# Interactions Between Marine Benthic Macroinvertebrates And Their Sedimentary Environment

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# GENERAL SUMMARY

(1) Three transect lines have been established at Ardmore Point, a site on the North Eastern shore of the Clyde estuary, approximately 20 miles from Glasgow. Each transect runs from High Water Neaps to Low Water Neaps.

The positions of the transects have been fixed and their level profiles determined, using standard surveying techniques. Sample sites have been positioned at 60 yard (54.864m) intervals down one of the transects, Sites on the other two, have been located at positions corresponding with the levels of High Water Neaps (HWN), Mid-Tide (MT) and Low Water Neaps (LWN).

(2) At each of the sample sites the following six physico-chemical properties of the sedimentary environment have been measured.

i) Sediment Particle Size Distribution.
ii) Sediment Organic Matter Content.
iii) Sediment Shear Strength.
iv) Sediment Redox Potential.
v) Sediment Interstitial Water Salinity.
vi) Level of the Water Table relative to the Sediment Surface.

The measurements have been taken at five depth intervals to a maximum depth of 22.5cm in Summer and Winter.

It has been shown that these properties vary, often in a uniform way, down the shore and within the sediment profile. This phenomenon has been interpreted as being indicative of a number of factors including:

(a) Origin of the sedimentary material.
(b) Current and Wave generated sorting of the sediment.
(c) The influence of surface and subsurface run-off from the adjacent land.
(d) Tidal cycle effects.
(e) Biological effects.

(3) Macroinvertebrate abundance has been determined using the same sampling pattern as in (2). Three techniques

have been used to estimate abundance:

Technique 1 - Faecal Cast counting to estimate the abundance of polychaete, Arenicola marina.

Technique 2 - Core samples in conjunction with a purpose built extraction apparatus to determine the abundance of the tube-dwelling polychaetes Pygospio elegans and Fabrica sabella.

Technique 3 - Core samples in conjunction with hand-sorting to determine the abundance of the remaining invertebrate species.

Species sampled using these techniques have been identified as belonging to the Macoma balthica community described by Barnes (1974) and others.

The distribution patterns of the species have also been examined and interpreted with regard to the influence of environmental factors. Three characteristic distribution patterns have been identified down the shore:

(a) Widely distributed species.
(b) High Water to Mid-Tide species.
(c) Mid-Tide to Low Water species.

Similar patterns have also been identified within the sediment profile.

(a) Species present throughout the full sampling depth.
(b) Surface species.
(c) Sub-surface species.

The community is generally most diverse towards High Water and at the sediment surface. The number of individuals within the community follows a similar pattern.

(4) The results of (2) and (3) have been analysed sep~rately and in combination using a Factor Analysis technique - Principal Components Analysis (PCA). This has enabled sub-groups of correlating variables to be identified.

Within the physico-chemical group of variables, the following sub-groups have been identified:

(1) General sediment properties.
(2) General sediment properties.
(3) Sediment Sorting properties.

(4) Sediment Strength properties.

(5) Sediment Nutrient status.

A similar analysis of the species data has confirmed that the species can be grouped on the basis of their distribution patterns as follows:

(a) Widely distributed species.

(b) High Water to Mid-Tide species.

(c) Mid-Tide to Low Water species.

Of the ten sediment variables under consideration, the following six are identified as being significantly correlated with the distribution patterns of one or more species:

(1) Mean Particle Size.

(2) Particle Size Standard Deviation.

(3) Particle Size Skewness.

(4) Particle Size Kurtosis.

(5) Sediment Peak Shear Strength.

(6) Sediment Interstitial Water Salinity.

For the community as a whole, Total Animal and Total Species numbers are correlated with sediment Redox Potential, Shear Strength and Sample Depth. Total Animal numbers are also correlated with Particle Size,Standard Deviation and Organic Matter Content.

(5) An experimental Seawater Flume has been designed, constructed, calibrated and tested. The Flume Trough has an effective width of 30cm and maximum flow-depth of 25cm. A 30cm square box core can optionally be located in the bed of the trough.

Equipment, capable of measuring flow-rates and velocities in the following ranges has also been designed, constructed and calibrated:

Flow-Rates = 0 to $0.025m^3/s$.

Flow-Velocities = 0 to 0.525 m/s.

The errors in these measurements have been analysed. Errors in Velocity measurement range between less than 2.5% at High velocities and 30% at very Low velocities.

Errors in Flow-Rate measurement are higher at between 4.5% for shallow, High flow-rates and 43% for deep, Low flow-rates.

(6) The Flume described in (5) has been used to investigate the effects of one organism - Arenicola marina on Sediment Stability/Resistance to Erosion.

Arenicola marina has been shown to modify the properties of the sediment, rendering it more resistant to erosion than the surface of the parent material. A number of possible mechanisms by which this is achieved are suggested. These mechanisms are:

(a) The addition of mucopolysaccharide or glycoprotein binding agents by A. marina.

(b) The build-up of microbial metabolites similar to those described in (a).

(c) Compaction of the sediment structure by pressure exerted on the sediment during its passage through the gut of A. marina.

(d) Reduction in the sediment moisture content as a consequence of water absorption in the gut of A. marina.

The significance of the enhanced stability is discussed in relation to traditional abiotic concepts of sediment erosion and transport.

# GENERAL INTRODUCTION

The intertidal zone represents the transition between the estuarine/marine and the terrestrial environments. In physico-chemical and biological terms it is of considerable importance to both. It acts as a sink for substances contained in surface runoff, and as a consequence, a source of these substances to the oceans. It serves as a buffer, absorbing much of the tide and wave energy of the sea before it reaches the land. Finally, it provides food sources which can be exploited by visiting species from the other environments.

Organisms living within this zone are confronted with a range of complex and potentially hostile environmental conditions. The sedimentary substrate encompasses a range from coarse, mobile particles on oceanic beaches to sheltered mud flats in shallow estuaries. Such substrates vary in particle size, mineralogy, bulk properties, organic matter content and oxygen availability. High wave energy generated by storms rendersthe habitat liable to severe physical disturbance. In addition, tidal oscillations in water level result in large variations in water availability and surface temperature. In ecological terms, any number of these environmental properties may operate, singly or in combination on a species. Any consideration of the relationship of organisms to sediments is therefore, complex.

To date, most of the work published on organism/sediment relations has focused on relationships between the distribution of the benthos and physico-chemical properties of the sedimentary environment, (Meadows and Campbell, 1972; Gray 1974). However, the activities of benthic organisms also modify the properties of the sediments. This latter aspect has been less extensively worked on, (Aller, 1978; Lee and Swartz, 1980). In setting the objectives of the experimental work for this thesis I have considered both aspects.

(A) Relationships between the distribution of the benthos and physico-chemical sediment features have been investigated using a Factor analytical technique - Principal Components Analysis.

The raw data for the analysis has been collected during a field survey at a site on the north eastern shore of the Clyde estuary in Scotland. The site, known as Ardmore Point is located approximately 20 miles from Glasgow at grid reference 55° 58' 23" N, 4° 41' 7" W. The survey has been conducted at sites along three transect lines, each of which runs from above High Water Neaps to below Low Water Neaps.

At predetermined positions along the transects, six physico-chemical sediment related features have been measured in summer and winter. These properties are:

i) Sediment particle size distribution
ii) Sediment organic matter content
iii) Sediment shear strength
iv) Sediment redox potential
v) Sediment interstitial water salinity
vi) Level of the Water Table relative to the sediment surface.

The distribution and abundance of the associated macroinvertebrate fauna has also been determined using the same sampling pattern.

The resulting data has initially been considered independantly. It has then been subjected to the Factor Analysis using computing facilities at the University of Glasgow.

Similar studies to the above have been reported by Cassie and Michael (1968), Hughes and Thomas (1971a, b) and Hughes et.al.(1972). The results presented in this thesis represent a significant advance: correlations have been identified between <u>and</u> within physico-chemical and faunal variables. A number of new correlations have also been identified.

(B) In controlled laboratory experiments, modifications by an abundant intertidal organism - the polychaete <u>Arenicola marina</u> - to a sediment property - stability/resistance to erosion - have been investigated.

<u>A. marina</u> ingests sediment in the process of feeding and after passage through its gut deposits it as a faecal whorl (cast) on the sediment surface. With <u>A. marina</u> densities frequently above 30-40/$m^2$, this material may cover virtually

the whole sediment surface.

A seawater Flume Tank, designed and constructed by myself, has been used to produce predictable and measurable flow conditions over the surface of a sediment sample. Velocity profiles measured over the sample have been used, in conjunction with fluid dynamics theory, to calculate bed shear stresses. In this way bed shear stresses at the onset of sediment surface breakdown have been calculated for samples with and without the presence of the casts. The only work directly related to this appears to be by Eckman et.al.(1981) which is discussed on Page 238.

* * * * * * * *

In presenting my results the following format has been adopted -

The thesis is divided into six sections -

<u>Section</u>

1 - Topographic survey of Transect Lines and positioning of the sample sites.

2 - The measurement of selected physical and chemical sediment features down the transects.

3 - The measurement of macroinvertebrate abundance down the transects.

4 - Multivariate analysis of the selected physico-chemical sediment features and the associated macroinvertebrate fauna.

5 - The design, construction, testing and calibration of the seawater Flume.

6 - The influence of the marine polychaete *Arenicola marina* on sediment stability/resistance to erosion.

Each section is self contained with Introduction, Materials and Methods, Results and Discussion, subsections. Relevant literature is cited and discussed within each section. As a consequence, to avoid repetition, the information contained in this General Introduction has been kept to a minimum.

# SECTION 1

## TOPOGRAPHIC SURVEY OF TRANSECT LINES AND POSITIONING OF SAMPLE SITES

# INTRODUCTION

Transect lines are often used as a basis for ecological studies on intertidal shores, (Wieser 1959, Dale 1974, Bloom et.al. 1972, Ott et.al. 1976, Anderson et. al. 1981.) Their use combines some of the advantages of two other frequently used methods:-

(a) Random Sample Site Positioning.

(b) Selective Sample Site Positioning.

The advantages of transect lines are:-

(i) The Sample sites can be positioned randomly or selectively along them.

(ii) The line can be positioned to optimize or minimize environmental variation.

(iii) The Sample sites can be accurately located and relocated along the line.

A further refinement - Surveying the line - confers an additional advantage.

(iv) The Sample sites can be accurately located geographically and their positions determined relative to tidal levels. There are however, two major disadvantages to this refined technique:-

(i) It requires specialized equipment.

(ii) It requires a high level of expertise.

Fortunately both requirements were available for this project. The technique has therefore, been used to establish three transect lines running from above High Water Neaps to below Low Water Neaps at Ardmore Point. All sampling and experimental work for the first four sections of this thesis has been carried out at selected sites along these lines.

## MATERIALS, METHODS

### (A) Establishing The Transect Lines

The three transect lines were established on the following dates:-

| Transect Line | Date Established | Height of Low Water |
|---|---|---|
| A | 23. 2. 82 | 0.3m |
| B | 2. 2. 82 | 1.0m |
| B | 1. 3. 82 | 0.6m |
| B | 10. 3. 82 | 0.2m |
| C | 22. 2. 82 | 0.5m |

The position of the lines was decided upon by inspections on site. 'A' and 'B' were chosed to represent conditions prevailing upstream and downstream of the Ardmore outcrop. 'C' was chosen to represent a typical profile away from the outcrop.

The origins of the lines were located close to the shore above the High Water Mark and their approximate position fixed with 40mm square x 300mm long wooden stakes driven into the ground. Precise location was achieved by driving a nail into the top of the stakes. The head of the nail was used as the fixed reference point in all subsequent survey work.

Spatial location of the fixed point was achieved using a triangulation method. A Theodolite (Vickers Instruments, England) Theodolite No. V22549 - Plates 1 and 2 was set up over the fixed reference point and the angles subtended between a fixed object, the fixed reference point and another fixed object measured to the nearest second of arc. (See Appendix 'A' for technique of setting-up and using Theodolite.) The corners of buildings were used as the fixed objects. They were chosen because they are readily discernable, have their position fixed on Ordnance Survey Maps, and are relatively permanent features. The angles subtended by the fixed reference points and three such objects were measured in this way.

Having determined the position of the fixed reference points, the transect lines were then established.

PLATE 1

The 'Vickers Instruments' Theodolite Used For Setting-out the Three Transect Lines.

PLATE 2

This shows the Instrument Mounted upon its Tripod.

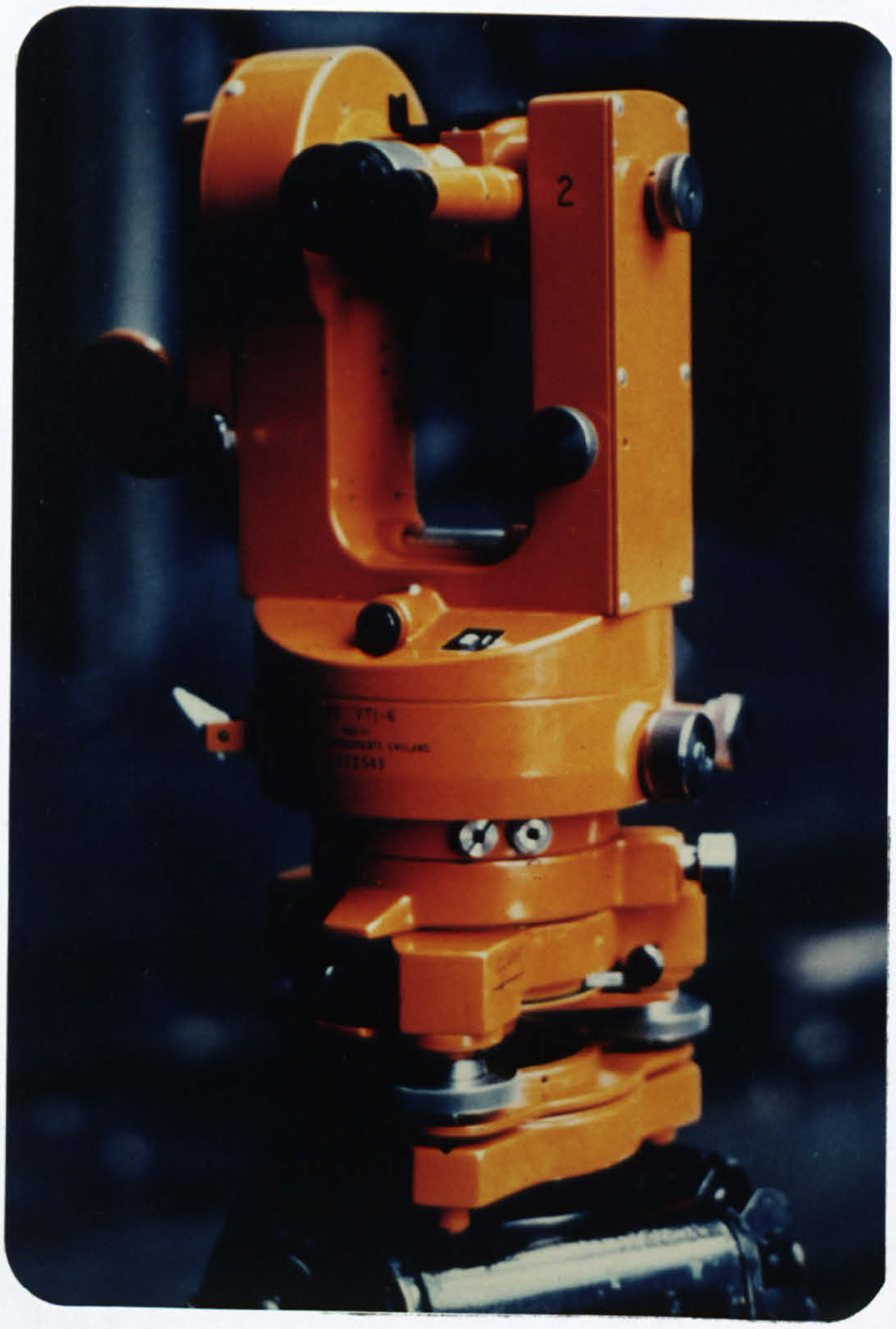



Plate 1.

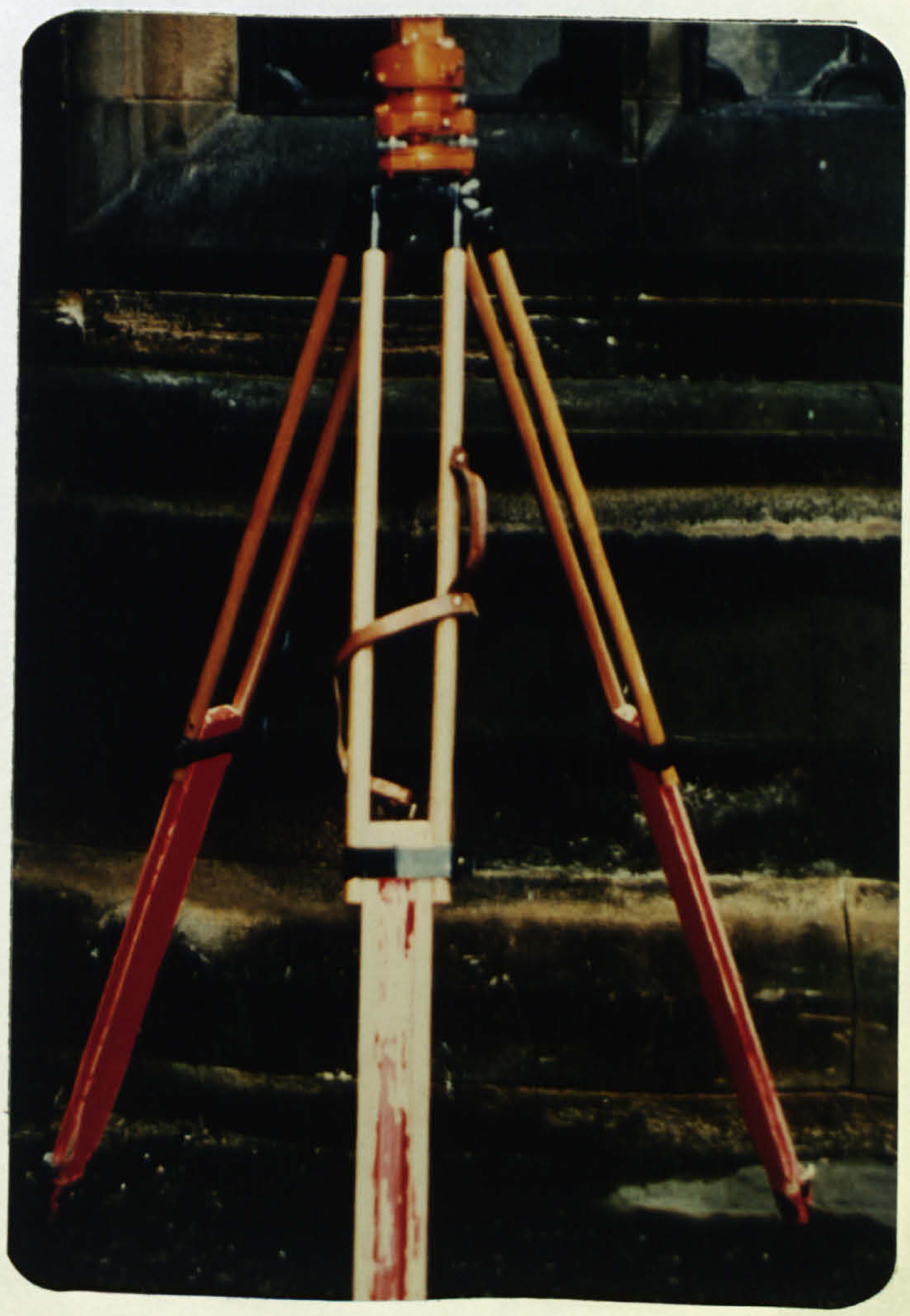


Plate 2.

A Ranging Rod (Plate 3 ) was positioned along each line at a distance of 100 yards (91.4m) from the fixed reference point. The position of the line was then located precisely by measuring the angles made between this line (Ranging Rod to fixed reference point) and the fixed objects used previously.

The above method provides a very accurate means for initially locating the line. For routine restablishment of the line however, it suffered from two major drawbacks:-

(i) The method was time consuming - each line requiring 15-20 mins. to establish.

(ii) The method is dependant on sophisticated equipment which was not always readily available.

A simpler technique was therefore required. Two such techniques were tried:

(a) Using the compass bearing of the line from the fixed reference point - the compass bearing of the line was determined using a surveyors compass (Plate 4 ) relative to the fixed reference point. Ranging Rods were then set out at intervals along the line on the same bearing.

Sighting errors were quantified by the following experiment:

The position of the line was set using the compass. The deviation from the true position of the line was then measured at a distance of 100 yards (91.4 metres) from the fixed reference point. This procedure was repeated 20 times and the results then analysed statistically.

(b) Using stakes permanently located along the transect line - stakes 30mm Dia. x 850mm long were driven into the sediment at distances of 150 and 300 yards along the transect line from the fixed reference point, approximately 100mm was left protruding.

The line of the transect was then determined by sighting between and beyond these fixed markers.

This method was faster than either the original or (a) and was subsequently used. However, it was

PLATE 3

A Typical Ranging Rod Used For Setting-out The Transect Lines.

PLATE 4

The Surveyors Compass Used For Setting-out The Transect Lines.

Plate 3

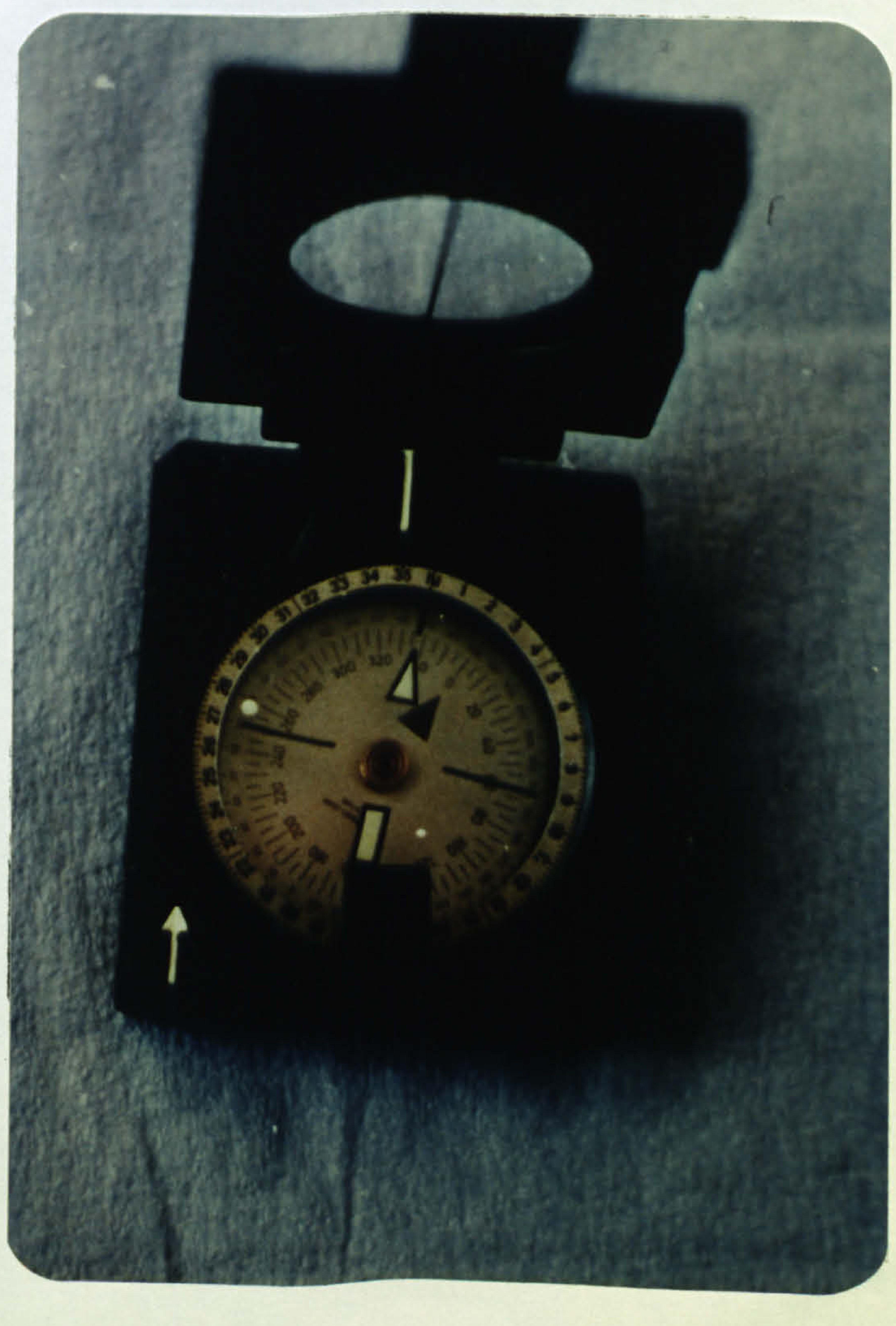


Plate 4

potentially very susceptable to disturbance of the stakes which were clearly visible on the shore. Frequent checks on their position were therefore performed.

Errors were assessed by resighting the position of a Ranging Rod at a distance of 100 yards (91.4m) from the furthest stake. Deviations from the known position were measured. The procedure was repeated 20 times and the results analysed statistically.

(B) Levelling the Transect Lines

The profiles of the transect lines were determined by taking level measurements down the transects from the fixed reference point to the level of low water or just beyond. Levels were measured in metres at 10 yard (9.141m) intervals using a Hilger and Watts Autoset Level in conjunction with a Metric Staff and Imperial Chain (Plates 5 to 9 ). The techniques used for setting-up and taking readings are described in Appendix 'B'.

To relate the level profiles of the three transect lines to each other, the differences in level of their origins were determined. This was achieved by using the same levelling technique.

A check on the accuracy of the levelling technique was performed. The difference in level between fixed shore points A and C was determined by levelling in both directions, A - C and C - A. The distance over which the levelling was carried out was also measured. The difference between the two estimates was used in conjunction with the total distance over which levelling was performed to express the error in terms of unit vertical error in 'x' units of horizontal distance levelled.

Level measurements were related to an accepted reference level to allow results from this and other studies to be compared. Mean Sea Level (MSL) was chosen because it is used as the basis for levelling by the Ordnance Survey (OS) of Great Britain.

The OS has positioned Bench Marks at known heights relative to M.S.L. at intervals all over the country. A list

PLATE 5

The Hilger and Watts Autoset Level Used For Measuring The Level Profiles of the Three Transects.

PLATE 6

This shows the Instrument mounted upon its Tripod.

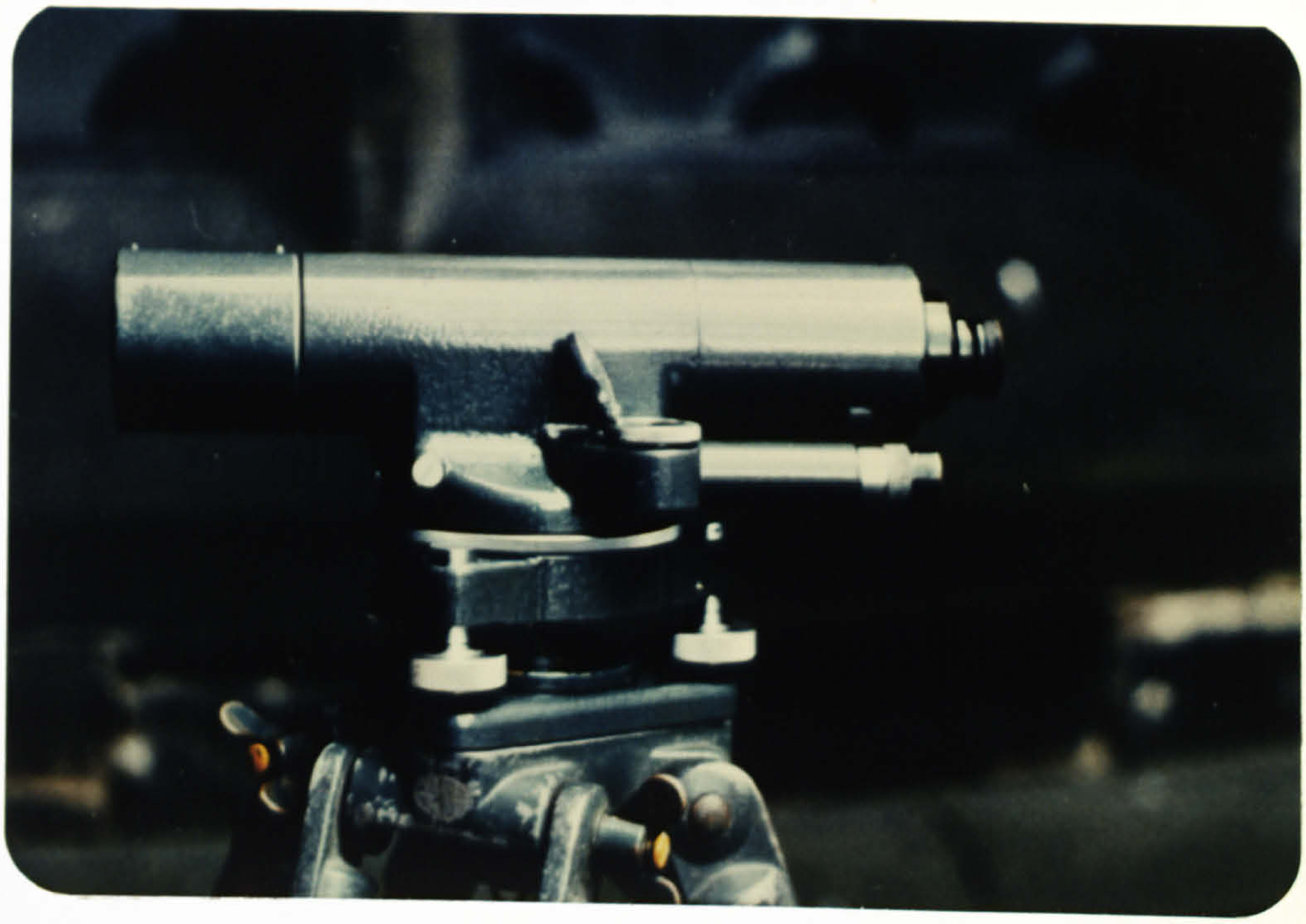


Plate 5

Plate 6

PLATES 7 AND 8

The Metric Staff Used For Measuring The Level Profiles of The Three Transects. The Staff is graduated in centimetres.

Plate 7

Plate 8

PLATE 9

The Surveyors Chain Used For Measuring The Intervals Between Levelling Points in The Transect Survey.

Each Link on the The Chain is 6 inches long(152.4mm).

Plate 9

of Bench Marks for the Ardmore area, giving their locations and height was obtained from the OS. (See Appendix 'B').

The same levelling technique previously described was used to determine the height of the fixed reference point on Transect A relative to the Bench Mark at Ardmore Farm and hence M.S.L. Using the calculated differences in level between the fixed reference points on Transects A,B and C, the heights of the latter two could then be expressed in a similar manner.

The positions of other standard tidal levels relative to M.S.L. were determined by reference to the Admiralty Tide Tables (1981 - 1984). These levels were:-

Highest Astronomical Tide (HAT)
Mean High Water Springs (MHWS)
Mean High Water Neaps (MHWN)
Mean Low Water Neaps (MLWN)
Mean Low Water Springs (MLWS)
Lowest Astronomical Tide (LAT)

(C) Positioning the Sampling Sites Along Transect Lines

Transect A was chosen for the most extensive survey. The reasons for its selection were as follows:-

(i) It was of intermediate length.
(ii) It had features common to B and C.
(iii) Access was easy.

Sample sites on B and C were positioned with a view to providing data which could be compared with that from A.

The positioning of the sites was as follows:-

Transect A - Sites were positioned at 60 yard (54.85 metre) intervals down the transect from the fixed reference point. An additional site was located at the position of High Water Neaps (HWN).

Transects B and C - Sites were located at positions corresponding to High Water Neaps (HWN), Mid Tide (MT) and Low Water Neaps (LWN). The distance from the fixed reference point to each of these was determined by reference to the earlier survey data. An additional site was located above HWN on Transect B.

A measuring wheel, circumference 1 yard (0.914m) was used for routine positioning of sites. This was much quicker than using a Measuring Tape and only required one person to operate.

Errors were assessed by repeatedly (20 times) measuring out a distance of 100 yards (91.4m) with the measuring wheel. The results were compared with a standard measured out using a Fibre Glass tape and the differences analysed statistically.

## RESULTS

### (A) Establishing The Transect Lines

Figure 1 shows the general survey area and its geographical location. The positions of the three transect lines within this area are shown in Figure 2 .

From the latter it is apparent that transects'A' and'B'bisect the bays upstream and downstream of the Ardmore outcrop. 'C' is representative of an area away from the outcrop. Transect 'B' is the longest and 'C' the shortest.

Setting-out details are shown in Figure 3 . These include the horizontal angles measured between the fixed shore points, the reference objects and the transect lines. The parts of the buildings used as fixed reference objects are also shown.

Compass bearings of the lines are given in Table 1 . The potential error incurred when setting-out using this method, is analysed in Table 2 . It is expressed as a mean deviation away from the line at a distance of 100 yards (91.4m) and is equal to ± 0.042 yards (0.040m) or 1 in 2285.

Table3 analyses the potential error incurred when setting-out using method (b). Expressed as above it is equivalent to ± 0.0083 yards (0.0080m) or 1 in 12,050.

### (B) Levelling The Transect Lines

Figure 4 shows the level profiles of the three transect lines together with the position of the standard reference tidal levels.

Shore slopes are steepest above the position of High Water Neaps but similar for all three transects. Below this position, 'B' has the shallowest slope and 'C' the steepest.

Surface irregularities are most noticeable along 'B'. The surface of 'A' is relatively uniform.

The differences in level of the fixed reference points on transects 'B' and 'C' relative to that on 'A' are given in Table4 . The table also shows the level of all three in relation to Mean Sea Level. 'A' is the highest and

FIG. 1

General Details of the Survey Area Including Latitude, Longtitude and The Position of Mean Spring Tide Levels.


55°58'N.
100 200 300 400 500 YARDS.
100 200 300 400 500 METRES.
MEAN LOW WATER SPRINGS.
4°42'W.
OLD FISH YAIR.
HILL OF ARDMORE.
ARDMORE
LODGE.
LODGE.
ROCKS
ROCKS
ARDMORE CROSSING.
ARDMORE FARM (BENCH-MARK)
ARDMORE FARM COTTAGES.
LYLESTON FARM.
4°41'W.
MEAN HIGH WATER SPRINGS.
BROOKS
ARDARDAN.
MOREPARK.
BALLYMANOCH.
A814
N
55°58'N.
4°40'W.

FIG. 2

The Position of The Three Transect Lines Within The Sampling Area.

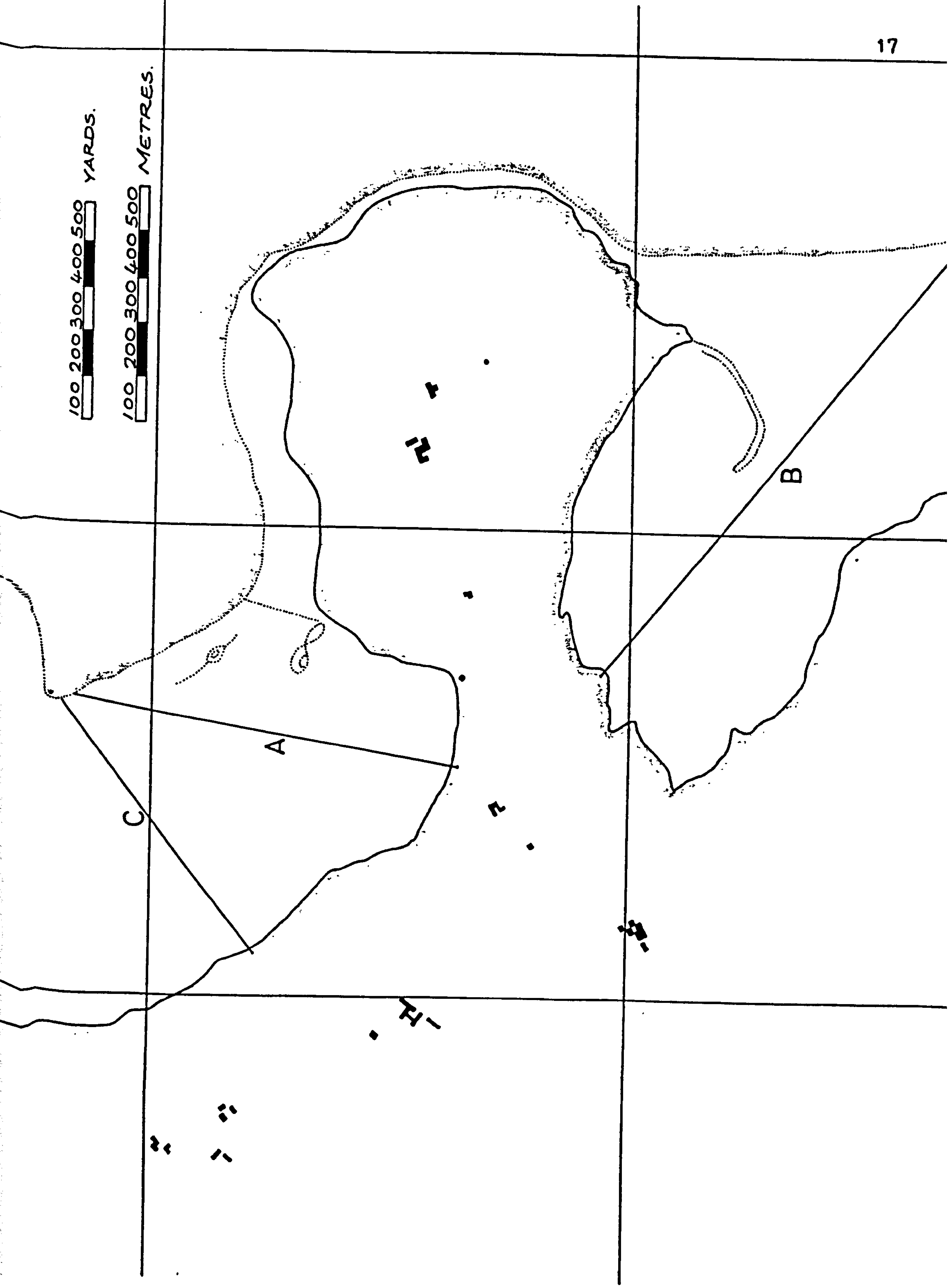

100 200 300 400 500 YARDS.
100 200 300 400 500 METRES.
A
B
C

FIG. 3

Setting-out Details For The Three Transect Lines.
The angles measured from the Fixed Reference Points between the Fixed Objects and the Transect Lines are shown. Enlarged details show the parts of the buildings used as Fixed Objects.

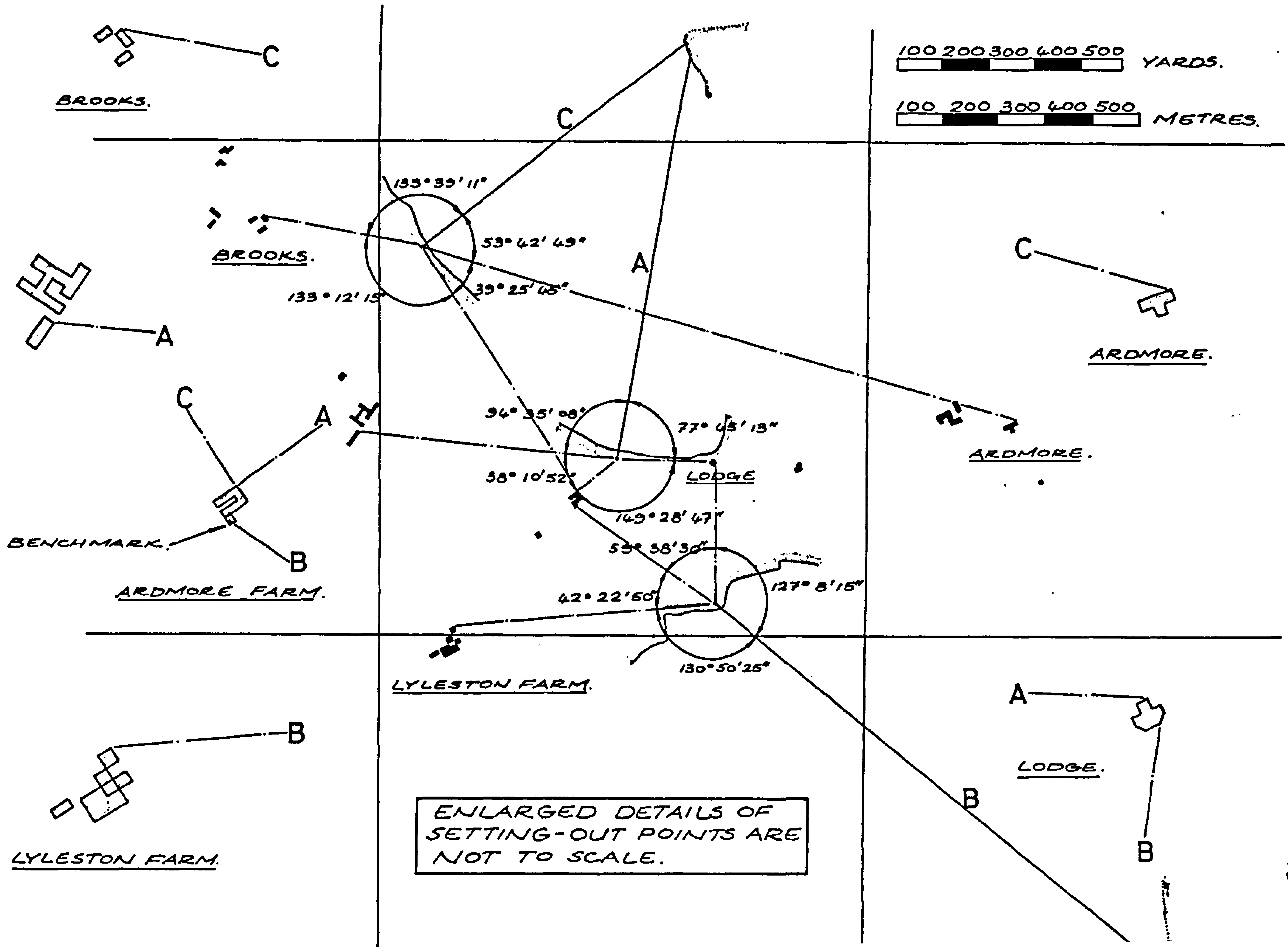

100 200 300 400 500 YARDS.
100 200 300 400 500 METRES.
BROOKS.
C
A
B
133° 39' 11"
53° 42' 49"
39° 25' 45"
133° 12' 15"
ARDMORE.
ARDMORE FARM.
BENCHMARK.
94° 35' 08"
77° 45' 13"
38° 10' 52"
LODGE
149° 28' 47"
55° 38' 30"
127° 8' 15"
42° 22' 50"
130° 50' 25"
LYLESTON FARM.
LODGE.
ENLARGED DETAILS OF SETTING-OUT POINTS ARE NOT TO SCALE.

TABLE 1

Compass Bearings of Transect Lines
Relative to Magnetic North (February/March, 1982).

| Transect | Bearing |
|---|---|
| A | 197.0° |
| B | 312.5° |
| C | 238.0° |

TABLE 2

Results of Experiment To Determine The Potential Error When Setting-out Transect Lines Using Method (a): Compass Bearing of Line

| No. of observations | Sighting Distance (Yards/Metres) | Mean Deviation From Line (Yards/Metres) | Standard Deviation (Yards/Metres) | Error (Unit Deviation in x Units Sighted |
|---|---|---|---|---|
| 20 | 100/91.4 | 0.042/0.040 | 0.035/0.030 | 1 in 2285 |

TABLE 3

Results of Experiment to Determine The Potential Error When Setting-out Transect Lines Using Method (b): Permanent Stakes Positioned Along Line.

| No. of observations | Sighting Distance (Yards/Metres) | Mean Deviation From Line (Yards/Metres) | Standard Deviation (Yards/Metres) | Error (Unit Deviation in x Units Sighted) |
|---|---|---|---|---|
| 20 | 100/91.4 | 0.0083/0.0080 | 0.0056/0.0040 | 1 in 12050 |

FIG. 4

Level profiles of The Three Transect Lines.
The position of the Standard Reference Tidal Levels is also shown. Tidal Levels are in metres. To convert to yards multiply by 1.094.

Level Survey Of Transect Lines.

TABLE 4

Levels of Fixed Points on Transects 'B' and 'C' Relative To That on 'A' and The Levels of all Three Relative To Mean Sea Level (MSL)

| Transect Fixed Point | Level Relative To A (Yards/Metres) | Level Relative To MSL (Yards/Metres) |
|---|---|---|
| A | - | $+4.374 \pm 0.007$, $+3.998 \pm 0.006$ |
| B | $-0.753 \pm 0.028$, $-0.688 \pm 0.026$ | $+3.621 \pm 0.028$, $+3.310 \pm 0.026$* |
| C | $-0.782 \pm 0.050$, $-0.715 \pm 0.046$ | $+3.597 \pm 0.050$, $+3.288 \pm 0.046$* |

* Error Determined by adding possible error in level of 'A' to that potentially incurred when levelling from 'A' to 'B' or 'A' to 'C'.

'C' the lowest.

Levelling error is analysed in Table 5 . It is of the order of 0.09 yards (0.082m) over a distance of 1,455 yards (1,330m) or 1 in 16,220.

(C) Positioning The Sampling Sites Along The Transect Lines

The positioning of the sampling sites is shown on Figure 5 . Differences in shore slope result in the distances to the various reference tidal levels varying. Distances can be converted to metres by multiplying by 0.914.

Potential errors incurred when positioning sampling sites with the measuring wheel are analysed in Table 6 . They are of the order of 0.085 yards (0.078m) per 100 yards (91.4m) measured or 1 in 1,176.

TABLE 5

Results of Experiment to Determine Levelling Errors

| Total Distance Levelled (Yards/Metres. | Difference In Level (Yards/Metres) | Error (Unit vertical in x units Horizontal) |
|---|---|---|
| 1455/1330 | 0.090/0.082 | 1 in 16220 |

FIG. 5

Positioning of Sampling Sites Along Transects A,B and C. Distances can be converted to Metres by multiplying by 0.914.

Position Of Sampling Sites On Transects.

TABLE 6

Results of Experiment to Determine The Potential Error When Setting-out Sample Sites using the Measuring Wheel.

| No. of observations | Distance Measured (Yards/Metres) | Mean Difference from Standard. (Yards/Metres) | Standard Diviation (Yards/Metres) | Error Unit length in x units Measured |
|---|---|---|---|---|
| 20 | 100/91.4 | 0.085/0.078 | 0.038/0.035 | 1 in 1176 |

## DISCUSSION

Two features of the estuarine environment are of significance to the siting of the three transects relative to the Ardmore outcrop, these are Tides and Waves.

Tides are important because they result in a twice daily flushing of the estuary. The resultant currents subject the surface sediments to a regular pattern of forces, in so doing they influence processes such as Sediment Transport and the accumulation or loss of Organic Matter.

Wave action is important because it contributes significantly to the physical hostility and hence stability of the environment. Unlike Tidal activity however, Wave action is not predictable, it is dependant upon the strength and direction of the winds which generate it.

Transect A is located in a position sheltered from currents associated with the incoming tide. It is also sheltered from winds - and hence waves - coming from Northerly and North Westerly directions.

Transect B experiences opposite conditions, it is exposed to the incoming tide and waves from Northerly and Westerly directions.

Transect C is positioned on the same side of the outcrop as A, the degree of shelter is however, much less. Conditions on this transect will therefore, reflect those more akin to an open shore.

The three transect profiles illustrated in this section are typical of those described by other workers, (Reineck and Singh 1980, Ott et.al. 1976). They can be divided into two distinct regions on the basis of slope and sediment type. Above approximately Mean High Water Neaps, slopes are steep - approximately 1 in 10 and Surface Sediments. coarse with an abundance of large pebbles and rocks. Below, the slopes are shallow. 2.5 to 3.5 in 1,000 and the surface sediments are made up of fine grained material. This latter region of shallow slope accounts for the greatest area exposed at low tide. It is this area between Mean High Water Neaps and Mean Low Water Neaps that has been extensively worked on in this project.

The significance of differences in sediment type are dealt with in Sections 2 and 4.

Slope differences are important for a number of reasons. In ecological terms they are important because they determine the amount of exploitable habitat available to a potential colonizing species within the various intertidal zones. In a physical context they are important because they govern the pattern of energy dissipation over the shore, (Meadows and Campbell,1978), hence steep slopes result in a relatively hostile environment because of the small area over which energy is dissipated.

Slope is also important to the positioning of suitable sampling sites on an intertidal transect. On shores of variable slope it is difficult to position sites accurately relative to tidal level without the use of the surveying techniques employed here. This is particularly evident if the positions of the reference tidal levels on transects A, B and C are considered. Slope differences between these three transects result in the horizontal distances to these reference levels varying considerably.

# SECTION 2

## THE MEASUREMENT OF SELECTED PHYSICAL AND CHEMICAL FEATURES DOWN THE TRANSECTS

# INTRODUCTION

Many marine ecological studies have included field or laboratory measurements of physical and chemical features of the intertidal sedimentary environment. The purpose of these measurements is often to provide data with which distribution patterns of the inhabiting species can be correlated. Tables 1 and 2 show typical examples of the features considered.

This section contains the results of a survey of six such features. Data has been collected from the sampling sites described in Section 1 during two seasons - Summer and Winter. The six features considered are as follows:-

## (1) Sediment Particle Size Distribution

Particle size distribution parameters are of importance to sediment dwelling species for the following reasons:-

(a) They determine the size of individual sediment particles which are available for ingestion.

(b) They determine the surface area of sediment available for colonisation by microbes.

(c) They determine the size of pore spaces available for colonisation by interstitial species.

(d) They influence sediment properties such as permeability and shear strength.

With this in mind it is not surprising that this is one of the most frequently measured parameters.

Folk (1966) has reviewed the statistics used to describe the particle size distribution of sediments. The four most commonly used are:

(1) Mean
(2) Standard Deviation
(3) Skewness
(4) Kurtosis

Raw data for the calculation of these statistics

TABLE 1

Physical Sediment Properties

| Worker | Property |
|---|---|
| Hulings and Gray (1976) | Particle Size, Temperature |
| Bloom, Simon & Hunter (1972) | Particle Size |
| Dale (1974) | Particle Size |
| Longbottom (1970) | Particle Size |
| Deans, Meadows & Anderson (1982) | Shear Strength, Permeability, Particle Size |
| Meadows and Ruagh (1981) | Temperature |
| Biernhaum (1979) | Particle Size |
| Grant (1981) | Bed Topography |
| Gordon (1966) | Temperature |
| Johnson(1971) | Particle Size |
| Krumbein (1971) | Microtopography, Particle Size |
| Rhoads & Young (1971) | Microtopography, Water Content |
| Tevesz, Soster & McCall(1980) | Particle Size, Water Content |
| Sanders (1958) | Particle Size |
| Tsernoglou & Anthony (1971) | Particle Size |
| Cadee (1976) | Particle Size |
| Cassie & Michael (1968) | Particle Size |

## TABLE 2

### Chemical Sediment Properties

| | |
|---|---|
| Dale (1974) | Carbon, Nitrogen |
| Longbottom (1970) | Organic Carbon, Nitrogen |
| Deans, Meadows & Anderson (1982) | Organic Carbon, Sulphides, Redox Potential, Chlorophyll 'a' |
| Anderson, Boonruang & Meadows (1981) | Chlorophylls, Carbon, Nitrogen |
| Meadows & Ruagh (1981) | Salinity |
| Gordon (1966) | Carbon, Sediment Pigments |
| Ott, Fuchs, Fuchs & Malasek (1976) | Redox Potential |
| Rhoads & Young (1971) | Carbon |
| Tevesz, Soster & McCall(1980) | Organic Carbon |
| Anderson & Meadows (1978) | Chlorophyll 'a', Phaeopigments, Organic Carbon, Total Carbon, Total Nitrogen, Total Sulphide, Redox Potential |
| Hodson, Holm Hansen & Azam (1976) | ATP |
| Bulleid (1977) | ATP |
| Cadee (1976) | Organic Carbon, Organic Matter, Chlorophyll'a' |
| Cassie & Michael (1968) | Organic Carbon. |

can be obtained using variations of two basic techniques - Sieving and Pipette Analysis. The method used is dependant upon the grade of sediment being analysed:

Sieve Analysis - Fine Sand upwards
Pipette Analysis - Silt and Clay.

The sediments encountered at Ardmore were predominantly of Fine to Medium sand size. Dry sieving was therefore chosen as the appropriate analytical technique.

The statistics were calculated from the raw data using the 'method of moments' (Krumbein and Pettijohn 1938; Inman 1952). Calculations were performed using a computer program designed by a fellow member (Miss M. Kirkham).

(ii) Organic Matter Content Of The Sediment

The Organic Matter Content of sediments provides a useful index of their nutrient status. In so doing, it gives us other useful information such as:

(a) The biomass the sediment is capable of supporting.
(b) The species which might be present.
(c) The possible Redox condition of the sediment.

The methods used to quantify organic matter can be divided into two basic types:

(1) Direct Measurements of Percentage Total Organic Matter Content - in which the content of all organic substances in the sediment are determined as one (Dean 1974).

(2) Measurements of the Percentage Content of Selected Organic Substances - such as Organic Carbon (Longbottom 1970), Organic Nitrogen (Dale 1974), and ATP (Hodson et.al. 1976).

Method (1) was used in this project. Dean (1974) has shown this method to give results comparable to those obtained using a C-H-N analyser with similar levels of accuracy and precision.

(iii) Shear Strength Of The Sediment

Shear Strength is best described as the maximum resistance to deformation by a shear force. It is of particular importance to burrowing animals for it determines the ease with which they can work their way into and through the sediment and the stability of burrows and other structures they form in doing so. Trevor (1977) has considered these aspects in relation to the burrowing activity of the polychaetes Nereis diversicola and Arenicola marina.

There are two measures of Shear Strength which can be determined simply in material of a sedimentary type. These are:

(a) Peak Shear Strength - The maximum shearing force the sediment can withstand without deforming significantly.

(b) Residual Shear Strength - The shearing force the sediment can withstand after it has been deformed.

There are a number of pieces of equipment and associated techniques which have been developed to measure Shear Strength. These include:-

(1) Triaxial Testing Apparatus - used to measure Shear Strength in the laboratory under conditions which simulate those in the field.

(2) Shear Box Apparatus - used to measure Shear Strength in the laboratory under standard conditions.

(3) Falling Cone Apparatus - used to measure the Shear Strength of the surface few millimetres of a sediment in the field or laboratory.

(4) Shear Vane Apparatus - used to measure Shear Strength at depths within the sediment profile. Two types have been developed - one suited to field use and the other for use in the laboratory.

Item (4) was used in this project to take Shear Strength measurements in the field.

## (iv) Redox Potential Of The Sediment

Redox Potential (Eh) is a quantitative measure of the tendency of a given system to oxidize or reduce susceptible substances (Zobell 1946). It therefore gives an indication of the amount of oxygen freely available in that system and the oxidation state in which we might expect to find given substances.

High Redox Potentials in sediments indicate an abundance of oxygen and conditions favourable to organisms. Low values, however, indicate little free oxygen and the possible presence of toxic substances such as Hydrogen Sulphide.

The processes contributing to observed Redox Potential profiles in sediments are discussed in Hayes (1964). These include the effects of the sediment biota. Organisms living in sediments reduce the Redox Potential by using up oxygen in the process of respiration. This is particularly true of the Bacteria. Zobell (1946) believes these to be the main dynamic agents controlling Redox Potential in sediments.

Redox Potential has been used by many workers to quantify the oxidation state of sediments, (Deans et. al. 1982, Ott et. al. 1976). Anderson and Meadows (1978) however, have considered it in the wider context of microenvironments in marine sediments.

In this study Redox Potential has been measured in the field using a portable Eh meter.

(v) <u>Salinity Of The Sediment Interstitial Water</u>

The mixing of fresh and salt water in estuaries results in a complex pattern of salinity gradients. At the mouths of inflowing rivers, gradients tend to radiate out as fresh and salt water are progressively mixed. Inflow from groundwater however, results in gradients which run at right angles to the shore. This pattern is further complicated by the nature and magnitude of mixing processes within the estuary. In poorly mixed estuaries,fresh and salt water may remain as separate entities for quite some time.

The net result of the above is that salinity in the sediments and overlying waters of estuaries varies markedly. Geographical location or position on the shore cannot therefore, be interpreted as indicating a particular salinity.

Salinity gradients have been considered by Gray (1974) in the context of restricting the area of substratum occupied by a species. Work on the amphipod Corophium volutator has shown this to be a very complex problem. This species has an optimal preferred salinity of 20‰, (Meadows and Ruagh 1981). However, it is found in salinities as low as 2‰ and will breed above 7.5‰, (McClusky 1968). The situation is further complicated by interactions with other environmental variables. Thus Meadows and Ruagh (1981) have shown Temperature to interact with Salinity in determining behaviour responses of C. volutator. In general terms Gray (1974) has considered that such interactions between salinity and other environmental variables may limit distribution patterns.

In this project the salinity of interstitial water samples has been measured using a calibrated conductivity mèter.

(vi) Position Of The Water Table Relative To The Sediment Surface At Low Water.

The free surface - ignoring capillary fringes - of the groundwater in a sediment or soil is known as the Water Table. Its position, however, is not restricted to below the sediment surface, as the presence of springs and ponds clearly shows.

The presence of a Water Table has important consequences to a number of features of the sedimentary environment including:

(a) Sediment Moisture Content - Below the level of the Water Table sediments are fully saturated. Above, the level of saturation is dependant upon other features of the sediment such as its type, size and organic matter content.

(b) Sediment Shear Strength - Water content is a critical factor in determining sediment shear strength (Trask and Rolston 1950).

(c) Gaseous Diffusion Into and Out of The Sediment - Gaseous diffusion occurs at a much faster rate in air than in water. Gaseous exchange will therefore, be much quicker in sediments above the level of the Water Table.

(d) Salinity Of The Interstitial Water - Groundwater flowing into marine sediments will result in interstitial salinities lower than those of the overlying water.

No direct reference could be found in the literature to studies which have considered the position of the water table as a factor limiting the distribution of species. In view of what has been said above, this is perhaps, surprising.

In this study, the position of the Water Table was recorded at each site within a few minutes of low water. Measurements taken then will represent its lowest position during the tidal cycle and the most extreme conditions to which organisms living in the sediment are exposed.

MATERIALS AND METHODS

(i) Sediment Particle Size Distribution

Key Words

Phi (Ø) Scale

The Ø scale was introduced by Krumbein in 1934 to simplify the arithmetic involved in computing the statistical parameters of sediments. The diameter of a sediment particle in Ø units is calculated using the following equation.

$$\emptyset = -\ LOG_2\ (\text{DIAMETER IN MILLIMETERS})$$

A conversion chart can be found in Inman (1952). It is important to note that on the Ø scale the smaller the particle, the larger its Ø value.

Method of Moments

The 'method of moments' (Krumbein,and Pettijohn, 1938; Inman,1952; Folk,1966) describes a technique used to calculate the descriptive statistics for particle size distributions. Unlike 'graphic methods' (Inman 1952; Folk and Ward 1957), the method of moments uses data from all size classes within the distribution. This feature is of particular importance in the calculation of two of the statistics - Skewness and Kurtosis.

Mean

The mean is the best measure of overall average size of the sediment particles within the sample. It reflects the source of supply and nature of the depositional environment.

Standard Deviation

The standard deviation is used to describe the extent to which a sediment is sorted. Well sorted sediments consist of particles of similar size. The standard deviation of such sediments will be small. Folk (1966) contains a scale of sorting. Standard Deviations range from 0.35Ø for very well sorted sediments to 4.00Ø for extremely poorly sorted ones.

Skewness

Skewness is used to describe the extent to which the mean particle size departs from the median. As such it indicates the extent to which sediments have been mixed.

A symmetrical distribution has a skewness value of zero. A distribution with its tail in the fines hasa positive value up to a theoretical maximum of +1.0. Conversely one with its tail in the coarse grains has a negative value up to a theoretical maximum of -1.0.

Kurtosis

Kurtosis is used as another measure to describe the extent to which sediments have been mixed. This time however, it measures the peakedness of the particle size distribution. It is computed as the ratio between the spread in the central part of the distribution and the spread in the tails (Folk 1966.)

Using the method of moments, Kurtosis equals three for a normal distribution (Inman 1952). Distributions which are more peaked than normal have values less than three. If the distribution is less peaked the value is greater than three.

* * * * * * *

Samples for subsequent laboratory analysis were obtained from 2 - 8.0cm diameter x 22.5cm long cores taken at each site. The cores were divided up on site into depth intervals of 0-2.5; 2.5-7.5; 7.5-12.5; 12.5-17.5 and 17.5-22.5cm. Each interval was placed into a separate labelled plastic bag for transport back to the laboratory. In the laboratory each sample was dried at 60°c for 12 hours prior to analysis.

Samples were analysed using the Dry Sieving technique described in British Standard 1377 (1975.) Test Sieves (Endecotts, London SW19) conforming to British Standard 410 were used in conjunction with a mechanical shaker (Endecotts, Model E.F.L1) to perform the analysis. The mesh sizes used were:-

| Mesh Size (μm) | Mesh Size (Ø)* | |
|---|---|---|
| 38 | 4.5 | Silt and Clay |
| 45 | 4.0 | |
| 63 | 3.5 | Fine Sand |
| 90 | 3.0 | |

| Mesh Size (μm) | Mesh Size (Ø)* (cont.) | |
|---|---|---|
| 125 | 2.5 | Medium Sand |
| 180 | 2.0 | |
| 250 | 1.5 | |
| 350 | 1.0 | |
| 500 | 0.5 | |
| 710 | 0.0 | Coarse Sand |
| 1000 | -0.5 | |
| 1400 | -1.0 | |
| 2000 | -1.5 | |

* These values are mid-points of the class intervals.

Sample weight and sieving time were set at 100 gms. and 10 minutes respectively after reference to British Standard 1377 and Allen (1975).

Following sieving, the weights retained by each sieve were determined to an accuracy of ±0.001gm using a Mettler, Type P120 Balance. These weights were then analysed using a computer program developed by a fellow worker (Miss M. Kirkham). Output from the program gave the following information.

(1) Percentage of total sample weight retained by each sieve.

(2) Cumulative percentage of total sample weight retained by each sieve.

(3) Mean Particle Size
(4) Standard Deviation
(5) Skewness
(6) Kurtosis

(3)–(6): As determined by the method of moments.

The following sources of error should be noted when considering the results:-

(a) Variation of sieve aperture.

(b) Wear.

(c) Errors of observation and experiment.

(d) Errors of sampling.

These errors were not quantified. However, by standardising the analytical technique it was hoped to keep these relatively constant for all samples. The precision of the technique was assessed using Mean Particle Size data. Six subsamples from the same sediment sample were analysed.

The deviation of each calculated mean from the overall mean was then determined as a percentage of the overall mean. The precision of the technique was then calculated as the mean of these six percentage deviations. The results of this exercise, shown in the following table, set a level of precision to the technique of better than 2%.

| Subsample No. | % Deviation From Overall Mean. | |
|---|---|---|
| 1 | 2.2 | Mean = 1.6 |
| 2 | 0.2 | |
| 3 | 0.2 | |
| 4 | 4.6 | |
| 5 | 0.6 | |
| 6 | 1.8 | |

(ii) Percentage Organic Matter Content Of The Sediment

The analytical technique used to determine the Organic Matter Content was based upon that described by Dean (1974) and Galle and Runnels (1960).

Sample material for analysis was obtained from the replicate core sections collected for particle size analysis. Subsamples of the sediment weighing approximately 2 gms. were placed into tared Porcelain Crucibles, (Staatlich Berlin 60). The crucibles were then placed in a Muffle Furnace (Gallenkamp, England) for 1 hour at a temperature of 110°C. After this period the crucibles were removed, cooled in a desiccator and then reweighed to an accuracy of ±0.00001gm using a Mettler, Zurich, Type H16 Balance. The furnace temperature was then adjusted to 550°C. When this temperature was attained, the crucibles were returned to the furnace for a further period of 25 minutes. The crucibles were then once more cooled in the desiccator and weighed. The Percentage Organic Matter Content could then be calculated as follows:-

W1 = Tare Weight of Crucible.

W2 = Dry Weight of Sediment + Crucible at 110°C.

W3 = Dry Weight of Sediment + Crucible at 550°C.

$$\% \text{ Organic Matter Content} = \frac{W2 - W3}{W3 - W1} \times 100$$

The Precision and Accuracy of this method has been investigated by Dean (1974). In a sample containing less than 1% Organic Matter, precision was better than 3.07% (coefficient of variation) for 25 ignitions. Accuracy was tested using a sample containing 18% organic matter. Deviations from this known amount were less than ±0.5%. These tolerances are as good as, or better, than those for the other methods he tested.

(iii) Shear Strength Of The Sediment

Key Terms

(1) Shear Stress - is the force applied to the sediment per unit of cross-sectional area of the plane in which shearing is being induced. It is expressed in units of $g.cm^{-2}$, $kgm^{-2}$, $kNm^{-2}$ or k Pascals.

(2) Peak Shear Strength - is the maximum shear stress the sediment can withstand without failing. It is expressed in the same units as Shear Stress.

(3) Residual or Reworked Shear Strength - is the shear strength the sediment retains in the plane of failure after it has been sheared.

* * * * * *

Shear Strength was measured in the field using a Direct Reading Shear Vane (Pilcon Engineering Limited, No.2043) fitted with either a 19 or 33mm diameter vane. This instrument is illustrated in Plates 1 and 2. The method of assembly and use is detailed in Appendix 'C'.

Two sets of readings were taken at each site at depths of 1.25, 5, 10, 15 and 20cm, measured from the sediment surface to the mid-point of the vane. These depths correspond to the mid-points of the sediment sections collected for Particle Size and Organic Matter analysis.

Serota and Jangle (1972) have tested the performance of the instrument. In laboratory tests they have shown it to give a deviation of less than 1% in two readings out of three. The validity of the calibration of the instrument was tested by comparing results with those obtained in quick, undrained Triaxial tests. The results were shown to be consistent with normal variation in the samples.

PLATES 1 AND 2

The Direct-Reading Shear Vane used to measure Sediment Shear Strength.

PLATE 1-The main body of the apparatus showing the scale.

PLATE 2-The vane positioned at the end of the extension rods.

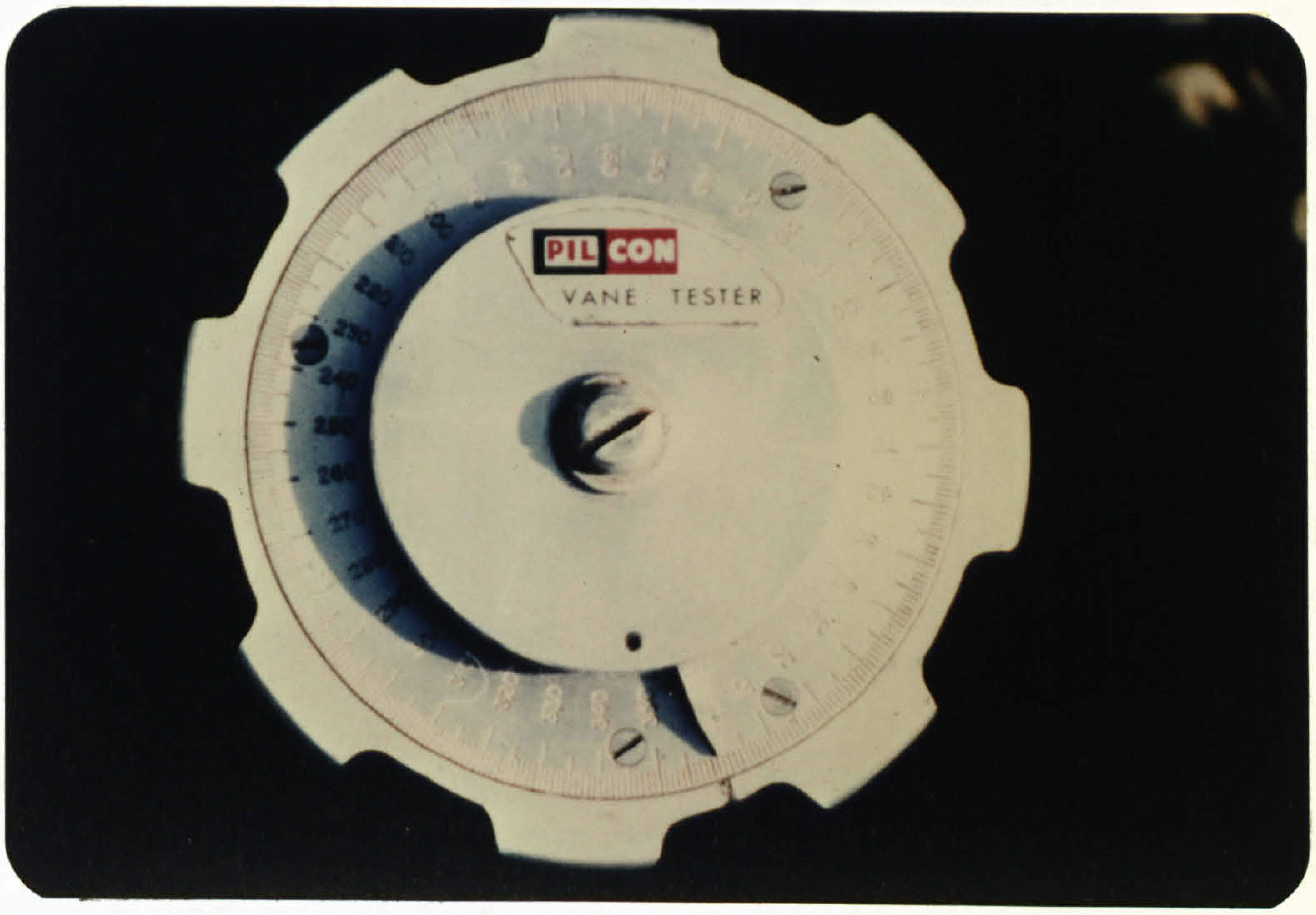



Plate 1

Plate 2

(iv) Redox Potential (Eh) Of The Sediment

Eh was measured using a portable Eh/pH Meter, (E.I.L. Model 30C) fitted with a Calomel reference electrode (E.I.L. 33-1370-210), and an inert Black Platinum electrode (E.I.L. 33-1213-400). Readings were taken on the millivolt (mV) scale.

Standardisation of the Eh electrode was achieved using a quinhydrone buffer (Jones 1966). Eh values for this solution at reference temperature and pH values are shown in Table 3 . Performance of the electrode was checked frequently with the buffer.

Corrections were made for temperature by extrapolating the data of Zobell (1946). These corrections are shown in Table 4 . The resultant readings were expressed in relation to a reference hydrogen electrode by adding +250 mV to the corrected field readings, (Zobell 1946.)

Eh profiles were measured in the field on two replicate core samples freshly extracted at each site. Readings were taken at depths of 1.25, 5, 10, 15 and 20cm, by inserting the electrodes into a freshly exposed area of the core sample. While waiting for the reading to stabilize the ends of the electrodes in the sediment were gently rotated back and forth. The electrodes were washed with and stored in distilled water between each reading.

The instrument was calibrated in units of 10mV. The accuracy of the measurements was therefore, in the order of $\pm$5mV. Precision was calculated as the average deviation of 30 readings, taken on the same sample, from their overall mean. This gave a result of $\pm$6.5mV.

(v) Salinity Of The Sediment Interstial Water.

Two replicate water samples were collected at low tide from each site. The samples were collected in 100 ml glass bottles, from holes approximately 25cm deep which had been dug in the sediment and then allowed to fill with the interstitial water. The bottles were then sealed and transported back to the laboratory.

In the laboratory, the salinity of the samples was

TABLE 3.

Redox Potential (mV) At Standard Temperatures (°C) and pH values for a reference Calomel electrode in a quinhydrone buffer solution.

| pH \ TEMP (°C) | 20 | 25 | 30 |
|---|---|---|---|
| 4 | +223 | +218 | +213 |
| 7 | +47 | +41 | +34 |

TABLE 4.

Corrections To Redox Potential Readings (mV) For Various Sample Temperatures

| TEMPERATURE (°C) | 2.5 | 3.0 | 10 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|
| CORRECTION (mV) | +9 | +9 | +5 | +4 | +3 | +3 | +2 |

measured using a Conductivity Meter (WPA.E1. Environmental Multiprobe). The meter was calibrated using Standard Seawater (I.O.S. Wormley, Surrey, England) of the following specification;

Salinity 34.996487‰

Chlorinity 19.372‰

Solutions of known concentration were made up using this standard and their conductivities measured at a temperature of $24^{o}C$. A graphical plot of salinity (‰) against conductivity (μmhos ) resulted in a straight line, the equation of which was:

$$\text{Salinity (‰)} = (7.72627 \times \text{Conductivity}(\mu\text{mhos})) - 1.5$$

The salinity of a sample was determined by measuring its conductivity and incorporating this into the above equation.

The precision of the experimental technique was assessed by calculating the standard deviation of 30 samples taken from the same hole. This fixed the level of precision at $\pm$ 0.04‰ .

The chemistry and hence, conductivity of the world's oceans is variable, the concept of 'standard seawater' is therefore purely theoretical. As a consequence it is not possible to determine the accuracy of the technique without a detailed chemical analysis of the samples ; this was not done. The values quoted in this thesis should therefore, be considered 'relative' rather than 'absolute'.

(vi) Position Of The Water Table Relative To The Sediment Surface At Low Water.

Measurements were made at each site within a few minutes of low water. The method used was dependant on the level of the water table relative to the sediment surface.

Positive Water Tables - those above the sediment surface - were measured using a calibrated Dip-stick. Negative ones - those below the sediment surface - required a different method. A hole was dug in the sediment to a depth below the Water Table. The hole was then allowed to fill with inflowing interstitial water until it stabilized at the level of the Water Table in the surrounding sediment.

Experiment showed this to take between 12 minutes in sandy sediments and 30 minutes in those containing a high percentage of clay. The level of the Water Table was then measured as the distance between the underside of a straight edge resting on either side of the hole and the stable water surface.

An experiment was performed to determine the precision of the measurements. The level of the Water Table was measured twice at each of 30 sites. Each measurement was taken separately and the order of sites chosen randomly. Differences between the first and second readings were then analysed, this resulted in a mean error of $\pm$1mm on the measurements.

The accuracy of the measurements should be of the order of $\pm$0.5mm, this being the limit of resolution of the measuring instruments.

## RESULTS

The results, from the survey of the six Physical and Chemical features down the transects, are presented in the form of histograms. Each histogram contains the data for both replicates. The raw data upon which these figures are based has been stored in computer files. Hard copies of these are available for inspection.

### (i) Sediment Particle Size Distribution

The results from the survey are presented as follows:-

| | | | |
|---|---|---|---|
| Mean Particle Size | (MPS) | - | Figures 1 to 4 |
| Standard Deviation | (S.D) | - | Figures 5 to 8 |
| Skewness | (Sk) | - | Figures 9 to 12 |
| Kurtosis | (Ku) | - | Figures 12 to 16 |

Transect 'A' can be divided into three identifiable zones on the basis of characteristic depth profiles of these four statistics. The features of these zones are summarised in Figure 17.

Zone 1 - Above High Water Neaps

Fine, fairly well sorted sand with a distribution close to normal overlays coarse sand. The latter material is poorly sorted and has a distribution which is peaked and skewed towards finer diameters. The transition between the two is very marked and occurs at a depth of between 10 and 15cm.

Zone 2 - Just Below High Water Neaps

Fine, fairly well sorted sand with a distribution which is peaked and skewed towards coarser diameters overlays material of silt size or finer. In the transition zone (depth 10-15cm) between these two types, the sediment is poorly sorted with a distribution pattern close to normal. Below this it is fairly well sorted with a distribution which is skewed towards coarser diameters.

Zone 3 - Remainder Of The Shore Below Zone 2

This is very much a zone of gradual change. Mean Particle Size is relatively constant with depth but shifts gradually from fine sand (2.5Ø) on the upper shore to medium sand (1.8Ø) on the lower shore. The degree of sorting

## FIGURES 1 TO 16

## Profiles of sediment Particle Size Distribution Properties down the transects.

Notes.

1) - These figures show profiles of the properties at each site down the transect.
2) - The area shaded black represents the difference between values for the two replicates.
3) - The vertical scale is non-linear.

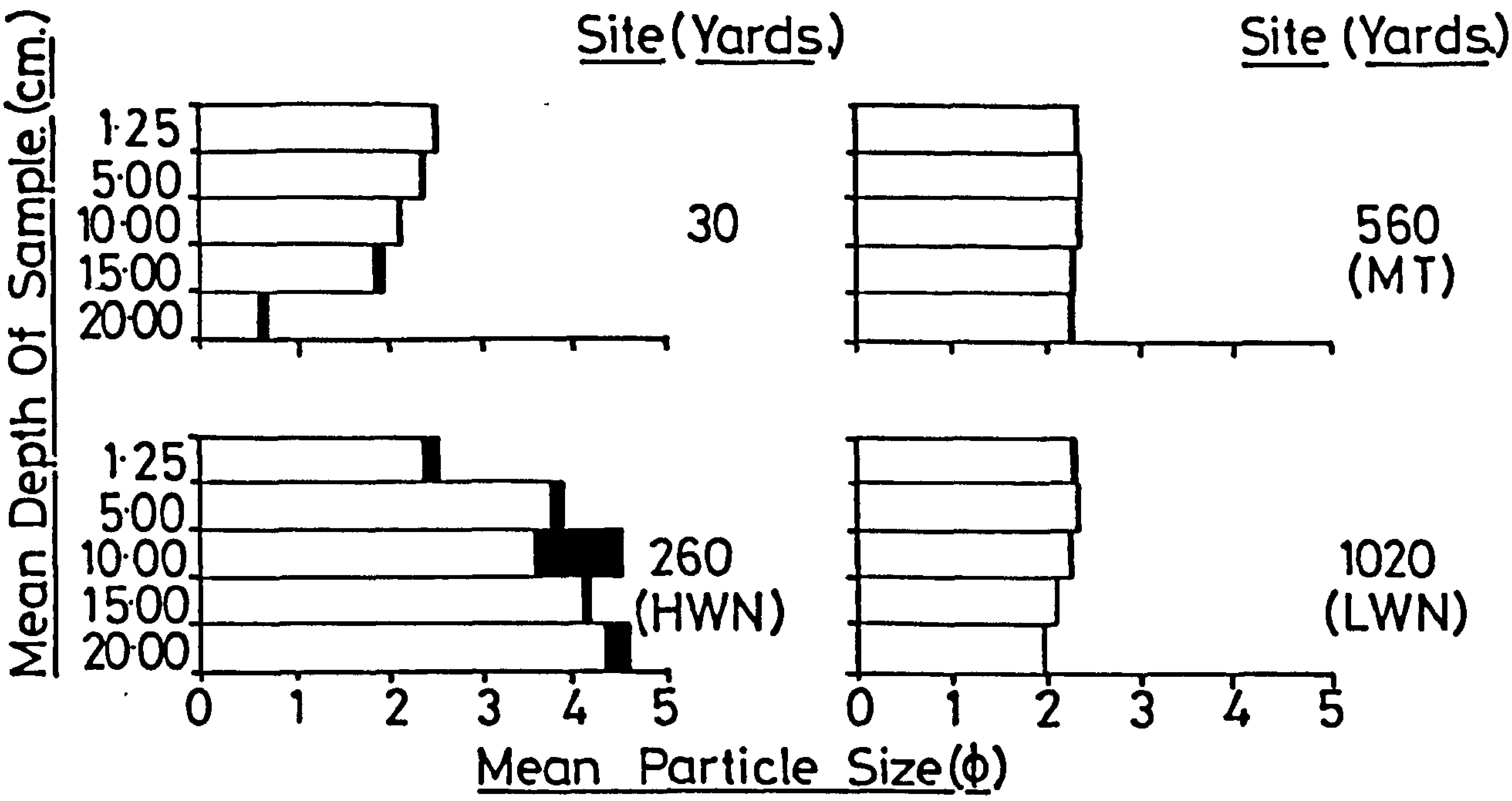
Fig. 1.

Mean Particle Size Profiles - Transect A - Summer.

Fig. 2.
Mean Particle Size Profiles - Transect A - Winter.

Fig. 3.

Mean Particle Size Profiles - Transect B - Summer.




Mean Particle Size Profiles - Transect B - Winter.

