I.O.S.

OBSERVATIONS OF THE CHANGES OF INTER-TIDAL BEDFORMS OVER A NEAP-SPRING TIDAL CYCLE

BY

D.N. LANGHORNE, J.O. MALCOLM
AND A.A. READ

REPORT NO. 203
1985

NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF
OCEANOGRAPHIC
SCIENCES

INSTITUTE OF OCEANOGRAPHIC SCIENCES

Wormley, Godalming,
Surrey, GU8 5UB.
(0428 - 79 - 4141)

(Director: Dr. A.S. Laughton FRS)

Bidston Observatory,
Birkenhead,
Merseyside, L43 7RA.
(051 - 653 - 8633)

(Assistant Director: Dr. D.E. Cartwright FRS)

Crossway,
Taunton,
Somerset, TA1 2DW.
(0823 - 86211)

(Assistant Director: M.J. Tucker)

When citing this document in a bibliography the reference should be given as follows:-

LANGHORNE, D.N., MALCOLM, J.O. & READ, A.A. 1985
Observations of the changes of inter-tidal bedforms
over a neap-spring tidal cycle.
Institute of Oceanographic Sciences, Report, No. 203,
101pp.

INSTITUTE OF OCEANOGRAPHIC SCIENCES

TAUNTON

Observations of the changes of inter-tidal bedforms over a neap-spring tidal cycle

by

D.N. Langhorne, J.O. Malcolm
and A.A. Read

I.O.S. Report No. 203

1985

CONTENTS PAGE

LIST OF FIGURES

LIST OF TABLES

LIST OF BOX CORES

BOX CORE NUMBER	DATE (1984)	PREVIOUS HIGH WATER	PAGE
1	15th July	1325	38 - 41
3	16th July	1420	42 - 45
4	16th July	1420	46 - 49
7	19th July	0515	50 - 53
9	20th July	0610	54 - 57
10	20th July	0610	58 - 61
11	21st July	0700	62 - 65
12	21st July	0700	
13	21st July	0700	
14	21st July	0700	66 - 69
15	21st July	0700	
16	21st July	0700	
17	22nd July	0745	70 - 73
18	22nd July	0745	
19	22nd July	0745	

1. INTRODUCTION

Stratigraphy, an important branch of both pure and applied geology, is defined as the study of the character of stratified rocks including their sequence in time and correlation in space (after Whitten and Brooks, 1972).

For the correlation of sedimentary strata in different localities it is necessary to assume that either the sedimentary processes were spatially uniform, or that sufficient is known about the processes and their changes so that different facies may be inter-related. An understanding of the processes leads to an understanding of the depositional environment and this is of considerable importance to geological interpretation. It is considered that all sedimentary structures observed in the geological record are represented by present day processes: "The present is the key to the past". This statement, attributed to James Hutton (1726-1797) clearly indicates the need for an inter-disciplinary approach embracing traditional geology and process orientated sedimentology. Such studies are rare (Terwindt, 1971; Nio, 1976; Terwindt, 1981; Allen, 1982; Van den Berg, 1982; Nio, Siegenthaler and Yang, 1983; Allen and Homewood, 1984) and only a few studies have reported empirical data on internal structures in present day tidal marine bedforms. (Imbrie and Buchanan, 1965; Boersma, 1969; Boersma and Terwindt, 1981 a and b; Langhorne, 1982) and most of these are restricted to the inter-tidal zone.

Examination of structures and sediment grain size gives valuable information about the hydraulic regime in terms of flow direction and flow velocity but, despite its importance, less can be concluded about flow depth. Indeed, are there unequivocal diagnostic differences between inter-tidal and sub-tidal bedforms? Relationships between flow depth and the wavelength and wave-height of bedforms have been proposed by Yalin (1972) and Allen (1982) but the correlations are poor, particularly in the tidal marine environment. For example, sandwaves with wavelengths of up to 1000 m and wave-lengths of up to 25 m occur in water depths of less than 10m (water surface to crest) in Start Bay, Devon (Langhorne, 1982), whilst others with similar wavelengths and wave-heights of up to 15 m occur on the shelf edge in water depths of approximately 150 m. Such contrasting data defy classification based upon morphology alone and the differences in their mode of formation and environment may be shown by their internal structure.

This IOS report presents the results of field studies carried out on a drying bank in the River Taw, Devon. The main objective of the work was to quantify bedform movement and resulting internal structures in relation to known time scales; normally one or two tidal cycles. Using repetitive levelling surveys across the bedforms, when they were exposed at low tide, master bedding could be inferred from cross sectional profiles. These could be verified and the sedimentological structures examined by analysis of carefully positioned box cores. This data, together with detailed knowledge of the flow environment could then be related to observed geological structures. Without such data, by necessity, much geological interpretation has to be based upon inference. Many further studies are required in this complex hydrodynamic/sedimentological environment, whilst parallel studies requiring similar precision of measurement, are needed in the sub-tidal zone. No technique used is considered to be "the ultimate" as all are capable and worthy of further refinement whilst others need to be introduced. This is particularly the case in making significant measurements of the flow field in relation to bedforms.

2. LOCATION

The River Taw is one of the principal rivers of Devon, with a catchment area extending from south-western Exmoor in the north, to northern Dartmoor in the south. It is tidal up to 20 km from the open sea at Bideford Bar. Downstream from Barnstaple, the river broadens to about 750 m as it meanders across its flood plain. Land adjoining the river, once marshy, has been drained and enclosed. The Taw joins the River Torridge 4 km from the sea. Opposite the confluence, a spit of sand and gravel terminating in Crow Point, projects from the north bank and shelters the River Taw from any significant sea-derived wave activity (Figure 1). Crow Point has formed since 1830 but it, together with Braunton Burrows to the north, is actively eroding at present.

Field studies were carried out approximately 2 km upstream from Crow Point; about 500 m above the coaling jetty of East Yelland power station. The site was on the downstream tail of a sandbank, which is approximately 800 m long and 300 m wide at its broadest and situated to the south of the main river channel and separated from the south bank by a secondary channel. Here, there is an area of flood tide dominated, flow-transverse bedforms (sandwaves) with amplitudes of up to 2 m and wavelengths of approximately 25 m, which dry for about 4 hrs at low tide. It was these features which were studied for a period of 13 days from 14th July 1982.

Other, smaller bedforms also occur around the flanks of the sandbank and the orientation of these features suggests that whilst the flood tide is dominant in the secondary channel, the ebb tide is dominant in the main channel. At low water, almost all the river water flows down the main channel.

The bedform orientations, together with the well sorted fine sand composition, tends to suggest that the sand circulates around the bank in an anti-clockwise direction in a virtually self-contained system. On the river banks there are zones of mud and stones but these sediments do not appear to encroach onto the bank. This sedimentary environment is temporarily upset when the river is in spate when it transports large quantities of fine run-off material from the catchment area. For example, heavy thunderstorms occurred in the area immediately before the commencement of this study and ephemeral deposits of fine sediments and organic debris were evident on the bank. At such times the river is capable of carrying larger material such as stones and boulders but none were observed on the bank.

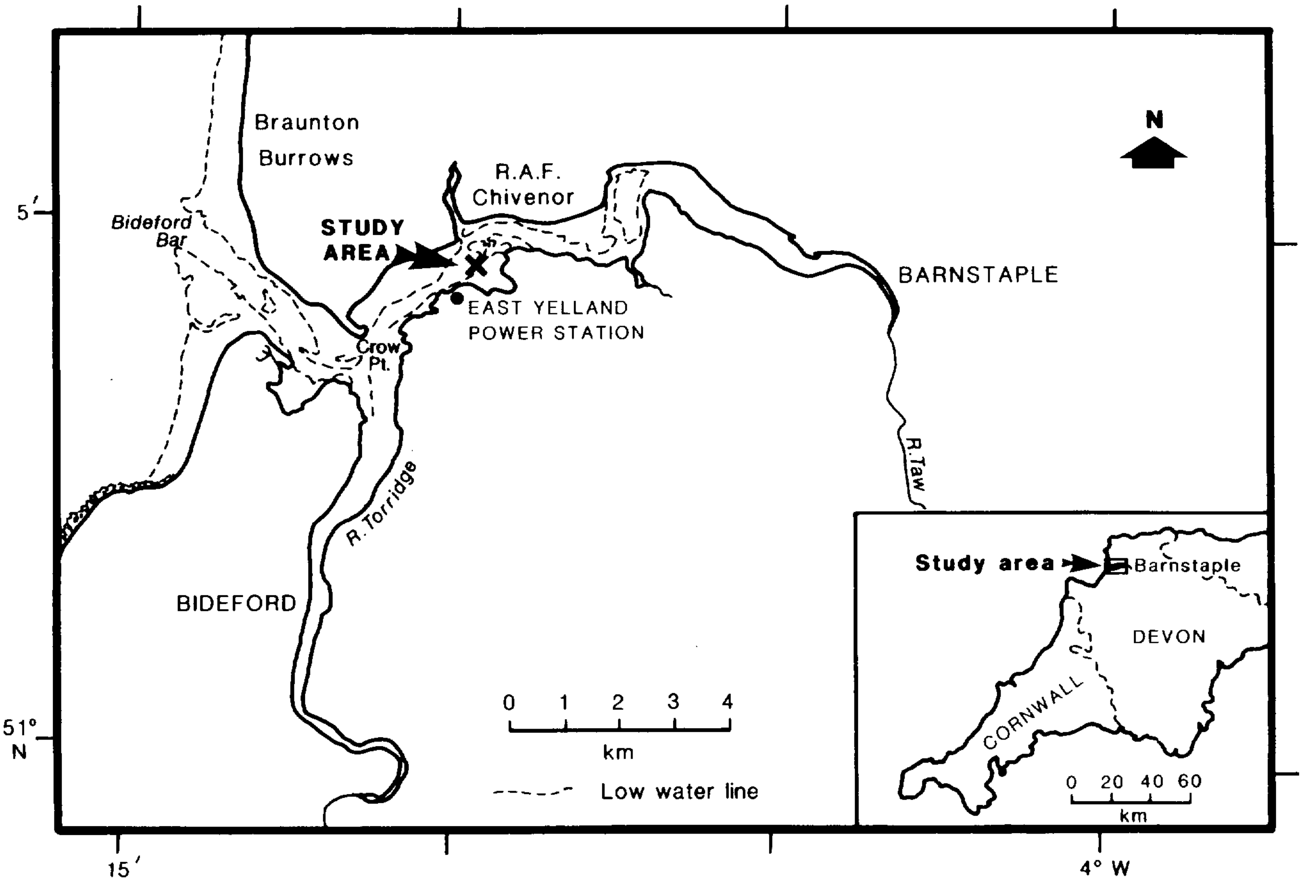


FIGURE 1 Location Map

3. PROCEDURE

A) Three consecutive sandwaves, located approximately in the centre of the bedform area, were chosen for the study. A line of 16 mild-steel reference stakes, spaced at 5 m intervals were levelled in across the sandwaves, perpendicular to their crests. Using the stakes as a permanent reference line, standard levelling techniques were used to obtain profiles of the sandwaves at low tides. Levelling was carried out at a horizontal interval of 1 m along the 75 m reference line to an estimated vertical accuracy of ± 0.5 cm.

B) Along the line of stakes, near to the crest of the central sandwave, a rig of three Braystoke impellor current meters was installed. The rig was designed to allow the instruments to swing freely with the flood and ebb tides. On installation, the impellors were 17 cm, 45 cm and 72 cm above the bed. The spacing of the meters was fixed whilst their position and height above the bed was obtained from the successive low water profiles. A cable, buried in the sand, connected the current meters to a Microdata logger installed in a portable hut located on the river bank.

C) In order to study the temporal and spatial variablity of the surface sediment, samples were taken at 1 m intervals across one sandwave at four low waters between neap and spring tides.

D) Box coring was carried out at seven low waters, in order to examine the internal structure of the sandwaves in relation to known periods of movement.

E) Sand, coloured with fluorescent dye, was inserted into the stoss slope of one sandwave and the dispersion of the tracer was examined at subsequent nocturnal low waters using an ultra-violet lamp.

F) The time of the study was chosen to cover a neap to spring tidal cycle and tidal range data were obtained from the tide gauge located on the coaling stage of the power station. Meteorological data were obtained from the observatory at RAF Chivenor, on the north bank of the river opposite the study site. Further rainfall and river flow data were obtained from the South West Water Authority from their recording stations in the river's catchment area.

4. TIDAL ENVIRONMENT

Minimum neap tides were recorded on the morning of the 15th with a range of 4.3 m, whilst maximum spring tides occurred on the afternoon tide of 22nd with a range of 7.25 m. These values compare with the predicted ranges of 4.3 m and 7.5 m respectively. Reduced tidal ranges were due to increasing atmospheric pressure during the study period. This had the effect of decreasing the level of high water. The low water level is determined by the level of the river water, which is largely unaffected by changes in the atmospheric pressure.

From the tide gauge record, it is apparent that the duration of flood and ebb tides becomes markedly unequal with progression towards spring tides. This is due to the level of the astronomical tide falling below the river level, which is normal for tidal rivers. In extreme cases in certain rivers, such as the River Severn, the rapid rise is shown by the generation of a bore (Doodson and Warburg, 1941).

Figure 2 shows the differences between flood and ebb tides in terms of the rate of change of tidal height as a function of tidal range. The mean flood and ebb rates were calculated by dividing the tidal ranges by the duration of flood and ebb tides. Deviations from the linear relationship are less than the estimated errors in determining the rise and fall rates. The differences between the maximum flood and ebb rates are not as great as is implied by the mean values shown. The absolute rates cannot be used in sediment transport studies because they are not directly related to the differences in flood and ebb velocities which occur in different channels within the estuary. As will be discussed later in this paper, flow velocities were measured in the study area and these are considered in relation to both sediment transport and tidal range.

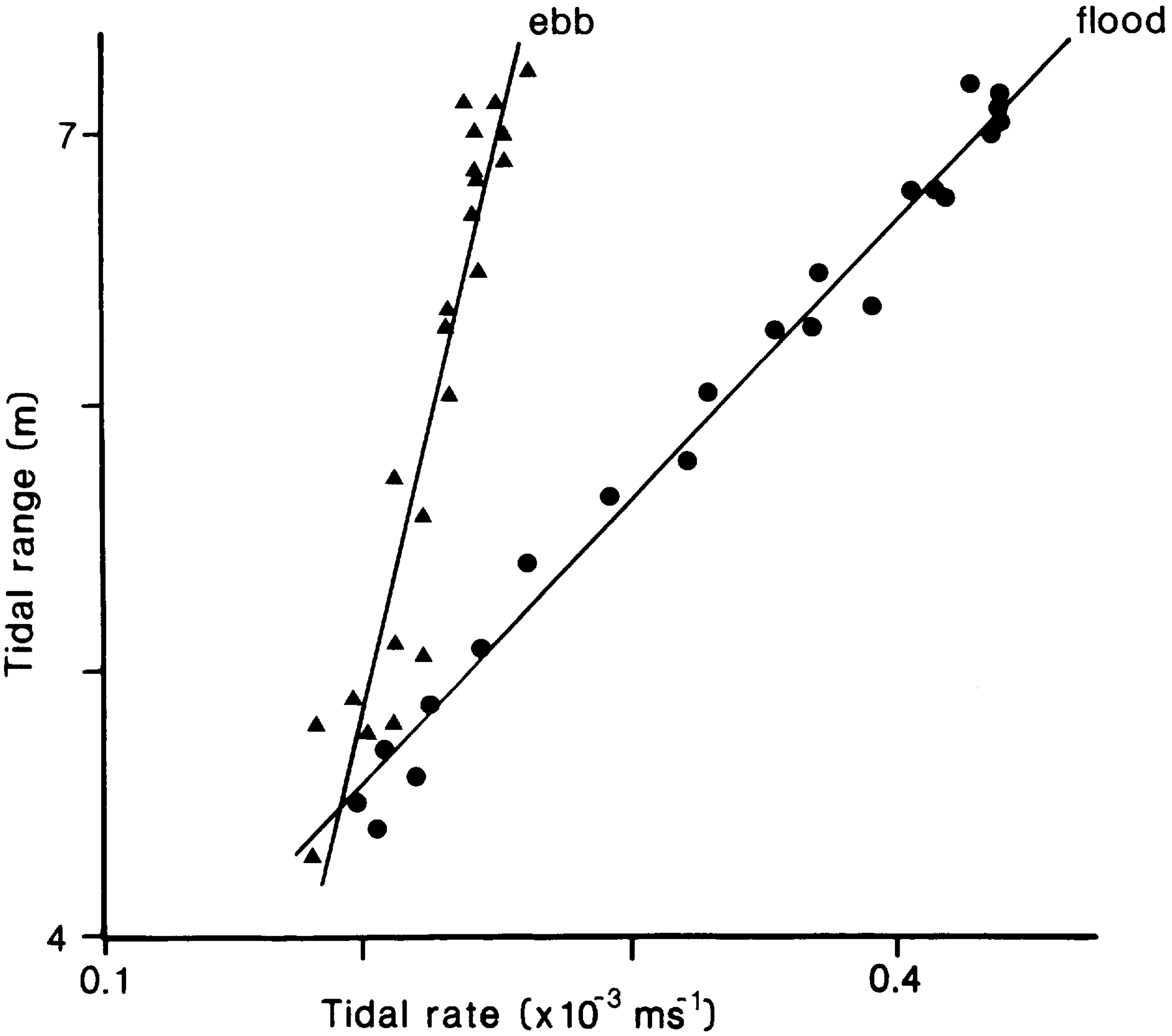


FIGURE 2 Rate of change of tidal height as a function of tidal range

5. RESULTS

5.1. Cross sectional profiles

Between the 14th and 20th July the reference line was surveyed twice daily at each low water, and from then until 26th July, at alternate low waters. The 18 profiles obtained are shown as a time series in figure 3. For indentification purposes the troughs are labelled A, B, C, D from west to east and the crests 1, 2, 3. The diagram clearly shows the systematic migration of the sandwaves. Despite this movement the wavelengths remained constant within the accuracy of the levelling. Maximum lee slope angles reached 29 degrees but were typically between 20 degrees and 25 degrees. The apparent considerable variation in slope angles is mainly due to the positions of the crest in relation to the 1 m levelling interval. Detailed consideration of the variations in crest and trough levels is given in figure 4.

Until the 17th, all bedforms steadily lost height, principally due to the reduction of summit level. It would appear that the bedforms were degenerating: that is the tidal flows were too weak to sustain them.

Lee slope 1B continued to lose height until 19th because of the continuing reduction of summit level. There was then a rapid increase in height, due to a decrease in the level of trough B. The subsequent loss of height resulted from a corresponding increase in the level of trough B. Summit 1 increased in level until 21st to be followed by a sudden decrease of 23 cm. After this, the level remained relatively constant.

