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SANDWAVE MOBILITY IN START BAY, DEVON

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A. D. Bailey
SUMMARY

The work presented in this thesis concerns the investigation of the movement and stability of the sandwaves on the Skerries Bank in Start Bay, Devon.

Initially, side scan sonar records of the sea bed of Start Bay were examined and an area on the Skerries Bank was selected for detailed study.

The positions of the sandwaves in this area were accurately found by echo sounder, using sextants for navigation. By repeatedly surveying the same areas, the progressive displacement of the sandwaves was found over a period of two years. The magnitude and direction of the sandwaves' displacement was predicted from tidal current measurements and there was good agreement with the measured displacement.

One particular sandwave was subjected to a very detailed investigation of its reciprocative displacement, for a period of several months. A diver-operated acoustic rangemeter system was used for this work. It was found that the reciprocative displacement, predicted from tidal current measurements, was an order of magnitude smaller than the measured displacement. Reasons for this are discussed. The reciprocative motion of the dunes has also been measured.

The effect of sediment grain size on sandwaves has been investigated. It has been found that sandwaves only occur when the sediment grain size lies between 0 and 2 phi. Also, the relationship between water depth and sandwave wavelength has been examined. Measurements have been made of the sediment characteristics at a number of points over a sandwave profile. The effect of storms on sandwave shape has been observed. It has also been found that the
'catback' sandwave cross-section occurs when sandwaves bifurcate.

From these results a better understanding has been obtained of the way in which sandwaves move and of the stability of sandwaves, on a tide-swept Bank, such as the Skerries.
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CHAPTER 1

INTRODUCTION

1.1 SANDWAVES IN START BAY

Sandwaves occur in many tide-swept areas with sandy sea beds. They are caused by the action of the current on the mobile sea bed. This action causes regular wave-like bedforms to appear. In Start Bay these sandwaves have wavelengths ($\lambda$) of about 200m and amplitudes ($H$) of between 1 and 20m. Two smaller bedforms also occur with the sandwaves. They are dunes ($\lambda \approx 10m$, $H \approx 20-100cm$) and ripples ($\lambda \approx 40 cm$, $H \approx 4 cm$) (Fig. 1.1.1).

Under the action of a uni-directional current, the sandwaves will have a saw-toothed cross-section (Fig. 1.1.2(a)) and will move in the direction of the current. If there are two currents of equal strength flowing alternately in opposite directions, the sandwaves will have a symmetrical triangular cross-section and, over a long period, will remain stationary (Fig. 1.1.2(b)). However, if one current is slightly stronger than the other, the sandwave will again assume a saw-toothed cross-section and will move in the direction of the stronger current (Fig. 1.1.2(c)).

Start Bay (Fig. 1.1.3) is situated on the south coast of Devon, England, near Dartmouth. It is bounded to the south by Start Point and to the north by the Mewstone. Most of the sea bed in the Bay is between 10m and 30m in depth. In the south the Skerries Bank rises to within 5m of the sea surface. The Skerries Bank consists mainly of coarse shelly sand. Over the Bank the ebb tide runs in a southerly direction and the flood tide runs in a northerly direction. The two tides are of similar strengths. Sandwaves occur over the Skerries Bank itself and also to the south east and north east of the Bank (Fig. 6.3.1).
Fig. 1.1.1  A cross-section of a typical sandwave in Start Bay.
Fig. 1.1.2 Showing the effect of different tidal currents on sandwave shape.
Fig. 1.1.5 Map to show Start Bay, Devon.
1.2 DEFINITION OF THE PROBLEM

When the work described in this thesis was started, it was decided that there were two main questions which should be answered. These were:

(a) How much do the sandwaves move?

and

(b) Why do the sandwaves form in a particular place?

There are three main parameters which control the movement and occurrence of sandwaves. These are:

1. Water depth and underwater topography.
2. Water current direction and speed.
3. Sediment type and grain size.

From the work of other authors (Chapter 2), these main parameters were known in some detail. Unfortunately, little was known about the sandwaves themselves; exactly where they occurred or how much they moved. Consequently, most of the work of this thesis is concerned with determining where the sandwaves occur, their size, shape, how much they move and in which direction. In addition, some measurements were made to determine how the water flow varies over a sandwave and the variations in sediment characteristics across a sandwave.

1.3 PRELIMINARY CONSIDERATIONS

The first problem was to determine where the sandwaves occur in Start Bay. The extensive series of side scan sonar surveys conducted by Chesterman (Chesterman and Hopkins, 1971) were examined and from these a map was drawn up delimiting the area in which sandwaves occurred (Fig. 6.3.1). From this map an area was selected for more detailed study; this area had to satisfy several requirements:

(1) Close to shore for easy access and accurate navigation.
(2) Shallow water to allow diving and accurate positioning from echo sounder records.

(3) An area which was well surveyed with respect to currents, water depth and sediment type.

An area which satisfied these requirements was found on the Skerries Bank (Fig. 1.1.3).

It was decided that the positions of the sandwaves in the selected area on the Skerries Bank would be found by making echo sounder surveys. By repeating these surveys at intervals the progressive movement of the sandwaves could be found (Chapter 4). An accurate and simple method of navigation was required. As the area was so close to the shore, it was decided that the simultaneous measurement of two horizontal sextant angles would be a suitable technique.

Use of the I.O.S. diver-operated acoustic rangemeter position system was offered to the author. This equipment would be used to measure the position of the sandwave crest at successive slack waters, thus allowing the daily movement of the sandwave crest, in response to the alternate ebb and flood tidal currents, to be found (Chapter 5).

1.4 ADDITIONAL MEASUREMENTS MADE

As the work progressed it was found that there were gaps in the information available. In order to reduce these gaps, and to test the theories that presented themselves, a number of additional measurements were made.

Firstly, although the series of current measurements made by Acton and co-workers provided a detailed map of the tidal currents in Start Bay, it was felt that the currents would be affected by the presence of the sandwaves. Consequently, the variation in current over a sandwave was investigated (Chapter 3). Also the current
measurements at positions 'P' and 'Q' were repeated taking into account the presence of the sandwaves.

Secondly, although the I.O.S. rangemeter provided accurate information on the short term movement of the sandwave crest, little was known about the movement of the dunes. Therefore, the 'rope' method was used to find this movement (Chapter 3).

Thirdly, the variation in sediment characteristics over a sandwave was investigated by taking sediment samples at intervals over a sandwave profile (Chapter 6).

Lastly, the side scan sonar measurements indicated the areas in which sandwaves occurred. However, it was difficult to determine the shape or amplitude of the sandwaves from these. To rectify this, a large scale echo sounder survey was made over the whole Bay (Chapter 6).

From the measurements made a number of theories were developed concerning the way in which sandwaves move and the factors controlling their occurrence. These will be described in more detail in Chapters 4 and 5.
CHAPTER 2
PREVIOUS WORK

In this chapter the work of other authors will be discussed. Firstly, the historical background will be briefly mentioned (2.1) and then the work that has been done in Start Bay will be described (2.2). This will be followed by a discussion of the measurements that have been made to determine sandwave movement (2.3) and sandwave occurrence and morphology (2.4). Finally, the work that has been done to relate the sediment transport rate to the tidal current strength will be considered (2.5).

2.1 HISTORICAL

Leonardo da Vinci (1452-1519) was the first person to investigate the flow of water on a scientific basis. Most of his work concerned the flow of water through canals and rivers. It was he who issued the warning, 'when you try to explain the behaviour of water, remember to demonstrate the experiment first and the cause next' (Graf, 1971). P. du Baut (1734-1809) wrote the first fundamental treatise on hydraulics (du Baut, 1786). As well as work on the hydraulics of open channels, he investigated the transport of sediment by water and the formation of ripples. He describes the way in which sediment is transported up the stoss slope of a ripple and then tipped over the avalanche slope. 'This work resembles the one of a ditch-digger who takes his wheelbarrow up the ramp to unload it and the soil tumbles into the depth' (Graf, 1971).

In the open sea, Playfair (1802) observed the distortion of the water surface caused by the presence of sandwaves, and Sial (1841) detected sandwaves using a lead line. Johnson (1879) measured the movement of sandwaves in the Mississippi River; the sandwaves had amplitudes of about 1.5 metres, wavelengths of about 100 metres and
moved at a speed of 5.41 metres per day.

Darwin (1883) and later Reynolds (1901) made flume studies, observing the eddy behind the sandwave crest. Gilbert (1914) also used flumes and investigated the bedforms that formed as a result of different water flow conditions and sediment type.

Cornish (1901) observed sandwaves at low tide on sandbanks around the coast of the British Isles. He measured their size, shape and also their movement. With the invention of the recording echo sounder, Van Veen (1935, 1936, 1937, 1938a and 1938b) investigated the sandwaves in the North Sea. He found that they had amplitudes of up to 10 metres and wavelengths of 200 metres. He found four different sandwave shapes; trochoidal, asymmetrical-trochoidal, progressive and 'catback' (see Chapter 6.3(a)). The sandwave crests were perpendicular to the main ebb and flood tidal currents and Van Veen suggests that asymmetrical sandwaves move in the direction of the steeper or avalanche slope. He also suggests that the direction of the avalanche slope is controlled by the stronger of the two currents.

2.2 **START BAY**

Between 1897 and 1902 shingle was removed from the foreshore at Hallsands for the construction of Devonport dockyards. Despite objections half a million cubic yards of shingle were removed. Hansford Worth (1901) surveyed the beach and found that as a result of this the beach level had dropped by as much as twelve feet. A later survey (Hansford Worth, 1909) showed little change. In January 1917 a combination of the removal of the shingle, a severe north-easterly gale and a high spring tide resulted in the destruction of the village and the loss of several lives. Later surveys (Hansford Worth, 1923; Robinson, 1961) showed no recovery of the former beach.
level. Robinson (1961) also described the presence of sandwaves on the Skerries Bank.

The first tidal current measurements were made by the Admiralty in 1951 and the results are shown on the Admiralty Chart of Start Bay (Hydrographer, 1953, 1972). From 1970 Acton (1972) collected further tidal current information and later Perring (1976) investigated the tidal currents in the southern part of the Bay. Chesterman (1971) conducted a number of side scan sonar surveys of the sea bed of Start Bay and these surveys showed that there were a number of distinct areas in which sandwaves occurred. The results were available to the author (Chapter 6.3(b)).

From 1971 onwards, an extensive geophysical survey of the Bay was conducted by the Institute of Oceanographic Sciences (I.O.S.) and others. This survey included the investigation of: the geology (Kelland and Hails, 1972; Kelland, 1975), the sediments (Hails, 1975; McManus, 1975), the foraminiferida (Lees, 1975), surface waves (Holms, 1975), the tidal currents (Acton and Dyer, 1975) and beach stability (Gleason, Blackley and Carr, 1975).

It was with the background of this work that the present author commenced his studies of the sandwaves.

2.3 SANDWAVE MOVEMENT

It has been suggested for many years that asymmetrical sandwaves migrate in the direction of their steeper face (Van Veen, 1938b; Stride, 1959; Stride and Cartwright, 1958). However, it is only with the introduction of more accurate methods of navigation that it has become possible to measure the direction and magnitude of sandwave migration in the open sea. The most common method of measuring sandwave migration rates is that of making repeated echo sounder surveys at intervals. Langeraar (1966) made very accurate,
closely spaced, parallel echo sounder runs but even after 2½ years the apparent movement of the sandwaves was less than the navigational accuracy (60m). Ludwick (1972) repeatedly surveyed a single traverse line in Chesapeake Bay. He found that asymmetrical sandwaves migrated between 35m and 150m per year in the direction of their steep faces. Symmetrical sandwaves showed no significant movement. Langhorn (1973a, 1973b) found that the sandwaves' crests showed sinuous flexing due to differential movement rather than the expected progressive movement. Pasenau and Ulrich (1974) found migration rates of up to 60m per year in the German Bight. Bokuniewicz, Gordon and Kastens (1977) measured the migration rate of sandwaves in Long Island Sound.

An alternative method that has been used to measure sandwave migration rate is for divers to measure the distance between the sandwave crest and a reference placed on the sea bed. Jones, Kain and Stride (1965) initially attempted to measure the migration rate of sandwaves on Warts Bank, Isle of Man, by making repeated echo sounder surveys. However, they found that the movement was less than the navigational accuracy. Consequently, they layed large concrete blocks on the sea bed and divers measured the distance from the concrete blocks to the nearest sandwave crest. This was done by attaching a rope to the concrete block and then laying it out perpendicular to the sandwave crest. A piece of twine was inserted into the lay of the rope at the sandwave crest. The rope was then taken to the surface and the distance measured. Progressive displacements of 5 cm to 10 cm per day and a reciprocative motion of 74 cm in one flood tide, were found. Salsman, Tolbert and Villars (1966) used divers to measure the migration rate of sandwaves in St. Andrews Bay, Florida. They found a progressive migration of 11.44m over a two year period.
Kelland and Bailey (1975, see Appendix 5) used a diver-operated acoustic ranging system to measure the reciprocative motion of a sandwave crest. The motion varied between 3m and 6m per tide during periods of neap and spring tides respectively.

Most of these measurements of sandwave migration have been combined with measurements of tidal current. In general, it has been found that the direction of the residual tidal current corresponds to the direction of asymmetry in the sandwave shape and the direction of sandwave migration.

2.4 OCCURRENCE AND MORPHOLOGY


Sandwaves have been extensively classified into many different types (Allen, 1966; Yalin, 1964; A.S.C.E., 1966) but theoretically only two distinct bedforms should occur in flows with Froude numbers of less than one. They are ripples, in which wavelength
\[ \lambda \approx 1000 \, d \] (d = sediment grain size) and dunes \( \lambda \approx 2h \) (h = water depth) (Yalin, 1972). However, in the open sea three different bed
forms are generally observed (see Chapter 1) (McCave, 1971; Dalrymple et al, 1978). This is probably due to the presence of a number of different tidal current flow regimes (Allen and Collinson, 1974; Simons and Richardson, 1962).

It has been suggested that the occurrence of sandwaves is controlled by the grain size of the sediment. Dalrymple et al (1978) suggest that megarippled sandwaves occur in sands coarser than 0.308 mm. Terwindt (1971) and Bokuniewicz et al (1977) suggest that sandwaves will not form if the silt content of the sediment exceeds 10% to 15% and if the coarse fraction (>1 mm) is greater than about 12%.

Changes in sediment grain size over sandwave profiles have been observed. In general, the sediment is coarser on the crest of the sandwave than in the trough (Smith, 1969; Terwindt, 1971; Dyer, 1972; Swift et al, 1972; Wells and Ludwick, 1974; Stewart and Jordon, 1964) (see Chapter 6).

Current velocity profiles have been measured or predicted theoretically at different positions over a sandwave. The main features that have been observed are the lee eddy and a strong current over the sandwave crest (Dyer, 1970; Engelund and Fredsø, 1971; Raudkivi, 1963). Ludwick (1972) has observed sandwaves with gentle slopes and no avalanche slope, these have no lee eddy.

The effect of storms on dunes has been investigated by Langhorn (1977). He found that immediately after a storm the wavelengths of the dunes is low (1.5m to 1.7m), while under good weather conditions the wavelengths slowly increase to their fair weather value of 4.5m.

2.5 **SEDIMENT TRANSPORT**

The sediment transported by moving water consists of firstly,
the bedload, which is the material carried by saltation close to the sea bed and secondly, the suspended sediment, carried higher in the water body. Observations by divers (Jones et al, 1965; Salisman et al, 1966) show that, in general, over sandwaves the sediment is transported as a sheet up to 1m thick. This suggests that the sediment is transported mainly as bedload.

Most of the formulae relating the sediment transport rate to the water velocity have been developed from measurements made in laboratory flumes and from theoretical studies. There are three main bedload equations, which were suggested by Bagnold (1941, 1956, 1966), Einstein (1950) and Yalin (1963). There have also been a number of other equations suggested, see Yalin (1972, Chapter 5) and Graf (1971).

The Bagnold equation (see Chapter 4) relates the rate of mass transport of sediment, as bedload, to the power expended by the fluid in moving over the boundary. Einstein's equation suggests that the bedload transport rate is related to the fluctuations of the fluid motion. The probability of particle motion resulting from the instantaneous hydrodynamic lift forces acting upon the particle weight is considered. Yalin's equation considers the average lift acting on a sediment particle. Particle motion takes place by saltation and it is considered that an increase in particle jump length causes an increase in transport rate rather than an increase in the number of particles. These equations are discussed in more detail in Graf (1971) and Yalin (1972).

Kachel and Sternberg (1971) and Gadd, Lavelle and Swift (1978) have made comparisons between the above three equations and the flume data obtained by Guy, Simons and Richardson (1966). They have also made measurements of the sediment transport rate and tidal velocity in the open sea. Kachel and Sternberg (1971) found that the Einstein
and Yalin equations predicted too high a value for the sediment transport rate. They suggest a modification to the Bagnold equation that provides satisfactory agreement with their measured results. Gadd, Lavelle and Swift (1978) suggest modifications to the Bagnold and Einstein equations as a result of analysis of the flume data of Guy, Simons and Richardson (1966). They used their modified equations and Yalin's equation, to make comparisons with the results of sediment transport rate measurements in the open sea obtained by Lavelle et al (1976). All the results agreed within an order of magnitude.

It has been suggested that during storms wave-induced bottom currents increase the sediment transport rate by a factor of up to ten (Johnson and Stride, 1969).
CHAPTER 3

PRACTICAL TECHNIQUES USED TO GATHER INFORMATION

In this chapter the techniques, which were used to obtain the information and data on which the conclusions of later chapters are based, are described. Firstly the navigation techniques used are discussed (3.1). This is followed by a description of the equipment used; the echo sounder (3.2), current meters (3.3) and side scan sonar (3.4). The procedure used for obtaining sediment samples is then discussed (3.5).

3.1 NAVIGATION

One of the major limitations in the determination of sandwave movement is the accuracy of the navigation technique used. If the movement of the sandwave is less than the accuracy of navigation, then the movement cannot be measured. Consequently, a great emphasis has been placed on obtaining a high standard of navigation.

Five methods of navigation which have been used in the course of this work will now be described. They are:

(a) Sextant.
(b) Diver-operated acoustic "Rangemeter".
(c) Direct measurement by diver.
(d) Decca navigator.
(e) Transits.

