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AN INVESTIGATION OF SAND MOVEMENTS IN THE RIBBLE ESTUARY USING RADIOACTIVE TRACERS

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USING RADIOACTIVE TRACERS

PREFACE

1. The work described in this report forms part of a field programme undertaken by the Hydraulics Research Station on behalf of the Corporation of Preston, to serve as a basis for recommendations directed at improving the navigable channel to the port of Preston. It should be read in conjunction with Report No. EX 281.

INTRODUCTION

2. The port of Preston stands several miles from the open sea at the lowest bridging point of the River Ribble (Fig.1). Throughout its length from Preston to the sea the river is tidal with a reasonably straight main channel. In the landward section of the estuary the channel is confined between flat saltings only about 500 ft apart, but widens westward to include extensive sand banks bisected by a 1,000 ft wide shipping channel held to the W-E orientation of the inner estuary by low water training walls of dumped stone. The restriction of the navigable channel, first by saltings and later by low walls and sand banks, extends to a point almost 15 miles west from Preston Dock.

3. The local practice of defining the position of any point in the channel with reference to the distance downstream of the dock entrance is adopted in this report.

4. Throughout its length the bed of the channel is principally mobile sand, and navigable depths are maintained only by extensive dredging. Records show that during the period 1949-1962 1.7 million cubic yards of material were dredged per annum, of which 47% was removed from the upper reach of the estuary between the Dock Entrance and the 6th mile and a further 31% from the reach extending seaward from the 13th mile. Thus accretion is critical in two zones; one at the head, the other at the mouth of the estuary,

separated by a 7-mile length of channel in which dredging amounts to 360,000 cubic yards per annum.

5. Survey records of the longitudinal bed profile of the landward eight miles exhibit a well defined seasonal shift of sand in the upper estuary. In winter, sand tends to accrete between the 5th and 8th mile concurrently with a lowering of bed levels upstream of the 5th mile. In summer the reverse occurs and bed changes of as much as 4 ft are normal in this recurring pattern. In the long term no progressive reduction in depths occurs, presumably because dredging holds natural accretion in check.

6. The seasonal cycle of erosion and deposition in the upper estuary appears to be in response to the influence of fresh water flow on the sediment drift. The more rainy winter period, when river discharges greater than 2750 cusecs are often superimposed on the tidal flow and reinforce the effect of the ebb tide, leads to a net seaward sediment drift in the upper estuary. In summer, on the other hand, with the relative absence of high river flows the tidal balance alone governs sediment movement. At such times the flood tide appears to have the greater sediment carrying capacity, resulting in a net landward drift.

7. The history of profile changes seaward of the 8th mile is not sufficiently documented to show whether the seasonal shift extends over the total length of the estuary. In any event the increasing width of the channel to seawrd makes bed level changes a less sensitive indicator of accretion and erosion in the downstream reach.

PURPOSE OF INVESTIGATION

8. To assess whether or not the movement in the upper reaches is only local in character, a study has been carried out to determine the net drift of sediment in the region of the 11th mile by means of radioactive tracer methods. Knowledge of the direction of drift in this intermediate reach is important in order to establish whether any link exists between the two problem areas at the two ends of the estuary. The dredging figures demonstrate that material is entering the estuary system as a whole. The amount of sediment reaching the estuary by way of the river from land sources is undoubtedly very small compared with the dredged quantities, so almost all the supply must be from seaward. However, it is not known whether the fresh material is introduced into the system from the sand banks over the walls of the outer estuary, or whether it enters at the mouth of the estuary to reach the more landward accretion zones by way of the main channel.

9. Radioactive tracer simulating sand particles was introduced onto the bed of the channel at a time of low river discharge when the upper reaches

were experiencing flow conditions conducive to a landward shift of sediment. A landward movement of the tracer from the 11th mile would suggest that the seasonal circulation covered the total length of the channel, whereas no net drift or a drift to seaward would demonstrate that the seasonal shift of sediment was restricted to the landward reaches only.

FIELD CONDITIONS

10. The low parallel walls training the outer estuary channel are no longer as effectively continuous as at the time of their completion in the 1930s; breaks of several hundreds of feet in wall crest level are evident in a number of places, while in others overtopping by sand from outside the walls has occurred. The seaward limits of the wall are at the 13¼ mile on the north side and at the 14¾ mile on the south side. In general, the zone of maximum water depth lies within the walls (Fig.2) apart from near the mouth; where a well defined channel, the South Gut, is developed outside the south training wall while on the north side of this wall Salter's Spit restricts depths at the 14¼ mile to 1 ft below mean low water springs (M.L.W.S.). The shipping channel reveals marked variation in depth along its length; eastward from Salter's Spit depths increase to a maximum of 23 ft below M.L.W.S. at the 12¼ mile before shoaling occurs once again to 2 ft below M.L.W.S. opposite the 1 mile long break in the north side wall in the vicinity of the 9th mile. Further landward shoaling to 7 ft above M.L.W.S. is recorded.

11. At the estuary entrance (15th mile) mean high water neaps and springs provide an additional 21 ft and 27 ft respectively to the depths given above, and so the channel is navigable for vessels of medium draught for a short period on either side of high water. When water covers the banks, waves generated in the Irish Sea have an easy passage well up the estuary, but at low water the general aspect of the outer estuary is transformed to that of a channel canalised between high banks, largely protected from wave action. The influence of waves with reference to the movement of the bed sediment is therefore only significant over the high water period.

12. Current velocities in the channel are determined by the summation of the tidal flow and the freshwater discharge. The latter measured 7 miles above Preston Dock is frequently in excess of 1750 cusecs, a figure which for a water depth of 8 ft at the 1st mile is equivalent to a mean seaward velocity of 1.5 ft/s. The influence of the freshwater component decreases seaward on account of the greater cross-sectional area of flow. Comparative measurements carried out in the channel with Kelvin and Hughes Direct Reading Current Meters show a striking change in the velocity pattern of the upper estuary between spells of high and low river discharge. These observations,

presented in summary form in Table 1, were made on average tides all having a high water at the estuary entrance of 23.5 to 24.0 ft above M.L.W.S.

Table 1 : Current Velocities 1 ft above the bed.

Mean River Discharge (Cusecs)		Distance Seaward from Dock Entrance (miles)	Duration of current velocity above 2.0 ft/s (h)		Maximum Velocity (ft/s)	
			Flood	Ebb	Flood	Ebb
HIGH FLOW	2600	1	0.2	4.5	2.1	2.6
	2600	7	2.5	5.2	3.9	3.8
	2200	11	2.0	1.0	3.0	2.2
LOW FLOW	375	1	2.2	0	6.3	1.5
	375	7	3.0	0	4.0	1.8
	375	11	0	0	1.7	1.8

13. The duration of velocities above 2 ft/s together with the peak velocity have been chosen arbitrarily to indicate the degree of disparity between flood and ebb flow conditions and hence the probable direction of sediment drift. The two landward positions emphasize the striking response of the upper estuary to changes in freshwater discharge; with marked westward drift under high river conditions and strong drift in the opposite direction at times of low river flow. At the 11th mile the position is by no means so clear-cut, the flood and ebb being more closely balanced but with a tendency towards a slight flood drift under high river discharge. The same pattern of changes is demonstrated if 1.5 ft/s is substituted for the 2.0 ft/s as the minimum velocity determining the duration of flow with a high sediment transporting capability.

14. High freshwater discharge would be expected to suppress flood velocities at all positions in the estuary to some degree. However, this has not been confirmed at the 11th mile, where on equivalent tides higher ebb and flood velocities were recorded at a time of increased river discharge. A change in bottom topography between the two sets of observations, or a possible error in re-establishing the earlier measuring position, could be responsible for this anomaly, but if this were the case it would suggest marked local flow variations.

15. Velocity measurements throughout the verticals at the above three positions and at the Deposit Buoy which lies 3 miles WNW of the estuary mouth have been expressed in terms of net linear water drift over one tidal cycle at 3 depths (Figs. 3a and 3b). The superimposed river discharge ensures that all stations exhibit an overall seaward drift, but the drift at

different levels is not necessarily in the seaward direction. Under low freshwater flow conditions the bed drift measured 1 ft above the bed is landward at the 7th mile, whereas at the 11th mile the water drift at all depths is seaward. Thus a reversal of bed drift is experienced at a point between the 7th and 11th mile, upstream of which a net landward movement of sediment may be inferred to occur when river discharge is low.

16. Samples recovered from the bed of the channel at intervals of $\frac{1}{4}$ mile from the 7th to the 13th mile and at a few positions outside this reach indicate that generally the bed of the channel is composed almost entirely of fine sand. The sand becomes finer in the landward direction, the median particle diameter being 0.20 mm at the $14\frac{1}{2}$ mile and 0.14 mm at 1 mile from the dock entrance. This pattern of sand grading with distance up the estuary does not hold, however, in the reach between 9 and $12\frac{3}{4}$ miles. There, the bed is very variable in character and includes shell, gravel and, in some places, mud in addition to sand. The sand component varies locally with median particle diameters ranging from 0.18 mm to 0. 42 mm, but is normally significantly coarser (Fig.4) than the sand on the channel bed to landward and seaward of the reach.

