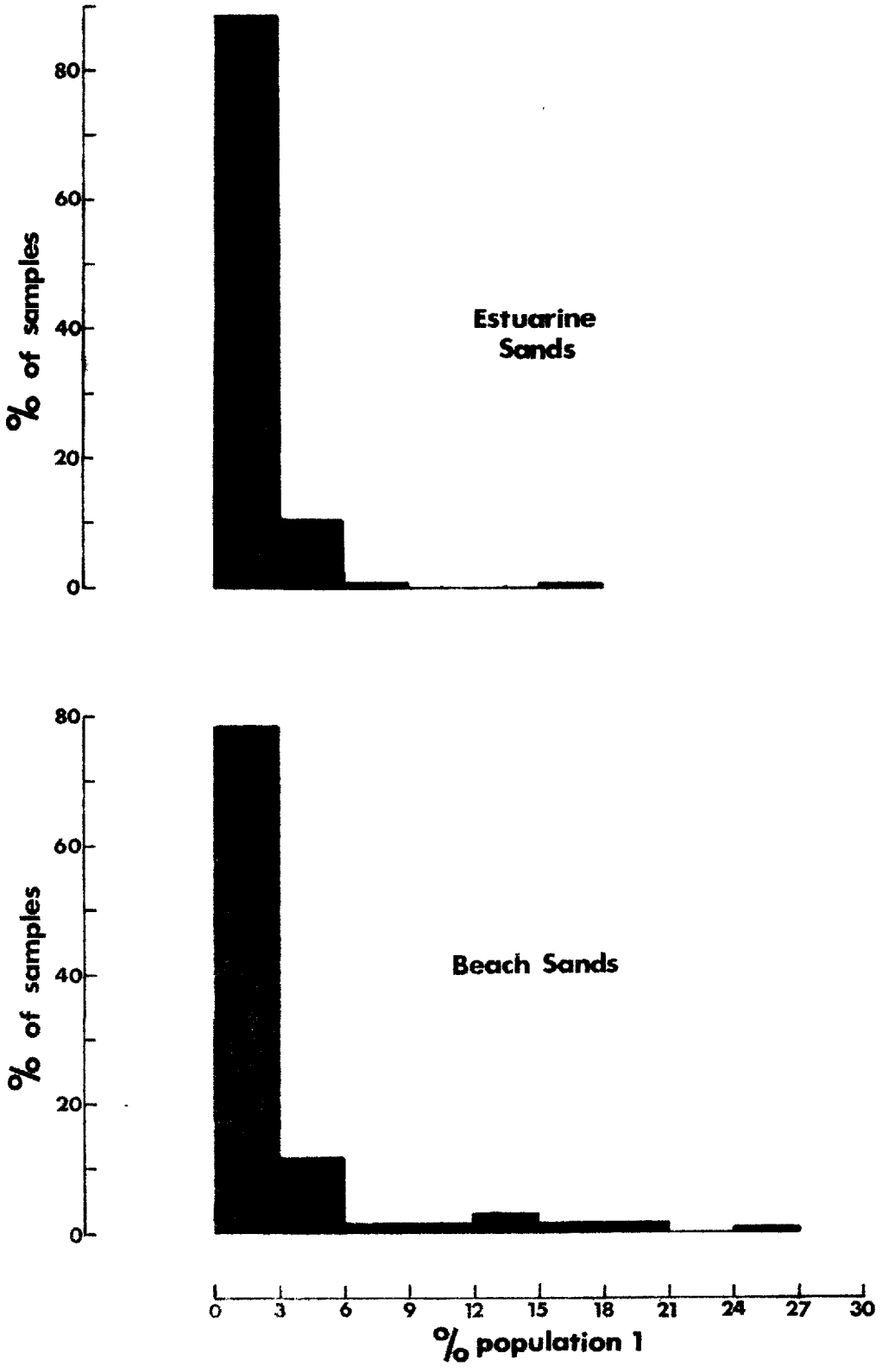


FIG. 7.33: COMPARATIVE HISTOGRAMS OF POPULATION 1 FREQUENCY.

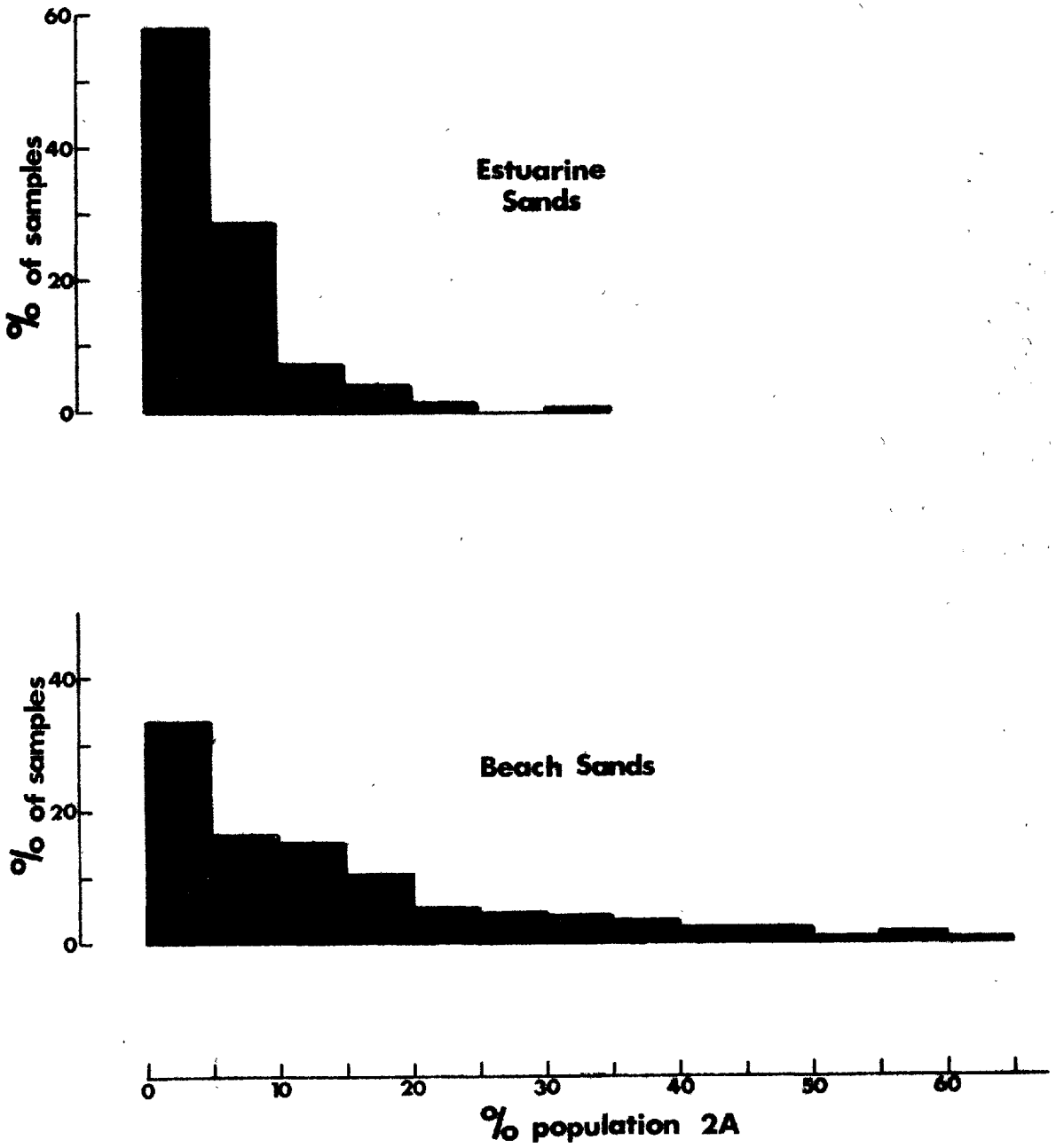


FIG.7.34: COMPARATIVE HISTOGRAMS OF POPULATION 2A FREQUENCY.