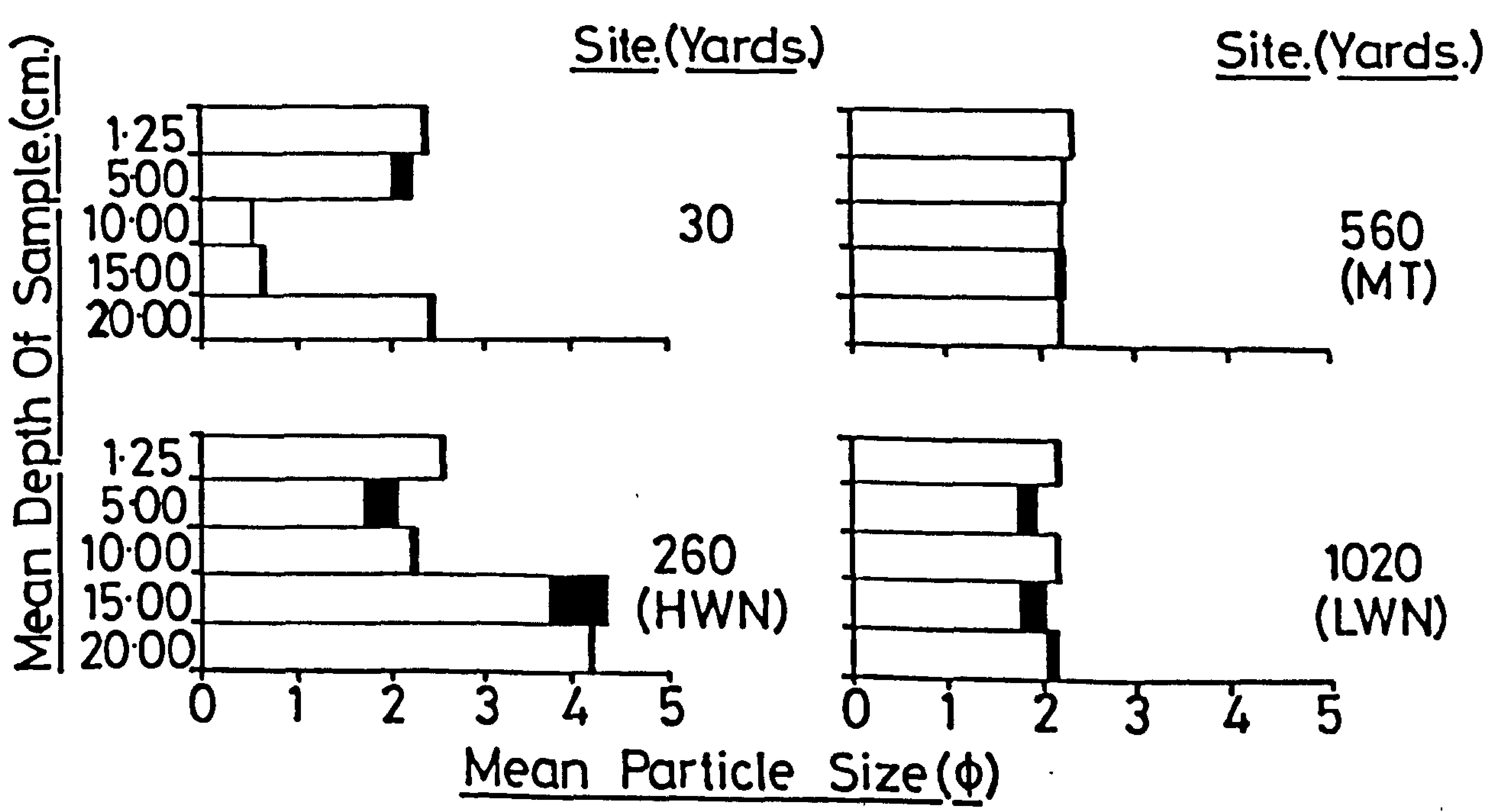
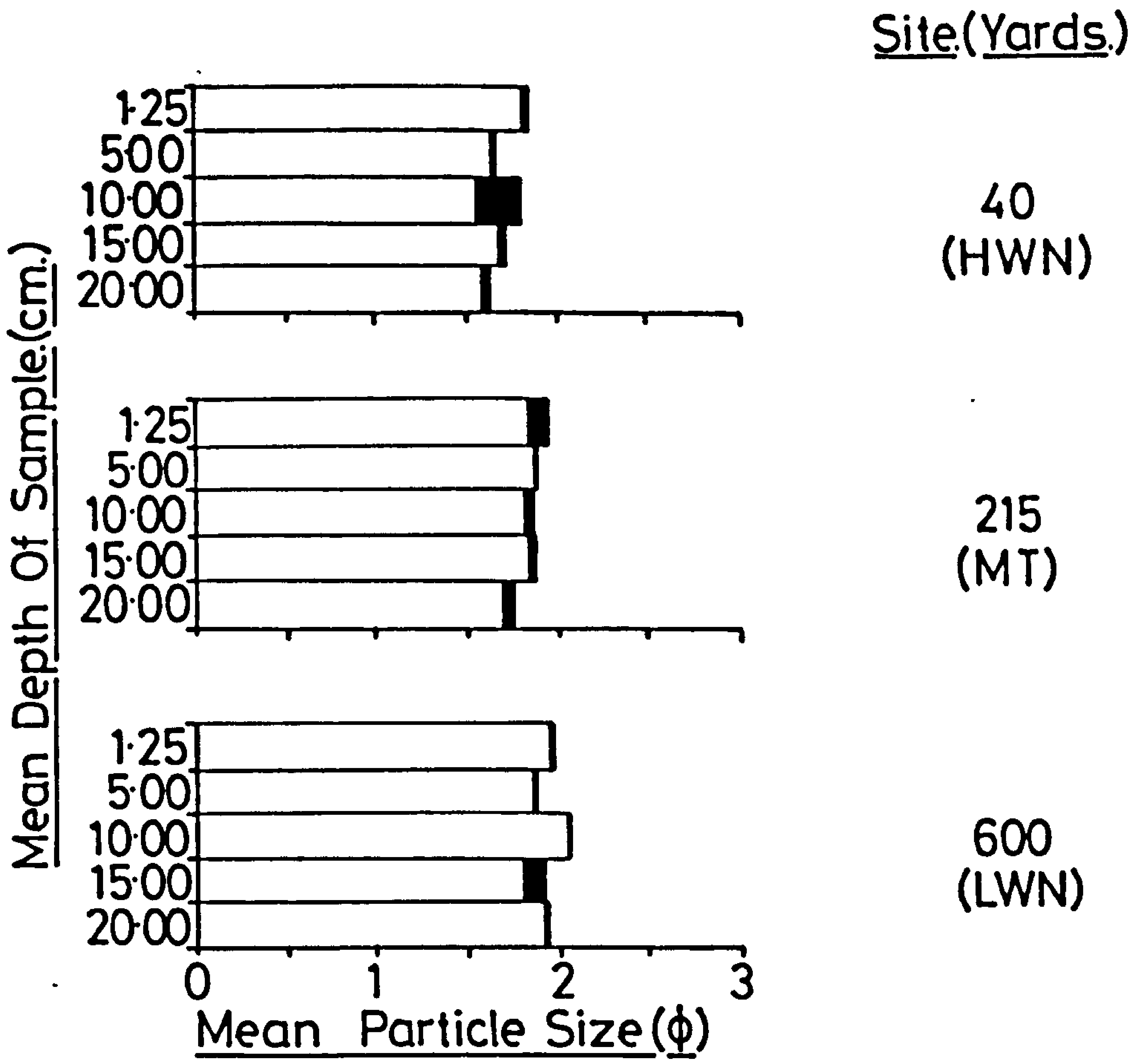


Fig. 4.

Mean Particle Size Profiles - Transect C - Summer.




Mean Particle Size Profiles - Transect C - Winter.

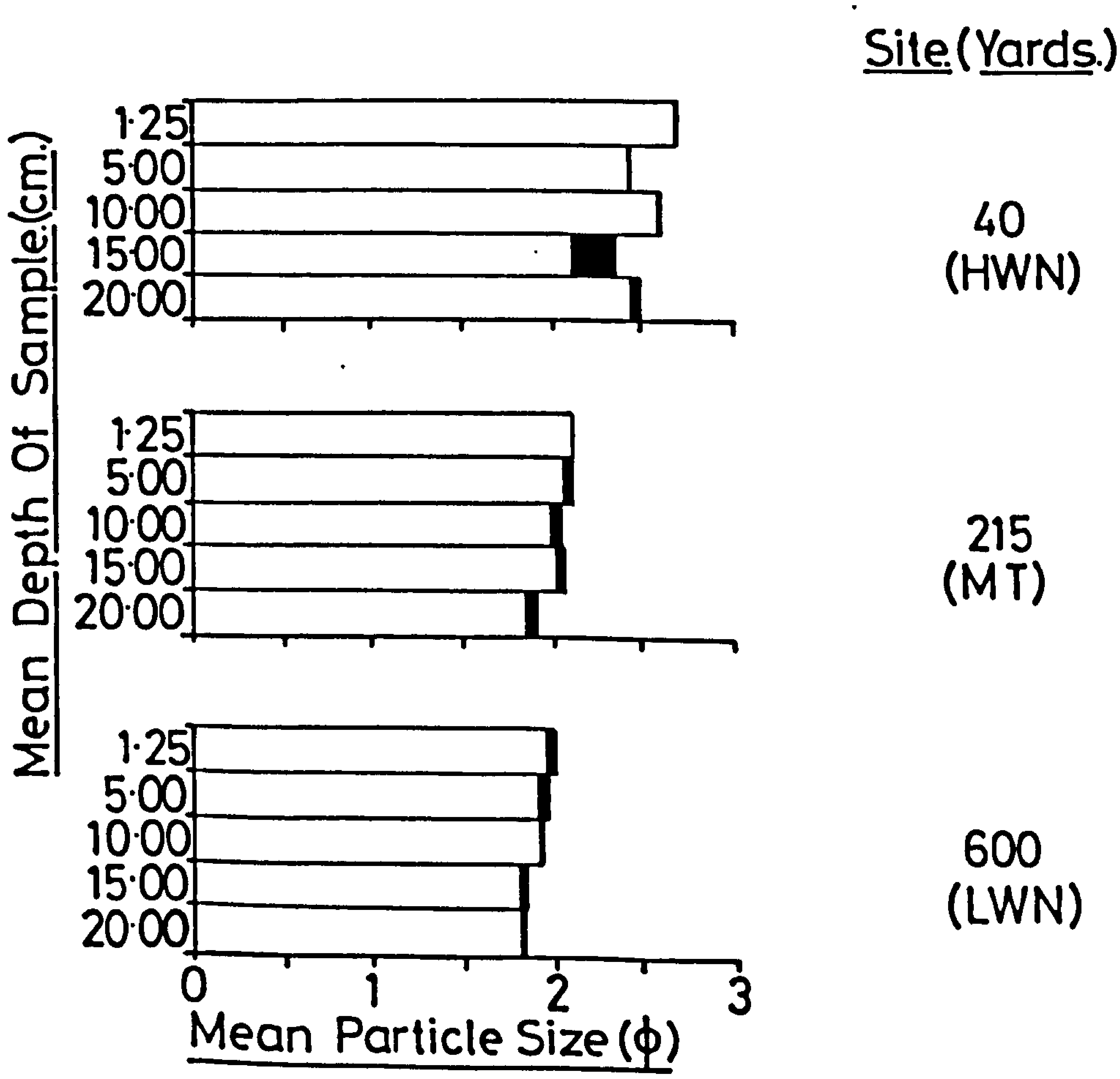


Fig. 5.

Particle Size Distribution Standard Deviation Profiles.

Transect A - Summer.

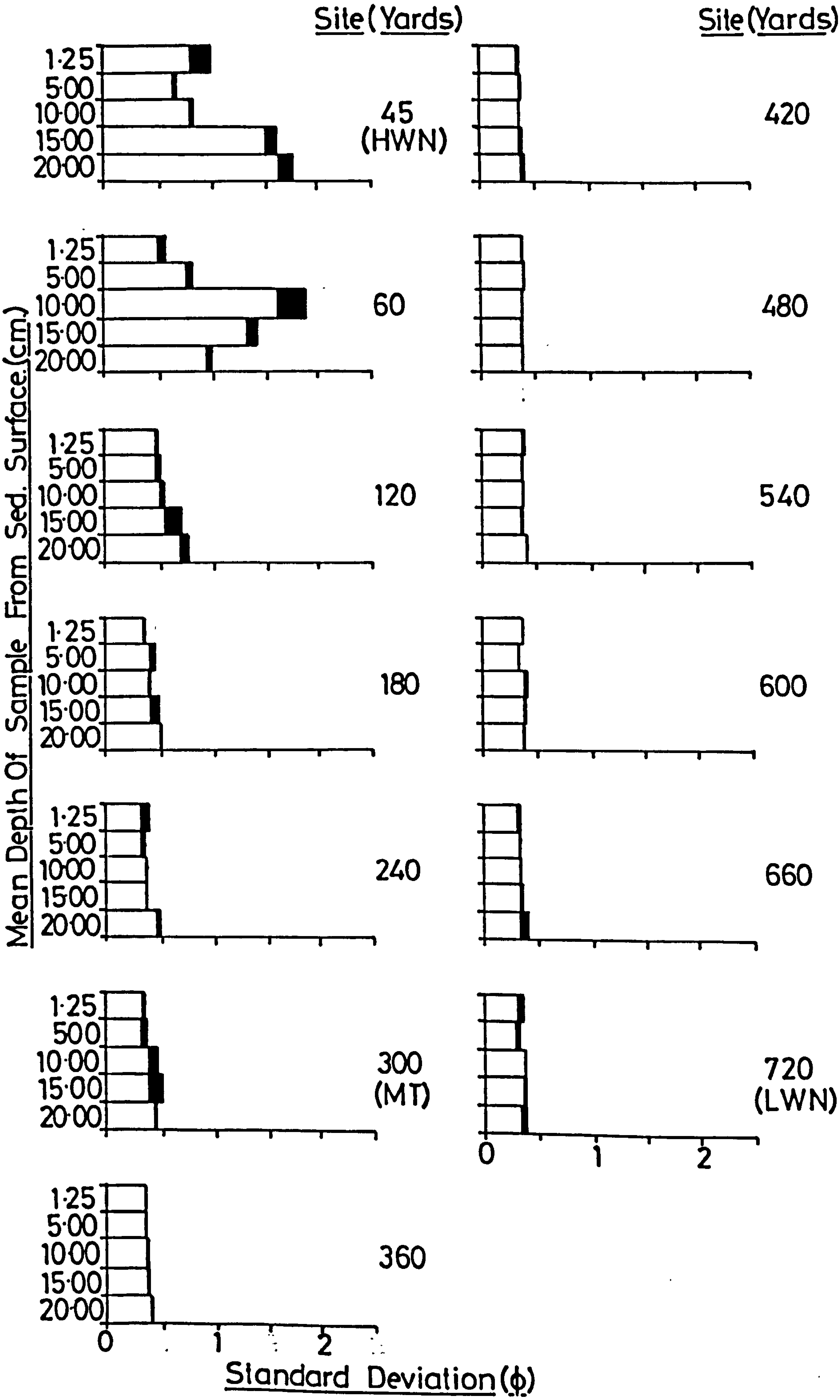


Fig.6.

Particle Size Distribution Standard Deviation Profiles.

Transect A - Winter.

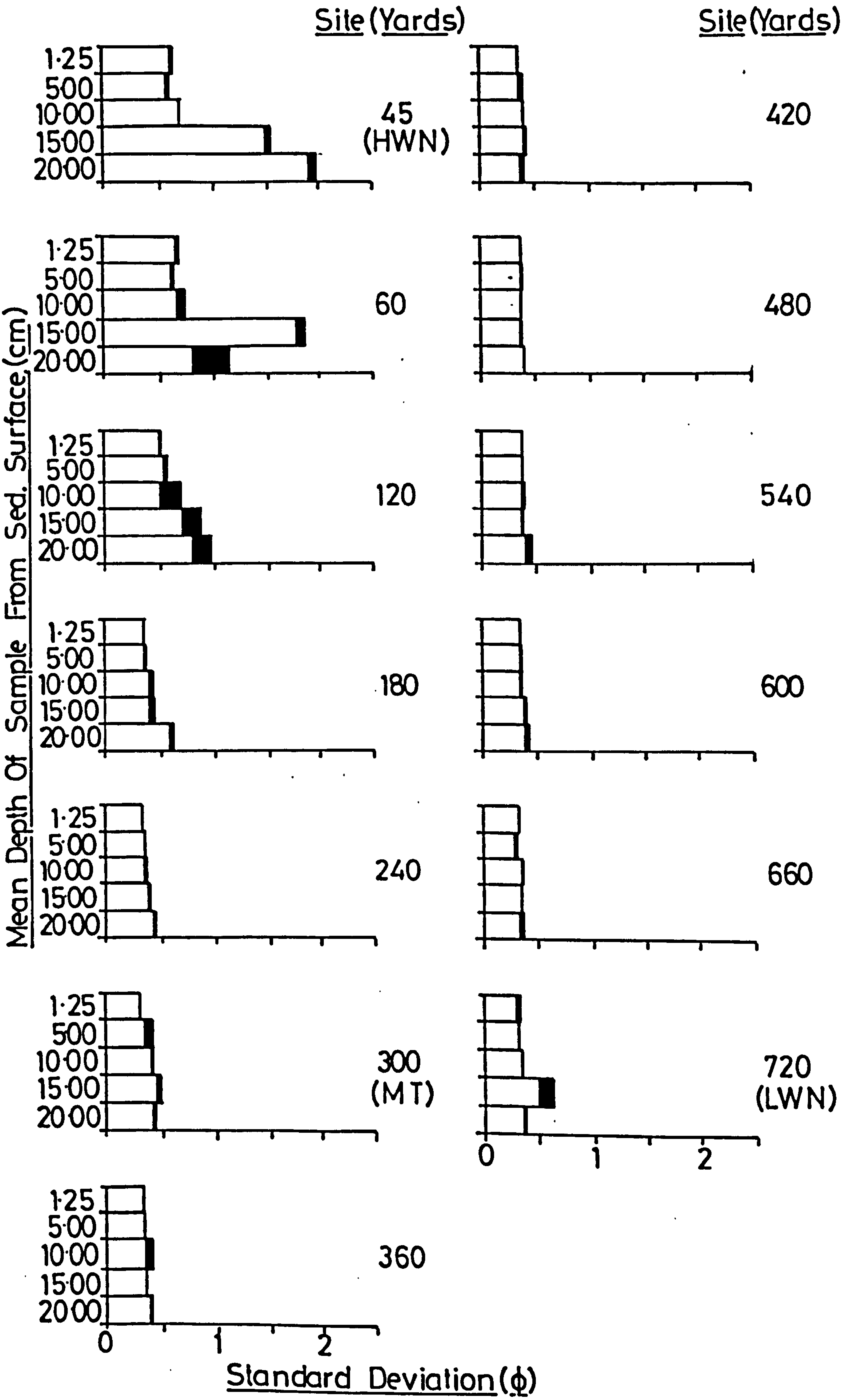
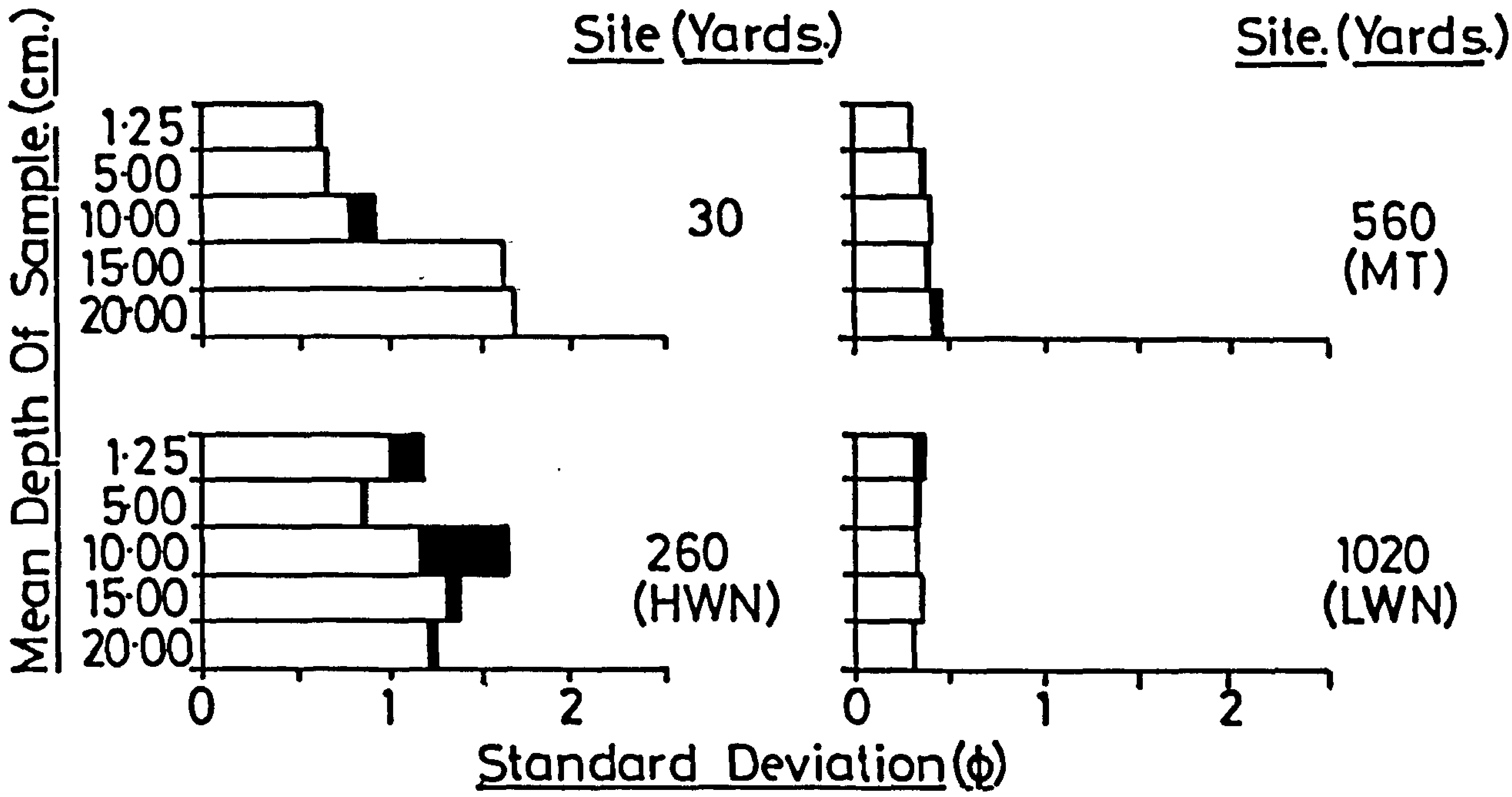


Fig. 7.

Particle Size Distribution Standard Deviation Profiles.

Transect B - Summer.




Transect B - Winter.

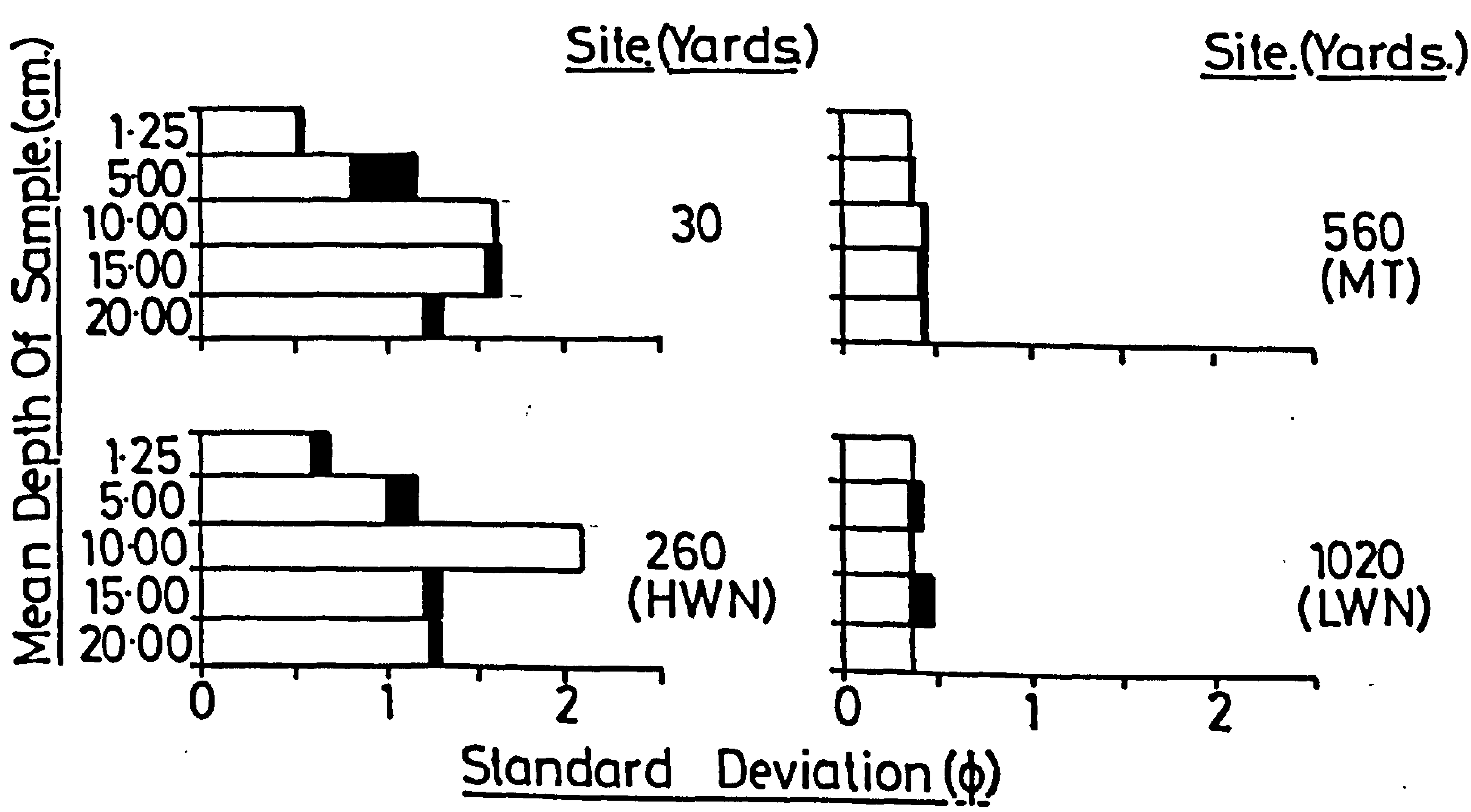
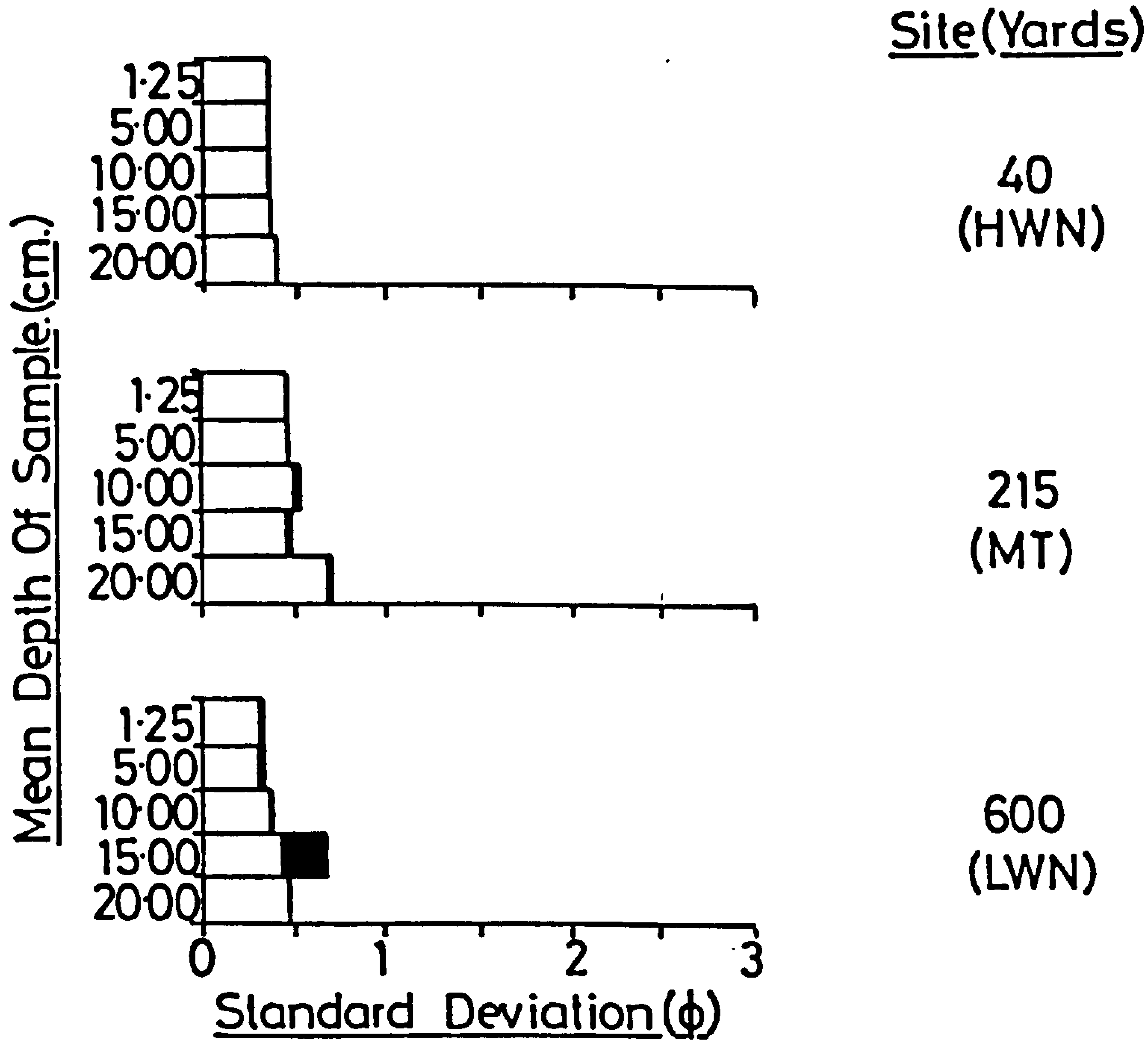


Fig. 8.

Particle Size Distribution Standard Deviation Profiles.

Transect C - Summer




Transect C - Winter

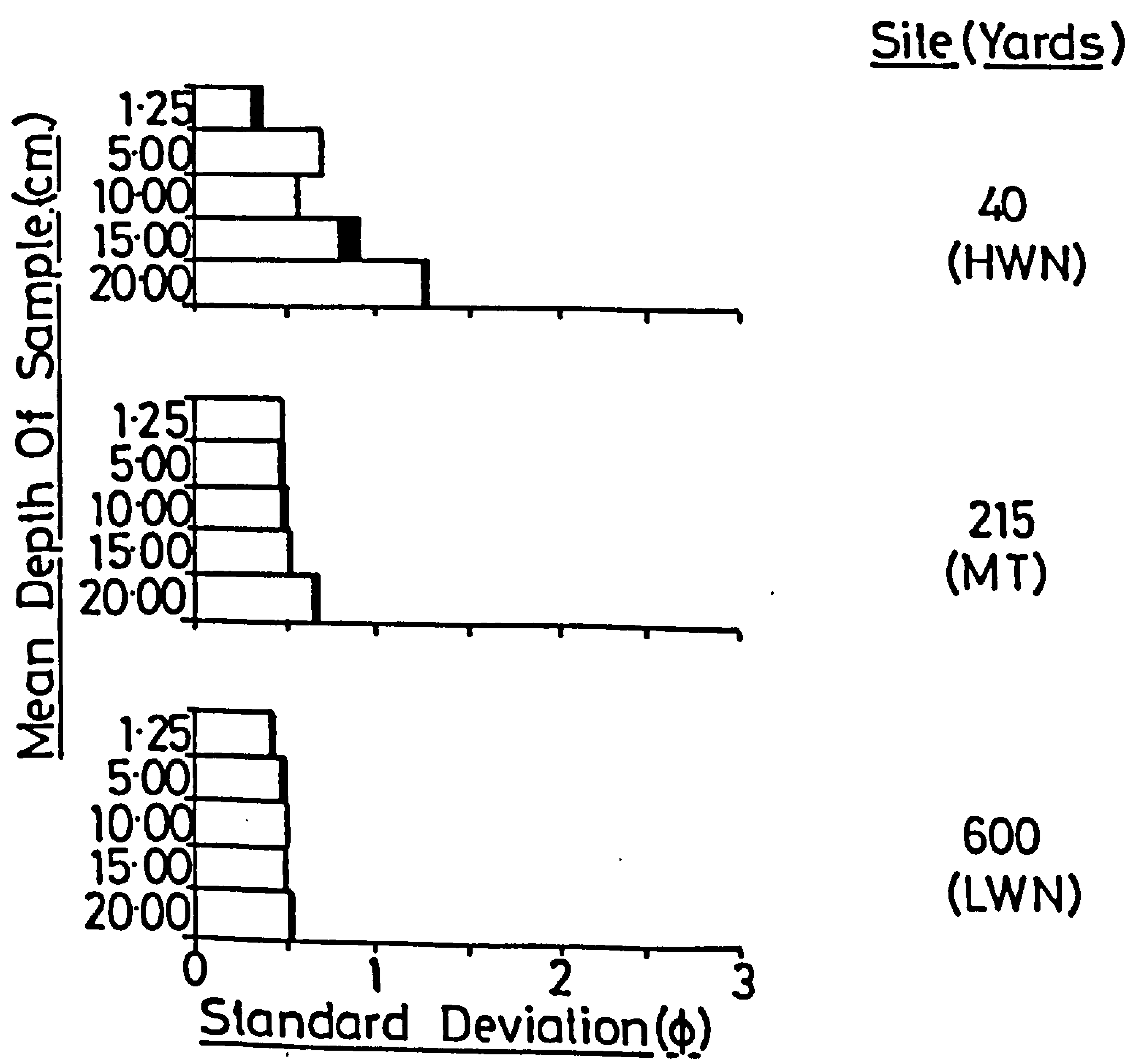


Fig.9.
Particle Size Distribution Skewness Profiles.
Transect A - Summer.

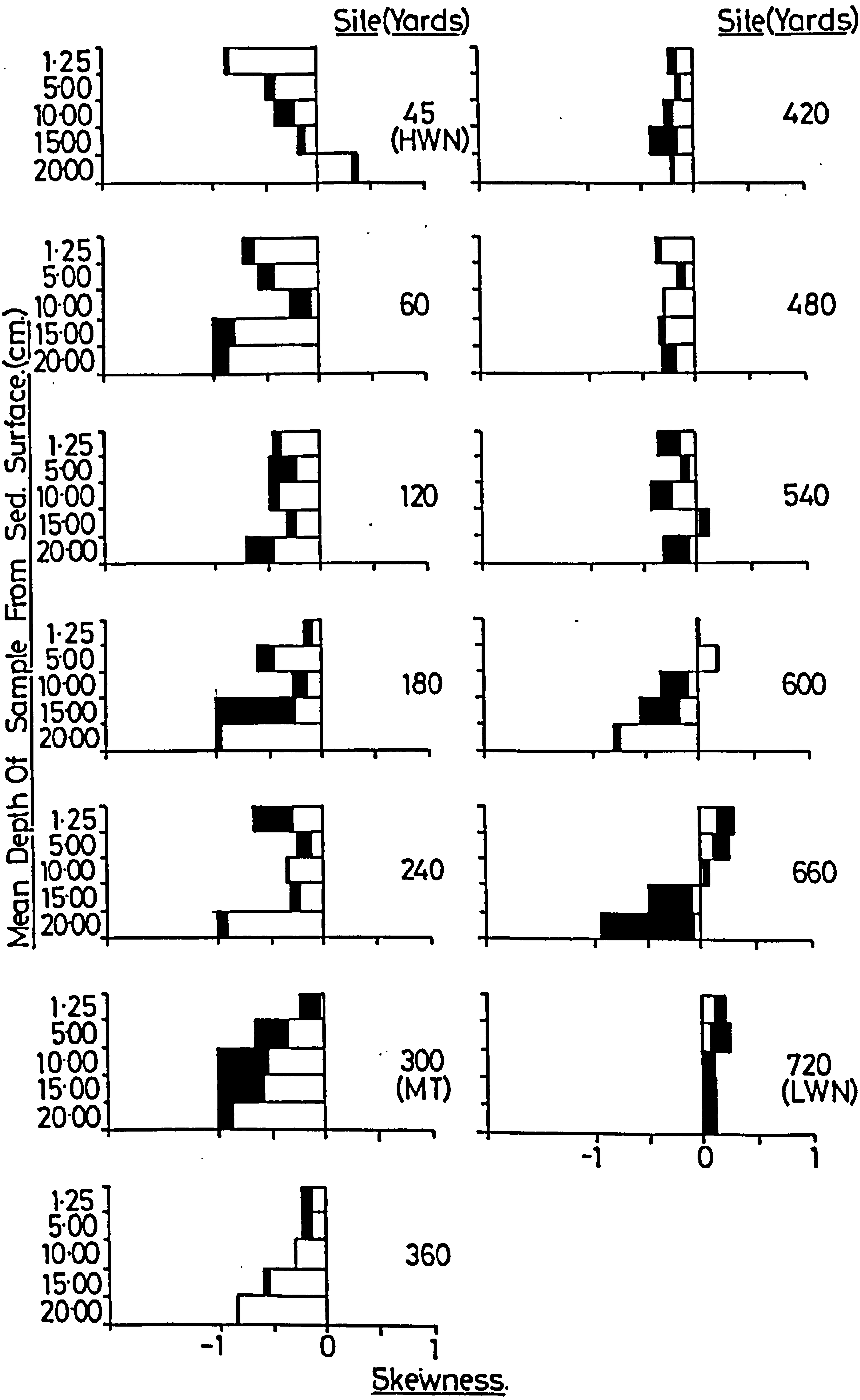


Fig.10.
Particle Size Distribution Skewness Profiles.
Transect A - Winter.

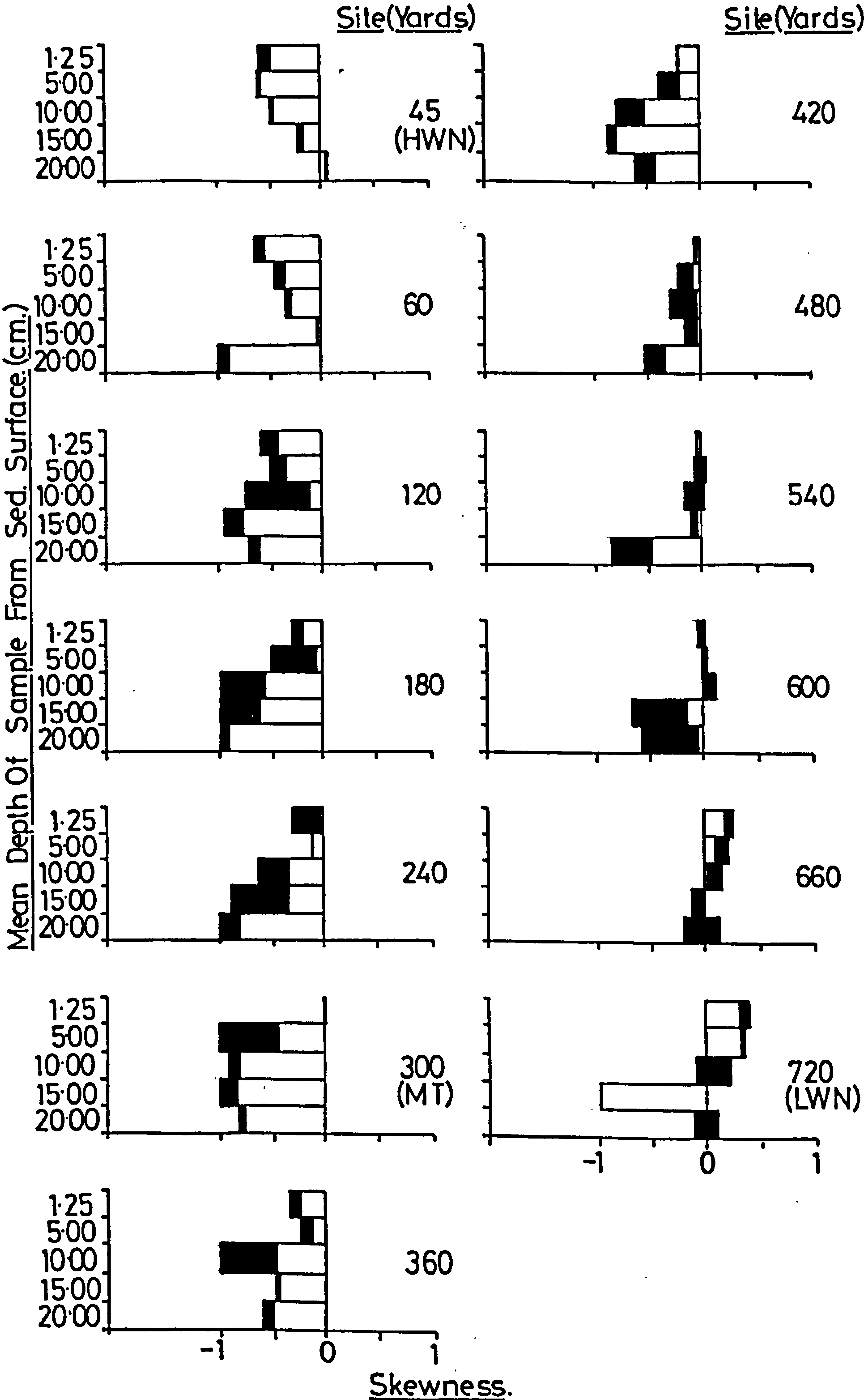
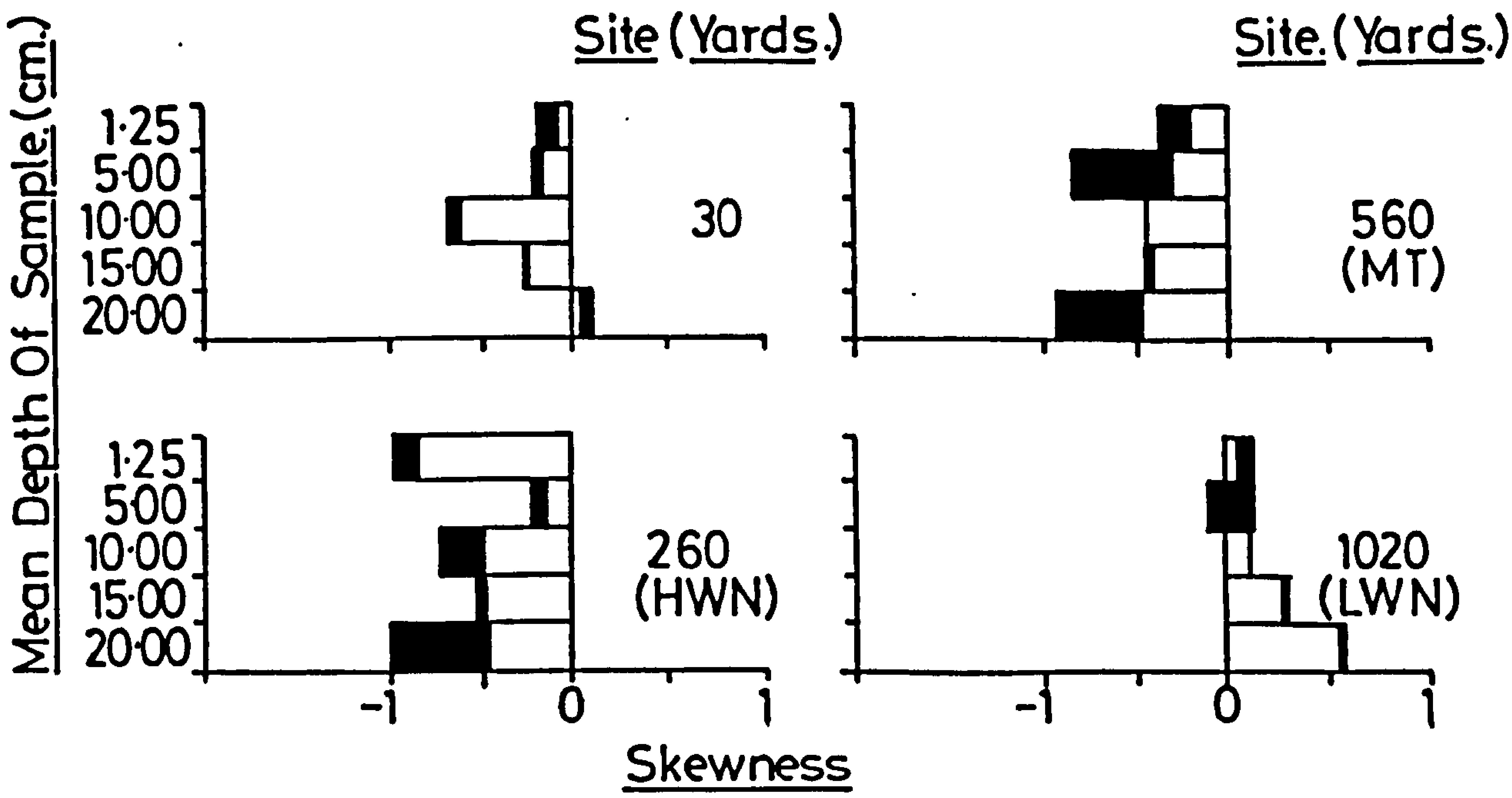


Fig.11.

# Particle Size Distribution Skewness Profiles.

## Transect B – Summer.




## Transect B – Winter.

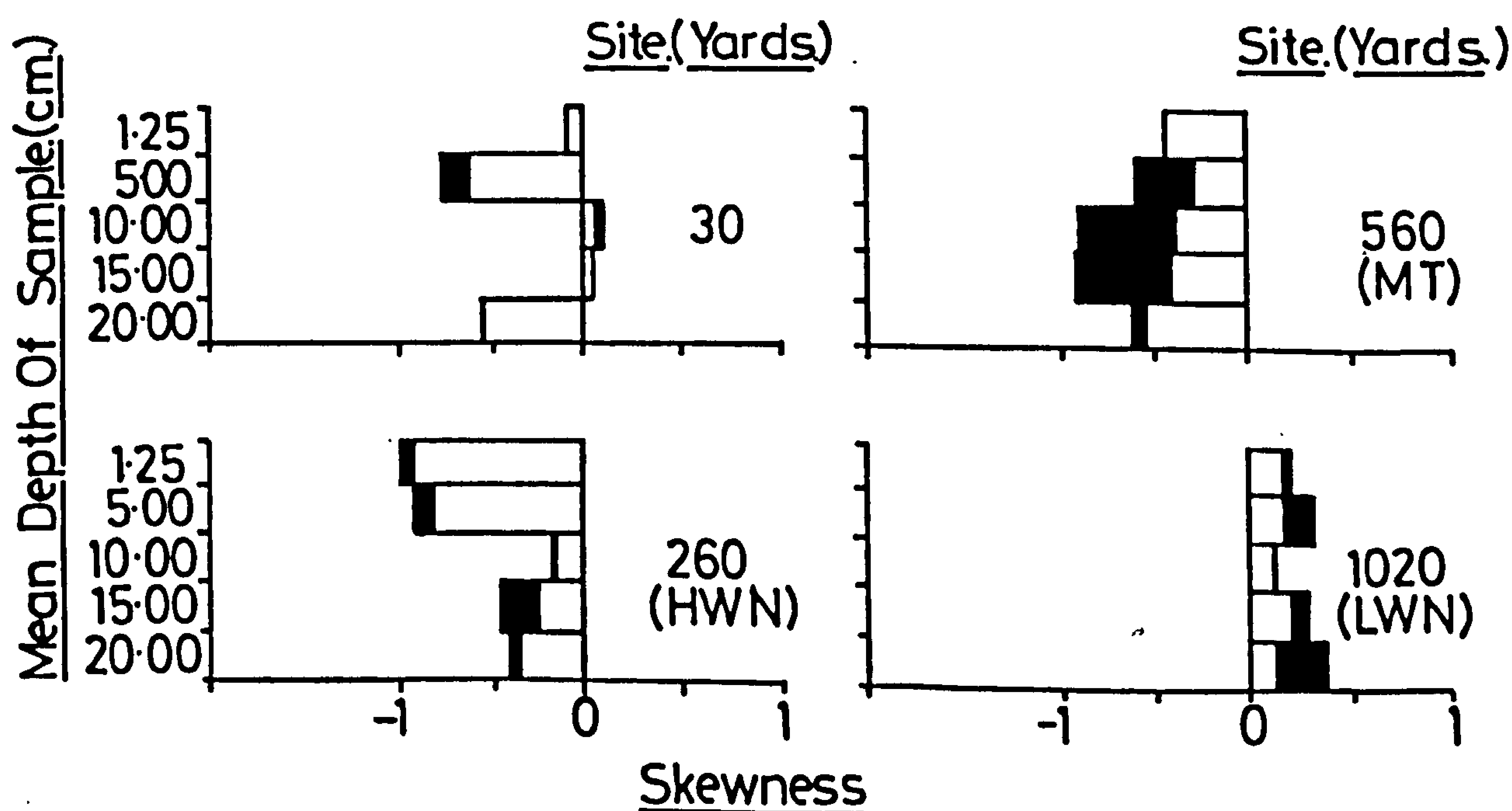
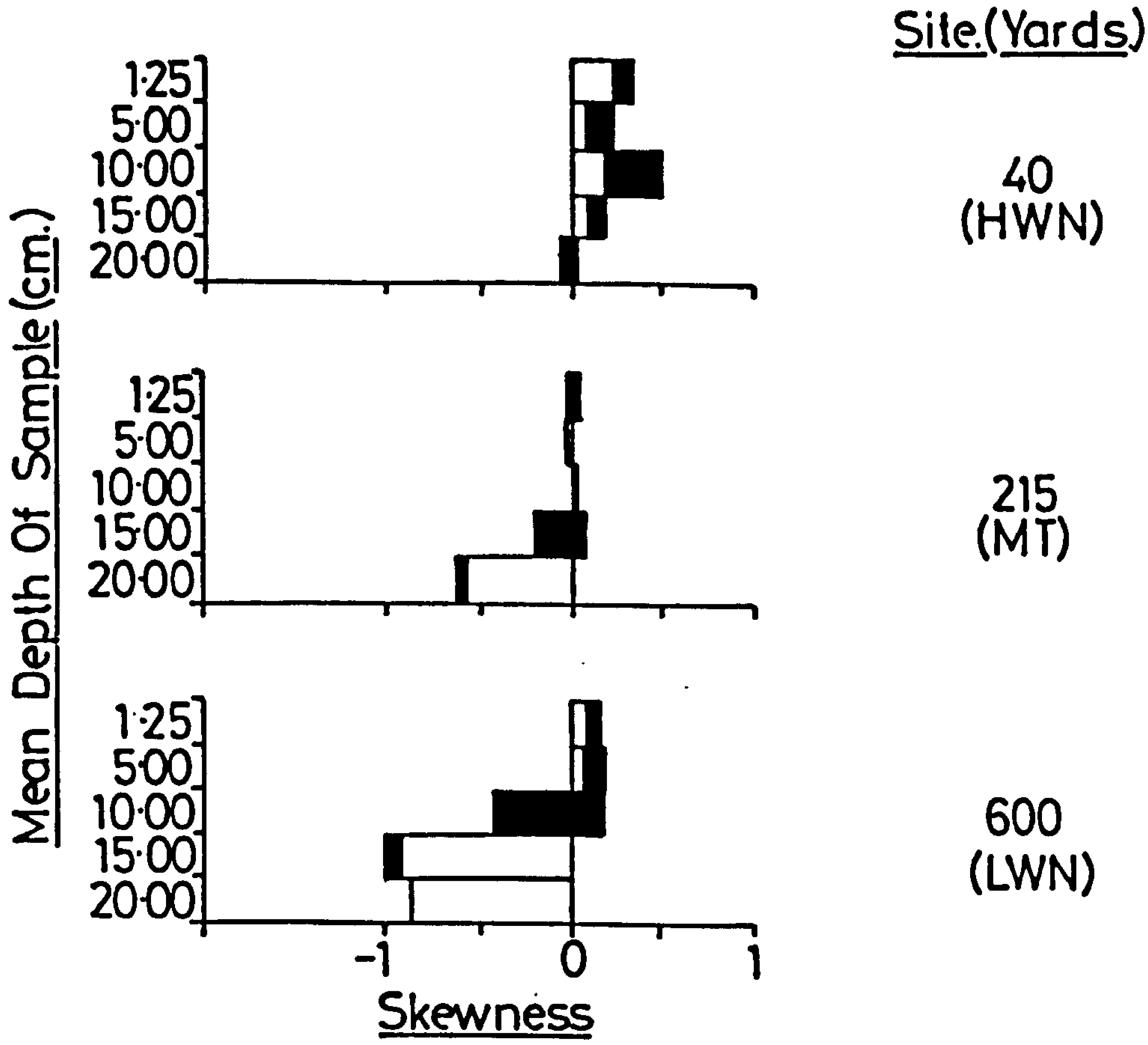


Fig. 12.

Particle Size Distribution Skewness Profiles.

Transect C - Summer.




Transect C - Winter.

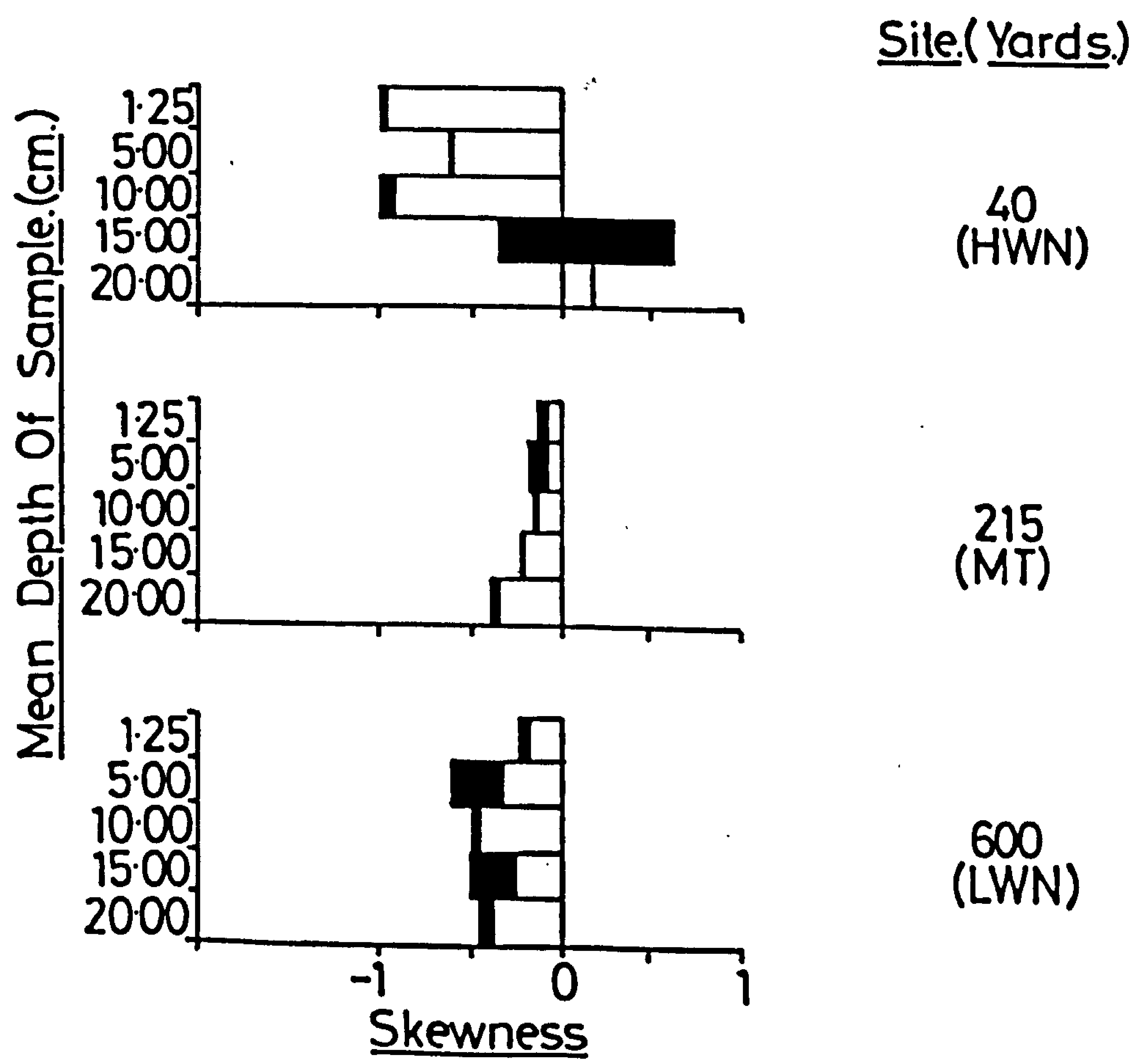


Fig.13.
Particle Size Distribution Kurtosis Profiles.
Transect A - Summer.

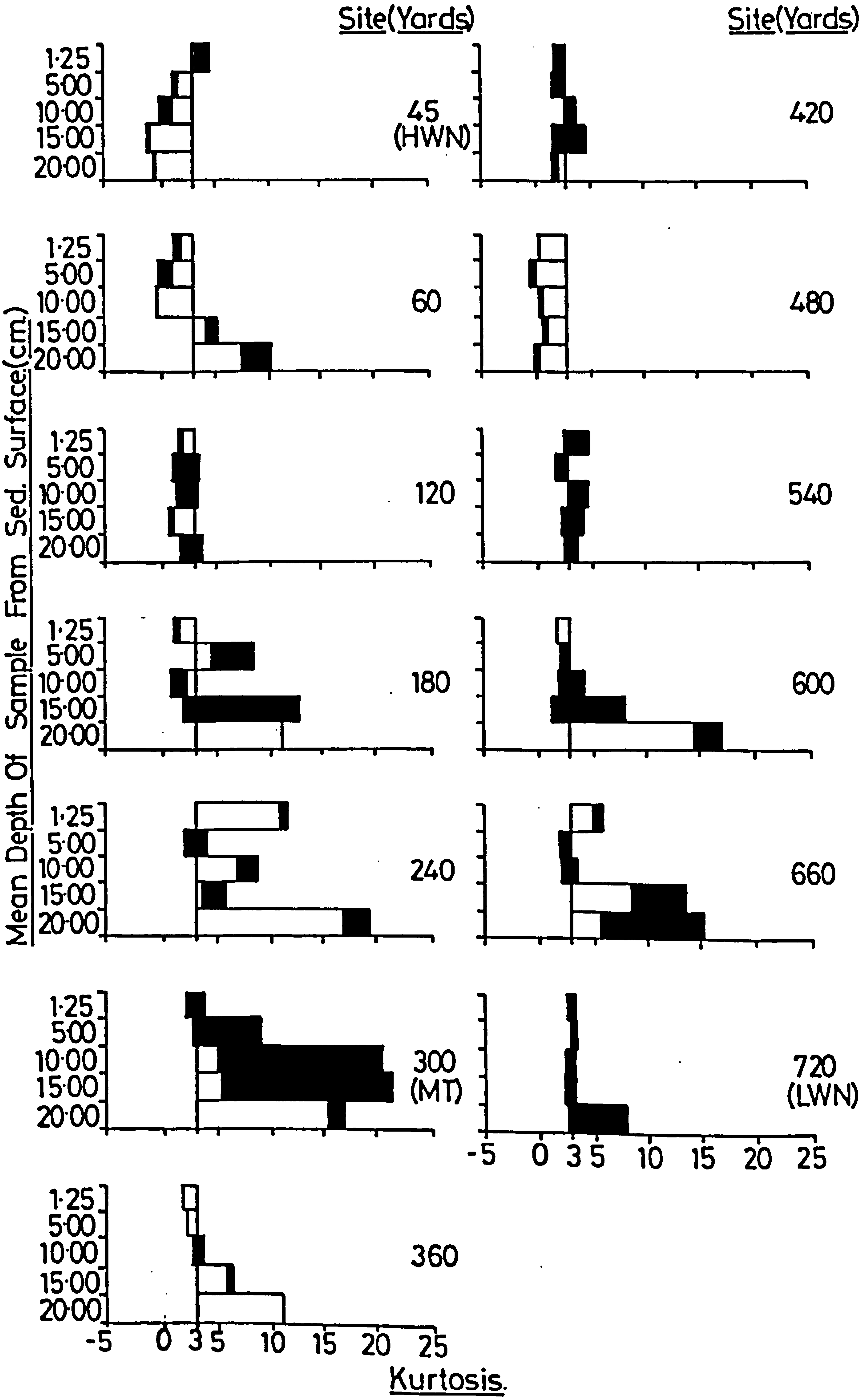


Fig.14.

Particle Size Distribution Kurtosis Profiles.

Transect A - Winter.

Fig.15.
Particle Size Distribution Kurtosis Profiles.

# Fig.16.
## Particle Size Distribution Kurtosis Profiles.
### Transect C - Summer.

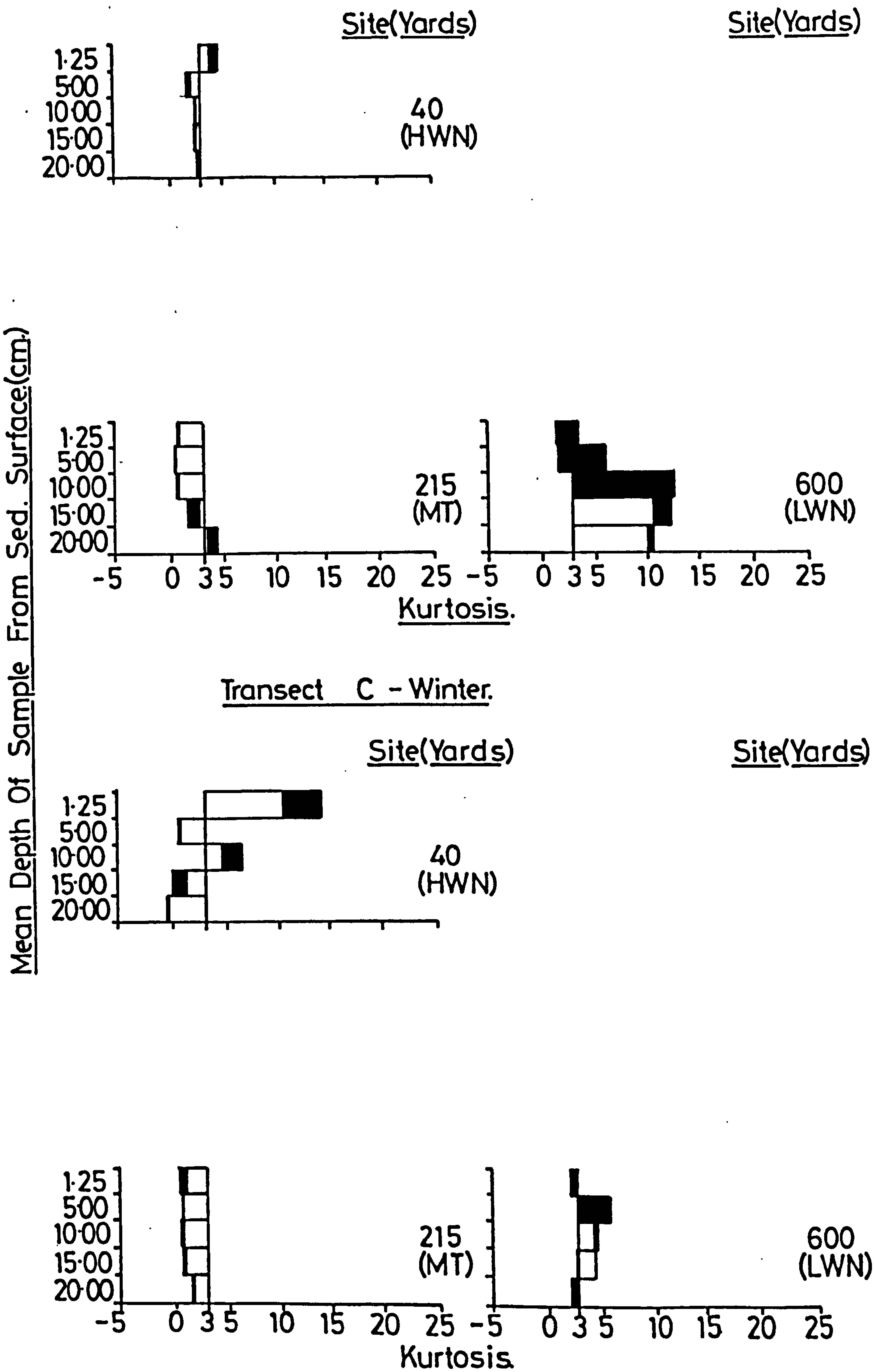


Fig.17.

Characteristic Profiles Of Sediment Particle Size Distribution Statistics Within Three Identifiable Zones On Transect A

increases down the shore and ranges from well to very well sorted. Superimposed upon this is a pattern of decreasing sorting with depth. The distributions are progressively skewed towards finer grain sizes down the shore but towards coarser sizes with depth. Peakedness of the distribution patterns oscillates down the shore. The distributions are approximately normal at four sites (120, 420, 540 and 720 yards). Between the first two and the last two of these they are less peaked. Between the middle two, they are strongly peaked. Peakedness decreases with depth at all sites.

Similar characteristic profiles are evident for the corresponding reference tidal levels on the other two transects. This would suggest a similar pattern of zonation.

With the exception of those for the High Water Neaps site on Transect 'C', there are no marked differences between the summer and winter profiles. The differences which are evident at this one site probably reflect the rapid transition between sediment types in this region of the shore (as illustrated by Transect 'A') rather than a seasonal effect.

(ii) Percentage Organic Matter Content Of The Sediment

The results of the survey are illustrated in Figures 18 to 21 . Overall the Organic Matter Content ranges between 0.3 and 8.2%. Within this range there are distinct trends down the transects.

Transect 'A' - This transect can be divided into two zones:

(i) Down to Mid-Tide - Organic Matter Content ranges between 0.4 and 8.2%. The content increases towards High-Water and with Depth into the sediment.

(ii) Below Mid-Tide - Organic Matter Content ranges between 0.3 and 1.5%. It remains relatively constant down to Low Water and there is no, or only a slight increase with Depth.

Transect 'B' - A comparison of the profiles at the three reference sites (HWN, MT and LWN) on this transect and the equivalent ones on Transect 'A' shows them to be almost identical. This would suggest a similar pattern of zonation. Data for the 30 yard site indicates a reduction in content

## FIGURES 18 TO 21.

Profiles of Organic Matter Content of the sediment down the transects.

Notes.

As for Figures 1 to 16.

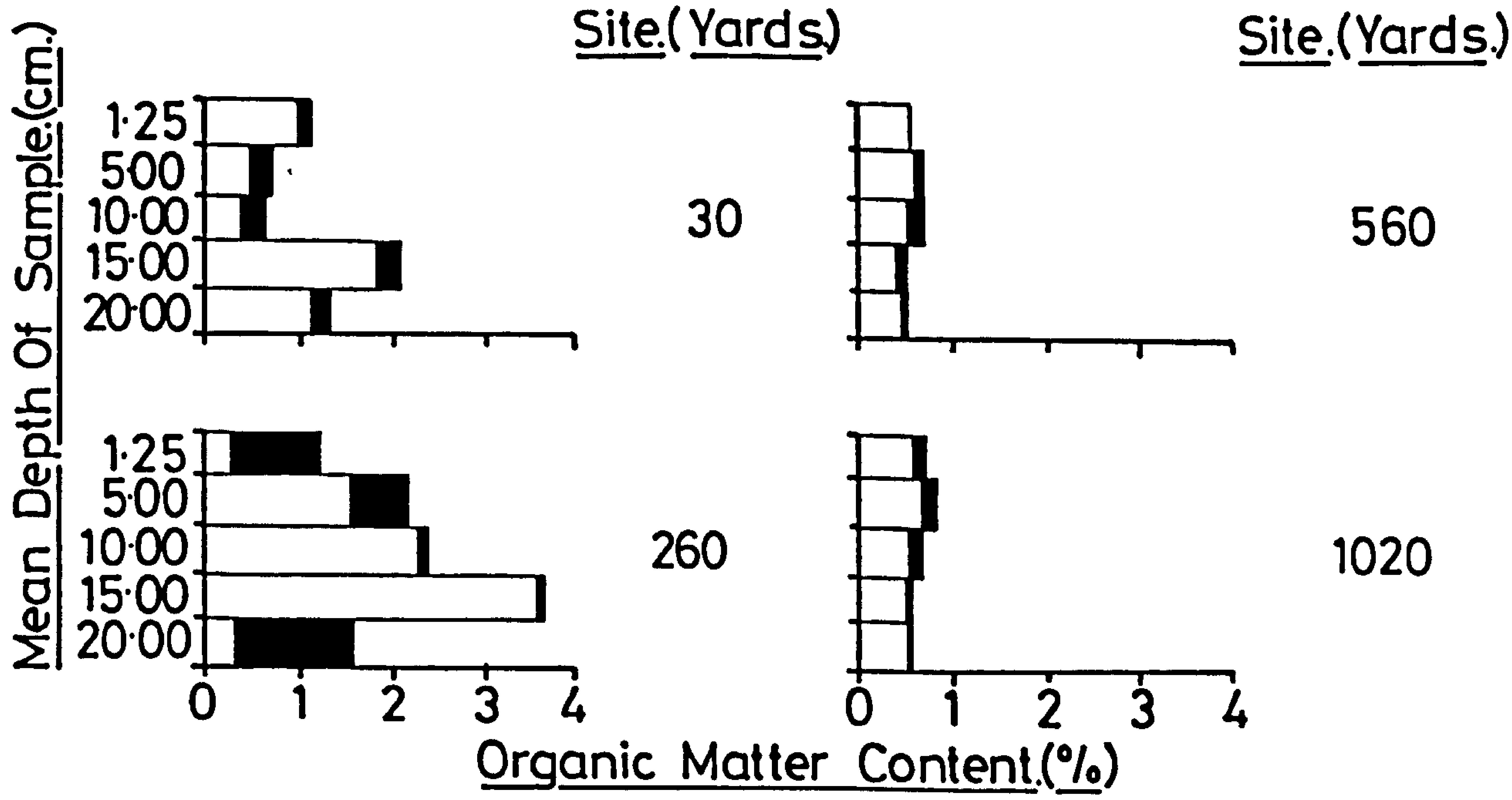
Fig.18.

Organic Matter Content Profiles-Transect A - Summer.

Fig.19.
Organic Matter Content Profiles-Transect A-Winter.

Fig. 20.

Organic Matter Content Profiles - Transect B - Summer.




Organic Matter Content Profiles - Transect B - Winter.

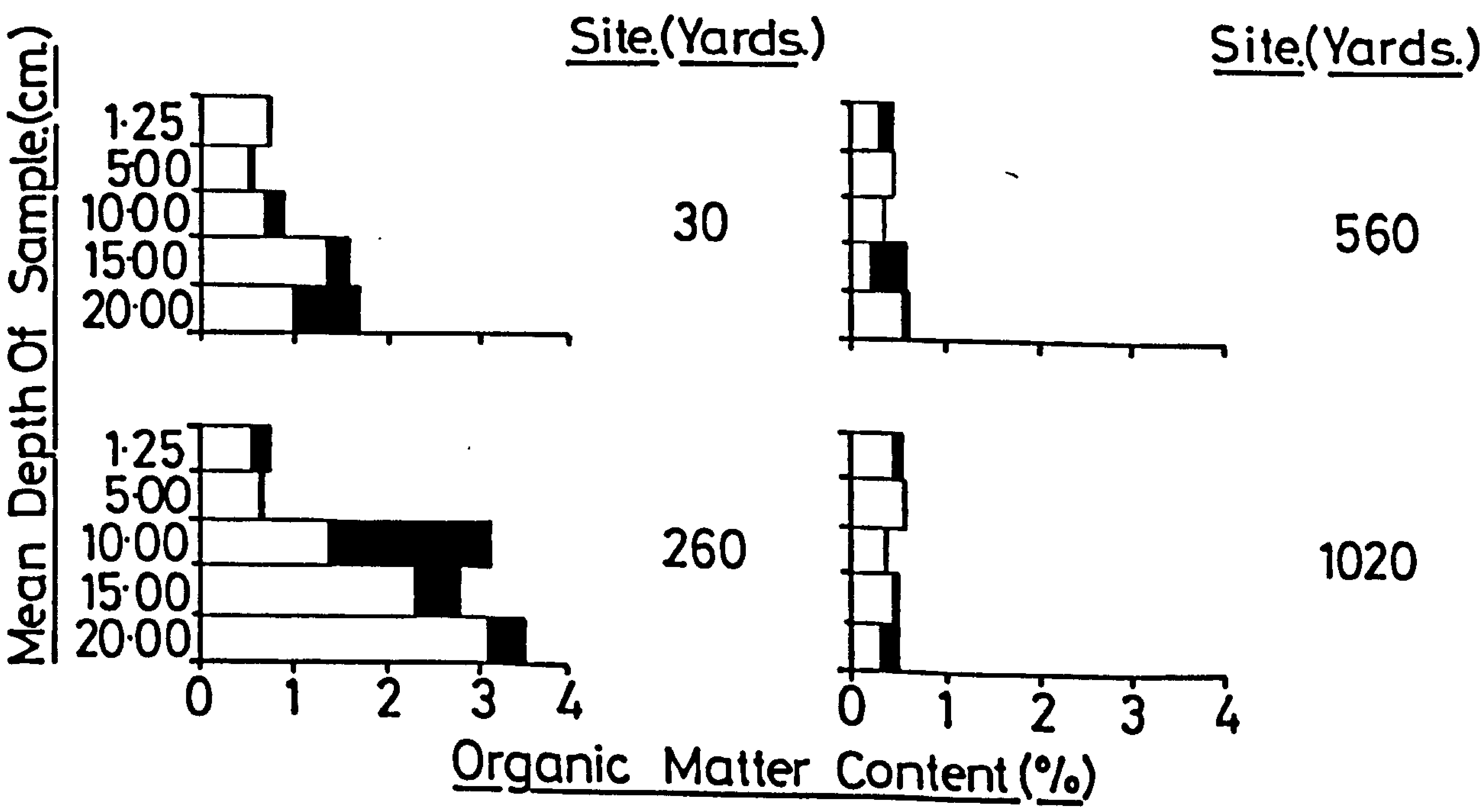
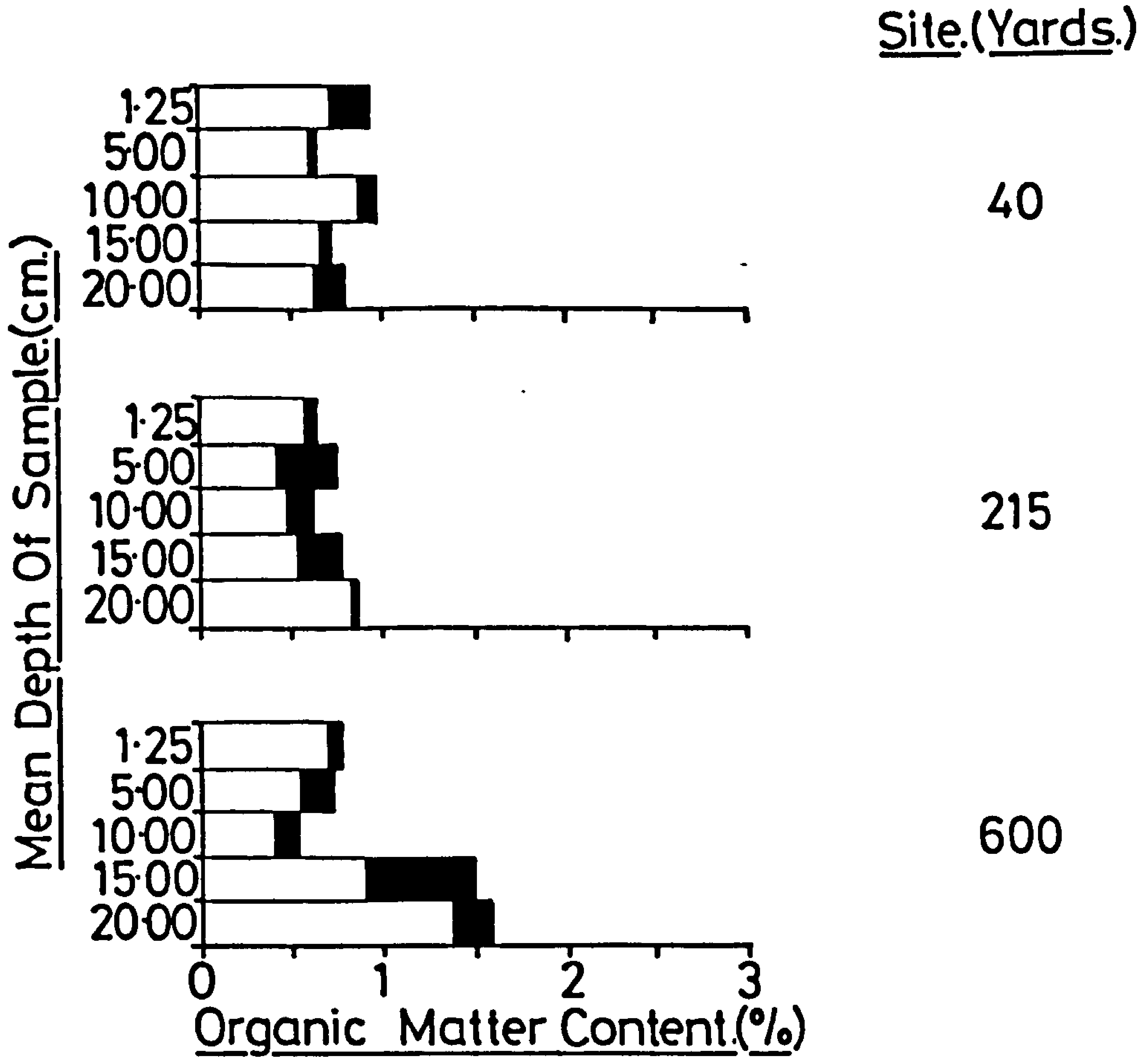
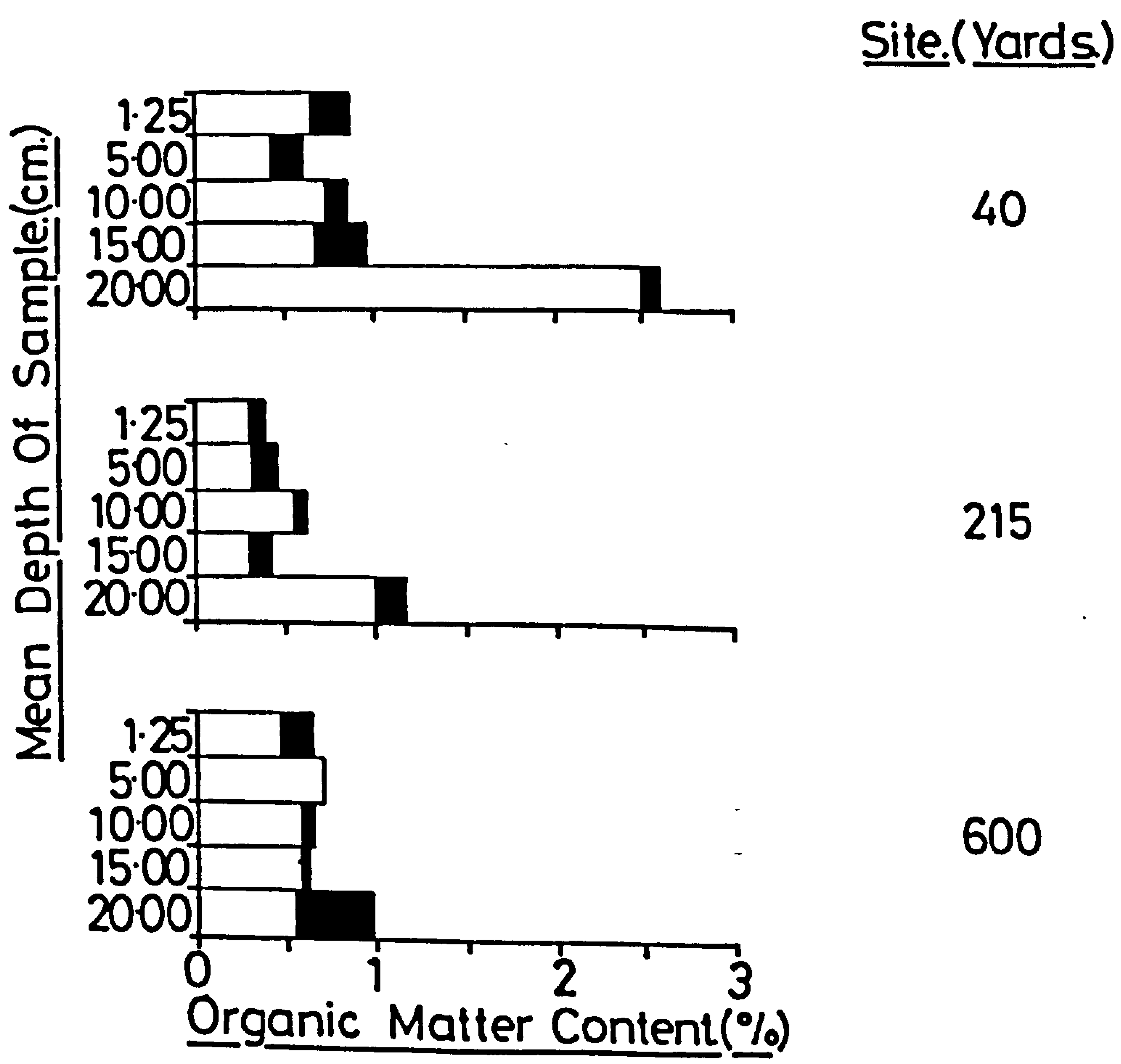


Fig. 21.

Organic Matter Content Profiles - Transect C - Summer.




Organic Matter Content Profiles - Transect C - Winter.



above HWN. There is still an increase in content with depth. Transect 'C' - Organic Matter Content profiles at the MT and LWN sites on this transect are similar to those at the equivalent sites on 'A' and 'B'. The content at the HWN site is however, significantly lower (0.5 to 2.5%) and there is no consistent increase with depth.

There are no obvious differences between the general characteristics of the summer and winter profiles. There is however, a strong indication that the content of the surface sediments is highest in summer. (See Table 5 ). This trend is absent in deeper samples.

(iii) Shear Strength Of The Sediment

Peak and Residual Shear Strength profiles down the three transects are shown in Figures 22 to 25 and 26 to 29 respectively.

Peak Strength is approximately two to four times higher than Residual, however, the overall characteristics of their profiles down the transects are very similar. There are no consistent differences between summer and winter profiles.

At all sites, Shear Strength increases with depth. The gradient of this increase varies; on Transects 'A' and 'C' it is steepest at sites close to High Water. It decreases to a minimum at Mid-Tide, then increases slightly before remaining stable down to Low-Water. On Transect 'B' it is a maximum at High Water and minimum at Low-Water. The Shear Strength values at the surface and 20cm depth which result in these gradients are shown in Table 6 .

Table 6 also serves to compare Shear Strength profiles between transects at the reference tidal levels HWN, MT, and LWN. The important points to note from this comparison are:

(i) The profiles are similar for all three transects at the MT and LWN positions.

(ii) The profiles are similar at the HWN position on Transects 'A' and 'B'.

(iii) At the HWN position on Transect 'C' the strength of the surface sediment is similar to that on

## TABLE 5

**A Comparison Of The Relative Organic Matter Contents Of Sediment Samples Collected in Summer and Winter Down Transects 'A', 'B' and 'C'**

| Depth Interval (cm) | Summer Content Highest | Summer & Winter Content Similar | Winter Content Highest |
|---|---|---|---|
| 0 - 2.5 | 17 | 2 | 1 |
| 2.5- 7.5 | 14 | 4 | 2 |
| 7.5-12.5 | 14 | 2 | 4 |
| 12.5-17.5 | 11 | 5 | 4 |
| 17.5-22.5 | 10 | 3 | 7 |

The data is expressed as the number of sites out of a total of 20.

FIGURES 22 TO 29.

Peak and Residual Shear Strength profiles down the transects.

Notes.

As for Figures 1 to 16.