17. In the outer estuary, sand dunes with crests running generally north and south are evident at low water on the drying sand areas adjacent to the main channel. Echo-sounder runs carried out in the Port of Preston survey launch on the centre-line of the channel between $9\frac{7}{8}$ and 13 miles confirmed the presence of dunes throughout this reach. The dune pattern was remarkably continuous with an average wavelength of 20 to 25 ft (Plate 1). The height of the dune measured as the difference in elevation between successive crest and trough ranged between 0.5 and 3.0 ft with a mean value of 1.5 ft. Although there is an indication that dune height increases to landward,many echo-sounder runs would be required to establish whether the differences in sand dune characteristics recorded along the channel could be regarded as statistically significant (Table 2).

Table 2 : Dune characteristics.

Reach (miles downstream od dock entrance)	Wavelength (ft)	Mean Height (ft)	Standard deviation in height (ft)
$9\frac{7}{8}$ - 10	26.4	1.71	0.53
10 - $10\frac{5}{8}$	23.6	1.66	0.51
$10\frac{5}{8}$ - 11	20.3	1.55	0.48
11 - $11\frac{1}{2}$	22.0	1.32	0.40
$11\frac{1}{2}$ - $12\frac{1}{4}$	23.5	1.63	0.44
$12\frac{1}{4}$ - 13	18.6	1.23	0.46
Mean $9\frac{7}{8}$ - 13	21.6	1.46	-

18. Further echo-sounder measurements were carried out to determine whether any changes in dune patterm occurred at the various stages of the tide. Buoyed 100 ft lengths of channel were surveyed at $\frac{1}{2}$ h intervals throughout the flood and ebb of a mean spring tide at two positions on the 11th mile cross-section (Plates 2 and 3). It was not possible to repeat the runs at a constant speed throughout the tide and so no common distance scale can be applied to the echo-sounder records. Fix marks A to F made at defined 20 ft intervals were necessary for the identification of the same position on each profile. All runs were carried out against the tide, with fix mark A representing the landward end of the profile. In this manner the response of a small number of dunes was recorded for the changing hydraulic conditions experienced during a tide.

19. The dunes in the observation section were typical of the reach generally, with wavelengths of 2o to 25 ft and a mean height of 1.5 ft. The peak water velocity at half depth was estimated to be 5 ft/s at 2 to 3 hours before high water. Even at such high velocities the bed retained the dune configuration throughout the entire tide without any significant reduction in height. The reversal of dune direction occurred some time after the change in tidal direction; at 3 hours 22 minutes before high water, when the flood tide had been running for over one hour, the steep face of the dune was still facing westward (Plate 2), while a similar time lag was evident in the response to the ebb tide. In this case, however, the change in dune direction was not so abrupt as on the flood tide, with the bed configuration passing through a transition stage during which the dune profile was approximately symmetrical.

20. It is doubtful whether the profiles can be interpreted quantitatively to give the nettranslation of the dunes along the channel. Recognition of the same dune on successive traces cannot be made with certainty because they have few distinguishing marks, and it is unlikely they retained the same form from one run to the next. Nevertheless, from a study of dune crests the indications are that the dunes retained the same positions relative to the fix marks at times of low velocity and exhibit some propagation in the current direction at the time of peak velocities, particularly on the flood. It is probable, therefore, that not only the sand in the immediate neighbourhood of the sand/water interface but the complete sand layer lying above the level of the dune troughs is acted on by the flow processes and is involved in movement.

EXPERIMENTAL DETAILS

Radioactive Tracer

21. As in many radioactive tracer experiments conducted by the Hydraulics Research Station, glass particles were chosen to simulate the movement of fine sand. A melt of 67.2% SiO_2, 11.9% CaO, 14.4% Na_2O, 5.0% PbO and 1.5% Sc_2O_3

was found by Messrs. Chance Brothers, Smethwick, to yield glass particles having a density of 2.66. After irradiation the Scandium 46 content of the glass proves an effective label of 84 days half life with the emission of gamma radiation at 0.89 and 1.12 MeV enabling ready underwater detection of the particles.

22. The glass was supplied in irregular fragments for crushing and sieving to the required particle size distribution. Annealing of the glass before grinding ensured that the final particle shape was similar to that of sand. A period of two weeks between removal from the pile and its use in the estuary was allowed for the elimination of short-lived radioactive products, of which Sodium 24 was the dominant component. Three week's irradiation at pile factor 10 gave a Scandium 46 activity of about 10 millicuries/g glass after this short decay period.

23. As interest centred on observing the behaviour of fine sand responsible for the shoaling in the upper estuary, the tracer size distribution was chosen to match the sand typical of the accretion zones rather than the coarser bed sand characteristic of the 11th mile (Fig.4). In general, 62% of the bed material in the vicinity of the 11th mile lay outside the size range of the tracer particles. Therefore the movement of the more mobile tracer cannot be taken as representative of the scale of the bed sand drift at the 11th mile, and can only be regarded as typical of the channel behaviour of sediment that may be destined to reach the upper estuary.

Detection.

24. The radioactivity surveys of the channel bed were carried out with an underwater scintillation counter designed by the Danish Isotope Centre (Ref.1). Briefly, the detector consists of a 3" diameter x 6" NE 102 plastic scintillator and associated electronic units housed in a brass and aluminium cylinder which is held in a protective stainless steel container by layers of soft foam packing. A heavy stainless steel nose cone fixed to the front of the outer casing prevents the detector leaving the bed during towing behind a boat. Half-inch diameter galvanised steel wire rope serves as both tow line and electrical conductor between the underwater probe and the instrumentation on board the survey vessel; the power supply for the probe and the returning signal being passed along a co-axial cable forming the core of the wire rope. A 35 ft fishing vessel, provided by the Port of Preston, was employed for towing the probe over the channel bed at a mean speed of 2 knots, while on board the bed radioactivity was monitored continuously by a logarithmic ratemeter with an output to a pen recorder. The range of the ratemeter covered 5 to 20,000 pulses/s. The position of the boat during the radioactivity surveys was determined by conventional hydrographic methods, using sextant observations on temporary marks erected on the sand banks on either side of the main channel and on the existing navigation beacons. A marker pen on the recorder enabled the position fixing times to be registered alongside the radioactivity trace.

25. Background surveys of the natural radiation in the main channel between the 8th and 14th mile were made prior to the introduction of the tracer material. In addition, some readings were taken on the banks outside the training walls, although the highly canalised nature of the shipping channel made tracer movement into these areas unlikely. The background radioactivity was found to be very variable, presumably as a result of the non-uniformity of bed sediment in this reach. Values were generally between 60 and 170 pulses/s with occasional peaks to 200 pulses/s. Higher values were of more frequent occurrence at the sides of the channel, particularly along the south training wall, but no distinct pattern emerged as a basis for the division of the estuary into zones of differing background. On account of the patchy distribution a very intensive survey would have been required to define the local changes in background activity. This would have been time-consuming, and so readings in excess of the recorded maximum background of 200 pulses/s were conservatively accepted as indicative of the presence of tracer material.

26. A ratemeter time constant of 5s was employed during tracking so that at normal towing speeds the reading corresponded to the mean activity experienced over 15 to 20 ft of travel. As the count was integrated over a period of 5s, the statistical fluctuations arising from the random variation of radiation with time were very small compared with the spatial variation in bed activity and could therefore be neglected. For instance, at a mean background value of 170 pulses/s there was less than a 2.5% probability of the reading at any instant exceeding 180 pulses/s.

27. The response of the detector to known amounts of Scandium 46 activity distributed through various depths of sand has been calibrated in the laboratory. The conditions of detector geometry existing in field practice have been closely simulated by spreading sand/tracer mixtures over an area of 15 ft^2 positioned in the centre of a large basin under 2 ft water depth. Measurements taken within the basin but at positions adjacent to the central active area have enabled the correction of readings to those that would be registered in the case of an infinite surface layer. The calibration showed that if the layer thickness is constant the detector response is proportional to the quantity of tracer present (Fig.5a). However, as tracer is mixed to different depths throughout the surface layers the absorption of radiation within the sand layer, together with the increase in the mean separation between active particles and the detector, leads to a reduction in the count rate (Fig.5b). Thus from Fig. 5 a rise above background of 200 pulses/s corresponds to a tracer density of 0.036 microcuries/ft^2 when spread uniformly through a surface layer 0.08 ft in depth, 0.067 microcuries/ft^2 in a layer 0.33 ft in depth, and 0.11 microcuries/ft^2 in a layer 0.75 ft in depth.

28. The total activity required for the experiment was calculated on the basis of introducing tracer sufficient to increase the background activity

value by 200 pulses/s throughout an area covering the width of the channel over a reach of 5 miles. The sand dune profiles suggested that, in the channel, mixing depths of 1 ft or more were likely; in which case the desired activity rise corresponded to an activity level of 0.15 microcuries/ft^2. Thus a total of 4 curies was necessary to satisfy the above areal considerations.