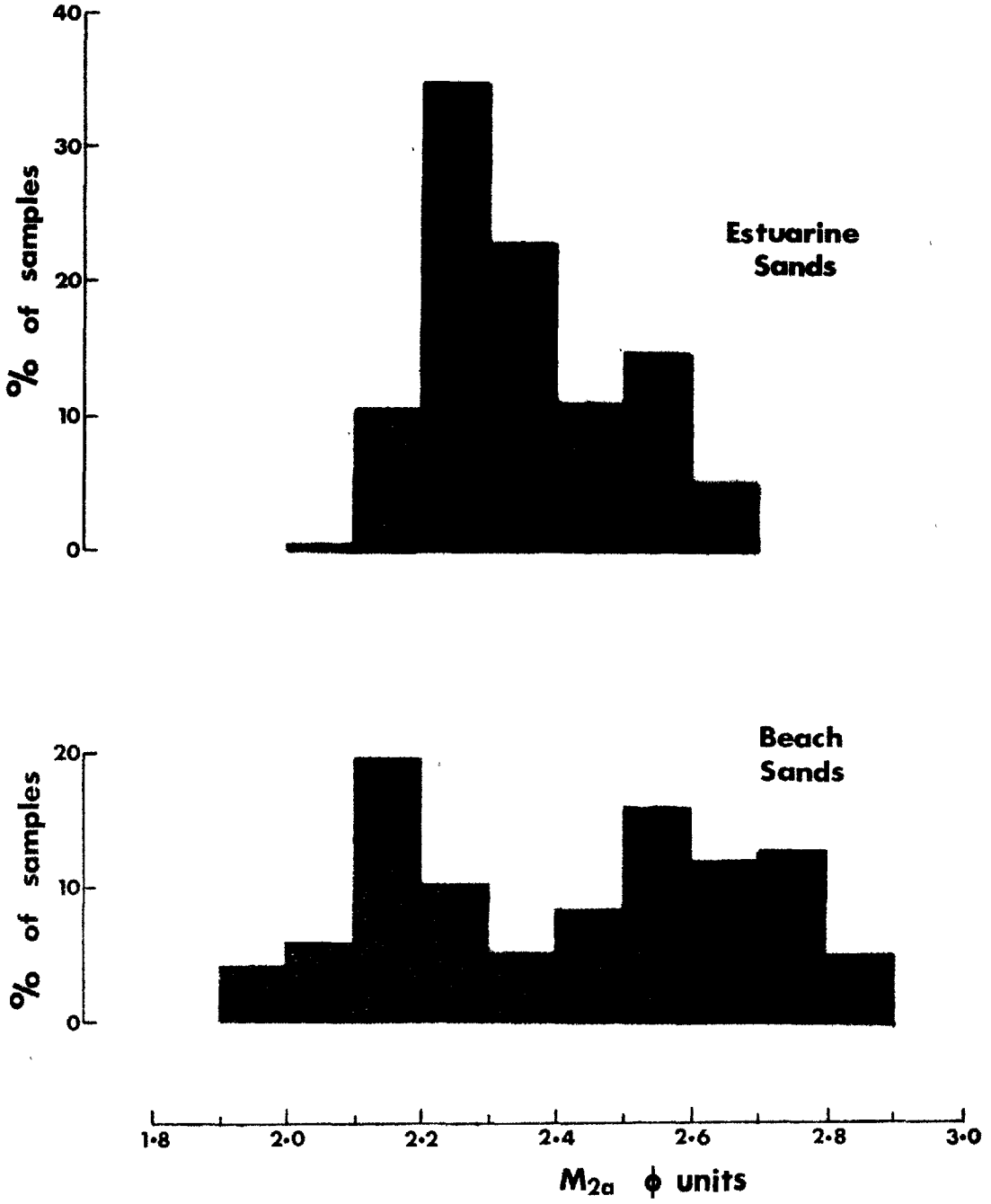


FIG.7.35: COMPARATIVE HISTOGRAMS OF POPULATION 2A MEAN GRAINSIZE.

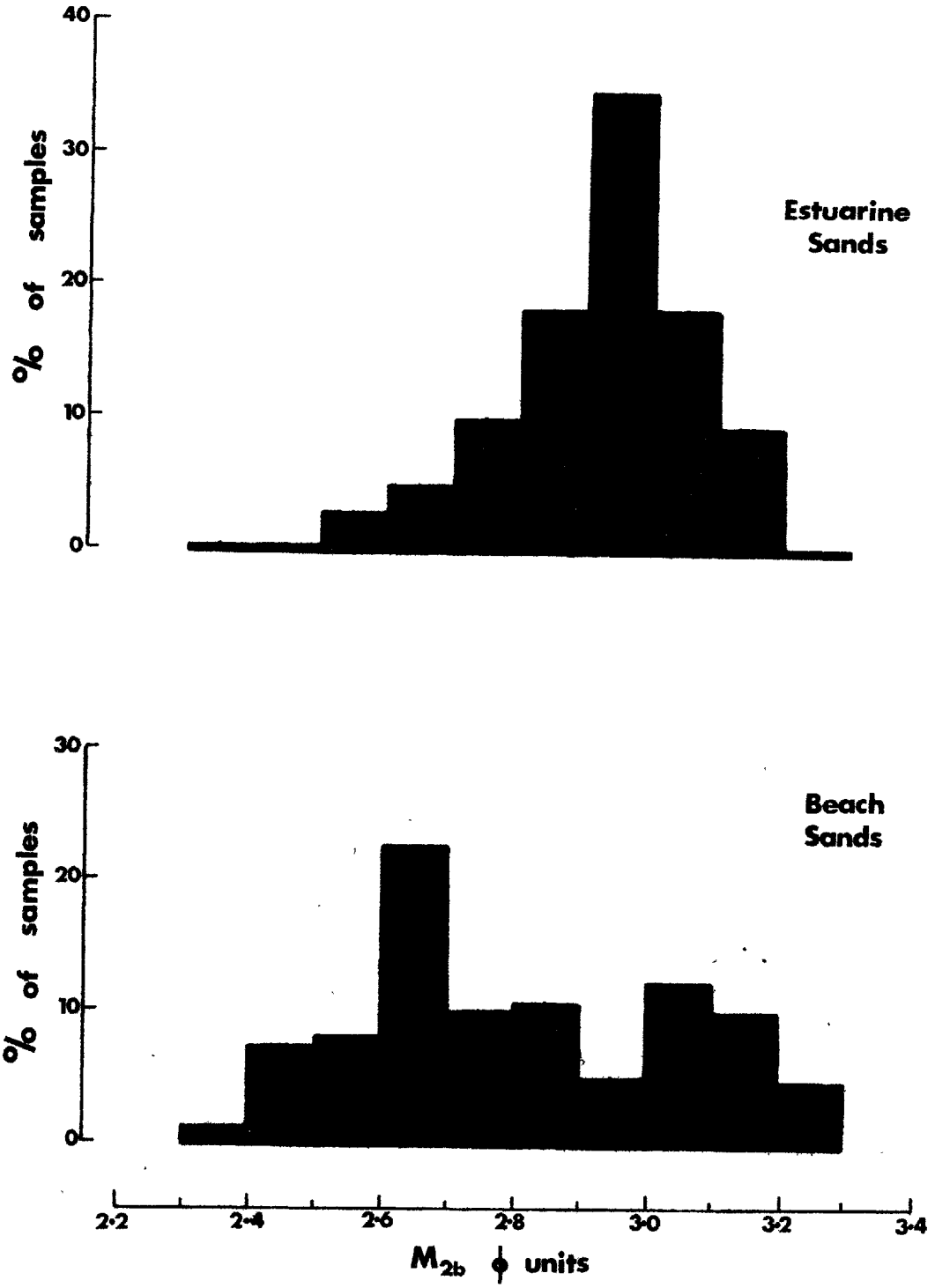


FIG. 7.36: COMPARATIVE HISTOGRAMS OF POPULATION 2B MEAN GRAINSIZE.

transects at the low-water mark, and the estuarine transects at the mud flat transition.

Perhaps the most important aspect of these frequency distributions is their demonstration of the complementary nature of the beach and estuarine sands. The mode of the estuarine distributions corresponds to a trough (point of inflexion on a cumulative frequency curve) on the beach distributions; this is apparent for both saltation populations. This does not necessarily support the simplistic notion that the beach has provided a source of sand for the estuary, but points to the existence of a certain dynamic equilibrium in the total nearshore environment. This topic cannot be pursued in the absence of data from the sublittoral, but almost certainly the range of mean grain sizes missing from the beach are present below the low-water mark (it is apparently not to be found in the dunes). Because of the seaward fining gradient of both populations, which seems to continue into the bay, the deficient grades must be concentrated in the eastern part of the bay, although not on the exposed barriers. It is from this area, naturally, that transport of sand into the estuary must occur (assuming a seaward source); however, because of a probably well-developed set of dynamic equilibria between beach and bay, bay and estuary, and within the individual environments, no one point of the system can be regarded as a source, and intrusion of sand into the estuary is simply the final move in an interconnected

chain of events. The initial impulse for such a chain reaction is probably the present day lowering of the land surface relative to sea-level and the mechanism that triggers off transport is a meteorological one (Chapters 2 and 4). Landward transport of sand, on a highly selective basis, then occurs in isolated pulses rather than as a continuous, every-day process. There would appear to be no hydrodynamic reason to explain the deficiency of some size grades on the foreshore (assuming that the sampling array is not contributing any bias), and it may be that these size grades are preferentially selected for longshore (sublittoral) transport into the estuary and are thus unavailable to the foreshore. Alternatively, as pointed out in Chapter 6, the variation of nearshore wave energy as it affects the foreshore is not a simple linear relationship with distance from the shoreline, and so certain size grades may be discouraged from foreshore deposition - it is interesting that the critical size grades, when they are present on the foreshore (on beach transects 1 - 5 predominantly, being virtually absent from transects 6 and 7), almost always are associated with the increased frequencies of populations 1 and 2A at mid-tide levels. This is most apparent if we consider the most critical grade (2.9 - 3.0 $\emptyset$ units for M_{2B}). As always, it is difficult to visualise how the present situation has developed; to separate cause and effect; whether the beach profile has influenced wave action or vice-versa; whether one, or both, of these

has enabled a surplus of grains, particularly with mean grain size 2.8 - 3.1 Ø units (saltation 2B), to be available for estuarine intrusion; or whether the preferential selection of these grains for estuarine intrusion has resulted in a deficit for beach transport, in turn influencing the shape of beach profiles (at mid-tide levels).

Returning to the frequency histograms, Figs. 7.37 and 7.38 show comparisons of the standard deviations of both saltation populations. Again there is a striking contrast between beach and estuarine distributions. In the case of saltation 2A, the shapes of the beach and estuarine distributions are very similar, but the mode of the former is rather smaller, by perhaps 0.8 Ø units, than the latter - size selection within the secondary saltation carpet is thus generally more rigorous on the foreshore than within the estuary. There is a similar, but smaller, difference between the modes of the standard deviation distributions of the primary saltation population 2B. It would appear, therefore, that grain selection (i.e. sorting) is more developed within the swash/backwash zone of the foreshore than on the estuarine sand flats, reversing currents being, on average, more efficient than unidirectional ones. In the case of saltation 2B, the dispersion distributions also differ noticeably in shape (standard deviation); in this respect, also, the estuarine sands are far more homogeneous than the beach sands, again because of the changes that occur

