THE

PALAECOECOLOGICAL SIGNIFICANCE OF INFAUNAS

AND THEIR

ASSOCIATED SEDIMENTS

by

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CONTENTS

	Page
CHAPTER 1. INTRODUCTION AND METHODS	
Introduction	1
Topography and Drainage	2
Climate	3
Tides and Current Circulation Patterns	4
Solid Geology	6
Glacial History	6
Post Glacial History	8
Raised Beach Section, Carsethorn	9
Carse Bay and the Carse Sands	13
Methods	15
CHAPTER 2. SEDIMENTOLOGY	
Introduction	21
Composition of the Sediments	21
Source of the Sediment	23
Thickness of the Aerobic Layer	24
Internal Sedimentary Structures	26
Lamination	26
Surface Sedimentary Structures	28
Megaripples	28
Minor Ripples	32
Rill Marks	34

Page

CHAPTER 2. SEDIMENTOLOGY (contd.)

Surface Sedimentary Structures (contd.)

Mud Cracks 35

Ridged Erosion Pools 35

Storm Structures 36

Sand Volcanoes 38

Granulometric Analysis 42

Grain-Size Frequency Distribution 43

Cumulative Curve Types 45

CHAPTER 3. TRANSECT STUDIES - LIVING FAUNA

Introduction 47

Phylum Protozoa 48

Phylum Coelenterata 48

Class Hydrozoa 48

Class Scyphomedusae 49

Aurelia aurita (L) 49

Chrysaora hysoscella (L) 50

Phylum Ctenophora 50

Pleurobrachia pileus (Müller) 50

Phylum Annelida 50

Class Polychaeta 50

Nereis diversicolor (Müller) 51

Polydora ciliata (Johnston) 52

Arenicola marina (L) 53

Pectinaria sp. 55

Page

CHAPTER 3. TRANSECT STUDIES - LIVING FAUNA (contd.)

Phylum Arthropoda 55

Class Cirripedia 55

Balanus balanoides (L) 55

Elminius modestus Darwin 56

Class Malacostraca 57

Gammarus sp. 57

Corophium volutator (Pallas) 57

Crangon vulgaris Fabricus 61

Carcinus maenas (L) 61

Phylum Mollusca 62

Class Gastropoda 62

Littorina littorea (L) 62

Hydrobia ulvae (Pennant) 63

Retusa obtusa (Montagu) 68

Class Lamellibranchia 70

Mytilus edulis L 70

Cardium edule L 72

Scrobicularia plana (da Costa) 78

Macoma balthica (L) 80

Tellina tenuis (da Costa) 88

Mya arenaria L 90

Phylum Chordata 97

Class Pisces 97

Pleuronectes platessa L 97

Platichthys flesus L 97

Page

CHAPTER 3. TRANSECT STUDIES - LIVING FAUNA (contd.)

Phylum Chordata (contd.)

Class Pisces (contd.)

Clupea harengus L 97

Salmo salar L 97

The Effects of Birds in Intertidal Areas 97

Discussion 100

CHAPTER 4. TRANSECT STUDIES - SHELLS, VALVES AND FRAGMENTS

Introduction 104

Phylum Arthropoda 105

Class Cirripedia 105

Balanus sp. 105

Phylum Mollusca 106

Class Gastropoda 106

Littorina littorea (L) 106

Littorina saxatalis (Olivi) 106

Hydrobia ulvae (Pennant) 107

Retusa obtusa (Montagu) 108

Class Lamellibranchia 109

Mytilus edulis L 111

Cardium edule L 113

Scrobicularia plana (da Costa) 117

Macoma balthica (L) 118

Tellina tenuis (da Costa) 122

Mya arenaria L 122

Page

CHAPTER 4. TRANSECT STUDIES - SHELLS, VALVES AND FRAGMENTS (contd.)

Phylum Mollusca (contd.)

Class Lamellibranchia

Mactra corallina (L) 123

Spisula subtruncata (da Costa) 123

Modiola modiolus (L) 124

Discussion 124

CHAPTER 5. REWORKING

General Discussion 126

Rapid Reworking During Storms 131

Development and Growth of a Meander 135

Migrations of the River Nith Channel 140

CHAPTER 6. SHELL-BEDS

Introduction 145

Accumulations on Sand Flats 145

Accumulations on Channel Floors 148

The Left-Right-Phenomenon 152

Surface Shell-Bed 154

Shallow Channel-Floor Shell-Bed 158

Deep Channel-Floor Shell-Bed 160

Buried Shell-Bed 163

Orientation of Valves on a Channel Floor 166

Discussion 167

	Page
CHAPTER 7. EXPERIMENTAL STUDIES	
Experimental Procedure and Results	170
Composition of Residual Populations	177
CHAPTER 8. SUMMARY AND CONCLUSIONS	180
ACKNOWLEDGEMENTS	186
REFERENCES	187
TABLES	
PLATES	

CHAPTER 1

INTRODUCTION AND METHODS

In recent years palaeontologists have become increasingly aware of the necessity to study fossil assemblages as ecological communities. The importance of this ecological approach to fossil faunas has been discussed by Craig (1964).

In-situ fossil assemblages are rare in most marine invertebrate groups. The majority of fossil faunas contain elements which have been reworked and concentrated from different faunal communities. Many fossil shell-beds contain both epifaunal and infaunal elements. In order to interpret fossil shell-beds, their mode of formation and their relationship to the living populations from which the shells were derived, it is essential to understand the processes operating in the formation of modern shell-beds. Any differences in composition between the original living population and the shell-beds formed from it as a result of reworking are of considerable importance in palaeoecology. An understanding of the effects of successive cycles of reworking on the composition is also essential if accurate palaeoecological inferences are to be drawn from the study of fossil shell-beds.

The Solway Firth was suggested as a suitable area in which to investigate these relationships between living faunas and their associated shell-beds as extensive sand and mud flats are exposed at low tide. The Scottish shores of the Solway are free from contamination from industrial effluents and thus the faunas are largely unaffected by the activities of Man.

The area of the Solway investigated lies at the mouth of the River Nith 22 kms south of Dumfries (Fig.1). The Carse Sands off Carsethorn village and the mud and silt flats of Carse Bay are especially suitable as they contain comparatively few living species, although the number of individuals of each of these species may be considerable. The differences between the true composition of the living fauna and the composition inferred from the studies of the local shell-beds can be more easily understood.

TOPOGRAPHY AND DRAINAGE (Fig.1)

The Solway basin is completely surrounded by hills. To the north are the deeply dissected Southern Uplands, while to the east lie the Northern Pennines and to the south are the mountains of the Lake District and West Cumberland. The low undulating coastal plain of the Solway Firth is largely composed of glacial deposits.

Several important river systems flow southwards from the Southern Uplands into the Solway Firth. These include the Nith (over 147 kms in length), the Dee and Annan (both 80 kms long) and the Cree, Fleet, Ken and Lochar.

George (1956) showed that the River Nith had a complex history. The modern course is a composite of three valleys forming the present mature valley by rapid weathering of the Permian rocks of the Thornhill and Dumfries synclinal basins. Rejuvenescence is seen above Sanquhar and between Mennock and Enterkinfoot. George (1956) and Marshall (1961) have shown that the pre-glacial course of the Nith from Dumfries to the sea was probably by way of the present

FIG. 1. LOCATION OF AREA AND DRAINAGE.

A .....Annan

C .....Carlisle

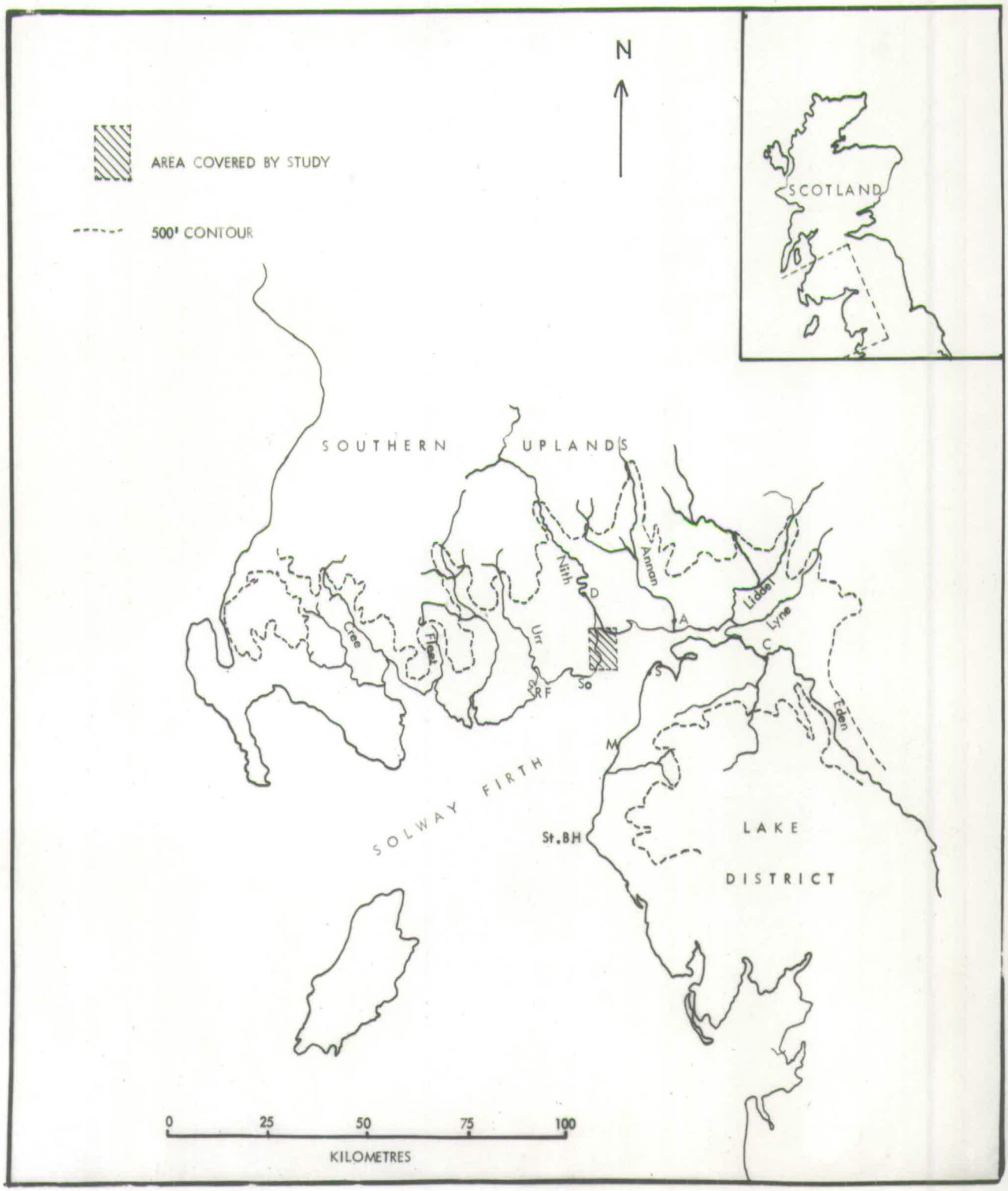
D .....Dumfries

RF .....Rough Firth

S .....Silloth

So .....Southerness

St.BH .....St. Bees Head


N
AREA COVERED BY STUDY
500' CONTOUR
SCOTLAND
SOUTHERN UPLANDS
Nith
Annan
Liddel
Lyne
Esk
Eden
Cree
Fleet
Urr
SRF
So
D
A
C
S
M
R
St.BH
SOLWAY FIRTH
LAKE
DISTRICT
0
25
50
75
100
KILOMETRES

Lochar valley. The river was diverted to its present course when this valley was blocked by moraines east of Dumfries.

The Esk with its tributaries from the Southern Uplands and the Eden with tributaries from the Northern Pennines flow into the head of the Solway Firth.

CLIMATE

Detailed climatic records from 1961 to 1964 have been published (Bailey, Perkins and Williams 1963a, b and Perkins, Bailey and Williams 1964a) as part of the United Kingdom Atomic Energy Authority investigation of the biology of the Solway Firth in relation to the movement and accumulation of radioactive materials.

The average annual rainfall for Dumfries is 75 cms and for Carlisle it is 102 cms. The wettest months are usually July, August, September and October. The winter rainfall is generally between 7 and 10 cms per month. Marshall (1961) showed that in the months of June and July potential evapotranspiration in the Solway area may exceed the rainfall. Heavy rainfall in the Southern Uplands frequently causes flooding in the lower course of the Nith from Dumfries southwards and the Nith Channel off Carsethorn is generally two to three times its normal width during floods at low tide.

Analyses of wind direction and strength given by Bailey, Perkins and Williams (1964b), Perkins, Bailey and Williams 1964b, c) and by Marshall (1961) show that the dominant winds come from the southwest and west and to a lesser extent from the northeast.

Winds from the southwest tend to be fairly strong and the writer's experience out on the sandflats suggests that these southwesterly winds may blow continuously for periods of at least several hours.

The combination of a strong southwesterly wind and a high spring tide sometimes produces flooding on the low lying ground just to the north of Carsethorn. A strong southwesterly wind may delay the ebb by up to forty minutes while a strong north-easterly wind blowing down the Solway may delay high water by a similar period.

Wind and rain storms have definite effects on the mud and sand flats. Details of some of these effects and of structures produced during storms are given in Chapter 2.

TIDES AND CURRENT CIRCULATION PATTERNS

The tidal stream entering the Solway passes between the north end of the Isle of Man and Wigtownshire coast. The strongest tidal currents are to be found on the Scottish shores of the Solway. Details of tidal currents published by the Admiralty Hydrographic Department (1933) show that during spring tides the rate of flow for both ebb and flood tides is between 3 and 3.5 knots. In channels the rates of ebb and flood may be as high as 5 knots for spring tides and 3 knots for neap tides. Perkins and Williams (1963a) found that flood tides in the upper Solway generally last four hours whereas ebb tides last eight hours. They showed that for the Solway as a whole flood currents are generally stronger than ebb currents.

The height of high water spring tides at Hestan Island at the mouth of Rough Firth varies from 7·78 metres to 9·18 metres and the height of high water neap tides varies from 5·49 metres to 6·67 metres.

The shingle beach at Carsethorn is submerged during high spring tides. At neap high tides, however, the inshore upper mud flats in Carse Bay are exposed. The tidal range in the Carsethorn area during spring tides is approximately 7·93 metres.

The current circulation patterns in the Solway Firth have been investigated by Bailey, Perkins and Williams (1964b) and Perkins, Bailey and Williams (1964b, c) using sea-surface and sea-bed drifters. They found that the general movement of sea-surface drifters was downstream, but the sea-bed drifters moved upstream. The surface residual currents deduced from the surface drifters indicate a slow drift towards the Irish Sea. Strong westerly winds alter this pattern, however, by holding water in the Solway Firth, whereas strong northeasterly winds increase the speed of the downstream surface currents.

The movements of the sea-bed drifters were largely governed by tides. Bottom residual currents did not appear to be related to fluctuations in fresh water inflow. Sea-bed drifters released in the upper Solway east of Southerness were transported downstream indicating the presence of strong bottom ebb currents, whereas in the outer Solway the reverse was seen, the dominant movement being upstream related to flood tides. Movement of drifters on the sea-bed was largely restricted to major flood channels.

On the Carse Sands the dominant current deduced from sedimentary structures is the ebb current. The flood currents appear to be very much weaker as sedimentary structures produced by flood tides are comparatively rare.

SOLID GEOLOGY

Silurian greywackes and shales form most of the coastline west of Kirkcudbright, while limestones, shales and sandstones of Lower Carboniferous age occur in the outlier on the southeast flank of the Dalbeattie and Criffel granodiorite intrusion between Kirkbean and Southerness, and to the west between Balcary Point and Abbey Head. Lower Carboniferous rocks are also found west of Annan. Permian rock occurs in Dumfries, on the eastern bank of the River Nith and beneath Caerlaverock Merse. Sandstones and shales of Triassic age underlie the boulder clays east of Annan on the north side and east of Maryport on the south side of the Solway.

GLACIAL HISTORY

Three advances of the ice sheet - the Early Scottish Glaciation, the Main Glaciation and the Scottish Readvance Glaciation - can be recognised in the Solway area. Detailed studies of the glacial history of the area have been made by Charlesworth (1926), Trotter (1929) and by the Geological Survey (1896, 1926, 1930, 1935) and a detailed summary is given by Marshall (1961).

The Early Scottish Glaciation is represented by occasional

outcrops of boulder clay containing Criffel Granite erratics. During the Main Glaciation boulder clay was deposited by ice sheets from the Southern Uplands which were deflected westwards along the Solway by ice from the Lake District. The retreat of this ice resulted in the deposition of sands and gravels. Widespread sandy boulder clays containing Southern Uplands erratics were deposited by the Scottish Readvance Glaciation. This last advance has been dated between 13,000 B.C. and 11,000 B.C. by Walker (1960, personal communication in Marshall 1961). The retreat of this ice left discontinuous deposits of sands and gravels.

The final retreat of the ice was marked by the presence of valley glaciers in the valleys of the Cree, Fleet, Ken, Nith and Annan. The sand and gravel outwash deposits of the Nith Valley Glacier, which are deltaic at their southern end, extend down the valley and merge into the raised beach deposits. At Kirkbean the raised beach backs on to sand and gravel mounds 200 - 250 feet high (Marshall 1961).

The general stratigraphy of the glacial deposits based on Marshall (1961) is given below:-

GLACIAL STAGE	DEPOSITS
Final Retreat	Nith Valley glacial deposits Outwash sands and gravels
Scottish Readvance	Upper sands and gravels Upper boulder clay
Main	Middle sands and gravels Lower boulder clay
Early Scottish	Basal boulder clay

Outcrops of the Upper sands and gravels (deposited during the retreat of the Scottish Readvance Glaciation) form much of the present day Solway coast line.

POST GLACIAL HISTORY

The two main features of the Post Glacial history of the Solway, namely the submerged forest and the raised beaches have been discussed in detail by Marshall (1961).

During the period of marine regression following the formation of the "100 foot" and "50 foot" raised beaches elsewhere in Scotland the undulating surface of the glacial sands and gravels in the Solway was colonised by Birch, Pine and Oak, and a forest peat was developed. Pollen analysis gives an age of approximately 5000 B.C. for this deposit. Isolated outcrops of the forest peat are exposed from time to time on the shores of the Solway. The Geological Survey (1935) recorded an outcrop at the mouth of the New Abbey Burn.

With further recession of the polar ice cap a eustatic rise of sea level soon after 5000 B.C. (Godwin 1956) resulted in a marine transgression which submerged the forest and deposited silts and sands reworked from the coastal glacial deposits. At this stage the level of mean high water was 1·8 to 2·4 metres above its present level. The beaches associated with this level are dated as 3500 B.C. on archaeological evidence. Isostatic uplift of the land resulting in a regression of the sea left this upper beach as an inland feature - the upper warp terrace. A pause in the isostatic uplift sometime between 3000 B.C. and

1500 B.C. (Donner 1953) resulted in the formation of a second terrace - the lower warp terrace - when mean high tide level was 0·9 to 1·2 metres above that of the present day.

It is possible that isostatic uplift is taking place at the present time in the Solway Firth. Valentin (1953) showed that the Scottish shore of the Solway is rising at a rate of 1 mm per year and the English shore by 0·5 mm per year. Evidence of an uplift of 5 to 10 cms in the last 100 years would be unlikely to be preserved in the Solway. Many major changes in the courses of ebb and flow channels producing changes of coastal and intertidal geography and in the position of mean high water mark have occurred during the same period (see Chap. 5 and Fig. 53).

RAISED BEACH SECTION, CARSETHORN

Good exposures of raised beach sections in the Solway area are rare. Details of one measured section in the ballast pit, Marshall Dock, Silloth are given in the Geological Survey Memoir (1926).

During August and September 1962 two temporary sections of the raised beach were exposed in excavations made by Kirkcudbrightshire County Council opposite the Steamboat Inn in Carsethorn village. These sections were examined and measured together with the "25 foot" raised beach section exposed by natural coastal erosion 400 metres to the south (Plate 1). The stratigraphy and relative positions of the three measured sections are given in Fig. 2. The size grades used are those proposed by Wentworth (1922) and the roundness classes by Pettijohn (1957).

FIG. 2. RAISED BEACH SECTIONS, CARSETHORN.

A. Coastal section 400 metres south of Carsethorn.

B. Excavation opposite Steamboat Inn.

C. Excavation opposite Steamboat Inn.

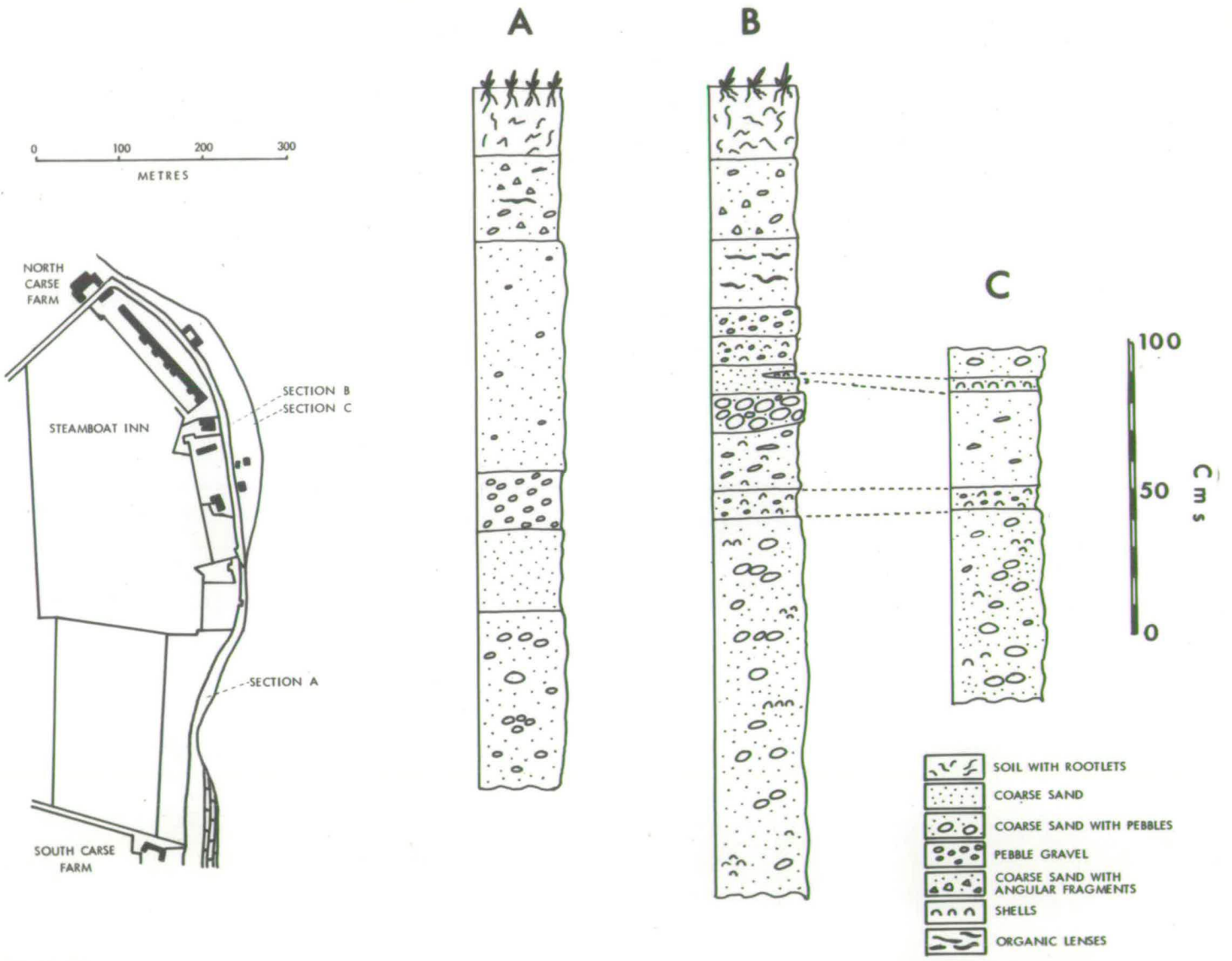

0
100
200
300
METRES
NORTH CARSE FARM
STEAMBOAT INN
SECTION B
SECTION C
SECTION A
SOUTH CARSE FARM
A
B
C
100
50
0
Cms
SOIL WITH ROOTLETS
COARSE SAND
COARSE SAND WITH PEBBLES
PEBBLE GRAVEL
COARSE SAND WITH ANGULAR FRAGMENTS
SHELLS
ORGANIC LENSES

FIG. 2

Details of Section A (Coastal Section)

Top soil with rootlets	23 cms
Coarse - very coarse sandy soil with small subangular to subrounded granules and pebbles, poorly sorted	30 cms
Coarse - very coarse sand, poorly sorted, loosely consolidated, distinctive dark brown colouration	79 cms
Pebble gravel with small rounded to well rounded pebbles, poorly sorted	20 cms
Very coarse fairly well sorted sand	28 cms
Very coarse sand with bands and lenses of flattened, subrounded to rounded pebbles, cobbles and occasional boulders	60+ cms

Details of Section B (Steamboat Inn excavation)

Top soil with rootlets	25 cms
Coarse sandy soil with angular to subrounded pebbles, poorly sorted	28 cms
Medium sand with occasional small rounded pebbles, poorly sorted	23 cms
Medium - coarse sand with small subrounded to rounded pebbles, poorly sorted	10 cms
Subrounded to rounded pebbles in medium to coarse sandy matrix, poorly sorted, *Littorina littorea* shells with *L. littorea*, *Cardium edule* and *Macoma balthica* fragments	10 cms
Medium to coarse sand, poorly sorted, with shell lens containing abundant fragments of *L. littorea*, *L. littoralis*, *Turritella communis*, *M. balthica*, *C. edule* and *Mytilus edulis*	10 cms
Pebble lens composed of red Dumfries Sandstone (Permian) in medium sand matrix formed by disaggregation of the sandstone	13 cms
Medium sand with occasional rounded to well rounded flattened pebbles, poorly sorted, with *L. littorea* shells and *C. edule*, *M. balthica* and *M. edulis* fragments	20 cms
Coarse sand with occasional small rounded to well rounded pebbles, poorly sorted, with fragments of *C. edule*, *M. balthica* and *L. littorea*	10 cms
Coarse sand with lenses of large subrounded to rounded flattened pebbles and cobbles, poorly sorted, with fragments of *C. edule* and *L. littorea*. Occasional shell lenses with *L. littorea*, *L. saxatalis*. *Patella vulgata* shells; *C. edule*, *M. balthica* valves and *Littorina*, *T. communis*, *C. edule*, *M. balthica* and *M. edulis* fragments	120+ cms

A correlation was possible between sections B and C as they were only 30 metres apart (Fig. 2). The details of these sections, however, reveal considerable lateral changes in the thickness of particular units and the lensing out of others which make correlation with section A impossible.

Frosted sand grains are of widespread occurrence throughout the raised beach sediments. They are identical in appearance to frosted sand grains obtained by disaggregation of a specimen of Dumfries Sandstone and it is probable that they were derived by glacial erosion of Permian sandstone outcrops of the lower Nith valley.

The fauna from Sections B and C is of the type commonly found on beach strand lines. L. saxatalis and P. vulgata live on rocky shores attached to rock faces and in crevices. L. littoralis lives on Fucus while L. littorea lives attached to rocks on the middle and lower shore. M. balthica and C. edule are typical members of the intertidal silt and sand infaunal community. T. communis, however, lives in muds and muddy gravels below mean low water and has been recorded by Perkins and Williams (1963b) from Blackshaw Bank and other muddy areas in the upper Solway.

The spires and apertures of the Turritella shells from the raised beach are always badly broken indicating transport on to the beach from some distance and probably considerable rolling while on the strand line. The Macoma valves are more or less intact, indicating local derivation. The Cardium valves are also probably from the local sand flats, although the shell is very robust and is not easily damaged during transportation. Patella/

Patella and the three species of littorina were probably all derived from rocky areas adjacent to the beach as most of the shells show little evidence of transportation. Patella vulgata and Littorina littoralis are not found living on the Carsethorn shore today, and therefore conditions at the time of formation of the beach must have differed slightly from the present time.

CARSE BAY AND THE CARSE SANDS

The size of the area studied was limited by the distances that could be examined on foot over the Carse Sands from Carsethorn during the period of low tide. The eastern boundary of the area was marked by the west bank of the Nith Channel.

Very few of the channels exposed below high water mark are named and for the purposes of this study they have been identified by the use of capital letters. Other localities referred to in the text are numbered. These localities and channels are indicated on Fig. 3.

The detailed geography of the sand flats changes from day to day but the positions of Channels B, C, D and G indicated on Fig. 3 were more or less constant for the period of the study. The positions of the tributaries to the head waters of Channels G and H changed from month to month and it was not possible to map them accurately. The positions indicated on Fig. 3 are those of summer 1962. The width and depth of the channels on a particular day depended on the rainfall during the previous 24 hours. At times of flood the Nith Channel was not confined to its normal banks and south of Locality 20 part of the flow was diverted down

FIG. 3. MAP OF CARSE SANDS SHOWING LINES OF TRANSECTS, CHANNELS AND LOCALITIES REFERRED TO IN THE TEXT.

Channels..... A to H, J and K

Isolated pool of water..... I

Localities.....(1) - (28)

(5 and 7 omitted).

Transect Stations:-

Transect 1..... 1 - 15

Transect 2..... 1 - 13

Transect 3..... 1 - 8

U.M.F. .....Upper Mud Flat.

L.M.F. .....Lower Mud Flat.

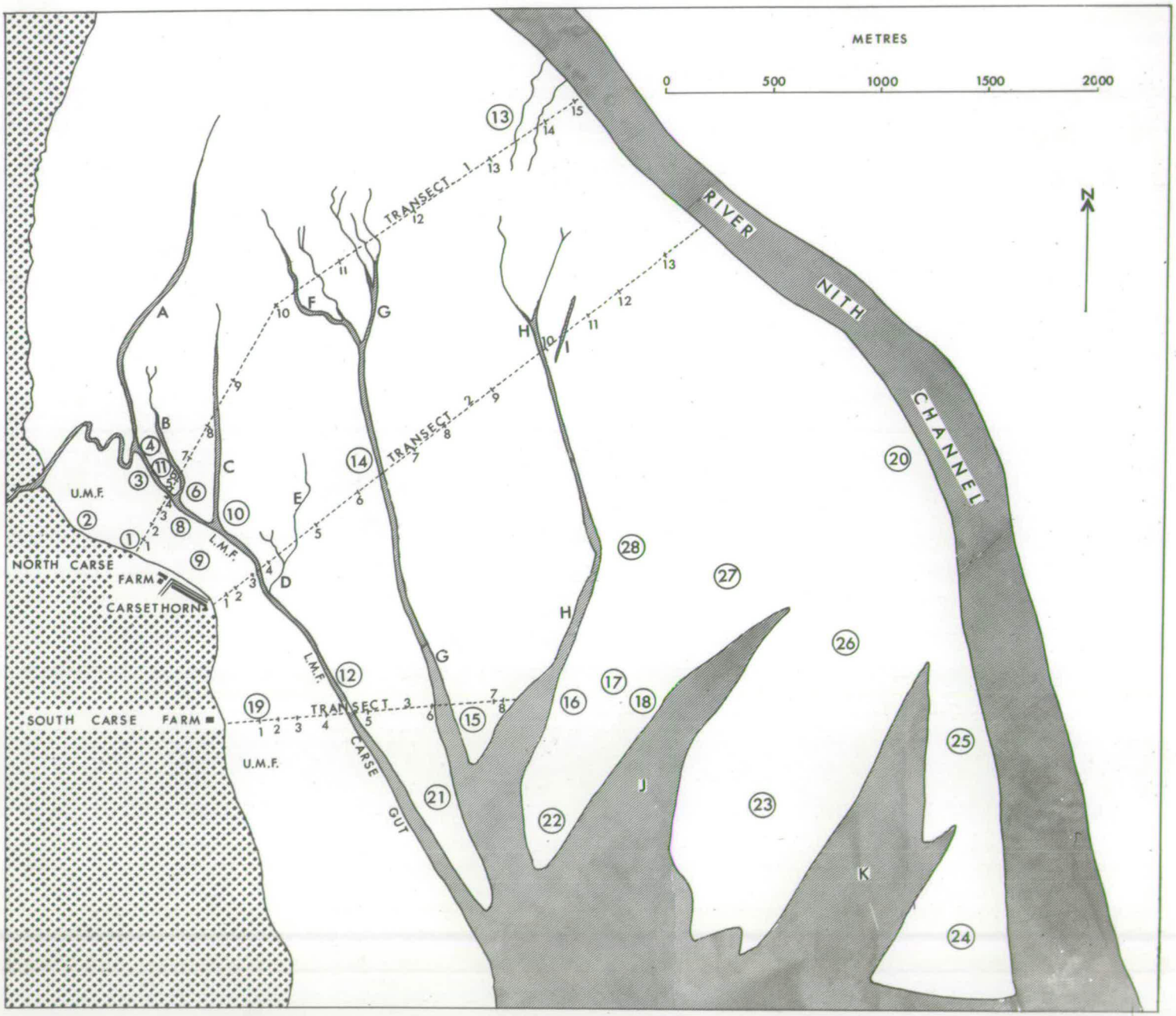

METRES
0
500
1000
1500
2000
N
RIVER NITH
CHANNEL
TRANSECT 1
TRANSECT 2
TRANSECT 3
A
B
C
D
E
F
G
H
J
K
L.M.F.
U.M.F.
NORTH CARSE FARM
CARSETHORN
SOUTH CARSE FARM
CARSE GUT

FIG. 5

Channels J and K. At these times it was not normally possible to ford the lower reaches of Channel H. The detailed position of low water mark at the mouth of the Carse Gut and Channels G, H, J and K is entirely dependent on the height of the tide and the direction of the prevailing winds and it changes at each tide. Many of the sandbanks near Localities 21, 22, 23 and 24 were only exposed at spring tides. A detailed discussion of the changes in the position of certain of the channels is given in Chapter 5.

The shingle beach is nowhere more than 50 metres wide and has an average slope of 6°. South of Carsethorn the configuration of the beach is controlled by two groynes and at South Carse Farm the coast is protected by a stone embankment.

At the foot of the beach there is an abrupt change of slope on to the upper mud flats where the gradient is approximately 1°. The width of the upper mud flat varies from 192 metres north of Carsethorn to 97·5 metres opposite the Steamboat Inn, Carsethorn, and to 366 metres at South Carse.

The mud slope at Carsethorn is 61 metres wide and has a gradient of approximately 3°. The edge of the upper mud flat north of Carsethorn is clearly defined whereas at South Carse, where the mud slope is up to 122 metres wide, the edge of the upper mud flat merges into the mud slope with no clearly defined boundary. The gradient of the mud slope is approximately 2°. Some parts of the lower mud flat north of Carsethorn are fairly stable but south of Locality 8, however, they are generally soft and unstable.

The western bank of the Carse Gut is poorly defined south

of the confluence of Channel C at Locality 10 and parts of the lower mud flats are often flooded following periods of heavy rainfall. The east bank of the Carse Gut is much steeper and better defined than the west bank.

East of the Carse Gut the sediments are much firmer and the highest parts of the sand flats and the slopes to the middle and lower reaches of Channels G and H tend to dry out at low tide. The sand flats between Channels A, B, C, F and the upper reaches of G and H retain sufficient water at low tide to remain fairly wet although they are exposed for a longer period. Detailed profiles across the sand flats are given in Fig. 49 and discussed in Chapter 5.

METHODS

In order to investigate the relationships between living faunas and shell-beds quantitative methods must be employed. In many of the studies of intertidal faunas and shell-beds described in the literature, scant attention was paid to the necessity of collecting an accurate volume of sediment from which to obtain the faunal density measurements. In some cases, although a measured area was marked out on the surface, no frame was used and as the sample was dug the sides of the square collapsed completely changing the dimensions of the sample taken. In other cases the samples were collected without any attempt to ascertain their dimensions and yet they were used to make detailed quantitative comparisons between different areas.

In this study quantitative samples were collected along two transects from the beach to the Nith Channel, and one from the beach to Channel H. Transect 1 ran from a point 230 metres northwest of North Carse Farm along compass bearing N 30° E across Carse Bay to a point 100 metres west of Channel F where the course was changed to N 55° E in order to maintain the line of the transect at approximately right angles to the shore. The original course along N 30° E, east of Channel F would have run approximately parallel to the curvature of the coast to the north of Carse Bay. Transect 2 ran from the beach opposite the Steamboat Inn, Carsethorn, along compass bearing N 50° E to the Nith Channel. Transect 3 ran from the beach opposite South Carse Farm along compass bearing N 85° E to the west bank of Channel H. This transect was not continued beyond Channel H owing to the considerable hazards involved in crossing Channel H while carrying the sampling equipment and the comparatively short time when the areas between Channels H, J and K were exposed at low tide.

Transect 1 was sampled in March 1962 and Transects 2 and 3 in September 1962. Sample stations were selected in order to show the distribution of the fauna in relation to the channels and the detailed geography of the mud and sand flats. Strict adherence to a statistical grid system with no regard to local conditions would not give a true picture of the faunal distribution. The lines of the transects and the location of sample stations are given in Fig. 3.

The composition of the living fauna in sand and mud flats varies with depth below the sediment surface. Preliminary

observations made in October 1961 indicated that Macoma balthica was not usually found living at depths greater than 10 cms. Cardium edule was rare below 8 cms and young lamellibranchs and Hydrobia ulvae were restricted to the top 2 to 3 cms of the sediment. Adult Mya arenaria individuals were only found at depths greater than 10 cms.

The sampling apparatus designed to investigate the quantitative variations in the fauna with depth consisted of a galvanised steel frame defining an area of 1/10th square metre on the sediment surface. The frame, shown on Plate 2a, was 25 cms deep. The sides of the frame were bent outwards to form a flange to strengthen the frame and prevent it from buckling thus altering the volume of sediment taken. At each station the frame was placed on the surface (Plate 2a) and was driven into the sediment by standing on opposite corners until the flange was flush with the surface of the sediment (Plate 2b). Care was taken to ensure that the sides of the frame remained vertical. Five successive layers of sediment were then removed from the frame using a flat steel plate and a trowel (Plate 3a). The accurate depth of the layers was ensured by having a series of holes at 2·5 cm intervals down each side of the plate and a bar of angle iron supplied with two bolts which fitted into the holes and which rested on the flange of the frame. The first four layers were each 2·5 cms thick and contained 2500 ccs of sediment. Plate 3b shows the frame after the first four layers have been removed. The living fauna - with the exception of Mya arenaria - was almost entirely contained in these four layers. As adult Mya shells attain a

length of at least 80 mms the removal of layers of only 2·5 cms thick at depths greater than 10 cms would not yield information of any value. The fifth layer was therefore taken from the depth of 10 cms to the base of the frame at 25 cms. The depth of each layer and the volume of sediment are given below:-

	Depth of layer from surface	Dimensions	Volume of sediment
Layer 1	0·0 - 2·5 cms	1000 sq.cms x 2·5 cms	2500 ccs
Layer 2	2·5 - 5·0 cms	" "	"
Layer 3	5·0 - 7·5 cms	" "	"
Layer 4	7·5 - 10·0 cms	" "	"
Layer 5	10·0 - 25·0 cms	1000 sq.cms x 15 cms	15000 ccs

The sediment from each layer was placed in a polythene bucket as soon as it was collected. It was found that if each layer was sieved before the next one was collected, the frame frequently filled with water, making the removal of the underlying layers very difficult and increasing the chances of contamination. It was therefore expedient to use five polythene buckets although this considerably increased the load which had to be carried. When the five layers were collected approximately 500 ccs of sediment was taken from each bucket and placed in a polythene bag for sediment and microfaunal analysis. The remaining sediment from each layer was sieved and the living fauna, dead shells, valves and fragments were collected into a polythene bag. A 30 mesh sieve was used for layer 1 in order to collect most of the larval shells. Layers 2 to 5 were sieved through a large 2 mm mesh sieve. Where possible the sediment was sieved in a channel or pool close to the station. If a suitable pool was not available a small channel had to be dammed or a pool dug in the sand. The

collection of the samples had to be accomplished as quickly as possible as much of the time available at each low tide was required to transport the equipment across the sand flats to and from the sample stations. A sledge was used to carry the equipment during the sampling of Transect 1. The Carnegie Trust for the Universities of Scotland, however, generously gave an additional grant which enabled an assistant, Robert Lamond, to be employed in September 1962, when the samples from Transects 2 and 3 were collected.

The numbering system adopted for the transect samples contained three numbers separated by oblique strokes; the first indicated the transect, the second the station and the third the number of the layer, e.g. 1/12/4 etc.

A solution of anhydrous industrial spirit and 20% cetrimide was added to the sediment and faunal samples as soon as possible after collection in order to prevent decomposition.

In the laboratory the faunal samples were separated into living and dead shells and valves and one parameter namely length was measured on each. Fragments were separated into species, counted and weighed. The sediment sample for each layer was divided into two by cone and quartering and the volume of one half of the sample, which was retained for sedimentary analysis, was accurately measured. The other half was wet-sieved through a 44 mesh sieve and the macrofauna was collected and measured as above. The numbers of macrofauna from this half sample were doubled to account for the fauna contained in the other half retained for mechanical analysis. The living and dead

"microfauna" - Hydrobia ulvae shells, lamellibranch spat etc. - collected on the 44 mesh sieve were counted and the total numbers were calculated for each layer using the value of the volume obtained from the half sediment sample.

The frame was also used to collect quantitative samples from the shell-beds. A metal plate was fitted to divide the frame into two halves in order to reduce the surface area of the sample to 1/20th square metre and hence reduce the number of shells in the sample. The thickness of the shell-bed was measured at the point of sampling so that volume comparisons between samples could be made. At each station the complete thickness of the shell-bed was removed.

Profiles were taken along the lines of the transects at approximately six-monthly intervals from April 1962 till April 1964 using an 8 inch compensated surveying aneroid. Variations in the thickness of the aerobic layer and changes in the positions of channels were measured at the same time. Distances were measured either by using a 60 foot tape or by pacing for longer distances. At several points along each transect compass bearings were taken on prominent landmarks in order to correct the paced distances between these fixed points.

Some of the other methods used in particular projects are described in the later Chapters where the results of these studies are discussed.

CHAPTER 2

SEDIMENTOLOGY

Intertidal sand and mud flats display a wide variety of internal and surface sedimentary structures. Detailed studies of the North German tidal flats have been made by Häntzschel (1939), of the Dutch Wadden Sea by Van Straaten (1951a, 1954, 1961) and others, and of the Firth of Tay by Mishra (1964).

The internal sedimentary structures in the Carse Sands were examined on the banks of meandering channels or in cut trenches. Undisturbed specimens of the tidal flat laminations were collected using the box sampler devised by Imperial College, London, for use in the Wash.

Only some of the more important sedimentary features recorded on the Carse Sands and mud flats will be discussed in this chapter. Sedimentary structures and erosional features formed during the reworking of the flats by laterally migrating channels are described in Chapter 5.

COMPOSITION OF THE SEDIMENTS

The fine-grained sands east of the Carse Gut are composed dominantly of quartz and several distinct types can be recognised in most samples. Well-rounded, frosted grains, which may be colourless or stained pink, are common throughout the sands. They are identical to those from the raised beach sands (see p. 12) and are presumably derived from local Permian sandstones. Yellow stained, subrounded grains, which may be reworked from Carboniferous

sandstones, are also very common. Angular to subangular grains of clear quartz showing little or no evidence of rounding or transportation are also common. These may be first-cycle grains partly derived from erosion of the granitic masses in the south-west of Scotland. Heavy minerals of several types and muscovite flakes are fairly common throughout the sands. In the fractions greater than 0·1 mm, shell fragments, Foraminifera and ostracod valves are present. Plant debris, including seeds and fragments of the vascular skeleton of deciduous leaves, is quite common in the coarser fractions. Much of the vegetable matter is thus of terrestrial origin. Coal fragments up to 1 mm in diameter are very common throughout the sands. In the more sheltered regions west of Channel H, plant detritus, coal and shell fragments are frequently deposited in ripple troughs at low tide. Under favourable conditions these accumulations could be preserved as small lenses within the sediment. Spines of Echinocardium cordatum are fairly common throughout the sands and occasionally small fragments of the test may be found. Fragments of hydrozoan perisarc are also fairly common.

West of the Carse Gut the silts are composed dominantly of quartz with some admixture of clay. Aggregates of very fine-grained silt and clay-grade particles derived from faecal pellets are common. Organic matter in all stages of decomposition is abundant in the silts. On the upper mud flats towards the beach and especially in the vicinity of Station 3/1 very coarse sand and granule gravel is mixed with the silt and many composite grains occur. "Remanie fossils" such as crinoid ossicles or

brachiopod fragments, derived from the Kirkbean outlier (Lower Carboniferous) are sometimes found in the silts.

Waterlogged driftwood is frequently found in the sand. Much of this is undoubtedly marine flotsam, but occasionally during periods of severe flooding in the middle reaches, the River Nith will bring down tree trunks and branches and deposit them on the sand flats. If these become sufficiently waterlogged they are gradually buried in the sand by the scouring action of the tidal currents around the trunk. An indication of the rate at which burial by scouring can take place was given by a large irregularly shaped tree (Plate 4a) which was first noticed on the sand flats at Locality 14 on 31st March 1963. Just over one year later - on the 9th April 1964 - the bulk of the trunk was buried (Plate 4b) and by September 1964 it was completely buried and no trace could be seen on the sediment surface.

SOURCE OF THE SEDIMENT

The abundance of Echinocardium spines in the sediment suggests that much of the sand is derived from the lower Solway Firth and probably the Irish Sea. Perkins and Williams (1963b) recorded Echinocardium cordatum in isolated areas west of a line between Southerness and Maryport. As the rivers flowing into the Upper Solway have very gentle gradients in their lower reaches little or no sediment other than clay-grade material in suspension is transported by them. Some sand and silt is however brought down during times of flood. Marshall (1961) found that the Upper Solway sediments were dominantly fine sands, and this uniformity

of grain-size throughout the estuary suggested derivation from the sea. Van Straaten (1960a) showed that the decrease in mean grain-size shorewards in the Wadden Sea, and the presence of Echinocardium spines and derived Cretaceous Foraminifera, indicated that most of the Wadden Sea sediment came from the North Sea.

The flood currents are stronger than the ebb currents over most of the Solway Firth except the Carse sands (See Chap.1 pp. 4 - 6). Marshall (1961) showed that a delicate balance is maintained in the Solway between the sediment transported into the Firth by the flood tides and the sediment removed by ebb channels fed by rivers. During the summer drought of 1959 sand accumulated in the upper Solway because the fresh-water flow into the ebb channels was reduced so much that the balance could not be maintained.

THICKNESS OF THE AEROBIC LAYER

The thickness of the aerobic layer (see Fig.49) was measured on the basis of colour changes in depth along the transects in September 1962, March and August 1963, and April 1964.

The thickness of the aerobic layer on the upper mud flats at a given locality is not constant for any length of time, and the thickness at a given time can vary from 1 to 4 cms in distances of less than 1 metre. The thickness is partly determined by the presence of such animals as Corophium volutator (See Chap. 3 p. 58).

Bruce (1928) found that the aerobic zone on a sandy beach was thinnest where the sediment was fine-grained. In general

the results from the Carse Sands agree with this, but the stability of the sediment appears to be of equal importance. In the soft unstable sediments in the vicinity of many meandering channels the aerobic layer is generally more than 30 cms deep and the boundary with the anaerobic layer is very diffuse and cannot be determined on the basis of a colour change. On the stable flats, away from the influence of the migrating channel, the aerobic layer may be only a few cms thick and the boundary of the zone can be easily detected by definite colour change to either grey or black although the grain-size-frequency distribution is virtually identical to that on the banks of the meandering channel.

In the area east of Channel G and to the south of the line of Transect 1 the aerobic layer is more than 30 cms thick. In most cases where pits were dug to depths greater than this no evidence of a colour change indicating a transition to anaerobic conditions could be detected. On the upper and lower mud flats the boundary between the zones was generally marked by an abrupt colour change. The anaerobic zone in the silts was generally black although in some cases the black zone passed downwards into a grey zone. In other cases alternating black and grey zones were developed in depth.

The sulphate-reducing bacterium Desulfovibrio desulfuricans was found in sediment samples from the upper mud flats. Bruce (1928) and Zobell (1946) have emphasised the role of bacteria in the sulphur cycle, and Kaplan, Emery and Rittenberg (1963) have shown on the basis of sulphur isotopic abundance, that biological sulphate reduction is the most important process in this cycle.

INTERNAL SEDIMENTARY STRUCTURES

LAMINATION

Lamination of the tidal-flat type described by Van Straaten (1954) is developed over much of the area and is best seen on the eroding banks of meandering channels (Plate 5a). The lamination in the bank is accentuated by the selective erosion of the sandy layers leaving the more resistant clay laminae. The slight dip of the laminae in Plate 5a towards the channel is due to minor slumping and is not primary.

On the upper mud flats the primary lamination is well developed. The individual sand laminae are generally 2 - 3 mms thick. The mud laminae are thinner and range between 1 and 2 mms in thickness. Individual laminae cannot be traced for any distance as they tend to be lenticular, but groups of laminae can be recognised over distances of up to 2 metres. The laminae in the top 2 - 3 cms of the sediment are disturbed by *Hydrobia ulvae* burrows. The zone from 5 - 7 cms down to 20 - 22 cms is completely disturbed by the burrowing activities of *Arenicola marina*, *Nereis diversicolor*, *Macoma balthica*, *Scrobicularia plana* and other organisms. Detailed descriptions of the effects of these burrowing organisms on the original lamination are given by Schäfer (1956, 1962), Reineck (1958), Seilacher (1957) and others. In some parts of the upper mud flats irregular lenses of mud up to 2 cms thick are present within this disturbed zone. The disruption of the sediment is such that only a few definite burrows can be recognised. The sediment has an indistinctly mottled appearance of the type described by Moore and Scruton (1957).

Between 22 and 30 cms below the sediment surface the laminae are largely intact and are only occasionally disturbed by the presence of an adult Mya arenaria burrow. Below 30 cms the laminae are completely undisturbed.

On the lower mud flats the sand laminae are up to 8 mms thick while the mud laminae are rarely thicker than 1 mm. Some of the sand laminae show ripple lamination. The comparative instability of the lower mud flats makes them largely unsuitable for colonisation by burrowers and hence disturbance of the lamination is comparatively rare.

East of the Carse Gut the lamination is largely preserved in the vicinity of Transect 1 and parts of Transect 2. To the south and east reworking of the sediment has removed the clay material and all traces of the original lamination have been destroyed.

Van Straaten (1954) showed that the lamination was tidal in origin, the mud laminae being laid down during the period of slack water at the turn of the tide. These mud laminae tend to be preserved, partly due to the "Hjulstroem effect" combined with the effects of slight compaction and drying out of the mud laminae at low tide, and the binding activities of benthonic diatoms. Van Straaten and Kuenen (1957, 1958) suggested that 'settling-lag' and 'scour-lag' effects may be partly responsible for the accumulation of fine-grained sediments in tidal flat areas. It is unlikely that these effects are of significance in the Carse Bay mud flats, however, as evidence from sedimentary structures shows that ebb currents are stronger than the flood currents and this will minimise any possible lag effects.

The restriction of burrowing structures on the upper mud flats to the top 25 - 30 cms of the sediment gives an indication of the rate at which the sediment was accumulated. All the burrowing structures can be related to the present sediment surface. If the accumulation of sediment had been slow with the frequent removal of newly deposited laminae, zones of disturbance by burrowing organisms related to former surfaces should be preserved at depths greater than 25 - 30 cms below the present surface. The absence of any such zone related to former surfaces suggests that accumulation was fairly rapid with only the occasional removal of groups of laminae by storm activity until the tidal flat had been built up to more or less its present height. The balance between sediment deposition by tidal currents and its removal by stronger currents and storms maintains the surface more or less at its present height. This equilibrium enables an infauna to develop within the upper mud flats. A discussion of the probable age of the upper mud flats is given in Chapter 5. It is possible that many of the apparent complexities in the study of fossil burrows in sections and cores through laminated sediments may be understood if an attempt is made to relate the zones of burrows to prominent bedding planes.

SURFACE SEDIMENTARY STRUCTURES

MEGARIPPLES

a) Longitudinal Megaripples

Longtudinal megaripples of the type shown on aerial photographs by Van Straaten (1953, 1960b) can be recognised on the

1946 aerial photographs of the Carse Sands. They would appear to be only temporary features as none were recognised on the sands between 1962 and 1964.

b) Transverse Megaripples

Transverse megaripples are developed along the banks and on the floors of Channels J and K, at the mouths of Channels G and H and on the banks between these channels at Localities 17, 21, 22, 23 and 24. Plate 6 shows a panorama of the megaripples taken from Locality 15 in September 1962. The distribution of megaripples shows some evidence of seasonal variation. During the late summer they are usually developed east of Channel H (In September 1962 they were also present at Locality 15 east of Channel G). In the spring, however, the megaripples may be absent altogether as in April 1964 or only developed east of Locality 18. It is possible that stronger tidal currents during winter storms are responsible for flattening out some of the most westerly megaripples.

On the banks of Channels G, H and J the steep face of the megaripple is directed downstream, indicating that these are ebb megaripples (Plate 5b). The wavelength varies from 2 to 8 metres and the amplitude from 30 to 100 cms. Both amplitude and wavelength decrease northwards towards Localities 27 and 28. Allen (1963) showed that the amplitude of transverse megaripples was directly proportional to the wavelength.

The troughs of the megaripples contain a series of pools which are at successively lower levels towards the channel (Plates 5b and 6). At ebb tide when the sea level falls below

the level of the megaripple crests the water flows along the ripple trough to the channel. After most of the water has drained away the isolated pools start to empty towards the channel. Water flows from the highest pool furthest from the channel into the next one and so on into the channel. This movement of water from pool to pool cuts a series of small troughs which join the chain of pools to the channel (Plates 5b and 6). The steep face (lee side) of these ebb megaripples is usually smooth while the shallower upstream face (stoss side) is covered by sets of asymmetric current ripples.

Flood megaripples were found at Locality 17 and about 100 metres north of Locality 15 on the parts of the banks which act as "watersheds" between Channels G, H and J. The lee side of these megaripples was much less steep than that of the ebb megaripples. In many cases the distinction between lee and stoss sides was largely obscured by modification of these flood megaripples by the ebbing tide. In all cases asymmetric current ripples were developed on both the lee and stoss sides. In some cases (Plate 7a) a distinct ridge was formed on the crest of the megaripple by the ebb tide. The final stages in the development of this ridge could be observed as the last of the ebb tide flowed across the crest. Sand grains from the lee side of the megaripple were transported up over the crest of the ridge and deposited on the former stoss side of the megaripple.

Trenches cut parallel to and at right angles to the crests of both ebb and flood megaripples failed to reveal any discernible internal structure.

Transverse megaripples are normally only found in the southern parts of the area at the mouths of the ebb channels. In late March 1963, however, transverse megaripples in their initial stages of formation were seen over most of the Carse Sands east and southeast of Channel C. These early-stage megaripples (Plate 7b) had amplitudes of 1 to 5 cms and were covered by normal asymmetric ebb current ripples. Van Straaten (1953) described similar early-stage megaripples and stated that they were frequently seen on large sandy tidal flats although they never developed into large scale transverse megaripples. Allen (1963) showed that there is a partial direct relationship between megaripple amplitude and the depth of water in which the ripple was formed. These early-stage megaripples were only observed on the Carse Sands during the period of the 1963 vernal equinoxial spring tides when tides of up to 9·2 metres were predicted for Hestan Island and the low-lying fields north of North Carse Farm were flooded at high tide. They were not observed in September 1962 during the autumnal equinoxial spring tides when, although a similar high tide was predicted for Hestan Island, no flooding of the North Carse fields took place. On 27th March 1963 at the time of high tide the wind direction was between 200 and 210° and varied in strength from 10 to 14 knots, while on September 15th 1962 the wind direction was 260° and the strength was 8 to 9 knots.* It is possible that the direction and strength of the wind on March 27th 1963 was partially responsible for the flooding of the fields giving sufficient depth of water at high tide to

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*Meteorological data kindly supplied by the Superintendent, Meteorological Office, Edinburgh.

exceed the minimum depth required for the initiation of transverse megaripples on the Carse Sands.

Tides of 9.1 metres or more are rare and it has not so far been possible to test whether or not the initiation of transverse megaripples on the Carse Sands only occurs when the depth of water at high tide is such that flooding of low-lying land takes place.

MINOR RIPPLES

A wide variety of different ripple patterns are developed by the ebbing tide. The patterns in a particular area change from week to week and in many cases from day to day.

a) Asymmetrical Ripples

Asymmetrical ripples formed by the ebb tide are very common over the Carse Sands. The ripples on the flat expanses generally have parallel crests and comparatively little bifurcation is developed. Irregular patterns with frequent bifurcation (Plate 8a) tend to be found in the vicinity of large ebb channels where the ebb current patterns are more complex. The wavelength of these ripples vary from 4 to 20 cms. Large irregular asymmetrical ripples with wavelengths of up to 25 cms and amplitudes from 3 to 8 cms are frequently developed on the banks of actively meandering channels. They indicate instability in the sediment and the sediments below them only rarely contain any fauna. Ripples of this type are common on the lower mud flats especially near Locality 3.

Lineations and longitudinal ripple marks (Plate 8b) may be

developed on the crests of asymmetrical ripples situated on the gently sloping banks of Channels C, G and H. Van Straaten (1951b) found that this type of longitudinal ripple was restricted to the sloping banks of gullies. He showed that they could be formed during the later stages of ebb flow and possibly also during the early flood tide before the water overflowed the banks of the channel on to the flats.

b) Superposed Ripples

Superposed ripples with parallel crests (Plate 9a) or with sub-parallel crests (Plate 9b) are sometimes developed on the sand flats near the mouths of Channels G and H. The primary ripple is possibly formed by the flood tide and the secondary crest superimposed on this by the ebb tide. Similar superposed ripples with parallel or sub-parallel crests have been described by Trefethen and Dow (1960) and Mishra (1964).

Superposed ripples with the crests at approximately right angles (Plate 10a) are common on the slopes draining towards major ebb channels. The initial asymmetrical ripples are formed by the ebb current flowing across the flats. When the upper parts of the flats become exposed the remainder of the water tends to drain away to the ebb channels along the troughs of these ebb ripples forming a series of secondary ripples in the troughs with crests at right angles to the dominant ebb direction. Trefethen and Dow (1960) found that these cross ripples were only formed when the lateral drainage is aided by cross winds. The wavelengths of the primary ebb ripples on the Carse Sands range from 12 to 15 cms. The ripples formed in the troughs were generally smaller with wavelengths of between 4 and 8 cms.

c) Interference Ripples

Interference ripples are not common on the sand flats. Occasionally an extremely regular rectangular pattern may be developed over a small area (Plate 10b). More commonly, however, an irregular polygonal pattern of the type shown in Plate 11a is developed. Towards the edge of the zone the polygons become much more irregular and the ripples tend to become flattened. At the limit of the zone (Plate 11b) the ripples are almost completely flattened and merge gradually into smooth sand. Twenhofel (1932) suggested that interference ripples are formed in shallow water as a result of waves being broken into two sets of crossing oscillations by stranded logs etc.

d) Lingoid Ripples

Well developed lingoid ripples with wavelengths of 15 to 25 cms are found on the floors of most of the ebb channels (Plate 12a).

RILL MARKS

Rill marks are commonly formed over the flats by water draining to lower levels. On the upper mud flats and mud slope the dendritic type is developed. Over the sand flats, however, where there is almost no organic matter to bind the sediment, the braided type is found.

On the banks of channels after the tide has receded, the water draining to the channel from the sand flats may cut a large number of isolated rills at regular intervals which gradually widen and join towards the foot of the bank (Plate 12b). The draining of the flat is completed, however, before the rills can coalesce completely.

MUD CRACKS

Incomplete mud cracks (Plate 13a) were seen on the upper mud flats at Locality 8 and at Locality 4. Both these localities were beside steep banks of channels where the water table falls away rapidly at low tide and these parts of the flats dry out. Van Straaten (1954) suggested that incomplete mud cracks could form under water.

It is probable that these cracks, although they were formed initially by drying out of the flats, remain for periods of several months. Movement of sediment on the surface may cover the cracks but they persist in depth. After the Carse Gut changed its course in March 1964 (see Chap. 5) the former channel past Locality 4 became filled with sediment largely derived from the flats beside the high bank and Locality 4. By September 1964 the bank had been lowered by several cms and former mud cracks were re-exposed. The mud lining the cracks was much more resistant to erosion than the surrounding sediment with the result that the mud cracks stood out as positive features up to 1·5 cms above the surface of the sediment (Plate 13b).

RIDGED EROSION POOLS

At the end of March 1963 a series of elongate pools of trapped water were seen on the sand flats at Locality 13 and Station 1/14 (Plate 14a). The long axes of the pools were approximately parallel to the west bank of the Nith Channel at that time. The northern end of each pool was shallow and merged gradually into the irregular asymmetrical and superposed

ripples on the flats. At the southern end the water was between 15 and 20 cms deep and a prominent cuspate margin was developed with a distinct low ridge (Plate 14b). The presence of the small polychaete Polydora in the sediment may be partly responsible for the formation of the ridge (See Chap. 3 p. 52). The pools were only seen in March 1963 after the vernal equinoxial spring tides at the same time as the early stage-megaripples. It is possible that the erosion pools were developed as a result of the enlargement of the small pools in the troughs of the megaripples by tidal eddies.

STORM STRUCTURES

Severe storms generally have a considerable effect on surface sedimentary structures on the flats. Heavy rain, if driven by a strong wind from a constant direction, produces several characteristic structures.

On the 2nd April 1962 heavy rain fell more or less continuously during the period of low tide. As the tide ebbed the winds became stronger and during the period when the tide was out a strong wind blew consistently from the south-southwest (200^{o}) with speeds ranging from 22 to 27 knots. The rain was driven across the mud flats and a series of shallow troughs 8 to 15 cms wide were formed on the upper mud flats parallel to the direction of the wind i.e. with an orientation of 200^{o} (Plate 15a). The troughs were gradually deepened by the action of wind-driven rain water. The sediment eroded from the top layers of the upper mud flat by this process was sorted in the troughs and the

organic matter and mica flakes were segregated into streams confined to the outer parts of the troughs while the finer silt and clay particles were carried down the middle (Plate 15b). When the trough pattern had become well established and the rain water flow was confined to the troughs, rain pitting was developed on the intervening ridges. The strength of the wind caused the individual raindrops to strike the surface of the ridges at an angle and individual pits tended to coalesce giving rise to small ridges at right angles to the direction of the wind (Plate 15b).

At the edge of the upper mud flat the flow of water from the troughs was concentrated into several larger gullies. The sediment-laden water driven by the wind flowed swiftly down these gullies and large lumps of sediment were torn from the banks (Plate 16a), giving the gullies very irregular courses. As the stream attempted to straighten its course other blocks of sediment were torn out. After two or three hours much of the surface sediment at the top of the mud slopes had been removed by these gullies. The majority of the gullies were filled with sediment after the storm but some of the deeper ones became relatively permanent drainage channels on the mud slopes. The organic matter in the sediments of the mud flats tends to give it considerable resistance to erosion and it is only during floods or rainstorms that much of the sediment is removed. Once a small tear is initiated in the sediment, current eddies enlarge the gap rapidly and quite large erosion pools can be formed by the removal of blocks of sediment bound by organic matter. These 'tear-away' erosional features tend to fill with sediment fairly rapidly.

In some cases the infilling sand laminae are up to 1 cm thick. These "wash-outs" can be recognised in vertical sections through tidal flats by this thicker lamination and the irregular shape of the infilling. Mats of organic debris which were torn but not detached from the sediment during the formation of the pool may be found cutting across the infilling laminae.

SAND VOLCANOES

Van Straaten (personal communication in Gill and Kuenen 1957) remarked that sand volcanoes could be produced in quicksand by jumping on the sand for a few seconds.

Areas of quicksand are sometimes developed on the west bank of the Nith Channel near Station 1/15. If the quicksand is stimulated by jumping for between 5 to 10 seconds sand volcanoes will form and erupt for up to 4 minutes until equilibrium is re-established. There is a delay of between 20 and 30 seconds after stimulation has ceased before the first eruption commences. Generally the eruption starts very quickly and often jets of sediment-laden water erupt 3 to 4 cms into the air. Cones of up to 20 cms in diameter can form within 5 seconds during violent eruptions of this type. Usually the violent phase does not last more than 3 to 4 seconds after which the rate of growth of the cone is much slower. Activity may cease in a particular cone for some time after which a second phase of eruption may commence. At least three distinct phases of eruption can be recognised in many cones. In these cases, the first or second eruptions may give irregular sand flows and only the last phase may produce a

symmetrical cone as in Plate 16b. In other cases the initial symmetry of the first cone is destroyed by more violent later phases. The majority of the volcanoes are between 10 and 20 cms in diameter and 2 to 3 cms in height but cones of up to 35 cms across have been produced in the Carse Sands. Only about 25% of the cones show well defined craters (Plate 17a).