3.1(a) Sextant

For the bulk of this work horizontal sextant angles were used for navigation. In this technique two sextants are used, on the boat, to measure the horizontal angles subtended by three fixed points (A₁, A₂, A₃; Fig. 3.1.1) on the shore. From these two angles (θ₁, θ₂) and the positions of the three points, the position of the boat can be determined by trigonometry or geometrical construction.
Fig. 3.1.1 Measurement by sextant of angles ($\theta_1, \theta_2$) subtended by three points on the shore (A1, A2, A3) to give the boat's position.

Fig. 3.1.2 Measurement by rangemeter of the distances (L1, L2, L3) to the three transponders (Tx1, Tx2, Tx3) to give the diver's position on the sandwave crest.
In Start Bay this method has an accuracy of between ±2m and ±10m, depending on the position in the Bay and the prevailing conditions. This high accuracy is possible because of the closeness of the shore and the way in which the Bay surrounds the survey area. Consequently, large angles can be used and the shore marks are not at too great a distance either from the boat or each other; this, coupled with good visibility and careful measurement of the angles, results in high accuracy. More information about the details of the techniques is given in Appendix 1.

3.1(b) Diver-operated Acoustic "Rangemeter"

The diver-operated acoustic rangemeter system belonging to the Institute of Oceanographic Sciences (Taunton) (Kelland 1975) was used for a period of two months in summer 1974. This apparatus measures the time required for an acoustic signal to travel from a diver-held meter, to one of three sea bed mounted transponders (Tx₁, Tx₂, Tx₃; Fig. 3.1.2) and return. The velocity of sound in water was found either from direct measurement or by calculation from the salinity and temperature of the water. From the velocity of the sound and the time taken, the distance (L₁, L₂, L₃) from each of the transponders to the diver could be found and from these his position.

Fig. 3.1.3 shows a diver in the process of measuring his position on a sandwave crest. The meter is held over a metal stake which is inserted into the sandwave crest to mark the position, in case the diver is swept off the station in between readings. The readings at each point are recorded on a tape recorder, in a watertight housing, mounted on the diver's air bottle. They can also be sent to the surface, via an acoustic link mounted on the diver's head, where they are written down in case the tape recorder fails.
Fig. 3.1.3 A diver measuring his position on a sandwave crest, using the I.O.S. acoustic rangemeter.
The diver uses a special mouth-piece with an air-filled voice box, so that speech is decipherable. The sound is picked up by a microphone in the voice box for the acoustic link; and for the recorder by a bone microphone tucked under the diver's wet suit hood, so that it presses against the bone of the forehead. Another bone microphone from the rangemeter is used as a loudspeaker so that the return signal from the transponder can be listened to. Since the transponder in the rangemeter is directional, the bearing of the transponder can be found approximately by maximising this return signal.

Fig. 3.1.4 is taken from an E.G. & G. high resolution side scan sonar record of the area. Two of the transponders can be seen, the third (Tx1) was on the other side of the boat. Also to be seen are the steep avalanche faces of two sandwaves, their associated dunes and even some large ripples. These are much distorted by surface wave induced motion of the sonar fish.

Using the rangemeter it was possible to measure the backward and forward movement of the sandwave crest to a relative accuracy of ± 1 metre. One major disadvantage of this method of navigation is that it is only possible to measure the relative positions of the sandwaves and not their absolute position in relation to the shore. Also, because the range of the equipment and the working time underwater are limited, only two sandwaves can be surveyed at one time. This apparatus is discussed in more detail in the paper in Appendix 5 and the results which were found by using it are discussed in chapter 5.

3.1(c) Direct Measurement by Diver

In 1975 an adaption of the technique described by Jones et al
Fig. 3.1.4 E.G. & G. side scan sonar record showing the area surveyed using the I.O.S. acoustic rangemeter.

Two of the transponders can be seen.
(1965) was used (Fig. 3.1.5). A heavy structure with a vertical rod was laid on the sea bed. This was marked by a buoy fixed to a separate concrete block, so that the drag of the buoy and of divers moving down the buoy rope would not move the structure. At slack water, a diver placed a loop in the end of a coil of rope, over the spike, and ran out the rope perpendicular to the crests of the dunes. At the crest of each dune, he tied a knot in the rope and at the crest of the sandwave he tied a double knot. This was repeated at the next slack water, when a different type of knot was tied in the rope.

The distance between each pair of knots gives the movement of the dunes, or sandwave crest, over half a tidal cycle but only at one place on each crest. The accuracy is of the order of $\pm \frac{1}{4}$ metre. Allowances were made for the rope used up when tying the second batch of knots. The main errors occurred in aligning the rope perpendicular to the dune crests and in the amount the rope stretched. Both of these could be overcome with care (See Fig. 6.2.3).

3.1(d) Decca Navigator

Decca navigator was used on a few occasions. It has an accuracy of about $\pm 50$ m in Start Bay. This was confirmed when it was found that some sandwave positions found by 'Decca' had a static error of about $50$ m compared to those found by sextant angles. Decca navigator has been used for laying the transponders for the I.O.S. diver rangemeter system and by Bath University when making side scan sonar surveys.

3.1(e) Transits

One useful technique which has been used by the local fishermen for centuries is that of shore transits. Two pairs of points on the shore are lined up and recorded. By re-aligning the shore marks, one can then return to the same position with surprisingly high
Fig. 3.1.5 Measurement of the position of dune and sand-wave crests by a diver (not to scale).
accuracy, probably better than $\pm 10m$. The use of this technique depends on good visibility but if suitable marks are chosen it can be used even in comparatively bad visibility.

**NOTE:** The navigation technique which was used on any particular occasion depended on the circumstances and on the equipment available. It was found that the use of sextants was a very cheap, effective and simple process but tended to be rather laborious. An automatic system, such as Decca Hi-Fix, with a data logger would have been useful, but would have required a special power supply, been expensive and would have used up a large proportion of the very limited space on the boat.

### 3.2 ECHO SOUNDING

In the main echo sounder surveys the object was to find the position and shape of the sandwaves. This was done by making parallel, closely spaced, echo sounder 'runs', roughly perpendicular to the sandwave crests. (A typical echo sounder record is shown in Fig. 3.2.1).

Sextants were used for navigation. Although it is possible to plot the sextant angles continuously, as they are measured, to give the boat's course, it is rather time-consuming and would considerably reduce the number of position fixes which could be made, thus reducing the accuracy of the position fixing. The normal time between 'fixes' was between 2 minutes and 20 seconds. Consequently, another navigation method has to be used to correct the boat's course. After some experimentation with different procedures a standard method was adopted. Three or four buoys were temporarily laid in a straight line parallel to the direction of the runs required. The runs were then made parallel to and at a specified distance from the line of the buoys. These buoys (30 cm diameter
Fig. 3.2.1 Example of an echo sounder record showing sandwaves and dunes, made 11th June 1975, run 12.
red plastic) were visible for a distance of 200-500m dependent on the prevailing sea state and the weather conditions. If a more accurate survey was required, this procedure was modified according to the requirements. (These modifications and the details of the method are described in Appendix 2).

The two requirements of accuracy and large survey area are conflicting. To survey a large area, it is necessary for the boat to move fairly rapidly. Consequently, small details are not recorded on the echo sounder record and the sextant angle fixes will be made at a greater distance apart. The boat must be moving slowly and the fixes made frequently, in order to examine the details of the sandwave's shape and to position these accurately. In addition, the sea must be very calm so that the vertical movement of the boat and hence that of the echo sounder transducer, is smaller than the amplitude of the features to be observed.

If the boat is driven slowly, against the direction from which the surface waves are arriving, the period of the surface waves on the record will be significantly less than that of the dunes ($\lambda = 10m$) (see Figs. 3.2.2/3). This can only be done if the surface waves are small. If their wave length is greater than twice the length of the boat (10m), the boat's motion will become more violent and spray will interfere with the measurement of sextant angles. In this case the 'runs' will have to be made with the waves. This results in the boat's motion being much less violent, but of fairly high amplitude. Also the boat tends to 'surf' down each wave as it overtakes the wave, resulting in considerable variations in speed and hence transducer depth (when using the swinging arm suspension system).

The direction of the tide has to be taken into account. If
Surface wave about 5 sec.

Fig. 3.2.2 Appearance of dunes and surface waves on an echo sounder record.

Fig. 3.2.3 Echo sounder record of above. Boat moving very slowly.
very accurate measurements are to be made, the boat is steered directly against the tide, which normally runs almost perpendicular to the sandwave crests. Consequently, the boat is moving slowly over the ground but at a fast enough speed through the water to allow good response to the helm, so that an accurate course can be steered.

3.3 CURRENT METERS

Current meters have been used in Start Bay for several years by Acton (1972) and later Perring (1976) for mapping the tidal currents. They have been used in this work to take more detailed measurements over a sandwave and to fill in a few gaps. The techniques used are described in detail by the above authors. A brief description of the techniques used in this work follows.

A Braystroke current meter is hung over the side of the anchored boat with a streamlined weight beneath it. The length of the suspension cable is adjusted so that the meter hangs at the depth at which the current is to be measured. On the surface, a counter indicates the number of revolutions of the rotor that have occurred. The readings on the counter are recorded every five minutes. This averages out the short period variations caused by surface wave motion and other turbulence. Since the pitch of the rotor is known the current speed can be calculated.

The current direction was found by measuring the bearing of a drogue towed behind the boat. This gives an integrated current direction, instead of the instantaneous direction which is usually measured and is very variable.

Occasionally a meter would give spurious results due to one of a number of causes. Therefore at least two, and if possible three, meters were used simultaneously, so that the mal-operation of one meter could be detected. All of the meters were calibrated in a
laboratory flume. There was no significant difference between the
meters' readings. Therefore any differences found when operating on
board the boat were due to some part of the system working incorrect-
ly. Possible sources of error which were found are:

1. Run down batteries.
2. Mis-match of meter to cable, so that the 'reed' switch
   was not operated by the magnet attached to the rotor.
3. Tension in the cable causing loose connections in the
cable to disengage. The cable can be easily damaged
   by kinking.
4. Weed or other material caught on and jamming or slow-
ing the rotor.

Precautions were taken to avoid these problems as far as pos-
sible.

In order to obtain the tidal current profile at different
places over a sandwave a special technique was used. Three meters
were arranged; one at 1m above the sea bed, mounted on a tripod
lowered from the boat, and the other two were suspended from the boat
at approximately one-third and two-thirds of the water depth. Three
stations were selected; one on the gentle slope of the sandwave,
one near to the crest and one in the trough. The boat was anchored
so that these three stations could be covered by taking in and
letting out the anchor cable (Fig. 3.3.1).

At each station, two five minute readings were made before
moving on to the next station. The cycle time for one set of
readings was about one hour so that in the three and a half hours of
peak tidal flow, three and a half sets of readings were made. The
standard static tidal current cycle was known from previous measure-
ments. Therefore the differences in the profile at the different
Fig. 3.3.1  Arrangement for measuring the water flow over a sandwave at three different points (not to scale).
points on the sandwave could be found. These results are discussed in chapter 5.

This experiment indicates another source of error, when making tidal current measurements in sandwave areas. The results obtained can vary by as much as 30% depending upon the position over the sandwave and the amplitude of the sandwaves. Consequently, the presence of sandwaves must be taken into account when measuring tidal currents. Perhaps, instead of recording just the water velocity, the volume of water passing the meter should be computed. This will be the same, by the continuity equation, at all points over a sandwave profile, with the exception of the eddy, in the lee of the sandwave crest (See Appendix 3).

3.4 SIDE SCAN SONAR

Side scan sonar has been used, during the course of this work, to survey the sea bed of Start Bay. From the results of these surveys, useful information was obtained on the general configuration and positions of the sandwaves and their variation throughout the Bay. From this information a small area was selected for detailed study.

Two different side scan systems were used during the course of this work. The first is that belonging to Bath University and has been developed over a number of years by Chesterman (1971).

Previous to the start of this work a number of side scan surveys had been made using this equipment. At the commencement of this work a further survey was made. From the raw data produced by these surveys, the author constructed detailed maps of the sandwave areas of Start Bay. Although the surveys spanned a period of five years, the positioning (Decca Navigator) was not sufficiently accurate for any information to be obtained on the movement of the sand-
waves. A summary map of the three main surveys is shown in Fig. 6.3.1.

The equipment used operates at a frequency of 48 KHz. Because of this low frequency and the long pulse length, the resolution of very small details of the sandwaves was not always obtainable (e.g. dunes and ripples). The sandwaves themselves, however, were clearly displayed and mapped. Because of the large physical size of this equipment, a large boat had to be used and consequently, it was not possible to survey the very shallow areas over the crest of the Skerries Bank.

The second system to be used was the I.O.S. Taunton E.G. & G. high resolution system.

This was used during the rangemeter survey in order to observe the area surrounding the transponders. A sample record is shown in Fig. 3.1.4. Two of the three transponders can be seen and also two sandwave crests, dunes and even ripples. This high resolution is due to the higher operating frequency of 150 KHz and to the shorter pulse length.

In operation a transducer is towed, by a boat, in a streamlined casing (a fish). The shape of this transducer is such that the beam pattern of the acoustic signal produced is broad in the vertical direction and narrow (1° - 2°) in the horizontal direction, perpendicular to the boat's track. This beam is pointed at the sea bed and at regular intervals a pulse of acoustic energy is released. Any objects on the sea bed produce a reflection signal; this return signal is recorded, usually as a trace across a strip of paper, so that signals returning at different times are recorded sequentially across the paper. The gain of the amplifier is increased with time throughout each trace because the return signals are of a
lower amplitude at greater distances. This is mainly due to three effects.

Firstly, the signal is attenuated by its passage through sea water. Secondly, at greater distances the angle of incidence of the signal on the sea bed is much lower, so that any reflected signals are also lower. Lastly, the signal strength is greatly weakened by its spherical spreading. The next trace is displayed parallel to the first and the third parallel to that, etc. A picture is thus built up showing objects which cause acoustic reflections in an area beside the boat's track. Often two transducers are used, pointing in opposite directions, so that a display is obtained from each side of the boat.

There are many possible reflected signals which can be received. Some are wanted, some are noise and are not required. In some cases that which would normally be regarded as noise is the required signal. A few of the signals observable will now be enumerated.

(1) Changes in the sea bed material resulting in changes of the reflection coefficient; for example, from sand, a fairly low reflector, to rock, a strong reflector.

(2) Man-made objects are usually of metal and often stick up from the sea bed; consequently, they show up as high amplitude signals. Examples of these are wrecks, telephone cables, oil or gas pipelines and the transponders used by I.O.S. Taunton, see Fig. 3.1.4. If the object is fairly high a shadow zone is created behind it and from the size of this shadow zone the height of the object can be calculated. Sandwaves, if they are viewed from the stoss side, produce a shadow zone behind the avalanche slope.

(3) Changes in gradient of the sea bed change the amplitude of the
signal returned. Sandwaves provide an example of this.

(4) Fish or man-made objects such as boats or submarines in the water body will produce reflections.

(5) If a strong tide is flowing in a sandwave area, the acoustic noise of the movement of sand at the crest of each sandwave produces a band of noise across the record, which is picked up as the boat crosses over the sandwave crest.

(6) Reflections will be obtained from surface waves and from air bubbles in the water caused by their turbulence. The turbulence in a ship's wake also produces a large reflected signal.

(7) Reflection patterns known as Lloyd Mirror are produced when the water body is layered. This layering can be due to changes in temperature or salinity. The northern half of Start Bay is affected in this way, due to the fresh water coming out of the River Dart on an ebb tide. The patterns are produced as a result of mutual interference of signals taking different paths through the layered water body.

(8) Deficiencies in the equipment itself can produce strong signals. For instance, if a strong signal is received on one side of the boat it may also appear on the record of the other side (cross talk). Also a strong reflector not actually in the main beam of the transducer may be illuminated by a side lobe of the transducer and produce a signal in the wrong place.

From this it can be seen that the record, while at first glance producing a visually satisfying picture of the sea bed, is, in fact, a very complex series of signals and requires considerable experience to interpret correctly. Often great care is needed if the wrong conclusions are not to be drawn from a particular combination of signals. Side scan sonar is therefore a very powerful tool, when the results are correctly interpreted, for the general observation of
of sea bed features. However, it is difficult to abstract information about the height of sea bed features. Also, although the boat's position can be found accurately, it is often difficult to determine the precise direction in which the transducer beam is pointing. This problem occurs particularly if a strong tide or high sea is running. These can result in quite high errors in the positioning of features. Although the recording in Fig. 3.1.4 was made in only a slight sea, less than 1 metre amplitude, it can be seen that this has had a large disturbing effect on the record. It was mainly for these two reasons that it was decided to concentrate on surveying the sandwaves by echo sounder rather than by side scan sonar.

3.5 SEDIMENT SAMPLING

On a number of occasions, a series of sediment samples were taken across a sandwave by divers. The object was to find out if there were any differences in the characteristics of the sediment across the sandwave (Wells and Ludwick, 1974).

Initially samples were taken at regular (20m) intervals but it was found that the results from these were very disappointing, the results having a very large scatter. This was considered to be due to the presence of the dunes.

Consequently, subsequent samples were taken from either the crest or the trough of a dune. The results from these samples were much more encouraging and are discussed in Appendix 4.

The samples were analysed using sieves of \( \frac{1}{2} \) phi intervals. The shaking was done using a mechanical shaker. This meant that all the samples could be treated in exactly the same manner, eliminating any variations which might result from variations in sieving time and the vigour with which the sample is shaken. The effects of variations in the amplitude of shaking and the shaking time were investi-
gated and optimum values chosen. If the sample is shaken for too long, or too violently, mechanical disintegration will take place; the shell fraction is particularly susceptible to this. If the sample is not shaken for long enough, not all the sediment will be shaken through as far as it will go. Also, if the time is short, inaccuracies in measurement of the time are more likely.

Each sample was shaken for $\frac{1}{2}$ hour with an amplitude of 1 mm for the fine sediment and $\frac{1}{2}$ mm for the coarse sediment.

The samples were taken from the sea bed, by a diver, using a cylinder which was inserted vertically into the sediment. Water escaped from the cylinder through a hole in the top. The holes in the top and bottom were closed by the diver's hands and the sample placed in a plastic bag. On return to the laboratory the sample was washed in fresh water to remove the salt, then dried in an oven and sieved. Later the sample was split and a quarter of the sample was used to determine the relative proportions of sand and shell. The shell was dissolved using dilute hydrochloric acid. The sample was then washed to remove traces of the acid, dried and the remaining sand was sieved. Cumulative percentage curves of the total sample, the sand and the 'missing' shell were plotted. From these graphs the phi values at 5%, 16%, 50%, 84% and 95% were found, from these phi values various parameters ($M_d, S_o, S_k_1, S_k_2$ and $K$) were calculated.
CHAPTER 4

PROGRESSIVE DISPLACEMENT OF SANDWAVES

In this chapter, firstly, the way in which sandwaves move under the influence of tidal currents is discussed (4.1). The correlation between the measured magnitude of the long term progressive movement and the residual tidal current is then investigated (4.2). This is followed by the development of a transport theory based on the modified Bagnold equation (4.3), which is then compared with the measured movement (4.4).