29. The Ministry of Housing and Local Government and the Fisheries Radiobiological Laboratory of the Ministry of Agriculture, Fisheries and Food were consulted at the planning stage of the experiment and confirmed that any radiation hazards to the general public and marine life would be negligible. However, to avoid undue artificial disturbance of the tracer, fishermen were requested not to drag nets in the vicinity of the 11th mile for the duration of the tests, and no dredging was carried out in the test reach in this period.

INJECTION

30. 400g of tracer particles with a total activity of 4 curies Scandium 46 were loaded into two injection devices at A.E.R.E., Harwell. These devices provided a sealed compartment which could be lowered to the sea bed and opened remotely to allow the tracer particles to deposit on the bed surface. The lead walls of the compartment were inadequate for shielding purposes during transport, so each device was loaded into 17 cwt lead pots to provide a total lead surround of at least 4 inches in thickness. The lead pots were transported to Preston Dock by road and transferred to the boat.

31. For injection the containers were lifted from the lead pots (Plate 4) and, after removal of a plug in the top of the sealed compartment, lowered over the side of the boat until fully submerged. When sufficient time had elapsed to allow thorough wetting of the glass particles the injection devices were lowered and the tracer released about 2 ft above the bed. On lifting (Plate 5), the empty containers were washed, monitored for residual activity, sealed in polythene and returned to the lead pots. All handling in the injection procedure was carried out remotely and no dose exceeding 30 millrontgens was recorded on the radiation film badges worn by the operators. Monitor checks over the boat confirmed that no measurable contamination had occurred as a result of the injection procedure.

32. The injection was carried out in 15 ft of water on the afternoon of 4th September 1964 on the last of the ebb tide over a period of $\frac{3}{4}$ to $\frac{1}{4}$ h before low water. Two positions 170 ft apart and lying on either side of the centre line of the main channel at the 11th mile were seeded with equal amounts of tracer. The predicted high water following the injection was 25.5 ft above M.L.W.S., and the maximum tide of the current spring cycle, occurring four days later, was predicted at 27.9 ft above M.L.W.S.

TRACKING

33. The spatial distribution of the tracer was obtained on a number of occasions over a period of 6 weeks following the injection. A summary of the circumstances and extent of each search in the tracking history follows as a preface to the comments on the net tracer drift given in the discussion section of the report.

After 0 to 1 hour

34. A survey immediately after injection confirmed that the tracer was deposited satisfactorily within a confined area on the bed of the channel. At this stage the immediate injection area was avoided because of the risk of disturbing the very high tracer concentrations with the underwater probe. Runs 400 ft to landward and 1,000 ft to seaward produced background radiation levels. 500 ft seaward of the origin, slightly increased activity values indicated a slight movement of the tracer with the last of the ebb tide.

After 1 day

35. An extensive survey was carried out on the following day, involving more than 40 cross-channel activity traverses to define the tracer distribution throughout a 3 mile reach centered on the 11th mile. Each cross-section gave a maximum activity reading in the deeper central part of the channel, while on either side activities dropped to background. Generally the active band was about 400 ft in width.

36. At the time of the major part of this survey the tracer had experienced two complete flood tides but only one complete and part of one ebb tide. It was not surprising, therefore, that the tracer distribution showed a landward bias with count rates exceeding 500 pulses/s above background being recorded over 4,000 ft landward, but only 2,500 ft. seaward, of the origin. The peak activity recorded on this survey occured at the origin and reached 13,000 pulses/s.

After 2 days

37. After 4 complete tides activity levels were significantly above background throughout the surveyed area which extended from 8,200 ft landward to 8,400 ft seaward of the origin. The landward extent of the 500 pulses/s above background zone had however receded to 3,000 ft while its seaward front remained virtually unchanged.

After 3 days

38. The onset of rough weather curtailed tracking to a reach extending 4,000 ft on either side of the origin. Activity levels were generally reduced as compared with the previous day.

39. Tracking was then abandoned for several days on account of heavy wave action in the outer estuary. Consequently, successive tracer distributions were not obtained to cover the peak of the spring tides.

After 6 days

40. After 6 days a further survey was possible and revealed a drastic reduction

in channel activity. No activities in excess of 220 pulses/s above background were recorded throughout the reach. The immediate injection zone was closely scanned for higher radiation levels, but without success.

After 18 days

41. A survey undertaken with the expectation of showing tracer dilution to concentrations beyond the sensitivity of the detector surprisingly revealed the reappearance of considerable quantities of tracer throughout a reach extending a mile both upstream and downstream of the 11th mile. At this time the peak activity level of all surveys was recorded; being greater than 20,000 pulses/s at about 250 ft landward of the origin.

42. It seems highly probable that the observed increase in activity was due to the late release of tracer which at the time of the 6 day survey was largely buried beyond the detectable range of the underwater probe.

After 45 days

43. A check on the channel activity between the 10th and 13th miles failed to reveal any significant amounts of tracer after 6 weeks. Activity values slightly in excess of the background figure of 200 pulses/s were still present in the injection area, but the longitudinal activity gradient was too flat to yield any indication as to the direction of the net drift.

After 47 days

44. The highly diffuse nature of the tracer distribution evident after 45 days was confirmed two days later. Spring tides were running in the interim, so that the associated increased bed movement favoured the release of hitherto buried tracer. It was concluded therefore from the general absence of significant activity levels demonstrated by the last two surveys that the tracer had dispersed to such an extent that further tracking was not worthwhile.

PRESENTATION OF RESULTS

45. All surveys showed the activity confined to a narrow zone about 400 to 500 ft in width lying along the channel. The survey after 2 days (Fig.6) illustrates the containment of the tracer within the width of channel lying between the training walls. On account of the absence of lateral dispersion beyond the walls, the chart method of presenting the tracer distribution has been discarded for the other surveys in favour of a more straightforward plot of the activity gradient along the channel. Using the activity trace from the recorder, marked with a distance scale given by the plotted boat positions, each transverse run has provided a value for the total radiation at the distance (X) from the origin by integrating the activity across the channel width (Fig.7).

$$\text{total radiation per unit length} = \int_0^\infty r\,dz$$

where r = measured activity corrected for background and decay;

dz = elemental width of channel.

In those instances where the run was not normal to the line of the channel, the distance (X) from the origin is taken for the centre of the active zone and the total radiation per unit length become $\cos\alpha\int_0^\infty r\,dz$, where α is the angle of departure from the normal. The integral values have been plotted against distance from the origin in both the landward and the seaward directions (Fig.8).

DISCUSSION

46. Once deposited on the bed of the channel, tracer particles are dispersed up and down the channel in response to the prevailing flow processes, so that at any time the spatial distribution of tracer represents the integrated effects of all conditions of flow experienced since the start of the experiment. For an idealised case of sediment moving in a uni-particle layer over a fixed bed, the direction and magnitude of net drift could be readily derived at a given time from the position of the centroid of the distribution with respect to the origin. In practice, however, the bed is not fixed and the problem is made more complex by the vertical mixing of the tracer particles throughout the upper layers of the bed. The vertical mixing of the particles has considerable bearing on the interpretation of the tracer results, and so it is appropriate to include a few general remarks regarding the physical processes involved before proceeding to a discussion of the measured distributions.

47. Sand particles normally move either in suspension, supported by the water, or by surface creep, supported by the underlying stationary bed particles. Considerable interchange occurs; any individual particle will move sometimes by surface creep, sometimes in suspension, and sometimes it will be stationary. A bed particle's mode of travel at any moment is dependent on its position and the local hydraulic circumstances occuring at the loose boundary at that instant. Thus, an important characteristic of sediment movement is the intermittent nature of a particle's progress in the flow direction. Even those particles travelling in suspension may return to the bed and be trapped by burial beneath other particles. Therefore any particle's advance is interrupted by rest periods during which the particle is stationary until it is subsequently re-exposed and subjected to flow capable of transporting it. The length of the rest period is a function of the depth of burial, so that with time, as the tracer particles mix through the bed, the mean rest period increases and the probability of

tracer movement decreases.

48. If it is assumed that sediment movement cannot occur below the surface particles, the depth to which the tracer particles penetrate is largely determined by the form of the bed irregularities. In the case of the Ribble, a dune configuration has been confirmed and it is probable that ripples co-exist with the dunes. Ripples for sand of this particle size are normally 0.1 ft in height and 0.8 ft in wavelength and would therefore have been too small for detection on the echo-sounder records. The propagation of the larger dune forms is largely achieved by the ripple movement. On account of the difference in size between the two bed forms, the rate of ripple movement can be expected to exceed that of the dunes by a large factor. The vigorous stirring action that particles experience in the rippled zone will result in the mixing of the tracer throughout the surface layers of the dunes very shortly after deposition of the tracer. Mixing to greater depths will not be long delayed, as the reversal in dune profile that occurs with the change of tidal direction (Plates 2 and 3) will enable particle interchange throughout the greater part of the body of a dune even if no translation of the dune form takes place. If, on the other hand, the dune is propagated, the tracer will mix quickly throughout the bed layers down to mean dune trough level and will ultimately approach a depth of mixing corresponding to the levels of the deepest troughs in a manner analogous to that described by Crickmore and Lean (Ref. 2) for the case of mixing in a rippled bed layer.