Sand and organic matter are erupted during the building of the cone. The sand grains tend to be deposited on the upper parts of the cone close to the crater and the lighter organic matter is concentrated on the lower slopes (Plate 16b). If considerable quantities of organic debris are erupted from adjacent cones the organic-rich lower slopes of the cones tend to coalesce (Plate 17b) and only the sandy tops of individual cones remain distinct.

During the later stages of the eruptive phase, subconcentric ring fracturing occurs in the non-thixotropic sand round the area of activity, and the central area sinks producing a cauldron about 2 metres in diameter (Plate 18a). As activity in the large cones dies down numerous small satellite cones up to 1 cm in diameter appear over the whole area of subsidence (Plate 16b).

After equilibrium has been reached further eruptions can be initiated by jumping or just standing at the edge of the area of subsidence, or by striking the sediment with a spade. Sometimes these eruptions take place from already established craters, but more often a new series of cones is formed. It has not so far been possible to see any relationship between the point of stimulation and the distribution of the resultant eruptions. In a few

cases some of the second series cones developed outside the region of subsidence created during the formation of the first series.

Approximately fifteen minutes after eruption has ceased and equilibrium has been restored, the sediment is no longer thixotropic and it is possible to dig out complete sand volcanoes. The spade was carefully inserted into the sediment at an angle at the edge of the volcano and great care was taken not to disturb the sediment and create further thixotropic conditions during this process. When the block of sediment containing the volcano had been removed, the excess water was allowed to drain away before vertical sections were cut in order to study the internal structure.

In all the volcanoes sectioned the cone and feeder were composed of grey anaerobic sediment. The aerobic layer contained some original lamination and organic-rich bands indicating that it had never been thixotropic otherwise these original sedimentary structures would have been completely destroyed. The distinct margin of the feeder which cuts cleanly through the aerobic layer also indicates that at least the upper 8 to 10 cms of the aerobic layer was non-thixotropic throughout the eruption. In most cases the boundary between the non-thixotropic layer and the thixotropic sediment was marked by an organic layer. It may be the presence of this organic layer that prevented the overlying sediment from becoming thixotropic. In some cases there was no disturbance to the organic layer adjacent to the feeder (Fig. 4a) but in other cases minor faulting, crumpling and upwarping of the organic layer occurs (Plate 18b and Fig. 4b). The anaerobic sediment is structureless as it was completely thixotropic during the eruption.

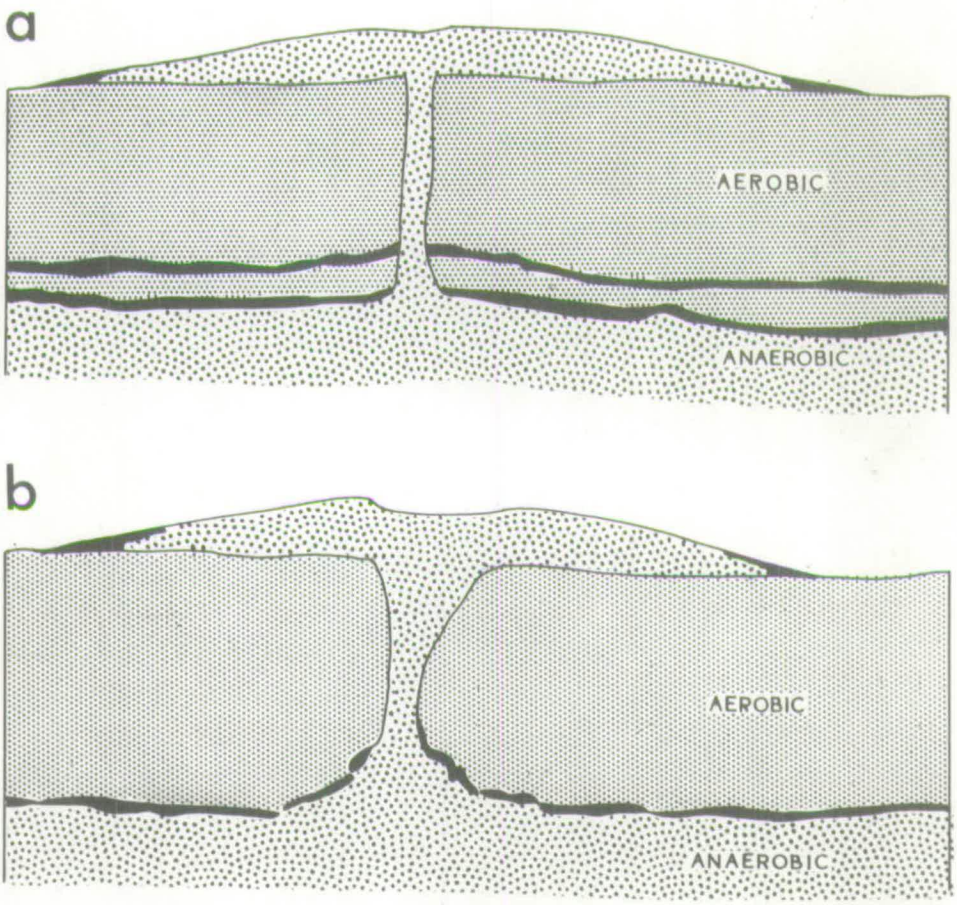
FIG. 4 SECTIONS OF SAND VOLCANOES

Sand volcano and feeder are composed of anaerobic sediment.

a. Feeder cuts cleanly through aerobic layer with no disturbance of organic layers.

b. Feeder cuts cleanly through aerobic layer but the organic layer is upwarped and shows minor faulting and crumpling.

FIG. 4



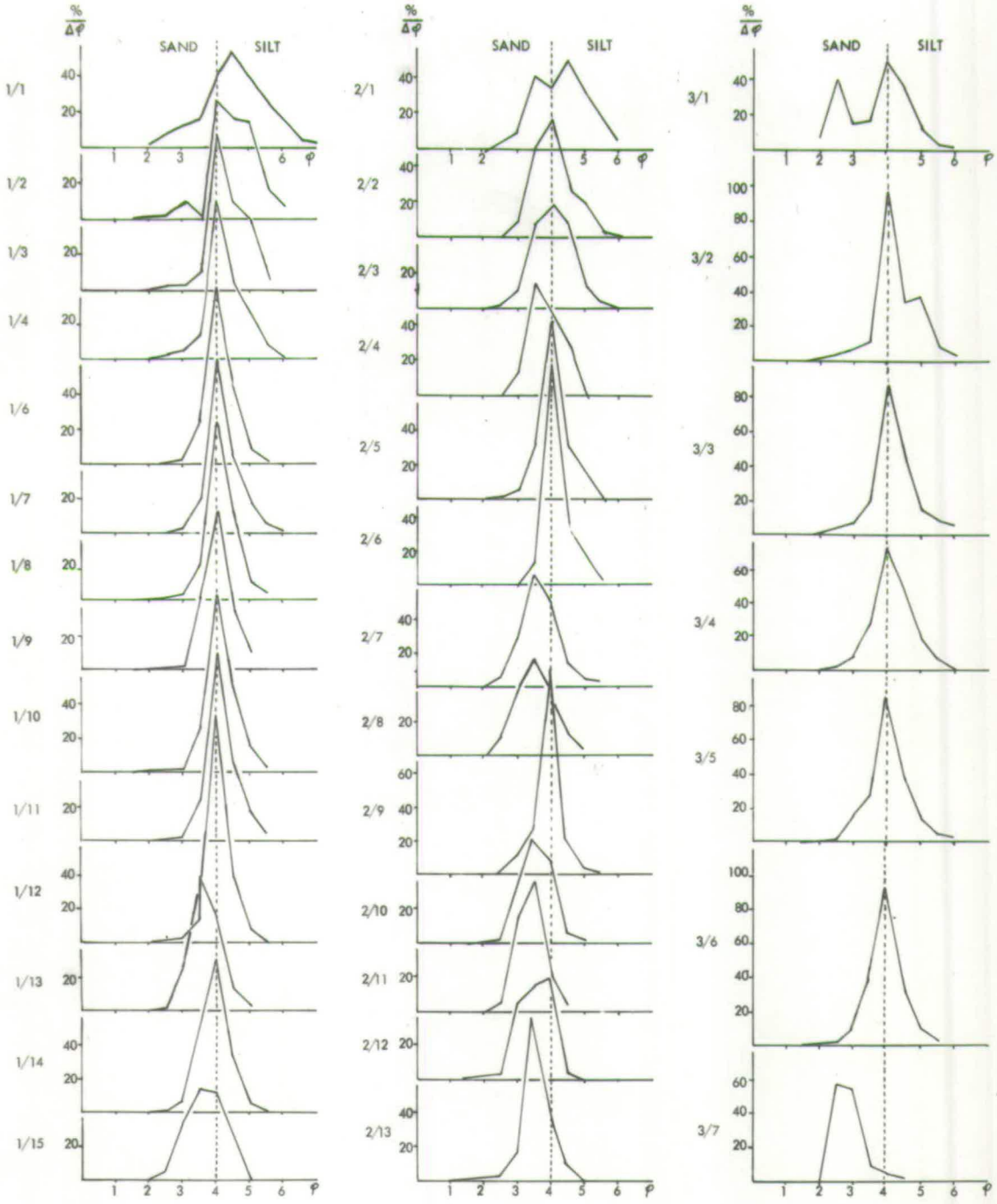
The evidence from the sectioned cones gives some indication of the conditions necessary for the formation of sand volcanoes. The thixotropic sediment must be covered by a non-thixotropic skin. When this is depressed by the application of stress in some form, sediment-laden water is expelled from the thixotropic layer and must escape before equilibrium can be restored. For reasons which are not clear the easiest route is upwards through the non-thixotropic skin and once a feeder has been established the sediment and water erupt onto the surface. It has not so far been possible to determine either the thickness or the nature of the lower boundary of the thixotropic zone. This boundary may be either a fine-grained layer, an organic-rich layer, or a change in the packing pattern of the sand grains.

Sand volcanoes were produced in silts, very-fine sands, and fine sands in different parts of the area. In each case, however, the quicksands were close to ebb channels. The volcanoes produced in silt near Station 1/6 were similar to those produced in the fine-grained sands near Station 1/15. The non-thixotropic skin was only 3 to 4 cms thick in the silts however, no sub-concentric ring fracturing was developed, and the amount of subsidence was generally much less than that developed in the sand.

GRANULOMETRIC ANALYSIS

Mechanical analyses of the sediments were carried out for all transect stations except 1/4 and 3/8. These stations were omitted because of their close proximity to adjacent stations. As most of the fauna lives in layers 1 to 4 (see Chap. 3) a composite sample was prepared from these layers for each station. Approximately 40 gms of sediment was taken from the sediment sample of each of the four layers at each station. The samples were not treated with dilute acid to remove carbonate as shell fragments are considered to be an integral part of the sediment. The composite sample was then dried in an oven at 30° C. When completely dry the sample was thoroughly mixed and was split using a rotary sample splitter to give approximately 20 gms of sediment. The sample was shaken on a Ro-Tap machine for 20 minutes using the following U.S. sieve mesh sizes - 35, 60, 85, 120, 170, 230, 300 and 400. In the case of samples 1/3 and 1/2 the sample was shaken for 1 hour to disaggregate some of the finest silt grades.

The results were plotted as cumulative curves on arithmetic probability paper. As the size-frequency distribution of the sediment is not readily obtained from cumulative curves, size-frequency polygons have been prepared by the method described by Shepard and Einsele (1962) and are given in Fig. 5. The grade classification proposed by Wentworth (1922) is used together with the phi scale and its mm equivalents. For convenience the mm equivalents of part of the phi scale (from Page 1955) are given below:-



GRAIN-SIZE-FREQUENCY POLYGONS PREPARED FROM MECHANICAL ANALYSIS CUMULATIVE CURVES.

Phi	mm	Wentworth Grade
0.0	1.0000	
0.5	0.7071	Coarse Sand
1.0	0.5000	
1.5	0.3536	Medium Sand
2.0	0.2500	
2.5	0.1768	Fine Sand
3.0	0.1250	
3.5	0.0884	Very Fine Sand
4.0	0.0625	
4.5	0.0442	
5.0	0.0313	Silt
5.5	0.0221	
6.0	0.0156	
6.5	0.0110	
7.0	0.0078	

The cumulative curves were grouped into curved types using the terminology proposed by Doeglas (1946, 1950) and Van Andel and Postma (1954).

GRAIN-SIZE FREQUENCY DISTRIBUTION

Over most of the area a largely symmetrical distribution is found with a strong mode at 4 phi (0.0625 mms) on the boundary between Wentworth's silt and very fine sand grades (Fig. 5). On the upper mud flats in Carse Bay, however, the modal grain-size and most of the sediment is in the silt grade. At 1/2, although the peak is at 4 phi, most of the sediment is silt. On the upper mud flats off Carsethorn village and to the south the bulk of the sediment is again composed of silt although the mode at Stations 2/2 and 3/2 is at 4 phi. The fine sand at Stations 1/1, 1/2, 2/1 and 2/2 is concentrated in the sand laminae. The strongly bimodal distribution at Station 3/1 is due to the high proportion of fine sand, very coarse sand and granule gravel from abrasion of the pebbles and boulders on the upper mud flats west of the station.

Towards the main Nith Channel there is a gradual increase in the proportion of fine sand. On Transect 1 the modal grain-size at Stations 13 and 15 is within the very-fine sand grade. Station 1/14 with its mode at 4 phi indicates the presence of a small lens of finer-grained sediment. On Transect 2 the mode at Stations 7, 8, 10, 11 and 13 is in the very-fine sand grade. On Transect 3 a similar increase in the proportion of fine sand occurs towards Channel G. East of Channel H the sand becomes much coarser with a mode at 2.5 phi.

In order to show the areal distribution of grain-size the phi median diameter (the 50th percentile) and the phi mean diameter (the mean of the 16th and 84th percentiles) have been measured from the cumulative curves for each sample as described by Inman (1952). The values of the mean and median grain-size converted to mms are given in Table 1. The median grain-size ranges from 0.053 mms at Station 1/2 to 0.174 mms at Station 3/7 and the mean grain-size ranges from 0.059 mms at Station 1/2 to 0.178 at Station 3/7. At all stations except 1/1 and 3/1 the values of the median and mean grain diameters do not differ by more than 0.010 mms. The high value at Station 3/1 is due to the wide separation of the two modes, whereas at Station 1/1 it is due to the rather wide range of the size-frequency polygon and the absence of a narrow, sharply defined, modal peak.

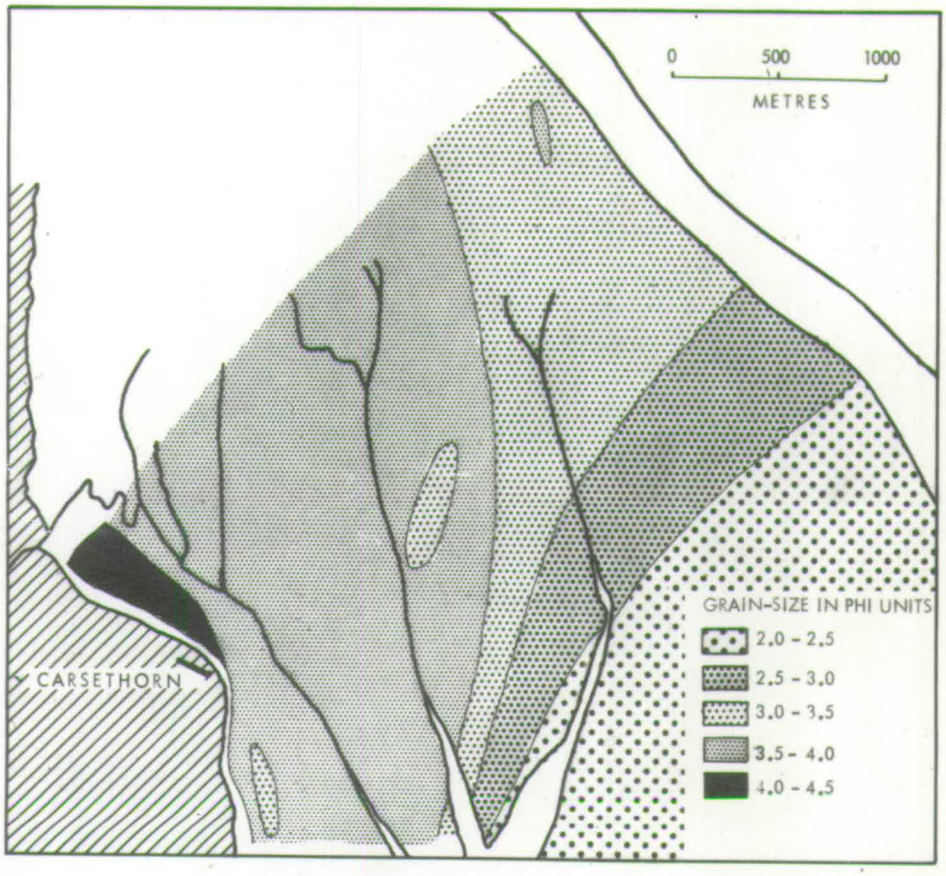
The distribution of the phi median grain-size is given in Fig. 6a. On the upper mud flats in Carse Bay the median grain-size is in the silt grade. On Transect 1 (except Stations 1 and 2) and along Transects 2 and 3 (except at Station 3/7) the median

FIG. 6. GRAIN-SIZE DISTRIBUTION MAPS.

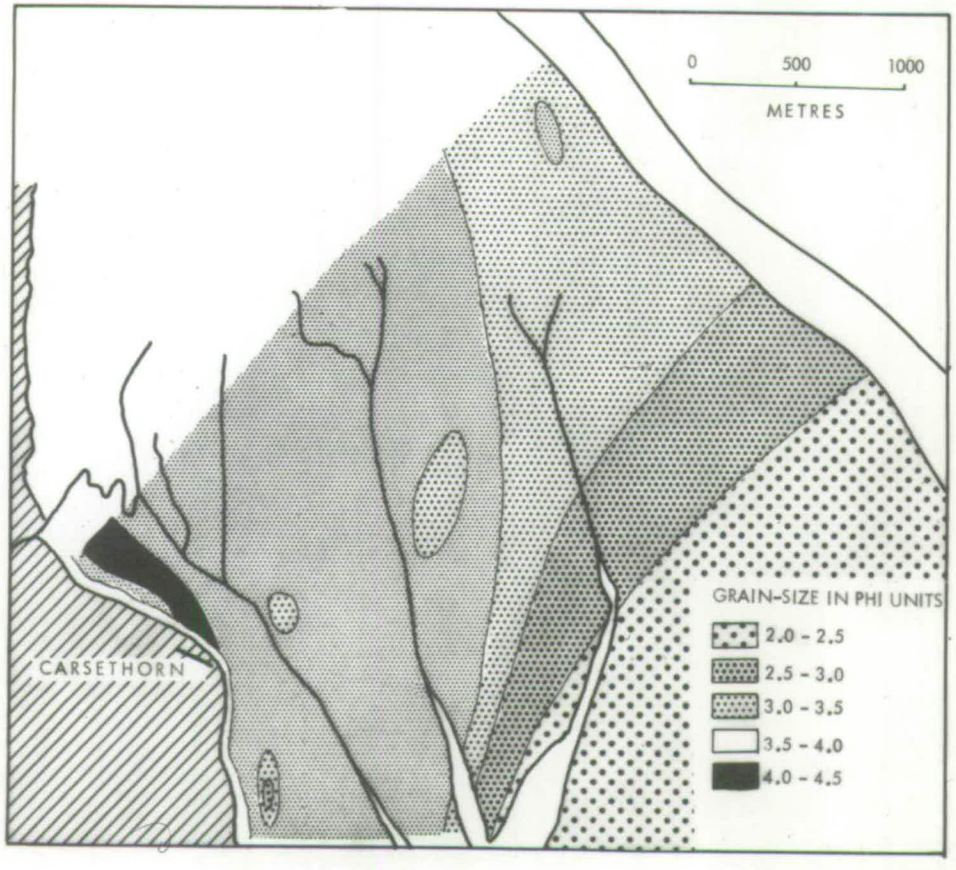
a. Distribution of Phi median grain-size.

b. Distribution of Phi mean grain-size.

a


0
500
1000
METRES
CARSETHORN
GRAIN-SIZE IN PHI UNITS
2.0 - 2.5
2.5 - 3.0
3.0 - 3.5
3.5 - 4.0
4.0 - 4.5

b


0
500
1000
METRES
CARSETHORN
GRAIN-SIZE IN PHI UNITS
2.0 - 2.5
2.5 - 3.0
3.0 - 3.5
3.5 - 4.0
4.0 - 4.5

grain-size is in the very-fine sand grade. There is, however, a general increase in median grain-size on Transects 1 and 2 towards the Nith Channel. A similar increase in median grain-size is seen towards the southeast. East of Channel G on Transect 3 the median grain-size is in the fine sand grade.

The distribution of phi mean grain-size (Fig. 6b) is very similar to that of the median grain-size. The lens of finer grained sand at Station 1/14 shown in Fig. 5 is present on both maps.

The general pattern of increasing grain-size towards the Nith Channel and towards the southeast of the area indicates an increase in current strength and a decrease in the stability of the environment in these areas.

CUMULATIVE CURVE TYPES

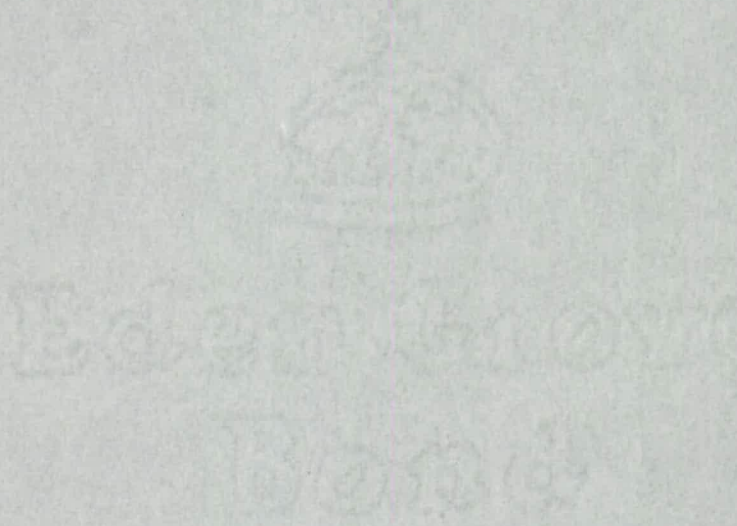
Doeglas (1946, 1950), Van Andel and Postma (1954) and others have shown that the shape of the size-frequency cumulative curve is a good indicator of the environment of deposition. Van Andel and Postma (1954) defined five types of curve related to particular environmental conditions. These include the F-type curve with a symmetrical distribution and fairly poor sorting found in fluviatile environments and the M-type curve with much better sorting found on beaches. Mixing of curve types frequently occurs and these mixed types are often diagnostic of particular environments.

The shapes of the curves from the Solway are similar to those obtained by Doeglas (1946, 1950) from the tidal flats of the Dutch Wadden Sea and by Mishra (1964) from the lower Firth of Tay. These are mixed curves of the FM-type typical of tidal flat areas.

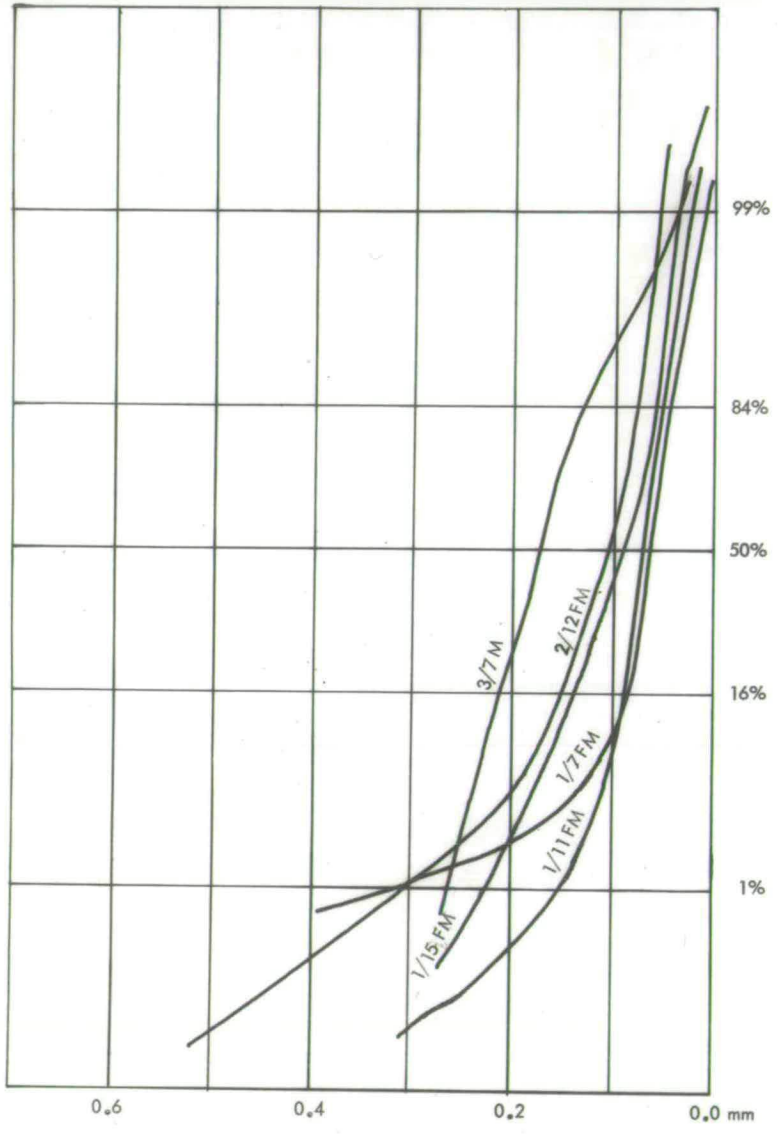
East of the mouth of Channel G and in the unstable sand banks near Channels J and K M-type curves are found. Some characteristic curves are given in Fig. 7a. The FM curves show a strongly symmetrical distribution in the finer grades. The strong curvature towards the left close to the first percentile indicates the presence of poorly sorted fine sands typically seen in the F-type curve. The curve 3/7 is of the M-type and does not show this concentration of coarser sand at the 1st percentile. The zone diagram of the FM curves (Fig. 7b) shows that the curves are similar in the finer grades and differ only in the value of the median grain-size while in the coarser grades a much greater divergence is seen.

FIG. 7. CUMULATIVE CURVES

a. Characteristic grain-size-frequency curves of the FM - and M - types.



b. Zone diagram of the FM - type Curves.


99%
84%
50%
16%
1%
3/7M
2/12FM
1/7FM
1/11FM
1/15FM
0.6
0.4
0.2
0.0 mm

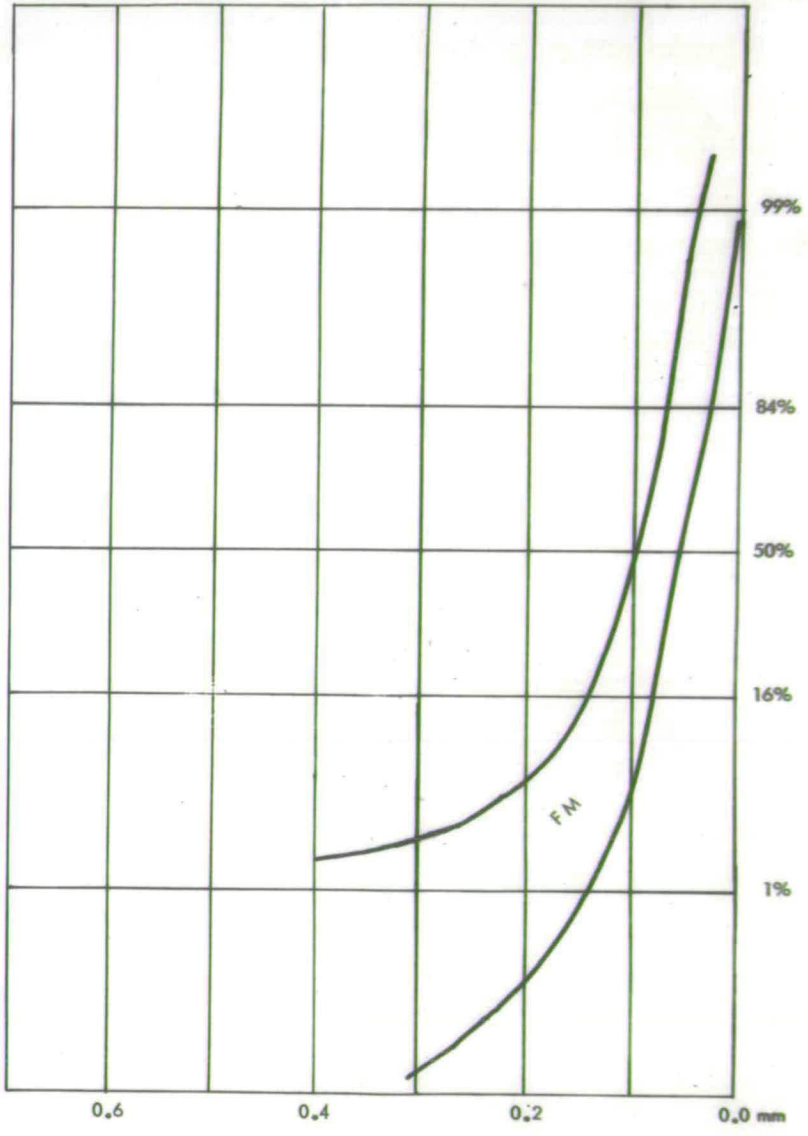

99%
84%
50%
16%
1%
FM
0.6
0.4
0.2
0.0 mm

FIG. 7

CHAPTER 3

TRANSECT STUDIES - LIVING FAUNA

The faunal analysis of the sand and mud flats is based on the quantitative samples collected on the transects described in Chapter 1 and additional observations made in the course of the study. The account is not a complete faunal survey as only those species capable of leaving fossil remains - either shells or trace fossils - have been considered. Most of the detailed work has been done on the molluscs. The density distribution maps are based on the transect data given in Tables 2 - 16 and refer to the period April to October 1962. The taxonomy used in this study is taken from the Plymouth Marine Fauna (Third Edition 1957).

In all previous biological studies of intertidal flats little attention has been paid to the depth at which the animals live and no detailed studies have been made of the changes in density with depth. Biological densities are conventionally quoted as number of animals per square metre, but this takes no account of the volume of sediment involved. In the case of Hydrobia the area measurement is reasonable as it only lives in the top 1 cm of the sediment. In the case of Macoma, however, which is found at all depths down to 12 cms the volume of sediment should be recorded in addition to the surface area of the sample. In order to compare the Solway densities with those of other areas (Tables 18 and 19) the bulk density, the sum of the densities in individual layers, is quoted. The volume of sediment in each layer is given in Chapter 1 but is repeated here for convenience:-

Layer 1	1000 sq. cms	x	2.5 cms	= 2500 cc
Layer 2	" "		"	"
Layer 3	" "		"	"
Layer 4	" "		"	"
Layer 5	1000 sq. cms	x	15 cms	= 15000 cc

In the text densities are quoted for each layer as number per 1/10th square metre.

PHYLUM PROTOZOA

CLASS SARCODINA

ORDER FORAMINIFERA

A systematic study of the distribution of Foraminifera was not undertaken and only a few qualitative observations are reported here. Benthonic Foraminifera are not uncommon in the top 2 cms of sediment and are found dominantly in mud, silts and fine sands, but are absent from the coarser clean-washed sands. In a sample from the top cm of the upper mud flat Elphidium, Haplophragmoides, Trochammina, Lagena and Nonion were obtained.

PHYLUM COELENTERATA

CLASS HYDROZOA

Hydrozoans are not uncommon on the masses of algae and other plant debris on the upper mud flats south of Carsethorn village and the cobble and pebble covered area on the upper mud flat at Locality 19.

The accumulations of weed round the bases of posts and stakes over the flats also form ideal sites for the growth of

hydroids. The commonest species present is Dynamena pumila (L) but several others are also found.

Numerous Mytilus spat are found in the summer on many of the larger colonies. The hydroids thus act as a substrate (Plate 19a) for the early growth of an epifaunal species. The stems are however not strong enough to support Mytilus greater than 5 mms in length. Thus, although growth can take place, there is no chance of these young mussels developing into an adult population.

CLASS SCYPHOMEDUSAE

Aurelia aurita (L)

This species is not infrequently found stranded on the banks of ebb channels at low tide during the summer months. The reduced salinity in the vicinity of the fresh water channels as the tide ebbs may be partially responsible for killing these jellyfish. They are not generally found on the sand flats. It is unlikely that they would be preserved under these conditions however, as the rate of burial is too slow, but they are a source of food for scavenging benthos.

Chrysaora hysoscella (L)

This species was found stranded on the west bank of the Nith Channel near Station 2/13 in September 1962. Two large individuals (Plate 19b) were seen in megaripple troughs at Locality 15.

This species is generally confined to the south and southwest coasts of England but during the summer of 1962 it was recorded in several localities on the west coast of Scotland.

PHYLUM CTENOPHORA

CLASS TENTACULATA

Pleurobrachia pileus (Müller)

This species is commonly stranded on the mud and sand flats in August and September. Many thousands were stranded on the banks of the Carse Gut during spring tides in August 1962. As the tide receded they were concentrated and eventually trapped in the troughs of large ripples on the lower mud flat. Individual concentrations of up to several hundred in one ripple trough (Plate 20a) were not uncommon. As in the case of the jellyfish it is probable that the reduction in salinity killed the stranded individuals. They are unlikely to be preserved however, and are again a source of food for scavenging benthos and for the bacterial populations in the top few cms of the sediment.

They are occasionally seen at other times of the year during storms when they can be driven close inshore. During the severe storm on 2nd April 1962 several hundred individuals were stranded on the upper mud flats within 3 - 5 metres of the pebble beach, and others were found at the Nith Channel near Locality 20.

PHYLUM ANNELIDA

CLASS POLYCHAETA

Many species of polychaete live in the mud and sand flats. They are important agents in the reworking of the sediment. No attempt has been made to obtain quantitative data for the distribution of polychaetes and only three species are discussed in detail.

Nereis diversicolor (Müller)

This species is common on the upper mud flat. It is found on the slopes to the lower mud flat and less commonly east of the Carse Gut. It is commonest above mid tide level and is absent from the coarser sand to the south. Smidt (1951) found that N. diversicolor showed a preference for the softer, more water-saturated sediments, and that the highest densities occurred where current activity was not great enough to disturb the sediment surface to any extent. Rees (1940) found that Nereis preyed on O-Group* Macoma and Hydrobia spat. Spooner and Moore (1940) showed that the distribution of N. diversicolor was in part governed by its preference for brackish conditions. The distribution seen in the Solway is in general agreement with these observations.

One interesting occurrence of N. diversicolor was in peat blocks on the lower mud flat. During the late spring of 1962 several blocks of peat were transported down the Carse Gut. They came to rest on the soft silts of the lower mud flats at Locality 3 where scouring action tended to embed them and prevent any further movement taking place. After a week or so sediment built up upstream of the blocks and they became completely stable. By September 1962 several nereids had burrowed through the blocks and thus, although N. diversicolor shows a preference for softer sediment where burrowing is easier, it is also able to bore successfully into waterlogged peat. The burrows (Plate 20b) which are 3 mms in diameter were lined with a thin layer of mud. They cut across the bedding and did not show any preference for particular

*Juvenile forms before the completion of their first winter.

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parts of the peat block. The severe winter storms of 1962 destroyed the blocks and all traces of them had gone by April 1963.

Such blocks of terrestrial sediment containing burrows of marine organisms are presumably quite rare in the fossil record, but no doubt palaoecological anomalies of this type do occur.

Adult nereid burrows occur in the sediment at all levels but are commonest between 8 and 20 cms below the surface. Young individuals are found in the top 6 cms of the sediment. The burrows followed an irregular course and frequently cut across the lamination. All the burrows found were actively in use by living worms. They appear to fill up rapidly after death and become virtually indistinguishable from the surrounding sediment.

Polydora ciliata (Johnston)

Species of Polydora including P.ciliata occur extensively on the Waddens in Denmark (Smidt 1951) and North Germany (Schäfer 1962).

In March 1963 a large region colonised by Polydora was seen about 300 metres west of the Nith Channel near Station 1/14. The tubes (Plate 21a) were exposed by the formation of the curious ridged erosion pools described in Chapter 2. The tubes occur behind the downstream face of these pools which was modified into a distinct low ridge (Plate 14b). It is possible that these tubes gave considerable strength to the sediment and the resultant resistence to erosion caused the formation of the ridge.

Large areas colonised by Polydora were exposed in ripple troughs east of Channel C and near Stations 1/9 and 1/10. Many troughs also contained loose accumulations of tubes.

Arenicola marina (L)

This species is very common in intertidal areas round the British coast and on the Dutch, Danish and German North Sea coasts. Spooner and Moore (1940) found that Arenicola was scarce in soft muds and concluded that some sand in the sediment was essential. Raymont (1955) obtained densities of up to 400 per square metre above mid tide line.

Newell (1948) found that fertilised Arenicola eggs are carried up towards the beach by the incoming tide. The eggs become trapped in the pebbles at the lower edge of the beach. The young worms burrow into the soft sands at the foot of the beach near high water-mark neap tides. These have been referred to as "nursery areas" (Holme 1949).

Thamdrup (1935) stated that at Skallingen spawning is in the late summer and autumn. Thorson (1946), Newell (1948)and Smidt (1951) also consider the main spawning to take place in Autumn.

A large concentration of juvenile worms in a nursery area was seen (Plate 21b) on the sands at MHWN at Borron Point in September 1962. A conservative estimate of the total number of worms in this nursery area would be in the region of 3800 - 4000.

There are however records of spawning at other times of the year. Cunningham and Ramage (1888) reported a spring spawning in the Firth of Forth. Kyle (1896) recorded spawning from January to March in St. Andrews but Howie (1959) found no evidence to support Kyle in St. Andrews. He did, however, find spring spawning on the Fairlie Sands at Millport. In the adjoining Kames Bay, Millport, only the main autumn spawning was seen.

Howie considered that the sheltered conditions of Fairlie Bay permitted two spawnings per year instead of the single autumn spawning in less sheltered areas. Records of spring spawning are very rare and it seems to be an uncommon phenomenon.

At the beginning of April 1964 a nursery area was seen at Locality 1 in the sand at the upper edge of the upper mud flat. This clearly contained juvenile worms from an early spring spawning. It was only found in the sheltered area of Carse Bay and was not seen at Borron Point. Spring spawnings were not seen in 1962 or 1963. Howie (1959) suggested that spawning was related to temperature change. The 1964 Solway spring spawning was probably the result of the mild winter of 1963/4.

Chapman and Newell (1947, 1949), and Chapman (1949) found that Arenicola could burrow best into thixotropic sediment which contained enough water to keep it soft. If an impervious layer is present beneath the sediment containing Arenicola sufficient water is retained to enable the worms to work the sediment at low tide. At Borron Point and at Locality 1 the boundaries of the nursery area were very sharply defined and coincided with the limits of the wet sand. Chapman (1949) showed that an increase in sand height of only a few cms with the resultant removal of water by drainage was sufficient to reduce the penetrability of the sediment and make burrowing impossible. A convincing demonstration of this can be seen in Plate 22a where the lines of castings are confined to the wet areas on either side of the raised zone. The upper boundary of the area is defined by the change to the pebble beach. The lower boundary is the change from sand to fine silt at the edge

of the upper mud flat. Thus the upper and lower boundaries of the nursery area in this case are defined by the change to unfavourable sediment types and the distribution of the worms within the area is determined by topographic control of the thixotropy of the sediment. The beach sand to the west of the Borron Point nursery area was very similar in grain-size to that of the nursery area itself. The boundary was however the result of an abrupt change in slope and a corresponding rapid reduction in the moisture content.

In the fossil record the presence of burrows in one rock and their complete absence from another seemingly identical rock is possibly simply a reflection of the differences in thixotropy and moisture content of the unconsolidated sediment.

Pectinaria sp.

One empty tube was found in October 1961 on the upper mud flat near Locality 9 but no live specimens have been found.

PHYLUM ARTHROPODA

CLASS CIRRIPEDIA

Balanus balanoides (L)

This species occurs on cobbles and smooth pebbles on the lower beach in association with Elminius. It is clear, however, that Balanus is unlikely to survive in any numbers in this area as its niche is being taken over by the more aggressive Elminius. Only isolated, old individuals (Plate 22b) occur surrounded by Elminius and when these die it is unlikely that Balanus larvae

will be able to compete successfully for the space. Balanus still survives, however, on old stake-net posts on the sand flats up to 1500 metres off shore.

Elminius modestus (Darwin)

This species was introduced to the British Isles from Australia and New Zealand on the bottom of a ship in the late 1940s and has spread round the coast from Chichester. It was abundant in the Solway on flat or smoothly rounded pebbles on the pebble beaches at Localities 1 and 19 in October 1961. Perkins and Williams (1963b) gave an account of its distribution in other parts of the Solway.

On flat cobbles which showed a dip of 5 - 10° down the beach there is a tendency for Elminius to be concentrated on the seaward parts of the cobbles and to be present on the lower edge facing the oncoming tide. Cobbles with a more triangular cross section show concentrations of barnacles on the faces but not on the ridges.

On many of the pebbles examined a definite preferred orientation could be detected. Barnes, Crisp and Powell (1951) found that Cypris larvae orient themselves towards the light when settling and this orientation persisted through the life of the barnacle.

The boulders and flat stones which occur sporadically on the mud flats usually carry an epifauna of barnacles. The larch stakes erected in April 1962 had a complete covering of barnacles within five months. During the severe winter of 1962/3 almost all the barnacles on these stakes were killed off and the shells

were easily detached from the rough surface by storm action. During the spring of 1963 a few larvae settled on the stakes but their area of settlement was restricted to the groove-like depressions left by the softer summer wood. The weathering of the posts thus restricted this recolonisation. The barnacles grew through the summer but the numbers never approached those of the previous year. The heavy growth of Enteromorpha on the posts may also be partially responsible for the reduction of the barnacle population. On a tree stump stranded on the upper mud flat at Locality 1 Elminius is seen to colonise only the parts of the trunk that are vertical or steeply sloping (Plate 23a).

CLASS MALACOSTRACA

ORDER AMPHIPODA

Gammarus sp.

Gammarus is present in the clean washed sands near the Nith Channel. A density of 11 per 1/10th square metre was obtained from layer 1 at Station 2/12.

Corophium volutator (Pallas)

This species occurs in estuarine mud flats in northwest Europe. Its distribution within estuaries is very patchy and the environmental factors controlling its distribution have been studied by several authors. Hart (1930) found that grain-size was not critical within the limits of muddy silt to fine sand. The organic content of the sediment is however critical and Corophium does not live in black muds containing high percentages of organic detritus. A soft grey mud which must never dry out during low

tide is the most suitable environment for successful colonisation. Beanland (1940) showed that its distribution was always associated with a fresh-water stream. Spooner and Moore (1940) and Beanland (1940) showed that Corophium was also restricted to sheltered areas where there is little disturbance of the surface sediment. Stopford (1951), however, found Corophium in unsheltered areas along the Dee foreshore. Its distribution in the Solway is fairly restricted. It occurs in sheltered regions in grey muds with low organic detritus content as follows:-

Localities	First recorded by Author
Top of mud slope near Station 1/3	August 1962
East bank of Carse Gut near Locality 11	"
West bank tributary B near Locality 4	"
Upper mud flat at Locality 8	September 1962
East bank Carse Gut near Station 2/4	"
Channels D and E	"
Lower mud flat near Station 3/4	August 1963

It lives in U-burrows up to 6 cms deep. Generally the aerobic - anaerobic boundary in the mud coincides with the bottom of the U-burrows. The boundary is irregular, however, as the burrows are not all the same depth and occasionally a burrow may penetrate the anaerobic zone. Thamdrup (1935) found that the young live in small tubes off the mother tube which lose their connection with the parent tube and become independent after the winter. Hart (1930) and Thamdrup (1935) showed that there are two broods per year, an early brood which becomes sexually mature in summer and dies in late autumn or winter and a late brood which becomes sexually mature in winter but does not spawn until April. The stock therefore survives for half a year. During severe winters the Corophium survives by burrowing deeper.

Thamdrup (1935) recorded densities of 7123 per square metre at Skallingen, Smidt (1951) obtained up to 24,800 at Hojer and Stopford (1951) found 24,000 per square metre in the Dee. Corophium was not seen at Easter 1962. This was due either to bad observations or the complete absence of any adult individuals. Very considerable fluctuations in numbers are not uncommon. Quatrefrages (quoted in Bate and Westwood, 1863) stated that Corophium appeared after April and disappeared abruptly in October. They were present on the mud flats in April 1963 although in much lower densities.

During the summer of 1962 very large accumulations of dead Corophium were seen in depressions on the upper mud flats near Station 1/3 and also in the scour pools formed round the stakes. A large accumulation was seen in an abandoned ox bow of a channel draining the upper mud flat. The largest accumulations, however, were in old footprints left from the previous days of crossing the flats (Plate 23b). Stopford (1951) noted numerous dead individuals in pools on the Dee foreshore. It seems that at a certain time in the summer a heavy mortality of the previous year's late brood occurs. It is unlikely that any of these concentrations could be preserved although those formed in footprints are covered by sediment after about seven days. In the accumulations that form within 5 to 10 metres of the site of the living burrows no disintegration of the skeleton occurs. In the pools round the stakes near Station 1/1 the remains tend to be more fragmented and frequently the head and antennae are separated from the rest of the body because of the fragility of the thorax and abdomen. The

type of locomotion adopted by Corophium on the surface depends on whether or not a layer of water is present (Hart 1930). If water is present then the Corophium tends to swim over the surface. If the surface is free of water the method used is "looping". The second antennae are lifted, thrust forward, and hooked into the mud. The animal hauls itself up on the antennae, the abdomen is then flexed vertically and the uropods are driven into the mud. The antennae are then withdrawn from the mud, the animal straightens itself out and the antennae are again pushed forward into the sediment ready for the next thrust. The animal thus progresses a distance equal to half of its length (excluding antennae) each time. This leaves a very distinctive trail on the surface of the sediment. (Plate 24a) which resembles the mould of a railway track. The uropods when thrust into the sediment leave a V-shaped depression marking the angle at which they were inserted into the mud. The distance between these depressions is about 4 mms showing that at each thrust the animal moves forward by about 4 mms. The "rails" are probably formed by the fourth pair of walking legs (much longer than the preceding three pairs) being dragged along the surface as the abdomen flexes. The other three pairs being shorter would not touch the ground during this movement. If the sediment is fairly firm the track persists, but if the surface is wet then the trail tends to lose its detail and becomes a structureless groove (Plate 24a).

Corophium is an important source of food for fish and for certain sea birds.

ORDER DECAPODA

Crangon vulgaris Fabricus

This species is abundant in ebb channels at low tide. Shrimping is carried on during the summer at low tide in some of the channels to the south of the mouth of the Nith Channel and shoals of shrimps occur in the Carse Gut of South Carse Farm. They are occasionally seen trapped in pools on the upper mud flats at low tide. The densities at Stations 2/11 and 2/12 in summer 1962 were 3 and 2 per 1/10 th square metre respectively. At low tide the shrimps scour into the sand and remain buried just below the surface. If disturbed they can very rapidly burrow back into the sediment.

Carcinus maenas (L)

This species occurs among the cobbles at Locality 19 and on the upper mud flats and mud slopes but it is not particularly common. It is found in areas where there is shelter as crabs are very vulnerable to attack from sea birds at low tide.

Carcinus is often associated with the dead Mya arenaria shells on the east bank of the Carse Gut at Locality 11. As the Mya shells are exposed in their living position the posterior gape protrudes 2 - 4 cms above the sediment surface. These exposed shells form a very suitable refuge for young and medium-sized crabs. The largest crab found in this rather specialised environment had a carapace diameter of 1.5 cms (Plate 31b).

Occasionally small crabs are found out on the sand flats. It is probable that they were carried out by ebb currents but they would be unlikely to survive for very long in these exposed areas.

Crabs can bury themselves in soft mud but this is a laborious process and takes up to one minute during which time they are very likely to be spotted and attacked by a passing bird.

PHYLUM MOLLUSCA

CLASS GASTROPODA

Littorina littorea (L)

Littorina occurs as an epifaunal associate of Balanus balanoides and Elminius modestus. It occurs on cobbles at the lower edge of the beach and the upper mud flat close to the beach. Its distribution is much more restricted than that of Balanus and Elminius and it only lives in sheltered areas where the chances of being knocked off the substrate by wave action are remote. On the old stakes and posts it is restricted to the bottom 10 cms. On the tree stump stranded on the upper mud flat several large Littorinas can be seen in the sheltered cleft between the two roots. (Plate 23a).

Throughout its life Littorina does not shift far from the few square metres of its home territory and will stay in the same position for many weeks without moving (Newell 1958a). The rate of movement is influenced by temperature and light intensity. The trails produced are based on a U-pattern. As the tide recedes the trails tend to be directed towards the sun. After some time a reversal takes place and the Littorina returns along the other limb of the U. A similar ascent and descent takes place in response to gravitation (Newell 1958b).

The trails seen on the Solway tended to be fairly straight and no definite evidence of U-trails was found, but no observations were

made during a complete tidal cycle. It is probable that portions of the trail in wet sand or mud would be destroyed soon after their formation and if this were at the base of the U the connection between the two limbs would be lost.

Two measurements of the rate of movement were made on the 13th August 1962. The sky was clear and the temperature was 17.5°C. One Littorina took 3 minutes and 40 seconds to cover a distance of 11.3 cms, giving an average rate of 1 mm per 2 seconds, but the movement was not absolutely regular. After covering the 11.3 cms on flat sand the Littorina reached the lee slope of a ripple (amplitude approximately 1 cm) and this change to an uphill gradient reduced progress to 1 cm in 2 minutes giving a rate of 1 mm per 12 seconds. Under certain conditions almost all the Littorinas in a particular area will move and a large number of criss-crossing trails approximately 1 cm wide and 2 - 3 mm deep will be produced. If these are on sand and are covered by a thin layer of mud it is possible that they could be preserved.

Hydrobia ulvae (Pennant)

This is one of the most abundant estuarine species in northwest Europe. It lives on mud flats in Great Britain and on the North Sea waddens of Holland, Denmark and Germany. At Skallingen the maximum density was at mean high tide level decreasing abruptly to mid tide level. (Thamdrup 1935). In the Tamar the maximum density - 13,800 per square metre - was at about mid tide level (Spooner and Moore 1940). Rees (1940) on the other hand found that the density tended to increase towards low tide in the Bristol Channel.

Spatfall

Smidt (1951) recorded the main spawning in April and May although egg capsules are found on adults from March to December. The late summer 1962 spatfall is shown in Fig. 8a. The spat are largely restricted to the upper mud flat and higher mud slope west of the Carse Gut and the only spatfall to the east is in the vicinity of the Carse Gut. The highest densities of spatfall do not coincide with the high adult densities.

Linke (1939) described the method of "air dispersal" in H. ulvae. At low tide air is trapped in the shell giving it considerable buoyancy. As the tide returns the shells are transported over wide areas and population dispersal is achieved. Active migration of adults to the upper mud flats as described by Smidt (1951) on the Danish Wadden Sea probably takes place in the Solway.

Post Larval Distribution

The distribution of H. ulvae is shown on Fig. 8b. The densities per $^{1}/_{10}$th square metre are calculated from one half of the sediment sample as described in Chapter 1. It is possible that these values are slightly lower than the actual densities and thus the values given in Tables 2 - 16 should be taken as minimal. The densities at Stations 1/1 and 1/2 are based on numbers obtained in the special study of density fluctuations on the upper mud flat (See pp. 66-68).

The highest densities occur on the upper mud flats (Fig. 8b). The Carse Gut is seen to be a major factor in controlling the distribution. The highest densities - 600 to 800 per $^{1}/_{10}$th square

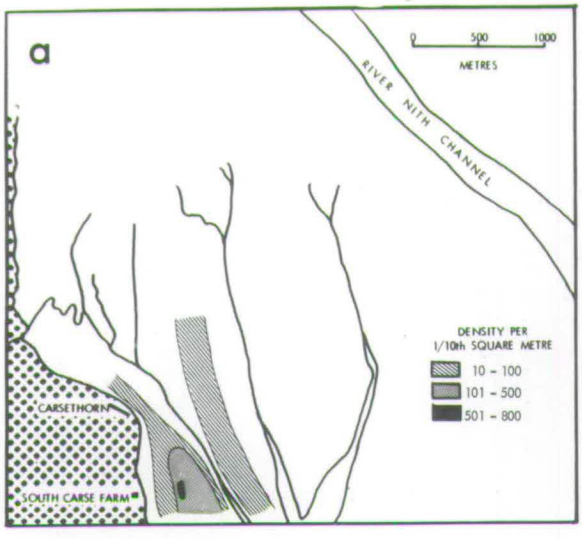
FIG. 8. DISTRIBUTION OF HYDROBIA ULVAE, RETUSA OBTUSA AND MYTILUS EDULIS SPAT.

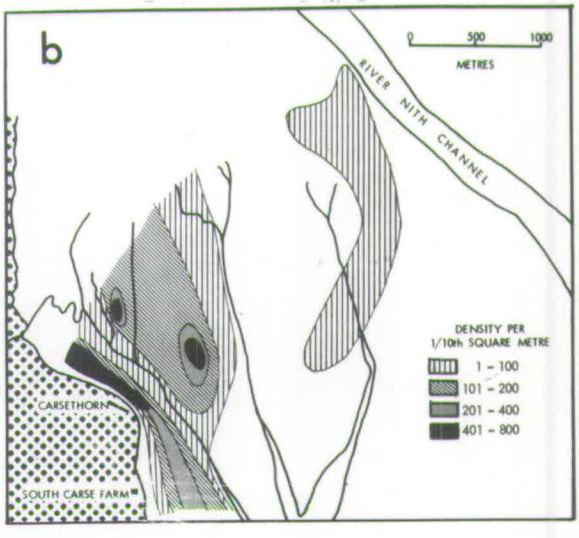
a. Hydrobia ulvae Spat.

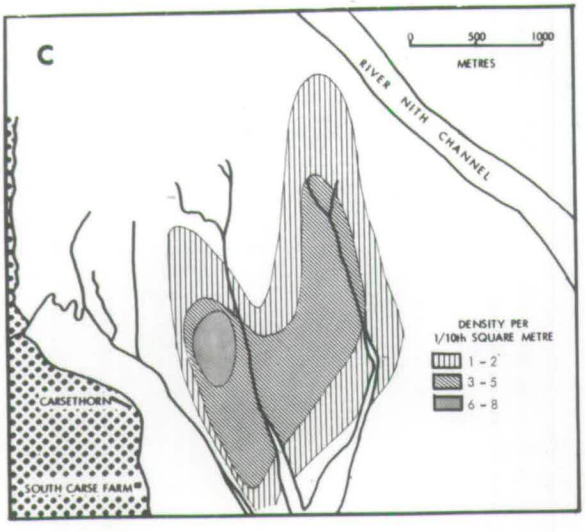
b. Adult Hydrobia ulvae.

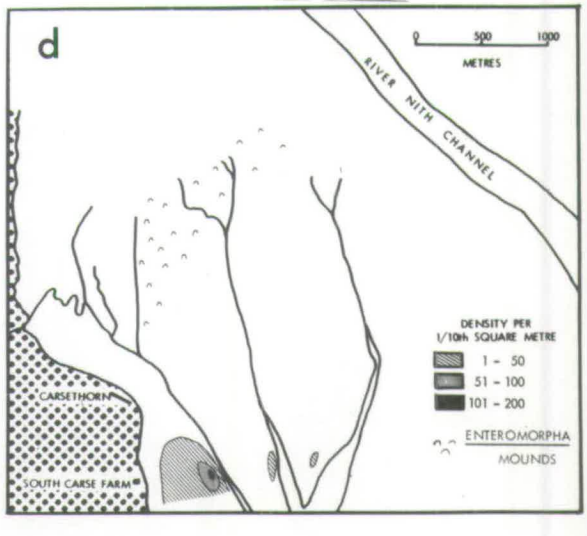
c. Retusa obtusa.

d. Mytilus edulis Spat.


a
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
10 - 100
101 - 500
501 - 800
CARSETHORN
SOUTH CARSE FARM


b
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 100
101 - 200
201 - 400
401 - 800
CARSETHORN
SOUTH CARSE FARM


c
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 2
3 - 5
6 - 8
CARSETHORN
SOUTH CARSE FARM


d
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 50
51 - 100
101 - 200
ENTEROMORPHA
MOUNDS
CARSETHORN
SOUTH CARSE FARM

metre - occur on the upper mud flat on Transect 1. The density gradually decreases towards the southeast, and near Stations 2/1 and 2/2 the average density is 550 per 1/10th square metre. Between Stations 3/1 and 3/2 it is down to 361 per 1/10th square metre. This decrease is probably due to an increase of turbulence and instability in the surface mud. The sheltered muds of Carse Bay afford the best environment for Hydrobia. The highest concentrations are close to small, shallow channels (Plate 24b) with only up to 2 cms of water in them at low tide. These areas probably contain the most abundant diatom floras and desiccation problems are not encountered.

The decrease in density to the southeast on the upper mud flat is reversed on the lower mud flat and mud slope. At Station 3/3 the density is 168 per 1/10th square metre. The much gentler gradient, and the more gradual change from mud flat to mud slope on Transect 3 form a more stable environment than the steep slope on Transect 1. Hydrobia is virtually absent from the quick silts and unstable fine sand ridges near Station 2/3. On the lower mud flat near Station 1/4 large irregular transverse ripples are present, indicating considerable current activity, and the instability of the sediment reduces the density of Hydrobia to under 25 per 1/10th square metre.

East of the Carse Gut, high densities were obtained from Station 1/7 in fine sand associated with superposed ripples and from Station 2/5 in fine sand with occasional concentrations of Cardium and Macoma shells on the surface. East of Channel H, the density is less than 25 per 1/10th square metre.

To the south the animal gradually disappears as the grain-size and instability of the sediment increases. Thus the high densities of Hydrobia are associated with areas of minimum disturbance where abundant food supply is available.

Living Hydrobia was very rarely found in layer 2 at transect stations and it is unlikely that it could survive at a depth greater than 2 - 3 cms.

Quantitative samples were taken at two sites on the upper mud flat near Locality 2 over a period of two years in order to determine fluctuations in the density of Hydrobia. The October 1961 and September 1962 samples were of ¼ square metre to a depth of 1 cm. These were later considered to be larger than was necessary and the samples taken in March and August 1963 were of a 1/10th square metre to a depth of 1 cm. The data from the 1961 and 1962 samples were corrected to 1/10th square metre.

The values obtained were as follows:-

	Density per 1/10th square metre	
Silty mud, upper mud flat	Living	Dead
4th October 1961	465	129
22nd September 1962	932	301
29th March 1963	567	83
9th August 1963	247	32
Sand at edge of upper mud flat		
29th March 1963	921	2206
9th August 1963	550	212

These figures show that densities of the living population fluctuate markedly on the mud flats. The summer 1962 density is approximately twice that in 1961, but by summer 1963 the density had dropped to about 25% of the 1962 figure.

The size-frequency distribution of both living and dead shells is given in Fig. 9. In October 1961 the division of the population into 1961 O-Group (1.5 to 3.5 mms) and the 1960 O-Group is well marked.

Smidt (1944) found that severe winters affect only the inshore individuals. Thus the severe winter of November 1962 to February 1963 would kill most of the upper mud flat population but would hardly affect Hydrobia east of Channel C. The 1961 O-Group was completely killed off as was most of the 1962 O-Group on the upper mud flat. The large numbers of late 1962 O-Group found in both samples in March 1963 were almost certainly "air dispersal immigrants" from east of Channel C where the heavy winter mortality among predators allowed an abnormally large number of the late 1962 O-Group to survive. By August 1963, however, the 1962 O-Group (represented by the 3.5 to 4.5 mm peak) had been considerably reduced. The August 1963 samples show that the density of the early summer 1963 O-Group was ten times greater in the sand than it was on the mud flat itself.

A fairly high mortality rate in the 1962 O-Group is seen in the dead-shell analysis. The large accumulation of dead shells (2108 between 0.5 and 2.5 mms) in the sand consists of shells from the upper mud flat and east of the Carse Gut, as well as from the sand itself. On death the shells become buoyant and are concentrated at the foot of the beach. It is also possible that the severe winter storms carried many individuals from the mud flats on to the sand where they died of exposure. By August 1963 all these shells were completely broken. This gives some indication

FIG. 9. SIZE-FREQUENCY DISTRIBUTIONS OF LIVING AND DEAD HYDROBIA ULVAE FROM UPPER MUD FLATS NEAR LOCALITY 2.

Number of shells plotted against height.

4th October 1961.

22nd September 1962.

29th March 1963

9th August 1963.

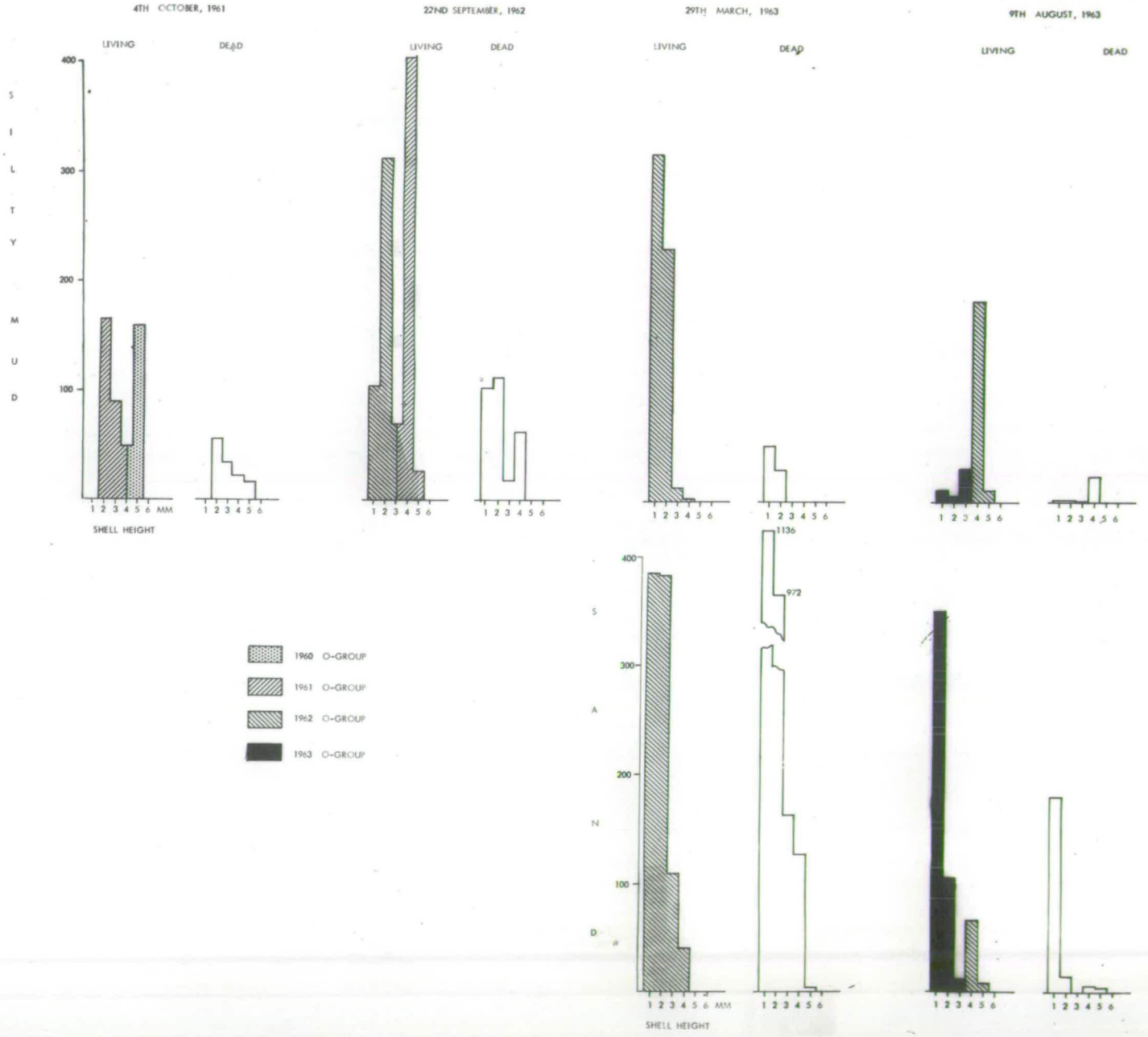

4TH OCTOBER, 1961
22ND SEPTEMBER, 1962
29TH MARCH, 1963
9TH AUGUST, 1963
LIVING
DEAD
SILTY MUD
400
300
200
100
1 2 3 4 5 6 MM
SHELL HEIGHT
1960 O-GROUP
1961 O-GROUP
1962 O-GROUP
1963 O-GROUP
SAND
1136
972

FIG. 9

of the rapidity at which shells are destroyed at the foot of the beach, even in the comparative calm of Carse Bay.