Lee slope 2C appears to be almost the inverse of 1B. The loss of height from 20th was due to the trough level rising. This appears to be because

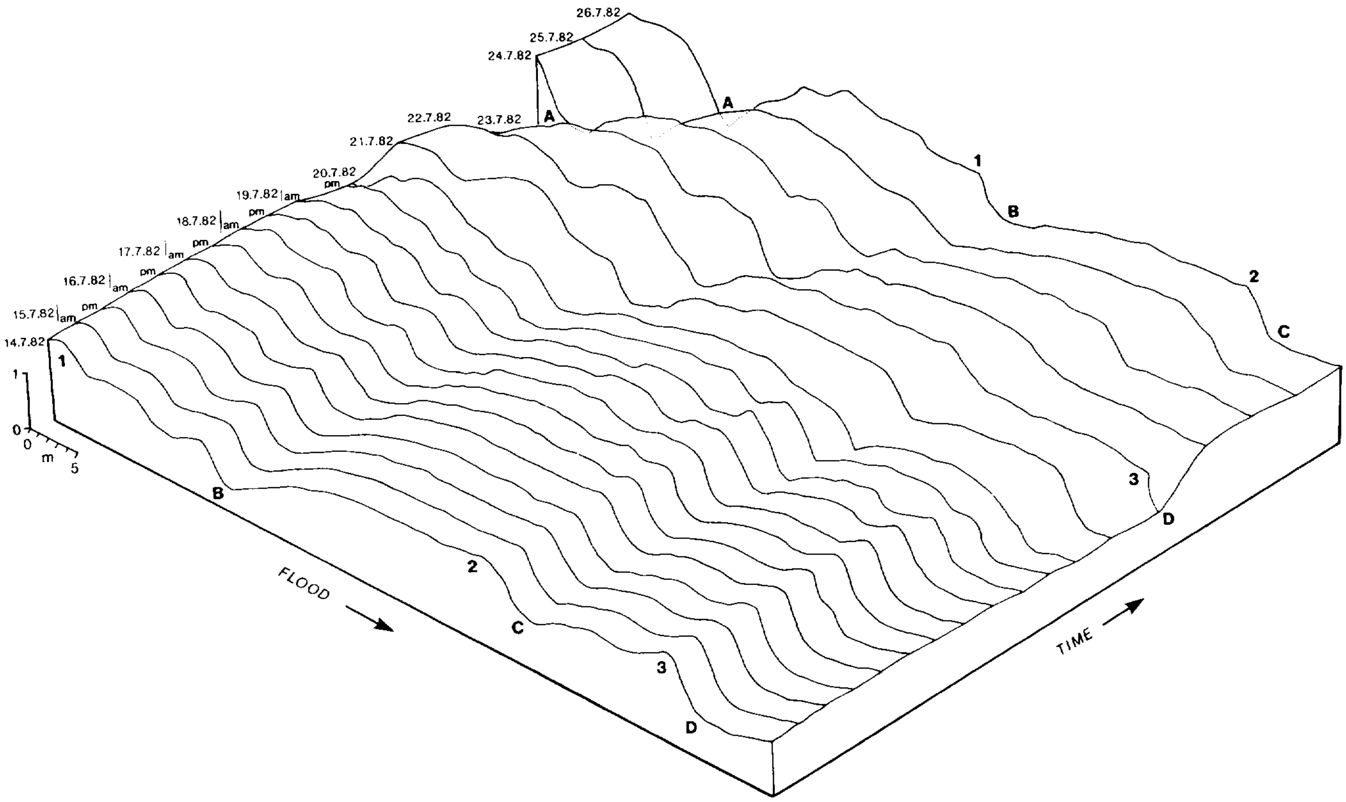


FIGURE 3 Time series of sandwave profiles

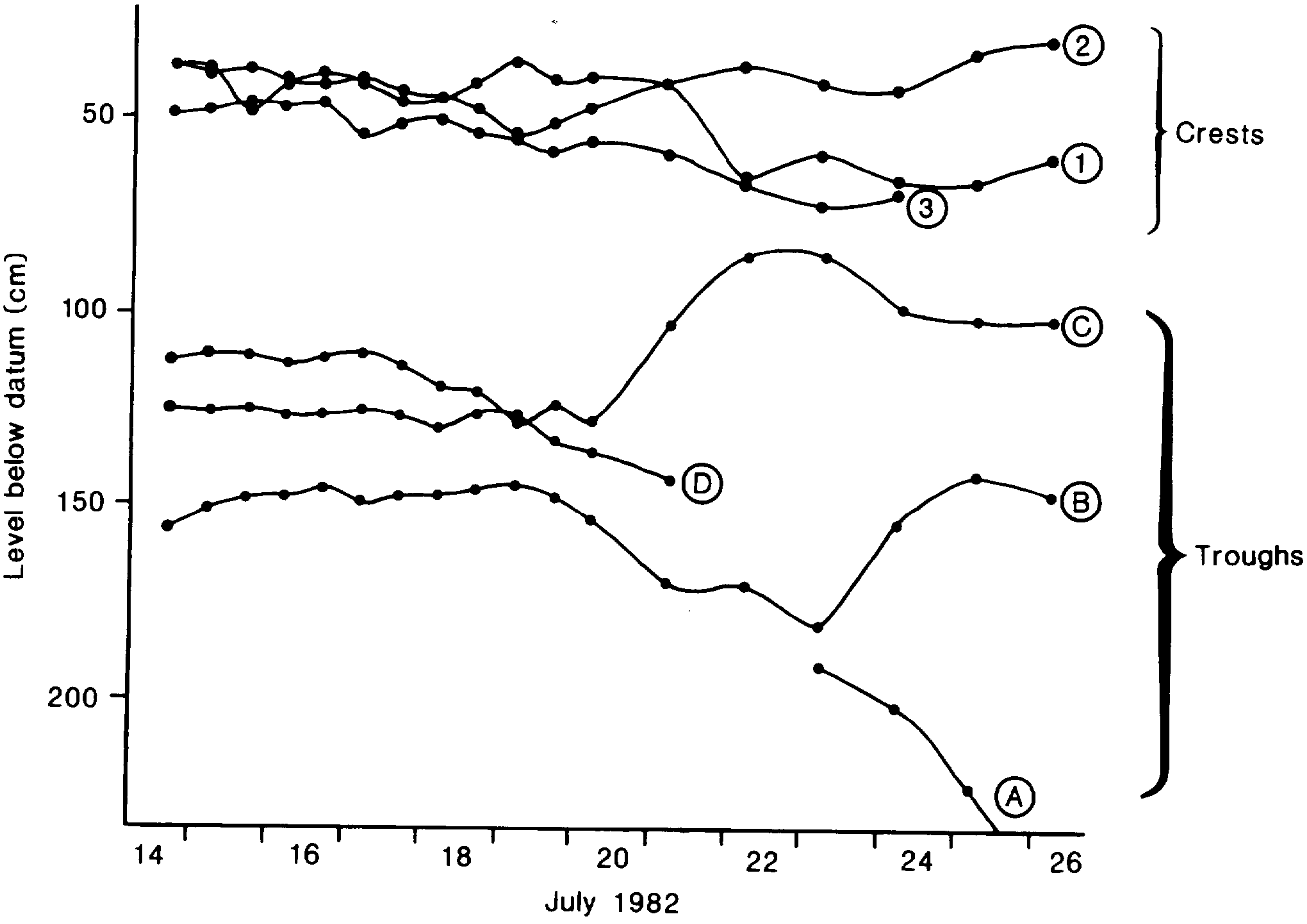


FIGURE 4 Time series of sandwave summit and trough levels

lee slope 2C was advancing up the stoss slope C3. As tidal range decreased after 23rd, trough C became more distinct again.

Crest 3 showed a steady decrease in level throughout. The height of lee slope 3D showed an overall decrease, but from 18th to 20th, a rapid decrease in height was followed by a rapid increase. Careful study of the level of summit 3 shows a drop in level corresponding to these changes. Before the 18th, the summit point of bedform C3D was coincident with the brink point of lee slope 3D. This is the form described for submarine sandwaves by Van Veen (1935) and termed 'cat-backed'. After the 20th, bedform C3D had a much more rounded form because the summit point and brink-point were no longer coincident. With this sandwave, the transition was gradual: the brink-point lost height as the new summit point developed. This resulted in a temporary reduction in the maximum level during the transition period: the volume of the bedform remained constant.

Sandwave B2C also underwent this change from the cat-backed form after the 19th and this is also shown by a dip in the summit point level during the transition.

The brink-point of sandwave A1B was never coincident with the summit point, but until 20th it was a 'secondary summit', but after that date it too lost its identity as this bedform also became more rounded.

In order to assess the nature of the changes shown in figure 3, surveys taken at two tide-intervals (approximately daily) were lag cross-correlated. The results of this, together with the observed tidal range curve, are shown in figure 5. The correlation shows the change in morphology and the lag shows the migration of bedforms. Although there is

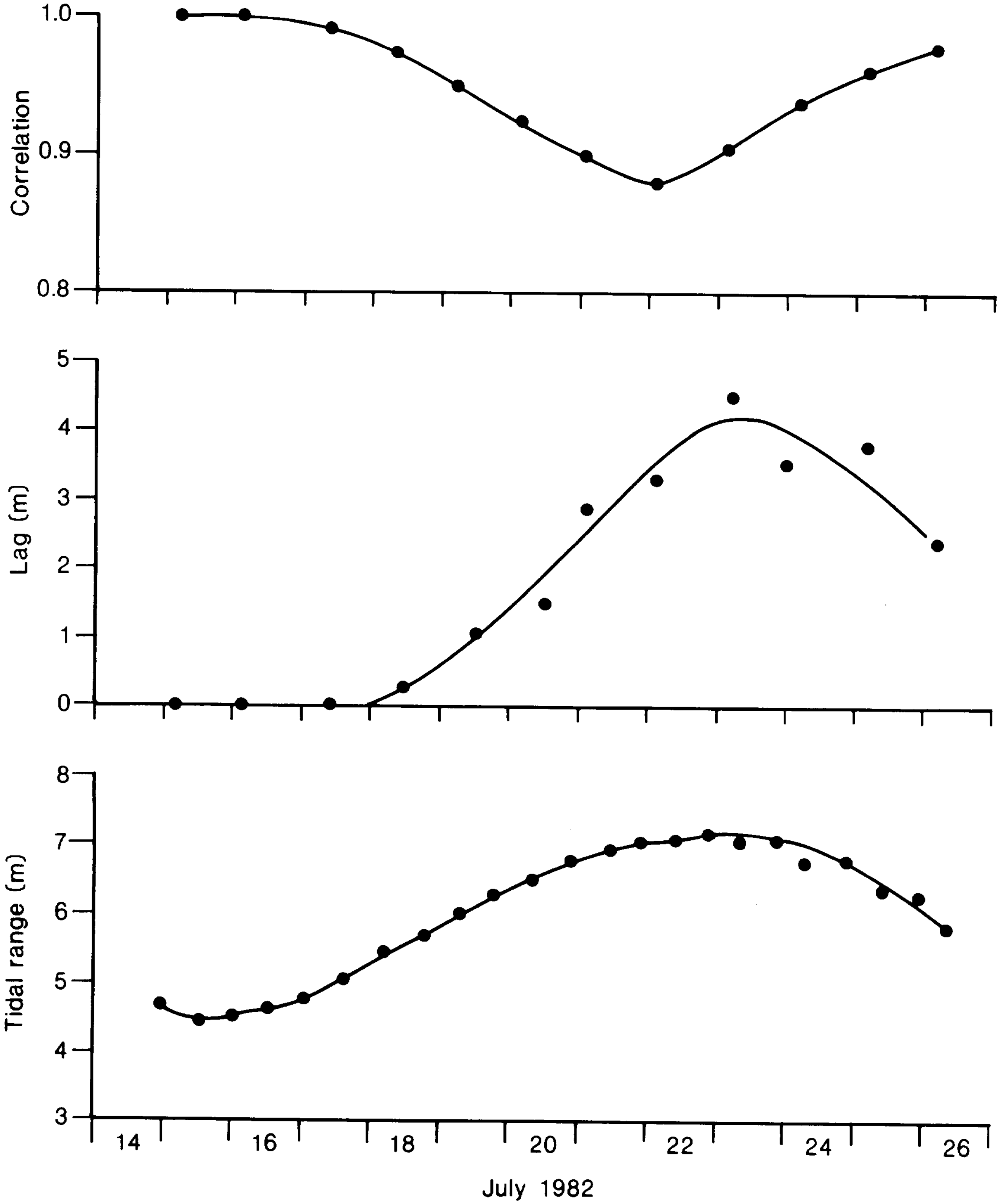


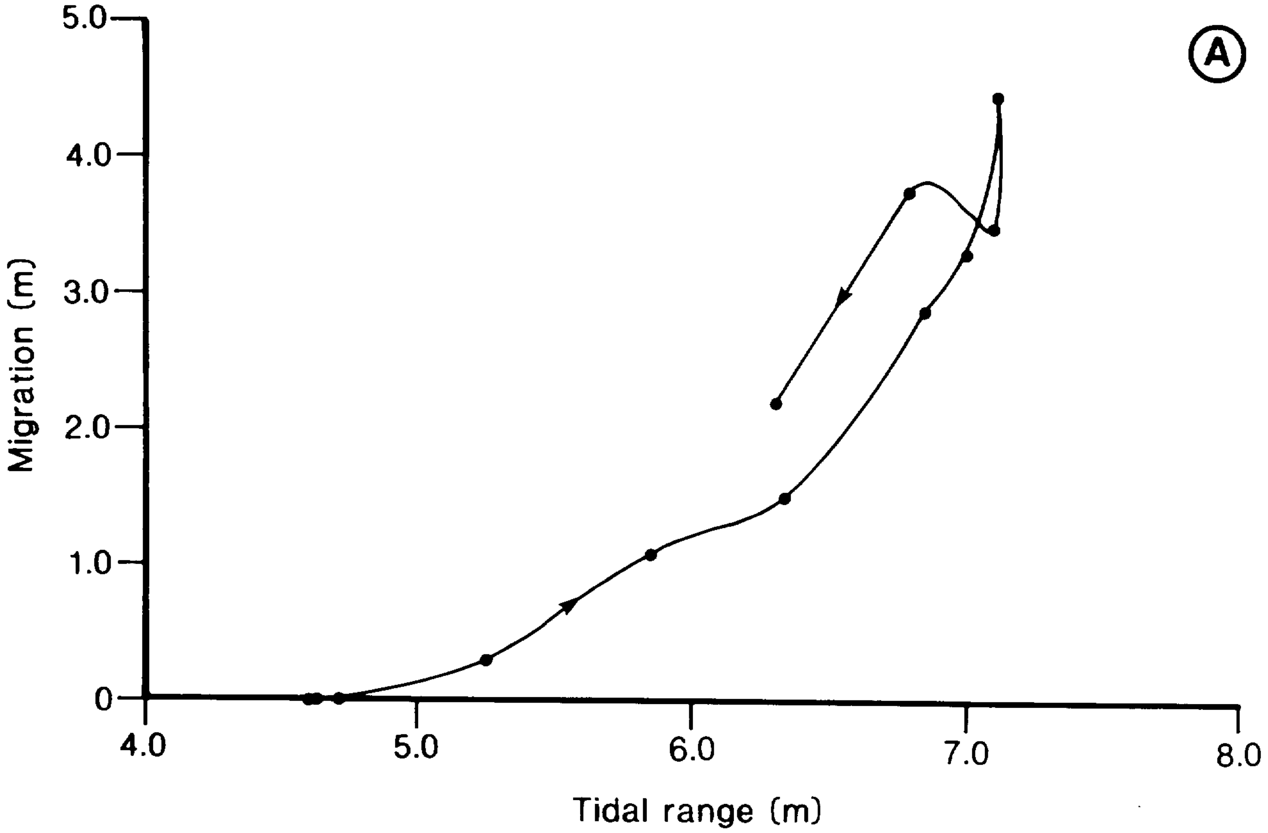
FIGURE 5 Sandwave lag correlation: lag, correlation and tidal range

a clear relationship between both migration and correlation with tidal range, these relationships are out of phase. Allen (1973) has discussed similar out of phase relationships between flow and the wavelength and wave height of bedforms.

Figure 6a shows the variation of migration with tidal range. This shows that migration was less on the increasing tide (neap to spring) than for the corresponding tidal range on the decreasing tide (spring to neap). This agrees with the conclusions of Allen and Friend (1976) where the time taken for a bedform to respond to the change in flow is termed the 'relaxation time'.

Figure 6b shows the variation of correlation with tidal range. In this case with increasing tidal range the correlation decreased (ie as greater form change occurred). Near maximum tidal range this trend reversed and there was a sudden increase in correlation indicating a reduced rate of change of the bedforms. This would suggest that they were reaching an equilibrium with the spring tidal flow. However, as the tidal range decreased, the correlation continued to increase, apparently contradicting both the migration data and the conclusions of Allen and Friend (1976) which both imply that the correlations should be lower on the decreasing tide than for the corresponding tidal range on the increasing tide.

The significance of these conclusions should be treated with caution as the study was less than one complete semi-lunar cycle and only covered the movement and form change of one and parts of two bedforms. These bedforms showed contrasting and often contrary changes and the lag cross-correlation is an average of these changes.



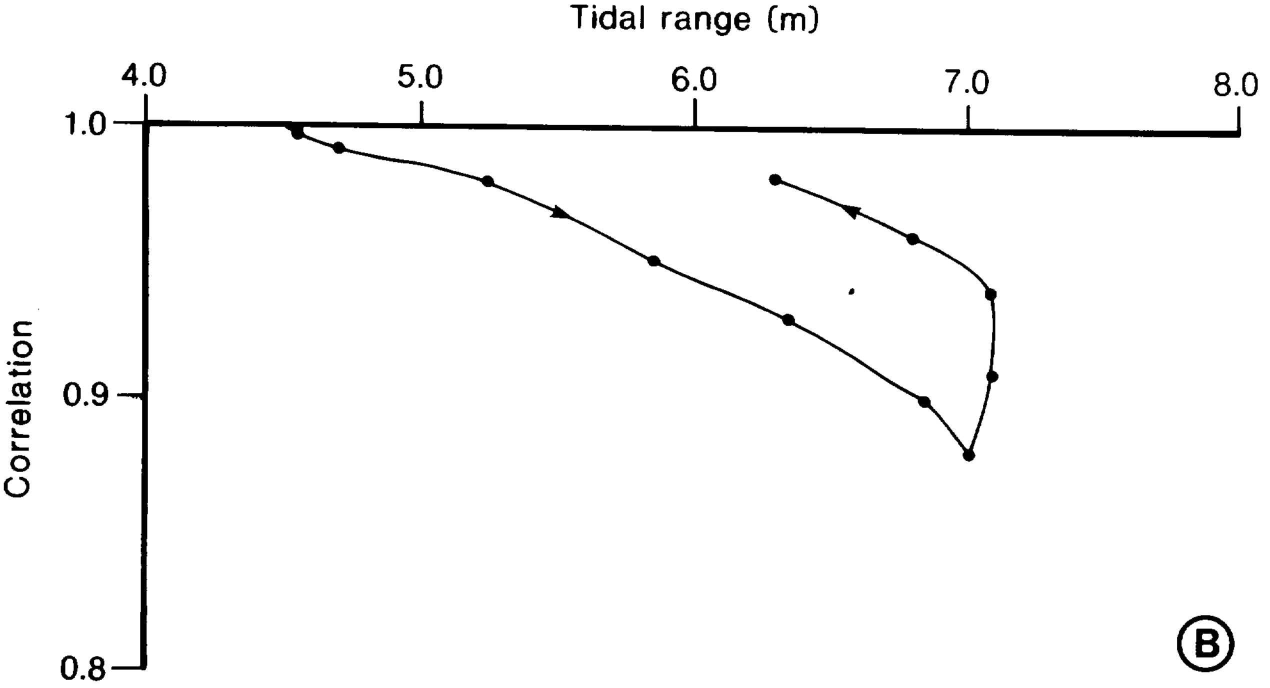


FIGURE 6A Sandwave migration (lag) as a function of tidal range

FIGURE 6B Sandwave correlation as a function of tidal range

Until the 19th sandwaves B2C and C3D trended towards the development of double crests. Over the following day this trend was negated with the filling, and indeed overfilling, of the topographic low to the extent that the summit point was displaced upstream from the crest. From the 19th until the 22nd the major changes associated with these bedforms was restricted to the merging of crest and summit and the filling of trough C. Sandwave A1B which was of more complex form, also continued to show marked changes until the 22nd. It is therefore tentatively suggested that at this time new forms had developed which, though migrating, changed their form less, which is indicated by the increase in correlation.

5.2. Inferred Internal Structure

5.2.1 Cross sectional profiles

Using the profile data, it is possible to infer the internal structure of the bedforms using the technique adopted by Langhorne (1982). This requires the indentification of those parts of the profile which are apparently buried by the subsequent movement of the bedform. Figure 7 shows the evolution of the inferred internal structure using this technique at two tide-intervals for the whole study.

The inferred structures shown correspond with master bedding (Allen, 1980a) or second order bedding (Allen 1980b). Between these would occur others associated with high tide slack waters. Structurally in the inter-tidal zone, high and low water master bedding are likely to be different. In the case of the former, in which the bed remains submerged, flood velocities decrease to be followed by a period of approximately 10 minutes slack water, in this area, before the reversal of flow with the ebb tide. During

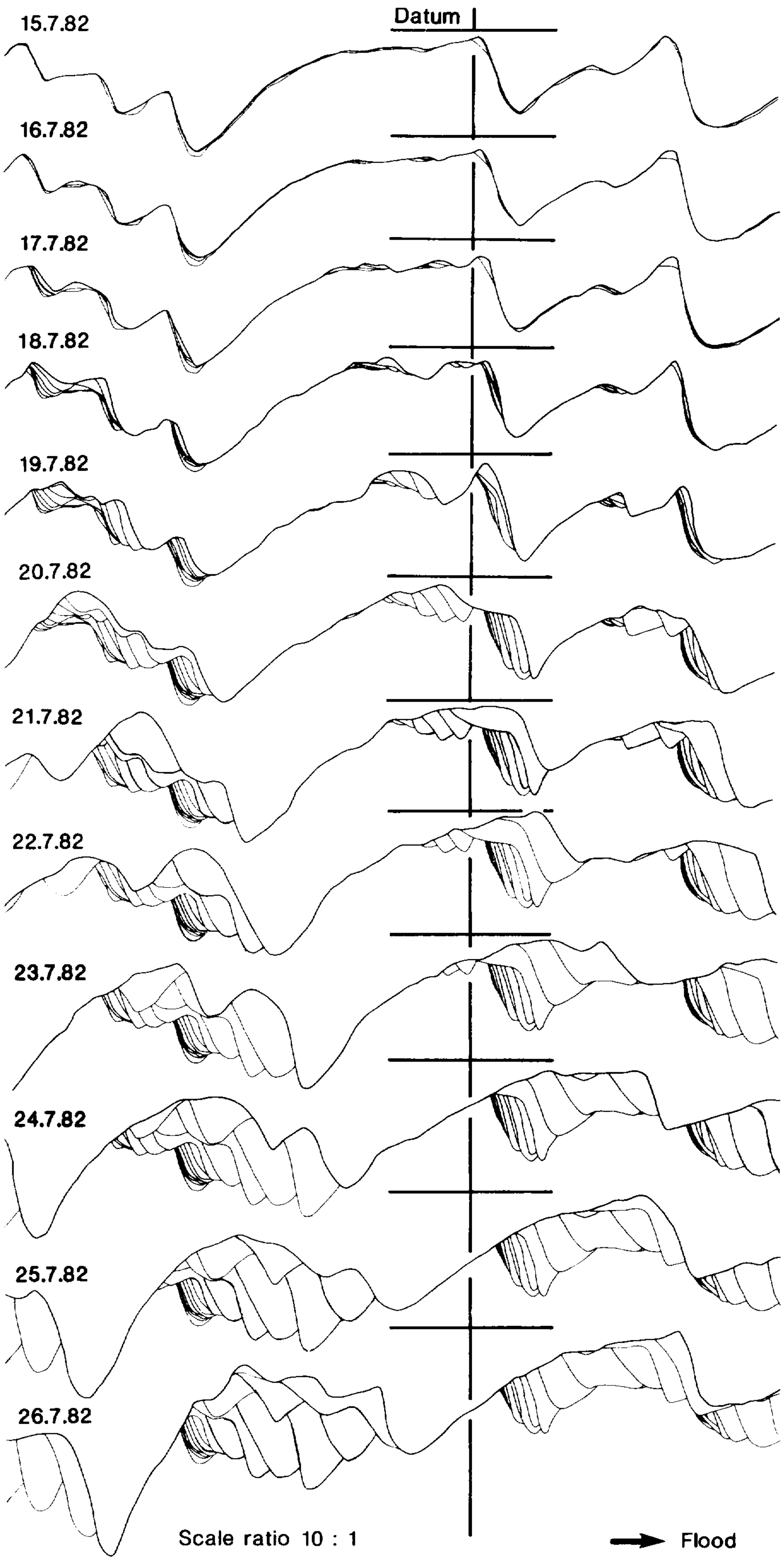


FIGURE 7 Time series of inferred internal structures

the slack water, fine sediment may settle from suspension to form a mud drape, which characteristically fines upwards as a result of differential settling velocities. The high water slack tide may also be indicated by the reversal of structure, or cross bedding, with or without an erosional discontinuity.