4.1 THE EFFECT OF TIDAL CURRENTS ON THE SHAPE AND MOVEMENT OF SANDWAVES

The sandwaves in Start Bay are subjected to ebb and flood tidal currents, which run almost perpendicular to the sandwave crests. The ebb tide flows more or less southwards and the flood tide flows in an opposite northerly direction. This change in the direction of the tidal current occurs approximately once every 6.2 hours.

In response to these tidal flows, the sediments of the sea bed are moved backwards and forwards once every 12.4 hours. This sediment motion mainly affects the shapes of the sandwave crest and of the dunes on the back of the sandwave (Fig. 4.1.1). The resulting reciprocative movement of the sandwave crest will be discussed further in the next chapter.

It has been found (Acton 1972) that the strength of the flood tide is rarely the same as that of the ebb tide. Consequently, more sediment is transported in one direction than in the other and the sandwave slowly migrates in the direction of the stronger current (Fig. 4.1.2). Some actual measurements of the motion of the sandwave crest, made using the I.O.S. diver-operated acoustic rangemeter system, are shown in Fig. 4.4.2.
a) Sandwave profile at slack water after an ebb tide (ebb profile).

b) Sandwave profile at slack water after a flood tide (flood profile).

c) Superposition of the ebb and flood profiles, to emphasise the difference.

Fig. 4.1.1 Showing the effect of tides flowing in alternating directions on the shape of the sandwave.
Position of sandwave crest at slack water,

- after ebb tide.
- after flood tide.

Fig. 4.1.2 Showing the way in which a sandwave crest moves under the influence of two opposing tidal currents, the ebb tide being slightly stronger than the flood tide.

This results in a slow progressive movement of the crest, superimposed on the reciprocating movement.

Note: For the sake of clarity the progressive motion has been exaggerated.
4.2 THE CORRELATION BETWEEN THE RESIDUAL TIDAL CURRENT AND THE SANDWAVE DISPLACEMENT

During the course of this work the sandwaves of the Skerries Bank have been extensively surveyed. Their positions have been measured by making repeated echo sounder surveys over a period of two years. The rate of sandwave migration has been found from the differences in the positions of the sandwave crests throughout the survey period. The detailed results are described in Appendix 2, in particular Table A2.3.3. A summary of the results is given in Fig. 4.2.1.

From this figure it can be seen that the sandwaves to the inside (west north west) of the crest of the Skerries have their steep avalanche slopes to the south, and are moving to the south (positive displacement). The sandwaves, in the deeper water to the outside (east south east) of the crest of the Skerries, have a northward asymmetry and are moving to the north.

Extensive tidal current measurements have been made in Start Bay by Acton and Dyer (1975) and the results of their work are shown in Fig. 4.2.2. This figure shows that the 'residual' current (peak ebb speed minus the peak flood speed) is to the south on the inside of the Skerries and to the north on the outside of the Skerries.

The results from Figs. 4.2.1/2 have been combined and are shown graphically in Fig. 4.2.3. These results show a strong correlation between the residual current, the direction of sandwave migration and the sandwave asymmetry.

Discrepancies in these results can usually be assigned to one or more of a number of causes, which will now be discussed.

Firstly, the tidal current measurements of Acton and Perring were made with a spacing of about 4 kilometres between the measurement
Fig. 4.2.1  Showing the results of the echo sounder surveys of the sandwaves of the Skerries Bank.

- Crest of Skerries Bank
- Mean position of sandwave crest with
  - Southward asymmetry
  - Symmetrical
  - Northward asymmetry
- Mean annual displacement of crest (m)
  (south positive)
- Sandwave 'G'

National Grid lines

100m

North
Contour map showing peak current speed during the flood half cycle at a tidal range of 4.0 metres. The sea trial locations, where data have been collected are indicated by A–Q.

Fig. 4.2.2

Taken from Acton and Dyer (1975), showing the tidal currents found in Start Bay.

Contour map showing the 'residual' current. This parameter is the peak ebb speed minus the peak flood speed.
Asymmetry of sandwave displacement

South
Symmetrical
North

Standard error

Error in residual current <0.15 m s⁻¹

Residual current m s⁻¹
-0.3 -0.2

Sandwave annual displacement m

Northward displacement
positions; the intermediate current speeds were found by interpolation (Acton (1972)). Over most of the Bay, where the sea bed is fairly flat, the interpolated results are very satisfactory. However, over the rugged topography of the Skerries Bank itself, where the water depth is varying rapidly, the errors in interpolation will be greater, particularly since there are only two measured positions on the Skerries Bank. These errors will be greatest mid-way between the measured positions and where the water depth is most rapidly varying.

Secondly, since there is comparatively little sediment in small sandwaves (less than 1.5m high), the shape and position of these sandwaves will change very rapidly, under the influence of freak variations in the currents, occurring as a result of meteorological disturbances. Consequently, measurements taken from small sandwaves are liable to larger errors than those taken from larger sandwaves.

Lastly, local conditions may greatly affect the shape and movement of a sandwave. For example, a large sandwave may shelter a smaller sandwave from the tidal current flowing in one direction. This will cause the small sandwave to have an unexpected asymmetry and movement. At grid reference 85.9, 39.4, a small (1.5 metres high) sandwave occurs to the south of the large sandwave. The small sandwave is sheltered from the southward current by the large sandwave and has a northward asymmetry with zero displacement. The large sandwave has slight southward asymmetry with southward displacement (Fig. 4.2.1 and Appendix 2, Table A2.3.3).

4.3 CALCULATION OF THE SANDWAVE MIGRATION RATE FROM TIDAL CURRENT MEASUREMENTS

At position 'Q' (Appendix 3, Fig. A3.1.1), two sets of current measurements were available. These were confirmed by
new measurements made by the author, as shown in Fig. 4.3.1. These measurements give the depth averaged tidal current speed, $\overline{S}$, for a tidal range of 4 metres at Dartmouth, throughout the 12.4 hour tidal cycle. Chapter 3 gives details of how these measurements were obtained.

The three sets of measurements were made on three separate occasions under different tidal conditions. The presence of the sandwaves causes the current speed to vary rapidly with position. Therefore, small errors in positioning will affect the results obtained. When this is considered, the agreement between the three sets of measurements is very good.

For most depth-velocity profiles,

$$\overline{S} \approx |\overline{U}_{\text{mid}}|$$

where $\overline{U}_{\text{mid}} = \text{mean mid depth current velocity}$. This has been assumed in this work.

In order to calculate the sediment transport rate, it is necessary to know the water velocity at 1 metre above the sea bed. During the course of this work a number of current measurements were made, by the author, at three positions over a sandwave profile (Appendix 3, Figs. A3.1.9/10). The tidal current on the gentle, or stoss, slope of the sandwave is the most significant in determining the progressive migration rate of the sandwave. The author's measurements made on the stoss slope, at positions P3 and Q, are given in Table 4.3.2 and from these it has been found that the average ratio of the mid depth current velocity to the velocity at 1 metre above the sea bed is 0.82 ($\sigma = 0.07$). It is concluded that,

$$\overline{U}_{100} = 0.82 \overline{U}_{\text{mid}}$$

(4.1)
TABLE 4.3.1.
LIST OF VARIABLES USED IN THIS SECTION

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{U}_d )</td>
<td>Mean water velocity at depth ( d ).</td>
</tr>
<tr>
<td>( \bar{S} )</td>
<td>Depth mean water speed.</td>
</tr>
<tr>
<td>( U_* )</td>
<td>Friction velocity = ((\tau_0/\rho)^{\frac{1}{2}}).</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Fluid density.</td>
</tr>
<tr>
<td>( \rho_s )</td>
<td>Sediment density.</td>
</tr>
<tr>
<td>( g )</td>
<td>Acceleration due to gravity.</td>
</tr>
<tr>
<td>( j )</td>
<td>Mass discharge of sediment per unit width.</td>
</tr>
<tr>
<td>( K )</td>
<td>Efficiency with which flow transports sediment.</td>
</tr>
<tr>
<td>( W )</td>
<td>Power expended by flow on unit area of sea bed.</td>
</tr>
<tr>
<td>( \tau_0 )</td>
<td>Boundary shear stress.</td>
</tr>
<tr>
<td>( \tau_c )</td>
<td>Threshold boundary shear stress.</td>
</tr>
<tr>
<td>( C_d )</td>
<td>Drag coefficient for ( \bar{U}_d ).</td>
</tr>
<tr>
<td>( H )</td>
<td>Sandwave height.</td>
</tr>
<tr>
<td>( V )</td>
<td>Sandwave migration rate.</td>
</tr>
<tr>
<td>( z )</td>
<td>Tidal range.</td>
</tr>
</tbody>
</table>
TABLE 4.3.2

TIDAL CURRENT MEASUREMENTS MADE ON THE STOSS SLOPE OF A SANDWAVE

(a) Position 'P3', 23rd August, 1974, Sandwave 'M'.

<table>
<thead>
<tr>
<th>Time from L.W. Dartmouth, hrs.</th>
<th>Velocity, ms(^{-1})</th>
<th>(\bar{U}_{100})</th>
<th>(\bar{U}_{2/3})</th>
<th>(\bar{U}_{1/3})</th>
<th>Ratio</th>
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</thead>
<tbody>
<tr>
<td>-1.29</td>
<td>0.33</td>
<td>0.40</td>
<td>0.47</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td>-1.21</td>
<td>0.35</td>
<td>0.42</td>
<td>0.48</td>
<td>0.78</td>
<td></td>
</tr>
<tr>
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<td>0.45</td>
<td>0.46</td>
<td>0.53</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>-0.44</td>
<td>0.47</td>
<td>0.49</td>
<td>0.56</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>0.51</td>
<td>0.49</td>
<td>0.50</td>
<td>0.59</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>0.60</td>
<td>0.49</td>
<td>0.51</td>
<td>0.76</td>
<td>0.77</td>
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<tr>
<td>1.39</td>
<td>0.53</td>
<td>0.55</td>
<td>0.65</td>
<td>0.88</td>
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</tr>
<tr>
<td>1.47</td>
<td>0.55</td>
<td>0.57</td>
<td>0.66</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>2.39</td>
<td>0.48</td>
<td>0.52</td>
<td>0.58</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td>2.47</td>
<td>0.45</td>
<td>0.52</td>
<td>0.57</td>
<td>0.81</td>
<td></td>
</tr>
</tbody>
</table>

(b) Position 'Q', 24th August, 1974, Sandwave 'G'.

<table>
<thead>
<tr>
<th>Time from L.W. Dartmouth, hrs.</th>
<th>Velocity, ms(^{-1})</th>
<th>(\bar{U}_{100})</th>
<th>(\bar{U}_{2/3})</th>
<th>(\bar{U}_{1/3})</th>
<th>Ratio</th>
</tr>
</thead>
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<td>-0.43</td>
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<td>0.39</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>-0.34</td>
<td>0.31</td>
<td>0.33</td>
<td>0.41</td>
<td>0.84</td>
<td></td>
</tr>
<tr>
<td>0.41</td>
<td>0.36</td>
<td>0.39</td>
<td>0.49</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td>0.49</td>
<td>0.33</td>
<td>0.45</td>
<td>0.51</td>
<td>0.68</td>
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</tr>
<tr>
<td>1.27</td>
<td>0.44</td>
<td>0.51</td>
<td>0.61</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>1.36</td>
<td>0.44</td>
<td>0.54</td>
<td>0.63</td>
<td>0.75</td>
<td></td>
</tr>
</tbody>
</table>

Mean ratio = 0.82
\(\sigma = 0.07\)

\[
\text{Ratio} = \frac{\bar{U}_{100}}{\bar{U}_{\text{mid}}} = \frac{2 \times \bar{U}_{100}}{\bar{U}_{2/3} + \bar{U}_{1/3}}
\]

Velocities corrected to 4m tidal range.
If the Admiralty tide tables are examined, it is found that the tidal range at Dartmouth varies between 1 and 5.5 metres. Fig. 4.3.2 shows the number of tides per year at different tidal ranges.

Perring (1976) found that the peak tidal current at position '0' could be related to the tidal range at Dartmouth by two formulae:

\[ S = 0.46 z^{0.55} \quad \text{for an ebb tide,} \]
\[ S = 0.57 z^{0.75} \quad \text{for a flood tide.} \]

These formulae can be re-arranged to compare the current at one tidal range with the current at another:

\[ \frac{S_2}{S_1} = z_2^{0.55}/z_1^{0.55} \quad \text{for an ebb tide} \quad (4.2) \]
\[ \frac{S_2}{S_1} = z_2^{0.75}/z_1^{0.75} \quad \text{for a flood tide} \quad (4.3) \]

According to Perring, these formulae are applicable to the whole of southern Start Bay. They have been used to adjust all current measurements to a standard tidal range of 4 metres. The formulae can also be used to compute the current at any tidal range, from the standard results at 4 metres tidal range.

The Bagnold equation may be used to calculate the sediment transport rate from the water velocity. The basic Bagnold equation which relates the rate of mass transport of sediment as bedload \( j \), to the power \( w \) expended by the fluid is:

\[ \frac{\rho_s - \rho}{\rho_s} g j = K w \quad (4.4) \]

\( w \) can be expressed in terms of the friction velocity \( U_* \):

\[ w = \rho U_*^3 \quad (4.5) \]

so

\[ \frac{\rho_s - \rho}{\rho_s} g j = K \rho U_*^3 \quad (4.6) \]

Kachel and Sternberg (1971) suggest that \( K \), the proportionality coefficient which expresses the ability of a flow to transport sediment, varies as a function of the excess boundary shear stress,
Fig. 4.3.2 Showing the number of tides per year at various tidal ranges, at Dartmouth.
(\tau_0 - \tau_C)\tau_C$. Their results, using this hypothesis, are shown in Fig. 4.3.3. The sediments of sandwave G have a similar grain size, 0.45 mm and density to those used to obtain this graph; it is therefore considered to be applicable to the sediments of sandwave G.

It should be noted that, whereas in the normal Bagnold equation, $j$ is dependent on the cube of the current velocity, in the modified Bagnold equation $j$ is dependent on, approximately, the sixth power of the current velocity. As a result, any small errors in the current velocity will have a large effect on the sediment transport rate computed by this method.

The friction velocity $U_\ast$ may be related to the velocity at 1 metre from the sea bed $\bar{U}_{100}$ by the Quadratic stress law. This law relates the mean velocity $\bar{U}_d$ at a depth $d$ to the boundary shear stress:

$$\tau_0 = C_d \rho \bar{U}_d^2$$  \hspace{1cm} (4.7)

where $C_d$ is the drag coefficient.

When the velocity is measured at 1 metre above the sea bed:

$$\tau_0 = C_{100} \rho \bar{U}_{100}^2$$  \hspace{1cm} (4.8)

and since

$$U_\ast = (\tau_0/\rho)^{1/3}$$  \hspace{1cm} (4.9)

$$U_\ast = C_{100}^{1/3} \bar{U}_{100}$$  \hspace{1cm} (4.10)

Sternberg (1972) suggests that a value for $C_{100}$ of $3 \times 10^{-3}$ is suitable for most natural sediments, so:

$$U_\ast = 5.47 \times 10^{-2} \bar{U}_{100}$$  \hspace{1cm} (4.11)

Using this formula, Fig. 4.3.3, eqns. (4.1), (4.2) and (4.3) and Fig. 4.3.1, the sediment transport rate throughout the tidal cycle was calculated for position 'Q', at four tidal ranges. These are shown in Fig. 4.3.4.

This instantaneous transport rate was integrated over the ebb and flood half cycles to obtain the quantity of sediment transported
Fig. 4.3.5  Taken from Kachel and Sternberg (1971), showing Bagnold's equation and the modified Bagnold equation.
in each direction, per tidal cycle (Table 4.3.3). The net quantity of sediment transported per tidal cycle was found by subtracting the sediment transported during the flood half cycle from the sediment transported during the ebb half cycle. This was then multiplied by the number of tides per year at that tidal range. The totals for each tidal range were added, to give the net quantity of sediment transported per year as:

\[ j = 2.10^5 \text{ gm cm}^{-1} \text{ year}^{-1} \]

If the sandwave is assumed to have a triangular cross section, the sandwave migration rate \( V \) is related to the sediment transport rate \( j \) (Fig. 4.3.5) by:

\[ j = \frac{1}{2} H \rho_s V \quad (4.12) \]

Sandwaves 'F' and 'G' at position 'Q' are 3 metres high and the sediment is assumed to have a density of 1.6 gm cm\(^{-3}\). Substituting these values and the value of \( j \) into eqn. (4.12) gives:

\[ V = 8.8 \text{ m year}^{-1} \]

This is the predicted progressive displacement of the sandwaves 'F' and 'G'.

4.4 COMPARISON OF MEASURED AND PREDICTED PROGRESSIVE DISPLACEMENT OF SANDWAVE CRESTS

Using the theory of the previous section, it has been predicted that a 3m high sandwave, subjected to the tidal currents at position 'Q', will move at a rate of 8.8m per year. Fig. 4.4.1 shows the mean annual positions of sandwaves 'F' and 'G' between 1974 and 1976. From Table A2.3.3 (Appendix 2) the measured migration rate of these two sandwaves, near position 'Q', is 12 ± 3 and 9.6 ± 3m/year respectively.

Considering the approximations made and that this is only an order of magnitude calculation, the agreement between the predicted
<table>
<thead>
<tr>
<th>Tidal Range in metres</th>
<th>A \times B</th>
<th>A</th>
<th>B</th>
<th>Net i</th>
<th>Tidal Range in metres</th>
<th>A \times B</th>
<th>A</th>
<th>B</th>
<th>Net i</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0</td>
<td>15</td>
<td>124</td>
<td>1,860</td>
<td>4</td>
<td>0.22</td>
<td>190</td>
<td>186</td>
<td>31,248</td>
</tr>
</tbody>
</table>
Mass in sandwave \[= \frac{1}{2} w l H \rho_s\]

Mass per unit width \[= \frac{1}{2} l H \rho_s\]

Mass per unit width per unit length \[= \frac{1}{2} H \rho_s\]

Transport rate \[= \frac{1}{2} H \rho_s V\]

\[H = \text{Height of sandwave.}\]

\[\rho_s = \text{Sediment density.}\]

\[j = \text{Transport rate.}\]

\[w = \text{Length of sandwave along crest.}\]

\[V = \text{Velocity of crest.}\]

\[l = \text{Wavelength.}\]

**Fig. 4.3.5.** Showing derivation of relationship between the sediment transport rate and the migration rate of a sandwave.
Fig. 4.4.1. Showing the measured positions of sandwaves 'F' and 'G', between 1974 and 1976.
migration rate and the measured result is very satisfactory. Providing that the current velocities and the sandwave height are known accurately, the same theory could be used to predict the sandwave migration rate in other areas.