# Fig. 22.

## Peak Shear Strength Profiles – Transect A – Summer.

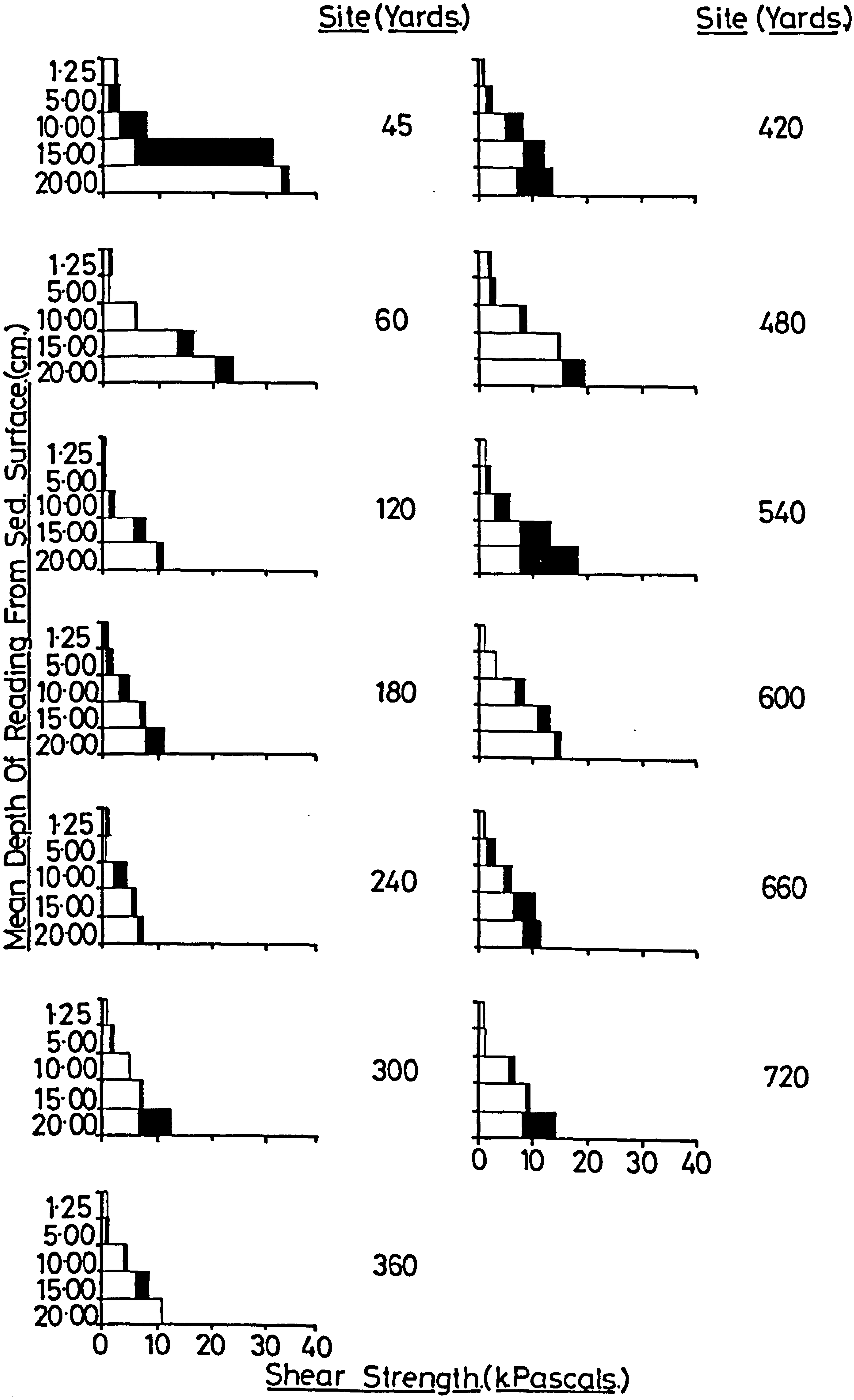
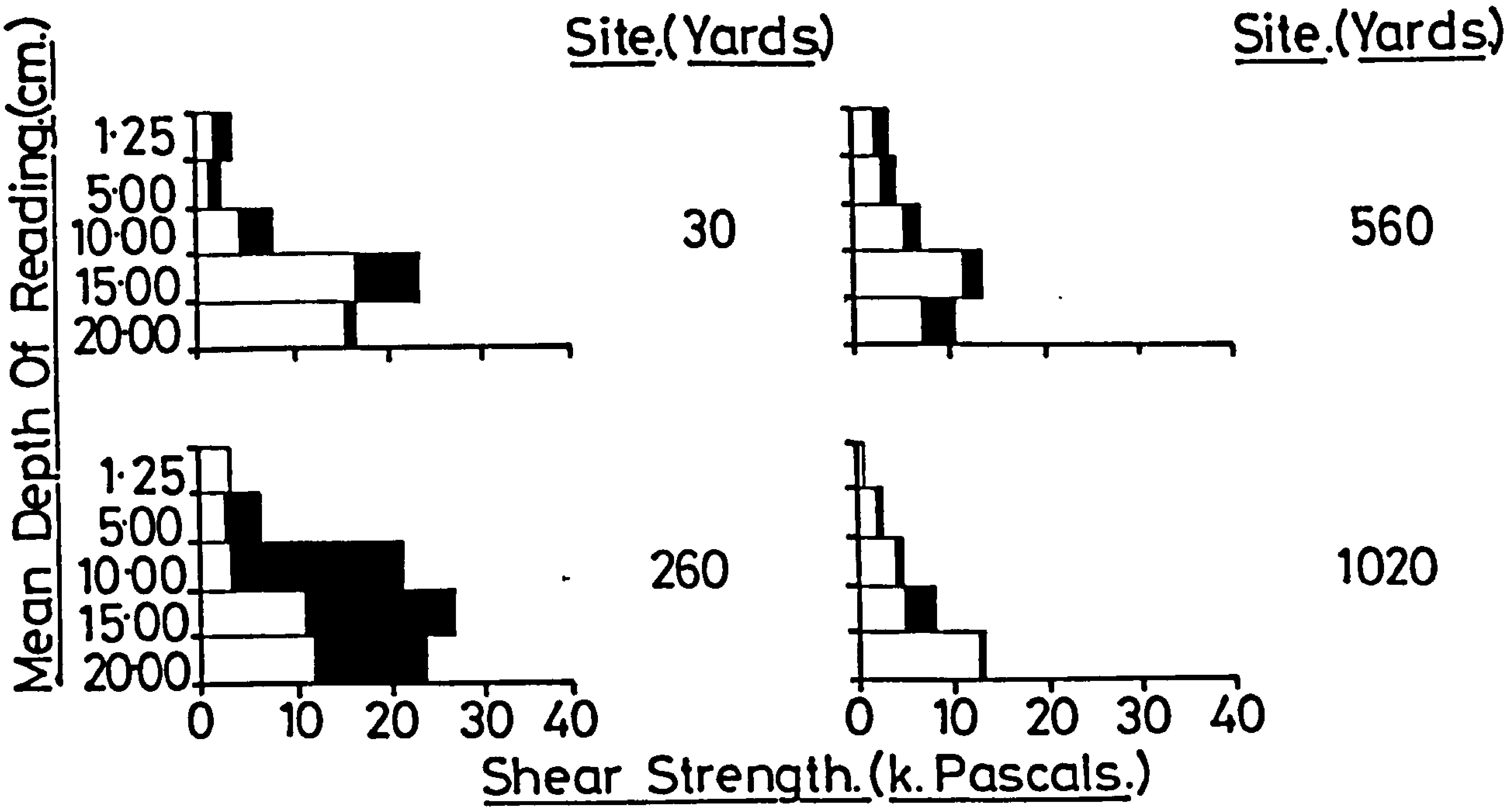


Fig. 23.

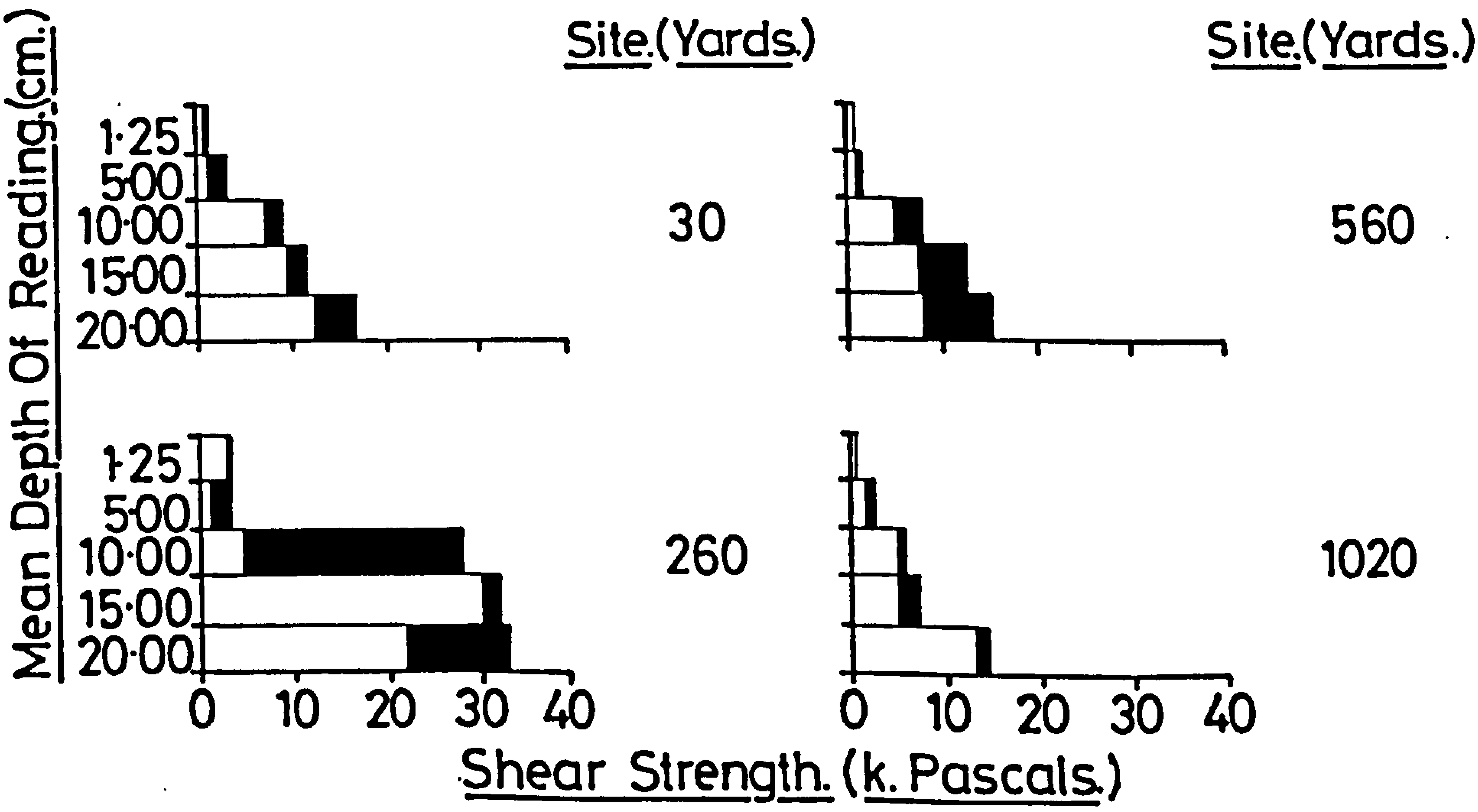
Peak Shear Strength Profiles - Transect A - Winter.

Fig. 24.

Peak Shear Strength Profiles - Transect B - Summer.

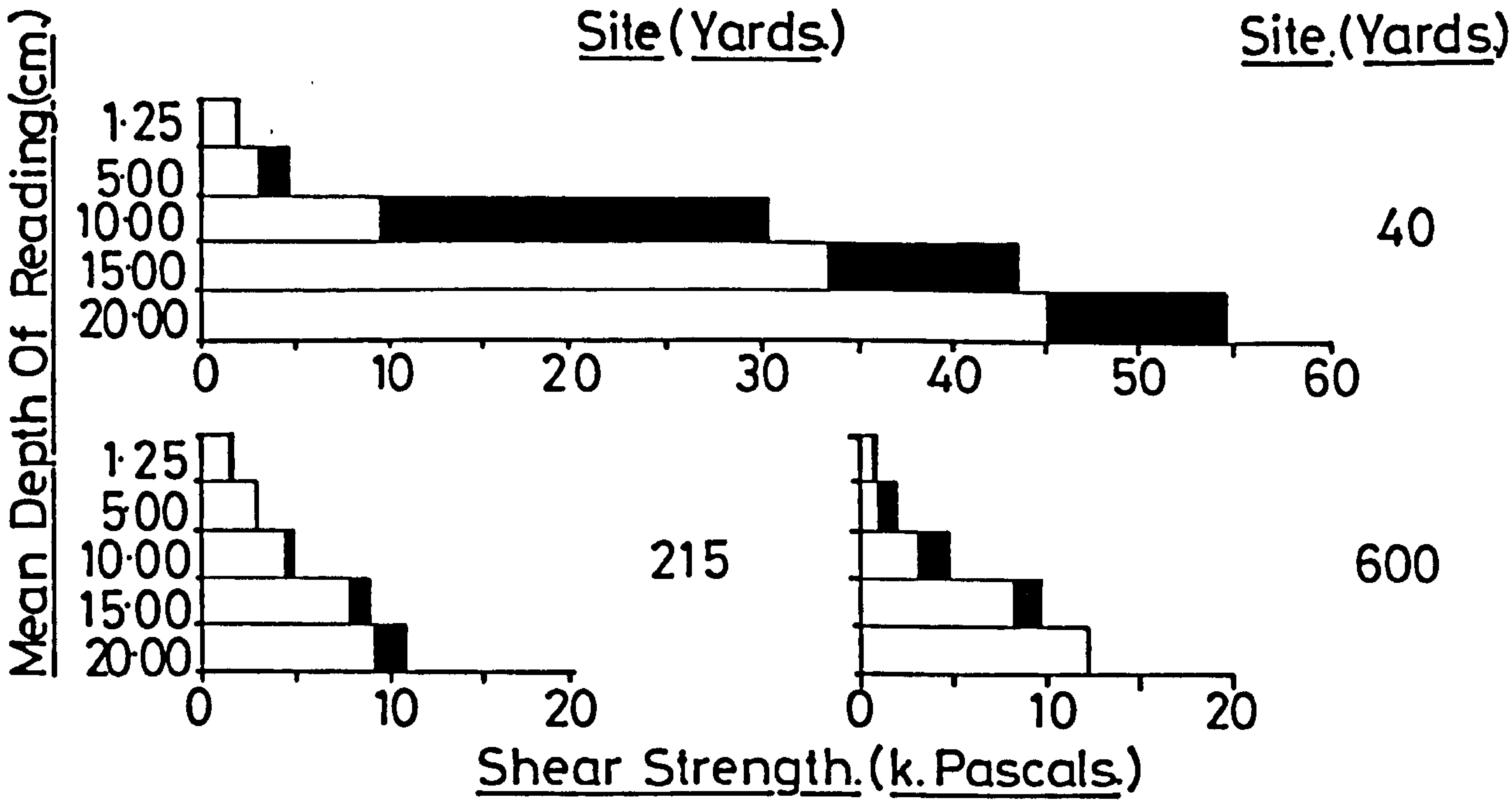



Peak Shear Strength Profiles - Transect B - Winter.



# Fig. 25.

## Peak Shear Strength Profiles - Transect C - Summer.




## Peak Shear Strength Profiles - Transect C - Winter.

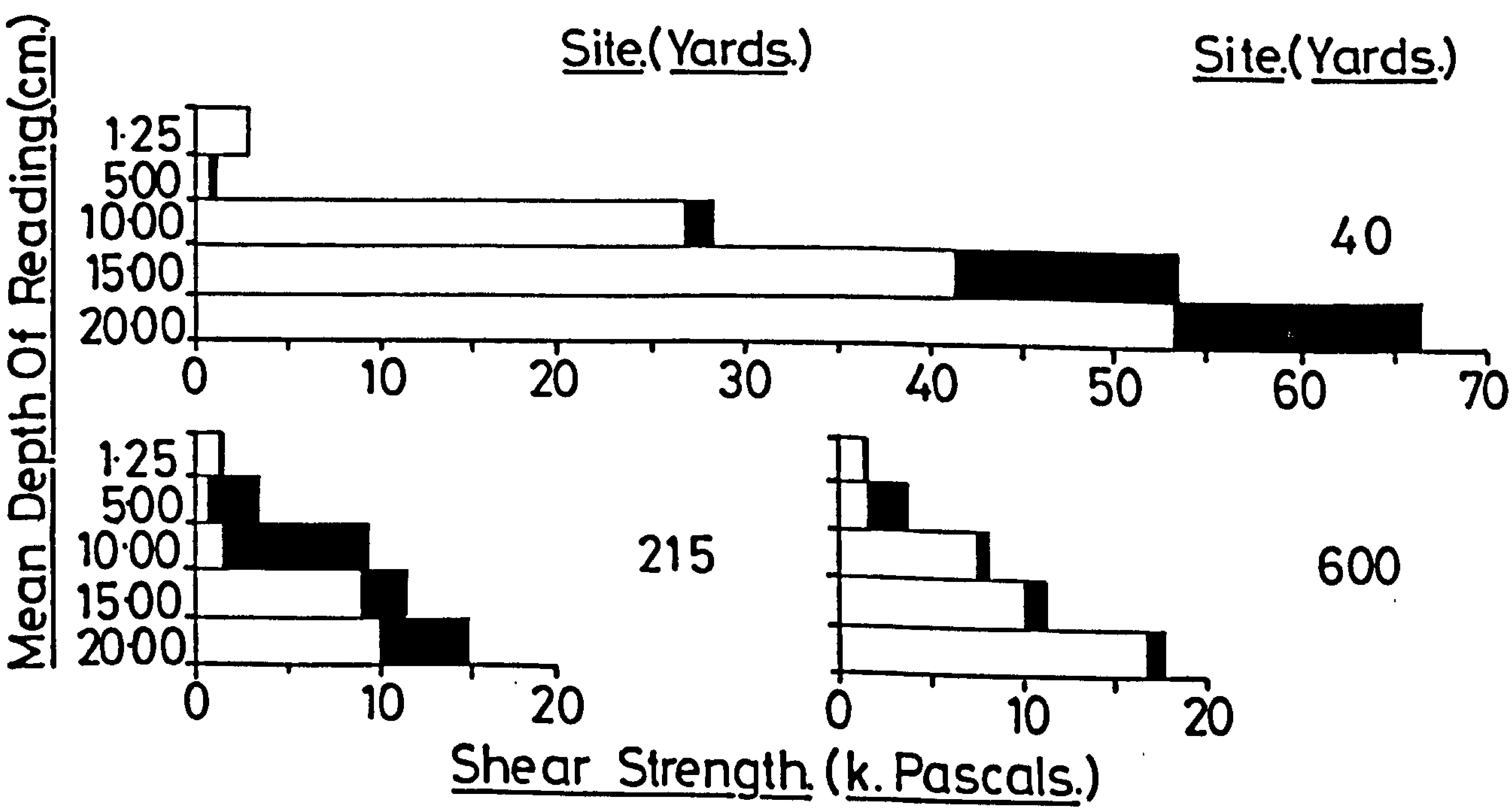


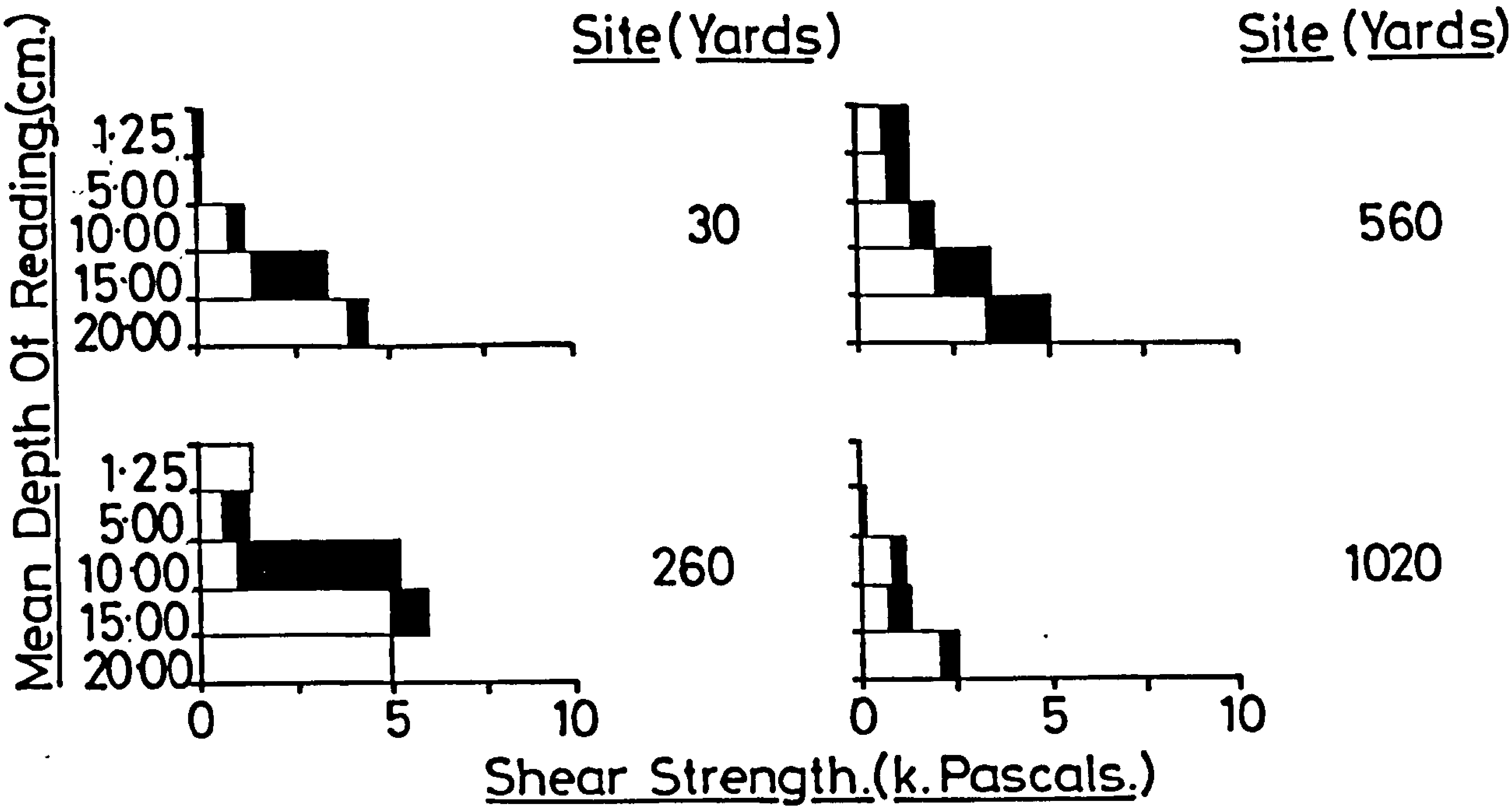
Fig. 26.

Residual Shear Strength Profiles - Transect A - Summer.

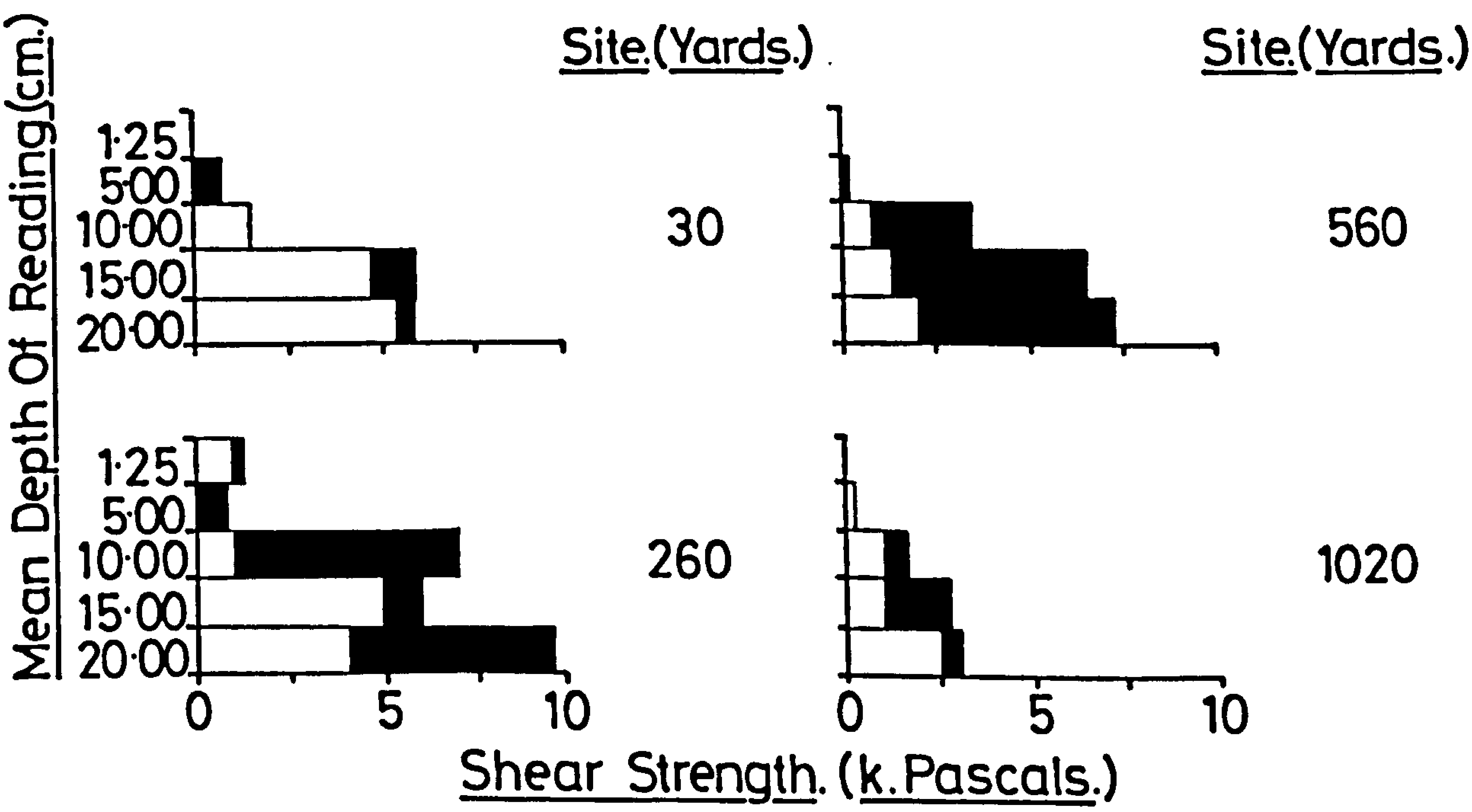
Fig. 27.
Residual Shear Strength Profiles - Transect A - Winter.

Fig. 28.

Residual Shear Strength Profiles - Transect B - Summer.

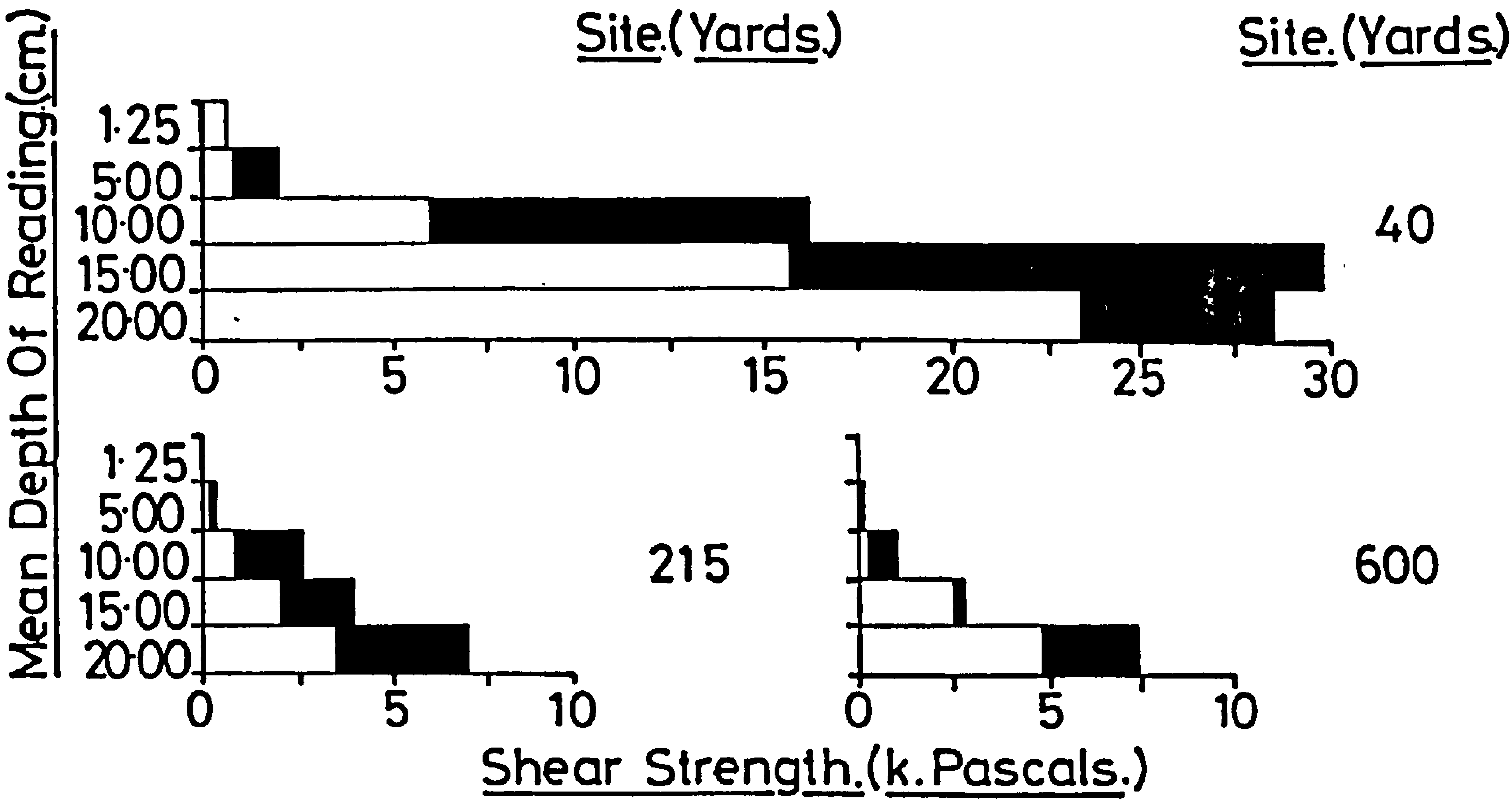



Residual Shear Strength Profiles - Transect B - Winter.

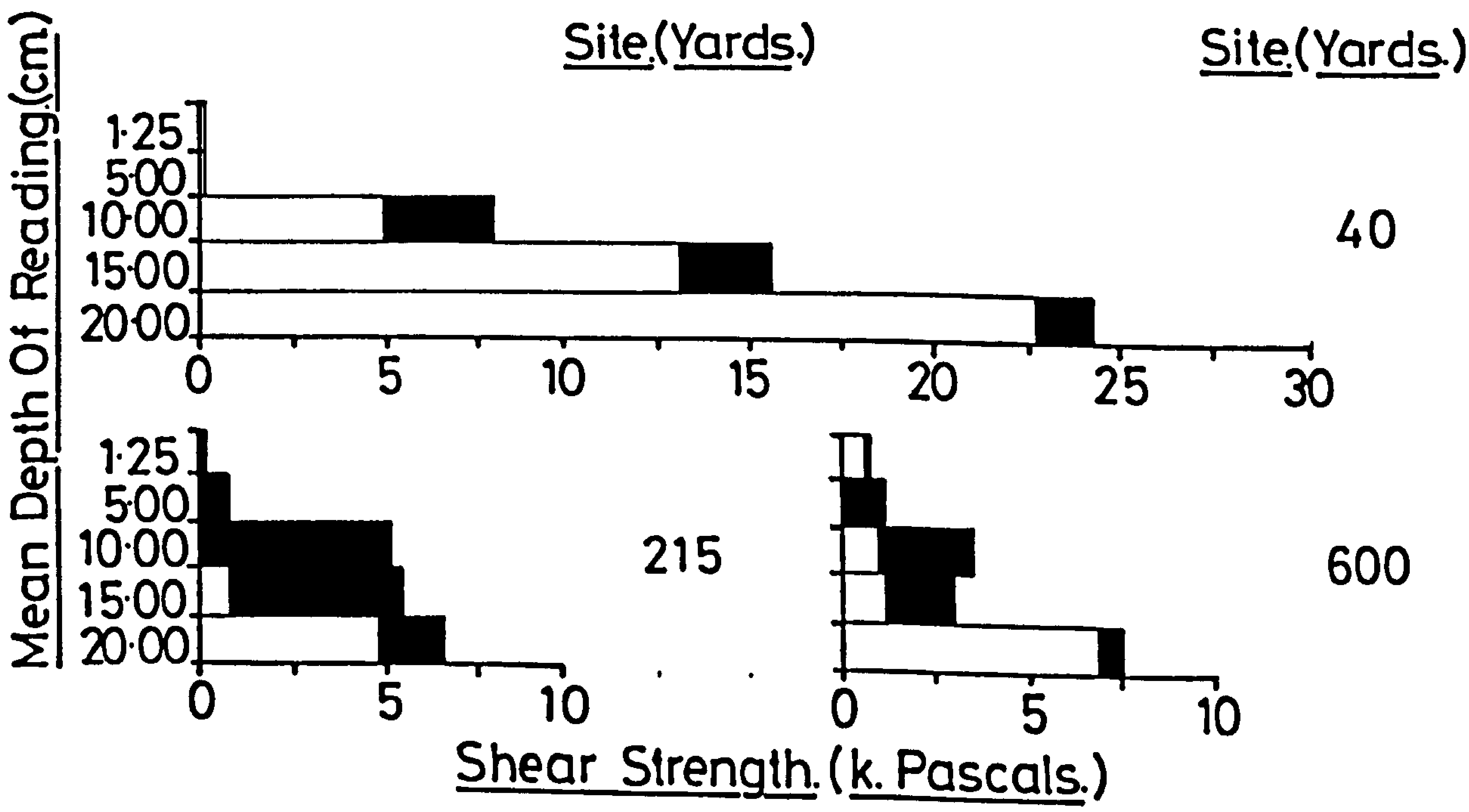


# Fig. 29.

## Residual Shear Strength Profiles - Transect C - Summer.




## Residual Shear Strength Profiles - Transect C - Winter.



## TABLE 6

Surface and 20cm Depth Shear Strength Values (k.Pascals) at Reference Sites Down The Three Transects.

| | TRANSECT | DEPTH (cm) | HWN | | MT | | LWN | |
|---|---|---|---|---|---|---|---|---|
| | | | SUMMER | WINTER | SUMMER | WINTER | SUMMER | WINTER |
| PEAK | A | 0-2.5 | 2.5 | 3.5 | 1.0 | 1.0 | 1.0 | 1.0 |
| | | 17.5-22.5 | 34.0 | 29.0 | 13.0 | 6.0 | 14.0 | 14.0 |
| | B | 0-2.5 | 3.0 | 3.0 | 2.0 | 1.0 | 1.0 | 1.0 |
| | | 17.5-22.5 | 25.0 | 33.0 | 13.0 | 15.0 | 13.0 | 14.0 |
| | C | 0-2.5 | 2.0 | 3.0 | 1.5 | 1.5 | 1.0 | 1.5 |
| | | 17.5-22.5 | 55 | 67.0 | 11.0 | 15.0 | 12.0 | 17.5 |
| RESIDUAL | A | 0-2.5 | 1.5 | 1.5 | 0.5 | 0.5 | 0.5 | 0.0 |
| | | 17.5-22.5 | 16.0 | 12.0 | 5.5 | 3.0 | 6.5 | 7.0 |
| | B | 0.2.5 | 1.5 | 1.5 | 1.5 | 0.0 | 0.0 | 0.0 |
| | | 17.5-22.5 | 6.0 | 9.5 | 5.0 | 7.0 | 2.5 | 3.0 |
| | C | 0-2.5 | 0.5 | 0.25 | 0.0 | 0.25 | 0.0 | 0.5 |
| | | 17.5-22.5 | 30.0 | 24.5 | 7.0 | 6.5 | 7.5 | 7.5 |

Note (i) The values quoted here are the largest of the two replicates. They have been rounded to ease interpretation.

(ii) Zero values represent those below the limit of detection of the apparatus.

'A' and 'B'. Below 10cm the sediment is significantly stronger on Transect 'C'.

(iv) Redox Potential Of The Sediment

The results of the survey of Redox Potential are shown in Figures30 to 33.

A typical Redox Profile exhibits the highest potential at the surface. As depth into the sediment increases there is a rapid fall-off in potential followed either by stabilization or a slight increase. There are exceptions to this typical profile, notably the High Water, Summer sites on Transects 'A' and 'B', here the lowest potentials are found in the surface sediments.

In absolute terms the highest potentials encountered on the transects were present in the surface sediments (0 - 2.5cm) from Mid-Tide downwards. The potentials were in the range +350 to +400mvolts and this range was common to all three transects.

The position of the lowest absolute potentials varied. On Transects 'A' and 'C' they were present in subsurface sediments from High Water sites and were in the range -100 to -200mVolts. The position of the lowest potentials on Transect 'B' varied with season. In Summer, they were present in surface sediments from High Water sites. In Winter, however, they were present in the deepest samples (12.5 to 22.5cm) from the Low Water Neaps site. The Redox Potential in both cases was approximately -50mVolts.

A seasonal comparison of the data for the three transects shows potentials in the surface sediments at sites above Mid-Tide to be consistently lowest in Summer. Beyond this position they are highest in Summer. The pattern in the subsurface sediments is much more variable. On Transect 'A' there are three regions:

(i) HWN to MT - potentials similar for both seasons.
(ii) MT to 540 yards - potentials highest in Summer.
(iii) 540 yards to LWN - potentials highest in Winter.

The patterns on the other two transects do not conform with the above. On 'B' the subsurface potentials are similar for

FIGURES 30 TO 33.

Redox Potential Profiles down the transects.

Notes.

As for Figures 1 to 16.

Fig.30.

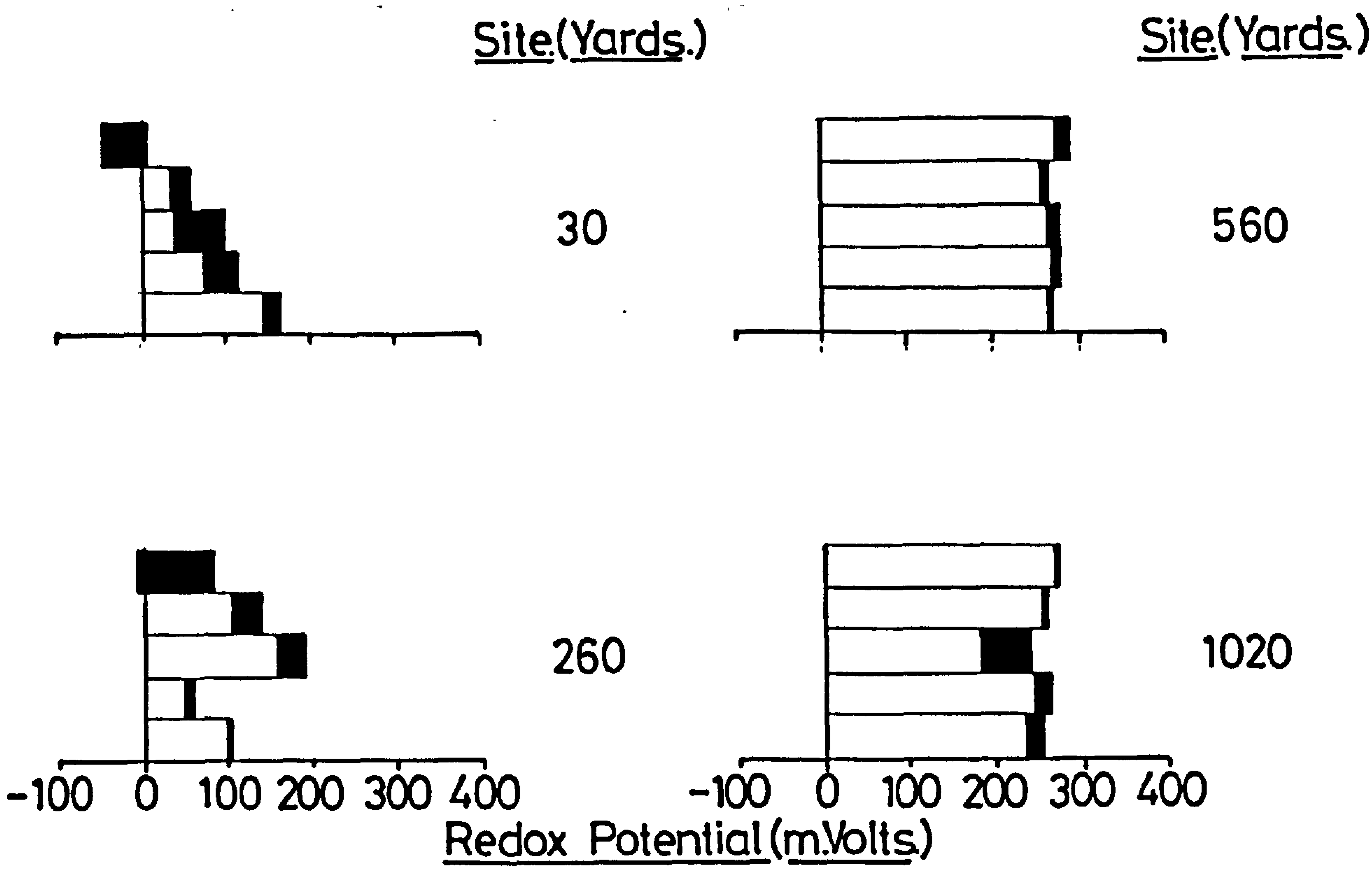
Redox Potential Profiles - Transect A - Summer.

Fig. 31.

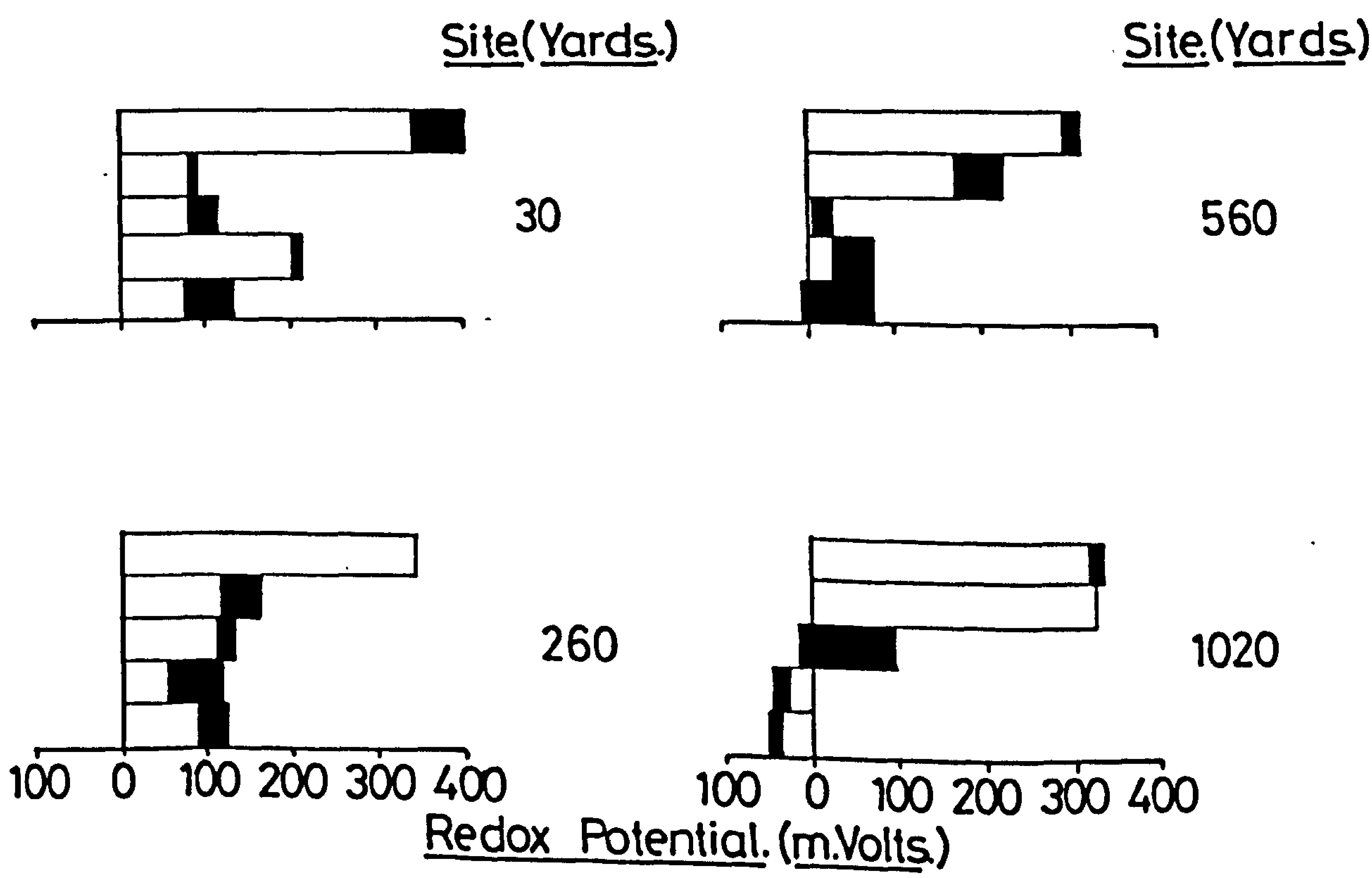
Redox Potential Profiles - Transect A - Winter.

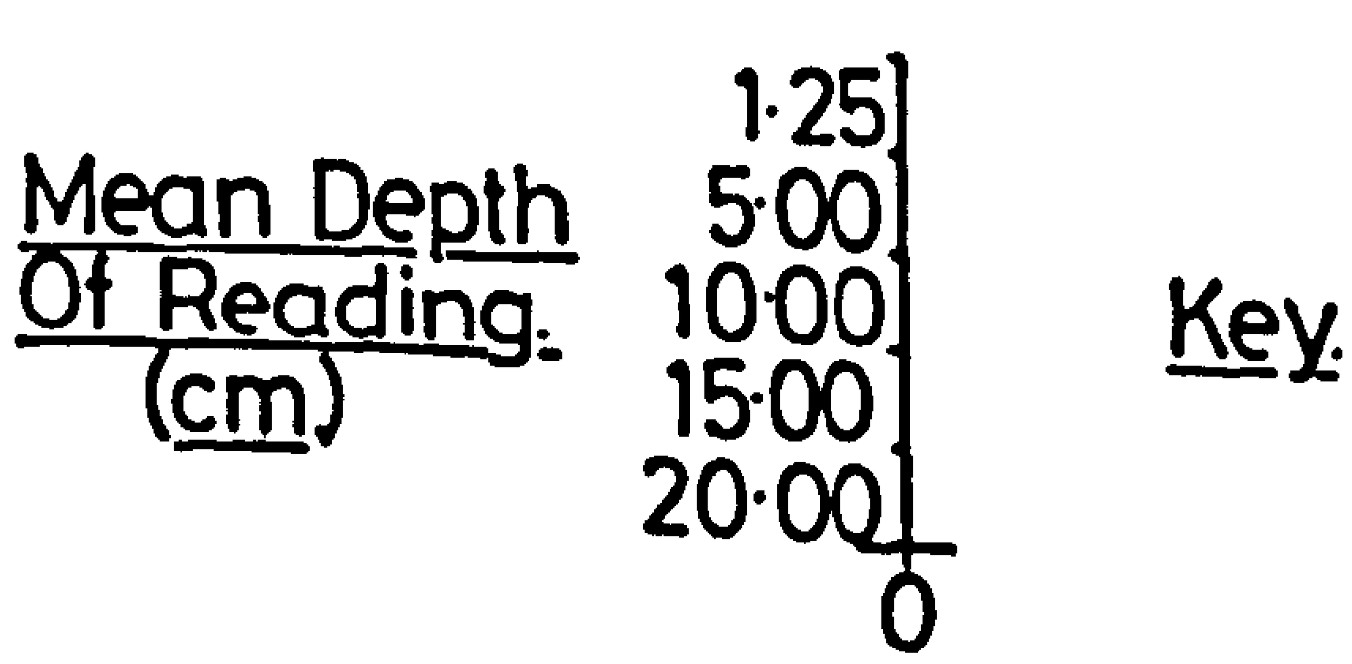
Fig. 32.

Redox Potential Profiles - Transect B-Summer.



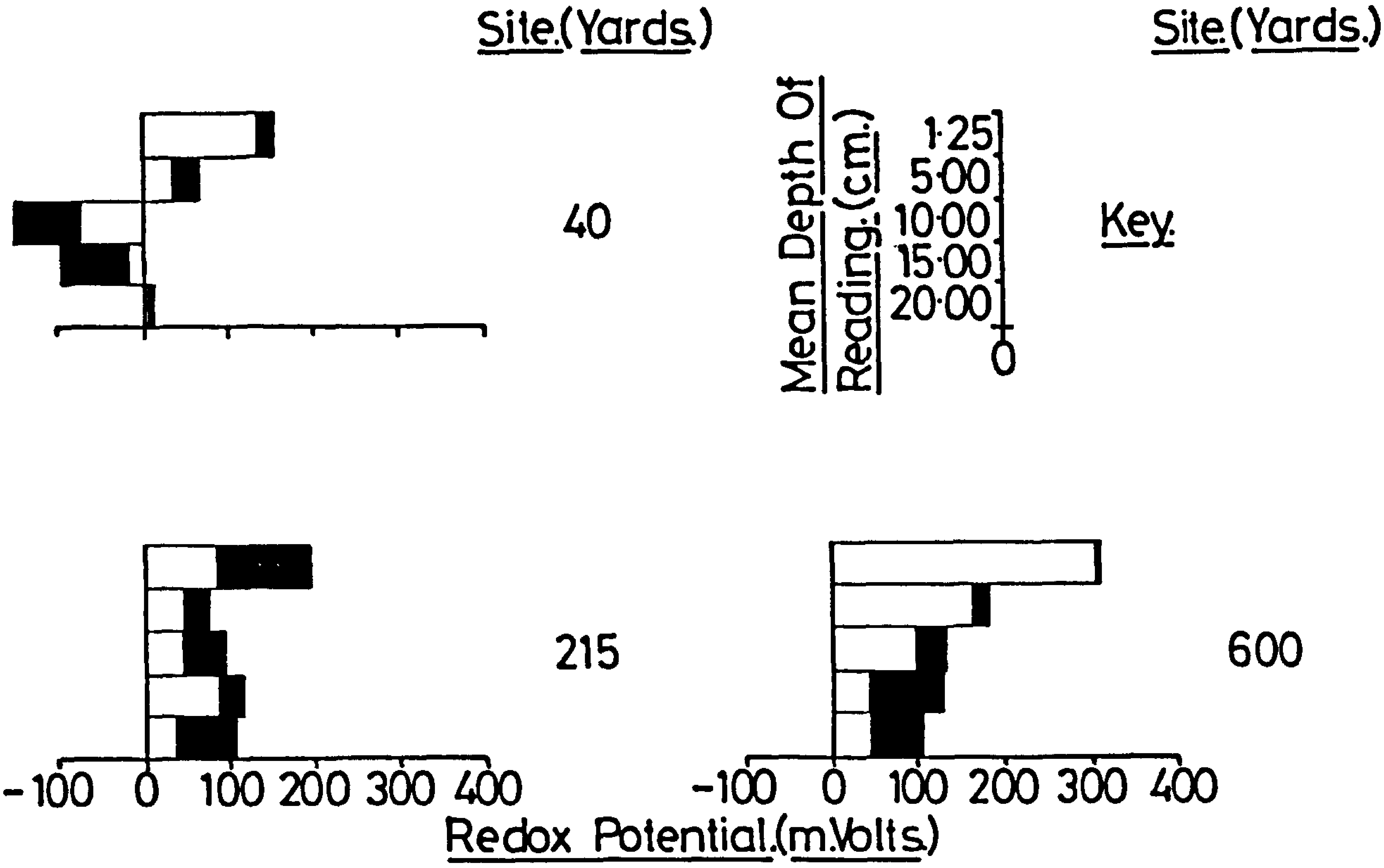

Redox Potential Profiles - Transect B-Winter.



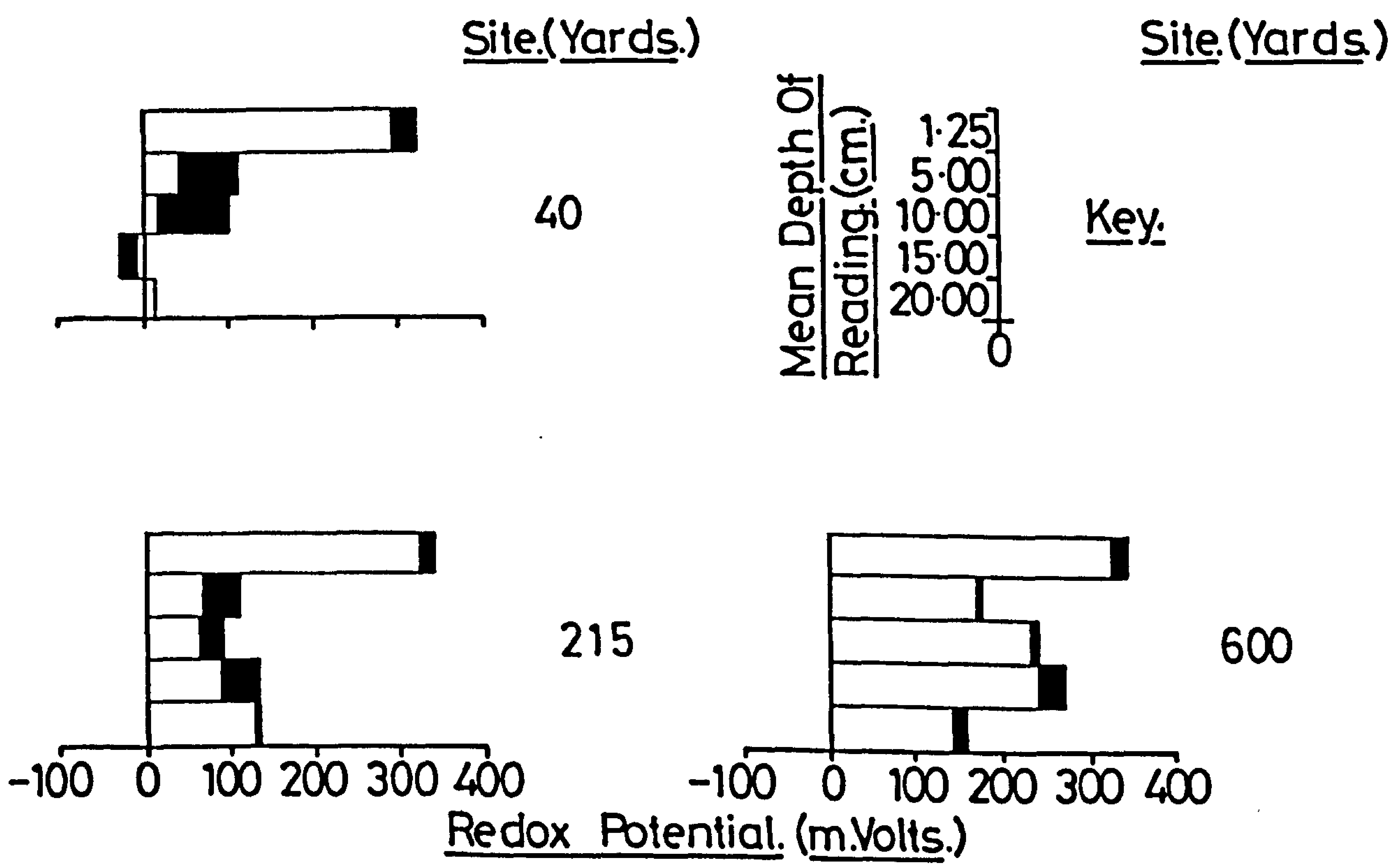



## Fig. 33.

### Redox Potential Profiles - Transect C - Summer.




### Redox Potential Profiles - Transect C - Winter.



both seasons at the High Water sites (30 and 260 yards) but higher in Summer at MT and LWN. On 'C' the potentials are consistently highest in Summer at all sites.

Table 7 compares, in general terms, the Redox Potentials of the surface and subsurface sediments at the reference sites on the three transects. There appears to be no consistent ordering of the transects at each of the sites. A seasonal comparison at the same reference sites shows the greatest similarity to exist between Winter profiles.

(v) Salinity Of The Sediment Interstitial Water

Figure 34 shows Summer and Winter Salinity profiles down the three transects.

The profiles for Transect 'A' show a rapid increase in salinity over the first 45 to 60 yards. This is followed by a very gradual increase to a relatively stable level at Low Water sites.

The range of salinities encompassed by these profiles varies with season. Summer values range between 26.5 and 31.5‰. The Winter range is lower at between 21 and 34‰.

Profiles for the other transects are similar in appearance to those for Transect 'A' but occupy different salinity ranges as shown below:

| Transect | Summer | Winter |
|---|---|---|
| B | 29.5 - 30.5‰ | 21 - 26.5‰ |
| C | 29 - 30.5‰ | 27.5 - 29.5‰ |

There is a considerable amount of variability between Salinity Readings taken at the same reference sites on the three transects in Winter. This variability is much reduced in the Summer data.

(vi) Position Of The Water Table Relative To The Sediment Surface At Low Water.

Figure 35 shows the position of the Water Table relative to the Sediment Surface along the three transects.

The data for Transect 'A' shows consistent differences between measurements taken in the two seasons. In Summer the Water Table is positioned above the sediment

TABLE 7

A Comparison Of Redox Potential Profiles At Each Of The Three Reference Tidal Levels (HWN, MT and LWN) Down The Transects.

Surface Sediments (0-2.5cm)

| SEASON | RELATIVE SIZE OF POTENTIAL. | HWN | MT | LWN |
|---|---|---|---|---|
| SUMMER | Highest | B | A | A |
| | Intermediate | C | B | C |
| | Lowest | A | C | B |
| WINTER | Highest | A | A | ABC |
| | Intermediate | B | | |
| | Lowest | C | BC | |

Sub-Surface Sediments (2.5-22.5cm)

| SEASON | RELATIVE SIZE OF POTENTIAL. | HWN | MT | LWN |
|---|---|---|---|---|
| SUMMER | Highest | B | B | B |
| | Intermediate | C | A | |
| | Lowest | A | C | AC |
| WINTER | Highest | B | C | AC |
| | Intermediate | C | B | |
| | Lowest | A | A | B |

Note  Sites grouped together, eg., AC have similar potentials.

Fig.34.
Salinity Readings Down Transects.

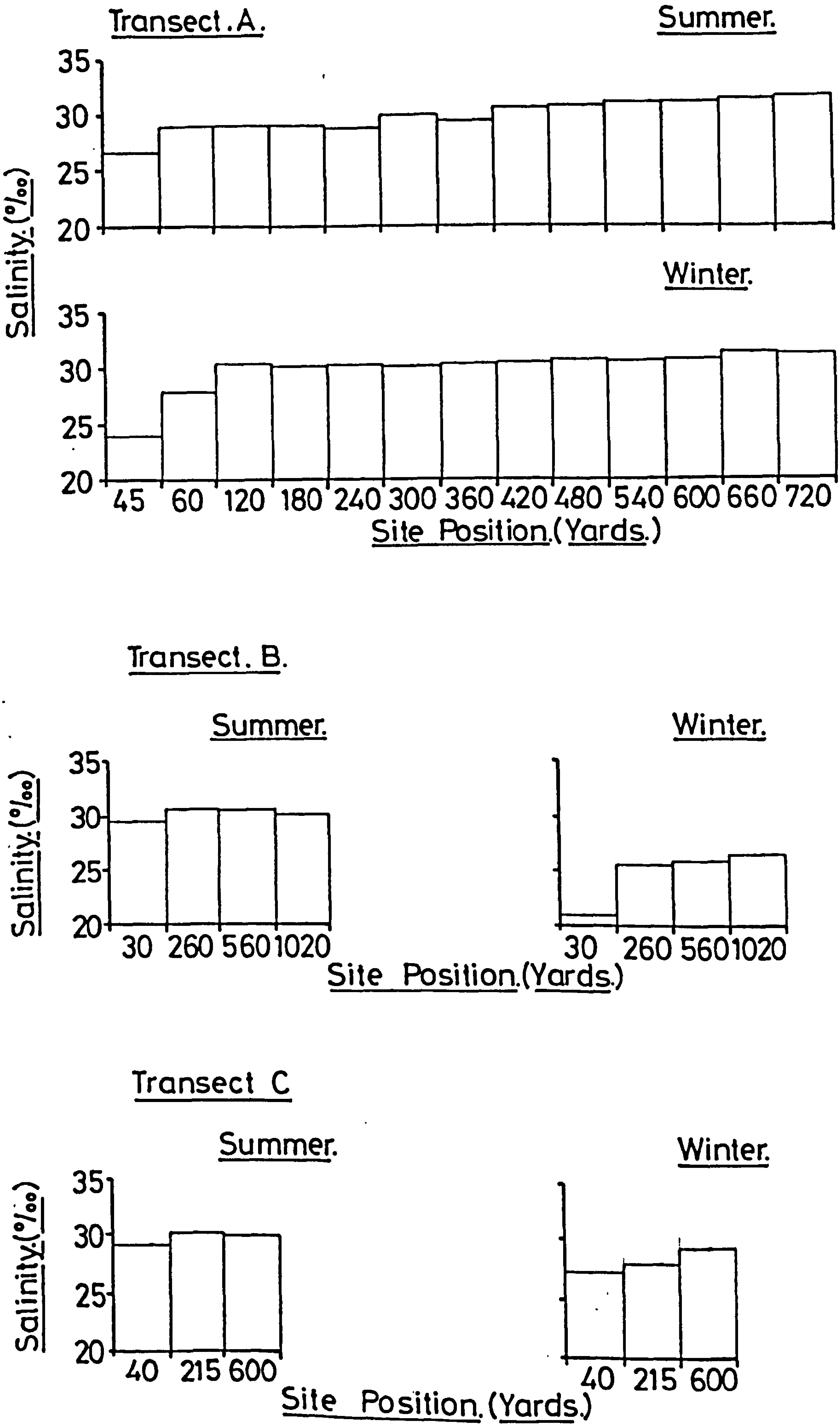
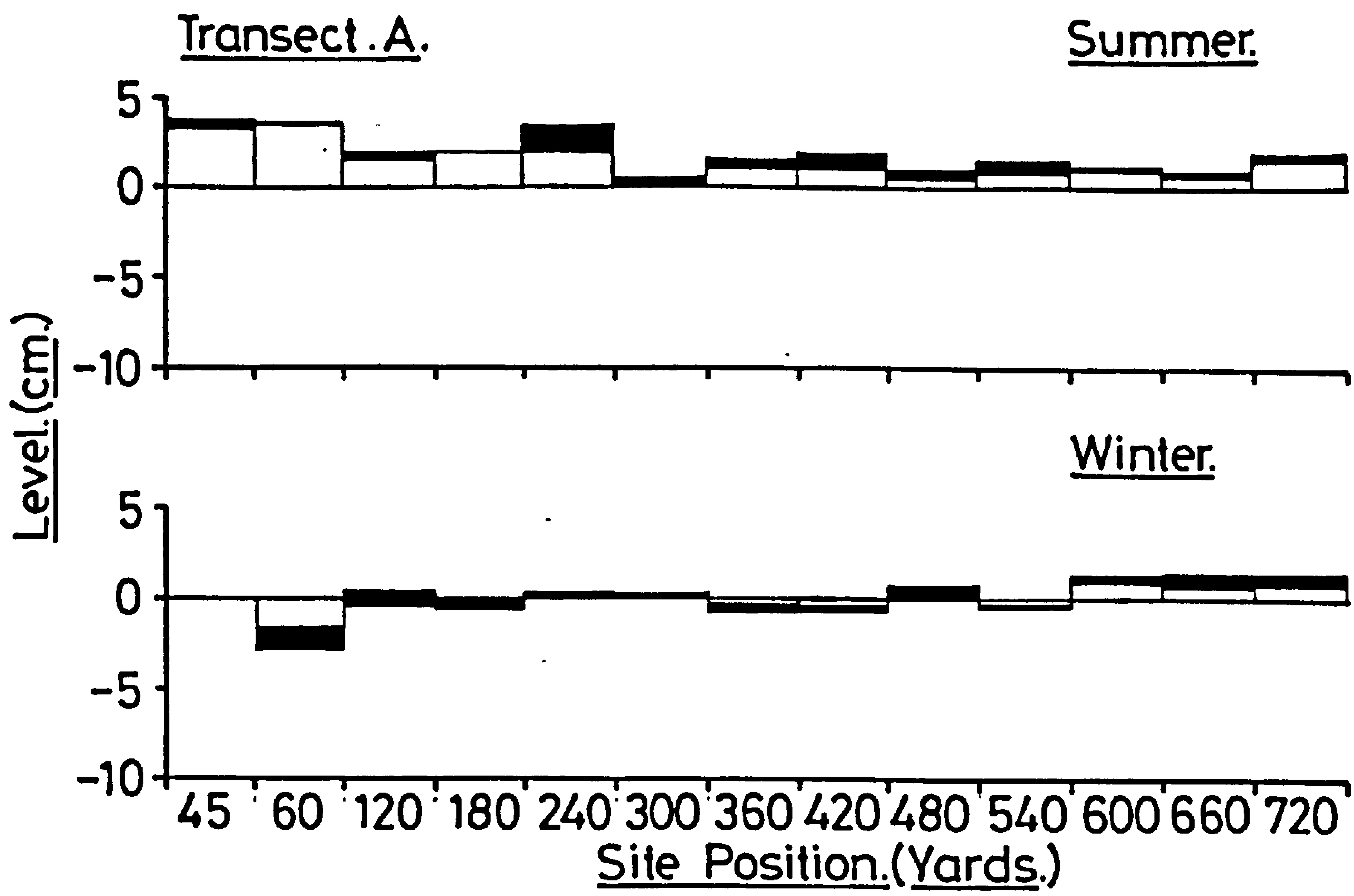
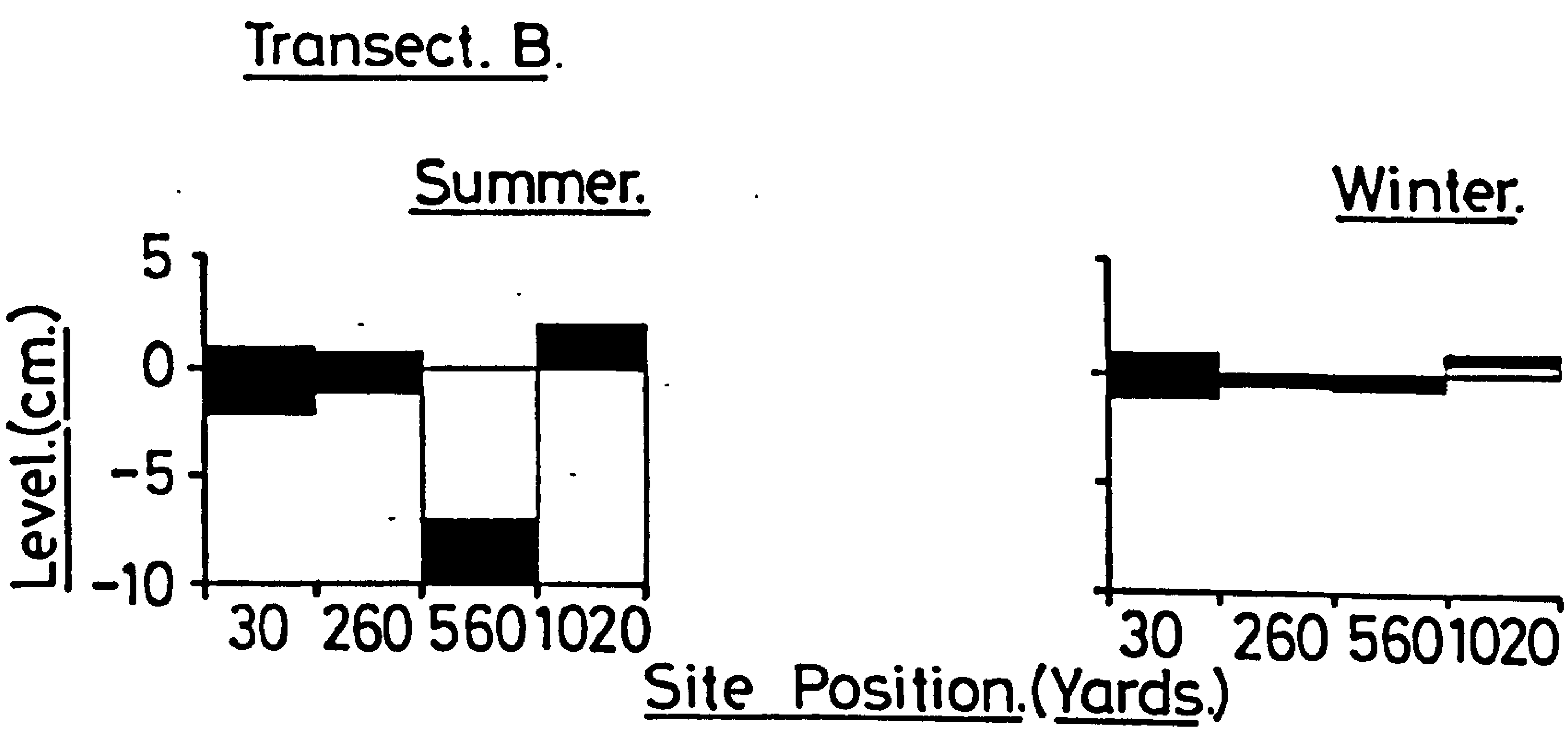
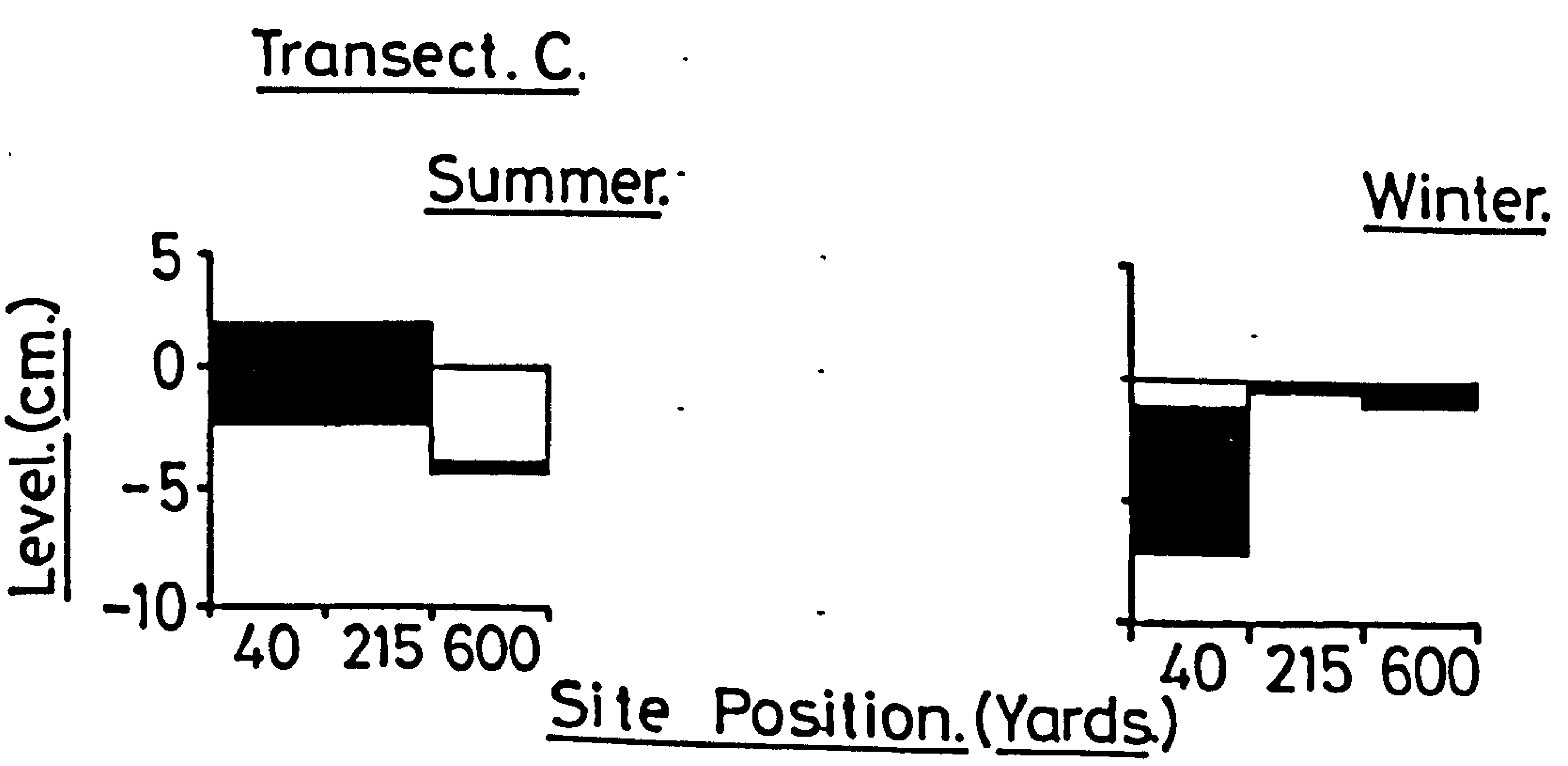


Fig. 35.

Position Of Water Table At Low Water Relative To Sediment Surface.



surface at all sites. Its height above the surface is a maximum at High Water (+3.5cm) and falls off to a minimum towards Low Water (+1.0cm). The Winter data is comparable below the 540 yard site. Above this position the Water Table is located close to the sediment surface at all but the 60 yard site.

The trend for the Water Table to be located close to the sediment surface in Winter is also common to the other two transects. No such similarities exist in the Summer data. The Summer data for Transect 'B' shows the Water Table to be located at or near the surface at High and Low Water but well below at Mid-Tide. On Transect 'C' its position fluctuates above and below the surface at High and Mid-Tide but is well below at Low Water.

## DISCUSSION

### (i) Sediment Particle Size Distribution

The size range of the four Particle Size Distribution statistics surveyed in this project are comparable to those found by other workers on intertidal shores. This is illustrated by the data in Table 8

The observed characteristic depth profiles of these statistics can be explained by a consideration of the source material available and the sorting forces operating within each of the three zones. (See Figure 17)

Zone 1.

Surface sediments within this zone are finer than in Zones 2 and 3. This is in agreement with the findings of Warme (1967). It reflects the decreasing energy of the water - and hence the strength of its sorting forces - in its passage over the intertidal shore.

With depth there is a coarsening of the sediment followed by a rapid fining. The former probably reflects burial of larger material and the latter, mixing of the surface material with a subsurface silt/clay layer. Both burial and mixing processes can be accounted for by the activity of burrowing organisms. Warme (1967); Tevesz et. al. (1980); Rhoads (1967) and Rhoads and Young (1971) have described such processes operating on intertidal shores resulting in the production of biogenically graded bedding. The mixing of this coarse material and the silt/clay with the fine sand will also account for the reduction in sorting with depth.

These mixing processes are also clearly evident in the Skewness and Kurtosis profiles. Values which deviate from normality are indicative of the mixing of sediment populations (Folk 1966; Folk and Ward 1957; Tanner 1964; Duane 1964.)

The sign of the Skewness value is environmentally sensitive (Duane 1964). Sediments from Beaches, Littoral Zones and Tidal Inlets which are subject to Winnowing by Tide, Wave and Current activity have a Negative Skewness. Those from Sheltered Lagoons have Positive Skewness. In real terms this represents a separation between material at the Silt/Fine

## TABLE 8

**Particle Size Distribution Statistics Calculated By Other Workers For Sediments From Intertidal Shores**

| Worker | Mean (Ø) | S.D. (Ø) | Skewness | Kurtosis |
|---|---|---|---|---|
| Folk & Ward (1957) | -1.7 - +3.2 | 0.4 - 2.58 | -0.68 - +0.53 | 0.54 - 2.85 |
| Duane (1964) | +0.7 - +6.2 | 0.32 - 2.45 | -1.59 - +1.60 | --- |
| Bloom et. al. (1972) | --- | 0.271 - 1.694 | -1.353 +2.720 | --- |
| Harrison et. al. (1964) | +2.3 - +6.0 | 0.480 - 2.790 | --- | --- |
| Dale (1974) | +2.35 - +7.0 | --- | --- | --- |
| Holmes & Goodell (1964) | $6.119 \pm 2.039$ | $2.775 \pm 0.557$ | --- | --- |

Sand boundary. The sediment in Zone 1 shows a change of sign with depth reflecting the mixing of material from these two size ranges.

Extreme Kurtosis values indicate that part of the sediment population received its sorting in a different energy environment (Folk and Ward 1957). The higher Kurtosis values at depth reflect the low energy sedimentary environment associated with the deposition of silts and clays.

Zone 2

The profiles of the four statistics in the upper 10 to 15cm of sediment in this zone reflect source material and sorting forces similar to those in the previous zone. Below this depth the statistics are indicative of a relatively pure silt/clay layer.

There is evidence of mixing of the two basic sediment types within the depth profile. This is provided by gradients which exist between the characteristic statistics of the relatively pure fine sand at the surface and the silt/clay at depth. The mixing can probably be attributed to biogenic activity.

Zone 3

The transition from fine sand on the upper shore to medium sand on the lower shore indicates the increased strength of sorting forces in this direction.

The depth profiles show the mean sediment size to be relatively constant with depth. This in conjunction with the consistently low standard deviation (sorting) values may indicate constant sorting forces operating in the sediment during its deposition and the presence of one dominant source material.

Skewness and Kurtosis values of the deeper sediments show that they contain particles much larger than the mean size. These are undoubtably shell fragments which have accumulated at this depth as a result of biogenic burial, probably by the polychaete Arenicola marina. Reineck and Singh (1980); Cadee (1976) and Baumfalk (1979) have described this phenomenon and call the resultant layer containing the coarse material, the "Hydrobia layer".

* ADDITIONAL NOTE.

The Clay and Silt fractions (38µm. diameter and below) were not seperated. To do this would have required the use of a different analytical technique - Pipette Analysis.

The similarity between profiles at the reference sites indicates that source material and sorting forces are consistent on the three transects.

(ii) Percentage Organic Matter Content Of The Sediment

Byers et.al. (1978) and Dean (1974) have compared methods of determining the Organic Matter Content of Marine Sediments. Both have found the Ignition Loss technique to provide reliable estimates of Total Organic Matter Content with Precision and Recovery in the region of 3% and 99% respectively. Results quoted in the literature are however, most frequently expressed in terms of the Organic Carbon or Nitrogen Content and are thus not directly comparable. (Sources of reference values for Organic Carbon and Nitrogen are shown in Table 2 .)

The same workers have also drawn attention to the effects of Clay and Carbonate present in the sediment on such estimates. At temperatures above 500-550$^{o}$C, weight loss can be expected due to the evolution of lattice OH water and $CO_2$ from these two substances respectively. For pure clays this loss may constitute 5% and for pure Calcium Carbonate 43%. The presence of these two substances in sediments at Ardmore has already been demonstrated (See Particle Size Analysis) and therefore care must be taken in interpreting the Organic Matter profiles.

* The high apparent Organic Matter concentrations in the deeper sediments at the High Water sites probably reflect the "clay" effect described in the above paragraph rather than a real trend. It is noticeable that the apparent concentration falls off towards the surface in the same way as the clay content.

The high concentration in the surface sediments at these sites is probably real. The contributing factors are likely to be the deposition of organic detritus by the tide and the presence of seaweeds. The latter are particularly abundant, growing on the sediment surface within this zone during Summer. In Winter, they die and are buried by the activity of organisms. This probably accounts for observed reductions in Organic Matter Content of the surface sediments during this period.

Further down the shore there are a few of the deeper samples which show apparently high concentrations. The absence of surface seaweeds and a subsurface clay layer rules these out as possible contributing factors. They may well however, be explained by the presence of the "Hydrobia layer". In addition to containing abundant Calcium Carbonate in the form of shell fragments, this layer also contains fragments of resistant Organic Matter such as wood. This material is likely to contribute with the "Carbonate Effect" to these high concentrations.

Concentrations in the other samples are likely to reflect genuine organic material of two major types:

(i) Organic detritus deposited on the surface and subsequently mixed into the sediment profile by biogenic activity.

(ii) The Standing Crop of Macro and Micro-organisms present in the sediment.

Both are subject to seasonal variability in abundance. Organic detritus will be most abundant in the Autumn and Winter months. The Standing Crop of Organisms will however, be highest in Summer. It is this latter factor which probably explains the higher concentrations in the surface sediments sampled during this period.

The only significant differences which are apparent between the three transects occur in the deeper samples from the High Water sites. It is probable that this reflects variations in the clay content of the sediments rather than differences in their Organic Matter Content. Data pertaining to these samples should be treated with considerable suspicion.

### (iii) Shear Strength Of The Sediment

Little work has been done on the Shear Strength properties of Estuarine sediments with the exception of routine engineering tests for foundation studies. Table 9 summarizes the results of some of the studies which have been performed. It is clear that, although Residual values are

TABLE.9.

Sediment Shear Strength Recorded By Other Workers In Estuarine Sediments

| Worker | Peak Shear Strength (kPa) | Residual Shear Strength (kPa) |
|---|---|---|
| Chapman (1949) | 1.088 - 2.272 | - |
| Kessler and Stiles (1968) | 5 - 50 | - |
| Deans et.al.(1982) | 05.3 ± 17 | - |
| Harrison et.al.(1964) | 12.5 - 88.4 | - |

lacking, Peak Shear Strength values recorded in this study are consistent with those found by other workers.

Peak and Residual Shear Strengths have been recorded in Offshore sediments by Sherif et.al.(1976). Values ranged between 1 - 18 and 1 - 5kPa respectively. The ratio between Peak and Residual values was similar to that found in this study.

The observed increase in Shear Strength with depth is well documented (Holmes and Goodell 1964; Harrison et.al. 1964). There are a number of contributing factors. -

(1) The increase in Overburden Stress resulting from the progressive increase in weight of the overlying water and sediment. This results in a greater resistance to displacement of the sediment particles by the shearing forces.

(2) A reduction in Water Content with depth, resulting in a tightly packed and poorly lubricated sediment structure. Harrison et.al.(1964); Rhoads and Young (1970) and Sherif et. al.(1976) have shown Shear Strength to increase and Water Content to decrease with depth in the field. In the laboratory, Holmes and Goodell (1964) and Trask and Rolston (1950) have demonstrated an inverse relationship between Shear Strength and Water Content.

(3) A reduction in Sorting of the Sediment particles with depth - as demonstrated in Particle Size Analysis section of this survey - resulting in a tightly packed structure which is resistant to deformation (Chapman 1949).

(4) A reduction in the compaction of the surface sediments due to reworking by organisms present in the sediment. This has been demonstrated by McMaster (1962 and 1967) and Rhoads and Young (1970).

Although not apparent from the results of this survey, seasonal variations in the strength of surface sediments have been demonstrated by other workers. McMaster (1962 and 1967) and Rhoads and Young (1970) have demonstrated a reduction in strength in summer due to the increased level of activity and hence disturbance of the sediments by organisms. Biernbaum (1979) has reported the reverse and attributes this to the breakdown in structure of the surface sediments by winter storms.

The similarity evident between Shear Strength profiles at sites below High Water is undoubtably a reflection of the consistency of Particle Size parameters within this region. These parameters are also the probable explanation for the profiles at the High Water sites. The marked increase in strength with depth mimics a pattern of reduced Mean Particle Size and Sorting. Holmes and Goodell (1964) have reported similar results. The same workers have also shown Shear Strength to increase with the ratio of kaolinite to illite in the clay. This ratio is not known for the sediments sampled in this survey.

It is interesting to note that the high strength readings recorded at the High Water sites on Transect 'C' are not associated with unusually low Mean Particle Size or Sorting values. This lack of correlation can possibly be explained by a low sediment moisture content at this site.

The importance of moisture content in determining sediment shear strength was demonstrated in an experiment, the results of which are shown in Appendix 'D'. Shear Strength was measured at High and Low Water on the intertidal shore. Strength readings were appreciably higher in the surface sediments at Low Water, presumably due to their partial drainage and hence, lower moisture content. These differences were not apparent in the deeper layers of sediment which remained fully saturated.

(iv) Redox Potential Of The Sediment

The measured Redox Potential of sediments represents a mixture of unknown, irreversible chemical reactions. As such they cannot be considered as conceptually defined oxidation-reduction potentials. In reality, they are a measurement of the Electromotive Force (emf) of the electrochemical cell (Platinum plus Calomel Reference Electrode.) (Bagander 1978).

These potentials are however, useful in ecological studies as they provide:

(1) An index of the progress of a system towards an oxidized or reduced state. (Whitfield 1969).

(2) A guide to the biological condition of the sediment (Pearson and Stanley 1979).

(3) An index of the degree of organic loading to which the sediment is exposed (Pearson and Stanley 1979).