49. The sensitivity of the detector, i.e. its response in pulses/s for a given quantity of tracer per unit area, decreases as the tracer is spread throughout sand layers of increasing thickness, on account of the absorption of radiation by the overlaying sand. This detector property can be employed to obtain the mean depth to which tracer is mixed throughout the area of its spread. The measured detector sensitivity (K) can be calculated from

$$K = \frac{1}{A}\int_0^\infty dx \int_0^\infty r dz$$

where $\int_0^\infty dx \int_0^\infty r dz$ = area under the activity distribution curves;

A = total activity injected;

and the corresponding thickness of uniform mixing (θ) read from the calibration curve (Fig.5b).

50. In the present case a large tolerance on the calculated value of θ must be allowed in view of the uncertainty of the extrapolation to $x = \infty$ to include the head of the tracer movement in either direction. The first complete survey, i.e., one day after injection, gave $\theta = 1.0$ ft and after three days $\theta = 1.5$ ft. These values indicate that mixing was rapid, with tracer penetrating to a mean depth slightly in excess of mean dune trough level in less than two tidal cycles. However, at a very early stage the tracer would have been present largely in the uppermost layers of the bed and highly vulnerable to movement. As the tracer was deposited on the bed surface close to low water,

the flood tide initiated the mixing process and at the same time transported tracer particles landward. The following ebb tide, even if it had identical hydraulic characteristics, would not have been able to effect an equivalent translation of the tracer, because the mean depth of mixing would have been greater than that operating throughout the first flood tide. Therefore, the timing of the injection biased the experiment in the flood direction and all tracer distributions bore the effects of this initial landward advantage.

51. The high mobility of the bed sediment was demonstrated not only by the rapid mixing with the bed layers, suggesting large scale dune movement, but also by the actual shape of the measured tracer distributions. Within 30 minutes of injection the low velocities on the last of the ebb transported measurable amounts of tracer to 500 ft from the origin. By the time of the first complete survey it is estimated that about 50 per cent of the injected tracer had travelled to positions lying outside a 2 mile reach centred on the injection sites. This high mobility resulted in flat tracer concentration gradients. The centroid for the tracer distributions could not be located precisely because of the sensitivity of the centroid determination to the form of the extrapolation necessary to define the head of the movement. Thus it has not been possible to estimate the net tracer drift from the positional shifts of the average tracer particle. However, by comparing the relative amounts of tracer lying to landward and seaward of the origin for the various surveys (Table 3) the net drift was apparently small.

Table 3: Net Tracer Drift.

Survey	Percentage of Total Tracer		Position of Maximum $\int_0^\infty r\,dz$
	Landward	Seaward	
After 1 day	78	22	300 ft landward
" 2 days	48	52	300 ft landward
" 3 days	62	38	200 ft landward
" 18 days	60	40	300 ft landward

52. The proportions recorded on either side of the origin remained virtually unchanged from 3 days to 18 days at values which seem no more than relics of the initial landward bias given by the circumstances of the injection.

53. Hubbell and Sayre (Ref.3) have demonstrated that the velocity of the maximum is sensibly the same as that of the centroid of a tracer concentration distribution apart from a short period following injection. The position of the maximum $\int_0^\infty r\,dz$ along the channel (Table 3) has been defined by the overall activity gradients neglecting any traverses in the immediate injection area, where localised patches of high tracer concentration could give untypical peak values. The constancy of the maximum activity position confirmed the absence of any pronounced sediment drift.

54. The freshwater discharge of the river throughout this period was generally low. The mean flow for the first 6 days of the experiment averaged 280 cusecs, rising to 800 cusecs over the following 12 days, with a peak daily discharge of nearly 1800 cusecs on the 13th day after injection. There is no doubt that the low river conditions at this time would have favoured the landward drift of sediment in the upper estuary. The tracer results suggest that the 11th mile channel reach lies beyond the sector that experiences seasonal shifts of sediment.

55. The general diminution of activity that characterised the survey after 6 days, and its subsequent reappearance as demonstrated by the survey after 18 days, call for some comment. A possible explanation is that the wave action following the survey after 3 days encouraged the movement of material from the adjacent banks to give accretion in the channel and consequent burial of the tracer particles. An inactive sand layer at least 0.5 ft thick would have given the necessary reduction in measured activity levels. Subsequent dispersion of the fresh sediment along the channel with a return approximately to the earlier bed levels would have led to re exposure of the tracer. It was hoped that the longitudinal profiles of the channel surveyed by the Port of Preston at 2-week intervals throughout the past year would serve to confirm this suggested inflow of sediment from the banks. Unfortunately, the relevant survey (September 14th) that might have confirmed accretion in the channel at the 11th mile was abandoned at the 9th mile owing to adverse sea conditions in the outer estuary.

CONCLUSIONS

56. It is evident that a major change in the hydraulic processes governing sediment behaviour in the Ribble Estuary occurs in the neighbourhood of the 9th mile. Landward of this position the bed consists of fine sand; the freshwater discharge has a considerable effect on the balance of water velocities between flood and ebb tides; and marked seasonal shifts of sediment occur. On the other hand, to seaward the bed sand is noticeably coarser, the river flow influence is greatly reduced and by the tracer experiment no pronounced shift of sediment has been revealed at a time when conditions were conducive to landward movement in the upper estuary. It is concluded therefore, that the outer estuary does not experience the seasonal shifts of sediment that characterize the more landward reaches, and bed levels in the region of the 11th mile are controlled mainly by tidal and wave action with freshwater flow changes having little effect.

57. The tracer particles were designed to simulate the sediment characteristic of the accretion areas of the upper estuary. The absence of a strong

directional net drift in the dispersion of tracer at the 11th mile suggests that the material that is at present being dredged between the 1st and 6th miles is not supplied by the transport of sand entering the channel at the mouth of the estuary in the vicinity of the 14th mile. If this had been the source, the channel would need to exhibit a net flood drift throughout its entire length in order to bring about the eventual deposition of sediment in the upper reaches.

58. The sandbanks of the outer estuary provide an alternative source of sand supply. The deeply encised channel is a natural trap for material moving from the banks that lie north and south of the channel. Wave action can disturb the outer banks for the flood to sweep the sand into the channel, where the deeper water precludes any compensating movement on the ebb. Once in the channel, the high mobility of the bed, as demonstrated by the radioactive tracer dispersion, will ensure a rapid distribution of the fresh sediment throughout the channel length. The experiment indicates that any material swept into the channel from the banks at the 11th mile will be distributed equally to landward and seaward.

59. The penetration of sand from the banks will be most effective in those areas where the low training walls are breached or overtopped. Analysis of the longitudinal channel profiles may suggest the most probable areas of sand entry. Surveys made shortly after heavy wave action and before sufficient time elapses to effect the redistribution of the fresh sand may display local accretion at the critical positions. The lack of net flood drift and the general stability of bed levels at the 11th mile suggests that with the estuary in its present state the most serious sand influx occurs to landward of the 11th mile.