Less satisfactory agreement was obtained when the I.O.S. Taunton Acoustic Rangemeter equipment was used to measure the position of sandwave crest 'G' over a period of 22 days. The tides during this period have been analysed by a similar method to that given in section 4.3 and the predicted displacement is shown in Fig. 4.4.2. From this figure it can be seen that the sandwave crest would appear to have moved much further (4m) than would have been expected (50 cm) from the predicted results. It is felt that this is due to the effect of wind and other meteorological disturbances on the tidal current strengths. Because the sediment transport rate is critically dependent on the current velocity, a small change in the current, as a result of meteorological action, would cause a large change in the sandwave migration rate. Over longer periods of a year or more, these small changes will tend to average out. This demonstrates the necessity of measuring the progressive migration rate of a sandwave over a long period of time.

It should be noted that this disagreement is with a single piece of isolated data, whereas the agreement with the displacement measured by echo sounding is with data supported by numerous measurements.
Fig. 4.4.2 Prediction of the progressive displacement of a sandwave crest and the actual positions measured by the I.O.S. rangemeter.
CHAPTER 5

THE RECIPROCATIVE DISPLACEMENT OF SANDWAVE CRESTS

In this chapter the short term reciprocative displacement of sandwave crests will be discussed. Firstly, the measurements which have been made will be described (5.1). An attempt to predict the sandwave crest displacement is then made (5.2), followed by a discussion of the results (5.3).

5.1 THE MEASUREMENTS MADE

During August 1974, use was made of the I.O.S. diver-operated acoustic rangemeter system (Appendix 5), to determine the reciprocative displacement of the crest of sandwave G (Fig. A2.3.10). The positions which were found for the sandwave crest are shown in Fig. 5.1.1. The measurements of sandwave crest displacement which have been taken from these figures are shown in Fig. 4.4.2 and Table 5.1.1. All measurements of positions were made at slack water, an 'ebb measurement' meaning that the measurement was made at the slack water after an ebb tide.

From the measurements in Table 5.1.1 it can be seen that the sandwave crest returns to substantially the same position after two tidal cycles (measurement 4). This agrees with the calculated progressive displacement over this period of only 5 cm (Fig. 4.4.2). Also, the greater the tidal range, and hence the tidal currents, the greater the displacement of the sandwave crest. A more detailed relationship between the current strength and the sandwave crest will be discussed in the next section.

5.2 PREDICTION OF RECIPROCATIVE DISPLACEMENT

In order to calculate the magnitude of the reciprocative displacement of the crest of sandwave 'G', a procedure similar to that used to predict the progressive displacement was adopted.
TABLE 5.1.1
DIVER RANGEMETER MEASUREMENTS AUGUST 1974

<table>
<thead>
<tr>
<th>1st Measurement</th>
<th>2nd Measurement</th>
<th>No. of tidal cycles</th>
<th>Tidal range m</th>
<th>Displacement m</th>
</tr>
</thead>
<tbody>
<tr>
<td>6th ebb</td>
<td>7th flood</td>
<td>1½</td>
<td>3.7</td>
<td>3.5 ± 0.25</td>
</tr>
<tr>
<td>20th ebb</td>
<td>21st flood</td>
<td>1½</td>
<td>5.0</td>
<td>5.5 ± 0.25</td>
</tr>
<tr>
<td>21st flood</td>
<td>21st ebb</td>
<td>½</td>
<td>5.0</td>
<td>5.5 ± 0.25</td>
</tr>
<tr>
<td>20th ebb</td>
<td>21st ebb</td>
<td>2</td>
<td>5.0</td>
<td>0 ± 0.25</td>
</tr>
<tr>
<td>28th flood</td>
<td>28th ebb</td>
<td>½</td>
<td>1.9</td>
<td>1.5 ± 0.25</td>
</tr>
</tbody>
</table>
In this case it is necessary to relate the current at Im above the sandwave crest \( U_{100(c)} \) to the tidal current measurements made at position 'Q' \( U_{\text{mid}(Q)} \) (Fig. 4.3.1). The position 'Q' measurements were made on the gentle slope of sandwave 'G'. From Table 5.2.1 it can be seen that the ratio between the mid-depth current at the sandwave crest \( U_{\text{mid}(c)} \) and \( U_{100(c)} \) varies throughout the tidal cycle. From Appendix 3, Figs. A3.1.9/10 it can be seen that:

\[
\frac{U_{100(c)}}{U_{\text{mid}(Q)}} \approx 5 \quad (5.1)
\]

For simplicity it has been assumed that this is true. The variation in the ratio will be discussed further in the next section (5.3).

Perrings' formulae (eqns. (4.2) and (4.3)) and the modified Bagnold equation (Fig. 4.3.3) were used in order to calculate the transport rate \( j \) (Table 5.2.2).

Since under reciprocative motion it can be assumed that only the crest of the sandwave is moving, it was felt that the model of Fig. 4.3.5 relating the progressive movement of a sandwave to the transport rate was inappropriate. Therefore the model of crest movement shown in Fig. 5.2.1 was used producing the formula:

\[
j = \frac{1}{\lambda} \frac{1}{H} V \rho_s \quad (5.2)
\]

The displacement of the sandwave crest predicted by this formula \( (V_2) \) and formula (4.12) \( (V_1) \), are given in Table 5.2.2 and the shape which was observed for the sandwave crest in Fig. 5.2.2 (see also Fig. 5.2.3).

5.3 DISCUSSION

From Table 5.2.2 it can be seen that the values of crest displacement predicted from the current measurements are too small by a factor of 5 for the ebb tide and by a factor of 25 for the flood tide. If the two equations (Bagnold equation (4.6) and Quadratic
### TABLE 5.2.1

**TIDAL CURRENT MEASUREMENTS ON THE CREST OF A SANDWAVE**

(a) Position 'P3', 23rd August, 1974, Sandwave 'H'.

<table>
<thead>
<tr>
<th>Time from L.W. (Dartmouth, hrs.)</th>
<th>Velocity, m s(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\bar{U}_{100}(c))</td>
</tr>
<tr>
<td>-0.23</td>
<td>0.65</td>
</tr>
<tr>
<td>-0.14</td>
<td>0.65</td>
</tr>
<tr>
<td>0.79</td>
<td>-</td>
</tr>
<tr>
<td>0.87</td>
<td>0.63</td>
</tr>
<tr>
<td>1.66</td>
<td>0.60</td>
</tr>
<tr>
<td>1.74</td>
<td>-</td>
</tr>
<tr>
<td>1.82</td>
<td>0.40</td>
</tr>
</tbody>
</table>

(b) Position 'Q', 24th August, 1974, Sandwave 'G'.

<table>
<thead>
<tr>
<th>Time from L.W. (Dartmouth, hrs.)</th>
<th>Velocity, m s(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\bar{U}_{100}(c))</td>
</tr>
<tr>
<td>0.71</td>
<td>0.42</td>
</tr>
<tr>
<td>0.79</td>
<td>0.34</td>
</tr>
<tr>
<td>1.54</td>
<td>0.31</td>
</tr>
<tr>
<td>1.62</td>
<td>0.18</td>
</tr>
</tbody>
</table>

\[
\text{Ratio} = \frac{\bar{U}_{100}(c)}{\bar{U}_{\text{mid}}(c)} = \frac{2 \times \bar{U}_{100}(c)}{\bar{U}_{2/3} + \bar{U}_{1/3}}
\]

Velocities corrected to 4m tidal range.
### TABLE 5.2.2
CALCULATED TRANSPORT RATE AND RECIPROCATIVE CREST DISPLACEMENT

<table>
<thead>
<tr>
<th>Tidal Range</th>
<th>j ebb ( \text{gm cm}^{-1} \text{ tide}^{-1} )</th>
<th>( V_2 ) ( \text{m tide}^{-1} )</th>
<th>( V_1 ) ( \text{m tide}^{-1} )</th>
<th>j flood ( \text{gm cm}^{-1} \text{ tide}^{-1} )</th>
<th>( V_2 ) ( \text{m tide}^{-1} )</th>
<th>( V_1 ) ( \text{m tide}^{-1} )</th>
<th>Actual ( V ) ( \text{m tide}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>113</td>
<td>0.2</td>
<td>0.03</td>
<td>5</td>
<td>0.008</td>
<td>0.0013</td>
<td>1.5</td>
</tr>
<tr>
<td>3.7</td>
<td>1400</td>
<td>0.7</td>
<td>0.25</td>
<td>280</td>
<td>0.14</td>
<td>0.05</td>
<td>3.5</td>
</tr>
<tr>
<td>5.0</td>
<td>4600</td>
<td>1.0</td>
<td>0.58</td>
<td>1600</td>
<td>0.36</td>
<td>0.2</td>
<td>5.5</td>
</tr>
</tbody>
</table>

\[
V_1 = \frac{2 j}{H \rho_s}
\]

\[
V_2 = \frac{2 j \lambda}{\frac{1}{k} H \rho_s}
\]

See Figure 5.2.3.
mass in sandwave = \frac{1}{2} w l H \rho_s

mass per unit width = \frac{1}{2} l H \rho_s

mass per unit width per unit length = \frac{1}{2} \frac{1}{\lambda} H \rho_s

transport rate, j, = \frac{1}{2} \frac{1}{\lambda} H \rho_s V

H = height of sandwave
\rho_s = sediment density
j = transport rate
w = length of dune along crest
V = velocity of crest
l = base length of dune
\lambda = wavelength of dune

Fig. 5.2.1 The derivation of the relationship between the sediment transport rate and the motion of a sandwave crest.
Fig. 5.2.2 Sandwave crest model showing the assumed changes in the shape of the sandwave crest after the ebb flow and after the flood flow. Three flood profiles are shown for three different tidal ranges.

<table>
<thead>
<tr>
<th>Tidal range</th>
<th>( z ) (m)</th>
<th>( H ) (m)</th>
<th>( l ) (m)</th>
<th>( V ) (m tide(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>0.5</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>0.7</td>
<td>3.5</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>1.0</td>
<td>5.5</td>
<td>5.5</td>
<td></td>
</tr>
</tbody>
</table>

\[ \rho_s = 1.6 \text{gm cm}^{-3} \]
\[ \lambda = 10 \text{m} \]
Fig. 5.2.3  Measured and computed sandwave crest displacement (see table 5.2.2).
The results of Table 5.2.2 suggest that, for reciprocative movement, the accepted value of the term \( K \frac{C_{100}^{3/2}}{U_{100}} \) is too low. It will now be shown that there are good reasons why this should be so.

Firstly, the coefficient \( K \) represents the efficiency with which the flow transports the sediment. Kachel and Sternberg (1971) suggest that \( K \) varies between 0.3 and 5.4 dependent upon the excess shear stress \( (\tau_o - \tau_c)/\tau_c \). Their results were obtained for a flat bed with small ripples (\( \lambda \approx 20 \text{ cm} \)), so the sediment would be transported slightly uphill. However, at the crest of a sandwave just after the tide has turned, the sediment will be transported downhill (Fig. 5.3.1). Consequently one would expect that the sediment will be transported much more easily, and the value of \( K \) will be much larger than usual.

The drag coefficient \( C_{100} \) relates the friction velocity to the water velocity at 1m above the sea bed (eqn. (4.10)). Sternberg (1972) suggests a value of \( 3.10^{-3} \) is suitable for natural sediments. This value was derived under normal flow conditions, when a logarithmic velocity profile existed. This profile is described by the Karman-Prandtl velocity profile equation:

\[
\overline{U}_d = U_* \frac{1}{k} \ln\left(\frac{d + d_o}{d_o}\right) \tag{5.4}
\]

where \( k \) is Von Karman's constant (\( k \approx 0.4 \)) and \( d_o \) is the roughness length (\( d_o \ll d \)).

This formula can be rearranged; (Charnock 1959):

\[
\overline{U}_d = 5.75 \ U_* \ \log \left( \frac{d}{d_o} \right) \tag{5.5}
\]

if \( C_{100} = 3.10^{-3} \). Then:
Fig. 5.3.1a  Sandwave crest shape at the start of the flood tide.

Fig. 5.3.1b  Sandwave crest shape at the start of the ebb tide.
This equation is shown plotted in Fig. 5.3.2.

If Figs. A3.1.9 - 11 (Appendix 3) are examined it can be seen that a logarithmic velocity profile does not hold at the sandwave crest. In fact, the velocity at 1m above the sea bed is greater than the velocity at \( \frac{2}{3} \) depth, at position 'P', at the start of the cycle. This is caused by the shape of the sandwave crest. Immediately after the tide has turned, the sandwave crest will be facing in the wrong direction for the tidal current. This will have the effect of increasing the current immediately above the sandwave crest. From Figs. A3.1.9/10 (Appendix 3) it can be seen that \( \bar{U}_{100} \) decreases throughout the tidal cycle, as the shape of the sandwave crest becomes more streamlined. This suggests that a larger value of \( C_{100} \) should be used, at the sandwave crest, where currents of alternating direction occur.

Both of these effects will be greater at the start of the flood tide, since the inverse sandwave crest, produced by the ebb tide, is then much greater (Fig. 5.3.1).

To obtain a factor of 5 increase in the sediment transport rate (ebb tide), \( K \) and \( C_{100} \) should both be increased by a factor of 1.9. To obtain a factor of 25 increase (flood tide), they should be increased by a factor of 3.6. In practice, the increase in the coefficients will be much greater at the beginning of the tidal cycle than at the end because the sandwave crest shape is more streamlined at the end of the cycle.

From the above discussion it can be seen how the position and shape of the sandwave crest can be stabilized. At the start of the weaker flood tide, the sandwave crest will be shaped as in Fig. 5.3.1a. The shape is very unstreamlined, so \( K \) and \( C_{100} \) will be large,
\[ \frac{\bar{U}_d}{\bar{U}_{100}} = 0.315 \log \left( \frac{d}{0.066} \right) \]

Fig. 5.3.2 Karman-Prandtl velocity profile

\( \left( c_{100} = 3 \times 10^{-3} \right) \)
and the weak current will transport the sediment far more efficiently than would normally be expected. As the crest becomes more streamlined $K$ and $C_{100}$ will decrease slightly, but before a fully streamlined shape is achieved and $K$ and $C_{100}$ reach normal values, the end of the tidal cycle will be reached. At the start of the ebb tide, the sandwave crest will be shaped as in Fig. 5.3.1b. This shape is unstreamlined but not to such an extent as for the flood tide. Therefore, the values of $K$ and $C_{100}$ will be higher than normal but not so high as for the flood tide. However, the ebb tide is stronger than the flood tide and all the sediment which was moved by the flood tide will be moved back into its original position before the end of the ebb tide. The sandwave crest will then be shaped as in Fig. 5.3.1a and $K$ and $C_{100}$ will have returned to more normal values. During the remaining flow of the ebb tide, sediment will continue to be moved, with normal values of $K$ and $C_{100}$ and the shape of the sandwave crest will remain the same. The sediment which moves during this time contributes to the progressive movement of the sandwave crest.
CHAPTER 6

BEDFORM MORPHOLOGY AND MOVEMENT

In this chapter the morphology and movement of ripples (6.1) and dunes (6.2) will be discussed. This will be followed by a description of the morphology of sandwaves (6.3(a)), the factors controlling sandwave occurrence (6.3(b)), sediment variation over a sandwave (6.3(c)) and the effect of storms on a sandwave (6.3(d)).

NOTE: The terms 'ripples', 'dunes' and 'sandwaves' are explained in chapter 1 (1.1).

6.1 RIPPLES

In the area of Start Bay surveyed in detail, it has been found, from observations made by divers, that there are numerous ripples with a wavelength of about 30-40 cm.

Under calm weather conditions the ripples are orientated perpendicular to the tidal current. However, when the surface waves are large, so that the bottom currents induced by the surface waves are larger than the tidal current, the ripples are parallel to the surface waves and symmetrical.

At neap tides, assuming calm weather conditions, it was observed that only the ripples were mobile. In the troughs of the sandwaves only the ripples which formed the crests of the dunes were mobile. Near the crests of the sandwaves only the ripples in the troughs of the dunes were stationary. This could be observed because a brown slimy algal growth appears on the surface of that sand which is immobile. This sand is also well packed and firm whereas the mobile sand is loose and clean. The compactness of the immobile sand also means that it will be more difficult for a current increasing in amplitude to start it moving. In addition, during neap tides there tended to be pieces of seaweed and other debris in the
troughs of the sandwaves, indicating the general lack of water movement. By contrast, at spring tides the whole of the sea bed is mobile. This was shown by the absence of the algal growth and looseness of the sand.

6.2 DUNES

The dunes, in the area of detailed study, have wavelengths of about 10m (Fig. 6.2.1). The size and shape of dunes varies with their position on the sandwave and with the particular sandwave on which they occur.

On the back of a sandwave, near the crest, the dunes are fairly large (1m high). The actual crest of the sandwave can be considered an extra large dune. As one moves down the back of the sandwave towards the trough the dunes become smaller and in the trough the amplitude is of the order of 20 cm. The dunes are normally of the classical asymmetrical shape. On one occasion, however, a curious type of dune structure was observed in the trough of a sandwave (Fig. 6.2.2). This was observed at slack water just after an ebb tide, half-way between spring and neap tides. The bulk of the material was compacted and brown with algae but on the crest of each dune was a small, reverse crest, avalanche slope, about 5 to 10 cm high, of loose clean sand (Fig. 6.2.3). This reverse crest faced north. The reverse crest is probably due to the low velocity reverse eddy current in the lee of the main sandwave crest.

The character of the normal dunes varies from sandwave to sandwave and also along the length of each sandwave (Fig. 6.2.1). To the east (B) dunes are normally parallel to the crest of the sandwave, i.e. perpendicular to the tidal currents. To the west (A), where the sandwave bifurcates, the dunes remain perpendicular to the tidal currents, consequently, they run at an angle to the sandwave crest. As
Fig. 6.2.1  Showing variation of sandwave cross-section.
Fig. 6.2.3  Dune shape found in trough of sandwave.