The drift which was apparent in potential readings over a period of time has been noted by other workers (Fenchel, 1969; Zobell 1946; Whitfield 1969). Fenchel and Zobell attribute this phenomenon to the Poising (Analogous to Buffering) capacity of the sediment. Experiments they performed showed the readings to stabilize after a period of approximately 10 minutes. A delay of this order was not practical in this survey. The readings were therefore, taken at a standard time of 5 minutes after insertion of the probe. The data of the above workers shows most of the drift to have occured within this period. (See Figure 36 ).

The general form of the profiles described in this project are typical of those found by other workers. Jørgensen (1977) has noted that marine sedimentary environments are generally reducing environments covered only by a thin oxidized surface layer. Moshiri (1978) has described the reduction in potential with depth as being approximately Parabolic in shape. In common with this project however, he also illustrates examples where there is a slight increase in potential in the deeper sediments. Pearson and Stanley (1979) have noted very low potentials in the surface sediments associated with enhanced organic loading. Organic enrichment of the surface sediments has been demonstrated (See Page 95 ) at the High Water Sites on Transects 'A' and 'B'. This is the probable explanation for their low surface potentials .

The range of potentials found by other workers in estuarine sediments is shown in Table 10 . Values recorded in this survey are consistent with this range. Fenchel (1969) has recorded potentials in the overlying water in estuaries of between 300 and 350mV. These values are comparable with those found in the corresponding surface sediments.

No direct reference could be found to a relationship between position on the shore and Redox Potential. Zobell (1946) has however, noted that coarser sediments and those

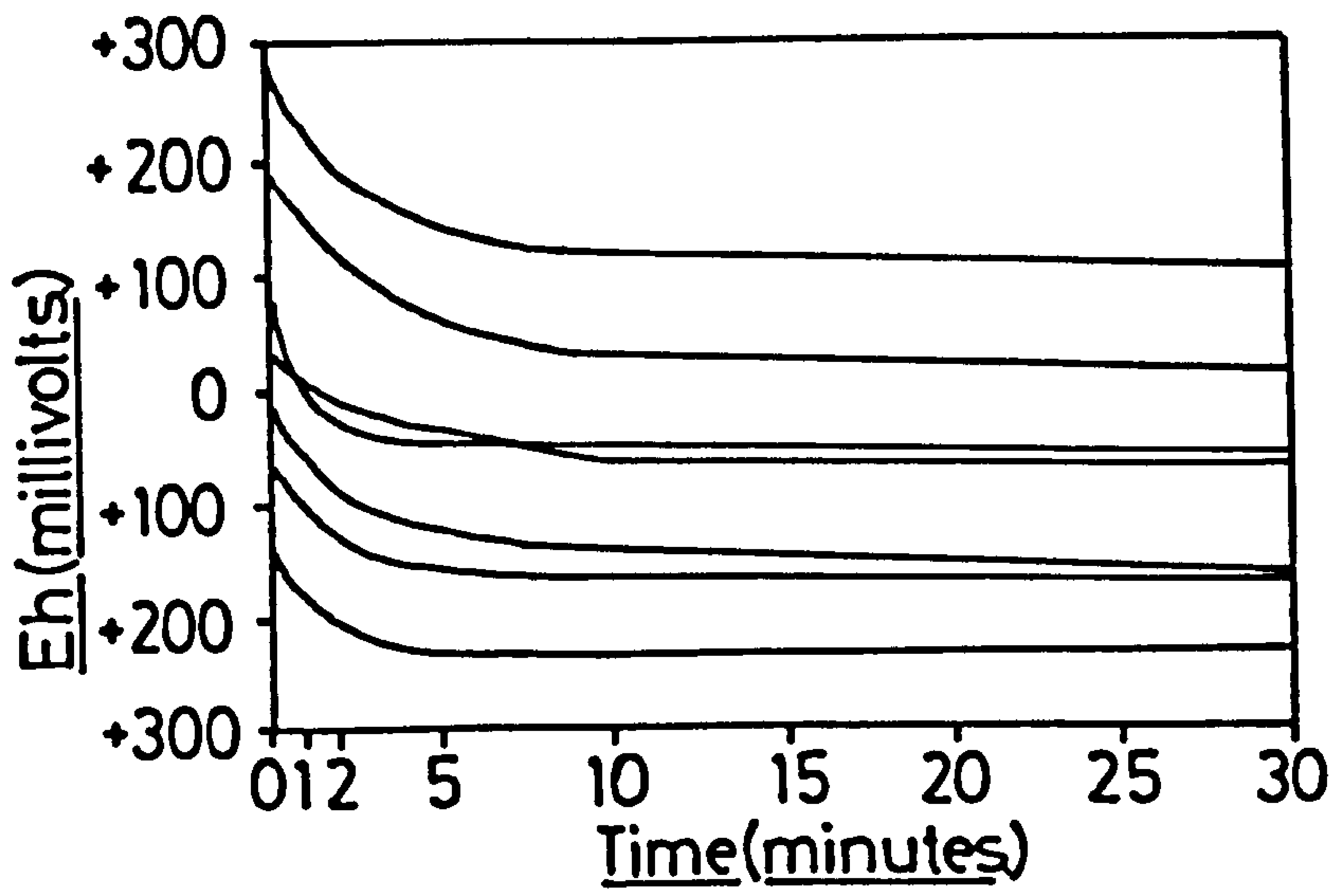



Figure. 36.

Curves depicting change with time in Redox Potential (Eh) values of seven different mud samples. From Zobell (1946).

TABLE 10

Range of Redox Potentials Found By Other Workers In Estuarine Sediments

| Worker | Redox Potential Range (mV) |
|---|---|
| Jørgensen (1977) | -150 to +300 |
| Pearson & Stanley (1979) | -200 to +200 |
| " " " | +100 to +400 |
| Fenchel (1969) | -100 to +450 |
| Hayes (1964) | -100 to +500 |
| Ott et.al.(1976) | -150 to +300 |
| Bagander & Niemisto (1978) | -210 to 0 |
| McLachan (1978) | -200 to +500 |
| Moshiri (1978) | +100 to +400 |
| Schnider and Honick (1971) | -180 to -130 |
| Fenchel and Jansson (1966) | -100 to +300 |

deficient in Organic Matter are generally less reducing. The increase in potential towards Low Water observed in this survey is consistent with this.

The seasonal migration of Redox Potential contours has been noted by other workers. McLachan (1978), Fenchel (1969) and Jorgensen (1977) have all shown the Redox Potential Discontinuity (RPD) - the region where there is a rapid transition between oxidized and reducing conditions - to shift closer towards the sediment surface during the summer months.

Jørgensen (1977) and McLachan (1978) have also demonstrated a general increase in Potential throughout the sediment profile during the winter months. This is presumably due to the decrease in respiratory oxygen demand associated with less biological activity during this period. This finding is consistent with measurements made at some of the sites in this survey but not at others. A possible explanation for this discrepancy can be found in the work of Ott et.al.(1976). These workers have shown the burrowing activity of organisms to considerably increase the Redox Potential of sediments. An increase in burrowing activity during the summer months could therefore, explain the trend at these other sites.

The similarity between profiles at the reference sites in winter can also possibly explained by the reduced biological activity in the sediments. Reduced activity will allow oxygen diffusing into the sediment to make the sediments more oxidized. Diffusion rates will be highest where the oxygen concentration gradient is steepest, i.e., in the most reducing sediments. These sediments will therefore, take up oxygen at a faster rate than the more oxidized ones. This difference in rate will be reflected as a progressive reduction in the difference between the values at any point in time. An analogous situation would be water pouring into an empty and a half full tank of the same volume at different rates. If the inflow rate into the empty tank is twice that of the half full tank. the difference between the amount of water they contain will progressively decrease. Eventually both tanks will be full and this will occur at the same point in time.

(v) Salinity Of The Sediment Interstitial Water

The salinity of the interstitial water of estuarine sediments has been measured by a number of workers. The ranges encountered are shown in Table 11 , and are consistent with the data in this survey.

Salinity gradients within the sediment have been noted by a number of workers. Fenchel et.al.(1967) have shown a gradient to exist between high and low water. In common with this survey the highest salinities were recorded at low water. Dilution by inflowing surface and ground water is the probable explanation for this gradient. Fenchel and Jansson (1966) have demonstrated a vertical salinity gradient within the sediment profile. High salinities in the deeper sediments were attributed to ion absorption on the sand grains.

Salinity gradients have also been shown to exist between the sediment and the overlying water. Frankel and Mead (1973) have recorded lower salinities in the surface sediment. Groundwater inflow is the probable explanation.

Seasonal variability in salinity has been observed by McLusky (1968) in the sediments of the Ythan estuary. In common with this survey, values were lowest in Winter. Enhanced dilution by high levels of surface runoff and groundwater inflow during this season were the probable explanation.

Seasonal differences in the quantity of surface runoff and groundwater inflow are also the probable explanation for the reduced variability in the summer data. The relative contribution of these two components to salinity values will be smallest during this season. Values will therefore, be dominated to a greater extent, by the relatively constant salinity values of the overlying water.

(vi) Position Of The Water Table Relative To The Sediment Surface At Low Water.

The importance of the Water Table in determining terrestrial soil properties has been recognised for many years. Ward (1967), White (1937) and Chorley (1969) have all drawn attention to its importance in determining the movement of water through the soil. They have also considered the

TABLE 11

Ranges Of Salinity Recorded In Interstitial Water Of Estuarine Sediments

| Worker | Salinity Range ‰ | Notes |
|---|---|---|
| Frankel & Mead (1973) | 8-29 | Bottom Water |
| " " " | 13-25 | Interstitial Water |
| McLusky (1968) | 1-10 | Winter |
| " " | 3.7-16.5 | Summer |
| Fenchel & Jansson (1966) | 6.1-6.5 | Surface Sediments |
| " " " | 6.9 | Deeper Sediments |
| Fenchel, Jansson and | 13-16 | Lower Shore |
| Von Thun (1967) | 2 | Upper Shore |
| Winston & Anderson (1971) | 29-33 | At Different Positions |
| " " " | 22-32 | In The Estuary |
| " " " | 17-31 | " " " |
| " " " | 17-31 | " " " |
| " " " | 12-30 | " " " |
| " " " | 4-28 | " " " |

consequent effects of this movement on soil moisture content and evaporation. Smith (1967) has noted its significance in determining engineering properties of the soil. Particular attention is drawn to the generation of quick conditions in saturated sands. Withers and Vipond (1974) have considered its implications to chemical properties of the sediment and its practical significance to problems of soil drainage and irrigation. Meidner and Sheriff (1976) have extended considerations to include its importance to the growth of plants.

With such a wealth of background knowledge in the terrestrial environment it is surprising that consideration of its importance has not been extended to the intertidal zone. No direct reference to its position or possible consequences could be found in studies relating to this environment. It is therefore, only possible to speculate what these consequences might be:

(1) Reduced shear strength and the generation of 'quick' conditions below its level.

(2) Reduced salinity, resulting from the inflow of fresh water from the terrestrial environment.

(3) Reduced diffusion rates into the saturated sediment.

(4) Seasonal effects associated with changes in its vertical position.

The data from this survey indicates that the water table is consistently highest - relative to the sediment surface - in Summer. A possible explanation for this lies in the activity of the polychaete Arenicola marina. This animal produces a pile of faecal sediment on the surface. In winter this pile is destroyed by turbulent water flow. In summer, however, when conditions are calm, they build-up until their tops are several centimeters above the adjacent sediment surface. Water therefore, collects in the spaces between the piles and its drainage is restricted by the increased tortuosity of its path. It is also probable that some sinkage of the sediment surface occurs between these piles associated with excavation of the material at depth by A. marina. In such circumstances the Water Table would be higher relative to the sediment surface even though in reality its position did not change relative to a constant datum. A further contributing factor on the upper shore is the presence in summer of large quantities of green filamentous seaweed (Enteromorpha sp.) At low water this material lies on the sediment surface and acts as a very efficient water retainer.

Other possible causes of seasonal differences in the position of the Water Table include the migration of bed sediment structures such as ripples, sand waves and dunes. Reineck and Singh (1980) have described these features in great detail. Brown (1982) has noted seasonal variations in the position and size of sand bars. At Ardmore, dunes were clearly evident from Mid-Tide downwards. The Wavelength of the dunes was of the order of 30m and the amplitude 10-20cm. Measurements taken on a dune ridge will show the Water Table in a more depressed position than those taken in the trough. This was the case at the 560 yard site on Transect 'B' and the 600 yard site on Transect 'C' in summer when the presence of a dune ridge was observed.

It is interesting to note that the position of the water table does not reflect the relative quantity of fresh water which is being transported onto the shore as surface runoff and groundwater inflow. It might be expected that the larger quantity being transported in Winter would be evident as an elevation of the Water Table. This does not however, appear to be the case.

# SECTION 3

## THE MEASUREMENT OF MACROINVERTEBRATE ABUNDANCE DOWN THE TRANSECTS

# INTRODUCTION

Quantitative estimates of animal numbers are essential to the understanding of the structure and functioning of communities. As a consequence they have been used widely in ecological studies. The purpose of such estimates has often been to relate the distribution patterns of a species to either:-

(a) The Distribution of Other Species - studies on predation or interspecific competion.

or (b) Environmental Parameters - relating species distribution to Physical and Chemical properties of their environment.

The measures commonly used to quantify distribution are:

(1) The number of individuals or density = Abundance

(2) The number of times a species is recorded within a given number of samples = Frequency

(3) The relative proportion of the total area occupied by a given species = Cover.

(After Mueller - Dombois and Ellenberg,1974).

The methods used to determine these measures are based upon sampling a fraction of the total habitat area. Results from this are then extrapolated to the whole. The choice of method depends on the species and its habitat. In the intertidal sedimentary environment two methods are frequently used:

(i) Quadrat Counts - in which the number of animals in a given area of the sediment surface are recorded.

(ii) Core Counts - in which the number of animals contained in a given volume of sediment are recorded.

Studies performed by other workers which have involved the use of these methods are shown in Table 1.

The area or volume sampled is of considerable importance - too small, and there is the risk of failing to sample species which are present - too large, and the time required to collect the data is excessive. This problem has been

TABLE 1

Ecological Studies Of Intertidal Marine Environments Which Have Used Quadrat and Core Count Methods To Determine Animal Numbers

| Worker(s) | Method Used To Collect Data On Which Estimate Is Based. |
|---|---|
| Cassie and Michael (1968) | Core Counts |
| Gray (1971) | |
| Penas and Gonzalez (1983) | |
| Bloom, Simon and Hunter (1972) | |
| Hulings and Gray (1976) | |
| Dale (1974) | |
| Grant (1981) | |
| Fager (1964) | |
| Fenchel, Kofoed and Lappalainen (1975) | |
| Rhoads (1967) | |
| Rhoads and Young (1971) | Quadrat Counts |
| Cadee (1976) | |
| Ott, Fuchs, Fuchs and Malasek (1976) | |
| Longbottom (1970) | |

considered in the field of terrestrial plant ecology by Mueller-Dombois and Ellenberg (1974); Krebs (1978) has extended this consideration to include the sampling of animal populations.

This section contains the results of a survey of the macroinvertebrates present at Ardmore. Sampling was carried out at the sites described in Section 1 during two seasons - Summer and Winter. In a later section (Section 4), the results from this and the previous sections are considered in relation to (b) above.

Three techniques were used to collect the data from which the Abundance and Frequency of the species present could be calculated. The first of these was based upon Quadrat Counts and was used to collect data for the polychaete *Arenicola marina*. The remaining two were based upon Core Counts. One was used for the polychaetes *Pygospio elegans* and *Fabricia sabella* and the other for the remainder of the species present in the sediment.

The different techniques were necessary because of variations in the size, life style and distribution of the species being sampled. To facilitate comparison of the results from the different techniques, all estimates have been standardised to numbers per square metre.

## MATERIALS AND METHODS

After preliminary experiments three sampling methods were used to assess the abundance of the following three groups of macroinvertebrates.

(1) Arenicola marina - this is the dominant species on the shore. It lives in 'U' shaped burrows which range in depth from 20-40cm. Densities of almost $100/m^2$ have been recorded by Cadee (1976). Individuals at Ardmore, may attain a length of 30cm with a wet weight of 30 to 40gms.

(2) Pygospio elegans and Fabricia sabella - these two species build dwelling tubes from fine sand particles and are restricted in their vertical distribution to the upper 5cm. Although numerical densities on the shore may reach several tens of thousands per metre square, the animals themselves are very small (< 2cm long).

(3) The Remaining Species - this group consists of the remaining species found in the upper 20cm of sediment. They could all be sampled satisfactorily using the same technique.

The three techniques were:-

(1) Quadrat Counts To Determine The Abundance Of Arenicola marina:

The conventional method of extracting A. marina from the sediment is to dig over the surface with a fork. This method suffers from a number of serious drawbacks which are relevant to an abundance survey.

(a) It is highly dependant upon the experience of the digger.

(b) A large percentage of worms are often either damaged or not extracted.

(c) It requires a considerable amount of time and effort to gather a representative sample.

(d) It is highly destructive and involves disturbance of a large area around the sampling site.

Fortunately A. marina also indicates its presence on the shore by whorls of faecal sediment (casts) on the surface at the tail end of its 'U' shaped burrow. Similarly it also produces a conical depression at its head end.(See Fig-

-ure 1. ). Longbottom (1970) and Evans (1977) have used these features as the basis of a method for estimating A.marina abundance. A modified version of their method has been used in this survey.

It is assumed in this method, that a single A.marina only produces a cast in one position. The numerical density of individuals at each site was then determined by counting the number of casts contained within two randomly positioned 1 metre square quadrats. It is appreciated that greater accuracy would have been achieved using more than two quadrats per site. This number was however, necessary to render the results compatible with those obtained using the other techniques.

An experiment was performed to compare the results obtained using these methods with those obtained by digging (See Appendix 'E' ). Casts were counted within nine 1 metre square quadrats, positioned randomly at each of three sites - High Water Neaps, Mid-Tide and Low Water Neaps. The area within each quadrat was then dug and the number of worms extracted recorded. Cast numbers were then compared with worm numbers.

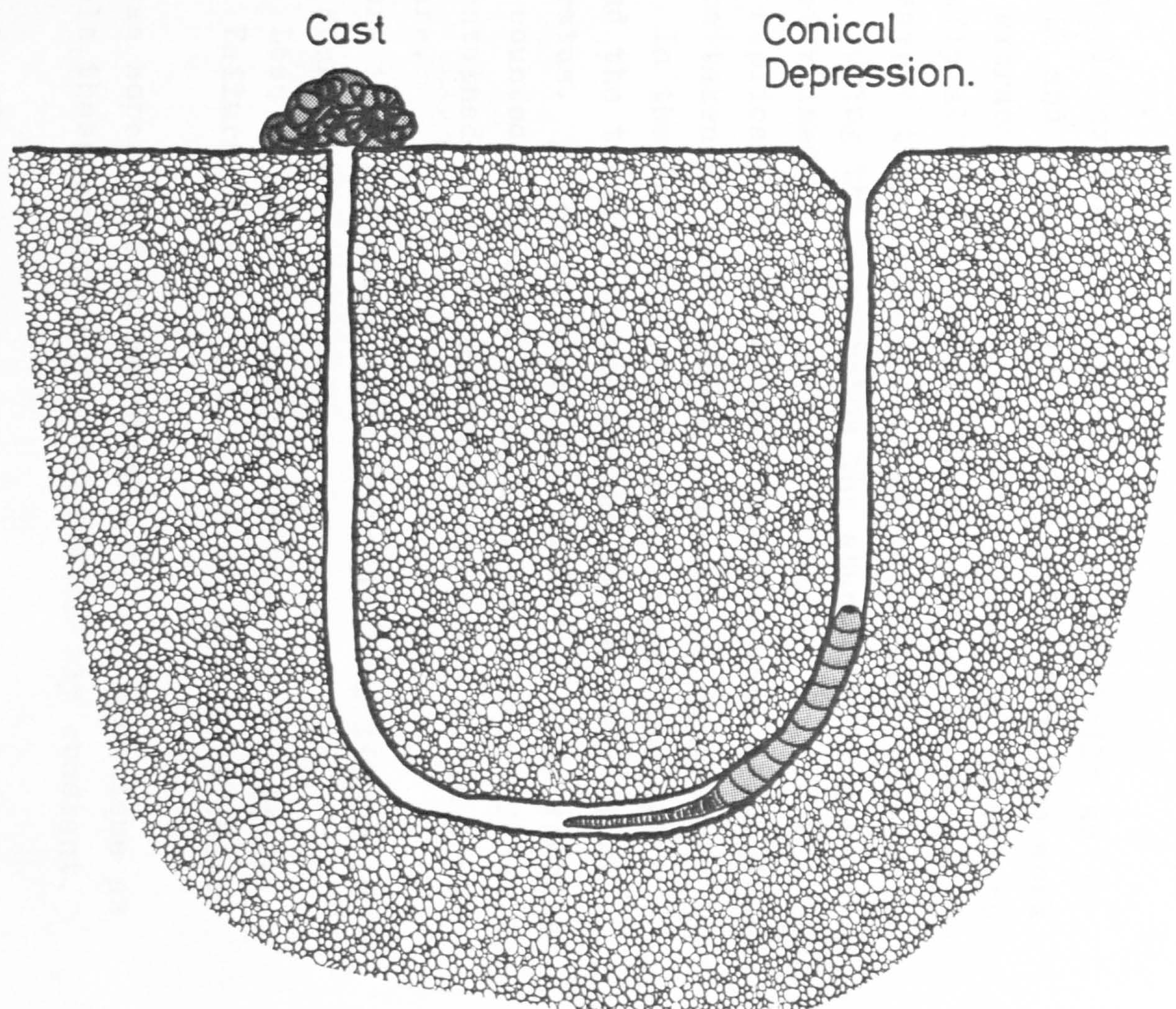
It is possible that errors are incurred in the cast counting technique. The major source of error is likely to be the failure of an individual to produce a cast. In this context Cadee (1976) has noted that individuals may be inactive and fail to produce casts for periods which range between 1 hour and several days. Other error sources include cast destruction by water flow and quadrat boundary effects. The former was hopefully kept to a minimum by only conducting the survey on calm days.

(2) Pygospio elegans and Fabricia sabella

The fact that both species construct and inhabit dwelling tubes presents the problem of extracting the animals from the tubes prior to counting. Sieving the sediment is sufficient to remove the tubes containing the animals from the bulk of the sediment but is insufficient to remove the animals from the tubes.

Fig. 1.

Arenicola marina - Typical Burrow Structure.



A fellow worker observed that P. elegans exhibited negative phototaxis when exposed to a strong light source. F. sabella was found to behave similarly. Tests were performed to confirm that it was light and not the associated heat production that resulted in the observed behaviour. (See Appendix F ). The results confirmed that light was the stimulus.

A simple extraction apparatus was then built as shown in Fig. 2 and tested. The apparatus was found to work well, with an extraction time of 24 hours being sufficient to extract virtually all the animals. Where both species were present in a sample they could easily be identified and counted separately. Using this apparatus the abundance of both species was determined at each site as follows:-

Two replicate cores, each 10.7cm diameter (See 3) and 5.0cm deep were taken at each site and placed in separate plastic bags. In the laboratory they were sieved through a 710 μm mesh and the tubes retained placed in two sets of extraction apparatus. After 24 hours the number of each species extracted was counted. Using a multiplication factor of 111.2, the numbers contained in each core were converted to numbers per square metre.

Errors incurred using this technique are likely to stem from two sources -

(i) Loss of animals during the sieving procedure.

(ii) Failure to extract all the animals from their tubes.

It was hoped that by standardizing the technique as much as possible these errors were kept reasonably constant.

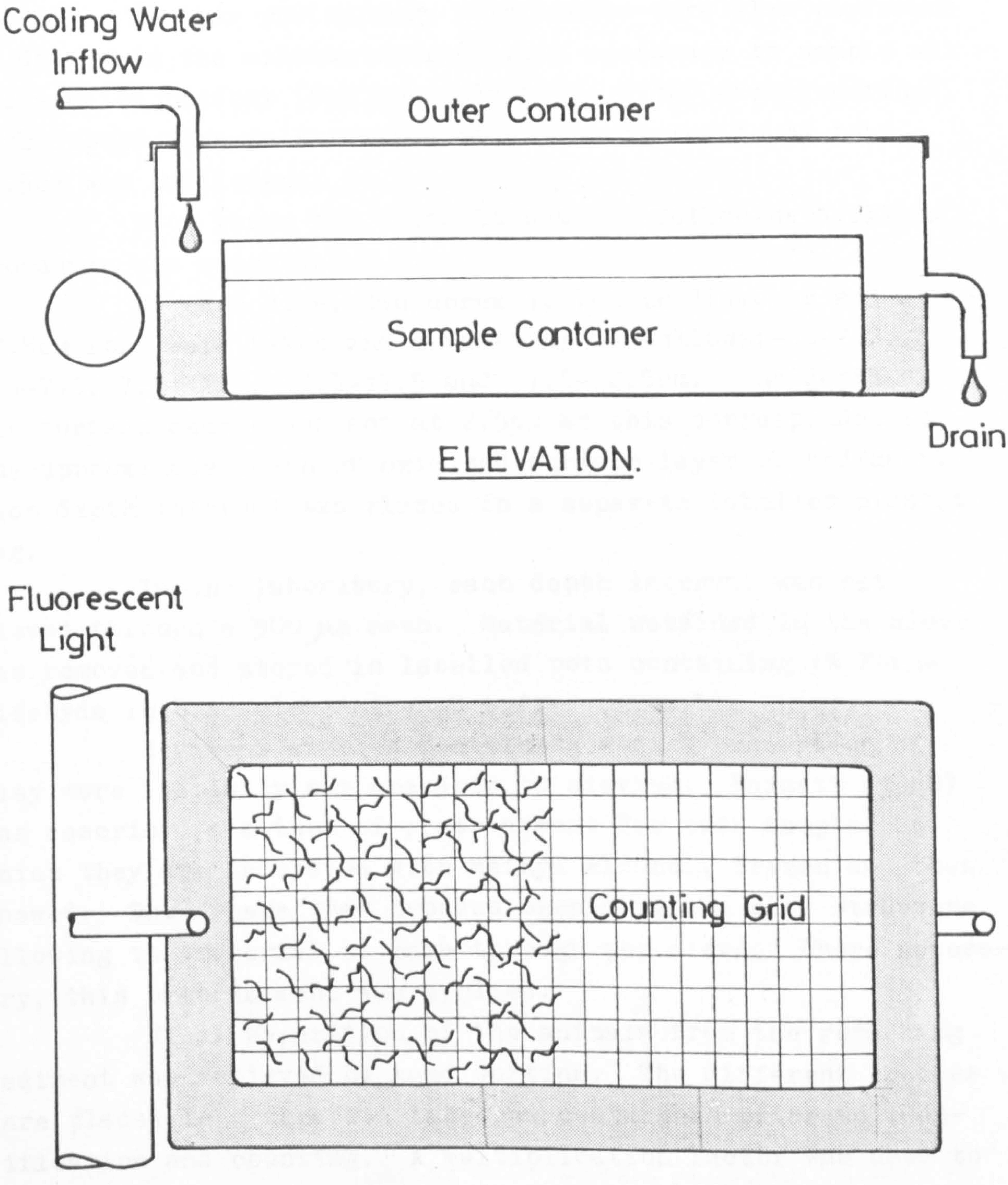
(3) The Remaining Macroinvertebrate Species

Preliminary experiments were conducted along the lines of those performed by Gray (1974) to determine the optimum core diameter. (See Appendix 'G' ). Three core sizes were experimented with, 5.1, 8.0 and 10.7cm diameter. The criteria upon which the optimum core size was decided upon were as follows:-

(a) That core size which gave the highest estimate

Fig. 2.

Pygospio elegans And Fabricia sabella Extraction Apparatus.




Note.

Scale- 1 : 2 Approx.

Both Containers Are Made From Clear Plastic.

of abundance expressed as a mean of a number of replicates.

(b) That size which gave the lowest error to the mean value calculated in (a).

Results indicated the 10.7cm diameter core to be the most suitable.

Further preliminary experiments were also performed to determine the minimum coring depth necessary to sample all the species present (See Appendix 'G' ). After experimenting with depths down to a maximum of 42.5cm it was found that 22.5cm was sufficient.

With these two criteria set the following sampling procedure was adopted:

At each site, two cores 10.7cm in diameter and 22.5cm long were taken and divided up as follows:- 0-2.5, 2.5-7.5, 7.5-12.5, 12.5-17.5 and 17.5-22.5cm. The depth of the surface sample was set at 2.5cm as this corresponded to the approximate depth of oxidized surface layer of sediment. Each depth interval was placed in a separate labelled plastic bag.

In the laboratory, each depth interval was wet sieved through a 500 μm mesh. Material retained in the sieve was removed and stored in labelled pots containing 4% Formaldehyde in Sea Water and a pH buffer (a marble chip).

Sediment samples containing a high proportion of clay were initially not amenable to sieving. Barnett (1980) has described a method of pretreatment for such samples in which they are saturated with Methyl Alcohol, frozen and then thawed. The freeze/thaw process breaks up the clay structure allowing the material to pass through the sieve. Where necessary, this pretreatment was applied.

Final separation of the animals from the remaining sediment was achieved by hand sorting. The different species were placed in separate labelled containers prior to identification and counting. A multiplication factor was used to convert the numbers contained in each core to the numbers per square metre.

Species Identification

The following texts were used to identify species present in the samples.

| | | |
|---|---|---|
| Campbell (1976) | - | Hamlyn Guide to the Seashore and Shallow Seas of Britain and Europe. |
| Tattersall and Tattersall (1951) | - | The British Mysidacea. |
| Fauvel (1927) | - | The Faune du France 16 Polychetes Sedentaries. |
| Fauvel (1923) | - | The Faune du France 5 Polychetes errantes. |
| McMillan 1968) | - | British Shells. |
| Sars (1895) | - | An account of the Crustacea of Norway. Volume 1 - Amphipoda. |
| McIntosh | - | A Monograph of the British Marine Annelids |

| | | | | |
|---|---|---|---|---|
| Vol. | I | Part | I | (1872) |
| " | I | " | II | (1898) |
| " | II | " | I | (1907) |
| " | II | " | II | (1908) |
| " | III | " | I | (1915) |
| " | IV | " | I | (1922) |
| " | IV | " | II | (1923) |

Type specimens of the various polychaete species were sent to Dr. D. George of the British Museum (Natural History) for confirmation of identity. His assistance is greatly appreciated.

## RESULTS

The results in this section are presented as Histograms. The raw data upon which these are based has been stored in a computer file, a hard copy of which is available for inspection. The form of presentation of the histograms is such that where applicable, the data for both replicates has been included.

*******************

The nineteen species or species groups of Macroinvertebrate sampled in the survey are shown in Table 2 .

Figures 3 to 5 show the number of sites at which each species was present expressed as a percentage of the total number of sites. Values ranged between 100% (Arenicola marina and Pygospio elegans) and 2.5% (Crangon vulgaris, Lanice conchilega and Littorina littorea). Approximately half the species were present at 30% or more of the sites. The percentage of sites occupied by a species was generally highest in Summer.

Figures 3 and 4 also show the largest number of species to have been sampled from Transect 'A' and the fewest from Transect 'C'. There were no seasonal differences in the number of species sampled on any of the transects.

The total number of species present at each site is shown in Figure 6 . Numbers increase towards High Water and are highest in Summer. A comparison between transects at the reference sites shows 'C' to have fewer species than 'A' or 'B' at HWN but a similar number at MT and LWN. Transects 'A' and 'B' have similar numbers at all three sites.

Variation in the number of species with depth into the sediment is shown in Table 3 . At all sites there is a reduction in the number of species present with depth. The upper 7.5cm of sediment contains the majority of the species, with most being present in the top 2.5cm. There is some indication that above Mid-Tide, species move deeper into the sediment in Winter. A comparison between transects at the reference sites shows the distributions to be similar.

Table. 2.

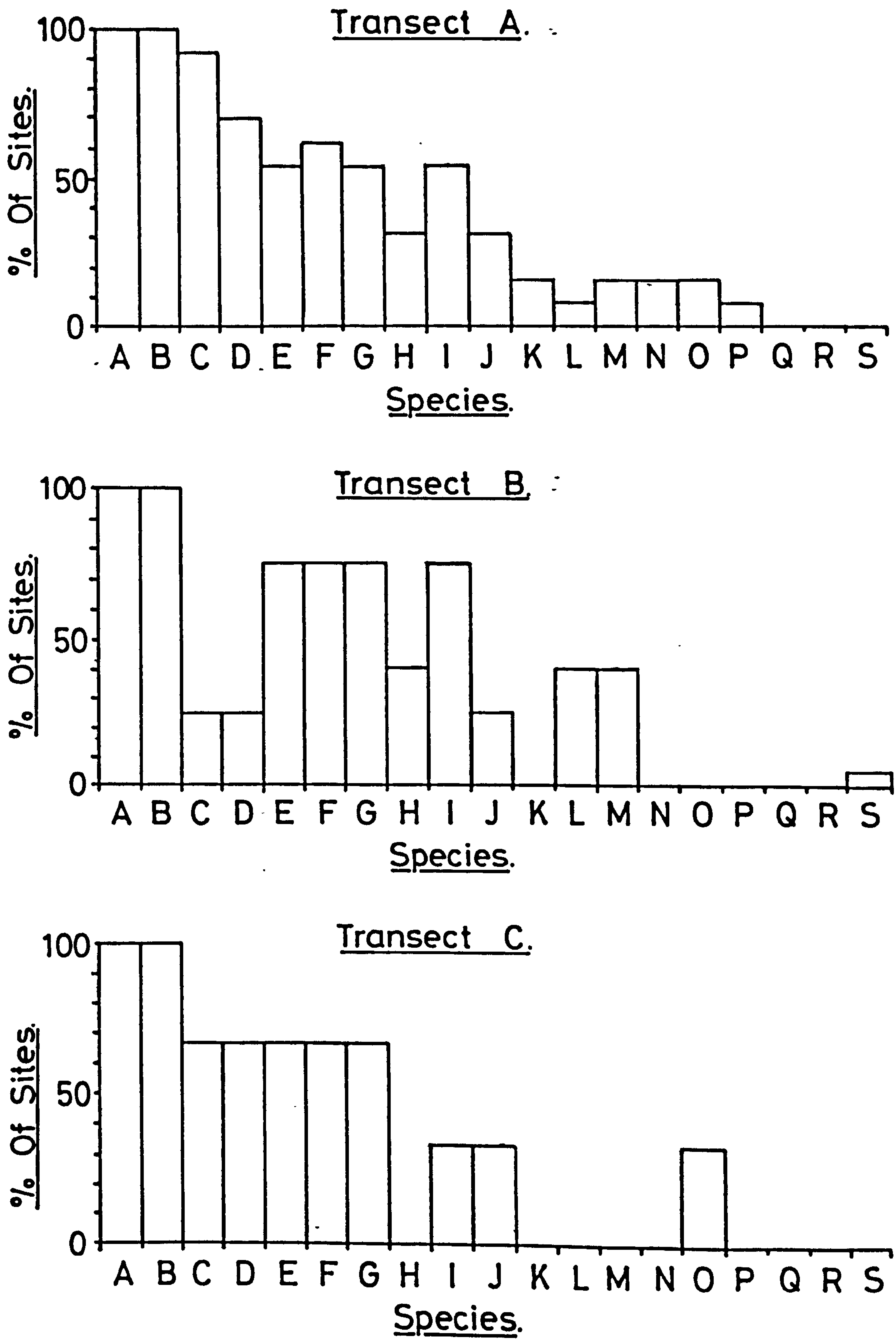
Macroinvertebrates Sampled In Transect Survey.

| SPECIES | IDENTIFICATION | CLASS |
|---|---|---|
| A | Arenicola marina | Polychaeta |
| B | Pygospio elegans | " |
| C | Macoma balthica | Bivalvia |
| D | Scoloplos armiger. | Polychaeta |
| E | Oligochaete species | Oligochaeta |
| F | Hydrobia ulvae | Gastropoda |
| G | Etione longa | Polychaeta |
| H | Fabricia sabella | " |
| I | Nereis diversicolor | " |
| J | Micrura species | Nemertina+ |
| K | Diptera species larvae | Diptera+ |
| L | Corophium volutator | Crustacea |
| M | Bathyporeia pilosa | " |
| N | Etione picta | Polychaeta |
| O | Nephthys hombergii | " |
| P | Cardium edule | Bivalvia |
| Q | Crangon vulgaris | Crustacea |
| R | Lanice conchilega | Polychaeta |
| S | Littorina littorea | Gastropoda |

+ PHYLUM

Fig. 3.

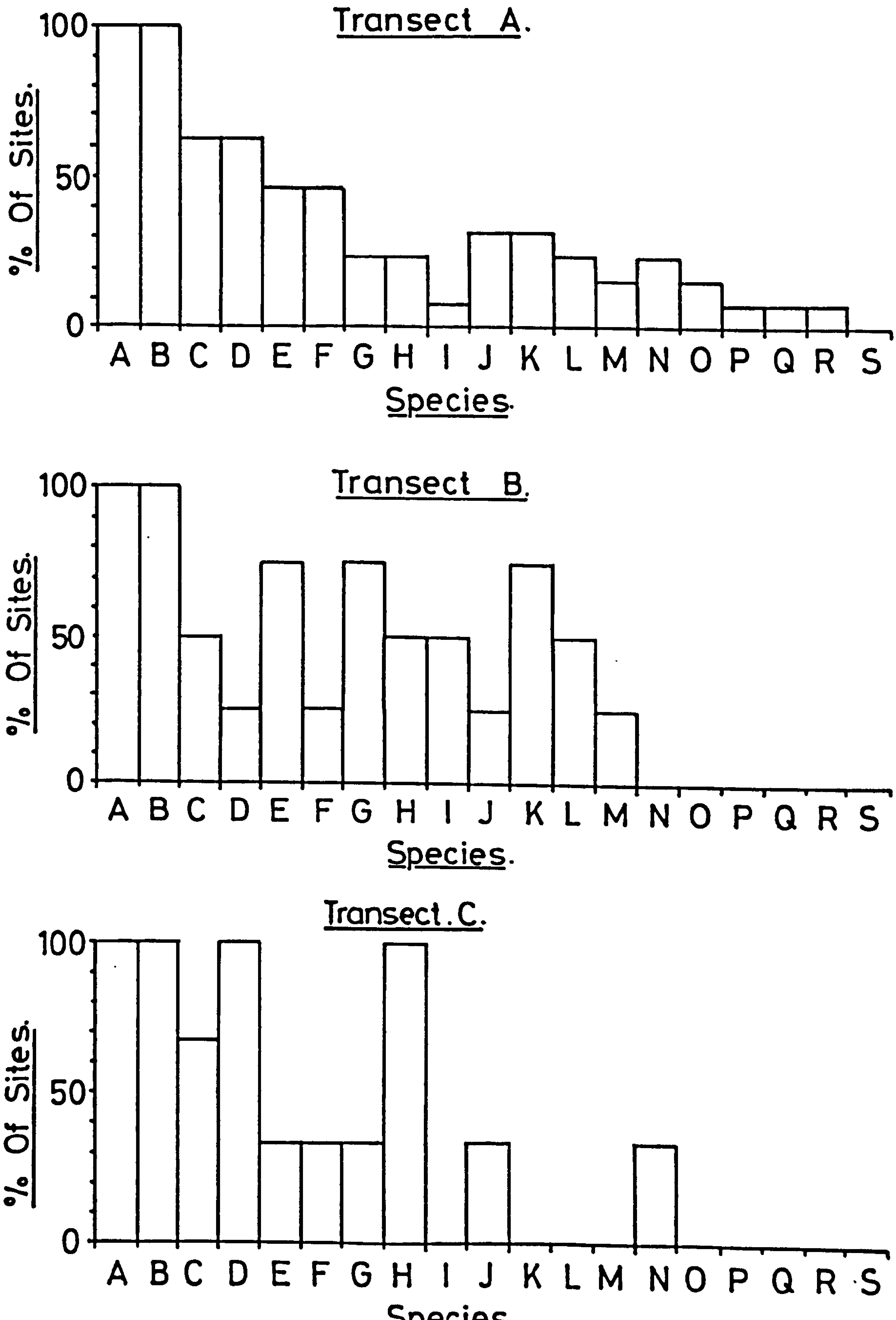
Histograms Showing The Number Of Sites Species Are Present Expressed As A % Of The Total Number Of Sites.




Summer.

Fig.4.

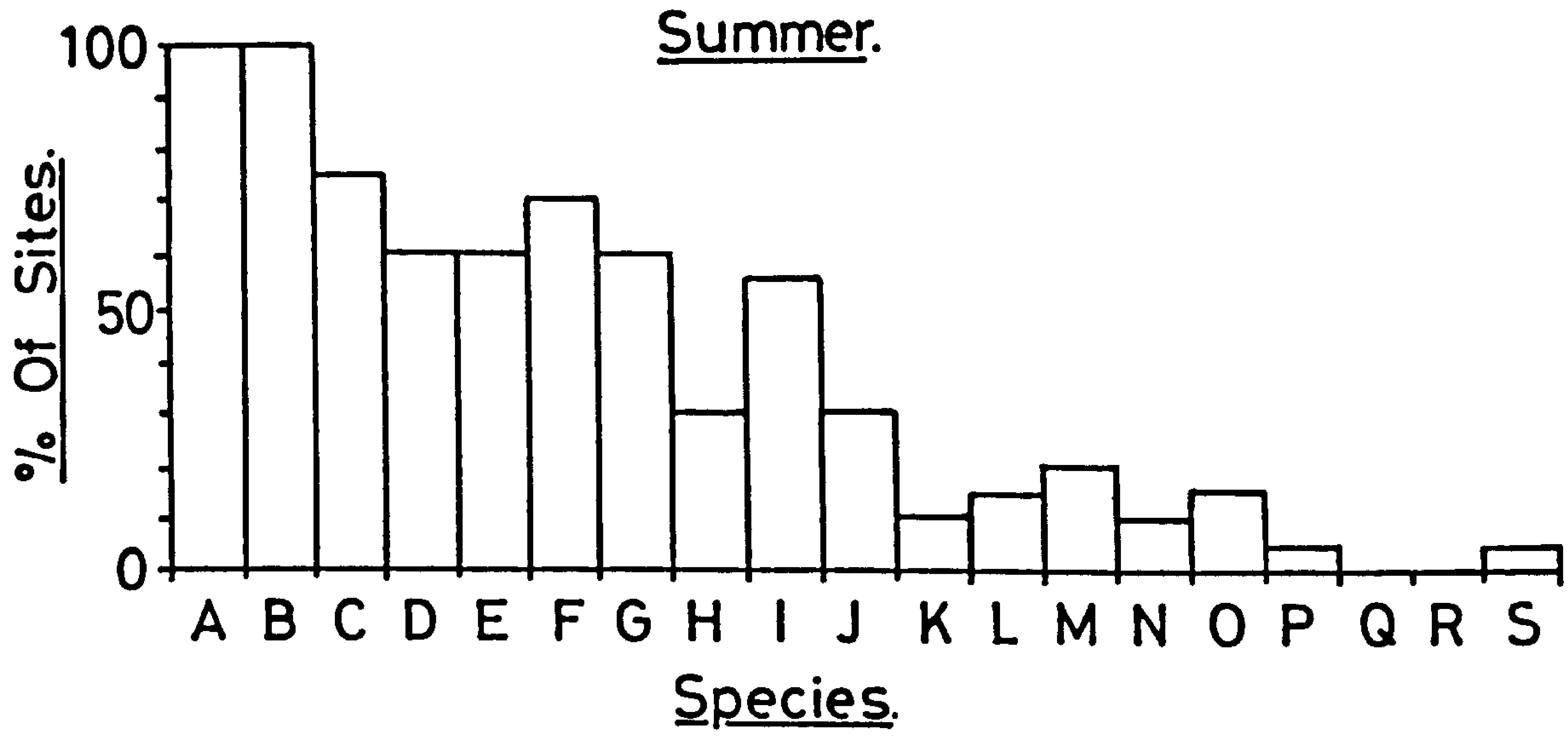
Histograms Showing The Number Of Sites Species Are Present Expressed As A % Of The Total Number Of Sites.

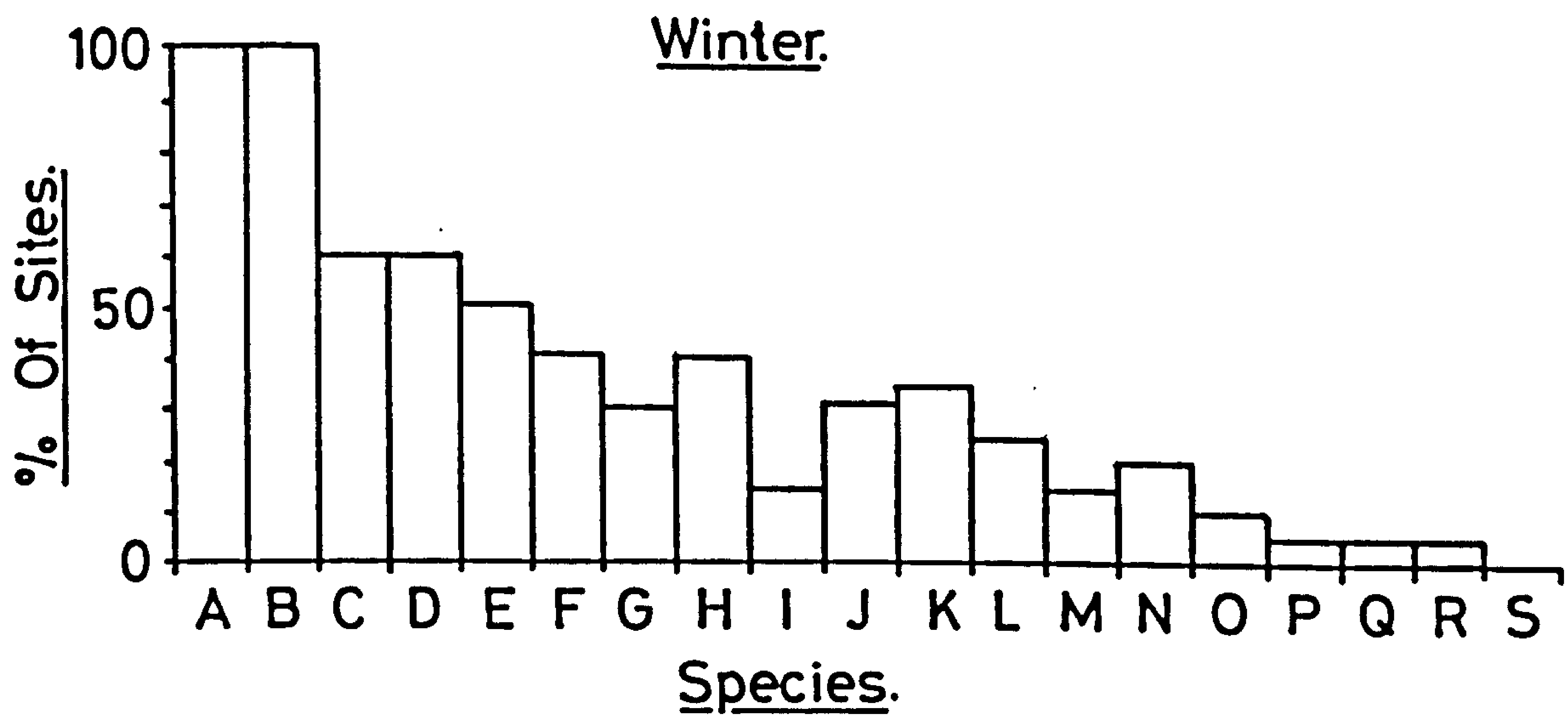



Winter.

Fig.5.

Histograms Showing The Number Of Sites Species Are Present Expressed As A % Of The Total Number Of Sites.



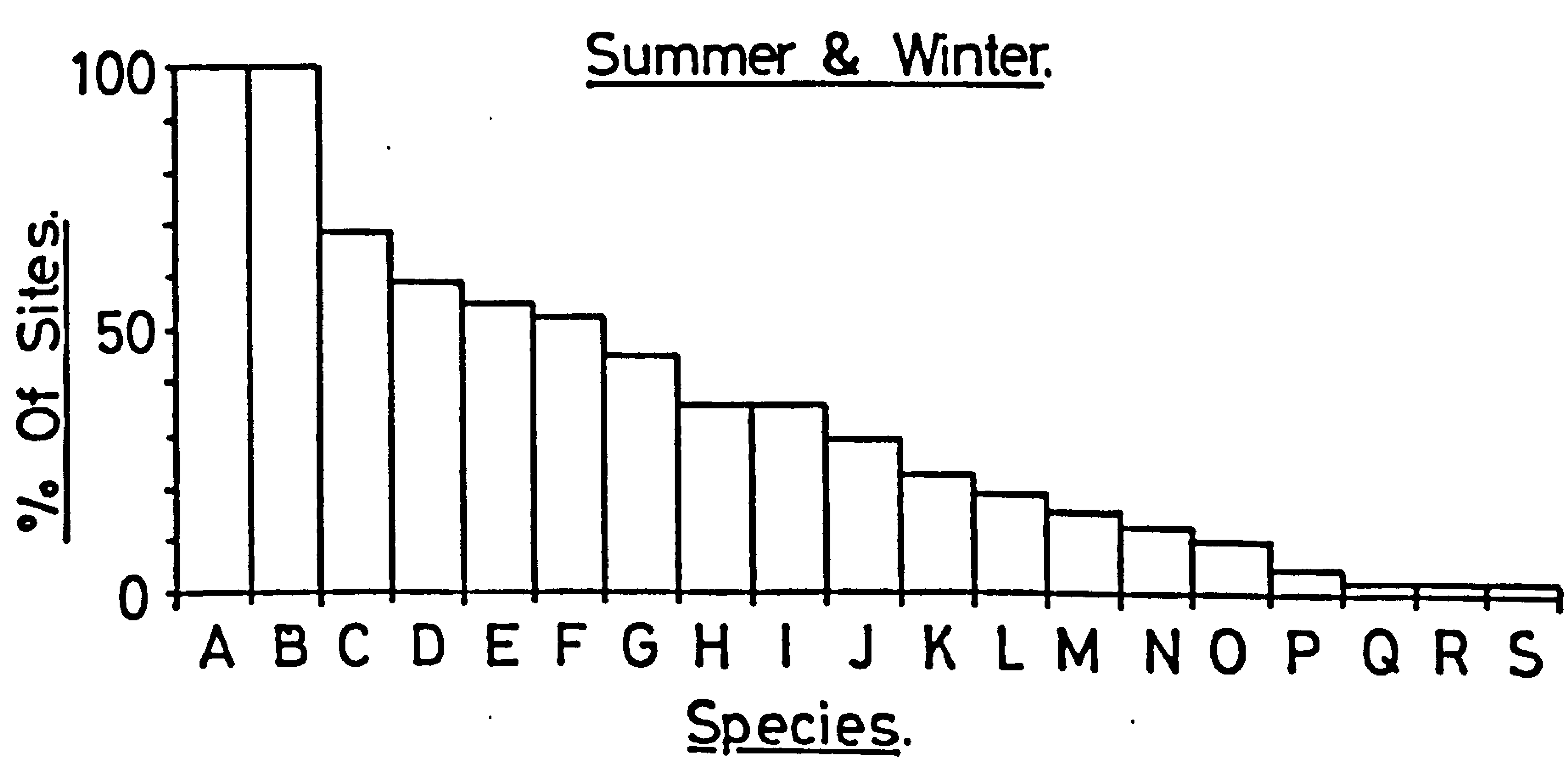



Fig. 6.

Total Number Of Macroinvertebrate Species At Each Site Down Transects.

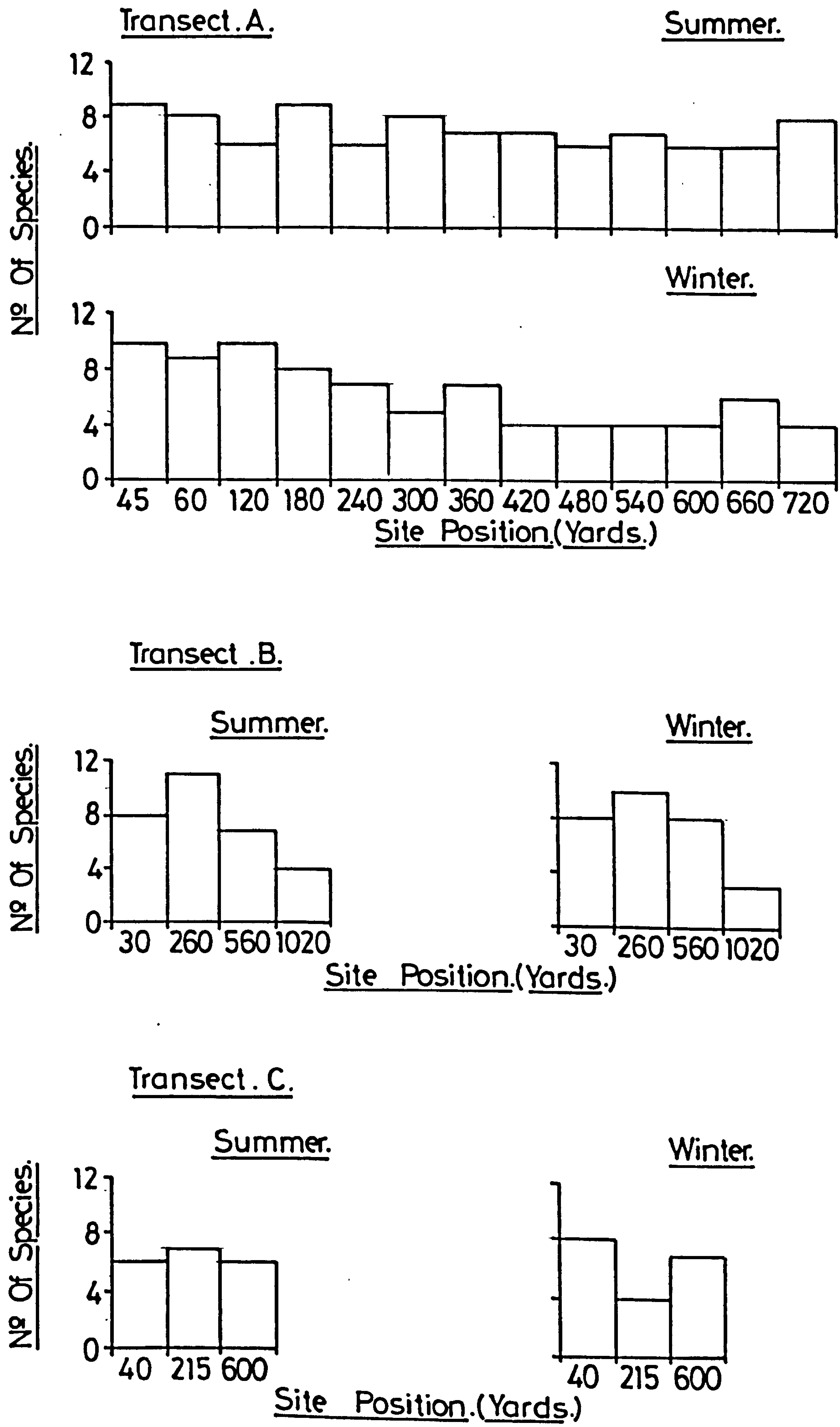


TABLE 3

The Number of Species of Macroinvertebrate Within Each Depth Interval

| Season | Transect | 'A' | | | | | | | | | | | | | 'B' | | | | 'C' | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Depth Interval (cm) / Site Yds. | 45 | 60 | 120 | 180 | 240 | 300 | 360 | 420 | 480 | 540 | 600 | 660 | 720 | 30 | 260 | 560 | 1020 | 40 | 215 | 600 |
| Summer | 0-2.5 | 9 | 8 | 5 | 6 | 3 | 5 | 6 | 6 | 4 | 6 | 5 | 5 | 6 | 7 | 10 | 6 | 4 | 6 | 7 | 5 |
| | 2.5-7.5 | 4 | 6 | 3 | 5 | 4 | 5 | 3 | 3 | 4 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 1 | 4 | 5 | 5 |
| | 7.5-12.5 | 2 | 2 | 1 | 3 | 1 | 2 | 2 | 1 | 2 | 1 | 3 | 2 | 1 | 1 | 3 | 2 | 1 | 3 | 1 | 2 |
| | 12.5-17.5 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 2 | 1 | 2 | 1 | 1 | 3 | 2 | 1 | 2 | 1 |
| | 17.5-22.5 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 1 | 2 | 1 |
| Winter | 0-2.5 | 8 | 8 | 6 | 6 | 3 | 4 | 6 | 4 | 4 | 4 | 3 | 4 | 2 | 6 | 9 | 4 | 2 | 6 | 4 | 4 |
| | 2.5-7.5 | 7 | 4 | 4 | 2 | 4 | 4 | 3 | 2 | 1 | 3 | 3 | 4 | 3 | 5 | 5 | 3 | 2 | 6 | 1 | 4 |
| | 7.5-12.5 | 3 | 3 | 2 | 3 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 4 | 1 | 2 | 1 | 4 | 1 | 2 |
| | 12.5-17.5 | 4 | 3 | 3 | 3 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 3 | 1 | 2 | 1 | 1 |
| | 17.5-22.5 | 2 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 1 | 1 | 1 |
| All | 0-2.5 | 9 | 9 | 6 | 8 | 4 | 6 | 7 | 7 | 5 | 6 | 6 | 5 | 6 | 8 | 12 | 8 | 4 | 7 | 8 | 7 |
| | 2.5-7.5 | 8 | 6 | 4 | 5 | 6 | 5 | 3 | 3 | 4 | 4 | 3 | 5 | 7 | 7 | 6 | 5 | 2 | 6 | 5 | 6 |
| | 7.5-12.5 | 4 | 4 | 2 | 4 | 2 | 2 | 2 | 1 | 2 | 2 | 3 | 2 | 1 | 4 | 3 | 3 | 1 | 5 | 1 | 3 |
| | 12.5-17.5 | 4 | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 1 | 2 | 2 | 1 | 4 | 2 | 2 | 2 | 1 |
| | 17.5-22.5 | 2 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 2 | 3 | 1 | 2 | 1 |

NOTE! These figures are calculated using the data for both replicates.

Table.3.

The horizontal distribution patterns of individual species down the Transects are shown in Figures 7 to 16 (Species present at 30% or more of the sites) and Tables 4 and 5 (Species present at fewer than 30% of the sites). Data for all the sites has been combined to produce Table 6 . This shows the vertical distribution of each species within the sediment profile.

The distribution patterns of the nineteen species/groups are summarized in Table 7 . An examination of this shows they can be grouped on the basis of their horizontal and vertical distribution patterns. The groupings are shown in Tables 8 and 9.

FIGURES 7 TO 16.

The horizontal distribution patterns of macroinvertebrate species sampled down the three transects.

The shaded area represents the difference between the values for the two replicate samples.

Fig.7.
Arenicola marina, Numerical Density Down Transects.

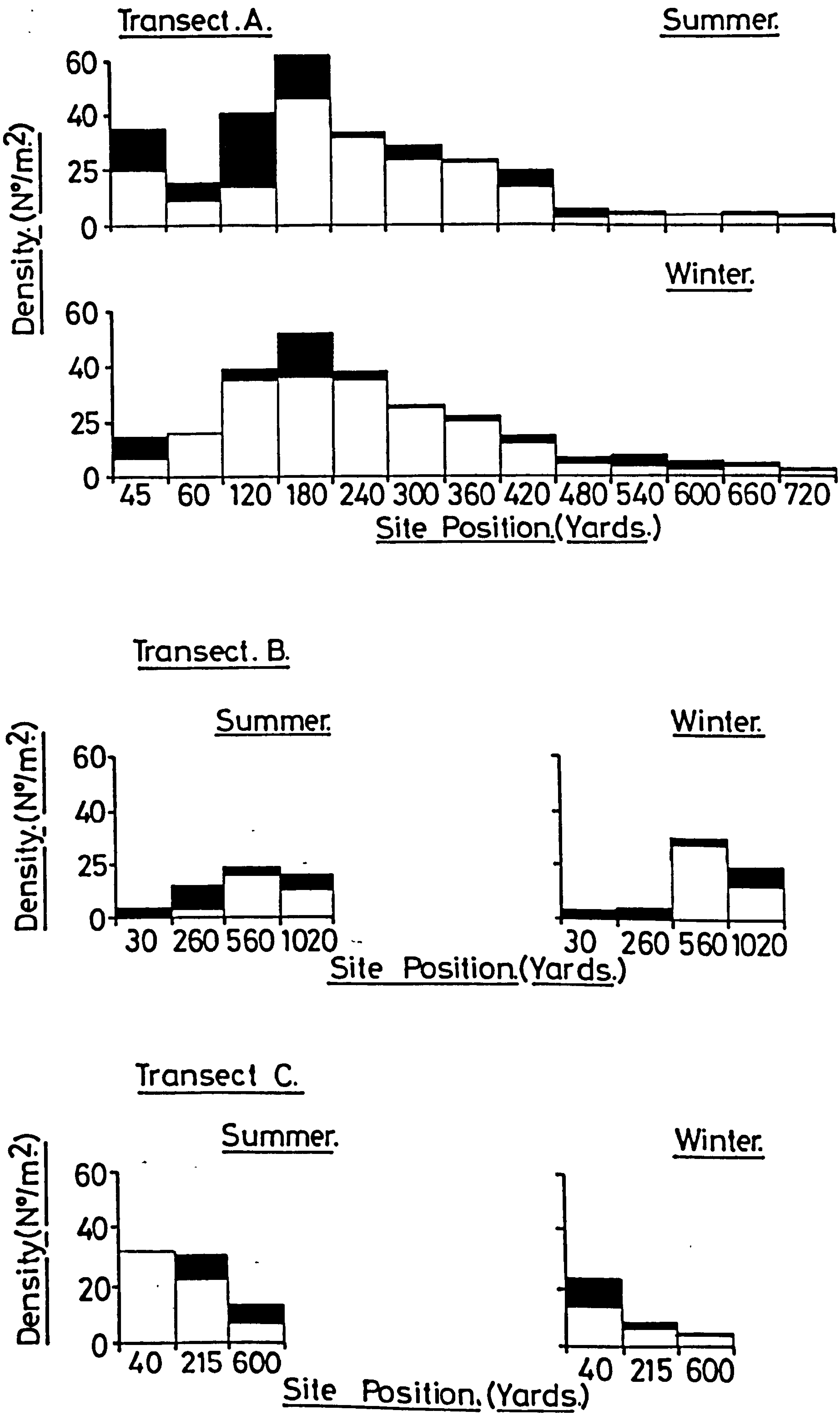


Fig.8.

Pygospio elegans Numerical Density Down Transects.

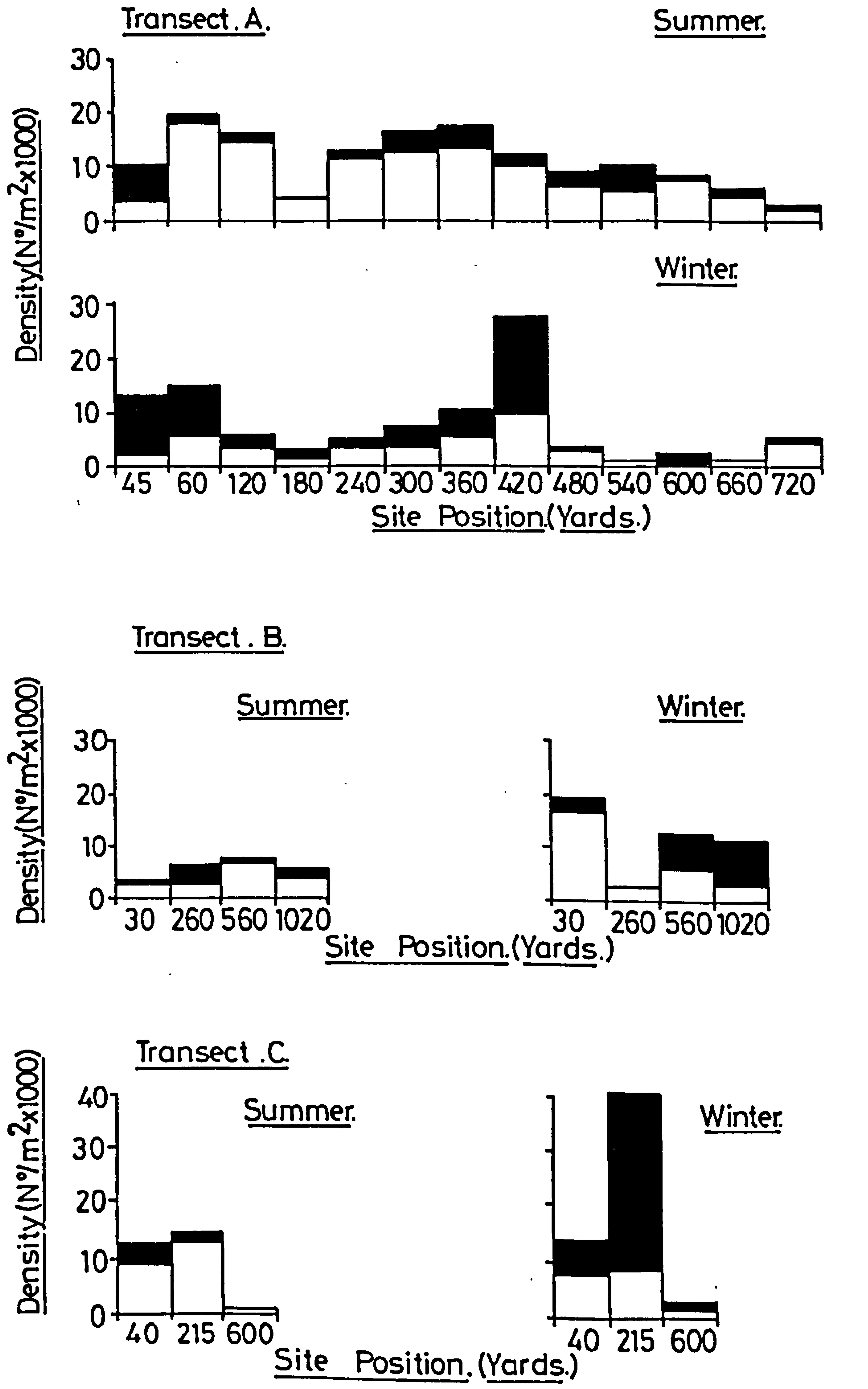


Fig. 9.

Macoma balthica Numerical Density Down Transects.

Fig.10.

Scoloplos armiger Numerical Density Down Transects.

Fig.11. Oligochaete species Numerical Density Down Transects.

Fig.12. *Hydrobia ulvae* Numerical Density Down Transects.

Fig.13. Etione longa Numerical Density Down Transects.

Fig.14.

Fabricia sabella Numerical Density Down Transects.

Fig.15. Nereis diversicolor Numerical Density Down Transects.

Fig.16.

Micrura species Numerical Density Down Transects.

**TABLE 4.**

**Macroinvertebrate Numerical Density Down Transects**
**(Species Present At Less Than 30% of Sites)**

| Transect | | | 'A' | | | | | | | | | | | | | 'B' | | | | 'C' | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Species | Season | Replicate | 45 | 60 | 120 | 180 | 240 | 300 | 360 | 420 | 480 | 540 | 600 | 660 | 720 | 30 | 260 | 560 | 1020 | 40 | 215 | 600 |
| Diptera Species Larvae | S | 1 | 1446 | 0 | | | | | | | | | | | | | | | | | | |
| | | 2 | 1112 | 1668 | | | | | | | | | | | | | | | | | | |
| | W | 1 | 1446 | 2780 | 556 | 0 | | | | | | | | | | 334 | 445 | 111 | | | | |
| | | 2 | 3356 | 778 | 111 | 111 | | | | | | | | | | 445 | 0 | 0 | | | | |
| Corophium volutator | S | 1 | 0 | | | | | | | | | | | | | | | | | | | |
| | | 2 | 445 | | | | | | | | | | | | | | | | | | | |
| | W | 1 | 111 | 556 | | | 0 | | | | | | | | | | | | | | | |
| | | 2 | 222 | 0 | | | 111 | | | | | | | | | | | | | | | |
| Bathyporeia pilosa | S | 1 | | | | | | 111 | | 0 | | | | | | | | 667 | 0 | | | |
| | | 2 | | | | | | 0 | | 222 | | | | | | | | 445 | 445 | | | |
| | W | 1 | | | | | | | 0 | | 111 | | | | | | 111 | | | | | |
| | | 2 | | | | | | | 111 | | 0 | | | | | | 0 | | | | | |
| Etione picta | S | 1 | 111 | | | 111 | | | | | | | | | | | | | | | | |
| | | 2 | 0 | | | 0 | | | | | | | | | | | | | | | | |
| | W | 1 | | | 0 | | 111 | | 111 | | | | | | | | | | | | | 111 |
| | | 2 | | | 111 | | 0 | | 0 | | | | | | | | | | | | | 0 |

Table.4.

TABLE 5

Macroinvertebrate Numerical Density Down Transects
(Species Present At Less Than 30% of Sites)

| Transect | | | 'A' | | | | | | | | | | | | | 'B' | | | | 'C' | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Species | Season | Replicate | 45 | 60 | 120 | 180 | 240 | 300 | 360 | 420 | 480 | 540 | 600 | 660 | 720 | 30 | 260 | 560 | 1020 | 40 | 215 | 600 |
| Nephthys hombergii | S | 1 | | | | | | | | | | 111 | | | 111 | | | | | | | 222 |
| | | 2 | | | | | | | | | | 0 | | | 222 | | | | | | | 0 |
| | W | 1 | | | | | | | | | | 222 | | 0 | | | | | | | | |
| | | 2 | | | | | | | | | | 334 | | 111 | | | | | | | | |
| Cardium edule | S | 1 | | | | | | | | 111 | | | | | | | | | | | | |
| | | 2 | | | | | | | | 0 | | | | | | | | | | | | |
| | W | 1 | | | | | | | | | | | | 111 | | | | | | | | |
| | | 2 | | | | | | | | | | | | 0 | | | | | | | | |
| Lanice conchilega | S | 1 | | | | | | | | | | | | | | | | | | | | |
| | | 2 | | | | | | | | | | | | | | | | | | | | |
| | W | 1 | | | | | | | | | | | | | 222 | | | | | | | |
| | | 2 | | | | | | | | | | | | | 334 | | | | | | | |
| Crangon vulgaris | S | 1 | | | | | | | | | | | | | | | | | | | | |
| | | 2 | | | | | | | | | | | | | | | | | | | | |
| | W | 1 | | | | 0 | | | | | | | | | | | | | | | | |
| | | 2 | | | | 111 | | | | | | | | | | | | | | | | |
| Littorina littorea | S | 1 | | | | | | | | | | | | | | | 111 | | | | | |
| | | 2 | | | | | | | | | | | | | | | 0 | | | | | |
| | W | 1 | | | | | | | | | | | | | | | | | | | | |
| | | 2 | | | | | | | | | | | | | | | | | | | | |

## TABLE 6

### Vertical Distribution of Macroinvertebrate Species

| Season | Depth Interval (cm) \ Species | *Arenicola marina* | *Pygospio elegans* | *Macoma balthica* | *Scoloplos armiger* | *Oligochaete species* | *Hydrobia ulvae* | *Etione longa* | *Fabricia sabella* | *Nereis diversicolor* | *Micrura species* | *Diptera species larvae* | *Corophium volutator* | *Bathyporeia pilosa* | *Etione picta* | *Nephthys hombergii* | *Cardium edule* | *Crangon vulgaris* | *Lanice conchilega* | *Littorina littorea* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Summer | 0-2.5* | 100 | 100 | 45 | 38 | 82 | 90 | 11 | 100 | 93 | 42 | 92 | 95 | 76 | 0 | 60 | 100 | 0 | 0 | 100 |
| | 2.5-7.5 | 100 | 0 | 55 | 59 | 18 | 9 | 59 | 0 | 2 | 53 | 5 | 5 | 8 | 100 | 40 | 0 | 0 | 0 | 0 |
| | 7.5-12.5 | 100 | 0 | 0 | 3 | 1.5 | 1 | 19 | 0 | 1 | 5 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 12.5-17.5 | 100 | 0 | 0 | 0 | 0.3 | 0 | 6 | 0 | 3 | 0 | 0 | 0 | 8 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 17.5-22.5 | 100 | 0 | 0 | 0 | 0.5 | 0 | 5 | 0 | 1 | 0 | 0 | 0 | 8 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | | | | | | | | | | | | | | | |
| Winter | 0-2.5* | 100 | 100 | 26 | 45 | 27 | 85 | 0 | 100 | 0 | 39 | 83 | 95 | 100 | 25 | 25 | 100 | 100 | 0 | 0 |
| | 2.5-7.5 | 100 | 0 | 67 | 41 | 31 | 15 | 13 | 0 | 29 | 36 | 13 | 5 | 0 | 75 | 75 | 0 | 0 | 50 | 0 |
| | 7.5-12.5 | 100 | 0 | 7 | 12 | 7 | 0 | 74 | 0 | 43 | 8 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 12.5-17.5 | 100 | 0 | 0 | 2 | 24 | 0 | 13 | 0 | 14 | 17 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 17.5-22.5 | 100 | 0 | 0 | 0 | 11 | 0 | 0 | 0 | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 50 | 0 |
| | | | | | | | | | | | | | | | | | | | | |
| All | 0-2.5* | 100 | 100 | 37 | 40 | 49 | 91 | 9 | 100 | 88 | 40 | 85 | 95 | 79 | 17 | 44 | 100 | 100 | 0 | 100 |
| | 2.5-7.5 | 100 | 0 | 58 | 53 | 26 | 8 | 51 | 0 | 3 | 42 | 11 | 5 | 7 | 83 | 56 | 0 | 0 | 50 | 0 |
| | 7.5-12.5 | 100 | 0 | 5 | 6 | 5 | 1 | 27 | 0 | 3 | 7 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 12.5-17.5 | 100 | 0 | 0 | 1 | 14 | 0 | 9 | 0 | 4 | 11 | 1 | 0 | 7 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 17.5-22.5 | 100 | 0 | 0 | 0 | 6 | 0 | 4 | 0 | 2 | 0 | 0 | 0 | 7 | 0 | 0 | 0 | 0 | 50 | 0 |

NOTE *0-5.0 for Pygospio elegans and Fabricia sabella.
Data is expressed as the percentage of the total number of individuals of each species present at each depth interval.

Table.6.

TABLE 7

Summary Of The Distribution Patterns of Macroinvertebrate Species and Species Groups Sampled In The Survey

| Figure or Table | Species | Distribution Down Transect | Distribution Within Sediment Profile | Seasonal Differences |
|---|---|---|---|---|
| Fig.7 | *Arenicola marina* | Present at all sites on all transects. Transect A - Density rises from 10 - 35/m2 at HWN to 40 - 60/m2 at 180 yds. it then falls off to 2 - 5/m2 at LWN. Transect B - Pattern similar to 'A' but HWN and MT densities lower at 0 - 5/m2 and 20 - 30/m2, LWN densities are higher at 15 - 20/m2. Transect C - Highest densities of 20 - 30/m2 and LWN lower still at 5 -10/m2. | Present throughout the full sampling depth. | Density is generally highest along all transects in Summer. |
| Fig.8 | *Pygospio elegans* | Present at all sites on the transects. Transect A.- Two density peaks in the Summer and Winter data. The first just below HWN has values which range between 5000 and 20000/m2. The second just below MT has values between 10000 and 30000/m2. Minimum densities occur at 180 yds. (2000 - 4000/m2) and around LWN (1000 - 3000/m2. Transect B - Summer data shows a peak density at MT (7000/m2). This falls off to 3000-6000/m2 at HWN and 4000 - 6000/m2 at LWN. There are two Winter peaks, one above HWN (17000 - 20000/m2) and the other at MT (5000 - 12000/m2) | Restricted to the upper 5cm of sediment. | Densities are highest along Transect A in Summer. No consistent pattern on Transects B and C |

TABLE 7 (continued)

| Figure or Table | Species | Distribution Down Transect | Distribution Within Sediment Profile | Seasonal Differences |
|---|---|---|---|---|
| Fig.8 | Pygospio elegans (continued) | Transect C - Peak densities occur at MT (9000 - 40000/m2). Densities at HWN and LWN range between 9000 - 14000/m2 and 1000 - 2000/m2 respectively. | | |
| Fig.9 | Macoma balthica | Distributed over most of the shore although somewhat sporadic in occurence.<br>Transect A - No obvious pattern to its distribution. Densities range between 100 and 300/m2.<br>Transect B - Restricted to HWN and MT sites. Highest densities at HWN (200 - 600/m2).<br>Transect C - Highest densities at HWN (200 - 400/m2). LWN and MT densities ranged between 100 and 200/m2. | Restricted to the upper 12.5cm with most present in the top 7.5cm | Present at more sites in Summer. Similar densities in both seasons. |
| Fig.10 | Scoloplos armiger | Generally most abundant at sites below MT.<br>Transect A - Common at sites below 240 yds. Densities range between 100 and 1000/m2.<br>Transect B - Only present in samples from MT and LWN. Densities ranged between 100 and 200/m2.<br>Transect C - Present at all sites. Densities ranged between 100 and 600/m2 with a maximum at LWN. | Present in all but the deepest samples but most abundant in the upper 7.5cm. | Densities are consistently higher on Transect A in Summer. Some indication that the species moves deeper into the sediment in Winter. |

TABLE 7 (continued)

| Figure or Table | Species | Distribution Down Transect | Distribution Within Sediment Profile | Seasonal Differences |
|---|---|---|---|---|
| Fig.11 | Oligochaete species | Restricted to sites above MT. Transect A - Densities are highest at HWN (14000 - 22000/m2) and fall off steadily to MT ( 1000/m2). Transect B - Pattern similar to 'A' with HWN densities of 1000 - 13000/m2 and MT densities of 1000/m2. Transect C - Only present in any number at HWN (4000/m2). A few individuals at LWN ( 300/m2). | Present throughout the full sampling depth. Densities are however highest in the upper 7.5cm | Similar horizontal distribution patterns and densities in both seasons. Some indication that the species move deeper into the sediment in Winter. |
| Fig.12 | Hydrobia ulvae | Most abundant at sites above MT although a few also present below. Transect A - Highest densities around HWN (8000 - 16000/m2). Below 180 yds. occurence is sporadic and density low ( 600/m2). Transect B - Highest densities of 1500 - 5500/m2 at HWN. Either absent or only present in low density ( 200/m2) at other sites. Transect C - Highest densities at HWN (600 - 2600/m2). MT densities of 0 - 1000/m2 absent from LWN. | Restricted to the upper 7.5cm with most present in the top 2.5cm. | Present at more sites in Summer. Similar densities in both seasons. |

TABLE 7 (continued)

| Figure or Table | Species | Distribution Down Transect | Distribution Within Sediment Profile | Seasonal Differences |
|---|---|---|---|---|
| Fig.13 | *Etione longa* | Most abundant at sites below MT, although some present above. Transect A - Densities range between 100 and 450/m2 with peaks around MT and LWN. Transect B - Present at all sites except 260 yds. (HWN). Densities range between 100 and 300/m2 with a peak at MT. Transect C - Present at MT and LWN. Densities range between 100 and 450/m2 with a peak at MT. | Found throughout the full sampling depth. Most abundant in the region 2.5 - 12.5cm. | Some indication that the species moves deeper into the sediment in Winter. It is consistently more abundant in Summer. |
| Fig.14 | *Fabricia sabella* | Most abundant at sites close to HWN. Transect A - Densities range between 1000 and 17000/m2 with a peak at HWN. Absent from sites below 180 yds. Transect B - Present only at High Water sites. Densities range between 13000 and 60000/m2 at HWN. Transect C - Only present in Winter Samples. Densities range between 1000 and 2000/m2. | Restricted to the upper 5cm. | Densities are highest in Winter. |
| Fig.15 | *Nereis diversicolor* | No general distribution pattern. Transect A - Only present at sites below MT in Summer and at HWN in Winter. Densities range between 100 and 1100/m2. | Present throughout the full sampling depth but most abundant in the upper 12.5cm. | Most abundant in Summer. The speci[illegible] appears to move deeper into the se[illegible]-ment in Winter. |

TABLE 7 (continued)

| Figure or Table | Species | Distribution Down Transect | Distribution Within Sediment Profile | Seasonal Differences |
|---|---|---|---|---|
| Fig.15 | *Nereis diversicolor* (continued) | Transect B - Present only at sites down to MT. Densities range between 100 and 4500/m2.<br>Transect C - Only present at MT in Summer with a density of 500 - 600/m2. | | |
| Fig.16 | *Micrura species* | Restricted to sites above MT.<br>Transect A - Densities range between 100 and 900/m2 with a peak at HWN.<br>Transect B - Found only at HWN with densities between 100 and 600/m2.<br>Transect C - Found only at HWN with densities between 300 and 500/m2. | Found down to a depth of 17.5cm. Most are however present in the upper 7.5cm. | Most abundant in Winter when it is also found deeper in the sediment. |
| Tab.4 | *Diptera species larvae* | Present only at sites down to MT. Absent from Transect C.<br>Transect A - Densities range between 100 and 3500/m2 with the highest values at and above HWN. Absent below 180 yds.<br>Transect B - Densities range between 100 and 450/m2 with the highest values at and above HWN. | Found down to a depth of 12.5cm. Most are however present in the top 2.5cm. | Present at more sites and in greater numbers in Winter. |
| Tab.4 | *Corophium volutator* | Only present on Transect A. Restricted to sites above MT. Densities range between 111 and 550/m2 with the highest values at and above HWN. | Only present in the upper 7.5cm with most being found in the top 2.5cm. | More abundant in Winter samples |

TABLE 7 (continued)

| Figure or Table | Species | Distribution Down Transect | Distribution Within Sediment Profile | Seasonal Differences |
|---|---|---|---|---|
| Tab.4 | *Bathyporeia pilosa* | Most abundant in samples from around MT. Transect A - Densities range between 100 and 200/m2. Transect B - Densities range between 100 and 700/m2. | Most abundant in the top 2.5cm, although specimens found deeper | Most abundant in Summer. |
| Tab.4 | *Etione picta* | Most abundant at sites above MT, although no-where abundant. Absent from Transect B. Transect A - A maximum density of 100/m2 was recorded at sites down to MT. Transect C - The species was only present at LWN with a density of 100/m2. | Restricted to the upper 7.5cm with most present between 2.5 and 7.5cm. | Most abundant in Winter samples. |
| Tab.5 | *Nephthys hombergii* | Present only at sites close to LWN. Absent from Transect B. Transect A - Densities range between 100 and 300/m2 at sites below 480 yds. Transect C - Only present at LWN in Summer samples. Densities are in the region of 200/m2. | Restricted to the upper 7.5cm. | Similar distributions in both seasons. |
| Tab.5 | *Cardium edule* | Only present at two sites below MT on Transect A. Densities were below 100/m2. | Present only in the top 2.5cm. | |
| Tab.5 | *Lanice conchilega* | Only present at LWN on Transect A. Densities were in the range 200-300/m2. | Present throughout the full sampling depth. | |

TABLE 7 (continued)

| Figure or Table | Species | Distribution Down Transect | Distribution Within Sediment Profile | Seasonal Differences |
|---|---|---|---|---|
| Tab.5 | *Crangon vulgaris* | Only present at one site on Transect A (180 yds.) Densities were less than 100/m2. | Present only in top 2.5cm. | |
| Tab.5 | *Littorina littorea* | Only present at one site on Transect B (HWN). Densities were less than 100/m2. | Present only in the top 2.5cm. | |

TABLE 8

Grouping of Species On The Basis Of Their Horizontal Distribution Patterns

| Widely Distributed Species | High Water To Mid-Tide Species | Mid-Tide To Low Water Species |
|---|---|---|
| Arenicola marina | Oligochaete species | Scoloplos armiger |
| Pygospio elegans | Hydrobia ulvae | Etione longa |
| Macoma balthica | Fabricia sabella | Bathyporeia pilosa |
| Nereis diversicolor | Micrura species | Nephthys hombergii |
| | Diptera sp. larvae | Cardium edule |
| | Corophium volutator | Lanice conchilega |
| | Etione picta | |
| | Crangon vulgaris | |
| | Littorina littorea | |

TABLE 9

Grouping Of Species On The Basis Of Their Vertical Distributions Patterns

| Species Present Throughout The Full Sampling Depth | Surface Species* | Sub-surface Species** |
|---|---|---|
| Arenicola marina | Pygospio elegans | Macoma balthica |
| Lanice conchilega | Oligochaete species | Scoloplos armiger |
| | Hydrobia ulvae | Etione longa |
| | Fabricia sabella | Micrura species |
| | Nereis diversicolor | Etione picta |
| | Diptera sp. larvae | Nephthys hombergii |
| | Corophium volutator | Cardium edule |
| | Bathyporeia pilosa | |
| | Cardium edule | |
| | Crangon vulgaris | |
| | Littorina littorea | |

* Most abundant in the upper 2.5cm

** Most abundant below the upper 2.5cm.

DISCUSSION

The results from this survey indicate that the species sampled are representative of the Macoma balthica community described by Barnes (1974); Gray (1981); Penas and Gonzalez, (1983) and Green (1968). This community has been described as being typical of British shallow waters and estuaries by Gray (1981) and Green (1968).