The master bedding associated with low water is likely to be dominated by the processes related to the bed becoming exposed above the water surface. Clearly settlement from suspension will not occur (except in special circumstances which will be discussed later) and structural discontinuities without erosion will probably be more rare.

It is proposed that the term 'pause plane' (Boersma and Terwindt, 1981a) should be used 'sensu stricto' and restricted to those structures associated with a pause in the tidal flow. These include mud drapes and structural discontinuities related to changes in flow direction and usually apply to conditions when the bed remains submerged. Erosional discontinuities, though they may be indicative of the beginning of the succeeding flood or ebb tide are, by definition, produced by sediment movement and are therefore not included in the term pause plane. This differs from the considerations of Boersma and Terwindt (1981a) who maintain that pause planes may be depositional or erosional.

It is well understood that bedform migration is brought about by erosion of the upstream stoss slope and deposition on the lee slope. This results in the formation of foreset and bottomset laminae of which the former become truncated by the erosion of the stoss slope. Such a mechanism is clearly indicated by the master bedding in figure 7. Throughout this report the upstream, or stoss slope is with reference to the dominant flood tide.

The progression of a trough (or indeed any topographic 'low') erodes the sediment between successive trough positions and also truncates existing structures thereby forming bottomsets. The actual positions of these bottomsets cannot be inferred from the profile data and are therefore indicated as being linear. This modified interpretation is shown for data from the 26th in figure 8A together with the original interpretation.

It should be noted that during the 13 days of observations, bedform B2C migrated 18 m; that is 60% of its own wavelength and a distance greater that the wavelength of the adjacent bedform C3D. The 'life expectancy' of the major part of the internal structures in this area is therefore in the order of 1 to 2 neap/spring cycles. The level of advance of trough C is higher than that of the preceeding trough D and therefore the bottomsets and lower parts of the foresets have not been reworked during this neap/spring cycle. The continuation of such events would lead to a build up of sediment in this position, but in view of the greater depth of trough A, any longer term accretion seems unlikely. Assuming that the bedform movement which has been monitored is representative, then the structures within the body of the bedforms will be composed of foresets and bottomsets with the former being truncated at the surface. Beneath the present day bedforms the sand bank may be expected to be composed of successive layers of truncated foresets and bottomsets which were formed by progressive accumulation of sediment in the area, causing bedforms to advance at higher and higher levels.

5.2.2 Master bedding

It need not necessarily be assumed that master bedding will be detectable in box cores, or indeed, in geological strata. In this study mud drapes are

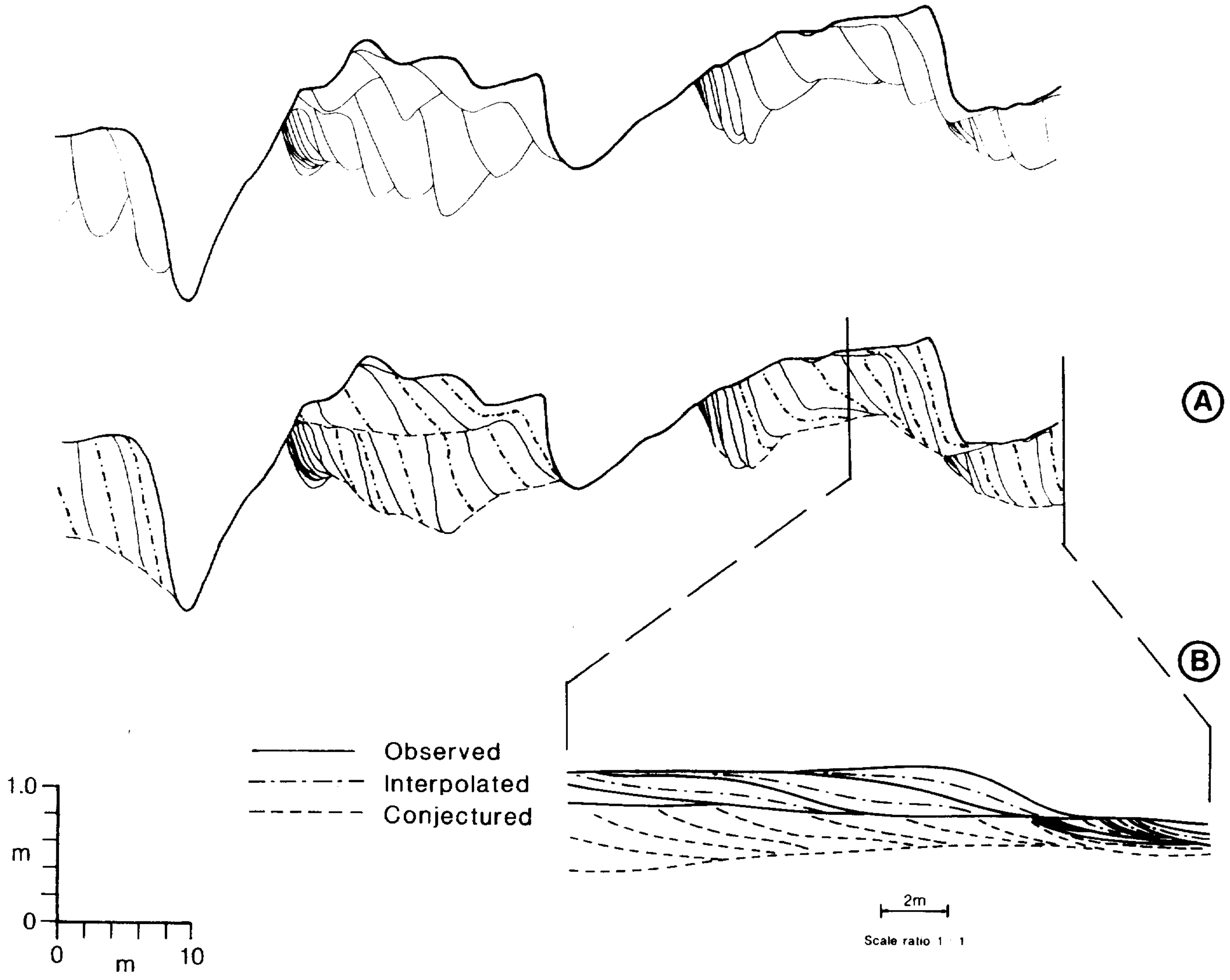


FIGURE 8A Structure for 26th July showing effect of bottomset truncation

FIGURE 8B Structure for 26th July as a true plan likely to be poorly developed owing to the sediment being well sorted. Soulsby (personal communication) has shown, in a parallel study, that the mean size of the suspended sediment (2.6 phi) is very similar to that in situ (mean 2.3 - 2.5 phi). It is only after periods of heavy rainfall that significant quantities of silt, clay and organic debris are carried to the area by the river. Deposition associated with the high water pause plane is likely to be very vulnerable to subsequent flow. Sediment deposited on the erosional stoss slope will probably be eroded by the dominant flood tide whilst that on the lee slope is likely to be reactivated by the ebb tide, which though weaker, acts upon a steep (often angle of repose) slope. However, ebb tide erosion will be less effective on the lower parts of the lee slopes and in these areas evidence of high water pause planes may remain.

As stated previously the existence of detectable master bedding associated with low water is determined by the processes related to the bed whilst drying out. These are different from those at high tide particularly because, in contrast to flow velocities decreasing and reversing as the water level decreases, the flow velocities often increase. For short periods before drying Froude numbers may exceed 1.0. In addition small surface waves which were of no significance to sediment transport at high tide may become important. Once the crestlines are exposed above the water surface two contrasting flow regimes can develop. In some cases the flow draining the bank area becomes entrained between the crestlines producing strong transverse flow. This is indicated by well developed transverse ripples and erosional undercutting of the sandwave flanks. In other cases, due to bifurcations and variations in trough depths, water becomes 'ponded' and drainage only occurs through the porous sediments. This permits fine sediments to settle from suspension to form discrete areas of mud drapes.

5.2.3 Ebb caps

All the profile data were obtained at the end of the ebb tide. Because no data were obtained at the end of the dominant flood tide, the true form and extent of movement of the bedform at that time was not recorded. The ebb tide, though weaker, reactivates the flood lee flank which is unstable with respect to the reversed flow. Some erosion must occur and this is indicated by the development of 'ebb caps' which often could be seen at low tide. These features are found down stream from the crests with angle of repose lee faces formed in the direction of the ebb tide. The thickness of the sediments forming ebb caps were normally only a few centimetres, but could be up to as much as 25 cm.

Despite ebb tide erosion, angle of repose slopes were frequently observed on the flood tide lee slope. However, these did not extend upwards to the crests which tended to be rounded off by ebb tide erosion. Owing to their size in relation to the 1 m levelling interval, the ebb caps are not indicated by the profiling surveys. Ebb caps are very vulnerable to erosion by the ensuing flood tides, but even partial preservation at neap tides would reveal additional structural horizons, whilst truncated foreset laminae, or erosional discontinuities may be evident on the lee slope.

Boersma and Terwindt (1981b) suggest that ebb caps are produced by ripples ascending the lee slope of a sandwave. In this location, the high slope angles (up to 29 degrees) are probably too great and unstable for this to occur and indeed, at no time were lee slope ripples observed at low tide.

5.2.4 Flaser bedding

Characteristically, at low waters, the stoss slopes of the sandwaves were formed into ripples which varied in size and form at each low water. Typically, wavelengths were of the order of 10 cm. At the beginning of the period of observations, after abnormally heavy rain and associated high silt and clay content in the river, mud drapes were apparent in the troughs of the ripples. This mud was a few millimetres thick and became partially consolidated at low water due to dessication during the period of exposure. Burial of such sediments by subsequent tides could result in the formation of simple flaser bedding as described by Reineck and Wunderlich (1968). It is considered that these clay deposits settled from suspension at high water slack tide (except for those associated with ponding) and were not re-eroded by the ebb tide. During the following flood tide the mud deposits would be likely to be eroded and therefore their potential for widespread and long period preservation seems small.

The mud drape, or flaser, occurences support the discussions of Terwindt and Breusers (1972) who conclude that flaser beds are tidally produced, but contradict the theoretical work of McCave (1970) and the experimental work of Hawley (1981) both of whom conclude that the rate of deposition of mud is too low for flaser bedding to form in a single slack water period. In this study the occurrence of mud deposits was probably exceptional in that it was associated with abnormally heavy rainfall. Nevertheless it does demonstrate that if the suspended silt content is sufficiently high then mud drapes can be formed during a single slack water period.

The mud drapes observed do not conform with any of the reactivation classes proposed by Visser and de Mowbray (1982). All the classes considered required mud deposition to occur at the end of the subordinate tide. In this study this could occur in isolated areas due to ponding.

5.2.5 Trapped air

At low water the sandwave field dried for several hours. Whilst the sediment did not dry sufficiently for any significant aeolian transport to occur, bubbles of air were seen escaping from the sand as it was covered by the rising tide. Pronounced bubbling tended to occur from particular locations and continued for several minutes. Examination showed that the air was escaping from depths of up to 30 cm beneath the sediment surface. Although these were not sampled by box coring, they would be likely to produce characteristic sedimentary structures perhaps similar to those noted by Reineck and Singh (1973) in beaches.

5.2.6 Profiles not observed

It should be noted that five low water profiles were not taken and are omitted from the inferred structure diagram. Although positions for these could be estimated, their exact positions should be evident in the box cores.

The scale distortion of these internal structure diagrams should be noted carefully as it could be misleading. Figure 8B shows part of the structure of the 26th drawn as a true scale. The solid lines represent part of sandwave B2C and the dotted lines are a hypothetical structure based on that of sandwave A1B. This structure, which was not observed, but possibly existed in some similar form, is included so that comparisons can be made with the observed structures of Van den Berg (1982) and Terwindt (1981) etc. Figure 8A also shows the effect of truncation by bottomsets of the underlying structure.

5.3. Internal structures recorded from box cores

Box coring, using Senckenberg boxes (Bouma, 1969) was carried out in order to examine the internal structure of the central sandwave (B2C) in the survey area. These structures were then used to verify the inferred structures which had been obtained from the profiling data.

On all occasions, which are being reported on in this paper, the cores were taken from the top of the stoss slope, immediately downstream (with respect to the flood tide) from the position of the crest as recorded at the previous low tide. This enabled structures to be related to measured deposition over known periods. Though it would have been advantageous to obtain cores on the lee slope, this was not generally possible on account of the steepnees of the slope and its tendency to slump. This was particularly the case when there was ponded water in the adjacent trough.

Positioning of the box cores, relative to one another and to the bedform, was achieved using slender marker rods and making measurements to the line of reference stakes, which had been used for the profiling surveys.

As neap tides progressed towards spring tides, with associated increase in bedform movement, larger numbers of cores had to be taken. However, this requirement was partially offset because the internal structures also became less complicated.

Figure 9 shows the positions of the box cores taken on sandwave C3D in relation to the inferred internal struture. Box core numbers 5 and 6 were taken elsewhere in the sandwave field and will not be discussed in this

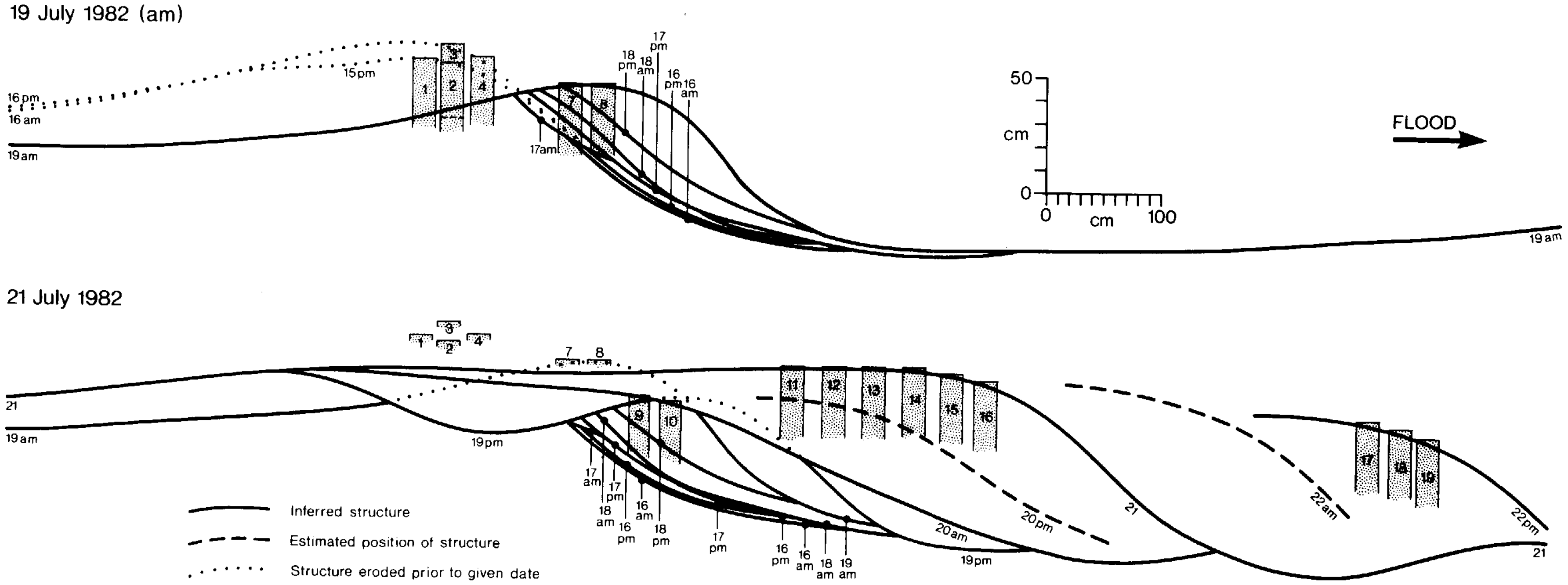


FIGURE 9 Location of box cores with relation to inferred structure

report. Box core numbers 2 and 8 are not illustrated. The position of number 2 was overlapped by number 3, in order to obtain continuity on the following day, whilst number 8 was badly distorted.

The box coring technique and the subsequent preparation of the cores is explained in the Appendix.

5.3.1 Box core analysis

Photographs of the lacquer impregnations of the box cores together with core analysis are presented on the following pages. In all cases, the structures are annotated with reference to the date and time of high tide. These are given high water numbers, eg: High water no 1 is 2215 on 12th July and High water no 2 is 1030 on 13th July. Between these times there is potential for both ebb and flood deposition. Such deposition is lettered alphabetically.

5.3.2 Structural interpretation

The first of four box coring surveys was conducted at low tide on 15th July; that is at neap tide (range 5.4 m). As is shown in figure 9, Box No 1 was taken at the crest of the sandwave (B2C) with Box No 2 adjacent at the top of the slope. Analysis of the cores showed that the bulk of the deposition was derived from the dominant flood tide. Apart from the surface deposition, which occurred during the ebb period prior to coring, only residual vestiges of ebb deposition were present. Master bedding associated with high water occurred either as depositional pause planes or as structural discontinuities.

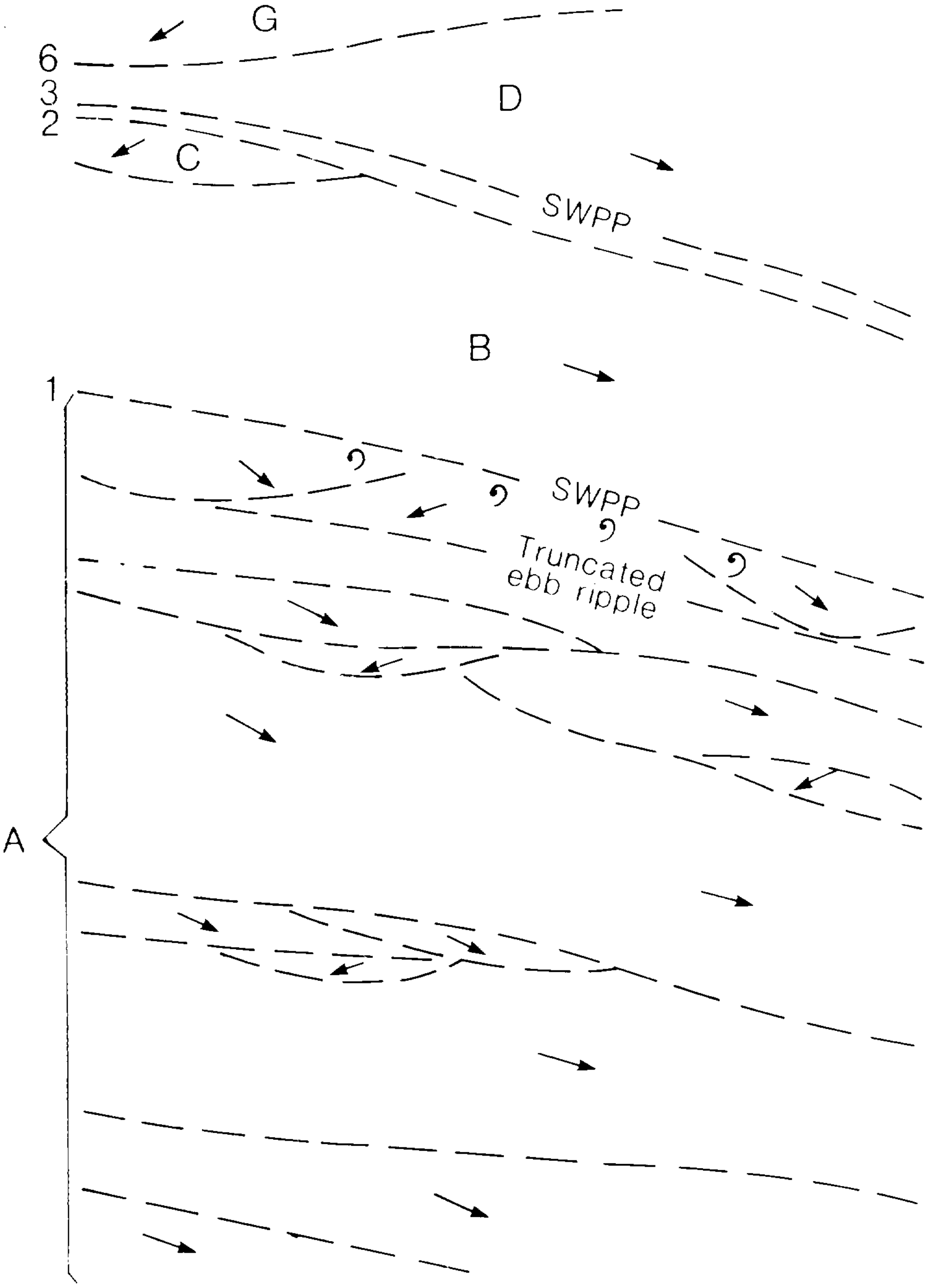
Prior to the field work exceptionally heavy rainfall occurred in the area

BOX CORE NO: 1.

