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HOW OFTEN ?
TOWARDS AN OPTIMUM SURVEY INTERVAL FOR MOBILE SEABEDS

by I.D. KEMBER(*)

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SUMMARY

This paper offers practical guidelines for any review of survey periodicity for offshore locations. Beginning with a review of the data sources which the hydrographic surveyor is likely to have to hand, the paper proceeds to an extended example (South Sand Head). Turning from the particular to the general, a two-stage operation is suggested for any offshore area :

(*a*) Investigation, using an historical series of hydrographic surveys as primary source, into changes occurring in the past — particularly during the recent past. Changes should be described in quantitative terms wherever possible.

(*b*) An attempt should be made to understand the sedimentary mechanism causing the changes noted in (*a*) above.

When both stages have been completed, the investigator will be ready to make his decision. Throughout, methods of graphical analysis are suggested.

1. INTRODUCTION

1.1. The risks associated with the use of hydrographic surveys are not, as a rule, accurately assessed by others, and the hydrographic surveyor has to be his own

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(*) Hydrographic Department, Ministry of Defence, Taunton, Somerset TA1 2DN, U.K.

actuary. These risks are :

(*a*) Failure to survey with sufficient frequency in order to monitor changes affecting navigational safety and efficiency.
(*b*) Design failure of the survey specification so that bathymetry is not examined in sufficient detail for the purposes of navigation.
(*c*) Failure of the finished survey to match the specification.

The last failure, if it occurred, would be a matter of professional competence and is not a subject on which the author is qualified to speak. The other possibilities take us outside the profession, since both survey frequency, which is our concern here, and survey specifications have financial implications. Hydrographic surveying is an expensive activity and it is to be expected that accountants do not want to see more of it than the strict requirements of safety and efficiency demand. Of course, the safety record of a port is a commercial asset, a fact that surveyors should drop into the ears of their accountants at regular intervals. Nevertheless, these are hard times and it is not to be expected that surveying will escape some financial scrutiny.

1.2. Set out above are three risks associated with use of hydrographic surveys; the accountant will turn these upside down and will find there three possibilities for "over-kill", "over-spend", "over-exercise of professional zeal". Softly, he may suggest some "good housekeeping"; if a place is surveyed, say, every two years, why not rest a year and make it three ? Averaged over a period, survey costs would be reduced by a third. Our surveyor is now under pressure to make the "right" decision. Genuinely anxious, he protests about safety. "How unsafe ?" is the cool reply. The surveyor is left to give voice to his opinion (which is, after all, an opinion backed by experience and understanding). But even as he puts his opinion into words, it sounds thin. Unless he is very skilful, the fact that he cannot back up his statements with firm evidence is painfully clear. Educated guesses are not enough.

1.3. This paper offers a Do-It-Yourself Kit on survey frequency. Please do not think there is encouragement here for distrust of the intellectual and the academic. The surveyor who has timely access to the advice of a good sedimentologist is fortunate indeed. But the good sedimentologist is likely to require — and this is entirely reasonable and proper — both time and plenty of data to work upon before he arrives at a solution. Our surveyor is likely to be a man with a deadline to meet. And so he rolls up his sleeves. At the outset, thoughts turn at once to data — what material does he have to hand upon which to base his recommendation about survey intervals ?

2. SOURCE MATERIAL

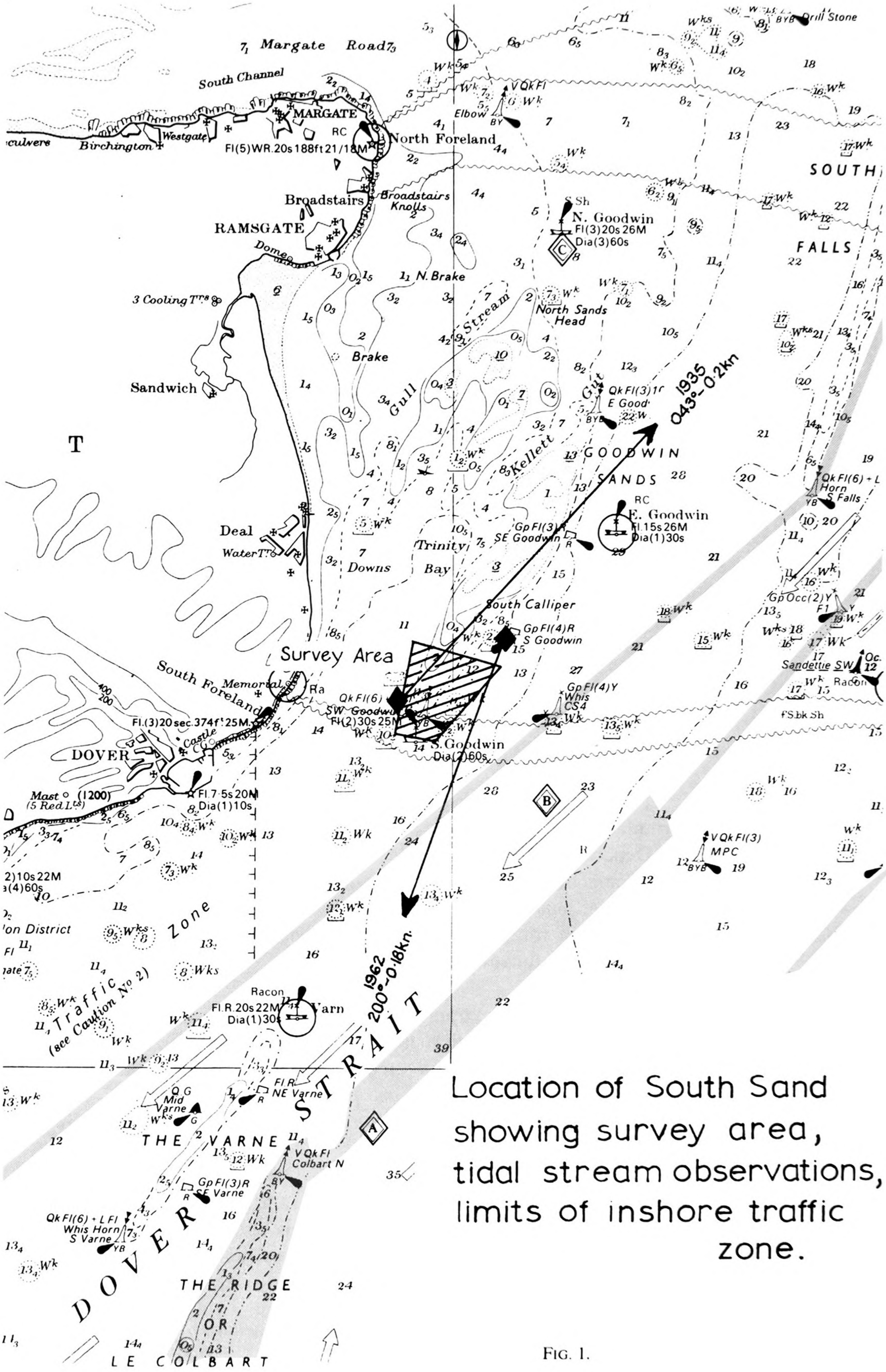
2.1. First, since he is presumably the survey authority, our investigator will have an historical sequence of hydrographic surveys. The span of the sequence may often be extended by the addition of early surveys from the archives of the Hydrographic Department. This survey series is no mean resource. Next, he will have tidal data, but this may have its limitations. Its most likely form will be tide gauge or tide pole observations made for the purpose of reducing soundings, and quite possibly the tidal station will lie outside the limits of the offshore area. However, in survey frequency studies, tidal stream observations are more valuable than height data and the former are usually in short supply. Casting around for further assets, the investigator may proffer a number of positions for horizontal control — a very valuable property of course — but having indirect rather than direct value for the work he has in hand.

2.2. And what else is there ? The Admiralty chart will give some tidal streams — not, unless he is very fortunate, inside the offshore survey area in question, but hopefully not too far from it. Charts will provide nature-of-the-sea-bed data although, if the surveyor has been prudent enough to hoard some old charts, they will yield rather more (but remember the bottom qualities may have changed). Perhaps of greater importance, the chart will show the survey area in its wider setting; it is always a mistake to zoom in close too early in an investigation. The remaining material will resemble a maritime junk shop, but nothing is to be despised or wasted : for instance, a geological map showing cross sections extending out to sea; a copy of a paper from a research student who, a few years back, undertook an investigation in the area in question and, by way of gratitude for services received, sent a copy of his findings; an informal word with a member of the local sub-aqua club who reports unusual scour around an old wreck. Vital first clues to understanding the sedimentary mechanism have come from lesser detail.

3. AN EXAMPLE : SOUTH SAND HEAD

3.1. At this point let us abandon generalities and look at an example. Later, we may be able to formulate some procedures and rules. One survey area for which the Hydrographic Department is responsible is South Sand Head, surveyed frequently down the years but annually from 1968. The mounting commitments made on our survey fleet made it imperative that time and effort were not dissipated on any areas which could be safely left to themselves for longer periods and so we began to study this location in 1980.

3.2. South Sand Head, the southern extremity of the Goodwin Sands, resembles a spearhead thrust into the narrow English Inshore Traffic Zone (fig. 1). South Goodwins Lightvessel, the sentinel for South Sand Head, and the outer limit of the Inshore Zone are separated by a mere 1 3/4 miles, easily the narrowest constriction in the zone. The traffic survey of June 1977 gave a sample daily flow rate for the English Inshore Zone of 43 vessels moving southwestward and 30 vessels moving northeastward. However, the count was made abreast of Dover and the proportion of these vessels utilising the Downs — Gull Stream route and thus avoiding South Sand Head is not known. If one assumes that 50 vessels a day pass the South Goodwins Lightvessel, that the constriction is 3 3/4 miles long and that the average speed is 15 knots, then, twice a day, 3 vessels are locked together in the narrows, 4 vessels every 4 days, and the 5-vessel situation occurs about 9 times in the year. At such times, the full 1 3/4 mile width of the Inshore Zone would be needed.