Of the species described by Green (1968) as common constituents of this community, twelve were present in this survey. These were:

| | | |
|---|---|---|
| Macoma balthica | Nereis diversicolor | Corophium volutator |
| Cardium edule | Nephthys hombergii | |
| Hydrobia ulvae | Pygospio elegans | |
| | Arenicola marina | |
| | Scoloplos armiger | |
| | Etione longa | |

Fabricia sabella and the Oligochaete species are not noted as being common to this community. Smyth (1974) has however observed that on the polluted shores of the Clyde Estuary F. sabella is common in mixed populations with P. elegans. The presence of the Oligochaetes at High Water is possibly indicative of the low salinity conditions prevailing there. (See Section 2). Meadows and Campbell (1978) state that these freshwater and terrestrial annelids can penetrate into the brackish water areas of estuaries.

The variation in the apparent number of sites occupied by the species may stem from two sources. It may represent a real phenomenon related to habitat preferences. Alternatively, it may reflect differences in their relative abundance. Thus, species which are numerically abundant at all sites stand a better chance of being sampled than those present at low densities.

Similar inadequacies in the sampling technique may also explain why more species were sampled on Transect 'A' than on 'B' or 'C'. In all, 52 cores were taken on 'A' compared with 16 on 'B' and 12 on 'C'. The probability of sampling a species on 'A' was therefore, much higher. Sanders,(1968) has considered this problem in some detail. He has shown that the relationship between the number of species sampled and the number of samples taken, takes the form of a rectangular hyperbola which rises to an asymptote.

The increase in species numbers towards High Water may possibly be related to increased habitat diversity. As noted in Section 2, the six measured sediment parameters all show the greatest variability in this region. This combined with the presence of rocks, seaweeds and material deposited by the tide, provides more exploitable habitat niches than exist at Low Water. Similar differences in habitat diversity also probably explain the differences in species numbers between transects at the reference sites.

A reduction in species numbers with depth into the sediment has also been noted by Friedrich (1969) and Brown (1982). The reasons for this are probably related to a reduction in food and oxygen content with depth. Lee and Swartz (1980) have shown that most species feed within a zone approximately 3cm deep and therefore, do not require to penetrate much further. Notable exceptions include Arenicola marina which inhabits depths of as much as 0.5m. However, even this species obtains most of its nutrients from the upper 1cm. The oxygen content of the sediment has also been shown to decrease rapidly below a depth of 1 to 5cm. (McLachlan 1978; Hayes 1964; and Fenchel 1969). Species may therefore, be limited in their distribution by its availability (Fenchel 1969). Once again A. marina is a notable exception. This species is able to inhabit the anoxic deep sediments by pumping water through its 'U' shaped burrow, thus maintaining an adequate oxygen supply.

Seasonal variations in the depth of the surface oxidized layer may cause in part, the movement of species deeper into the sediment in Winter. McLachan (1978) has shown the depth of the oxidized surface layer to increase by 5 - 10cm during this season. Species may also move deeper into the sediment in Winter in order to escape low surface temperatures, McLusky (1968) has shown Corophium volutator to do this when surface temperatures fall below 4$^{o}$C. Both causative factors are likely to decrease in significance towards Low Water. This may explain the absence of vertical migration below Mid-Tide.

Densities of the species sampled in this survey recorded by other workers are shown in Table 10 . On the whole the two sets of data are comparable. A notable exception is however, Corophium volutator. This species has consistently lower densities in this survey.

The horizontal distribution of individual species down the shore has been considered by many workers. Table 11 summarizes their findings with regard to some of the species sampled in this survey. A comparison between this table and Table 8 shows good agreement with the distribution patterns determined in this survey. Exceptions are Hydrobia ulvae and Corophium volutator, both of which have more restricted distributions at Ardmore.

The factors controlling species distribution are many and varied. Friedrich (1969) divides them into Abiotic and Biotic groups and discusses them in some detail. The controlling factors determined by other workers for some of the species sampled at Ardmore are shown in Table 12 . It is clear that the observed distribution patterns result from complex interactions between a number of environmental variables. These interactions are investigated for some of the species sampled in the following section.

The vertical distribution of individual species within the sediment profile has mainly been studied indirectly in relation to their oxygen requirements and feeding behaviour. Fenchel (1969) has shown that the vertical distribution of sediment dwelling Cilliates can be correlated with measured Redox Potentials.Data for Macroinvertebrate species is however, lacking. Feeding zones have been identified for six of the species sampled in this survey. These are:

| | | | |
|---|---|---|---|
| Nereis diversicolor | - down to | 20cm | (Anderson & Meadows 1978) |
| Scoloplos armiger | - " " | 20cm | (Lee & Swartz 1980) |
| Nephthys hombergii | - " " | 20cm | " " " |
| Macoma balthica | - " " | 1cm | " " " |
| Hydrobia ulvae | - " " | 3cm | " " " |
| Arenicola marina | - " " | 10cm | " " " |

Clearly there is a good chance that a species will be present

TABLE 10

Species Population Densities Recorded By Other Workers (Includes species sampled in this survey and closely related species)

| Species | Density (No/m2) | Worker |
|---|---|---|
| Arenicola marina | 10 - 100 | Cadee (1976) |
| " " | Up to 220 | Barnes (1974) |
| Pygospio elegans | 175 - 5925 | Gray (1981) |
| " " | Up to 20300 | Green (1968) |
| Macoma balthica | Up to 750 | Kraeuter (1976) |
| " " | 25 - 700 | Gray (1981) |
| " " | 10 - 5900 | Green (1968) |
| " " | 32 - 4736 | Barnes (1974) |
| Scoloplos armiger | 1 - 92 | Hughes et.al. (1972) |
| Scoloplos fragilis | 100 - 447000 | Brown (1982) |
| Oligochaete sp. | - | - |
| Hydrobia ulvae | 5440 - 7950 | Smyth (1974) |
| " " | Up to 42000 | Green (1968) |
| " " | 24 - 36120 | Barnes (1974) |
| Etione longa | 0 - 15 | Hughes et.al. (1972) |
| Fabricia sabella | - | - |
| Nereis diversicolor | 80 - 1650 | Smyth (1974) |
| " " | 12 - 2000 | Barnes (1974) |
| Micrura species | - | - |
| Diptera sp. larvae | - | - |
| Corophium volutator | 8000 - 28000 | McLusky (1968) |
| " " | 1000 - 16000 | " " |
| " " | Up to 63000 | Green (1968) |
| " " | 312 - 22560 | Barnes (1974) |
| Bathyporeia pilosa | - | - |
| B. parkeri | 30 - 310 | Biernbaum (1979) |
| B. quoddyensis | 0 - 10 | " " |
| Etione picta | | |
| Nephthys hombergii | 1 - 47 | Gray (1981) |
| Cardium edule | - | - |
| Crangon vulgaris | - | - |
| Lanice conchilega | - | - |
| Littorina littorea | - | - |
| Littorina irrorata | 73 | Kraeuter (1976) |

TABLE 11

Horizontal Distribution Patterns Of Species Sampled In The Survey As Determined By Other Workers.

| Species | Distribution | Most Abundant | |
|---|---|---|---|
| Arenicola marina | HWN→LWS | MT | Meadows & Campbell(1978) |
| Pygospio elegans | - | - | - |
| Macoma balthica | Below HWN→LWS | MT→LWN | Friedrich (1969) |
| Scoloplos armiger | - | - | - |
| Oligochaete sp. | HWN→MT | HWN | Friedrich (1969) |
| Hydrobia ulvae | HWN→LWN | MT→LWN | Friedrich (1969) |
| Etione longa | - | - | - |
| Fabricia sabella | - | - | - |
| Nereis diversicolor | HWN→Above LWN | HWN→MT | Friedrich (1969) |
| Micrura species | - | - | - |
| Diptera sp.larvae | - | - | - |
| Corophium volutator | Below HWN→LWS | MT | Meadows & Campbell(1978) |
| Bathyporeia pilosa | - | - | - |
| Etione picta | - | - | - |
| Nephthys hombergii | LWN→Subtidal | - | Perkins (1974) |
| Cardium edule | MT→Subtidal | LWN | Meadows & Campbell(1978) |
| Lanice conchilega | LWN→Subtidal | - | Perkins (1974) |
| Crangon vulgaris | - | - | - |
| Littorina littorea | HWN→LWS | HWN→LWS | Friedrich (1969) |

Note - HWN = High Water Neaps
MT = Mid-Tide
LWN = Low Water Neaps
LWS = Low Water Springs

TABLE 12

Factors Controlling The Distribution Of Species Sampled In This Survey As Determined By Other Workers.

| Species | Controlling Factor | Reference |
|---|---|---|
| *Arenicola marina* | Organic Matter - +vely correlated | Longbottom (1970) |
| | Particle Size - -vely correlated | " " |
| | Salinity - Tolerates salinities down to 8 - 10‰ | Shumway and Davenport (1977), Green (1968). |
| | Depth of Sand over Substrate - Must be sufficient to develop burrow. | Meadows and Campbell (1972). |
| | Presence of Kaolin or Clay - Scarce where these are present. | Baumfalk (1979) and Meadows and Campbell (1972). |
| | Presence of Ulva lactuca - Avoids areas where this is abundant. | Baumfalk (1979) |
| | Sediment Moisture Content - difficulty in burrowing into dry sand. | Meadows and Campbell (1972) |
| *Pygospio elegans* | Salinity - Tolerates salinities down to 8‰ continuously and 2‰ for short periods. | Green (1968) |
| *Macoma balthica* | Organic Matter - +vely correlated | Green (1968); Perkins (1974) |
| | Particle Size - -vely correlated | Longbottom (1970) |
| | Micro-organisms - +vely correlated | Perkins (1974) |
| | Time available For Feeding - +vely correlated. | Green (1968) |
| *Scoloplos armiger* *Scoloplos fragilis* | --- | --- |
| | Sediment Penetrability - +vely correlated | Brown (1982) |
| | Predation - -vely correlated | Brown (1982) |
| | Erosional Forces - -vely correlated | Brown (1982) |

TABLE 12 (continued)

| Species | Controlling Factor | Reference |
|---|---|---|
| Oligochaete species | Salinity - -ve correlated. | Meadows and Campbell (1972) |
| Hydrobia ulvae | Salinity - prefers higher salinities to closely related species 10 - 33‰ .<br>Exposure - abundant in exposed areas.<br>Particle Size - -vely correlated<br>Organic Matter - +vely correlated<br>Micro-organisms - +vely correlated with the abundance of Bacterial and Diatoms. | Green (1968); Gray (1981)<br>Green (1968)<br>Longbottom (1970)<br>Longbottom (1970)<br>Fenchel, Kofoed and Lappalainen (1978). |
| Etione longa | -- | -- |
| Fabricia sabella | -- | -- |
| Nereis diversicolor | Sediment Moisture Content - Has difficulty in burrowing into dry sand.<br>Salinity - Tolerates salinities down to 1‰.<br>Particle Size - Prefers muddy sands<br>Organic Matter - Prefers sediments rich in Organic Matter. | Meadows and Campbell (1972)<br>Green (1968)<br>Penas and Gonzalez (1983)<br>Penas and Gonzalez (1983) |
| Micrura species | -- | -- |
| Diptera sp. larvae | -- | -- |
| Corophium volutator | Salinity - Tolerates salinities down to 2‰ but prefers 10 - 30‰ - 2 - 5‰ present but in reduced numbers<br>- 7.5‰ breeds<br>- 5‰ distribution controlled by Substrate. | McLusky (1968) and Meadows and Campbell (1972) |

TABLE 12 (continued)

| Species | Controlling Factor | Reference |
|---|---|---|
| *Corophium volutator* (continued) | - Prefers lower salinities to closely related species. | Meadows (1964(b)) |
| | | Gamble (1971) |
| | Temperature - Temperature preferences over-ride salinity preferences when both vary | Meadows and Ruagh (1981) |
| | Particle Size - Prefers fine sands and muds 4 - 63 um | Green (1968) and Fenchel, Kofoed and Lappalainen (1975) |
| | Oxygen Availability - Prefers low Oxygen Tensions. | Gray (1974) |
| | Sediment Depth - avoids beaches where mud depth is less than 1cm. | Meadows and Campbell (1972) |
| | Micro-organisms - prefers sediments rich in microbes. | Meadows (1964) |
| | Predation - Low spring numbers may be attributable to bird predation. | McLusky (1968) |
| *Bathyporeia pilosa* | Salinity | Gray (1974) |
| | Sediment Moisture Content - avoids dry sand | Gray (1974) |
| | Particle Size - Prefers coarse sands. | Green (1968) |
| *Etione picta* | -- | -- |
| *Nephthys hombergii* | -- | -- |
| *Nephthys incisa* | Particle Size - Highest populations in in sediments with 10 - 20% Clay. | Sanders (1958) |
| *Cardium edule* | Salinity - Stenohaline species which tolerates down to 30‰. | Meadows and Campbell (1972) |
| *Lanice conchilega* | -- | -- |

TABLE 12 (continued)

| Species | Controlling Factor | Reference |
|---|---|---|
| Crangon vulgaris | Particle Size - Prefers sandy shores<br>Breeding - inhibited by Low Temperatures and Salinities<br>Migratory - Moves our of estuaries in Winter. | Green (1968)<br>Green (1968)<br>Green (1968) |
| Littorina littorea | Salinity - Euryhaline species which tolerates salinities well below 30‰. | Meadows and Campbell (1972) |

within these depth ranges during sampling. This is confirmed by reference to Table 9 .

Arenicola marina was noted earlier as being exceptional in occupying sediment much deeper than its feeding depth. Baumfalk (1979) and Meadows and Campbell (1972) have however, pointed out that this species may be restricted to shallow depths by the presence of a subsurface kaolin or clay layer.

Factors controlling the vertical distribution of the Ardmore species are further considered in the following section.

# SECTION 4

## MULTIVARIATE ANALYSIS OF THE SELECTED PHYSICO-CHEMICAL SEDIMENT FEATURES AND ASSOCIATED MACROINVERTEBRATE FAUNA AT ARDMORE.

# INTRODUCTION

## General

In the previous sections data has been collected which describes:

(i) Some of the Physico-chemical features of the intertidal environment at Ardmore.

(ii) The associated Macroinvertebrate fauna.

This section examines relationships between (i) and (ii) with the object of relating species distribution patterns to key features of the sedimentary environment. A Multivariate Analytical technique has been used to do this.

The purpose of this type of analysis is to identify key variables within sets of data and establish their interrelationships. The methods used can be broadly categorised by whether the focus of attention is on the variables or on the individuals. In this study the former is true. The biotic and abiotic sets of data have therefore, been subjected to one of the Factor Analysis techniques known as Principal Components Analysis (PCA) (Cooper and Weekes 1983; Sokal and Rohlf 1969). In PCA a small number of derived variables are calculated which identify correlated and uncorrelated variables within the original data. This method of analysis has been used by Cassie and Michael (1968) in a similar study of an intertidal mud flat.

The analysis was carried out on the ICL 2900 series computer at the University of Glasgow,using programs from the SPSS Statistical Package (Nie et.al. 1975).

## Theoretical Background - (Cooper and Weekes,1983; Anderson,1958; Child,1970; Cassie and Michael, 1968.)

The space occupied by data points on a graphical plot of two highly correlated variables often takes the form of an ellipse. If the correlation between them is positive, the elongation is upward from left to right across the graph. Relationships of this type can be examined using simple two-dimensional correlation and regression techniques.

The technique of Principal Components Analysis (PCA) is used to determine similar relationships in multivariate data sets. Here, instead of a two dimensional ellipse, the data takes the form of clouds of observations describing hyper-ellipsoids in a multidimensional space. PCA provides a means of relating the data points to new axes represented by the major and minor axes of these ellipsoids. Unlike the original "natural axes", these new ones contain components from a number of the variables.

The first axis or Principal Component(PC) is chosen to account for most of the variance in the data. In the simple two-dimensional data plot, this would be represented by the long axis of the ellipse. Successive axes are chosen which remove the greatest, second greatest and progressively smaller sources of variation. PCA can therefore, be looked upon as a method of reallocating the total variance of the data between the derived variables (Principal Components). In theory there are as many Principal Components as there are variables. In practice however, only those with Eigenvalues (see later) greater than '1' are considered.

The relative contribution of a variable to a Principal Component is determined by its PC or Factor Score. These are effectively coefficients which describe the position of the Principal Component. For each variable contributing to a PC there is a coefficient. Variables contributing most to the Principal Component have the largest coefficients and therefore, the highest score. Those variables with high Factor Scores for the same Principal Component are correlated. The sign associated with the score tells whether the correlation is positive or negative.

Eigenvalues - These are analogous to variances along the axes of the Principal Components. In highly correlated data - represented in two dimensions by a long narrow ellipse - most of the variance can be accounted for by the major axis. The value of the major axis Eigenvalue would therefore be very great compared with that for the minor axis. If both Eigenvalues are equal the major and minor axis are of equal length and the scatter plot of the data is represented by a circle. There would be no correlation between the variables.

## MATERIALS AND METHODS

A basic requirement of the computational technique is the production of a raw data matrix. In constructing the matrix for the Ardmore survey data, a decision was made to exclude species present at fewer than 30% of the sites. This resulted in 10 species being included in the analysis.

The format of the matrix is shown in Table 1 , it consists of 28 columns, representing the variables and 400 rows representing replicates at each site and depth interval. In this format the data was coded onto Fortran Coding sheets and then subsequently put into a computer file.

The multivariate model assumes that all variates are normally distributed. Cassie and Michael (1968) state that as a consequence of this, the variables are also assumed to be linearly related. Graphic tests of normality were therefore, applied to the data and where necessary, transformations applied. An example of such a test is shown in Appendix H . The resultant transformations are shown in Table 2 . The high frequency of the $Log_{10}$ transformation is typical of benthic invertebrate populations. (Penas and Gonzalez,1983). Such populations show a trend to aggregation resulting in the variance of the distribution of the densities being greater than the corresponding mean.

With the relevant transformations applied, the data was now ready for analysis. I wrote Fortran programs which linked the data files with the appropriate SPSS statistical package and then performed the analysis.

I then applied six basic programs which analysed different combinations of variables. The variables considered by each were as follows:-

(i) All sediment, sample site and species variables.

(ii) Only sediment and sample site variables.

(iii) Only faunal variables.

(iv) All sediment and sample site variables plus the total number of species in each sample.

(v) All sediment and sample site variables plus the total number of animals in each sample.

TABLE 1

Format Of Data Matrix For Principal Components Analysis.

| Season | Transect | Site Position | Sample Depth | Replicate | Site Level | Peak Shear Strength | Residual Shear Strength | Redox Potential | Water Table | Salinity | Organic Matter Content | Mean Particle Size | Standard Deviation | Skewness | Kurtosis |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| Sample Site Variables | | | | | | Sediment Variables | | | | | | | | | |

| *Arenicola marina* | *Pygospio elegans* | *Fabricia sabella* | *Macoma balthica* | *Scoloplos armiger* | *Oligochaete species* | *Hydrobia ulvae* | *Etione longa* | *Nereis Diversicolor* | *Micrura sp.* | Total Species | Total Animals | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | Cases |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| Species Variables | | | | | | | | | | | | |

## TABLE 2

## Data Transformations For Principal Components Analysis

| Variable | Transformation |
|---|---|
| Peak Shear Strength | $Log_{10}$ (Peak Shear Strength + 0.1) |
| Residual Shear Strength | $Log_{10}$ (Residual Shear Strength + 0.1) |
| Redox Potential | As is |
| Water Table | $Log_{10}$ ((-1 x Water Table) + 50) |
| Salinity | $Log_{10}$ (34.562 - Salinity) |
| Organic Matter | $Log_{10}$ (Organic Matter) |
| Mean Particle Size | As is |
| Standard Deviation | $Log_{10}$ (Standard Deviation) |
| Skewness | $Log_{10}$ (1.6213 - Skewness) |
| Kurtosis | $Log_{10}$ (Kurtosis + 2) |
| *Arenicola marina* | $Log_{10}$ (*A.marina* Density + 1) |
| *Pygospio elegans* | $Log_{10}$ (*P. elegans* Density) |
| *Fabricia sabella* | $Log_{10}$ (*F. sabella* Density + 1) |
| *Macoma balthica* | $\sqrt{\textit{M.balthica}\ \text{Density} + 1}$ |
| *Scoloplos armiger* | $\sqrt{\textit{S.armiger}\ \text{Density} + 1}$ |
| *Oligochaete Species* | $Log_{10}$ (*Oligochaete Species* Density +1) |
| *Hydrobia ulvae* | $Log_{10}$ (*Hydrobia ulvae* + 1) |
| *Etione longa* | As is |
| *Nereis diversicolor* | $Log_{10}$ (*Nereis diversicolor* Density +1) |
| *Micrura Species* | *Micrura Species* Density + 1 |
| Total Number of Species | $Log_{10}$ (Total Number of Species + 1) |
| Total Number of Animals | $Log_{10}$ (Total Number of Animals + 1) |

(vi) All sediment and sample site variables plus the total number of individuals of each species in each sample.

These programs are available for inspection.

A detailed breakdown of the mathematics involved in the analysis of the data can be found in Lawley and Maxwell (1963) and Anderson (1958). Cassie and Michael (1968) have summarised the process.

Examples of the output from this type of analysis are also available for inspection. In the context of the objectives of this section, the 'Varimax Rotated Factor Matrix Scores' are the important source of information. These indicate the relative contribution of each variable to any given Principal Component. Variables with large scores of the same sign for the same Principal Component may be regarded as constituents of a common community. Large scores of opposite sign occuring in the same Principal Component define negatively correlated variables.

At the present time no statistical test is available that can establish the exact significance level of a Rotated Factor matrix Score (Comrey,1973). Child (1973) quotes three empirical methods for determining which scores are to be considered significant. These are:

(i) A rule of thumb, i.e., scores greater than 0.3.

(ii) Treating the scores as correlation coefficients.

(iii) Using the Burt-Banks formula. This is based upon the work of Burt and Banks (1947) and provides a method of adjusting for the Principal Component number.

Significance rating values quoted by Comrey (1973) have been used in the interpretation of the results. These values are shown in Table 3 .

In presenting the results of the Analysis, Factor Matrix Scores greater than 0.3 are plotted against their respective variables. The sign of the score is also included.

TABLE 3

Scale of Variable - Factor Correlations (From Comrey, 1973)

| Factor Matrix Score | Rating |
|---|---|
| 0.71 | Excellent |
| 0.63 | Very good |
| 0.55 | Good |
| 0.45 | Fair |
| 0.32 | Poor |

## RESULTS

The results of the analysis are presented as histograms in Figures 1 to 7 . The following points should be noted when interpreting them.

(i) In general only variables with Factor (Principal Component) Scores greater than 0.3 have been included. Lower scores have been included for key variables in a particular analysis, for example, Scoloplos armiger in Figure 6 .

(ii) Positive and Negative Scores are both represented by histogram bars drawn above the abscissa. The sign of the score is shown above each bar.

(iii) The dashed lines on the histograms indicate scores of 0.3 and 0.5. On Comreys Scale (See Table 3 ) scores above 0.5 are good to excellent and those between 0.3 and 0.5, poor to good.

**Figures 1 to 3** show the results of analysing all the Sediment, Sample Site and Species variables in one PCA. The analysis has been performed separately on the Summer and Winter data and then again on the aggregated data.

The plots for each Factor have been arranged so that those exhibiting similar properties are located in the same position on the three figures. This has resulted in a rearrangement of some of the Factor Numbers.

Analysing the data in this way results in strong correlations within the Sediment and Sample Site group and the Species group. Correlation between these groups are,with the exception of those listed below, few. The exceptions are:

(1) The Negative Correlation between Sample Depth and the abundance of most of the species.

(2) The Positive Correlation between Redox Potential, the abundance of Pygospio elegans, the Total Number of Animals and the Total Number of Species.

(3) The Positive Correlation between Site Level and Arenicola marina density.

These patterns are consistent to the Summer, Winter and Aggregated data.

Figures 4 to 7 show the results of analysing

## GENERAL NOTE FOR FIGURES 1 TO 6.

The factor scores presented in Figures 1 to 6 represent the Varimax Rotated Factor Matrix Scores obtained from the computer analysis of the data. These scores indicate the relative contribut -ion of each variable to any given Principal Component(=Factor). Variables with high scores for the same Principal Component may be regarded as possibly correlated. The sign of the score indicates the nature of the correlation ie. positive or negative.

In presenting the results as histograms in Figures 1 to 3 the Varimax Rotated Facter Matrix Scores greater than 0.3 are plotted for each variable against each Factor(=Principal Component). The sign of the score is shown above the bar for each variable.

The results in Figures 4 to 6 are presented in a slightly different way. Factor scores above 0.3 have been extracted from the Varimax Rotated Factor Matricies for variables within the same Factor. These scores have been plotted to show those variables which possibly correlate with the 'dependant variables' (see page 169) listed down the right hand side of the page.The sign of the score is shown above the bar for each variable.The data has been analysed in three ways: All, Summer and Winter. These categories are denoted by the key in the bottom right hand corner of the page.

Fig.1. - Factor Scores - All Data - Summer.

Fig. 2.- Factor Scores - All Data - Winter.

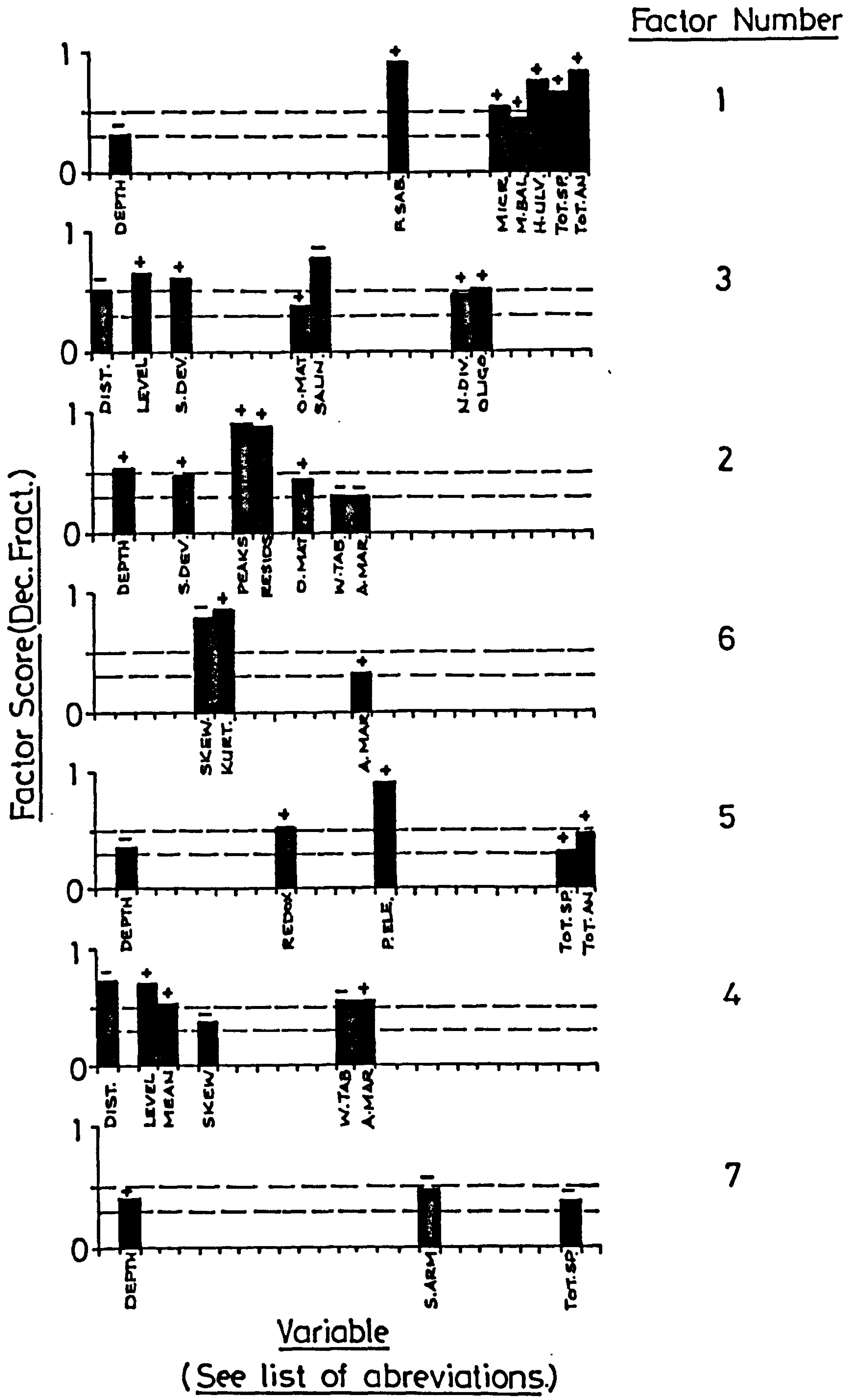


Fig.3.- Factor Scores - All Data - Summer & Winter

components of the data separately. Factor Scores for the dependant variables - listed on the horizontal axis - are plotted against the independant variables - listed down the right-hand side. The terms dependant and independant are based upon the convention of Cassie and Michael (1968). The 'dependant' variable is that to which the other 'independant' variables are being related.

The results of analysing the Sediment and Sample Site variables are shown in Figure 4 . The variables can be placed into the five mutually correlating sub-groups shown in Table 4 . The sub-groups can be classed as follows:

1 and 5 - General
2 - Sediment Sorting
3 - Sediment Strength
4 - Sediment Nutrient Status

Only one variable - Organic Matter - appears in more than one group (1 and 4).

The correlating variables are, in general, seasonally consistent. There are however exceptions, notably those correlating with Mean Particle Size and Water Table position. These show several significant correlations in Winter but few in Summer.

The results of a similar analysis performed on the species data are shown in Figure 5 , Table 5 shows the seven resultant subgroups, four of which contain one species and the others, two. The latter groups can be classed, on the basis of the results from Section 3, as follows:

1 - Species occuring generally
4 - Low to Mid-Tide Species
6 - Mid to High Tide Speeies

There are seasonal differences in some of the correlating variables.

Figure 6 shows the results of analysing the data for each species in conjunction with the Sediment and Sample Site variables. Only data applicable to the sample containing the species has been included in the analysis.

Table 6 summarises the variables which correlate with scores better than 0.5 for the combined Summer and Winter

FIGURE 4.

Factor Scores- Sediment and Sample Site Data.


Factor Score (Dec. Fract.)
Mean
S. Deviation
Skewness
Kurtosis
Peak S.S.
Residual S.S.
Redox Pot.
Organic Mat.
Salinity
Water Table
Distance
Depth
Level
Mean
S. Deviation.
Skewness
Kurtosis
Peak S.S.
Residual S.S.
Redox Pot.
Organic Mat.
Salinity
Water Table
Key
Summer
Winter
All

FIGURE 5

Factor Scores - Species Data.

A.marina
P. elegans
F. sabella
S.armiger
E.longa
N.diversicolor
Oligochaete sp.
Micrura sp.
M. balthica
H.ulvae
Factor Score.(Dec.Fract.)
A.marina
P.elegans
F.sabella
S.armiger
E.longa
N.diversic.
Oligochates
Micrura sp.
M.balthica.
H.ulvae.
Key.
Summer
Winter
All

## TABLE 4

### Correlating Sediment and Sample Site Variables

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| Distance + | Skewness + | Depth + | Redox Pot. + | Mean P.S. + |
| Level - | Kurtosis - | Peak S.S. + | Organic Matter - | Water Table - |
| Stan.Devn. - | | Residual S.S. + | | |
| Organic Matter - | | | | |
| Salinity + | | | | |

## TABLE 5

### Correlating Species

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| A. marina + | P. elegans | F. sabella | S. armiger + | Oligochaetes | Micrura sp. + | M. balthica |
| N. Diversicolor - | | | E. longa + | | H. ulvae + | |

FIGURE 6

Factor Scores - Individual Species and Sediment/
Sample Site Data.


Factor Score (Dec. Fract.)
A.marina
P.elegans
F.sabella
S.armiger
E.longa
N.diversic.
Oligochaete sp.
Micrura sp.
M.balthica
H.ulvae
Distance
Depth
Level
Mean
S.Deviation
Skewness
Kurtosis
Peak S.S.
Residual S.S.
Redox Pot.
Organic Mat.
Salinity
Water Table
Species
Key.
Summer
Winter
All

# TABLE 6

## Correlating Sediment, Sample Site and Species Variables

| Variable | *Arenicola marina* | *Pygospio elegans* | *Fabricia sabella* | *Scoloplos armiger* | *Etione longa* | *Nereis Diversicolor* | *Oligochaete species* | *Micrura species* | *Macoma balthica* | *Hydrobia ulvae* |
|---|---|---|---|---|---|---|---|---|---|---|
| Distance | − | − | | + | | | − | − | | − |
| Depth | | | | | | | | | | |
| Level | + | + | | − | | | + | + | | + |
| Mean | | + | + | − | | | | | | + |
| Stand. Dev'n. | | | | | | | | | | + |
| Skewness | | | − | + | | | | | − | − |
| Kurtosis | | | + | | | | | | + | |
| Peak S.S. | | | + | | | | | | | |
| Residual S.S. | | | | | | | | | | |
| Redox Pot. | | | | | | | | | | |
| Organic Mat | | | | | | | | | | |
| Salinity | | | | + | + | | | − | | |
| Water Table | | | | | | | | | | |

data. The species can be divided into three groups on the basis of their relationship to Distance down the shore and Site Level. These are:-

(1) Positively Correlated with Distance and Negatively Correlated with Level - Scoloplos armiger.

(2) Negatively Correlated with Distance and Positively Correlated with Level - Arenicola marina
- Pygospio elegans
- Oligochaete species
- Micrura species
- Hydrobia ulvae

(3) No correlation with Distance or Level -
- Fabricia sabella
- Etione longa
- Macoma balthica

Of the ten Sediment variables under consideration, six appear to be significantly correlated with the distribution patterns of the species. These, together with the associated species and nature of the correlation are listed below -

| | | | |
|---|---|---|---|
| (a) Mean Particle Size | - | Pygospio elegans | + |
| | - | Fabricia sabella | + |
| | - | Hydrobia ulvae | + |
| | - | Scoloplos armiger | - |
| (b) Standard Deviation | - | Hydrobia ulvae | + |
| (c) Skewness | - | Scoloplos armiger | + |
| | - | Fabricia sabella | - |
| | - | Macoma balthica | - |
| | - | Hydrobia ulvae | - |
| (d) Kurtosis | - | Fabricia sabella | + |
| | - | Macoma balthica | + |
| (e) Peak Shear Strength | - | Fabricia sabella | + |
| (f) Salinity | - | Scoloplos armiger | + |
| | - | Etione longa | + |
| | - | Hydrobia ulvae | - |

The species can be further divided subjectively on the basis of the seasonal data yielding the best correlations.

This results in the following three groups -

| Summer | Winter | Summer & Winter |
|---|---|---|
| Pygospio elegans | Arenicola marina | Micrura Species |
| Etione longa | Scoloplos armiger | Macoma balthica |
| Nereis diversicolor | Oligochaete species | Hydrobia ulvae |
| | Fabricia sabella | |

Figures 7 and 8 show the results of PCA's conducted on the Sediment and Sample Site variables in conjunction with the Total Number of Animals and Total Number of Species present within each sample. Total Animal and Species Numbers are Positively Correlated with Redox Potential and Negatively correlated with Sample Depth and Sediment Shear Strength. In addition the Total Animal Numbers appear to be positively and negatively correlated with Standard Deviation and Organic Matter Content respectively.

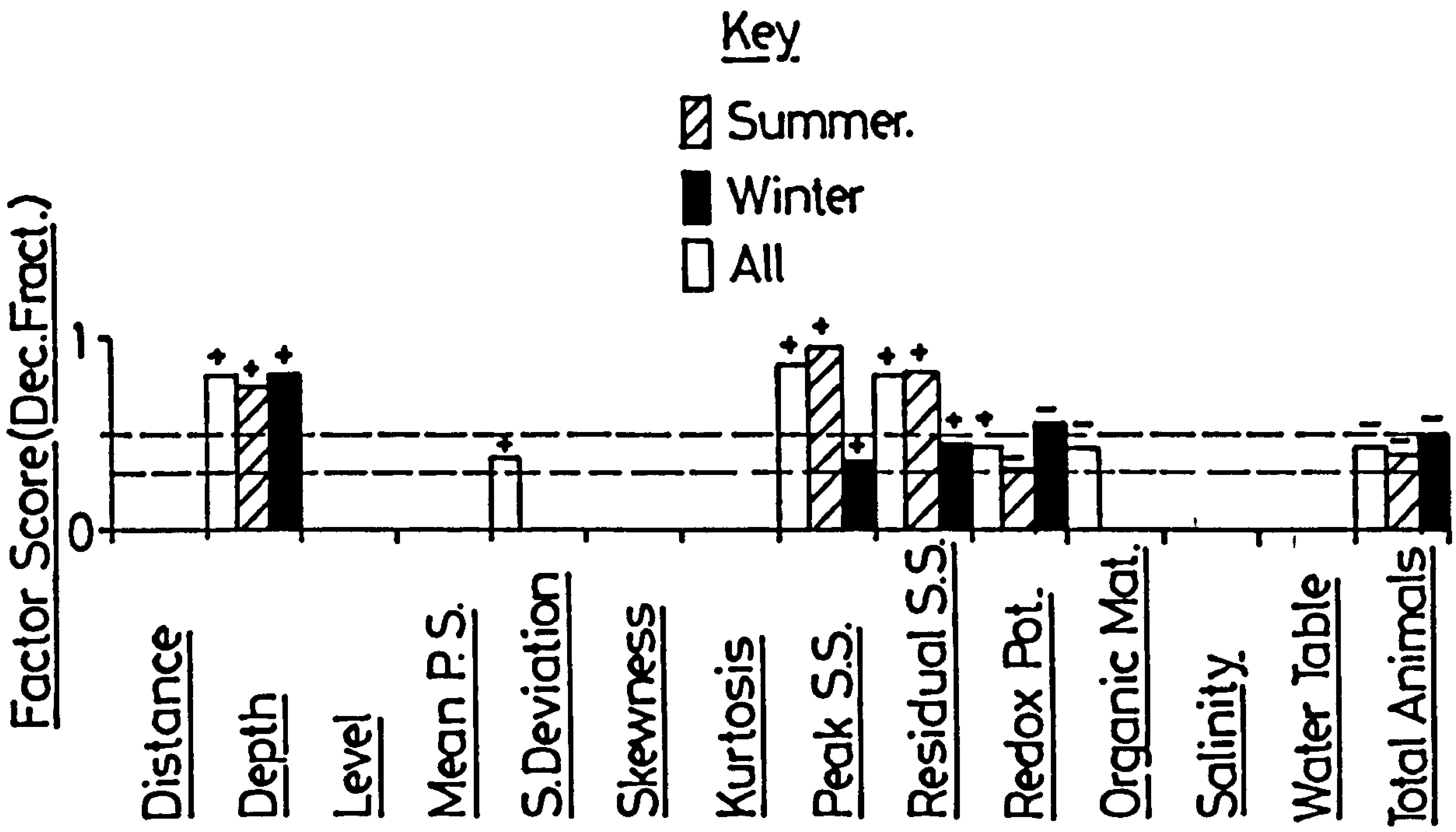



Figure. 7.

Factor Scores For Total Animal Numbers And Sediment And Sample Site Variables.

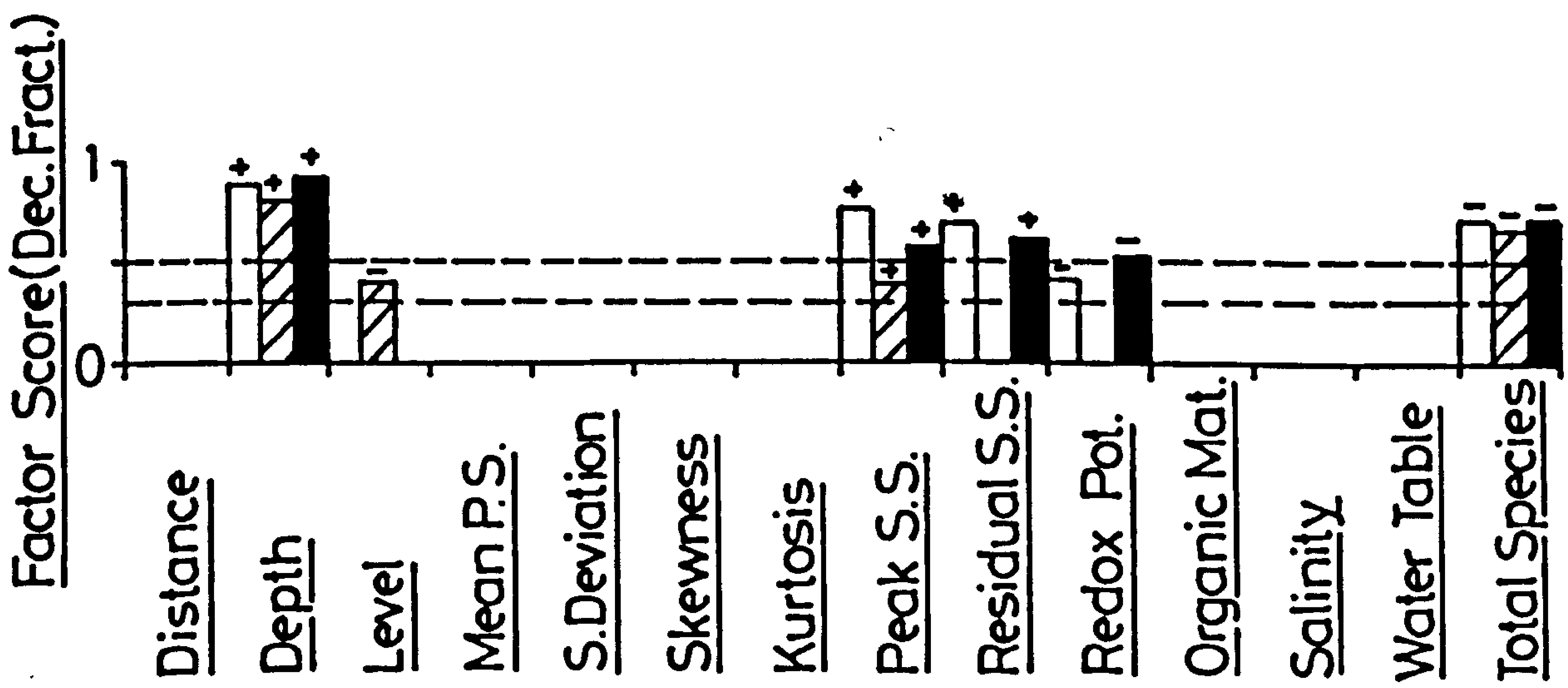



Figure. 8.

Factor Scores For Total Species Numbers And Sediment And Sample Site Variables.

## DISCUSSION

Multivariate analytical techniques have been used by a number of workers to investigate relationships between the distribution patterns of species and properties of their sedimentary environment. Examples of studies similar to this one, which have used Principal Components Analysis include the following:-

Biernbaum (1979) - analysed correlations between measured sedimentary factors and faunal distributions. It was concluded that Gravel Content was the most important sedimentary factor. There was also a correlation between faunal distribution and increased sediment instability caused by Winter storms.

Cassie and Michael (1968) - identified two clearly defined communities which were correlated with Sediment Particle Size.

Hughes et.al.(1972) - isolated trends in the frequencies of occurence of polychaetes and echinoderms. These were associated with Sediment type and distance from the head of a bay.

Hughes and Thomas (1971a) - attempted to identify the causes of the distribution patterns of benthos. They concluded that a large proportion of the variance in the data was correlated with a Salinity gradient. A further correlation was identified between sediment type and species distribution.

Hughes and Thomas (1971b) - correlated species distribution in the littoral zone to a gradient of tidal immersion. Sublittoral stations were influenced by several factors correlated with distance from the shore including the extent of Sea-ice in Winter and the influx of fresh water during the Spring thaw.

A number of other multivariate techniques have also been used to investigate similar relationships. These include:

Multiple Regression - used by Hulings and Gray (1976) to construct equations relating sediment Particle Size Distribution properties to Total Meiofaunal numbers - sorting was the most important property. Holmes and Goodell (1964) also used this method to relate sediment strength to a number of other sediment characteristics. Sediment strength was found to:

1) decrease as water content increased

2) increase with depth into the sediment

3) increase with an increase in the ratio of kaolinite to illite.

Correlation Tests - used by Bloom, Simon and Hunter (1972) to correlate species Trophic Type with sediment Particle Size Distribution properties.

Cluster Analysis - used by Hughes et.al.(1972) in addition to Principal Components Analysis to identify trends in the frequencies of occurence of polychaetes and echinoderms. The results from the two methods were comparable. (See earlier).

Coefficients of Association )
Indices of Similarity ) - used by Nichols (1970 to elucidate the relationship between small scale changes in species, composition of polychaete assemblages and changes in the physical character of the sediment. Clay content was found to be important.

Canonical Correlation - used by Penas and Gonzalez (1983) to relate species distribution patterns to three environmental factors - Organic Matter Content, Mud Content and Desication of the sediment; the first two of these were found to be most important.

Further correlations have been established between variables relevant to this study using the Bivariate analytical techniques of Correlation and Regression. These include inverse correlations between:

(1) Shear Strength and Water Content (Trask and Rolston, 1950).

(2) Shear Strength and Particle Size (Trask and Rolston, 1950).

(3) Organic Matter Content and Particle Size, (Longbottom, 1970)

(4) Redox Potential and Depth into the sediment, (Whitfield, 1969).

(5) Bacteria numbers and Particle Size (Dale, 1974)

and positive correlations between:

(1) Bacteria numbers and Organic Carbon and Total Nitrogen Content of the sediment (Dale 1974).

The results contained in this section represent a significant advance on those reported elsewhere. In contrast to other investigations, correlations have been established between and within Sediment, Site and Species variables. A number of new correlations are also reported and others, already established, are confirmed.

Results from the analysis of the Sediment and Sample Site variables confirm the correlations between Shear Strength and Depth into the sediment reported by Holmes and Goodell (1964). A correlation between Organic Matter Content and Particle Size (Longbottom, 1970) was, however, not evident.

A number of other sets of correlating Sediment and Sample Site variables have been identified. The relationship between some, notably; Salinity and Organic Matter Content/ Standard Deviation and Mean Particle Size and Water Table Position, may be coincidental. The others are probably real. The following factors are suggested as contributing to these correlations.

1) Redox Potential and Organic Matter Content - The oxidation of organic material by anaerobic bacteria is the primary cause of reducing conditions in the aquatic environment (Fenchel, 1969). Reducing conditions are associated with the presence of Organic Matter (Zobell, 1946). It is therefore, probable that a negative correlation exists between Organic Matter content and Redox condition.

2) Organic Matter Content and Distance Down The Shore - The same processes which allow finer sediment particles to settle out towards High Water, also allow more Organic Matter to be deposited. There is also an increase in the abundance of marine algae in this direction.

3) Salinity and Distance Down The Shore - Mixing of Fresh Ground Water with Sea Water results in a Salinity gradient down the shore.

4) Peak and Residual Shear Strength - The relationship between these two strength properties is dependant upon a number of variables including:

(a) Particle Size Distribution - shown to vary regularly over the shore.

(b) Mineralogy - not investigated but presumably relatively constant with the exception of the Clay at High Water.

(c) Compressive Stress - to which Smith (1980) indicates the two strength properties to be linearly related.

5) Skewness and Kurtosis - These are both dependant upon the proportions of sediment within the size interval classes. Folk and Ward (1957) have shown a three dimensional plot of Mean, Standard Deviation and Skewness to take the form of a helix as these proportions change. Along this helix, Kurtosis is shown to change in a regular, pulsating, manner.

6) Standard Deviation and Distance Down The Shore - The increase strength of bottom currents away from High Water, results in more efficient sorting of the sediment (Visher, 1969). As a consequence, the range of particle sizes contained within a sample reduces in this direction resulting in smaller Standard Deviations.

The seasonal differences evident in the Mean Particle Size and Water Table data suggest that during summer these variables are controlled by others not considered. A strong contender for this role is biological activity. The activity of dominant sediment reworkers such as Arenicola marina can result in significant alterations to Particle Size Distribution (Baumfalk,1979; Cadee, 1976) and bed topography. The latter is clearly illustrated by Plates 1 and 2.

The correlations evident between species suggest common variables controlling their distribution. In their broadest sense these variables may be classed as:

Habitat Preferences - related to Physical and Chemical properties of their environment,(Meadows,and Campbell, 1972 a,b).

Food Preferences - related to the type and availability of food sources (loc.sit.)

Predator/Prey Interactions - not considered in this study but of undoubted importance, particularly with regard to the seasonal impact of migratory wading birds.

None of the food and habitat related variables considered appears responsible for the weak negative correlation between A. marina and N. diversicolor distribution patterns. Competition between the species is a possibility but was not

PLATES 1 AND 2

Alterations to bed topography as a consequence of sediment reworking by *Arenicola marina*.

Plate 1 - Sediment surface topography dominated by ripples produced by wave and current action.

Plate 2 - Sediment surface topography dominated by casts produced by *Arenicola marina*.

Plate 1

Plate 2

investigated. Salinity variations are consistent with changes in the distribution patterns of the S. armiger/ E.longa and Micrura sp/H. ulvae pairings. The latter also correlate with distance down the shore and site level.

Salinity and Site Position (Distance, Level) are also correlated with distribution patterns of most of the other species. This is consistent with the findings of Hughes and Thomas (1971 a,b) and Hughes et.al. (1972). Salinity was however, not found to be an important variable in a similar study by Penas and Gonzalez (1983).

Properties of the sediment particle size distribution are the most important of the other variables considered. Five of the ten species are correlated with at least one of the properties. Other workers have found a similar relationship, (Biernbaum, 1979; Penas and Gonzalez, 1983; Hughes et. al. 1972; Hulings and Gray, 1976; Cassie and Michael, 1968; Bloom et.al. 1972).

It is interesting to note that the distribution of the dominant species at Ardmore - A. marina - does not correlate with either Mean Particle Size or the Organic Matter Content of the sediment. These findings contrast with those of Longbottom (1970).

Seasonal differences in the correlations may be attributed to:

1) Seasonal population fluctuations.
2) Seasonal changes in sediment properties.
3) Seasonal changes in other population control factors (for example, Temperature effects, Predation and Migration).

These factors remain to be investigated.

The results of the final two PCA's suggest that the variables correlated with the population as a whole are different to those correlated with individual species. Highest Total Animal and Species Numbers are correlated with surface, oxidized sediments of relatively low strength. Highest animal numbers are also associated with poorly sorted sediments of relatively low Organic Matter Content. The relationship to Sorting is in agreement with the findings of Hulings and Gray (1976) and Bloom et.al.(1972). Penas and Gonzalez (1983) however, found the opposite relationship to Organic Matter Content.

The results from this section indicate that the distribution patterns of species in the sediment dwelling community can be correlated with properties of their environment. Further experimentation is however, required to determine if these correlations are causal or coincidental. An investigation of this type is performed in the next two sections.

# SECTION 5

## DESIGN, CONSTRUCTION, CALIBRATION AND TESTING OF THE SEA-WATER FUME.

# INTRODUCTION

Marine organisms are subject to a range of water flow conditions induced by Wave Action and Tidal Currents. It is therefore, surprising that few laboratory studies on animal/ sediment relationships have introduced this variable into model systems. The following are examples of those which have;

Rhoads and Young (1970) - carried out experiments to determine differential resuspension between burrowed and unburrowed muds.

Grant et. al. (1982) - examined the initiation of sediment motion in biotic and abiotic samples.

Eckman et.al.(1981) - tested the influence on sediment stability of varying densities of a tube building polychaete, *Owenia fusiformis*.

Taghon et.al.(1984) - investigated the influence of faecal pellets produced by a polychaete - *Amphicteis scaphobranchiata* - on sediment transport.

The reason for this lack of coverage possibly stems from a shortage of suitable experimental equipment. Work of this type requires complex, specialised and expensive equipment if satisfactory results are to be obtained.

This section contains details of a medium sized Sea Water Flume, suitable for a wide range of experimental work. The Flume was designed by myself with help from Mr. P. Tanner, Dept. of Naval Architecture, Glasgow University. The Flume has an effective width of 0.3m and maximum flow depth of 0.25m. A 0.3m square box core can optionally be located in the base of the trough. The water is circulated by a 1.5kwatt electric pump capable of delivering 0.025$m^3$ $s^{-1}$.Water velocity in the trough can be measured using a differential pressure measuring device linked to a digital readout meter.

The Flume has been used to investigate the effects of one organism - *Arenicola marina* - on Sediment stability and resistance to erosion. The results of these experiments are reported in the following section. A wide range of other applications, including physiological, are envisaged for the apparatus.

## MATERIALS AND METHODS

### Flume Specification

Preliminary measurements taken in the field revealed the following characteristic dimensions of the intertidal sediment surface environment at Ardmore.

Maximum Flow Velocity (Measured using a propeller-type current meter - Manufacturer A.Ott) = 0.25m/s
Maximum Height of Roughness elements = 0.05m
Maximum Diameter of Base of Roughness elements = 0.10m

A system capable of accomodating these dimensions was therefore required. To this end, the following design specification was decided upon for the Flume.

Sample Size ( Box Core ) = 0.30m Wide x 0.30m Long.
Water Depth = 0.25m
Maximum Flow Velocity = 0.25m/s

### Design

Two basic Flume designs have been used in other studies. The first consists of a rectangular cross-section, straight trough with a large stilling tank at either end. Water is circulated from one tank to the other via the trough. The return leg of the ciruit is completed by a pipe running between the two tanks, usually located under the trough. It is along this pipe that the pump is mounted. The second design consists of a rectangular trough in the shape of a racetrack. Water is circulated around the trough by a paddle wheel.

After a detailed consideration of the two designs, particularly with regard to the available space, the former design was decided upon.

With the above specification in mind, a number of critical dimensions had to be determined prior to the detailed design of the Flume. These dimensions were:

(1) The length of trough upstream of the sample, to give the required permissible shear stress loss over the length of the sample.

(2) The Boundary Layer thickness at the sample position. This was necessary to determine the extra trough

width required to keep the sample away from the trough wall boundary layer.

(3) The power output of the pump necessary to circulate the water at the required rates.

To facilitate the calculation of these dimensions, computer programs were developed. These, together with specimen calculations and details of their theoretical basis, are included in Appendix 'I'.

A detailed design of the apparatus was then undertaken and a complete set of working drawings prepared. At this stage, an important calculation was carried out to determine a suitable design for an Orifice Plate flow-rate measuring device. Details of the calculation and design are included in Appendix 'I'.

## Construction

A number of components were fabricated by contractors in accordance with my working drawings. Other items were fabricated in the workshops of the Zoology Department, Glasgow University. The help given by Mr. J. Baird and the late Mr. D. McFarlane is gratefully acknowledged.

The Flume was assembled in the 10$^{o}$C Aquarium of the Zoology Department. Great care was taken to ensure that the Stilling Tanks and Support Framework were accurately positioned and levelled.

The installation of a three phase, 415 volt, 50Hz.AC supply to the pump was carried out by the University Works Department. The help given by Mr. D. Little is gratefully acknowledged.

Connections were made to existing Sea Water and Air supplies using standard temporary fixtures and fittings. Further connections were made to existing drains.

## Calibration (Including an evaluation of Errors)

Two steps were involved in the calibration of the apparatus.

1) Calibration of the Flow Velocity measuring device

The apparatus used to calibrate the Flow Velocity measuring device is shown in Figure 1. The pitot tube was

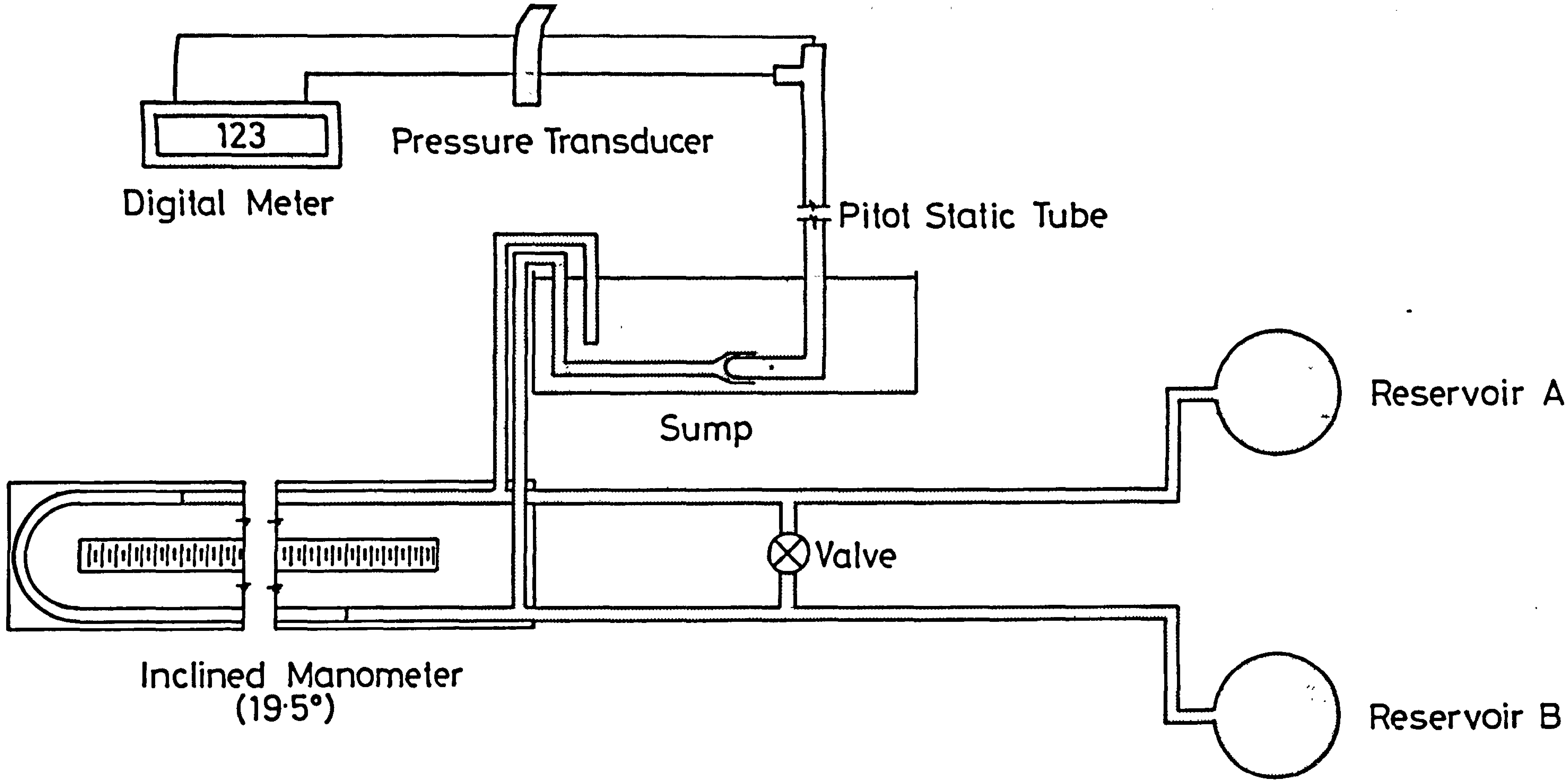



Fig.1.

Arrangement Of Apparatus For Calibrating Flow Velocity Measuring Device connected to a manometer inclined at 19.5°. This angle gave a 3x magnification to vertical pressure head measurements.

The device was calibrated for a maximum velocity pressure head of 14mm $H_2O$, equivalent to a velocity of 0.524m/s. The Digital Meter was adjusted to read 140 units at this velocity head.

Flow Velocity (V) is related to Pressure Head (h) by the equation:

$$V^2 = h \times 2g \quad \text{(Massey, 1979)}$$

where g = Gravitational Acceleration.

The relationship is therefore non-linear. A calibration curve based upon this equation was therefore determined.

2) <u>Calibration of the Flow-Rate measuring device</u>

The Orifice Plate and Manometer were calibrated using two methods -

(a) <u>Calculation</u>

Theoretical flow-rates were calculated for a range of pressure drops across the Orifice Plate using the method described in BS1042, Part 1, 1964, Appendix B (B1). The resulting values were plotted against their equivalent Manometer readings.

(b) <u>Experimentation</u>

Flow-velocities were measured at a large number of points across and down the trough cross-section. A Velocity contour plot was then drawn and the areas contained within the contours measured using a Planimeter. The Flow Rate was then obtained by multiplying each area by its mean velocity and summing the results for the whole cross-section.

This process was repeated for a range of Flow-Rates. The resulting values were plotted against their corresponding Manometer readings - recorded during the experiment.

The relationship between Flow Rate (Q) and Pressure Head (h) (Manometer Reading) is also non-linear. Thus,

$$Q \propto \sqrt{h} \quad \text{(Massey, 1979).}$$

A transformation of $Q^2$ was therefore applied to the data for both (a) and (b). The results were then replotted.

<u>Evaluation of Errors</u>

An error analysis was performed for the Velocity and Flow-Rate measurements. The sources of error which were identified for each are listed below.

Errors in Velocity Measurements

(a) Temporal variations in flow - Velocity measurements are the mean of two readings which may differ by as much as 20%.

(b) Error in calibrating device - Errors in setting and reading the manometer.

Errors in Flow-Rate Measurements

(a) Temporal variations in flow.

(b) Errors in setting and reading the manometer.

(c) Dimensional errors in the pipe and Orifice Plate resulting from temperature fluctuations and errors in manufacture.

(d) Additions to the basic tolerance due to non-conformity with the ideal BS1042 system - optimum number of upstream pipe diameters not available.

Details of the analysis are included in Appendix 'J'. The results have subsequently been presented in graphical form.

Testing

Three experiments were performed to test the performance of the Flume.

Experiment 1 - To observe the development of flow down the Flume Trough.

Velocity contours were determined along the centre line of the trough for a flow depth of 0.1m and three rates of flow - High, Medium and Low.

Experiment 2 - To observe the flow profiles across the Flume Trough at the Sample position.

Velocity contours were determined across the Flume Trough for a flow depth of 0.1m and three rates of flow - High, Medium and Low.

Experiment 3 - To examine the heating effects resulting from prolonged circulation of the water.

Changes in temperature of the circulating water were measured over a period of 90 mins. at three flow rates, high, medium, and low. The results were plotted as Temperature Increase ($^{o}C$) against Time (mins).

# RESULTS

## Design

After performing the calculations in accordance with the design specification, the following dimensions were obtained.

(1) Required length of trough upstream of sample = 1.09m

(2) The Boundary Layer thickness at the sample position = 0.040m

(3) The power output of the pump = 1.34 kwatts.

These dimensions were incorporated into the Flume design shown in Figure 2. The complete set of working drawings has not been included. Copies of these are, however, available for inspection. The finished apparatus is illustrated in Plates 1 to 11.

## Construction

The basic features of the overall Flume design are as follows:

Trough (T) - Walls - 6mm thick glass. Glass was chosen in preference to plastic in view of its good optical properties. (D and N Glass Ltd., Glasgow).

- Base - 6mm thick plastic overlaying 4mm thick plywood. (University Works Department).

Upstream and Downstream Stilling Tanks (UST and DST)

- 5mm thick mild steel plate with angle iron reinforcing (Andrew Young & Sons, 45 Midwharf Street, Glasgow).

Support Framework (SF) - Mild steel angle irons (Hillington Fabrications, Ltd., 18/20 Thornwood Avenue, Glasgow.

Pump (P) - 1.5 kwatt, MSK Myson Inline Circulator, Size 125 - 6210 with 5" BS10 on 125mm BS45c4 suction and discharge terminations. (Ritchie Mackenzie & Co., Ltd., Broomhill Industrial Estate, Kirkintilloch, Glasgow).

Valve (V) - 4" BS10, Saunders Diaphragm Valve, Cast Iron Construction (Ritchie Mackenzie & Co., Ltd.,).

## FIGURE 2

### Experimental Seawater Flume

#### Key To Figure.

UST = Upstream Stilling Tank
DST = Downstream Stilling Tank
C = Flow Collimator
T = Flume Trough
AW = Adjustable Weir
VMA = Velocity Measuring Apparatus
V = Valve
P = Pump
M = Manometer
OP = Orifice Plate
BC = Box Core
SF = Support Framework

For a full description of items see text.

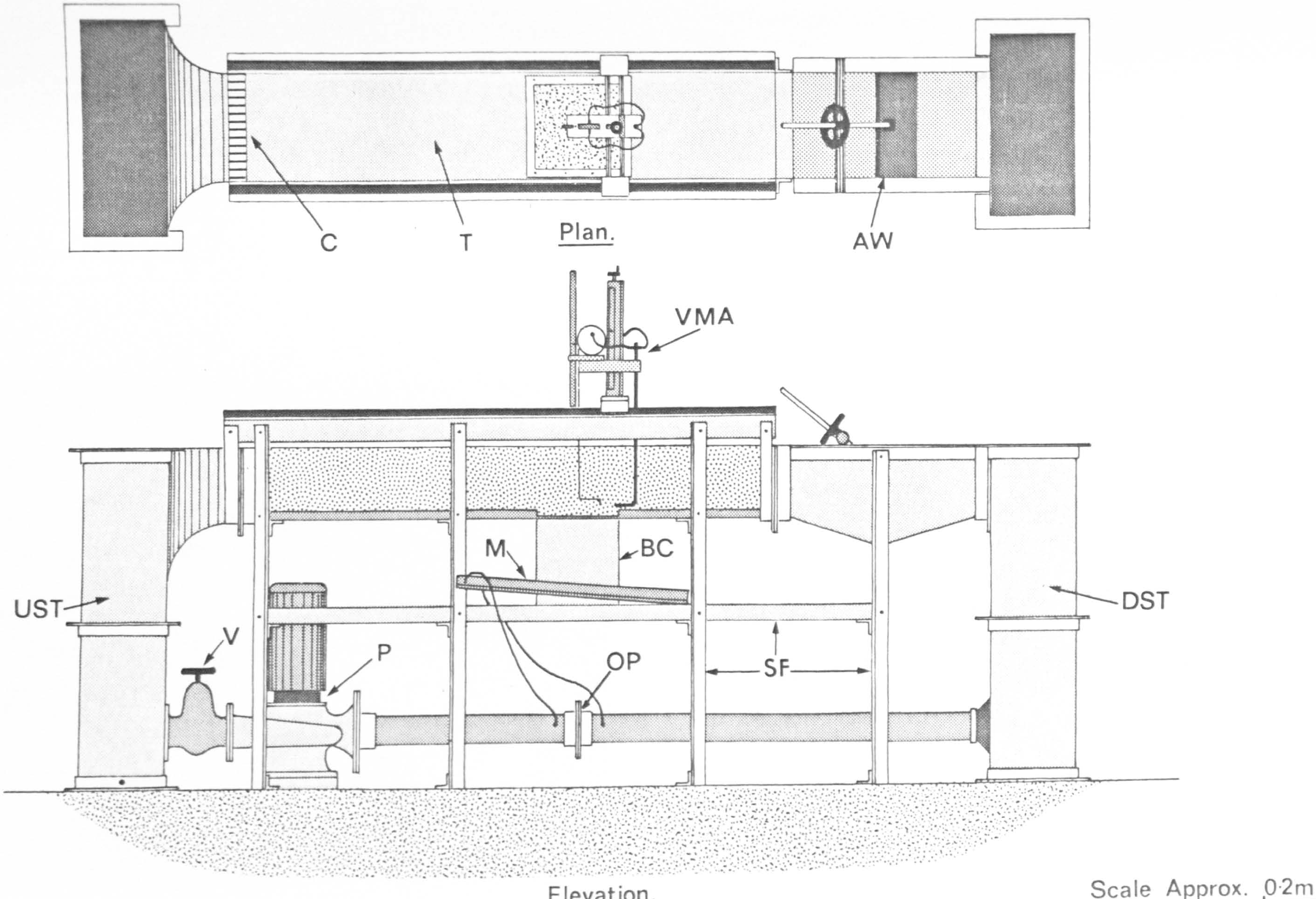

C
T
Plan.
AW
VMA
M
BC
UST
DST
V
P
OP
SF
Elevation.
Scale Approx. 0·2m.

PLATE 1

A general view of the Flume Trough from the Upstream Stilling Tank.(UST)

PLATE 2

A general view of the Flume Trough from the Downstream Stilling Tank.(DST)

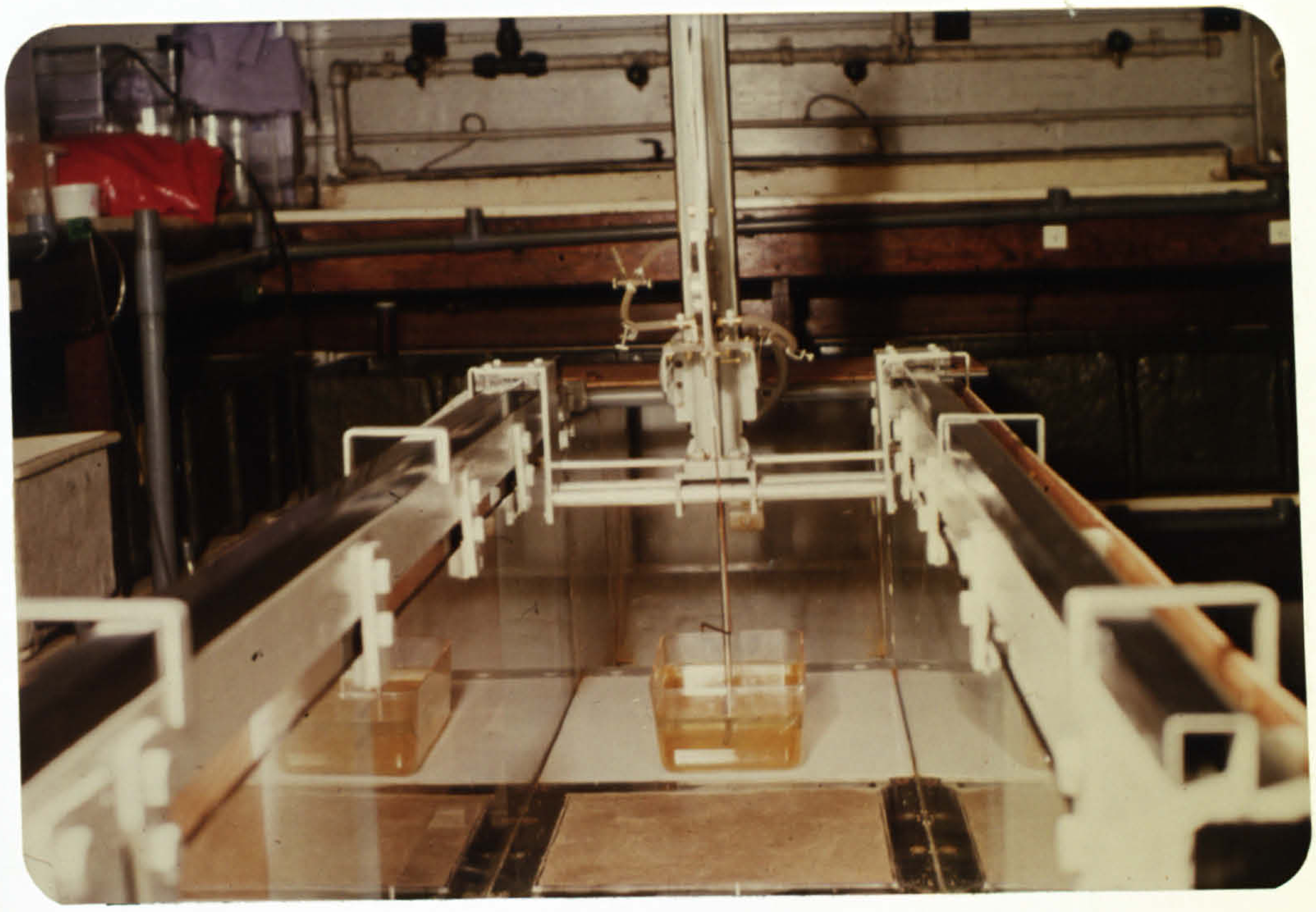


Plate 1

Plate 2

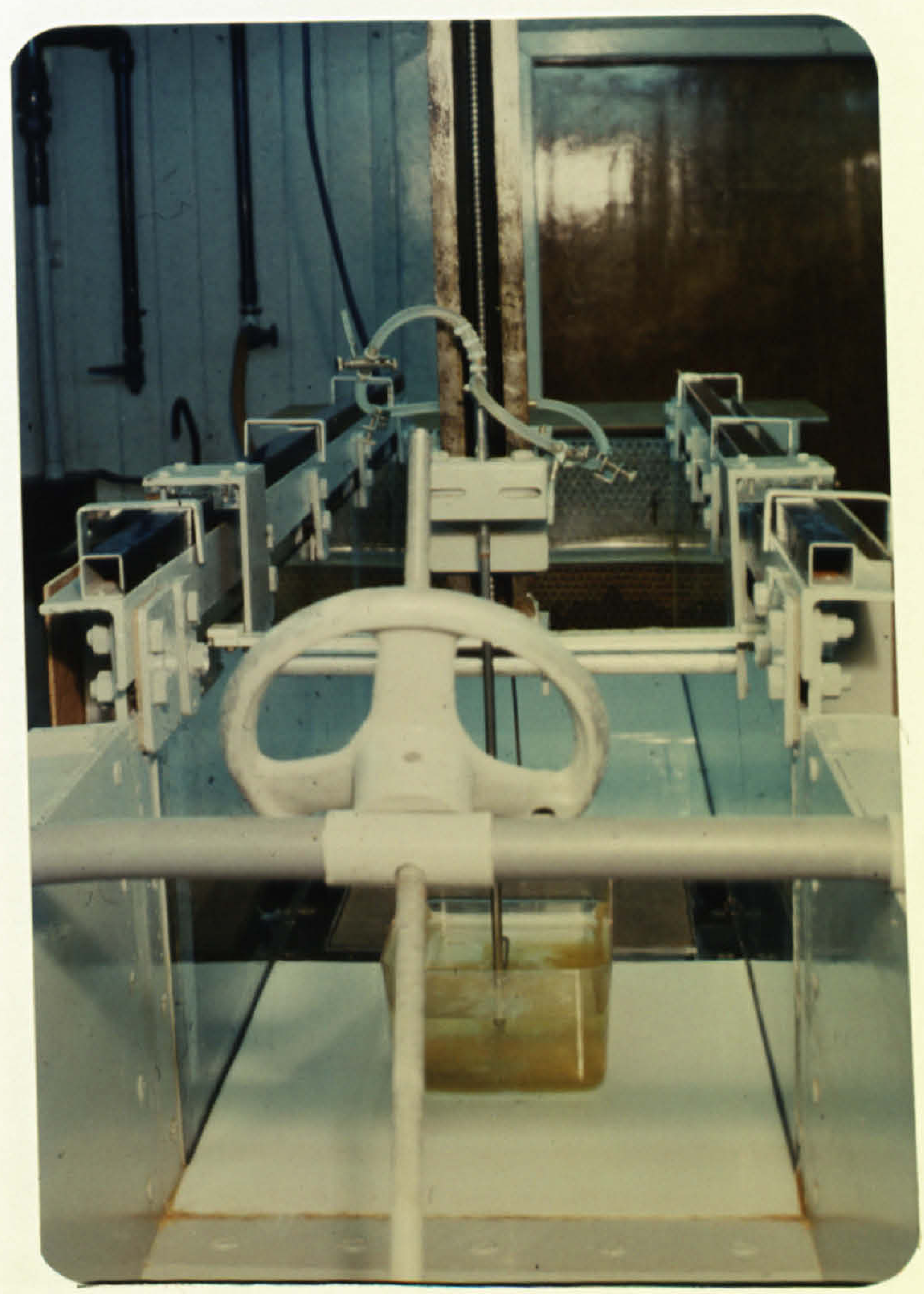


PLATE 3

The Flow-velocity measuring apparatus.(VMA)

PLATE 4

The Flow-velocity measuring apparatus.(VMA)

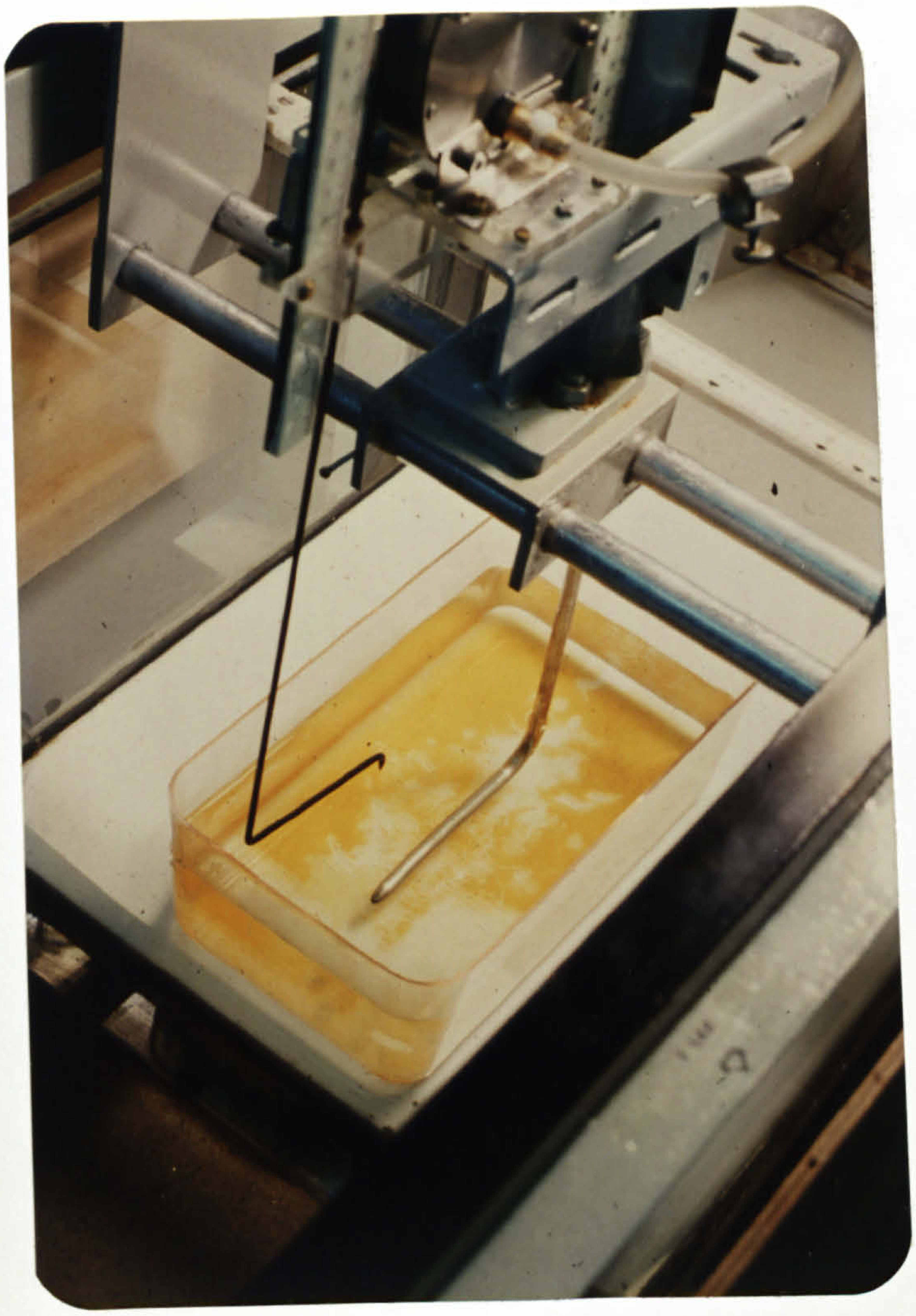


Plate 3

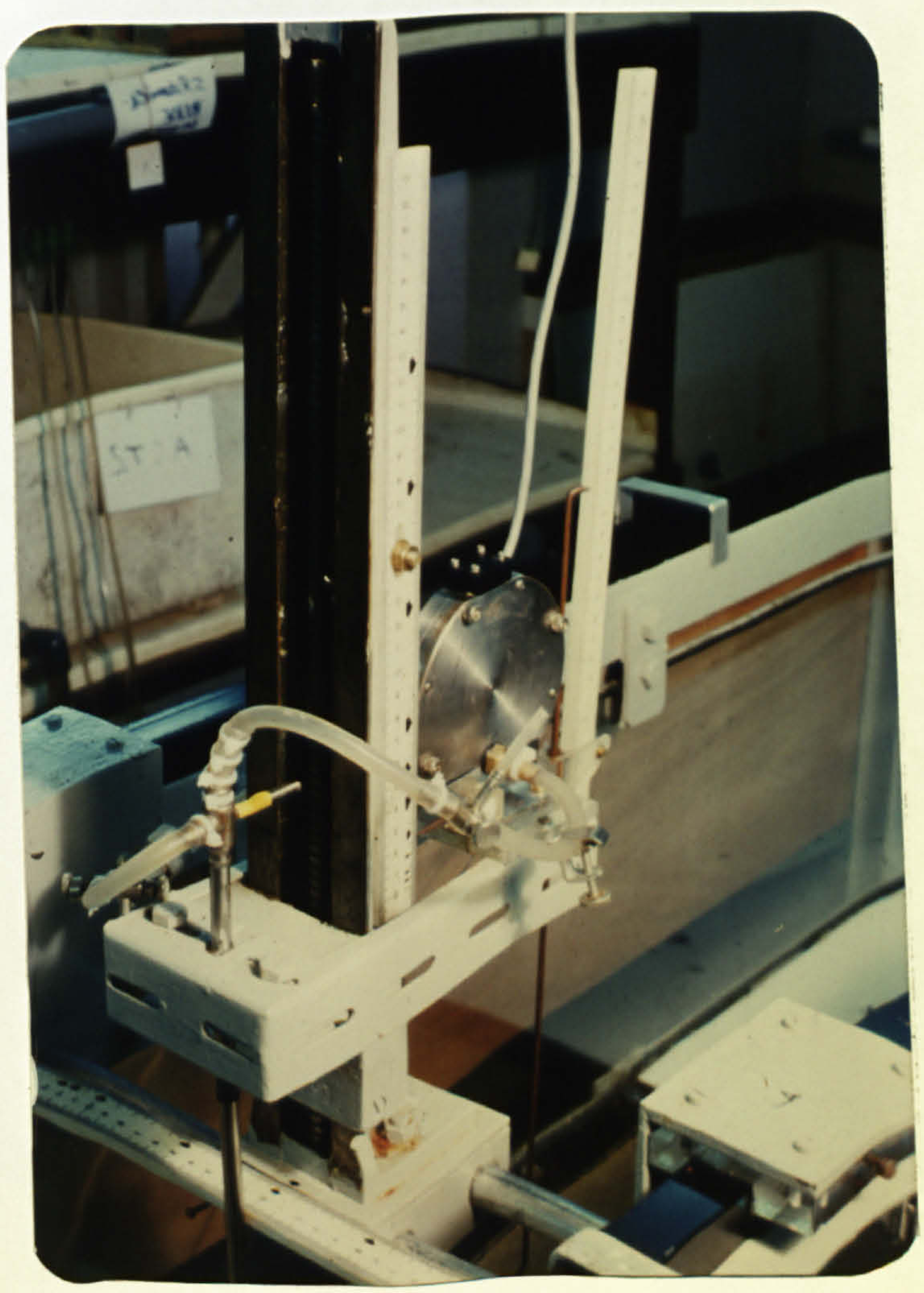


Plate 4

PLATE 5

The Flow-velocity measuring apparatus.(VMA)