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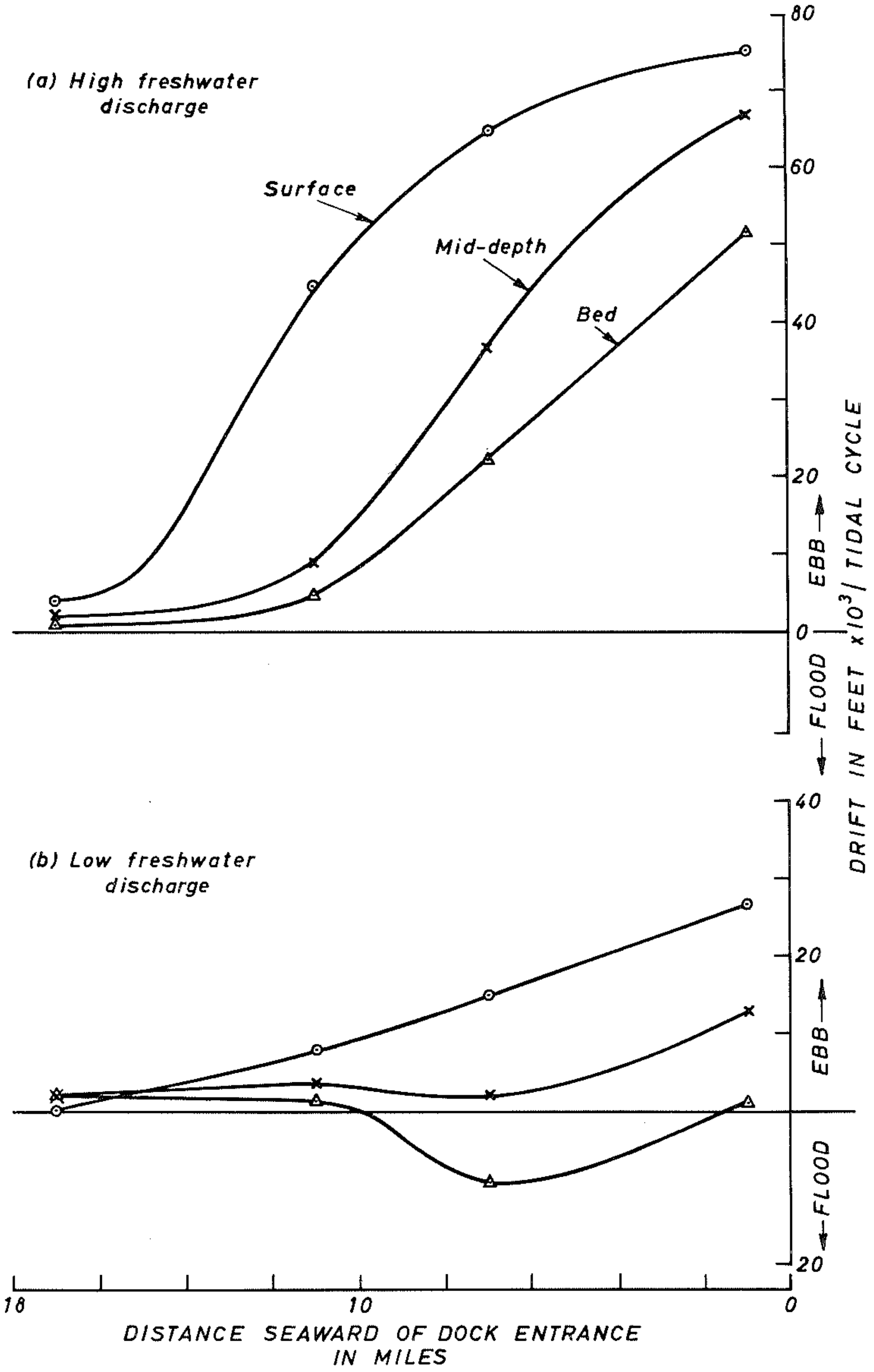
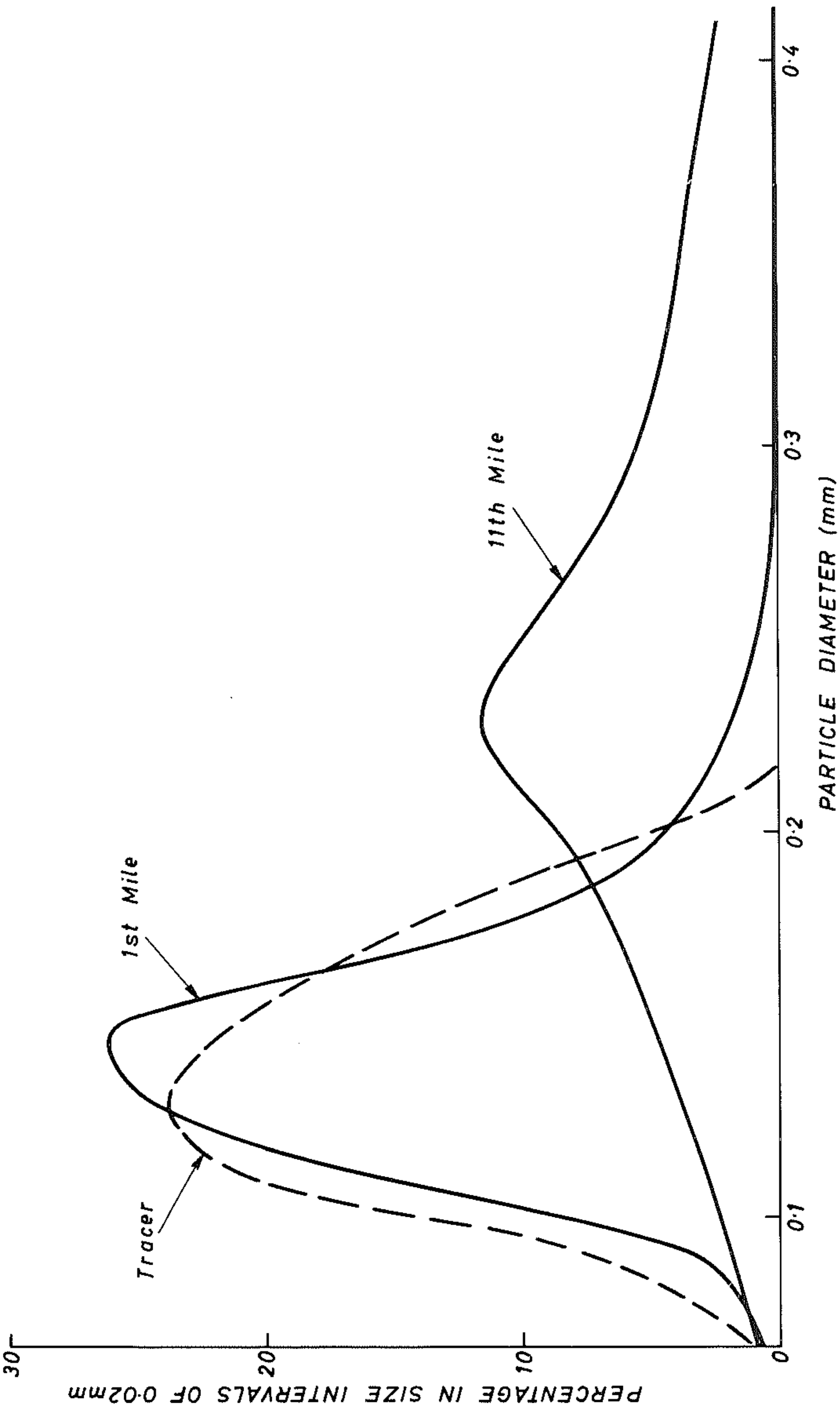
2. Crickmore M.J. and Lean G.H. "The measurement of sand transport by means of radioactive tracers". Proc.Roy.Soc.A., 266, 1962, 402-421.
3. HubbellD.W. and Sayre W.W. "Sand Transport Studies with Radioactive Tracers" Proc.American Soc.Civ.Eng.Hydraulic Div., Vol. 90, No. HY3, Part 1 1964.