Fig. 6.2.2  Profile of sandwave showing region in which reverse crested dunes occur.
each dune crosses the sandwave crest, it becomes large and forms the crest.

In this region, although the sandwaves have a lower amplitude, the dunes tend to be larger. When diving, it can be very difficult to determine which particular dune forms the crest of the sandwave, as the sandwave tends to be a pile of dunes. In the region (B) this problem does not occur, as the sandwave has a large avalanche slope which is easily distinguished. Between the two regions there is a gradual change from area (A) to area (B). Underwater it is impossible to determine the point of bifurcation.

Variations from one sandwave to another are caused mainly by variations in the bifurcation position and by variations in the shape of the sandwave. The large sandwaves with large crests tend to have small dunes which are more regular and even in size. The smaller and more rounded sandwaves tend to have larger dunes which vary in wavelength and amplitude.

The movement of the sandwave crest itself has been described in detail in the previous chapter. Two techniques were used to measure the movement of the rest of the dunes. These measurements were made on sandwave 'G' where it had bifurcated, thus giving two sandwave crests about 50m apart and a number of large dunes (height 50 cm to 1m).

The first method used, to measure their movement, was that of making echo sounder 'stars' (Appendix 2). Measurements were made, at intervals, throughout the tidal cycle. From these it was found that the dunes moved by less than one wavelength. In order to determine the dune movement more accurately the rope method was used, by divers, to determine the positions of the dunes at two successive slack waters (chapter 3.1(c)). Fig. 6.2.3(b) shows the sandwave
profiles found. The upper profile is the shape after an ebb tide and the lower profile is the shape after a flood tide. The difference between the positions of the dune crests, at the two slack waters, gives the dune crest displacement. The displacements found on two separate occasions are shown in Fig. 6.2.3(a). This shows that the sandwave crest moves about twice as far as the dunes, even though the dunes contain less sediment, indicating that the water currents immediately above the sandwave crest are capable of moving far more sediment than those away from the crest.

6.3 SANDWAVES

6.3(a) Sandwave Morphology

The sandwaves in Start Bay vary in amplitude and shape dependent upon their position in the Bay. The sandwaves on and around the Skerries Bank have been investigated most thoroughly so they will be discussed in greatest detail.

The shape of sandwaves is generally recognised as a powerful indication of direction of sediment transport (Stride 1965). If a sandwave is symmetrical, the currents are equally strong in both directions and no net sediment transport takes place. If the sandwave is asymmetrical one current is stronger than the other and transport of sediment takes place (see chapter 4).

Another characteristic shape which occurs is the catback sandwave (Fig. 6.3.1) (Van Veen 1935, McCave 1971). This is caused by the weaker current producing an eddy in the lee of the sandwave crest, on the opposite side to the main avalanche slope. This generally occurs on fairly large sandwaves with strong currents in both directions. In Start Bay the reverse current is not strong enough to produce this effect on a large scale. Instead, the large dune, which forms the crest of the sandwave, turns round and faces the opposite direction.
Normal asymmetrical sandwave profile.

'Catback' sandwave profile.

Fig. 6.3.1 Showing the catback sandwave profile.
There are a number of sandwaves in Start Bay which would appear to have a catback cross-section. An example of this can be seen in Fig. A2.3.3 (in particular for sandwave G lines 6 and 10 and sandwave F lines 6 and 4). However, from this figure it can be seen that this cross-section occurs because the sandwave is bifurcating. It is suggested by the present author that this could, in fact, be the cause of catback sandwaves in other areas. This demonstrates the dangers of making echo sounder surveys of sandwaves, in which the survey profiles are spaced too far apart. Sandwaves should be considered as three-dimensional objects (Also suggested by Langhorn, 1973b).

The sandwaves on the Skerries Bank itself show interesting variations in shape, which can be correlated with the residual tidal currents found by Acton and co-workers (chapter 4).

The sandwaves along the crest of the Bank are symmetrical and fairly small in amplitude. The amplitude varies from 0 metres to 2 metres. The low amplitude is probably due to the shallower water and also to the higher amplitude of wave-induced bottom currents. These two mechanisms are related. The symmetry of the sandwaves is due to there being no residual tidal current across the crest of the Skerries.

The sandwaves to the seaward increase in amplitude rapidly, to 15 metres, as the depth of water increases to 40 metres. These sandwaves have the steep avalanche face to the north, which agrees with a residual tidal current to the north.

The sandwaves to the landward of the crest of the Skerries increase in amplitude but to a lesser extent, up to about 4 metres. The steep avalanche slope faces to the south, agreeing with the residual current to the south.

As one moves further towards the land into deeper water, lower
currents and finer sediment, the amplitude decreases and the sandwaves bifurcate, resulting in a decrease in wavelength. The sandwave eventually disappears in a mass of dunes.

6.3(b) The Factors Controlling the Occurrence of Sandwaves

In the previous sections it has been shown how the shape of sandwaves is controlled by the relative strengths of the two opposing tidal currents. However, the correlation of the sandwave wavelength, height and occurrence with the factors which control them is a little more difficult. Several factors have been suggested. Examples of these are water depth (Yalin 1972) and sediment grain size (Dalrymple et al 1978).

From the measurements made by the author in Start Bay, one clear correlation can be made. This is between the occurrence of the sandwaves and the sediment grain size. Fig. 6.3.1 is a map of the sandwaves in Start Bay prepared, by the author, from three side scan sonar surveys, made using Bath University equipment and personnel (Chesterman and Hopkins 1971). The sandwave amplitudes and directions were obtained from an echo sounder survey made, on the 10th October 1975, by the author. Fig. 6.3.2 is taken from Hails (1975) and shows the sediment grain size distribution in Start Bay. Comparison of these two figures shows that the 0.0 phi and 2.0 phi sediment grain size contours delineate the area in which sandwaves occur (Dalrymple et al 1978).
Fig. 6.3.1 Sandwave crest positions found from side scan sonar surveys.
It has been suggested (Yalin 1972) that sandwave wavelength $\lambda$ is related to water depth $d$ by the relation,

$$\lambda = 2\pi d$$

In Start Bay the correlation between the two is poor (Fig. 6.3.3). However, if only the sandwaves away from the Skerries Bank, in deeper water, are considered, the correlation is better. Indeed, Fig. 6.3.3 shows that $\lambda/d$ must be very close to the value of $2\pi$ suggested by Yalin.

The poor correlation in the shallow water of the Skerries Bank may be due to problems in defining the water depth and sandwave wavelength. The water depth varies with the state of the tide; this will have the greatest affect in shallow water. On the shallowest part of the Skerries, the water depth can change by a factor of up to two, every 6.2 hours. The determination of the sandwave wavelength is complicated by two factors. Firstly by the bifurcation of sandwaves. Secondly, in this area on the Skerries, often a rounded hump appears between two sandwave crests (Fig. A2.3.2). Should this hump be considered to be a sandwave or not? The result of this decision can change the sandwave wavelength by a factor of two.

The above discussion demonstrates the problems in applying formulae such as this, that have been derived from experiments made in laboratory flumes, to the conditions occurring in the open sea.

6.3(c) Sediment Variation over a Sandwave

A series of sediment samples were taken, by divers, at various positions over a sandwave crest (Appendix 4, Fig. A4.4.1). Most of the samples were taken from the crests of the dunes, in order to remove any variations in sediment characteristics over the dunes themselves. These sediment samples were analysed and the results are shown in Appendix 4, Figs. A4.4.2 - 7. Five parameters
Fig. 6.3.3 Comparison between sandwave wavelength and water depth for sandwaves in Start Bay.

- X deep water away from Skerries.
- O shallow water and near the Skerries.
were calculated from the sediment analysis, they are:

1. Proportion of insoluble material.
2. Median diameter.
3. Sorting coefficient.
4. Skewness.
5. Kurtosis.

The meaning of each of these parameters is described in Appendix 4(b). In this section the way in which the sediment parameters can be related to the tidal current condition, at different points over the sandwave, will be discussed. The sediment consists of two fractions, the shelly soluble material and the insoluble sand. The shelly material consists mainly of flat plates. Consequently, its hydrodynamic radius is smaller than its physical radius (see Appendix 3). As a result of this, the sediment is better sorted than one would at first think from the analysis of the whole sediment. The physical properties of the sandy portion are a more reliable guide to the hydrodynamic properties of the whole sediment than the physical properties of the whole sediment.

In the regions where there is strong tidal activity, in particular at the sandwave crest and also at the crests of the dunes on the stoss slope of the sandwave, the sediment has been subjected to strong reciprocative movement. As a result the sediment is well sorted, with a general lack of coarse, shelly material and fine, sandy material. The coarse, shelly material has been tipped over the edge of the sandwave crest on to the avalanche slope. The avalanche slope consists of 35% shelly material and consequently the grain size is high. The fine material has been carried a greater distance into the quieter waters in the trough of the sandwave. Here there is also a high proportion of shelly material (up to 40%) and therefore the sediment
is poorly sorted, with a high proportion of fine and coarse material.

The dunes themselves show a similar trend. At the crests of the dunes, where the current is strong, the sediment is coarse and well sorted. In the troughs of the dunes the sediment is fine and poorly sorted. There does not appear to be any significant difference between the proportion of shelly material at the dune crest and trough.

From this it can be seen that the sediment characteristics, at different points over a sandwave, correlate with the hydrodynamic conditions that have been suggested in the previous chapters.

6.3(d) The Effect of Storms on Sandwaves

On the 26th November 1974 an attempt was made to measure the position of the sandwave crest using the rangemeter equipment. However, in the fortnight before, a force ten storm had occurred and no trace could be found of the sandwave crest, avalanche slope, or any of the dunes. The only bedforms present were numerous ripples aligned with the tidal current. However, it was shown that the sandwave itself was present in a 'smoothed out' form. Fig. A5.1.3, Appendix 5, shows the path followed during this dive. It was found that the water was deep where the trough should have been and shallow where the crest should have been. Unfortunately, it was not possible to make an echo sounder survey on this occasion. The results of the next year's echo sounder surveys showed that the sandwave was of almost identical shape to that before the storm but had shifted south by about 15 metres. Therefore, the factors which control the position and shape of the sandwave cannot have been affected by the storm.

Another conclusion which can be drawn from these observations is that, in spite of over a week elapsing since the storm, the sandwave crest and dunes had not reformed. This was a period of neap
tides, suggesting that the dunes are formed by the stronger spring tides; hence, their characteristics (wavelength and amplitude) must be related to the velocity of the maximum tidal currents rather than of the average current. Thus confirming the hypothesis of Acton (1972).

Langhorn (1977) has also observed changes in the wavelengths of dunes after storms.
CHAPTER 7

SUMMARY OF RESULTS AND SUGGESTIONS FOR FUTURE WORK

In this chapter firstly the results concerning the sandwave movement (7.1(a)), occurrence and morphology (7.1(b)) will be enumerated. This will be followed by some suggestions for future work (7.2).

7.1 SUMMARY OF MAIN RESULTS

7.1(a) Results concerning Sandwave Movement

1. The long term progressive migration rates of sandwaves on the Skerries Bank have been measured over a period of two years (Chapter 4 and Appendix 4, Table A4.3.3).

2. The theoretical progressive migration rate of the sandwaves has been calculated from the measured tidal current velocity, sediment characteristics and the sandwave shape, using the modified Bagnold equation (Kachel and Sternberg, 1971). This calculated value has been found to agree with the measured value.

3. The reciprocative motion of a sandwave crest, in response to the alternating ebb and flood tidal currents, has been measured for a number of different tidal ranges (Chapter 5).

4. The reciprocative displacement of the sandwave crest has been calculated from the measured tidal currents etc and it has been found that the measured displacement is larger by an order of magnitude or more. It is suggested, by the author, that this is due to a failure of the Bagnold equation and the Quadratic stress law at the sandwave crest. Reasons for this are discussed in Chapter 5.

5. The reciprocative displacement of the dunes has been measured. It has been found that the reciprocative displacement of the crest of the sandwave is about twice as great as the reciprocative displacement of the dunes in the trough of the sandwave (Chapter 6).
7.1(b) Results concerning Sandwave Occurrence and Morphology

6. The direction of migration of the sandwaves has been found to correlate with the 'residual' tidal current and the asymmetry of the sandwave shape (Chapter 4, Fig. 4.2.3). This confirms the commonly-held view that this is so (Stride, 1965).

7. It has been found that the sandwaves in Start Bay occur in areas where the sediment grain size lies between 0 and 2 phi (1 mm and 0.25 mm). This agrees with the work of Dalrymple et al (1978) and Bokuniewicz et al (1977).

8. A comparison has been made between the wavelengths ($\lambda$) of the sandwaves and the water depth ($h$). It has been found that for the sandwaves in the deep water away from the Skerries $\lambda \approx 2\pi h$. This agrees with the relationship suggested by Yalin (1972). However, in the shallow water on the Skerries this does not hold.

9. The sediment characteristics have been found to change over a sandwave profile. The sediment occurring in areas of high current activity (crest of the sandwave and dune crests on the stoss slope of the sandwave) are better sorted and contain less shelly material than those in quieter areas (trough of sandwave and troughs of dunes). The avalanche slope of the sandwave is particularly high in shelly material.

10. It has been found that after storms the small scale features (sandwave crest and dunes) of a sandwave are removed. They had not reformed after a week during which neap (weak) tides predominated. However, they had been restored when next surveyed, several months later. Langhorn (1977) has observed changes induced by storms.

11. It has been observed that bifurcating sandwaves have a similar cross-section to the 'catback' cross-section of Van Veen. It is suggested that this is an alternative cause of catback sandwaves. This
has also been suggested by Langhorn (1973b).

7.2 SUGGESTIONS FOR FUTURE WORK

In this thesis a number of theories have been proposed concerning the movement and character of sandwaves. These theories are supported by evidence obtained during this work and from the work of other authors. However, it is possible that, in the light of more evidence, some of these theories may prove to be incorrect. The suggestions that will be made in this section for future work are designed to provide the evidence to test these theories further.

It has been shown that the modified Bagnold equation can be used to successfully predict the progressive displacement rate of two particular sandwaves, for which accurate tidal current information was available. This method of predicting the progressive displacement rate should be tried for other sandwaves in Start Bay and also for sandwaves in other areas. The results should be compared with the measured displacement rates.

The reciprocative movement of the sandwave crest should be investigated in greater detail. In this work it has been shown that the Bagnold equation and the Quadratic stress law break down at the sandwave crest. It is suggested that simultaneous measurements be made of the following. Firstly, the tidal current velocities, at a number of depths and positions over a sandwave profile, should be found. Particular attention should be given to those near the seabed and at the sandwave crest. Secondly, the position of the sandwave crest should be recorded at successive slack waters, so that the reciprocative displacement may be calculated. The results of these measurements will allow the effect of alternating tidal flows on the sediment of the sandwave crest to be investigated more fully.

In this work a correlation has been found between sediment
grain size and the occurrence of sandwaves. Other authors (Dalrymple et al. (1978) and Bokuniewicz et al. (1977)) have suggested similar relationships. It is suggested that the relationship between sediment characteristics and sandwave occurrence be investigated more fully in Start Bay. The effects of other factors, such as tidal strength and water depth, should also be considered.

It has been found that the sandwave wavelength is related to the water depth (as suggested by Yalin (1972)) for water depths greater than 30m, in Start Bay. The reasons for its failure on the shallow Skerries Bank should be investigated. The problems involved in defining the water depth and sandwave wavelength, which have been described in Chapter 6, should be considered.

It has been found that the detailed features of a sandwave are affected by storms. An investigation of the recovery of these features after a storm would provide information as to the tidal conditions that play the most important part in the formation of sandwaves.

Catback sandwaves in other areas should be investigated more fully, to determine whether they are caused by the bifurcation of the sandwave crest.
APPENDIX 1

NAVIGATION USING SEXTANTS

Sextants can be used, on the boat, to measure the horizontal angle subtended by fixed points on the shore (A1, A2, A3; Fig. 3.1.1). If two such angles (θ1 and θ2) are measured simultaneously and the positions of the points (A1, A2, A3) are known, then the position of the boat can be found.

Various conspicuous buildings on the shore were used as shore marks (see Table Al.1.1). The positions of these with respect to the National Grid was found from '25 inches to the mile' maps.

The accuracy of the positions of the shore marks used was checked by repeated measurement of the angles concerned, from an anchored boat. This was done at several positions in the survey area (see Fig. Al.1.1). It was found that these readings produced a series of 'cocked hat' error triangles (Fig. Al.1.2). The shape and orientation of these remained fairly constant when re-measured. Therefore, it was assumed that a large portion of the error was due to errors in the assumed position of the shore marks.

A series of corrections was calculated for each pair of angles, such that the position was brought to the average position for each series of measurements (Table Al.1.2/3). By calculating the standard deviation (σ) of all the values found for the correction of each pair of angles, an indication of the accuracy of that pair of angles was found. Any individual pair of angles with a correction of more than 2σ away from the average correction was discarded.

During the calculation of the average position of a series of angles, certain pairs of angles were ignored because the position lines for these pairs were almost parallel. Therefore, a small error in the measured angle produced a large error in the position
### TABLE A1.1.1

**FIXMARK POSITIONS**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>National grid reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
<td>82.9388 37.1221</td>
<td>Start Point Lighthouse</td>
</tr>
<tr>
<td>HS</td>
<td>81.7686 38.7760</td>
<td>Hallsands Hotel</td>
</tr>
<tr>
<td>BS</td>
<td>81.9125 40.5452</td>
<td>Beesands Houses</td>
</tr>
<tr>
<td>TX</td>
<td>82.3261 42.0025</td>
<td>Torcross Hotel</td>
</tr>
<tr>
<td>SL1</td>
<td>83.3795 45.5270</td>
<td>House at Slapton</td>
</tr>
<tr>
<td>SL2</td>
<td>82.3697 45.1733</td>
<td>House at Slapton</td>
</tr>
<tr>
<td>WT</td>
<td>87.1887 50.5541</td>
<td>Water Tower (centre)</td>
</tr>
<tr>
<td>DB</td>
<td>90.3337 50.2826</td>
<td>Day Beacon (centre)</td>
</tr>
</tbody>
</table>

**Pairs of marks normally used to obtain angles**

<table>
<thead>
<tr>
<th>SP HS</th>
<th>HS BS</th>
<th>BS TX</th>
<th>TX SL1</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP BS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BS SL1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>BS SL2</td>
<td></td>
</tr>
</tbody>
</table>
Fig. A1.1.1 Showing positions of sextant shore marks and areas used for sextant angle corrections.
Fig. A1.1.2 Example of the output from programme PLOT2 showing the circles of constant angle.