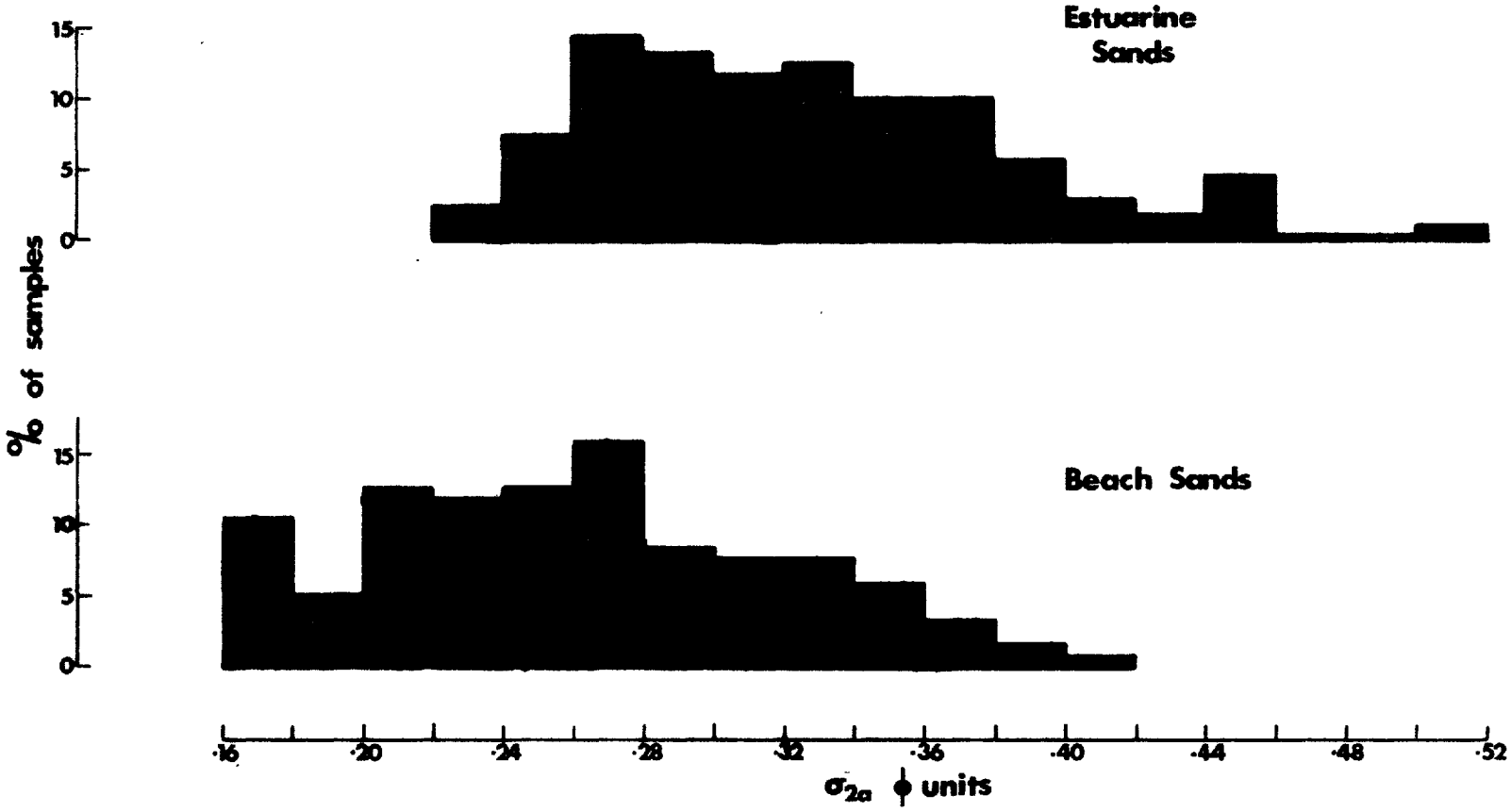


FIG. 7.37: COMPARATIVE HISTOGRAMS OF POPULATION 2A STANDARD DEVIATION.

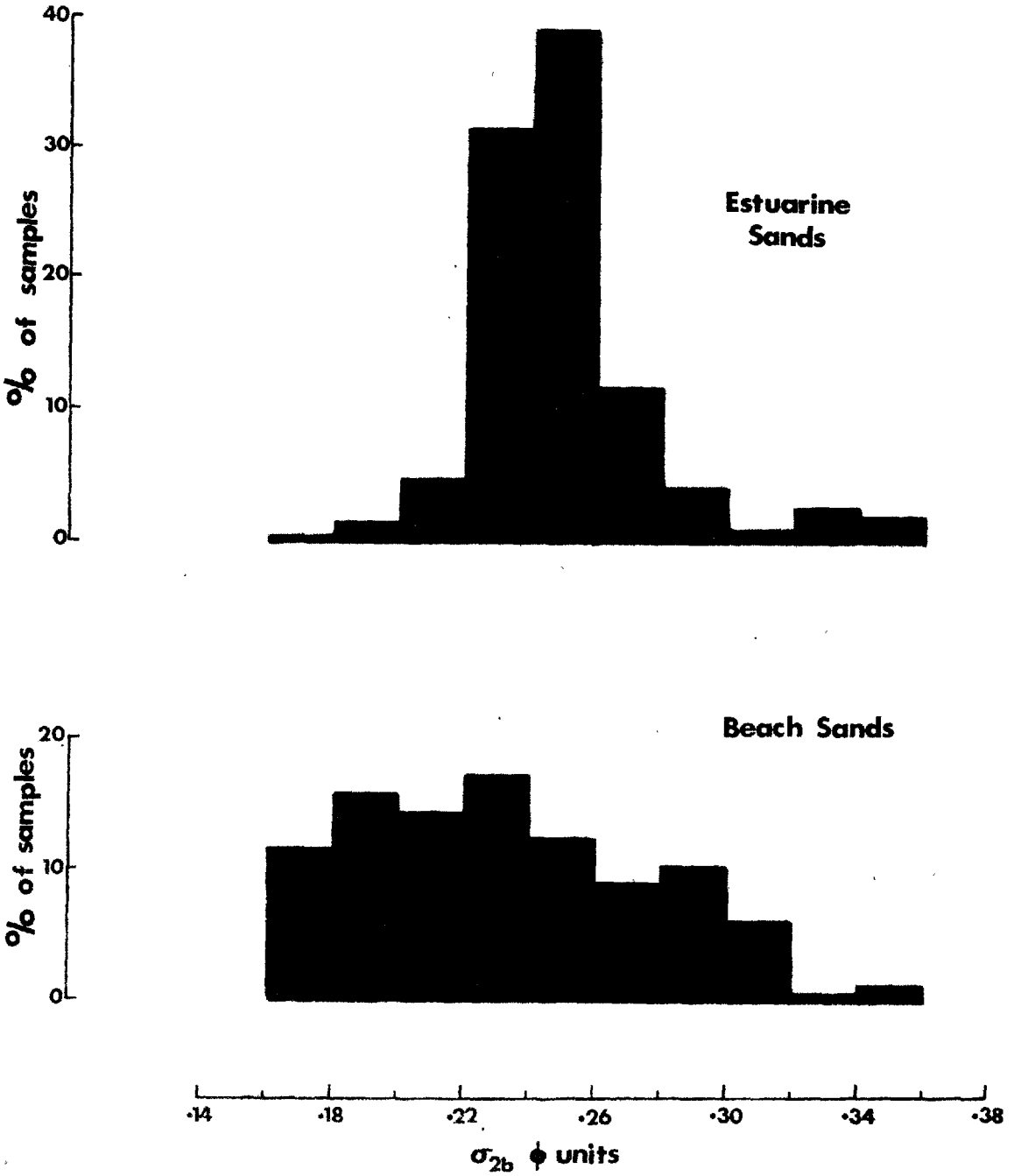


FIG.7.38: COMPARATIVE HISTOGRAMS OF POPULATION 2B STANDARD DEVIATION.

across the foreshore from high to low water marks; the reversing currents on the foreshore therefore show a range of sorting efficiencies, sometimes greater than, occasionally worse than, the currents within the estuary. The frequency distributions of σ_{2A} and σ_{2B} both show abrupt cut-offs at 0.16 ϕ units in the beach samples; hence this must represent the limit of grain selection that can be achieved within the saltating carpets by foreshore currents.

Although there are striking contrasts in these frequency distributions between beach and estuarine sand parameters, they are probably useful only when, as here, the two environments are separated first by other-than-textural criteria; the shapes and properties of individual histograms may also have little significance beyond the Carmarthen Bay realm. In other words, given a mass of data from ancient sediments, it would be virtually impossible to separate beach and estuarine environments by texture alone, and even when this was done it might be difficult to firmly decide which group of data represented the beach, which the estuarine, environment. The histograms thus suffer limitations similar to those of the scatter plots.

Finally, frequency histograms are compared between beach and estuarine sands for the composite graphical parameters. These are shown in Figs. 7.39 - 7.42. The complementary nature of the distributions of composite mean grain size, M_Z, is very apparent.