Table 17 is a summary of densities of H.ulvae in different areas together with data from the present survey. The Solway densities are not as high as they are in some of the other comparable areas. This is partly due to the fact that they are not maximum but average densities from stations selected at random.

When the tide recedes, Hydrobia comes to the surface of the mud or fine-grained sand to feed. The resultant trails are fairly distinctive and appear to be based on a spiral pattern rather than a U, although this is rarely as perfectly developed as it is in Plate 25a. The normal pattern (Plate 25b) is usually a curved trail up to 6 to 8 cms long. Hydrobia feeds on the surface for only an hour or so immediately following the retreat of the tide after which it burrows just beneath the surface.

Kristensen (1959) found that Retusa obtusa and many waders prey extensively on Hydrobia.

Retusa obtusa (Montagu)

It appears from the literature that this species is not common in Great Britain. It is not recorded by Eales (3rd Edition 1961), Chumley (1918) or by Bruce, Coleman and Jones (1963). The Plymouth Marine Fauna (1957) listed only dead shells off Eddystone and at Salt Mills Creek. One living specimen was found in the Tamar Estuary in October 1937. Forbes and Hanley (1853) recorded it below low tide mark and therefore not as an intertidal species. Thorson (1946) reported it off Copenhagen. Linke (1939) listed R. truncatula as a predator of H. ulvae but Lemche (personal

communication in Smidt 1951) considered this to be a confusion with Retusa obtusa. R. obtusa has not been previously recorded from the Solway so far as the author is aware. Fig. 8c shows the distribution of R. obtusa on the Carse Sands. This map is based partly on information obtained from transect stations and partly on extensive observations over the sand flats. Densities of 6 per 1/10th square metre and 8 per 1/10th square metre were obtained at Stations 2/5 and 2/6 respectively. These high densities are adjacent to the high-density Hydrobia area east of the Carse Gut. Retusa does not occur west of the Carse Gut or west of Channel C. The north-northwest extension of the range east of Channel G and including the upper reaches of Channel H is adjacent to the isolated low-density area of Hydrobia near the Nith Channel. Retusa is an active form and prefers medium to coarse-grained sand. It cannot tolerate silt or mud. Lemche (in Thorson 1946) considers it to have a non-pelagic development. On 11th April 1962 at Station 1/10 5 young individuals 1 to 1.5 mms high and probably representing a spring spawning were obtained. No young individuals were found in the September 1962 transects.

R. obtusa lives approximately 1 mm below the sand surface and when moving it leaves a very distinctive sinusoidal trail (Plate 26a). None of the individuals studied were moving, however, and no observation on the rate of movement could be made. In one intertidal cycle the average movement seems to be of the order of 6 to 8 cms, although one trail found was 36 cms long. On the trails in dry sand small depressions occur every 8 to 10 mms (Plate 26a). It is possible that these represent times when the individual has dug

deeply into the sediment causing the long axis of the shell to be almost at right angles to the sediment surface instead of parallel to it as in forward movement. The explanation of these vertical movements is uncertain but it may possibly be a feeding position.

CLASS LAMELLIBRANCHIA

Mytilus edulis L

This species does not now occur over the Carse sands and mud flats. In the late 1920s (Truckell and Robson, personal communications) mussel banks existed on the east bank of the Carse Gut near Locality 11 and at the "Scaur" in the Nith Channel. Both these communities were destroyed when the Nith Channel changed its course in the 1930s and Mytilus is now absent from the area except for a spatfall and isolated individuals which manage to survive for a few months on the upper mud flat among the cobbles.

Spatfall

Chipperfield (1953) showed that spawning takes place from mid April to the end of May and that settlement occurs from May to early July. Fig. 8d shows the distribution in the Solway of the late 1962 spatfall. Spat were only found in samples from Transect 3 where the highest density - 128 per 1/10th square metre - came from the lower mud flat. On the upper mud flat the density was between 20 and 30 per 1/10th square metre. Spat were found in the coarse sands at the mouth of Channel G and in the megaripples. Spatfall is heaviest below MLWS (Chipperfield 1953) and these occurrences are probably part of that settlement.

In these areas the spat grow to about 2 mms but as there is no substrate for attachment they soon die.

At Locality 19 on the upper mud flat spat survive and become byssally attached to the cobbles. They grow for a few months but only rarely attain lengths of more than 8 mms. They do not survive the winter.

In order to become established the Mytilus spat must have a permanent substrate for attachment. Two temporary substrates are found in this area. One is the settlement on hydroids described on p.49 , the other is on Enteromorpha described below.

About the beginning of March the green algae Enteromorpha compressa appears on the fine-grained sands between Channel C and the upper reaches of Channel G. By the end of March the filaments have grown but they are still fairly small (Plate 26b) and do not protrude above the level of the sand. Growth continues through April and May and sediment becomes trapped by the filaments. Small mounds develop and these act as a substrate for further growth of new filaments which in turn trap more sediment, and so on until in August and September the mounds are up to 60 cms long, 25 to 35 cms across and up to 20 cms high (Plate 27a). The mounds are all oriented with their long axes parallel to the direction of the ebb current. On the up-current face of many of the larger mounds considerable scouring occurs and in some cases the pools are up to 20 cms deep.

The structure of one of these mounds is shown in Fig. 10. The aerobic layer is colonised by Corophium volutator and the anaerobic part by Nereis diversicolor.

FIG. 10. VERTICAL SECTION THROUGH AN ENTEROPORPHA MOUND PARALLEL TO THE EBB CURRENT DIRECTION.

Note scour pool on upstream face.

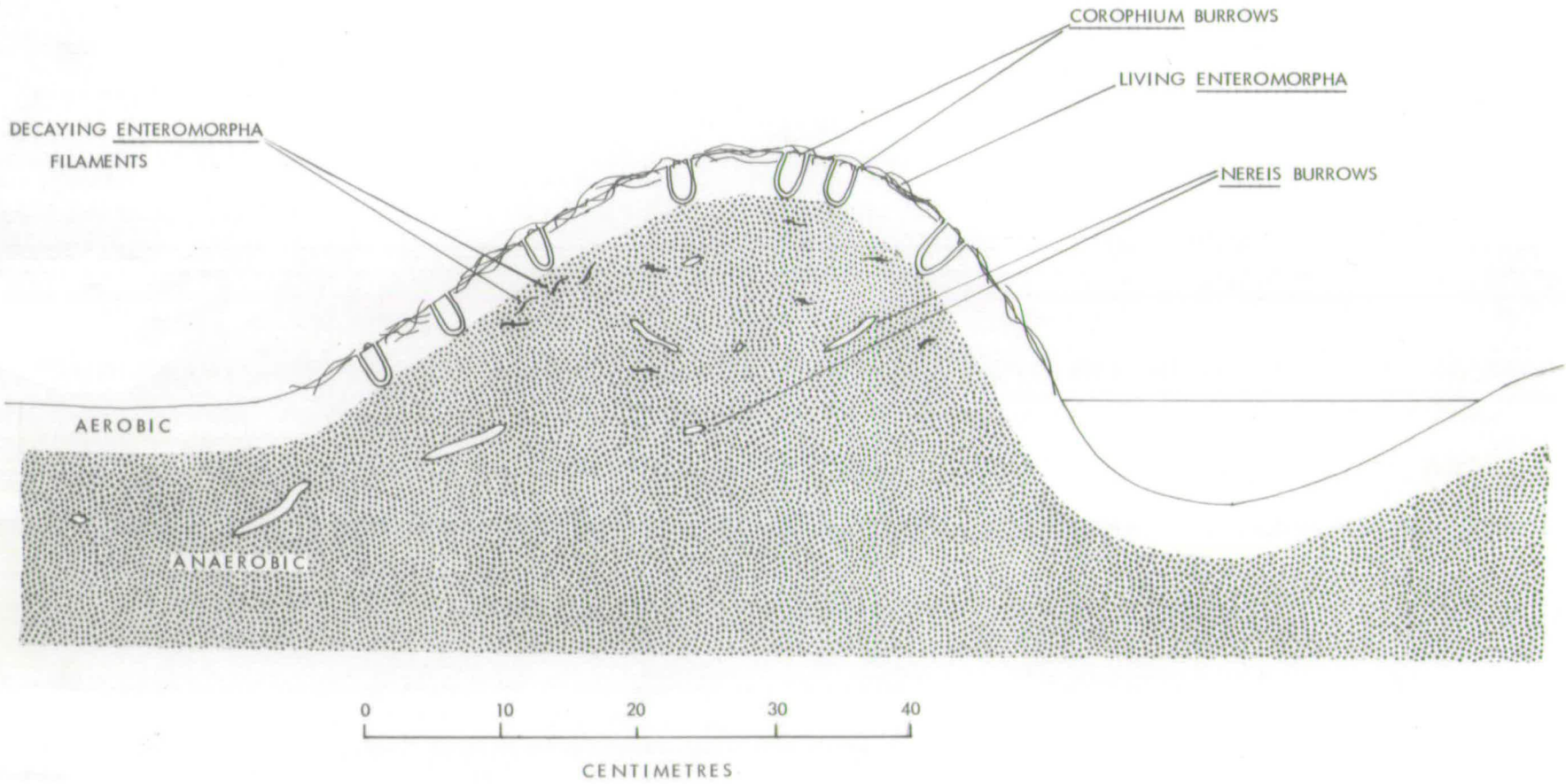

COROPHIUM BURROWS
LIVING ENTEROMORPHA
DECAYING ENTEROMORPHA
FILAMENTS
NEREIS BURROWS
AEROBIC
ANAEROBIC
0
10
20
30
40
CENTIMETRES

FIG. 10

From May to mid-July during the period of Mytilus spatfall these mounds form ideal substrates. The spat attach themselves to the filaments (Plate 27b) and grow throughout the summer.

At the beginning of October the mounds are destroyed by strong current action and fragments of Enteromorpha from the mounds are found in the megaripple troughs. By mid-October all traces of Enteromorpha have disappeared, and in March the following year the cycle begins again.

Mytilus shells up to 4 mms grow on these mounds as epifaunas in dominantly infaunal areas, and small shells and valves are found in the sediment when all traces of the epifaunal substrate have disappeared.

Cardium edule L

Cardium is common in estuarine sands throughout northwest Europe and many studies have been made of its quantitative distribution. Thamdrup (1935) showed that the growth rate was higher the longer the period of submersion but that it is independent of the grain-size of the sediment. Growth on the sides of deep channels was therefore more rapid than on the waddens. Stephen (1932) found that the growth rate was greatest at the seaward end of the range. Thamdrup (1935) and Stephen (1931, 1932) showed that a particular year group would dominate the population for several years. 0-Group densities of up to 100,000 per square metre were recorded by Thamdrup (1935) but they become more reduced throughout the summer (Wohlenberg 1937):-

July	39,460
August	14,000
December	4,300

The 0-Group density fluctuates from year to year. The densities of 0-Group and adult C.edule from sand and mud flats in different areas are given in Tables 18 and 19 .

There is some discrepancy in the literature about the growth rate of Cardium edule and the lengths of individuals of particular ages.

No. of Winter Ring	ORTON 1926	STEPHEN 1931	BRADY 1943	RAYMONT 1955	SMIDT 1951
0	---	3 - 10	3 - 6	1 - 3.5	3 - 9
1	19 - 22	12 - 13	11	10 - 13	10 - 16
2	28 - 32	---	21	23 - 24	24 - 26
3	33 - 36	---	30	---	---
4	35 - 39	---	36	---	---
5	---	---	39	---	---

The discrepancy between Orton and the others is based on the different interpretation put on the first conspicuous ring by Stephen and later workers. Orton (1926) considered the first conspicuous ring to be the first winter ring, while Stephen (1931) considered it to be the second winter ring. The growth estimates by Raymont (1955), Brady (1943) and Smidt (1951) and in this study are based on Stephen's interpretation.

Spatfall

Cardium larvae occur in the plankton from May to October and newly settled spat were found in June on the Danish Wadden Sea (Smidt 1951) and at the end of August in the Clyde (Stephen 1931). The distribution of the late summer 1962 spatfall on the Carse Sands is shown in Fig. 11a. The highest densities occur on the upper mud flat on Transect 3, and on the east bank of the Carse Gut at Station 2/4. On the upper mud flat the density decreases

FIG. 11. DISTRIBUTION OF CARDIUM EDULE AND SCROBICULARIA PLANA.

a. Cardium edule Spat

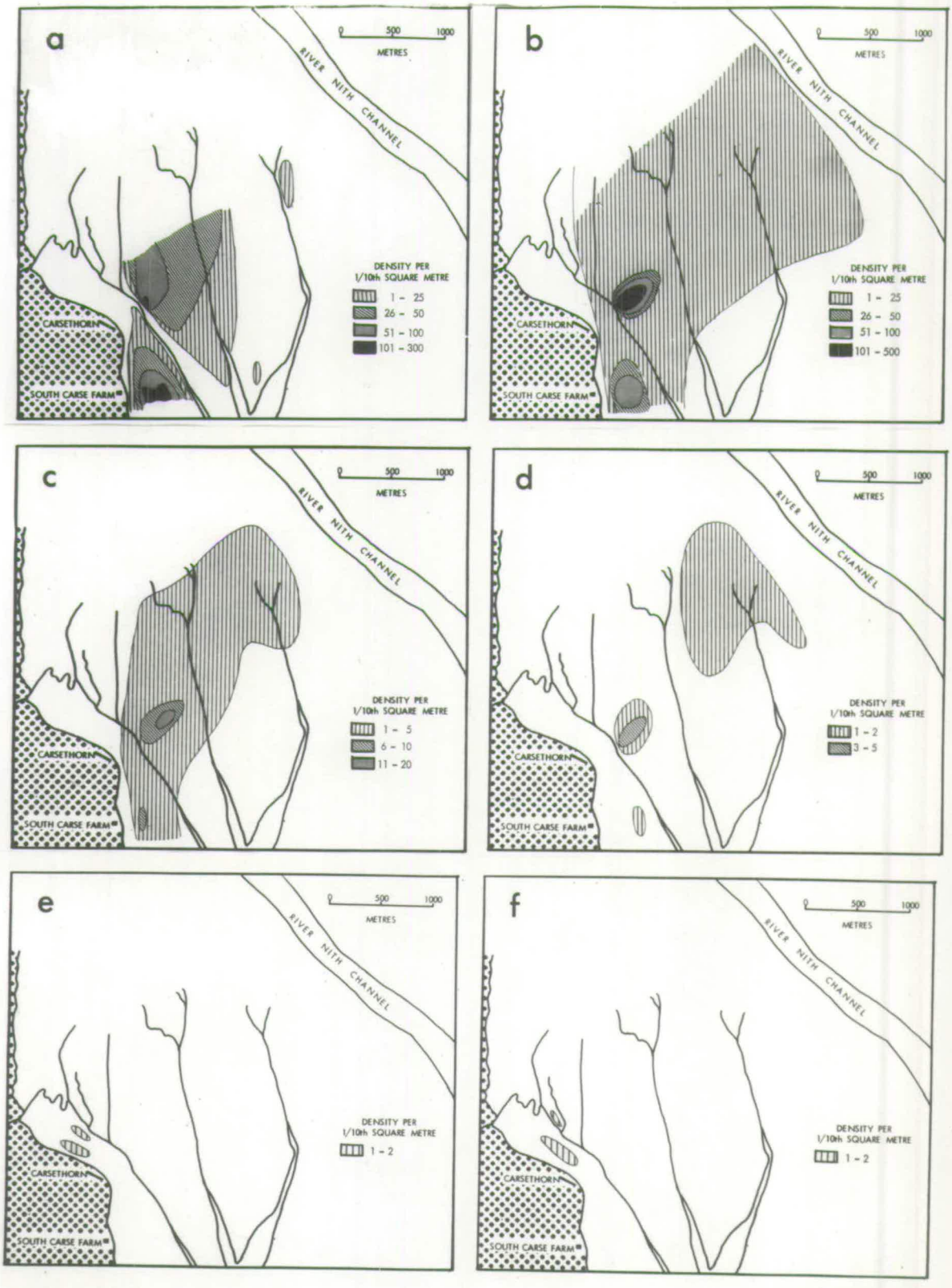
b. Cardium edule Layer 1.

c. Cardium edule Layer 2

d. Cardium edule Layer 3

e. Scrobicularia plana Layer 4

f. Scrobicularia plana Layer 5


a
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 25
26 - 50
51 - 100
101 - 300
CARSETHORN
SOUTH CARSE FARM
b
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 25
26 - 50
51 - 100
101 - 500
CARSETHORN
SOUTH CARSE FARM
c
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 5
6 - 10
11 - 20
CARSETHORN
SOUTH CARSE FARM
d
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 2
3 - 5
CARSETHORN
SOUTH CARSE FARM
e
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 2
CARSETHORN
SOUTH CARSE FARM
f
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 2
CARSETHORN
SOUTH CARSE FARM

northwards and east of the Carse Gut it decreases towards Channel G and to the south, it decreases as the grain-size and mobility of the sediment increases. Kristensen (1959) has shown that young stages of C. edule are very sensitive to bottom disturbance and spat are not found in regions where the sand is relatively unstable. An apparent exception to this rule was the occurrence of a few spat on the upstream face of an ebb megaripple. It is probable, however, that these had been transported from a more stable area and would certainly not survive.

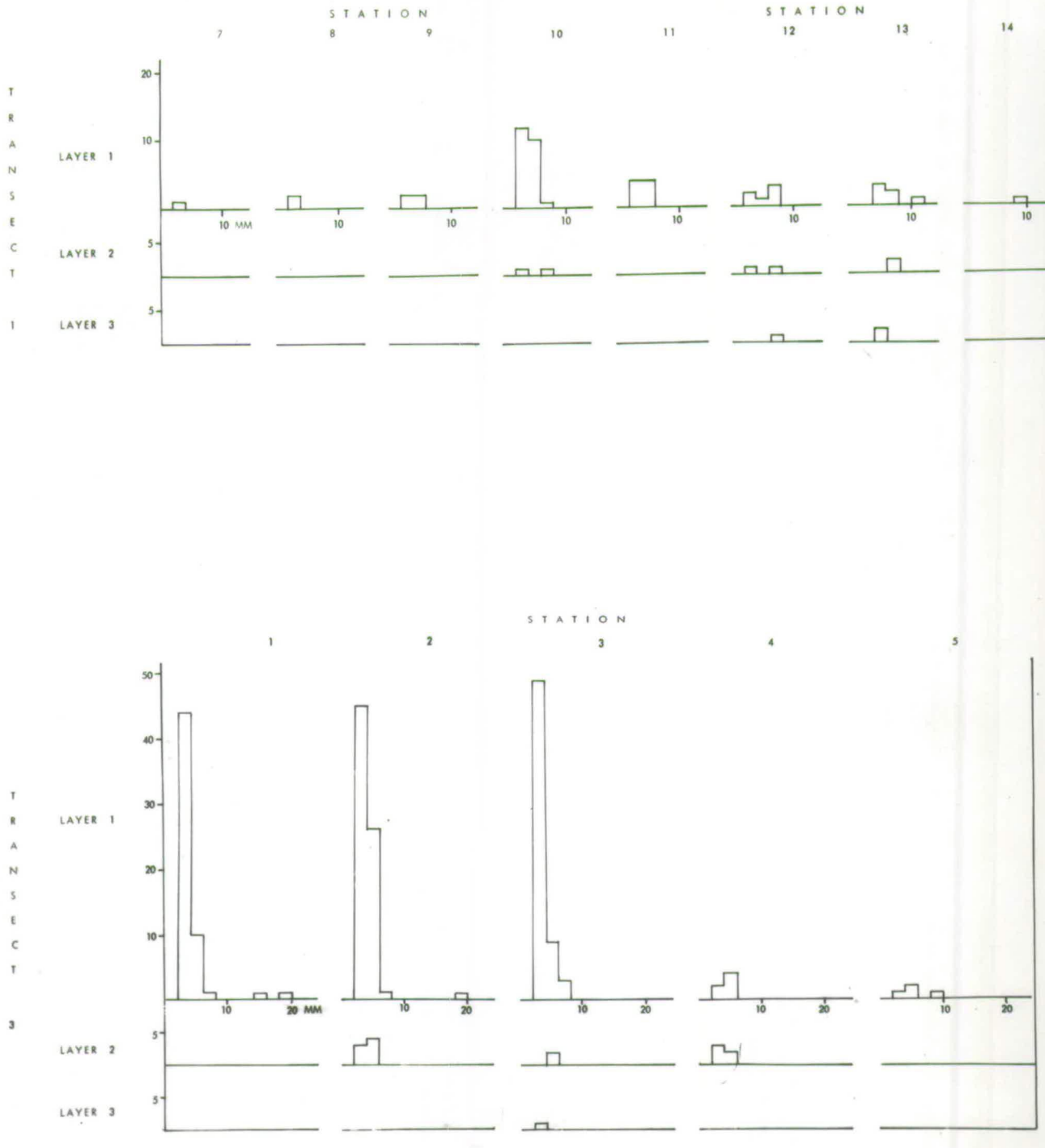
Post Larval Distribution

Cardium was present in layer 1, layer 2 and layer 3, and can thus be found up to 7.5 cms below the sediment surface.

Layer 1 (Fig. 11b)

The highest density - 416 per 1/10th square metre - was found at Station 2/4. This area is covered by a surface shell-bed (see Chap. 4 p.115) and is also the site of a high density spatfall (Fig. 11a). The highest densities of Cardium in the Tamar were associated with a high admixture of dead mollusc shells in the surface layer (Spooner and Moore 1940). The high density area on the upper mud flat at Stations 3/1, 3/2 and 3/3 corresponds to the other area of high spatfall density. Cardium is not found on the upper mud flat north of Carsethorn village. East of the Carse Gut the density gradually decreases towards the Nith Channel.

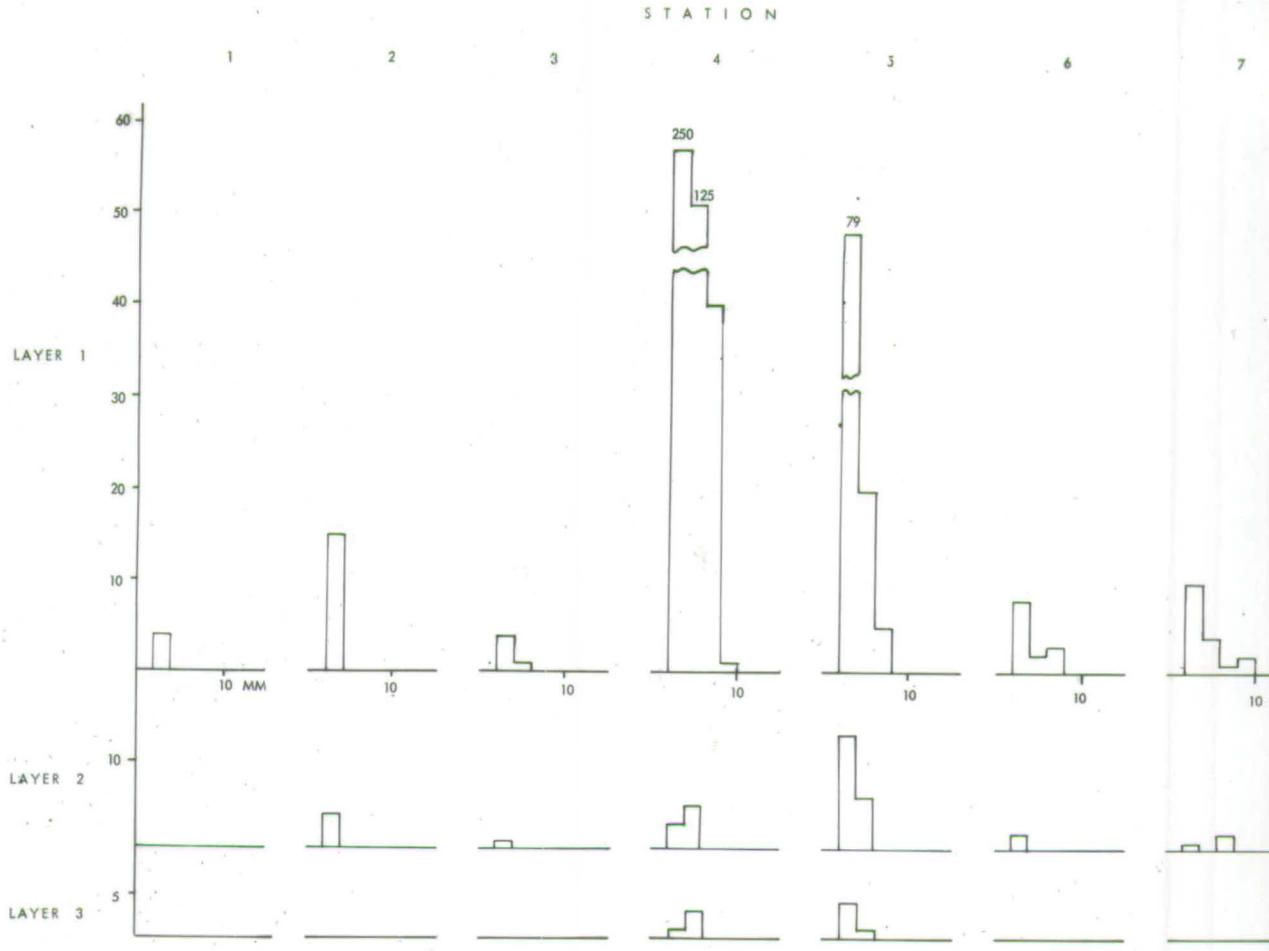
The size-frequency distribution of C. edule is given in Figs. 12 and 13. The September peaks on Transects 2 and 3 are all between 3 and 6 mms. As the shells are smooth and are less than 11 mms in length, they all belong to the 1962 O-Group. Three shells

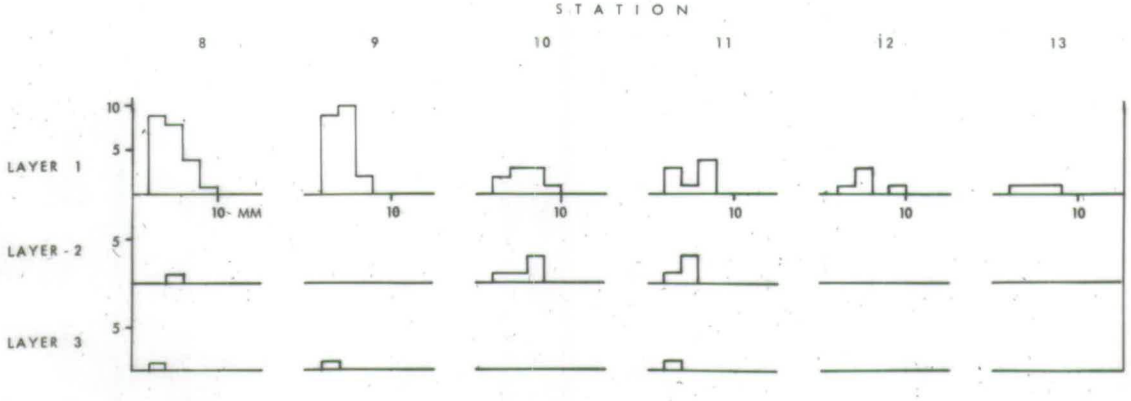


SIZE-FREQUENCY DISTRIBUTION OF LIVING CARDIUM EDULE, TRANSECTS 1 AND 3.

Number of shells plotted against length.

FIG. 13





SIZE-FREQUENCY DISTRIBUTION OF LIVING CARDIUM EDULE, TRANSECT 2.

Number of shells plotted against length.

greater than 11 mms were obtained from Stations 3/1 and 3/2. One was 15 mms in length and was probably an early summer 1962 shell as no growth rings were seen. The other two shells were 19 mms in length and had a growth line - the 1961/62 winter ring - between 3 and 5 mms from the umbo and were therefore from the late 1961 0-Group. On Transect 1 sampled in early April 1962 all shells show a distinct ring very close to the margin. This is the 1961/62 winter ring and growth in 1962 had only just commenced when the samples were collected. The majority of these shells are 3 - 6 mms long and therefore represent a late 1961 spatfall possibly corresponding to the spatfall of September 1962. The largest shell on Transect 1 from Station 13/1 is 11 mms in length and represents the early summer 1961 spatfall.

The oldest shells in layer 1 were therefore no more than fourteen months old and most of the shells were less than one year old.

Layer 2 (Fig. 11c)

The density of cockles between 2.5 and 5 cms below the surface is very much less than that in the top layer. The two highest densities are found at the same stations as the high density in layer 1. East of Channel C densities of less than 5 per 1/10th square metre are not uncommon. From Figs. 12 and 13 the size-frequency distribution is seen to be very similar to that in layer 1 and the peaks are in the same size range. No cockles larger than 8 mms were found. Cockles from Transects 2 and 3 again belong to the summer 1962 spatfall and those from Transect 1 show the winter ring as in layer 1 and are therefore late 1961 0-Group.

Layer 3 (Fig. 11d)

The highest density - 4 to 5 per 1/10th square metre - was again at Stations 2/4 and 2/5, but over the rest of the area the distribution was discontinuous. The size-frequency distribution was similar to that in layer 2.

Discussion

Cardium tolerates a wide range of environments. Its distribution in the Carse Sands does not appear to be controlled by grain-size although it is not found in the Carse Bay mud flats where a high percentage of clay in suspension would be deleterious to Cardium as it is a suspension feeder. It is not found in the megaripples or the unstable coarse sands to the south.

The distribution in depth shows that Cardium can live down to 7.5 cms (layer 3) below the surface but it is commonest in the top 2.5 cms (layer 1) of the sediment. The highest densities in layers 2 and 3 are below areas of high density in layer 1. As little difference is seen in the size-frequency distributions with depth it is probable that vertical movements as well as horizontal ones are common, and considerable interchange of position takes place in the population. It is unlikely that a cockle could survive for any length of time - especially individuals less than one year old - at depths greater than 3 to 5 cms as the siphons are short in relation to shell length.

The complete absence of 1960 0-Group cockles from all three transects and the virtual absence of 1961 0-Group individuals from the September 1962 transects show that conditions are not suitable for the survival of cockles for more than one year. The bulk of

the September population is less than four months old. Therefore, although relatively successful spat settlement occurs and growth takes place throughout the summer, very few individuals survive for more than six months. The highest densities in the Carse Sands (Table 19) are comparable with those obtained by Stephen (1930), Spooner and Moore (1940) and Raymont (1955) in similar estuarine environments. Stephen and Spooner and Moore found that their highest densities were also dominated by O-Group individuals.

C. edule O-Group form an important part of the diet of the Plaice (Pleuronectes platessa) and the Flounder (Platichys flesus) (Smidt 1951). Drinnan (1957) has shown the effect of predation by the Oystercatcher (Haematopus ostralegus) to be equivalent to a mortality rate of 20%. The young spat less than 2 mms are also liable to predation by Crangon vulgaris. Constant predation thus occurs with flounders and plaice at high tide and oystercatchers at low tide.

During periods of very high wind at low tide, erosion causes the redistribution of large numbers of cockles. When the wind is strong the current ripples on the sand surface are flattened and the wind travels over completely smooth surfaces. This tends to dry out the top 2 cms of the sand. Water released from the siphons of cockles living in the surface layer when the tide is out makes the sand round each shell wetter than the surrounding sand. The dampness binds the sand grains and this offers some resistence to the wind and wind-blown surface sands. Turbulence is set up on the windward side of the cockle and the sand is gradually eroded away. The resultant depression gradually enlarges

through action of eddies until it has exposed the cockle. The depression further enlarges until it is about 1.5 times the size of the cockle (Plate 28a). The cockle then rolls into the hole thus formed and after a few seconds it is lifted out by the wind on to the smooth sand surface where the wind proceeds to roll it along the sand at considerable speed. The shells will continue to roll as long as no obstacle is encountered in their path. Cockles up to 10 mms can be transported in this manner. On 9th April 1964 with a wind of 25 knots blowing from the south-southwest (210^{o}) many hundreds of cockles were transported as far as the Nith Channel through distances of up to 1200 metres. Probably only a few of these managed to dig themselves back into the sand in time to avoid predation.

Scrobicularia plana (da Costa)

This species has a fairly restricted distribution in inter-tidal estuarine brackish muds. Spooner and Moore (1940) found that Scrobicularia extended above the limits for C. edule and this is also the case in the Solway. Thamdrup (1935) observed considerable fluctuations in densities from year to year. Older age groups are particularly sensitive to severe winters (Smidt 1944). Densities of 136 adult and 72 young per square metre were recorded in the Exe Estuary (Holme 1949) and of 100 - 250 adults per square metre from the Tamar Estuary (Spooner and Moore 1940). Green (1957) obtained densities of up to 1025 per square metre in the Gwendraeth Estuary, Carmarthenshire. Further north, however, densities appear to be much less.

No information is available on spatfall in the Solway as it proved to be impossible to separate the spat of S. plana,

M.balthica and T. tennuis. In most lists (Boysen Jensen in Thorson 1946) they are designated as "dirty lamellibranch larvae" and are not differentiated. Rees (1950) does not attempt to separate them and in this study all are considered to be Macoma spat.

The distribution of adults is shown in Figs. 11e and 11f. Scrobicularia is restricted to layers 4 and 5 in the upper mud flat in Carse Bay and is not seen south of Carsethorn village or east of Channel B. It appears to be able to tolerate mud and silt and perhaps fine sand and is restricted to areas with considerable fresh-water dilution at low tide. No living Scrobicularia were found in the unstable silts of the lower mud flat.

The lengths of shells in layer 4 range from 16 - 30 mms and in layer 5 from 28 - 30 mms. If the growth rates obtained by Green (1957) are applied to the Solway then the shells in 1/1/4 are four years old (1958 0-Group). The others on Transect 1 are possibly six years old (1956 0-Group). In stations with Scrobicularia in layer 4 it is not present in layer 5 and vice versa (Figs. 11e, f). Thus only a single Scrobicularia layer is present at depths of 7.5 to 12 cms. The characteristic siphon thrash-mark is not particularly common.

When moving, Scrobicularia comes to the surface and leaves a characteristic trail (Plate 28b) in the form of an arc of a circle of radius 35 to 40 cms. The animal moves through the sediment with the umbo just above the surface. The long axis of the shell (= length) makes an angle of approximately 30°

with the sediment surface. The anterior of the shell with the foot is below the surface and the posterior part is directed upwards and backwards. While at the surface the animal is particularly vulnerable to attack from oystercatchers and relatively few survive the surface movements. These movement trails are only occasionally seen on the mud flats. The living Scrobicularia 18 mms in length found in layer 1 at Station 2/1 was probably moving near the surface when the sample was taken as an animal of that length normally lives at depths greater than 5 cms.

Macoma balthica (L)

This is one of the commonest intertidal estuarine lamellibranchs and is widely distributed in northwest Europe. Thamdrup (1935) found Macoma in both sand and mud and detected no difference in growth rate between them. He considered that as Macoma is a deposit feeder growth is independent of the length of the period of submersion. Holme's densities of up to 24 per square metre in the Exe estuary are comparable with Petersen's so-called "typical" density of 20 per square metre. Petersen (1918), however, stated that the actual densities depend on the abundance of food and the length of time available for feeding. Rees (1940) obtained densities between 140 and 800 per square metre near Cardiff while Thamdrup (1935) recorded up to 1000 at Skallingen. Fraser (1932) noted very high densities - between 1000 and 3000 per square metre - on a mud flat in the Mersey, but this is associated with an abnormally rich diatom flora at a sewage outflow.

Smidt (1951) found abundant 0-Group Macoma - up to 16,000 per square metre - on soft waddens. During the first three months after spatfall however, these numbers decrease rapidly:-

June	16,000
July	5,000
August	500

Spatfall

Macoma larvae occur in the plankton from May to October and the main spatfall is in June (Smidt 1951, Stephen 1931). Fig. 14a shows the distribution of the late summer 1962 spatfall. The highest densities - up to 792 per 1/10th square metre - are on the upper mud flat south of Carsethorn village. East of the Carse Gut the density is between 10 and 25 per 1/10th square metre except at Station 2/4. The distribution of spat east of the Carse Gut seems to be related to the Carse Gut "catchment areas" and no spat were found east of the "watershed" between the Carse Gut and Channel G. The high density areas are seen to be the same as they were for Cardium spat but the Macoma spatfall is much more restricted.

Post Larval Distribution

Macoma is found in all layers but is not particularly common greater than 7.5 cms below the surface.

The problem associated with determination of growth rates and the age of particular individuals are considerable. Only in a few cases can definite winter rings be recognised. Usually the rings are indistinct and cannot be separated easily from the other fine concentric rings which may possibly be disturbance

FIG. 14 DISTRIBUTION OF MACOMA BALTHICA.

a. Macoma balthica Spat

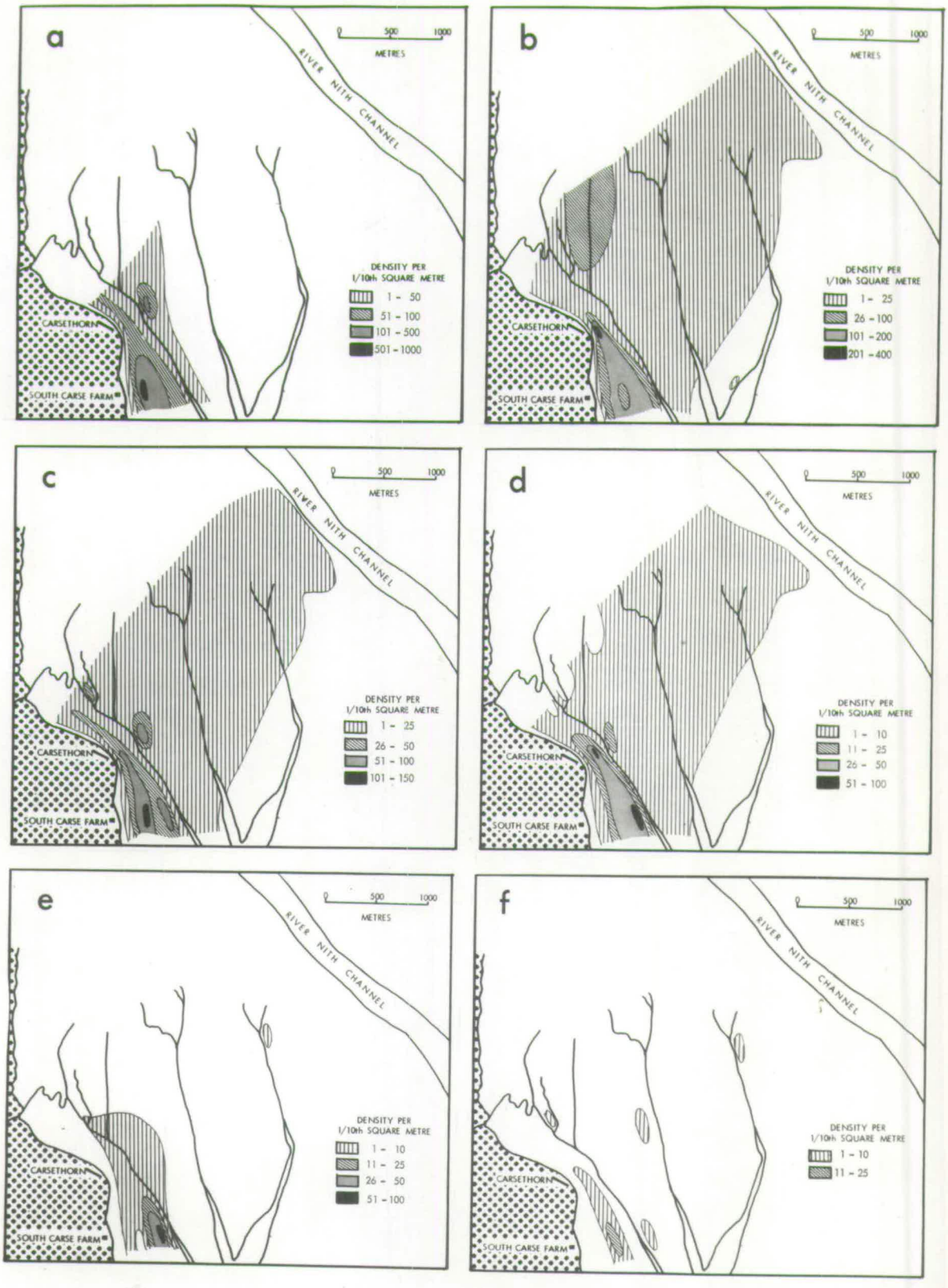
b. Macoma balthica Layer 1

c. Macoma balthica Layer 2

d. Macoma balthica Layer 3

e. Macoma balthica Layer 4

f. Macoma balthica Layer 5


a
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER 1/10th SQUARE METRE
1 - 50
51 - 100
101 - 500
501 - 1000
CARSETHORN
SOUTH CARSE FARM
b
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER 1/10th SQUARE METRE
1 - 25
26 - 100
101 - 200
201 - 400
CARSETHORN
SOUTH CARSE FARM
c
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER 1/10th SQUARE METRE
1 - 25
26 - 50
51 - 100
101 - 150
CARSETHORN
SOUTH CARSE FARM
d
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER 1/10th SQUARE METRE
1 - 10
11 - 25
26 - 50
51 - 100
CARSETHORN
SOUTH CARSE FARM
e
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER 1/10th SQUARE METRE
1 - 10
11 - 25
26 - 50
51 - 100
CARSETHORN
SOUTH CARSE FARM
f
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER 1/10th SQUARE METRE
1 - 10
11 - 25
CARSETHORN
SOUTH CARSE FARM

rings of the type seen by Orton (1926) on Cardium and may perhaps represent the times when the Macoma was moving at the surface. Macoma is smaller in estuaries and inshore areas than in fully marine conditions.

Estimates of growth have been made by Stephen (1929), Brady (1943) and Stopford (1951):-

Year	STEPHEN Aberlady	BRADY Northumberland	STOPFORD Dee
1	5	6	4 - 10
2	8 - 9	12	---
3	---	16	---
4	---	18	---
5	---	19	---

Stopford showed that by December the earliest summer spat could grow to 10 mms, whereas the late summer spat (corresponding to the September 1962 spat in the Solway) only grew to 4 mms. The growth rates obtained by Brady were in more marine intertidal conditions and are therefore greater than those obtained by Stephen in Aberlady Bay. The growth rates in the Solway appear to be of the same order as those at Aberlady and a tentative age to length relationship might be:-

Year	Length (mms)
1	3 - 7
2	7 - 10
3	10 - 13
4	13 - 15
5	15 - 17

These estimates are based on Stephen and on the size-frequency distribution from the Solway. Stephen found a heavy mortality after two years. Brady found that very few exceeded 18 mms and most died at the end of their fourth year. In the Solway the largest are 17 mms and may be over five years old.

Layer 1

The distribution of Macoma in the top 2.5 cms of the sediment is given in Fig. 14b. The highest densities are found on the upper mud flat from Carsethorn village southwards. Size-frequency analysis of these high-density samples (Figs. 16 and 17) show that the bulk of the individuals are between 2 and 4 mms long and are the early summer 1962 0-Group. Only 17% of the individuals on the upper mud flat in September 1962 were older than 4 months. East of the Carse Gut the densities of 0-Group are lower and the overall density gradually decreases towards the Nith Channel.

On Transect 1 (Fig. 15) sampled in April 1962 the 3 - 4 mm individuals represent the late summer 1961 0-Group. The larger sizes on Transect 1 are two and three-year-old shells. The larger individuals seen in layer 1 are animals which have come to the surface and were moving when the sample was collected.

Layer 2 (Fig. 14c)

The overall distribution is similar to that in layer 1. The highest density is again on the upper mud flat south of Carsethorn village. It is lower on the mud slope and over most of the lower mud flat except at Station 3/4 where 61 per 1/10th square metre were found. A high density is also found at Station 2/4. (This is the same station as the high density of C. edule in layer 1, but the Cardium density in layer 2 is only 8 per 1/10th square metre.)

The size-frequency distributions in layer 2 of Transect 1 show modes between 5 and 8 mms and 12 and 15 mms probably

FIG. 15

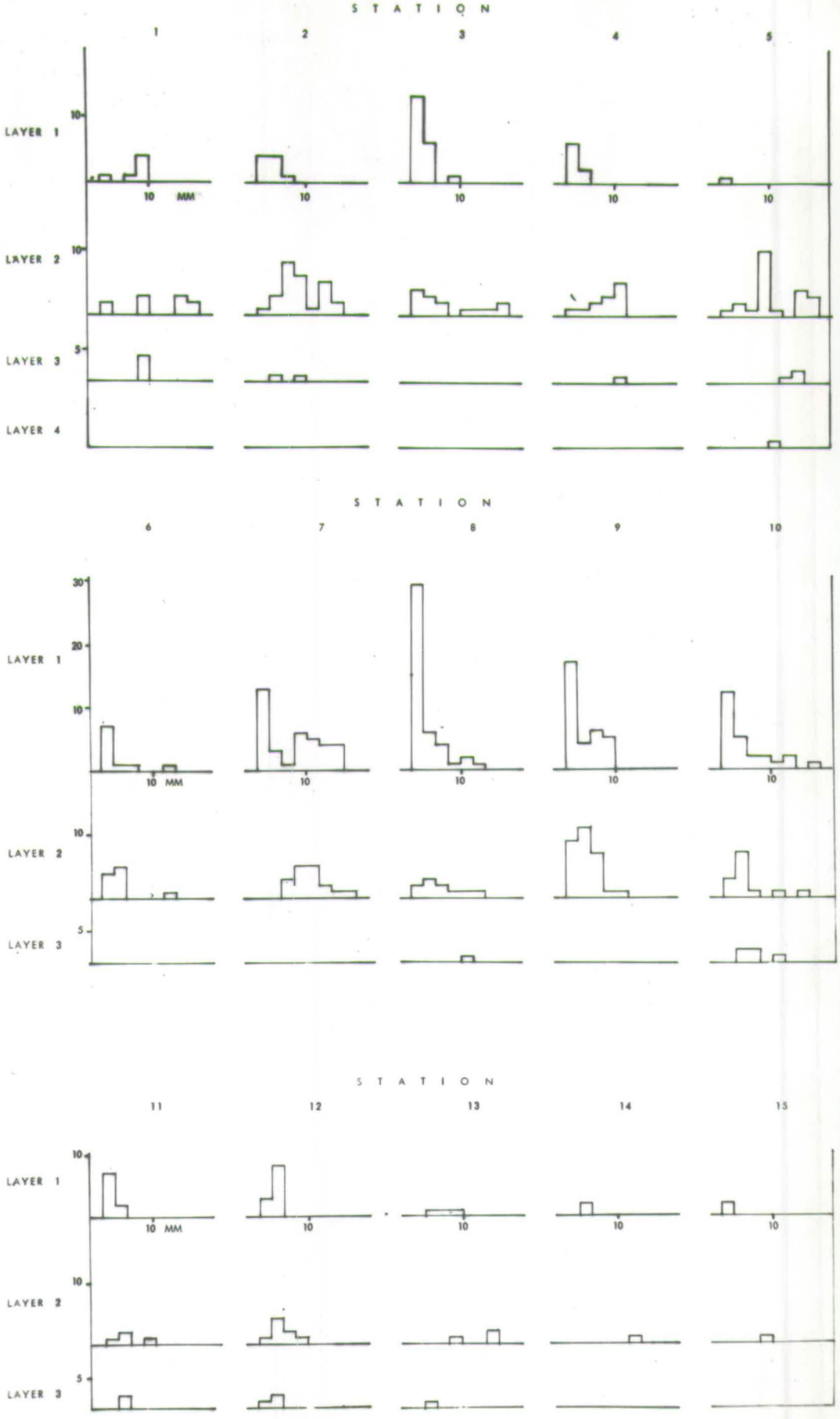
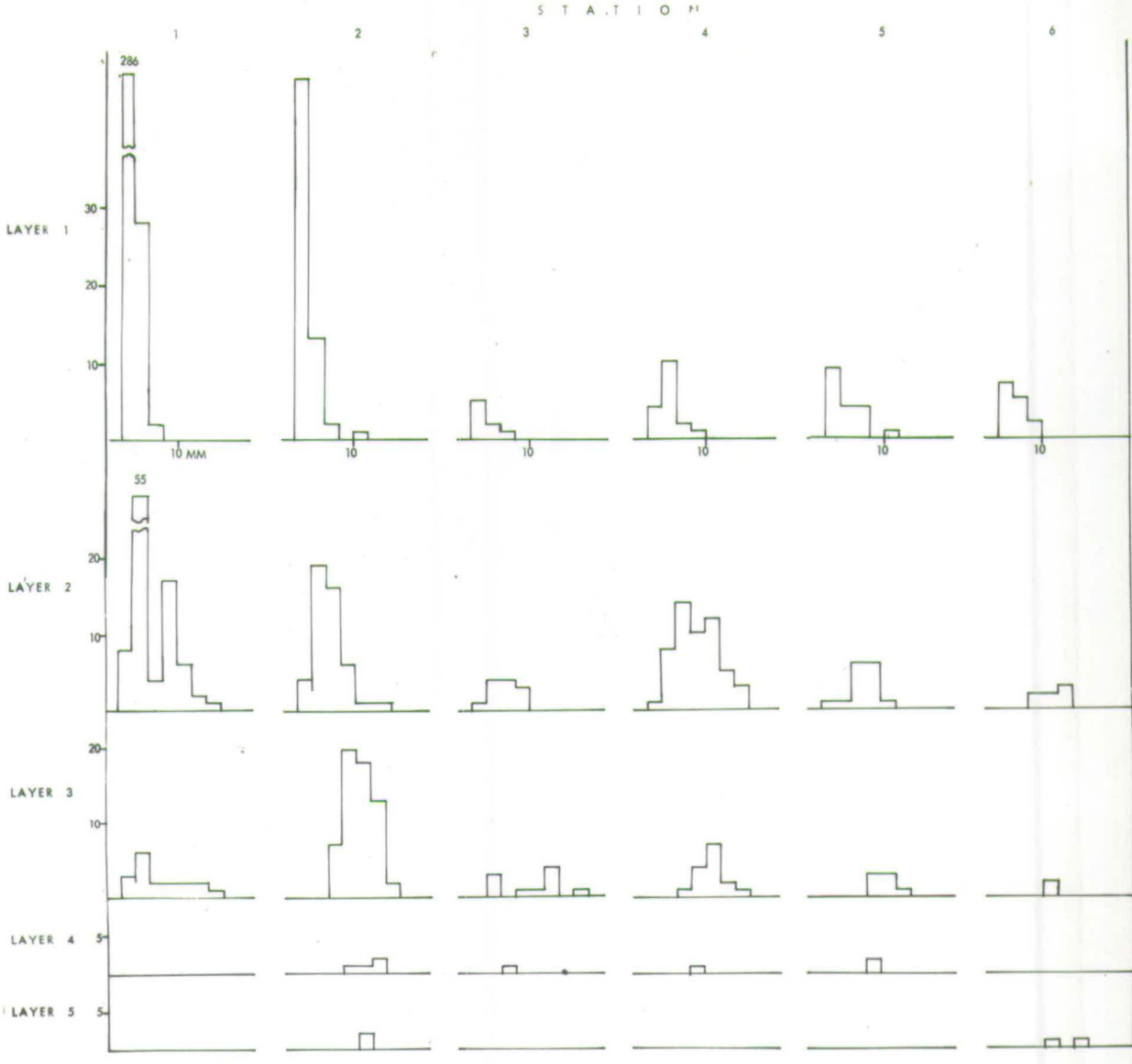

STATION
1
2
3
4
5
LAYER 1
LAYER 2
LAYER 3
LAYER 4
10
5
10 MM
STATION
6
7
8
9
10
LAYER 1
LAYER 2
LAYER 3
30
20
10
10
5
10 MM
STATION
11
12
13
14
15
LAYER 1
LAYER 2
LAYER 3
10
10
5
10 MM

FIG. 16


STATION
1
2
3
4
5
6
286
55
LAYER 1
LAYER 2
LAYER 3
LAYER 4
LAYER 5
30
20
10
5
10 MM
10

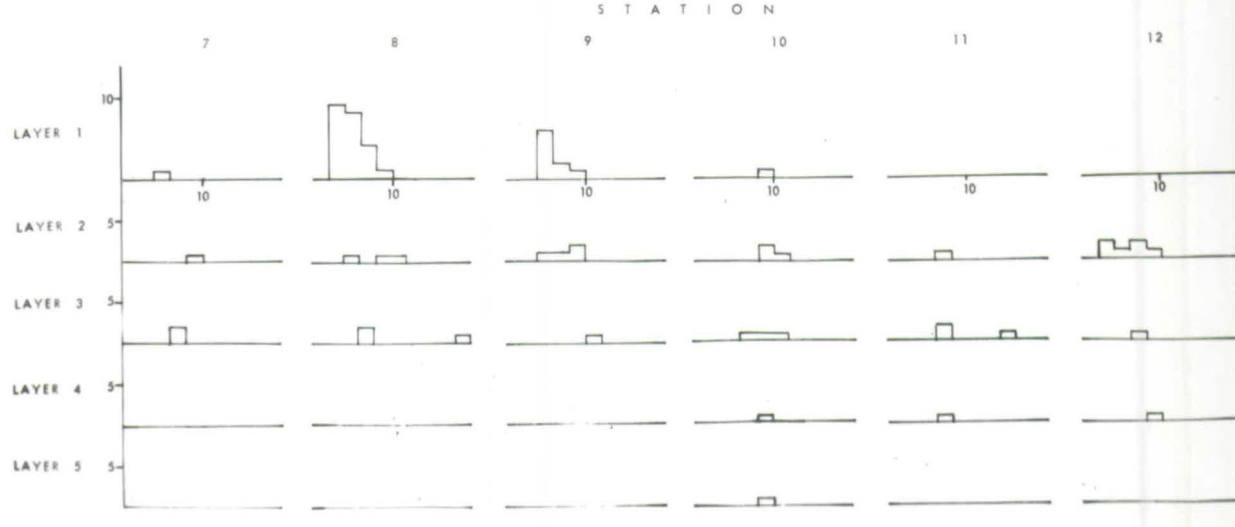
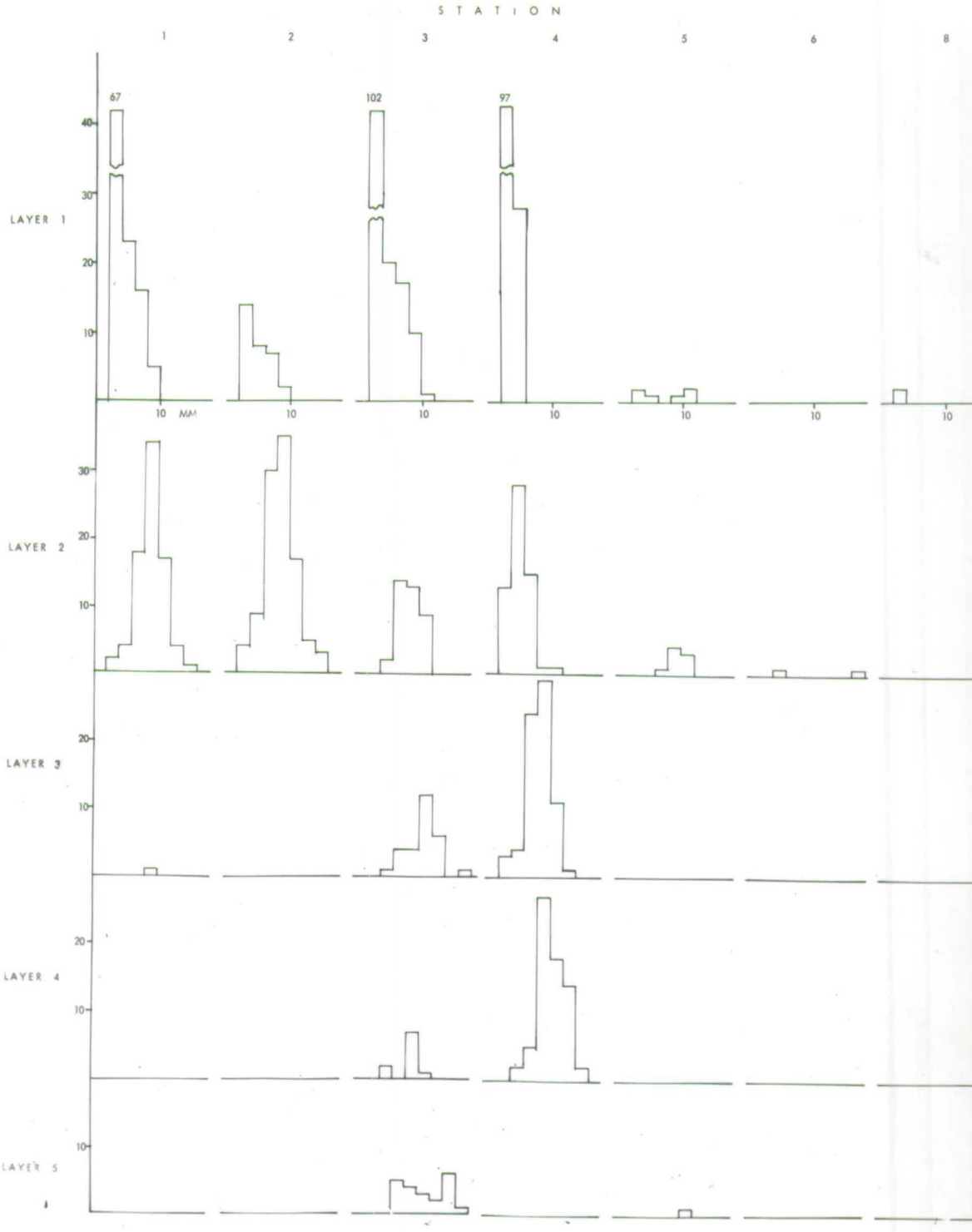

STATION
7
8
9
10
11
12
LAYER 1
LAYER 2
LAYER 3
LAYER 4
LAYER 5
10
5
10

FIG. 17



SIZE-FREQUENCY DISTRIBUTION OF LIVING MACOMA BALTHICA, TRANSECT 3.

Number of shells plotted against length.

representing two and four-year-old individuals. On Transects 2 and 3 the modal size range is 6 to 9 mms representing late 1961 0-Group shells. At Station 2/1 the marked peak between 5 and 6 mms is probably the early summer 1962 0-Group which have grown sufficiently to burrow deeper than 2.5 cms. The other peak at Station 2/4 is the one year class. In general the mode in layer 2 is up to 3 mms longer than in layer 1.

Layer 3 (Fig 14d)

The highest density is again on the upper mud flats but towards the top of the mud slope on Transect 2. The high density at Station 3/4 on the lower mud flat in layer 2 is also seen in layer 3. East of the Carse Gut a fairly uniform decrease in density occurs towards the Nith Channel with densities of up to 7 per 1/10th square metre east of Channel E going down to 1 per 1/10th square metre at the Nith Channel itself. On Transect 1 the densities in layer 3 are generally low, the highest being 5 per 1/10th square metre at Station 10. In the September 1962 transects the modal length is from 9 to 12 mms and includes two and three-year-old individuals. The modal length is 2 to 3 mms longer than in layer 2.

Layer 4 (Fig. 14e)

The distribution is much more restricted and apart from one isolated area east of Channel H at Station 2/10 Macoma is mainly found west of Channel E and associated with the Carse Gut. The highest density is on the lower mud flat at Station 3/4. The modal length - 9 to 13 mms - is similar to that in layer 3 but the average length in layer 4 of Station 3/4 is 10.7 mms whereas in layer 3 it is only 8.8 mms.

Layer 5 (Fig. 14f)

Here the distribution is discontinuous. The highest density - 25 per 1/10th square metre - is at Station 3/3 while elsewhere it is never more than 2 per 1/10th square metre. These isolated areas are all within 100 metres of a channel or tributary and may be related to increased food supply associated with the channels. The modal length at Station 3/3 was 15 to 16 mms and represents individuals up to five years old.

Discussion

Macoma is present in both silt and fine to medium-grained sand but is not found in coarse sand. This is only partly a grain-size restriction however, as the coarse sands are unstable and it is the instability that restricts Macoma. Although no definite sediment preference can be detected the densities in silt are higher than those in sand. This is probably due to the higher concentration of organic detritus and diatoms on silt giving increased food supplies. The grain-size therefore only indirectly influences the density.

The highest concentration of 0-Group are in the surface layer of the upper mud flat. The 0-Group density drops rapidly east of the Carse Gut. Older individuals occur in layers 2 and 3 and 2.5 to 7.5 cms is the optimum depth for Macoma balthica in its normal burrowing position. Yonge (1949) found that the inhalent siphon of M. balthica extends to at least 5 cms. It is probable that Macoma at depths greater than 7.5 cms are capable of greater extensions than this (M. calcarea, a more northern species, has siphons which can extend 10 cms - Blegvad 1915). The density at

depths greater than 7.5 cms is much less and in layer 5 occurrences are few. An exception to this is at Station 3/4 on the lower mud flat where the density in layers 3 and 4 are almost the same. The softness of the sediment on the lower mud flat, making burrowing to greater depths relatively easy, possibly accounts for this. The density of 25 per 1/10th square metre in layer 5 of the adjacent station on the mud slope may also be related to the softness of the sediment, allowing movement nearer the surface to be made without much difficulty.

As a general rule the length of Macoma increases with depth. Thus the smaller and younger individuals live close to the sediment surface and the older ones progressively deeper down. The modes of the size-frequency distributions for layer 2 are in general 2 mms longer than in layer 1 and in layer 3 the mode is 2 mms longer than in layer 2 etc. The high density Stations - 2/2, 2/4, 3/3 and 3/4 (Figs. 16 and 17) - demonstrate this particularly well.

A complication occurs when Macoma moves up to the surface and the exceptions to the rule such as the 17 mm individual in Station 3/2/2 possibly represent individuals moving up and down from the surface.

The highest densities on Transect 1 in layer 1 are found between Channel B and Channel G . The low densities on the upper mud flat in Carse Bay may possibly be due to a higher rate of predation during the winter of 1961/62.

In order to compare the Solway densities with those of other workers the values for each layer have been summed and corrected

to one square metre. From Table 18 the Solway mud flat densities are seen to be higher than those in other British areas, and are comparable with the Danish Wadden Sea. The density on sand flats (Table 19) is also higher than the other areas with the possible exception of the Dovey estuary. The figures suggest that Macoma is extremely successful in the Solway.

When moving, Macoma produces a characteristic trail. Brafield and Newell (1961) observed that at regular intervals of 15 seconds the foot was extended forward and moved so as to thrust the Macoma on its side. In four minutes the foot contracted 15 times and the Macoma moved 5 cms. MacGinitie (1935) noted that the Californian species Macoma nasuta lies on its left side in the sediment and Holme (1961) showed that various species of Tellina including T. tennuis also lie on their left side in the sediment. Macoma balthica also lies on its left side when moving but it is more or less vertical when in its burrow.

The trail is best seen in fairly dry fine-grained sand where the details are not easily destroyed (Plate 29a). The clean cut margin on the upper side of the trail is made by the umbo of the shell cutting through the surface layer. The trace made by the ventral margin is more complex. With each contraction of the foot the shell is moved forward as the animal lies on its side. This pushes the sediment up into a small rounded ridge corresponding in shape to the anterior outline of the shell. With the next contraction another ridge is formed between 3 and 4 mms in front of the first one. This corresponds exactly to the rate of movement observed by Brafield and Newell (1961). A trail

is thus produced showing curved ridges at 3 - 4 mm intervals as shown in Fig. 18a. In finer-grained and wetter sediments the individual anterior ridges coalesce and only a long compound ridge is seen parallel to the sharp line of the umbo trace (Fig. 18b). In silt the long ridge is not usually seen as the sediment tends to flow over the surface and the ridge disappears. The silt on the umbo side of the ridge collapses into the trough left by the shell and the umbo trough becomes wider and shallower (Fig. 18c). Thus, although the type of movement is the same, the appearance of the trail depends on the water content and grain-size of the sediment.