Location of South Sand showing survey area, tidal stream observations, limits of inshore traffic zone.

FIG. 1.

3.3.1. The need for surveillance can be well illustrated by comparing principal contours from the 1947 and the 1979 surveys (fig. 2). The southward march of the Head is inescapable — an average rate of about 48 metres a year. At such a rate, the Inshore Zone would be blocked off in about 65 years and would become uncomfortably narrow many years before that. In this light, the original decision to survey the Head annually can be well understood.

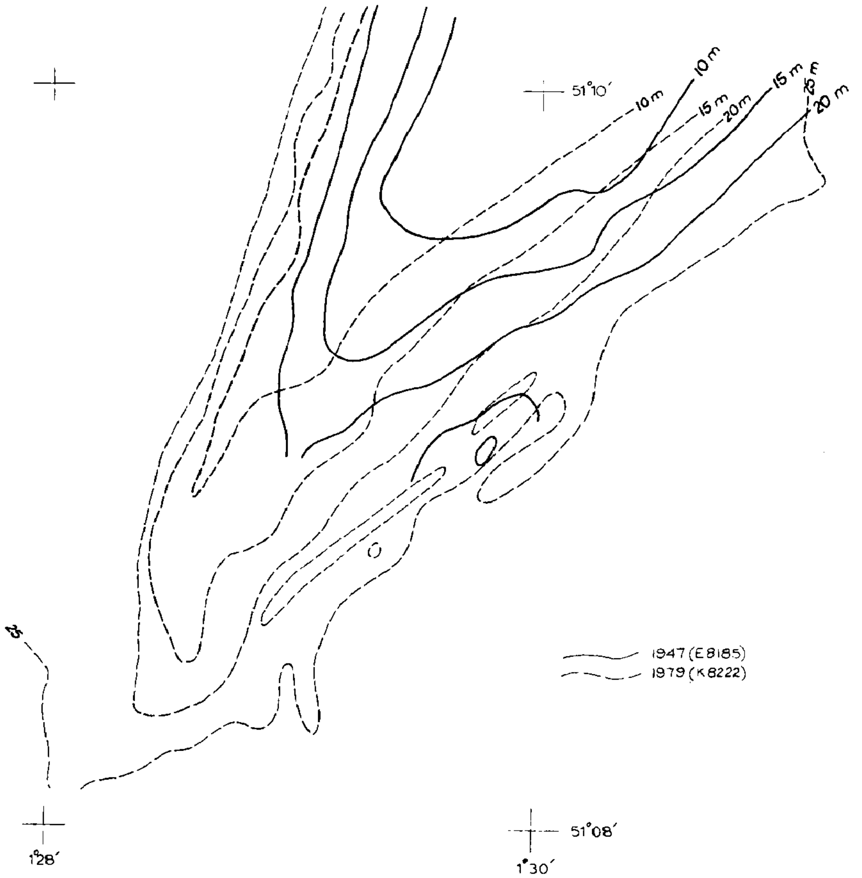


FIG. 2. — South Sand Head. Comparison of 1947 and 1979 hydrographic surveys.

3.3.2. Next we asked ourselves whether the advance from 1947 to 1949 was uniform and undeviating. So, on separate sheets of transparent Ozatex, we made a contoured drawing at 5-metre intervals for each survey. Earlier surveys were, of course, in Imperial units and we had to interpolate metric contours. Chart datum has not been uniform throughout the period and adjustment to LAT was made where necessary. Placing the contour drawings in sequence and examining successive pairs, we came across the first of many interesting aspects of the South Sand Head case. First, the advance was uneven both in rate and direction. Figure 3 shows the most south-southwesterly point of principal contours measured along the

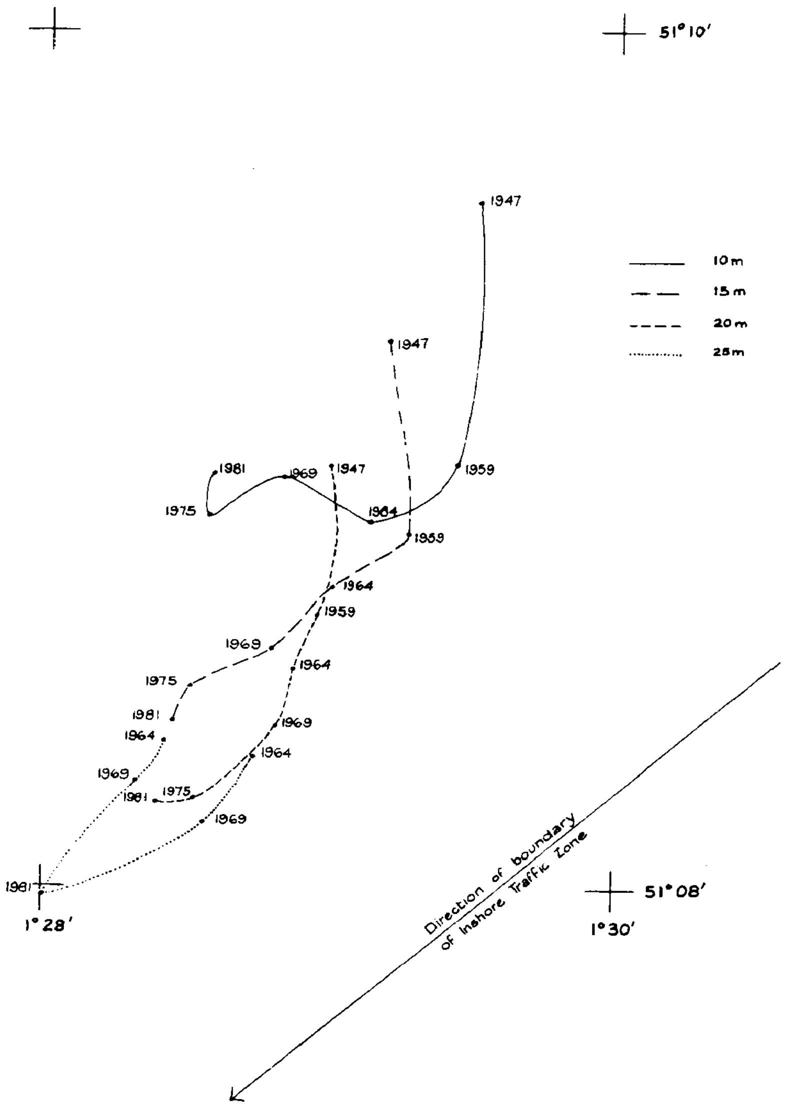


FIG. 3. — Diagram showing movement of southernmost points of 10, 15, 20 and 25-metre contours, 1947-1981.

primary axis of the Head. From 1947 to 1957, contours were moving southwards — moving, that is, to block in the Inshore Traffic Zone (which, of course, at that time was no more than a shadowy vision). Recently, however, the movement has had a strong westerly element and the Head has run safely parallel with the traffic zone boundary. Here was the first hint of reassurance.

3.3.3. A simple metric grid (origin 3,000 metres west of 51° 08'N, 1°30'E) was placed over each survey (1958 to 1979) and the coordinates of the most southerly points of the 10-, 15- and 20-metre contours were read off. Taking each contour in turn, eastings and northings of the southernmost point were plotted separately against time and an orthogonal polynomial (fourth order) was calculated by means of a computer program to give best least squares fit. Figure 4 illustrates the general trends, showing strong westerly movements but with the southerly thrust now weak or even reversed. Most curves show flattening out in recent years — an indication of stability. Using actual coordinates, it is possible to extract values for the greatest observed movements that have occurred over any specified interval of time. Thus, if a 3-year interval is chosen, it is possible to read off and tabulate the greatest advance of the Head we are likely to experience over this period.

Maximum movement over 3 years

	Eastward	Westward	Southward
10 m contour	180 m	310 m	200 m
15 m contour	20 m	240 m	260 m
20 m contour	80 m	240 m	340 m

Bearing in mind that the steepest curves (i.e; the maximum rate of change) occurred during the early part of the period of study (the westward movement of