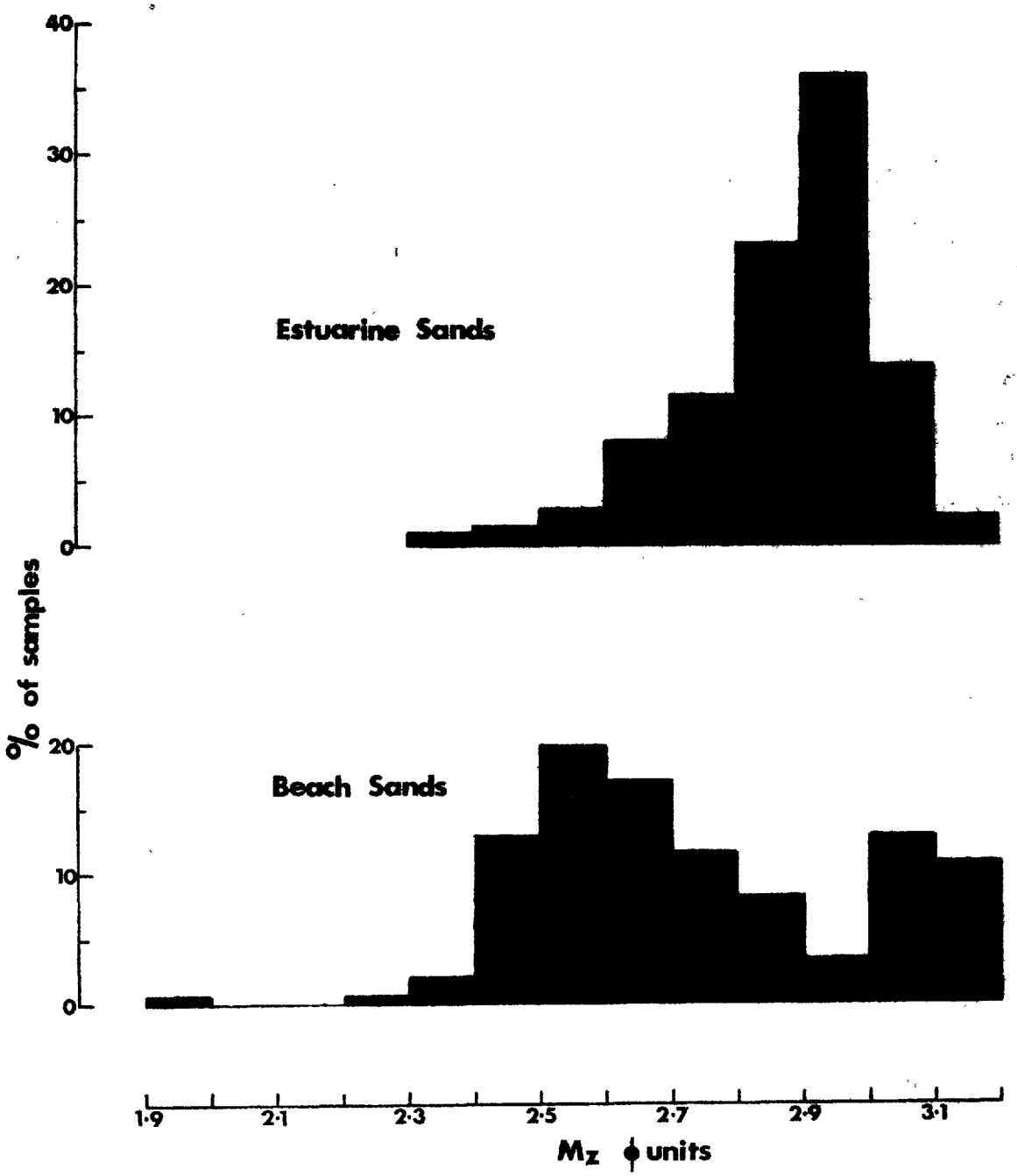


FIG.7.39: COMPARATIVE HISTOGRAMS OF COMPOSITE MEAN GRAINSIZE.

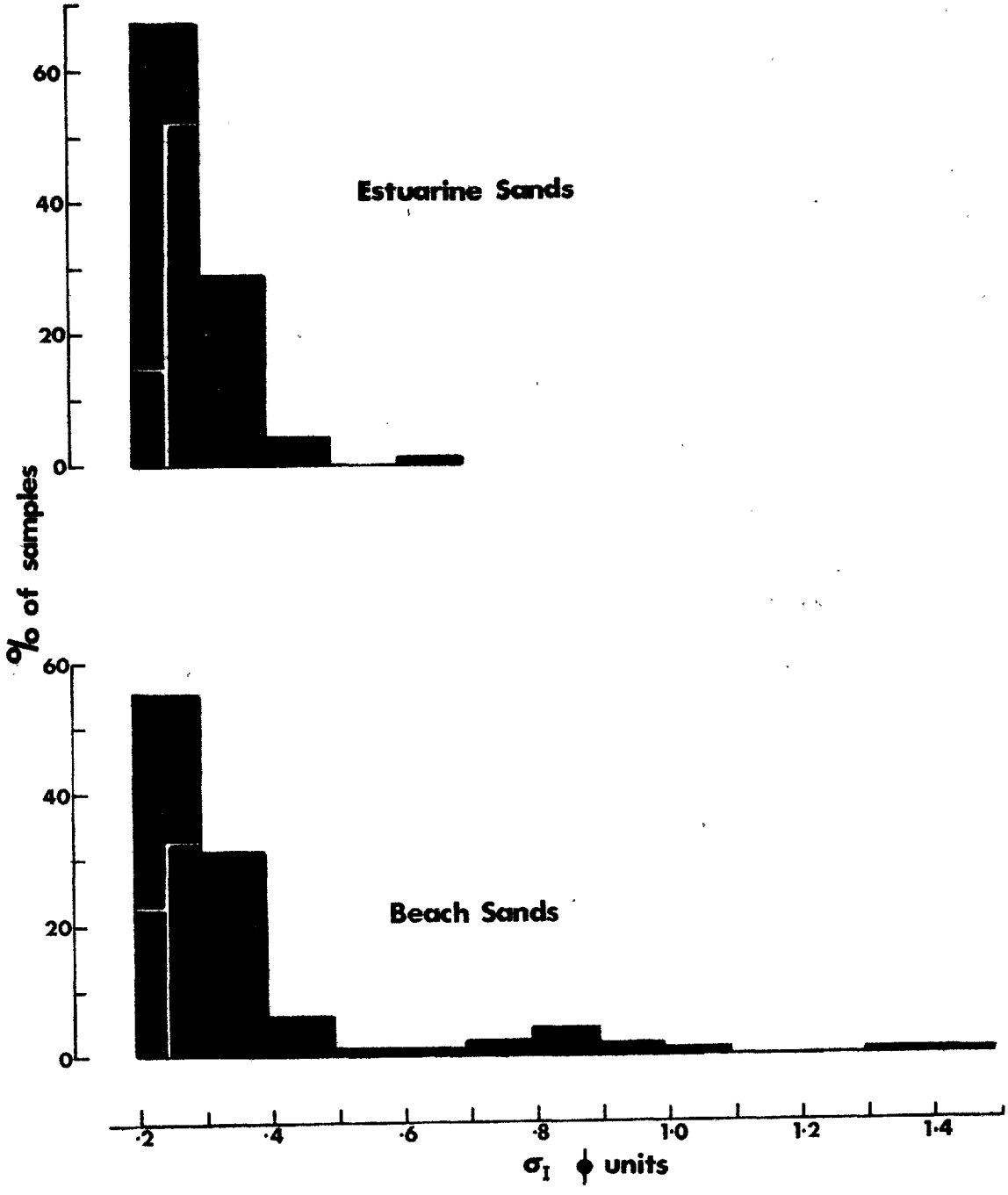


FIG.7.40: COMPARATIVE HISTOGRAMS OF COMPOSITE STANDARD DEVIATION.

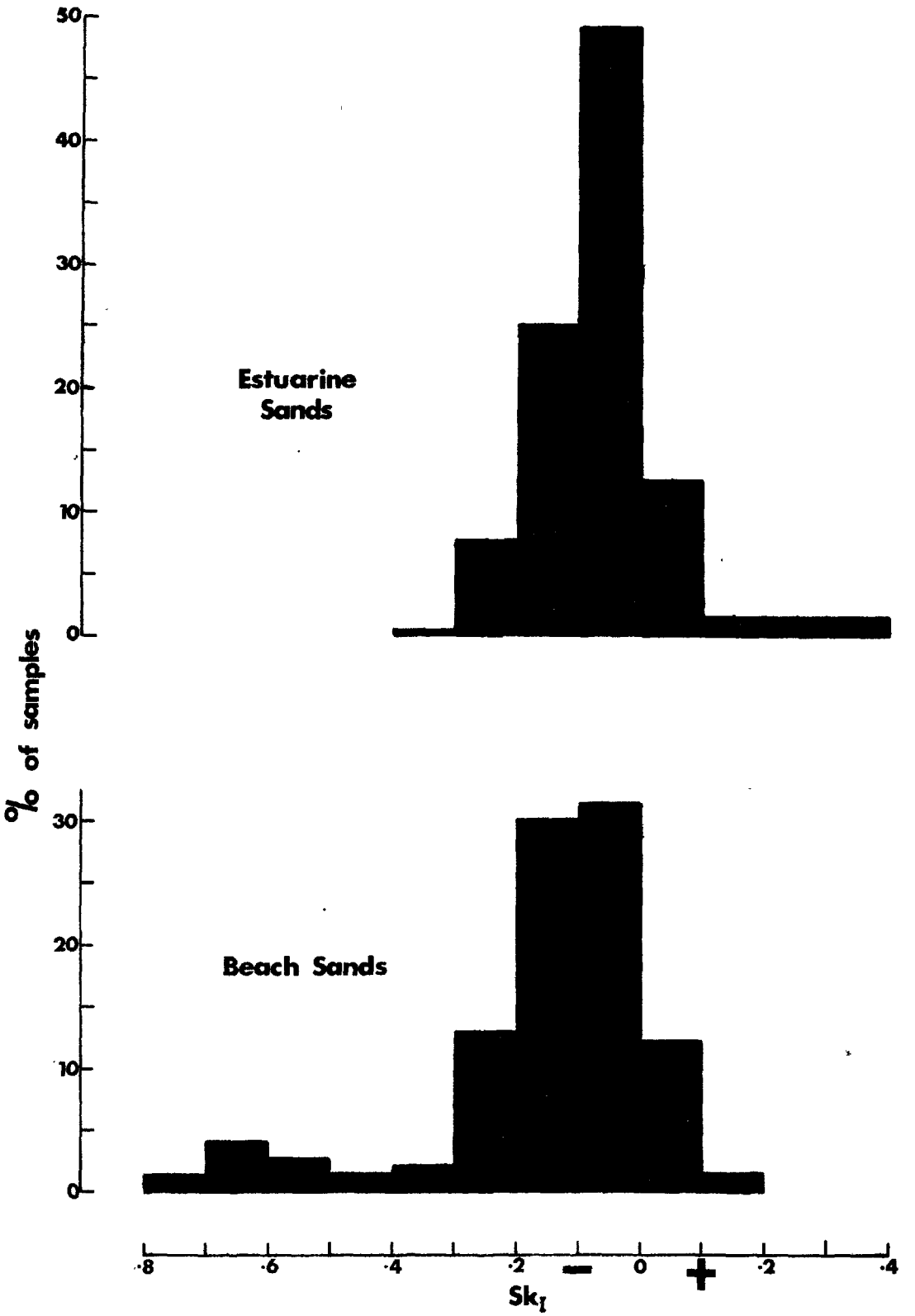


FIG.7.41: COMPARATIVE HISTOGRAMS OF COMPOSITE SKEWNESS.