DATE: 15th July 1982 PREVIOUS HIGH WATER: 13.25

SEDIMENT	DEPOSIT CODE	HIGH WATER DATE/TIME	HIGH WATER NUMBER	DISCONTINUITIES
Ebb deposit	G			
		15th. 13.25	6	Ebb erosion surface.
Ebb and flood deposits completely removed by erosion (can be seen from the relative levels in Boxes Nos. 3 & 4).	F			
		15th. 00.50	5	Not present (see Boxes 3 & 4).
" " " " "	E			
		14th. 11.30	4	" " " " " "
Flood deposit : cavernous sand	D			
		13th. 23.00	3	Prominent SWPP of silty-sand. (Continued to Box No. 7).
Ebb lens: cavernous sand.	C			
		13th. 10.30	2	Ebb erosion surface (can be seen more clearly in Box No.3).
Flood deposit : cavernous sand.	B			
		12th. 22.15	1	SWPP - 1mm clay drape resulting from river borne detritus. Very prominent and precisely dated. (Continued to Box No.7).
Sequence of rippled, cross bedded, well sorted, shelly sediments with maximum dip of 37 degrees. 13 discontinuities. Data indicates that the lowest deposits in this core date from 6th July at the latest. (Continued to Box No. 7).	A			

BOX CORE NO.1 15-7-82

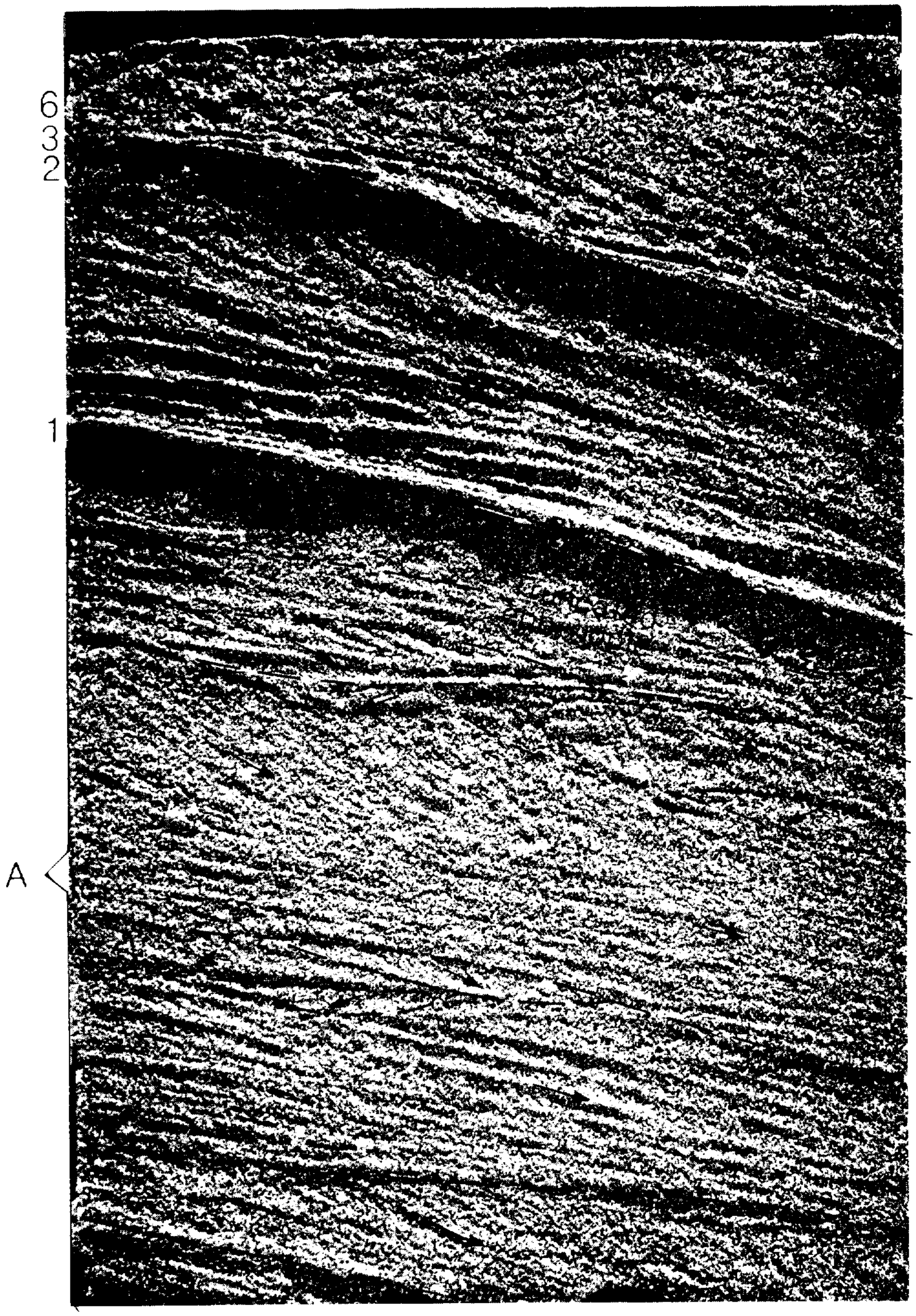


Flood →

Slack water pause plane - SWPP

Random grain orientation - ɂ

BOX CORE NO.1 15-7-82



Flood →

Slack water pause plane - SWPP

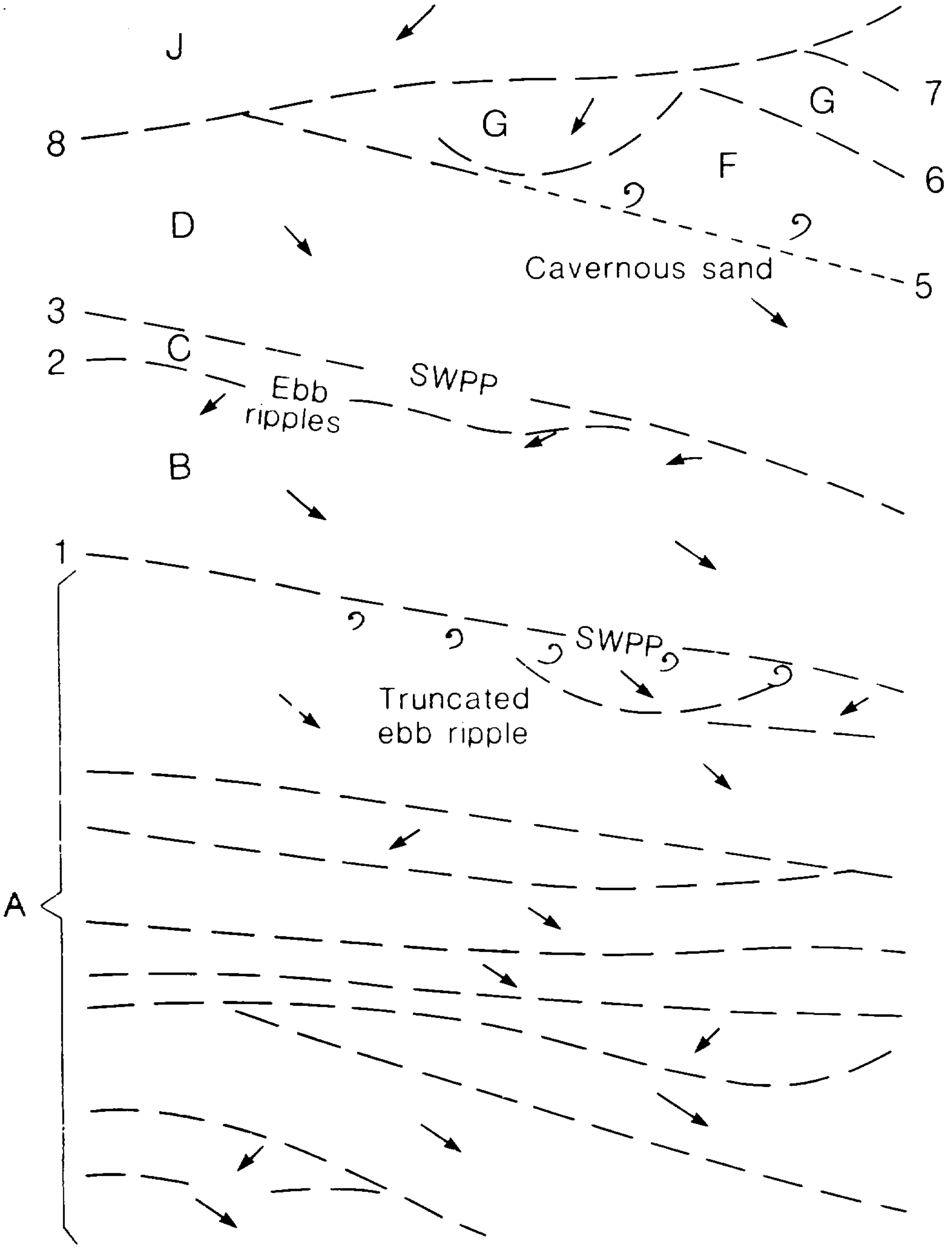
Random grain orientation - ↺

BOX CORE NO: 3.

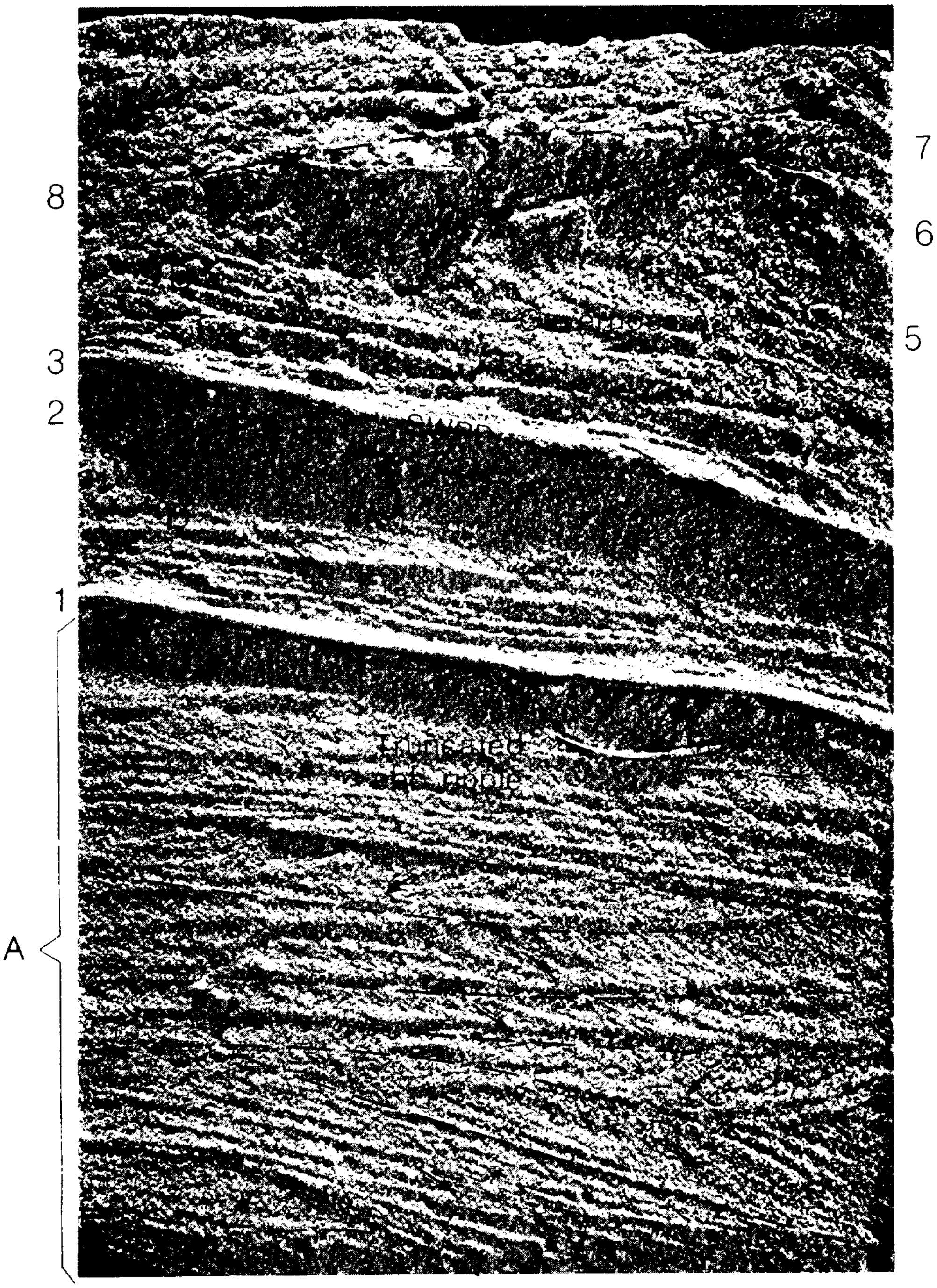
DATE: 16th July 1982 PREVIOUS HIGH WATER: 14:20

SEDIMENT	DEPOSIT CODE	HIGH WATER DATE/TIME	HIGH WATER NUMBER	DISCONTINUITIES
Ebb cap on sandwave crest.	J			
		16th. 14.20	8	Ebb erosion surface.
Flood deposit not present. (see Box No.4).	H			
		16th. 02.05	7	Remnant of eroded SWPP. (Continued to Box No.7).
Flood deposit: ebb lens.	G			
		15th. 13.25	6	Remnant of eroded SWPP.
Flood deposit: cavernous sand	F			
		15th. 00.50	5	Remnant of eroded SWPP. (Continued to Box No.7).
Flood deposit: cavernous sand	E			
		14th. 11.30	4	Not detectable (see Box No.4).
Flood deposit: Indistinguishable from deposit E (see Box No.4).	D			
		13th. 23.00	3	Prominent SWPP. (Continued to Box No.7).
Thin remnant of flood deposit overlying ripples with ebb orientated grains.	C			
		13th. 10.30	2	Rippled ebb surface.
Flood deposit.	B			
		12th. 22.15	1	Prominent SWPP. (as in Box No.1).
Complex cross bedding. (as in Box No.1).	A			

BOX CORE NO.3 16-7-82



BOX CORE NO.3 16-7-82

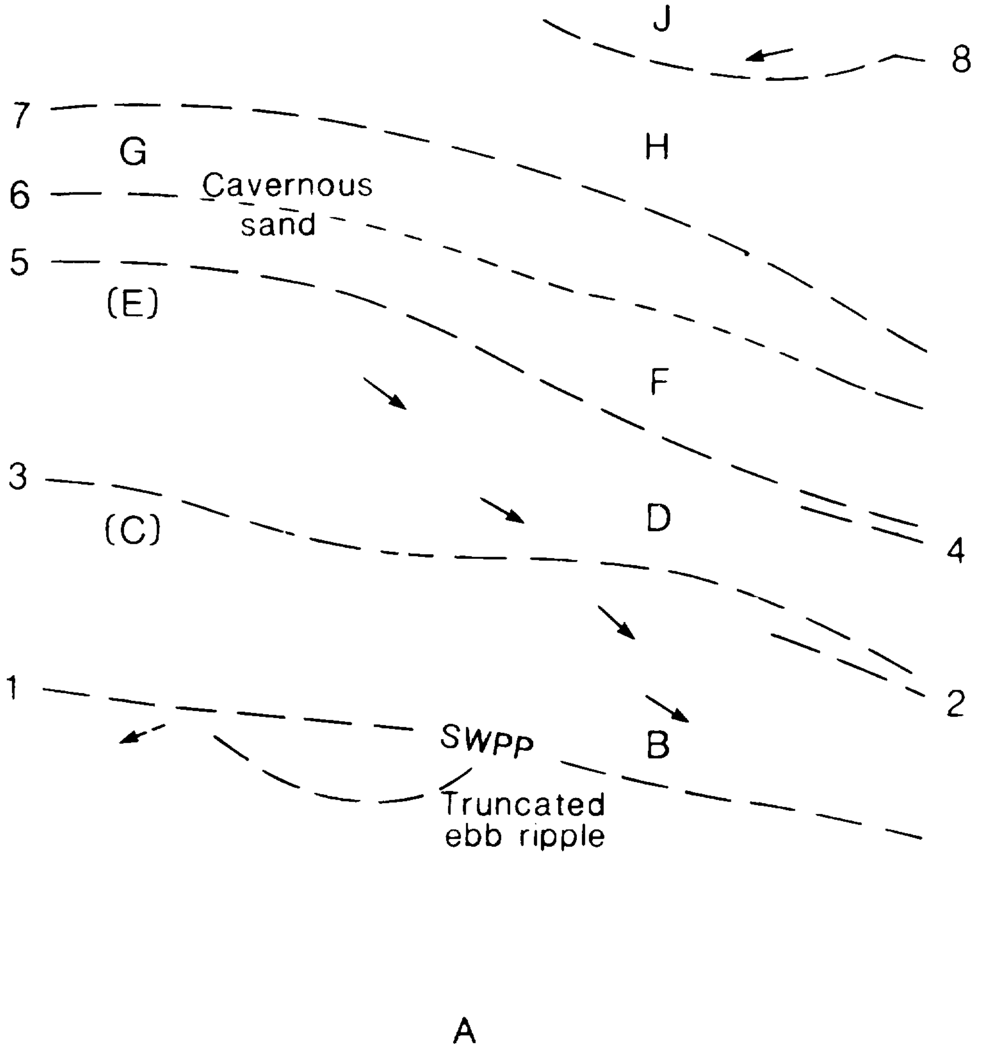


BOX CORE NO: 4

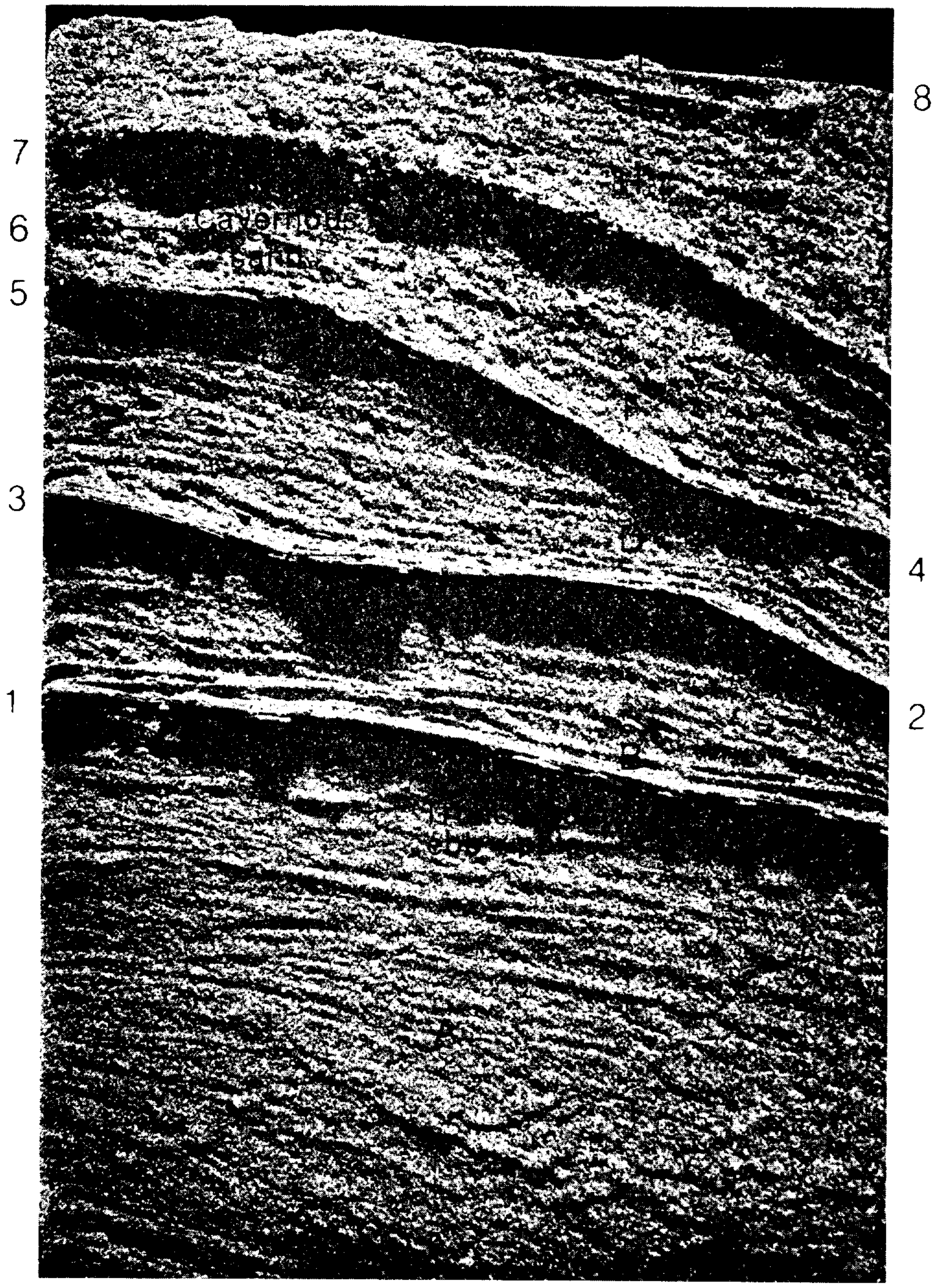
DATE: 16th July 1982 PREVIOUS HIGH WATER: 14.20