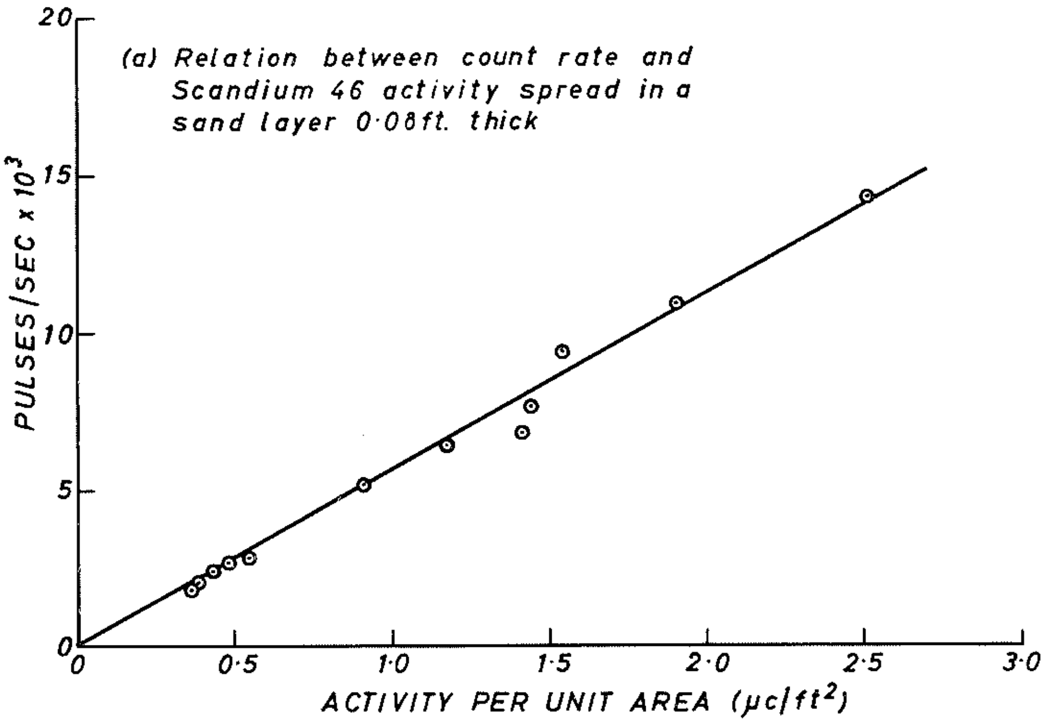
LINEAR DRIFT PATTERN

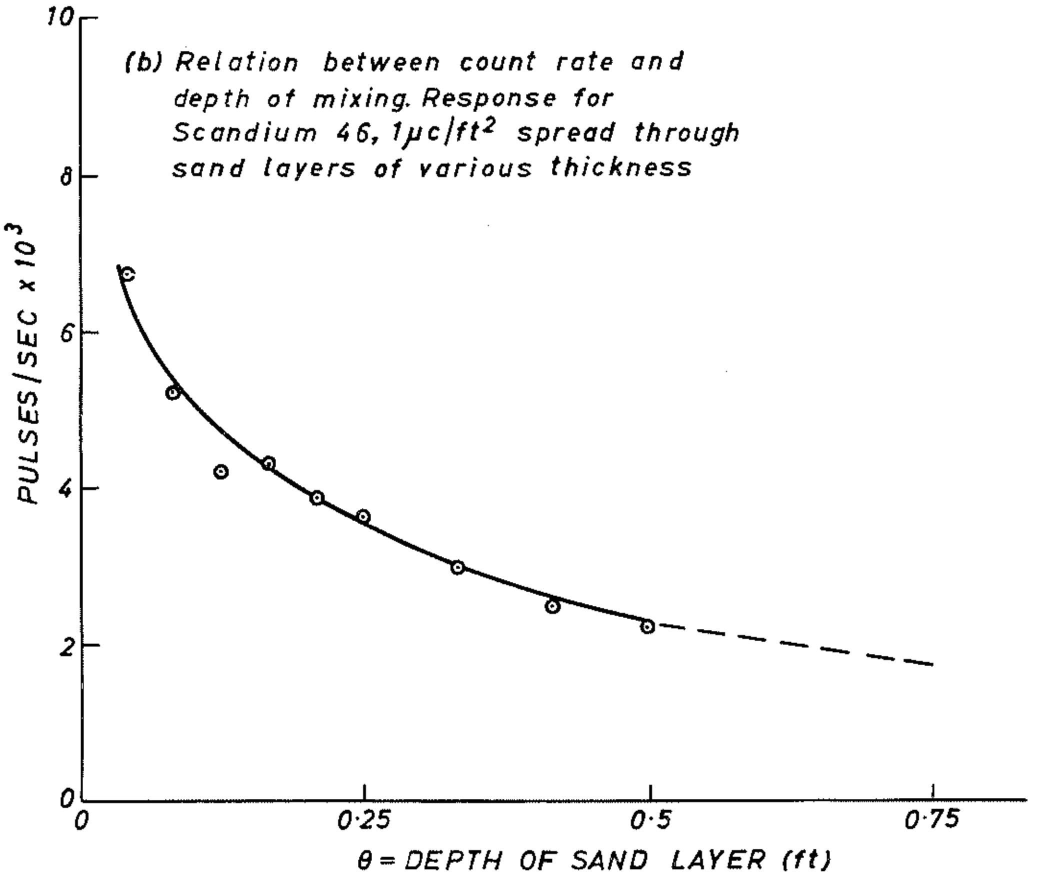
FIG 3



PARTICLE SIZE DISTRIBUTIONS

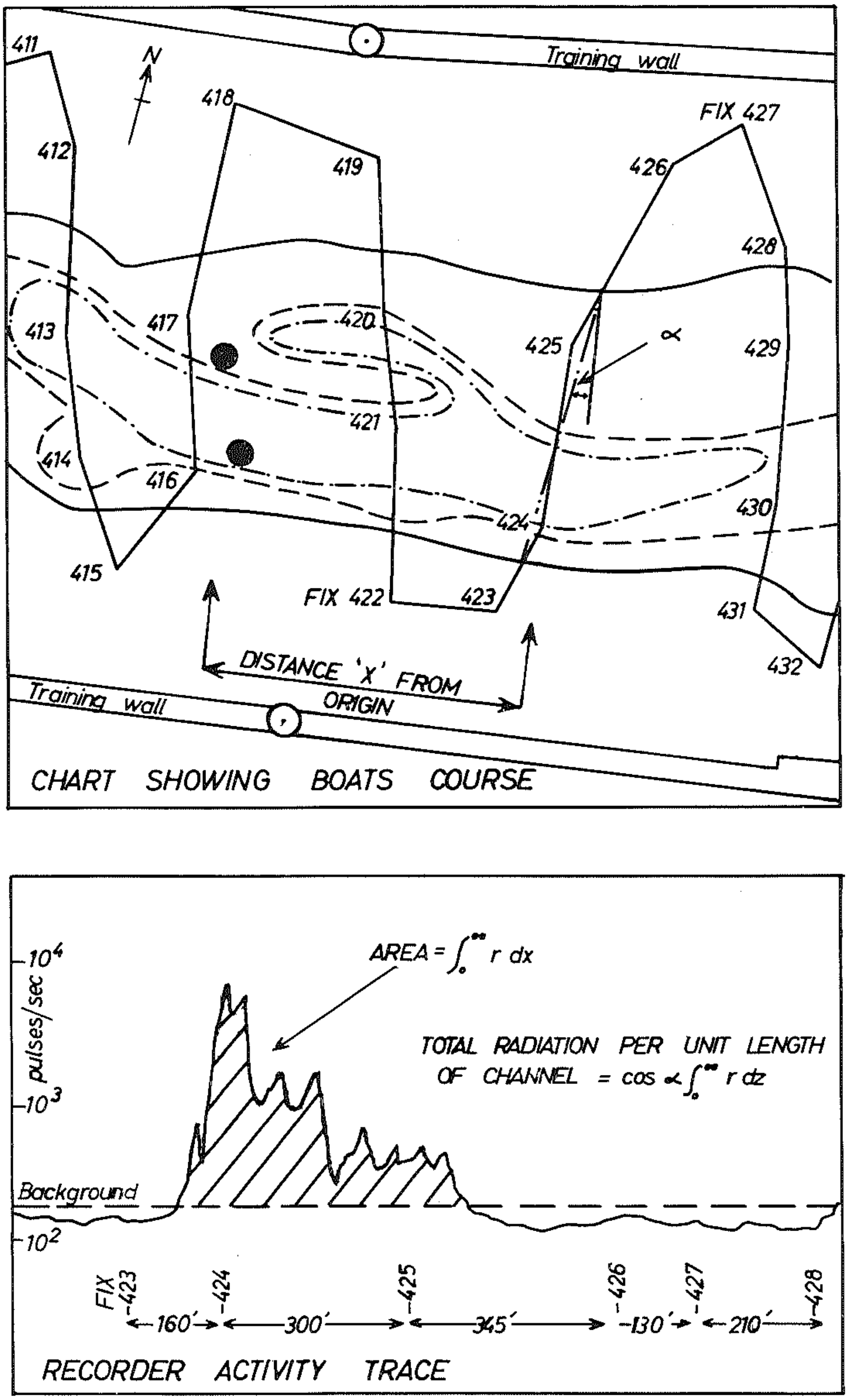
FIG 4


(a) Relation between count rate and Scandium 46 activity spread in a sand layer 0·08ft. thick


(b) Relation between count rate and depth of mixing. Response for Scandium 46, $1\mu c/ft^2$ spread through sand layers of various thickness