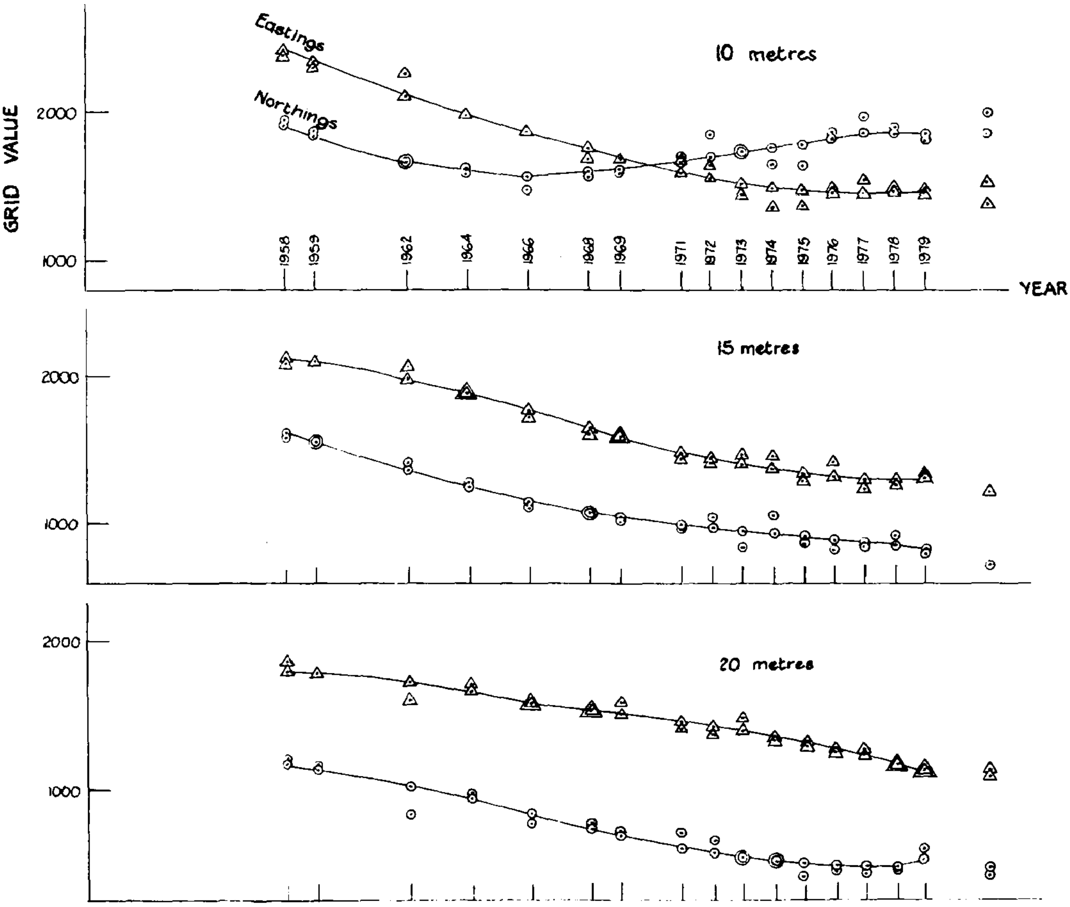


FIG. 4. — South Sand Head. Graphs showing movement of southernmost points of 10, 15 and 20-metre contours, 1958-1979.

the extremity of the 20-metre line being the only exception), it is reasonable to infer that the figures tabulated above are unlikely to be exceeded in the near future. Thus we have further grounds for confidence in the measured and regulated nature of the changes that are taking place.

3.4. However, it would be premature to conclude that all is well; our simple contour drawings indicate some puzzling features. We have already noted that the southward advance was not uniform and that in recent years, say since 1958, the rate was reduced and the thrust to the south coupled with a roughly equal westerly component, so that the resultant movement was approximately southwestward. Associated with the change in rate and direction was a change in the structure of the Head itself. Before about 1958, the Head was symmetrical in transverse cross-section; after 1958, the Head developed a pronounced asymmetry with the crest offset to the west giving a steep scarp slope facing west and a gentler dip slope facing southeast. It is unlikely that our static contour drawings will give us a clue to the mechanism creating the asymmetry and it is time to look at dynamic aspects of the situation, but not before noting one final point from our contour drawings : a shadowy indication of irregularities in the seabed close eastward of the Head itself. Tantalisingly, most surveys cut off at this point of interest and none were detailed enough to reveal the substance behind the shadow. But we note this point for future reference. To sum up, our 1980 understanding of the morphology of the Head is given in figure 5.

3.5.1. Turning to dynamic elements, we look first for tidal stream data. No observations have been made within our survey area; this is typical but, to be fair, also typically, we find stations not too far away. Figure 1 shows the location of a tidal station on either side of the Head and the residual currents extracted from observations. While it is prudent not to place too much weight on residual rates calculated from 25-hour observations, their contrary directions are in accord with both the usual pattern of opposing flows on the two flanks of linear sand banks in the southern North Sea and with the flood/ebb regime postulated by CLOET [1] for the Goodwins. In addition to measurements made at these two tidal stations, it is known (The Dover Strait Pilot) that there is a net transport of water from west to east through the Dover Strait. The rate and direction of this current at South Sand Head are not precisely known but are of the order of 0.2 knot north-easterly.

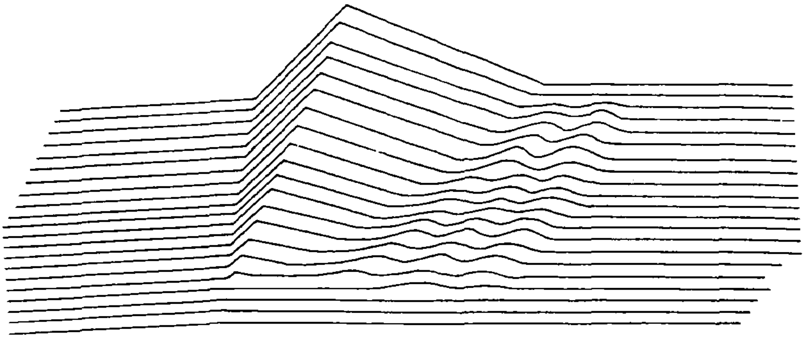


FIG. 5. — South Sand Head : schematic diagram.

Thus the known elements may be summarized in the manner of figure 6. This scheme is clearly incomplete, and we need to look for further evidence to finish the picture.

3.5.2. Here it is worth recalling that South Sand Head is very exposed. Waves and currents generated by wind may frequently reinforce, modify, cancel or reverse normal residual currents. Waves and currents originating in the English Channel are likely to affect both flanks of the Head more or less equally, but those generated by winds from south anti-clockwise through north-northeast must be felt, unabated, on the southeast-facing side of the Head. The western side, however, is protected by the coast and by the bulk of the Goodwins from the severest consequences of all but southwesterly winds. However, in general, we may expect that waves resulting from gales and strong winds are probably chiefly responsible for limiting the southward growth of the Head.

3.6.1. Our 1980 investigation finished at this point. Study of the movements of the extremities of the Head were reassuring, but there were too many unanswered questions for real confidence. Why is the Head asymmetrical ? Is asymmetry the result of sand transport across the spine from east to west ? Does the irregular seabed off the eastern tip of the Head offer a significant clue ? What happens to the conflicting residual currents at the Head itself ? Fortunately, another survey was due in 1981 and we were able to specify revised limits (to include the interesting irregularities in deeper water to the east of the Head) and to state sounding direction. Best of all, our request for sonar was acceded to. The 1981 survey was first class and, although we knew we were asking for a good deal in specifying sonar cover up and over the shallow spine of the Head, we got all we asked for. The changed line direction was successful, 035°-215° as opposed to 105°-285°. The former direction looked right but, in fact, worked well only for large features — which are not difficult to extract from almost any survey. The improvements were telling, in spite of the fact that there seemed to be little change from the earlier survey. A westward thrust on part of the western flank close northward of the Head itself was the only feature of note; a simple calculation based on cross sections told us that sand was accumulating here at a rate of over 1 1/4 million cubic metres per year along a front of some 2 kilometres.

3.6.2. But although the 1981 survey showed little change from its predecessor, it was in every way a revelation. Rather like someone with poor sight peering at pictures in the National Gallery, then suddenly seeing a painting through properly-prescribed spectacles, we were able to see the fine detail of South Sand Head for

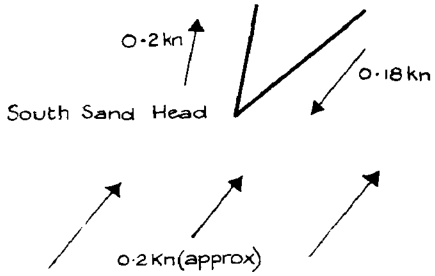


FIG. 6. — Summary of known tidal stream data.

the first time. The most vivid feature now brought into focus was the irregular seabed close eastward of the Head, now revealed as a sharply defined sand wave field. Major waves were seen to be orientated approximately 130°/310°, to have maximum amplitudes varying from 4 to 6 metres and an average wavelength of 175 metres (see fig. 7). The waves were aligned at right angles to the eastern flank