Brafield and Newell (1961) found that Macoma shows both photopositive and photonegative reaction to strong sunlight and that the reaction is reversed at some stage of the tidal cycle giving a basic U-pattern to the trail.

In the Solway in sand with ebb current or transverse ripples on the surface the trail is usually at right angles to the crest. In Plate 1 of Brafield and Newell (1961) the trails are also seen crossing the ripple crests at right angles. It is possible therefore that in addition to the phototropism the nature of the sediment surface plays a large part in controlling the direction of movement of Macoma.

Tellina tenuis (da Costa)

This species is not found in the brackish parts of estuaries. It is characteristic of coarse clean-washed sands with strong current action where densities of over 4000 per square metre are not uncommon. In the outer parts of estuaries in clean-washed

FIG. 18. MACOMA BALTHICA TRAILS.

a. Fairly Dry Fine-Grained Sand.

The umbo makes a clean-cut trace and the ventral margin produces the longitudinal ridge. Successive contractions of the foot result in the formation of the transverse ridges which persist in the fairly dry sand.

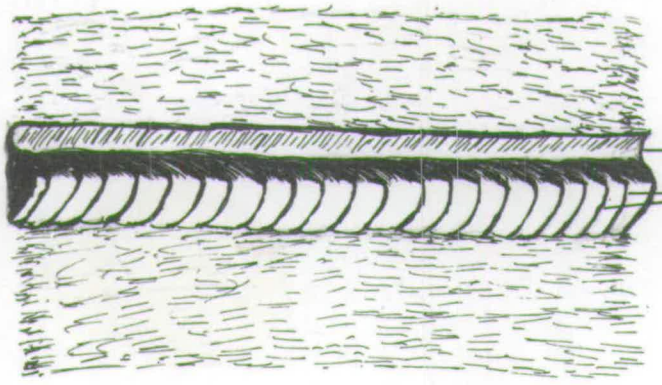
b. Wet Fine-Grained Sand.

The clean-cut trace of the umbo and the longitudinal ridge persist but the sand is too wet for the transverse ridges to be preserved.

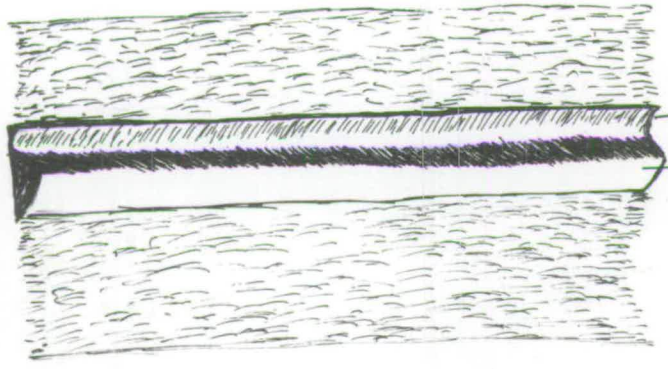
c. Wet Silt.

The umbo trace is shallower and wider than in a. or b. due to the collapse of most of the longitudinal ridge into the trough. Frequently, flowage in the silt flattens out the remains of the longitudinal ridge.

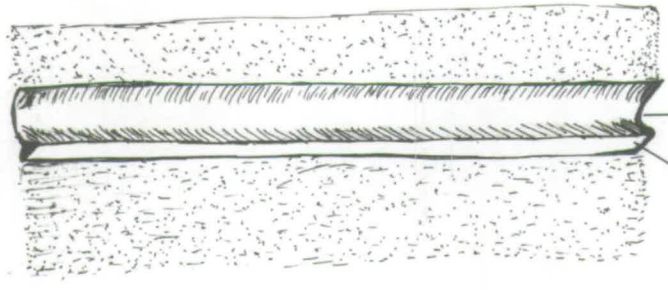
a


UMBO TRACE
MINOR TRANSVERSE RIDGES
ON LONGITUDINAL RIDGE.

b


UMBO TRACE
LONGITUDINAL RIDGE

c


UMBO TRACE
(WIDENED BY COLLAPSE OF
VENTRAL WALL)
REMAINS OF LONGITUDINAL
RIDGE

0
1
2
3
4
5
CENTIMETRES

FIG. 19. DISTRIBUTION OF TELLINA TENUIS.

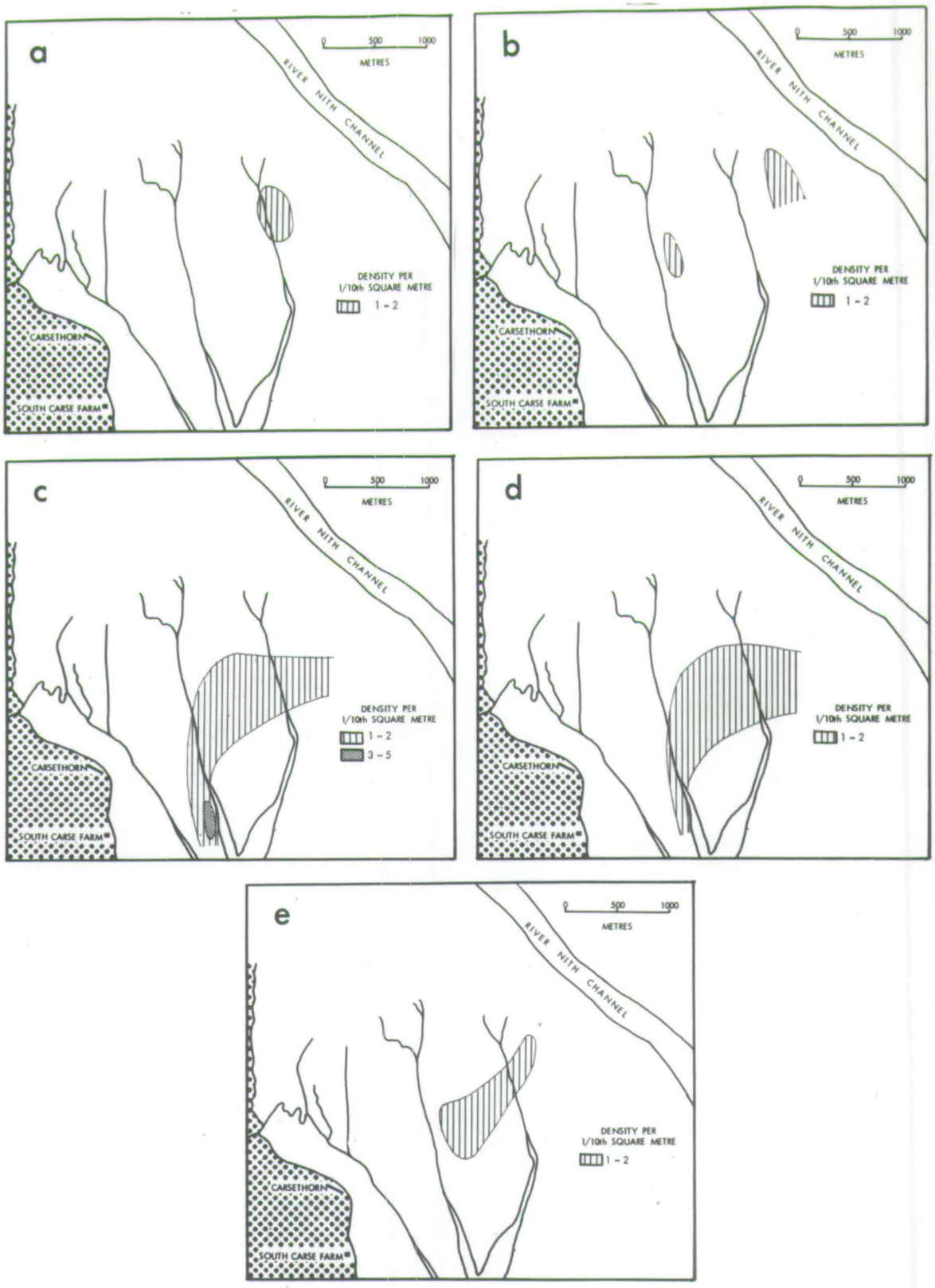
a. Tellina tenuis Layer 1

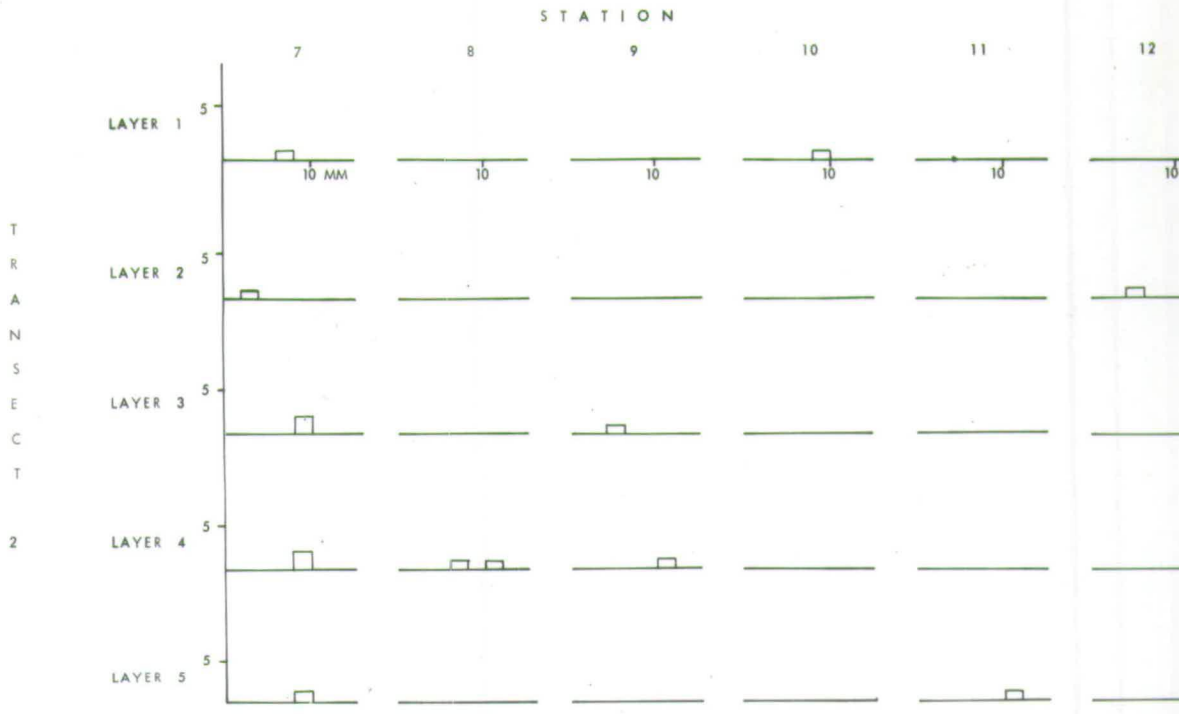
b. Tellina tenuis Layer 2

c. Tellina tenuis Layer 3

d. Tellina tenuis Layer 4

e. Tellina tenuis Layer 5


a
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 2
CARSETHORN
SOUTH CARSE FARM
b
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 2
CARSETHORN
SOUTH CARSE FARM
c
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 2
3 - 5
CARSETHORN
SOUTH CARSE FARM
d
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 2
CARSETHORN
SOUTH CARSE FARM
e
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 2
CARSETHORN
SOUTH CARSE FARM



SIZE-FREQUENCY DISTRIBUTION OF LIVING TELLINA TENUIS TRANSECTS 2 AND 3.

Number of shells plotted against length.

sands the densities are very much less. Stephen (1929 found only 20 per square metre at Nairn on the Moray Firth and only 75 per square metre at Carnoustie at the mouth of the Firth of Tay. Holme (1949) found up to 184 per square metre in clean sands at the mouth of the Exe and Stopford (1951) recorded it from clean sands in the Dee.

Tellina is restricted to the coarse clean-washed sands of the southern and southwestern Carse Sands. The highest density - 5 per 1/10th square metre - was in layer 3 of Station 3/6 at the western bank of Channel G. The distribution in layers 1 to 5 is shown in Fig. 19. The distribution in layer 1 and layer 2 is sporadic and the density is only 1 per 1/10th square metre. Layer 3 and layer 4 probably represent the optimum depth for Tellina as the densities (in addition to the high density at Station 3/6)are up to 2 per 1/10th square metre. In layer 5 the distribution is much more restricted.

The distribution of Tellina in depth is not as significant as that for Cardium, Macoma, Mya or Scrobicularia as Tellina burrows to depths of 12 cms when the tide is out (Yonge 1949) but rises to the surface when the sea returns. Size-frequency distributions are given in Fig. 20, but the numbers are far too small for any study to be made. Stephen (1928) showed that the size decreased towards the lower limits of the intertidal zone. Stephen's growth rates are:-

Year	Upper Shore	Lower Shore	Carse Sands
0+	4	3	3
1+	9.5	6	6
2+	11.5	8	9
3+	14.5	9.5	11

The third column is a tentative age length scheme for the Carse Sands which will require to be tested on a much larger population.

Mya arenaria L

Mya is widespread in intertidal sands and silts. It is a deep burrower and adults are normally 20 to 30 cms below the sediment surface. It is probable that Mya has been missed in many studies because of its depth. One exception was recorded by Fraser (1932) from the Mersey where Mya was only found associated with abundant cobbles and small boulders, and was restricted to the top 7 cms of the sediment. These were, however, probably juveniles which would not be found at greater depths. Stopford (1951) obtained young individuals in the top layer of the sediment. Smidt (1951) showed that 0-Group could be abundant but it declined rapidly through the late summer:-

June	43,000
July	26,000
August	11,600
October	Nil

The older age groups showed a sporadic low density distribution. The maximum density at Skallingen was 20 per square metre (Thamdrup 1935).

Spatfall

Settling takes place throughout the summer months with a maximum in June. The late summer 1962 spatfall in the Solway is restricted to the mud flats south of Carsethorn village (Fig. 21a). The highest density - 16 per 1/10th square metre - is on the lower mud flat. 0-Group Mya were heavily preyed on by plaice and flounders and were taken in preference to other lamellibranchs during the summer (Smidt 1951).

Post Larval Distribution

Fig. 21b-d shows the distribution in layers 1, 2 and 5 respectively. In layer 1 the highest density is on the upper mud flat. The size-frequency of these young Myas shows a runge from 3 to 8 mms. Growth in the first season was 2 to 3 mms on average (Smidt 1951), but could be as great as 5 or 6 mms. Matthiessen (1960) showed that by November the summer 0-Group ranged from 2 to 12 mms in length. Reworking of the surface layer formed a concentration of 0-Group Mya at the shoreward change of slope of the beach profile. The individuals in layer 1 are therefore 1962 0-Group. A similar reworking process concentrates 0-Group shells on the upper mud flat towards the foot of the beach. The distribution in layer 2 is sporadic. The shells are all 7 - 8 mms long and are also 1962 0-Group.

The absence of Mya from layers 3 and 4 suggests that possibly the 1961 and 1960 0-Groups have not survived. As Mya grows it burrows deeper and thus 1960 and 1961 0-Group would be expected in layers 3 and 4.

The distribution in layer 5 at depths between 10 and 25 cms

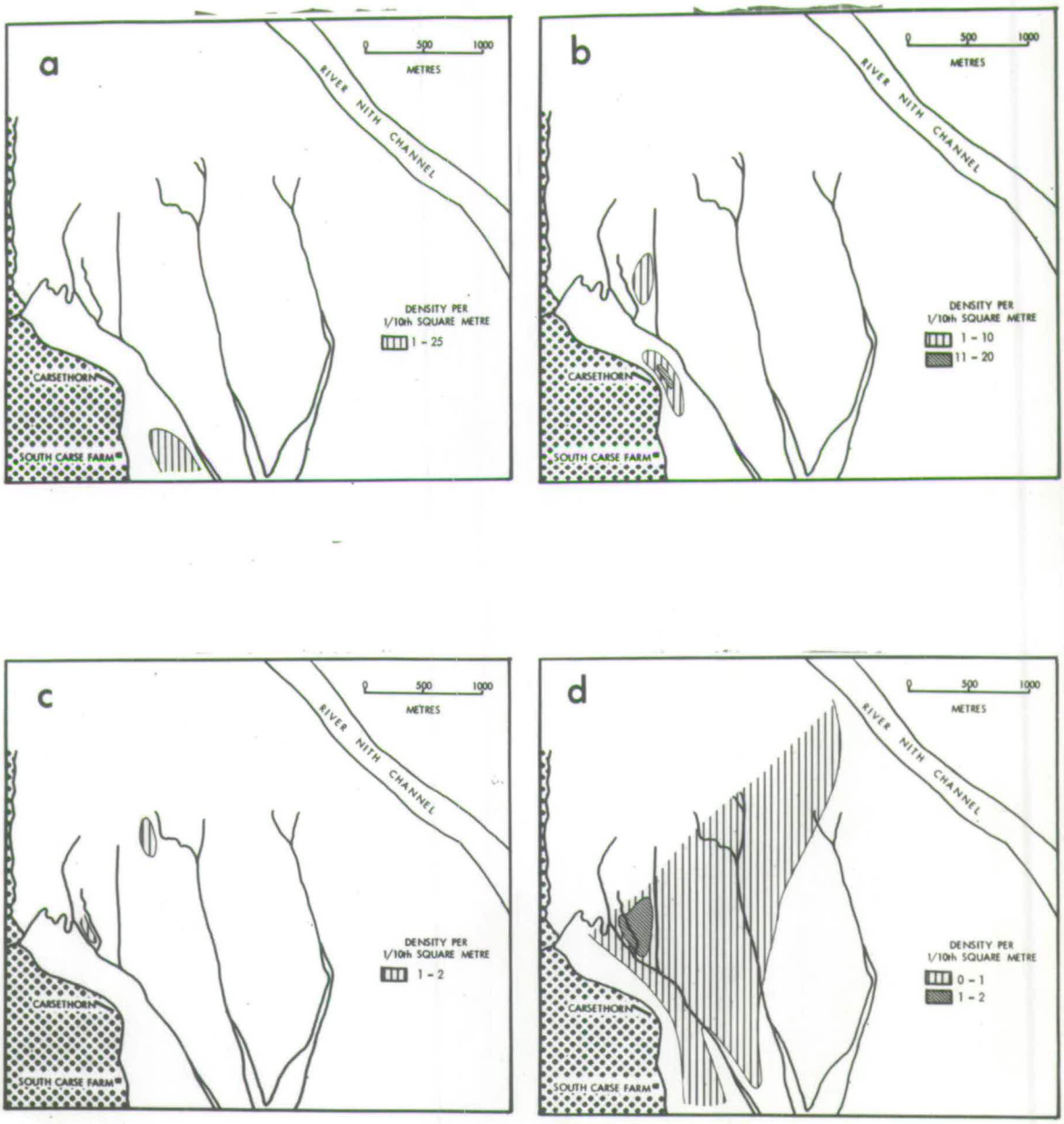
FIG. 21. DISTRIBUTION OF *MYA ARENARIA*.

a. *Mya arenaria* Spat

b. *Mya arenaria* Layer 1

c. *Mya arenaria* Layer 2

d. *Mya arenaria* Layer 5


a
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 25
CARSETHORN
SOUTH CARSE FARM
b
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 10
11 - 20
CARSETHORN
SOUTH CARSE FARM
c
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 2
CARSETHORN
SOUTH CARSE FARM
d
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
0 - 1
1 - 2
CARSETHORN
SOUTH CARSE FARM

is based partly on transect sampling and partly on observation. As the density is less than 10 per square metre over most of the area a sampling scheme based on 1/10th square metre would not give an accurate picture of the distribution. The highest density is in the triangle bounded by Channel C and the Carse Gut, and the shells are between 65 and 90 mms long. No data are available on the growth rates of Mya. Swan (1952) showed that Mya shells in sand were longer than shells of comparable age in mud but the shells were lighter and were narrower and thinner.

On the east bank of the Carse Gut at Locality 11 the erosion of the bank to the 1962 profile has exposed a population of dead Mya shells in their living position. The exposed area is parallel to the channel and is up to 80 cms wide and 80 metres long (Plate 29b). A strip measuring 50 cms by 40 metres was sampled using a ¼ square metre frame. This scheme gave 80 adjacent squares in which the density and orientation of the shells were measured. The shells in living position and any isolated valves were collected and labelled with the number of each square.

The density of shells in living position ranged from 0 to 20 per ¼ square metre, the average being 8 per ¼ square metre. The density increased northwards along the strip. A total of 622 complete shells was obtained from the 80 ¼ square metre samples and the length, breadth, width and weight of each was measured. Total regression analysis of length against breadth and width showed that the growth indices of Mya arenaria in the Solway Firth were almost identical to those obtained by Newcombe

and Kessler (1936) from the Atlantic coast of North America and by Swan (1952b) from Oregon and Washington. The regression equations obtained using an Atlas computer were as follows:-

$L = 1.701B - 0.821$ $\quad$ L = length
B = breadth
$L = 2.708W + 6.355$ $\quad$ W = width

In order to obtain a relationship for weight in terms of length, breadth and width a partial regression analysis was carried out on the data using a computer programme kindly written by Dr. T.V. Loudon. The resulting equation of calculated weight in terms of length, breadth and width using a cube transformation was:-

$$Wt = K + (a \pm b)(L \pm c) \times (d \pm e)(B \pm f) \times (g \pm h)(W \pm i)$$

where

K	= 3.061	e	= 0.2640
a	= 1.4537	f	= 3.887
b	= 0.2480	g	= 0.9565
c	= 4.407	h	= 0.1657
d	= 0.8866	i	= 3.329

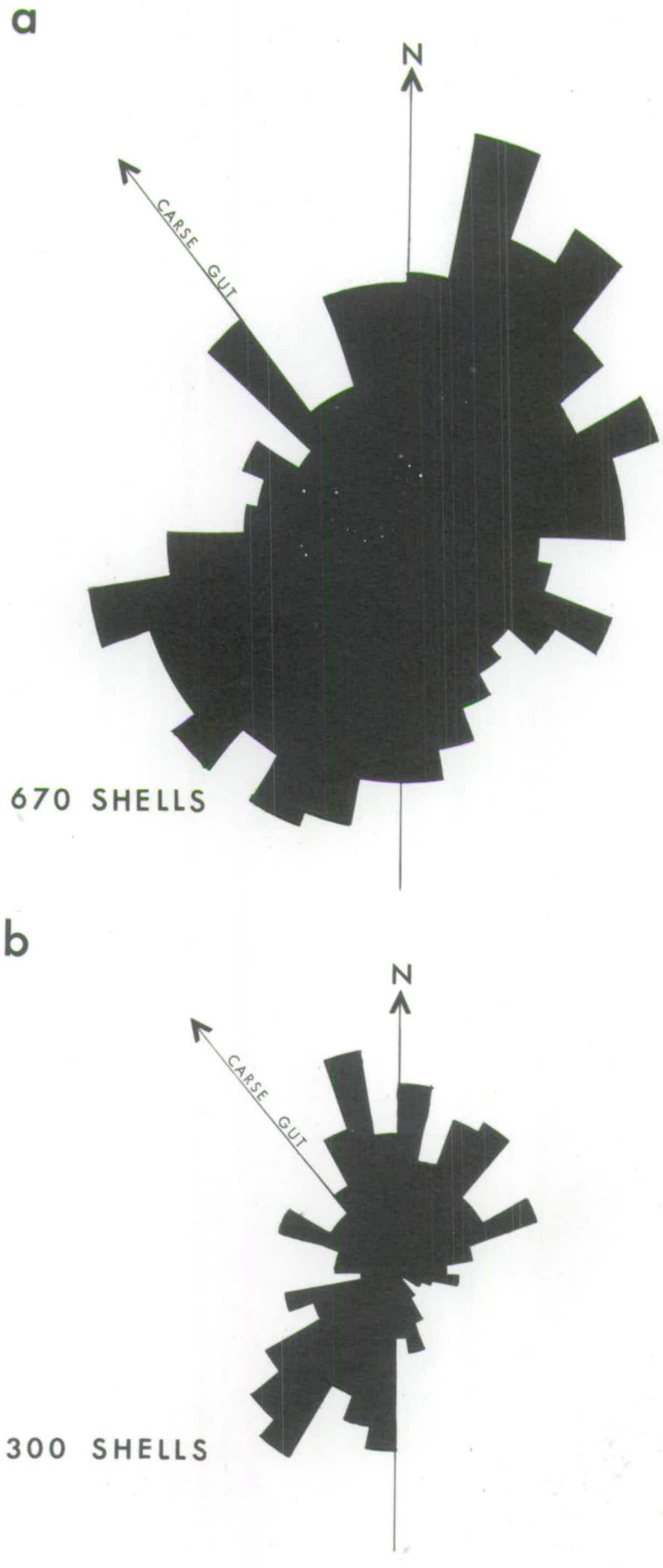
For most shells the difference between the actual weight and the weight calculated from the above equation was small.

The orientation measured was the dorso-ventral plane of bilateral symmetry in the direction of the umbo. All the shells measured were more or less vertical so no attempt was made to measure the inclination of the long axis. Fig. 22a shows the umbo direction of the sample of 670 shells from Locality 11 in relation to the present course of the Carse Gut. It shows marked maxima in the northeast and southwest quadrants. It was possible that this orientation was an effect produced by the minimum resistence to erosion offered by shells oriented parallel to the late ebb current draining the slope to the Carse Gut (Plate 30a). Shells at right angles to these currents i.e. with

FIG. 22. ORIENTATION OF THE DORSO-VENTRAL PLANE IN THE DIRECTION OF THE UMBO IN MYA ARENARIA.

a. Sample of 670 shells from east bank of Carse Gut at Locality 11.

b. Sample of 300 shells from lower mud flat near Station 1/4.


a
N
CARSE GUT
670 SHELLS
b
N
CARSE GUT
300 SHELLS

their dorso-ventral planes parallel to the Carse Gut would offer maximum resistance and the resultant scour effect would remove the shells easily, leaving only those at right angles to the Carse Gut and parallel to the late ebb current.

In order to test whether this was an important factor a separate sample of 300 Mya shells exposed on the lower mud flat west of the Carse Gut was measured. Here the ebb current is at right angles to that on the east bank, and as at Locality 11 only the posterior third of the shell was exposed. Fig. 22b shows the orientation of this second sample and it is clear that same maxima are present with an additional maximum to the north-northwest. The orientation is therefore not an effect produced by the exposure of the shells but is present in the living population. As roughly 40% of the umbos are oriented to the southwest and 40% to the northwest it would suggest that the factor controlling the orientation was from either the northwest or southeast i.e. at right angles to the dorso-ventral plane. The direction of the umbo is not therefore significant. In Mya the inhalent and exhalent siphons are encased in a sheath and therefore no wide separation is possible and no advantage is gained by having the umbo directed down current.

Mya does not normally come out of its burrow, its only movements being vertical ones within the burrow. It is unlikely therefore that it takes up this orientation in adult life. It is more likely to be imposed when in the top 2 to 4 cms of the sediment. Little work has been done on the orientation of lamellibranchs. Morton (1960) found that the byssally attached

form Lasaea rubra showed a photopositive orientation and Brafield and Newell (1961), as already quoted, showed the effects of sunlight on Macoma while at the surface. Fraenkel and Gunn (1940) suggested that the geotactic response in Ensis is probably due to the presence of statocysts. But neither light nor gravitational response will account for the type of orientation seen in Mya.

The present course of the Carse Gut is at right angles to the dominant orientation of Mya but it is unlikely that this is the cause of the orientation, as the course of the Carse Gut changes not infrequently (see Chap. 5) and would most likely differ from its present course when the Mya population was living. It is possible, however, that the orientation is a current response, although not one giving any selective feeding advantage. When the Mya is 2 to 3 mms long it has a much more rounded shell and is byssally attached. Subsequent growth changes its shape to that of a miniature adult and it loses its byssal attachment and proceeds to burrow. The reworking of the top 5 to 10 mms of the sediment during periods of strong current activity would expose the posterior ends of the young Mya shells. Those oriented with their dorso-ventral planes at right angles to the current would tend to be removed by scouring whereas those shells oriented parallel to the current would be sufficiently streamlined to avoid the scour effects and so could survive. Thus an orientation would be produced by the selective removal of most of the shells at right angles to the dominant current during their first few months. It is possible that the shoreward migration of 0-Group

individuals observed by Matthiessen (1960) consisted of those shells reworked from further out which initially burrowed at right angles to the prevailing current direction. In the Carse Sands and in other areas visited and reported in the literature the majority of sedimentary structures are produced by the ebb tide and it is probable that ebb currents are responsible for this selective reworking of young Mya shells.

When the Mya population died the soft parts decayed and the shell filled with sediment. As erosion lowered the banks the Mya population came to the surface and animals living in the top 6 cms of the sediment colonised the protected environment inside the shells. Polychaete U-burrows (Plate 30b) are not uncommon and inside many shells communities of young Macoma and Cardium were found (Plate 31a).

When erosion exposed the posterior gape of the shells the protected environment was utilised by Carcinus (see p.61 and Plate 31b). Shell fragments and valves can also be washed in and trapped in the posterior gape. Plate 32a shows a Mytilus valve in a small Mya shell.

Polychaete burrows and fragile shells would be destroyed by lateral erosion of migrating channels but the sediment inside the Mya shells would not be disturbed. After reworking the Mya shell containing the protected fauna is redeposited parallel to the bedding plane. Thus living faunas may be preserved in large lamellibranch shells such as Mya, Lutraria, Ensis, Solen or Pinna which would be unlikely to be preserved under the environmental conditions in which they normally live.

PHYLUM CHORDATA

SUB-PHYLUM VERTEBRATA

CLASS PISCES

Pleuronectes platessa L

Plaice occur on the bottoms of channels to the south of the area at low tide but during high tide they come up over the sand and mud flats. They feed on O-Group Mya, Cardium and Macoma and also Hydrobia, Retusa, Arenicola and Nereis (Smidt 1951, Williams, Perkins and Hinde 1963).

Platichthys flesus L

Flounders are very common in channels at low tide and are taken regularly in stake nets on the upper mud flats and east of the Carse Gut. They feed on O-Group Mya, Cardium and Macoma and also Crangon and Corophium (Smidt 1951, Williams et. al. 1963).

Clupea harengus L

Young herrings are occasionally stranded on the sand flats at low tide.

Salmo salar L

The salmon is found in the main Nith Channel during the summer months and is occasionally taken in stake nets on the west bank of the Carse Gut.

THE EFFECTS OF BIRDS IN INTERTIDAL AREAS

As the tide recedes large flocks of Oystercatchers (Haematopus ostralegus) descend onto the sand flats and mud flats. The birds follow the tide out feeding voraciously on the

intertidal faunas. The resultant mortality due to this predation is considerable. Drinnan (1957) estimated that the food intake for one oystercatcher per day was 315 cockles between 20 and 30 mms. In October 1954 the figure was 214 per day between 25 and 35 mms. The average feeding rate in January was 51 cockles per hour and in October 28.5 per hour. Not all the oystercatchers were feeding for the duration of low tide and if a correction is made for this the rates for the entire flock are 21 cockles per hour in January and 14.25 per hour in October. During one low tide Drinnan obtained 2840 opened shells in an area of 12,960 square metres.

Cardium is preyed on by oystercatchers in the Solway and after every low tide numerous opened shells are found on the sand flats towards the Nith Channel. The Cardium density is not high enough to support the oystercatcher population and other molluscs are preyed on extensively.

In March 1963 erosion of the west bank of the Nith Channel lowered the level of the sediment up to 500 metres west of the channel. As a result Mya shells were within 7 cms of the surface and during low tide the siphons were only 2 or 3 cms below the surface. In many cases the oystercatcher removed the shell from the sediment and laid it on its side. The upper valve (either right or left, no apparent preference was found) was smashed and the animal eaten. Usually only a portion of the valve was broken as in Plate 32b but occasionally the whole valve was smashed and the fragments could be seen in the sand beside the other valve. If the left valve was destroyed the chondrophore

was usually left attached to the ligament. If the oystercatcher fails to remove the shell from the sediment it eats the siphons and posterior parts of the animal while in its burrow, leaving a distinctive hole in the sediment (Plate 33a). The mark is made by the head rotating the beak from side to side while inserted into the siphon sheath. Mya is probably not often exposed to attack by oystercatchers but it must happen sufficiently often for the birds to learn how to attack it.

Macoma is frequently taken when it comes to the surface. The shells are usually opened without damage and the contents removed. Empty shells are found lying open on the surface over most of the area west of Channel G. The elasticity of the ligament opens the valves out so that they generally lie concave side down on the surface. Many hundreds or even thousands of individuals must be eaten each tide by oystercatchers.

On the upper mud flat Scrobicularia is also taken when it is moving at the surface. Like Macoma the shells are opened without damage and are not uncommon on the upper mud flat near North Carse Farm.

Another method of feeding is represented by the numerous "coprolites" composed of Macoma shell fragments that are found in the vicinity of the Carse Gut. It is possible that these are made by oystercatchers but they are more likely to be the work of gulls. The bird crushes the Macoma and the shell fragments are stored in the crop until it is filled. Regurgitation takes place and the pellet is deposited on the mud (Plate 33b). The pellets are from 2 to 4 cms long. One was collected and it

contained approximately 1,600 fragments and weighed 8.54 grams and probably contained the remains of up to 30 shells. These crop pellets are very loosely bound with mucous but the fragments are easily distributed by the incoming tide. This is of great importance as a source of fragments in an area where current activity is not great enough to produce fragmentation (Wilson 1963). One pellet was found containing Mytilus fragments and must have been disgorged by a gull passing over which had been feeding on mussel beds possibly near Rockcliffe or Southerness.

Carcinus is frequently attacked by gulls at low tide. The carapace is usually detached and the soft parts removed leaving only legs and claws which are readily disintegrated by current action.

Birds are responsible for many tracks across the mud and sand flats. Occasionally beak prod marks are seen where the bird has jabbed its beak into the sediment looking for food. A curious trace is sometimes seen on the upper mud flat (Plate 34a). It appears to be formed by a bird (possibly a snipe, personal communication Van Straaten 1963) moving forwards with its beak on the surface of the sediment sweeping round from side to side, producing a "Helminthoid" trace.

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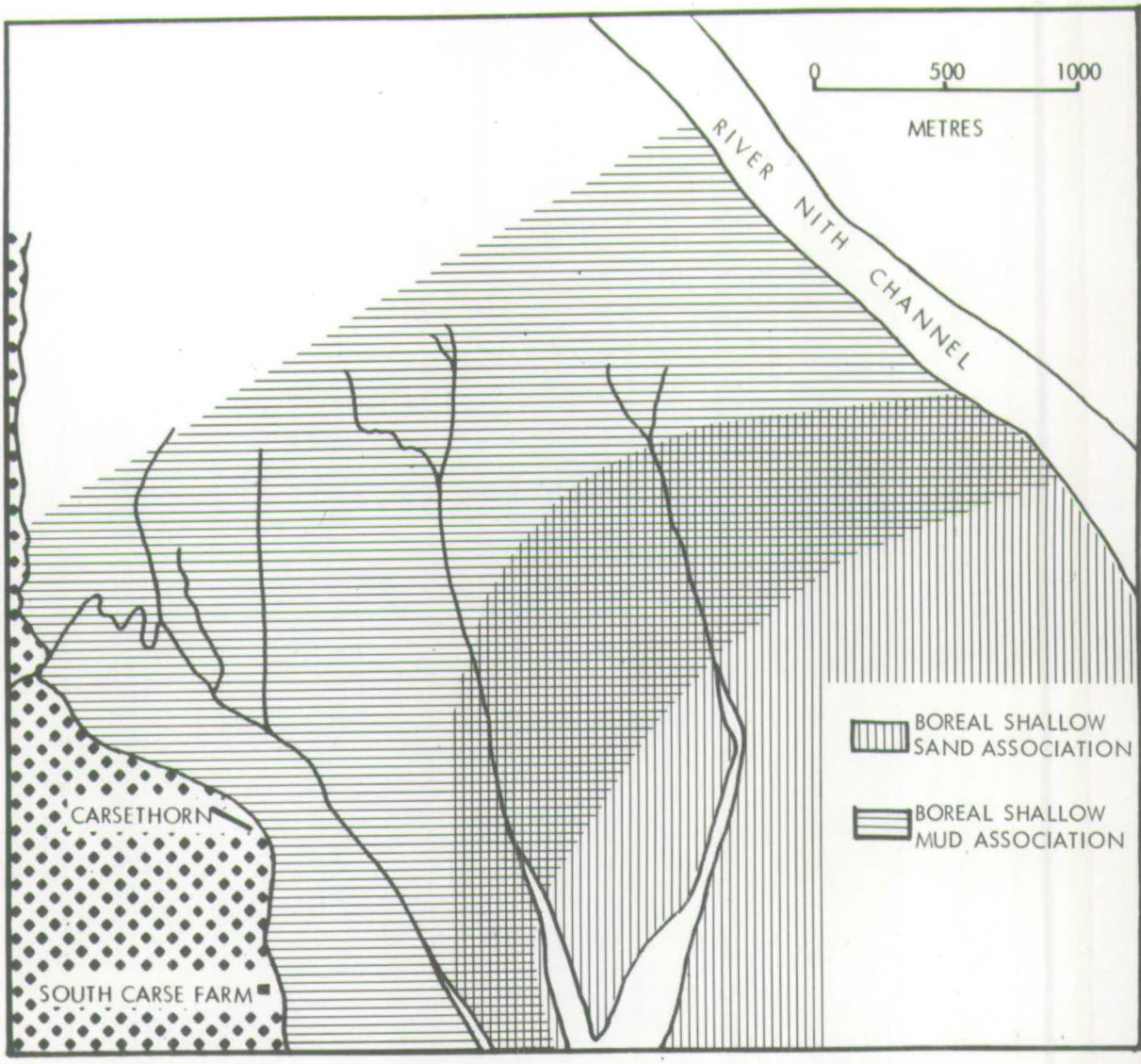
DISCUSSION

The faunas described above can be considered in terms of Petersen's community concept. The upper and lower mud flats; the area of the Carse Gut on Transect 1; most of Transect 2,

and Transect 3 to Station 5 fit the Macoma or Baltic Community defined by Petersen (1918). The rest of the area does not fit this classification. Spärck (1935) defined a Tellina tenuis Community characterised by T. tenuis and Donax vittatus which is typically found in clean sands with a fairly heavy surf. Jones (1950) redefined these communities on a zoogeographical basis and included them in his Atlantic Boreal Region defined by a temperature range of 3 - 16°C. The Macoma Community is redefined as the Boreal Shallow Mud Association and is characterised by M. balthica, A. marina, M. arenaria, C. edule and C. volutator, the Boreal Shallow Sand Association by T.tenuis, D. vittatus and A. marina.

Donax, Tellina and Arenicola are present in the Mersehead Sands at Southerness. This region therefore corresponds exactly to the Boreal Shallow Sand Association. Donax is not found in the Carse Sands and thus the extension of the Boreal Shallow Sand Association into the southern Carse Sands is defined by T. tenuis alone. The change to the Boreal Shallow Mud Association is gradual and a transition zone between 100 and 300 metres wide is present where M. balthica, C. edule, M. arenaria and T. tenuis occur together. The boundaries of the zone based on the limits of Macoma and Tellina are shown in Fig. 23.

The faunal zonation on sandy shores from HWM to LWM was first recognised by Flatteley and Walton (1922) and Stephen (1929, 1930) demonstrated it quantitatively in his classic studies of the Scottish marine fauna. In this present study



DISTRIBUTION OF FAUNAL ASSOCIATIONS.

Note transition zone containing species common to both associations.

the zonation between HWM and LWM and also in depth within the sediment have been investigated and the results are summarised in Fig. 24. The faunal density decreases sharply east of the Carse Gut and again east of Channel G. It decreases sharply below depths of 5 cms (below layers 1 and 2) on Transect 1, below 7.5 cms (below layers 1 to 3) on Transect 2, and below 10 cms (below layers 1 to 4) on Transect 3 west of Channel G. This decrease in total faunal density in layers 4 and 5 to the north may be related to the decrease in length of time of submersion to the north. As the tide ebbs the sediments over most of Transect 1 are exposed at least 45 minutes before those on Transect 3.

Tables 18 and 19 show that the bulk faunal densities in the Carse Sands and mud flats compare favourably with other areas. In particular, the mud flat density of Macoma is considerably greater than those recorded in most other British areas, and the density of Tellina is much higher in the Carse Sands than in other estuaries.

The size-frequency distributions for Macoma and Mya - but not Cardium - show an increase in shell size with depth. The distribution in depth of the lamellibranch species shows a distinct zonation and 5 depth zones may be recognised:-

FIG. 24. DISTRIBUTION DIAGRAM SHOWING RELATIVE FREQUENCY WITH DEPTH ALONG TRANSECTS 1 - 3.

Number of living animals per 1/10th square metre plotted against distance along the transect.

N.B. Vertical scale differs for each species.

Note the reduction of faunal abundance with depth in all three transects and the decrease in faunal density in layers 4 and 5 on Transect 1 compared with layers 4 and 5 of Transects 2 and 3.

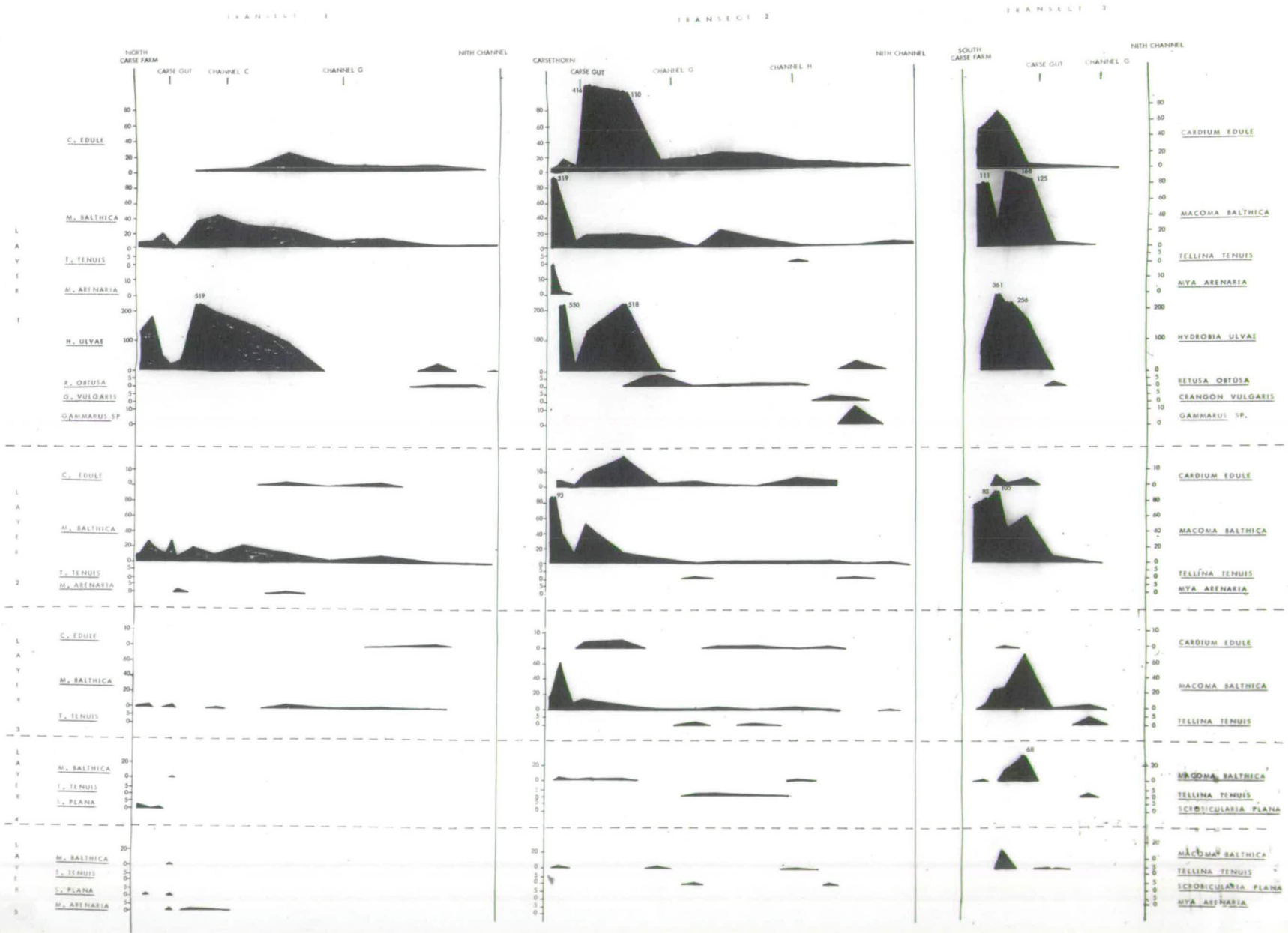

TRANSECT 1
TRANSECT 2
TRANSECT 3
NORTH CARSE FARM
CARSE GUT
CHANNEL C
CHANNEL G
NITH CHANNEL
CARSETHORN
CHANNEL H
SOUTH CARSE FARM
LAYER 1
LAYER 2
LAYER 3
LAYER 4
LAYER 5
C. EDULE
M. BALTHICA
T. TENUIS
M. ARENARIA
H. ULVAE
R. OBTUSA
G. VULGARIS
GAMMARUS SP
L. PLANA
CARDIUM EDULE
MACOMA BALTHICA
TELLINA TENUIS
MYA ARENARIA
HYDROBIA ULVAE
RETUSA OBTUSA
CRANGON VULGARIS
GAMMARUS SP.
SCROBICULARIA PLANA

FIG. 24

Depth	Shallow Mud Association	Shallow Sand Association
0 - 1 cms	Hydrobia: lamellibranch spat; Mya, Cardium and Macoma 0-groups	lamellibranch spat
1 - 5 cms	Cardium: young Macoma	Tellina
5 - 10 cms	Adult Macoma	Tellina
9 - 12 cms	Adult Scrobicularia	Tellina
20 - 30 cms	Adult Mya	---

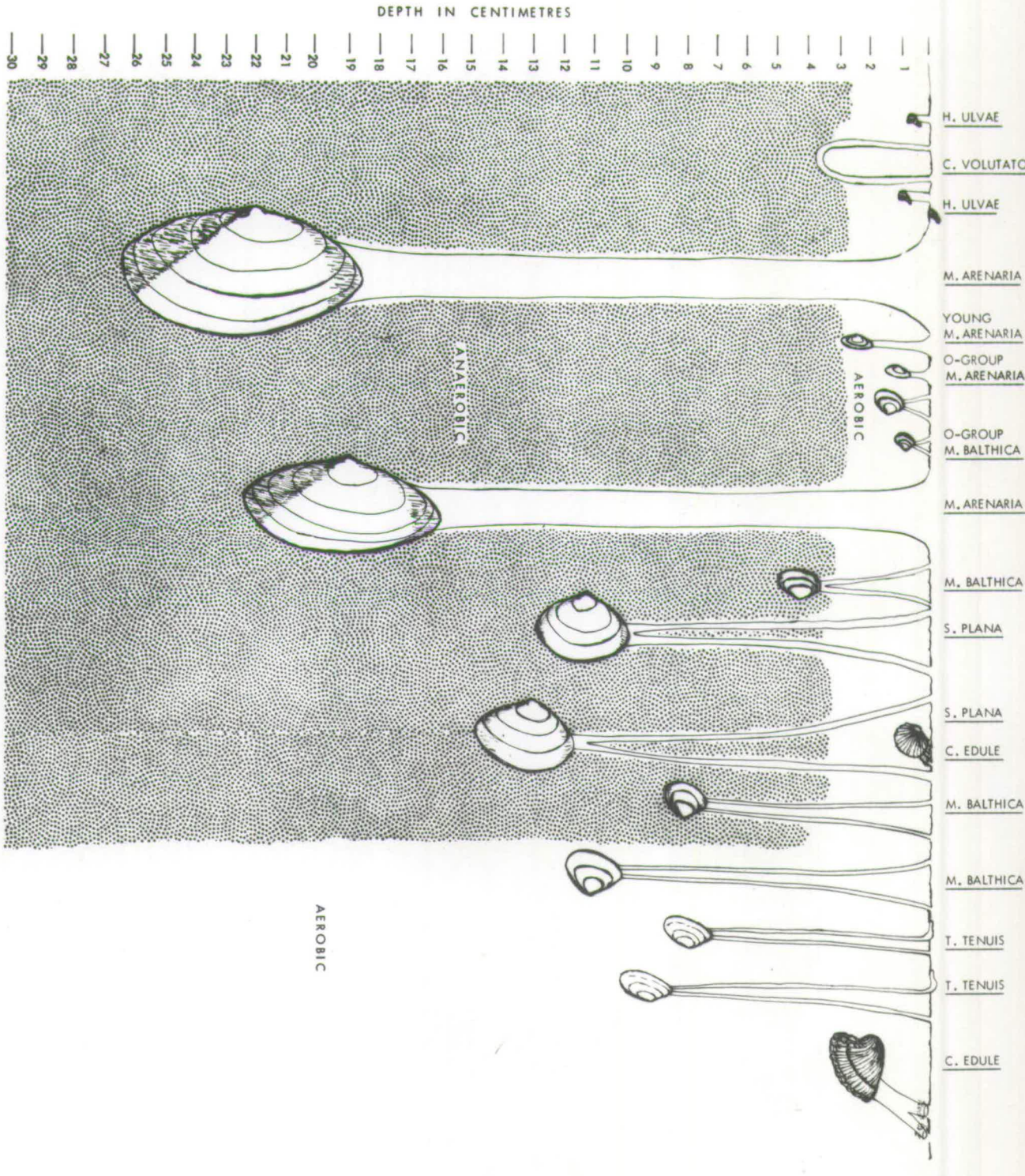
The depth distribution of the fauna is summarised in Fig. 25.

In any discussion of the reworking of faunas and sediments the densities of the faunas, their geographical distribution and their distribution in depth must be taken into consideration as these factors are of fundamental importance in determining the composition of shell-beds.

FIG. 25. DEPTH DISTRIBUTION OF LIVING FAUNA.

Note increase in shell length with depth in Macoma balthica and Mya arenaria, and depth zonation in adult M. balthica (5 - 10 cms), adult Scrobicularia plana (9 - 12 cms) and adult M. arenaria (20 - 30 cms). The top 3 cms contain 0-Group M. balthica and M. arenaria and adult Hydrobia ulvae. Tellina tenuis is restricted to the aerobic sands.

FIG. 25


DEPTH IN CENTIMETRES
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
H. ULVAE
C. VOLUTATO
H. ULVAE
M. ARENARIA
YOUNG
M. ARENARIA
O-GROUP
M. ARENARIA
O-GROUP
M. BALTHICA
M. ARENARIA
M. BALTHICA
S. PLANA
S. PLANA
C. EDULE
M. BALTHICA
M. BALTHICA
T. TENUIS
T. TENUIS
C. EDULE
ANAEROBIC
AEROBIC
AEROBIC

CHAPTER 4

TRANSECT STUDIES - SHELLS, VALVES AND FRAGMENTS

A general picture of the distribution of dead shells, lamellibranch valves and other calcareous organic remains can be obtained from the quantitative samples collected on the transects. Any studies into the effects of reworking and the formation of shell-beds by the lateral migration of channels must include details of the distribution of all the potential fossil material contained in the sediments.

In order to show the distribution of dead shells, valves etc. a series of maps of the type used in the living faunal study have been prepared from the data given in Tables 2 - 16 It is not generally possible to distinguish empty shells which represent animals that died in situ from shells deposited as a result of reworking, nor is it possible to distinguish between valves that have been reworked only once from those which have been reworked several times. The distribution maps of dead shells and valves therefore represent material from many different sources and of different ages and as such are difficult to construct and must be interpreted with care. They do, however, indicate what is likely to be reworked by a meandering channel at any given locality. In order to show the overall distribution of shells and valves available to a laterally migrating channel reworking the flats to a minimum depth of 30 cms, total density distribution maps - the sum of the densities from each of the five layers - have been drawn for most species.

PHYLUM ARTHROPODA

CLASS CIRREPEDIA

Balanus sp.

Barnacle plates are fairly common in the sediment on the upper mud flat at Stations 3/1 and 3/2. The plates are dispersed throughout the sediment with the greatest concentration in layer 5. No significant differences in density occur in the other layers and therefore only the total density distribution is given in Fig. 26a. The density decreases rapidly towards the mud slope, and east of the Carse Gut plates are only very rarely encountered.

The assemblages of plates consist almost entirely of rostrums, carinas and lateral compartments. In most cases the plates are free but occasionally a group consisting of up to three fused compartments may be found. Opercular valves are extremely rare. Many of the compartments are abraded and portions of the outer laminae are worn off revealing the longitudinal septa. The virtual absence of opercular plates suggests that either these plates are less resistant or that the empty shells remained attached to the substrate for some time after the soft parts had decayed and the opercular plates were lost before the shell broke up into its separate compartments and was washed into the sediment.

The compartments all appear to be Balanus and are probably Balanus balanoides (L). The living barnacle fauna is dominated by Elminius modestus (see p. 55). It is probable that the concentrations of Balanus plates in the sediments near

FIG. 26. DISTRIBUTION OF *BALANUS* PLATES, *RETUSA OBTUSA* SHELLS, *SCROBICULARIA PLANA* SHELLS AND LEFT VALVES, *MYA ARENARIA* LEFT VALVES

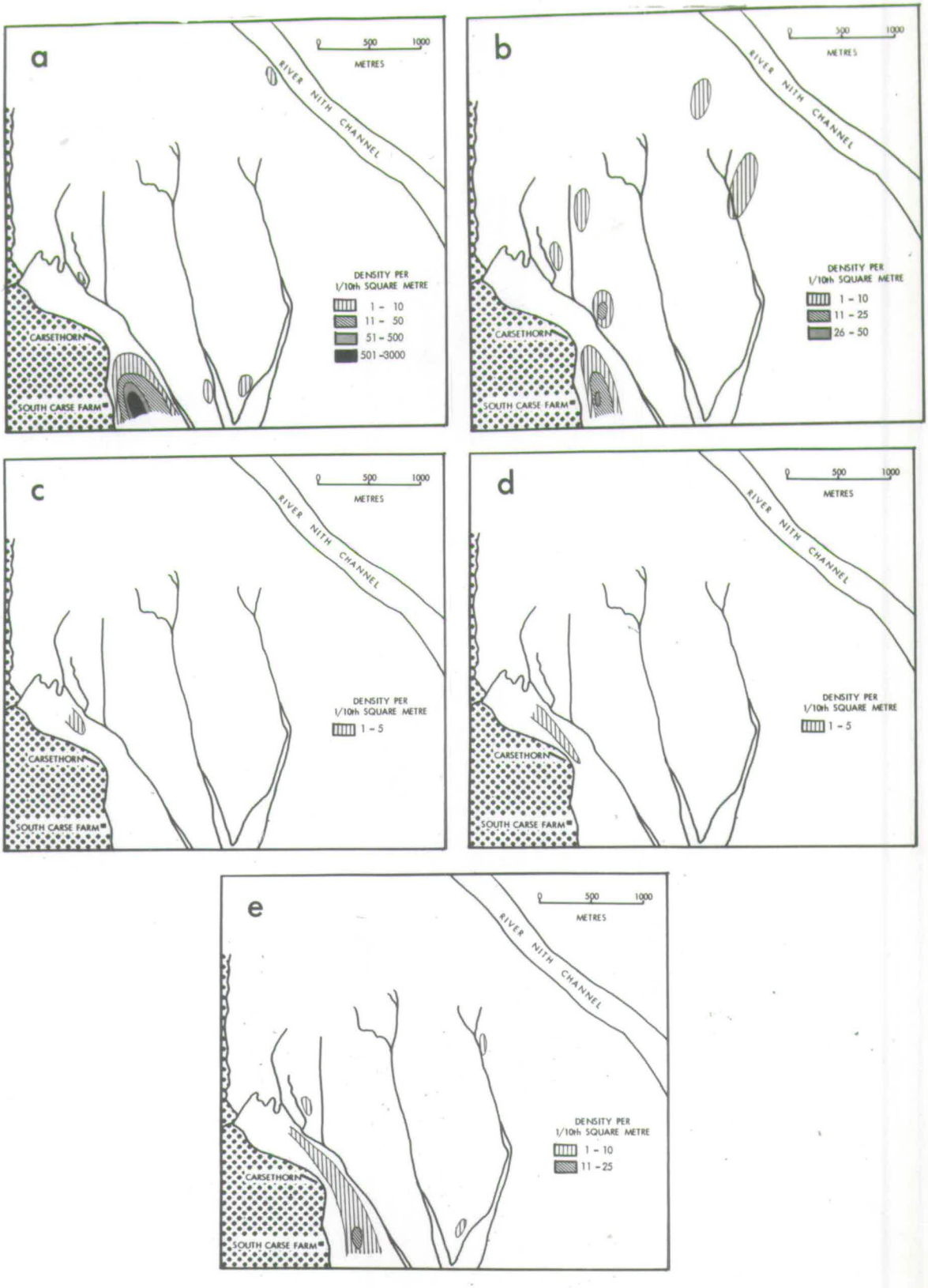
a. *Balanus* Plates, Total, Layers 1 - 5

b. *Retusa obtusa* shells, Total, Layers 1 - 5

c. *Scrobicularia plana* Shells, Total, Layers 1 - 5

d. *Scrobicularia plana* left valves, Total, Layers 1 - 5

e. *Mya arenaria* left valves, Total, Layers 1 - 5


a
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 10
11 - 50
51 - 500
501 -3000
CARSETHORN
SOUTH CARSE FARM
b
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 10
11 - 25
26 - 50
CARSETHORN
SOUTH CARSE FARM
c
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 5
CARSETHORN
SOUTH CARSE FARM
d
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 5
CARSETHORN
SOUTH CARSE FARM
e
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 10
11 - 25
CARSETHORN
SOUTH CARSE FARM

Stations 3/1 and 3/2 represent the remains of the Balanus population which thrived on the boulders and cobbles on the beach and upper mud flat prior to the invasion of Elminius.

Other arthropod remains are extremely rare. Crab carapaces, claws and legs are sometimes seen on the surface, but only small fragments of exoskeleton have been found in the sediment. Corophium legs and antennae may be preserved in the silts of the upper mud flats. Beetle elytra were present in several samples from the surface layer on the upper mud flats north of Carsethorn village. They were probably carried on to the mud flat by the Carse Gut.

PHYLUM MOLLUSCA

CLASS GASTROPODA

Littorina littorea (L)

The shells are restricted to the upper mud flat sediments and occur at Stations 1/1, 3/1, 3/2 and 3/3. Densities of up to 7 per 1/10th square metre are found in layers 1 to 4, but 96 were obtained from layer 5 at Station 3/1.

Littorina saxatalis (Olivi)

L. saxatalis shells have a slightly wider distribution being present at Stations 1/1, 3/1, 3/2, 3/3 and 3/4, and east of the Carse Gut at Station 3/5. It is only found in layers 3 to 5, the highest density being 68 per 1/10th square metre in 3/1/5.

Hydrobia ulvae (Pennant)

Hydrobia shells are common at most stations on the upper and lower mud flats and in certain areas east of the Carse Gut. The distribution of shells in layers 1 to 5 is given in Fig. 27a-e. The shells are concentrated into distinct areas of high density which persist in depth so that the total density distribution map (Fig. 27f) gives a generally similar distribution pattern to that given by any of the maps for an individual layer. Dead Hydrobia shells are not found in the sands between Channels G and H except in small isolated pockets or east of Channel H and south of the line of Transect 2.

The overall distribution of dead shells is broadly similar to that of living Hydrobia except for the concentration of dead shells at Station 3/7 associated with the ebb megaripples. The areas of highest density of dead shells in layer 1, however, (Fig. 27a), do not correspond with those of the highest density of living Hydrobia shown on Fig. 8a except in the area between Channels B and C. The maximum density of dead shells on the upper mud flats in Carse Bay is 60 per 1/10th square metre whereas the living population densities exceed 400 per 1/10th square metre. Most of the dead shells in Carse Bay are concentrated at the foot of the beach (see p. 67). On the upper mud flats of South Carse, however, densities of living and dead shells are very similar.

In parts of the Dutch Wadden Sea a widespread zone of dead Hydrobia shells 2 to 4 cms thick occurs at depths between 20 and 30 cms below the sediment surface. Van Straaten (1952)

FIG. 27. DISTRIBUTION OF HYDROBIA ULVAE SHELLS

a. Hydrobia ulvae shells ...Layer 1

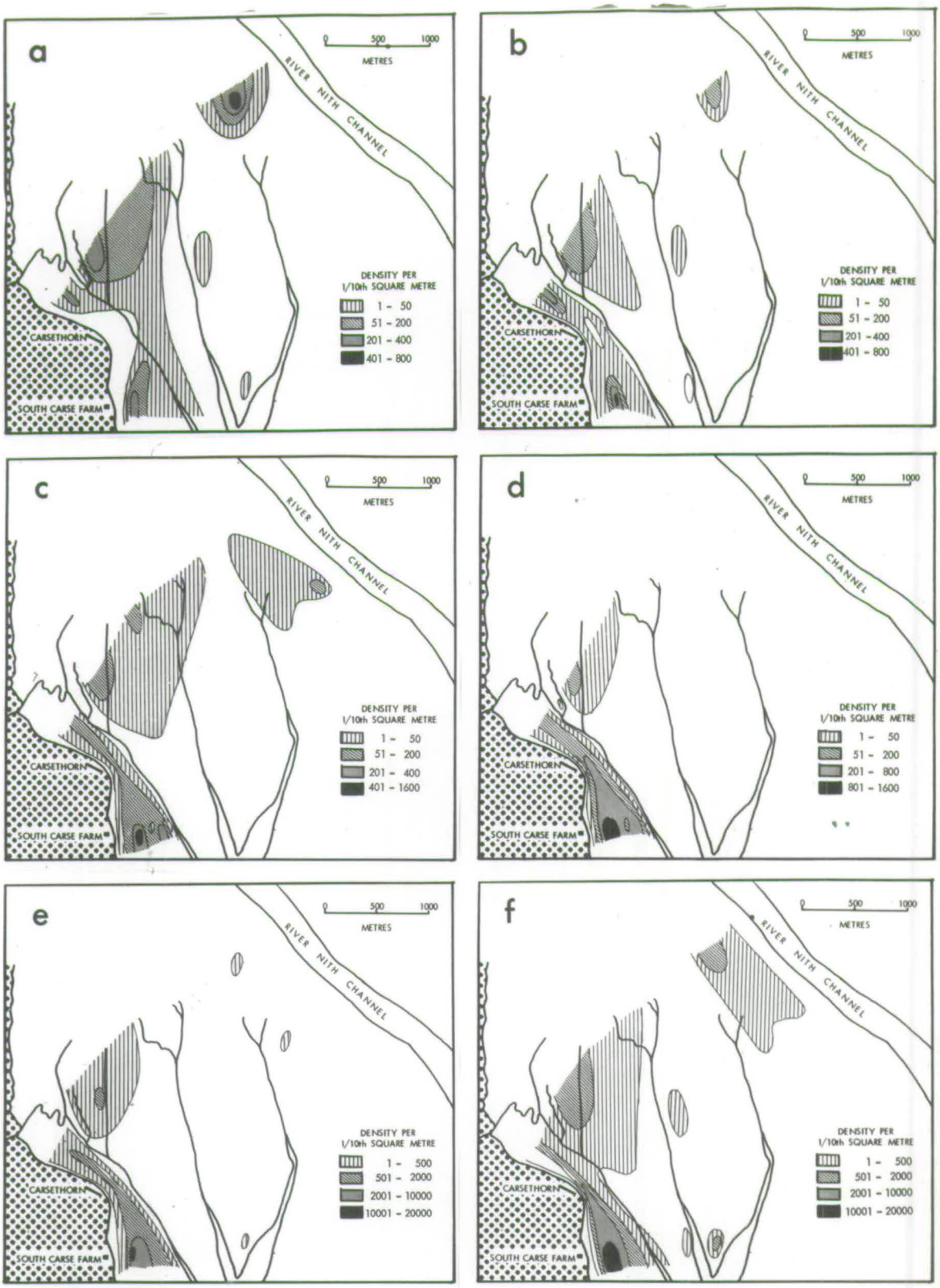
b. " " " Layer 2

c. " " " Layer 3

d. " " " Layer 4

e. " " " Layer 5

f. " " " Total, Layers 1 - 5


a
0 500 1000
METRES
RIVER NITH CHANNEL
CARSETHORN
SOUTH CARSE FARM
DENSITY PER
1/10th SQUARE METRE
1 - 50
51 - 200
201 - 400
401 - 800
b
0 500 1000
METRES
RIVER NITH CHANNEL
CARSETHORN
SOUTH CARSE FARM
DENSITY PER
1/10th SQUARE METRE
1 - 50
51 - 200
201 - 400
401 - 800
c
0 500 1000
METRES
RIVER NITH CHANNEL
CARSETHORN
SOUTH CARSE FARM
DENSITY PER
1/10th SQUARE METRE
1 - 50
51 - 200
201 - 400
401 - 1600
d
0 500 1000
METRES
RIVER NITH CHANNEL
CARSETHORN
SOUTH CARSE FARM
DENSITY PER
1/10th SQUARE METRE
1 - 50
51 - 200
201 - 800
801 - 1600
e
0 500 1000
METRES
RIVER NITH CHANNEL
CARSETHORN
SOUTH CARSE FARM
DENSITY PER
1/10th SQUARE METRE
1 - 500
501 - 2000
2001 - 10000
10001 - 20000
f
0 500 1000
METRES
RIVER NITH CHANNEL
CARSETHORN
SOUTH CARSE FARM
DENSITY PER
1/10th SQUARE METRE
1 - 500
501 - 2000
2001 - 10000
10001 - 20000

showed that this zone was formed by the worm Arenicola. The worm swallows the sand at depths of 20 to 30 cms below the surface but rejects any shells contained in the sediment. These rejected shells therefore accumulate at the foot of the burrow and over a period of years, after several generations of Arenicola have reworked the sediment, the layer of Hydrobia shells becomes more or less continuous over large areas of the flats. Van Straaten (1952 and personal communication 1963) showed that these conditions are only found in areas where there is no lateral reworking of migrating channels and where there has been almost no vertical accretion for periods of up to 100 years. As the Carse Sands and mud flats are reworked by migrating channels at much more frequent intervals (see Chap. 5) there is little chance of a Hydrobia bed of this type being developed in spite of the presence of Arenicola marina in considerable numbers.