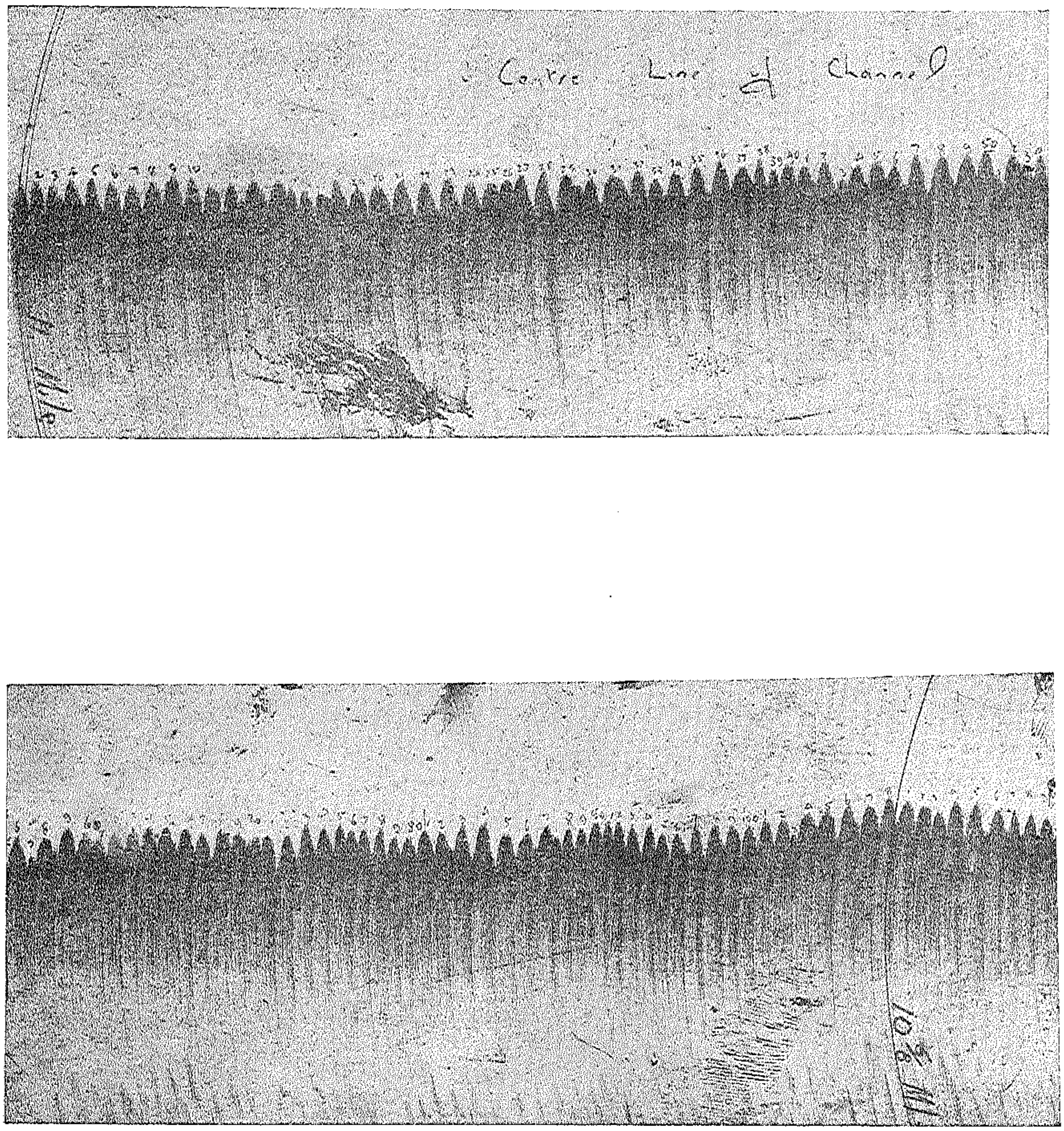
DETECTOR CHARACTERISTICS

FIG 5



DERIVATION OF TOTAL RADIATION PER UNIT LENGTH

FIG 7



Ft 0 10 Ft

Vertical Scale

Ft 0 200 Ft

Horizontal Scale

PLATE 1. Sand waves - longitudinal profile

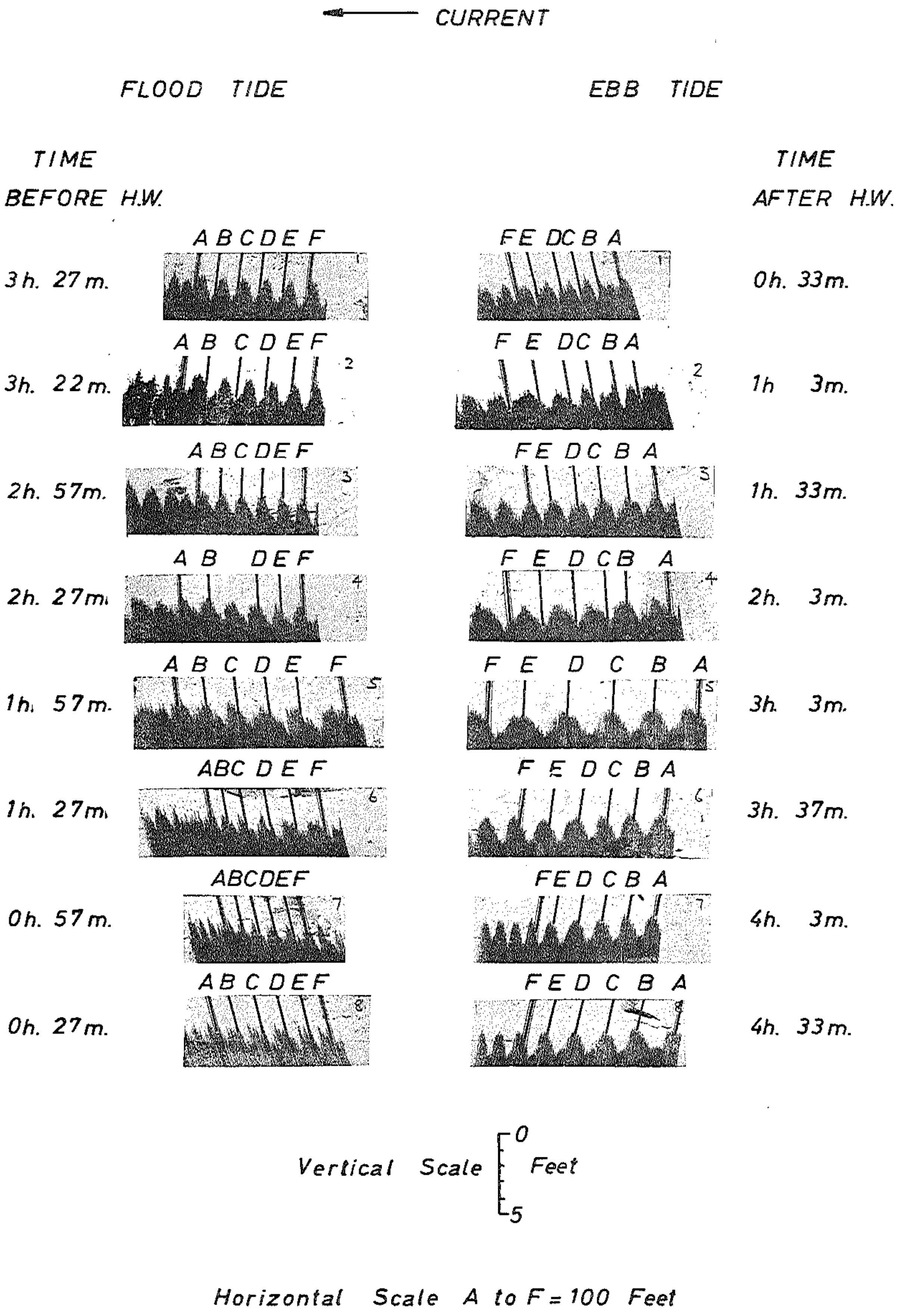


PLATE 2. Movement of sand waves in the Ribble Estuary