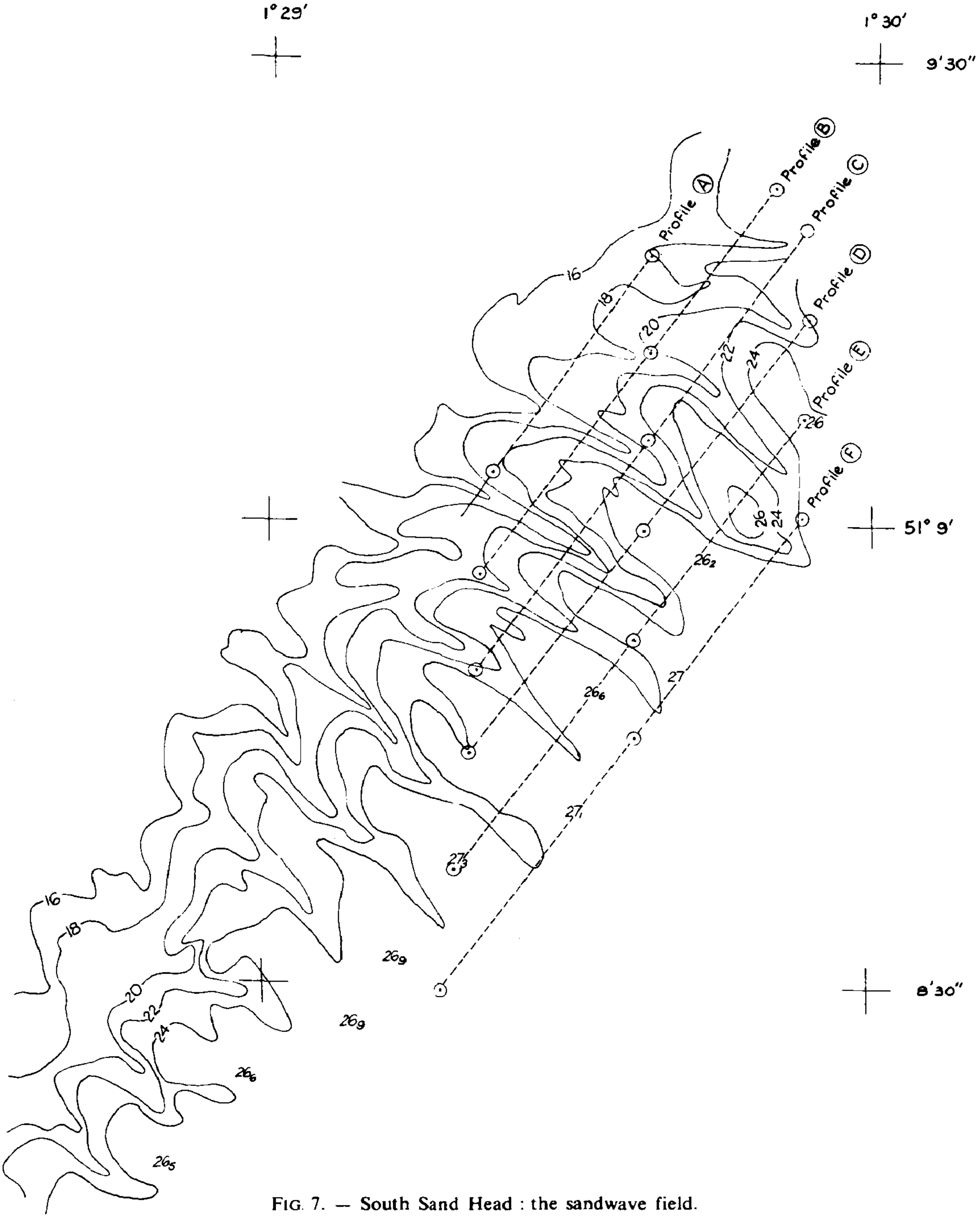


FIG. 7. — South Sand Head : the sandwave field.

of the Head, to which they were firmly attached, springing from a level well up the eastern slope (14 to 16 metres below CD); they merged in the east with the generally even sea floor at about 27-28 metres depth. Figure 8 shows a number of north-northeast/south-southwest profiles taken across the grain of the field. The cross sections A to F reveal that most waves are symmetrical in form, particularly at shallower depths. The most marked asymmetry is demonstrated in profile D, where the steeper scarp slopes are consistently southwest facing. Such asymmetry as can be detected in profiles C, E and F generally has the same emphasis. Thus we may infer from the shape of the major waves that movement of sand through the field is from northeast to southwest. The movement does not seem to be vigorous and is confined principally to the deeper parts of the field.

3.6.3. At this point it is interesting to speculate on the reasons for the existence of the sand wave field at this location. Apart from the 1981 survey, information and clues are sparse. However, the general circulation pattern suggests that the residual tidal stream off the southeastern slopes of the Goodwin Sands is south-going. Thus it follows that the probable direction of bed transport is also southwards, that is towards South Sand Head. On reaching the Head, further movement of material southwards is doubly opposed. First, movement is stemmed by the northeast-going Dover Strait current. Secondly, mobile material enters an entirely new environment in which random but more powerful wave energy is the prime motor. Thus the sand wave field lies at or near a zone of transition in which the mechanism of tidal streams is superseded or overcome by that of wave and tempest.

3.6.4. We may judge the sand wave field to lie at the southern extremity of the area governed by the regime of the tidal streams. We suggest this first because conditions in the turbulent area of the Head itself are not conducive to the formation and maintenance of regular forms (bottom features moulded here by tidal streams are probably ephemeral) and secondly because the creation of sand waves requires regular flows of the linear tidal stream type. Sand waves are, in brief, the progeny of steady and regular water movements and not of erratic and random flows.

3.6.5. The other essential condition for a sand wave field is an accumulation of material sufficient for the tidal stream to work upon and to shape into characteristic forms. This suggests either that the field in question is an area of accretion or that the accumulation is of historical origin. It would require a programme of careful on-site observations or repeat surveys over a long period in order to answer this question. One may speculate that the first alternative is more likely. We have already noted that under the influence of the Goodwins' circulation system the field receives new material from the north-northeast at a steady rate. In quieter times, when wind and waves are diminished, this gain is probably matched by an equal loss from the southern exit of the field. However, when the Head is battered, particularly by high seas from the southwesterly quarter, movement out of the sand wave field may be slowed down, halted or even reversed. Thus over a long period there may be a small net gain of sand. Alternatively, an equilibrium may have been attained with the sand wave field acting as a reservoir in which sand is detained for a period on its passage to the Head.

3.6.6. It is obviously impossible to assess the stability of the field from a single survey. However, the generally unstressed symmetry of the wave forms, the regularising and stabilising influences of the dominant motor mechanism (the tidal

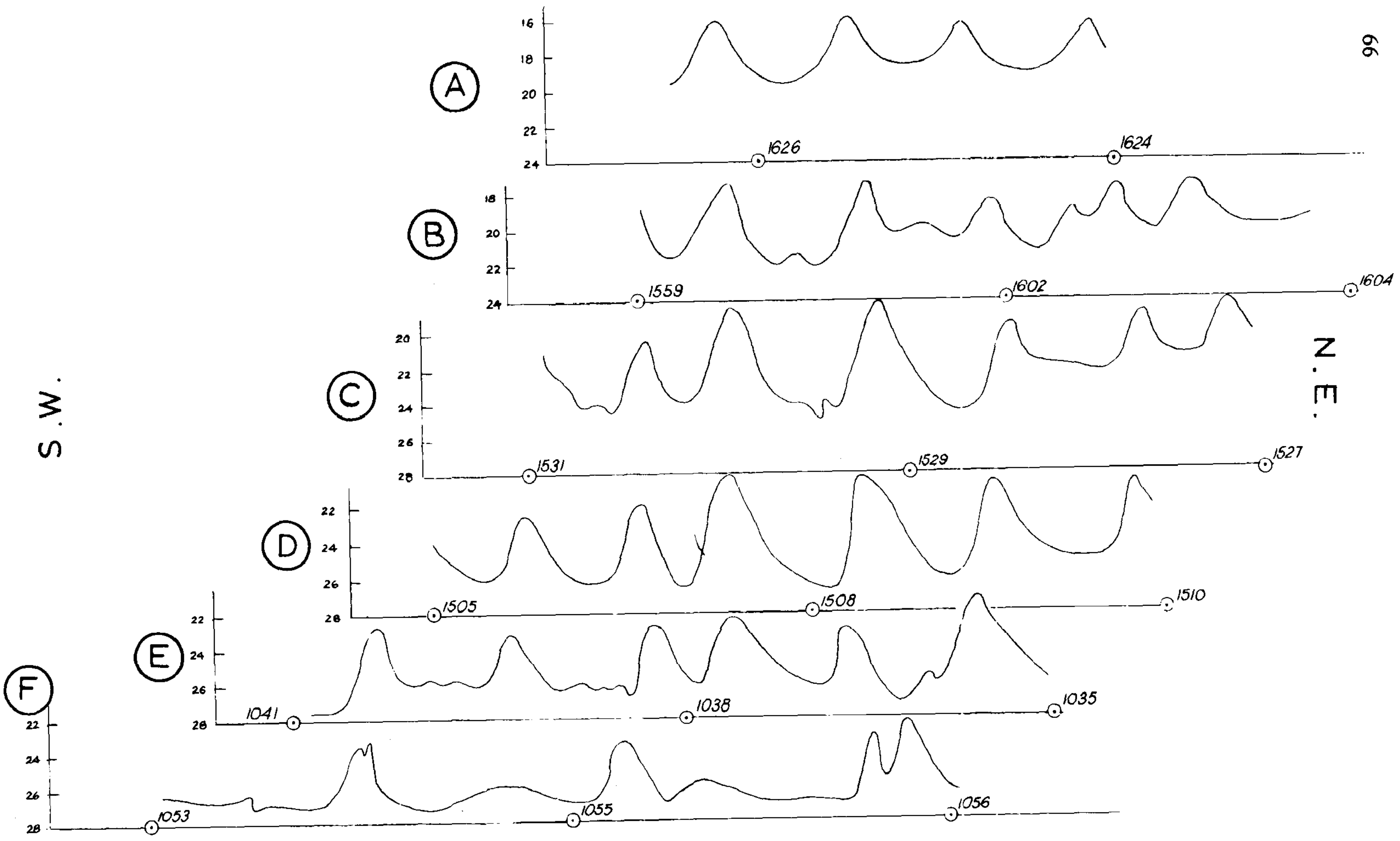


FIG. 8. — South Sand Head : analysis of sand ripples.

streams) and the probability of the tidal stream residual not being large, suggest that the field is reasonably stable both in its limits and in the size and location of its separate waves.

3.6.7. Turning from this particular feature to more general considerations, the minor wave features detected by echo-traces and sonar permit a wider view of the sand transport mechanism throughout the Head area. Small waves, mostly with an amplitude of 1 metre or less, are found widely at South Sand Head and are also superimposed as secondary topography or grain upon the waves of the major field described above. The orientation of crest lines of minor waves is shown on figure 9. Where waves demonstrate asymmetry, the direction faced by the scarp slope is also shown.