Retusa obtusa (Montagu)

The total density distribution of Retusa shells obtained from layers 1, 2, 4 and 5 is given in Fig. 26b. The density in layers 1, 2 and 4 varied from 1 to 5 per 1/10th square metre. At Station 2/4 the density in layer 1 was 18 per 1/10th square metre, but this was in a surface shell-bed and represented a concentration of dead shells derived from the sand flats east of Channel G. In layer 5 densities of 36 and 16 per 1/10th square metre were obtained from Stations 3/1 and 3/2 respectively. As Retusa does not live west of the Carse Gut at present, these shells were probably transported onto the mud flats by onshore

flood currents. The shells at Station 3/7 were transported from the sand flats to the north by ebb currents.

The distribution of dead Retusa shells is very sporadic and bears little resemblance to the distribution of the living animal. The majority of the shells were found outside the probable limits of the living population given in Fig. 8c.

CLASS LAMELLIBRANCHIA

Complete shells and undamaged valves were separated from the transect samples and the length of each was measured. In practice, it proved to be fairly difficult in many cases to determine whether or not the valve was damaged, and the criteria used depended largely on the strength and rigidity of the valve margin. In Cardium any slight damage to the crenulation was considered as breakage, whereas in Scrobicularia small nicks in the margin were overlooked. In all the lamellibranch species present the densities and size-frequency distributions of left and right valves were generally very similar and no significant differences could be detected, and therefore, following Craig and Hallam (1963) only data for left valves will be given. The growth rates for each species used in the interpretation of shell and valve size-frequency distributions are the same as those used in Chap. 3.

Incomplete shells of each species were separated into those with the left valve intact, those with the right valve intact, and those with both valves damaged. In extreme cases almost the entire shell had been lost, but if the ligament persisted and the dorsal areas of the valves were joined, it was considered to be an incomplete shell and not a fragment.

Shell fragments from Transect 1 and Transect 3 retained on a 2 mm sieve were separated into species. Fragments less than 2 mms were not analysed quantitatively. As each of the six lamellibranch species present has a fairly distinctive type of shell structure it was not difficult to identify even the smallest fragments. The fragments, complete and incomplete shells, and valves of each species were weighed and the weight of fragments was calculated as a percentage of the total combined weight of valves, shells and fragments. As percentages alone are misleading the actual number of fragments was also recorded.

In the samples from Transect 3 the fragments were divided into three categories on the basis of the approximate percentage of the valve preserved in the fragment. The categories were less than $\frac{1}{3}$, between $\frac{1}{3}$ and $\frac{2}{3}$, and greater than $\frac{2}{3}$ of the valve present. In most cases it was easy to assign the fragments to these categories but in border-line cases a subjective assessment was used.

Van Straaten (1956) used the weight percentage of fragments as a 'crush factor' in Cardium edule and he considered it as an indication of the degree of wear of the shell material during transport. It is probable, however, that the majority of shell fragments in intertidal areas are not produced by the break-up of the shell or valve during transportation. The effect of birds on intertidal molluscan populations has been discussed in Chap. 3 (pp. 97-100). Drinnan (1957) showed that oystercatchers generally open cockle shells by chipping the posterior part of the shell close to the siphons. In shells of 1 to 2 cms

in length one valve of the shell was broken in order to gain entry and in many cases at least half of the valve was destroyed. In larger shells up to 3 cms in length the shell was stronger and damage was generally restricted to the posterior margins of the valves where the region adjacent to the siphons was chipped away producing a gap in each valve up to 4 mms deep. Cardium valves damaged in this way are not uncommon in the transect and shell-bed samples. Dewar (1913) showed that oystercatchers break open Mytilus shells by smashing the posterior portion of one valve. He found that the left valve was more frequently broken than the right valve. The feeding activities of birds are also responsible for the fragmentation of many Macoma shells (see p. 99).

Predation and crushing of lamellibranchs is carried on by flat fish during high tide in intertidal areas, and constantly on the continental shelf and estuarine regions below low water mark. It is probable, therefore, that the majority of shell fragments are produced as a result of the feeding habits of predators and damage to the shells and fragments during transportation is of minor importance in most cases. Generally the current action in estuaries is not sufficiently strong to have much effect on even small valves.

Mytilus edulis L

Complete Shells

Mytilus shells are very rare and were only recorded from layer 5 at Station 2/1 and layer 3 at Station 2/2.

Left Valves

Mytilus valves were obtained from Stations 2/2, 3/1 to 3/4 and a single valve was found at Station 1/5 in layer 4. The distribution of valves in layers 1 to 5 is given in Fig.28a-e and the total density in Fig. 28f. The valves are almost entirely restricted to the mud flats west of the Carse Cut and south of Carsethorn village. The distribution does not differ much from layer to layer and the densities are generally low except at Station 2/1 where 139 and 131 were obtained from layers 3 and 4 respectively.

The size-frequency distribution (Fig. 29) shows that all the valves are less than 30 mms long. The populations from 2/1/4 and 2/1/5 show peaks at about 10 mms and 20 mms. Savage (1956) obtained growth rates for Mytilus edulis in the Conway estuary giving a mean length of 10 mms after six months, 20 mms after twelve months and 28 mms after eighteen months while Craig and Hallam (1963) found corresponding lengths of 10 mms in six months, 13 mms in twelve months and 20 mms in eighteen months in the Firth of Forth. Whichever growth rate is applicable to the Solway the maximum age of the longest valves on the mud flats must be 2½ years.

Mytilus edulis does not now live on the Carse Sands (see pp. 70, 143). Colonies of mussels do however flourish 6 kms to the south at Southerness and 14 kms further west at Kippford and Rockcliffe on Rough Firth. It is probable that the valves on the upper mud flats were largely derived from these colonies by flood current transportation and longshore drift.

FIG. 28. DISTRIBUTION OF MYTILUS EDULIS

LEFT VALVES

a. Mytilus edulis left valves Layer 1

b. " " " " Layer 2

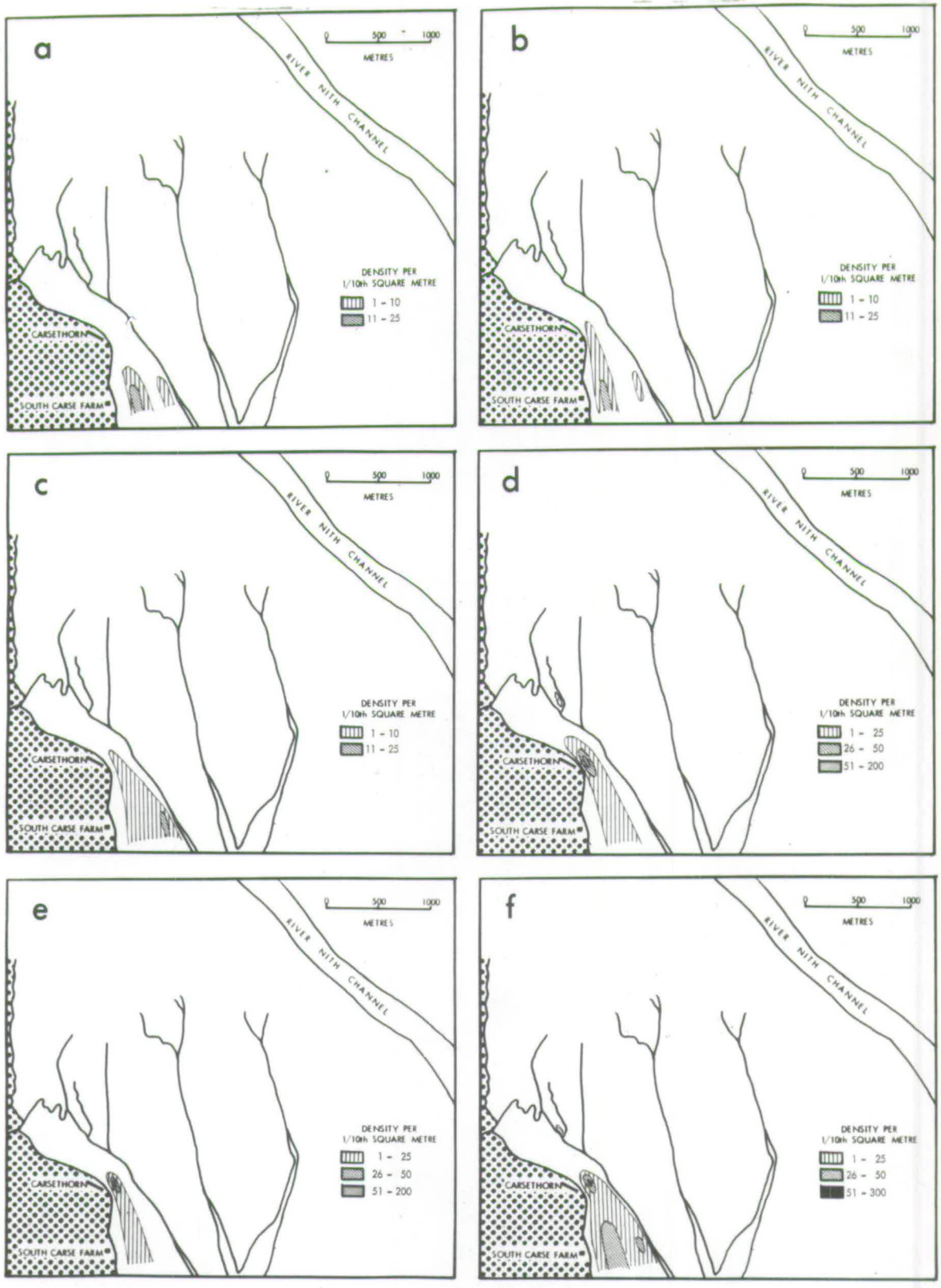
c. " " " " Layer 3

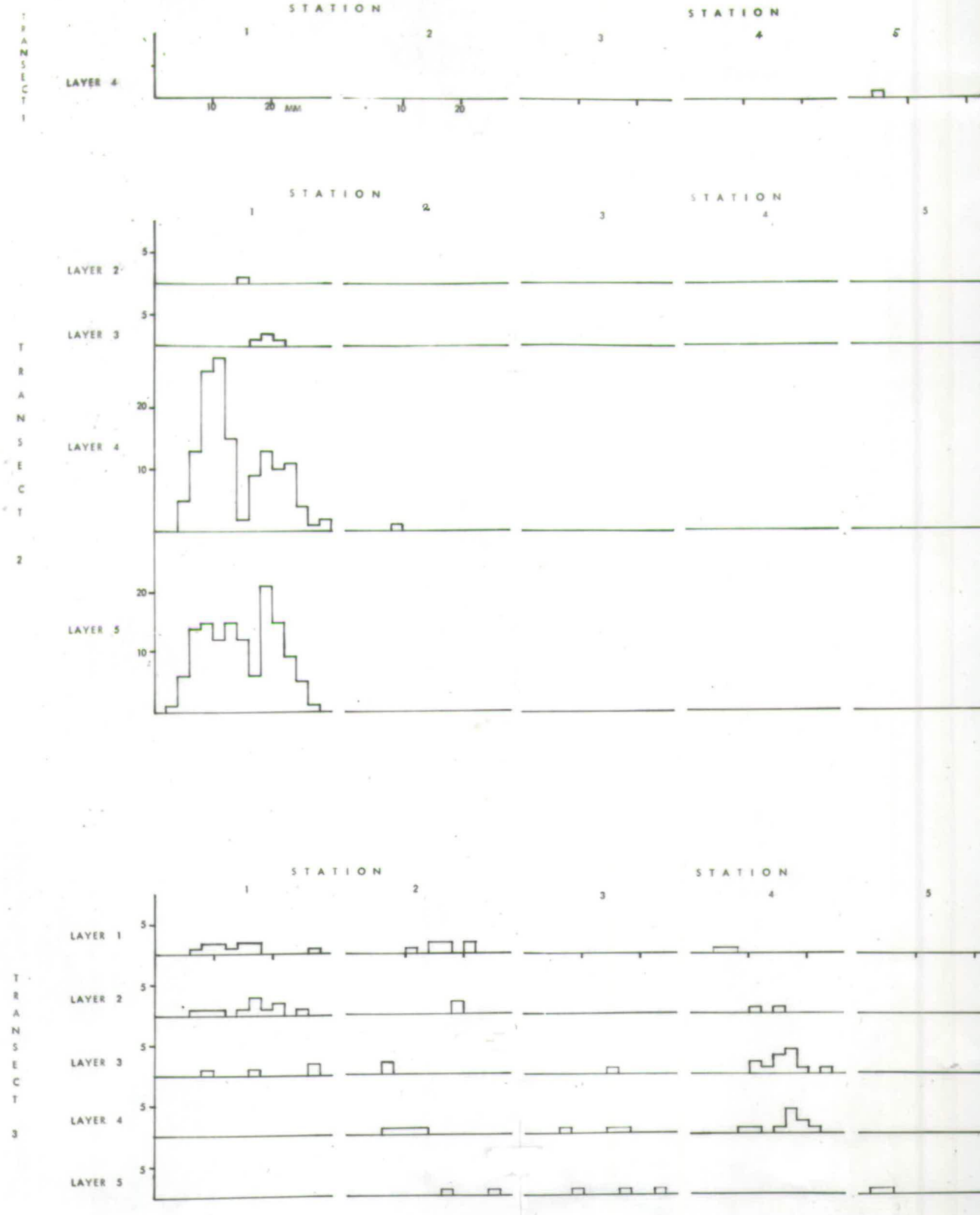
d. " " " " Layer 4

e. " " " " Layer 5

f. " " " " Total, Layers 1 - 5

Edelstone
Bond
TUB SIZED - AIR DRIED
4.


a
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 10
11 - 25
CARSETHORN
SOUTH CARSE FARM
b
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 10
11 - 25
CARSETHORN
SOUTH CARSE FARM
c
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 10
11 - 25
CARSETHORN
SOUTH CARSE FARM
d
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 25
26 - 50
51 - 200
CARSETHORN
SOUTH CARSE FARM
e
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 25
26 - 50
51 - 200
CARSETHORN
SOUTH CARSE FARM
f
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 25
26 - 50
51 - 300
CARSETHORN
SOUTH CARSE FARM



SIZE-FREQUENCY DISTRIBUTION OF MYTILUS EDULIS LEFT VALVES, TRANSECTS 1 TO 3.

Number of valves plotted against length.

Fragments

The majority of the fragments occur west of the Carse Gut (Fig. 30a) although they are occasionally found in the sands east of Channel G on Transect 3. Fragments are very rare on Transect 1. Fig. 30b shows that on average more than 95% of the fragments consist of less than $\frac{1}{3}$ of the valve and that there are roughly equal numbers of fragments consisting of $\frac{1}{3}$ to $\frac{2}{3}$ and greater than $\frac{2}{3}$ of the valve.

Bøggild (1930) found that the structure of the blue calcitic layer in M. edulis is very variable. In some cases it is completely homogeneous while in others it is either distinctly or indistinctly prismatic. The inner aragonitic layer has a nacreous structure.

This variable structure appears to have some effect on the type of fragmentation shown by Mytilus valves. In many cases once a valve is broken, the inner nacreous layer becomes detached from the calcitic layer (Plate 34b-A). In other cases when the posterior portion of the valve is lost, the calcitic layer becomes detached from all but the umbonal and hinge area exposing the nacreous layer (Plate 34b-B). Fragments of the calcitic layer with prismatic structure are fairly common throughout the sands (Plate 35a-E).

Cardium edule L

Complete Shells

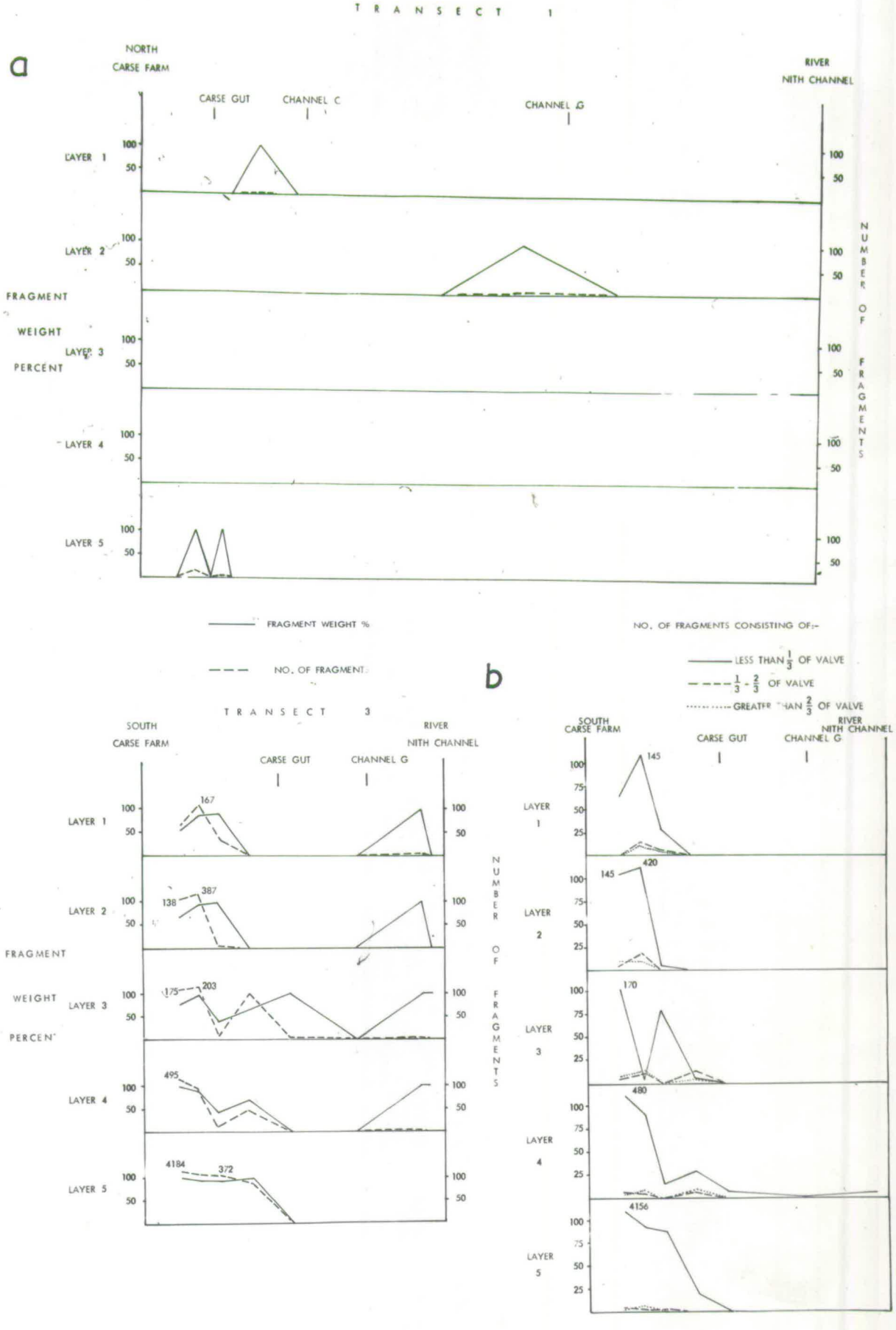
The distribution of shells in each layer is given in Fig. 31a-e. In layers 1 to 4 the shells are largely concentrated on the mud flats west of the Carse Gut to the south of Carsethorn

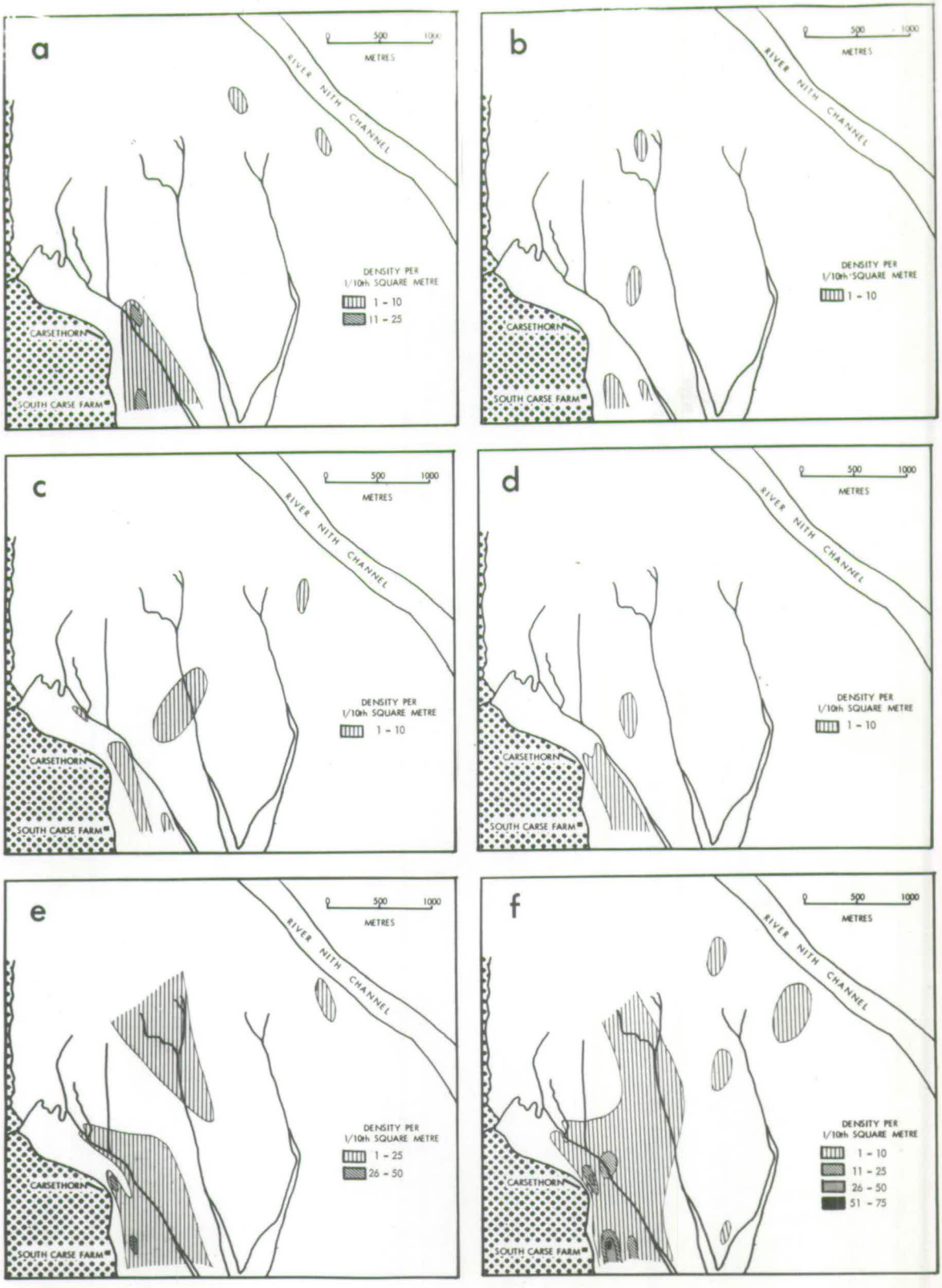
FIG. 30. DISTRIBUTION OF MYTILUS EDULIS FRAGMENTS ALONG TRANSECTS 1 AND 3.

a. Fragment weight percentage and number of fragments plotted against distance along Transects 1 and 3 for layers 1 to 5.

b. Number of fragments consisting of less than 1/3rd, 1/3rd - 2/3rds and greater than 2/3rds of the valve plotted against distance along Transect 3.

FIG. 30


TRANSECT 1
a
NORTH
CARSE FARM
RIVER
NITH CHANNEL
CARSE GUT
CHANNEL C
CHANNEL G
LAYER 1
LAYER 2
LAYER 3
LAYER 4
LAYER 5
100
50
FRAGMENT
WEIGHT
PERCENT
NUMBER OF FRAGMENTS
FRAGMENT WEIGHT %
NO. OF FRAGMENTS
NO. OF FRAGMENTS CONSISTING OF:-
LESS THAN 1/3 OF VALVE
1/3 - 2/3 OF VALVE
GREATER THAN 2/3 OF VALVE
b
TRANSECT 3
SOUTH
CARSE FARM
RIVER
NITH CHANNEL
CARSE GUT
CHANNEL G
167
138
387
175
203
495
4184
372
145
420
170
480
4156
25
75


a
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER 1/10th SQUARE METRE
1 - 10
11 - 25
CARSETHORN
SOUTH CARSE FARM
b
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER 1/10th SQUARE METRE
1 - 10
CARSETHORN
SOUTH CARSE FARM
c
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER 1/10th SQUARE METRE
1 - 10
CARSETHORN
SOUTH CARSE FARM
d
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER 1/10th SQUARE METRE
1 - 10
CARSETHORN
SOUTH CARSE FARM
e
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER 1/10th SQUARE METRE
1 - 25
26 - 50
CARSETHORN
SOUTH CARSE FARM
f
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER 1/10th SQUARE METRE
1 - 10
11 - 25
26 - 50
51 - 75
CARSETHORN
SOUTH CARSE FARM

village. The distribution east of the Carse Gut is sporadic and changes from layer to layer, the maximum density being 2 per 1/10th square metre. In layer 5 (Fig. 31e) densities of up to 42 per 1/10th square metre were obtained from Stations 2/1 and 3/2, and shells were found on the mud slope north of Carsethorn village (Station 1/4), and at Station 1/6. The total density distribution (Fig. 31f) therefore indicates a much wider distribution than any of the individual layers although the total density over most of the area is less than 10 per 1/10th square metre.

Most of the shells are less than 10 mms in length (Fig. 32) and are therefore probably less than 1 year old. Shells greater than 10 mms are rare and only 2 more than 30 cms were found. These large shells may be about 3 years old.

Only 3 living cockles greater than 11 mms in length were found (p. 75 and Figs. 12 and 13), all the rest were 0-Group individuals less than 10 mms in length. Most of the dead shells may therefore be derived from the sand flats themselves, but the three or four year old shells were probably transported into the area.

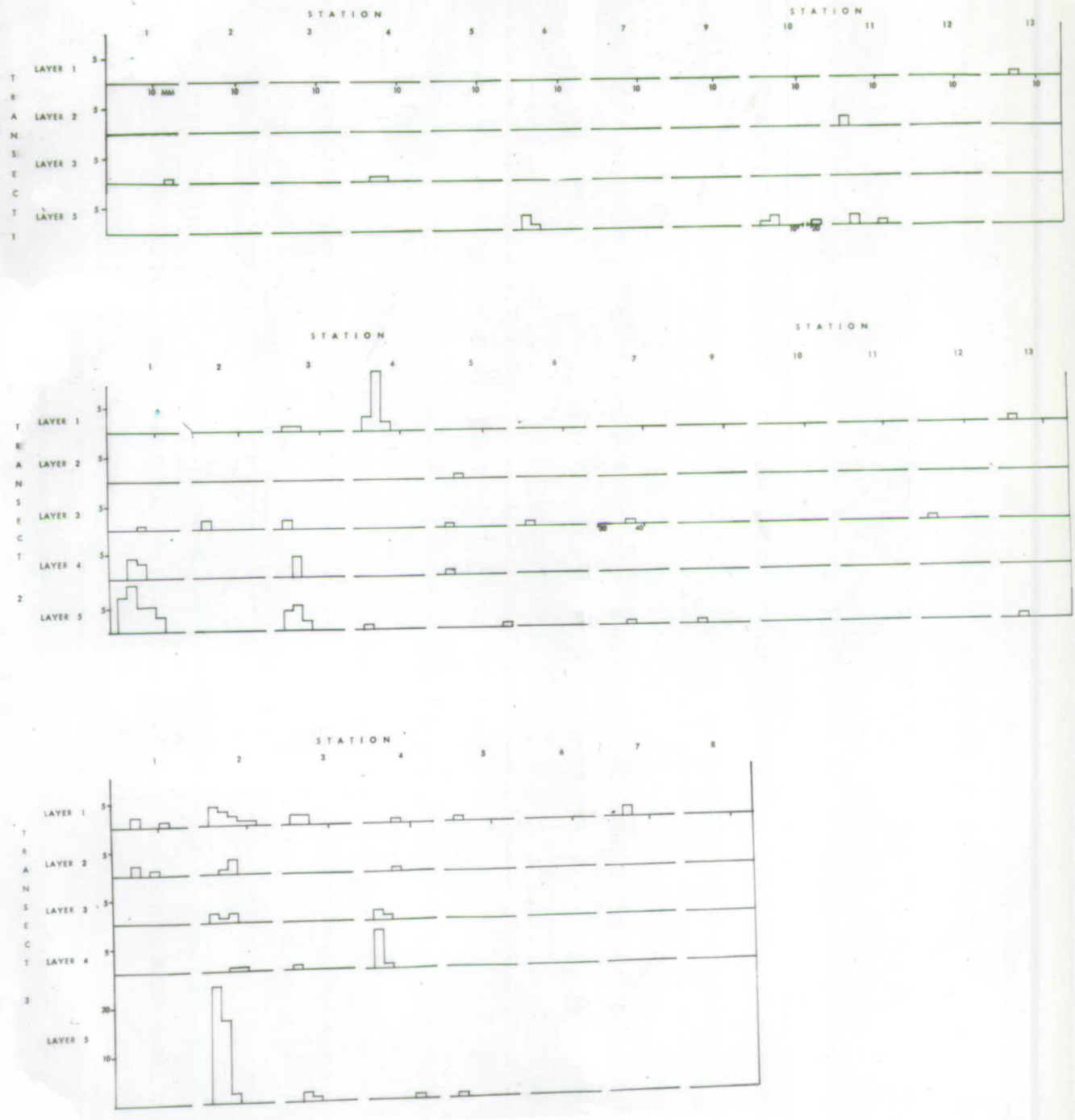
Left Valves

The distribution of valves in layers 1 to 5 is given in Fig. 33a-e. Valves are found in three main areas:-

i) The mud flats west of the Carse Gut south of Carsethorn village.

ii) The sand flats between Channels B and G to the north of Channel E.

iii) East of Channel H northwards from the line of Transect 2.



SIZE-FREQUENCY DISTRIBUTION OF CARDIUM EDULE COMPLETE SHELLS, TRANSECTS 1 to 3.

Number of shells plotted against length.

FIG. 33 DISTRIBUTION OF *CARDIUM EDULE*

LEFT VALVES.

a. *Cardium edule* left valves Layer 1

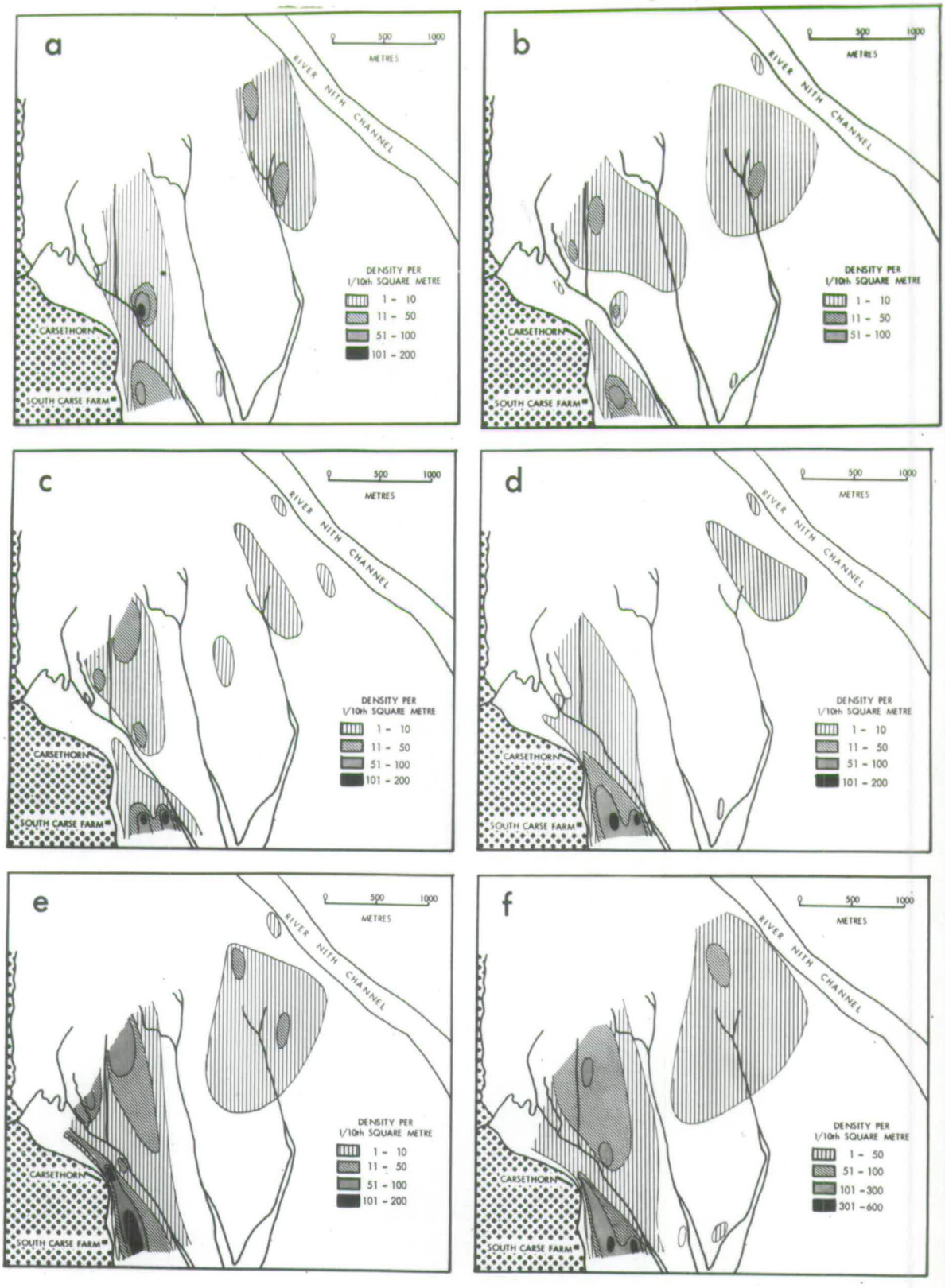
b. " " " " Layer 2

c. " " " " Layer 3

d. " " " " Layer 4

e. " " " " Layer 5

f. " " " " Total, Layers 1 - 5


a
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 10
11 - 50
51 - 100
101 - 200
CARSETHORN
SOUTH CARSE FARM
b
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 10
11 - 50
51 - 100
CARSETHORN
SOUTH CARSE FARM
c
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 10
11 - 50
51 - 100
101 - 200
CARSETHORN
SOUTH CARSE FARM
d
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 10
11 - 50
51 - 100
101 - 200
CARSETHORN
SOUTH CARSE FARM
e
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 10
11 - 50
51 - 100
101 - 200
CARSETHORN
SOUTH CARSE FARM
f
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 50
51 - 100
101 - 300
301 - 600
CARSETHORN
SOUTH CARSE FARM

The actual distribution of valves in these general areas varies from layer to layer. Areas i and ii are connected in layers 1, 4 and 5 but they maintain their identity in the total distribution pattern (Fig. 33f) as areas of high density. The highest density in layer 1 is at Station 2/4. This is in a surface shell-bed and it is probable that these valves have become concentrated from the sand flats to the east. The highest density of living cockles is also in this area (see p. 74). West of the Carse Gut the highest densities (102 - 175 per 1/10th square metre) were obtained from Stations 2/1, 3/1, 3/2 and 3/4 in layers 3, 4 or 5. In area iii east of Channel H the densities are much lower. The highest values in individual layers were never more than 27 per 1/10th square metre and the highest total density was only 58 per 1/10th square metre.

The size-frequency distributions (Figs. 34, 35, 36) indicate that most of the valves are less than 10 mms in length and are therefore largely derived from 0-Group cockles. A secondary peak at 20 mms is present in the surface shell-bed (2/4/1) and in 3/1/5. These smaller peaks probably represent valves from two year old cockles. Valves greater than 20 mms are rare. The majority of the valves could therefore be derived from the local living cockle population.

There is some similarity between the distribution of the living fauna (Fig.11b-d) and the total distribution pattern of valves, although the areas of high valve density do not correspond to the living cockle high density areas except at Station 2/4. Off South Carse Farm the high living density is in layer 1 whereas the high valve density is in layers 3 to 5.

FIG. 34. SIZE-FREQUENCY DISTRIBUTION OF *CARDIUM EDULE* LEFT VALVES, TRANSECT 1.

Number of valves plotted against length.

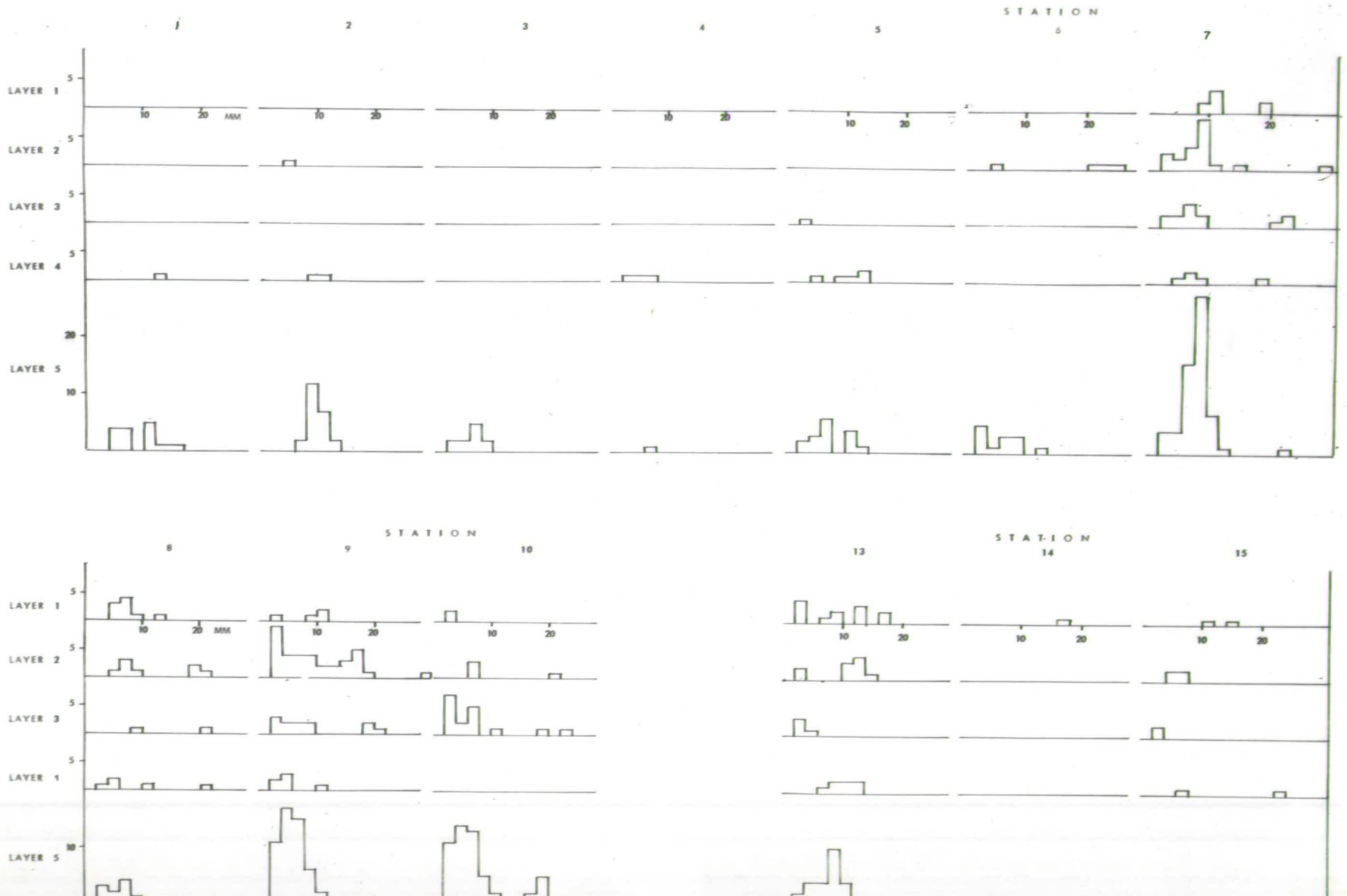
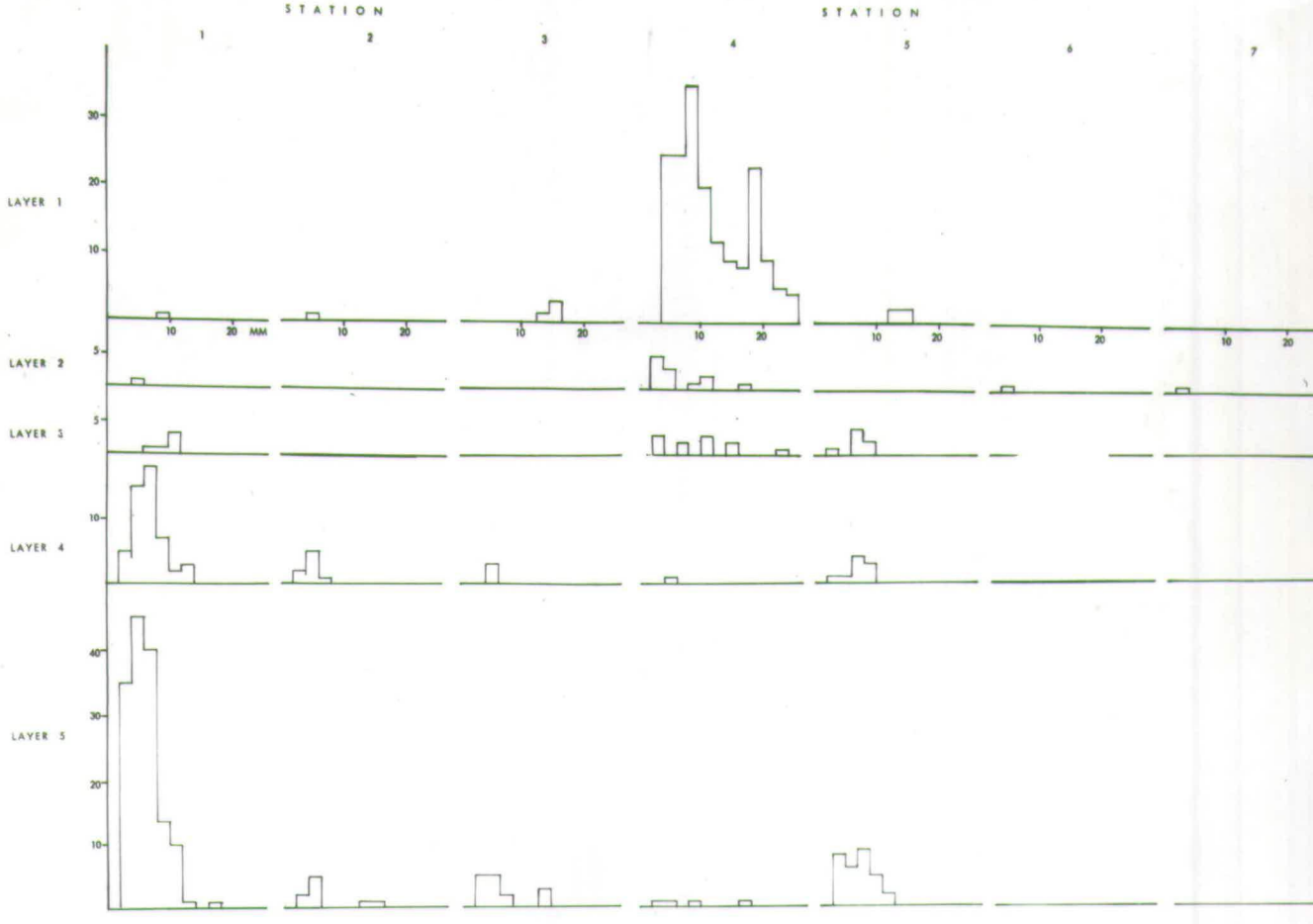
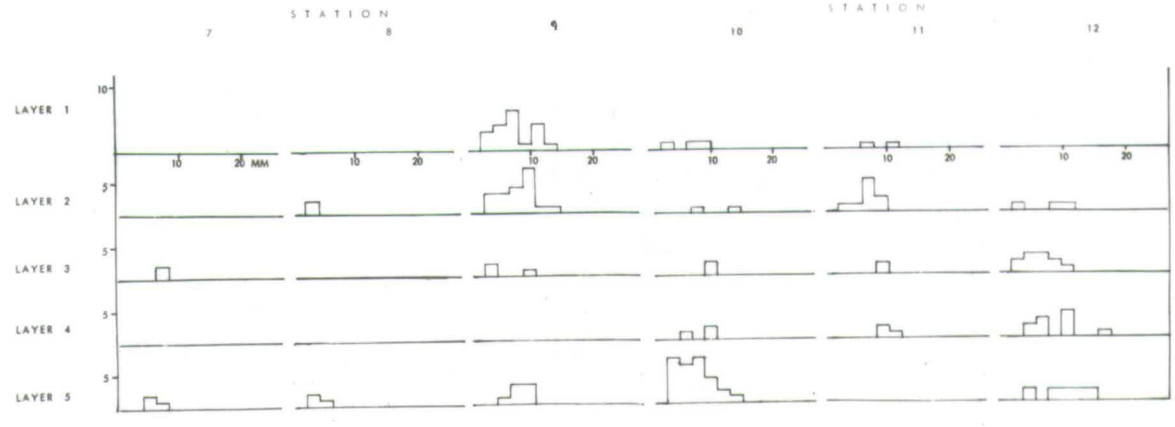

STATION
1
2
3
4
5
6
7
LAYER 1
LAYER 2
LAYER 3
LAYER 4
LAYER 5
10
20
MM
STATION
8
9
10
STATION
13
14
15

FIG. 34

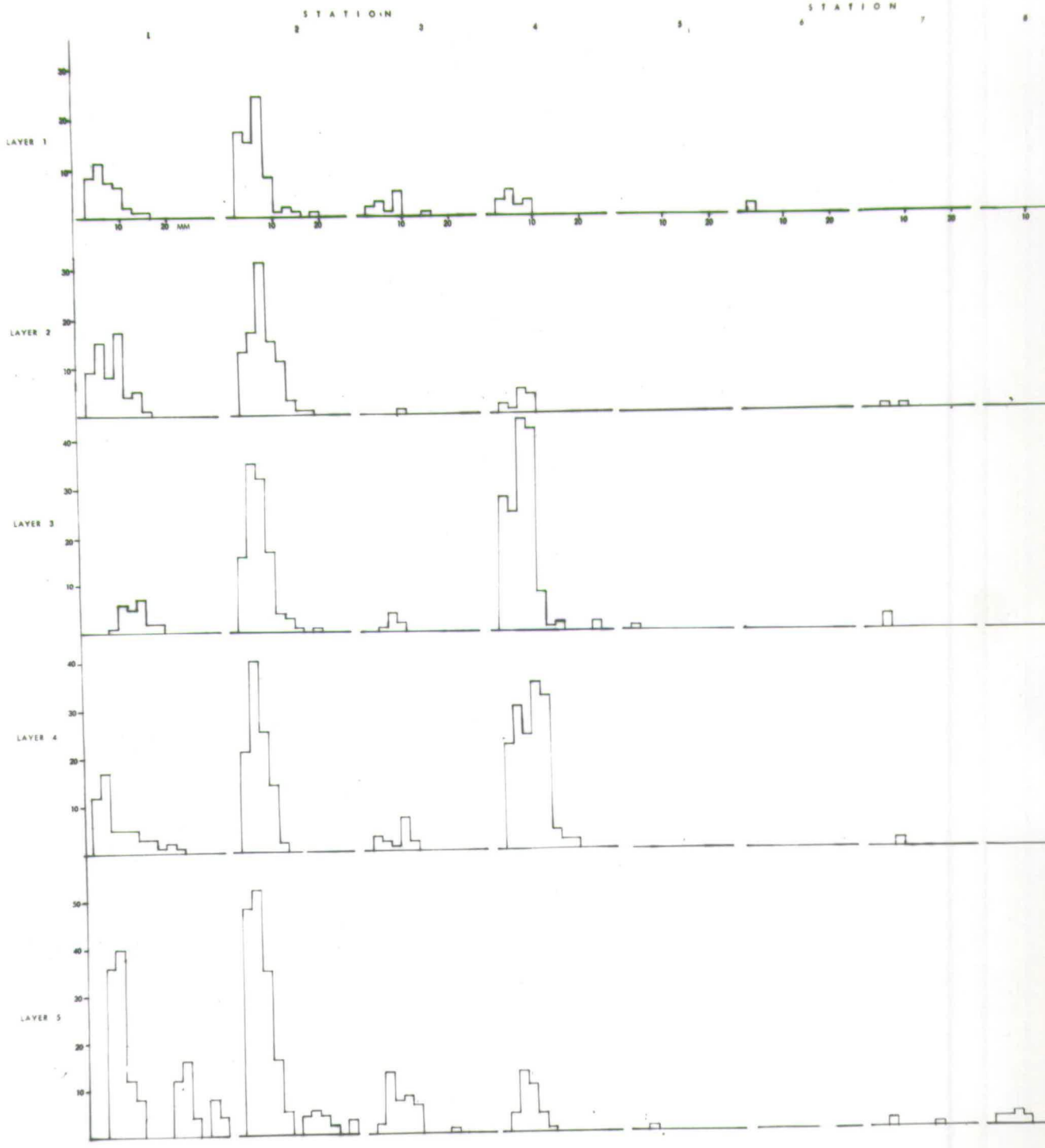




SIZE-FREQUENCY DISTRIBUTION OF CARDIUM EDULE LEFT VALVES, TRANSECT 2.

Number of valves plotted against length.

FIG. 36



SIZE-FREQUENCY DISTRIBUTION OF CARDIUM EDULE LEFT VALVES, TRANSECT 3.

Number of valves plotted against length.

Fragments

Cardium fragments are found at most stations. The weight percent distribution and numbers of fragments are given in Fig. 37a. The highest numbers of fragments are found in those stations which have the highest densities of valves. East of Channel G on Transect 1 the actual number of fragments in each layer only exceeds 15 per 1/10th square metre in two samples. On Transect 3 the number of fragments decreases sharply east of the Carse Gut. The value of the fragment weight percentage shows a slight tendency to increase as the number of fragments decreases but there are frequent exceptions to this. The relative abundance of fragments in the upper mud flat off South Carse Farm is indicated by the fact that the fragment weight percentage values are rarely less than 50%. Fig. 37b shows that the percentage of fragments less than $\frac{1}{3}$ of the valve increases with depth. The total percentage of fragments less than $\frac{1}{3}$ of the valve is very similar for each station.

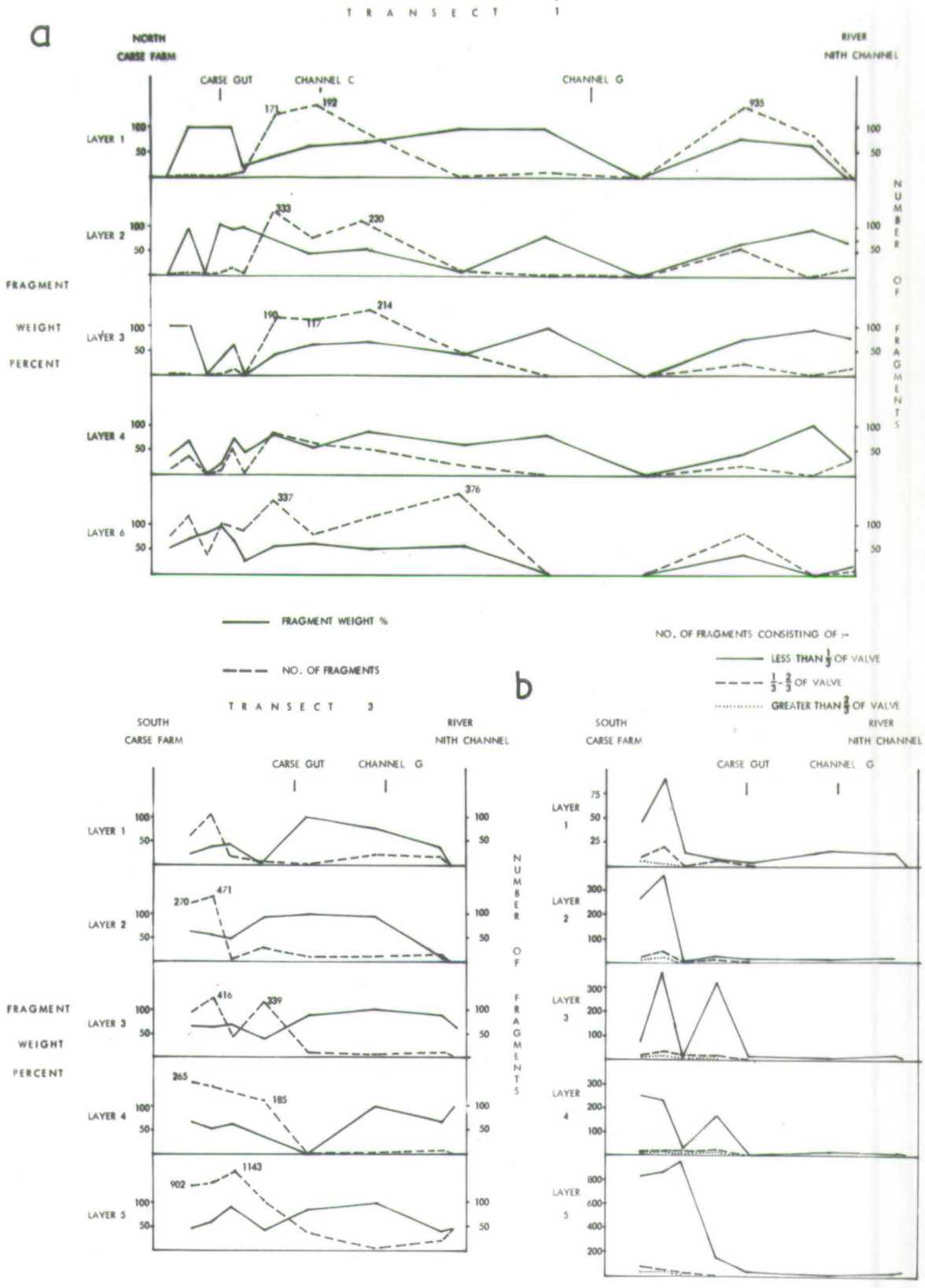
Bøggild (1930) showed that the Cardium edule shell is made up of three layers, and, although the structure is variable, the outer two layers have a crossed lamellar structure and the inner layer has alternate crossed lamellar and thin prismatic laminae. This crossed lamellar structure gives a shell of very great strength.

The weakest part of the shell is the area ventral to the umbo where the greatest width occurs. Valves with this central portion missing are not uncommon throughout the sediment and in shell-beds (Plate 34b-C). Sometimes the valve may break cleanly

FIG. 37. DISTRIBUTION OF CARDIUM EDULE FRAGMENTS ALONG TRANSECTS 1 AND 3.

a. Fragment weight percentage and number of fragments plotted against distance along Transects 1 and 3 for layers 1 to 5.

b. Number of fragments consisting of less than 1/3rd, 1/3rd - 2/3rds and greater than 2/3rds of the valve plotted against distance along Transect 3.


a
TRANSECT 1
NORTH CARSE FARM
RIVER NITH CHANNEL
CARSE GUT
CHANNEL C
CHANNEL G
LAYER 1
LAYER 2
LAYER 3
LAYER 4
LAYER 6
171
192
935
333
230
190
117
214
337
376
FRAGMENT WEIGHT PERCENT
NUMBER OF FRAGMENTS
FRAGMENT WEIGHT %
NO. OF FRAGMENTS
b
NO. OF FRAGMENTS CONSISTING OF :-
LESS THAN 1/3 OF VALVE
1/3 - 2/3 OF VALVE
GREATER THAN 2/3 OF VALVE
TRANSECT 3
SOUTH CARSE FARM
RIVER NITH CHANNEL
CARSE GUT
CHANNEL G
LAYER 1
LAYER 2
LAYER 3
LAYER 4
LAYER 5
270
471
416
339
265
185
902
1143

along a rib furrow (Plate 34b-D). Once the initial break has occurred the strength of the valve is lost and the central position is easily destroyed leaving the umbonal area and the ventral crenulate margin which are much stronger. Further breakage occurs along the rib furrows and small portions of the crenulate margin consisting of one, two and occasionally three ribs are left. The dorsal margin breaks down into two types of fragment, one containing a single lateral tooth, and the other containing the tip of the umbo and the cardinal teeth. Fragments of these types are shown in Plate 35a-A, B, C, D, F and their relationship to the Cardium valve are demonstrated in Fig. 38.

In a shell accumulation such as a surface shell-bed where the shells and fragments are continuously being abraded only the strongest fragments tend to survive. Fragments of the type described above are common in the surface shell-bed at Station 2/4 and in the sediments east of Channel G. In rare cases where a living cockle has been completely crushed by a predator, the umbones may be found still attached by the ligament.

Scrobicularia plana (da Costa)

Complete Shells

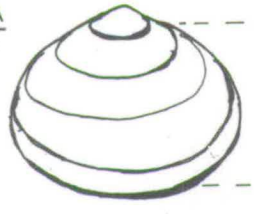
S. plana shells were only found on the upper mud flat in Carse Bay (Fig. 26c). The shells range in length from 8 to 24 mms (Fig. 39a) and, applying the growth increments postulated by Green (1957), are possibly one to four years old.

TYPES OF FRAGMENTS

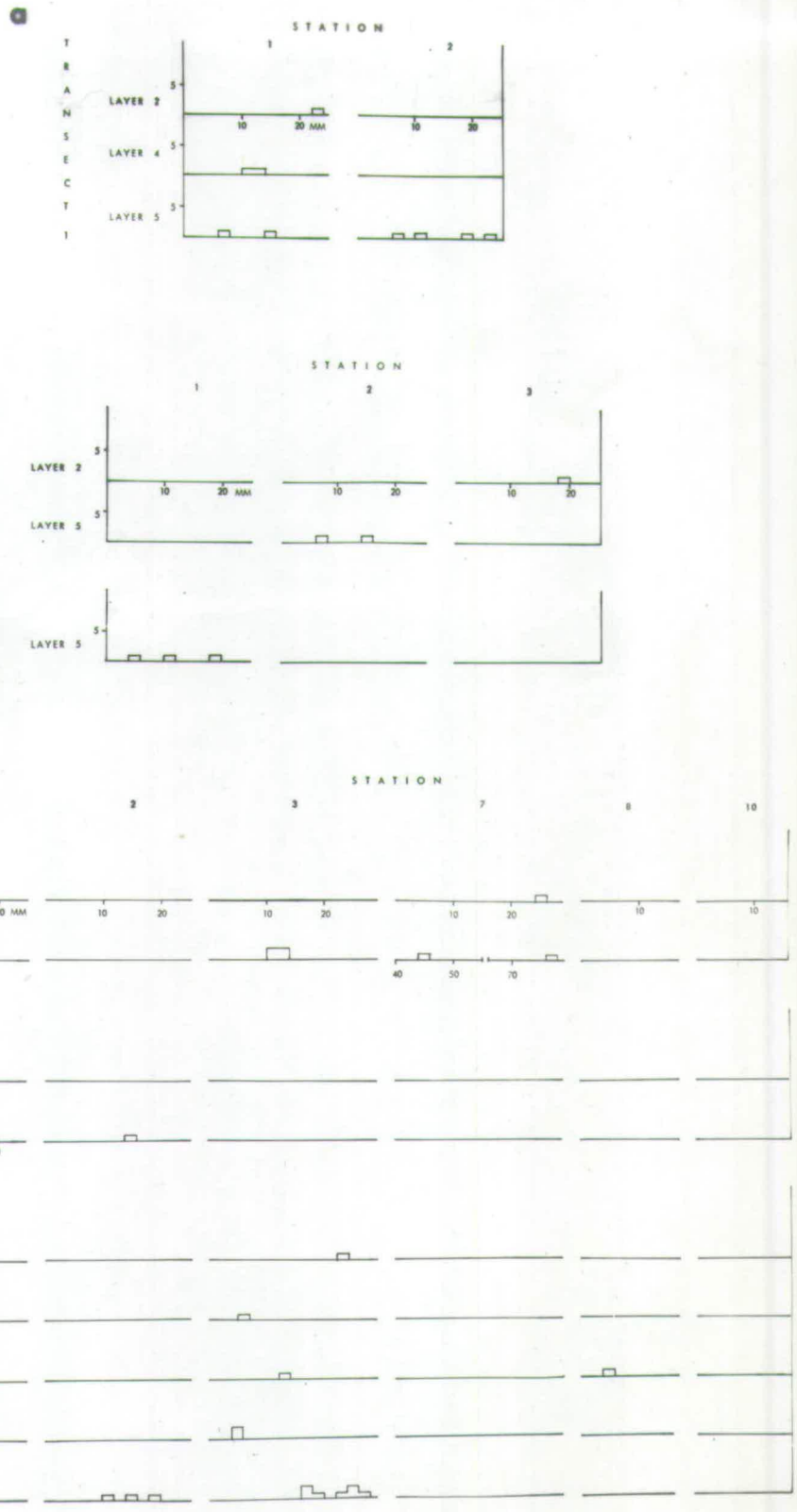
CARDIUM

MACOMA

SCROBICULARIA



MYA


a
STATION
1
2
TRANSECT 1
LAYER 2
LAYER 4
LAYER 5
5
10
20 MM
b
STATION
1
2
3
TRANSECT 1
LAYER 2
LAYER 5
TRANSECT 2
LAYER 5
c
STATION
1
2
3
7
8
10
TRANSECT 1
LAYER 3
LAYER 5
40
50
70
TRANSECT 2
LAYER 1
LAYER 5
60
70
TRANSECT 3
LAYER 1
LAYER 2
LAYER 3
LAYER 4
LAYER 5

Left Valves

Valves were found at Stations 1/2, 1/3 and 2/1. Valves have a slightly wider distribution than the shells but are also restricted to the upper mud flats (Fig. 26d). They range in length from 8 to 40 mms (Fig. 39b).

Fragments

Scrobicularia fragments are not found east of the Carse Gut (Fig. 40). The highest concentration of fragments is in layer 5 at Stations 1/1 and 1/2. The weight percentage of fragments is generally 100% except in layer 5 of Stations 3/1 - 3/3 where it is reduced by the presence of several broken shells.