PLATE 6

The Flow-rate measuring apparatus.(OP & M)

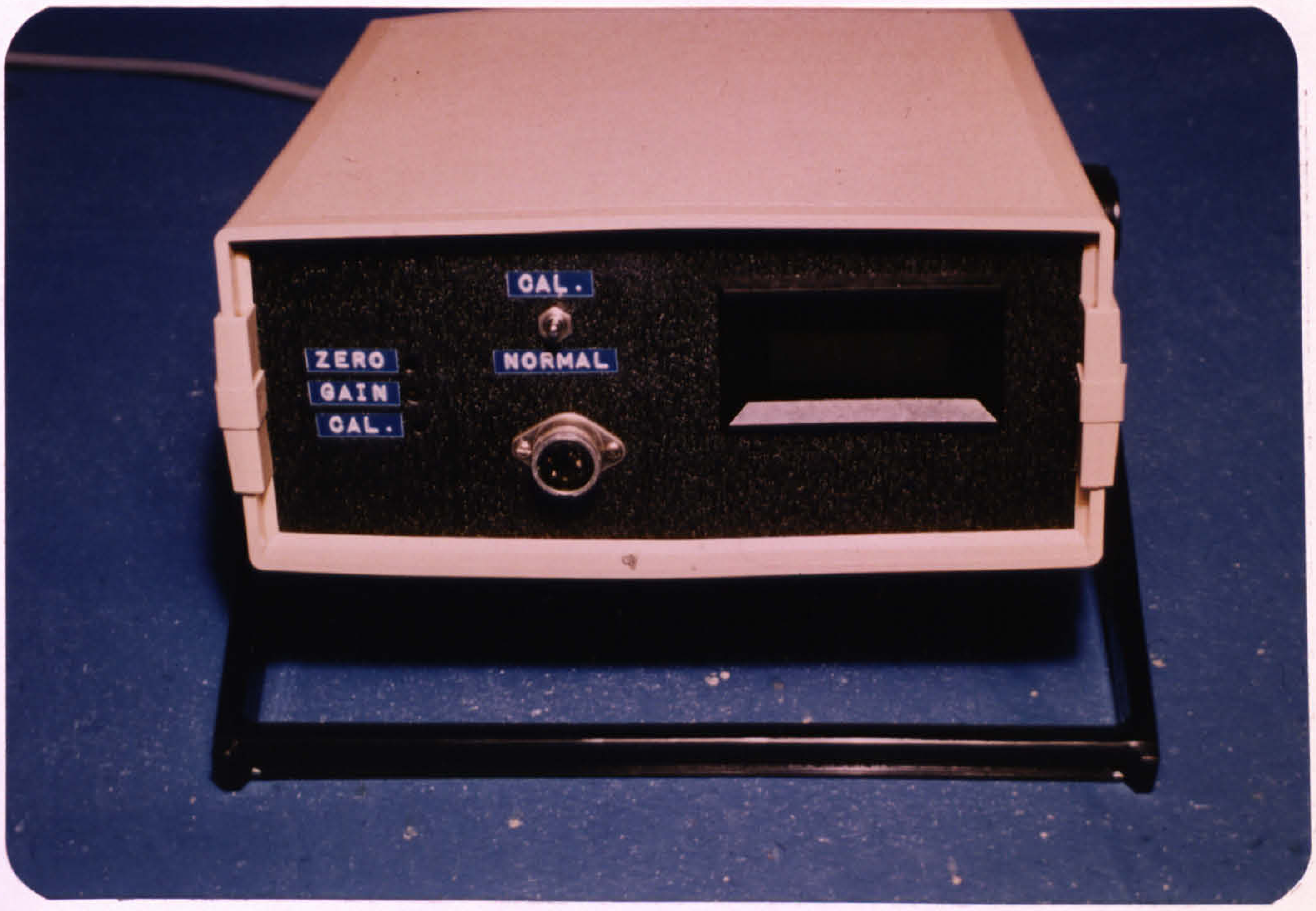



Plate 5

Plate 6

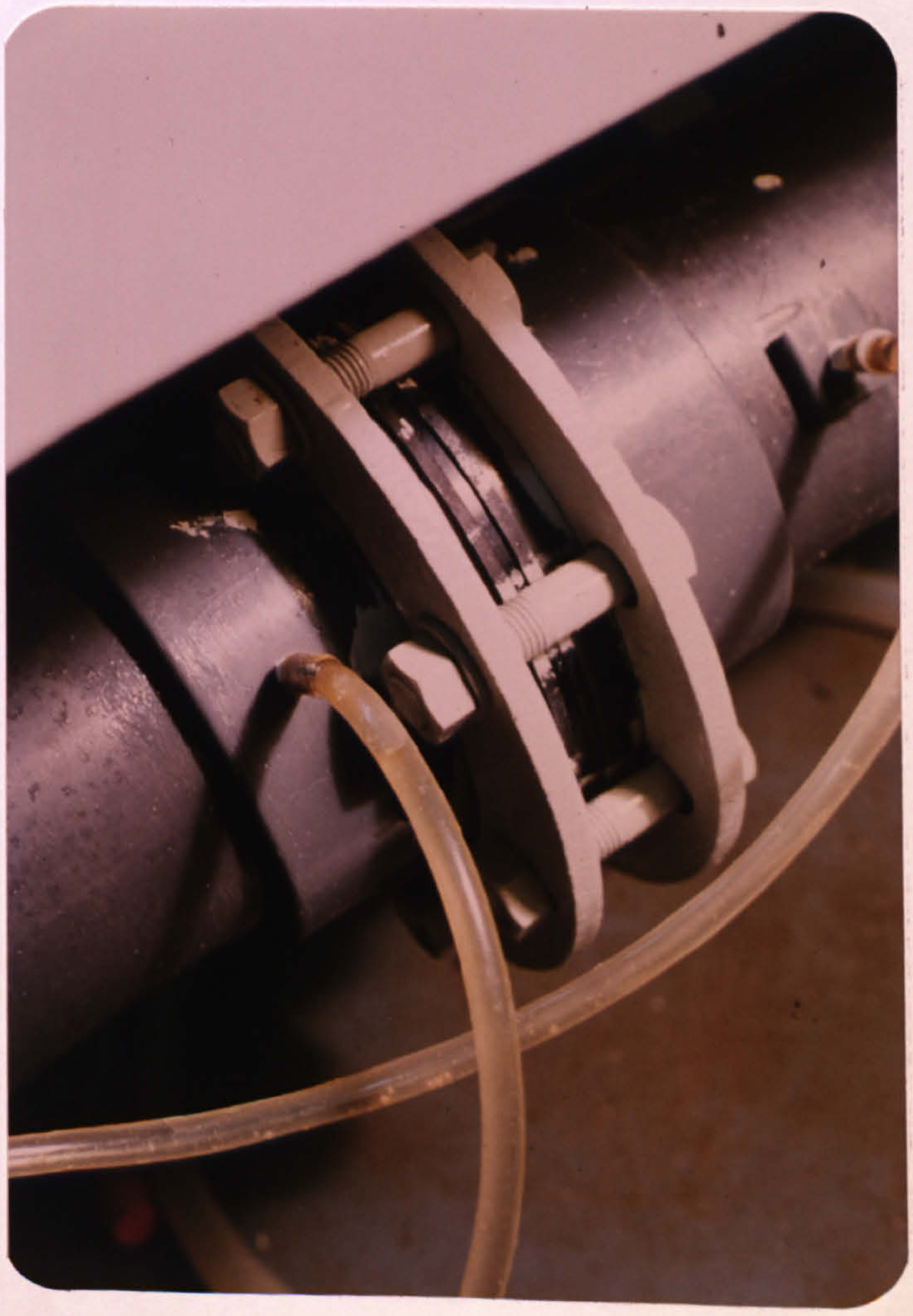


PLATE 7

The Flow-rate measuring device.(OP & M)

PLATE 8

The Pump.(P)

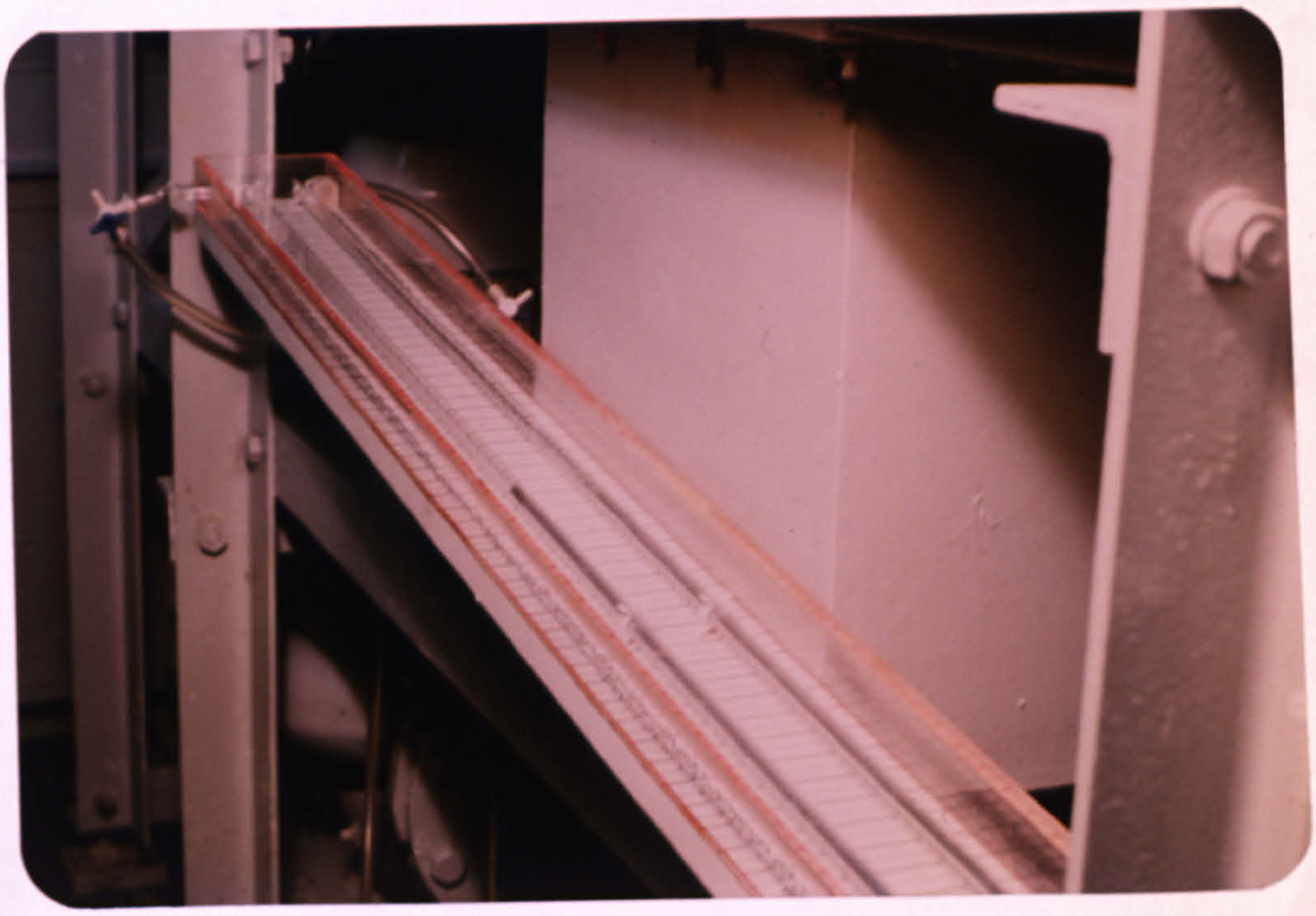


Plate 7

Plate 8

PLATE 9

The Flow control Valve.(V)

PLATE 10

The Flow Collimator.(C)

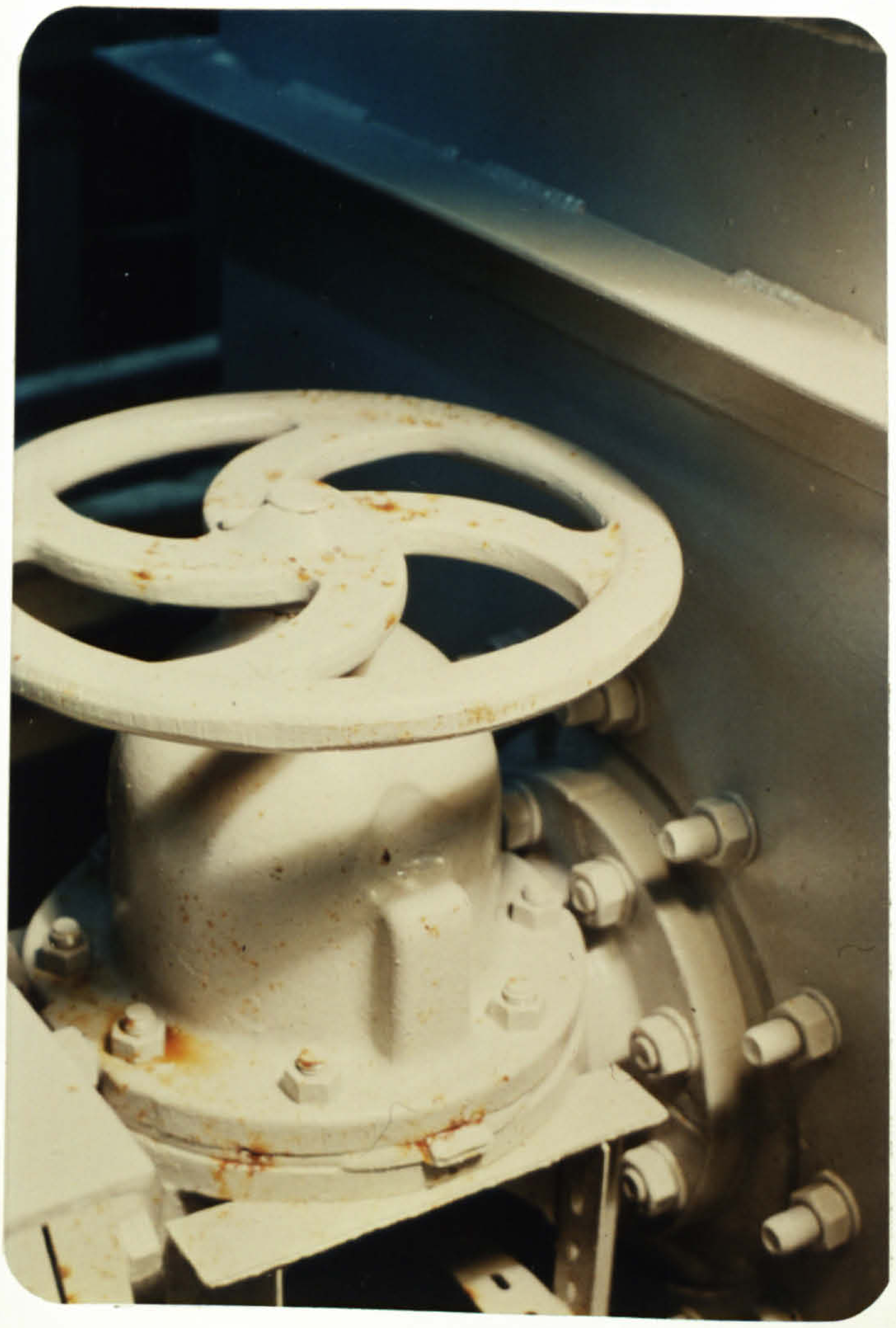


Plate 9

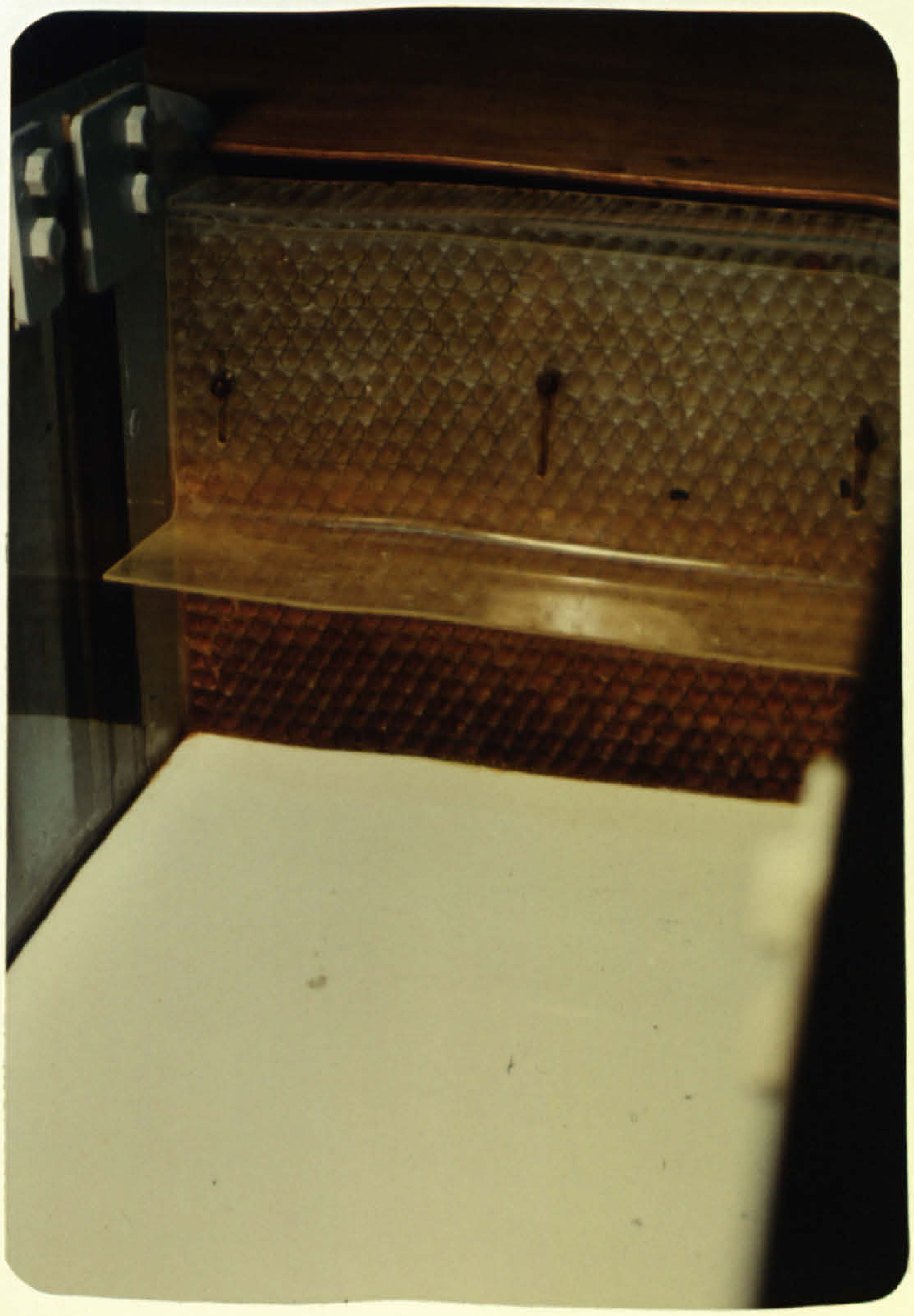


Plate 10

PLATE 11

The Adjustable Weir.(AW)

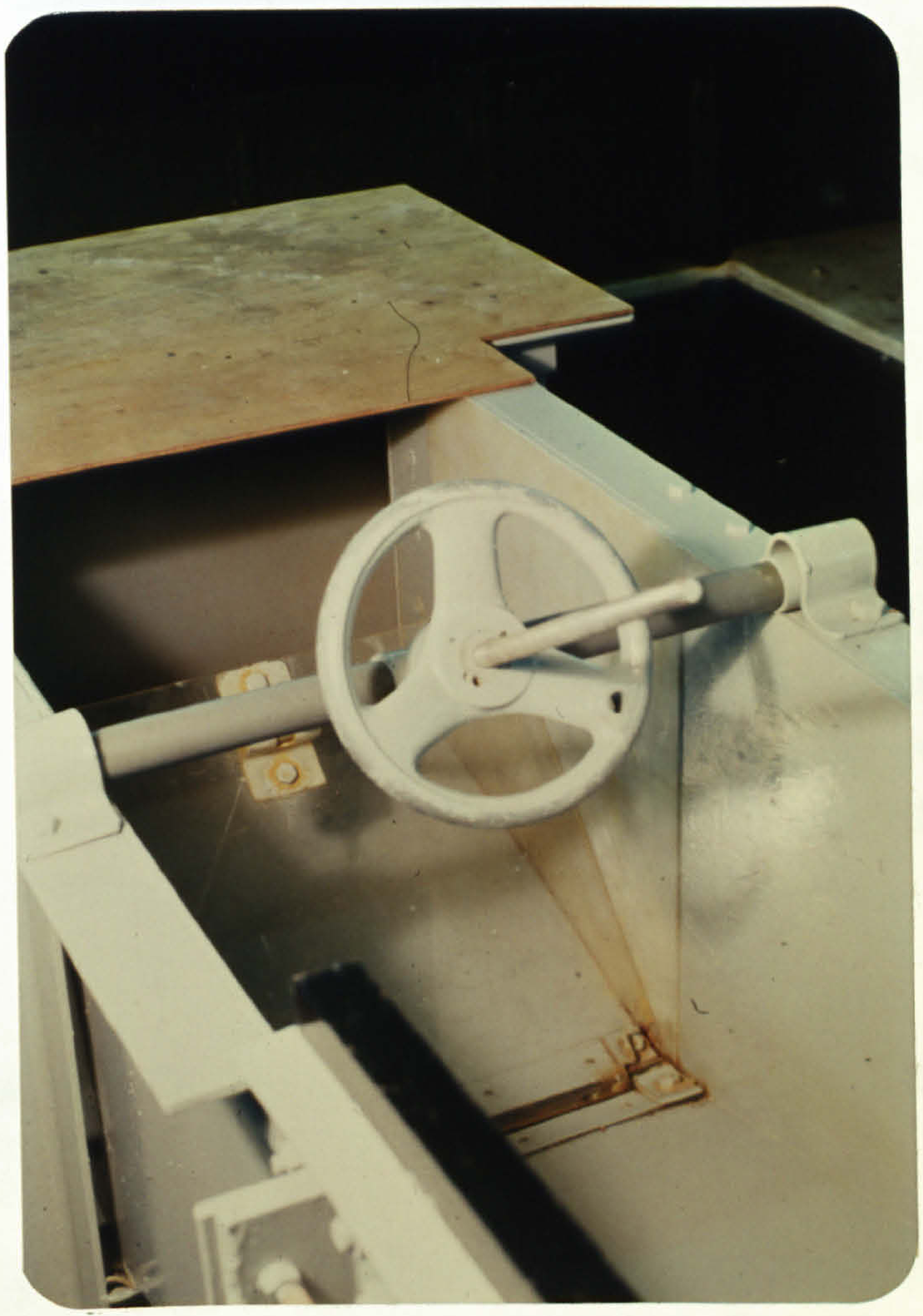


Plate 11

Pipework and Orifice Plate (OP) - 5"u PVC with standard George Fischer Sales, Ltd, Fixtures and Fittings (Brown & Tawse, Ltd., Kings Inch Road, Renfrew).

Velocity Measuring Apparatus - (VMA) -

Pitot Static Tube - 8mm dia. x 0.48m long. (Airflow Developments, Ltd., Lancaster Road, High Wycombe, Bucks.)

Pressure Transducer - Validyne DP103, fitted with Diaphragm No. 14 (0 - 0.55in $H_2O$). (REL PCI, Ltd., Croft House, Bancroft, Hitchin, Herts)

Digital Panel Meter - DPM 2B LCD Panel Meter with 0.5" character height (Pendix Components, Ltd., England.)

Collimator (C) - Fabricated from 8mm bore glass tubing.

Manometer (M) - Fabricated from 3mm bore glass tubing.

Finish - All water-tight joints were sealed with rubber gaskets and clear Silicone Rubber aquarium sealant (Interpet, Dorking, Surrey). Mild steel surfaces were galvanised after manufacture and given several coats of non-toxic polyurethane paint. ("Poly-Rock" Matthews, Maclay and Manson, Ltd., Hyde Park Street, Glasgow.)

## Calibration

(1) Calibration of The Flow-Velocity Measuring Device

The Calibration Curve for the device is shown in Figure 3.

(2) Calibration of The Flow-Rate Measuring Device

The Calibration Curves obtained for the device using the two methods are shown in Figure 4. The linearly transformed plots are shown in Figure 5.

Experimentally determined Flow-Rates are approximately 5% lower than calculated values. The difference was analysed statistically using a slope difference 't' test (Bailey, 1959) and was found to be highly significant - ($t = 13.2745$, d.f. = 13, P 0.001 (H.S)). Transformed experimental values show a good fit to a straight line, the equation to which is shown overleaf.

Fig.3.

Calibration Curve For Flow Velocity Measuring Device.

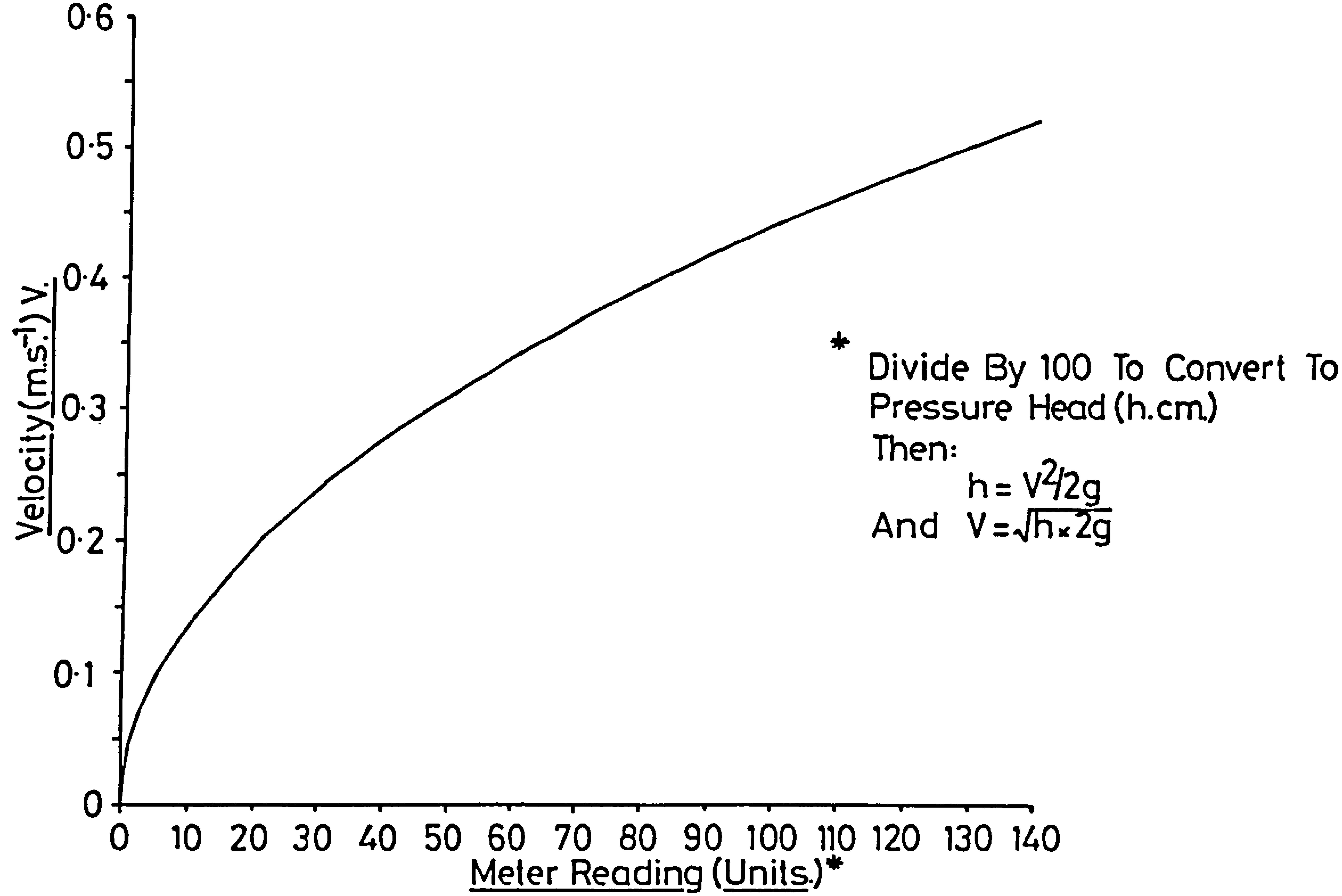


Fig. 4.

Calibration Curve - Manometer Reading Versus Flow Rate.

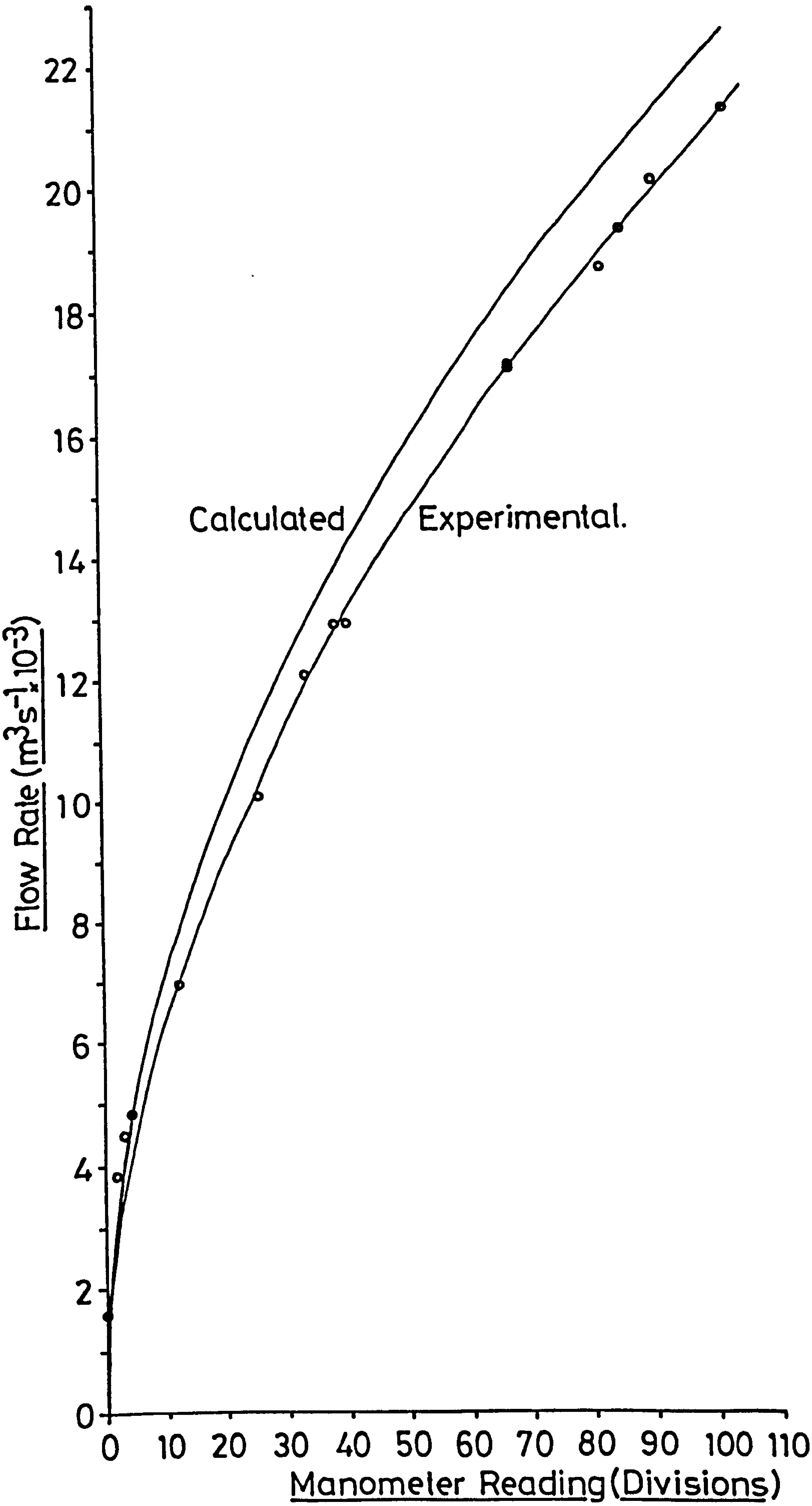


Fig.5. Transformed Calibration Curve - Manometer Reading Versus Flow Rate.$^2$

$$(\text{Flow Rate})^2 = (4.360 \times 10^{-6}) \times \text{Manometer Reading} - 0.3064 \times 10^{-6}$$

$$t = 82.2338$$

$$df = 13$$

$$P = 0.001 \text{ (Highly Significant)}$$

(3) Evaluation of Errors

Errors in Velocity Measurements

Errors in velocity measurement are summarised in Figure 6. The sources and magnitudes of the constituent errors contributing to the total error are included.

Above a velocity of approximately 0.125m/s (10 units on the meter) the total error is less than 2.5%. Below this velocity the error increases rapidly to approximately 30% at 0.05m/s (1 unit on the meter.

Errors in Flow-Rate Measurements

Errors in Flow-Rate measurement are summarised in Figures 7 and 8. The sources and magnitudes of the constituent errors contributing to the total error are included for a range of flow depths. Data for other depths can be obtained by interpolation.

The total error is largest for any given flow-rate in the deepest flows. Total errors range between 7.5 and 43% at low flows ($2 \times 10^{-3}$ $m^3/s$ = 1 manometer division) and 4.5 and 6.5% at high flows ($20 \times 10^{-3}$ $m^3/s$ = 110 manometer divisions). They are however, relatively constant at the lower values for the following ranges of flow-rates.

0.25m Flow Depth = 11 to $20 \times 10^{-3}$ $m^3/s$
= 35 to 110 manometer divisions

0.05m Flow Depth = 3 to $20 \times 10^{-3}$ $m^3/s$
= 2 to 110 manometer divisions.

Testing

Experiment 1 - The development of flow down the Flume Trough

The development of flow down the Flume Trough at the three flow-rates is shown in Figures 9, 10 and 11.

At all flow-rates, velocity contours close to the bed indicate uniform flow conditions down the trough. Away from the bed, at low flows, the contours are disturbed. This

Fig.6.
Errors In Velocity Measurement.

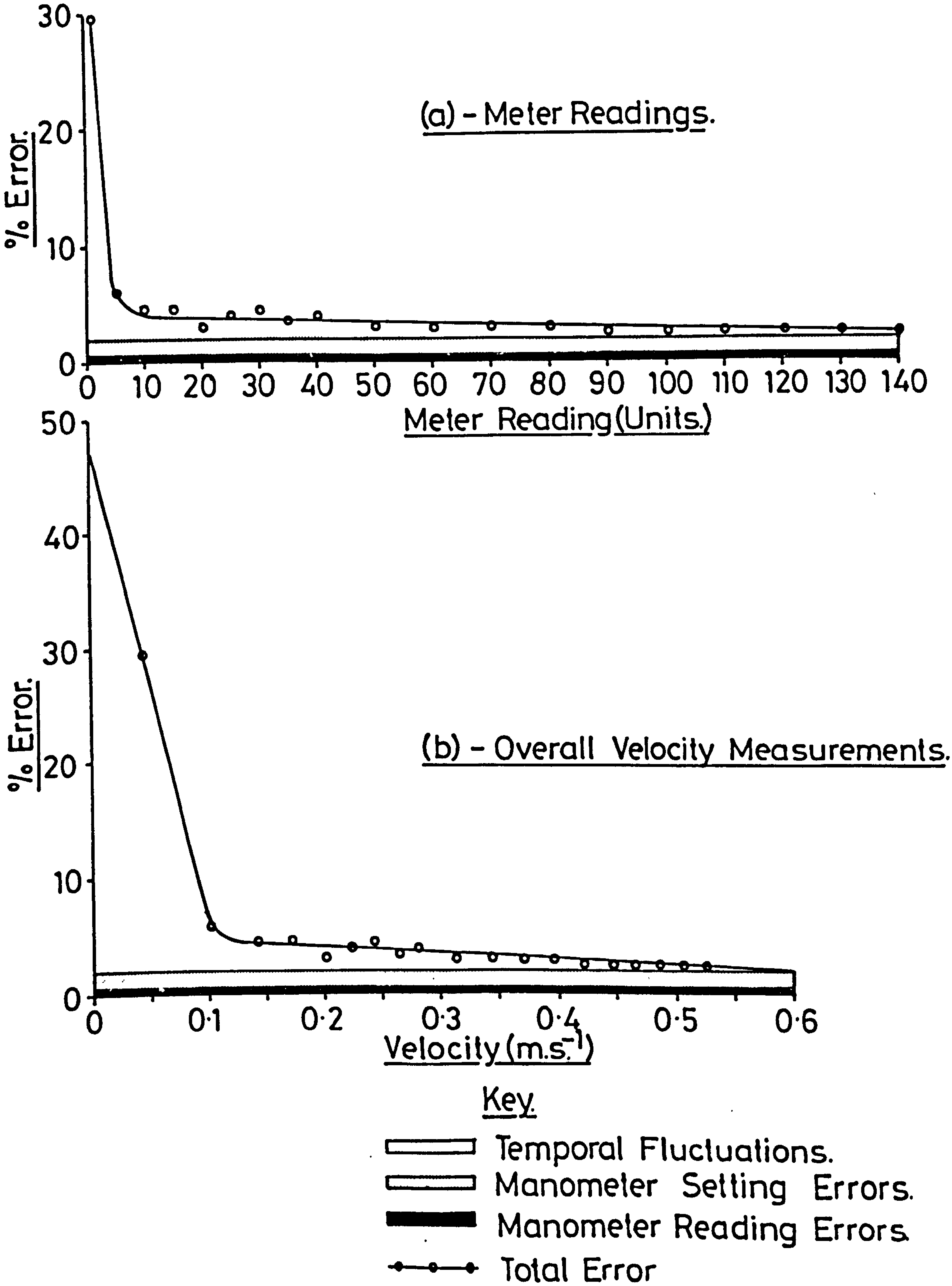
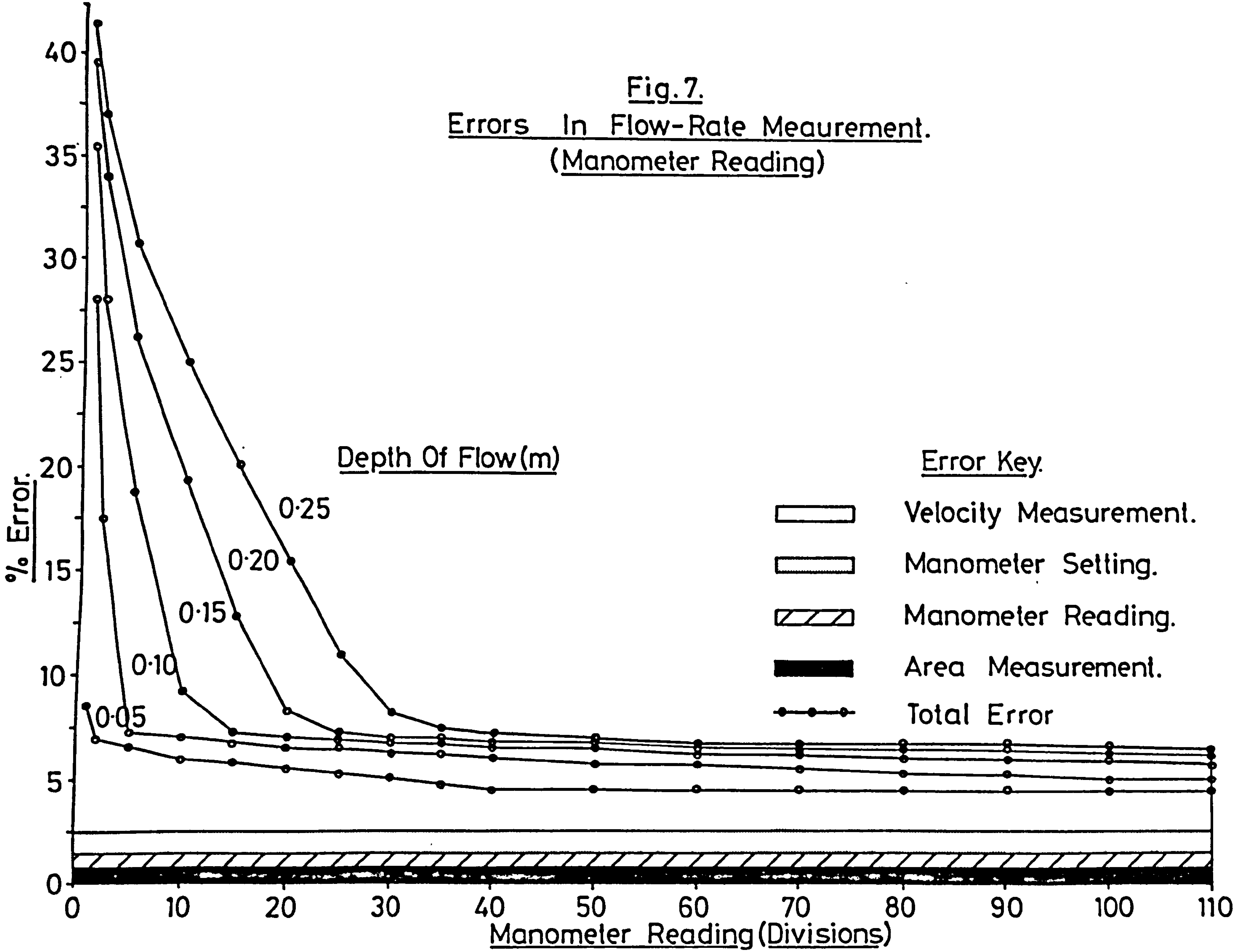


Fig. 7.

Errors In Flow-Rate Meaurement.

(Manometer Reading)



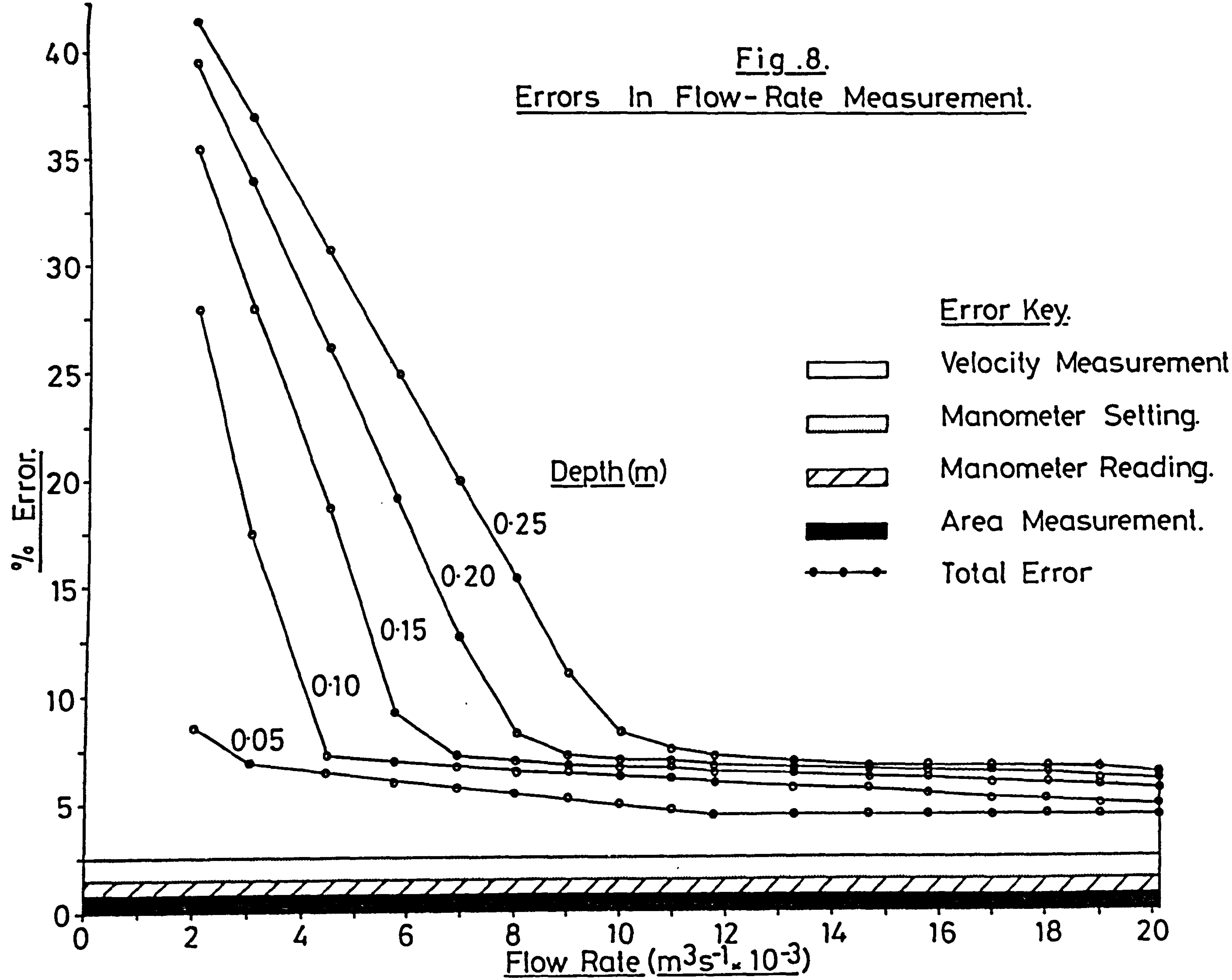
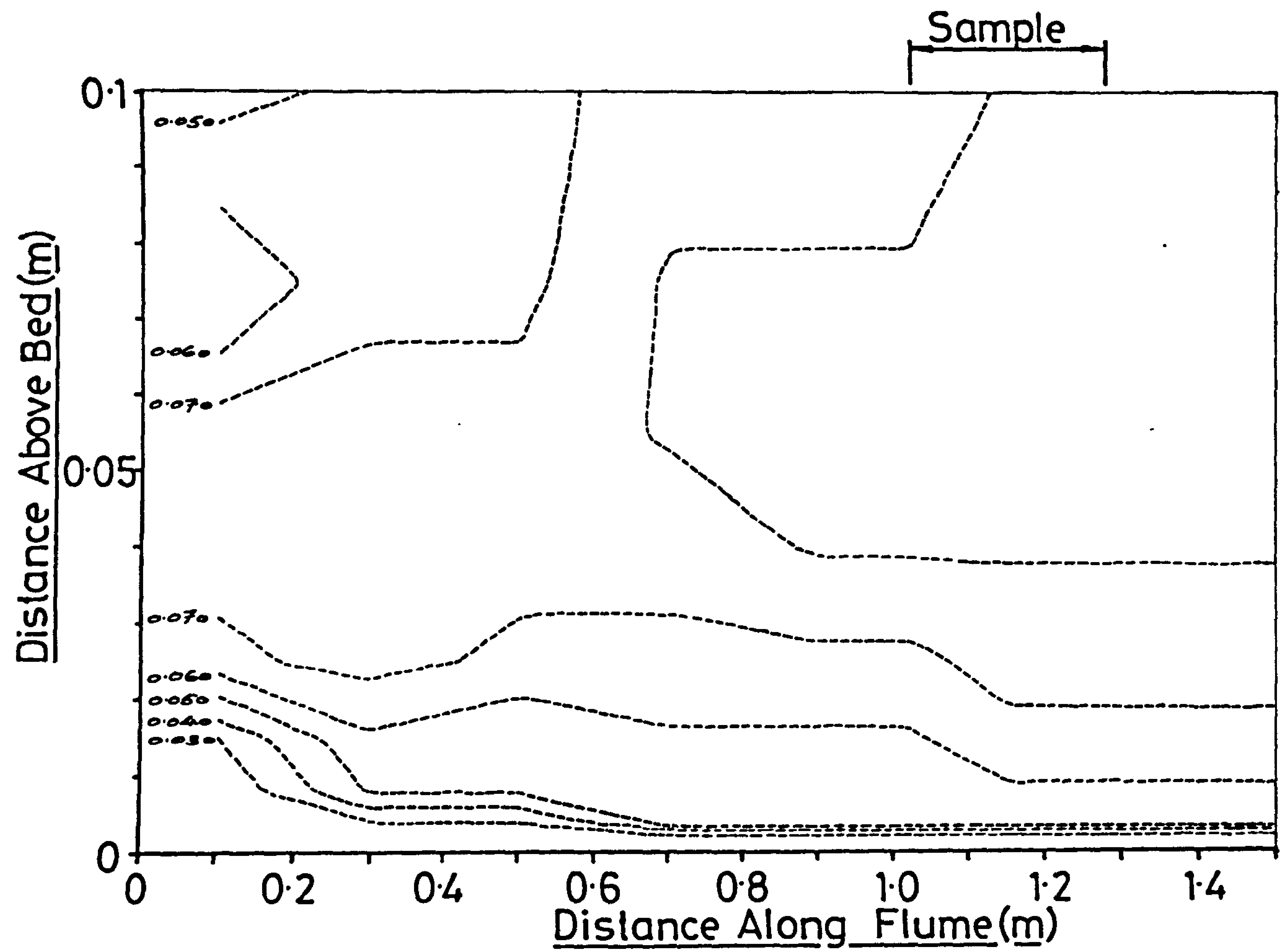



Fig .8.
Errors In Flow-Rate Measurement.

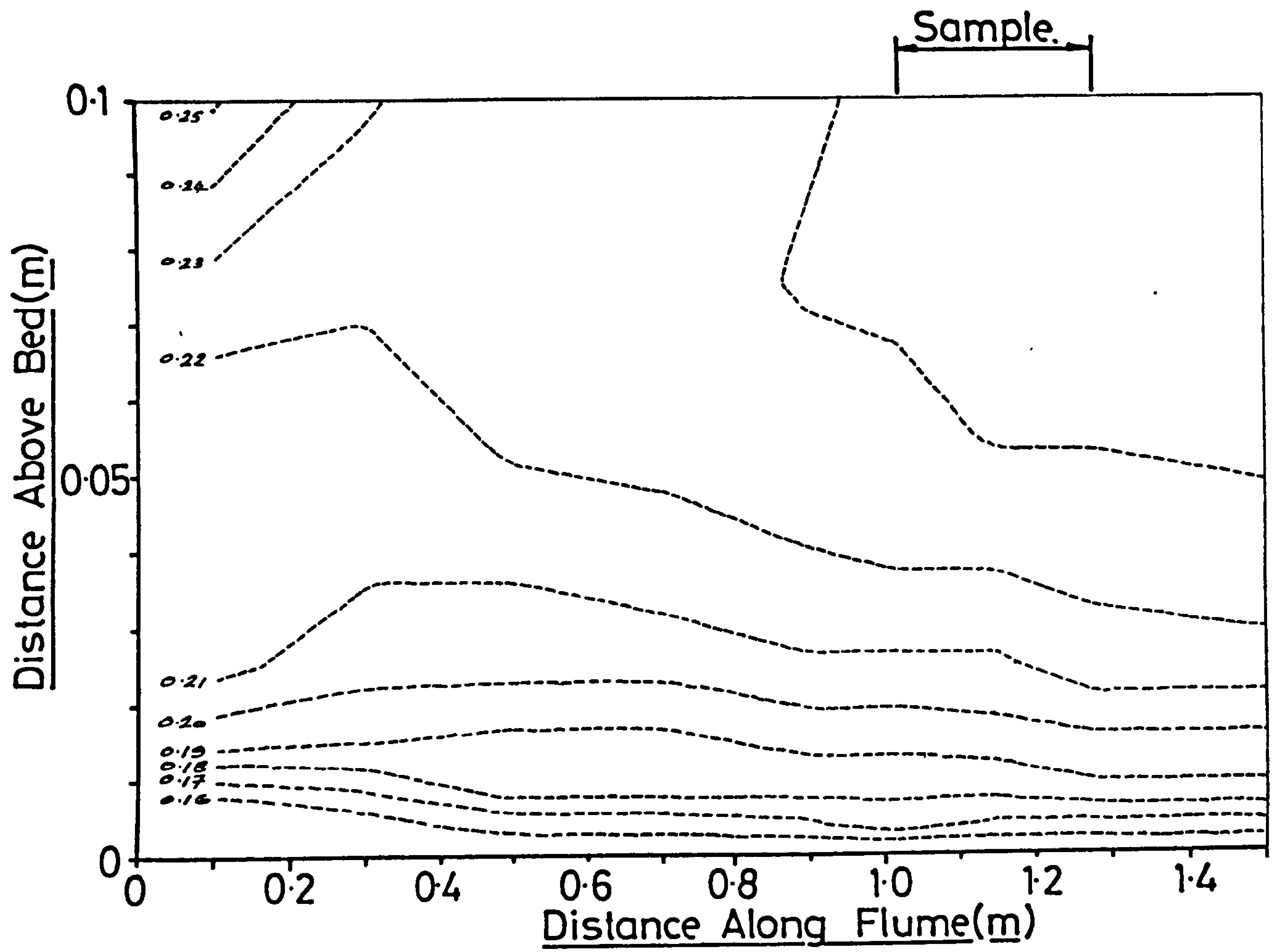



Flow Rate = 0·0035 $m^3 s^{-1}$
(Low)

Fig.9.

Velocity Contour Plot Illustrating Development Of Flow Down Flume.

(Contours In $ms^{-1}$)

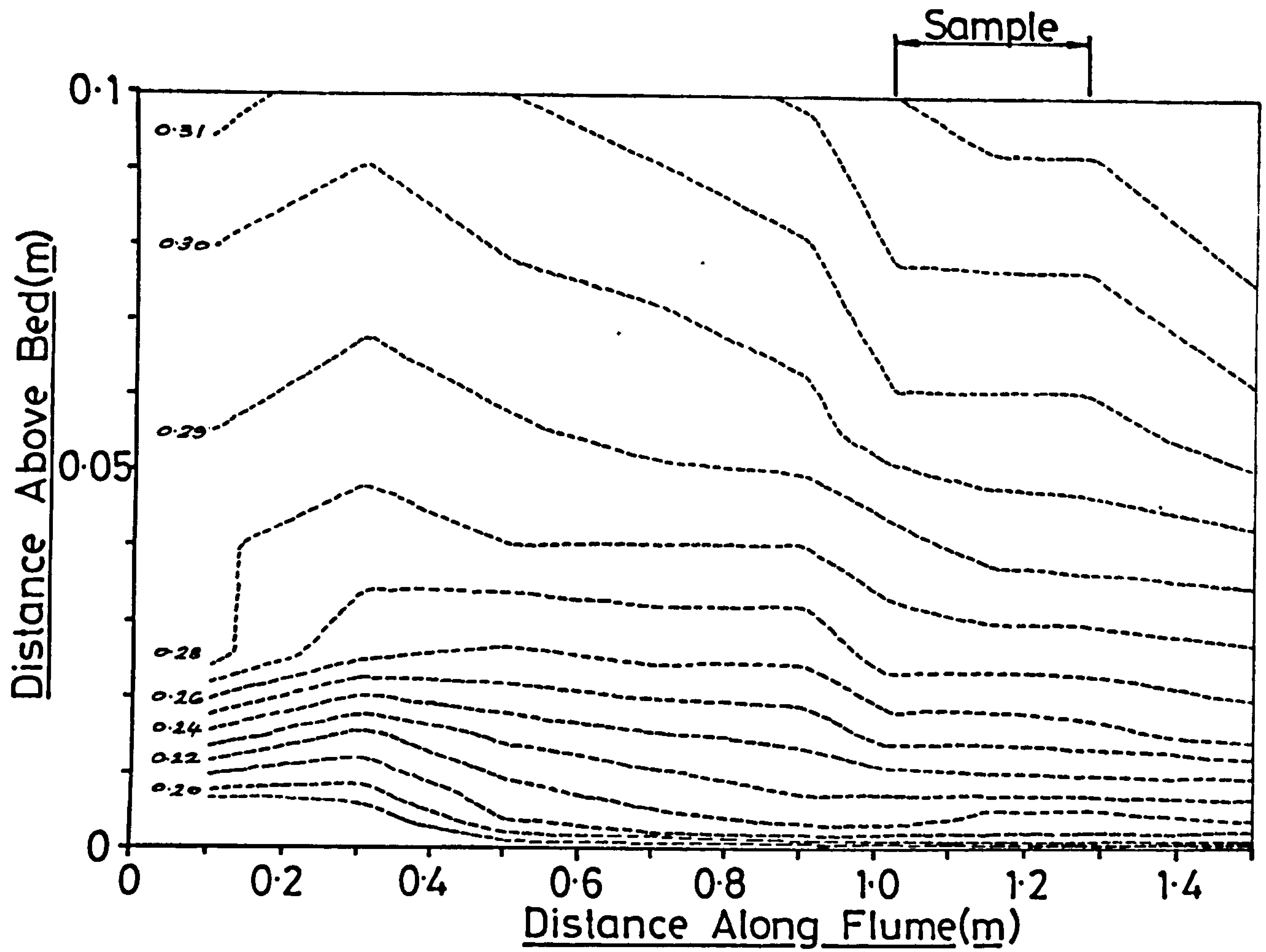



Flow Rate = $0.0115 m^3 s^{-1}$
(Medium)

Fig. 10.

Velocity Contour Plot Illustrating Development Of Flow Down Flume.

(Contours In $ms^{-1}$)




Flow Rate = $0{\cdot}0165\,m^3s^{-1}$
(High)

Fig.11.

Velocity Contour Plot Illustrating Development Of Flow Down Flume.

(Contours In $m.s^{-1}$)

phenomenon is absent at high flows.

<u>Experiment 2</u> - <u>Flow profiles across the Flume Trough at the Sample position</u>.

The flow profiles across the Flume Trough, at the Sample position, for the three flow-rates, are shown in Figure 12.

Boundary Layer effects are clearly evident as a slowing of the water adjacent to the trough walls and base.

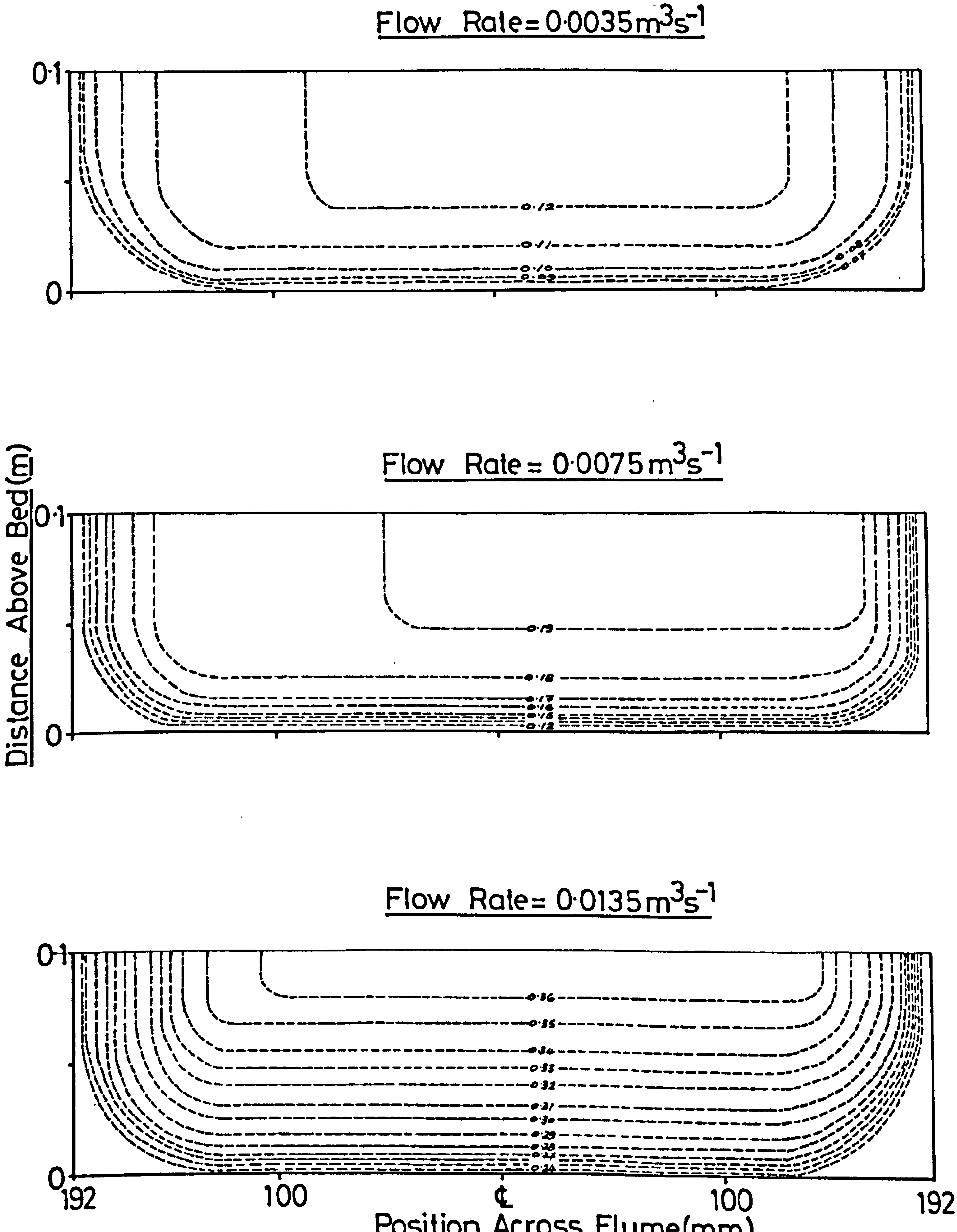
The flow is noticeably assymmetric about the centre line of the trough at Medium and Low flow-rates. However, adjacent to the bed, velocities are uniform across most of the troughs width.

<u>Experiment 3</u> - <u>Heating effects resulting from prolonged circulation of the water</u>.

The heating effects resulting from prolonged circulation of the water are shown for the three flow-rates in Figure 13.

After 90 minutes, a temperature increase was evident at all three flow-rates. The increase ranged between 0.5$^{\circ}$C (Low flow) and 2.3$^{\circ}$C (High flow). The rise to these maximum values was fairly constant over the duration of the experiment.

Velocity Contour Plots Illustrating Flow Profiles Across Flume At Position Of Sample For Three Flow Rates.

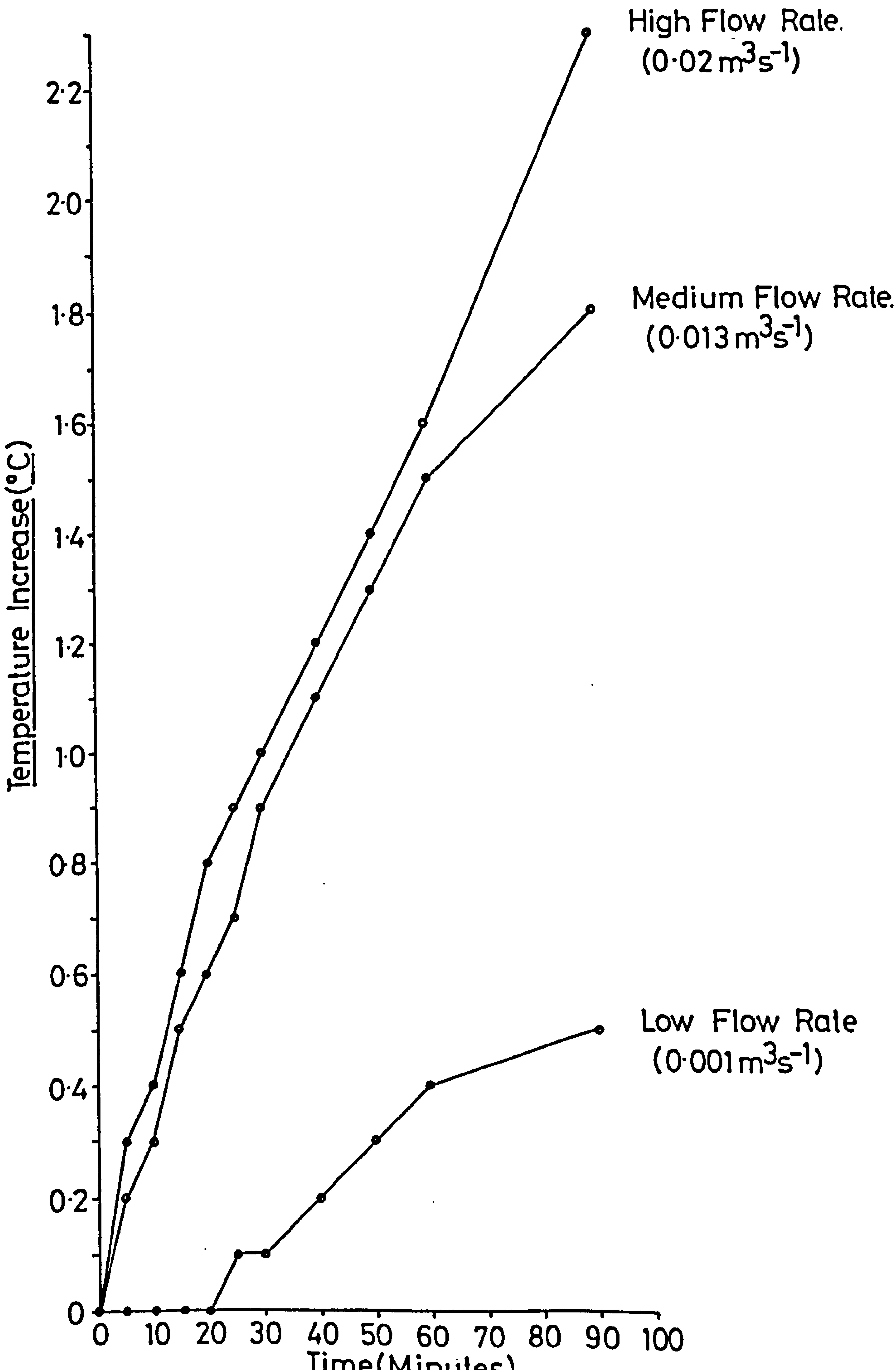



Velocity Contours Are In m.s.-1

Fig.12.

Fig. 13.

Graphs Illustrating Heating Of Water Resulting From Prolonged Circulation.



## DISCUSSION

Flume designs, comparable with that described here, have been reported by other workers. Vogel and LaBarbera (1978) and Grant et.al. (1982) contain details of smaller versions with Trough widths of 16 and 10cm respectively. These dimensions are too small for the type of work envisaged for my design. In addition, Boundary Layer development at the Trough walls further reduces their effective width. The design detailed in Eckman et.al. (1981) has a width of 50cm. This is well suited to this type of work but too large to be accommodated in the space available to me.

Removable Box Cores are included in the designs described in Grant et.al. (1982) and Eckman et.al.(1981). The core dimensions are 10 x 20cm and 25cm square respectively. Both are therefore, smaller than the 30cm square core contained in my design. The location of the core is only given by Eckman et.al.(1981). It is located 1.75m from the start of the Trough. This results in a 2.5% shear stress loss over the sample length, which is better than the 5% worked to in my design.

In all three of the above designs, a 'clear plastic' has been used to construct the walls of the Trough. The poor optical properties of this material impose severe restrictions on the use of photographic techniques in subsequent experimental work. Preliminary experiments with photographic and video techniques have shown my design, incorporating glass, to be ideally suited to this type of work.

One feature of my design which could have been improved, is the material from which the pump and valve were constructed. Stainless steel construction would have ensured long service and eliminated contamination of the water with iron oxide. The latter necessitated frequent water changes. Unfortunately the additional cost to incorporate this feature was prohibitive.

The tests carried out on the equipment showed it to perform well. The uniform nature of the flow, adjacent to the bed indicates that consistent, accurate and reproducible results can be expected from subsequent experiments. The flow profiles across the Trough further indicate that Wall Boundary Layer effects do not extend to the sample position.

The experiments carried out to investigate the effects of prolonged circulation, show heating of the water at all flow-rates. As expected, the greatest temperature increase was apparent at the highest flow rate. The maximum increase of 2.3$^{o}$C recorded over the 90 minutes is well within the tolerance range of most intertidal species. Indeed, this increase is probably within the limits experienced in the field as a consequence of annual and diurnal fluctuations coupled with tidal effects. For example, Cadee (1976) has shown temperatures at the sediment surface in the Dutch Wadden Sea to vary by as much as 25$^{o}$C in the course of a year.

Errors estimates have not been reported in the above three Flume studies. Results from my experiments show errors to be highest at low flow velocities and rates. In order to keep errors in the two measurements below 5 and 7.5% respectively, the following guidelines should be adopted -

Velocity - velocities should ideally be above 0.1 m/s (5 units on the meter)

Flow-Rate - Shallows Flows (0.05m) - Flow-rates should ideally be above 3 x $10^{-3}m^3/s$ (5 Divisions on the manometer)

- Deep Flows (0.25m) - Flow-rates should ideally be above 12 x $10^{-3}$ $m^3/s$ (40 Divisions on the manometer).

With due consideration, a wide range of flow conditions can be obtained - by varying depth and velocity - whilst maintaining tolerances within the above limits.

# SECTION 6

## THE INFLUENCE OF THE MARINE POLYCHAETE ARENICOLA MARINA ON SEDIMENT STABILITY AND RESISTANCE TO EROSION.

# INTRODUCTION

Studies in which equations have been developed to describe aspects of sediment erosion and transport have largely focused attention on purely physical aspects. For example, the criteria of Shields (1936); Miller et.al. (1977) and Yalin (1963) for determining the conditions necessary for the initiation of sediment motion only consider the following variables:

Liquid Viscosity
Liquid Velocity
Liquid Density
Sediment Particle Diameter
Sediment Particle Density

These criteria are empirically based upon the results of laboratory experiments on abiotic control sediments.

Differences between predicted and observed initiation of sediment motion in natural sediments are often attributed to biological effects, (Neumann et.al. 1970; Grant et. al. 1982; Eckman et. al. 1981 and Taghon et.al. 1984). These effects can be broadly classified as Stabilization and Destabilization. In the context of this study these terms are defined respectively as an increase or decrease of the critical value of the shear stress necessary to initiate sediment motion, relative to the theoretical abiotic value.

Biological stabilization processes have been reviewed by Lee and Swartz (1980). They include:

1) Microbial Binding - Micro-organisms release a diversity of organic compounds as extracellular products and by autolysis. These substances are viscid, viscous and elastic polysaccharides, (Martin, 1970; Frankel and Mead, 1973). They act as grain binders and cushions, and in so doing, effectively inhibit disruption of the sediment structure. Holland et. al.(1974) has demonstrated sediment stabilization by substances of this type produced by diatoms. Similar effects have been noted by Aspiras et.al. (1971) working with fungi, bacteria and streptomycetes.
2) The Presence of Animal Tubes, Rooted Aquatic Vegetation and other Biological Structures. - Dense populations of tubicolous species are known to stabilize sediments in two ways.

(a) By acting as reinforcing and in so doing physically binding the sediment and increasing its strength.
(b) By projecting above the sediment surface and thus reducing turbulence at the surface and increasing the thickness of the Boundary Layer.
Fager (1964); Lynch and Harrison (1970) and Shillaker and Moore (1978) have all reported increased sediment stability as a consequence of these effects.

Rooted aquatic vegetation functions in much the same way. Thus, Neumann et.al. (1970) has reported that mats of algae increased the resistance to erosion of a sediment surface. The same worker also draws attention to the binding effects of mucilaginous secretions produced by the algae.

Other biological structures, such as Corals, physically bind the sediment surface and deflect flow away from it, thus reducing erosion.

3) Modifications by Organisms to sediment Bulk Properties

Organisms are known to modify sediment bulk properties. Typical modifications resulting in increased stability include:

Reduced Moisture Content - this results in a tighter sediment structure in which frictional and cohesive forces are high. Kermack (1955) has observed water absorption from ingested sediment in the gut of *Arenicola marina*.

Aggregation - the aggregation of sediment into faecal pellets results in a structure which is more resistant to breakdown. This has been demonstrated by Taghon et.al. (1984) and Kraeuter (1976).

Sediment Mixing - the mixing of sediment particles of different sizes by biological activity results in a tightly packed structure which is resistant to deformation. Sediment mixing by *Arenicola marina* has been demonstrated by Baumfalk (1979).

Sediment Compaction - species are known to compact sediment in the walls of their burrows. In so doing, they stabilize the structure of the sediment. This has been demonstrated by Trevor (1977) for *Nereis diversicolor* and *Arenicola marina*. Attention has been drawn to the stabilizing effects of these burrows by Anderson and Meadows (1978).

Destabilization processes have been similarly considered. These include:

1) Increased Boundary Roughness - resulting from bioturbation activity - effectively reduces critcal Erosion Velocities by increasing turbulence and resultant frictional effects. This has been demonstrated by Grant et.al. (1982); Tevesz et.al. (1980) and Rhoads and Young (1971).

2) Modifications To Flow - resulting from the presence of animal tubes and other biogenic structures - may result in flow velocities exceeding the Critical value. The consequence of local scour around the structure, has been demonstrated by Eckman et.al.(1981) working with the tube-dwelling polychaete, *Owenia fusiformis*.

3) Modifications to Bulk Properties - the reworking of sediment and the production of faecal sediment material may reduce its Bulk Density. Erosion and suspension velocities are therefore, reduced as reported by Rhoads and Yound (1970; 1971) and Tevesz et.al. (1980). McMaster (1967) has noted similar effects on Bulk Density resulting from microbial activity.

It is only possible to determine if biological processes are stabilizing or destabilizing by performing controlled experiments. This is particularly so when both mechanisms are possible - for example, where stabilization or scour is dependant upon animal tube density.

This section reports the results of controlled laboratory flume experiments performed to investigate the effects of the polychaete *Arenicola marina* on sediment stability and resistance to erosion. The effects have been analysed quantitatively using fluid dynamics theory. The results are presented in the form of bed shear stresses which induce sediment movement. They have not been extended to include a consideration of Shields relationship. Had time been available, this would have been a logical step.

As far as I am aware, these experiments represent the first of their kind performed on this species. Attention is drawn to the significance of the results in view of the numerical dominance of this species on many intertidal shores.

# MATERIALS AND METHODS

## General Description of Experiments

The surface of a sediment sample, with and without A. marina casts present, was subjected to increasing flow velocities in the Flume. At the onset of surface and cast breakdown, vertical velocity profiles were measured over the sediment. These profiles were used, in conjunction with standard theoretical relationships from Fluid Dynamics theory, to calculate Bed Shear Stresses at the point of breakdown. The Stability and Resistance to Erosion of the sediment and casts was compared on the basis of these stresses.

## Preliminary Experiments to Test the Method

A.marina specimens and sediment samples were collected along Transect 'A'. In the laboratory the Flume Box Core was filled with the sediment and six A.marina specimens introduced.

Following burrowing of the worms below the sediment surface, the surface was levelled so that it was flush with the surface of the Trough base. With a flow depth of 150mm, the Flume was then switched on.

Flow velocities were increased by opening the Valve (V) until breakdown of the sediment surface was observed. Two stages were identified in the breakdown process -

1) Transport of loose organic debris over the surface at low velocities.
2) Breakdown of the sand surface at higher velocities.

Velocity profiles were recorded over the sediment on the centre-line of the Trough at both stages. Readings were taken, using the Velocity Measuring Device (VMD) at the following heights above the bed, 4, 8, 15, 25, 40, 55, 75 and 100mm.

The Flume was then switched off and the sediment surface relevelled. A. marina was then allowed time to produce its whorls of faecal sediment at the surface. The process of cast production usually took 6 - 12 hours during which time care was taken to ensure that the overlying water was kept well oxygenated. The resulting casts, (Plate 1) were, as far as

PLATE 1

Casts produced by *Arenicola marina* in the Flume Box Core.

Plate 1

could be observed, similar in all respects to those found in the field.

Once the cast had been formed, the experiment was re-run. This time, however, velocity profiles were measured at the onset of breakdown of each case. This process typically occured at higher velocities than in the previous experiment and took the form of large chunks of aggregated faecal material breaking off the main faecal pile.

Bed Shear Stresses at the three stages in breakdown; Loose Organic Bed Material (LBM); General Bed Breakdown (GBB); and Cast Breakdown (CB) were then calculated as follows:

(a) Velocity profiles were plotted on linear scales - See Figure 1.

(b) A plot of the theoretical relationship - described in Section 5 - between Flow Velocity (U) and Boundary Layer Thickness ($\delta$) shown in Figure 2 was then superimposed.

(c) The $\delta$ and U values at the intersection of the two plots (a, and b) were then fed into the formula of Blasius (1883-1970) in Massey, 1979) to calculate Bed Shear Stress ($\tau_0$) - See Figure 3.

The resulting values were plotted as histograms of their means, together with error estimates of one standard deviation.

<u>Definitive Experimental Design</u>

Two definitive experiments were performed to investigate in detail, the effects of <u>A. marina</u> on Sediment Stability and Resistance to Erosion. Sediment samples and specimens of <u>A. marina</u> were collected in March/April, 1984, from three sites on Transect 'A' - HWN, MT, and LWN. In both experiments velocity profiles were measured and shear stresses calculated using the methods previously described.

<u>Experiment 1</u> - To confirm the results of the preliminary experiment and to extend considerations to include:

(a) Differences which might be apparent in results obtained using sediment and worms collected from the three different positions on the shore.

FIGURE 1

Results of a preliminary experiment showing velocity profiles associated with the sequential breakdown of sediment surface structure.

The lines represent the replicate velocity profiles measured at each stage in the sequential breakdown of the sediment surface structure.

NOTE.

The theoretical velocity profiles have been calculated using the relationship:

$$U_y = \left(\frac{y}{\delta}\right)^{\frac{1}{5}} \quad \text{(Francis, 1979)}$$

Where $U_y$ = Velocity at distance 'y' above bed.

Um = Main stream velocity.

$\delta$ = Boundary layer thickness.

Sequential Breakdown Of Sediment Surface Structure.


Note: The dashed line identifies the 5th replicate General Bed Breakdown profile.
The lines shown thus —·— denote the theoretical velocity profiles base upon the mean Um and σ values calculate from Figure 4 (See calculation on facing page.)

## Fig. 2.

**Plot Of Theoretical Boundary Layer Thickness Versus Main Stream Velocity.**

Equation To The Line is ;

$$\delta = \frac{0{\cdot}37X}{(U_m X/\nu)^{1/5}} \times 100$$

Where; $X$ = Distance Down Flume. (m).
$\nu$ = Kinematic Viscosity. ($m^2 s^{-1}$).

# Fig.3.

## Sequential Breakdown Of Sediment Surface Structure.

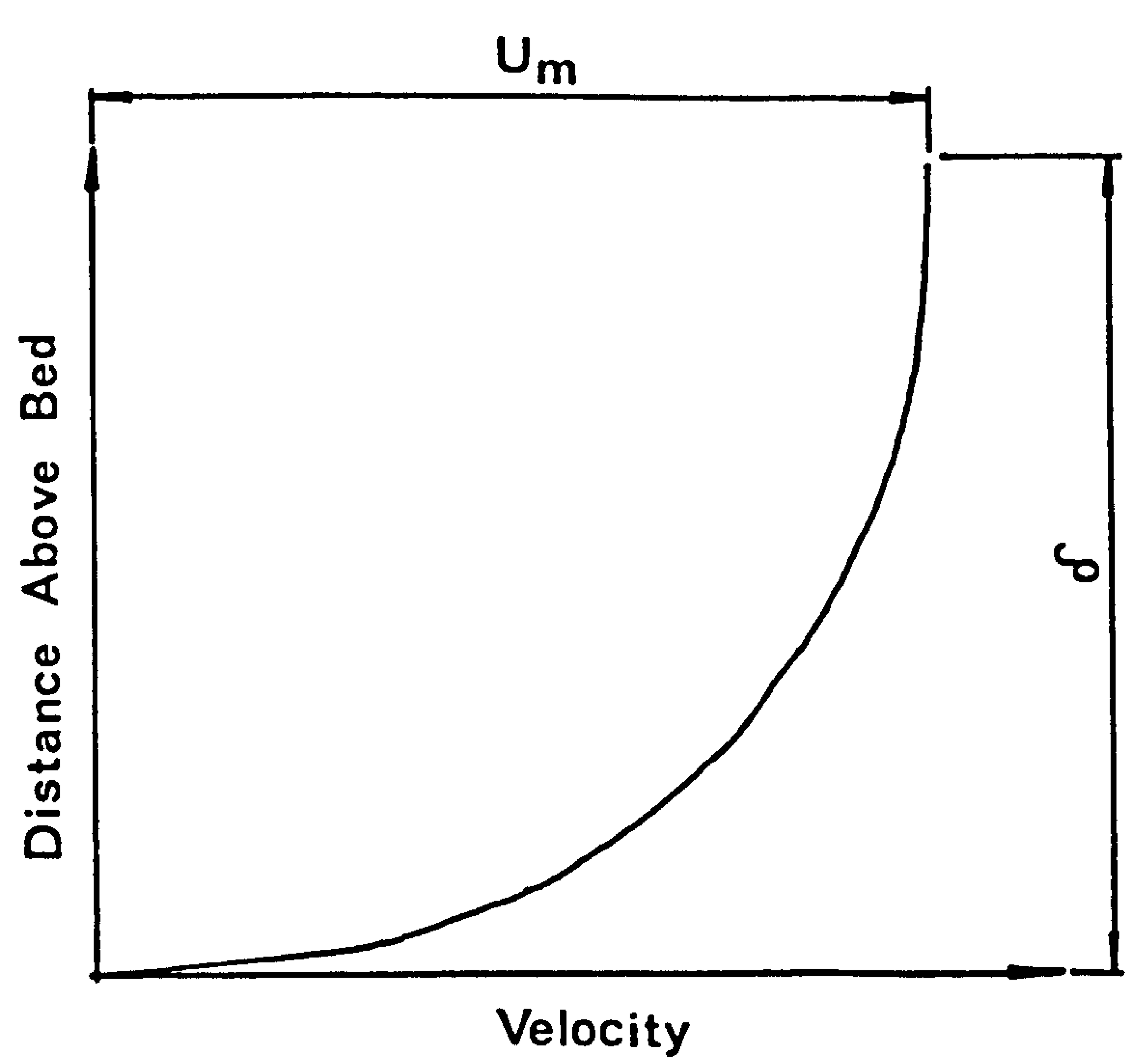
## Calculation Of Bed Shear Stress.