3.6.8. The distribution of minor waves is primarily marginal. Where they exist, waves on the spine of South Sand Head are smaller, less regular in form and exhibit no marked asymmetry. Perhaps it would be unwise to deduce from this that east-to-west sand transport up and over the spine is negligible. Asymmetrical wave forms are not essential concomitants of sand transport, particularly in an area like the spine which is very exposed and where wave activity would limit development of lasting and pronounced sand waves. Indeed, if east/west transport exists in such an environment, it may be expected to be spasmodic or even, on occasion, reversible. On the other hand, given wave building conditions, east/west sand transport would produce wave forms with north/south crests; several waves were found on the spine of the Head, but none had north/south crest lines. Thus, on evidence available, transport of sand over the spine would not seem to be a major element in the circulation system.

3.6.9. As we have seen, most minor sand waves lie in water deeper than 15 metres. The evidence of asymmetry gives a clear overall pattern of sand transport parallel to the sides of the head, southwest on the eastern flank and north-northeast on the western. Only a few asymmetries defy this pattern and almost all these opposing waves may be found at the southern exit from the major sand wave field. This exit, noted above, marks the boundary between areas in which wave energy on one hand and tidal streams on the other provide the principal mechanisms. The asymmetry here, and of course possibly elsewhere, may be reversible. Nevertheless, the general picture is clear and the broad clockwise circulation is strikingly proved. The circulation is summarised in figure 10. The Head is thus attempting to restore its former symmetry by loss of material on the east and gain on the west.

3.7.1. We had now reached the stage at which a decision could reasonably be made about the interval between surveys. We had not completed a full academic study of the Head and many unanswered questions remained. What caused the asymmetry of recent years and the associated change of direction with its strongly accented westerly element ? Did, perhaps, the former southerly thrust advance the Head into exposed waters, no longer sheltered by the Kent coast, where new or much augmented forces of storm and wave began to work on the Head ? Or, more probably, were there changes in the total Goodwins circulation system ? Those who have noted the vicissitudes of the channel bisecting the Goodwins, known as Kellett Gut, will appreciate that the system is subject to quite large perturbations. So our study is incomplete and, as a subject of an academic paper, must be reckoned thin stuff. But it has proceeded sufficiently far for our purposes.

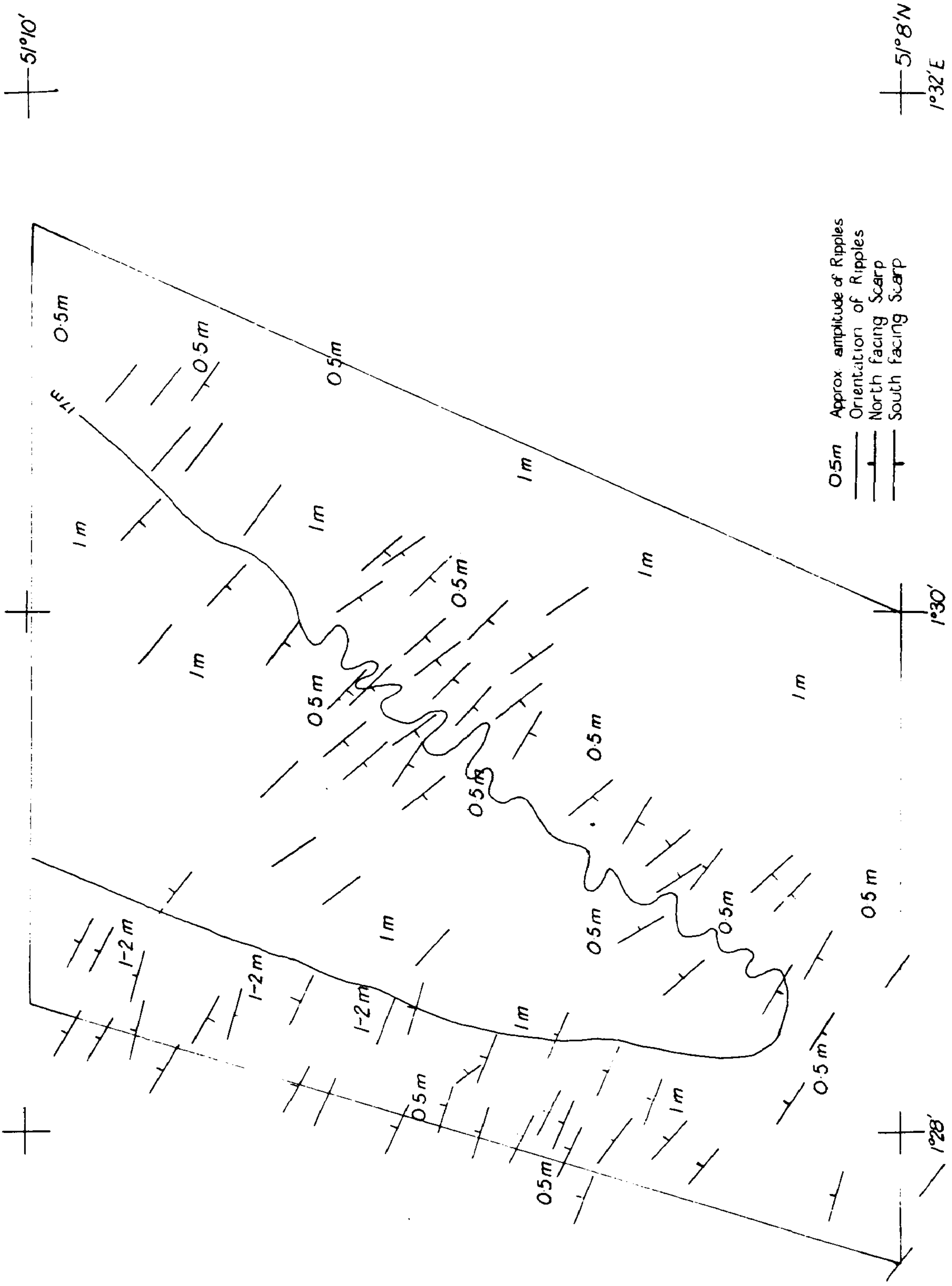


FIG. 9. — South Sand Head : analysis of sand ripples.

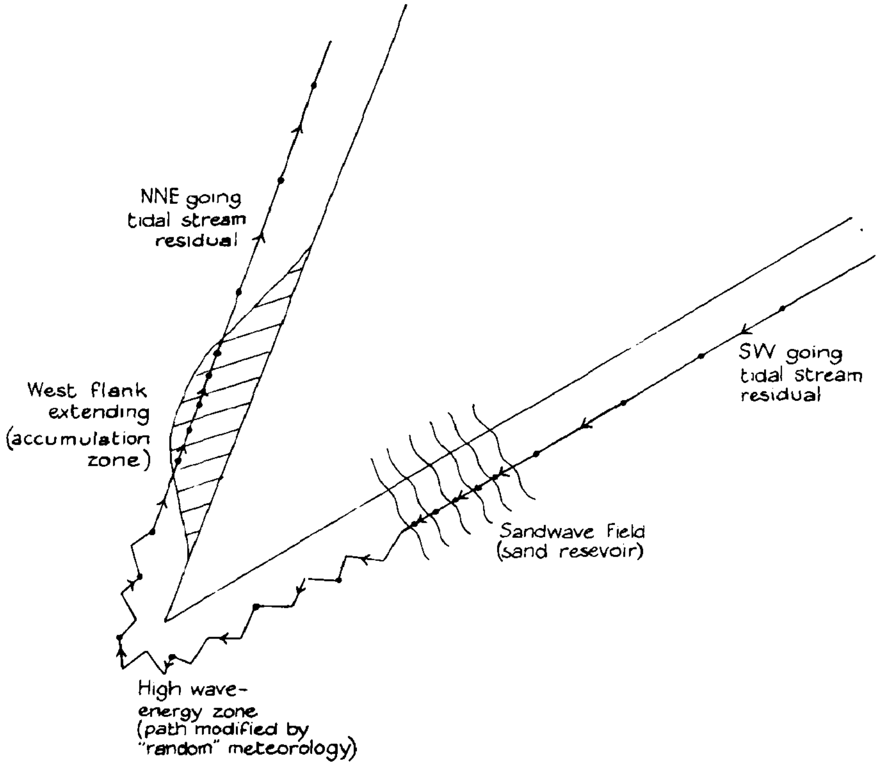


FIG. 10. — South Sand Head. Sediment circulation — schematic diagram.

3.7.2. Let us summarise our findings. First, we have a fair knowledge of the detailed topography of the Head; secondly, we have an understanding of the general pattern of the bed transport; finally, we have tracked the movement of identifiable points on the Head over a long period and can quantify the worst that is likely to happen over any specified period of time. Thus armed, we felt confidently able to recommend reducing the survey interval from 1 to 3 years; this recommendation has been accepted.

3.7.3. It is worth noting that the exercise was carried through using fairly ordinary resources. The only piece of good fortune was the opportunity before the 1981 survey to ask for sonar. We were most grateful for this but, in fact, almost all the underwater topography, including minor waves, was very adequately depicted on echo-traces. Here it must be said that an investigator's view of any area will be much sharper if he is able to choose the direction of the sounding lines and perhaps to order some lines at right angles to the principal sounding axis.