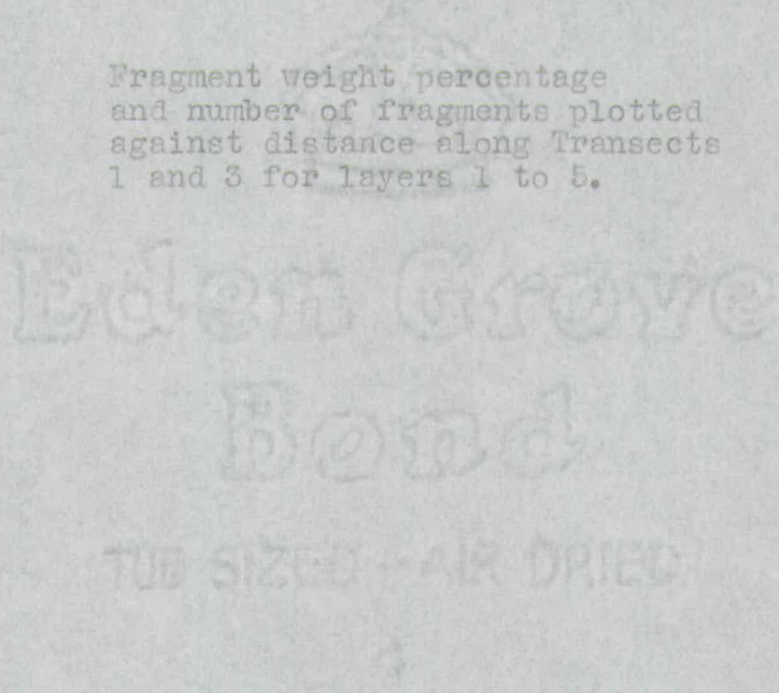
Bøggild (1930) showed that the shell has an upper cross lamellar layer and a lower homogeneous or complex layer. Scrobicularia shells less than 40 mms in length are generally thin and correspondingly easily broken. The prominent growth rings act as lines of weakness and frequently crescent shaped fragments of the type shown in Plate 35b-D become detached. The most resistant part of the valve is the umbo with the resilifer and cardinal teeth (Fig. 38).

Macoma balthica (L)

Complete Shells

The distribution of Macoma shells in layers 1 to 5 is given in Fig. 41a-e. They are largely restricted to the mud flats west of the Carse Gut and to the area between the Carse Gut and Channel C. Isolated shells were found west of Channel G, but only the shells east of Channel G were at Station 1/12 in layer 4. The distribution of dead shells is therefore much more restricted than that of the living population (Fig. 14b-d).

FIG. 40. DISTRIBUTION OF SCROBICULARIA PLANA FRAGMENTS ALONG TRANSECTS 1 AND 3.



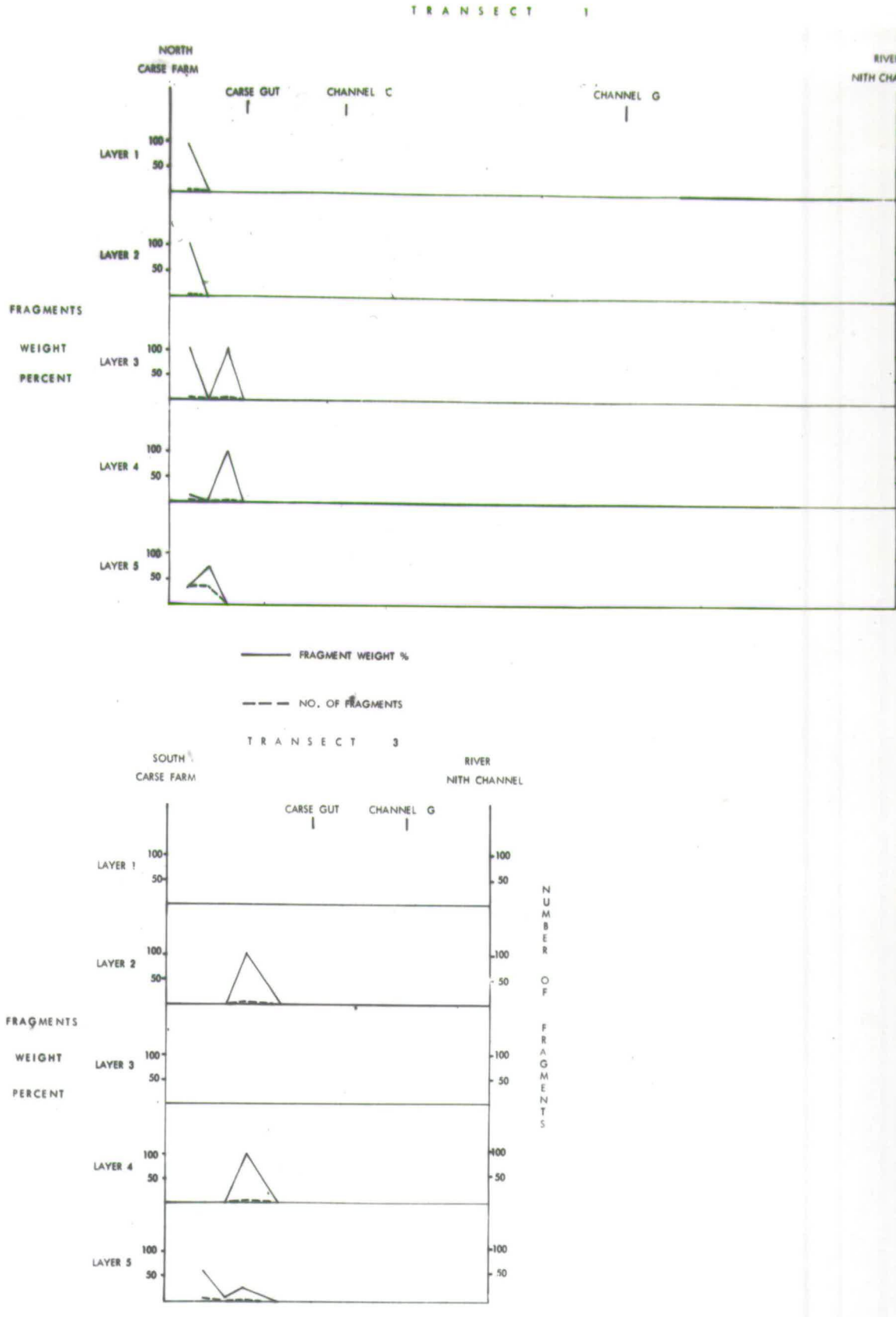

TRANSECT 1
NORTH CARSE FARM
CARSE GUT
CHANNEL C
CHANNEL G
RIVER NITH CHANNEL
LAYER 1
LAYER 2
LAYER 3
LAYER 4
LAYER 5
100
50
FRAGMENTS
WEIGHT
PERCENT
FRAGMENT WEIGHT %
NO. OF FRAGMENTS
TRANSECT 3
SOUTH CARSE FARM
RIVER NITH CHANNEL
CARSE GUT
CHANNEL G
NUMBER OF FRAGMENTS

FIG. 41. DISTRIBUTION OF MACOMA BALTHICA SHELLS.

a. Macoma balthica shells Layer 1

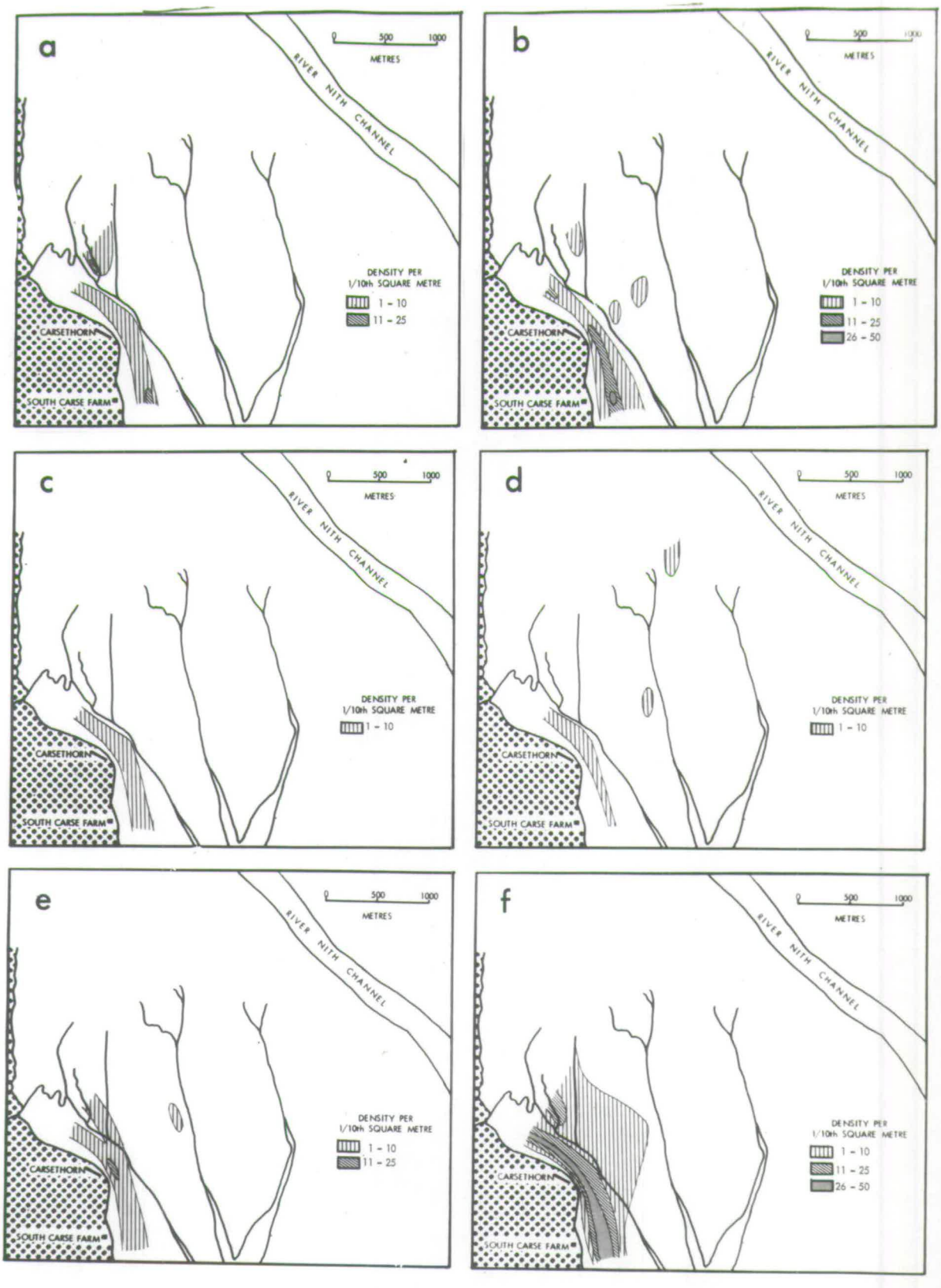
b. " " " Layer 2

c. " " " Layer 3

d. " " " Layer 4

e. " " " Layer 5

f. " " " Total, Layers 1 - 5


a
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 10
11 - 25
CARSETHORN
SOUTH CARSE FARM
b
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 10
11 - 25
26 - 50
CARSETHORN
SOUTH CARSE FARM
c
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 10
CARSETHORN
SOUTH CARSE FARM
d
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 10
CARSETHORN
SOUTH CARSE FARM
e
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 10
11 - 25
CARSETHORN
SOUTH CARSE FARM
f
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER
1/10th SQUARE METRE
1 - 10
11 - 25
26 - 50
CARSETHORN
SOUTH CARSE FARM

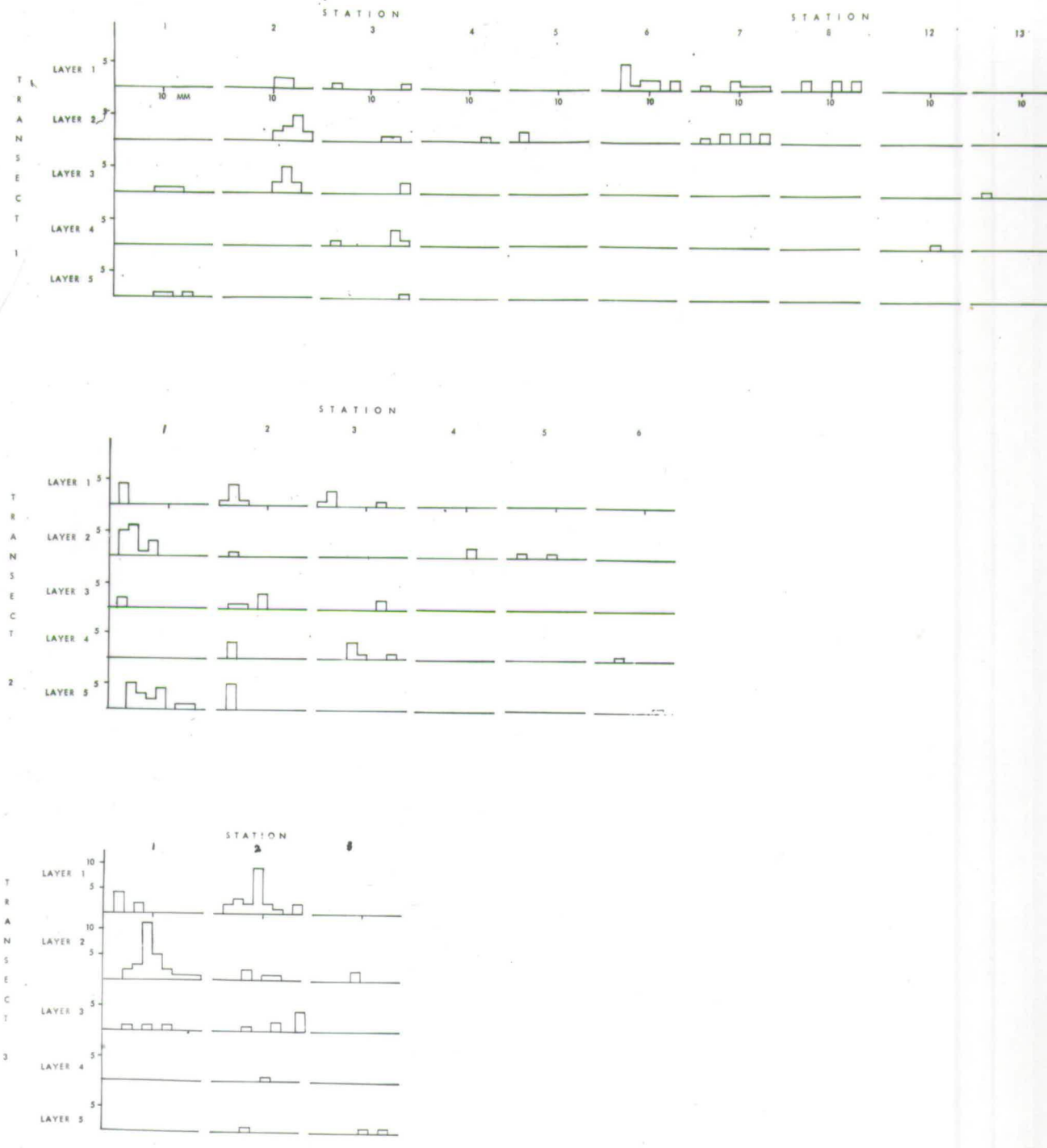
The density decreases with depth. The highest densities - up to 27 per 1/10th square metre - are in layers 1 and 2 whereas in layers 3 to 5, with the exception of 2/1/5, the density is less than 10 per 1/10th square metre. The total distribution is given in Fig. 41f.

The shells rarely exceed 16 mms in length (Fig. 42). If the growth rates suggested on p. 82 are applied to the peaks at 6 mms, 10 mms and 15 mms, then these represent one, two and four-year old shells respectively.

Incomplete Shells

Macoma shells with both valves damaged are widely distributed throughout the sediment, the highest densities are however in layer 1. In many cases more than $\frac{2}{3}$ of the shell is missing and frequently only the umbo and cardinal teeth of each valve remain attached by the ligament (Plate 35b-C). This type is common in shells less than 10 mms in length as the ligament is stronger than the actual shell. In shells longer than 10 mms the shell is thicker and correspondingly stronger and therefore the ligament breaks much more easily allowing the valves to become disarticulated.

On Transect 3, 10 incomplete shells had only the left valve broken whereas 26 had the right valve broken. As the right and left valves of Macoma appear to be structurally identical and of equal strength (see p. 153), it is probable that this predominant breaking of the right valve has some significance. As Macoma, when moving at the surface, lies on its left side the right valve would be uppermost and therefore most likely to be



SIZE-FREQUENCY DISTRIBUTION OF MACOMA BALTHICA COMPLETE SHELLS, TRANSECTS 1 to 3.

Number of shells plotted against length.

damaged by a bird or other predator attacking the animal. It is probable, therefore, that these right valves were damaged when the animal was being removed from its shell by a predator.

Left Valves

Macoma valves are common in the mud flats west of the Carse Gut, and between the Carse Gut and Channel C. Over the sand flats the distribution is sporadic and the density is rarely more than 3 per 1/10th square metre. The distribution of valves in layers 1 to 5 is given in Fig. 43a-e. The density of valves on the mud flats increases southwards from Carse Bay. In layers 1, 2 and 3 the densities on the mud flats are fairly similar although the areas of high density differ from layer to layer. In layers 4 and 5, however, the densities are very much greater. There is thus an increase in the density of valves with depth in contrast to the decrease in shells with depth.

East of the Carse Gut at Station 2/4 Macoma valves from the surrounding sand flats are concentrated into the surface shell-bed. The actual density of Macoma valves (26 per 1/10th square metre) is very much less than that of Cardium valves. It is probable that this is partly due to the greater densities of Cardium valves in the surrounding sand flats, but other factors including the differing shell structure and strengths of the valves have accentuated this initial difference and greatly increased the proportion of Cardium valves. The total distribution of valves (Fig. 43f) shows that Macoma valves are distributed over most of the area west of Channel G but the highest densities are on the upper mud flat.

FIG. 43. DISTRIBUTION OF MACOMA BALTHICA LEFT VALVES.

a. Macoma balthica left valves Layer 1

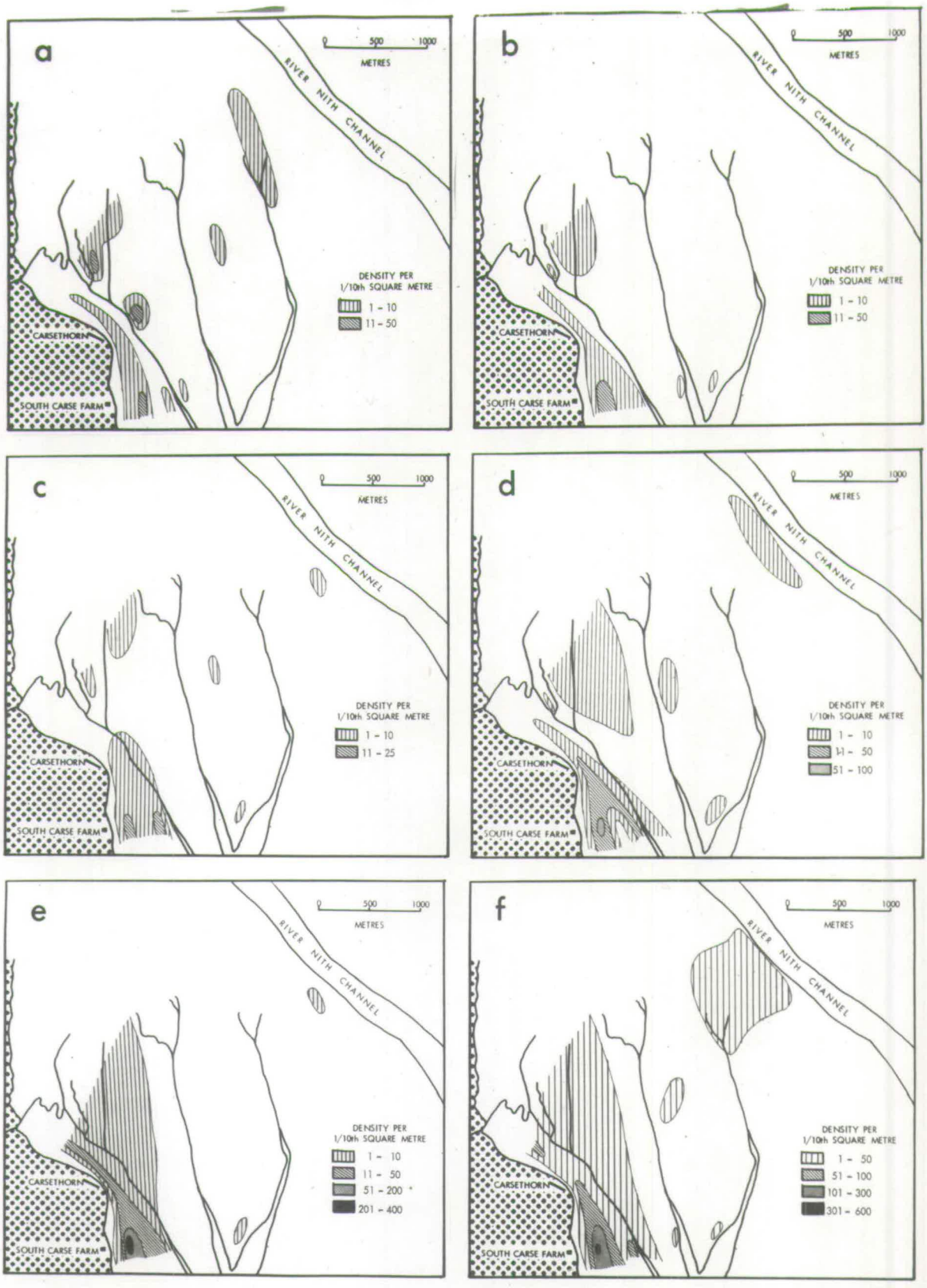
b. " " " " Layer 2

c. " " " " Layer 3

d. " " " " Layer 4

e. " " " " Layer 5

f. " " " " Total, Layers 1 - 5


a
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER 1/10th SQUARE METRE
1 - 10
11 - 50
CARSETHORN
SOUTH CARSE FARM
b
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER 1/10th SQUARE METRE
1 - 10
11 - 50
CARSETHORN
SOUTH CARSE FARM
c
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER 1/10th SQUARE METRE
1 - 10
11 - 25
CARSETHORN
SOUTH CARSE FARM
d
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER 1/10th SQUARE METRE
1 - 10
11 - 50
51 - 100
CARSETHORN
SOUTH CARSE FARM
e
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER 1/10th SQUARE METRE
1 - 10
11 - 50
51 - 200
201 - 400
CARSETHORN
SOUTH CARSE FARM
f
0 500 1000
METRES
RIVER NITH CHANNEL
DENSITY PER 1/10th SQUARE METRE
1 - 50
51 - 100
101 - 300
301 - 600
CARSETHORN
SOUTH CARSE FARM

Valves greater than 18 mms in length are rare. The size-frequency distribution (Figs. 44 and 45) shows that the strongest peaks are between 11 and 13 mms, and represent 3 year old valves. The 10 mm peak (2 year old valves) is only identifiable in 2/4/1 and 3/1/5 but the peak between 13 and 15 mms (4 year old valves) is not uncommon and can be identified in all samples from Stations 3/2, 2/1/4, 1/7/1, 2/4/1, 3/3/5 and others. It is probable that many of the valves are derived from the living Macoma populations in the area.

Fragments

The number of fragments (Fig. 46a) decreases markedly east of the Carse Gut on Transect 3 whereas on Transect 1 (with the exception of layer 5) the number of fragments increases east of the Carse Gut but decreases towards Channel G. The weight percentage of fragments in the areas of high fragment and valve density is generally between 25 and 40%. East of the Carse Gut on Transect 3 where the densities are much lower the weight percentage of fragments is usually between 50 and 75%, on Transect 1, however, the pattern is much more variable. West of the Carse Gut up to 91% of the fragments consist of less than $\frac{1}{3}$ of the valve (Fig. 46b); east of the Carse Gut, however, the percentage of larger fragments was generally greater.

Bøggild (1930) showed that the Macoma balthica shell has a two-layered structure. The upper layer is composed of concentric crossed lamellae and the lower layer consists of alternating crossed lamellae and prismatic laminae.

The prominent growth lines towards the ventral margin of the valve are lines of weakness, and crescent-shaped fragments

FIG. 44. SIZE-FREQUENCY DISTRIBUTION OF MACOMA BALTHICA LEFT VALVES, TRANSECTS 1 AND 2.

Number of valves plotted against length.

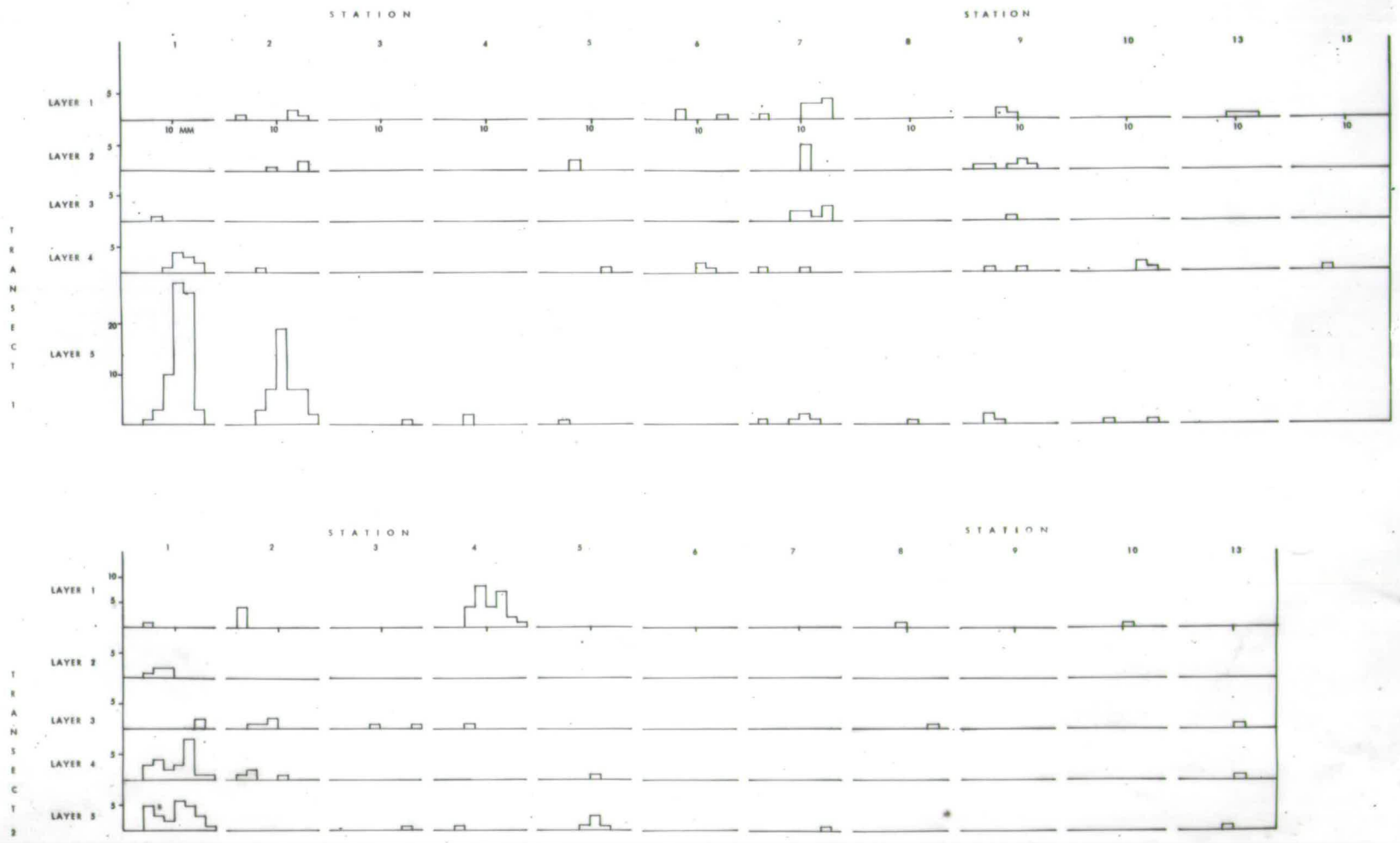

STATION
1
2
3
4
5
6
7
8
9
10
13
15
LAYER 1
LAYER 2
LAYER 3
LAYER 4
LAYER 5
10 MM
TRANSECT 1
STATION
1
2
3
4
5
6
7
8
9
10
13
LAYER 1
LAYER 2
LAYER 3
LAYER 4
LAYER 5
TRANSECT 3

FIG. 44

FIG. 45. SIZE-FREQUENCY DISTRIBUTION OF *MACOMA BALTHICA* LEFT VALVES, TRANSECT 3.

Number of valves plotted against length.

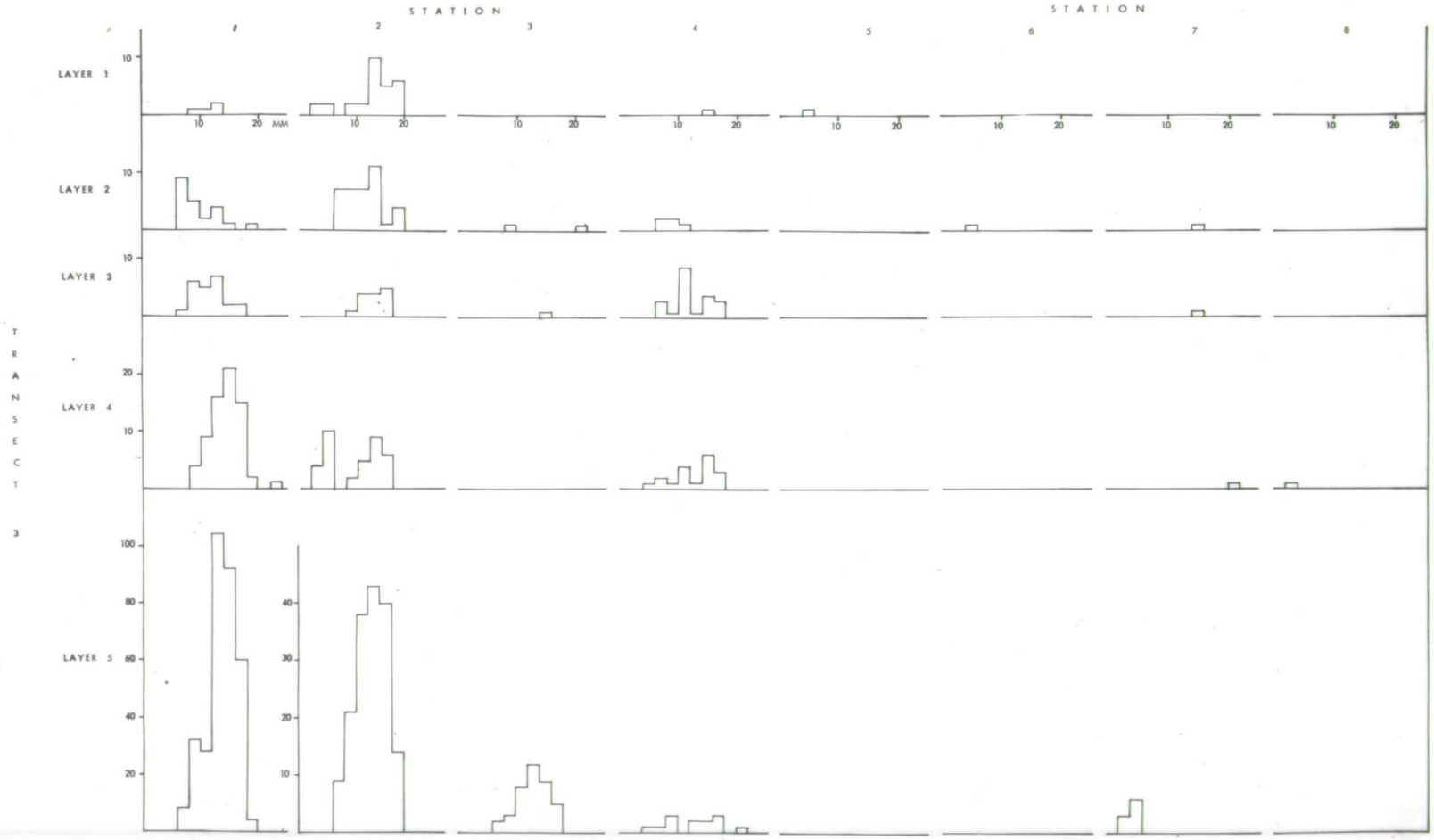
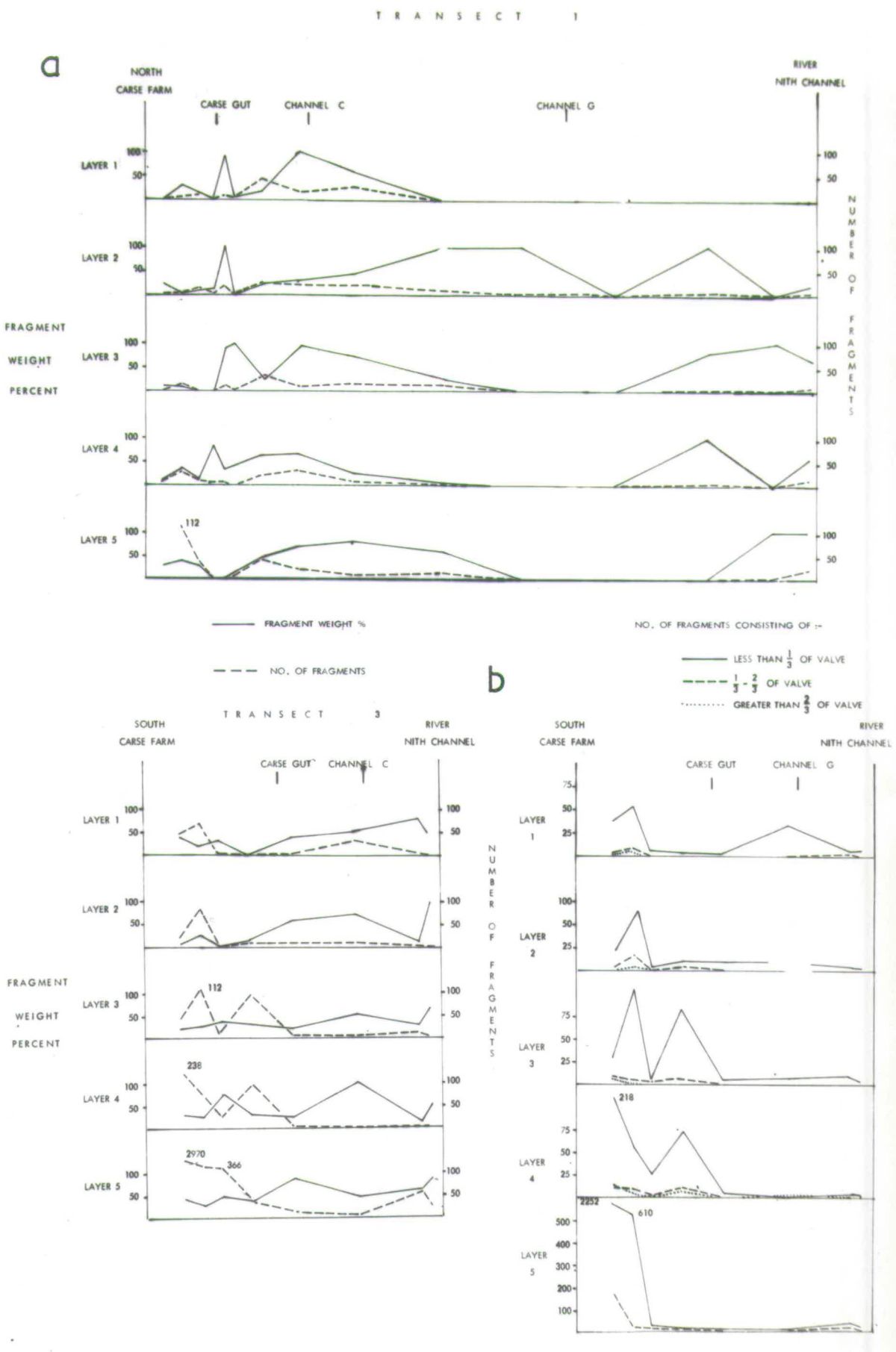

STATION
1
2
3
4
5
6
7
8
LAYER 1
LAYER 2
LAYER 3
LAYER 4
LAYER 5
10
20
MM
TRANSECT 3

FIG. 45

FIG. 46. DISTRIBUTION OF MACOMA BALTHICA FRAGMENTS ALONG TRANSECTS 1 AND 3.

a. Fragment weight percentage and number of fragments plotted against distance along Transects 1 and 3 for layers 1 to 5.

b. Number of fragments consist- of less than 1/3rd, 1/3rd - 2/3rds and greater than 2/3rds of the valve plotted against distance along Transect 3.


TRANSECT 1
a
NORTH CARSE FARM
CARSE GUT
CHANNEL C
CHANNEL G
RIVER NITH CHANNEL
LAYER 1
LAYER 2
LAYER 3
LAYER 4
LAYER 5
112
FRAGMENT WEIGHT PERCENT
NUMBER OF FRAGMENTS
FRAGMENT WEIGHT %
NO. OF FRAGMENTS
NO. OF FRAGMENTS CONSISTING OF :-
LESS THAN 1/3 OF VALVE
1/3 - 2/3 OF VALVE
GREATER THAN 2/3 OF VALVE
b
TRANSECT 3
SOUTH CARSE FARM
RIVER NITH CHANNEL
CARSE GUT
CHANNEL C
CHANNEL G
112
238
2970
366
218
2252
610

(Plate 35b-B and Fig. 38) are fairly common in the sediment and shell-beds. The dorsal margin and umbonal area is not very much stronger than the central parts of the valve and therefore there is little tendency for further preferential breakage to occur.

Tellina tenuis (da Costa)

At Station 3/6 one broken shell and one fragment were obtained from layer 3 and a complete shell 16 mms in length from layer 5. As the shell is so thin and brittle it is not surprising that shells and fragments are so rare.

Mya arenaria L

Left Valves

The total distribution of Mya left valves is given in Fig. 26e. They are mostly found on the mud flats west of the Carse Gut, but occasional valves occur over the sands. All but three of the valves were less than 28 mms in length (Fig. 39c). The three larger valves were in layer 5 at Stations 1/7 and 2/1. Most of the valves are probably derived from the local living population.

Fragments

Mya fragments are not very common in the sediments east of the Carse Gut and Channel C. They are present on the mud flats although the actual number of fragments is never more than 25 except in layer 5. The weight percentage of fragments is generally over 75% and in many cases is 100% (Fig. 47a).

In layer 3 Station 3/2, fragments less than $\frac{1}{8}$ only made up 10% of the total number of fragments while in layers 1 and 2

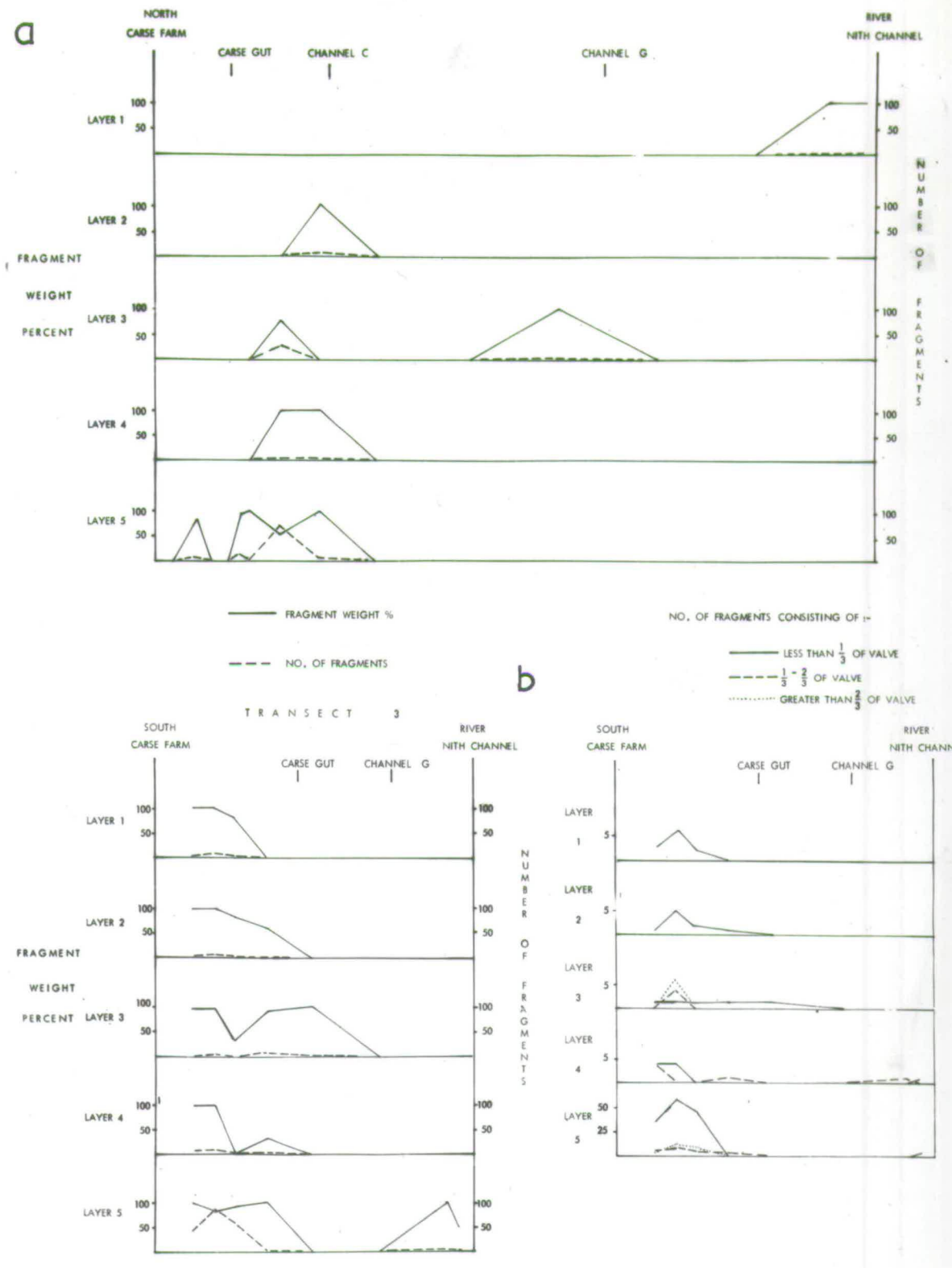
FIG. 47. DISTRIBUTION OF *MYA ARENARIA*

FRAGMENTS ALONG TRANSECTS 1 AND 3.

a. Fragment weight percentage and number of fragments plotted against distance along Transects 1 and 3 for layers 1 to 5.

b. Number of fragments consisting of less than 1/3rd, 1/3rd - 2/3rds and greater than 2/3rds of the valve plotted against distance along Transect 3.

FIG. 47


TRANSECT 1
a
NORTH CARSE FARM
CARSE GUT
CHANNEL C
CHANNEL G
RIVER NITH CHANNEL
LAYER 1
LAYER 2
LAYER 3
LAYER 4
LAYER 5
100
50
FRAGMENT WEIGHT PERCENT
NUMBER OF FRAGMENTS
FRAGMENT WEIGHT %
NO. OF FRAGMENTS
NO. OF FRAGMENTS CONSISTING OF :-
LESS THAN 1/3 OF VALVE
1/3 - 2/3 OF VALVE
GREATER THAN 2/3 OF VALVE
b
TRANSECT 3
SOUTH CARSE FARM
CARSE GUT
CHANNEL G
RIVER NITH CHANNEL
LAYER 1
LAYER 2
LAYER 3
LAYER 4
LAYER 5
FRAGMENT WEIGHT PERCENT
NUMBER OF FRAGMENTS
5
50
25

there were no fragments greater than ½. The percentage of fragments less than ½ varied from 15% at Station 4 to 100% at Stations 5 and 7. On the upper mud flats the average percentage less ½ was 83% (Fig. 47b).

Bøggild (1930) showed that Mya has a three-layered shell. The upper layer has a fine-grained homogeneous structure while the middle layer is made up of concentric crossed lamellae and the lower layer consists of complex lamellae.

If the growth lines close to the ventral margin are distinct and deep, they may act as lines of weakness giving a type of crescentric fragment, but these are not very common. The dorsal portion of the right valve is only slightly stronger than the rest of the valve and therefore does not often develop any definite breakage pattern. In the left valve, however, the chondrophore and the anterior and posterior thickenings of the dorsal margin are substantially stronger than the rest of the valve and therefore fragments consisting of the chondrophore and umbonal region of the left valve are fairly common (Plate 35b-F and Fig. 38).and in extreme cases the chondrophore alone is preserved (Plate 35b-E).

Valves of species not living in the area are occasionally found in the sediments.

Mactra corallina (L) valves probably derived from the living population in the Mersehead Sands west of Southerness are sometimes seen near Locality 15 and on the banks of Channel J.

A Spisula subtruncata (da Costa) right valve 19 mms long was found on the west bank of the Nith Channel in layer 5 of

Station 1/15. Bruce, Colman and Jones (1963) recorded a few individuals from muddy sand off Sellafield, 10 kms south of St. Bees Head, Cumberland. It does not live in the Solway Firth.

A Modiola modiolus (L) valve 75 mms in length with several species of seaweed attached to it (Plate 36a) was stranded in the Carse Gut flood channel on the lower mud flat near Station 1/6. M. modiolus lives in the deeper water between Southerness and Maryport (Perkins and Williams 1963b). The attached seaweed would greatly increase the buoyancy of the valve and make it possible for flood-tidal currents to transport the valve as far as Carse Bay.

DISCUSSION

Evidence from overall distribution patterns and size-frequency characteristics suggests that almost all the shells and valves of Littorina, Hydrobia, Retusa, Cardium, Macoma, Scrobicularia and Mya distributed throughout the sediment could be derived from the local living fauna of the sand and mud flats. The proportion of elements that were possibly transported into the area such as large Cardium shells etc. is very low and is almost negligible.

The Mytilus valves have almost all been transported into the area as Mytilus no longer lives in the Carsethorn area.

The total distribution maps indicate that in all cases the main concentration of shells and valves is in the sediments west of Channel G. The highest densities in all groups are on

the mud flats west of the Carse Gut or between Channel C and Channel G to the north of the line of Transect 2. Many shells such as barnacle plates Mytilus valves and Scrobicularia shells and valves are virtually restricted to the mud flats.

East of Channel G only Cardium valves have a widespread distribution although the total density is much lower than it is west of the Carse Gut. Hydrobia shells are not uncommon east of Channel G but again the densities are much lower than those west of the Carse Gut. Macoma shells and valves, Mya valves and Cardium shells are all rare east of Channel G.

The composition and density of the shell and valve assemblages encountered by a laterally migrating channel therefore vary considerably throughout the area. The significance of this variation in the formation of shell-beds will be discussed in Chapter 6.

CHAPTER 5

REWORKING

Lateral migrations of channels are responsible for the majority of the reworking of intertidal sediments. Erosion of the flats by tidal and storm action rarely involves more than the top few cms of the sediment. Migrations of channels such as the Carse Gut, or Channels G or H will rework sediment to depths of up to 2 metres, and in major migrations of the Nith Channel, sediments down to depths of 5 - 8 metres may be reworked. Migrations of minor channels associated with the major ebb channels rework large areas of the mud and sand flats adjacent to the major channel to depths of between 20 and 40 cms.

The shape and slope of the bank of a meandering channel depends on the rate of lateral migration. If the migration is rapid, the stream undercuts the bank and a vertical cliff is formed (Fig. 48a and Plates 36b, 39), with no grading of the bank and no lowering of the level of the adjacent flat. The undercutting action of the stream causes large blocks of sediment to fall into the channel underneath the retreating bank. The current is usually strong enough to break up these blocks rapidly and transport the sediment downstream. In some cases, however, if the sediment is well laminated and there is sufficient organic matter present to give the block some strength it may well resist erosion by the channel currents and may survive as an isolated block in the soft sediment at the foot of the cliff. When the block falls into the channel it comes to lie with the lamination

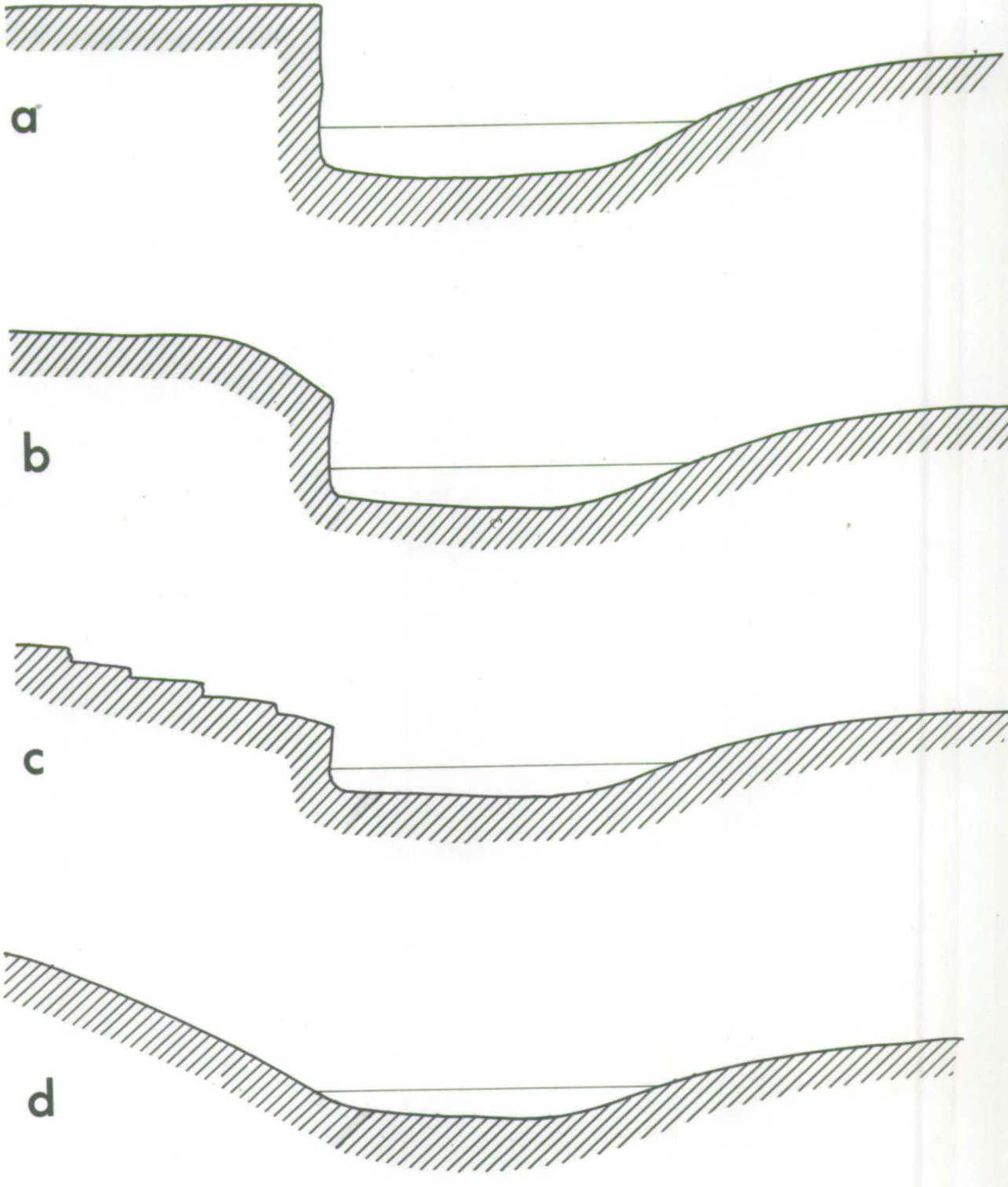
FIG. 48. CHANNEL CROSS SECTIONS.

a. Active undercutting of the bank during lateral migration producing a vertical cliff.

b. Grading of the top of the bank in unlaminated sands during less rapid lateral migration to produce a rounded shoulder.

c. Grading of the top of the bank in laminated sediments during lateral migration to produce terrace erosion. The floor of each terrace is a resistant clay lamina.

d. Complete grading of the bank when the rate of lateral migration is slow.


a
b
c
d

at a high angle - often almost 90° - to the floor of the channel (Plate 36b). The selective erosion of the sand laminae by the channel current tends to accentuate the clay laminae in the block. Fallen blocks of this type are not uncommon on the banks of the Carse Gut at Localities 3 and 4. Under favourable conditions these blocks may be buried in the sediment on the prograding bank and may be preserved as a type of 'intraformational conglomerate'.

When the rate of migration is less rapid some grading of the level of the flats adjacent to the bank takes place (Fig. 48b) although the actual bank is marked by a small cliff. In the Carse Sands where reworking has destroyed the original lamination by removal of the clay material the graded shoulder of the retreating bank is generally smooth. In areas where the lamination is preserved, however, the grading of the bank takes place by the formation of a series of small terraces (Fig. 48c and Plate 37a). Each terrace may be over 1 metre in width but the height of the edge is rarely more than 20 cms. The floor of each terrace is usually a particularly resistant clay laminae but in some cases it may be a buried shell layer. The edge of each terrace is irregular (Plate 37a) and several prominent clay laminae are usually to be seen. Often one of these laminae forms the floor of a small secondary terrace developed at the edge of the main terrace (Plate 37b). At every ebb tide when the water drains off the flats into the ebb channels the edge of each terrace is eroded and may retreat several cms. If terrace erosion occurs along the banks of the smaller temporary channels draining the ebb channel a much more irregular pattern of terraces and isolated terraced areas is developed (Plate 38a).

Coarser sediment may be deposited on the terraces and the edges of individual terraces may become buried. This is frequently observed at the west bank of the Nith Channel near Station 1/15 where redistribution of sand by the Nith Channel may bury terraces developed on the banks of minor tributary channels. Much of the lowest terrace shown on Plate 38a is obscured by asymmetric ripples developed in sand deposited in this way. Similar terrace-erosion structures in Old Red Sandstone siltstones of the Welsh Borderlands have been described by Allen (1962).

When lateral migration is slow, no cliff is developed and sufficient time is available for the banks to become completely smooth and to grade down gradually to the edge of the channel (Fig. 48d). Smooth banks of this type are often found on parts of the lower reaches of the Carse Gut and Channels G and H.

Reworking and lateral migration of the channels alters the detailed geography of the area from day to day (see pp. 13-14 and Fig. 49).

The course of the Carse Gut south of Locality 10 shows little change in position although the shape of the channel cross-section varies. The small island present on Transect 3 in September 1962 had disappeared by April 1963. North of Locality 10 a meander developed on the lower mud flats at Locality 11 in the winter of 1962 which resulted in a change in the course of the Carse Gut in March 1964. A detailed account of this is given later in the chapter.

There was little or no lateral migration in the middle reaches of Channel G during the period of the study. An island

FIG. 49. PROFILES ALONG LINES OF TRANSECTS.

Numbers below each profile indicate the thickness of the aerobic layer in centimetres.

D = aerobic layer greater than 30 cms in thickness.

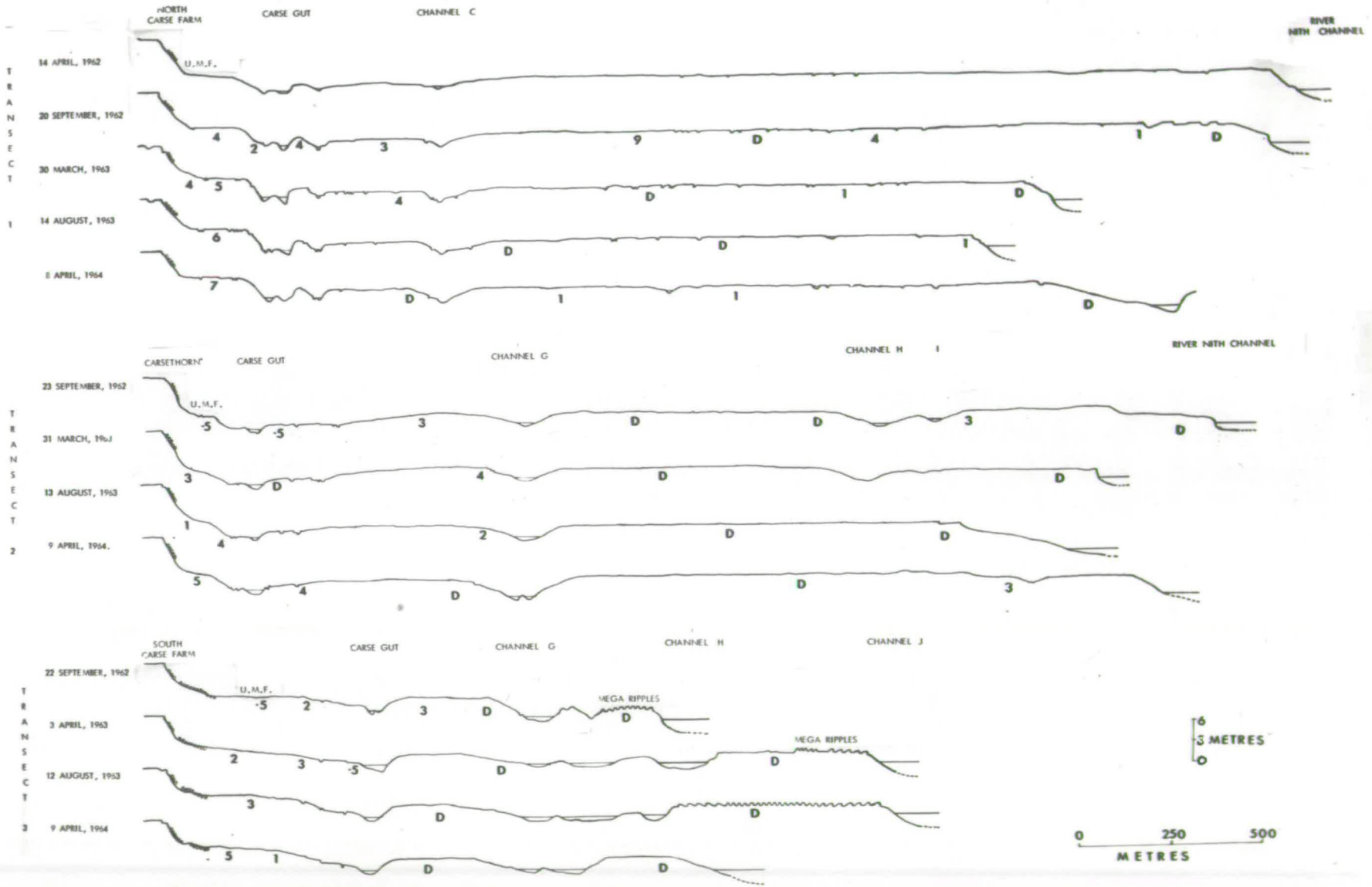

TRANSECT 1
NORTH CARSE FARM
CARSE GUT
CHANNEL C
RIVER NITH CHANNEL
14 APRIL, 1962
U.M.F.
20 SEPTEMBER, 1962
30 MARCH, 1963
14 AUGUST, 1963
8 APRIL, 1964
TRANSECT 2
CARSETHORN
CARSE GUT
CHANNEL G
CHANNEL H
I
RIVER NITH CHANNEL
23 SEPTEMBER, 1962
U.M.F.
31 MARCH, 1963
13 AUGUST, 1963
9 APRIL, 1964.
TRANSECT 3
SOUTH CARSE FARM
CARSE GUT
CHANNEL G
CHANNEL H
CHANNEL J
22 SEPTEMBER, 1962
U.M.F.
3 APRIL, 1963
12 AUGUST, 1963
9 APRIL, 1964
MEGA RIPPLES
MEGA RIPPLES
6
3 METRES
0
0
250
500
METRES

FIG. 49

was present on the line of Transect 2 in April 1964. At the mouth of Channel G, however, the pattern was continually changing. By April 1963 the channel had divided into two separate branches, a shallow minor branch to the west and the main channel to the east. The position and number of tributaries making up the head waters of Channel G changed frequently and it was impossible to correlate them from one profile to the next.

The position and degree of development of Channel H varied considerably. From September 1962 to April 1963 the course was more or less constant. Between April and August 1963, however, the upper reaches silted up and the channel declined in importance and by April 1964 all trace of it had disappeared. The isolated body of water (I) also disappeared between April and August 1963. The westward migration of Channel J between August 1963 and April 1964 may be related to the decline and disappearance of Channel H.

The differences in the type of slope on the west bank of the Nith Channel on Transects 1 and 2 are related to the westward migration of the Nith between summer 1962 and summer 1963 and its eastward retreat through the winter of 1963.

Minor tributaries less than 20 cms deep draining the mud and sand flats cannot be traced from profile to profile and therefore the majority of these probably have a life of less than six months.

Erosion and reworking by lateral channel migration is therefore taking place at all times in different parts of the area. The rate of migration at a given time varies considerably from place to place, and at the same locality it alters from day to day as conditions change.

In general three different types and rates of reworking can be recognised.

The first is the rapid reworking of a small area during a storm by an ebb channel swollen by flood waters. The local effects of this type are dramatic but the meander or new course created during the storm only lasts for a few days after it has abated, and within a week or so the meander or new course is abandoned and the channel reverts to more or less its original course.

The second type is the development of a large meander in a major ebb channel. The development of the meander may take two or three years, and the rate of growth changes from time to time. Storm action and floods may greatly accelerate the growth at particular times but the main development is largely independent of these factors.

The third type is the large-scale reworking of the whole area during major migrations of the River Nith Channel. These east-west migrations only occur at 10 to 30 year intervals but when they take place they completely rework most of the sediments of the Carse Sands and mud flats and they effectively destroy the animal communities living in the area. Thus, although they are rare, the large-scale migrations of the channel have a profound effect on the area and the effects of each migration persist until they are obliterated by the next one.

RAPID REWORKING DURING STORMS

Heavy rainfall during the second week of September 1962 caused a great increase in the volume of water carried by the Carse Gut. On the 12th September as the last of the ebb tide left the banks, a cane was placed in the centre of a meander which was growing on the east bank of the Carse Gut at Locality 12 (Plate 38b). The fast-flowing torrent of water undercut the bank rapidly and large blocks of sediment were continually falling into the channel (Plate 38b). These were rapidly broken up by the current however and within one minute or so they had completely disappeared. 50 minutes later the east bank had receded a further 2.3 metres (Plate 39a) and just under 90 cubic metres of sediment with a calculated dry weight of 126 tons had been removed. In the next 35 minutes the bank receded a further 1.2 metres (Plate 39b). During the following 2 - 3 hours, although active undercutting of the bank took place over the whole length of the meander, the point at which the most rapid erosion was taking place gradually moved a few metres to the south and the length of the bank involved in the meander increased considerably (Plate 40a). During the next 24 hours the bank receded a further 3.7 metres from the cane (this period included two high tides when the rate of erosion was probably quite low) but active undercutting had more or less ceased. The main effect of the ebbing tide on the afternoon of the 13th September was to lower the height of the bank and create a slope (Plate 40b) similar to the type shown in Fig. 48b. As the ebb waters drained off the flats, planes of weakness in the bank were

rapidly channelled out forming deep narrow clefts (Plate 41a). A resistant terrace (Plates 40b and 41a) was formed by the 5 cm black anaerobic zone present 3 cms below the surface (Plate 38b). In the next 24 hours the bank only receded a further metre and the small cliff present on the 13th September (Plate 40b) had been almost completely graded down until the slope approximated to the type shown in Fig. 48d although the terrace formed by the black layer persisted.

During the forty-eight hours when the bank was being eroded at Locality 12 almost 350 cubic metres - about 500 tons (dry weight) - of sediment had been reworked by the Carse Gut while in spate. The rate of erosion was not constant, however; after the first two hours it started to decline (Fig. 50a) and after eight hours, over half the total weight of sediment removed in the forty-eight hour period had been reworked. During the second twenty-four hours only 40 tons of sediment were reworked.

During the next week the Carse Gut abandoned the meander developed between the 12th and 14th September and returned to its pre-flood course (Plate 41b). The meander gradually filled with sediment and the only relic of the former flood bank that persisted was the erosion terrace created by the anaerobic zone (Plate 41b).