SEDIMENT	DEPOSIT CODE	HIGH WATER DATE/TIME	HIGH WATER NUMBER	DISCONTINUITIES
Infilled ebb ripple.	J			
		16th. 14.20	8	Ebb erosion surface.
Flood deposit: cavernous sand.	H			
		16th. 02.05	7	Prominent SWPP of silty-sand. (Continued to Box No.7).
Flood deposit: cavernous sand	G			
		15th. 13.25	6	Eroded remnant of SWPP
Flood deposit: Indistinguishable from (G) where SWPP (6) is eroded.	F			
		15th. 00.50	5	Prominent SWPP of silty-sand. (Continued to Box No.7).
Flood deposit.	E			
		14th. 11.30	4	Eroded remnant of SWPP.
Flood deposit: Indistinguishable from (E) where SWPP (4) is eroded.	D			
		13th. 23.00	3	Prominent SWPP of sandy-silt. (Continued to Box No.7).
Flood deposit.	C			
		13th. 10.30	2	Eroded remnant of SWPP.
Flood deposit: Indistinguishable from (C) where SWPP (2) is eroded	B			
		12th 22.15	1	Prominent SWPP (as in Box No.1, and continued to Box No.7).
Complex cross bedding. (as in Box No.1).	A			

BOX CORE NO.4 16-7-82



BOX CORE NO.4 16-7-82

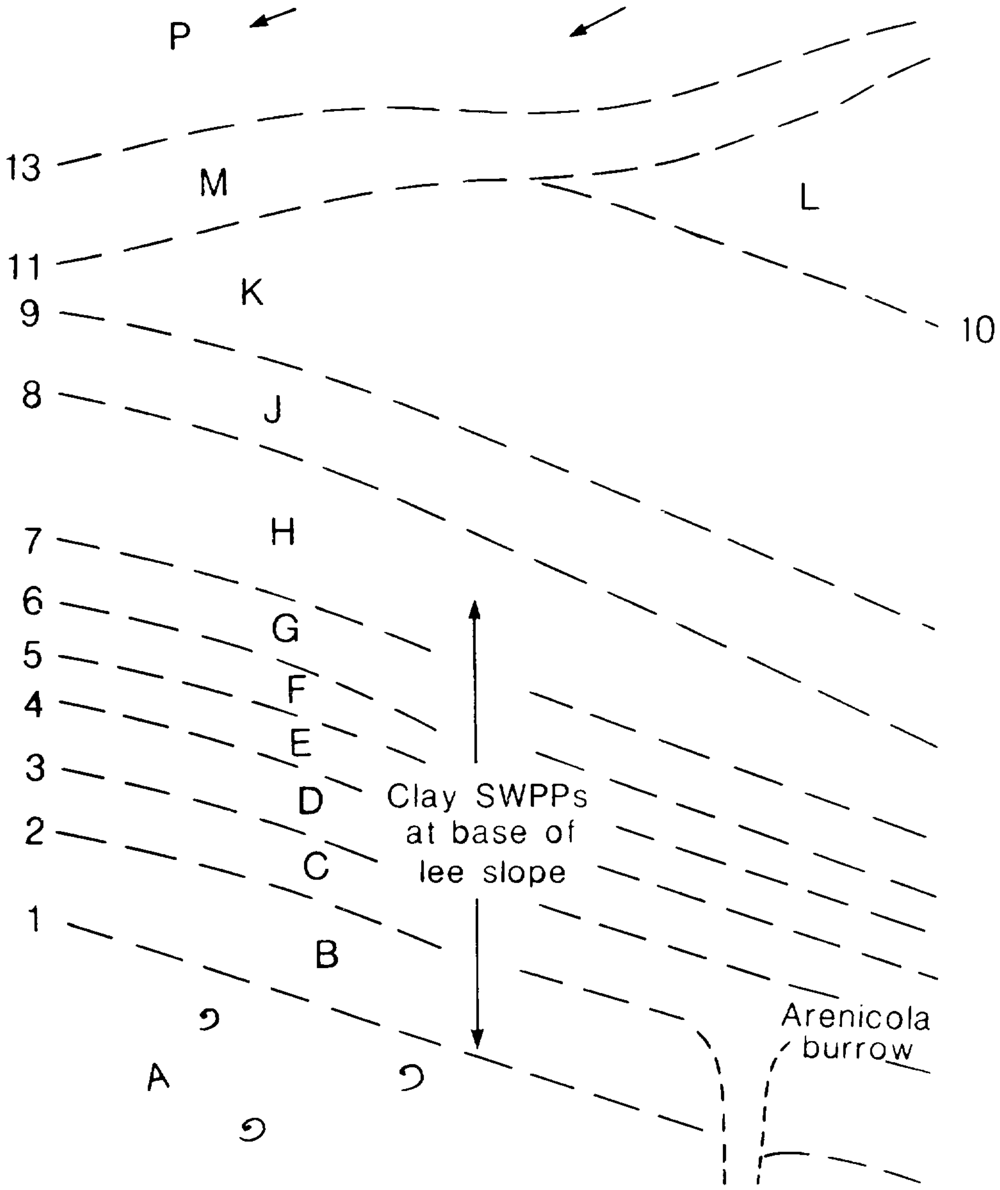


BOX CORE NO: 7.

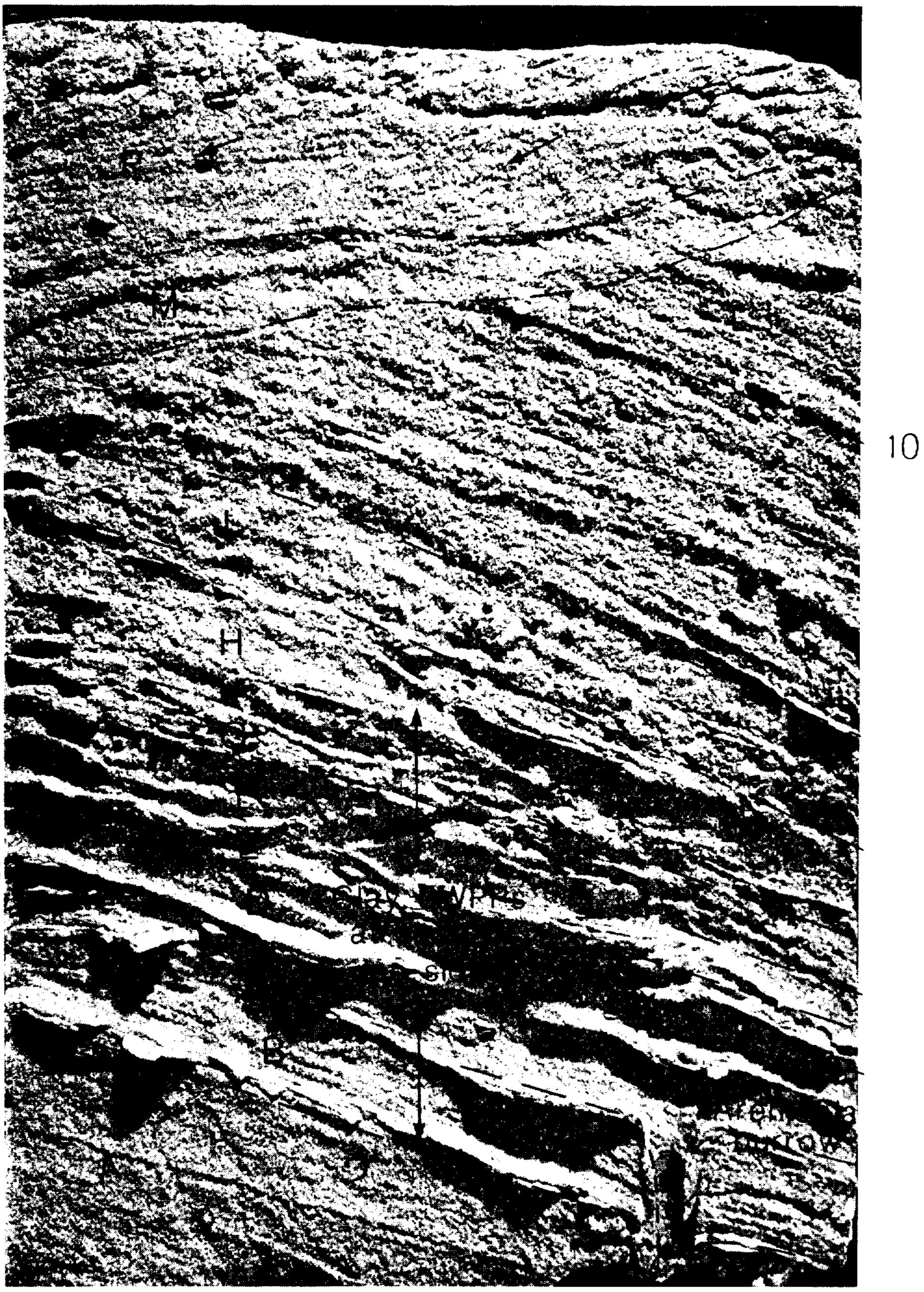
DATE: 19 July 1982 PREVIOUS HIGH WATER: 05.15

SEDIMENT	DEPOSIT CODE	HIGH WATER DATE/TIME	HIGH WATER NUMBER	DISCONTINUITIES
Ebb deposit on crest of sandwave.	P			
		19th. 05.15	13	Ebb erosion surface.
Flood deposit not present. (see Box No.8).	N			
		18th. 16.45	12	Not present. (see Box No.8).
Flood deposit. (Continued to Box No.8)	M			
		18th. 04.15	11	Ebb erosion surface.
Flood deposit.	L			
		17th. 15.35	10	Insignificant SWPP.
Flood deposit.	K			
		17th. 03.15	9	SWPP with thin clay drape.
Flood deposit.	J			
		16th. 14.20	8	SWPP with thin clay drape.
Flood deposit.	H			
		16th. 02.05	7	SWPP with thin clay drape.
Flood deposit.	G			
		15th. 13.25	6	SWPP with thin clay drape.
Flood deposit.	F			
		15th. 00.50	5	SWPP with thin clay drape.
Flood deposit.	E			
		14th. 11.30	4	Prominent SWPP with clay drape.
Flood deposit.	D			
		13th. 23.00	3	Prominent SWPP with clay drape.
Flood deposit.	C			
		13th. 10.30	2	Prominent SWPP with clay drape.
Flood deposit.	B			
		12th. 22.15	1	Prominent SWPP with clay drape.
Structure destroyed by Gammarus burrows.	A			

BOX CORE NO.7 19-7-82



BOX CORE NO.7 19-7-82

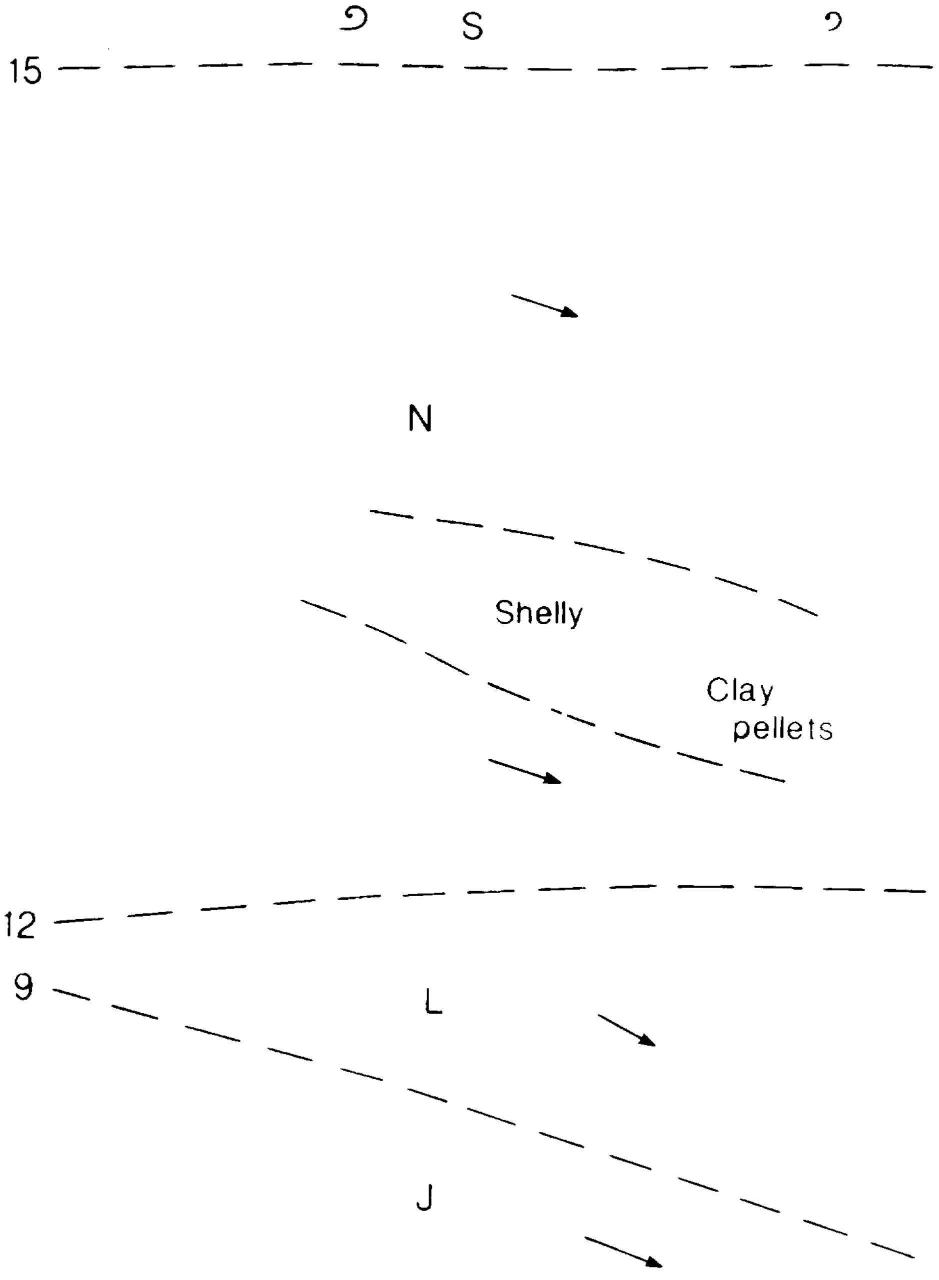


BOX CORE NO: 9

DATE: 20th July 1982 PREVIOUS HIGH WATER: 06.10

SEDIMENT	DEPOSIT CODE	HIGH WATER DATE/TIME	HIGH WATER NUMBER	DISCONTINUITIES
Ebb deposit	S			
		20th. 06.10	15	Insignificant ebb erosion surface
Flood deposits (P) and (R) not present (see profile)	R			
		19th. 17.40	14	Eroded (see profile)
	P			
		19th. 05.15	13	" " "
Flood deposit with steeply dipping shelly lenses (35°) and flat mud pellets	N			
		18th. 16.45	12	Erosion surface
Eroded (see Box No 10)	M			
		18th 04.15	11	Eroded (see Box No 10)
Flood deposit (continued from Box No 7)	L			
		17th. 15.35	10	? Eroded (see profile)
? Eroded (see profile)	K			
		17th. 03.15	9	Insignificant discontinuity?
Flood deposit	J			
Burrowing by Gammarus is pronounced in this sample				