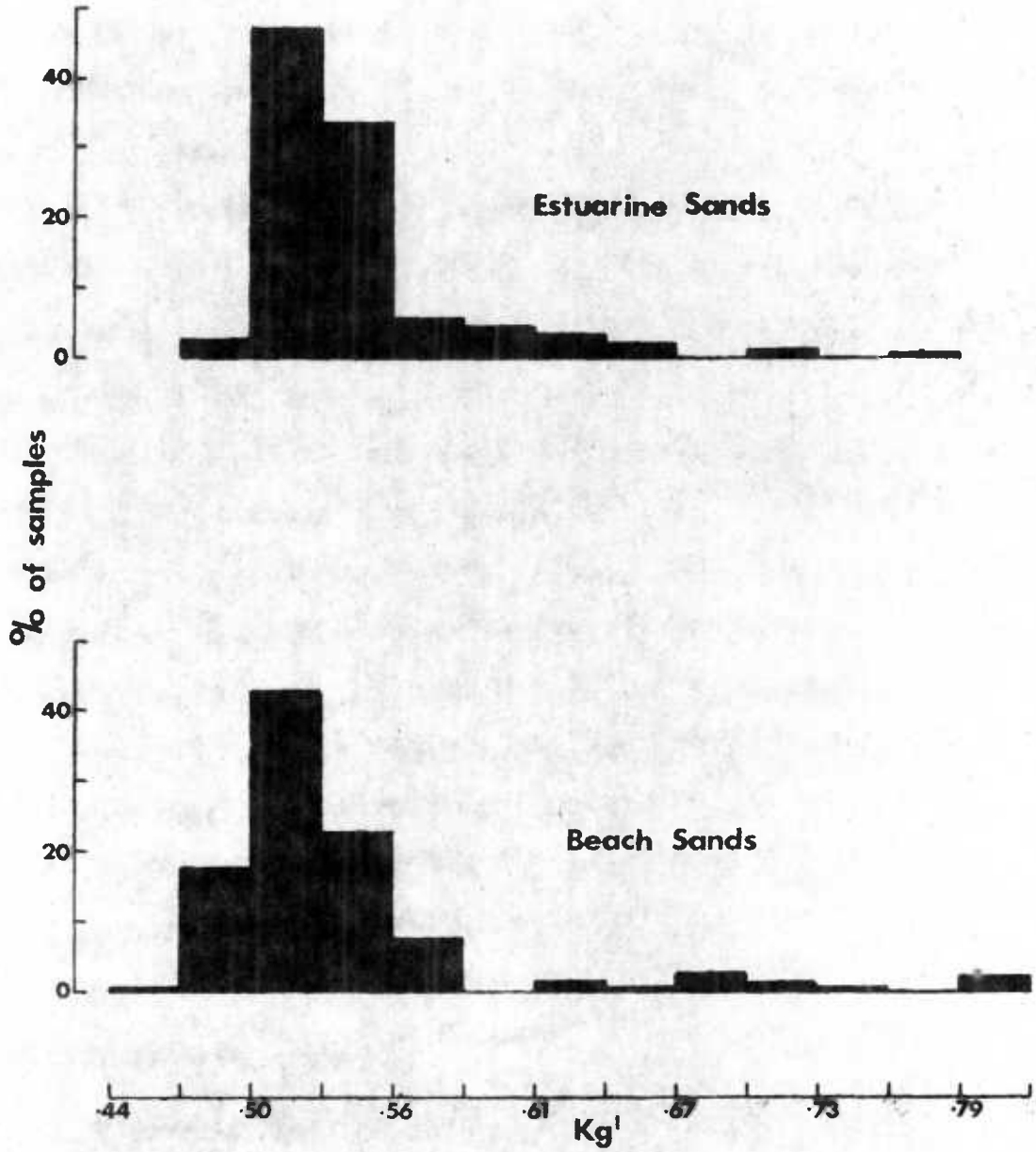


FIG. 7.42: COMPARATIVE HISTOGRAMS OF COMPOSITE KURTOSIS.

This has already been commented upon in terms of the individual saltation population parameters. Here, M_z represents an average measure of hydrodynamic competency, inclusive of mineralogical and hydraulic variations of the constituent grains; it is predominantly an average measure of the mean grain sizes of the saltation populations.

The distributions of the sorting coefficient, σ_I, are very similar, that of the beach sands having a pronounced tail of poorly sorted values; otherwise there is no great difference, even when the class limits are reduced.

Beach sands occur with greater negative skewness than do estuarine sands because of the surface creep traction clogs at mid-tide levels of the foreshore; estuarine sands are a little more prone to positive skewness near the mud flats.

Similarly, beach sands are more often on the platykurtic side (just) of normality than are estuarine sands, but they also show more extreme values of leptokurtosis.

These distributions add nothing to the discussion, but may be useful because of their brevity and compactness.

7.7 Summary and Conclusions

It has been shown that the sediments of the Taf estuary are composed of three or four subcomponents. Of these, a quartzose saltation population is predominant on the open sand flats; a

suspension population is subdominant or predominant on the mud flats and saltmarsh. A subordinate, shelly saltation population and a coarser, shelly surface creep population are present, but generally as minor admixtures only.

The open sand flats compose the major subenvironment of the estuary, and its most dynamic unit. Fast currents and strong turbulence, as well as winnowing by waves, ensure that suspended grains are rejected by the mobile beds of both banks and channels, so that a fine grained suspension population is barely represented in the sandy deposits. The major component of the deposits, a fine grained saltation population, is distinctively uniform in its textural characteristics, there being no great differentiation between banks and channels. Such differentiation as does exist supports the view that currents rather than waves are the primary agent of sand transport within the estuary, since there is a slight coarsening of texture towards the channels, particularly on the channel margins where the fastest currents and greatest turbulence occur on both flood and ebb tides. Wave action is influential locally, affecting the texture of some of the higher banks; its effect is undoubtedly of greater importance during stormy weather. Some differentiation between banks and channels also occurs in the distributions of the coarser saltation and surface creep population, ebb tide concentration of water flow in the channels producing a parallel concentration of the shelly, more angular, grains. Since

these concentrations are also somewhat random, the major ebb streams must fluctuate in position during the tidal phase. The overall longitudinal variation of texture within the sand flats is notable, but also small; the saltation populations fine landward as the tidal currents and turbulence diminish.

Marginal to the sand flats, the suspension population increases in frequency across the mud flats and saltmarsh, becoming exclusive on the higher marsh. This follows from the reduction of tidal energy towards the estuarine margins, as both currents and turbulence are reduced. Silt and clay-size grains are deposited in increasing quantities. This process is encouraged by flocculation and compaction, and by the cover of vegetation on the marsh. Within the saltmarsh, creeks are distinguished by an increased lag deposit of shelly grains (derived from estuarine animals) and by a greater intrusion of saltating grains from the sand flats.

Both texturally and mineralogically, the estuarine sand flats offer an unbroken continuation of the sublittoral and foreshore sands. They are quite different in both respects from the fluviatile sediments, which are predominantly much coarser. Because of the contemporary influx of sand into the estuary; the homogeneity of this sand, composed predominantly of a small range of grain sizes; the absence of sands within the critical size grades in the fluviatile sediment; their presence, in significantly high proportions, in Carmarthen Bay : there can be no doubt that the

bay is acting as the major source of the material that is building up the sand flats.

That the nearshore and estuarine environments are linked by a critical dynamic equilibrium is demonstrated by the strikingly complementary nature of beach and estuarine sand textures. The size grades of the saltation populations most abundant in the estuary are those that are least abundant on the foreshore. There would appear to be a certain spectrum of energy distributed from bay to estuary, with the appropriate grain-sizes acting as tangible markers within the bottom sediment. This spectrum is formed by a complex series of dynamic equilibria which may be in constant flux (within unknown limits) so that the energy balance is always readjusting to any independent, outside source of change. At present, meteorological processes are able to act upon an imbalance created by a rising sea-level relative to the land surface. Westerly gales enable sand to infill the estuary as a result. The actual mechanism is complex and beyond the comprehension of the writer after such a short-term investigation and with limited data. There must be many feedback mechanisms operating between waves and currents, sand sorting, foreshore profiles, estuarine channel configuration, and offshore bathymetry. Although at any given time, the spectrum of energy, and therefore sand textures, is a continuum from nearshore to estuary, the equilibrium is itself not fixed. Therefore, there may be some change in the character of

the intruding sand textures within the estuary as conditions alter; a few subsequent samples taken after the major sampling operation suggest that any such change is of minor importance. This implies some unknown sorting mechanism within Carmarthen Bay, whereby sand grains of limited size range only are moved into the estuary, regardless of meteorological energy (above a critical transporting value), even though both finer and coarser grains are available. Sand available for estuarine intrusion consists of those grain sizes which are not in equilibrium elsewhere, either in the shallow bay, on the offshore bars or on the exposed foreshore. The equilibrium that exists at any moment is the one established by the previous critical transporting process - probably the previous gale. It is the unusual, rather than the prevailing meteorological processes that are responsible for establishing the pattern of sand dispersal, and it may be for this reason that the intruding estuarine sand is of a limited textural range. During storms, fine grained sand (some released from the foreshore) moves offshore into the comparatively low energy region of Carmarthen Bay (west), coarser sand is concentrated into the offshore barriers, and sand of intermediate grain size is channelled into the estuary. It is possible that preferential selection of certain grain size grades for estuarine transport occurs because there is a surfeit of these in the offshore sands, or because these are the most readily transportable by water movements (whatever their strength).

It should be pointed out that the term 'equilibrium', cited often here, is not used in the sense of physical stability and non-deposition often implied by stratigrapher's usage. Here it has been adopted as a description of a state, or condition, of energy. The dynamic condition of the study region is best conceived as one of nice energy balance which must be continually compensating for a slow lowering of the land surface. Although in equilibrium, changes occur and estuarine deposition proceeds, because the axis (or axes) of energy balance is in (probably spasmodic) flux. As the land is lowered an energy imbalance is created and when this reaches a critical condition, the elements which compose the dynamic unit (a conceptual one which cannot have much physical reality) are readjusted to comply with a new state of equilibrium.