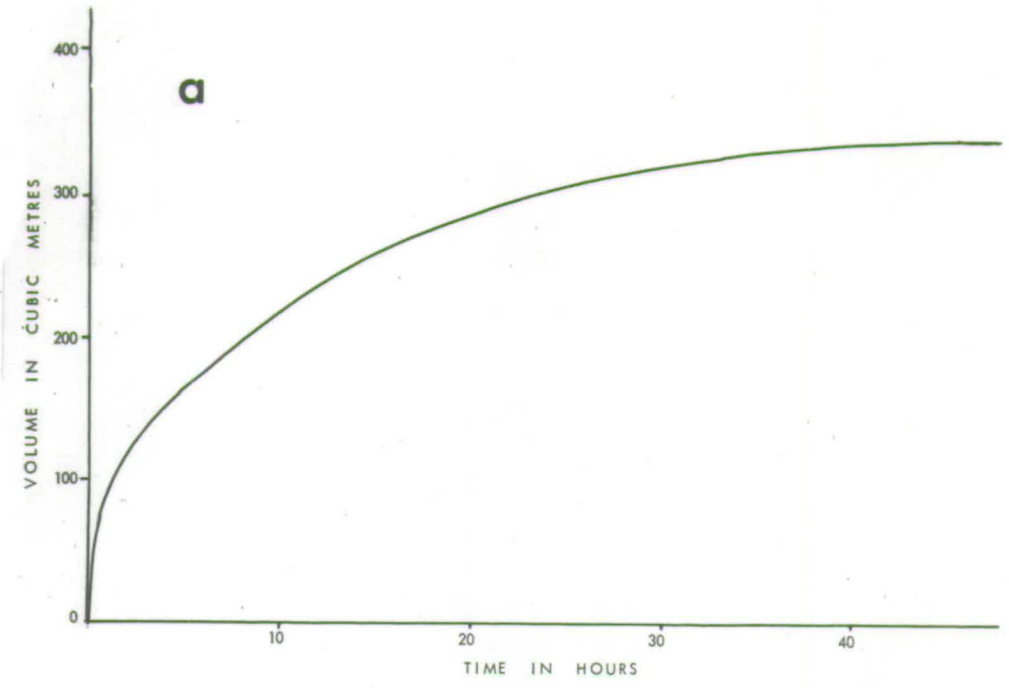
One of the minor tributaries of the Carse Gut affected by the rapid recession of the east bank at Locality 12 is shown in Plate 42a. The tributary, which drained part of the sand flats to the east, continued to carry water to the Carse Gut for approximately one hour after the last of the ebb tide had left the

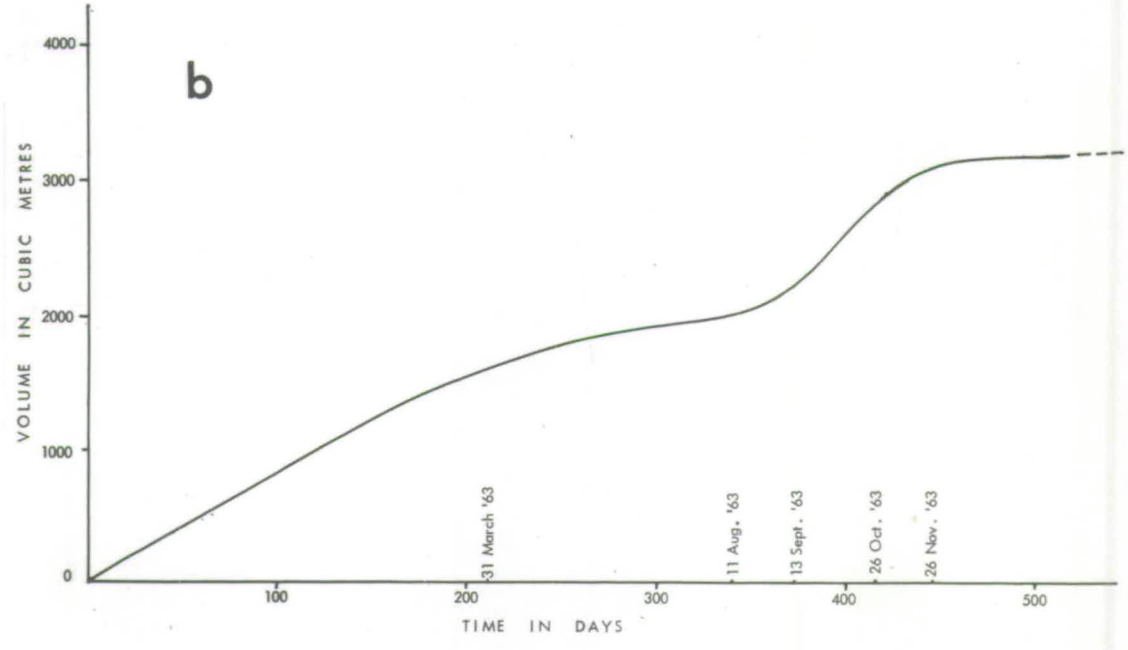
FIG. 50. RATES OF REWORKING.

Volume of sediment reworked plotted against time.

a. Rapid reworking during a storm, east bank Carse Gut at Locality 12. 12th - 13th September 1962.

b. Reworking of lower mud flat at Locality 3 during the formation of the Carse Gut meander.
September 1962 - March 1964.


a
VOLUME IN CUBIC METRES
400
300
200
100
0
10
20
30
40
TIME IN HOURS


b
VOLUME IN CUBIC METRES
4000
3000
2000
1000
0
31 March '63
11 Aug. '63
13 Sept. '63
26 Oct. '63
26 Nov. '63
100
200
300
400
500
TIME IN DAYS

area, after which it gradually dried up. During this time the bank of the Carse Gut had receded 3.5 metres and, as the rate at which the tributary cut its way down through the sediment could not keep pace with this retreat, a 'hanging valley' was formed (Plate 42b). The further recession of the bank during the next twenty four hours removed most of the lower course of the tributary and a small delta, associated with the grading of the bank of the Carse Gut, was formed at the mouth (Plate 43a). After the Carse Gut had resumed its old course, the delta continued to enlarge (Plate 43b).

As the bank was undercut, all the living fauna and dead shells and valves contained in the sediment were reworked and transported downstream by the strong currents. Living Mya arenaria were frequently exposed in the vertical face as the bank receded (Plate 44a). During a 45-minute period on 12th September when active undercutting was taking place over most of the length of the meander, 10 living Mya were seen exposed in this way. It is probable that many more were eroded during this period but were enclosed in blocks of sediment and were therefore not observed. A minimum estimate of the total numbers of living Mya reworked during the development of the meander can be made based on the volume of sediment removed during this 45-minute period. The minimum number was 380, and it is probable that the actual number of living Mya reworked was considerably greater than this. The majority of the Mya were not transported more than a few metres from the site of their living burrow. On the 13th September, when the flow of water past the bank was

somewhat reduced, several dead Mya individuals were seen lying on the soft mud at the foot of the bank and all the shells were oriented with their siphons pointing up current (Plate 44b). Some of these were subsequently damaged by seabirds but the majority were buried by sediment washed off the bank or by sediment deposited in the abandoned meander after the Carse Gut had resumed its old course.

Large numbers of Arenicola marina burrows containing living worms were also exposed in the vertical face of the receding bank (Plate 45a). The sand grains forming the tail limb of the Arenicola burrow are bound with mucilage in order to prevent the tube collapsing. The tail tube is therefore much more resistant to erosion than the surrounding sediment. The water draining off the flats into the Carse Gut at ebb tide rounds off the top of the bank by the removal of some sediment. The tail tube resists this erosion, however, and tends to stand out up to 5 cms above the level of the surrounding sediment (Plate 45b).

Using the density data obtained from the transect studies the numbers of living animals and dead shells and valves reworked can be estimated. It is probable that at least 55,000 living Macoma balthica, 11,000 living Cardium edule and 2,000 living Retusa obtusa were reworked from Locality 12, in addition to approximately equal numbers (5,000) of Cardium complete shells, left and right valves, and Macoma left and right valves.

The lateral migration of channels during storms can therefore have profound effects over small areas for short periods of time. The course changes made during storms are only rarely permanent, however, and the channel normally returns to its former course when the flood waters have subsided.

DEVELOPMENT AND GROWTH OF A MEANDER

The course of the Carse Gut across the lower mud flats past Locality 11 started to change in September 1962 and a detailed study of the growth of the meander and the eventual change of course was made between then and October 1964. Rows of small stakes were placed at intervals in both banks of the Carse Gut in order to measure the rate of growth of the meander and a detailed photographic record was kept of all the changes. A series of maps (Fig. 51) were drawn from these measurements and photographs to illustrate the growth of the meander.

From October 1961 until the summer of 1962 no perceptible change in the course of the Carse Gut was observed. Active erosion at Locality 4 maintained the bank as a vertical cliff but the rate of erosion was slow and only small changes in the position of the edge of the bank could be observed from month to month.

In September 1962 active erosion of the west bank of the Carse Gut forming a vertical cliff was observed at the downstream end of the meander past Locality 4 at the point where the main current crossed from the east to the west bank (Fig. 51a). Associated with this some sediment had been deposited on the east bank opposite the actively eroding cliff. At Locality 3 the rate of erosion of the west bank was much less and terrace erosional features were developed. The Carse Gut flood channel was generally empty after the last of the ebb tide had drained from the lower mud flats and mud slope.

By March 1963 (Fig. 51b) active erosion forming vertical

FIG. 51. DEVELOPMENT OF MEANDER IN THE CARSE GUT AT LOCALITY 11, SEPTEMBER 1962 - OCTOBER 1964

a. September 1962

b. 31st March 1963

c. 11th August 1963

d. 15th September 1963

e. 26th October 1963

f. 26th November 1963

g. 4th January 1964

h. Estimated position just before capture, March 1964

i. 8th April 1964

j. 30th September 1964

k. 27th October 1964

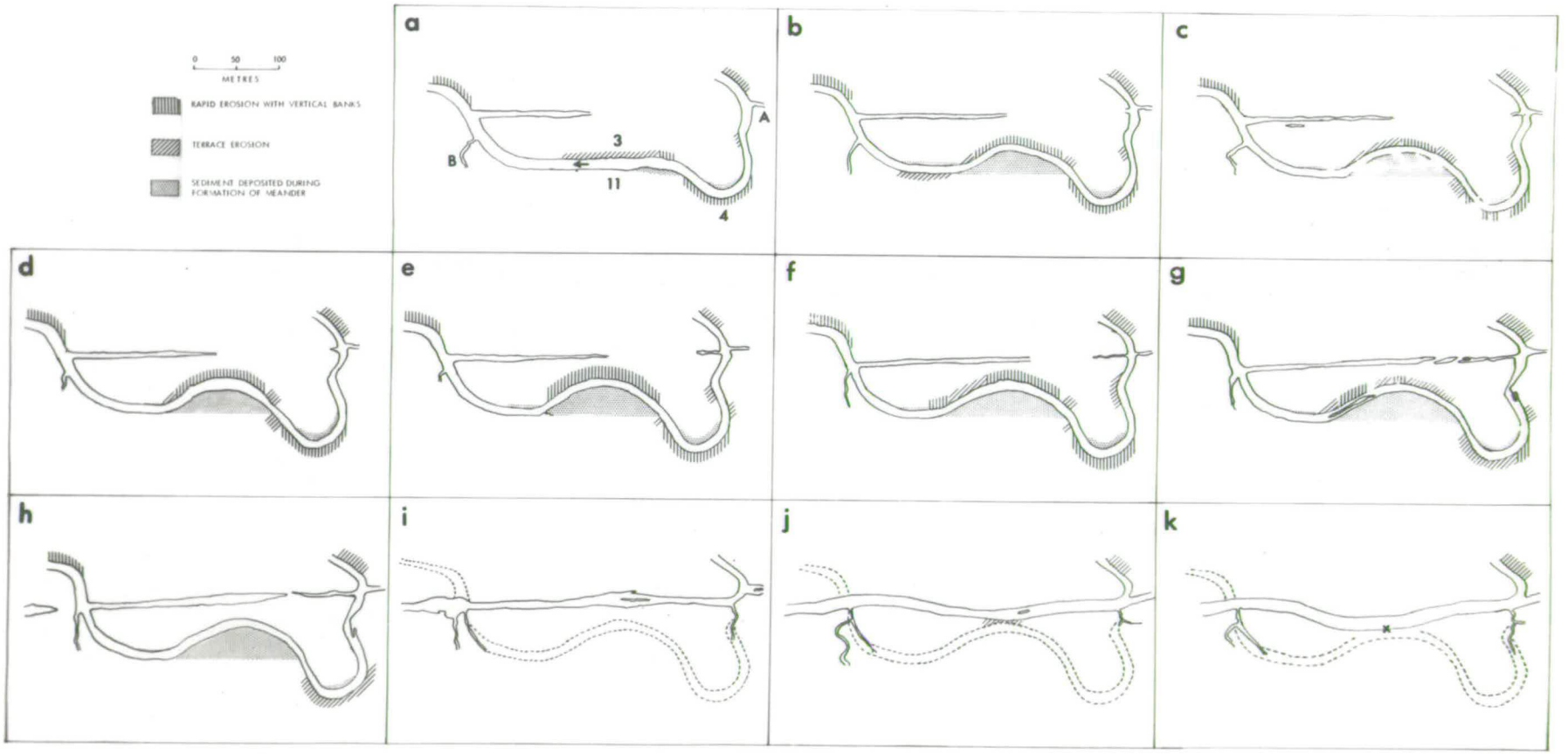

0 50 100
METRES
RAPID EROSION WITH VERTICAL BANKS
TERRACE EROSION
SEDIMENT DEPOSITED DURING FORMATION OF MEANDER
a
b
c
d
e
f
g
h
i
j
k
A
B
3
11
4

FIG. 51

banks had taken place on the west bank at Locality 3 and the new bank at Locality 11 had built out 10 metres from the position of the bank in September 1962. The sediment was extremely soft, however, and very loosely consolidated. On the west bank of the Carse Gut opposite the confluence of Channel A a small tributary had developed draining the lower mud flat.

In August 1963 (Plate 46a) the west bank of the Carse Gut had receded up to 2.3 metres from the September 1962 position but active erosion was largely restricted to a small sector of the bank (Fig. 51c). The size of the bank at Locality 11 had increased correspondingly and it was much better consolidated than in March. A number of small drainage channels had developed on the bank and it was possible to walk over most of it without much difficulty.

The rate of erosion of the west bank then increased and by September 1963 (Fig. 51d) active erosion was taking place along most of the bank involved in the meander. A small portion of the new bank at Locality 11 was cut off and an island was formed (Plate 46b). The rate of erosion increased considerably through October 1963 and the west bank receded up to 3 metres over much of its length between September 13th and October 26th (Fig. 51e). The rate declined in November, however, and some irregularities developed in the west bank (Fig. 51f). During October and November the small tributary draining the lower mud flats opposite the confluence of Channel A increased considerably in length and importance.

In January 1964 the new bank at Locality 11 had increased its width by up to 1 metre over its northern half. To the south,

however, no accretion took place but a long narrow island was formed in the channel (Fig. 51g). The Carse Gut flood channel had been gradually increasing in length over the winter and definite banks were developed over parts of its length. The tributary opposite Channel A was now much larger and its headwaters had incorporated some of the pools of water on the lower mud flat left by the ebbing tide. The mouth of the tributary had been partly drowned by the waters of the Carse Gut. Plate 47a shows a panorama of the Carse Gut flood channel and the small tributary and its confluence opposite Channel A taken on 4th January 1964. The closeness of the head of the flood channel and the head of the tributary, and the low-lying nature of the intervening area can be appreciated from the panorama.

The Carse Gut flood channel and the small tributary continued to develop through January and February, and towards the end of March 1964 the headwaters of the channels joined and the course of the Carse Gut was changed. The estimated position just before capture is shown in Fig. 51h. By April 8th 1964 the Carse Gut flowed down the course of the former flood channel and the old course past Locality 4 and the new meander was abandoned (Fig. 51i). A panoramic view of the new course taken on 8th April 1964 from the same position as Plate 47a is given in Plate 47b. Small drainage channels were developed at the beginning of the abandoned portion close to the confluence of Channel A and at the other end near the confluence of Channel B. The former course of the Carse Gut in the abandoned channel could be detected from the remains of the west bank and the pools of water trapped in the old channel (Plate 48a).

The new course was completely established by September 1964 and terrace erosion was developed on a short stretch of the new east bank indicating that the new channel was beginning to meander from its more or less straight course (Fig. 51j). By the end of October 1964 the new course had developed a slight curvature. The channel eroding the east bank at point X (Fig. 51k) had completed the reworking of the remaining part of the original lower mud flat left at Locality 3 before the former course was abandoned and was reworking sediment only recently deposited in the abandoned channel.

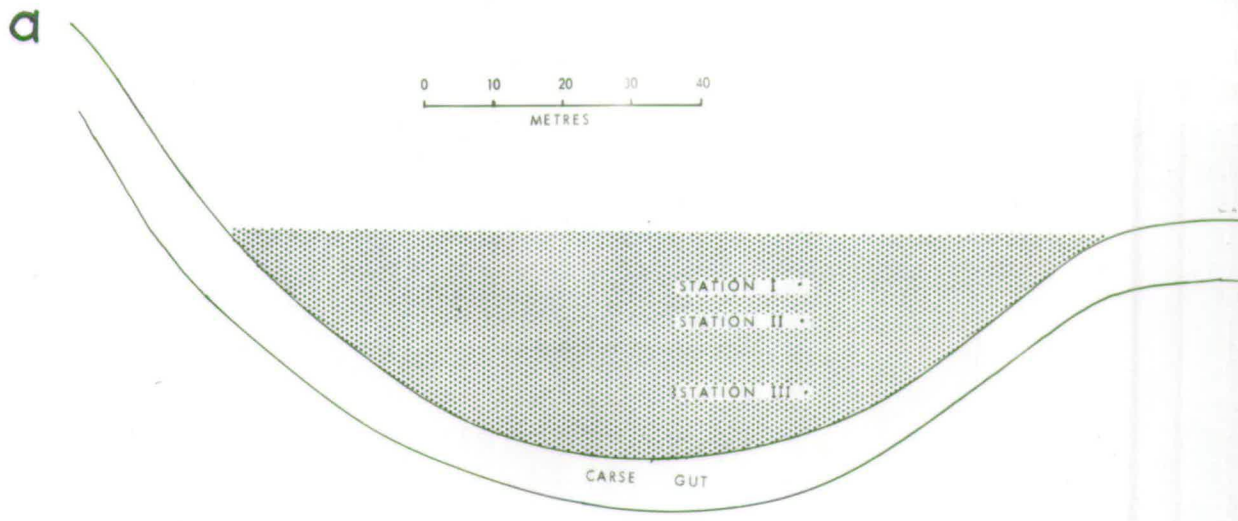
The rate of reworking of sediment from the west bank of the Carse Gut (Fig. 50b) was more or less constant between September 1962 and September 1963 but increased from September until the end of October 1963 after which it gradually decreased until the change of course in March 1964. It is probable that at least 4,600 tons (dry weight) of silt were reworked from the lower mud flat at Locality 3 during the formation of the meander.

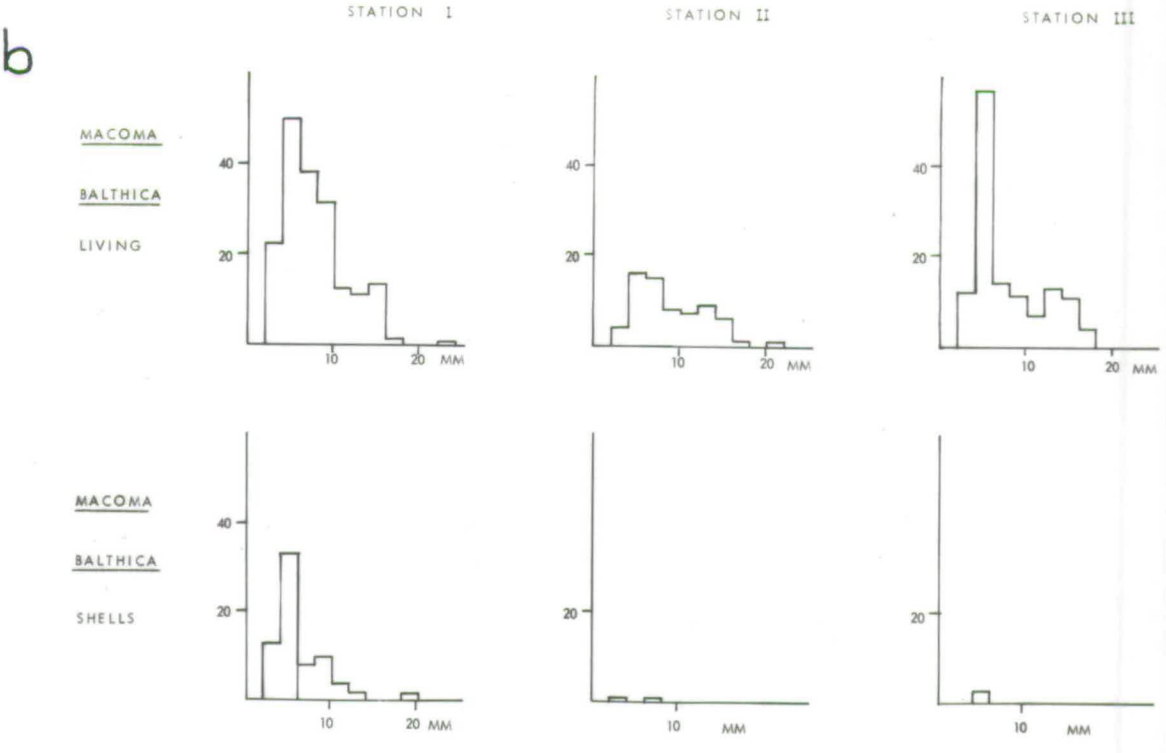
In August 1963 three samples were collected using the 1/10th square metre frame from the new sediment at Locality 11. The location of the stations is given in Fig. 52a. At each station all the sediment to a depth of 10 cms (equivalent to layers 1 to 4) was removed, sieved and the fauna separated. The faunal densities obtained are given below:-

	Station I	Station II	Station III
Macoma balthica (Living)	179	68	128
Macoma balthica (Shells)	72	2	3
Mya arenaria (Living)	1	-	-

The size-frequency distribution of both living and dead shells of Macoma balthica is given in Fig. 52b. The dominant

FIG. 52


a
0
10
20
30
40
METRES
STATION I
STATION II
STATION III
CARSE
GUT


b
STATION I
STATION II
STATION III
MACOMA
BALTHICA
LIVING
MACOMA
BALTHICA
SHELLS
40
20
10
20 MM
MM

peak in the living population probably represents the early summer 1963 0-Group which has grown rapidly in the new sediment. The living Macoma greater than 10 mms in length must be at least 2 years old on the basis of the growth increments suggested on p.82 The peak between 12 and 14 mms at Stations II and III represent 3 or 4 year old individuals, and the larger shells in all three stations are at least 5 years of age. The maximum age of the bank in August 1963 was 8 months. It is unlikely, however, that there was any fauna living in the bank in March 1963 as the sediment was so soft and unstable and the bank was probably only suitable for colonisation by an infauna after April 1963 at the earliest. All the living Macoma greater than 8 - 10 mms in length present in the bank had therefore migrated into the area as they were in most cases several years older than the bank in which they were now living. Many of the animals reworked from the west bank may have been able to re-establish themselves in the new bank, but densities of living Macoma in the lower mud flats are far too low to account for more than a small proportion of the fauna in the new bank. The majority of the older Macoma individuals therefore migrated into the bank from the silt flats to the east. The dead Macoma shells in the new bank are probably all derived from this living fauna. Thus the age of the older members of a fauna living in a sediment cannot be used as an indication of the age of the particular sediment in which the animals are living.

The Mya arenaria individual in Station 1 was 9 mms in length and probably belonged to the early summer 1963 0-Group. Nereis diversicolor and Corophium volutator were also found in the new bank.

At Locality 8 on the edge of the upper mud flat a deep gully was formed by the enlargement of the valley of a small channel by a waterfall (Plate 48b). The 'fall-maker' was a resistant zone of organic debris. As this receded large blocks of sediment were removed and the resulting gully was three to four times as deep as the original valley. Between 15th September 1962 and 3rd April 1964 the waterfall had cut back a distance of 23 metres. After the Carse Gut changed its course in late March 1964 the channel no longer drained directly into the Carse Gut and the gully began to silt up. By September 1964 it was almost completely filled leaving only a small, shallow valley. Thus any change in the course of a major ebb channel has a considerable effect on the development of its tributaries.

MIGRATIONS OF THE RIVER NITH CHANNEL

Most of the information about the position of the Nith Channel in historical times is derived from early maps, documents and charts. In more recent years Ordnance Survey maps and air photographs can be used. Most of the evidence prior to the first Ordnance Survey maps must be interpreted with caution as little attention was paid to the detailed geography of the intertidal zone. In all cases, however, the precise position of low water mark is not of great significance as it is dependent on the state of the tide and wind directions at the time of surveying or photographing the flats (See p. 14). The earliest reliable map is that made by General Roy in 1774 (Fig. 53) showing the channel across at the Caerlaverock shore. Mackenzie in his Navigational

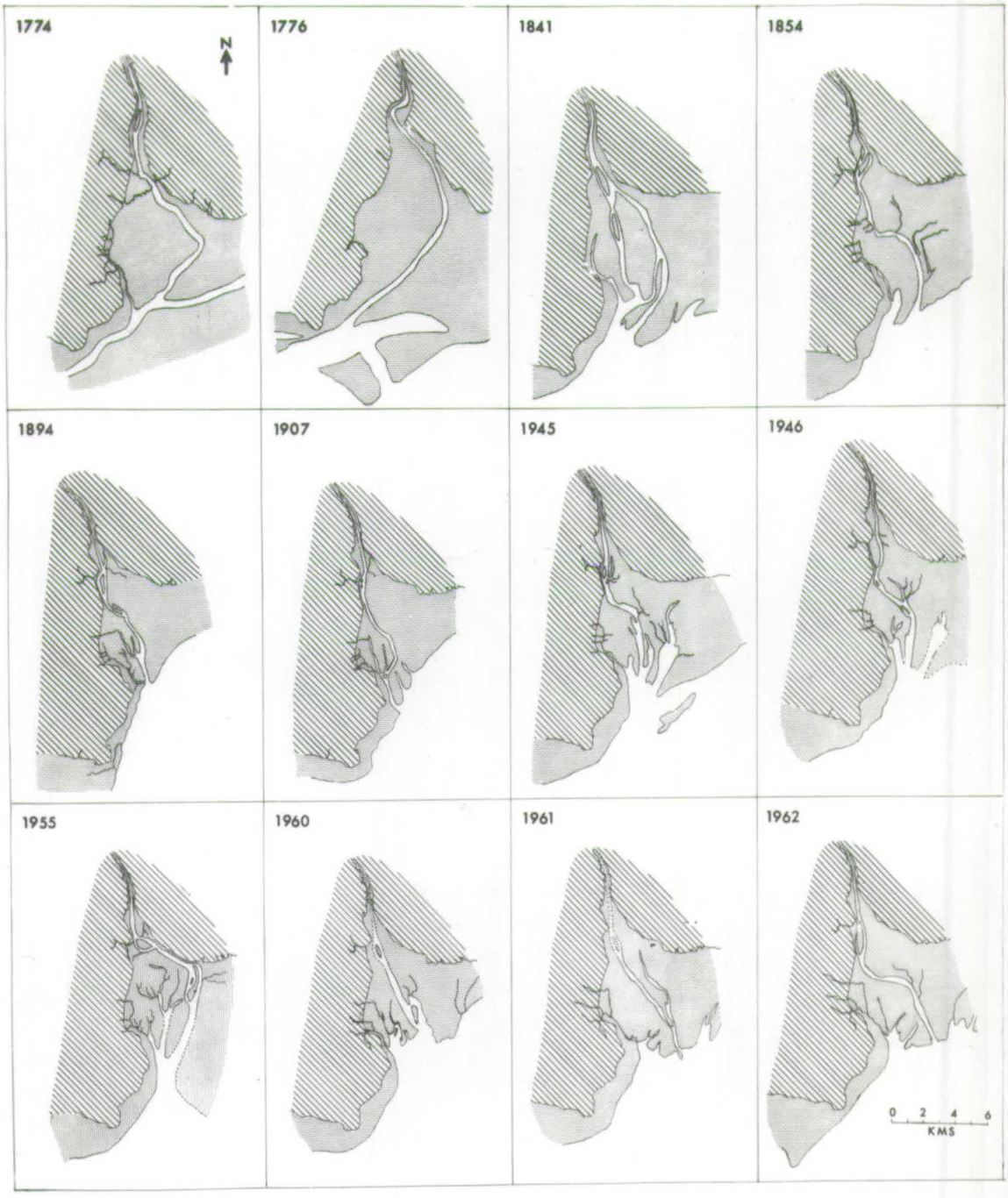

1774
N
1776
1841
1854
1894
1907
1945
1946
1955
1960
1961
1962
0 2 4 6
KMS

Chart of the Solway published in 1776 indicated a similar position (Fig. 53). The first Admiralty Chart of the Nith Channel was made in 1841 (Fig. 53)*. The detailed maps for 1854, 1894 and 1907 (Fig. 53) are based on the six-inch surveys and revisions of Dumfriesshire and Kirkcudbrightshire made by the Ordnance Survey in 1854-1856, 1894, 1898 and 1907-1908. The second edition of the Admiralty Chart (number 1346) published in 1890 gives a generalised position for the Nith Channel and no attempt was made to make a precise chart of the channel. All subsequent editions of the Admiralty Charts indicate this same general position and cannot therefore be used to make accurate maps. The maps for 1945, 1946 and 1955 (Fig. 53) are taken from air photographs and the maps for 1960, 1961 and 1962 (Fig. 53) are based on information kindly supplied by the Health and Safety Dept., U.K.A.E.A. Chapelcross Works, Annan.

The maps for consecutive years (1945-1946 and 1960-1961-1962) show that the course of the Nith Channel changes from year to year and that other ebb channels present one year may have disappeared by the next. It is therefore probable that in the years not covered by maps or air photographs frequent large-scale migrations of the channel took place, and that the Carse Sands are reworked every few years. The activities of the Nith Navigation Commission and Messrs. D. & T. Stevenson, the Edinburgh engineers, in confining the flow of the River Nith north of Glencaple by the construction of rubble walls in 1861, stabilised the course to a

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*This drawing is taken with permission from Marshall (1961) as the original chart is in manuscript form.

certain extent and reduced the degree of migration. By 1920, however, the rubble walls had fallen into disrepair and the flow was no longer confined. A summary of the work of the Nith Navigation Commission is given by Marshall (1961).

An indication of the rate at which the channel can migrate is given by the transect profile studies. Between September 1962 and March 1963 the west bank of the Nith at the end of Transect 1 migrated 579 metres to the west. In the Nith Navigation Commission minutes quoted by Marshall (1961) a wreck in the channel exposed in October 1894 was covered by November 1894, exposed again in August 1899 and covered by October 1899. Thus the sands east of Channel G are reworked at frequent intervals. The living faunal and dead shell densities in this area are low, however, and shell-beds are unlikely to be formed in spite of the frequent reworking.

Any migrations of the Nith Channel westwards towards Carsethorn would have a considerable effect on the configuration of the mud flats and would rework the sediments in the areas of high living and dead shell densities.

The following account is based on personal communications from Mr. J. Robson, Carsethorn, Mr. A.E. Truckell, Dumfries, and Mr. J. Wilson and Mr. T. Willacy, both of Annan. In the late 1890s and 1900 the Nith Channel was only 800 metres offshore opposite Carsethorn village and 400 metres offshore opposite South Carse Farm. In 1927 the channel started to migrate westwards once again and by 1928 it flowed past Carsethorn village at the foot of the beach. The Carse Gut flowed directly into the channel

north of the village. The west bank of the channel opposite the village was a vertical cliff 6 metres in height and the floor of the channel was almost down to rock. In places rock outcrops could be seen and colonies of Mytilus edulis developed on these. By 1932 - 1933 the channel had started to migrate eastwards again reworking all the sediments of the mud and sand flats. The Carse Gut flowed past the village along the channel abandoned by the River Nith, thus preventing rapid silting. The Mytilus population kept pace with the gradual sedimentation on the floor for about five years after which it was killed off.

Between 1950 and 1951 the Nith Channel was close inshore opposite South Carse Farm and about this time the Carse Gut changed its course to more or less that of the present time. This change of course was responsible for killing (probably by salinity reduction) and exposing the Mya arenaria population at Locality 11.

Most of the sediment forming the upper mud flats and the sediments east of the Carse Gut must therefore have been deposited by lateral sedimentation as the Nith Channel reworked its way across the Carse Sands in 1933. The sediments east of the Carse Gut south of the line of Transect 2 were reworked again in 1950 and 1951. The absence of burrowing structures at depths greater than 30 cms below the present surface indicates that sedimentation was rapid until equilibrium had been reached (See. Chap. 2). The present configuration of the upper mud flats and the parts of the area east of the Carse Gut unaffected by the 1951 migration therefore date from 1933. The sediments of the lower mud flat and the rest of the Carse Sands date from 1951. The areas

reworked by the 1951 migration of the Nith Channel were recolonised by spatfalls in the mid 1950's although some faunal migration from adjacent unaffected areas possibly took place. Reworking of the flats during the past 10 - 30 years by shallow migrating tributaries and storms has redistributed the dead shells and valves from faunas living in the top 20 to 30 cms of the sediment to give the distribution discussed in Chapter 4.

The existence of a rock floor to the channel at a depth of 6 metres below the foot of the present beach gives an indication of the thickness of the sediments forming the mud flats. In August 1963 a rock "scar" was exposed on the floor of the Nith Channel at the end of Transect 1. It is possible therefore that over most of the Carse Sands the sediments are only 6 - 9 metres thick. Any migration of the Nith Channel therefore probably reworks most of the recent sediments in the area.

CHAPTER 6

SHELL - BEDS

The living molluscs, and dead shells and valves reworked from the sand and mud flats may become concentrated into shell-beds in other parts of the area. Some shells and valves may be carried into the deeper parts of the estuary by strong ebb currents while others from the deeper water may be transported on to the tidal flats by flood currents.

Two distinct types of shell concentrations can be recognised in the area namely shell accumulations on the surface of the sand flats and accumulations on channel floors. The concentrations of shells at the foot of the beach and on strand lines are not of importance except in the case of Hydrobia ulvae discussed in Chapter 3.

ACCUMULATIONS ON SAND FLATS

These surface shell-beds are formed by tidal currents which concentrate the shells into particular areas on the sand flats (Plate 49a). The ebb and flood current systems create small scale 'gyres' and shells and valves are reworked and concentrated from large areas of the flats. The greatest concentration is in the centre of the 'gyre' and the density decreases towards the edge of the shell-bed. The boundaries are generally imprecise as the shells on the perimeter of the bed are in the process of being concentrated towards the centre and being replaced by others from further out. Surface shell-beds formed in this way are

normally only 1 to 3 cms thick, and the thickness is uniform over most of its area. As the tidal currents responsible for the formation of this type of shell-bed only rework the sediments to a depth of 2 to 5 cms only living animals and shells and valves in layers 1 and 2 will be concentrated in this way. The shells derived from living animals likely to be found in this type of shell-bed therefore include Hydrobia ulvae, Retusa obtusa, Cardium edule, and young Macoma balthica up to about 15 mms in length, and 0-Group Mya arenaria. Larger Macoma and the occasional Scrobicularia plana may be present if individuals moving at the surface were reworked by the current. Adult Mya and Scrobicularia (other than those moving at the surface) would not be affected by this surface reworking and would therefore be absent from the shell-bed. As most of the Cardium population lives in layers 1 and 2, reworking of the top layers may concentrate almost all the living cockles from a particular area into a surface shell-bed. Macoma also has high densities in layers 1 and 2 but these are generally younger shells. The adults tend to be found in layers 3 and 4 (See Figs. 15 - 17 and 24).

If only shells from living fauna were concentrated in this way the composition of the shell-bed would be sufficiently precise to enable it to be recognised in 'fossil' sand flats. In addition to the living fauna, however, dead shells and valves of Cardium and Macoma are involved in the reworking. The size-frequency characteristics of these are similar to the living fauna over most of the area (See Chap. 4). They would not

therefore markedly affect the overall composition of a shell-bed formed from the living fauna although they may alter the relative proportions of particular species. Mya and Scrobicularia valves are rare in the top two layers and are therefore unlikely to be found in surface shell-beds. Mytilus valves are largely restricted to the upper mud flats south of Carsethorn and therefore would only rarely be found in surface shell-beds on the Carse Sands.

Surface shell-beds do not normally form on mud flats. Reworking of the top 2 to 5 cms of the mud flats by tidal currents is reduced to a minimum by the presence of organic matter binding the sediment.

East of Channel G the densities of living Cardium and Macoma, and Cardium valves are not great enough for the surface reworking processes to produce any appreciable concentration and therefore surface shell-beds do not form. In the area between the Carse Gut and Channel G, however, the densities of living Macoma and Cardium, and to a lesser extent Cardium and Macoma valves are much greater and surface shell-beds, such as the one associated with Station 2/4, do form.

Surface shell-beds therefore do not appear to form in areas where the living lamellibranch and dead shell densities are less than 5 to 8 per 1/10th square metre on average in each layer for each species, or in areas where the sediments contain a high proportion of binding organic detritus.

Shell-beds of this type may form rapidly as a result of storm activity, or they may accumulate slowly over periods of several

months. They are rarely preserved, however, as the rate of vertical sedimentation on the Carse Sands is not great enough to ensure the burial of the shell-bed before that particular part of the sand flat is reworked by a migrating channel.

ACCUMULATIONS ON CHANNEL FLOORS

During the lateral migration of a channel all the living fauna and dead shells and valves contained in the sediment of the receding bank are reworked down to the depth of the channel floor. The shells and valves are generally carried some distance downstream by the current into an area of slacker water out of the main stream of the channel. As the channel migrates, shells and valves from large areas of the flats at all depths above the base level of erosion (the floor of the channel) become concentrated in this part of the channel floor and a shell-bed is developed. Some sorting of the shells according to size and shape takes place during transportation to the site deposition and small shells such as early 0-Group lamellibranchs may be carried downstream beyond the site of deposition of the larger shells.

The degree of concentration of the shells, and the thickness and lateral extent of the shell-bed depends on the rate of migration of the channel. Rapid migration during storms (see pp.131-134) does not result in the formation of a shell-bed since current strengths are such that much of the fauna is transported far downstream and little or no concentration takes place. The most favourable rate of migration both in terms of rate of erosion of the receding bank and of deposition on the prograding bank for the

formation of channel-floor shell-beds is that typified by the development of the meander in the Carse Gut (see pp. 135-140) as sufficient time is available for the concentration of the fauna reworked from the receding bank. Channel-floor shell-beds are also formed during the large scale migrations of the Nith Channel provided the rate of migration is comparable with that of the Carse Gut meander.

The faunal composition of the resulting shell-bed partly depends on the depth of the migrating channel. In the case of a shallow channel with the floor at a depth of 10 cms, all the living fauna and dead shells and valves in layers 1 to 4 are reworked. The living fauna therefore includes Hydrobia, Retusa, all the living cockles, most of the living Macoma (living Macoma is only rarely found in layer 5) and the shallower Scrobicularia individuals. The deeper ones and adult Mya shells are largely unaffected.

A migrating channel with the floor at depths of between 30 and 40 cms below the level of the flats reworks all the living fauna and the associated shells and valves. The depth of the floor of the channel down to depths of 30 cms therefore determines the composition of the shell-bed formed from the living fauna. Thus ideally a shell-bed containing only Macoma and Cardium would be formed by a channel reworking the top 8 cms of the sediment, but if Scrobicularia was also present the channel would have reworked sediment down to 20 cms, and if Mya was present the depth of reworking would exceed 20 cms (See Fig. 25). This pattern is complicated, however, by the presence of rare Mya and Scrobicularia

valves in the sediment at shallower depths than the living population.

East of Channel G, although lateral migrations of transient ebb channels are not infrequent, the living faunal and dead shell and valve densities are not great enough for any concentration of shells to take place on the channel floors. The rate of lateral migration of channels east of Channel H would probably be too great to allow time for shell concentrations to form even if the fauna was sufficiently abundant. West of Channel G, however, the densities of both living faunas and dead shells increase considerably and small isolated shell-beds occur on the floors of many of the minor channels and Channel C. There are local shell accumulations on parts of the floor of the Carse Gut. West of the Carse Gut, where the faunal and dead shell densities are very high, small shell-beds are not uncommon on the floors of many of the smaller shallow tributaries draining the mud flats (Plate 49b).

The composition of potential shell-beds will vary according to the shell material in the flats being reworked. Van Straaten (1956) recorded channel-floor shell-beds composed almost entirely of the valves of one species. In the case of an eastward migration of the Carse Gut towards Channel G the resultant shell-bed would contain Retusa and Hydrobia shells and shells and valves of Macoma, Cardium and Mya. If on the other hand, the migration was westward and the lower and upper mud flats were reworked the resultant shell-bed would contain Hydrobia shells, shells and valves of Macoma, Mya, Cardium and Scrobicularia, Mytilus valves, and barnacle plates. Thus the composition of

the shell-beds in these two cases would be quite different and the relative proportions of shells and valves of species common to both would also differ. The probable composition of a channel-floor shell-bed forming in a particular area can therefore be predicted by combining the information from the living faunal and dead shell and valve distribution maps.

Complications arise, however, when the migrating channel reworks a flat containing a buried shell-bed formed by a former channel reworking the same area (Plate 50). The shells and valves from the shell-bed undergo a second cycle of reworking and are mixed with shells, valves and living fauna being reworked for the first time. If the flat being reworked is covered by a surface shell-bed then these shells and valves also undergo a second cycle of reworking to become incorporated in the channel-floor shell-bed. In this case the proportion of such forms as Cardium and Macoma in the channel-floor shell-bed may be much greater than that predicted from the living faunal and dead shell distribution in the sand flat.

Care must also be taken in interpreting the relative proportions of complete shells and valves as this depends largely on the strength of the ligament and the structure of the hinge. As this is different for each species - and differs within the same species for shells of different ages - it cannot easily be used as an indication of the distance of transport for different species unless the relative strengths of the ligaments and the effects of transportation are accurately known for each species.

A special study was made of the composition of four different shell-beds in the area (Fig. 54a). These were:-

FIG. 54. SHELL-BED LOCATIONS AND SAMPLING SCHEMES.

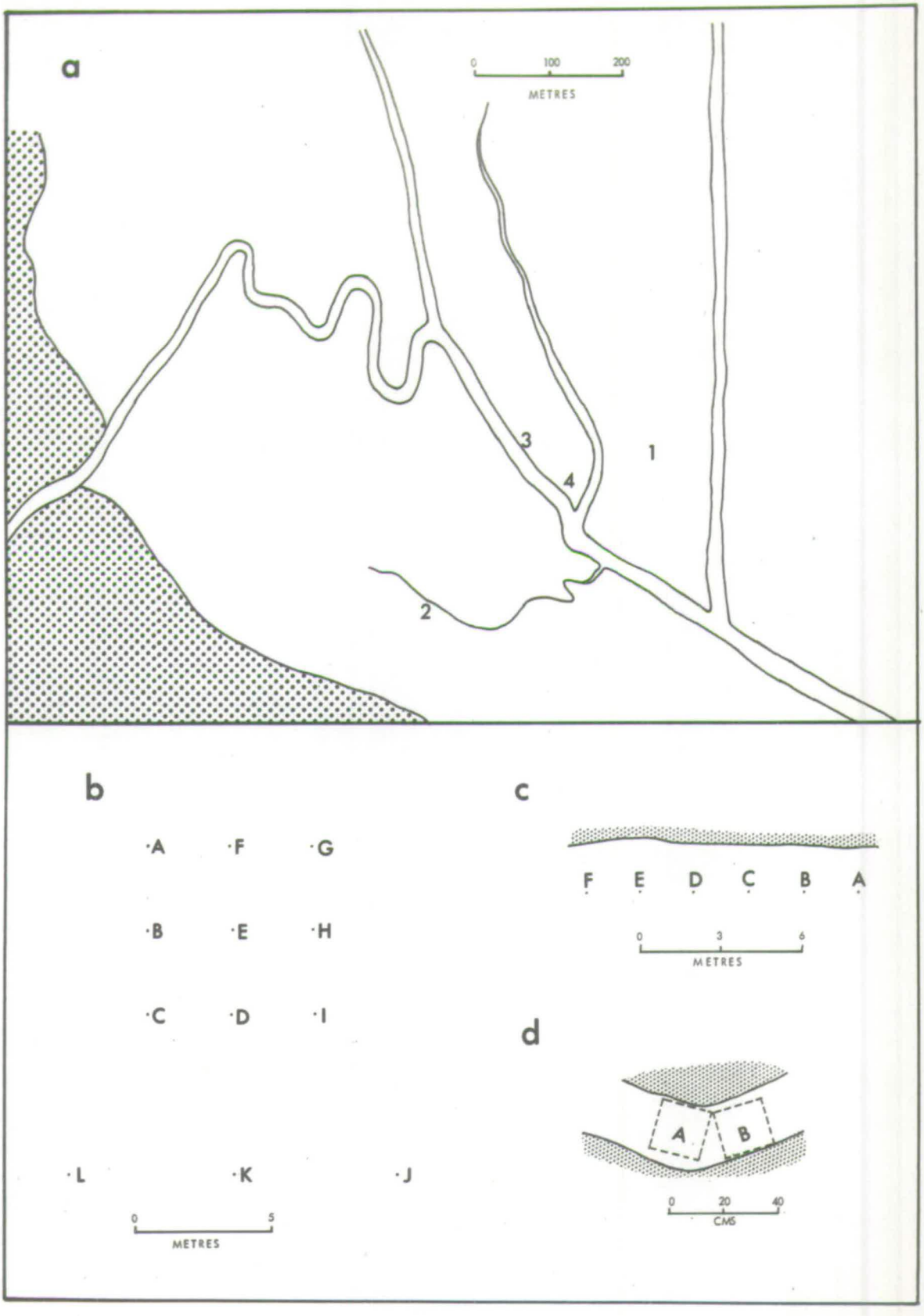
a. Location of Shell-beds

1. Surface shell-bed
2. Shallow channel-floor shell-bed.
3. Deep channel-floor shell-bed.
4. Buried shell-bed.

b. Sampling scheme for surface shell-bed.

c. Sampling scheme for deep channel-floor shell-bed.

d. Sampling scheme for shallow channel-floor shell-bed.


a
0 100 200
METRES
1
2
3
4
b
A F G
B E H
C D I
L K J
0 5
METRES
c
F E D C B A
0 3 6
METRES
d
A B
0 20 40
CMS

a) A surface shell-bed east of Channel B.

b) A channel-floor shell-bed in a shallow tributary on the upper mud flats.

c) A channel-floor shell-bed in the Carse Gut.

d) A buried shell-bed.

In a, c and d quantitative samples defining 1/20th square metre were collected (See Chap. 1) but it was only possible to collect samples of 1/25th of a square metre from b. In each case the complete shells and valves for each species were separated and the length of each was measured. Fragments were separated into species, counted, and the weight percentage of fragments was calculated as in the transect samples (See p. 110). Although there were differences in the numbers of left and right valves present in the shell-beds the size-frequency distributions of both valves were similar for each species and therefore only histograms for left valves are given.

THE LEFT-RIGHT-PHENOMENON

Lever (1958) in his investigations into the sorting of lamellibranch valves on sandy beaches on the Dutch North Sea coast found that right valves of Macoma were consistently more frequent than left valves, and that preliminary observations into Cardium edule suggested that left valves were generally more frequent than right valves. He suggested that the predominance of the right valve in Macoma was due to the fact that the right valve was consistently heavier and therefore stronger than the left valve and would be more likely to survive surf action.

The right and left valves from a number of Macoma complete shells from the Carse Sands were weighed and in all but one case the right valve was heavier than the left valve, although in all cases the difference in weight was less than 5% of the weight of the lighter valve. It is unlikely that this small difference in weight makes much difference to the relative strengths of the valves although it may have some slight effect on their hydrodynamic properties.

Lever compared the values of the ratio of the number of left valves / the number of right valves (the L/R ratio) for several intertidal lamellibranch species. The use of this ratio alone is however misleading as the sample must be large enough for any difference between the number of right and left valves to be statistically significant. In 50% of the cases quoted by Lever (1958 Table 5) the differences in the numbers of left and right valves are not statistically significant on the basis of the Chi Squared test. The values of the L/R ratio from a number of samples can only be compared when the differences in the numbers of left and right valves in each sample are statistically significant.

The differences in the numbers of right and left valves of Cardium and Macoma in most of the individual samples from the four shell-beds are not statistically significant, but in most samples there were more Cardium right valves than left valves and more Macoma left valves than right valves. The total numbers of Cardium and Macoma right and left valves for each shell-bed, together with the L/R ratio in those cases where the differences are significant are given below:-

Cardium	LV	RV	L/R	Significance Level
Surface Shell-Bed	1230	1390	0.88	1%
Carse Gut Shell-Bed	404	418	-	-
Buried Shell-Bed	6326	6576	0.96	5%
Macoma				
Surface Shell-Bed	356	340	-	-
Carse Gut Shell-Bed	116	102	-	-
Buried Shell-Bed	2094	1818	1.15	1%

Lever obtained values of 0.9 for the L/R ratio in Macoma and 1.3 in Cardium from two samples collected on sandy beaches in which the differences in the numbers of left and right valves are significant at the 1% level.

The ratios from the Carse Sands which are significant at the 1% level - 1.15 for Macoma in the buried shell-bed and 0.88 for Cardium in the surface shell-bed - indicate the opposite sorting effect to that obtained by Lever on the Dutch sandy beaches.

SURFACE SHELL-BED

This shell-bed was located 60 metres east of Locality 6 and covered an area of approximately 50 square metres. Twelve samples each of 1/20th square metre were collected to a depth of 1 cm according to the scheme shown in Fig. 54b. Samples A to I were taken in the central part of the shell-bed and samples J, K and L were collected towards the edge where the densities of valves and shells were lower.

The numbers of Cardium valves lying concave upwards were counted in six randomly selected areas each of 1/20th square metre in the central part of the shell-bed. On average, between 24 and 40% of the total number of Cardium valves were lying in the

'unstable' position, and nests of 3 or 4 valves, all concave upwards, were not uncommon. At each flood tide movement of valves takes place on the shell-bed as the majority of the valves are not in a stable position. Many of the valves lying convex upwards are turned over as the incoming tide covers the shell-bed. Air trapped under the valve at low tide increases the buoyancy and the edge of the valve lifts, the air is released, and the force of the escaping bubble turns the valve over.

The densities of shells and valves in the 12 samples given in Table 20 and the size-frequency distributions of shells and left valves are given in Fig. 55.

The composition of the shell-bed indicated by the 12 samples shows little areal variation. The densities of valves and shells in samples A to I are generally similar except in sample C where densities of Cardium and Macoma were considerably greater than the average (Table 20). The densities of Cardium and Macoma valves in samples J, K and L were much lower. Hydrobia shells, Cardium and Macoma valves and Macoma complete shells were present in all samples. Mya left valves were obtained from five samples but the highest number in any sample was 2. All the Mya valves were juvenile forms less than 20 mms in length. One Cardium complete shell 7 mms in length was obtained from sample F, and a disarticulated adult Scrobicularia shell 30 mms in length was found in sample D. The density of Hydrobia shells in samples 1 to 9 varied from 80 to 940 and in samples 10 to 12 from 170 to 560.

The main peak in the size-frequency distribution of Cardium

FIG. 55 SURFACE SHELL-BED SIZE-FREQUENCY DISTRIBUTIONS.

Number of shells and valves plotted against length.

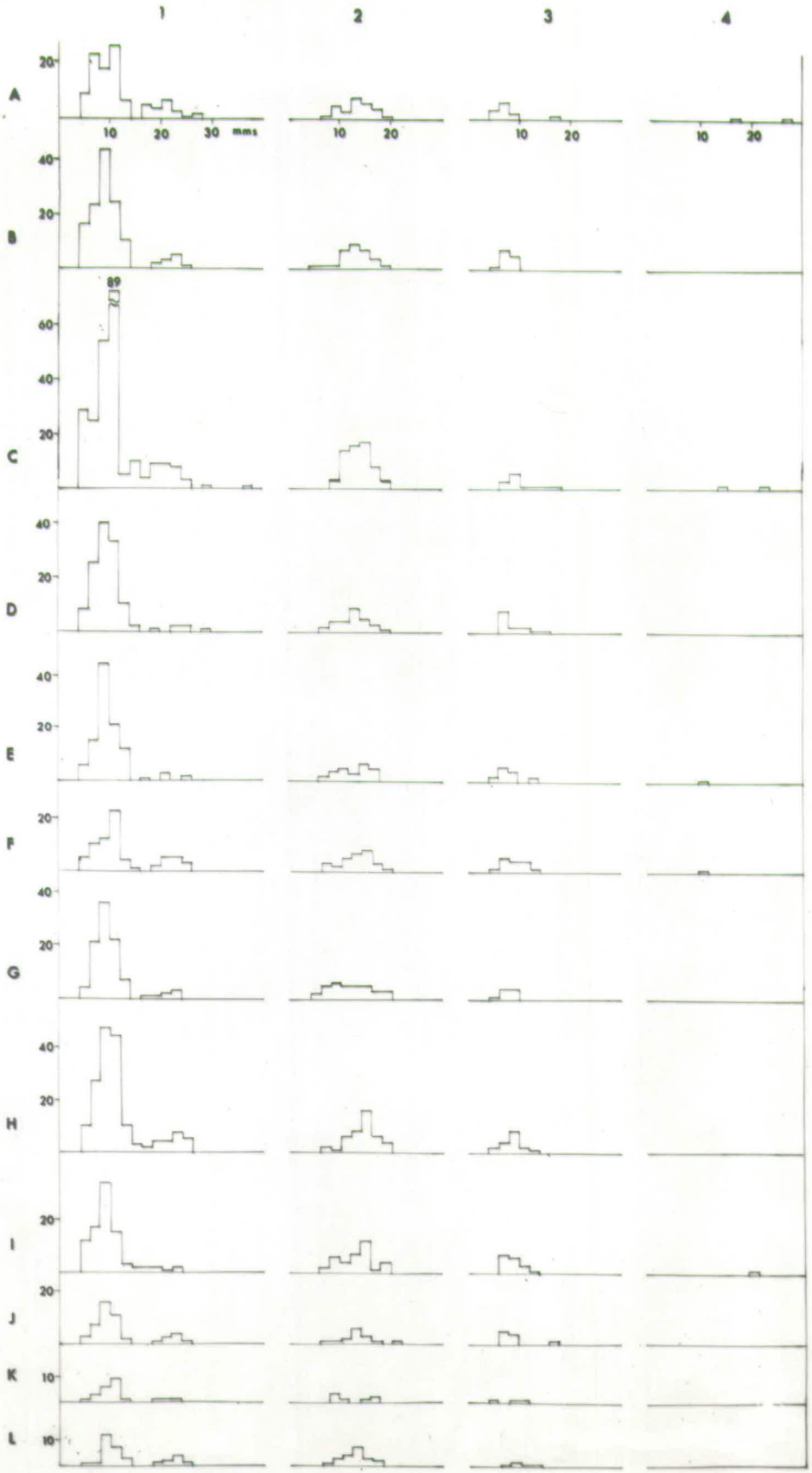
A - L .....Samples

1 ...*Cardium edule* left valves

2 ...*Macoma balthica* left valves

3 ...*Macoma balthica* complete shells

4 ...*Mya arenaria* left valves


1
2
3
4
A
B
C
D
E
F
G
H
I
J
K
L
20
40
60
89
10
20
30
mms
10

left valves (Fig. 55) lies between 9 and 12 mms but its actual position within this range varies slightly from sample to sample. The position of the peak therefore differs from that obtained from the transect samples of valves and from the living cockle population. It cannot be applied to a particular age group on the basis of the growth rates successfully applied to the transect samples, but probably includes large one-year-old valves 9 - 10 mms in length and small valves in their second year 11 - 12 mms in length. The initial division in a living population of the one and two-year-old shells into distinct peaks is therefore modified as a result of transportation and current sorting of the valves.

A second peak occurs in all the samples between 21 and 24 mms but it is very much flatter as there are fewer large valves present in the shell-bed. These larger valves range from 19 to 30 mms in length and are probably from two to three-year-old cockles. One valve 38 mms in length (five years old) was found in sample C. As living cockles greater than one-year-old are very rare in the Carse Sands, the majority of these valves must either have been transported into the area by flood tidal currents from other parts of the Solway or possibly they may be partly derived from more successful cockle populations which lived in the area in the past.

In almost all the size-frequency distributions of Cardium right and left valves from the surface shell-bed, the Carse Gut shell-bed and the buried shell-bed a distinct gap is present between 15 and 18 mms. This gap is in the same size range as

that which was preferentially removed in the experimental studies on the behaviour and transport of Cardium valves discussed in Chapter 7. It is probable therefore that this is a sorting phenomenon at the site of formation of the shell-bed and does not represent an absence of this size range among the valves initially transported into the shell-bed. A detailed discussion of the formation of this gap and its palaeoecological implications is given in Chapter 7.

The size-frequency distributions of Macoma valves from the surface shell-bed show that in most samples the majority of the valves are between 9 and 20 mms in length and a peak may be present in the 13 - 14 mm range. This peak lies between the probable growth lengths of valves from three and four-year-old individuals and indicates some degree of current sorting. The peak at 15 - 16 mms in samples H and I represents four to five-year-old valves. The majority of the valves could therefore be derived from the local Macoma population. Most of the Macoma complete shells are less than 10 mms in length and the peaks between 7 and 10 mms represent two-year-old shells largely derived from the area between Channels B and C.

The values of the weight percentage of fragments for each sample are given in Table 20. The average weight percentage of Cardium fragments was 40.1%. The majority of the smaller fragments were of the types described on p. 117 and many of the larger ones were the remains of shells attacked by oystercatchers. Macoma fragments were much less numerous, the average weight percentage being only 14.0%. Isolated Scrobicularia and

Mytilus fragments were obtained from several stations. Mya fragments were present in most stations but the maximum number recorded was 7. One Tellina tenuis fragment was found in sample H. The average total weight percentage (the sum of the weights of fragments of all species expressed as a percentage of the total weight of shells, valves and fragments of all species) in the surface shell-bed was 36.6%.

The actual composition of the shell-bed is similar to that which could be predicted from the study of the living faunal and dead shell distribution maps in Chapters 3 and 4 except that the concentration of Cardium valves is considerably greater than is suggested by the valve distribution data. A similar situation was described in the surface shell-bed at Station 2/4.

In the surface shell-bed therefore Cardium and Macoma are the dominant species and their size-frequency distributions indicate some degree of current sorting as the dominant peaks do not coincide with particular year classes. Up to 40% of the Cardium valves may be lying concave upwards. Valves from deep burrowers tend to be rare but high densities of surface forms such as Hydrobia are common. The fragment weight percentage of Cardium is greater than that of Macoma and Mytilus fragments are very rare.

SHALLOW CHANNEL-FLOOR SHELL-BED

This shell-bed was located on the floor of the channel 30 metres east of Station 1/1 on the upper mud flats. The channel was only 10 cms deep and 40 cms wide, and as the shell-bed just

covered an area of approximately 1,000 sq. cms only 2 samples, each of area 400 sq. cms, could be collected (Fig. 54d). The composition of the shell-bed is given in Table 21 and the size-frequency distribution of valves and shells is given in Fig. 56.

The shell-bed consisted largely of Macoma valves and shells and Scrobicularia valves; Cardium valves were rare. Mya valves less than 18 mms in length occurred in both samples, and one Mytilus right valve of 27 mms and one left valve of 17 mms were found in sample A. Almost all the valves were lying convex upwards.

The peaks in the distributions of Macoma left valves are between 13 - 14 mms and 15 - 16 mms and represent four and five-year-old individuals. The peaks for complete shells indicate derivation from one, two and four-year-old individuals. Many of the Scrobicularia valves were derived from living animals killed by predators while moving at the surface but a few were certainly from living animals reworked by the shallow channel. The weight percentage of Macoma fragments is much higher than that found in the surface shell-bed but the total weight percentage of fragments is lower. These weight percentages must be interpreted with caution, however, as the samples are so small. The overall composition of the shell-bed is similar to that which would be predicted for a channel reworking layers 1 to 4 on the upper mud flat in Carse Bay.

FIG. 56. SHALLOW CHANNEL-FLOOR SHELL-BED SIZE-FREQUENCY DISTRIBUTIONS.

Number of shells and valves plotted against length.

A - B .....Samples

1 ... *Cardium edule* left valves

2 ... *Macoma balthica* left valves

3 ... *Macoma balthica* complete shells

4 ... *Mytilus edulis* left valves

5 ... *Mya arenaria* left valves

6 ... *Scrobicularia plana* left valves

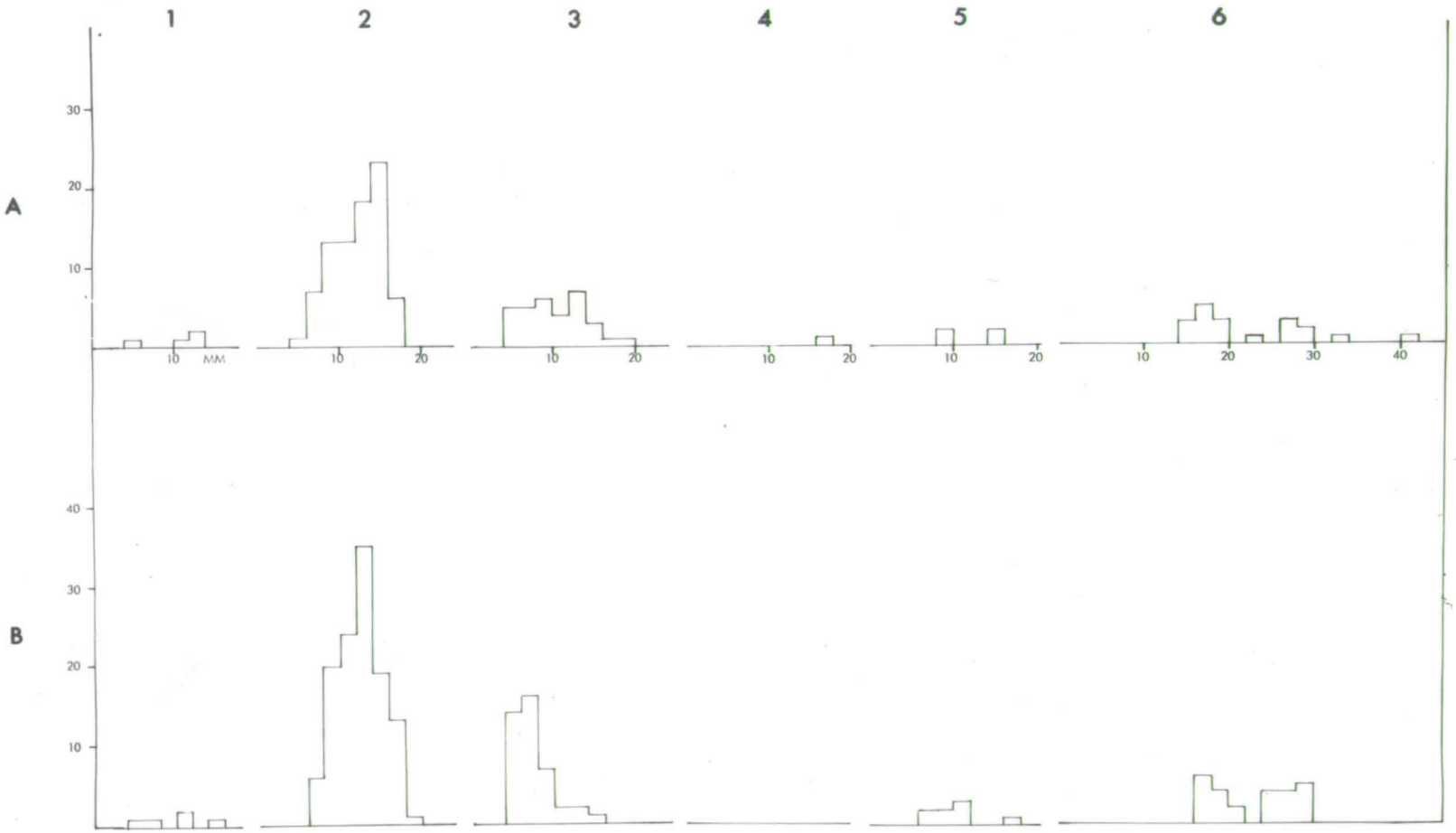


FIG. 56

DEEP CHANNEL-FLOOR SHELL-BED

It was not possible to collect quantitative samples from the shell-beds on the floors of many of the major ebb channels as they were permanently under water. The edge of the channel-floor shell-bed in the Carse Gut was exposed, however, in August 1963 near Station 1/5 and six samples, each of 1/20th square metre to a depth of 1 cm, were collected (Fig. 54c). The densities of shells and valves are given in Table 22 and the size-frequency distribution in Fig. 57.