BOX CORE NO.9 20-7-82



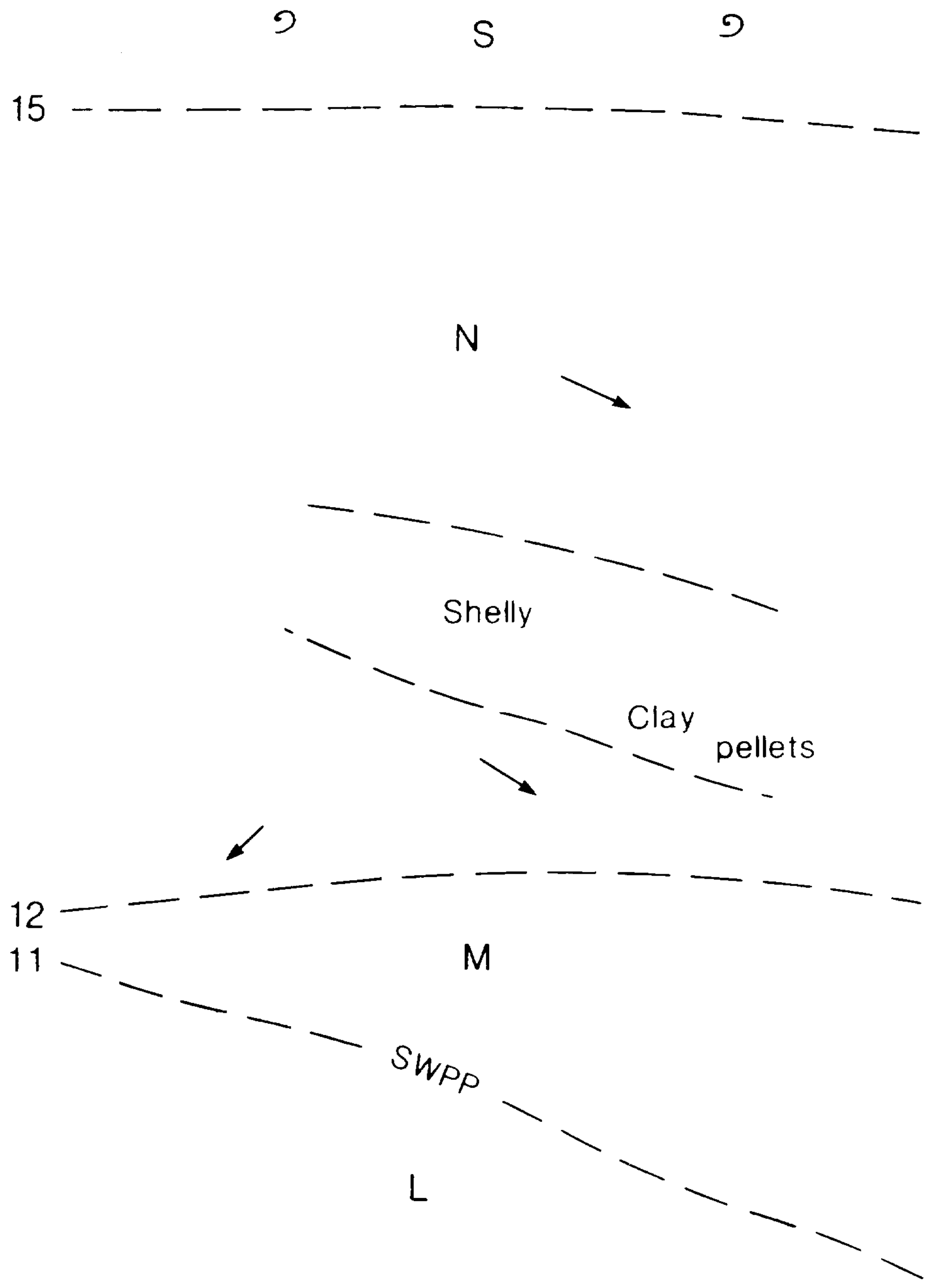
BOX CORE NO.9 20-7-82

BOX CORE NO: 10

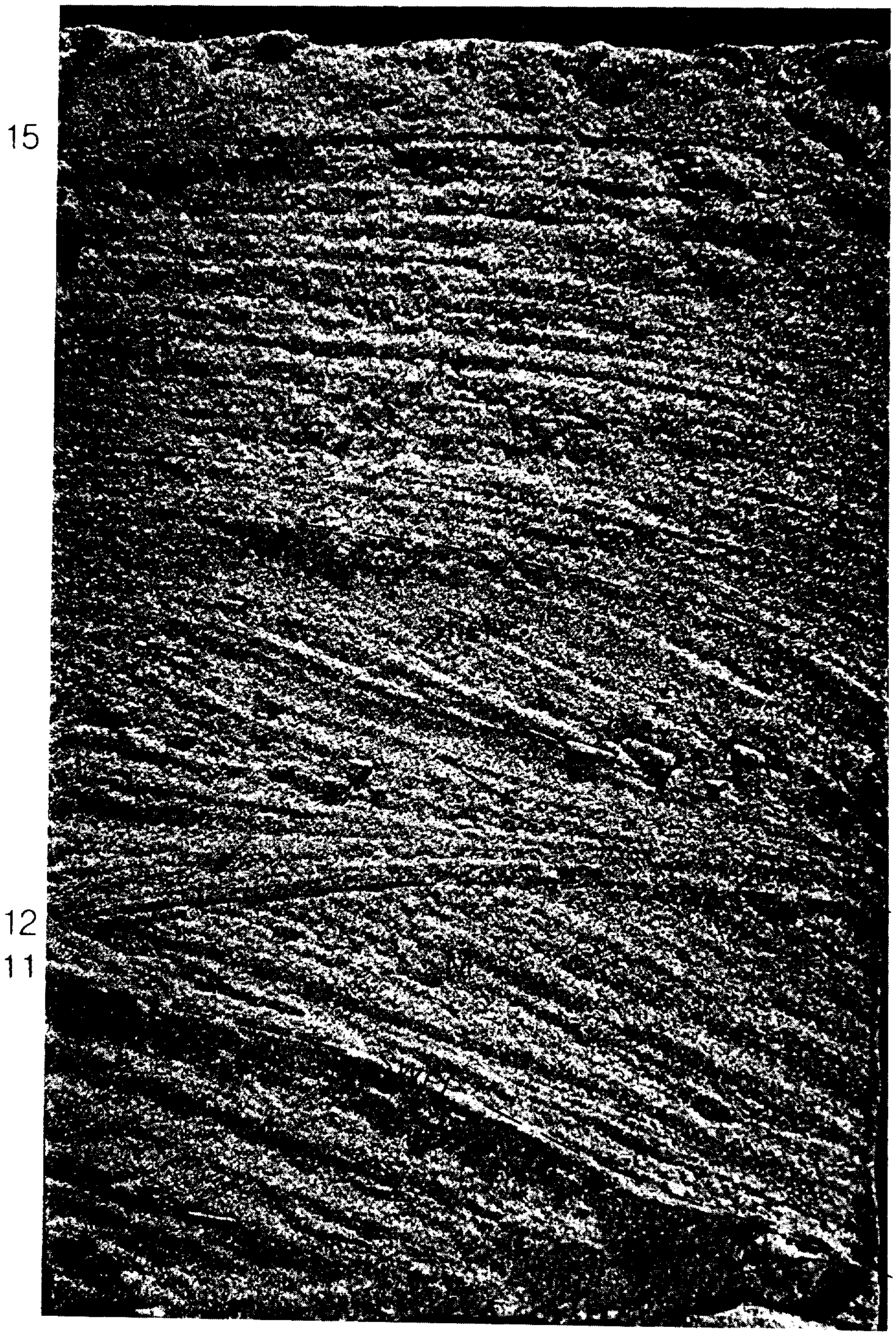
DATE: 20th July 1982 PREVIOUS HIGH WATER: 06.10

SEDIMENT	DEPOSIT CODE	HIGH WATER DATE/TIME	HIGH WATER NUMBER	DISCONTINUITIES
Ebb deposit	S			
		20th. 06.10	15	Insignificant ebb erosion surface
Flood deposits (P) and (R) not present (see profile)	R			
		19th. 17.40	14	Eroded (see profile)
	P			
		19th. 05.15	13	" " "
Flood deposit with shell	N			
		18th. 16.45	12	Erosion surface
Flood deposit	M			
		18th. 04.15	11	SWPP
Flood deposit Burrowing by Gammarus is pronounced in this sample	L			

BOX CORE NO.10 20-7-82



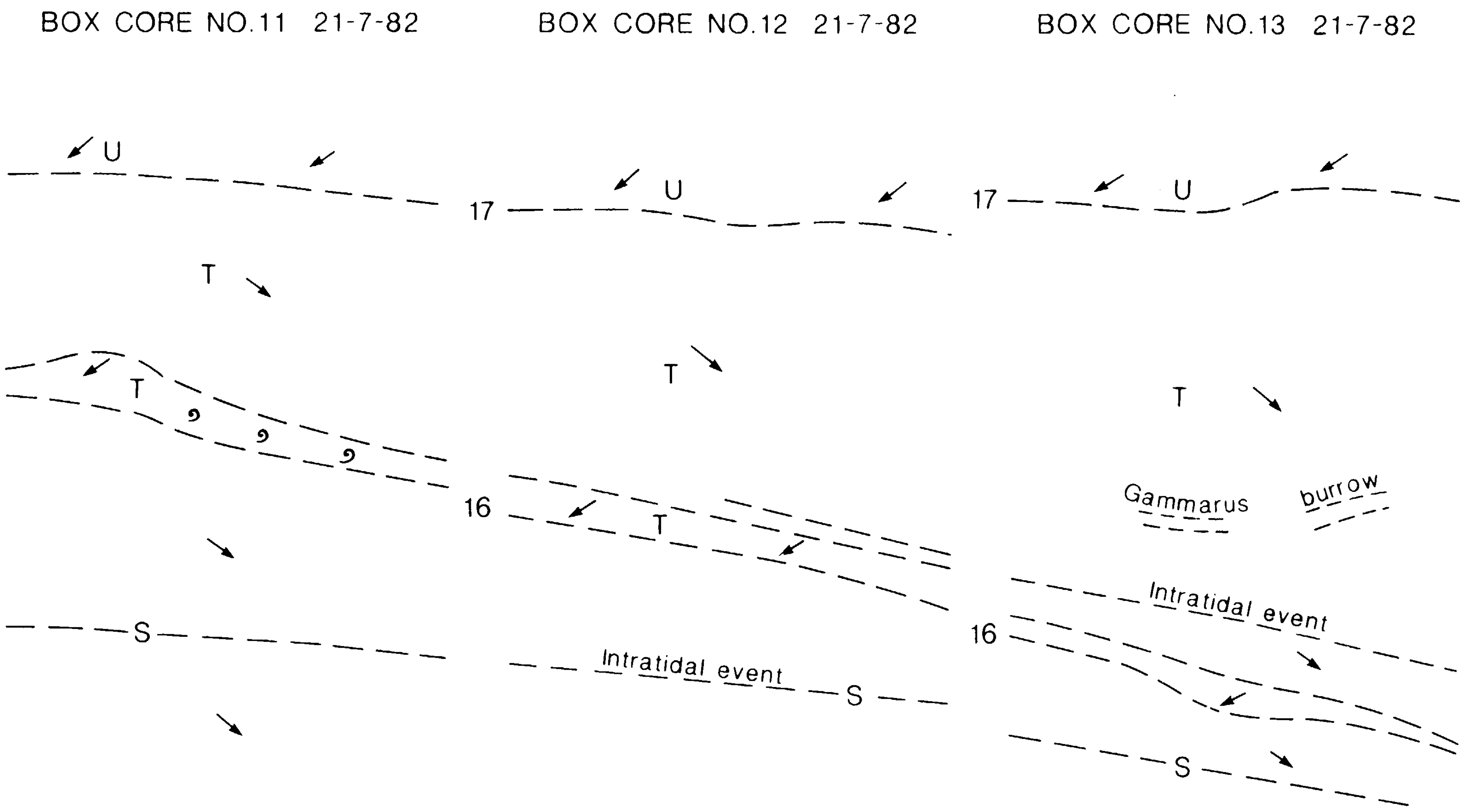
BOX CORE NO.10 20-7-82



BOX CORE NO: 11, 12 and 13

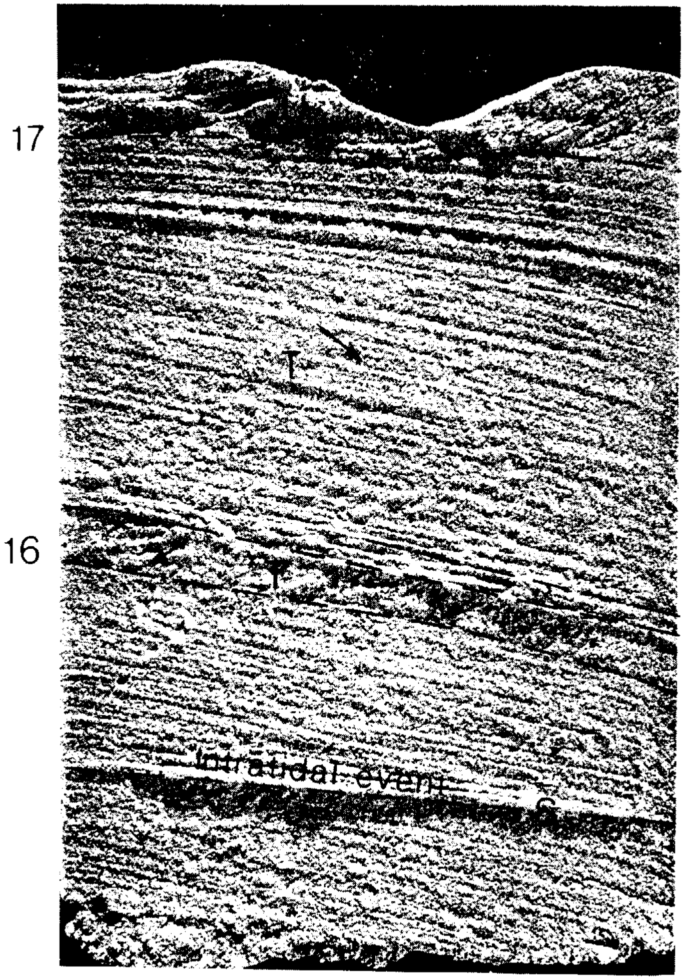
DATE: 21st July 1982 PREVIOUS HIGH WATER: 07.00

SEDIMENT	DEPOSIT CODE	HIGH WATER DATE/TIME	HIGH WATER NUMBER	DISCONTINUITIES
BOX No 11				
Strongly rippled Ebb deposit with prominent laminae	U	21st. 07.00	17	Ebb erosion surface
Both Flood and Ebb deposits preserved	T	20th. 18.30	16	Ebb erosion surface. Intra-tidal event showing shallower dipping laminae truncating and overlying steeper dip. More pronounced in Boxes 12 and 13 (see profile and text)
BOX No 12				
Strongly rippled Ebb deposit with prominent laminae	U	21st. 07.00	17	Ebb erosion surface and intra-tidal event (see Box No 11 and profile and text)
Flood deposit with shelly laminae Ebb deposit	T	20th. 18.30	16	Ebb erosion surface. Prominent intra-tidal event with marked change in packing and/or grain size shown by a change in relief on the impregnation. Shallower dipping laminae truncate and overlay steeper dipping laminae
BOX No 13				
Strongly rippled Ebb deposit with prominent laminae	U	21st. 07.00	17	Ebb erosion surface
Flood deposit with shelly laminae and Gammarus burrows. Rippled Ebb deposit	T	20th. 18.30	16	Ebb erosion surface. Prominent intra-tidal event showing shelly laminae dipping at 15° truncating and overlying sandy laminae dipping at 30°
Flood deposit	S			

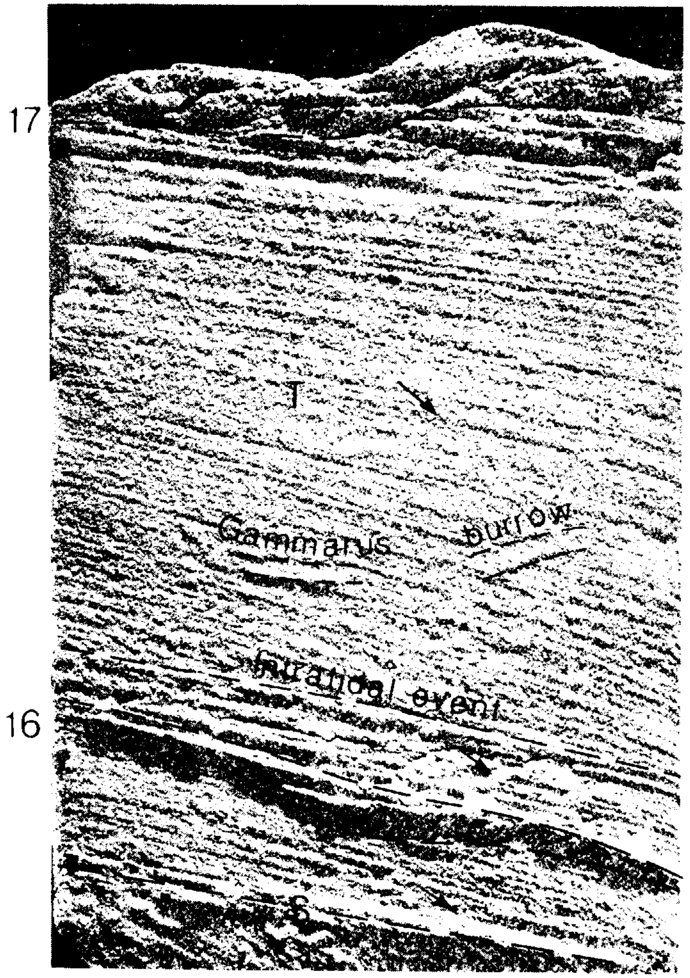

BOX CORE NO.11 21-7-82
BOX CORE NO.12 21-7-82
BOX CORE NO.13 21-7-82
U
U
U
17
17
T
T
T
T
T
16
16
Gammarus
burrow
Intratidal event
Intratidal event
S
S
S

BOX CORE NO.11 21-7-82

BOX CORE NO.12 21-7-82



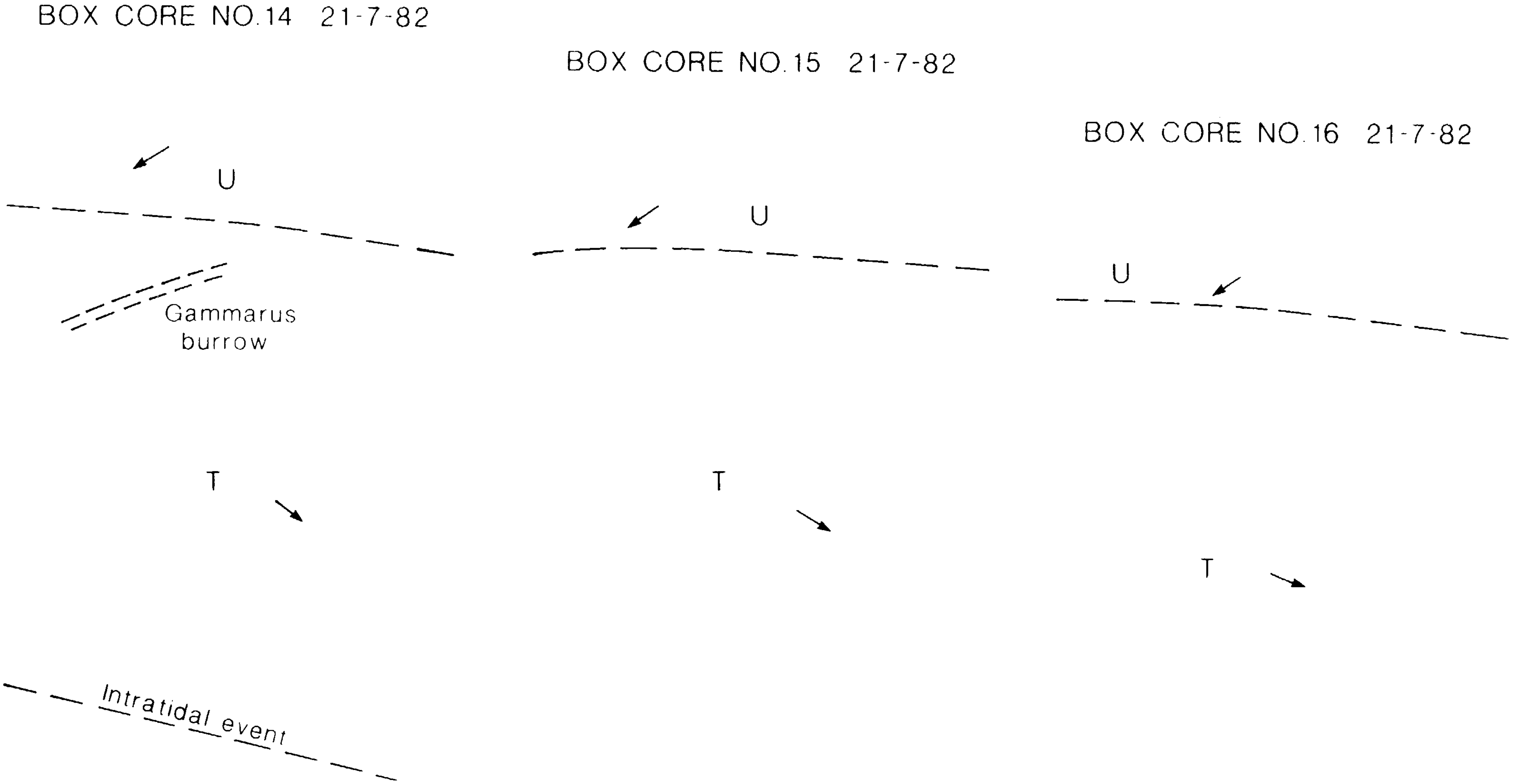
BOX CORE NO.13 21-7-82



BOX CORE NO: 14, 15 and 16

DATE: 21st July 1982 PREVIOUS HIGH WATER: 07.00

SEDIMENT	DEPOSIT CODE	HIGH WATER DATE/TIME	HIGH WATER NUMBER	DISCONTINUITIES
<u>BOX No 14</u>				
Strongly rippled ebb deposit with prominent laminae	U			
		21st. 07.00	17	Ebb erosion surface
Flood deposit disturbed by Gammarus burrowing	T			Intra-tidal event showing steeply dipping laminae overlying shallower dipping laminae
<u>BOX Nos 15 and 16</u>				
Rippled ebb deposit	U			
		21st 07.00	17	Ebb erosion surface
Flood deposit showing laminae decreasing in dip with time	T			


BOX CORE NO.14 21-7-82
BOX CORE NO.15 21-7-82
BOX CORE NO.16 21-7-82
U
U
U
Gammarus burrow
T
T
T
Intratidal event

BOX CORE NO.14 21-7-82

BOX CORE NO.15 21-7-82

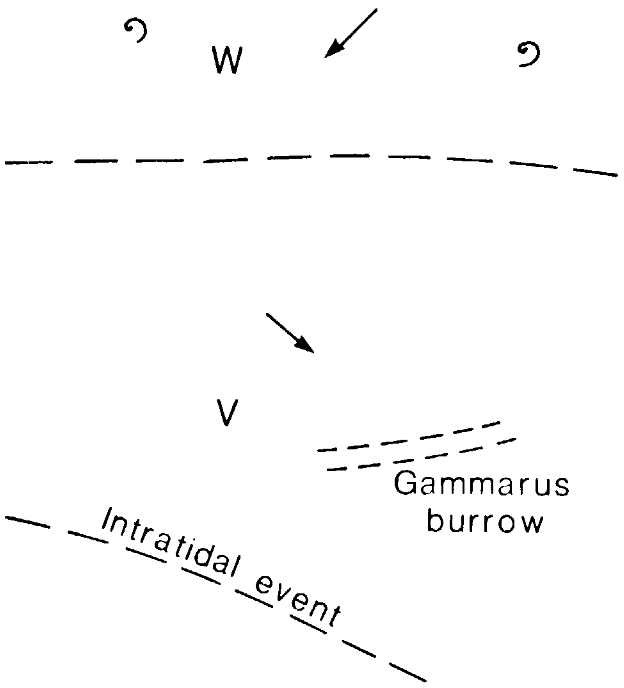
BOX CORE NO.16 21-7-82

BOX CORE NO: 17, 18 and 19

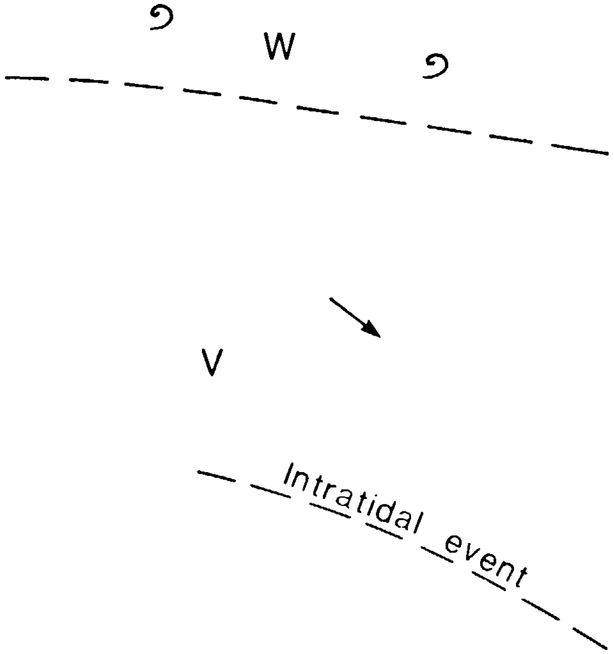
DATE: 22nd July 1982 PREVIOUS HIGH WATER: 07.45