It is difficult to project the character of estuarine intrusion into the future, supposing that the present-day lowering of the land surface is continued. Such a projection could be attempted only if a detailed knowledge of offshore sediment distribution and origin was available.

CHAPTER 8.

CONCLUSIONS

8.1 Summary

An attempt has been made to determine the dynamic processes that have produced, and continue to modify, the coastal barrier and estuarine complex fringing the northern part of Carmarthen Bay. Because of the nature of these complex processes, and because of the limitations inherent in the present study (both in its scope and application), the results presented here must be considered as incomplete and the conclusions as tentative.

Although some efforts have been made in recording the periodic (or rather, continuous) fluctuations in the volumes of both coastal barrier and estuarine complex, it must be acknowledged that they are probably not justified in the light of the limited information produced; on the other hand, some useful experience has been gained from the exercise should opportunities arise for further study of the area.

As all surveys of beach profiles were carried out during spring tides, no information is available on the importance of tidal variation in establishing beach morphology. But it has been shown that meteorological processes were instrumental in promoting small, but measureable, changes in the heights and, to a lesser extent, shapes

of the beach profiles. In terms of vertical change, the estuary profiles were less stable than those of the beach, and these too can be attributed to meteorological processes, although there is some evidence that tidal action produces a periodic influx of sand during spring tides and a seaward flushing of sand during neaps.

The beach was least stable near Pendine, in the west, and towards Ginst Point, in the east. This is, in part, the result of offshore bathymetric control since in both areas the existence of comparatively deep water nearshore allows for a greater landward penetration of wave energy. However, the nature of offshore bathymetry is itself controlled by other factors, both meteorological and fluvial. It has been shown that westerly processes of winds and waves, particularly those generated by oceanic storms, were the prime movers of sediment entrainment and transport. Inevitably, therefore, the most westerly part of the coastal barrier is most exposed to such processes and most prone to instability. The concentration of wave energy round the rocky headland at Pendine probably encourages this. In the east, the nearshore deep water is produced by the outflowing waters from the Taf which have carved a channel between the exposed foreshore and the periodically exposed sandbanks offshore; the latter are also probably promoted by westerly meteorological processes. The occurrence, and persistence, of these offshore bars, which are only the exposed portion of an extensive shoaling at the confluence of the outflows of the Taf,

Towy and Gwendraeth estuaries, indicates a significant surfeit of sand in that part of the bay. This is also suggested by the formation of a ridge and runnel system on the foreshore, at the point where the strandline changes orientation.

This system was always present during the period of study, but was susceptible to the effect of large waves during storms, to which processes it probably owes its formation. The mobility of the foreshore ridge is undoubtedly matched by a mobility of the offshore bars, but no information is available for the sublittoral.

Because of these effects, the profiles in the west generally responded to change as homogeneous units, while those in the east were most unstable on their lower portions due to the influence of the Taf channel and, locally, the ridge and runnel system. Above the mean high water mark of spring tides, most profiles showed slightly increased instability due to the effect of aeolian activity on the usually dry beachface, and to the proximity of the dunes.

The most pronounced changes could be related to westerly meteorological processes and, in particular, to south-westerly gales, which are most frequent in the winter months. At other times, and during calm weather conditions, some of the eroded sand returned to the foreshore.

Near Ginst Point, both onshore and offshore processes produced erosion, the former resulting from winds and waves from the bay, the latter from winds and waves generated in the estuary.

Littoral drift occurred in the east in response to Taf discharge during the winter months, this movement being from east to west, and confined to the lower foreshore (and probably sublittoral). A periodic, and compensating, eastwards drift in response to prevailing westerly vectors was also noted on most parts of the foreshore.

The influence of southwesterly storms, particularly when coincident with high spring tides, was shown by the summer time accretion and winter erosion of the uppermost foreshores of the western profiles. However, the dunes in the west were stable during the period of study, whilst those in the east were more variable, apparently in response to alongshore winds for the most part, but this variation was not consistent.

Within the estuary, the most unstable area (in terms of vertical change) was that round Ginst Point and the estuary mouth. This can be attributed to the proximity of the bay and the comparatively greater influence of both tidal and meteorological processes. Local instability was also pronounced at Laugharne because of the tortuous shape of the overall estuarine configuration.

Meteorological processes accounted for much of this instability. At the estuary mouth, prevailing onshore winds were associated with sand accumulation; sand was then periodically moved into the inner estuary by westerly processes, and, in particular, by westerly storm waves. As a result, there was a highly significant net influx of sand during the period of study.

Both westerly and easterly meteorological processes brought about redistributions of sand within the estuary, between its inner and outer portions, by modifying estuarine circulation. Westerlies encouraged accretion in the middle and upper estuaries, erosion in the lower; easterlies tended to reverse this process. Westerly winds and waves of local origin were associated with a resultant loss of sediment, easterlies with a resultant gain. However, westerly storm waves produced a net accretion.

River flow was apparently insignificant in its influence on sand movement, although it did cause local instability, where the main channel was curved, as off Laugharne. However, river flow is probably critical in its interaction with the more dominant processes; the most areally consistent accumulation of sand occurred when low river flows coincided with a high frequency of westerly and onshore winds and waves.

It has been postulated, largely by statistical prediction, that there was a net mean influx of sand of 0.11 metres per year during the period of study due to meteorological processes (in conjunction with the necessary tidal action), and perhaps half as much again due to unconsidered processes. This movement occurred at the greatest rate during the period September - April, a reversed, but smaller, resultant movement occurring at other times. An increased influx of sand also probably occurred during spring tides. Whether or not these landward movements can be correlated with apparently

converse seaward movements off the foreshore has yet to be determined quantitatively, but there appears to be some correspondence between them, as described in Chapter 4.

No data on offshore hydrography was collected, but some efforts were made to describe estuarine hydrography. The character of estuarine circulation is reflected by the lateral variation of sand stability as well as by the distribution of sand textures. The most important features of the circulation in this respect are the very fast currents and intense turbulence produced by the early flood tide and to a lesser extent by the late ebb tide. The former are linked with the markedly asymmetrical tidal wave produced by the offshore shoals and bars, the latter with the concentration of the tidal stream into separate channels as the estuarine sandflats emerge. Because there is a tendency for the early flood surge to avoid the still ebbing flow in the main channel, the greatest instability of the estuarine sandflats is situated in those areas adjacent to the main channel.

The turbulence generated by the flood surge maintains a high degree of vertical mixing through most of the tidal cycle except during neap tides, calm weather and high river flows; when the latter conditions coincide then marked vertical salinity stratification can occur, as well as some lateral gradient, both of velocity and salinity, as a result of the geostrophic effect.

Generally however, the circulation may be described as

laterally homogeneous with moderate or poor vertical stratification. The vital processes are tidal control of horizontal advection and vertical diffusion as a result of turbulence induced by bottom friction, eddying and wind wave surface drag. At times this circulation can become modified to one of partial vertical stratification with some lateral variation.

The textural characteristics of beach and estuarine sands have been examined in detail. Less attention has been paid to dune sands, sublittoral sands, estuarine muds and fluvial gravels, but a few samples of each have been examined. Using a procedure of graphical dissection of heterogeneous distributions first developed by zoologists, it has been possible to recognise that most samples consisted of several discreet and near-lognormal subpopulations. These have been related to the distinct hydrodynamic processes of surface creep, saltation and suspension.

On the foreshore, these subpopulations are distributed in a manner which clearly indicates that the critical zones of sorting which establish the exposed, low water sand distributions are the swash and collision zones. Two saltation populations are invariably present in the beach sands, and these may result from dual sedimentation by swash and backwash currents or they may represent preferential sorting within the swash and collision zones of rounded detrital grains and angular organic grains. Since the two saltation populations are also present in the estuarine sands, the

latter process is probably the most important, although on the foreshore it appears that a combination of both processes may be in operation.

At mid-tide levels, particularly on the western sands, significant proportions of a surface creep population occur. This is composed predominantly of shelly fragments derived from the marine benthos, but it also contains a small proportion of lithic grains.

A fourth population, composing a small proportion of the total surficial sand, also occurs in increased proportions near high-water mark, and to a lesser extent near low-water mark. This is a suspension population which contains a significant proportion of heavy minerals.

The textural gradient across the exposed, low water foreshore profile is a seaward fining one in the two major saltation populations, but this is masked in the composite populations by the mid-tide level concentrations of the surface creep population. The gradient, which may be a diagnostic feature of many such beaches, is intimately related to the concave-upwards shape of most of the beach profiles which permits increased swash zone velocities at higher stages of the tide. Because of the shallow depths of Carmarthen Bay, nearshore wave energy must be at a minimum at low tide, increasing to a maximum near high tide. It is this energy profile which forms the concave-upwards shape of the beach profiles; the effect is both enhanced and complicated in the eastern area by

the presence of the offshore bars which are periodically emergent. However, this wave energy profile is not directly responsible for the seaward fining textural gradient, but certainly aids a parallel velocity profile developed in the swash zone, and it is the latter which fixes the textural gradient.

Several factors may be operative in creating the mid-tide level concentrations of the surface creep population. Postulated maxima of tidal current velocities halfway through both flood and ebb phases of the tide have not been examined in detail and may have been underestimated in importance; only direct hydrographic measurements in the bay can confirm their existence. For the present, it is assumed that the shelly concentrations are formed from a combination of conflicting trends; a seaward decreasing trend of surf zone shear stresses; a seaward fining trend of the saltating carpet which enables surface creep grains to be more readily moved on the lower foreshore than on the upper. Gravity may also be a crucial factor, and the increased bottom slope associated with the Taf channel may explain the low frequency of this population in the east; but it also appears that the increased foreshore wave energy in that area, also due to the deep water of the Taf channel, converts the surface creep population into the organic saltation population by eroding the larger shelly fragments to smaller grains (on the other hand, the greater frequency of the smaller organic grains, and lower frequency of the larger ones, may indicate that

the marine benthos is less developed in the east where the bottom is less stable).

In most respects, there is no longshore variation of texture in the western sands; only the surface creep population shows any variation, occurring with the greatest frequency at Pendine where nearshore wave action (from the southwest) is greatest (see above). On the eastern sands, the saltation populations are coarser than in the west because of the increased wave energy created by the deepwater of the Taf channel.