See Table A1.1.2

Circles of constant angle

Scale 1 cm = 2 m
TABLE Al.1.2
EXAMPLE OF A SET OF MEASUREMENTS
USED TO OBTAIN SEXTANT ANGLE CORRECTIONS

Readings taken: 13th June, 1975

See Fig. Al.1.2

Scale: 1 cm to 2m

Area 'D': (See Fig. Al.1.1)

Co-ordinates: 84.685 38.86

<table>
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<tr>
<th>Circle</th>
<th>Angle</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>SP HS</td>
<td>42° 38.5'</td>
<td>42° 31.5'</td>
<td>42° 54'</td>
<td>42° 52.5'</td>
</tr>
<tr>
<td>2</td>
<td>HS BS</td>
<td>33° 8'</td>
<td>33° 3'</td>
<td>32° 45'</td>
<td>32° 43'</td>
</tr>
<tr>
<td>3</td>
<td>BS TX</td>
<td>22° 25'</td>
<td>22° 25'</td>
<td>21° 50'</td>
<td>21° 47'</td>
</tr>
<tr>
<td>4</td>
<td>BS SL1</td>
<td>48° 54'</td>
<td>48° 52'</td>
<td>47° 41'</td>
<td>47° 39'</td>
</tr>
<tr>
<td>6</td>
<td>BS SL2</td>
<td>39° 42'</td>
<td>39° 42.5'</td>
<td>38° 37'</td>
<td>38° 36'</td>
</tr>
</tbody>
</table>

Time of reading (hrs): 1005 1100 1300 1340

Corrections obtained in area 'D' (see Table Al.1.3)

<p>| SP HS | HS BS   | 4 ± 0.5m  | -96° |
| SP BS | BS SL1 | 0 ± 0.5m  |
| SP BS | BS SL2 | 0 ± 0.5m  |</p>
<table>
<thead>
<tr>
<th>Pair of Marks</th>
<th>Correction</th>
<th>Amplitude</th>
<th>Direction from West</th>
</tr>
</thead>
<tbody>
<tr>
<td>AREA 'B'</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SP HS</td>
<td>BS TX</td>
<td>2.8 ± 0.5m</td>
<td>13°</td>
</tr>
<tr>
<td>SP BS</td>
<td>BS TX</td>
<td>3.9 ± 0.5m</td>
<td>-51°</td>
</tr>
<tr>
<td>SP BS</td>
<td>BS SL1</td>
<td>1.1 ± 0.6m</td>
<td>129°</td>
</tr>
<tr>
<td>SP BS</td>
<td>BS SL2</td>
<td>1.1 ± 0.6m</td>
<td>-51°</td>
</tr>
<tr>
<td>AREA 'C'</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SP BS</td>
<td>BS SL2</td>
<td>1.7 ± 0.3m</td>
<td>-120°</td>
</tr>
<tr>
<td>SP HS</td>
<td>HS BS</td>
<td>4.4 ± 2m</td>
<td>-81°</td>
</tr>
<tr>
<td>SP BS</td>
<td>BS SL1</td>
<td>1.8 ± 1m</td>
<td>101°</td>
</tr>
<tr>
<td>SP BS</td>
<td>BS TX</td>
<td>7.5 ± 1m</td>
<td>-81°</td>
</tr>
<tr>
<td>AREA 'D'</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SP HS</td>
<td>HS BS</td>
<td>4 ± 0.5m</td>
<td>-96°</td>
</tr>
<tr>
<td>SP BS</td>
<td>BS SL1</td>
<td>0 ± 0.5m</td>
<td></td>
</tr>
<tr>
<td>SP BS</td>
<td>BS SL2</td>
<td>0 ± 0.5m</td>
<td></td>
</tr>
<tr>
<td>AREA 'E'</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SP HS</td>
<td>HS BS</td>
<td>10 ± 2m</td>
<td>120°</td>
</tr>
<tr>
<td>SP BS</td>
<td>BS SL1</td>
<td>0 ± 0.5m</td>
<td></td>
</tr>
</tbody>
</table>

For areas see Fig. Al.1.1
(e.g. BS SL1 : BS SL2, see Fig. A1.1.2). A computer programme, PLOT2, was written to do these calculations.

Normally, sextant angles are resected using a triple arm plotter. The measured angles are set up between three arms which are then aligned on a chart with the marks on the shore. The centre mark gives the required position. This method tends to be rather inaccurate and time consuming, particularly when working to a large scale. However, it is useful if only a small number of angles are to be plotted with only moderate accuracy.

The locus of points from which two shore marks subtend the same angle is a circle. These circles can be constructed for a number of angles to form a set of circle charts. The position for two particular angles can be found from the intersection of the two circles involved.

Alternatively, the positions can be found by calculation. A computer programme, PLOTM, was written to do the necessary calculations and apply the corrections in Table A1.1.3. These positions were then plotted as a boat's track on the graph plotter by a programme GPLOTM.

The straightness of the boat's tracks gave a crude check on the accuracy of the sextant angles. If any positions differed markedly from the track they were checked and the angles corrected or discarded.

On the echo sounder record a vertical line is recorded at each position fix by pressing a button. Since the chart paper moves at a constant known rate, the time (t) between fixes can be found. The position of each line on the chart paper was found using the D.Mac. digitising table at Bristol University Computer Unit.

Since the distance (d) travelled over the ground between fixes
is known from the sextant angle positions, the speed \( s \) of the boat over the ground can be calculated. This was done using a programme TIME.

These speeds, between each pair of fixes, were plotted on a graph and provided a very powerful check of the accuracy of the position fixing. During the survey the boat's speed was kept constant, or varied by a known amount, hence, any apparent variations in speed were due to errors in position fixing. Again, any such errors were corrected or discarded. Variations in speed could also be due to variations in tidal current speed over the crests of the sandwaves. However, these are usually predictable.

After these two above effects have been accounted for, there are still small residual variations in speed. These can give an indication of the accuracy of the position fixing.

Since: \[ s = \frac{d}{t} \]
\[ \Delta s + s = \frac{\Delta d + d}{t} \]
so \[ \Delta d = t \Delta s \]

A Polynomial least squares fit was made of speed \( s \) against time \( t \) for each line and for the deviations in speed \( \Delta s \) found for each pair of position fixes. Hence the error in position \( \Delta d \) was found. The average value of \( \Delta d \) \( (\overline{\Delta d}) \) and the standard deviation \( (\sigma) \) were found for each line. If a value of \( \Delta d \) exceeded \( 2\sigma \) the position fix involved was suspected. The value of \( \overline{\Delta d} \) gave an indication of the accuracy of the particular line.

Errors could be due to several different causes.

(a) Misreading of the sextant, often by a whole degree. For example, when the angle was 60° 59' it could very easily be misread as 61°59'. This error was usually obvious and easy to correct.

(b) Misalignment of the marks when measuring the angle, due to
poor visibility, or boat motion. These errors were not correctable and the reading had to be discarded.

(c) Errors in transferring the data from the records to punched cards. Again, these errors were easily corrected on checking the data.

(d) If the moving part of the sextant was not clicked home properly, into the rack of the measuring scale, a completely inaccurate reading would be made. This was rather a poor design feature of these sextants but with experience this could be avoided.

The value of $\Delta d$ could usually be correlated with several factors:

1. The sea state.
2. The experience of those reading the sextant.
4. Visibility and clarity of shore marks.
5. Time between fixes.
6. Choice of shore marks (i.e. angle of cut of circles, and size of the angles).

The occasional line would have exceptionally high value of $\Delta d$, this could usually be attributable to some cause and, dependent on this, the whole line would be discarded.

In order to reduce the errors involved in position fixing a two point moving average was taken of the positions and fix times. This should, on average, reduce the errors by $\sqrt{\sigma}$. These calculations were made in a programme SMOOTH.

At the same time as the fix times were digitised, the positions of the crests of the sandwaves on the echo sounder chart were digitised. From these the positions of the sandwave crests were calculated by linear interpolation between the moving average fix positions.
These positions were then plotted by a graph plotter. This was done using a programme CREST and then GPLOTM again to do the plotting (see Fig. A1.1.3).
Fig. A1.1.3 Examples of the output from programs PLOTM (a) and CREST (b). Measurements made 9th August, 1974.
<table>
<thead>
<tr>
<th>Source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy of sextant angle (0.5'- 2')</td>
<td>0.5 - 3m</td>
</tr>
<tr>
<td>Fix time error (0.1 sec. speed 3 m/s)</td>
<td>0 - 3m</td>
</tr>
<tr>
<td>Distance between observers</td>
<td>1 - 3m</td>
</tr>
<tr>
<td>Accuracy of shore mark positions after correction</td>
<td>0.5 - 1m</td>
</tr>
<tr>
<td>Accuracy of positioning</td>
<td>2m - 10m</td>
</tr>
</tbody>
</table>
A2.1 ECHO SOUNDING PROCEDURE

Three different procedures were adopted when echo sounding, depending on the information required from the survey. These procedures will now be described.

Firstly, if a large scale survey covering several sandwaves was required, three or four buoys were laid in a straight line parallel to the intended boat's tracks (Fig. A2.1.1). This was most easily accomplished if the line ran through a prominent shore feature such as the Day Beacon or Start Point lighthouse. The first buoy would be laid in the correct position using sextants and the next would be laid at the limit of visibility of the first, when the shore mark and the first buoy are in line; this is repeated for the other buoys.

The echo sounder runs were then made parallel to the buoys at various estimated distances from them. With practice and good conditions, surprisingly straight lines could be steered. Those lines further away from the buoys tended to be straighter and smoother because the helmsman made fewer small scale corrections to the course.

When the required lines had been run with the buoys in one position, the buoys were moved over, individually, perpendicular to the direction of the lines, by a distance of about 200-300m. The process was then repeated. Usually there was only time in one day to make runs with the buoys in two positions.

Secondly, when a more detailed survey of one or two sandwaves was to be made, the four buoys were laid in a square (Fig. A2.1.2). This was usually close to the crests of the two sandwaves, the positions of which could be determined by the echo sounder, or the
Fig. A2.1.1 Echo sounder surveying of a large area using four buoys which are moved half-way through the survey.
Fig. A2.1.2 Showing the second echo sounder procedure described.

Fig. A2.1.3 Showing the third echo sounder procedure described.
turbulence in the water. This turbulence appears over the crest of a sandwave when the tide is running strongly.

Using this technique, it was possible to make several repeated runs, in order to compare the shape of the sandwave, at different states of the tide.

Lastly, if the orientation of the dunes was required, a special technique was used. One buoy, in practice this was usually one of the buoys in the square above, was laid near to the crest of the sandwave (Fig. A2.1.3). In this position the largest dunes are found and, consequently, can be resolved most easily on the echo sounder record.

Runs were then made around the buoy in a star formation, the boat moving slowly against the tide, so that the best resolution of the dunes could be obtained.

From these results the dune orientation and wavelength could be found by one of two alternative methods. If the intersections of the boat's track with the crests of the dunes are plotted, and if navigation is very good, individual dunes can be followed from one run to the next, starting from the crossing points of the runs (Fig. A2.1.4). Alternatively, the apparent wavelength of the dunes was found in the direction of each run and from these, the true wavelength and orientation of the dunes could be found.

The accuracy of this method was affected in several unsuspected ways. Because of the slow speed of the boat and the strength of the tide, it was very difficult to steer a straight course at a constant speed over the ground. This was particularly so when runs were made at an angle to, or perpendicular to, the tidal current direction, because a small change in the boat's heading caused a considerable change in the boat's speed over the ground. In addition, over the
Dune position
Sandwave crest

Line no. and direction

Measurements made 27th Aug. 1974
Navigational accuracy ±2m
Scale 1cm = 20m

Fig. A2.1.4 Showing dune positions found using the third procedure described.
sandwave crest itself, there are fairly large changes in the tidal current speeds, which are difficult to allow for when deciding the correct course to steer.

Since the runs are short, there are not very many fixes (usually approximately 7). Therefore, if there is an error in more than one fix it reduces the accuracy considerably, as there are few remaining fixes.

When making an echo sounder run, the shore marks were chosen so that the most accurate intersections of the arcs were obtained consistent with good visibility of those marks. If possible, it was also arranged so that one of the angles was changing rapidly and the other slowly. The person measuring the rapidly changing angle would decide when the fix was to be made and press the 'fix' button on the echo sounder. Meanwhile, the other person would continuously follow the slowly changing angle, recording it when the fix was called. Fixes were made at fairly uniform time intervals, whenever both angles were acceptably lined up and visible and when the boat was reasonably steady.

Initially, the fixes were made on whole degrees of the rapidly changing angle but this was found to be difficult, and hence, inaccurate. Often at the critical moment, when the marks were about to line up, the boat would lurch, or something would obscure the view of one of the marks. Consequently, that fix had to be left out. Therefore, the procedure was adjusted to that described above.

A2.2 ECHO SOUNDER CONSTRUCTION

When making the echo sounder surveys, it was necessary to resolve the dunes on the backs of the sandwaves. These had wavelengths of about 10m, and an amplitude of up to 1m. Consequently, an echo sounder was required with a narrow beam angle and a large vertical
scale on the recorder. In addition, if possible, the recorder should have a rectilinear scale, so that the true shapes of the sandwaves could be observed.

This was accomplished by combining a Seafarer echo sounder with a Marconi recorder, using the recorder to trigger the transmitted pulse through suitable circuits. The return signal is brought back through an amplifier to the recorder stylus (Fig. A2.2.1). The recorder has a vertical scale of one inch to thirty feet and a horizontal scale of one inch to one minute. It requires a power supply of 116V at 60 Hz and a power of 60 watts to drive the motor, so an inverter was built to provide this from lead acid batteries.

The Seafarer echo sounder has a high transmitted frequency of 150 KHz permitting high resolution of water depth. However, the depth of water in which an echo signal could be obtained was limited (particularly when using the reflector). The beam angle of the transducer was about 45°, so a reflector was built which increased the effective aperture of the transducer and, thus, reduced the beam angle to about 7° (Fig. 2.2.2).

The beam angle of a transducer is given by:

\[
\sin \alpha = 1.22 \frac{\lambda}{D}
\]

where D is the diameter of the transducer

\( \lambda \) is the wavelength of the signal

\( \alpha \) is the angle between the perpendicular to the transducer face and the first node of the beam pattern (Urick, 1967).

To reduce the effect of the boat's motion, the transducer and reflector were mounted in a streamlined fish which was suspended over the side of the boat.

In order to further reduce the effect of the boat's motion a pivoted arm was constructed (Fig. A2.2.3). This was very effective
Fig. A2.2.1 Block diagram of echo sounder

Fig. A2.2.2 Reflector for echo sounder.
Fig. A2.2.3 Pivoting arm used to reduce the effect of the boat's motion.
in removing the effect of the rolling motion of the boat produced by small surface waves. However, under the influence of a long swell, the boat and fish were both lifted bodily by the swell and little could be done to remove the effect.

In large waves, when the boat was running with the waves, the boat tended to surf down the wave. The increase in speed resulted in an increase in drag on the fish, so the depth of the fish decreased. When the wave overtook the boat it slowed down rapidly and the fish dropped deeper in the water. This resulted in large variations in depth and oscillations on the echo sounder trace.

If, under these conditions, one attempted to make runs against the waves, the boat's motion became very violent, producing large quantities of spray and it was impossible to make sextant angle measurements. The solution to these problems was to use a standard 45° beam angle transducer mounted in the boat's hull and the runs were made with the waves.

A2.3 ECHO SOUNDER SURVEY RESULTS

The method used to obtain plots of the crest positions of the sandwaves is described in Appendix 1. The results of the main surveys were all plotted at a scale of 20 cm to 1 km. The area that was surveyed in detail (sandwaves F to I, Fig. A2.3.10) was plotted at a scale of 50 cm to 1 km and the 'stars' were plotted at scales of up to 100 cm to 1 km (Fig. A2.1.4).

The surveys had been made with the echo sounder runs close enough together, to allow the positions of the sandwave crests to be interpolated between the measured positions with confidence. The results of the rangemeter surveys (Fig. 5.1.1) showed that the sandwave crests were reasonably straight over lengths of up to 200m. Examples of the results of individual surveys are shown in Figs. A2.3.1/3. Table A2.3.1 gives a list of the surveys made.
The results for each individual survey were combined with those taken throughout the season to obtain the average position, of the sandwave crest, during that period. Figs. A2.3.4-7 show the results of all the major surveys. The variations in position over each period can be assigned to a number of causes. The surveys made in July 1974 show a particularly large difference of, on average, about 10m. This is probably because these were the first surveys made, consequently, the skill and techniques required for the most accurate use of the sextants had not been fully acquired. In later surveys, the differences are much smaller (less than 5m) and are probably due partly to positioning inaccuracies and partly to the sandwave crest itself moving.

The average sandwave crest position for each years' survey are shown in Fig. A2.3.8 and an enlargement of the area on the outside edge of the Skerries in Fig. A2.3.9. From larger scale versions of these maps, measurements were obtained of the sandwave displacement for each 200 metre section of sandwave crest. These measurements are given in Table A2.3.3 with an estimate of their errors; also given are the weighted mean displacements with their standard errors. These results are discussed in Chapter 4.