Formula-After Blasius.

$$\tau_o = 0{\cdot}0225 \rho U_m^2 \left(\frac{\nu}{U_m \delta}\right)^{1/4} \times \frac{1}{1000}$$

Where ;

$\tau_o$ = Bed Shear Stress (kPascals ≡ $kN.m^{-2}$)
$\rho$ = Seawater Density ($1025\,kg.m^{-3}$)
$U_m$ = Main Stream Velocity. ($m.s^{-1}$.)
$\nu$ = Kinematic' Viscosity. ($1 \times 10^{-6} m^2 s^{-1}$)
$\delta$ = Boundary Layer Thickness. (m.)



(b) An investigation of the possible consequences of variations in worm and cast size.

LBM and GBB shear stresses were determined for a sediment sample from one of the three sites. Worms collected from the same site were then allowed to produce their casts. Prior to erosion of these casts, the following dimensions were recorded:

(i) Basal Diameter.
(ii) Height from sediment surface to top of cast.
(iii) The diameter of the faecal cylinder (An index of worm size) = Cast Coil Diameter.
(iv) The position of the cast in the box core.

CB shear stresses were then determined.

This procedure was repeated until data was obtained for between 12 and 20 casts from each site. The results were then plotted and analysed as follows:

(a) Mean values and error estimates were plotted for the three shear stresses at each of the sites.
(b) GB and CB shear stresses were compared between the three sites.
(c) CB shear stress values were plotted against the following dimensions:
    1) Cast Height = (ii)
    2) Cast Coil Diameter = (iii)
    3) Cast area exposed to flow = (i) x (ii) ÷ 2.

Experiment 2 - To compare CB shear stresses calculated for real casts with those determined for 'artificial casts' of approximately the same geometry.

The data for twenty-one of the casts from the previous experiment was selected at random. Using the dimensions (i) and (ii), artificial casts were constructed of approximately the same geometry by pouring sediment onto the core surface in conical piles of the appropriate dimensions (Plate 2). The position of the casts was fixed using dimension (iv) above. CB shear stresses were then determined in exactly the same way as for the real casts.

PLATE 2

Artificial *Arenicola marina* casts.

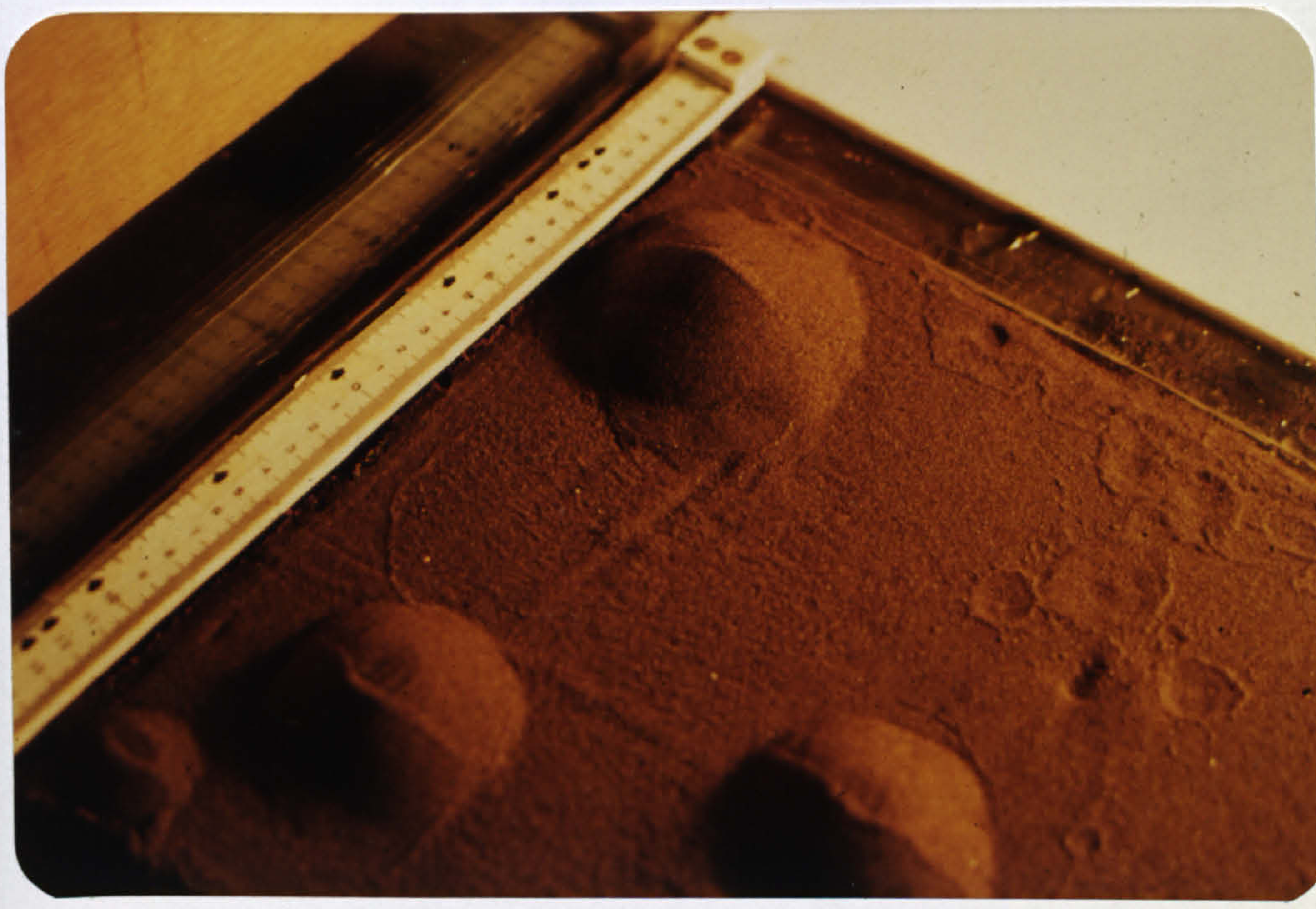


Plate 2

The resulting CB and previously determined GBB shear stress mean values and error estimates were then plotted for both 'Real' and 'Artificial' sets of data. The mean values were also plotted against Cast Height and Area Exposed to Flow on the same axes used in Experiment 1 (c).

## RESULTS

### Preliminary Experiments

Velocity profiles measured above the sediment surface at the onset of the three stages in breakdown are shown in Figure 1. The profiles are clearly non-linear and typical of the shape described by Massey (1979) for turbulent flow over a flat plate.

The plot of theoretical Boundary Layer Thickness versus Main Stream Flow Velocity is shown in Figure 2. This relationship is also non-linear - a consequence of the power function in the denominator of the equation.

The formulae used to calculate Bed Shear Stress, together with a description of the input variables is shown in Figure 3. Results of subsequent calculations using this formula are expressed in k.Pascals to render them compatible with units used in Section 2. (Shear Strength measurements.)

Results of the calculations are presented in Figure 4. They clearly illustrate the sequence in the breakdown of the surface structure. Typically the three stages occurred at the following Shear Stress values:

Loose Bed Material (LBM) - 0·00007 k.Pascals
General Bed Breakdown (GBB) - 0·00015 k. Pascals
Cast Breakdown (CB) - 0·00039 k. Pascals

### Definitive Experiments

#### Experiment 1

The results presented in Figures 5 and 6 confirm those from the Preliminary experiments. Shear Stresses are similar to those previously quoted. There are no significant differences in the results for samples from the three shore positions other than slightly higher GBB values for HWN.

The plots of Bed Shear Stress versus Cast Dimensions (Figures 7 to 9) show no obvious trends. Resistance to erosion does not therefore, appear to be a function of Cast Size. This observation is true for the data from each site and the data as a whole.

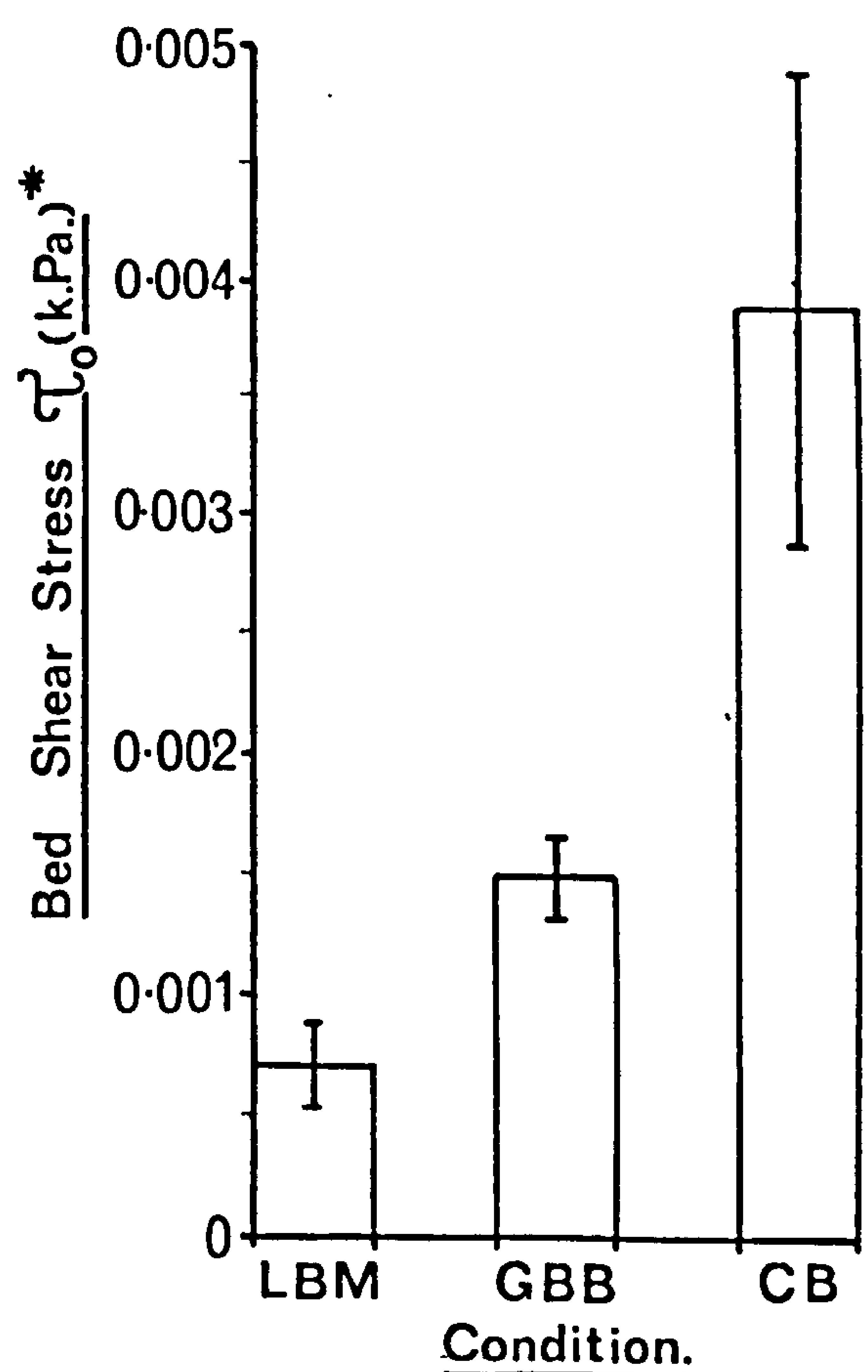
# Fig.4.

## Sequential Breakdown Of Sediment Surface Structure.

### Calculated Bed Shear Stresses.

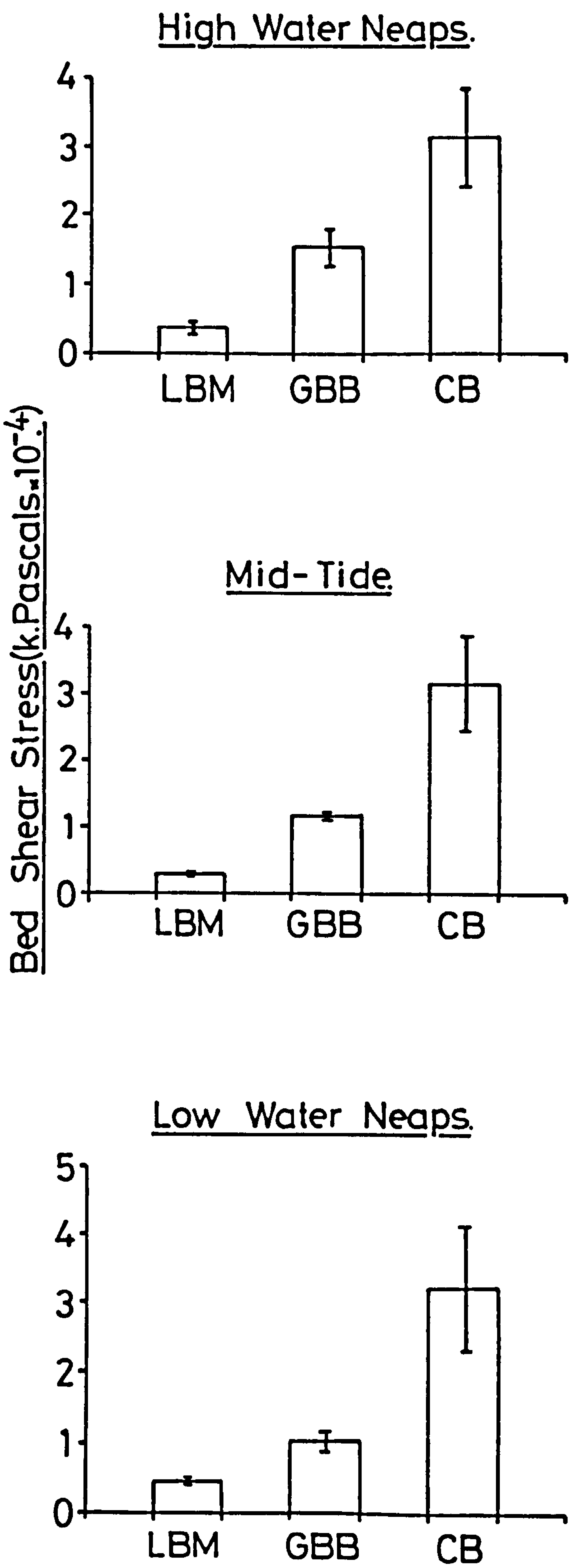
| CONDITION | $U_m$ (m.s$^{-1}$) | $\delta$ (m) | $\tau_o$ (k.Pa.)* | Mean* | S.D* |
|---|---|---|---|---|---|
| Loose Bed Material | 0·153 | 0·045 | 0·00058 | 0·00071 | 0·00018 |
| | 0·187 | 0·043 | 0·00084 | | |
| General Bed Breakdown | 0·232 | 0·041 | 0·00123 | 0·00150 | 0·00018 |
| | 0·254 | 0·040 | 0·00145 | | |
| | 0·256 | 0·040 | 0·00147 | | |
| | 0·268 | 0·0395 | 0·00160 | | |
| | 0·279 | 0·039 | 0·00172 | | |
| Cast Breakdown | 0·337 | 0·0375 | 0·00242 | 0·00389 | 0·00099 |
| | 0·380 | 0·0365 | 0·00301 | | |
| | 0·461 | 0·0355 | 0·00425 | | |
| | 0·461 | 0·0355 | 0·00425 | | |
| | 0·461 | 0·0355 | 0·00425 | | |
| | 0·514 | 0·035 | 0·00516 | | |

* ALL $\tau_o$ VALUES MULTIPLY BY 1/9·81



## Fig.5.

## Histograms Showing The Sequential Breakdown Of Surface Sediment Structure In Samples From 3 Sites.




Key.

LBM-Loose Bed Material Movement.

GBB-General Bed Break--down.

CB -Cast Breakdown.

Fig.6.

Histograms Comparing The Influence Of Arenicola marina Casts, Produced By Animals From Different Shore Positions, On The Stability Of Sediment From The Same Positions.

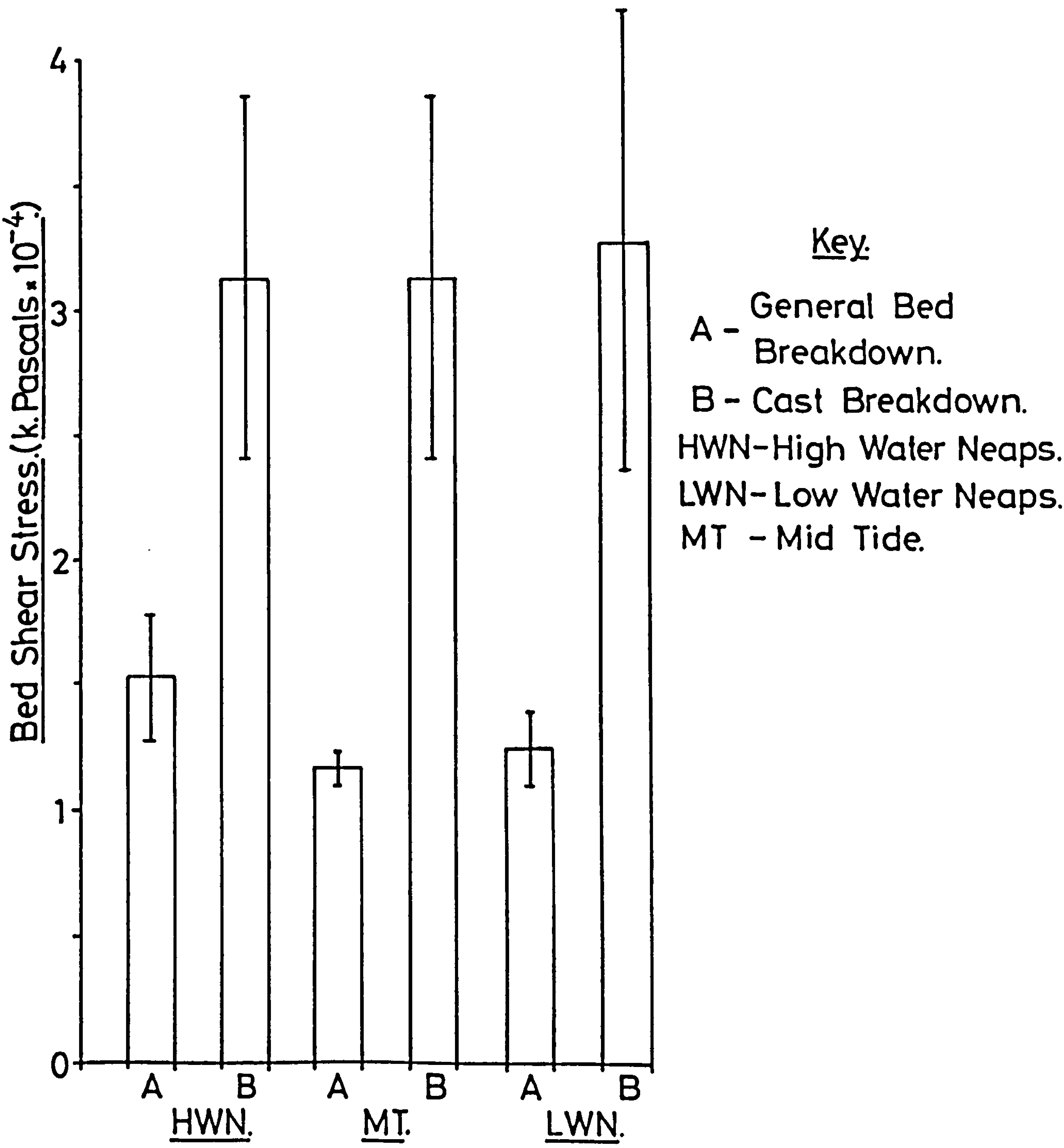


Fig.7. - Plot Of Bed Shear Stress At Point Of Breakdown For Real And Artificial *Arenicola marina* Casts versus Cast Height.

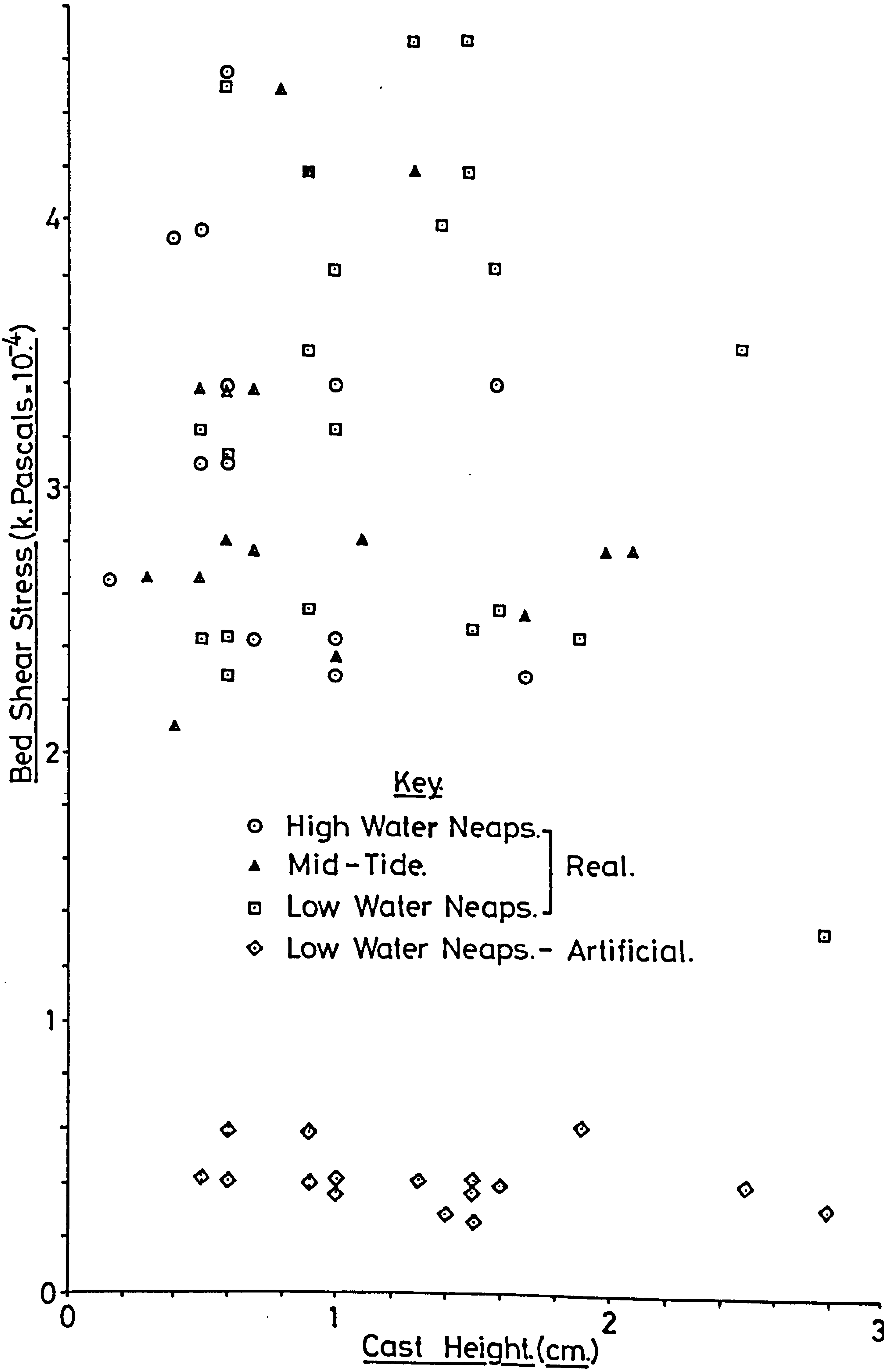


Fig. 8.- Plot Of Bed Shear Stress At Point Of Breakdown For Arenicola marina Casts versus Cast Coil Diameter.

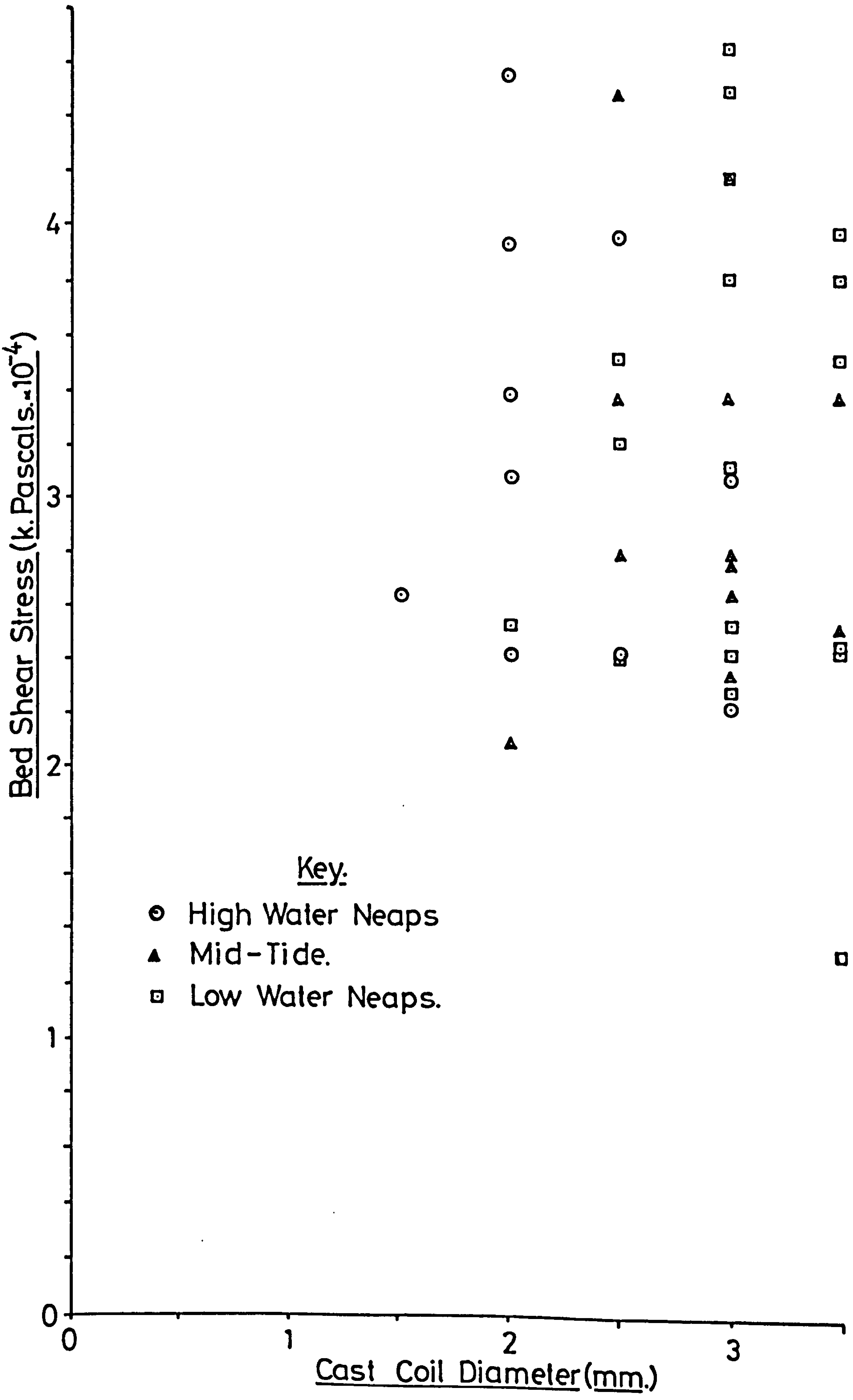
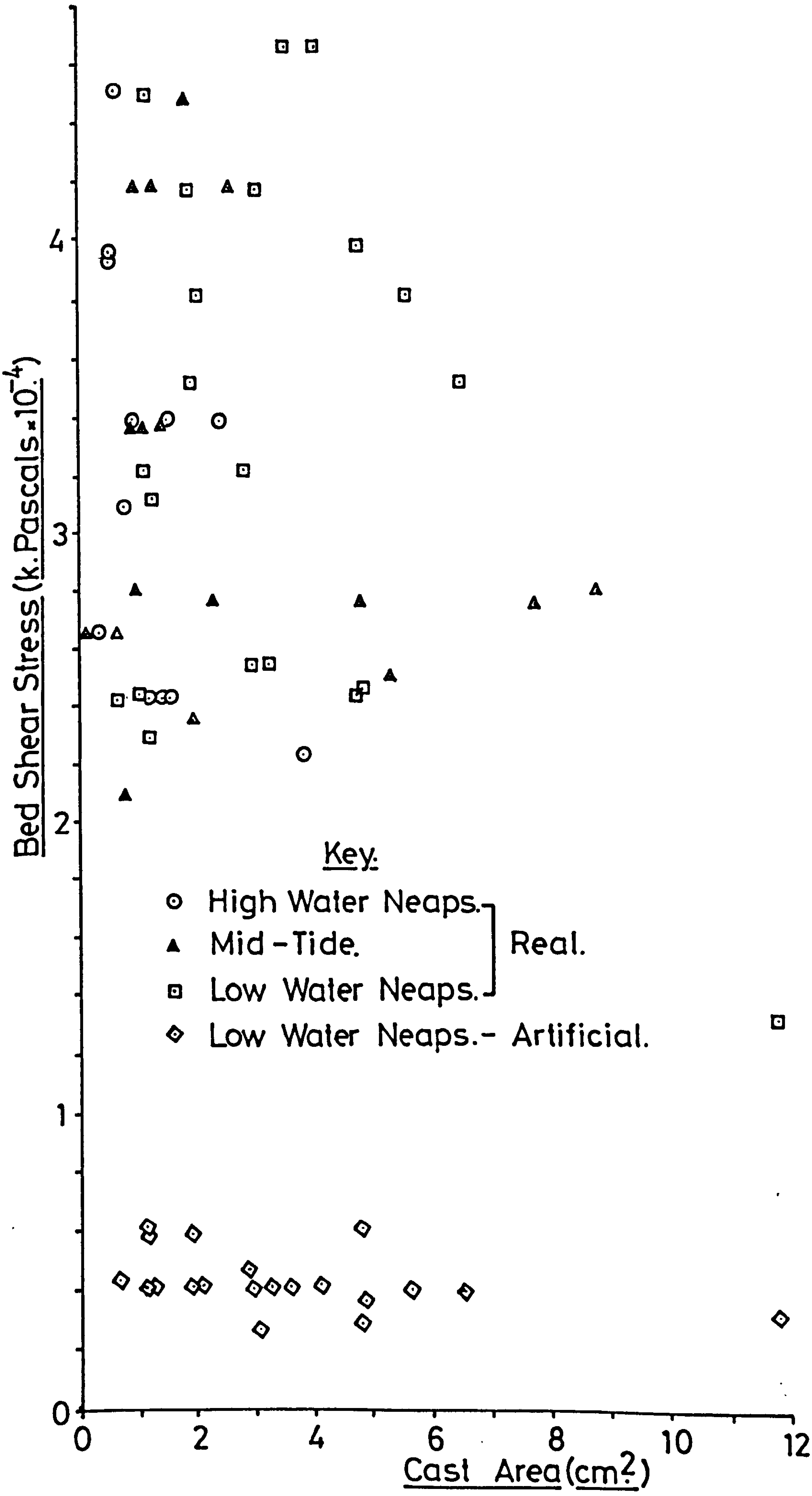


Fig.9.- Plot Of Bed Shear Stress At Point Of Breakdown For Real And Artificial *Arenicola marina* Casts versus Cast Area Normal To Flow Direction.



Experiment 2

The results of the experiment with 'artificial' casts are presented in Figure 10. The equivalent data for 'real' casts is also included.

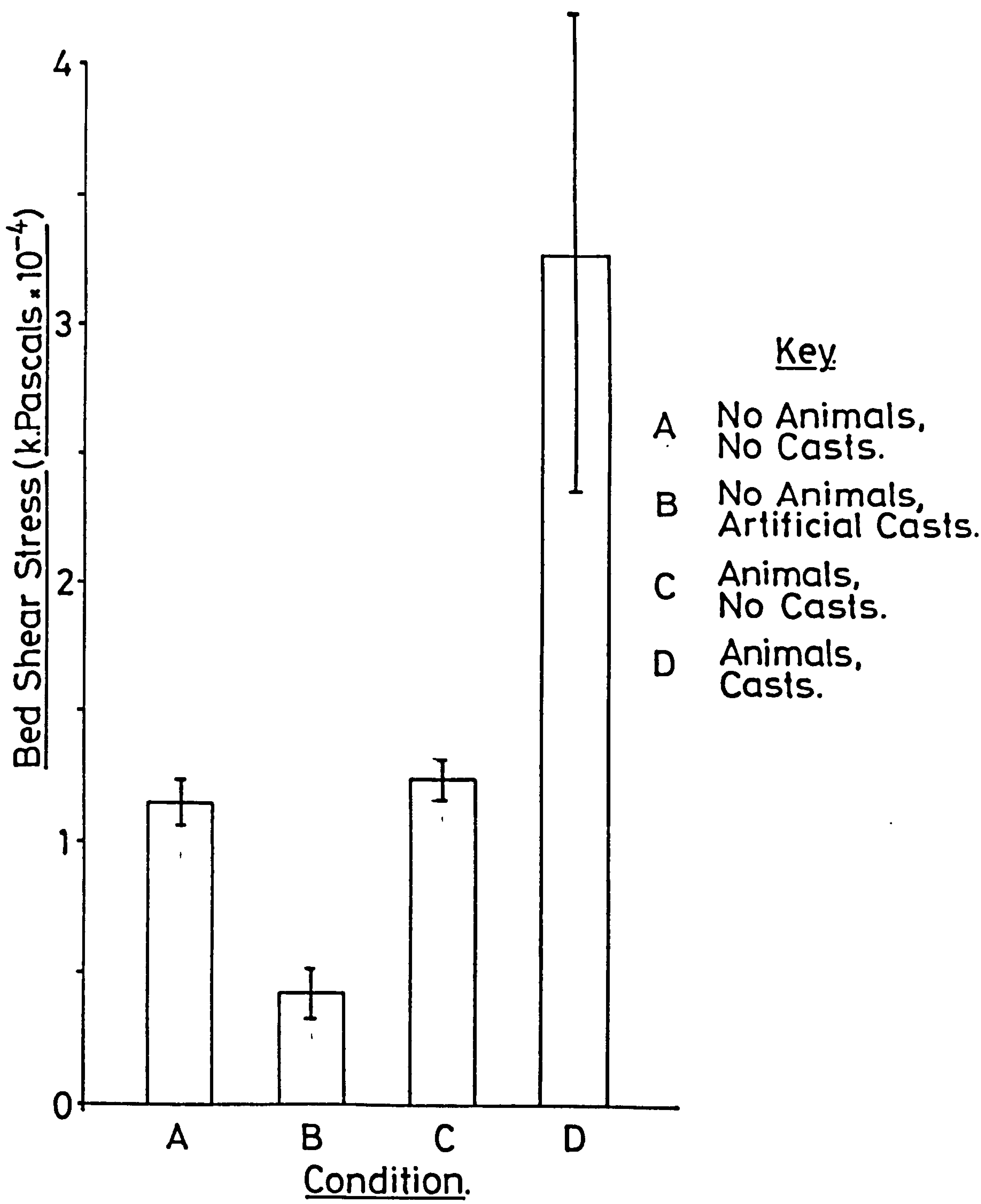
General Bed Breakdown (GBB) stresses are similar for both sets of data at approximately 0.00013 k.Pascals. Cast Breakdown (CB) stresses are, however, much higher for the 'real' casts ($>$ 0.0003 c.f $<$ 0.00005 k.Pascals). As a consequence, the CB values for the 'real' and 'artifical' casts are respectively higher and lower than the GBB value.

The CB values for the artifical casts, plotted against Cast Height and Area are shown in Figures 7 and 9. There is some indication of an inverse relationship between cast size and its resistance to erosion.

The general conclusion, therefore, is that casts produced by Arenicola marina have modified properties. These modified properties, compared with those of the original sediment, confer the cast with additional stability and resistance to erosion.

Fig. 10.

Histograms Comparing The Influence Of Real And Artificial Casts On Sediment Stability.



## DISCUSSION

The results presented in this section show that faecal sediment casts produced by Arenicola marina are more resistant to erosion than the surface of the sedimentary material from which they are derived.

The factors contributing to this increased resistance cannot at this stage be uniquely identified - a problem also noted by Grant et.al. (1982). The results indicate however, that changes in bed topography - a consequence of the physical dimensions of the casts - are not a contributing factor. Indeed, we might expect such changes to contribute to reduced stability as a result of the increased bed roughness. Although this was apparent with the 'artificial' casts, no such effect could be observed with the 'real' casts.

There are four other factors, already mentioned in the Introduction, which A. marina could be modifying with the result of enhancing the stability of the sediment. These are:

1) The addition of Binding Agents. In its passage through the gut of the worm, various metabolites are added to the sediment (Trevor, 1977). These substances are usually mucopolysaccharides or glycoproteins (Grant et.al. 1982). Uhlinger and White (1983), have shown a direct correlation between the critical erosion velocity of sandy sediments and their content of such substances.

2) The build-up of Microbial Metabolites. The metabolites mentioned in (1) above provide a source of nutrients which can be utilized by a range of micro-organisms including bacteria diatoms and blue-green algae, (Anderson and Meadows, 1978). Longbottom (1970), has shown that as a consequence, A.marina faeces are rapidly collonized.

The microbes release substances similar to those described in (1) as a consequence of autolytic and extracellular activity (Martin, 1970; Holland et.al. 1974; Frankel and Mead, 1973). The interstices between the sand grains are therefore filled, and the sediment structure bound. The unexpected strength of 'Gulf of Maine' surface sediments has been attributed to this effect by Hulbert and Given (1975).

3) Compaction of the Sediment Structure

Trevor (1977) has shown A. marina to be capable of exerting coelomic trunk pressures of at lease 6 k.Pascals during burrowing. These pressures, combined with those exerted by the gut during defaecation, will almost certainly result in some degree of compaction to the cast sedimentary material. With sediment shear strength known to be a function of compaction (Smith, 1980), a concomitant rise in shear strength, and hence, resistance to erosion is to be anticipated.

4) Reduction in Sediment Moisture Content.

A reduction in the moisture content of the sediment during its passage through the gut of A. marina has been noted by Kermack (1955). With the results of Trask and Rolston (1950) in mind, it would appear than an associated increase in the shear strength of the sediment is to be expected. Working with silts and clays, Trask and Rolston (1950) have demonstrated strength increases in excess of 100% associated with only a 5% reduction in sediment moisture content. Similar, although perhaps not quite so dramatic, effects can be expected with the medium to fine sand from Ardmore.

* * * * * * *

It is worth re-emphasising that the above four proposed stabilizing mechanisms are speculative. Future experimental work performed with a view to elucidating these mechanisms should yield results of considerable importance to the understanding of biological sediment stabilization.

The significance of bioturbation structures to other members of the sediment dwelling community has been discussed in the context of microenvironments by Anderson and Meadows (1978). The presence of Arenicola casts on what is otherwise a relatively uniform sediment surface must be included in such considerations. With their modified physical and chemical properties, they provide a niche - albeit temporary - which is open to exploitation by other species. I am not aware of any studies which have considered this aspect in detail.

The results of my experiments are particularly relevant to the general study area of the initiation of sediment

ADDITIONAL NOTE.

For abiotic sediments Shields(1936) determined a non-dimensional relationship between the density of the sediment ($\rho_s$), the grain diameter(D), the fluid density($\rho$), the shear stress of the fluid flow($\tau$), and the gravitational acceleration (g). Thus:

$$\frac{\tau}{(\rho_s - \rho)gD} = \frac{\rho U_*^2}{(\rho_s - \rho)gD}$$

Where $U_* = \sqrt{\frac{\tau}{\rho}}$ = Friction Velocity

The critical erosion shear stress for abiotic sediment of mean diameter 100µm. (the approximate size of sediments in my experiments) as determined from a graphical plot of this relationship (Miller et al,1977) is in the region of 0.00015 k.Pascals. This value compares favourably with the General Bed Breakdown value of 0.00013 k.Pascals determined for the Ardmore sediment.

movement. As noted earlier, traditional concepts make no allowance for adhesion of the sediment particles or other biogenic modifications. My results show that these modifications result in higher critical erosion velocities and stresses.

Subsequent transport of the faecal material has not been considered in these experiments. The production of aggregated material will however, undoubtably modify its transport and settlement characteristics. Taghon et.al.(1984) has considered these aspects in relation to faecal pellets produced by the deposit feeding polychaete Amphicteis scaphobranchiata. Aggregation into faecal pellets resulted in higher settling velocities. The distance travelled by the pellets was shown to be a function of their age - fresh pellets travelled furthest before disintegration.

Observations made during these experiments, showed modifications to flow-paths by the faecal casts to be responsible for two other important phenomena.

Firstly, acceleration of flow around the casts resulted in local scour on the up-stream side. This effect is similar to that reported by Eckman et.al.(1981) around the dwelling tubes of the polychaete Owenia fusiformis. This effect may possibly result in an apparent destabilization of this region.

Secondly, an accumulation of organic debris was noted in the lee of the cast. A similar effect has been noted in the field by Rhoads and Young (1971). Uncompacted organic faecal material was found accumulated between sediment mounds formed by the holothurian, Malpadia oolitica. Both observations can be attributed to the relatively still conditions prevailing in these regions which allow this material to settle-out. The implications of this phenomenom included the provision of a further exploitable habitat niche on an otherwise barren sediment surface. It is also probable that chemical reactions between the sediment and the overlying water will be affected.

# APPENDICES

## APPENDIX 'A' - SETTING-UP AND USE OF THEODOLITE

The Theodolite used in the transect survey is shown in Plates 1 and 2 (Section 1).

(i) Setting-Up (See Fig. 1 )

The Theodolite is set up on its tripod over a fixed reference point such that the position of the latter falls within the limits of adjustment of the instrument. It is then levelled accurately using the following technique The telescope of the Theodolite is positioned so that it lies directly over one footscrew and bisects the other two. (See Fig. 2 ). The footscrew lying below the telescope is then adjusted until the bubble in a spirit level mounted on the Theodolite is central. The telescope is then rotated so that it now lies vertically over one of the other two foot-screws. This is then adjusted to re-centralize the bubble. The process is repeated a number of times until no adjustment of the footscrews is required. The Theodolite should now be level to within one second of arc. The top section of the Theodolite can now be adjusted so that the vertical alignment site is centred on the fixed reference point (the nail head). The Theodolite is now ready for use.

(ii) Using the Theodolite to measure angles

The Theodolite can be used to measure both horizontal and vertical angles to the nearest second of arc.

Horizontal angles are measured by sighting the first object and then recording the angle indicated on the scale viewed through the horizontal angle scale eye-piece. Seconds are measured using the Vernier Scale. The top half of the Theodolite is then rotated about its vertical axis and the second object sighted. The horizontal angle is read again. The difference between the two recorded angles is the angle subtended between the first object, the fixed reference point and the second object. Occasionally one reading may fall above the $360^{o}$ mark and the other below. In this case the one below $360^{o}$ is subtracted from $360^{o}$ and the difference added to the one above. To avoid making mistakes it is advisable to look through the horizontal angle sight when rotating

## KEY TO FIGURE 1

HA = Horizontal Axis

VAMS = Vertical Angle Measuring Site

HAMS = Horizontal Angle Measuring Site

VAS = Vertical Alignment Site

FS = Foot Screw

VA = Vertical Axis

LA = Limits of Adjustment

NS = Nail Site

GS = Ground Surface

# Setting-Up And Use Of Theodolite.

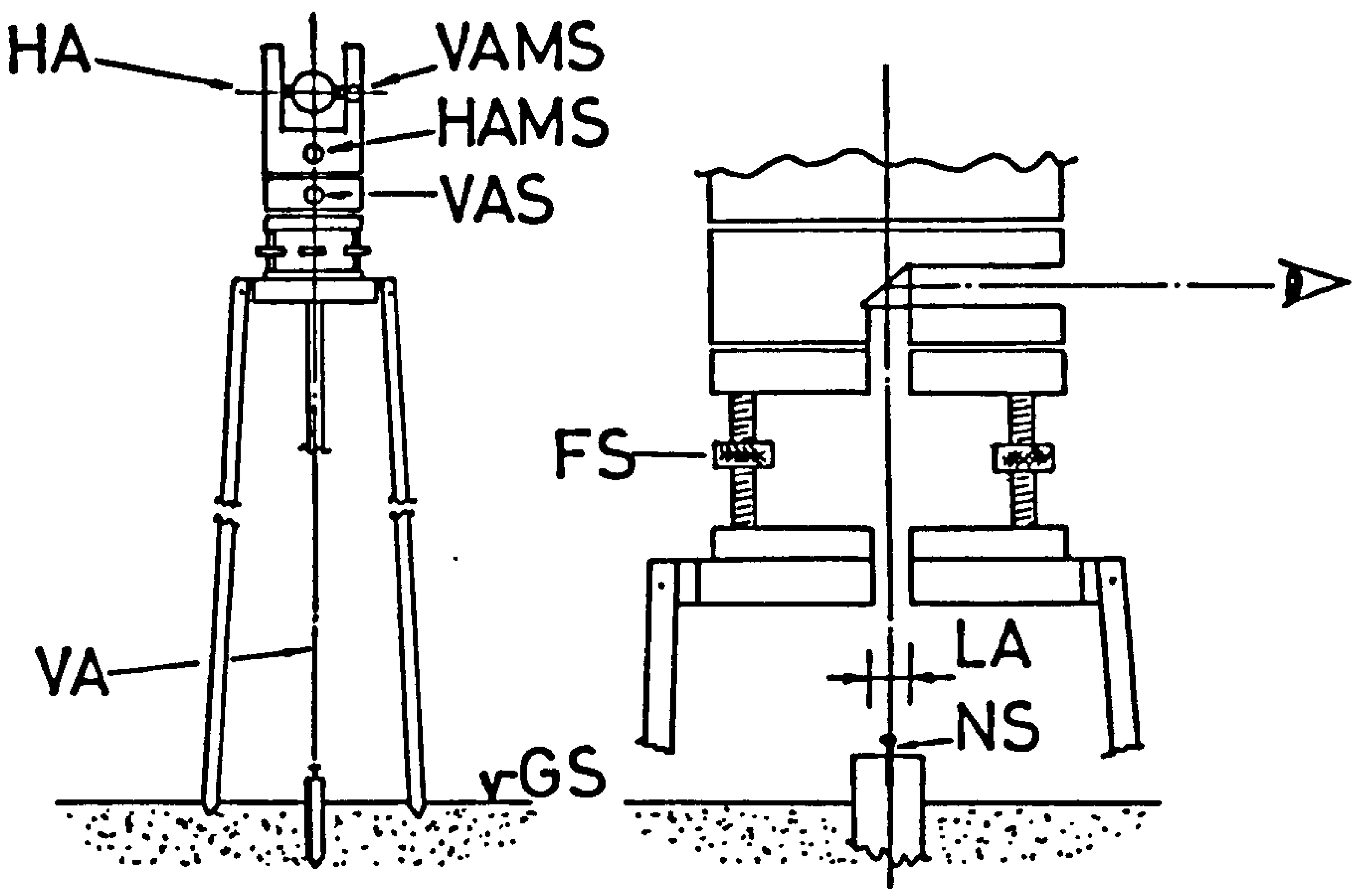



Figure. 1.

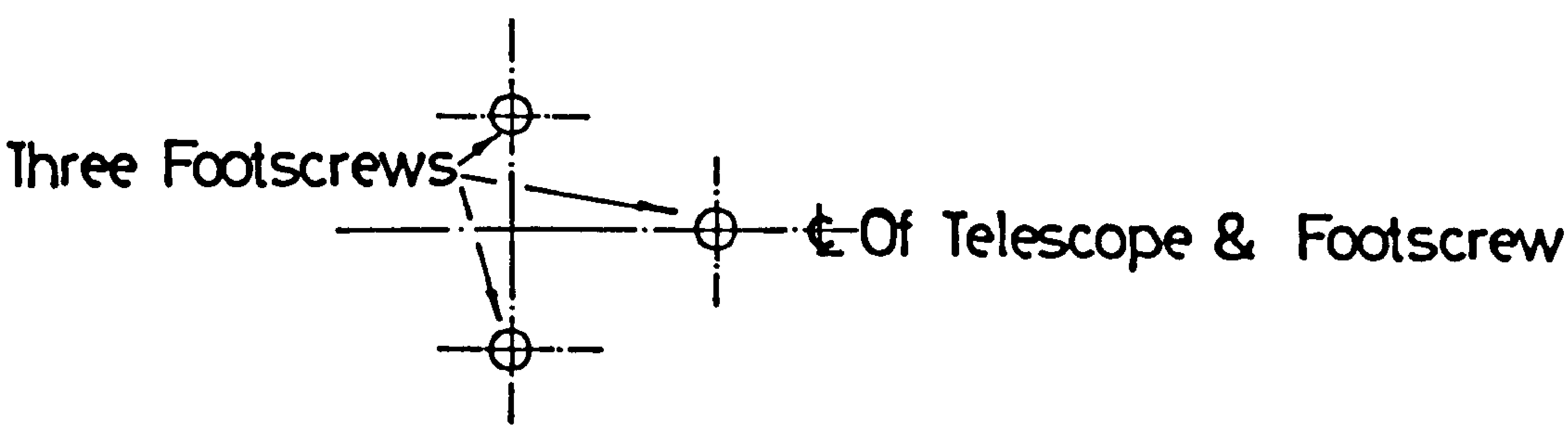



Figure. 2.

the Theodolite. If this is done, any overlap of the 360$^{0}$ mark is noted.

Vertical angles are measured similarly, except that the Theodolite is rotated about its horizontal axis and the angles read off through the vertical angle scale eye-piece.

In both cases it may be necessary to rotate the Theodolite about the other axis to the one being used to measure the angle, in order to sight the object.

## APPENDIX 'B' - SETTING-UP AND USE OF LEVEL

The Level used in the shore transect survey is illustrated in Plates 5 and 6 (Section 1).

### (i) Setting Up

It is essential that the Level is levelled accurately. The tripod on which is stands is levelled using the Spirit Level mounted on it. The level is then mounted on the tripod and levelled using its footscrews. (See Theodolite levelling, Appendix 'A'). The level is now ready for use.

### (ii) Errors

Failure to level the instrument accurately will result in Collimation Errors; these tend to increase or decrease the apparent distance from the ground surface to the true horizontal axis of the level (See Fig. 1 ). The magnitude of this error increases with distance from the level. The effects of collimation errors can be partially offset by positioning the instrument approximately mid-way along the line of points being levelled. The reasons for this are described below.

### The Effect of Instrument Positioning on Collimation Errors

(a) Setting up level mid-way between first and last point
(+ ve Error Case) See Fig.2

All points are subject to a collimation error. The size of the error increases with distance from the level.

However if $l_1 = l_2$ the error at point 1 = error at point 8.

The difference in level between 1 and 8 is therefore independant of error and equal to $h_1 - h_8$.

This technique does not eliminate errors in the intermediate points, i.e. 2 to 7. To eliminate these errors an exercise must be performed to determine the vertical error per unit distance away from the level.

(b) Level not set up mid-way between first and last point
(+ ve Error Case) See Fig. 3

$l_1$ does not equal $l_2$, therefore the error at point 1 does not equal the error at point 8. The difference in

# Levelling Collimation Errors.

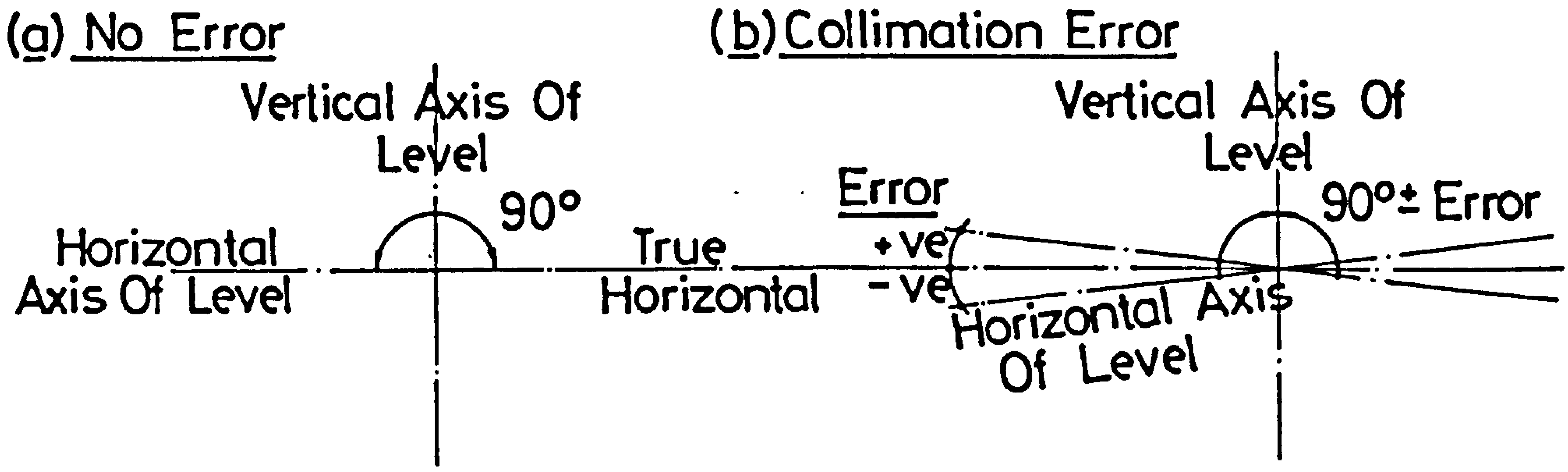



Figure .1.

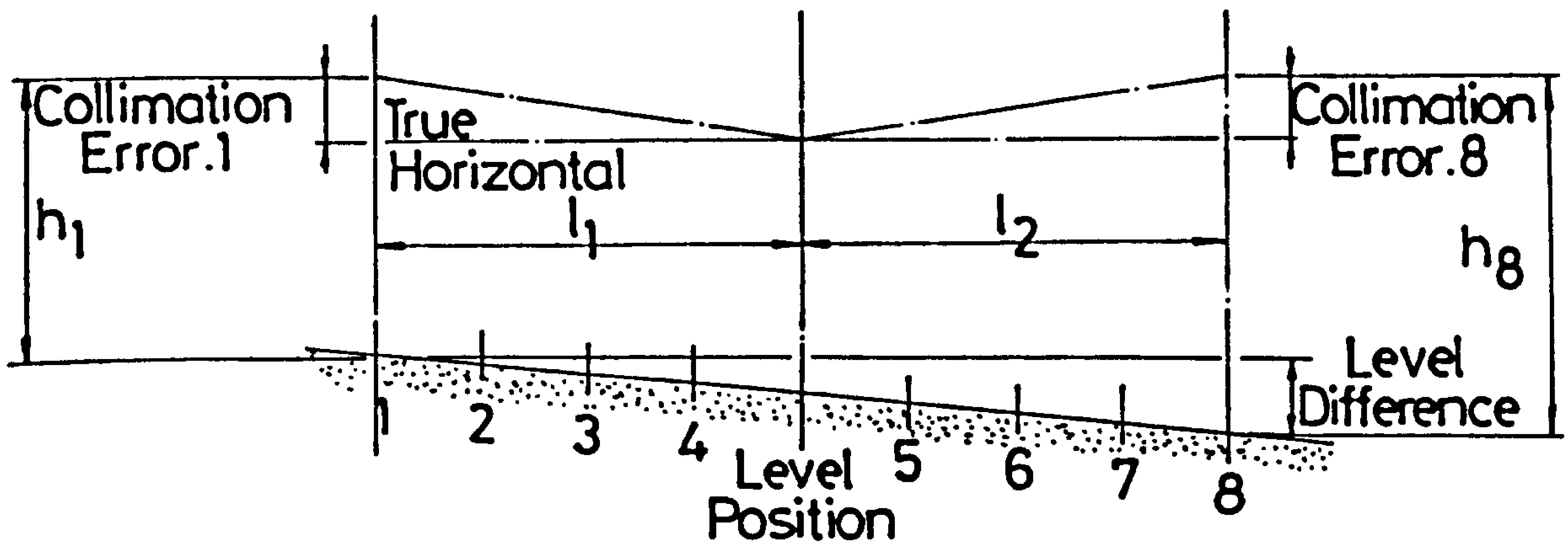



Figure .2.

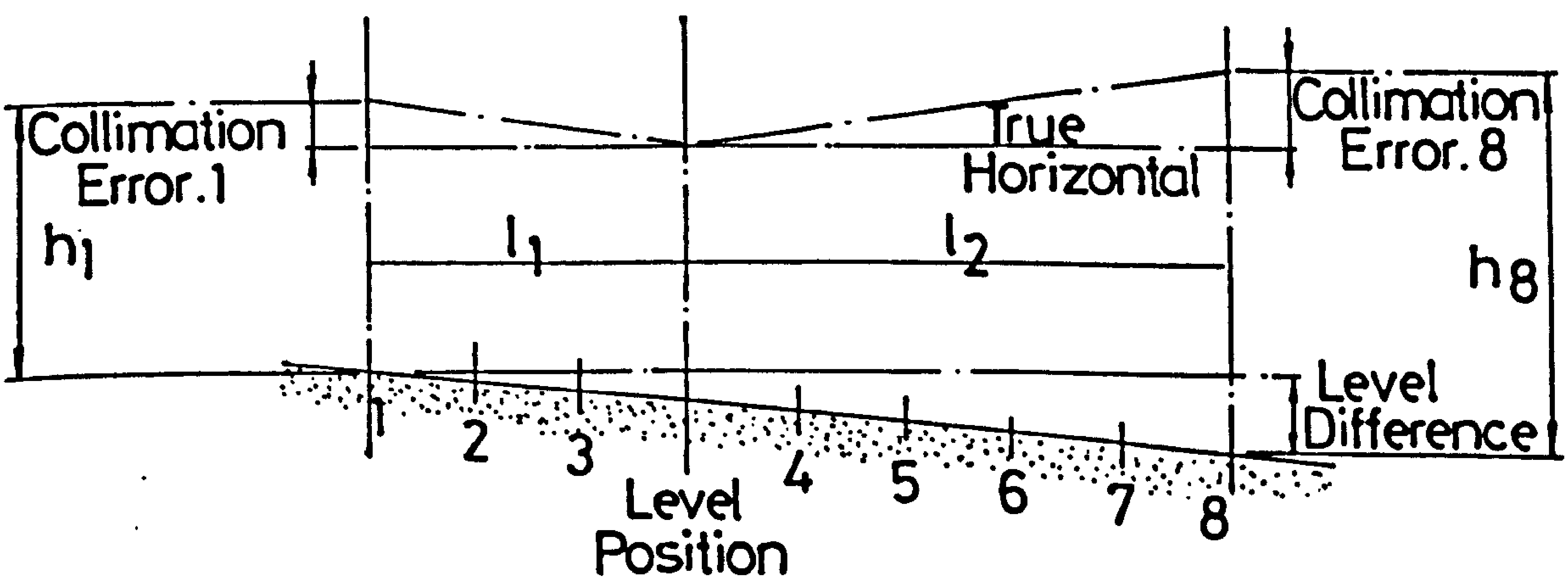



Figure .3.

level is therefore subject to error. Thus the true difference in level between 1 and 2 equals ($h_1$ - error 1) -($h_8$ - error 2) not $h_1 - h_8$ as previously.

If the correct result is to be obtained, an exercise to determine the magnitude of the errors at points 1 and 8 must be performed.

(iii) Using the Level to measure differences in height.

The Level is set up in the manner described previously. A staff (Plates 7 and 8, Section 1) is positioned on each point in turn. The distance from a horizontal line viewed through the telescope eye-piece to the ground surface is then read off the staff. The staff is graduated in half centimetres allowing measurements to this level of accuracy - or better at close range.

When levelling over long distances it is necessary to move the level. This avoids problems with reading the staff at long distances and ensures collimation errors are kept small. In this survey sighting distances between level and staff were kept below 100 yards.

Levels taken with the level set up in more than one position need to be related to each other. This is achieved by taking levels at the same point(s) from each level position. Both sets of readings therefore, have one or preferably more readings taken at a common point. The difference in level between the levelling stations can then be determined.

Table of Bench Marks

A table of Bench Marks for the Ardmore area, obtained from the Ordnance Survey is shown in Table 1.

## TABLE 1

A table of Bench Marks for the Ardmore area obtained from the Ordnance Survey.

# ORDNANCE SURVEY BENCH MARK LIST

BATCH 543 OS 678

BATCH 543 ALL BENCH MARKS ON THIS LIST FALL WITHIN KM SQ NS3278 DATUM NEWLYN PAGE 1

| DESCRIPTION OF BENCH MARK | NATIONAL GRID TEN METRE REFERENCE | ALTITUDE | | HEIGHT OF BM ABOVE GROUND | | DATE OF LEVELLING |
|---|---|---|---|---|---|---|
| | | FEET | METRES | FEET | METRES | |
| RIVET SEA WALL S SIDE TK PROD JUNC FENCES OPP | 3204 7834 | 11.24 | 3.43 | -1.9 | -0.6 | 1968 |
| LO N SIDE TK SE ANG S FACE | 3214 7864 | 21.32 | 6.50 | 1.0 | 0.3 | 1968 |
| BLDG ARDMORE FM N ANG NW FACE | 3259 7873 | 26.02 | 7.93 | 1.3 | 0.4 | 1968 |

APPENDIX 'C' - 'Pilcon Vane' Apparatus for Shear Strength Measurement - Assembly and Method of Use.

Assembly - The 'Pilcon Vane' is illustrated in Section 2. To assemble the instrument for use, the extension rods (if necessary) are screwed into the main body. The rod with the Vane is then screwed onto the end of these. All connections are tightened using the spanners provided.

Method of Use - The Vane of the instrument is inserted vertically into the sediment to the required depth. The pointer on the main body is zeroed on the scale. The main body is then rotated clockwise at a rate of approximately one revolution per minute about the axis of the Vane and extension rods. This induces a Torque about the Vane and a shearing action on the sediment. The magnitude of the Shear Stress is indicated directly by the position of a pointer on the scale. The scale is calibrated in k.Pascals.

To obtain the Peak Shear Strength of the sediment, rotation is continued at the above rate until shearing of the sediment takes place. The reading at which it stops represents the Peak Shear Stress attained.

Residual Shear Strength (Reworked) can then be measured by rezeroing the pointer whilst keeping the Vane in the same position. Rotation of the instrument until the pointer stops will then give a reading lower than the first, equivalent to the Residual Shear Strength.

Note Although Shear Strength is recorded against a given depth, the Vane actually records the Mean Shear Strength over a depth range of 2.5cm (the depth of the Vane.) Variations in Shear Strength within the depth of the Vane cannot therefore, be detected.

# APPENDIX D

## A Comparison of Peak Shear Strength Profiles Measured at The Three Reference Sites on Transect 'A' at High and Low Tide.

### Introduction

To investigate possible differences in Peak Shear Strength profiles measured on Flooded and Exposed shores,the following experiment was performed.

### Materials and Methods

At low tide, two peak shear strength profiles were measured at each of the three reference sites. The profiles were measured at depth intervals into the sediment of 5cm, to a maximum of 52.5cm.

At high tide, a further two profiles were measured at the same sites by workers wearing SCUBA diving equipment.

The resulting pairs of profiles were plotted on the same axes and compared.

### Results and Discussion

Figure 1 shows the profiles at each of the three sites. Surface sediments consistently exhibit the highest strength values at low water. The deeper sediments have similar strengths at both tidal levels.

The higher strength readings for the surface sediments at Low Water possibly reflects their partial drainage and lower moisture content. Holmes and Goodell (1964) and Trask and Rolston (1950) have both reported an inverse relationship between Shear Strength and Water Content.

Peak Shear Strength Profiles - Ardmore Transect 'A' 2/3.6.82

Profiles measured at low(▭) & high(▭) water.

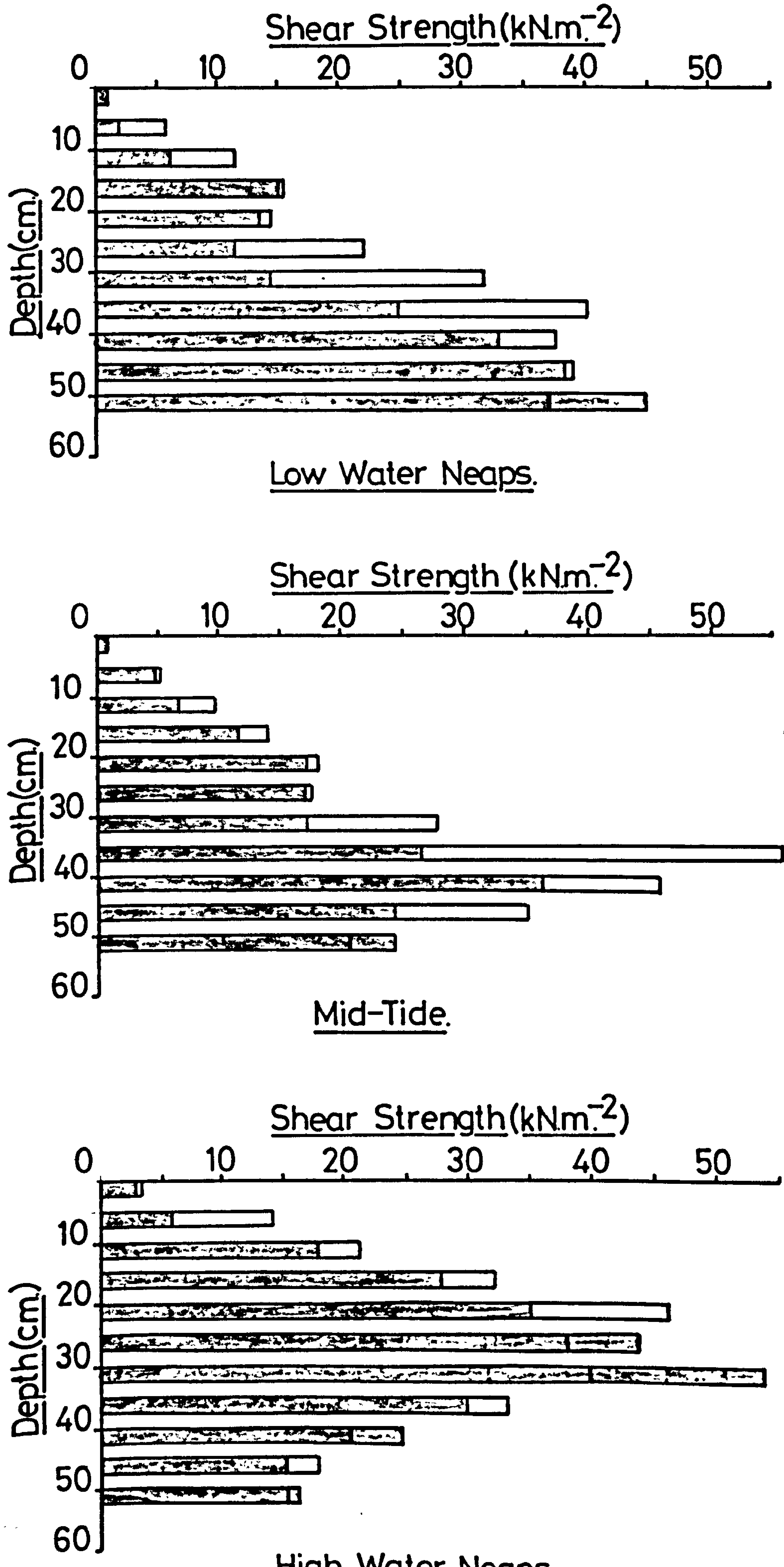



Figure 1

## APPENDIX E

## An Experiment To Determine a Method Of Estimating Arenicola marina Abundance

### Introduction

Although living virtually all its life below the sediment surface, Arenicola marina indicates its presence by whorls of faecal sediment (casts) at the excretory end of its 'U' shaped burrow. A count of these should result in a fairly accurate estimate of abundance. Physical extraction of the worms by digging should also allow an estimate of abundance to be made.

### Materials and Methods

Cast densities were counted within 10 quadrats placed randomly at each of three sites - HWN, MT and LWN. The area within each quadrat was then dug and the worms collected and counted.

### Results

Figure 1 shows the number of worms collected per unit area plotted against the number of casts present per unit area. The points lie about a straight line, the equation of which is:

No. of Casts Present = 1.75 + 1.295 x No. of Worms Collected

Correlation Coefficient = 0.949

$t = 15.0663$

$df = 25$

$p < 0.001$

### Discussion

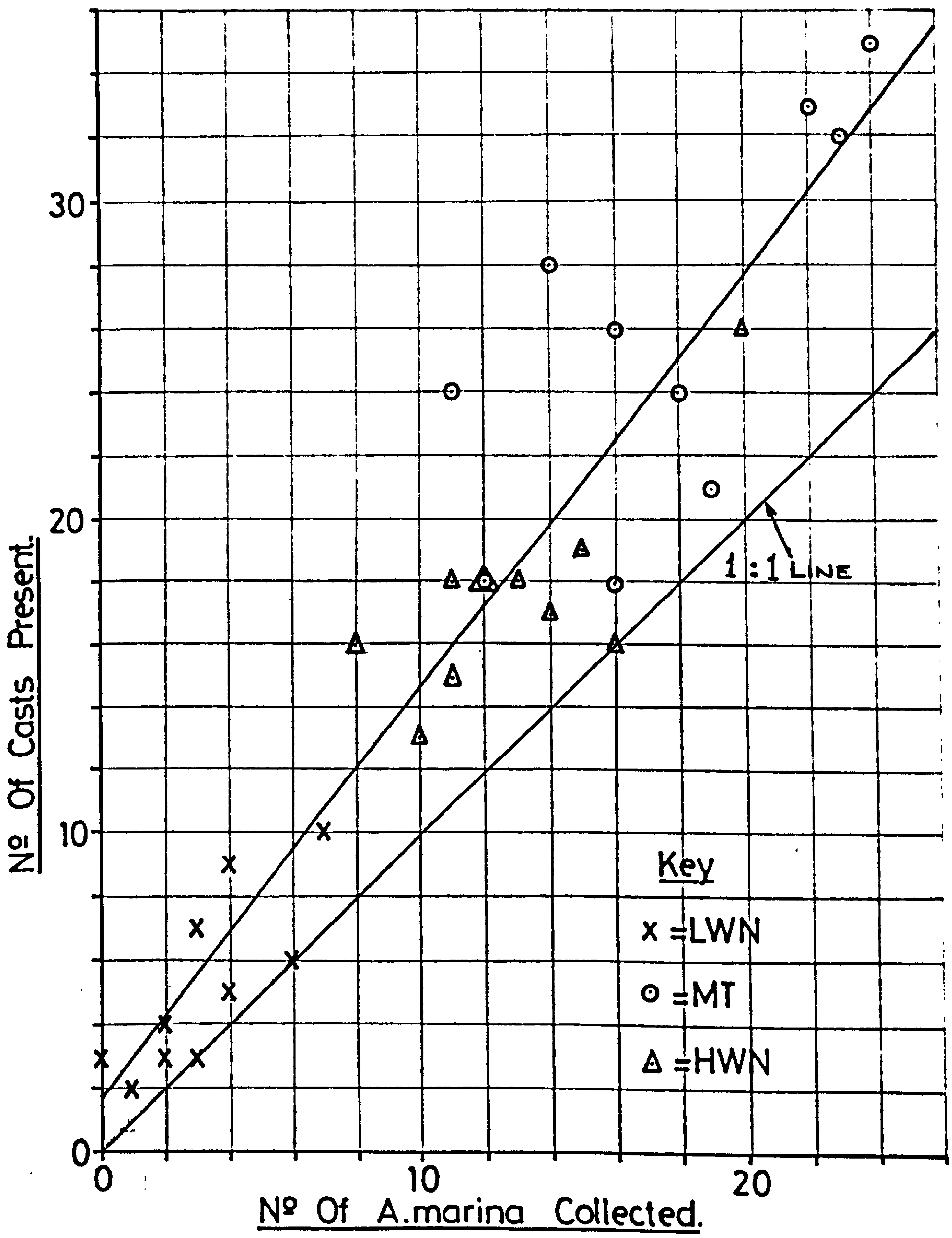
The results indicate a highly significant relationship between the number of *A. marina* collected by digging and the number of casts present on the sediment surface. The former method however, yields an estimate which is 27% lower than that obtained using the latter.

Both methods are likely to yield underestimates for the following reasons:

Digging:- it is extremely difficult to extract all the speci- in a given area.

Fig. 1.

Result Of Exeriment To Compare Methods Of Estimating Arenicola marina Abundance.



Cast Counting:- (i) Edge effects around the quadrat.
(ii) Cast destruction by water flow.
(iii) Failure of A. marina to produce casts.

The higher estimate abundance achieved by the Cast Counting technique would indicate that this method yields the best results. It also has the additional advantages of being non-destructive, fast and independant of the experience of the operator. A similar technique has been used by Longbottom (1970) and Cadee (1976).

## APPENDIX F

## An Experiment To Determine A Method Of Extracting Pygospio elegans and Fabricia sabella From Their Dwelling Tubes.

### Introduction

Pygospio elegans and Fabricia sabella are small intertidal polychaetes which live in tubes constructed from sediment particles. The tubes are located in the top 5cm of sediment.

Animal numerical density may be high, giving a 'Carpet Pile' appearance to the sediment surface when the interstitial sediment is washed away. Problems however, exist in estimating the density. It is insufficient to count the tubes contained in a sample as these are often branched and broken. Direct counting of the animals within the tubes is possible but very labourious.

With these problems in mind, a method of extracting the animals from the tubes was required which would then allow easy counting. A fellow worker observed that P. elegans exhibited negative phototaxis. F. sabella was found to behave similarly. It was thought that this attribute could be used as a means of extracting these species from their tubes. The following experiment was therefore, performed to confirm this.

### Materials and Methods

Six clear plastic boxes were obtained of the following sizes:-

Three - 11.5 x 17.5 x 5.0 cm.

Three - 16.0 x 28.0 x 10.0 cm.

1cm square grids were marked on the bases of the three smaller boxes. One of the larger boxes was made light-proof by lining the inside with silver paper and spraying the outside with black paint.

The dark box and one of the large clear boxes had a water supply and overflow system fitted. The purpose of this was to allow any heat build-up within the larger container to be transported away from the smaller container which was placed inside. The absence of this water supply from the other large container was used as a control to ensure that light and not heat was the cause of animals leaving their tubes. Thermometers were located at the front and rear of the large containers to monitor this effect. A fluorescent strip light was used as a light source to minimize heating effects. The experiment set-up is shown in Figure 2 (Section 3)

To perform the experiment the smaller containers were filled with seawater and tubes containing both species placed in them. The tubes were distributed evenly in the half of the container closest the light source. At time intervals of 1, 2, 3, 21½ amd 67 hours the boxes were examined and any animals contained in the half of the box away from the light source removed and counted.

At the end of the experiment, the tubes were dissected and any animals remaining in the tubes collected and counted.

## Results

Figure 1 shows the number of animals extracted in each container over the duration of the experiment expressed as a percentage of the total number of animals present. (Final number extracted + Those remaining in their tubes.)

Numbers extracted in the light container are much higher than those in the dark container. Results for the two light containers are similar and indicate that after a period of 24 hours virtually all the animals have been extracted from their tubes.

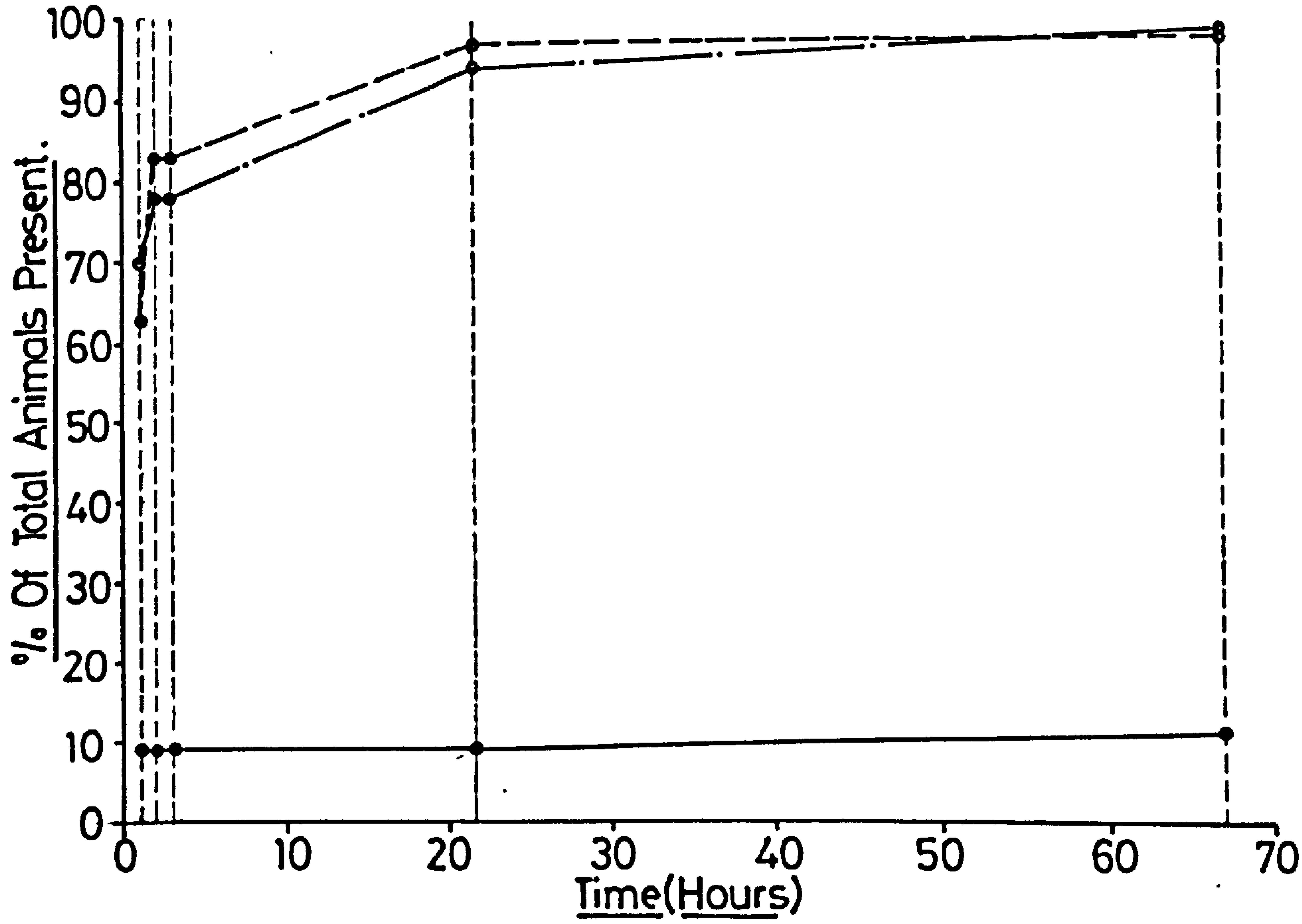
## Discussion

The method of extraction described above would appear to be suitable for extracting P. elegans and F.sabella from their dwelling tubes. Results indicate that after an extraction period of 24 hours virtually all animals in the sample are accounted for.

Fig. 1.

Results Of Pygospio elegans and Fabricia sabella

Extraction Experiment.




Key.

—— Dark Container.

– – – Light Container Without Cooling.

–·– " " With " .

## APPENDIX G

**Experiments To Determine The Optimum Core Diameter and Depth For Sampling The Remaining Macroinvertebrate Species.**

### Introduction

Core samples have been used by many workers to sample quantitatively the fauna of sediments.(Dale,1974 ; Grant,1981 and Fager,1964). Core size has two dimensions:
(a) Diameter - determines the surface area of the sediment sampled. It is important in identifying the small scale and overall horizontal distribution patterns of species.
(b) Depth - is important when considered in conjunction with the vertical distribution of a species. A depth value should be selected which ensures that all individuals within the sediment profile can be sampled.

Selection of appropriate values for these dimensions is a critical step in the design of a sampling programme. This appendix contains the results of two preliminary experiments carried out along Transect 'A'. The first was conducted along the lines of Gray (1971) and was used to determine the optimum core diameter from a selection of three available sizes - 5.1, 8.0 and 10.7cm. The second experiment was designed to determine the minimum coring depth necessary to sample the species present. Depths to a maximum of 42.5cm were considered.

### Materials and Methods

#### (a) Selection of Optimum Core Diameter

A 1m square quadrat was positioned at each of three sites down the shore - High Water Neaps (HWN), Mid-Tide (MT) and Low Water Neaps (LWN). The area within each quadrat was then divided into 16 - 0.25 x 0.25m 'sub-quadrats'. These were numbered 1 - 16 and then eight selected using a table of random numbers.

Within each of the selected sub-quadrats, three cores - one of each size - were taken to a depth of 15.0cm. Each core was then placed in a separate labelled plastic bag.

In the laboratory the samples were sorted and the species identified and counted using the techniques described in Section 3 (3).

The criteria upon which the optimum core diameter was to be decided on were as follows:

(i) The core diameter which gave the highest estimate of animal numbers expressed as a mean of the eight samples of each core size at each site.

(ii) The diameter which gave the lowest error to the mean values calculated in (1).

(iii) Should (i) and (ii) prove to be inconsistent for all three sites, then that diameter which yields consistent results for either (i) or (ii) over the majority of the shore. In making this decision it was decided that MT and LWN were most typical of the shore.

(iv) If two diameters yielded similar results, then the smallest one in order to reduce the work load.

It was initially decided that interest centred on all the species present rather than a few selected ones. Thus in any analysis of the data total animal numbers were used. A flow diagram illustrating the logic behind the statistical analysis of the data is shown in Figure 1 .

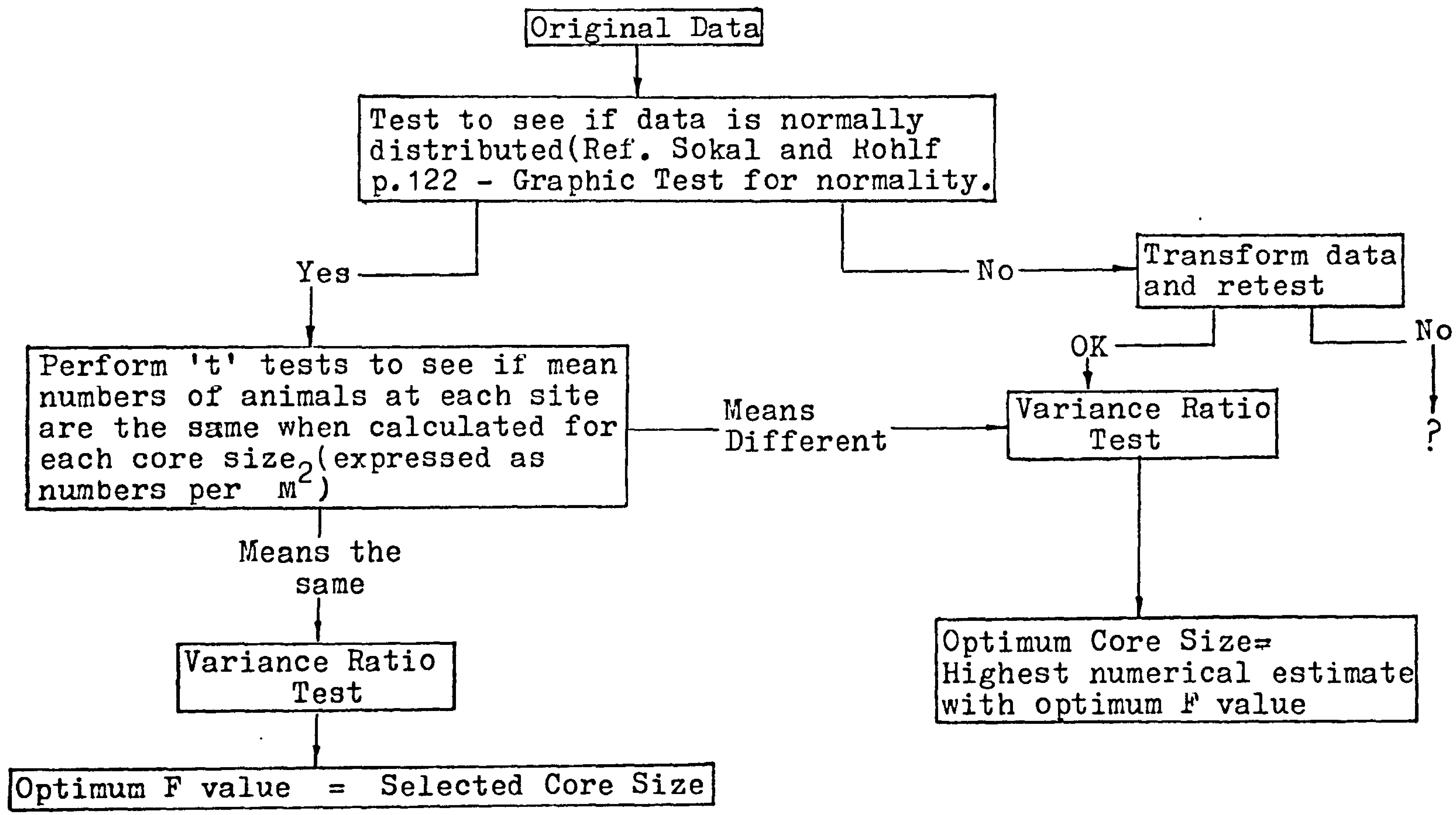
(b) Selection of Optimum Core Depth

At each of three sites, HWN, MT and LWN, two cores 8.0cm diameter were taken to a depth of 42.5cm. Each core was divided up as follows: 0-2.5cm and then in intervals of 5.0cm to maximum depth. Each section was placed in a separate labelled plastic bag. Sorting, identification and counting were as for (a).