SEDIMENT	DEPOSIT CODE	HIGH WATER DATE/TIME	HIGH WATER NUMBER	DISCONTINUITIES
Ebb deposit disturbed by Gammarus burrowing	W			
		22nd 07.45	19	Ebb erosion surface
Flood deposit with shelly laminae varying in dip from horizontal at the surface to 30° at the base. Diverging laminae present in steeper zones	V			

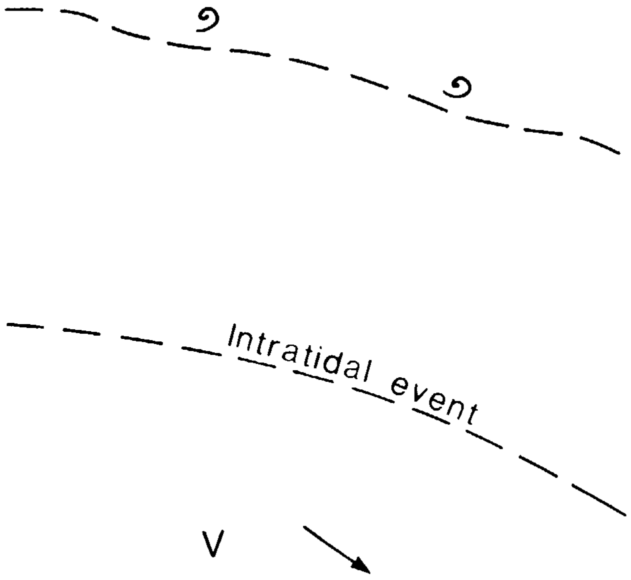
BOX CORE NO.17 22-7-82



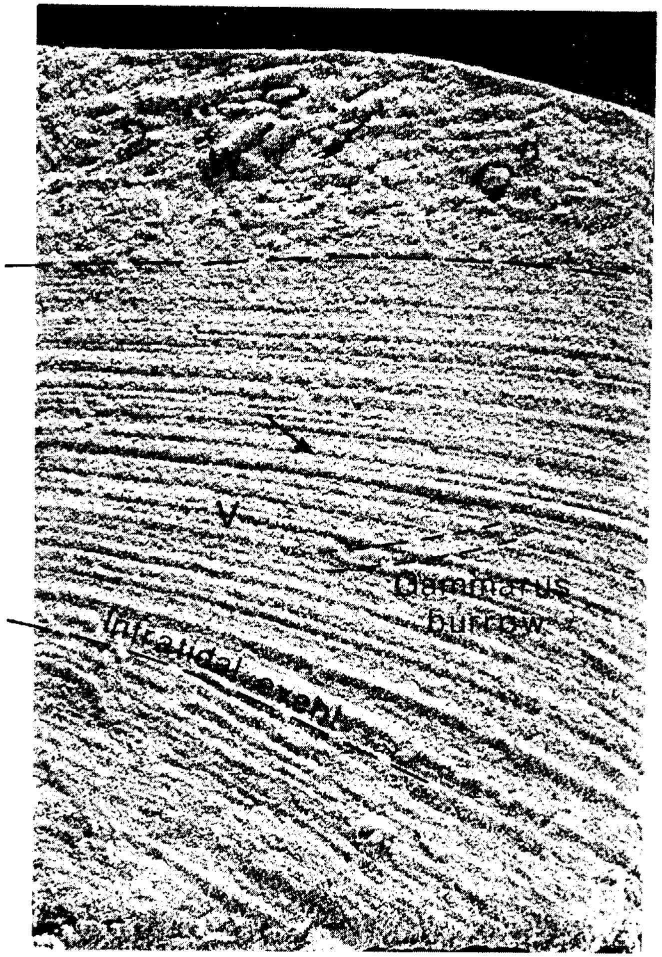
BOX CORE NO.18 22-7-82



BOX CORE NO.19 22-7-82



BOX CORE NO.17   22-7-82



BOX CORE NO.18   22-7-82

BOX CORE NO.19   22-7-82

with 62 mm of rainfall being recorded on Exmoor during the 24 hours leading up to 1600 on 12th July. The effects of this could be seen at the tide gauge at Barnstaple where on the morning of 12th July the water level began to rise two and a half hours before the predicted time. The water level at the following low tide (2000 hrs) was 0.76 m above that predicted. The river water carried large quantities of silt and organic debris into the estuary which resulted in the deposition of mud on the drying banks.

Two high water pause planes were sampled by Box No 1 and they, when correlated with Box No 2 and Boxes No 3 and 4 which were obtained on 16th July, are attributed to the high tides at 2215 on 12th and 2300 on 13th July. The later pause plane, being a further 25 hours after the period of heavy rainfall, contained a smaller proportion of fine sediment. The intervening high water at 1030 on 13th July was represented by a slight fining of the grain size which developed into a rippled erosion surface in Boxes No 2 and 3. Potentially a further three master beds associated with high tide could have been present but, in this crestal area where erosion is likely to be at its maximum, it is not surprising that they were not preserved.

Much of the flood deposition is characterised by cavernous sand. Such microstructure is produced by rapid flooding of sand, containing significant proportions of silts and clays, which trap air in the pore spaces.

Beneath the mud drape associated with the high water pause plane of 2215 on 12th July, which is very distinctive in Boxes 1, 2, 3 and 4 on account of its high silt content, there is a complex series of well-sorted sediments showing crossbedded ripple laminations. Thirteen discontinuities can be detected within a thickness of 10 cm. Four sedimentary layers are definitely ebb orientated. If it is assumed that none of these discontinuities were intra-tidal (see Boxes 11 - 13) (as opposed to inter-tidal) then the latest possible date of deposition of the earliest flood deposit would be 7th July; that is at the preceeding spring tides. However, these structures do not resemble spring tide deposition (see Boxes 14 - 19), but are more akin to those derived from the inter-play of flood and ebb tides at the crest of a bedform at neap tides (Langhorne, 1982). If this is the case then they must pre-date the 7th July and the fact that they have been preserved means that the sand body was more stable during the preceeding semi-lunar cycle and a trough had not passed through the area. This does not seem unreasonable because of the sinuous nature of the bedforms.

Analysis of Box No 7, obtained on 19th July, shows a complete sequence of clay draped, slack water pause planes from the 12th until the 17th July. In its position the box sampled master bedding which would have been in the lee of the crest at the earlier dates, hence the greater degree of preservation. As was the case with Boxes No 1 - 4, the dominant slack water pause plane of 2215 on 12th was very distinct and therefore provided a good reference for inter-relating the box cores.

Comparison of Boxes No 7 and No 4 shows that in the latter, alternate slack water pause planes only existed as remnants. This trend continued into Boxes No 2 and 3 in which the slack water pause plane of 1130 on 14th was not detected whilst that of 1030 on 13th only existed as a rippled ebb surface. It is tempting to infer that the absence of alternate slack water pause planes is related to the semi-diurnal inequality in the tidal flow and the sample positions near the crest but this cannot be verified without more detailed flow measurements.

In Box No 7 the master bedding associated with the high waters of 0415 on 18th and 0515 on 19th is represented by ebb erosion surfaces, whilst the intervening high water of 1645 on 18th, though not present in Box No 7 can be detected as a poorly developed slack water pause plane in Box No 8.

The younger structures in Box Core No 8 support the interpretation from Box No 7, but the older structures (prior to 1535 on 17th July), were disturbed during sampling probably due to high water content within the sediments at the time of sampling.

Box cores No 9 and 10 were obtained on 20th July. Both cores revealed ebb structures formed during the tide preceding the coring. Examination of the profiling data shows the upper part of the cores should consist of foreset bedding associated with the flood tide leading up to high water at 0515 on 19th (N). Beneath this should lie flood deposits from the previous tides (M and possibly L and K). This sequence can be seen in Box No 10, but in Box No 9 there is no clear evidence to differentiate the flood deposits associated with high tide at 1645 on 18th (M).

Box cores No 11 to 16 were obtained on 21st July and the profiling data shows that 11, 12 and 13 contained deposits associated with both the flood tides leading up to 0700 on 21st (T) and 1830 on 20th (S). The intervening master bedding is indeed well marked, but unexpectedly there is an equally pronounced horizon dipping in the flood direction beneath this horizon and a less marked discontinuity above it. The profiling data shows that these can only be intra-tidal, but on account of their prominence in comparison with the known inter-tidal horizon their presence is of considerable geological importance. A similar, but less obvious feature, occurs in Box core No. 14.

Box cores No. 14, 15 and 16 are solely flood deposits leading up to high tide at 0700 on 21st July. Box cores No. 17, 18 and 19 consist of thick flood foreset beds deposited on the tide leading up to high water at 0745 on 22nd July. They also contain intra-tidal changes of laminar divergence. Slope angles of flood laminae range from 0 degrees to 32 degrees.

The occurrence of erosional discontinuities and slack water pause planes for each of the Box cores is summarised in Table I.

5.4. Surface sediment sampling

Surface sediment samples were taken, on four occasions, at 1 m intervals across the sandwave C3D. The samples were taken by pressing a stiff plastic ring (diameter 5 cm) into the sand to a depth of 2 cm and then undercutting the ring to extract the sample contained within it. The samples were obtained from a larger area than was strictly necessary for grain size analysis, in an attempt to reduce any errors arising from grain size variation across ripples. This was most marked with the occurrence of mud drapes at the beginning of the survey.

The samples were split to give 25 g sub-samples suitable for grain size analysis at 0.25 phi intervals. Using the data obtained, statistical parameters were calculated using the method described by Seward-Thompson and Hails (1973) with standard deviations between 0.290 and 0.450. Most samples were negatively (coarse) skewed (up to -2.35). All positively skewed (up to +1.20) samples had a silt and clay fraction exceeding 1% of

DATE (JULY 82)	HIGH WATER TIME	HIGH WATER NUMBER	BOX CORE NUMBERS																
			1	2	3	4	7	8	9	10	11	12	13	14	15	16	17	18	19
22	0745	19															ED	ED	ED
21	1920	18																	
21	0700	17									ED	ED	ED	ED	ED	ED			
20	1830	16									ED	ED	(ED)	ED	ED	ED			
20	0610	15							ed	ed									
19	1740	14							-	-									
19	0515	13					ED	ED	-	-									
18	1645	12					-	(PP)	ED	ED									
18	0415	11					ED	ED	-	PP									
17	1535	10					(PP)	(PP)	-										
17	0315	9					PP		ed										
16	1420	8			ED	ED	PP												
16	0205	7			(PP)	PP	PP												
15	1325	6	ED		(PP)	(PP)	PP												
15	0050	5	-		(PP)	PP	PP												
14	1130	4	-	(PP)	-	(PP)	PP												
13	2300	3	PP	PP	PP	PP	PP												
13	1030	2	(ED)	ED	PP	(PP)	PP												
12	2215	1	PP	PP	PP	PP	PP												

SLACK WATER PAUSE PLANES:

- : Missing
pp : Possible
(PP) : Probable
PP : Definite

EROSIONAL DISCONTINUITIES:

- : Missing
ed : Possible
(ED) : Probable
ED : Definite

TABLE I The occurrence of erosional discontinuities and slack water pause planes in Box Cores the total dry weight. All samples were leptokurtic (excessively peaked) with kurtosis values in the range 4.0 to 10.2.

One sample, obtained underwater in a ponded trough on 15th July; that is three days after exceptionally heavy rainfall, contained an anomalously high silt and clay content of 10.8%. This obviously gave it a correspondingly finer mean grain size of 2.65 phi, a higher standard deviation of 0.59 phi and a high positive skewness of 1.47. Because it was obtained in an exceptional location, this sample has been omitted from the regression analysis. It does however show that in these circumstances mud deposition can also occur at low water. The mud, having been deposited in the trough, stands a good chance of being preserved as a bottomset with the advance of the adjacent bedform on the ensuing flood tide. The fact that the sediment is well sorted and that the variation in mean size is slight, inevitably means that it is difficult to draw conclusions about the temporal and spatial variation of the sediment across the sandwaves in this area.

The four graphs in figure 10 show the variation in sediment grain size across the bedform as sampled on 15th (neap tides), 18th, 20th, and 22nd July (spring tides). The profile level (Y axis) is measured below datum and therefore higher numbers indicate lower positions on the bedform flanks.

The sediment/profile distributions have correlations significant at the 99% confidence level on 15th and 18th July demonstrating a coarse to fine sediment grading from crest to trough. This suggests that at, or near neap tides, the finer sediments are winnowed from the area of high bed shear stress at the crest and are deposited on the lower slopes. No such

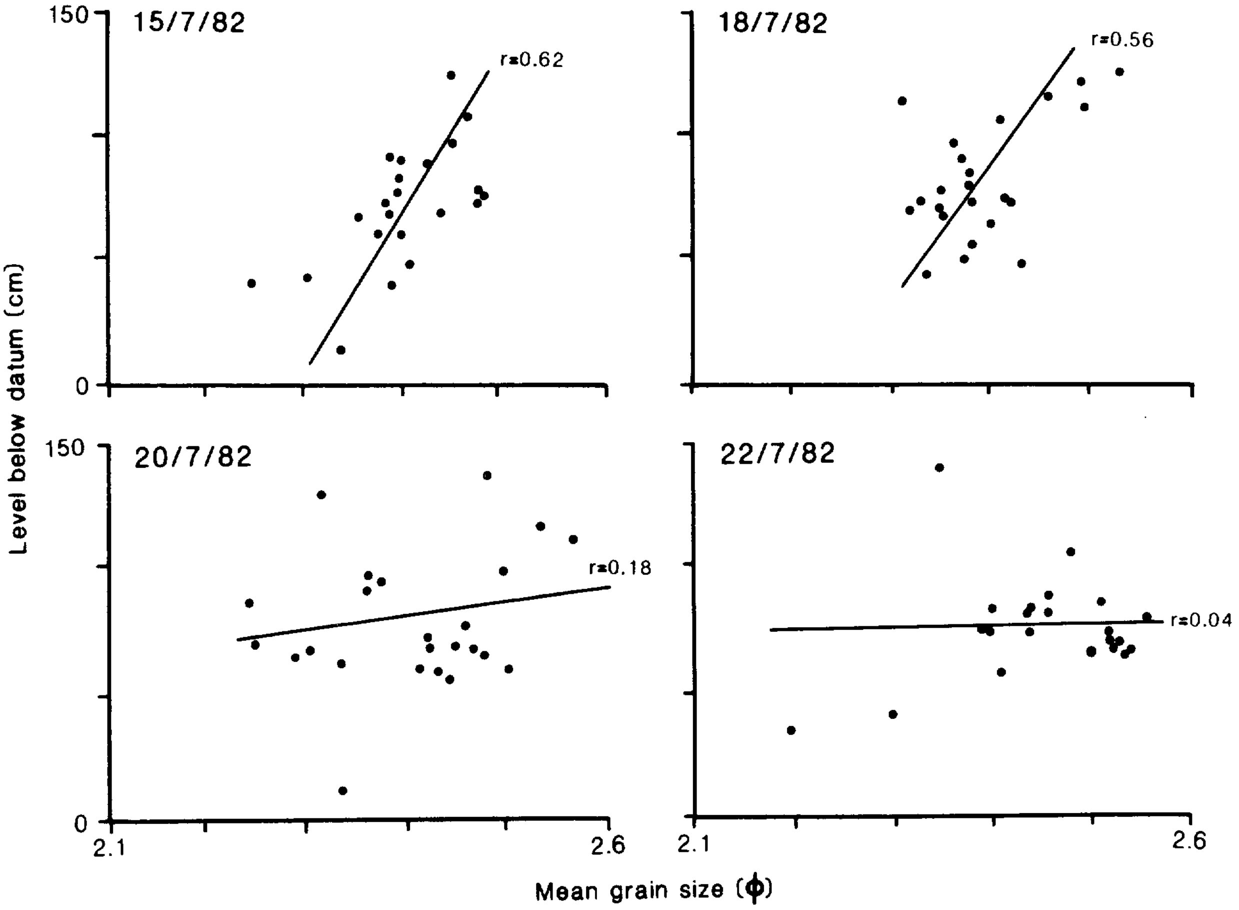


FIGURE 10 Mean sediment grain size as a function of sandwave profile

correlation exists for the data from 20th and 22nd July. A possible explanation for this lack of correlation is that at spring tides, large quantities of sediment is transported in suspension. Soulsby (personal communication) has observed concentrations of up to 1.8 kg m $^{-3}$, 13 cm above the bed at spring flood tides. The mean grain size of the suspended sediments, based upon pumped samples is 2.60 which is comparable with sediment sampled at low tide. At spring tide high water the suspended sediments will settle to form a blanket with no spatial variation. As no blanket could be formed at low water because the bedforms dry out, this theory assumes that bedload transport on the ebb tide is not sufficient to significantly affect the blanketing. Most of the samples were obtained from the flood tide stoss flank which is indeed sheltered from ebb tide flow.

The variation in surface sediment grain size across a sub-aerial dune has been described by Barndorff-Nielsen, Dalsgaard, Halgreen, Kuhlman, Møller and Schou (1982). They conclude that the grain size increases with increasing shear stress towards the crest and decreases rapidly down the lee slope. The latter being aided by the development of a vortex which carries finer sediment back towards the base of the lee slope. No such data seems to be available from the marine environment where, at best, most authors give a poorly defined mean grain size.

5.5. Sediment dispersion

Sand coloured with red fluorescent dye was inserted into the stoss slope of sandwave B2C on the low water of the morning 17th July. Figure 11 shows the dispersion of this dyed sand after one and after three tidal cycles. A further experiment utilising sand dyed blue failed, due to the difficulty

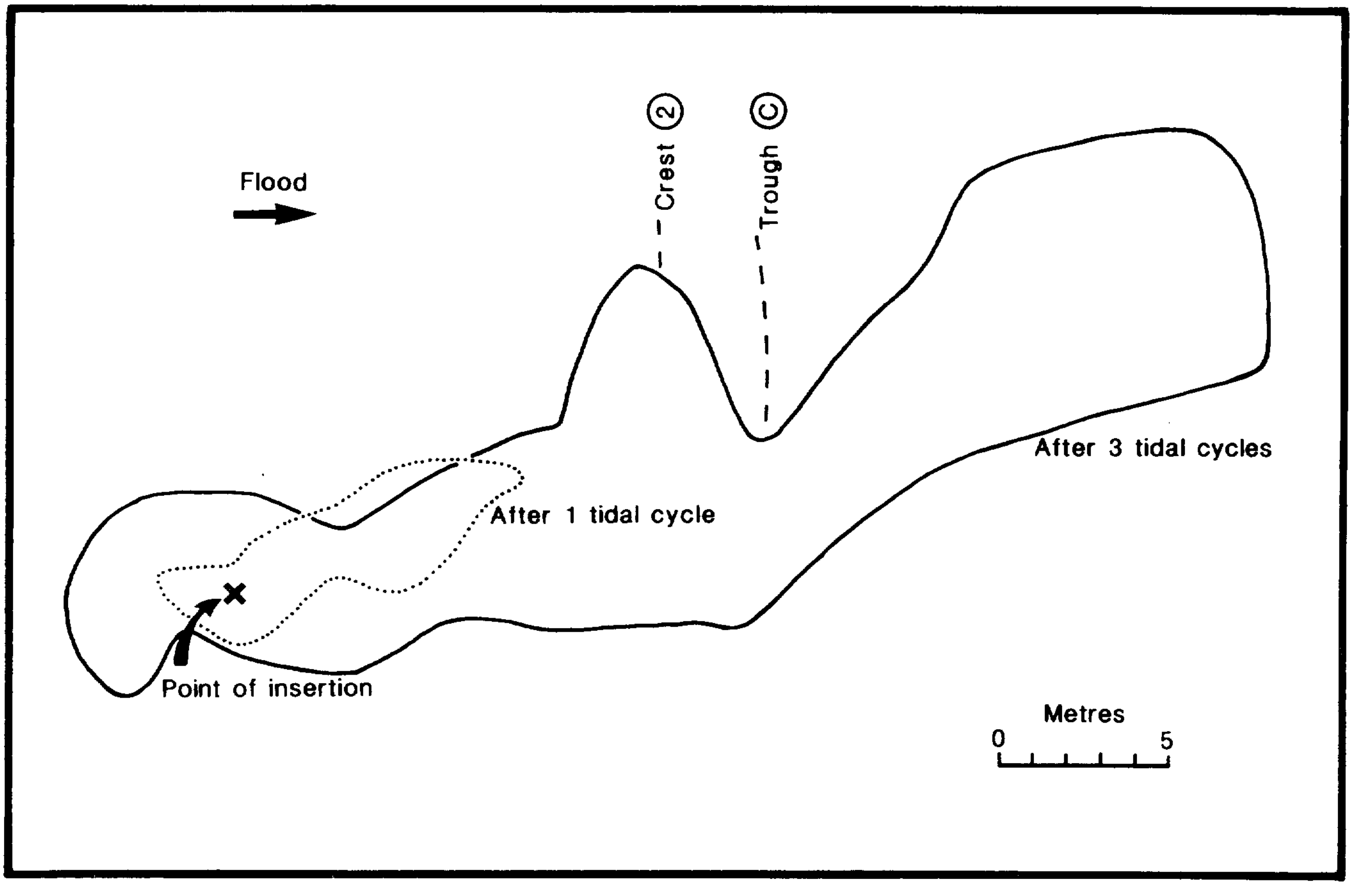


FIGURE 11 Fluorescent tracer dispersion

in distinguishing it from naturally occurring shell material which fluoresced with a similar colour in ultra violet light.