4. RECONSIDERING SURVEY INTERVALS — AN OVERVIEW OF THE PROCEDURE

4.1. Given a survey area and the ordinary sources of information at his command, our investigator is required to make recommendations on survey frequency. He should approach the task in two stages :

a) He should determine, to the best limits of his information, what changes occurred in the recent past. This investigation should be expressed in quantitative terms so far as this is possible. His chief resource for this stage will be the chronological sequence of hydrographic surveys.

b) Next, he should try to work out why the changes occurred. The aim, which he may not fully achieve, is full understanding of the sedimentary mechanism. The sources are tidal stream data and clues that may be picked up from the shapes of underwater features. It must be said, frankly, that these sources are scarce and, when found, are often more enigmatic than the hydrographic surveys used in the earlier stage of the task.

4.2. In practice, the two stages will not be as distinct as has been suggested. If, for example, in stage 1, the investigator discovers a major reversal of an earlier trend, he will be a very dull fellow indeed if he does not immediately ponder on the reason for this. Similarly, stage-2 ideas about a possible sedimentary mechanism may cause the investigator to return to his survey data to look for concealed changes he had failed to observe before. Sometimes he may find what he is looking for, but always the sound enquirer will give absolute priority to observation. The order in which the stages are set out is not random. Find out what happens first; explain it next. The temptation to make facts fit theory is as real here as in any other area of scientific enquiry.

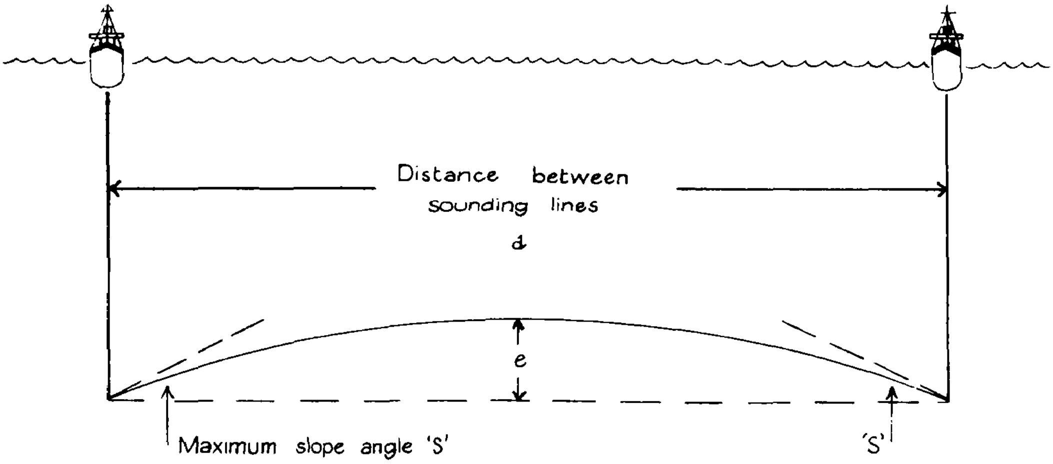
5. STAGE 1 : GETTING ACQUAINTED

5.1.1. Identifying and measuring changes in the past. This stage is characterised by a long, hard look at the study area, a look that takes in not only its present but its past. The surveyor's prompt and understandable retort to this advice is that he knows his survey ground pretty thoroughly already. But, to take the South Sand Head example, the area was not known in sufficient detail to make an entirely satisfactory decision until the 1981 survey, when the closer interval between sounding lines, the carefully-chosen line directions, some new thoughts on survey limits, and the advent of sonar not only showed detailed topography not hitherto perceived, but revealed those details that gave valuable clues about sand transport movements.

5.1.2. This stage is not as straightforward as it may appear. Few offshore areas are simple; all, including the complex ones, are more complicated than a first view would suggest. Further, the surveys by which one gets to know an area, were often designed for other purposes and are often disappointing. A rigid approach at this stage will almost certainly fail — the mind must be alert and flexible, ranging over space and time for clues, seeking to recognise the illusive patterns.

5.2.1. Using the series of hydrographic surveys. The investigator using a sequence of surveys must be alert to differences in vertical and horizontal datum and to differences in unit. Other variations in survey specification are subtler. For example, earlier Admiralty surveys rounded off depths over 7 fathoms to whole fathoms; later, only depths in excess of 11 fathoms were so rounded off. Thus 8 fathoms on a later survey means 8 fathoms plus or minus inches, but on an old survey the range is far greater : from 7 fathoms 5 feet to 8 fathoms 4 feet, inclusive. Two or three minutes' careful inspection and a look at the survey memoir will usually identify these problems.

5.2.2. Differences of unit and datum do not end the matter. Innovations in survey techniques do not merely make things easier or speed them up; they have a direct effect on survey accuracy and rigour which needs to be borne in mind by the investigator. Value judgements of this kind do not have to be entirely subjective. For example, it is important to ask ourselves what the likelihood is of determining true least depths over shoals and ridges. Here, we can begin with maximum bottom slope angles which can be determined from echo-traces (preferably from traces run in two directions at right angles). Given a line spacing, it is possible to calculate the most serious error; this arises when the summit of the shoal lies exactly half way between two lines of soundings. Figure 11 shows the most serious case for an area of rounded bed-forms. The average error, of course, is only a tiny fraction of this value. However, the matter is altogether more serious if the bottom is not uniformly sandy or muddy but is rocky or has rocky outcrops.



Approximate maximum error $e = (d \tan S)/4$
(for low values of S ie. natural slope angles of sand)

FIG. 11. — Diagram showing maximum sounding error.

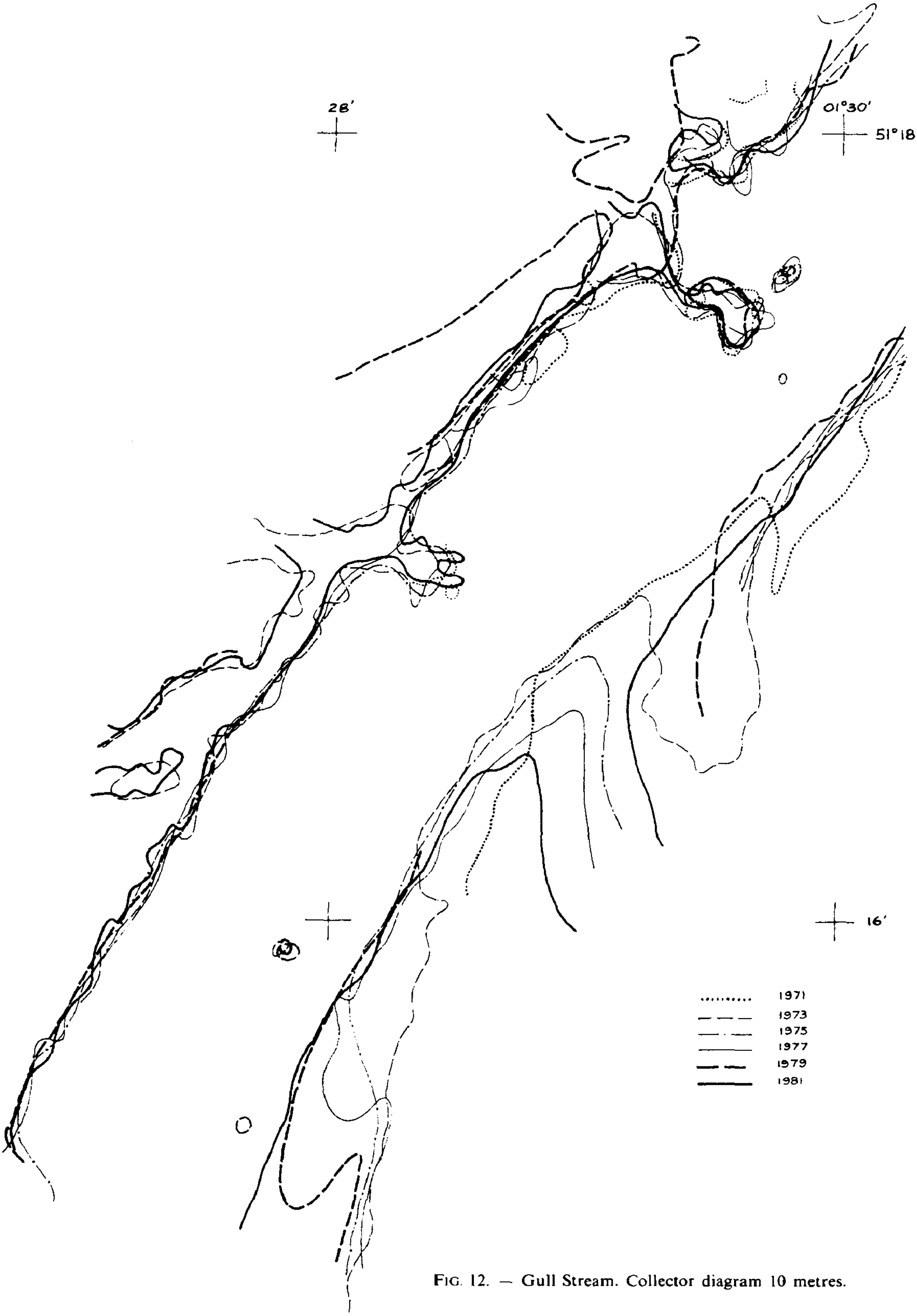


FIG. 12. — Gull Stream. Collector diagram 10 metres.

5.3.1. An inspection of surveys, however accurately their strength and weaknesses are perceived, will take the investigator so far but not far enough. Each survey is like a separate frame in a moving film — a dynamic situation held motionless at some repeated interval. Like the film, each image must be set in a uniform format if true movement is to be seen. It facilitates comparison if all surveys are reduced or enlarged to a common scale. Normally, the choice of scale is not difficult and is that which best balances the urgent need to keep and cost to a minimum and the requirement to work on a scale that does justice to the complexities of an area. At South Sand Head we chose 1:25 000, which was the scale of the most recent series of surveys.