Dune sands and upper foreshore sands are texturally identical, both being deposited by unidirectional currents, so that they consist of one saltation population only. Upper foreshore sands may have a greater proportion of the suspension population.

Like the beach sands, the sands of the estuarine sand flats are composed of two saltation populations, but with minor admixtures of both surface creep and suspension populations. The major saltation population is virtually texturally homogeneous throughout the estuary. Small lateral variations that do occur tend to produce a slight coarsening of grainsize towards the channels, particularly on the channel margins, where the fastest currents and greatest turbulence are developed. There is also a small longitudinal variation, with a slight fining of grainsize landwards, as tidal currents gradually diminish. Sedimentation therefore responds to current rather than wave action, although the latter is effective

on some shoals, and may be more important during stormy conditions. The subsidiary organic saltation population and surface creep population tend to occur in greater concentrations in the channels, but they are also apparently randomly distributed, probably because of the mobility of the main channels during the tidal cycle.

The suspension population becomes dominant on the marginal mud flats and low marsh, and exclusive on the high marsh where currents are reduced and turbulence absent.

Both texturally and mineralogically, the estuarine sands are similar to the sands of Carmarthen Bay, but quite different from the sediments of the River Taf and its tributaries. On textural grounds alone, it has been demonstrated that the bay has been, and continues to be, the primary source of estuarine sand.

It is suggested that the present study has been to some extent successful in presenting a qualitative picture of the dynamic milieu of the study area. A satisfactory understanding of its nature and mechanism must await more comprehensive quantitative work. For the moment, there is good evidence to show that the separation of the nearshore and estuarine zone into two or more physiographic units, while convenient, is nevertheless artificial since they represent only facets of a dynamic continuum; for this reason, the coastal barrier and estuarine complex are best considered as physical manifestations of energy rather than as physiographic entities. Unfortunately, the lack of information on the energy characteristics

existent in Carmarthen Bay is a serious handicap in presenting a synthesis of the present-day energy spectrum; indeed these characteristics are probably of greater importance in a genetic sense that those of either the coastal barrier or the estuary.

For this reason, it is impossible to portray the exact nature of the energy continuum from beach to estuary, or to comment on the undoubted flux of certain dynamic equilibria between them. It has been shown that there was a considerable movement of sand, of limited grain-size, into the estuary during the period of study. There is some evidence that there may have been a comparable movement of sand off the foreshore. Even if this was the case, however, the two volumes of sand cannot be one and the same because of the discrepancy of texture between them; the grainsize range most abundant in the estuary is comparatively infrequent on the foreshore (and was at the beginning of the study period when beach sampling was carried out). Rather, these sand movements were separate, though related, physical responses to a flux of dynamic equilibrium initiated by a continuing present-day rise of sea level relative to the land, and brought about by meteorological processes, principally winds and waves associated with oceanic storms from the southwest. It may be convenient to think of two constituents of the overall energy continuum in this context; a dynamic equilibrium between coastal barrier and bay, and another between estuary and bay; the beach and estuary being connected only through

the energy sink of the bay in which the principal energy crises are resolved.

Certainly, during much of the present century, the estuary has been infilling. There is little evidence to suggest a continuous erosion of the coastal barrier. Obviously the beach/bay dynamic equilibrium is not quantitatively identical to the estuary/bay equilibrium, so that a periodic adjustment of the one need not be matched by a comparable flux of the other. The immediate, and historical, source of the estuarine sand is Carmarthen Bay, and in historical terms the coastal barrier must have drawn upon the same source. Having built up the coastal barrier, the forces of change are now infilling the estuary, using a carefully selected grade of sediment for each purpose (a range of size grades have been adopted for the beach, but each grade responds to certain energy conditions pertaining at the place of deposition). This switching of priorities may be because the beach/bay equilibrium has been settled before the estuary/bay equilibrium; or because of a change in the axes of energy imbalance in the area (such as a differential downwarping of the land); or more probably because the infilling of the estuary could begin only after a surfeit of sand had accumulated in the nearshore zone (principally by southwesterly gales moving sand to the north-east) by which means accumulation of the coastal barrier was essentially complete.

This does not mean that the coastal barrier is immobile (this

would imply a misunderstanding of the term 'equilibrium'). Small-scale volumetric changes were monitored during the study period, and these were probably accompanied by textural changes within the deposited sand. Historically, too, there is evidence to show that the prograding of the barrier was not continuous, but periodic. Obviously the adjustment of energy equilibria occurred spasmodically, either in response to unusually prolonged stormy conditions or as a result of a spasmodic, rather than continuous, changes of relative sea-level. At present the coastal barrier may be comparatively stable, responding to meteorological processes within a strictly limited range of variation. On the other hand, the estuary appears to be still infilling; certainly the sand within the estuary is not immobile, and considerable mixing and transport accompanies every tidal influx. Because the competence (theoretical) of the estuarine currents exceeds the modern sand bed-load, sand entrainment within the estuary is accomplished with ease and the bed-load, and channel configuration, are correspondingly unstable. Coarser sand is available for intrusion (on the offshore bars, or barriers), and landward transport of these size-grades may be the next stage of energy adjustment. Future developments however depend not only on the current estuary/bay imbalance (if it exists) but also on future meteorological trends, as well as on the continuation of the present-day lowering of the land. A critical limitation may also be introduced by the availability of sand in the bay (see below).

8.2 Limitations of the Study

Many of the limitations inherent in the present study programme have been discussed in earlier chapters. Some of these were encountered as a result of inappropriate techniques and were probably unavoidable; others resulted from unsatisfactory forethought as to the aims and scope of the programme. To some extent such errors are inevitable in any field study.

Criticisms offered here are primarily intended as a subjective guide to assist other students working in the Carmarthen Bay, or similar, area, so that the mistakes made in the present study may have some creative application:

1. The study area should have included some part of Carmarthen Bay itself since the physical responses observed on the coastal barrier and estuarine complex depend primarily on the process/response interaction developed in the bay.

2. Surveying of both beach and estuary profiles should have been rigorously controlled to avoid otherwise inevitable errors. Probably this would necessitate closer spacing of transects, at least for a short period, so as to ascertain among-profile variations and to determine just how representative of real volumetric change the measured profiles can be. In this way, a useful idea of an optimum number of transects could be gained and the techniques, or scope, of the surveying programme adjusted accordingly.

3. Possibly more useful data would have been provided by an intensive monitoring of one or more transects over a short period, surveying on every, or alternate, tides.

4. The use of a micropticlevel and staff is probably not the most efficient surveying technique because it is both time consuming and requires two operators. Some simple device is needed to enable the operation to be carried out accurately and speedily; a development of a method using subsurface plates detected by electrical means suggests itself, although it would be inappropriate for work in the estuary where temporal vertical variations are large. On the foreshore, for most profiles, markers need be not less than 100 feet apart.

5. Greater ease of measurement would then facilitate more frequent monitoring of profiles and provide replication of data in order to determine within-profile variation. In the present study it was unknown whether a measured profile was representative of a 'seasonal' or 'daily' position. Replication of surveys over several days would help to resolve this dilemma.

6. Whenever possible, beach surveys should extend below the low-water mark.

7. Monitoring of volumetric changes is useless unless accompanied by simultaneous observations of nearshore process elements - winds and waves - which should then be correlated with the regional meteorological data collected by local observation posts, so as to

provide a continuous record of meteorological processes in the nearshore zone.

8. Understanding of sediment transport, particularly in the estuary, would be greatly enhanced by the surveying of transects at high, as well as at low, tide.

9. Current measurements in the bay are important, but because of practical difficulties of boat application, they were not attempted here. Hydrographic measurements in the estuary were taken over a period of 25 hours at the most, and may not be representative of average conditions. This sort of restriction is inevitable but must always be considered.

10. None of the measurements carried out during a period of two years may be typical of long-term trends.

11. Sampling of sediments should have been rigorously controlled according to a statistically random arrangement. The beach sampling array approximated to such an arrangement, the estuarine sampling certainly did not. The large number of samples collected hopefully counterbalanced this shortcoming.

12. More readily comprehensible results would have been obtained if single sedimentation units, as well as composite channel samples, had been collected. Ideally, the depth of disturbance (or rather of deposition) by each tidal cycle should be determined and sampling adjusted to it. The sampling of single sedimentation units alone would probably have failed to pick out the important mid-tide traction clogs.

13. Possibly, sieving is too gross a technique for subtle discernment of sedimentation processes. If the problem of obtaining very small, but representative, subsamples can be solved, then a volumetric counting device, such as the Coulter Counter, may offer an improved alternative technique.

14. The technique of graphical dissection of heterogeneous mixtures adopted by the writer is open to many criticisms, but is considered to be a real improvement on the 'traditional' reliance on composite textural parameters. The distinction between beach and estuarine sand textures (if it exists) is a subtle one and has not been satisfactorily achieved here. However, it is believed that emphasis on sand populations, rather than on perhaps accidental (in terms of sampling) mixtures, offers a fruitful course for future development. Concentration on the morphology of single grains using the electron scanning microscope is most unlikely to enable any distinction to be made between sediment masses as closely, and recently, linked as the beach and estuarine sands studied here.

15. It would be very useful if variations of sediment textures with time had been studied; also the textural distributions at high tide and during tidal phases other than low tide.

16. The absence of any direct assessment of sand transport by waves and currents in the bay, foreshore and estuary is a serious omission in any study professing to an understanding of the dynamics of sedimentation. The observation of grains in suspension can be

attempted with some success, but that of grains in saltation seems to be impossible, unless tracer techniques are adopted; to do this on a comprehensive scale must be a crucial undertaking if the problems of sand dispersion are to be mastered, but that merits a study programme of its own.

17. In this study, attention has been focussed on two aspects of a complex dynamic environment. Whether or not concentration on volumetric changes and sediment textures represents the best choice of priorities is a mute point; with the hindsight afforded by the fruits of this choice, it must be acknowledged that more useful results would have followed from a broader-based sedimentological approach. Studies of sediment mineralogy and grain shape should have been incorporated.