The dispersion of the red dyed sand confirms the marked flood-dominance of the area. The lack of material in trough C indicates a lateral run-off which either removed or buried the tracer. The surfeit of material near the crest was probably associated with the formation of an ebb cap structure.

The profiling data for these days showed only 1 cm change in the overall height of the bedform. The fluorescent tracer was initially buried to a depth of 2 cm and so a 'dynamic equilibrium' of the bedforms has to be envisaged in which, though surficial sand movement takes place, little change occurs in the overall shape of the bedform.

5.6. Hydrodynamic environment

In this report bedform dynamics and internal structure have been related to tidal range. At any particular location tidal range may be expected to correlate with tidal flow, in terms of velocity and duration. However, owing to the effects of morphology, it is not generally possible to use such relationships to assess the flow regime elsewhere in the same estuary, or indeed on the same bank. Therefore, in order to draw conclusions on the sediment transport processes which may be applied elsewhere, correlation with tidal range is not sufficient and flow measurements have to be made in the area of study. However, the making and interpretation of flow measurements in areas of bedforms continues to elude many sediment transport projects.

The rate of mass sediment transport is proportional to a high power of the bed shear stress, or friction velocity. These values are usually obtained by extrapolation from near bottom velocity profiles, but the results are only valid if the profiles are logarithmic and continue as such beneath the lowest measuring sensor to the bed. Logarithmic velocity profiles are only likely to occur if the bed roughness, derived from both the sediment grain size and bedform, is uniform upstream from the measuring position. The necessary distance upstream is considered to be between 30 and 100 times the height of the measuring sensors. In this study an array of velocity sensors were nominally mounted at 17, 45 and 72 cm above the bed and the resulting calculated values of the roughness length, Zo, fluctuated through several orders of magnitude. This was not unexpected and is typical of the results which have been obtained in many other studies conducted in areas of bedforms. Such results indicate that this is not a satistactory method to calculate the friction velocity, U_*. As an alternative, the velocity profile data was used for extrapolation upwards to calculate the flow velocity at a height of 100 cm above the bed (U_{100}). Although these values are still dependent upon the shape and goodness of fit of data points to the velocity profile, the errors are smaller. U_{100} therefore used to characterise the flow, but though relatively more accurate, its relevance to sediment transport is of course dependent upon the form of the velocity profile.

The velocity sensors were attached to a mast which was hammered into the stoss flank of the sandwave (B2C) close to the crest. The position of the mast was optimised to measure the flow on the dominant flood tide, but in this position it was of little value in measuring the flow on the ebb tide. Table 2 gives the duration of flow in excess of given veloctities at U_{100}

on the flood tide. This characterisation of the flow only covers the period when all three velocity sensors were submerged (ie depth > 72 cm at the measuring position). It does not cover the period of up to 40 minutes prior to this when, with relatively high Froude numbers, sediment transport would have been taking place.

Accepting a threshold velocity $U_{100}(c)$ for the initiation of movement of sand with a median diameter of 0.21 mm of 20 cm s^{-1} ($U^* = 1.6$ cm s^{-1}) (Miller, McCave and Komar, 1977) then even at neap tides the flood tide velocities are well in excess of threshold (see Table 2). Comparison of cross-sectional profiles obtained at neap tides gives a mean change in bed level of 2.5 cm. This would suggest that though sediment transport is taking place, erosion is approximately equal to deposition resulting in only a small net change in bed level.

Date	High water time (BST)	Tide No	Range (m) (Flood)	Duration that U_{100} exceeded given velocities (cms^{-1}) in minutes									
				40	50	60	70	80	90	100	110	120	130
15 July	0050	5	4.7	138	111	42							
	1325	6	4.4	121	88	14							
16 July	0205	7	4.55	141	96	16							
	1420	8	4.6	135	96	10							
17 July	0315	9	4.85	153	115	63	18						
	1535	10	5.05	NO DATA OBTAINED									
18 July	0415	11	5.42	138	108	84	39	4					
	1645	12	5.67	>90	>83	73	18						
19 July	0515	13	6.02	>140	125	100	78	37	11				
	1740	14	6.27	>135	126	90	75	48	8				
20 July	0610	15	6.5	>135	116	96	78	51	18				
	1830	16	6.8	>130	118	95	85	49	28	18			
21 July	0700	17	6.9	>110	>105	>90	70	55	37	25	1		
	1920	18	7.12	>130	>120	117	100	87	61	48	36	24	7
22 July	0745	19	7.05	NO DATA OBTAINED									
	2020	20	7.2	>130	>115	102	84	66	46	27	14	3	
23 July	0830	21	7.0	NO DATA OBTAINED									
	2050	22	7.13	>130	120	102	91	70	47	33	7		
24 July	0950	23	6.75	>130	118	105	96	83	60	35	7		
	2130	24	6.8	>130	124	110	90	(75)	(50)	(35)	(20)	4	
25 July	1000	25	6.35	137	120	105	93	80	53	25			
	2220	26	6.3	145	126	116	100	89	47	33	1		

—— = rig repositioned

( ) = estimate due to incomplete data

> = duration exceeded given time: first recorded velocity exceeded given velocity

TABLE II The duration of flow in excess of given velocities on the flood tide (calculated at 100 cm above the bed)

6. DISCUSSION

Much economic and academic geology is based upon the interpretation of sedimentary structures in order to establish the nature of the palaeo-environment.

Accepting that bedforms and their corresponding structures are restricted to particular flow conditions, the concept which makes stratigraphic interpretation possible, it is necessary to consider how such structures are preserved. The preservation of a bedform in a dynamic environment requires that the movement of the bedform is arrested and, in most cases, that it becomes buried. If complete bedforms are to be preserved, the arresting of movement brought about by reduction in flow, must be very rapid. A gradual change in flow would result in the modification of the form of the bedform in order to maintain equilibrium with the new flow regime. If this was not the case then the concept of stratigraphy would be ill founded. The best documented examples of arresting of movement and burial are those from the Netherlands where in most cases man's interference has caused rapid and marked changes in the flow regime (Boersma and Terwindt, 1981a and b, Van den Berg, 1982, Nio, Siegenthaler and Yang, 1983). Similar natural examples must be expected in other deltaic environments and sedimentary basins but in these cases the time scales need not be so well understood. Nevertheless, all sedimentary rocks produced by sediment movement exhibit structure, be it large scale or microscopic, unless it has been subsequently destroyed by bioturbation or chemical action.

In reality structures of complete bedforms from a dynamic environment are seldom preserved. Most structures from such environments are limited to those from the base of the bedforms; the higher levels having either been removed or modified by changes in the flow conditions. For example if we consider tidal bedforms, be they large sandwaves or ripples, migrating through an area, the passage of a trough will remove the structure of the preceding bedform. It is only if there is net deposition in a particular area that troughs will pass at higher and higher levels and the basal structures will be truncated and preserved. The possibilities of preserving the crestal structures of mobile bedforms seems remote (Langhorne,1982). In those places where crestal features are preserved, basal structures must also be preserved, except in exceptional geological circumstances.

In decreasing flow environments, the once dynamic bedforms will degenerate and become moribund (Kenyon, Belderson, Stride and Johnson, 1981). Angle of repose slopes will slump and these sediments, together with those from suspension and intermittent bed load transport will collect in the relatively low bed shear stress regions of the lower flanks and troughs. It is important that these sediments and their structures should be distinguished from those associated with active bedforms.

The foregoing discussion suggests that sedimentary stratigraphy should concentrate on the formation and behaviour of troughs and their associated flow regime. The sedimentology of these, less elegant, areas is made complicated by such factors as: the development of lee eddies and reversal of flow, transverse flow channelled between bedforms, reduction in bed shear stress and better potential for deposition of fine sediments, lee slope avalanching and the accumulation of coarse sediments at the base of the slopes and hence less likelihood for subsequent erosion, and sediment settling from suspension, all of which may contribute to the direction and size of particles moving and the resulting structures.

7. CONCLUSIONS

The inter-tidal zone affords the opportunity to make measurements in precise positions in relation to accurately known time scales. In this study such control was obtained by conducting levelling surveys, on a daily basis, with reference to fixed marks and verifying internal structures using box cores.

Regrettably, it is less easy to obtain data of a similar accuracy from the sub-tidal zone. When making comparisons between inter-tidal and sub-tidal sedimentary structures it is important to appreciate the differences in hydrodynamic processes and to assess their relative importance. For example, the effect of surface waves is depth dependant and therefore will vary with tidal range. Similarly, prior to exposure, high flow velocities may occur, possibly channelled between bedforms. In both cases, the actual modification to the bedform and its internal structure will be limited by the duration of the action.

The main conclusions from this study may be summarised as follows:

1. Using repetative cross sectional profiles obtained on a drying bank, it is possible to postulate internal structures which correspond with master bedding as defined by Allen (1980b).

   In all cases where the positions of master bedding were anticipated they were confirmed by detectable sedimentary structures in box cores. However, even in areas of net accretion, erosion can occur and master bedding may be truncated or lost. Examination of box cores also revealed that additional structures, similar to those associated with high and low water pause planes, also occured. These could not be correlated with pause planes and are considered to be formed by intra-tidal events. Further complications in the analysis of box cores can be caused by meteorological conditions distorting the neap/spring depositional sequences. All these factors effect the number and thickness of sedimentary bundles and may lead to false assumptions being made in their interpretation when preserved in the geological record.

2. The mechanism of movement indicates that crestal structures are unlikely to be preserved. In those cases where they are found in the geological record, particular consideration should be given to the uniqueness of the sedimentological and hydrodynamic conditions. Because of the limited potential for crestal structures to be preserved, more attention should be given to studies of the lower flanks and troughs of present day bedforms. However, in such positions, the hydrodynamic processes are probably more complex.

3. Surface sediment sampling surveys conducted across the bedforms revealed the well sorted nature of the sediments in the area. This suggests an equilibrium sedimentological environment with mobile sand circulating around the bank. Sampling surveys conducted near to neap tides showed a coarse to fine sediment grading from crest to trough. No such correlation was detected towards spring tides. Despite suspended sediment samples being of comparable grain size, the lacquer impregnation technique for analysing box cores consistantly revealed slack water pause planes.

4. Sediment dispersion studies using fluorescent dyed sand supported the concept that, even when the form of a bedform remains stable (at

neap tides), the surface sediments may be mobile.

5. Field observations showed that, in the flood dominated study area, ebb caps were formed by the erosion of the subordinate ebb tide. The form and positions of these features make them particularly vulnerable to erosion by the subsequent flood tide and therefore their potential for preservation seems remote.

6. The deposition of fine sediment from suspension was observed at low tide at the beginning of the field study thereby potentially forming flaser bedding. Such deposition was particularly pronounced after a period of heavy rainfall which caused large volumes of fine sediment to be carried into the estuary. Limited examples of flaser bedding also occurred when the receeding tide left ponds in troughs between the sandwaves.

7. Microscopic examination of box cores frequently revealed the presence of cavernous sand. These structures can only be formed when the sediments are exposed above the water surface and therefore may be a major diagnostic indicator discriminating inter-tidal from sub-tidal sediments. They are however easily destroyed by compaction and therefore their absence need not be significant.

8. Lag cross correlation techniques were used with the sequential profile data to study form change and migration. Because of the out-of-phase relationships with tidal range they indicated hystereses. For a given tidal range, the migration was less when the tidal range was increasing between neap and spring tides than it was when the range was decreasing. In contrast, the correlation was greater with

decreasing tidal range. However, these conclusions must be treated with caution because the data was limited.

The main objective of this report is to emphasise that even in a carefully controlled study, in which the time scales are known accurately, it is nevertheless often difficult to interpret individual structures. This should be appreciated by those who attempt to detect diurnal or semi-lunar cycles in rocks which were formed several million years ago.

It is regrettable that only a few sedimentologists have experience from working on both present day hydrodynamic bedforms and palaeo-stratigraphy, because it is probably only they who, in this context, can distinguish between fact and inference (Nio, Schuttenhelm and Van Weering, 1981).

8. ACKNOWLEDGEMENTS

The authors wish to acknowledge and thank their colleagues at IOS Taunton who have assisted with this project. Particular thanks are owed to Christine Kemp for the preparation of the diagrams and Christine Hollands for her efficiency in word processing.

9. REFERENCES

ALLEN, J.R.L. 1973. Phase differences between bed configuration and flow in natural environments, and their geological relevance. Sedimentology, 20, 323 - 329.

ALLEN, J.R.L. 1980a. Sand-wave immobility and the internal master bedding of sand-wave deposits. Geological Magazine, 117, 437 - 446.

ALLEN, J.R.L. 1980b. Sand-waves: a model of origin and internal structure. Sedimentary Geology, 26, 281 - 328.

ALLEN, J.R.L. 1982. Mud drapes in sand-wave deposits: a physical model with application to the Folkestone Beds (early Cretaceous, southeast England). Phil. Trans R.Soc. London, A306, 291 - 345.

ALLEN, J.R.L. and FRIEND, P.F. 1976. Relaxation time of dunes in decelerating aqueous flows. Journal of the Geological Society London, 132, 17 - 26.

ALLEN, P.A. and HOMEWOOD, P. 1984. Evolution and mechanics of a Miocene tidal sandwave. Sedimentology, 31, 63 - 81.

BARNDORFF-NIELSEN, O., DALSGAARD, K., HALGREEN, C., KUHLMAN, H., MØLLER, J.T. and SCHOU, G. 1982. Variation in particle size distribution over a small dune. Sedimentology, 29, 53 - 65.

BOERSMA, J.R. 1969. Internal structure of some tidal mega-ripples on a shoal in the Westerschelde estuary, the Netherlands. Report of a preliminary investigation. Geologie en Mijnbouw, 48, 409 - 414.

BOERSMA, J.R. and TERWINDT, J.H.J. 1981a. Neap-Spring tide sequences of intertidal shoal deposits in a mesotidal estuary. Sedimentology, 28, 151 - 170.

BOERSMA, J.R. and TERWINDT, J.H.J. 1981b. Berms on an intertidal shoal: shape and internal structure. In: Holocene Marine Sedimentation in the North Sea Basin. IAS Special Publication no. 5: Blackwell, Oxford, 39 - 50.

BOUMA, A.H. 1969. Methods for the study of sedimentary structures: John Wiley and Son, New York, 458pp.

DOODSON, A.T. and WARBURG, H.D. 1941. Admiralty Manual of Tides: Hydrographic Department, London, 270pp.

HAWLEY, N. 1981. Flume experiments on the origin of flaser bedding. Sedimentology, 28, 699 - 712.

IMBRIE, J. and BUCHANAN, M. 1965. Sedimentary structures in modern carbonate sands of the Bahamas. In : Primary sedimentary structures and their hydrodynamic interpretation. Special Publication of SEPM no. 12, 149 - 172.

KENYON, N.H., BELDERSON, R.H., STRIDE, A.H. and JOHNSON, M.A. 1981. Offshore tidal sand-banks as indicators of net sand transport and as potential deposits. In: Holocene Marine Sedimentation in the North Sea Basin. IAS Special Publication no. 5: Blackwell, Oxford. 257 - 268.

LANGHORNE, D.N. 1982. A study of the dynamics of a marine sandwave. Sedimentology, 29, 571 - 594.

McCAVE, I.N. 1970. Deposition of fine grained suspended from tidal currents. Journal of Geophysical Research, 75, 4151 - 4159.

MILLER, M.C., McCAVE, I.N. and KOMAR, P.D. 1977. Threshold of sediment motion under unidirectional currents. Sedimentology, 24, 507 - 527.

NIO, S.D. 1976. Marine transgressions as a factor in the formation of sandwave complexes. Geologie en Mijnbouw, 55, 18 - 40.

NIO, S.D., SIEGENTHALER, C. and YANG, C.S. 1983. Megaripple cross-bedding as a tool for the reconstruction of the palaeo-hydraulics in a Holocene subtidal environment, S.W. Netherlands. Geologie en Mijnbouw, 62, 499 - 510.

NIO, S.D., SCHUTTENHELM, R.T.E. and VAN WEERING, T.C.E. 1981. Holocene marine sedimentation in the North Sea Basin: an introduction. In: Holocene Marine Sedimentation in the North Sea Basin. IAS Special Publication no. 5: Blackwell, Oxford. 1 - 3.

REINECK, H.E. and SINGH, I.B. 1973. Depositional Sedimentary Environments with reference to terrigeneous clastics: Springer-Verlag, Berlin, 439pp.

REINECK, H.E. and WUNDERLICH, F. 1968. Classification and origin of flaser and lenticular bedding. Sedimentology, 11, 99 - 104.

SEWARD-THOMPSON, B.L. and HAILS, J.R. 1973. An appraisal of the computation of statistical parameters in grain size analysis. Sedimentology, 20, 161 - 169.

TERWINDT, J.H.J. 1971. Lithofacies of inshore estuarine and tidal inlet deposits. Geologie en Mijnbouw, 50, 515 - 526.

TERWINDT, J.H.J. 1981. Origin and sequences of sedimentary structures in inshore mesotidal deposits of the North Sea. In: Holocene Marine Sedimentation in the North Sea Basin. IAS Special Publication no. 5: Blackwell, Oxford. 4 - 26.

TERWINDT, J.H.J. and BREUSERS, H.N.C. 1972. Experiments on the origin of flaser, lenticular and sand-clay alternating bedding. Sedimentology, 19, 85 - 98.

VAN DEN BERG, J.H. 1982. Migration of large scale bedforms and preservation of cross bedded sets in highly accretional parts of tidal channels in the Oosterschelde, S.W. Netherlands. Geologie en Mijnbouw, 61, 253 - 263.

VAN VEEN, J. 1935. Sandwaves in the North Sea. International Hydrographic Review, 12, 21 - 29.

VISSER, M.J. and DE MOWBRAY, T. 1982. Large-scale cross-bedded sets in sub-recent and fossil depositional environments. IAS 3rd European Meeting, Copenhagen, Abstracts, 91 - 92.

WHITTEN, D.G.A. and BROOKS, J.R.V. 1972. The Penguin Dictionary of Geology: Penguin Books, Harmondsworth, 520pp.

YALIN, M.S. 1972. Mechanics of sediment transport: Pergamon Press, Oxford. 290pp.

10. APPENDIX

BOX CORING - THE TECHNIQUE

The larger section of the Senckenberg box, which is open at one side and at the base, is pushed (or hammered) vertically into the bed, taking care not to disturb any surface features. The other section, or lid, is then pushed in alongside the open side of the box thereby enclosing the sample except at the base. Because the boxes are open at the base, and have no closing mechanism, they have to be excavated from one side and tipped horizontally before being removed. The excavation of course, destroys the natural structure, but if the sediment is replaced and the position carefully marked further samples can be taken avoiding the disturbed zone. After extraction the lid is removed. Any surface features are preserved by covering them with soft paper or plastic membrane and filling the void with loose sand. The lid is then replaced from the opposite end, which totally encloses the sample.

In the laboratory the lid is removed and replaced from the same end, under the box, exposing the vertical section. The sample is allowed to dry at room temperature. Any attempts to force dry at higher temperatures are likely to cause a hard crust of salt to form which inhibits subsequent lacquer impregnation. The impregnating medium is a lacquer/thinner mixture; the viscosity and amount of which is adjusted according to the grain size and packing so that penetration occurs to about 1 cm into the exposed surface (area: 20 x 30 cm). In practice, for fine/medium sand 300 cm^3 of 50/50 mixture is required. A piece of cheese cloth is placed over the exposed, dry surface to prevent disturbance and this is painted evenly with the lacquer. After about three days, when the lacquer is dry, the impregnation is carefully removed from the box and all loose, unimpregnated sand gently brushed off (Figure 12). This leaves the structural features exposed with deeper impregnation occurring in the finer less compacted sediment.

FIGURE 12 Laboratory preparation of box core