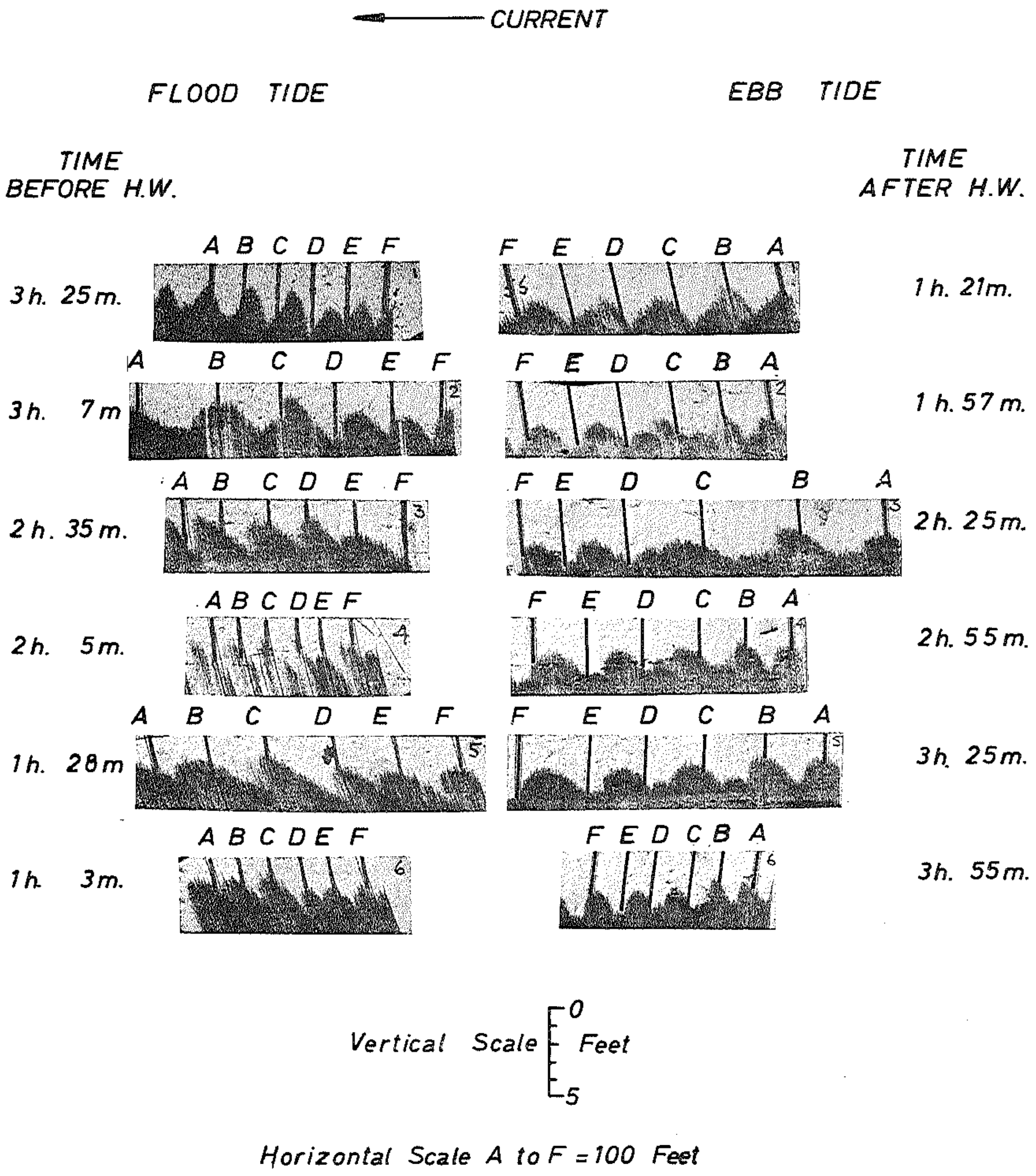


PLATE 3. Movement of sand waves in the Ribble Estuary

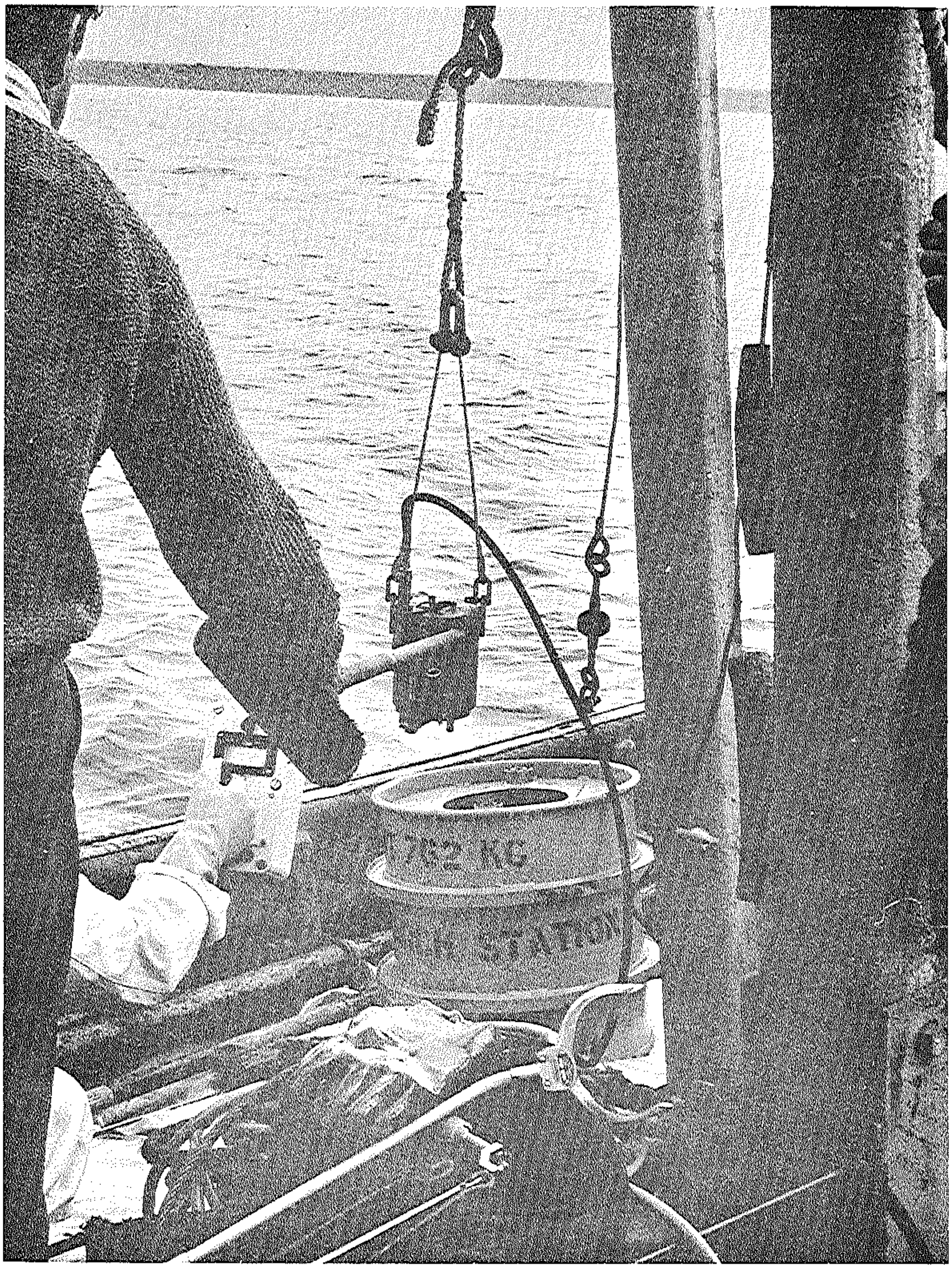


PLATE 4. Radioactive tracer injection - before dumping

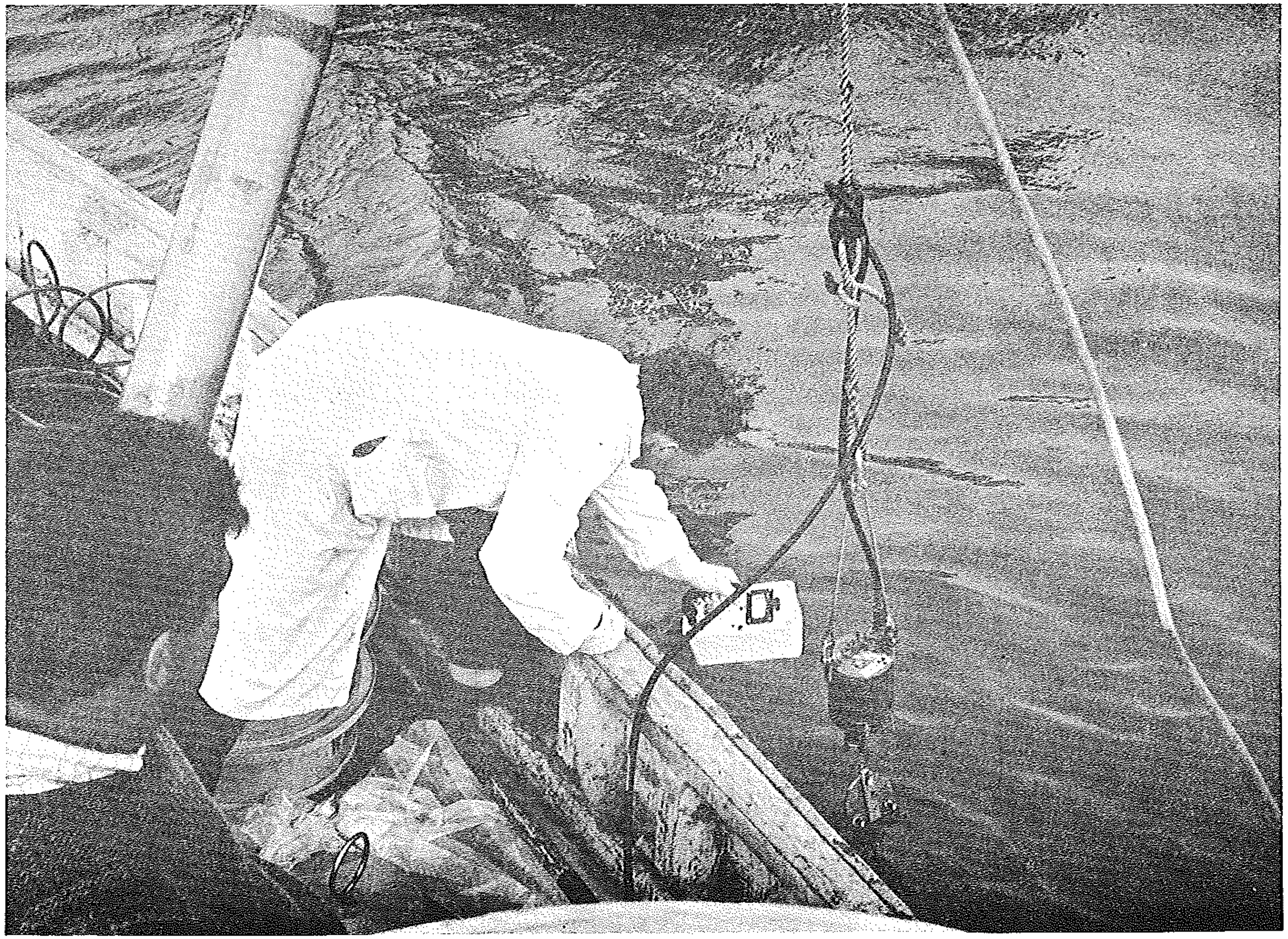


PLATE 5. Radioactive tracer injection - after dumping