18. All attempts to bring some order to the collected data have been empirical. No excuses are proffered for this as, at present, the mathematics of sedimentation processes are barely understood (at least by the writer) and the empirical approach becomes productive when a large number of trends have been delineated, so as to afford some measure of comprehension.

8.3 Environmental Implications

Whenever human activities intrude into coastal environments, important, and invariably destructive, consequences follow. Much energy is devoted to the problems of coastal erosion and longshore

drift, the maintenance of harbour entrances, the stabilising of dunes. Recently there has been a long overdue recognition of the biological reaction to chemical pollution of estuaries and oceans, and the far-reaching influence this has on food chains and, ultimately, human life. In order to maintain our overpopulated, industrial societies, some physical deterioration of the coastline and chemical pollution of the oceans must be inevitable. Hopefully, with a growing awareness of the results of such unacceptable trends, and a consensual rejection of their causes, the worst excesses of the past may be avoided in future. Rather than seeking egoistically to control the environment for our own, short-term advantage, we would surely be better advised to pursue a more enlightened course of adaptation to the undeniable physical and biological realities external to, but inherent within, our own existence; especially as our own preservation (in an acceptable world) may ultimately be at stake.

Once destroyed, the fragile constructions of coastal formations, such as intertidal flats, beaches, dunes and estuaries, may never be recreated (within a human time scale). In order to conserve these unique and precious formations, it is vital that future developments on the coastline be conducted with some knowledge of the irreversible consequences. To this end, it is hoped that studies such as the present one may contribute a useful and significant support.

Naturally, such a contribution is non-existent in the absence of any proposed development. Fortunately, at present, no plans exist for any major coastal operations in the Carmarthen Bay area, although some minor adjustments to human activities are perhaps noteworthy.

The most important of these, on the coastal barrier, has been the construction, by the Ministry of Defence, of concrete causeways carrying roads through the dunes onto the foreshore. These have produced significant dune erosion. The first stage of this was observed in the dunes immediately adjacent to, but particularly on the eastern side of, the causeways, and was due, presumably, to the creation of strong eddy currents mainly in the lee of the structures in response to westerly waves coincident with very high spring tides. Subsequent wave action then stripped the exposed dune flank eastwards of the causeways. Initial attempts to halt this erosion were unsuccessful, but the installation of boulder 'breakwaters' in front of the dunes, although visually offensive, appear to have achieved their end. It seems possible from the fluctuating nature of dune progradation in the past, that temporary periods of dune erosion may be a normal response to exceptional meteorological conditions, in which case human interference merely encouraged an inevitable process. However, it is important to realise that the dynamic equilibrium existent on the coastal barrier today may be transitory (so that the dunes may in future

be attacked, or built up, again) and is certainly fragile. Removal of beach sand for various purposes (at one time suggested, and periodically carried out, near Pendine) must result in an immediate wave attack on the dunes; over a long period the foreshore might retain its present level if sufficient sand were available in the offshore zone.

In the estuary, too, human interference has probably speeded up a natural process. The introduction of Spartina townsendii a half-century ago certainly encouraged the growth of the mudflats and salt marsh and its influence must contribute to the eventual silting up of the whole estuary (assuming that present-day tectonic/eustatic trends continue).

The bed of the estuary is far from stable in terms of banks and channels, and even an overall continuance of a recognisable status quo is maintained by a continual circulation of sediment. This circulation would need to be taken into account before any engineering work could be contemplated. Any tampering with such a dynamic environment must have its physical consequences. Dredging of the main channels for purposes of navigation would need to be a continuous process if the dredged material was dumped in Carmarthen Bay since it must immediately be returned by tidal and wave action.

Dredging off the estuary mouth, as has been attempted recently, would increase the flushing activities of the river and help to reverse the present-day infilling of the estuary. However, the

offshore shoals must afford some degree of protection to the estuary and their removal would expose both estuary and dunes near Ginst Point to greater wave attack. Whether or not the infilling of the estuary would then proceed anew, with sand originating from deeper water in Carmarthen Bay, would depend on sand availability.

However, because of the intricately interwoven dependence of the coastal barrier, estuarine complex and nearshore area on the energy spectrum contemplated earlier, the removal of sand from one part of the system may have unexpected repercussions in its other parts.

The writer is not qualified to undertake any prediction of biological reactions to pollution in this area. But it may be pertinent to make a few observations on this theme. The most likely future introduction of industrial and/or domestic waste into the area would be via the estuary. The intense turbulence of the estuarine circulation would ensure maximum mixing of any soluble pollutant, and the daily total flushing of the tidal prism would result in its exclusion from the estuary; obviously, discharge of a particularly toxic or otherwise obnoxious fluid should proceed at high tide only. Estuarine macrofauna being in any case barred from the unstable sand flats, any biological reaction to toxic wastes would there be confined to the meiofauna. On the comparatively quiet saltmarsh, however, a significant increase of toxicity with time may affect the abundant mud-burrowing organisms living in it.

Although flushed from the major part of the estuary, a possible anti-clockwise circulation in the bay might encourage a toxic build up; in which case, the flourishing marine benthos must be affected and the animal populations decline. As yet unpublished work shows that whilst the short life span of the meiofauna enables successful mutants to withstand quite high toxic levels, the macrofauna are not so fortunate, and their numbers immediately decline. The removal of the marine benthos would noticeably affect the appearance of the foreshore, at present littered with animal shells; this would not however be the most serious objection to such an occurrence.

8.4 Geological Implications

An attempt has been made in this study to relate the textural properties of dune, beach and estuarine sediments to their formative hydrodynamic agencies; thence to explain textural variations in the same terms. An application of this type of study then lies in our improved ability to recognise similar process/response relationships in other environments, both ancient and modern, where dynamic processes may be largely, or completely, unknown.

Geologically, this sort of application is viable only if the deposits described here are preserved, and their textural characteristics retained.

Preservation of nearshore and littoral deposits may or may not occur as determined by several factors. These include the rate of

sediment supply, the nature and intensity of nearshore oceanographic and meteorological processes, the width and configuration of the shelf, and the rate and direction of relative sea-level change. Of these, rate of deposition, and rate and direction of relative sea-level change are the two most important (Curray, 1964).

Without direct information on the three-dimensional morphology of the coastal barrier and the nature of the low-lying area landward of the dunes, it is impossible to decide on the mode of formation of either dunes or beach. Howevever, some drilling through the dunes by the Ministry of Defence does provide some data. This shows that the sand deposit extends at least sixty feet below the base of the dunes; no textural data is available and so it is unknown whether this accumulation represents beach, dune, lagoon or bay deposits. However, it does represent a considerable thickness of accumulation. Assuming a persistent post-glacial transgression, we must conclude that the rate of deposition of sand has been comparatively high during that time. With an initial surfeit of sand in the present-day offshore zone (presumably supplied by retreating glaciers), meteorological processes will have been able to transport sand landwards. With a discontinuous depositional transgression, in which the rate of transgression fluctuated, a barrier island formation with a lagoon behind may have developed.

One feature of the data from the drilling programme is noteworthy. In two of the boreholes, a distinctive zone, some six to

fourteen feet thick, was encountered in which the otherwise uniform sand was characterised by a large (25% by weight) concentration of shelly fragments. This occurrence recalls the mid-tide level traction clogs of the present-day foreshore. Moreover, the shelly zone occurs at the same horizon (relative to O.D.) as does the present-day one. If these deposits are one and the same, and there is a continuous shelly zone at this depth, then we may suppose that the mid-tide level of the foreshore has been constant during the period of dune formation (the borehole shelly horizon relates laterally to the inner line of dunes, just as the present-day shelly zone corresponds to the outer). In which case, the deposits of the present-day coastal barrier may be indicative of a depositional regression, deposition and accumulation of sand occurring during a period of relatively stable sea-level with a moderate-to-high rate of deposition. This implies that relative sea-level has not changed much since the building of the dunes during the past two millenium (although there is evidence to suggest that dune formation was not a continuous process). The net loss of sand from the coastal barrier during the period of study would suggest, however, that its seaward growth is at present being halted and reversed, either temporarily or permanently.

Below the dune complex and much of the present-day foreshore, there should be a considerable thickness of beach sand - at least 30 feet if the interpretation of the borehole shelly zone is correct.

A subsequent transgression is unlikely to rework much of this, particularly when associated with an offshore surfeit of sand which should ensure a persistent long-term supply of material for the foreshore and nearshore zones. An erosional transgression can occur only when wave-action intensity is sufficient to effect a negative sediment supply under conditions of relative stability; because of the modification of a dynamic equilibrium between waves and sediments this may be happening today; it would occur at an increased rate only if the rise of the sea-level was rapid enough.

In the event of a regression, erosion of the beach accumulation would result from rapid uplift of the land or relative lowering of the sea if the supply of sediment was low; this is not happening today and would be unusual in a tectonically sluggish area. With a relatively stable sea-level, and a surfeit of available sediment, a depositional regression would occur.

Should the coastal barrier sand body persist, then its recognition as such can be contemplated. In this context, the seaward-fining textural gradient of the saltation populations and the mid-tide level surface creep population become important. The one determines the foreshore aspect, the other determines its height, relative to the sea. Vertical drilling through the coastal barrier should show the same textural sequence as was observed normal to the present-day foreshore; hence a comparable environment among ancient deposits should be recognisable.

The estuary presents rather a different picture. There is no information on the thickness of the present-day deposits, though studies of the Dovey and Mawddach estuaries suggest that this may be considerable. Whether or not all, or some, of the sand accumulation will be preserved will of course depend on future tectonic and eustatic changes. If preserved, then its identification as estuarine will be assisted by its relationship to the saltmarsh deposits. Textural variations within a vertical section of the sand body are unknown. Certainly the marine sand must ultimately rest on fluvial deposits; above these the textural gradient may be an upward-coarsening one as the rising sea-level brought wave action shorewards enabling coarser sands to be transported into the estuary. Alternatively, assuming a constant adjustment of the equilibrium between process and response elements suggested for the coastal barrier, then an infilling of sand with uniform grain-size may have persisted for some time; in which case a vertical section through the sand body would show the same homogeneity of texture as has been noted in the present-day areal variation.

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