Fig. A2.3.10 gives the average positions of the sandwave crests throughout the whole survey period and also the sandwave identification letters.
<table>
<thead>
<tr>
<th>Date</th>
<th>No. of lines</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>24th June 1974</td>
<td>4</td>
<td>Trials</td>
</tr>
<tr>
<td>25th June 1974</td>
<td>-</td>
<td>Trials</td>
</tr>
<tr>
<td>27th June 1974</td>
<td>5</td>
<td>Trials</td>
</tr>
<tr>
<td>23rd July 1974</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>25th July 1974</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>27th July 1974</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>29th July 1974</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>30th July 1974</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>9th August 1974</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>22nd August 1974</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>26th August 1974</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>27th August 1974</td>
<td>18</td>
<td>'Star'</td>
</tr>
<tr>
<td>11th June 1975</td>
<td>29</td>
<td>'Stars'</td>
</tr>
<tr>
<td>12th June 1975</td>
<td>21</td>
<td>'Stars'</td>
</tr>
<tr>
<td>17th June 1975</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>4th October 1975</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>10th October 1975</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>14th June 1976</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>15th June 1976</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>16th June 1976</td>
<td>19</td>
<td>'Stars'</td>
</tr>
</tbody>
</table>
**TABLE A2.3.2** Key for Figs. A2.3.1/3/10

<table>
<thead>
<tr>
<th>7</th>
<th>Position of the crest of the sandwave from the echo sounder record, with the depth of the crest in metres.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Interpolated position of the sandwave crest. The thickness of the line indicates the distance from the crest to the trough of the sandwave.</td>
</tr>
<tr>
<td>1</td>
<td>Less than 1.5 metres.</td>
</tr>
<tr>
<td>2</td>
<td>1.5 to 3.5 metres.</td>
</tr>
<tr>
<td>3</td>
<td>3.5 to 10 metres.</td>
</tr>
<tr>
<td></td>
<td>Greater than 10 metres.</td>
</tr>
<tr>
<td></td>
<td>Interpolation uncertain.</td>
</tr>
<tr>
<td>4</td>
<td>Indicates the avalanche slope side of the sandwave, with the crest to trough distance in metres.</td>
</tr>
<tr>
<td></td>
<td>Symmetrical sandwave.</td>
</tr>
<tr>
<td></td>
<td>Symmetrical sandwave with rounded crest.</td>
</tr>
<tr>
<td>5</td>
<td>Line of echo sounder record number 12.</td>
</tr>
<tr>
<td></td>
<td>Indicates the presence of dunes.</td>
</tr>
<tr>
<td>6</td>
<td>National Grid lines.</td>
</tr>
</tbody>
</table>
Fig. A2.3.1 Echo sounder measurements made 15th June 1976
Fig. A2.5.2 Selected echo sounder records, 15th June 1976.
Fig. A2.3.3 Echo sounder measurements made 16th June 1976.
Fig. A2.3.4
Echo sounder measurements made July 1974.
Fig. A2.3.5
Echo sounder measurements made August 1974.
Fig. A2.3.6 Echo sounder measurements made June/October 1975.
Scho sounder measurements made June 1976.
Fig. A2.3.8
Comparison of measurements made throughout the whole survey period.
Fig. A2.3.9 Echo sounder measurements made on the outside edge of the Skerries Bank.
**TABLE A2.3.3**

SANDWAVE DISPLACEMENTS FROM ECHO SOUNDER RECORDS

**NOTES:**

Each measurement represents 200m of sandwave crest.

Southward displacement is positive.

The errors given for the measured displacements are the estimated experimental errors.

The following weights were used to calculate the weighted mean.

<table>
<thead>
<tr>
<th>Experimental error</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>± 5m</td>
<td>4</td>
</tr>
<tr>
<td>± 10m</td>
<td>2</td>
</tr>
<tr>
<td>± 15m</td>
<td>1</td>
</tr>
<tr>
<td>± 20m</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The error given for the weighted mean is the standard error.

F855 refers to the 200m of sandwave crest F, extending eastwards from National Grid Easting 855.

F855N (or F855S) refers to the North (or South) branch of sandwave F if it has bifurcated.

Sandwave symmetry:

- **S** = steep slope faces South
- **Sym** = symmetrical sandwave
- **N** = steep slope faces North

Residual tidal currents taken from Acton (1975), standard error does not exceed 0.15 ms$^{-1}$.
**TABLE A2.3.3 (Cont'd)**

(a) SCALE OF MAP 50 cm to 1 km

<table>
<thead>
<tr>
<th>Sandwave Identification</th>
<th>Annual displacement in metres</th>
<th>Sandwave Weighted Mean</th>
<th>Sandwave Height m</th>
<th>Sandwave Symmetry</th>
<th>Residual Current $\text{ms}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>F855N</td>
<td></td>
<td>7.5 ± 7</td>
<td>0.5</td>
<td>S</td>
<td>0.1</td>
</tr>
<tr>
<td>F856S</td>
<td></td>
<td>5 ± 15</td>
<td>15 ± 5</td>
<td>1</td>
<td>S</td>
</tr>
<tr>
<td>F858</td>
<td></td>
<td>0 ± 15</td>
<td>15 ± 5</td>
<td>1</td>
<td>S</td>
</tr>
<tr>
<td>G855N</td>
<td></td>
<td>10 ± 10</td>
<td>15 ± 5</td>
<td>2</td>
<td>S</td>
</tr>
<tr>
<td>G855S</td>
<td></td>
<td>-5 ± 10</td>
<td>12 ± 5</td>
<td>2</td>
<td>S</td>
</tr>
<tr>
<td>G857</td>
<td></td>
<td>0 ± 15</td>
<td>12 ± 5</td>
<td>3</td>
<td>S</td>
</tr>
<tr>
<td>H854</td>
<td></td>
<td>0 ± 10</td>
<td>12 ± 5</td>
<td>2</td>
<td>S</td>
</tr>
<tr>
<td>H856</td>
<td></td>
<td>0 ± 10</td>
<td>15 ± 5</td>
<td>4</td>
<td>S</td>
</tr>
<tr>
<td>I854</td>
<td></td>
<td>5 ± 10</td>
<td>20 ± 5</td>
<td>4</td>
<td>S</td>
</tr>
<tr>
<td>I856</td>
<td></td>
<td>-5 ± 10</td>
<td>-5 ± 7</td>
<td>4</td>
<td>S</td>
</tr>
<tr>
<td>J856</td>
<td></td>
<td>0 ± 15</td>
<td>0 ± 15</td>
<td>1</td>
<td>S</td>
</tr>
</tbody>
</table>

Total Weighted Mean = $10 ± 1$
TABLE A2.3.3 (Cont'd)

(b) SCALE OF MAP 20 cm to 1 km

<table>
<thead>
<tr>
<th>Sandwave Identification</th>
<th>Annual displacement in metres</th>
<th>Sandwave Height</th>
<th>Sandwave Symmetry</th>
<th>Residual Current ms⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>'74+75</td>
<td>'75+76</td>
<td>Weighted Mean</td>
<td></td>
</tr>
<tr>
<td>D856</td>
<td>15 ± 15</td>
<td>1</td>
<td>S</td>
<td>0.1</td>
</tr>
<tr>
<td>D859</td>
<td>0 ± 10</td>
<td>20 ± 5</td>
<td>13.3 ± 4</td>
<td>4 S</td>
</tr>
<tr>
<td>E860</td>
<td>-8 ± 15</td>
<td>25 ± 10</td>
<td>14 ± 9</td>
<td>1 Sym</td>
</tr>
<tr>
<td>I852</td>
<td>0 ± 10</td>
<td>20 ± 5</td>
<td>13.3 ± 4</td>
<td>3 S</td>
</tr>
<tr>
<td>L851</td>
<td>25 ± 10</td>
<td>25 ± 5</td>
<td>25 ± 6</td>
<td>2 S</td>
</tr>
<tr>
<td>M850</td>
<td>20 ± 10</td>
<td>20 ± 7</td>
<td>3 S</td>
<td>0.15</td>
</tr>
<tr>
<td>N850</td>
<td>5 ± 10</td>
<td>5 ± 7</td>
<td>1 Sym</td>
<td>0.12</td>
</tr>
<tr>
<td>O849</td>
<td>15 ± 10</td>
<td>15 ± 7</td>
<td>1.5 S</td>
<td>0.05</td>
</tr>
<tr>
<td>P848</td>
<td>15 ± 10</td>
<td>15 ± 7</td>
<td>1 Sym</td>
<td>0</td>
</tr>
<tr>
<td>K858</td>
<td>25 ± 10</td>
<td>25 ± 10</td>
<td>1 Sym</td>
<td>0</td>
</tr>
<tr>
<td>K861</td>
<td>-10 ± 15</td>
<td>-15 ± 10</td>
<td>-13 ± 7</td>
<td>3 Sym</td>
</tr>
<tr>
<td>T857</td>
<td>10 ± 15</td>
<td>30 ± 5</td>
<td>26 ± 4</td>
<td>3 S</td>
</tr>
<tr>
<td>T861</td>
<td>10 ± 15</td>
<td>20 ± 5</td>
<td>18 ± 4</td>
<td>3 S</td>
</tr>
<tr>
<td>T863</td>
<td>-10 ± 15</td>
<td>-10 ± 5</td>
<td>-10 ± 3</td>
<td>4 Sym</td>
</tr>
<tr>
<td>U857</td>
<td>-20 ± 15</td>
<td>10 ± 5</td>
<td>4 ± 6</td>
<td>3 S</td>
</tr>
<tr>
<td>U860</td>
<td>-15 ± 20</td>
<td>0 ± 5</td>
<td>-3 ± 3</td>
<td>5 N</td>
</tr>
<tr>
<td>V856N</td>
<td>15 ± 5</td>
<td>15 ± 3</td>
<td>2.5 S</td>
<td>-0.1</td>
</tr>
<tr>
<td>V856S</td>
<td>0 ± 10</td>
<td>0 ± 7</td>
<td>3 S</td>
<td>-0.1</td>
</tr>
<tr>
<td>V858</td>
<td>-10 ± 20</td>
<td>-5 ± 5</td>
<td>-6 ± 3</td>
<td>6 Sym</td>
</tr>
<tr>
<td>V860</td>
<td>-30 ± 20</td>
<td>-10 ± 5</td>
<td>-14 ± 4</td>
<td>6 N</td>
</tr>
<tr>
<td>W860</td>
<td>-40 ± 20</td>
<td>5 ± 5</td>
<td>-4 ± 9</td>
<td>6 N</td>
</tr>
<tr>
<td>X861</td>
<td>-20 ± 20</td>
<td>-5 ± 5</td>
<td>-8 ± 3</td>
<td>10 N</td>
</tr>
<tr>
<td>Y860</td>
<td>-30 ± 10</td>
<td>-30 ± 10</td>
<td>12 N</td>
<td>-0.3</td>
</tr>
</tbody>
</table>
Fig.A2.3.10 Average positions of sandwave crests from echo sounder measurements.

'A' Sandwave identification
APPENDIX 3

RESULTS OF TIDAL CURRENT MEASUREMENTS

In this Appendix the results of the tidal current measurements will be given. The measurements made and their positions are given in Table A3.1.1 and Fig. A3.1.1.

All current speeds are corrected to a tidal range of 4.0m at Dartmouth.

Zero time is low water at Dartmouth.

Current direction is relative to true north.

For the methods used to obtain Figs. A3.1.2 - 8 see Acton (1972) and Perring (1976).

For an explanation of Figs. A3.1.9 - 11 see Chapter 3.

If a comparison is made between the results given here and the results of Acton (1976) and Perring (1976), the agreement is very good (Fig. 4.3.1). This is in spite of the presence of sandwaves. An exception to this is the measurements made at position '0'. The measurements made by the present author were made slightly closer to the Skerries Bank than those of Perring (Fig. A3.1.1), and as a result the measured currents are lower by about 40%. It was not possible to re-occupy the true position '0' because of the presence of crab pots.
## TABLE A3.1.1

**CO-ORDINATES OF CURRENT METER MEASUREMENTS**

<table>
<thead>
<tr>
<th>Date</th>
<th>Position</th>
<th>Duration (hrs)</th>
<th>Co-ordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 3rd Aug. 1974</td>
<td>P2</td>
<td>4</td>
<td>50° 14.61'N 3° 36.41'W</td>
</tr>
<tr>
<td>2. 23rd Aug. 1974</td>
<td>P3</td>
<td>4</td>
<td>50° 14.63'N 3° 36.70'W*</td>
</tr>
<tr>
<td>3. 24th May 1974</td>
<td>Q</td>
<td>4</td>
<td>50° 15.26'N 3° 36.08'W*</td>
</tr>
<tr>
<td>4. 9th June 1975</td>
<td>P</td>
<td>8</td>
<td>50° 14.24'N 3° 37.15'W</td>
</tr>
<tr>
<td>5. 10th June 1975</td>
<td>Q2</td>
<td>5</td>
<td>50° 13.92'N 3° 36.32'W</td>
</tr>
<tr>
<td>6. 11th June 1975</td>
<td>Q</td>
<td>1</td>
<td>50° 15.24'N 3° 36.07'W</td>
</tr>
<tr>
<td>7. 13th June 1975</td>
<td>P</td>
<td>4</td>
<td>50° 14.33'N 3° 37.03'W</td>
</tr>
<tr>
<td>8. 18th June 1975</td>
<td>Q</td>
<td>5</td>
<td>50° 15.25'N 3° 36.02'W</td>
</tr>
<tr>
<td>9. 8th July 1975</td>
<td>Q</td>
<td>2½</td>
<td>50° 15.25'N 3° 36.19'W</td>
</tr>
<tr>
<td>10. 3rd Oct. 1975</td>
<td>P</td>
<td>5</td>
<td>50° 14.28'N 3° 37.08'W</td>
</tr>
</tbody>
</table>

*Measurements made at 3 positions over the sandwave profile.

Co-ordinates of positions O, P and Q according to Perring (1976)

<table>
<thead>
<tr>
<th>Position</th>
<th>Co-ordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>50° 13.93'N 3° 36.43'W</td>
</tr>
<tr>
<td>P</td>
<td>50° 14.33'N 3° 37.07'W</td>
</tr>
<tr>
<td>Q</td>
<td>50° 15.28'N 3° 35.94'W</td>
</tr>
</tbody>
</table>
Fig. A3.1.1 Tidal current measurement positions.
Fig. A3.1.2  Current measurements, position 'O_2'.  10th June 1975
Fig. A3.1.3 Current measurements, position 'P', 3rd Oct. 1974. Water depth 6m.
Fig. A3.1.4  Current measurements, position 'P2', 3rd. August 1974.
Fig. A3.1.5  Tidal current speed, position 'P', 9th./13th. June 1975.
Fig. A3.1.6 Current direction, position 'P', 9th./13th. June 1975.
Fig. A3.1.7  Current speed, position 'Q', 18th June/8th July 1975
Fig. A3.1.8  Current direction, position 'Q', 18th June 1975.
Fig. A3.1.9  Current measurements, position 'P3', 23rd. August 1974.
Fig. A3.1.10  Current measurements, position 'Q', 24th. August 1974.
Fig. A3.1.11 Showing the current velocity profiles at various positions over a sandwave.

A4.1 SEDIMENT SAMPLE ANALYSIS

Many different parameters have been devised in order to determine the various characteristics of sediments (Folk, 1964). In this work those proposed by Inman (1952) have been used. They are:

- \(Md\) median diameter
- \(So\) sorting coefficient
- \(Sk\) skewness
- \(K\) kurtosis

These will be discussed in more detail later and plots of these variables across a sandwave are shown in Figs. A4.4.2 to 7.

The sediment samples were analysed using nine sieves with equally spaced (\(\frac{1}{2}\)) phi diameters. The phi scale of grain size is a logarithmic scale defined by:

\[
\phi = -\log_2 d
\]

where \(d\) is the grain size in millimeters.

The largest sieve used had a phi size of \(-1.5\) phi (2.83 mm) and the smallest 2.5 phi (0.177 mm) (Table A4.1.1).

In order to check that the sieves were of the size stated, all the results of sieve analysis for each sieve were added together. The plots were inspected to determine whether any individual sieve was consistently showing a value out of line with the others. In fact no such inconsistencies were found (see Fig. A4.1.1).

If they had been, the phi value for that sieve would have been adjusted accordingly.

The results from the analysis of a sample can be plotted as a histogram (Fig.A4.1.2) but it is more useful to plot the results as a cumulative percentage curve on a probability scale of percentage.
### TABLE A4.1.1

**BRITISH STANDARD SIEVES**

Phi values, and relation to Wentworth's Grade Scale.

<table>
<thead>
<tr>
<th>Sieve No.</th>
<th>Mesh aperture mm</th>
<th>Phi</th>
<th>Diameter mm</th>
<th>Grade term</th>
<th>Phi</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3.353</td>
<td>-1.75</td>
<td>3.36</td>
<td></td>
<td>-2</td>
</tr>
<tr>
<td>6*</td>
<td>2.812</td>
<td>-1.49</td>
<td>2.83</td>
<td>Granule</td>
<td>-1.5</td>
</tr>
<tr>
<td>8*</td>
<td>2.057</td>
<td>-1.04</td>
<td>2.0</td>
<td></td>
<td>-1</td>
</tr>
<tr>
<td>10</td>
<td>1.676</td>
<td>-0.75</td>
<td>1.69</td>
<td></td>
<td>-0.75</td>
</tr>
<tr>
<td>12*</td>
<td>1.405</td>
<td>-0.49</td>
<td>1.41</td>
<td>Very coarse sand</td>
<td>-0.5</td>
</tr>
<tr>
<td>14</td>
<td>1.204</td>
<td>-0.27</td>
<td>1.19</td>
<td></td>
<td>-0.25</td>
</tr>
<tr>
<td>16*</td>
<td>1.003</td>
<td>0</td>
<td>1.0</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>18</td>
<td>0.835</td>
<td>0.23</td>
<td>0.84</td>
<td></td>
<td>0.25</td>
</tr>
<tr>
<td>22*</td>
<td>0.699</td>
<td>0.52</td>
<td>0.71</td>
<td>Coarse sand</td>
<td>0.5</td>
</tr>
<tr>
<td>25</td>
<td>0.599</td>
<td>0.74</td>
<td>0.595</td>
<td></td>
<td>0.75</td>
</tr>
<tr>
<td>30*</td>
<td>0.5</td>
<td>1.0</td>
<td>0.5</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>36</td>
<td>0.422</td>
<td>1.24</td>
<td>0.420</td>
<td></td>
<td>1.25</td>
</tr>
<tr>
<td>44*</td>
<td>0.353</td>
<td>1.50</td>
<td>0.351</td>
<td>Medium sand</td>
<td>1.5</td>
</tr>
<tr>
<td>52</td>
<td>0.295</td>
<td>1.76</td>
<td>0.297</td>
<td></td>
<td>1.75</td>
</tr>
<tr>
<td>60*</td>
<td>0.251</td>
<td>1.99</td>
<td>0.25</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>72</td>
<td>0.211</td>
<td>2.24</td>
<td>0.21</td>
<td></td>
<td>2.25</td>
</tr>
<tr>
<td>85*</td>
<td>0.178</td>
<td>2.49</td>
<td>0.177</td>
<td>Fine sand</td>
<td>2.5</td>
</tr>
<tr>
<td>100</td>
<td>0.152</td>
<td>2.72</td>
<td>0.149</td>
<td></td>
<td>2.75</td>
</tr>
<tr>
<td>120</td>
<td>0.124</td>
<td>3.01</td>
<td>0.125</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>150</td>
<td>0.104</td>
<td>3.26</td>
<td>0.105</td>
<td></td>
<td>3.25</td>
</tr>
<tr>
<td>170</td>
<td>0.089</td>
<td>3.49</td>
<td>0.088</td>
<td>Very fine sand</td>
<td>3.5</td>
</tr>
<tr>
<td>200</td>
<td>0.076</td>
<td>3.71</td>
<td>0.074</td>
<td></td>
<td>3.75</td>
</tr>
<tr>
<td>240</td>
<td>0.066</td>
<td>3.91</td>
<td>0.0625</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>300</td>
<td>0.053</td>
<td>4.25</td>
<td>0.053</td>
<td>Silt</td>
<td>4.25</td>
</tr>
</tbody>
</table>

*Sieves used
Fig. A4.1.1 Mean of all sediment sample analyses. (Used to check sieve sizes).
Fig. A4.1.2 Sample A3.2. Plotted as a histogram and as a cumulative percentage curve.
This scale makes a binomial distribution into a straight line. A curve was interpolated through the points by a computer least squares fit. Phi values for percentages of 5, 16, 50, 84 and 95 (as suggested by Inman, 1952) were found from these curves. The values of 16% and 84% were chosen because they were one standard deviation from the mean, and the values of 5% and 95% because the accuracy of measurement falls off very rapidly beyond these values.