5.3.2. It is reasonable to ask, at this stage, how many surveys should be included in the investigation ? In some areas, the total number of surveys could run into dozens and it would be time consuming and frankly wearying to subject each survey to careful analysis. The ideal is a sequence with a time interval of a logarithmic type, frequent in the immediate past, so that recent and ongoing changes can be studied in detail, and then opening out progressively as the survey series recedes into the past in order to provide, with economy, the longer perspective. About 8 surveys is a practicable number; during the course of the work some discarded surveys may be reassessed as important landmarks or turning points and it may be necessary to admit 2 or 3 other surveys to your series. Constraints of time, of the complexity of the area in question, and the idiosyncrasies of survey cover will have their own influence on the number of surveys you are able to subject to detailed scrutiny.

5.3.3. Contour drawings. Nothing more complicated is suggested as a first step than preparation on transparent material of contour sheets on a common scale for each survey. Even if units and datums are right, you will almost certainly need more contours than those given on the survey itself. This seemingly tedious exercise affords the drafter a detailed understanding of the shapes of the sea floor, revealing nuances which may not have been apparent before. The completed sheets may then be compared with other surveys; this year with last year, the first with the last, and all manner of other helpful comparisons. Furthermore, even at this early stage, we can begin to depart from the merely descriptive. If carefully drawn, the contour sheets will permit the enquirer to put some firm values on the movements of shoals, contours or whole features. The contour sheets have another function; they are source drawings from which more specialised graphics can be prepared.

5.3.4. Perhaps the simplest drawing which can be compiled from the original series of contour drawings is a single-value contour collector. Selecting a depth contour which is likely to have some significance, say 10 metres, the contour of this value is extracted from each contour drawing in turn and entered on the collector until a complete suite of 10-metre contours is gathered. The example (figure 12) is taken from the Gull Stream and clearly shows a marked difference between the two sides of the channel. The drawing demonstrates the stability of the west side of the channel at the 10-metre level, but shows lively movement to the east where a new channel was forming and can be seen moving progressively southwards, cutting deeper into the mass of the Goodwins itself.

5.3.5. Lengthy but straightforward in preparation, yet often telling, are drawings showing the maximum and minimum extent of each contour. The "minimum" sheet indicates a reference surface below which the sea has not cut during the

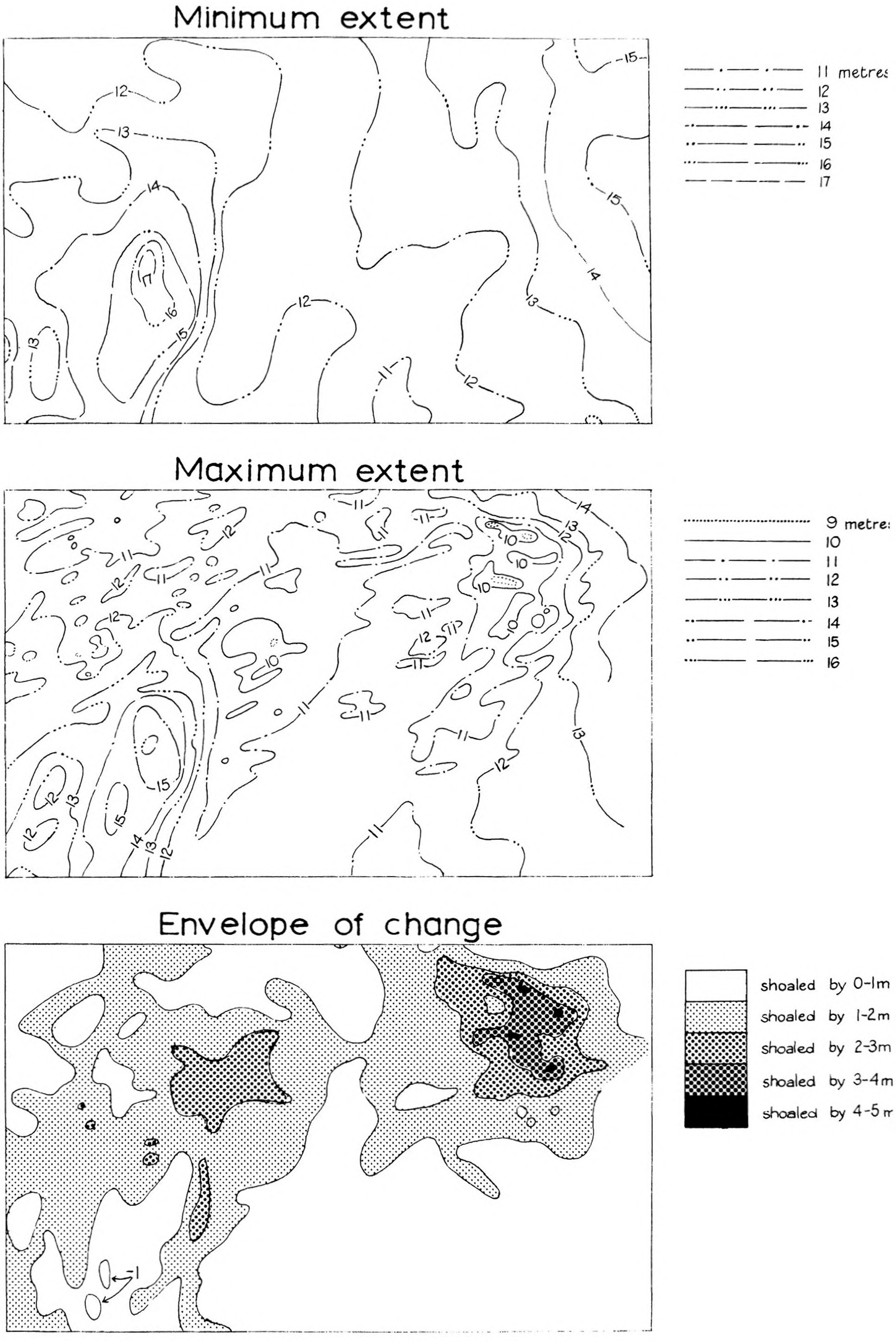


FIG. 13. — Roughs Tower spoil ground.

period of study (unless possibly in the interval between surveys). Clues about the underlying geological structure are sometimes found in such drawings. Conversely, the diagram of maximum extent of contours reveals the area at its most hazardous and can be a useful tool, in conjunction with other evidence, in determining best routes and channels. Subtract the minimum from the maximum and the result is a contoured drawing showing the envelope of change and indicating vividly where the greatest changes are taking place and where — of equal importance — the bed is stable. Figure 13 shows drawings of maximum and minimum extent, together with the envelope of change at Roughs Tower spoil ground off Harwich, and shows where repeated dumping has reduced depths.

5.4. Profiles. The cross-section is a traditional tool and should not be forgotten. Figure 14 shows superimposed cross-sections from west to east across South Sand Head. The westward movement of the Head is evident and the change from symmetrical to asymmetrical cross-sections is clearly brought out. Actual measurements of movement can be made from carefully chosen profiles. However, it must be said that cross-sections are usually brought into play at a late stage in the game. Profiles are often used when the investigator has a shrewd idea about sedimentation processes, wants to prove his point, and knows where to go in order to do so. By way of caution it should be noted that even experienced workers sometimes get taken in by the profile's exaggerated vertical scale; deep significance is read into differences of depth which, in reality, are equivalent to the length of a small ruler.

5.5. Measurement of volumes. Growth or contraction of complex undersea features can often be determined only after volumetric measurement applied to a series of surveys. Volumes may be calculated from areas measured on parallel cross-sections or from the areas enclosed by contours. Pairs of areas are averaged, then multiplied by interprofile distances or by contour intervals to give volumes. The fortunate will be able to follow contours using a digitiser, leaving a computer to calculate volumes. This is a timely reminder that volumetric thinking is important whether you carry out volume calculations or not.

5.6.1. Significant depths. Thus far we have considered the identification and measurement of change over a significant area. In navigation it is often a few least depths that dominate an area. They may represent dangers to avoid, in which case

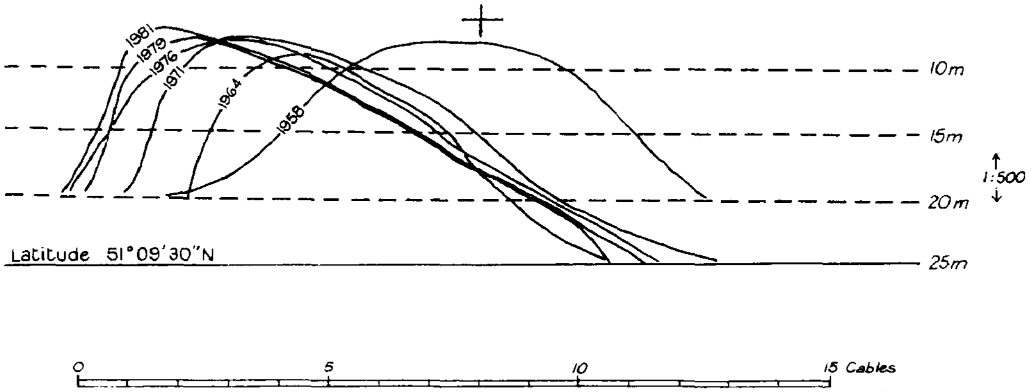


FIG. 14. — South Sand Head : cross sections.

routes will be determined to pass them safely. However, they may not be avoidable at all and will be important regulating depths in a channel or over a bar. Analysis of these depths forms an important element in any study aimed at determining survey periodicity. However, the investigator must ask whether surveyed least depths are equivalent to actual least depths. Line direction, line spacing and the extent of interlining, and the nature of the seabed are primary considerations in this matter. In the Gull Stream a number of underwater outcrops of bare sandstone were detected. Surveyed least depths over these features have been consistently lower since the outcrops were identified, the result of conscious efforts to locate them and to search for an accurate clearance.