The criterion upon which the optimum depth of coring was to be decided was as follows - That depth within which it could reasonably be assumed that all individuals of the species being sampled would be contained. The decision was made by a visual inspection of the data.

# FIGURE 1

## Flow Diagram Illustrating Logic Behind Statistical Analysis of Core Diameter Selection Data



# Results

## (a) Selection Of Optimum Core Diameter

The raw data is shown in Tables 1 , 2 and 3 Figures 2 , 3 , 4 , 5 , 6 , and 7 , show the results of Graphic Rankit tests of Normality for the data. The best fit to normality is obtained using the untransformed data at MT and LWN. A $Log_{10}$ transformation gives the best fit at HWN.

Table 4 shows the results of 't' tests. These show there is no significant difference in the Mean Number of Animals per metre$^2$ at each site as calculated using the data from the three core sizes.

Table 5 shows the results of 'F' tests to determine the core size giving the lowest error (variance) to the estimate of animal density. Significant differences in variance are evident between the Medium and Large cores at MT and the Small and Medium,and Small and Large cores at LWN.

## (b) Selection Of Optimum Core Depth

The raw data is shown in Table 6 . No animals were present in the samples below a depth of 12.5cm.

# Discussion

## (a) Selection of Optimum Core Diameter

On the basis of the criteria set out initially, the large core was chosen as the optimum size. The reasons for this are as follows:-

(1) No significant difference is apparent in the mean number of animals per metre$^2$ when calculated using the data for the three sizes.

(2) The large core gives a significantly lower variance at two of the three sites. This satisfies the second criterium.

## (b) Selection of Optimum Core Depth

The data shows that all the animals sampled were contained within the upper 12.5cm of the core. A sampling depth of 22.5cm was therefore chosen for subsequent work.

TABLE 1

Data For Selection Of Optimum Core Diameter

HIGH WATER NEAPS

| Core Size (cm) | Species Sample | *Macoma balthica* | *Hydrobia ulvae* | *Cardium edule* | *Corophium volutator* | *Scoloplos armiger* | *Nephthys hombergii* | Oligochaete species | Diptera Species larvae | Micrura species | Total Animals |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5.1 | 1 | | 2937 | | | | | 2448 | | | 5385 |
| | 2 | | 5874 | | | | | 979 | | | 6853 |
| | 3 | | 1958 | | | 979 | | 1175 | | | 4112 |
| | 4 | | 3916 | | | | | 979 | | | 4895 |
| | 5 | 490 | 6853 | | | | | 490 | | | 7833 |
| | 6 | | 8811 | | | | | 490 | | | 9301 |
| | 7 | | 2937 | | | | | 3916 | 490 | 490 | 7833 |
| | 8 | 490 | 8322 | | | | | 2937 | | 490 | 12239 |
| 8.0 | 1 | | 4974 | | | 199 | 199 | 11340 | 199 | 398 | 17309 |
| | 2 | | 5570 | | | | | 1393 | | | 6963 |
| | 3 | | 1790 | | 398 | | | 1989 | | | 4177 |
| | 4 | | 1989 | | | | | 3581 | | | 5570 |
| | 5 | | 1592 | | 398 | | | 12931 | | | 14921 |
| | 6 | | 5769 | 199 | | | | 4178 | | | 11340 |
| | 7 | | 3183 | | | | | 4178 | 995 | 199 | 7361 |
| | 8 | 398 | 7162 | | | | | 4775 | 597 | 199 | 13131 |
| 10.7 | 1 | 111 | 3447 | | 222 | | | 5783 | | | 9546 |
| | 2 | | 5783 | | | | | 1891 | | 222 | 7881 |
| | 3 | | 4004 | | 556 | | | 1335 | | 222 | 6105 |
| | 4 | 111 | 4560 | | | | | 3559 | | 222 | 8436 |
| | 5 | | 4226 | | | | | 334 | | | 4551 |
| | 6 | 111 | 11566 | | | | | 2224 | 556 | 334 | 14763 |
| | 7 | | 5227 | | | 222 | | 890 | | 111 | 6438 |
| | 8 | 334 | 3336 | | | | | 890 | | | 4551 |

Table.1.

# TABLE 2

## Data For Selection Of Optimum Core Diameter

## MID-TIDE

| Core Size (cm) | Species / Sample | *Hydrobia ulvae* | *Bathyporeia pilosa* | *Scoloplos armiger* | *Nephthys hombergii* | *Nereis diversicolor* | *Etione longa* | *Oligochaete species* | *Total Animals* |
|---|---|---|---|---|---|---|---|---|---|
| 5.1 | 1 | | | | | | | | 0 |
| | 2 | | | | | | | | 0 |
| | 3 | 490 | | | | | | | 490 |
| | 4 | | | 490 | 490 | | | | 980 |
| | 5 | | | | | | | 490 | 490 |
| | 6 | | | | 979 | | | | 979 |
| | 7 | | | 490 | | | | | 490 |
| | 8 | | | 979 | | | | | 979 |
| 8.0 | 1 | | | 199 | 597 | | | | 796 |
| | 2 | 398 | | | 199 | | | | 597 |
| | 3 | | | | | | | | 0 |
| | 4 | | | 398 | 199 | | | | 597 |
| | 5 | 199 | | 199 | 199 | 199 | | 199 | 995 |
| | 6 | 398 | 199 | 398 | 199 | 199 | | | 1393 |
| | 7 | | | | | 199 | | | 199 |
| | 8 | | | | | | | | 0 |
| 10.7 | 1 | | | | | | | | 111 |
| | 2 | | | 444 | 111 | | | | 555 |
| | 3 | | | | 111 | | | | 111 |
| | 4 | | | 556 | 111 | | | | 666 |
| | 5 | 111 | | 222 | 222 | | | 111 | 666 |
| | 6 | | 111 | | 111 | 111 | | | 333 |
| | 7 | | | | | 111 | | | 111 |
| | 8 | | | 222 | 222 | | | | 444 |

**TABLE 3**

**Data For Selection Of Optimum Core Diameter**

**LOW WATER NEAPS**

| Core Size (cm) | Species / Sample | *Macoma balthica* | *Hydrobia ulvae* | *Cardium edule* | *Corophium volutator* | *Scoloplos armiger* | *Nephthys hombergii* | *Nereis Diversicolor* | *Etione longa* | *Etione picta* | *Choetozone species* | *Oligochaete species* | Total Animals |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5.1 | 1 | | | | | | | | | | | | 0 |
| | 2 | | | | | 490 | | | | | | | 490 |
| | 3 | | | | | 979 | | | | | | | 979 |
| | 4 | | | | | 979 | | | | | | | 979 |
| | 5 | | | | | | | | | | | | 0 |
| | 6 | | | | | | | | | | | | 0 |
| | 7 | | 490 | | | 490 | 979 | | | | 490 | | 2449 |
| | 8 | | | | | 979 | 490 | | | | | | 1469 |
| 8.0 | 1 | | | 199 | | 199 | 199 | | | | | | 597 |
| | 2 | | | | | 597 | 398 | | | | | | 995 |
| | 3 | | | | | 398 | 199 | | | | 199 | | 796 |
| | 4 | | | | | 398 | 199 | | | | | | 597 |
| | 5 | | | | | 199 | | | | | | | 199 |
| | 6 | | | | | | | | | | | | 0 |
| | 7 | | | | | 199 | 398 | | 199 | | | | 796 |
| | 8 | | | | | 597 | | | | | | | 597 |
| 10.7 | 1 | 222 | 111 | 111 | | 556 | 222 | | | | 111 | | 1332 |
| | 2 | | | | | 445 | | 111 | | | | | 555 |
| | 3 | | | | | 334 | | | | | | | 334 |
| | 4 | | | | | 334 | 111 | | | | | | 445 |
| | 5 | 111 | | | | 334 | | | | | | | 445 |
| | 6 | | | | | 1112 | 111 | | | | | | 1223 |
| | 7 | | | | | 222 | 222 | | | | | | 444 |
| | 8 | 111 | | | 111 | 222 | 111 | | | 111 | | | 666 |

Table.3.

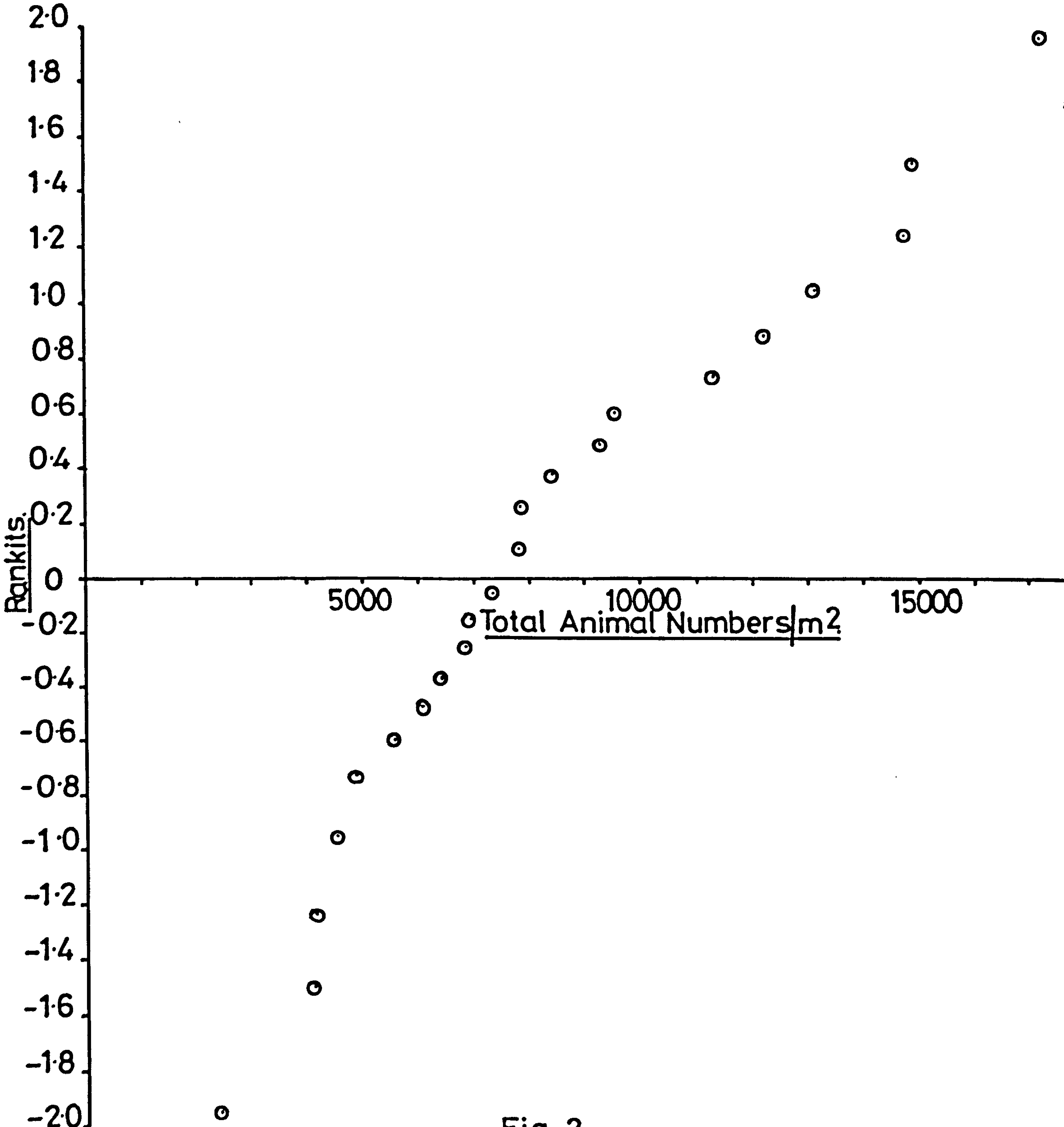



Fig. 2.

Graphic analysis of Total Animal Numbers/$m^2$ using Rankits. High Water Neaps. Transect 'A'. 11/12.5.1982.

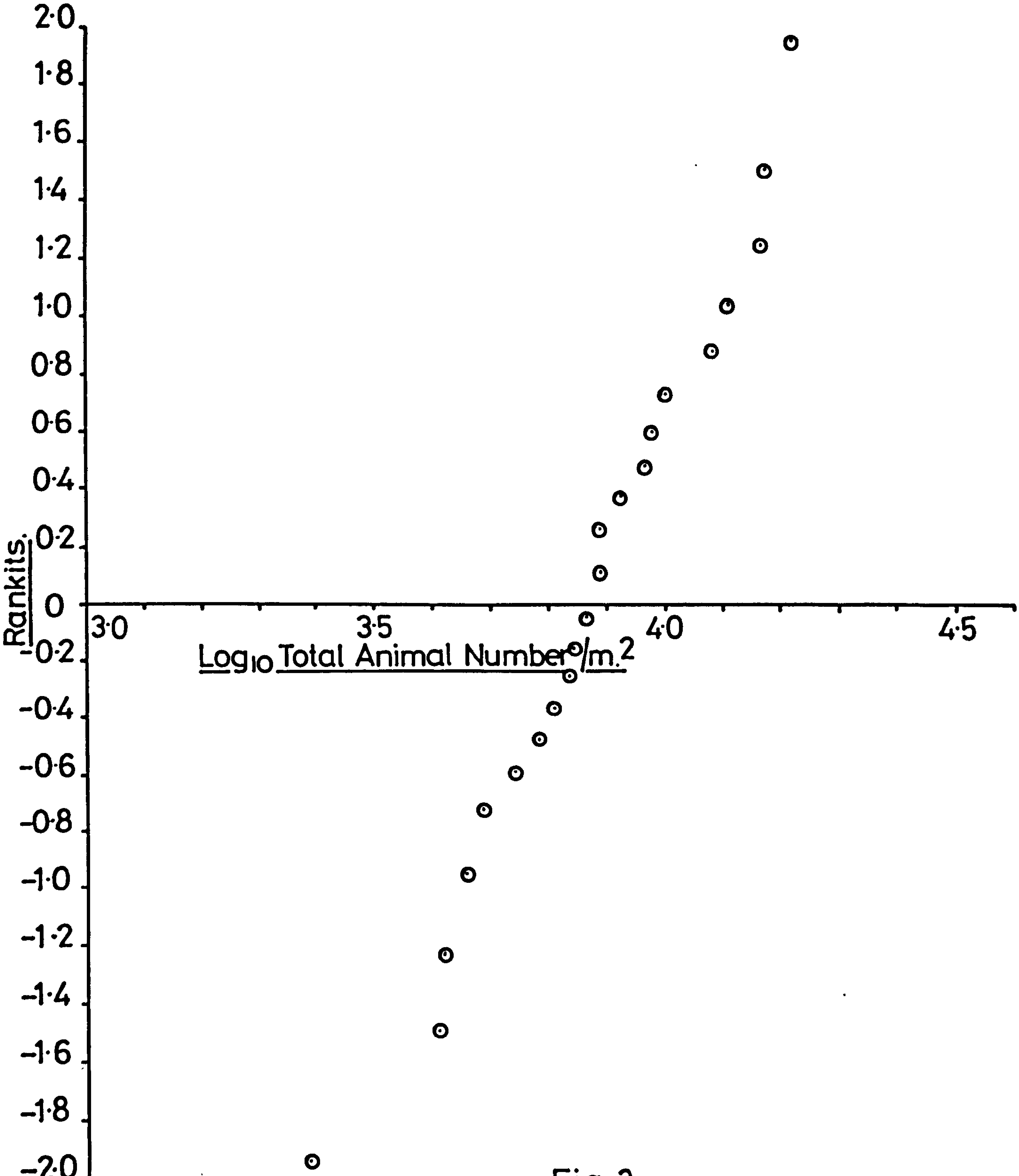



Fig. 3.

Graphical analysis of $\log_{10}$ Total Animal Numbers/$m^2$ using Rankits. High Water Neaps. Transect 'A'. 11/12.5.1982.

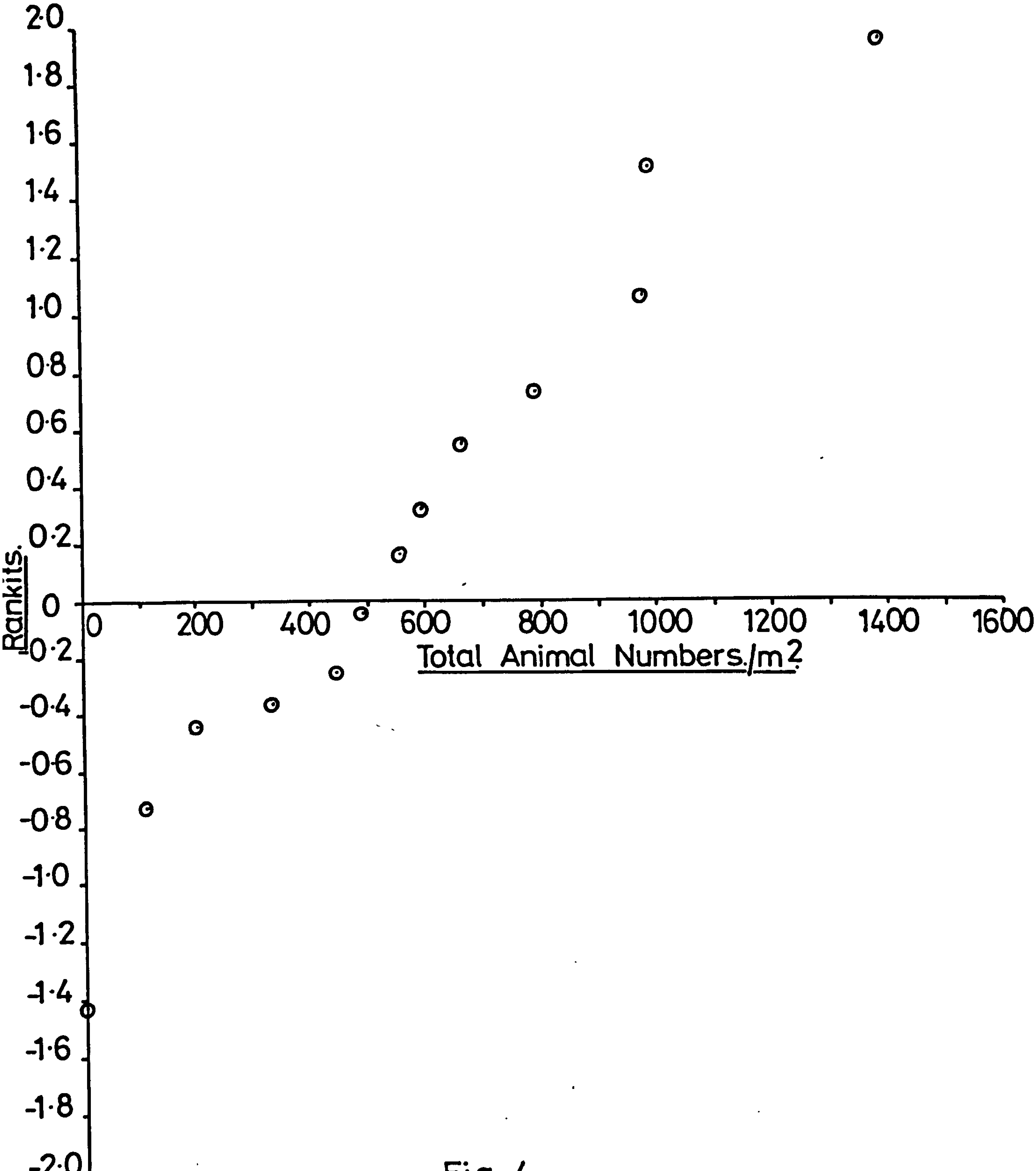



Fig. 4.

Graphic Analysis of Total Animal Numbers using Rankits. Mid-Tide. Transect 'A'. 11/12.6.1982.

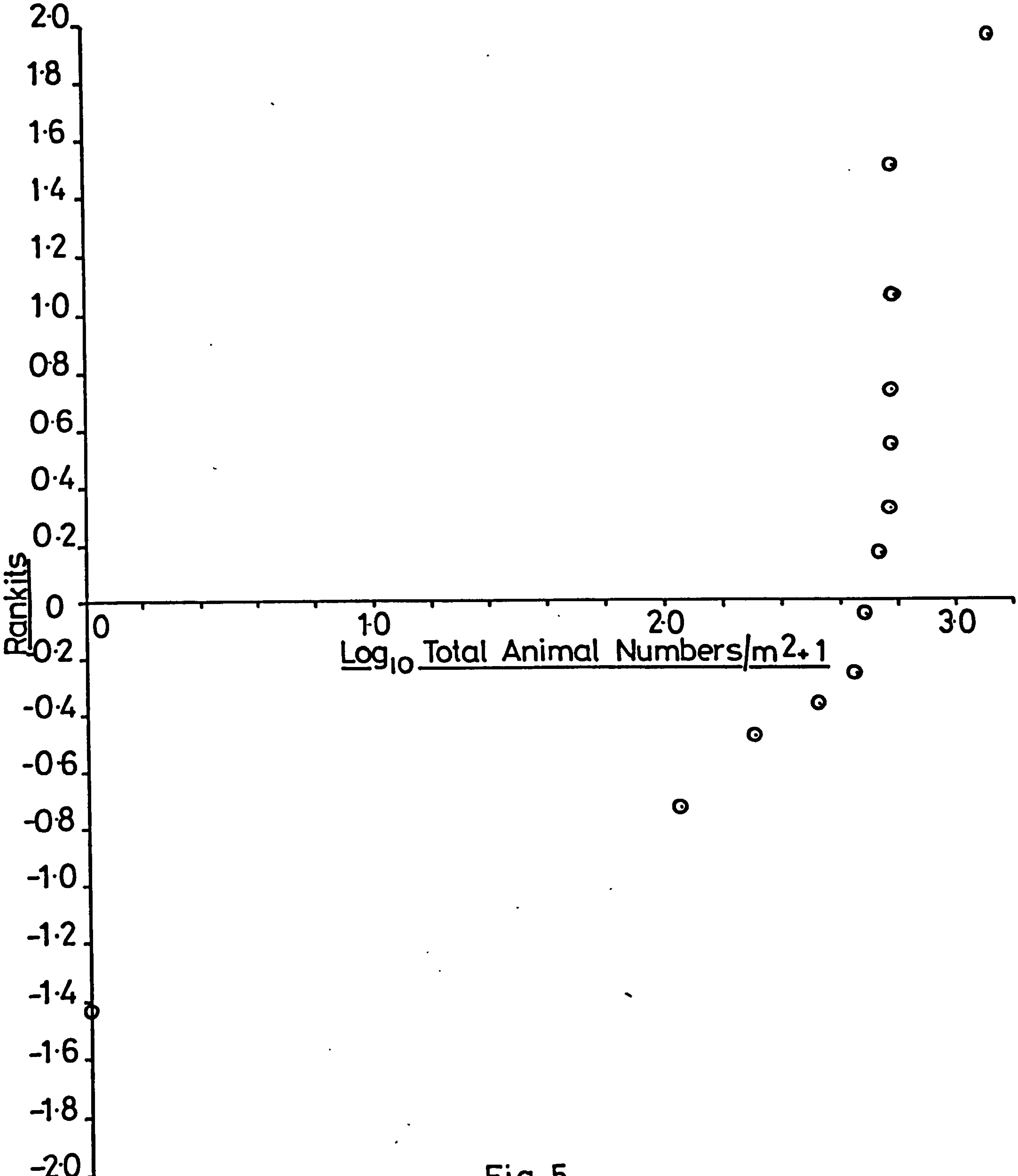



Fig. 5.

Graphic Analysis of $\log_{10}$ Total Animal Numbers using Rankits. Mid-Tide. Transect 'A'. 11/12.6.1982.

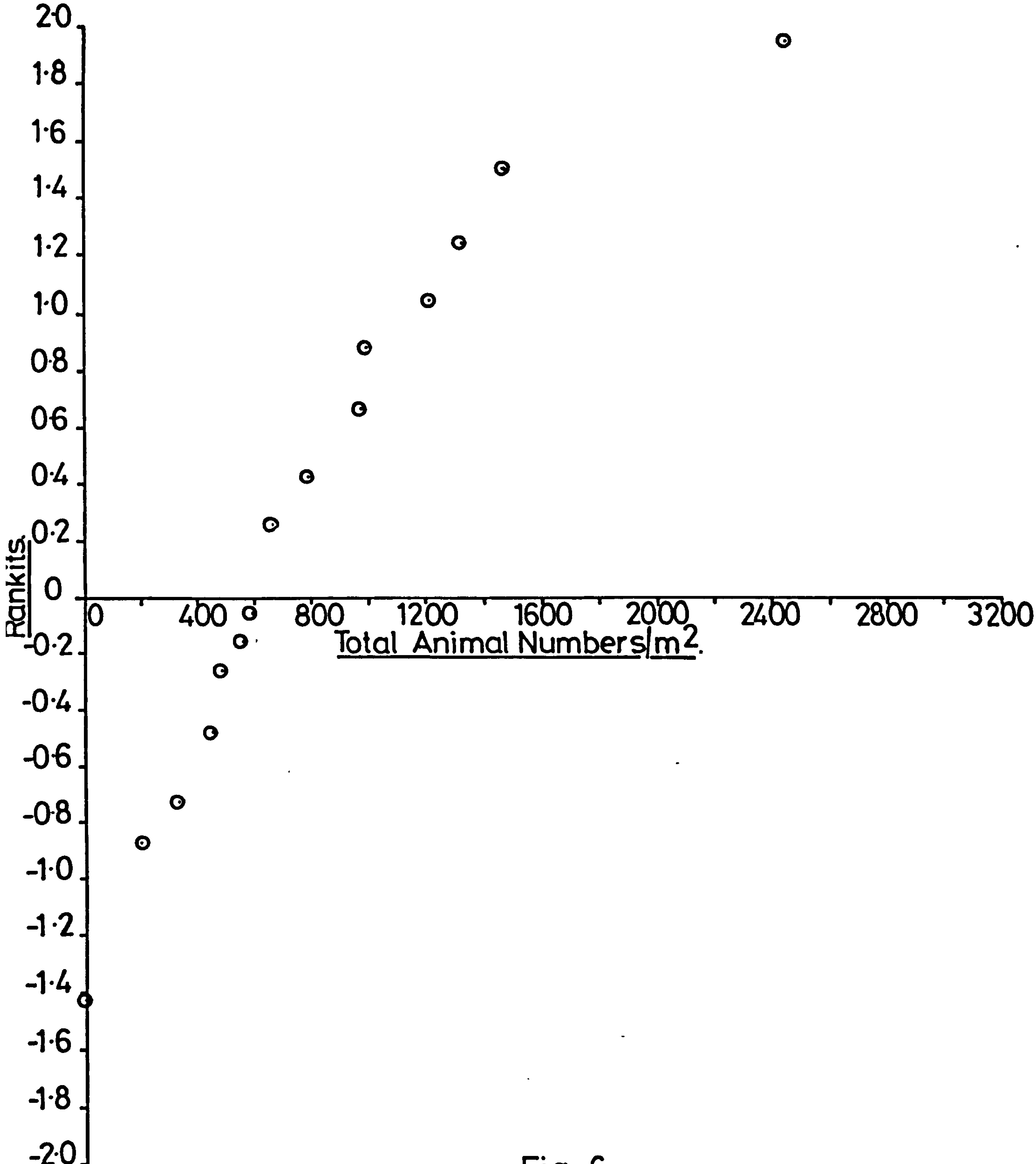



Fig. 6.

Graphic Analysis of Total Animal Numbers/m$^2$ using Rankits. Low Water Neaps. Transect 'A'. 11/12. 5. 1982.

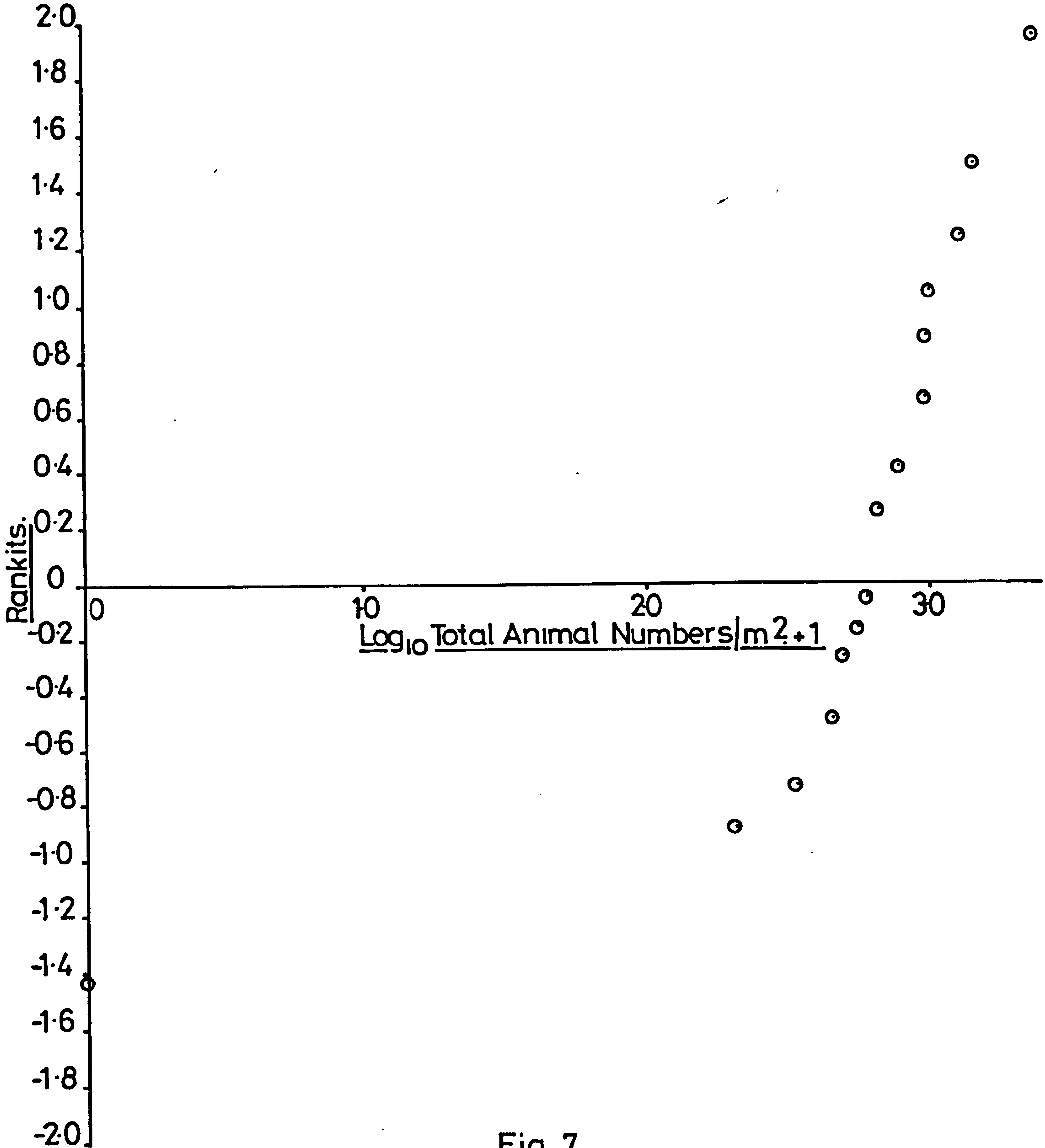



Fig. 7.

Graphic Analysis of $\text{Log}_{10}$ Total Animal Numbers/$m^2$+1 using Rankits. Low Water Neaps. Transect 'A'. 11/12. 5. 1982.

TABLE 4

Results of 't' Tests To Determine if Mean The Number of Animals Per Metre$^2$ is Different When Calculated Using Data For The Three Core Sizes

| Site | Size Comparison | Mean | S.D. | 't' Equal.var. | DF | Signif. | 't' Unequal.var. | DF | Signif. |
|---|---|---|---|---|---|---|---|---|---|
| HWN | 5.1 8.0 | 3.7966 / 3.9577 | 0.22225 / 0.22051 | 1.4556 | 14 | 0.25 P 0.1 | 1.4556 | 16 | 0.25>P>0.1 |
| | 5.1 10.7 | 3.7966 / 3.8603 | 0.22225 / 0.17127 | 0.64312 | 14 | P 0.25 | 0.64312 | 15 | P>0.25 |
| | 8.0 10.7 | 3.9577 / 3.8603 | 0.22051 / 0.17127 | 0.98656 | 14 | P 0.25 | 0.98656 | 15 | P>0.25 |
| | | | | | | | | | |
| MT | 5.1 8.0 | 551 / 572.12 | 408.62 / 492.50 | 0.093369 | 14 | P 0.25 | 0.093369 | 15 | P>0.25 |
| | 5.1 10.7 | 551 / 374.63 | 408.62 / 244.18 | 1.0479 | 14 | P 0.25 | 1.0479 | 13 | P>0.25 |
| | 8.0 10.7 | 572.12 / 374.63 | 492.50 / 244.18 | 1.0161 | 14 | P 0.25 | 1.0161 | 11 | P>0.25 |
| | | | | | | | | | |
| LWN | 5.1 8.0 | 795.75 / 572.13 | 865.76 / 326.77 | 0.68351 | 14 | P 0.25 | 0.6851 | 10 | P>0.25 |
| | 5.1 10.7 | 795.75 / 679.87 | 865.76 / 381.93 | 0.34636 | 14 | P 0.25 | 0.34636 | 10 | P>0.25 |
| | 8.0 10.7 | 572.13 / 679.87 | 326.77 / 381.93 | 0.60632 | 14 | P 0.25 | 0.60632 | 16 | P>0.25 |

Table.4.

## TABLE 5

**Results of 'F' Tests To Determine The Core Size Giving The Lowest Error (Variance) To The Estimated Number of Animals Per Metre$^2$**

| Site | Size Comparison | | Mean (x/y) | S.D. | F (x/y) | DF | | Signif. |
|---|---|---|---|---|---|---|---|---|
| HWN | 5.1 | 8.0 | 3.7966 / 3.9577 | 0.22225 / 0.22051 | 1.0159 | 7 | 7 | P>0.05 |
| | 5.1 | 10.7 | 3.7966 / 3.8603 | 0.22225 / 0.17127 | 1.6840 | 7 | 7 | P>0.05 |
| | 8.0 | 10.7 | 3.9577 / 3.8603 | 0.22051 / 0.17127 | 1.6576 | 7 | 7 | P>0.05 |
| MT | 5.1 | 8.0 | 572.13 / 551 | 492.50 / 408.62 | 1.4527 | 7 | 7 | P>0.05 |
| | 5.1 | 10.7 | 551 / 374.63 | 408.62 / 244.18 | 2.8003 | 7 | 7 | P>0.05 |
| | 8.0 | 10.7 | 572.13 / 374.63 | 492.50 / 244.18 | 4.0680 | 7 | 7 | 0.05>P>0.025 |
| LWN | 5.1 | 8.0 | 795.75 / 572.13 | 865.76 / 326.77 | 7.0194 | 7 | 7 | 0.01>P>0.001 |
| | 5.1 | 10.7 | 795.75 / 679.88 | 865.76 / 381.93 | 5.1384 | 7 | 7 | 0.025>P>0.01 |
| | 8.0 | 10.7 | 679.88 / 572.13 | 381.93 / 572.13 | 1.3661 | 7 | 7 | P>0.05 |

**Table.5.**

## TABLE 6

### Data For Selection of Optimum Core Depth

| Site | Replicate | Species / Depth Interval (cm) | *Macoma balthica* | *Hydrobia ulvae* | *Corophium volutator* | *Scoloplos armiger* | *Nephthys hombergii* | Oligochaete species | Diptera species larvae | Total number of animals |
|---|---|---|---|---|---|---|---|---|---|---|
| HWN | 1 | 0-2.5 | | 6167 | 199 | | | | | 6366 |
| | | 2.5-7.5 | | | | | | 199 | | 199 |
| | | 7.5-12.5 | | | | 199 | | | | 199 |
| | | 12.5-17.5 | | | | | | | | |
| | | 17.5-22.5 | | | | | | | | |
| | 2 | 0-2.5 | 199 | 4178 | 398 | | | 10345 | 995 | 16115 |
| | | 2.5-7.5 | | 1393 | | | | 1790 | | 3183 |
| | | 7.5-12.5 | | 199 | | | | | | 199 |
| | | 12.5-17.5 | | | | | | | | |
| | | 17.5-22.5 | | | | | | | | |
| MT | 1 | 0-2.5 | | 199 | | | | | | 199 |
| | | 2.5-7.5 | | | | | | | | |
| | | 7.5-12.5 | | | | 199 | | | | 199 |
| | | 12.5-17.5 | | | | | | | | |
| | | 17.5-22.5 | | | | | | | | |
| | 2 | 0-2.5 | | | | | | | | |
| | | 2.5-7.5 | | | | | 199 | | | 199 |
| | | 7.5-12.5 | | | | | | | | |
| | | 12.5-17.5 | | | | | | | | |
| | | 17.5-22.5 | | | | | | | | |
| LWN | 1 | 0-2.5 | | | | 199 | | | | 199 |
| | | 2.5-7.5 | | | | | | | | |
| | | 7.5-12.5 | | | | 199 | | | | 199 |
| | | 12.5-17.5 | | | | | | | | |
| | | 17.5-22.5 | | | | | | | | |
| | 2 | 0-2.5 | | | | | 398 | | 199 | 597 |
| | | 2.5-7.5 | | | | 199 | 199 | | | 398 |
| | | 7.5-12.5 | | | | | | | | |
| | | 12.5-17.5 | | | | | | | | |
| | | 17.5-22.5 | | | | | | | | |

**Note** No animals were present in samples from depths below 22.5cm.

Table.6.

# APPENDIX H

## An Example of a Graphic Test of Normality For A Variable - Skewness - Which Is To Be Subjected To Principal Components Analysis.

### Introduction

A basic assumption of the multivariate model is that variates are normally distributed. To satisfy this requirement it is sometimes necessary to apply mathematical transformations to the data. Typical examples of the type of transformation used include the following:

$$x' = \mathrm{Log}_{10}\,(x)$$
$$x' = \mathrm{Log}_e\,(x) = \mathrm{In}\,(x)$$
$$x' = \sqrt{(x)}$$
$$x' = \mathrm{Arc\ Sine}\ \sqrt{(x)}$$

The choice of transformation is dependant upon the distribution of the variates about their mean. Experimental work has shown that certain transformations can be applied to data of a particular type. For example $x' = \mathrm{Arc\ Sine}\sqrt{(x)}$ is applicable where x is a proportion (Snedecor and Cochran 1980).

For data of unknown distribution, a number of tests for normality have been developed. These include Graphic Tests by Rankits and Graphic Tests on Probability Paper (Sokal and Rohlf 1969).

In this appendix, the latter test has been applied to one of the variables. Particle Size Skewness. The objective has been to determine the transformation - if any - which best fits the data to a normal distribution. This test has been applied to all the variables in the Principal Components Analysis.

### Method and Results - (Sokal and Rohlf 1969)

A frequency distribution of Skewness values was prepared with class intervals of 0.1 units. From this, a Comulative frequency distribution was obtained. Cumulative frequency (ordinate) was then plotted against the upper limit of each class interval (abscissa) on Normal Probability Paper. A straight line was then fitted to the points by eye.

Data points from a normal distribution plotted in this way lie on a straight line. Examination of the above plot showed however, a poor fit. Several transformations were therefore applied to the data.

The best transformation was $Log_{10}$ (1.6213 - Skewness). 1.6213 was chosen as a constant because the highest Skewness obtained was +0.6213. This gives $Log_{10}$ (1.6213 - 0.6213) = 0. The transformed data therefore, runs from zero upwards. Zero Skewness (Normal Curve) gives a value of 0.2099.

The frequency distribution of untransformed Skewness values is shown in Figure 1. It is apparent that the distribution is skewed to the left.

Figures 2 and 3 show respectively the untransformed and transformed plots on Normal Probability Paper. It is noticiable that the upper frequencies on the untransformed plot deviate to the left of the line. This is typical of data which is skewed to the left. (Sokal and Rohlf 1969). Data points on the transformed plot fit the line well.

A comparison of the untransformed and transformed plots therefore, shows the data points on the latter to best fit the straight line. This indicates that the distribution of Skewness values expressed as logarithms, closely approximates Normality. In the subsequent Principal Components Analysis Skewness data will therefore be analysed in this form.

Fig. 1.

Histograms Showing The Number Of Samples With Skewness Values In The Given Intervals.

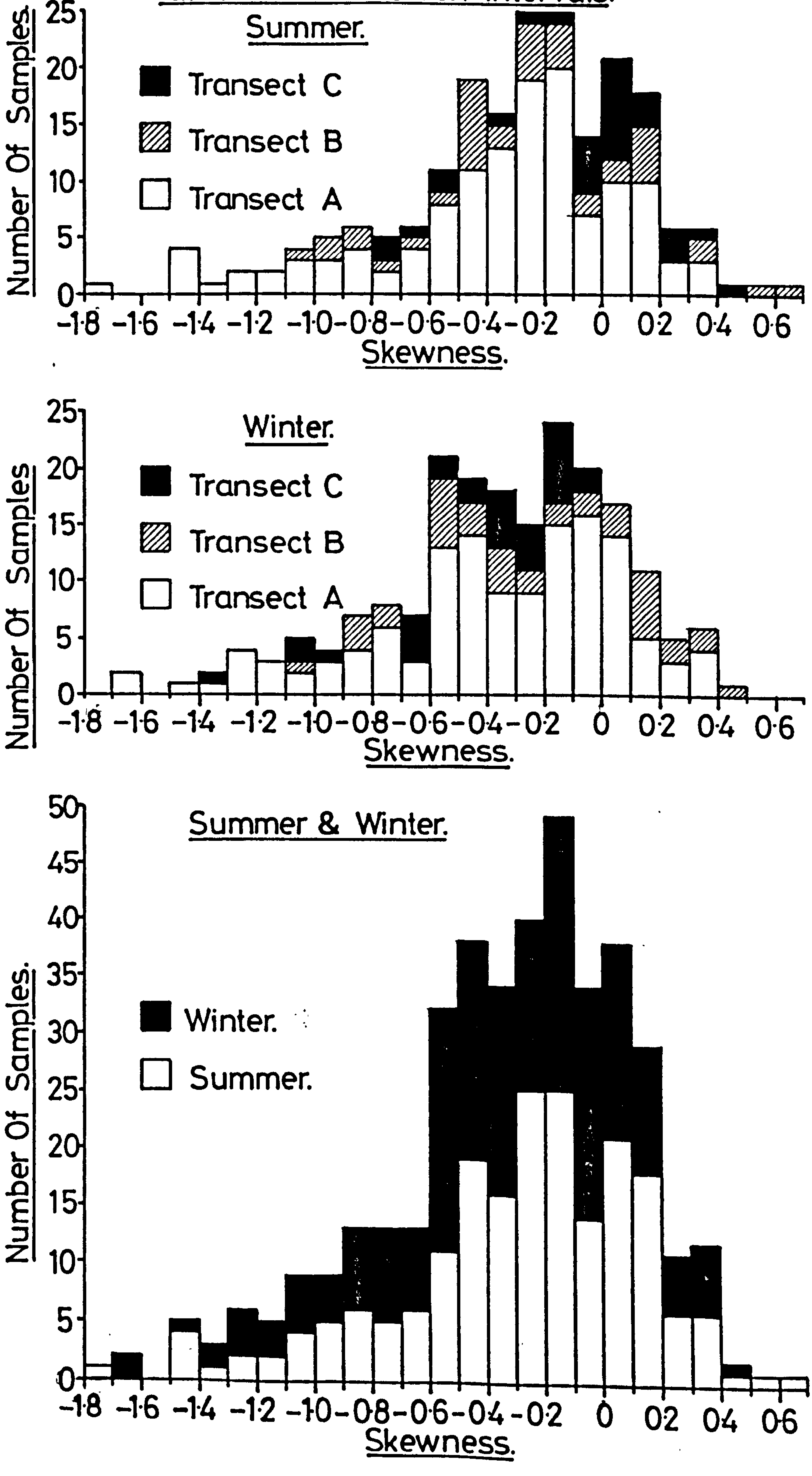


Fig. 2.

Plot Of Sediment Particle Size Skewness Values Versus Cumulative Percentage Of Total Number Of Samples.

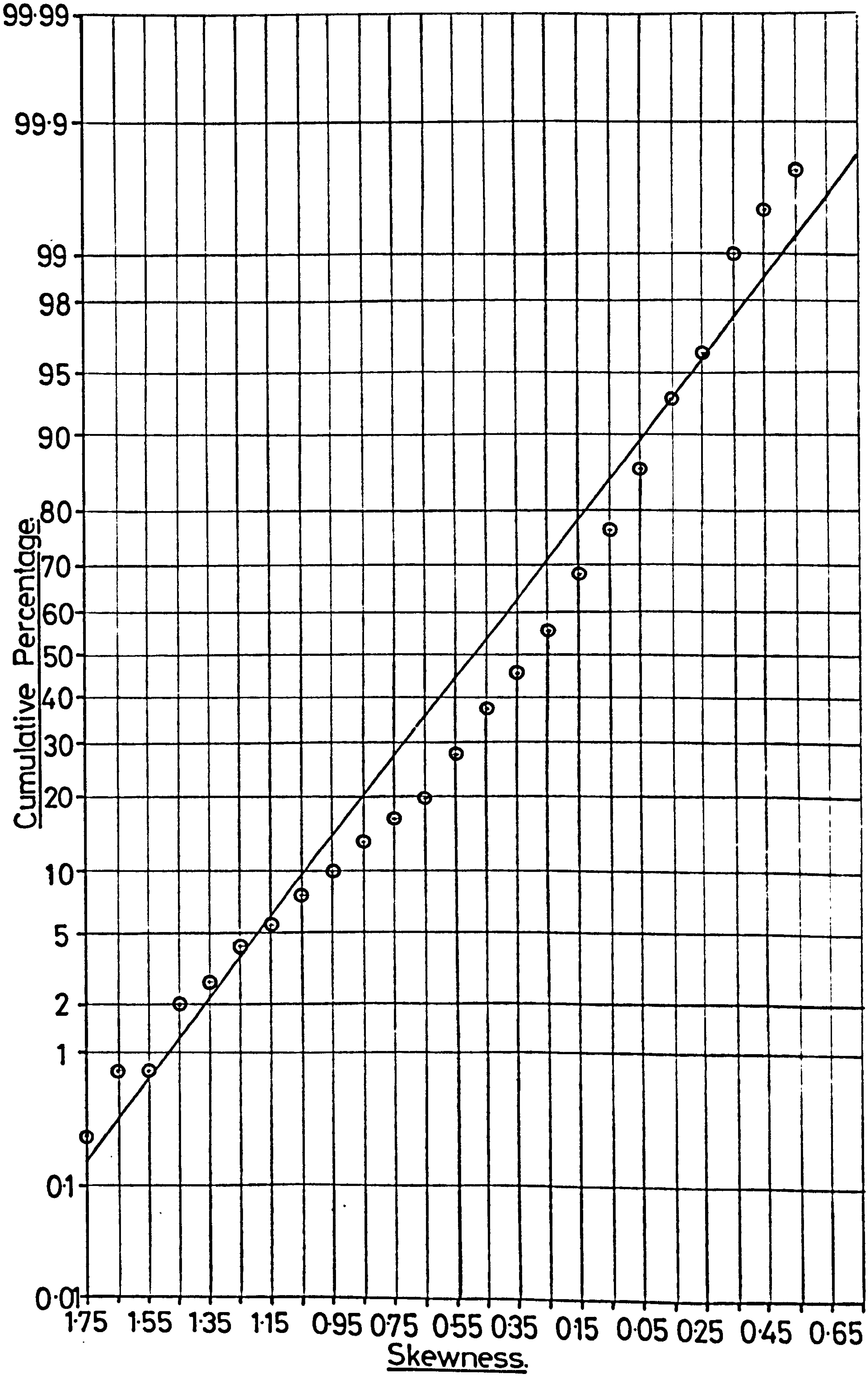
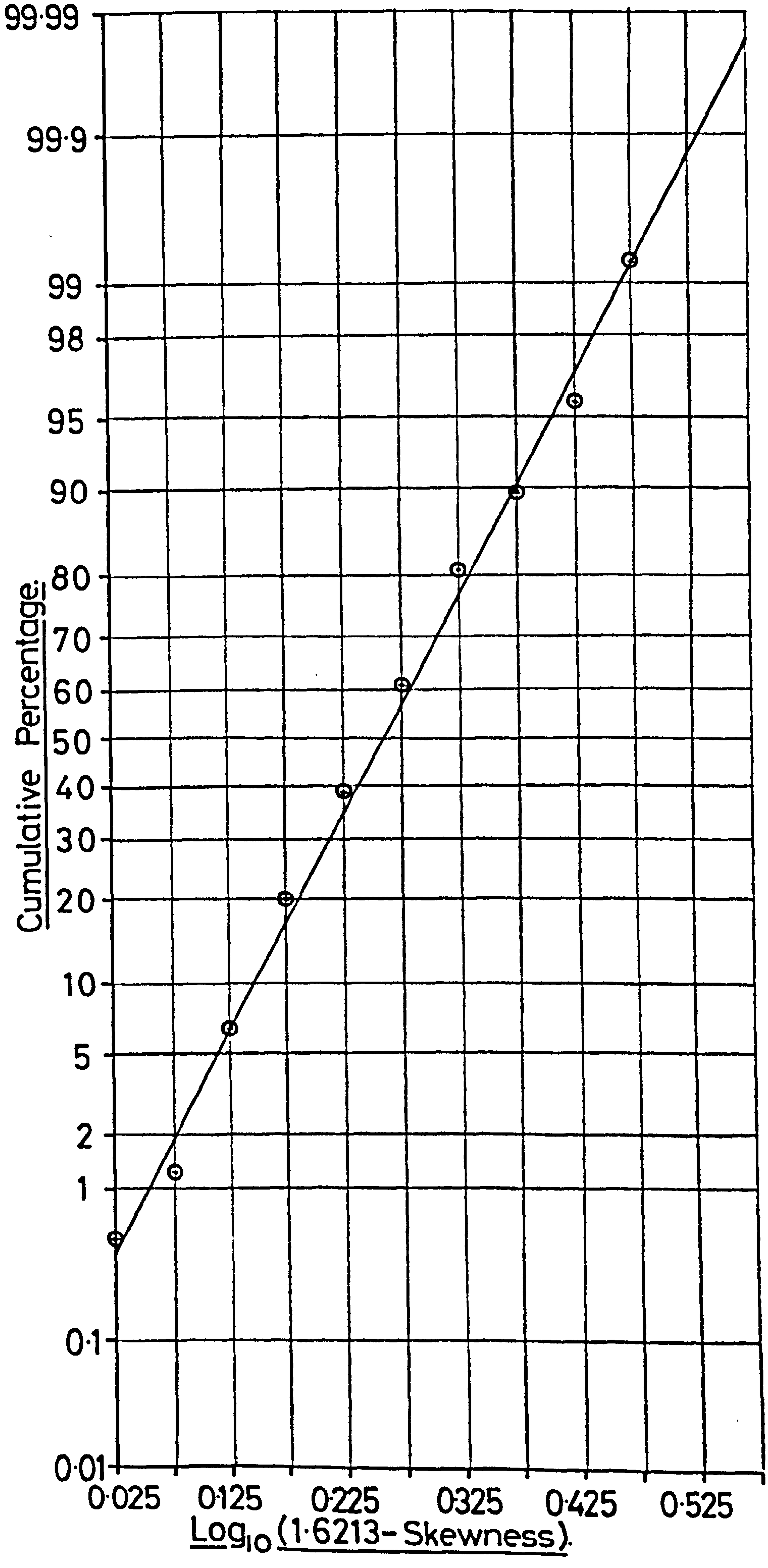


Fig. 3.

Plot Of $Log_{10}$(1·6213-Sediment Skewness Values) Versus Cumulative Percentage Of Total Number Of Samples.



# APPENDIX 'I' - CALCULATIONS IN FLUME DESIGN

## Introduction

As part of the design phase of the Flume, calculations were necessary to determine:

1) The required length of trough, upstream of the sample, to give the required permissible shear stress loss over the length of the sample.

2) The boundary layer thickness at the sample position - necessary to determine the extra trough width required to keep the sample away from the trough wall boundary layer.

3) The power output of the pump necessary to circulate the water at the required rates.

4) The dimensions of an orifice plate, used to measure the rate of flow in the system.

The following are details of these calculations, including their theoretical origins and worked examples. To facilitate rapid recalculation, computer programs were developed for (1), (2) and (3). These programs and their appropriate flow diagrams are also included in this Appendix.

## (1) Required length of trough upstream of sample

A liquid moving over the surface of a plate experiences frictional effects at the interface. This results in a reduction in the velocity of the liquid adjacent to the plate surface. As the liquid progresses over the plate the cumulative effects of friction progressively reduce its velocity. The reduction in velocity is a non-linear function of distance travelled.

A consequence of the reduction in velocity is a reduction in the Shear Stress exerted by the liquid on the plate. The magnitude of the stress is a non-linear function of velocity.

The shear stress at any point along the plate can be calculated by one of two formulae depending upon the nature of the liquid flow. The nature of the flow, i.e., Laminar or Turbulent can be determined using the concept of Reynolds Number (Re). This non-dimensional parameter is a function of flow velocity, a relevant dimension of the system, the viscosity of the liquid and its density.

The formulae used to calculate Reynolds Number and the Shear Stress at any point along the plate are as follows:

<u>Reynolds Number (Re)</u>

From Massey, (1979)

$$Re = (Us \times l)/\nu \qquad (1)$$

<u>Shear Stress ($\tau o$) - Laminar Flow</u> (Re < 800)

From Douglas, et.al. (1979) After Blasius)

$$\tau o = 0.332\, \mu\, (Us/x)\, Re_x^{\frac{1}{2}} \qquad (2)$$

<u>Shear Stress ($\tau o$) - Turbulent Flow</u> (Re > 800)

From Douglas, et.al. (1979)

$$\tau o = 0.029 \rho Us^2\, (u/\rho\, Usx)^{1/5} \qquad (3)$$

<u>where:</u>

$Us$ = Liquid Velocity (m/s)

$l$ = A dimension of the system (m)

$\nu$ = Kinematic Viscosity ($m^2/s$)

$\mu$ = Liquid Viscosity (kg/m/s)

$x$ = Linear dimension in flow direction (m)

$\rho$ = Liquid Density ($kg/m^3$)

Equations (2) and (3) can be rearranged and simplified to calculate the required upstream trough length for both types of flow. The resultant formulae are:

<u>For Laminar Flow</u>

$$\text{Upstream Trough Length } (xu) = (L/\delta\tau) - L \qquad (4)$$

<u>For Turbulent Flow</u>

$$xu = L/((1 + \delta\tau)^5 - 1 \qquad (5)$$

<u>where:</u>

$L$ = Sample Length (m)

$\delta\tau$ = Stress Loss over sample Length (Decimal Fraction)

See over for worked example.

Worked Example

Typical Input Values

$Us = 0.25m/s$

$l = 0.2m$ (Depth of Flow)

$\nu = 1.14 \times 10^{-6}\ m^2/s$

$L = 0.40m$

$\delta\tau = 0.05$ (5%)

Reynolds Number (Re)

$$Re = (Us \times l)/\nu$$
$$= (0.25 \times 0.2)/1.14 \times 10^{-6}$$
$$= \underline{5 \times 10^4}$$

Flow is therefore Turbulent

Upstream Trough Length (xu) - Turbulent Flow

$$xu = L\ ((1 + \delta\tau)5-1)$$
$$= 0.40\ ((1 + 0.05)^{5-1})$$
$$= \underline{0.65m}$$

2) The Boundary Layer Thickness at the Sample Position

The frictional effects of the liquid flowing over the surface of a plate are not restricted to the molecules immediately adjacent to the surface. The liquid has a resistance to deformation termed its viscosity. Thus liquid above the surface is subject to a shear stress, the strength of which is proportional to its viscosity, its velocity and the distance from the surface.

Away from the plate surface the shear stress on the liquid decreases to zero. The distance over which this takes place is known as the Boundary Layer Thickness. ($\delta$)

Turbulence results in an increase in the apparent viscosity of the liquid. Thus a modified viscosity parameter known as Eddy Viscosity must be incorporated into any calculation where turbulent conditions prevail.

The formulae used to calculate the Boundary Layer Thickness for both types of flow are as follows (After Blasius, 1883 - 1970):

Laminar Flow

(Douglas, et.al.(1979)

$$\delta = 5.48 \times Re_x^{-\frac{1}{2}} \qquad (6)$$

Turbulent Flow

Douglas, et.al. (1979)

$$\delta = 0.37x/(Us\ x/\nu)^{1/5} \qquad (7)$$

where:

x = Linear Dimension in Flow Direction (m)

Us = Liquid Velocity (m/s)

$\nu$ = Kinematic Viscosity ($m^2/s$)

Worked Example.

Typical Input Values

x = Upstream Trough Length + Sample Length

= 0.65 + 0.40

= 1.05m

Us = 0.25m/s

$\nu$ = $1.14 \times 10^{-6}\ m^2/s$.

From previous example flow is identified as being Turbulent. Equation (7) is therefore appropriate.

$= 0.37\ x/(Us\ x/\nu)^{1/5}$

$= (0.37 \times 1.05)/(0.25 \times 1.05/1.14 \times 10^{-6})^{1/5}$

= 0.033m

3) The Required Power Output of the Pump

In a closed circulatory system, such as a Flume, power is required to accelerate the liquid to the required velocity. Additional power is also required to maintain it at this velocity by compensating for energy lossed due to Friction. The following factors must therefore be considered when selecting a suitable pump:

(a) The power required to accelerate the liquid to the required velocity.

(b) Frictional losses in the system.

(c) The efficiency of the pump.

(a) The power required to accelerate the liquid

This can be determined from equations describing the Kinetic Energy of the flow. Thus from Massey, (1979)

$$\text{Kinetic Energy} = \text{Power (Watts)} = \tfrac{1}{2}\rho Us^2 \times Q \qquad (8)$$

where:

$\rho$ = Liquid Density ($kg/m^3$)

Us = Liquid Velocity (m/s)

Q = Flow Rate ($m^3/s$)

(b) Frictional losses in the system

A consideration of the major frictional losses is based upon formulae developed by Darcy (1803-1858). These formulae express energy (power) losses as a reduction in pressure head (hf).

For an open trough the formula (from Massey, 1979) is:

$$hf = f\,l\,\bar{U}_t^{\,2}/m\,2g \qquad (9)$$

where:

f = A coefficient of friction for the surface (Dimensionless)

l = Length over which losses are being determined (m)

$\bar{U}_t$ = Mean liquid velocity in trough (m/s)

m = Hydraulic mean depth of the channel = C.S.A. of liquid in channel ÷ wetted perimeter of channel (m)

g = Gravitational Acceleration ($m/s^2$).

Similarly the head loss for the circular return pipe is:

$$hf = 4\,f\,l\,\bar{U}_p^{\,2}/d\,2g \qquad (10)$$

where:

d = diameter of the pipe (m)

$\bar{U}_p$ = Mean Liquid velocity in pipe (m/s)

Head losses at the bends are calculated using a similar formula:

$$hf = N\,k\,\bar{U}_b^{\,2}/2g \qquad (11)$$

where:

k = Bend Loss Constant (Dimensionless)

N = Number of Bends

$U_b$ = Mean liquid velocity at bend (m/s).

In all three cases the constants or coefficients can be determined from standard tables. Examples of such tables are to be found in Massey (1979), pp. 193 and 205.

These head losses can be converted into a power requirement as follows:

Power = Head Loss (hf) x Liquid Density ($\rho$) x Gravitation Acceleration($g$) x Flow Rate (Q)

For a system like the Flume where these are the major frictional losses, the power required to compensate is therefore:

$$\text{Power} = \rho g Q \left( \frac{f l_t \bar{U}_t^2}{m 2g} + \frac{4 f l_p \bar{U}_p^2}{d 2g} + \frac{N k \bar{U}_b^2}{2g} \right) \qquad (12)$$

(c) The Efficiency of The Pump

No mechanical device is 100% efficient in converting input power into output. To allow for this, an adjustment is made to the total power requirement (Acceleration requirement + losses) as follows:

Required Pump Power Output = Acceleration Requirement + Losses ÷ Pump Efficiency

$$= \frac{(8) + (12)}{\mu} \qquad (13)$$

where:

$\mu$ = Pump Efficiency (Decimal Fraction)

Overall Equation For The Required Power Output of The Pump

Combining equations (8), (12) and (13) yields, the following:

$$\text{Pump Power} = Q \frac{\left[\left(\frac{1}{2}\rho \bar{U}_t^2\right) + \left(\frac{f}{m}\frac{1}{2} l_t \rho \bar{U}_t^2\right) + \left(\frac{f}{d} 2 l_p \rho \bar{U}_p^2\right) + \left(N \frac{1}{2} \rho \bar{U}_b^2\right)\right]}{\mu}$$

In view of the complexity of the calculation, a worked example has not been included.

Development of Computer Programs

Two computer programs were written in BASIC language for the PET Microcomputer.

Program FTD1 - was designed to calculate Reynolds Number, the Upstream Trough Length and Boundary Layer Thickness in accordance with equations (1), (4) and (5).
Program FPD1 - was designed to calculate the required pump power output in accordance with equation (14).

These two programs are shown, together with their appropriate flow diagrams, in Boxes 1 and 2 and Figures 1 and 2.

(4) The Dimensions of an Orifice Plate, used to measure the Rate of Flow in the Flume.

The velocity of a liquid in a pipe increases if it passes through a constriction. The kinetic energy of the liquid, which is related to the square of the local velocity, increases correspondingly. The consequent decrease in potential energy is manifest as a decrease in the pressure of the liquid on the wall of the pipe or device.

This phenomenon has been utilized in the design of a number of flow-rate measuring devices, notably Venturi Tubes/ Nozzles and Orifice Plates.

The pressure difference across the device for a given flow-rate depends on: (From BS1042: Part 1: 1964),

(a) The type of device, its geometrical shape and proportions.
(b) The position of the upstream and downstream tappings,
(c) The dimensions of the device.

For measuring the rate of flow in the Flume, an Orifice Plate with pressure-tappings positioned as follows was chosen:

Upstream Tapping = One pipe diameter (D) from plate
Downstream Tapping = Half a pipe diameter (D/2) from plate

This was to be linked to a manometer to indicate the pressure difference.

The device was designed in accordance with BS1042): Part 1: 1964: Appendix B(B2) and constructed by myself from standard UPVC pipework and fittings. The steps involved in calculating the Orifice Diameter (d) were as follows:

1) Choice of Device = Orifice Plate with D and D/2 pressure tappings.

BOX 1

Computer Program "FTD1".

For calculation of Upstream Trough Length(X) and Boundary Layer Thickness(DB).

# COMPUTER PRORGRAM "FTD1".

```
10 OPEN4,4
20 REM***A.GIRLING***15/6/82
30 PRINT "FLUME TROUGH DESIGN 1(FTD1)"
40 PRINT"CALCULATION OF UPSTREAM FLUME LENGTH X(M) AND"
45 PRINT "BOUNDARY LAYER THICKNESS DB(M)"
50 FOR J= 1 TO 1000: NEXT J
60 PRINT "PRESS"
70 PRINT "L TO CHANGE SAMPLE LENGTH (M)L"
75 PRINT "D TO CHANGE WATER DEPTH IN TROUGH (M)D"
80 PRINT "U TO CHANGE MAIN STREAM VELOCITY (M/S)U"
90 PRINT "V TO CHANGE FLUID KINEMATIC VISCOCITY (M↑2/S)V"
110 PRINT "S TO CHANGE SHEAR STRESS LOSS OVER SAMPLE
120 PRINT "C TO CONTINUE"                LENGTH (DEC.FRACT.)S"
130 GET G$:IF G$="" GOTO 130
140 IF G$="L" GOTO 190
145 IF G$="D" GOTO 200
150 IF G$="U" GOTO 210
160 IF G$="V" GOTO 230
180 IF G$="S" GOTO 270
185 IF G$="C" GOTO 290
190 PRINT"ENTER SAMPLE LENGTH IN DIRECTION OF FLOW L(M)":INPUT L
195 GOTO 60
200 PRINT"ENTER WATER DEPTH IN TROUGH D(M)":INPUT D
205 GOTO 60
210 PRINT"ENTER MAIN STREAM VELOCITY U(M/S)":INPUT U
220 GOTO 60
230 PRINT"ENTER FLUID KINEMATIC VISCOSITY V(M↑2/S)":INPUT V
260 GOTO 60
270 PRINT "ENTER SHEAR STRESS LOSS OVER SAMPLE LENGTH S(DEC.
280 GOTO 60                                   FRACT.)": INPUT S
290 PRINT#4,"REYNOLDS NUMBER IS NR.FOR:"
295 PRINT#4,""
300 PRINT#4,"STREAM VELOCITY U(M/S)      =";U
310 PRINT#4,"WATER DEPTH IN TROUGH D(M)  =";D
320 PRINT#4,"KINEMATIC VISCOSITY V(M↑2/S)=";V
330 PRINT#4,""
340 NR=(U*D)/V
350 PRINT#4,"NR=";NR
355 PRINT#4,""
360 PRINT#4,"IF NR < 800 FLOW IS ASSUMED LAMINAR"
370 PRINT#4,"IF NR > 800 FLOW IS ASSUMED TURBULENT"
375 PRINT#4,""
380 REM TRANSITION ZONE, 800<NR<5000 IS INCLUDED IN TURBULENT
390 IF NR < 800 GOTO 420                                   ZONE
400 IF NR > 800 GOTO 650
410 PRINT#4,""
420 PRINT#4,"LAMINAR CONDITION"
425 PRINT#4,""
430 PRINT#4,"UPSTREAM TROUGH LENGTH IS X(M) AND"
440 PRINT#4,"BOUNDARY LAYER THICKNESS DB(M),FOR:"
445 PRINT#4,""
450 PRINT#4,"SAMPLE LENGTH L(M)    =";L
460 PRINT#4,"STREAM VELOCITY U(M/S)=";U
470 PRINT#4,"KIN.VISCOSITY V(M↑2/S)=";V
480 PRINT#4,"STRESS LOSS S(DEC.FR.)=";S
490 PRINT#4,""
```

COMPUTER PROGRAM "FTD1" CONTINUED.

```
500 X=(L/S)-L
510 DB=5.48*(X+L)*(NR↑-0.5)
610 PRINT#4,"X=";X
620 PRINT#4,""
630 PRINT#4,"DB=";DB
640 GOTO 780
650 PRINT#4,"TURBULENT CONDITION"
655 PRINT#4,""
660 PRINT#4,"UPSTREAM TROUGH LENGTH IS X(M) AND"
670 PRINT#4,"BOUNDARY LAYER THICKNESS DB(M),FOR:"
675 PRINT#4,""
680 PRINT#4,"SAMPLE LENGTH L(M)      =";L
690 PRINT#4,"STREAM VELOCITY U(M/S)=";U
700 PRINT#4,"KIN.VISCOSITY V(M↑2/S)=";V
710 PRINT#4,"STRESS LOSS S(DEC.FR.)=";S
720 PRINT#4,""
730 X=L/(((1+S)↑5)-1)
740 DB=(0.37*(X+L))/(((U*(X+L))/V)↑0.2)
750 PRINT#4,"X=";X
760 PRINT#4,""
770 PRINT#4,"DB=";DB
780 PRINT "PRESS:"
790 PRINT "C TO ENTER MORE DATA"
800 PRINT "E TO END"
810 GET A$: IF A$="" GOTO 810
820 IF A$="C" GOTO 60
830 CLOSE 4:END
```

BOX 2

Computer Program "FPD1".

For calculation of the required Pump Power Output(P).

## COMPUTER PROGRAM "FPD1"

```
10 OPEN4,4
20 REM***A.GIRLING***18/6/82
30 PRINT "FLUME PUMP DESIGN 1(FPD1)"
40 PRINT"CALCULATION OF REQUIRED PUMP POWER OUTPUT(WATTS)"
50 FOR J= 1 TO 1000:NEXT J
60 PRINT "PRESS"
70 PRINT "N TO CHANGE NUMBER OF PIPES N"
75 PRINT"L TO CHANGE LENGTH OF A PIPE(M) L"
80 PRINT "E TO CHANGE DIAMETER OF PIPE(M)E"
90 PRINT "G TO CHANGE FRICTION COEFF.OF PIPE(RATIO)G"
95 PRINT "O TO CHANGE NUMBER OF HOLES IN DISTRIBUTOR HEAD O"
97 PRINT"I TO CHANGE DIA.OF HOLES IN DISTRIBUTOR HEAD(M)I"
100 PRINT"Y TO CHANGE LENGTH OF TROUGH(M) Y"
110 PRINT "Z TO CHANGE WIDTH OF TROUGH(M)Z"
115 PRINT "D TO CHANGE WATER DEPTH IN TROUGH(M)D"
120 PRINT "V TO CHANGE VELOCITY OF WATER IN TROUGH(M/S)V"
130 PRINT "F TO CHANGE FRICTION COEFF.OF TROUGH(RATIO)F"
135 PRINT "J TO CHANGE WATER LEVEL DIFF. FROM TROUGH TO
140 PRINT "B TO CHANGE NUMBER OF BENDS B"    STILLING TANK (M) J
150 PRINT "K TO CHANGE BEND LOSS CONSTANT(RATIO)K"
160 PRINT "R TO CHANGE WATER DENSITY(KG.M↑3)R"
170 PRINT "A TO CHANGE PUMP EFFICIENCY(DEC.FRACTION)A"
180 PRINT "C TO CONTINUE"
190 GET G$:IF G$="" GOTO 190
200 IF G$="N" GOTO 320
205 IF G$="L" GOTO 333
210 IF G$="E" GOTO 340
220 IF G$="G" GOTO 355
225 IF G$="O" GOTO 365
227 IF G$="I" GOTO 368
230 IF G$="Y" GOTO 380
240 IF G$="Z" GOTO 400
245 IF G$="D" GOTO 413
250 IF G$="V" GOTO 420
260 IF G$="F" GOTO 440
265 IF G$="J" GOTO 450
270 IF G$="B" GOTO 460
280 IF G$="K" GOTO 480
290 IF G$="R" GOTO 500
300 IF G$="A" GOTO 520
310 IF G$="C" GOTO 540
320 PRINT"ENTER NUMBER OF PIPES N":INPUT N
330 GOTO 60
333 PRINT"ENTER LENGTH OF SINGLE PIPE(M) L":INPUT L
336 GOTO 60
340 PRINT"ENTER DIAMETER OF PIPE(M)E":INPUT E
350 GOTO 60
355 PRINT"ENTER FRICTION COEFF.OF PIPE(RATIO)G":INPUT G
360 GOTO 60
365 PRINT"ENTER NUMBER OF HOLES IN DISTRIBUTOR HEAD O":INPUT O
366 GOTO 60
368 PRINT"ENTER DIA. OF HOLES IN DISTRIBUTOR HEAD(M)I":INPUT I
370 GOTO 60
380 PRINT"ENTER LENGTH OF TROUGH(M) Y":INPUT Y
```

COMPUTER PROGRAM "FPD1" CONTINUED.

```
390 GOTO 60
400 PRINT"ENTER WIDTH OF TROUGH(M)Z":INPUT Z
410 GOTO 60
413 PRINT"ENTER WATER DEPTH IN TROUGH(M)D":INPUT D
416 GOTO 60
420 PRINT"ENTER VELOCITY OF WATER IN TROUGH(M/S)V":INPUT V
430 GOTO 60
440 PRINT"ENTER FRICTION COEFF.OF TROUGH(RATIO)F":INPUT F
445 GOTO 60
450 PRINT"ENTER DIFF.IN WATER LEVEL FROM TROUGH TO
                                         STILLING TANK (M)J":INPUT J
455 GOTO 60
460 PRINT"ENTER NUMBER OF BENDS B":INPUT B
470 GOTO 60
480 PRINT"ENTER BEND LOSS CONSTANT(RATIO)K":INPUT K
490 GOTO 60
500 PRINT"ENTER WATER DENSITY(KG/M↑3)R":INPUT R
510 GOTO 60
520 PRINT"ENTER PUMP EFFICIENCY(DEC.FRACT.)A":INPUT A
530 GOTO 60
540 PRINT#4,"REQUIRED PUMP POWER IS P(WATTS) FOR:"
550 PRINT#4,""
560 PRINT#4,"NUMBER OF PIPES N=";N
565 PRINT#4,"LENGTH OF A PIPE(M)L=";L
570 PRINT#4,"PIPE DIAMETER(M)E=";E
580 PRINT#4,"PIPE FRICTION COEFF.(RATIO)G=";G
585 PRINT#4,"NUMBER OF HOLES IN DISTRIBUTOR HEAD O=";O
587 PRINT#4,"DIA.OF HOLES IN DISTRIBUTOR HEAD(M)I=";I
590 PRINT#4,"LENGTH OF TROUGH(M)Y=";Y
600 PRINT#4,"TROUGH WIDTH(CM)Z=";Z
605 PRINT#4,"WATER DEPTH IN TROUGH(M)D=";D
610 PRINT#4,"WATER VELOCITY IN TROUGH(M/S)V=";V
620 PRINT#4,"TROUGH FRICTION COEFF.(RATIO)F=";F
625 PRINT#4,"DIFF. IN WATER LEVEL FROM TROUGH TO
                                         STILLING TANK (M)J=";J
630 PRINT#4,"NUMBER OF BENDS B=";B
640 PRINT#4,"BEND LOSS CONSTANT(RATIO)K=";K
650 PRINT#4,"WATER DENSITY(KG/M↑3)R=";R
660 PRINT#4,"PUMP EFFICIENCY(DEC.FRACT.)A=";A
670 PRINT#4,""
680 M=(Z*D)/(Z+(2*D))
690 REM M=HYDRAULIC MEAN DEPTH OF TROUGH(CSA.OF WATER IN
                                         TROUGH/WETTED PERIM.)
700 H=(Y*F*0.5*R*(V↑2))/M
710 REM H=FRICTIONAL LOSSES IN TROUGH
720 S=0.25*E
730 REM S=HYDRAULIC MEAN DEPTH OF PIPE(CSA OF WATER IN
                                         PIPE/WETTED PERIM.)
740 T=(V*Z*D)/(0.7855*N*(E↑2))
750 REM T=VELOCITY OF WATER IN PIPE
760 U=(L*0.5*G*R*(T↑2))/S
770 REM U=FRICTIONAL LOSSES IN PIPE
780 W=(B*K*0.5*R*(T↑2))
790 REM W=LOSSES AT BENDS
800 X=0.5*R*(T↑2)
810 REM X=PRESSURE HEAD TO PUMP WATER THROUGH PIPE AT
                                         DESIRED VELOCITY
815 Q=(T*N*((3.142*(E↑2))/4))
817 REM Q=FLOW RATE IN SYSTEM(DISCHARGE RATE(M↑3/S))
820 EL=(((4*Q)/(O*0.6*3.142*I*I))↑2)*0.5*R
822 REM 0.6=COEFF.OF DISCHARGE FOR HOLE
825 REM EL=EXIT LOSS FROM DISTRIBUTOR HEAD
```

## COMPUTER PROGRAM "FPD1" CONTINUED.

```
830 LD=R*9.81*J
835 REM LD=LOSS FROM TROUGH TO STILLING TANK
840 REM Q=FLOW RATE IN SYSTEM(DISCHARGE RATE(M↑3/S))
845 P=(Q*(H+U+W+X+EL+LD))/A
850 REM P=REQUIRED POWER OUTPUT OF PUMP
860 PRINT#4,""
870 PRINT#4,"FRICTIONAL LOSSES IN TROUGH (N/M↑2)=";H
880 PRINT#4,"FRICTIONAL LOSSES IN PIPE U(N/M↑2)=";U
890 PRINT#4,"LOSSES AT BENDS W(N/M↑2)=";W
900 PRINT#4,"REQUIREMENT FOR DESIRED FLOW VELOCITY IN PIPE X(N/M↑2)
903 PRINT#4,"EXIT LOSS FROM DISTRIBUTOR HEAD EL(N/M↑2)=";EL   =";X
906 PRINT#4,"LOSS FROM TROUGH TO STILLING TANK LD(N/M↑2)=";LD
910 PRINT#4,""
920 PRINT#4,"P=";P
930 PRINT"PRESS"
940 PRINT"C TO ENTER MORE DATA"
950 PRINT"I TO END"
960 GET A$:IF A$=""GOTO 960
970 IF A$="C" GOTO 60
980 CLOSE 4:END
```

FIGURE 1

Flow Diagram for Computer Program "FTD1".

FLOW DIAGRAM FOR COMPUTER PROGRAM – FTD1;

Calculation of Upstream trough length X(m) & Boundary layer thickness DB(m).

FIGURE 2

Flow Diagram for Computer Program "FPD1".

FLOW DIAGRAM FOR COMPUTER PROGRAM — "FPD1": Calculation of required power output of Flume Water Pump.

2) Pipe Diameter (D) = 5" (127mm)

3) Number of pipe diameters available upstream of device = 13D

4) Maximum permissible value of area ratio (m) = 0.5

5) Flow Rate (Q) = 2135.83 $ft^3/hr$.

6) Upstream Pressure (p) = 0.9374 $lbf/in^2$.

7) Atmospheric Pressure (pb) = 14.693 $lbf/in^2$.

8) Absolute Upstream Pressure (P) = p + pb = 15.630 $lbf/in^2$.

9) Density of Sea Water ($\rho$) under working conditions = 63.9887 $lb/ft^3$.

10) Sea Water Absolute Viscosity (u) at Working Conditions ($10^oC$) = 1.38768 Centipoise).

11) Suitable value of pressure difference (h) across the measuring device (manometer) = 30 in.$H_2O$.

12) Quantity N =

$$N = \frac{Q\sqrt{\rho}}{359.2\, D^2\sqrt{h}} = \frac{2135.83\sqrt{63.99}}{359.2 \times 5^2 \times \sqrt{30}} = 0.3474$$

13) From Figure 3. BS1042: Part 1: 1964

$m = 0.49$

14) From Figure 38. BS1042

$C = 0.606$

15) $$mE = \frac{N}{C} = \frac{0.3474}{0.606} = 0.5733$$

16) From BS1042: Appendix J $\frac{d}{D} = 0.7052$

17) Orifice Diameter (d) is therefore:

$$d = 0.7052 \times D = 0.7052 \times 5 = 3.526 \text{ in.}$$

18) New Area Ration (m) $= \frac{d^2}{D^2} = \frac{3.526^2}{5^2} = 0.4973.$

19) Reynolds Number (Re) $= \dfrac{Q\rho}{15.8\ \mu D\sqrt{m}}$

$= \dfrac{2135.83 \times 63.9887}{15.8 \times 1.38768 \times 10^{-2} \times 5 \times \sqrt{0.4973}}$

$= \underline{176785}$ (Turbulent)

20) From Figure 38: BS1042. For m = 0.4973

$Z_R = 1.013$

and $Z_D = 1.004$

21) Improved value for CmE $= \dfrac{N}{Z_E}$

E = 1 for liquids $= \dfrac{0.3474}{1.017 \times 1}$

$= \underline{0.3416}$

22) From Figure 3: BS1042. m is now 0.485

23) From Figure 38: BS1042. C is still 0.606

24) mE is therefore CmE $= \dfrac{0.3416}{0.606}$

$= \underline{0.5637}$

25) From Figure 63: BS1042: Appendix J

$\dfrac{d}{D} = \underline{0.7007}$

26) Therefore $\dfrac{d}{D} = 0.7007$

$d = 5 \times 0.7007$

$= \underline{\underline{3.5035 \text{ in}}}$

A device was therefore designed with an orifice diameter of 3.5035in.(88.99mm). It was located in the 5" (127mm) diameter return pipe with pressure tappings positioned 127mm upstream and 63.5mm downstream. Comprehensive details of the design are available for inspection.

APPENDIX 'J'.

## An Analysis of Errors in Measurements of Flow-Rate and Velocity for the Flume.

The sources and magnitudes of errors in measurements of Flow Rate and Velocity are analysed. The results of the analysis have been used to produce Figures 6 to 8 included in the main text. (Section 5).

(a) Errors in Velocity Measurement

Accuracy - No estimate possible - a more accurate means of measuring velocity was not available for comparison.

Precision

(1) Temperal Variations in Flow

Low Flow: Fluctuations are in the order of 1 unit on the meter. At low velocities ($< 0.0425$m/s) this is equivalent to an error of 27.8%.

High Flow: Fluctuations are in the order of 4 units on the meter. At high velocities ($> 0.525$m/s), this is equivalent to an error of 0.5%.

(2) Calibration Errors

(i) Manometer Setting Error

Error in setting the angle of the manometer is approximately $0.25^{\circ}$. This is equivalent to an error of approximately 1.1%.

(ii) Manometer Reading Error

The error in reading the manometer is approximately 0.25mm. Over a length of 42mm this is equivalent to 0.6%.

(3) Combined Errors

Maximum Error (Low Flow) = 27.8 + 1.1 + 0.6
= 29.5%

Minimum Error (High Flow)= 0.5 + 1.1 + 0.6
= 2.2%

(b) Errors in Flow-Rate Measurement - Based upon experimentally Determined Flow-Rates.

Accuracy - As for (a)

Precision

(1) Errors in Velocity Measurement - See (a)

Low Flow = 29.5%

High Flow = 2.2%

(2) <u>Planimeter Area Measurement Error</u> = 0.8%

(3) <u>Manometer Errors</u>

(a) Setting = 1.1%

(b) Reading = 0.6%

(4) <u>Combined Errors</u>

Maximum Error (Low Flow) = 29.5 + 0.8 + 1.1 + 0.6

= <u>32%</u>

Minimum Error (High Flow)= 2.2 + 0.8 + 1.1 + 0.6

= <u>4.7%</u>

(5) <u>The Consequences of Variations in Flow-Depth</u>

Flow-Rate is a combination of two variables: Velocity and Depth. Low, deep flows are subject to more error than low, shallow flows because of the large velocity measuring error component. Allowance has been made for this in the production of Figures 7 and 8.

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