The parameters calculated from these phi values will now be described.

**Median Diameter Md**

\[ Md = \phi_{50} \]

This is the value at which half the sediment is present. There are other ways of measuring the central tendency of the distribution. For example, the mode, which is the most common value, or the maximum value of the histogram and the mean diameter (\( M_{\phi} \)), which is the centre of gravity of the histogram and is defined by Inman (1952) as:

\[
M_{\phi} = \frac{1}{2} (\phi_{16} + \phi_{84})
= Md + (\sigma_{\phi} \times a_{\phi})
\]

Since the median diameter is not independent of the other variables found and the mode is rather difficult to obtain accurately, only the median diameter was calculated.

**Sorting Coefficient So**

\[ So = \sigma_{\phi} = \frac{1}{2} (\phi_{84} - \phi_{16}) \]

The phi values of 16% and 84% are used because they enclose two standard deviations. Therefore, So is a measure of the standard deviation of the sample about the median diameter, thus indicating how well the sample is sorted. This quantitative description of sorting can be related to qualitative values (Folk and Ward, 1957).
<table>
<thead>
<tr>
<th>Description</th>
<th>So</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very well sorted</td>
<td>0.35</td>
</tr>
<tr>
<td>Well sorted</td>
<td>0.5</td>
</tr>
<tr>
<td>Moderately well sorted</td>
<td>0.75</td>
</tr>
<tr>
<td>Moderately sorted</td>
<td>1.0</td>
</tr>
<tr>
<td>Poorly sorted</td>
<td>2.0</td>
</tr>
<tr>
<td>Very poorly sorted</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Start Bay sediments

A low value of So indicates a narrow distribution with good sorting. A high value is produced by a wide distribution with poor sorting.

**Skewness**  $Sk$

Skewness is a measure of the ratio of coarse material to fine material. Two skewness values have been found:

$$Sk_1 = \alpha_\phi = \frac{\frac{1}{2} (\phi_{84} + \phi_{16}) - \phi_{50}}{\frac{1}{2} (\phi_{84} - \phi_{16})}$$

$$= \frac{M_\phi - Md_\phi}{\sigma_\phi} $$

$$Sk_2 = \alpha_2\phi = \frac{\frac{1}{2} (\phi_{5} + \phi_{95}) - \phi_{50}}{\frac{1}{2} (\phi_{84} - \phi_{16})} $$

The first value $Sk_1$ is a measure of the skewness over the central portion of the distribution.

The second value is a measure of the skewness over a wider range.

A symmetrical curve has a $Sk = 0.0$. A curve with a greater proportion of fine material in the tail of the distribution has a positive value of up to +1.0, a distribution with a coarse tail has a negative value down to -1.0.

This is true for the first value, $Sk_1$, which is independent of the sorting. $Sk_2$ is not independent of So; so values of over 1 can occur. However, in this set of samples this does not happen.
Kurtosis \( K \)

This is a measure of the peakedness of the distribution, or the ratio of the amount of material in the tails of the distribution to that in the centre.

\[
K = \beta_\phi = \frac{\frac{1}{2} (\phi_{95} - \phi_5) - \sigma_\phi}{\sigma_\phi}
\]

A curve with a normal distribution has a \( K = 0.65 \). A large \( K \) indicates a narrow distribution, i.e. low in fine and coarse material; a small \( K \) indicates a wide distribution, i.e. more fine and coarse material.

A4.2 THE EFFECT OF HYDRODYNAMIC RADIUS

When one examines the material of these samples, it very obviously consists of two fractions, one of sand and the other of shell. The sand particles are almost spherical but the pieces of broken shell are usually flat. Consequently, the 'hydrodynamic radius' of the shell is smaller than the radius found by sieving. Because of this, it was believed that the samples were much better sorted than was apparent at first sight.

To determine how much smaller the hydrodynamic radius was, the following procedure was adopted. The whole sample was first sieved; a sub-sample from each of the size fractions was then dropped down a fall column. The times for 25% and 75% of the sample to reach the bottom were recorded (Emery, 1938). The fall column was calibrated using Balitini (artificial glass spheres) of a known size. From the fall times the hydrodynamic radius of that size fraction of the sample was calculated and the bounds of that block on the histogram were adjusted accordingly, keeping the area constant, Figs.A4.2.1/2. The results of this modification have a considerable effect.
Fig. A4.2.1

Size analysis of sample B2

by Sieves
and by
Fall Column

% weight per
0.5 Phi

Diameter Phi
Size analysis of sample B2

by Sieves

and by

Fall Column

Fig. A4.2.2

Weight

Diameter Phi

% Weight

0.1% 0 1 2
An alternative method of finding the 'true' (hydrodynamic) grain size of the sample is to dissolve away the shell particles with acid. The sample is then re-sieved. This method is easier and more consistent and was, therefore, adopted for the samples which are described in this work.

A4.3 EFFECTS OF SIEVING SEDIMENT SAMPLES FOR DIFFERENT LENGTHS OF TIME

Fig. A4.3.1 shows the results of progressively sieving a sample for longer times. This shows the effect of variation in sieving time.

Fig. A4.3.2 shows the results of sieving a sediment sample for 5 and 20 minute periods. After each period the sample was removed from the sieve and sieving was restarted from the top sieve. These graphs show the effects of mechanical degradation of the sample.

An optimum sieve time of \( \frac{1}{2} \) hour was chosen as a result of these investigations.

The effect of varying the sieve shaker amplitude was not investigated. An amplitude of \( \frac{1}{2} \) mm was used for the coarse sediments and an amplitude of 1 mm for the fine sediments. These amplitudes were chosen by observation so that the material was not thrown around too violently but moved around sufficiently for it to be passed rapidly through the sieves.

A4.4 RESULTS OF SEDIMENT SAMPLE ANALYSIS

Key for diagrams A4.4.3 to A4.4.7.

- original sample
- sand (insoluble material)
- 'missing' shell (soluble material).

Points not connected together are from the troughs of the dunes.

Points connected together are from the crests of the dunes and from the avalanche slope of the sandwave.
Fig. A4.3.1

Showing how quickly the sediment passes through the sieves.

% Weight of sample

- 10%
- 5%

0.5 to 0.0 Phi
0.0 to -0.5 Phi
-0.5 to -1.0 Phi
Greater than 2.5 Phi

Time in minutes

0.5 1 2 5 10 20 40 80
Fig. A4.3.2

Showing the effect of degradation of the sample for extended sieve times.

○ sieved for 20 minutes

× sieved for 5 minutes

% Weight of sample.

- 20%

- 15%

- 10%

- 5%

Time in minutes 25 35 50 115 135
Great region in greater detail
Vertical/Horizontal = 1/6 (Approx.)

Fig. A4.4.1

Depth of water

Cross-section of sand wave showing sample positions.

Vertical/Horizontal = 1/30 (Approx.)
Figure A-1.2 shows the proportion of insoluble material found in the samples taken across the sandwave.

Dune crests

Dune troughs

Sandwave crest

Percentage sand

Sample no.
\[ S_0 = \frac{1}{2}(\phi_{15} - \phi_{16}) \]
Fig. A4.4.6  Second Skewness.

\[ Sk2 = \frac{1}{2}(\phi_{50} + \phi_{95}) - Md \]
Fig. A4.4.7 Kurtosis.

\[ K = \frac{1}{\phi_25 - \phi_{10}} - \phi_0 \]
APPENDIX 5

RESULTS OF ACOUSTIC RANGEMETER MEASUREMENTS

In this Appendix the results of the acoustic rangemeter surveys are given. See Chapter 5 for a discussion of the results. For more information on the technique see Chapter 3, Partridge (1970), Kelland (1973, 1975) and Kelland and Bailey (1975). This last paper is reproduced in this Appendix.
TABLE A5.1.1
DIVING MEASUREMENTS

<table>
<thead>
<tr>
<th>Date</th>
<th>Party</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>8th July 1974</td>
<td>Bath University</td>
<td>Rope measurements and sediment samples taken</td>
</tr>
<tr>
<td>1st Aug. 1974</td>
<td>Sub-Aqua Club</td>
<td></td>
</tr>
<tr>
<td>5th Aug. 1974</td>
<td>I.O.S. Taunton</td>
<td>Rangemeter measurements</td>
</tr>
<tr>
<td>6th Aug. 1974</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20th Aug. 1974</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21st Aug. 1974</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28th Aug. 1974</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17th Nov. 1974</td>
<td></td>
<td>Transponders lifted</td>
</tr>
</tbody>
</table>

TABLE A5.1.2
CO-ORDINATES OF TRANSPONDER POSITIONS

<table>
<thead>
<tr>
<th>Position</th>
<th>Co-ordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx1</td>
<td>50° 15.29'N 3° 35.89'W</td>
</tr>
<tr>
<td>Tx2</td>
<td>50° 15.28'N 3° 36.01'W</td>
</tr>
<tr>
<td>Tx3</td>
<td>50° 15.32'N 3° 35.96'W</td>
</tr>
</tbody>
</table>
Fig. A5.1.1 Map to show the effect of different strength tides on sandwave crest position.
Fig. A5.1.2 Map to show the variation of sandwave crest position with time.
Fig. A5.1.3 Map to show search profile after a storm (sandwave crest was not found).
Fig. A5.1.4 Map to show the sandwave crest to the north of the transponders. Note that the dunes forming the crest are not parallel to the crest.

AN UNDER WATER STUDY OF SAND WAVE MOBILITY IN START BAY

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ABSTRACT

This report describes the application of a diver operated acoustic ranging device, the 'Rangemeter', to detect accurate changes in the planimetric position of a sandwave crest in Start Bay, Devon, following various tidal states. Movements varied between 3 and 6 inches between flood and ebb tides during periods of neaps and springs respectively.

INTRODUCTION

Since 1968, workers at Bath University and the Institute of Oceanographic Sciences have undertaken marine studies in Start Bay, Devon. Chesterman (1971) used side scanning sonar to map the sea-bed to the north and east of the Skerries Bank, and determined that a large number of sand waves with an approximately east-west orientation and having amplitudes up to 15m and wavelengths of the order of 200-300m existed seaward of a line joining Start Point to the Day Beacon on Proward Point (Fig. 1). Kelland and Hailes (1975) carried out continuous seismic profiling and core sampling in this sandwave area and showed they were composed predominantly of a coarse shelly sand and formed part of the 'Bank Deposits' which occur on the Skerries, and which overlie a thick sequence of argillaceous material which in turn overlies bedrock.

In 1970, Acton (Acton et al., 1975) commenced a research programme to map the tidal currents in Start Bay. He developed a mathematical model which interpolates between tidal measurements taken at selected positions in the Bay, and found that the residual current (the difference between the peak flood and peak ebb values) is zero along the axis of the Skerries Bank, flows to the south on the landward side, and to the north on the seaward side of the Bank. His work also suggested that the flood and ebb currents were much weaker on the top of the Skerries than previously thought.

One of the authors (Bailey) undertook a comprehensive study of the sandwaves in Start Bay in the summer of 1974. He determined that those sandwaves on the landward side of the Skerries Bank had average amplitudes of 3 m and a marked south facing asymmetry. The sandwaves on top of the bank were symmetrical with amplitudes generally less than 1.5 m, whereas those found in the deeper waters on the seaward side of the Skerries had amplitudes up to 10 m and were asymmetrical with north facing avalanche slopes. These observations on the sandwave morphology substantiated Acton's tidal current work, since it is generally accepted that if any net sediment mobility occurs in a sandwave field it gives rise to asymmetrical sandwaves which face in the direction of the residual current flow. (Stride, 1965)
Fig. 1. The sand wave field and study area in Start Bay.
Repetitive echo sounding runs were carried out over a selected part of the sandwave field (Fig. 1) using sextants for horizontal control in an attempt to demonstrate that individual sandwave movement occurred. However, there was no indication of sandwave movement during the two-month study period, and it had to be concluded that if any movement occurred, it was less than the accuracy with which the survey craft, and thus the positions of the sandwave crests, could be established. It was therefore decided to carry out detailed studies of one sandwave within the study area using the Institute of Oceanographic Sciences' underwater acoustic ranging system (Kelland, 1975). This equipment incorporates a diver-operated Rangemeter which can be used to determine independent ranges to three acoustic transponders installed on the sea-bed. With this system, it is possible for a diver to undertake rapid planimetric surveys of the sea-bed and achieve positional accuracies better than 0.25 m over ranges up to 300 m.

**METHOD**

Three transponders mounted in sea-bed rigs were installed on the sea-bed in the troughs between two sandwaves. The rigs, which were designed to be heavy and stable, had a railway wagon wheel as a baseplate, and a framework which supported the transponder and provided some protection from trawls. They were installed from a trawler using Decca Main Chain for positional control. The locations had been chosen to give good angles of cut between the three position circles (ranges measured from each transponder constitute position circles) along the study sandwave, and to keep ranges less than 300 m. Two of the transponders were positioned approximately 120 m apart along a line parallel to and approximately 100 m from the sandwave crest to form the main survey baseline. The third transponder was positioned about 180 m from the sandwave along a line drawn midway between the first two transponders.

Once deployed, the baselines between each transponder were carefully determined in both directions using the Rangemeter, and mean values derived. Since the equipment records distance as two way travel time in milliseconds, in order to derive true distances it was necessary to determine the velocity of acoustic propagation. This was established using a Plessey velocimeter.

The position of the sandwave crest adjacent to one of the main baseline transponders was established from the surface using an echo sounder and marked with a pellet buoy. Divers then swam approximately 150 m along the crest from this point and measured the ranges to the three transponders from positions separated by distances between 3 and 5 m (Plate 1). The exact measuring point was marked at each position by a 1 m metal stake pushed into the crest. This was necessary in case the diver was swept off station whilst taking a set of readings. Various methods were adopted for logging the results; the most efficient proved to be an underwater tape recorder which was strapped to the divers air cylinder, together with a through water acoustic communication system. The diver read out the appropriate transponder number and range reading and these were recorded both on tape and at the surface. He also noted the depth at each position and recorded relevant comments about the sandwave.
Plate 1. Diver using the Rangemeter to determine the crest position.
The measurements were repeated during periods of slack water after flood and ebb tides. The first readings were taken over a two day period during the spring tides in early August. Similar measurements were taken two weeks later during the subsequent spring tides, and then after a further week during neaps. These three series of measurements were all taken during an extended period of calm weather. An attempt was also made to obtain measurements during the Autumn following periods of strong gales.

Before the positions of the sandwave crest determined on successive dives could be compared it was necessary to ensure that the seabed control points had not moved, since any movement would give rise to false results. In order to lessen the chance of their being towed away it was decided not to mark the site in any way; consequently, they had to be refound during each series of measurements. On each occasion the general area was relocated using sextants and the diver then homed onto each transponder in turn using the Rangemeter to determine its range and bearing. The diver visually inspected each seabed rig (checking for possible instability) and remeasured the baseline values. Thus, since three control points were used, it was possible to establish from the repeat baseline values if the seabed rigs had moved, it being most unlikely that all three would move in an identical manner.

**RESULTS**

**Accuracy.**

The relative cartesian co-ordinates of each central point were determined from the baseline values and depths of each transponder. The co-ordinates of each survey position were then calculated from the range readings taken to the main baseline transponders, and the distances between these positions and the third transponder derived. These were then compared with the recorded ranges to this transponder to give a measure of the consistency of each data set. Only those readings were accepted where the "inconsistency" was less than half a metre. This was true for 95% of the surveyed positions (out of a total number of 107). The accepted positions were plotted out using a Hewlett Packard desk top plotter.

**Data Rate.**

With practice and using the underwater tape recorder 25 survey positions (corresponding to 75 range values) separated by 3 to 5 m could be mapped accurately in a dive time of 30 minutes. It was also found that the diver could invariably decode his own recorded speech, especially numerals.

**Crest Movement.**

Following a period of calm weather the sand wave had a trough to crest amplitude up to 5 metres and the position of the crest was clearly defined by a one to two metre high asymmetrical ridge. The direction of the avalanche slope was the same as the direction of the preceding tidal flow, and its surface was smooth and composed in the main of poorly sorted material with an increase in coarse grain fraction towards the base. In contrast, small sand ripples occurred on the lee slope, being truncated by the crest.
Fig. 2. Crest positions determined after flood and ebb tides during periods of spring and neap tides.
The crest line was straight in some sections but sinuous in others (Fig. 2) and its position changed after each survey, the amount of movement being the same along the 150 m section surveyed. No measureable displacement could be determined in the crest positions surveyed after successive flood tides, but there were average differences in positions of 3 m and 6 m between the flood and ebb tides during neaps and springs respectively. Insufficient data was gathered to estimate any overall pattern in the movement, although results taken on successive spring tides suggested an oscillatory movement.

The ridge was destroyed during periods of strong gales and the sandwave reduced in amplitude to a smooth symmetrical profile. However, the sandwave with its associated crestal ridge did reform after a period of calm.

CONCLUSIONS

The experiment was concluded following the loss of one of the transponder rigs (presumed towed away by illegal trawling) and the remaining two rigs successfully recovered. It is considered that the method and operational techniques evolved are eminenently suitable for carrying out accurate and detailed studies of bedform mobility in localised areas. Positional accuracies better than 0.20 m were achieved over ranges up to 250 m and 150 m. Profiles were surveyed by a single diver in dive times less than 30 minutes. The movement of the sandwave crest studied in Start Bay varied between 3 and 6 m between flood and ebb tides during periods of neaps and springs respectively. However, before any conclusion can be drawn about the long term pattern of movement it would be necessary to measure series of profiles daily along more than one sandwave over a longer period than one month. The method described would admirably lend itself for such an investigation.

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