5.6.2. We now come to a particularly tricky problem which can best be described by way of an example. The following example is uncommon but by no means unique. East of Nab Tower the chalk sub-strata is covered by a layer of deep sediment, part of which has been moulded by tidal streams into a field of gently undulating sand waves. Depths over the sand waves were generally well regulated and a check on 16 minor summits gave an average range of values of only 0.86 metres over a period of 15 years. There was everything to suggest that new sedimentary material was not entering the area at any significant rate and that the material already present was well graded and not mobile. But one location with a hitherto consistent depth of 13.5 metres suddenly produced a depth of 11.4 metres in 1973, although the depth was restored to average by the following survey. The 1973 survey data (echo-sounding traces and field books) have been destroyed but examination of the survey strongly upheld the authenticity of the sounding; it was supported by other depths of almost similar value and the shoal graded away easily into depths which were usual at this location. Normally, the sand-wave-building forces and the wave-destroying forces were well balanced, but what occurred in 1973 was the temporary ascendancy of the constructional element. The 11.4 metre summit probably only lasted for a few months and may have been destroyed when the next heavy sea struck the location. But for a short period it existed and was as capable of causing a grounding as the most regular and permanent feature. As a general rule, it is not possible to undertake surveys with sufficient frequency to monitor the life and death of such short-lived shoals. Although sand wave fields have been shown to be better regulated than was at one time feared, of all bed-forms the sand wave is the most likely to produce a "surprise" depth. It is for this reason that the responsible surveyor will wish to define the limits of sand wave fields in areas within his jurisdiction and to consider them in relation to shipping routes.

5.6.3. Given an historical sequence of surveys, the two simple things to do, and most certainly not to be despised for that, are to plot and list least depths over a particular feature. If the least depth is always to be found in the same place, or is strongly linear in location, it will be worth while looking for a structural or other reason for this. In the example (fig. 15), located in the approaches to the Solent, a chalk outcrop thrusts through the seabed sediment. A wider scatter will show that the forces shaping an area are subject to some considerable variability. Listing the minimum depths at a location, determining range and mean are basic operations. Plotting them on a bar graph may reveal interesting distribution. Bunching of depths near the upper end of the range may indicate a feature regulated by wave action, while bunching at the other end of the range suggests an erosion-resistant

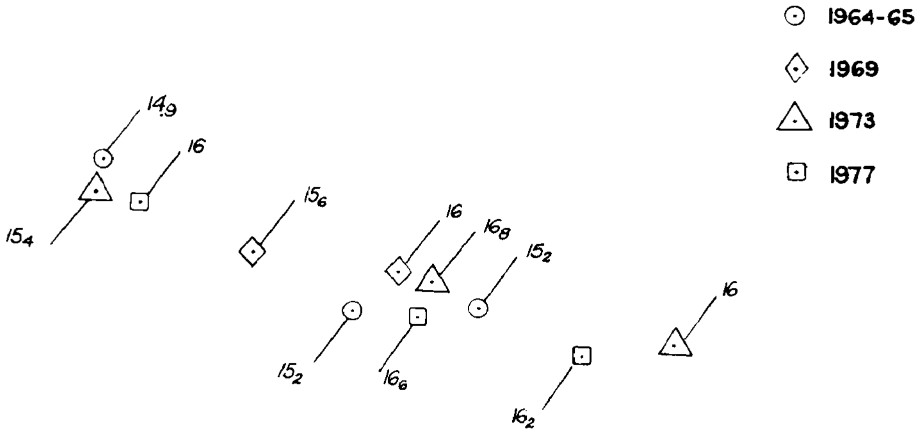


FIG. 15. — Off Isle of Wight : position of least depth over shoal features.

surface underlying a sediment layer of varying thickness. Standard deviations may be calculated, but I doubt the value of this unless the researcher is confident that the range of values at a place has a normal distribution.

5.6.4. Finally, in order to determine long-term trends or to extrapolate into the future, positions of significant points or depth values may be plotted against time and their best least squares linear or curve fit obtained by regression analysis. The South Sand Head exercise has presented an example of this. Computers will provide curves, tenth order or so, that will fit points remarkably well, but they may behave strangely between data points, looping the loop or misbehaving in other ways. Lower order curves are likely to give the sort of fit that a practical man might acknowledge.

6. PART 2 : THE SEARCH FOR A MECHANISM

6.1. If the key to the first part of our task was "close acquaintance" the word for part 2 is the interrogative "Why ?". With diligence and a little ingenuity it is possible to detect the changes that are taking place and to measure them in a quantitative way. It must be tempting to stop at this point and to contend that, since we have measured the past, it is probable that the future will be something like it. In most instances, such an approach will provide the right answer. However, most investigators will not rest content until they have some understanding of the sedimentary mechanism. It is this that will give reassurance that the system is self-regulating or is developing in a particular way. Only an understanding of this sort will exorcize the spectre of sudden calamity, the fear that forces operating at a place will, one dark and lawless night, combine to move sands in an arbitrary and sudden manner to the terrible distress of navigation and to the loss without trace of the surveyor.

6.2. The dynamic elements. Thus far the changing seabed has been treated in a rather static way; it is now time to look for dynamic elements. The Admiralty Tidal

Stream Atlas is a good place to start; it will provide a good general understanding of the tidal regime, not only within the area of study but in a wider context. However, the investigator will quickly wish to move to a more quantitative approach and the Admiralty chart, and perhaps the MIAS service, will provide him with observations, if not actually within his area of study, reasonably close to it. Observations will be variable in quality; 31-day readings are to be preferred but, frankly, most are of the 25-hour kind and much subject to the vagaries of wind and wave operating at the time. Further, it is likely that observations will have been made at or near the surface and not, as required, close to the seabed. Nevertheless, the investigator should not be too high-minded; data are in short supply and he will almost certainly have to press every item into service. But remember, no item of information can so firmly plant the enquirer's steps on the wrong path if stream observations, by reason of aberration of season or weather, are not typical of the general trend.

6.3. At this point there is much to be said for drawing a sketch showing such information about residual tidal currents (and therefore bed transport direction) as the investigator possesses. As he does this, he will have in mind results of his earlier work with the series of hydrographic surveys and he will know where material is accumulating and where it is being eroded. Without being too dogmatic about it, perhaps some kind of pattern is already beginning to emerge. Or perhaps he will have an instinct that some important element is still missing.

6.4. The final clues in piecing together the pattern of bed transport are almost certain to be found in the small print. Sand waves are often the key — but seen in detail, minor features as well as major ones. Sand waves are aligned at right angles to the principal directions of tidal streams. This narrows the bed transport direction to two opposing bearings, the solution to these alternatives often lying in the lack of symmetry of the waves, material moving up the long dip slope and plunging down the steep scarp slope. Fully symmetrical waves suggest that there is little transport in or out of the area. The investigator is now looking for fine detail and it is doubtful whether the survey fair sheet will be adequate for his purposes. It will be necessary to look closely at echo-traces or the sonar record in order to extract the information about the morphology of sound waves that he requires. Horizontal movements of sand waves are very difficult to detect; in general they are not as mobile as had been thought and often their movements are subsumed within the limits of survey accuracy. Other clues are offered by the direction of scouring around wrecks and obstructions and by sand ribbons which align themselves parallel to the dominant tidal stream. Unfortunately, sand ribbons are not easily detected even on an echo-trace and sonar is needed to unlock this particular door.

6.5. Our experience is that this stage is both stimulating and unsatisfactory. It is unsatisfactory because it is unlikely that the investigator will have arrived at definitive conclusions. If he commits himself to paper, phrases like "it is possible that" or "I suggest" will keep interrupting the firm thrust of his prose. There are reasons for this. First, he was starved of facts from the outset and absolute conclusions were beyond his grasp from the beginning. Secondly, his area of investigation, wherever it is, will form only part of a large sedimentary system, the study of which requires resources of time, and possibly of training and experience, beyond the command of the investigator. So why start the race if he cannot complete it ? Because the act of running is itself healthy and expansive. The man who tries will be granted a better understanding than the man who does not. However, the trier must have a degree of humility : a good try is not to be confused with total success. The investigator must have a lively sense of the deficiencies of his sources and of the limitations of his understanding of the sedimentary mechanism. But this sense, important although it is in arriving at a balanced conclusion, should not inhibit the investigator. He will properly remember that he has taken the problem further than anybody else and that, among others, it is his voice which is best informed and most confident. Clearly, he is now the man to take the decision.

7. THE DECISION ON SURVEY INTERVAL

Before coming to such a moment it is required of the investigator that he understands the navigational significance of every part of his area. He will know the shipping routes and channels — and the short cuts. He knows the safe areas and the hazardous ones. He will have considered fisheries, spoil grounds and the needs of small boats. He will bear in mind the trade he has and the trade he is trying to attract. This will permit him to put a navigational value on every seabed movement and change. Since we have also stressed the importance of putting a quantitative value on each movement he will be able to make a well-founded estimate of the worst that can happen in any specified period of time. Balancing navigational importance in one hand and observed, measured change in the other, he will be equipped to make his decision.

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