Almost all the valves were lying convex upwards on the channel-floor. Cardium, Macoma and Mytilus valves were present in all samples, and Macoma complete shells were found in four samples. One Mya valve was obtained from each sample; left valves from samples A, C and E, and right valves from B, D and F. A Cardium complete shell 18 mms in length was obtained from Sample F. Although the numbers of Cardium and Macoma valves varied from sample to sample, the greatest fluctuation was seen in Mytilus where the numbers ranged from 2 in sample D to 46 in sample B with an average value of 20 per 1/20th square metre.

The size-frequency distributions of Cardium valves have peaks at 7 - 8 mms and 9 - 10 mms representing 0-Group valves, and at 11 - 12 mms representing valves from one-year-old cockles. The smaller peaks between 15 and 25 mms probably represent two to four-year-old cockles, and the largest valves present may be from cockles over five years of age. Some degree of current sorting has taken place but the presence of the prominent peak at 7 - 8 mms representing 0-Group valves and the irregular

FIG. 57. DEEP CHANNEL-FLOOR SHELL-BED SIZE-FREQUENCY DISTRIBUTIONS.

Number of shells and valves plotted against length.

A - F .....Samples

1 ...*Cardium edule* left valves

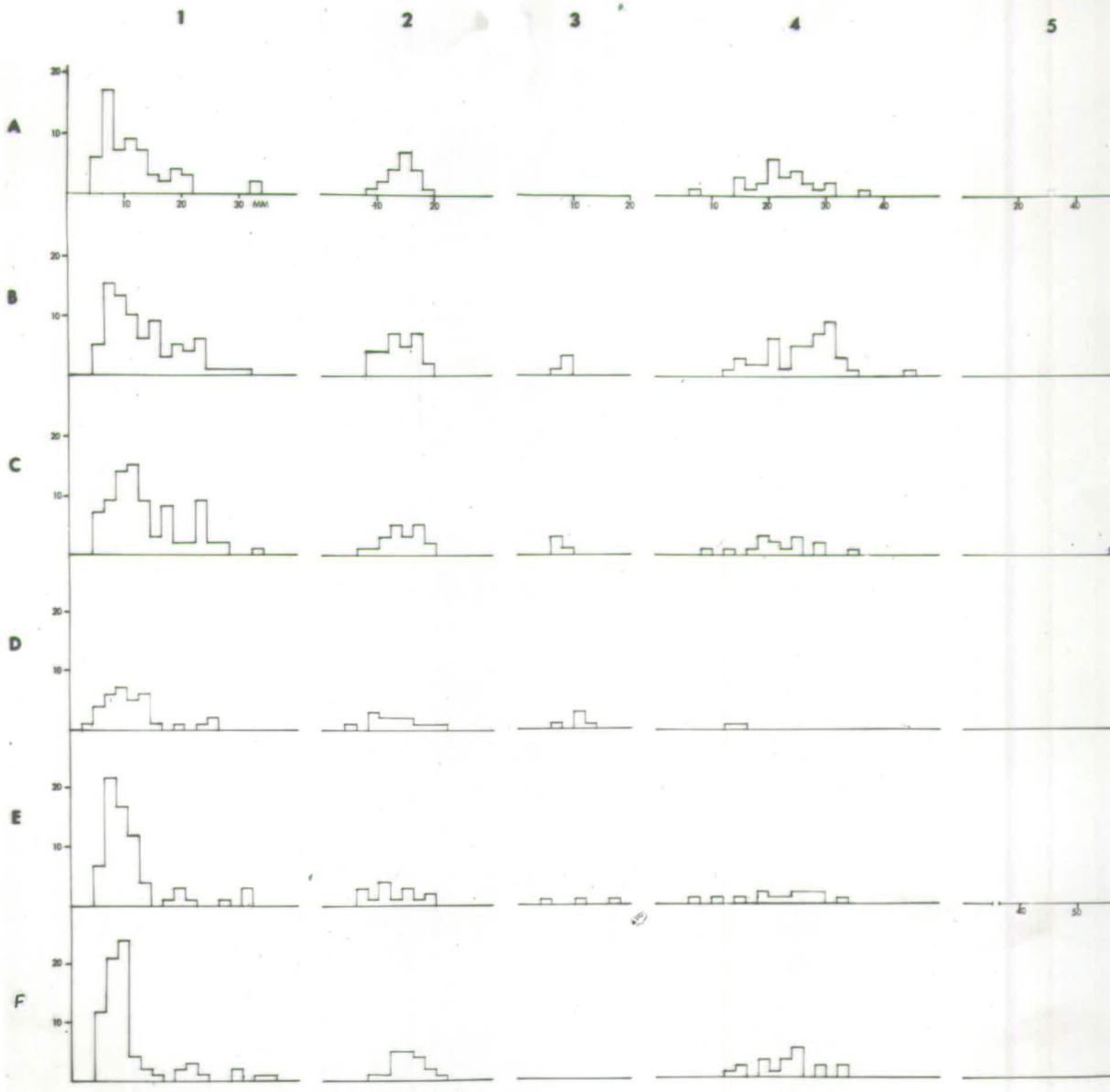
2 ... *Macoma balthica* left valves

3 ... *Macoma balthica* complete shells

4 ... *Mytilus edulis* left valves

5 ... *Mya arenaria* left valves

FIG. 57



polymodal nature of the histogram suggest that sorting is much less marked than in the surface shell-bed. As in the surface shell-bed, most of the valves have been transported into the Carse Sands from other parts of the Solway Firth.

Most of the Macoma valves are between 9 and 18 mms in length, and are probably from three to five-year-old individuals. There are several valves between 19 and 22 mms in length, and in sample B, two right valves of 31 mms and one left valve of 28 mms were found. These large valves are almost certainly derived from the deeper, more marine waters of the outer Solway Firth as estuarine individuals do not grow to these lengths (See p. 82). Thus, some of the Macoma valves have been transported into the area. The Macoma complete shells are from two, three and five-year-old individuals and are probably derived from the reworking of the flats east of the Carse Gut.

The size-frequency distributions of Mytilus valves are very irregular. The peaks at 21 - 22 mms and 31 - 32 mms probably represent one and two-year-old valves based on the growth rates obtained by Savage (1956). The larger valves are from three or four-year-old shells. Most of the valves are between 20 and 30 mms whereas in the transect samples the majority of the valves were less than 20 mms in length. The numbers of Mytilus right and left valves show no consistent trend. Many of these Mytilus valves must have been transported along the floor of the Carse Gut by flood tidal currents from outside the area although the irregular nature of the size-frequency distributions suggests that little current sorting has taken place. In many of the valves the

nacreous layer is slightly abraded along the posterior parts of the pallial line suggesting transportation although the margins of the valves are undamaged even in those valves with a distinctly prismatic calcitic layer. A number of the valves may be reworked from the outcrop of the buried shell-bed on the east bank of the Carse Gut.

Hydrobia shells were found in all samples, but the densities - which varied from 8 to 32 - were very much less than those from the surface shell-bed.

The average total weight percentage of fragments in the Carse Gut shell-bed - 38.6% - is very similar to that from the surface shell-bed, but the weight percentages for each species are quite different in most cases. The average weight percentage of Cardium fragments (24.4%) is just over half that obtained from the surface shell-bed whereas the average weight percentage of Macoma fragments (32.1%) from the Carse Gut shell-bed is more than twice that from the surface shell-bed. Mytilus fragments were abundant in all samples, the average weight percentage being 67.2%. Mya fragments were obtained from most samples but the maximum number was only 5, and one Scrobicularia fragment was obtained from each of three samples.

In the Carse Gut shell-bed therefore Cardium and Macoma are also the dominant species but unlike the surface shell-bed the year classes tend to be recognisable in the size-frequency distributions. Mytilus valves and valves from deep burrowers are present but Hydrobia is not common. Almost all the valves are lying convex upwards. The fragment weight percentage of Macoma is greater than that of Cardium and Mytilus fragments are abundant.

There are therefore significant differences in composition, size-frequency characteristics and fragment weight percentages between surface shell-beds and channel-floor shell-beds as typified by the examples described above.

BURIED SHELL-BED

In order to test the validity of these differences in interpreting the environment of formation of a 'fossil' shell-bed, a similar study was made into the buried shell-bed exposed on the east bank of the Carse Gut near the confluence of Channel B (Fig. 54a).

Fifteen samples were collected from a grid as shown in Fig. 58a. The actual co-ordinates for the position of each sample within the grid were obtained by using a table of random numbers. At each station the complete thickness of the shell-bed was removed. In samples I, K and M this was removed in 2 cm layers in order to investigate any variation of composition with depth within the shell-bed. The thickness of the bed, which varied from 1 to 15 cms, increased westwards (Fig. 58b). On the eastern edge where the shell-bed cropped out on the bank of the Carse Gut, secondary reworking had almost certainly taken place although the actual thickness of the shell-bed had probably not been reduced. Density data are given in Table 23 and size-frequency distributions are given in Figs. 59 - 61. As the samples are taken from a bed of variable thickness the actual densities and peak heights cannot be compared directly but this does not affect the trends indicated in the size-frequency distributions. Samples

FIG. 58. BURIED SHELL-BED SAMPLING SCHEME AND ISOPACH MAP.

a. Sampling scheme.

b. Isopach map.

(Shell-bed thickness data obtained from sampling stations and from additional observations.)

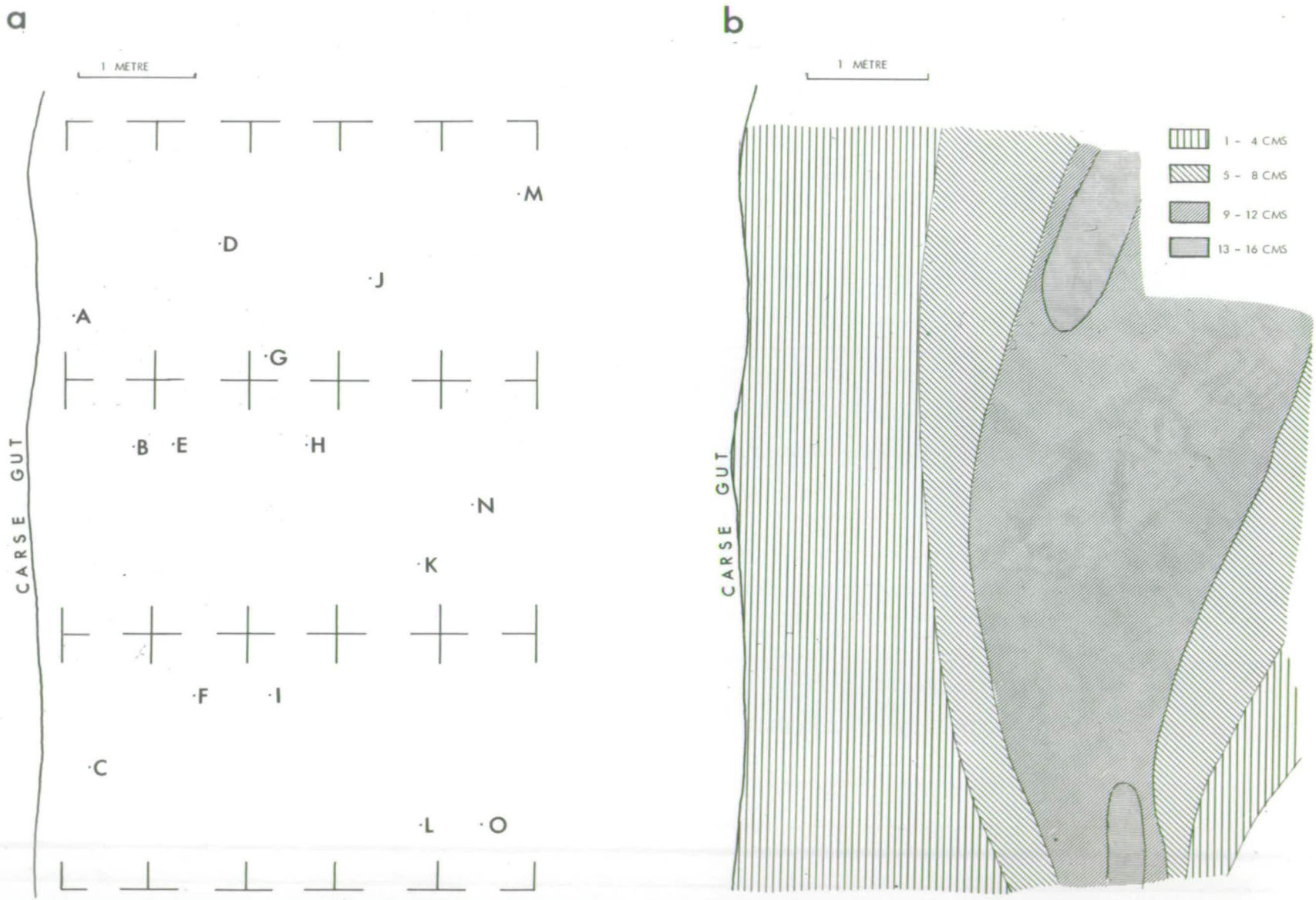

a
1 METRE
CARSE GUT
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
b
1 METRE
CARSE GUT
1 - 4 CMS
5 - 8 CMS
9 - 12 CMS
13 - 16 CMS

FIG. 58

FIG. 59. BURIED SHELL-BED SIZE-FREQUENCY DISTRIBUTIONS

Number of shells and valves plotted against length

A - H .....Samples

1 ....Cardium edule left valves

2 ....Macoma balthica left valves

3 ....Macoma balthica complete shells

4 ....Mytilus edulis left valves

5 ....Mya arenaria left valves

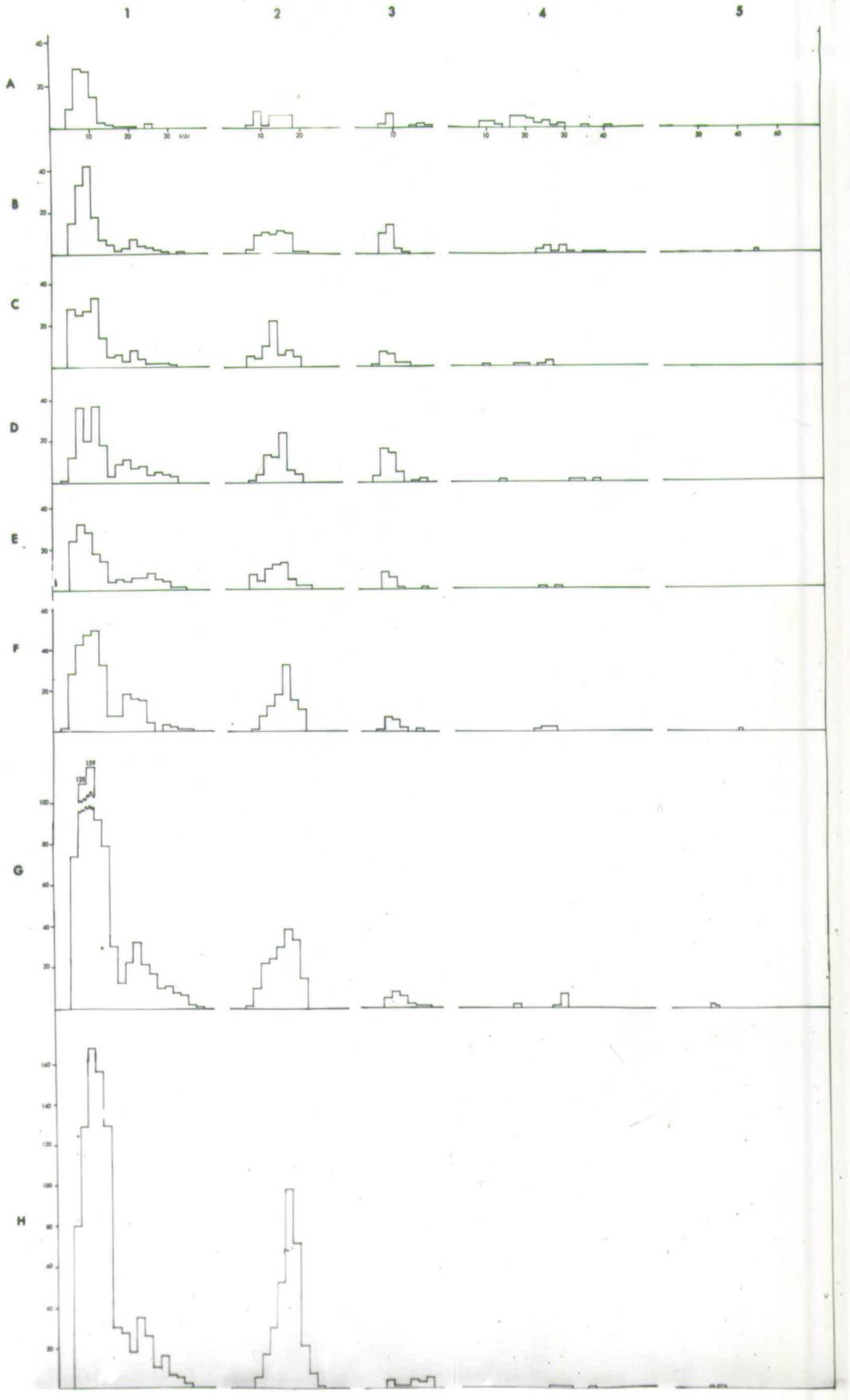

1
2
3
4
5
A
B
C
D
E
F
G
H

FIG. 60. BURIED SHELL-BED SIZE-FREQUENCY DISTRIBUTIONS

Number of shells and valves plotted against length

J, L, N, O .....Samples

1 .. *Cardium edule* left valves

2 .. *Macoma balthica* left valves

3 .. *Macoma balthica* complete shells

4 .. *Mytilus edulis* left valves

5 .. *Mya arenaria* left valves

FIG. 60

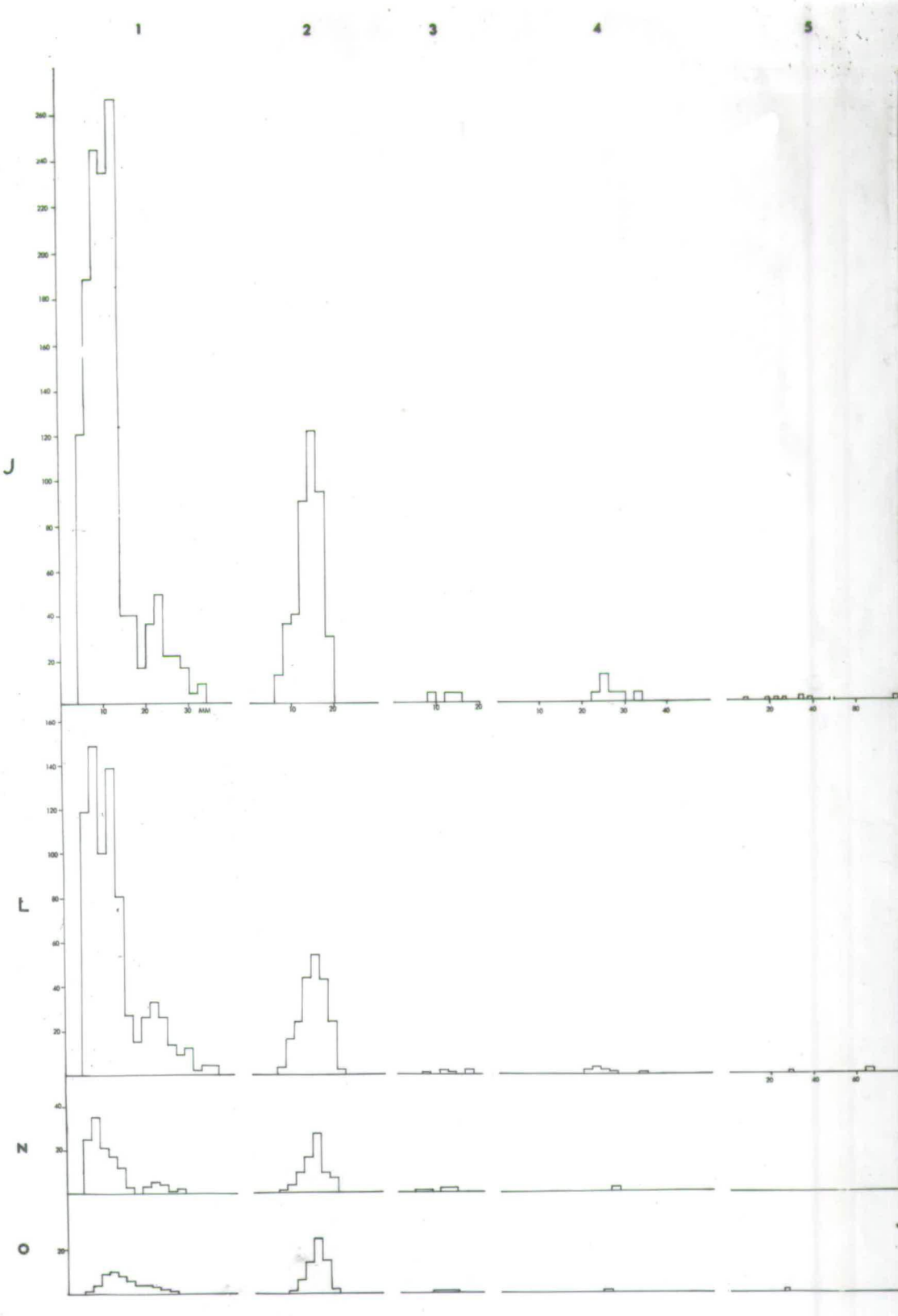


FIG. 61. BURIED SHELL-BED SIZE-FREQUENCY DISTRIBUTIONS.

Number of shells and valves plotted against length.

Total thickness of shell-bed removed in 2 cm layers.

Sample I.	I/1	Layer 1
	I/2	Layer 2
	I/3	Layer 3
	I/4	Layer 4
Sample K.	K/1	Layer 1
	K/2	Layer 2
	K/3	Layer 3
	K/4	Layer 4
	K/5	Layer 5
Sample M.	M/1	Layer 1
	M/2	Layer 2
	M/3	Layer 3
	M/4	Layer 4
	M/5	Layer 5

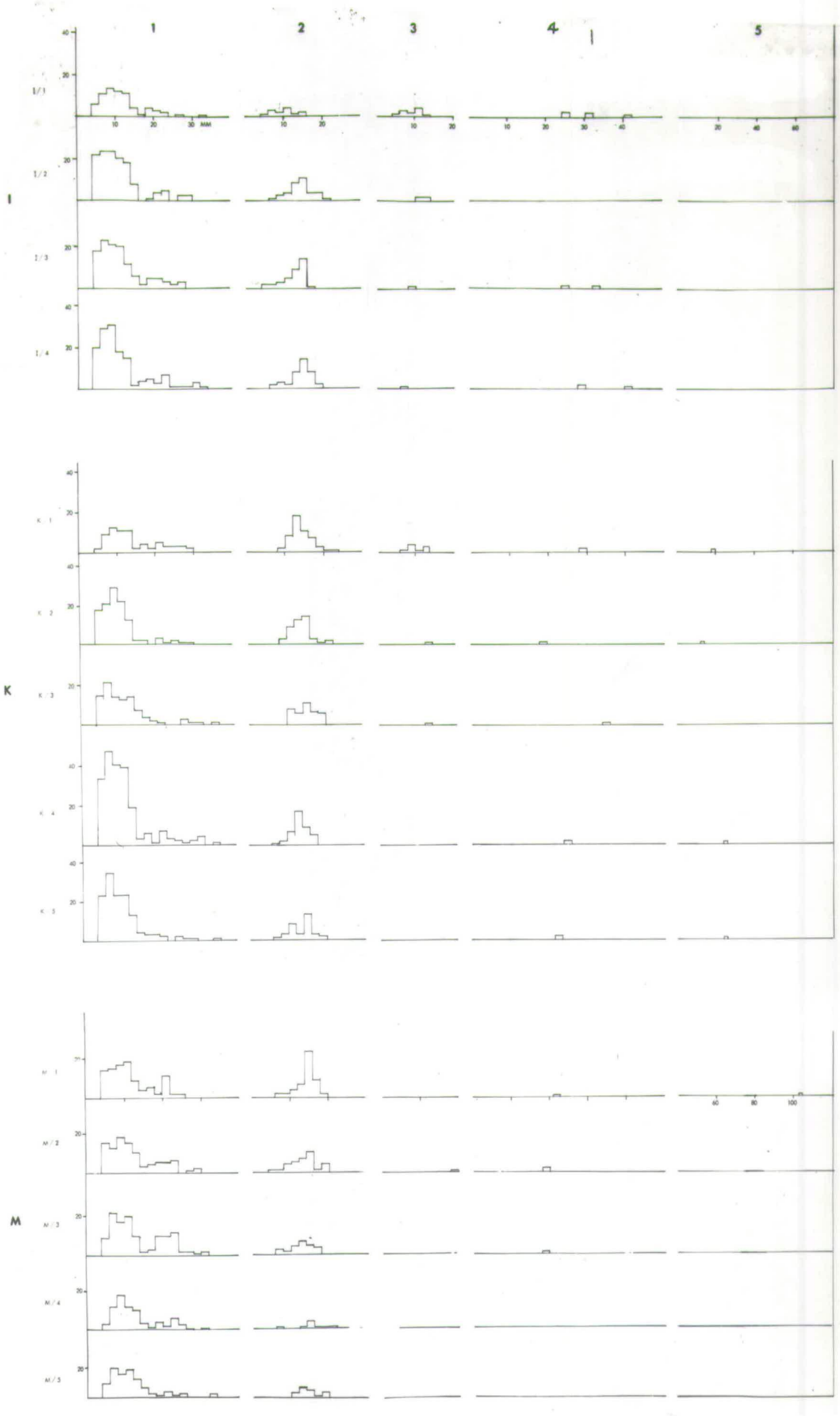
1.....Cardium edule left valves.

2.....Macoma balthica left valves.

3.....Macoma balthica complete shells.

4.....Mytilus edulis left valves.

5.....Mya arenaria left valves.


1
2
3
4
5
I
I/1
I/2
I/3
I/4
K
K. 1
K. 2
K. 3
K. 4
K. 5
M
M. 1
M/2
M/3
M/4
M/5

A, B, C, D, E and F are significantly different from the others in that both Macoma complete shells and Mytilus valves are relatively much more abundant.

The dominant peak in the distribution of Cardium valves is generally between 7 and 8 mms although in several cases the 9 - 10 mm peak may be as strong or even stronger. The overall range of sizes and the irregular nature of the distributions of valves greater than 12 mms are similar to those obtained from the Carse Gut channel-floor shell-bed. Cardium complete shells are rare.

The dominant peak in the distribution of Macoma valves is between 15 and 16 mms and probably includes four and five-year-old valves. The majority of the Macoma complete shells range from 7 to 10 mms and are two years old. A number of these were probably derived from individuals which were living in the sediment immediately above the shell-bed, and on death the shells became part of the shell-bed although they had never been reworked.

Mytilus valves were found in most samples although they were only numerous in samples A and B. Mya valves were present in most of the samples. These ranged up to 113 mms in length but most were between 20 and 40 mms. Scrobicularia valves were rare.

The average fragment weight percentages are closer to the valves obtained from the Carse Gut shell-bed than those of the surface shell-bed. In both the buried shell-bed and the Carse Gut shell-bed the fragment weight percentage of Macoma exceeds that of Cardium while the reverse is true in the surface shell-bed.

The numbers of Hydrobia shells (Table 23) are comparable with those from the surface shell-bed. Isolated Littorina littorea, Littorina saxatalis shells and Balanus plates were obtained from several samples, and 3 fragments of Echinocardium test, a Retusa shell and part of a Carcinus claw were also found.

The thickness of the bed, the presence of Mytilus and adult Mya valves, the general size-frequency characteristics and the fragment weight percentages suggest that the buried shell-bed was formed on the floor of a migrating channel. The abundance of Hydrobia shells and comparatively high density of Macoma complete shells in several samples suggest that material from a former surface shell-bed may have been reworked by the migrating channel and redeposited on the channel floor.

The three samples I, K and M which were removed in 2 cm layers (Fig. 61) show that there is little consistent variation in density and size-frequency characteristics with depth within the shell-bed. In samples K and I there is a general trend to increasing density of both Cardium and Macoma valves with depth, but the reverse is seen in sample M. The highest number of Macoma complete shells in K and I were in the top layer (K/1 and I/1).

The preferential concentration of Cardium valves is seen in all samples but is perhaps most dramatically displayed in samples G, H. L and J.

ORIENTATION OF VALVES ON A CHANNEL FLOOR

In September 1962 the long-axis (= length) orientations of all the valves present in six randomly selected ¼ square metre areas on the floor of the Carse Gut flood channel were measured. Only data for Mya, Macoma and Cardium will be considered as there were insufficient Scrobicularia and Mytilus valves to be of significance. Orientation diagrams for right and left valves of Mya, Macoma and Cardium are given in Fig. 62. The direction of the ebb and flood currents in the flood channel were accurately known to be 320° (northwest-southeast) from observations and ripple orientations.

The most definite orientation parallel to the current was given by Mya left valves. The Mya right valves show a similar orientation although the lesser orientation of long-axis at 280° is almost as prominent. The Macoma left valves show no preferred orientation. The general picture given by the right valves is similar to that of the left valves although a very slight preferred orientation can be detected at 270°. The Cardium left valves indicate an orientation parallel to the current direction but with strong secondary directions at 280° and 0°. The Cardium right valves on the other hand indicate a preferred orientation at 0° with secondary directions parallel to the current and at 40°.

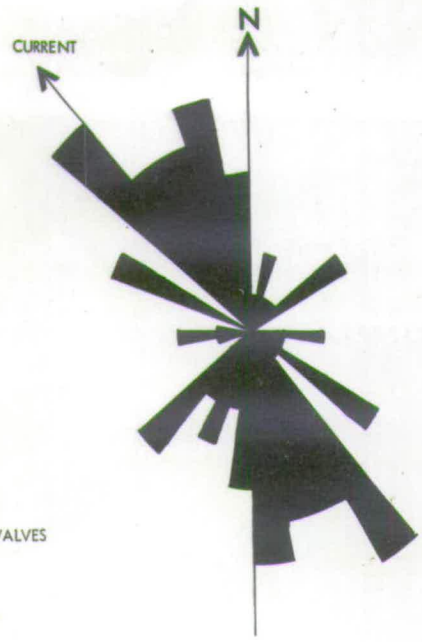
Thus only Mya left valves gave a definitive current direction. This may be due to the influence of the chondrophore. Mya right valves and Cardium left valves also indicate the current but they have strong secondary directions. Macoma valves gave

FIG. 62. ORIENTATION OF MYA ARENARIA, MACOMA BALTHICA AND CARDIUM EDULE LEFT AND RIGHT VALVES ON THE FLOOR OF THE CARSE GUT FLOOD CHANNEL.

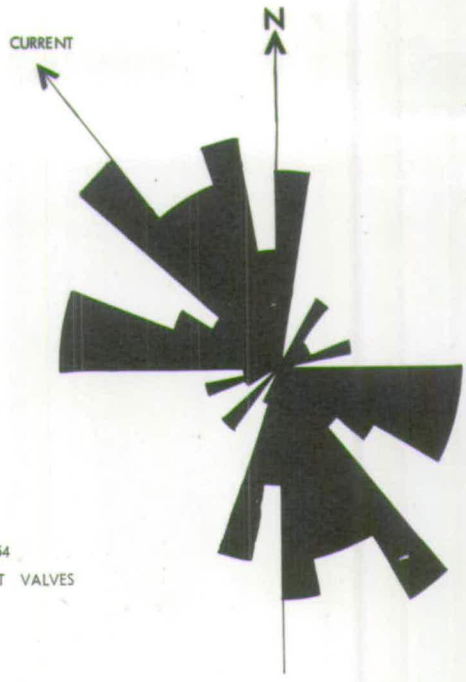
The orientation measures was that of the long axis (= length) of the valve.

Direction of flood and ebb current = 320°.

MYA



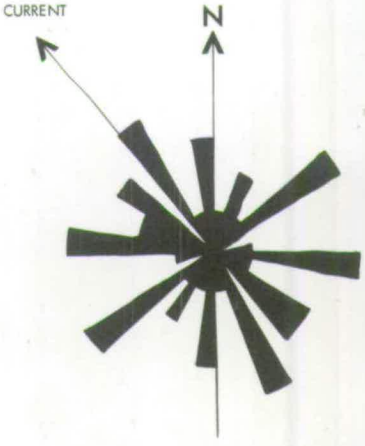
48
LEFT VALVES



54
RIGHT VALVES

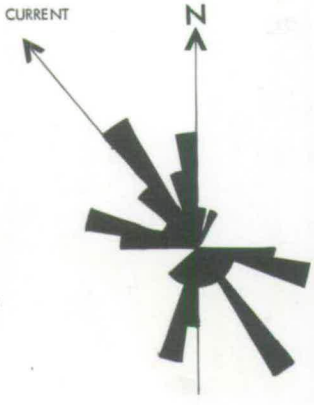
MACOMA

42
LEFT VALVES

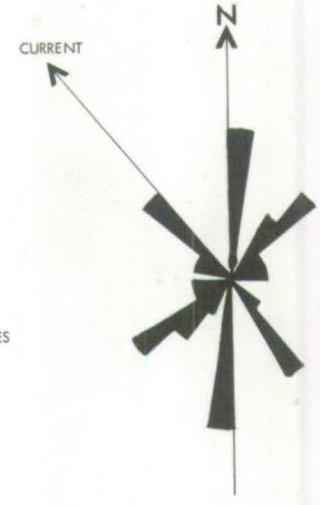


30
RIGHT VALVES

CARDIUM



26
LEFT VALVES



20
RIGHT VALVES

a completely erroneous picture of the current regime and Cardium right valves indicated a false current direction. These results indicate that palaeocurrent directions based on shell orientations alone must be treated with caution. Further work is required to determine the shell shapes most likely to be suitable for palaeocurrent determinations.

DISCUSSION

Since shell concentrations and shell-beds are much more common in the fossil record than in-situ molluscan faunas it is important to assess the accuracy of the composition of the living fauna presented by the shell-beds in terms of the known characteristics of the living fauna.

In the Carse Gut shell-bed, the surface shell-bed and buried shell-bed, the dominant species was Cardium edule. The size-frequency distributions of the Cardium valves indicate that the majority of the valves were from one to three-year-old cockles but that valves up to five years of age were present. The virtual absence of Cardium complete shells implies either that the shell became disarticulated during transport or the ligament was not sufficiently strong to hold the valves together. Thus although some degree of current sorting is indicated the composition suggests that Cardium was the dominant species in the area and that individual cockles lived for up to five years. The presence of Macoma complete shells implies a lesser degree of current sorting and/or a stronger ligament. The size-frequency characteristics of Macoma valves indicate a thriving population mostly about three

to four years of age, although several individuals up to five years of age were present. This picture is fairly similar to that indicated by the living populations of adult Macoma.

The shell-bed, however, implies that Macoma is much less common than Cardium although they both live successfully in the area. The living faunal studies indicate that Macoma is the dominant species in the Carse Sands and that Cardium is much less common, and individual cockles do not appear to be able to survive in the area for more than one year or so.

Small fragments can be transported much more easily than valves and therefore if the fragment weight percentage is high in a particular species in a shell-bed and the majority of the fragments are small it is probable that many of the fragments have been transported into the shell-bed from outside the area. These transported fragments may however merely supplement the fragments derived from the local population.

The presence of Mytilus edulis is indicated by the valves in the Carse Gut and buried shell-beds, but Mytilus is not known to have lived in the area since 1935. The high fragment weight percentage would, however, indicate that at least some of the valves could have been transported into the area. Scrobicularia valves are largely restricted to the shallow-channel shell-bed on the upper mud flat. In the other shell-beds only fragments transported from the upper mud flats are found.

The presence of a living population of Tellina tenuis in the Carse Sands would certainly not be indicated by the composition of the shell-beds.

The lamellibranch fauna of the Carse Sands and mud flats suggested by the shell-beds would be dominated by Cardium edule with Macoma balthica as the second most common species. Mytilus edulis would also be present together with Mya arenaria and Scrobicularia plana, but these species would not be particularly abundant.

The actual living fauna is dominated by M.balthica with C. edule and M. arenaria as other common species. S. plana is present in Carse Bay and T. tenuis occurs east of the Carse Gut in the more sandy sediments. The composition of the living molluscan fauna suggested by the shell-beds therefore differs from the actual living fauna in several important respects.

CHAPTER 7

EXPERIMENTAL STUDIES

In recent years a number of experimental studies have been made by Menard and Boucout (1951), Johnston (1957), Lever (1958), Kornicker and Armstrong (1959) and Lever et al (1961) on the movement and burial of shells and valves on beaches and in hydraulic flume tanks. Lever (1958) and Lever et al (1961) obtained important results by studying the movement of valves which had been stained different colours.

A series of experiments using dyed shells and valves of Cardium edule were carried out on the mud and sand flats in Carse Bay in August 1962 in order to study the effects of tidal currents at different localities.

The following ethyl alcohol soluble dyes were used giving six colours:-

Zapon Violet	Purple
Zapon Black	Black
Savinyl Yellow	Yellow
Savinyl Red	Red
Irisol Blue	Blue
Savinyl Yellow + Irisol Blue	Green

Each colour was used to dye an assemblage of valves. The complete shells were dyed using combinations of two colours, one for the umbo and the other for the ventral margin of the shell, so that any valves from shells which became disarticulated during the experiments could be detected.

Six identical populations, each of a different colour, were prepared consisting of the following shells and valves:-

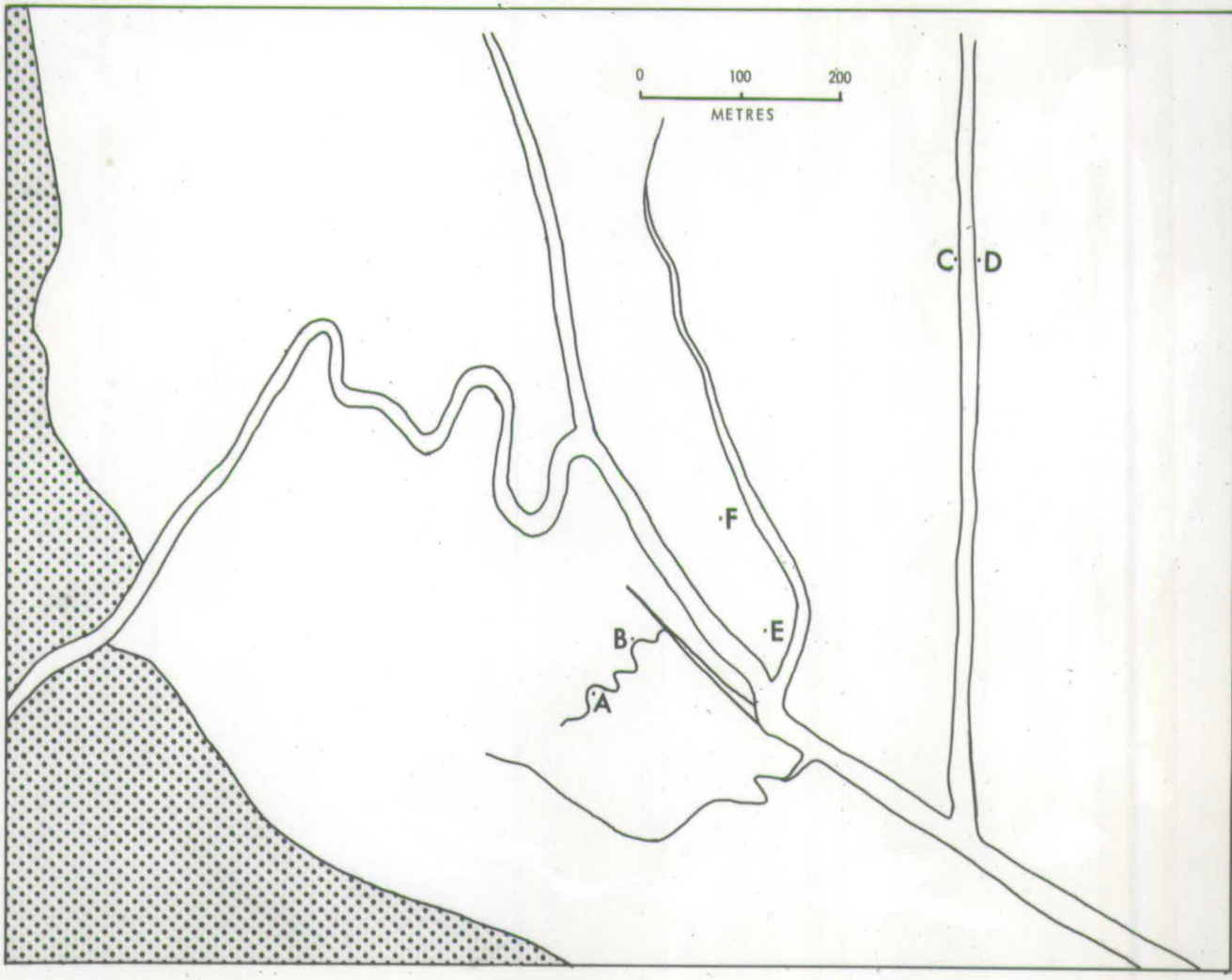
Valves	Size range in mms	Number
	10 - 14	100
	14 - 17	200
	17 - 23	148
	23 - 28	100
	28 - 32	24
	Greater than 32	3
Shells	23 - 32	50

These were laid at the six localities A, B, C, D, E and F shown on Fig. 63.

The experiments were carried out at a time when both periods of low tide occurred during daylight hours so that the populations could be studied and photographed after each high tide. The times of the low tides and the times of laying and lifting each population are given below:-

Date	Time of low tide	Tide Number	Remarks
15/8/62	6.22 p.m.	L 1 H 1	A and B laid
16/8/62	6.29 a.m.	L 2 H 2	C and D laid
	7.05 p.m.	L 3 H 3	E laid
17/8/62	7.10 a.m.	L 4 H 4	F laid
	7.47 p.m.	L 5 H 5	
18/8/62	7.54 a.m.	L 6 H 6	A, B, C, D lifted
	8.31 p.m.	L 7	E, F lifted

At localities A, B, C, D and E the valves and shells were laid down in rows according to the following scheme:-



LOCATION OF DYED SHELL AND VALVE EXPERIMENTAL POPULATIONS.

Row	Number	Size Range	Concave/Convex	Direction of Umbo
1	25	10 - 14	convex	up current
2	25	"	concave	"
3	25	"	convex	down current
4	25	"	concave	"
5	50	14 - 17	convex	up current
6	50	"	concave	"
7	50	"	convex	down current
8	50	"	concave	"
9	37	17 - 23	convex	up current
10	37	"	concave	"
11	37	"	convex	down current
12	37	"	concave	"
13	25	23 - 28	convex	up current
14	25	"	concave	"
15	25	"	convex	down current
16	25	"	concave	"
17	6	28 - 32	convex	up current
18	6	"	concave	"
19	6	"	convex	down current
20	6	"	concave	"
21	3	greater than 32	concave	up current
22	25	23 - 32	shells	up current
23	25	"	"	down current

At Locality F all the valves were laid convex upwards and in random positions.

Each population was laid in an area of approximately 1 square metre and the numbers of shells and valves which remained within the original area after each high tide were counted from photographs. In most cases there was a decrease in the number of valves after each high tide. This was partly due to the transport of valves out of the original area and partly to the burial of valves by scouring action within the original area. In certain cases valves which were rapidly buried were re-exposed after later tides and therefore the general trend towards a decrease in the number of valves was reversed at times. The numbers of valves lying concave upwards were also counted after each tide. These results are given below:-

Low tide

number	ss	vv	cve	ss	vv	cve	ss	vv	cve
		A			B			C	
L1	50	575	286	50	575	286	-	-	-
L2	3	335	18	3	293	16	50	575	286
L3	2	286	9	0	226	9	6	81	28
L4	0	207	10	0	206	11	3	31	10
L5	0	234	9	0	266	7	0	8	0
L6	0	213	12	0	239	13	no data		
L7	-	-	-	-	-	-	-	-	-
		D			E			F	
L1	-	-	-	-	-	-	-	-	-
L2	50	575	286	-	-	-	-	-	-
L3	2	95	11	50	575	286	-	-	-
L4	1	54	3	0	80	2	50	575	0
L5	0	22	2	0	58	4	0	201	31
L6	no data			no data		3	no data		29
L7	-	-	-	0	54	4	0	109	15

ss - complete shells
vv - valves
cve - concave valves

Observations could be made on the behaviour of the valves as the flood tide covered them at Stations A and B. Many of the valves lying convex upwards became buoyant, and as the air trapped below the valve was released, a number of them turned over. This probably accounts for the presence of 31 valves lying concave upwards after one high tide at Station F. A number of the smaller valves lying concave upwards floated on the incoming tide and were carried up to two metres before being swamped. Occasionally Mya valves were seen floating down the Carse Gut, and left valves experimentally floated were carried up to 20 metres even along turbulent stretches. Redistribution of valves lying concave upwards by flotation may be of some importance in quiet water areas such as mud flats or salt marshes.

At all six stations the major redistribution of valves took place during the first high tide after the assemblages were laid. The valves remaining within the original one square metre area, including those buried to a depth of 4 cms by scour action, were collected after five high tides at Stations A and B, four at Stations C, D and E, and three at Station F. In all cases the valve assemblages were more or less stable and would probably have been buried by scouring had they been left on the flats.

At Stations A, B, D, E and F a number of the apparently stable valves were lying concave upwards. It is probable, therefore, that in any stable shell-bed a small percentage of the valves may be lying concave upwards.

At each station a study was made of the directions in which shells and valves from the assemblages were transported.

Station A

The complete shells moved in two directions (Fig. 64a). Several were found at the foot of the mud slope near the mouth of the tributary. These shells had not been carried down the tributary, they were transported by the tide draining the upper mud flats. Several others were found on the mud slopes east-northeast (bearing 78^{o}) of Station A during L2 and L3. After L3, however, no trace of the complete shells could be found.

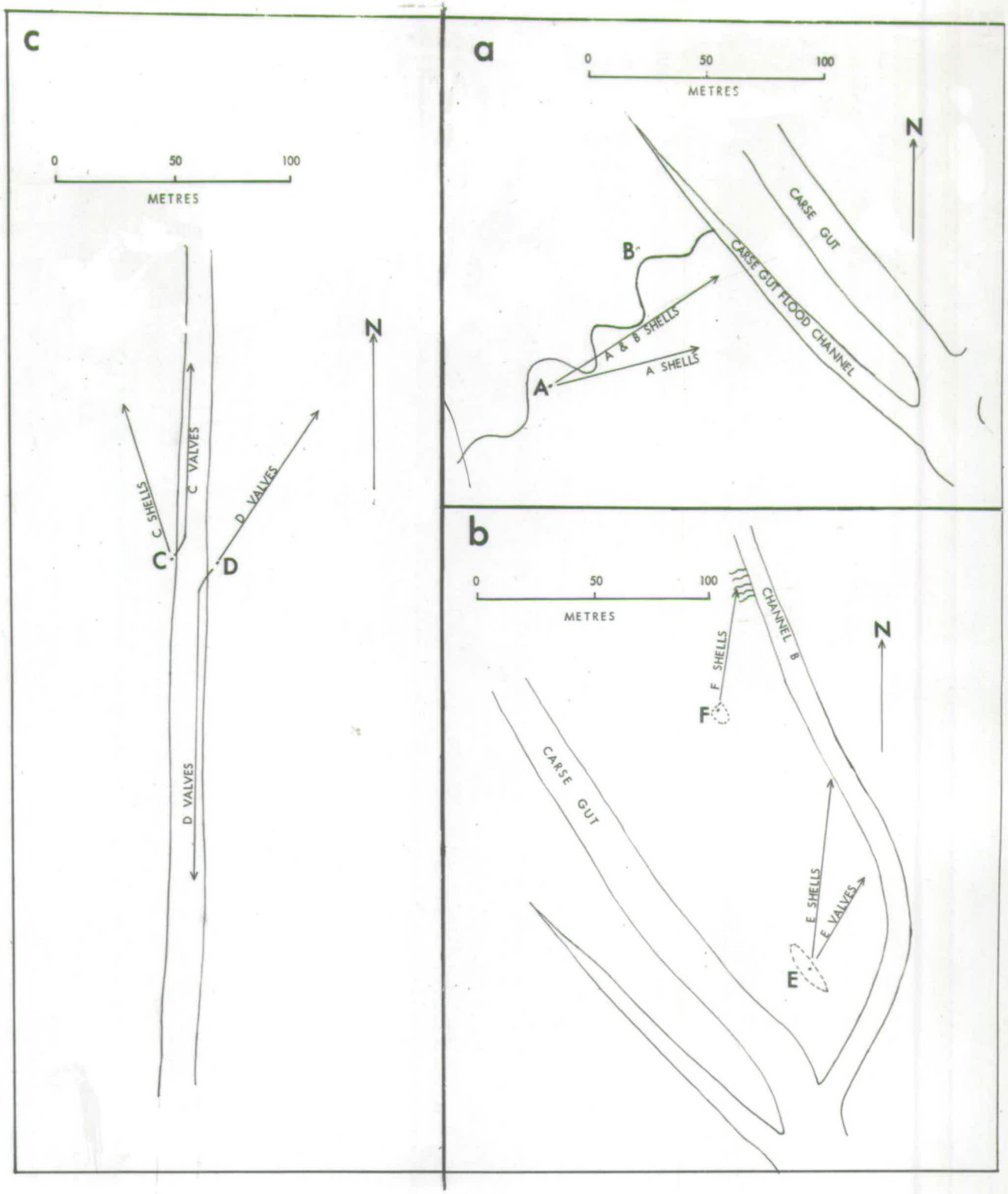
The valve movements were difficult to follow. Several lying convex upwards were found on the floor of the tributary. A few of the larger valves were transported just outside the original area and became buried by scour after two or three high tides.

FIG. 64. DIRECTIONS of TRANSPORT OF DYED SHELLS AND VALVES.

a. Populations A and B

b. Populations E and F

c. Populations C and D


c
0
50
100
METRES
N
C. SHELLS
C VALVES
D VALVES
C
D
D VALVES
a
0
50
100
METRES
N
CARSE GUT
CARSE GUT FLOOD CHANNEL
B
A & B SHELLS
A SHELLS
A
b
0
50
100
METRES
N
CHANNEL B
F SHELLS
F
CARSE GUT
E SHELLS
E VALVES
E

Station B

Most of the complete shells were transported parallel to the tributary to the foot of the mud slope and were deposited beside the shells from Station A. As in Station A, they were not found after L3. Several valves were found on the floor of the tributary and isolated ones were seen within a 2 metre radius of Station B but no definite directions of transport could be recognised.

Station C

After one high tide (H2) a small nest of six shells was found in a ripple trough 2 metres north-northwest of Station C. These shells had disappeared, however, after the next high tide. Three shells were found on the floor of Channel C one metre north of Station C.

The only direction of transport of valves was upstream along the bed of Channel C. Valves were found up to 60 metres north of Station C after only three high tides. In general the smaller valves in the 14 - 17 mm range had been transported furthest and the valves in the 23 - 28 mm range were closer to Station C. After three high tides all but 8 of the valves remaining within the original square metre area had scoured into the sediment and were buried up to 4 cms below the surface.

Station D

None of the shells transported out of the original square metre were found.

The valves were transported along two definite directions. Between 80 and 100 valves were found over a distance of 12 metres to the northeast (bearing 34°) of Station D. The remaining

transported valves were all found on the floor of Channel C up to 130 metres downstream from Station D.

Most of the valves at Station D were removed and only 2.4% were recovered as against 52.1% from Station C on the opposite bank of Channel C. The separation between the lines of yellow stained valves from Station C and black stained valves from Station D on the floor of Channel C was complete, those from Station C being transported upstream by flood currents and those from Station D being transported downstream by ebb currents (Fig. 64c).

The results from Stations C and D show that the responses of valve assemblages on opposite banks of an ebb channel to current action may be completely different even although they are only 2 metres apart.

Station E

The only complete shell recovered was found in a small tributary of Channel B 75 metres north-northeast (bearing 8°) of Station E. The main effect of current sorting was to redistribute the valves into a lens-shaped shell-bed with its long axis running northwest-southeast (Fig. 64b). Three valves were found to the northeast (bearing 30°) of the original population over a distance of 4 metres.

Station F

13 shells were recovered in a small tributary of Channel B 45 metres north-northeast (bearing 10°) of Station F (Fig. 64b). The tributary was one of a series of five, 2 - 3 metres apart,

draining the flats west of Channel B. This result is remarkable in that no other shells were found although a careful search was made in the other tributaries.

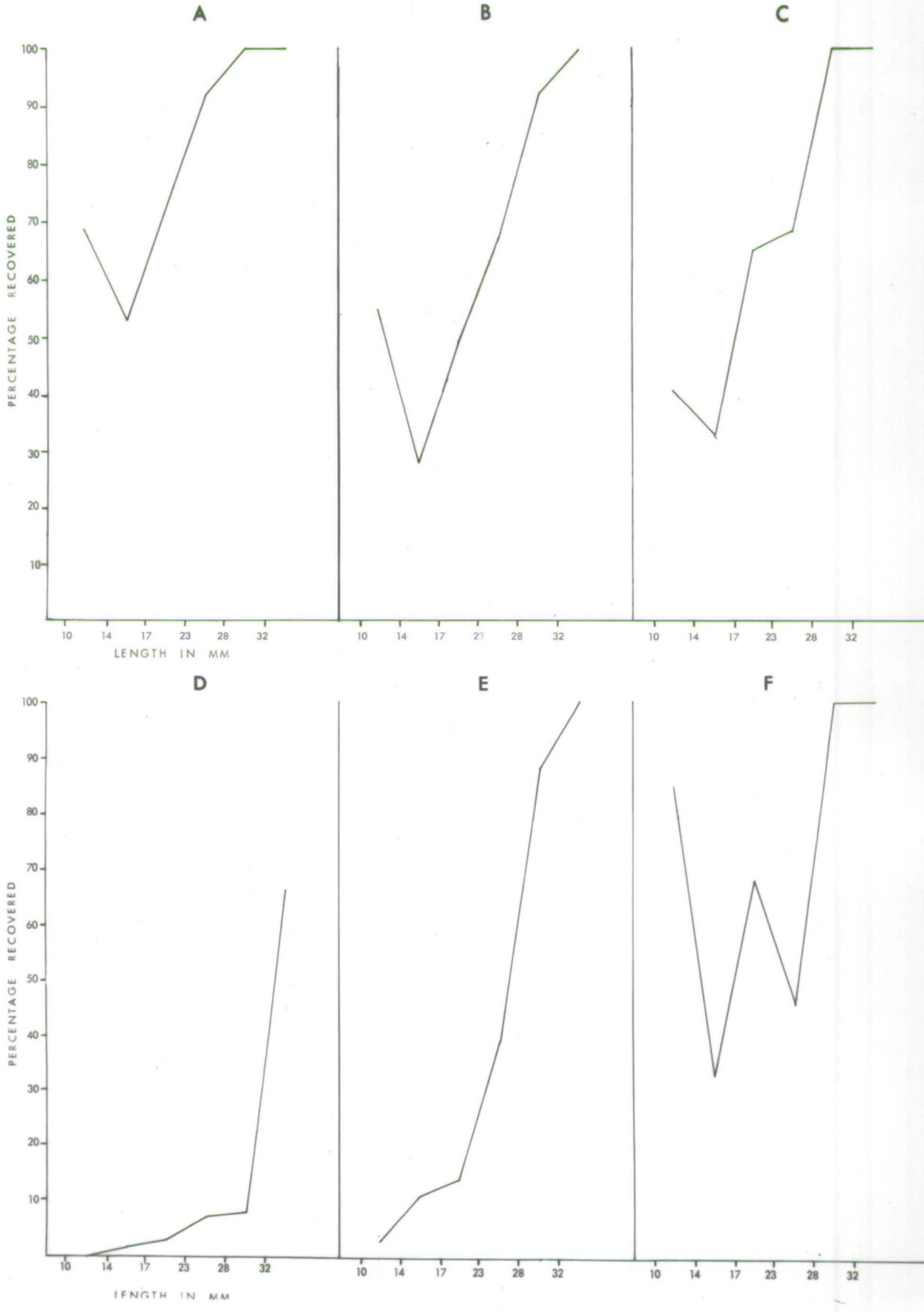
There was some redistribution of the valves to the southeast as at Station E. 21 valves were found over a distance of five metres to the north-northeast of the original population.

These results from the six stations indicate that the directions of current transport are precisely defined and that valves and shells are transported along straight lines until they either encounter a change in conditions such as a channel or are buried by scour action. In most cases the directions of transport of complete shells were different from those of valves.

COMPOSITION OF RESIDUAL POPULATIONS

The valves collected from the original square metre areas were separated, the number in each size range counted, and the percentage recovery for each size range was calculated. These results are given in Table 24 and Fig. 65.

In populations A, B, C and F (Fig. 65) the percentage of valves recovered in the 14 - 17 mm range was considerably less than in the 10 - 14 and 17 - 23 mm ranges. It would be reasonable to expect that the percentage recovery would be lowest in the smallest sizes as they would be most easily transported by current action, and that the percentage recovery would increase as the size range increased. These results, however, indicate that the percentage recovery in the smallest range (10 - 14 mms) was up to 50% greater than in the next largest size range (14 - 17 mms) and therefore current action preferentially removed



COMPOSITION OF RESIDUAL POPULATIONS.

Percentage of valves recovered plotted against length.

this size range rather than the smallest valves. The probable explanation of this depends on the differential rates of burial by scouring for valves of different sizes. Many of the 10 - 14 mm valves were rapidly buried by scouring as the first high tide covered them before the transport threshold velocity had been exceeded. The valves in the 14 - 17 mm range had a much lower rate of scour and were transported when the tidal currents exceeded the threshold velocity. Many valves in this size range were therefore transported and a much smaller percentage were buried by scour. The valves in the 17 - 23 mm range were less easily transported by the current velocities developed during the tidal cycle and they tended to become scoured into the sediment. In most cases between 90 and 100% of the valves greater than 23 mms were largely unaffected by the current velocities and were gradually scoured into the sediment. Thus the inter-relationship of the rate of burial by scour and the threshold velocity of transportation partly determines the size-frequency distribution of a valve assemblage preserved in a shell-bed.

This preferential removal of one size range as a result of current action could lead to erroneous conclusions in the interpretation of palaeoecological size-frequency distributions. Gaps in fossil shell size-frequency distributions could be misinterpreted as indicating the absence of a particular size range in the original living population. The gap in the size-frequency distributions of Cardium valves from the shell-beds described in Chapter 6 could be interpreted as indicating an absence of valves in the 14 - 17 mm length range in the original population,

whereas it is probably the result of preferential removal of valves in this size range by current action.

Only Cardium valves were studied but it is possible that this preferential removal of a particular size range occurs in most lamellibranch species although the size ranges involved will be different for each species in different environments. Further work on this problem in different species is planned both in the field and in a hydraulic flume tank.

CHAPTER 8

SUMMARY AND CONCLUSIONS

Investigations into the formation of shell-beds and the relationships of the shell-beds to the living faunas from which they were derived were carried out in the Solway Firth on the intertidal mud and sand flats off Carsethorn at the mouth of the River Nith 22 kms south of Dumfries. The River Nith, the Carse Gut and their associated ebb channels form the main drainage of the flats.

Quantitative samples were collected from stations along three transects using a frame defining an area of 1/10th square metre. At each station the living fauna and dead shells were collected from successive layers to a depth of 25 cms.

The living fauna over most of the area contains species typical of the Boreal Shallow Mud Association (Jones 1950). Towards the south and east a transition to the Boreal Shallow Sand Association takes place. Only species capable of leaving fossil remains - trace fossils or shells - were considered in detail. Nereis deversicolor and Arenicola marina are common over the mud flats. Arenicola normally only spawns in the autumn but young worms from a spring spawning were found in April 1964 in the sheltered muds north of Carsethorn. The barnacle population on the beach cobbles is dominated by Elminius modestus. It is clear that Elminius is replacing Balanus as the plates from former populations found in the sediment are all from Balanus. Corophium volutator is common in certain restricted areas on the

mud flats. Hydrobia ulvae is abundant on the mud flats and on parts of the sand flats. Its density on the mud flats fluctuates from year to year. Retusa obtusa is fairly common on the sand flats. It has not been previously recorded from the Solway so far as the writer is aware. Macoma balthica is the dominant lamellibranch species in the area. It is common in both mud and sand at depths down to 10 cms. There is a general increase in the size of Macoma with depth within the sediment. Scrobicularia plana is restricted to the silts of Carse Bay and lives at depths of 8 - 12 cms. Mya arenaria is common at depths of 20 - 30 cms over much of the area. Cardium edule is common at depths down to 7.5 cms in the fine-grained sands east of the Carse Gut and on the mud flats south of Carsethorn. Although successful spat settlement and growth takes place throughout the summer, conditions in the flats do not appear to be suitable for the survival of living cockles for more than 12 to 15 months. Tellina tenuis occurs in the coarser clean-washed sands in the south and east of the area. Mytilus edulis is not known to have lived in the area since the 1930s but Mytilus spat grow throughout the summer on temporary substrates such as Enteromorpha until the Enteromorpha mounds are destroyed by strong current action in early October.

Oystercatchers and other seabirds prey extensively on Cardium and Macoma at low tide. The shells may either be chipped or completely crushed by the birds. Predation and crushing of lamellibranchs is continued at high tide by flat fish in intertidal areas. The majority of shell fragments are therefore produced as a result of predation, and damage to shells and fragments during transportation is of minor importance.

The structure of the shell partly determines the fragmentation pattern in lamellibranch shells such as Cardium, Macoma, Scrobicularia and Mya, and characteristic types can be recognised throughout the flats and in the shell-beds.

Most of the dead shells and valves distributed throughout the sediment are derived from the local living fauna. The Mytilus valves in the mud flats were however transported into the area. The highest densities of dead shells and valves are in the mud flats west of the Carse Gut. In some species the dead shell and valve distributions were similar to those of the living population although the areas of highest dead shell density did not correspond to the areas of high living faunal density. Dead shells and valves of most species including surface dwellers are found at all depths down to 25 - 30 cms.

West of the Carse Gut the sediment is composed dominantly of silt with a considerable proportion of organic matter. East of the Carse Gut the proportion of fine-grained sand increases towards the Nith Channel. There is a general increase in grain-size to the east and the southeast. Most of the sediment is derived from the sea. Granulometric analysis indicates that sediments giving FM-type curves are found over most of the area but M-type curves were obtained from the unstable medium-grained sands in the southeast of the area. Transverse megaripples are developed in the south of the area and minor ripples of several types are common on the flats. Tidal flat lamination is well developed on the mud flats. A number of distinctive sedimentary structures are produced on the mud flats at low tide during rain storms.

Reworking of the flats by tidal or storm action rarely involves more than the top few cms of the sediment. The main agents of reworking are laterally migrating channels. The slope of the receding bank of the migrating channel gives some indication of the rate of lateral migration. Erosion and reworking is taking place at all times in different parts of the area and the detailed geography of the flats changes from day to day.

Three different types and rates of reworking can be recognised. The first is the rapid reworking of a small area during a storm by an ebb channel swollen by flood waters. The local effects may be dramatic for a few days but the channel then reverts to its pre-flood course. The second is the development of a large meander in an ebb channel over a period of two or three years. This rate of growth which is the most favourable for the formation of shell-beds is largely independent of floods and storm action. The third type is the reworking of the whole area by the large-scale east-west migrations of the River Nith Channel which occur at 10 to 30-year intervals. The present configuration of the flats date from the 1933 and 1951 migrations of the Nith Channel. The absence of burrowing structures at depths greater than 30 cms indicates that sedimentation was rapid until the equilibrium height of the flats had been reached.

The migration of faunas from the surrounding area into the prograding bank of a meandering channel takes place as soon as the sediment has become sufficiently stable for an infauna to develop.

The living faunas, dead shells and valves reworked from the flats may become concentrated into shell-beds on the surface of

the sand or on the floor of channels. Surface shell accumulations are formed by the concentration of shells and valves by small scale 'gyres'. Only the top five cms on the flat is reworked by this process and therefore the shell-bed is composed of molluscs such as Cardium and Macoma which live close to the surface. Deep burrowers such as Mya are rare. An analysis of a surface shell-bed showed that in both Cardium and Macoma valves some degree of current sorting had taken place and up to 40% of the Cardium valves were lying concave upwards. Hydrobia shells were abundant. The fragment weight percentage (weight of fragments expressed as a percentage of the total combined weight of shells, valves and fragments) of Cardium was greater than that of Macoma. The composition of channel-floor shell-beds depends on the depth of the floor of the laterally migrating channel. Major ebb channels rework all the living fauna and dead shells contained in the flats whereas reworking by shallow channels may only involve the top 10 cms of the sediment. An analysis of a channel-floor shell-bed in the Carse Gut showed that Cardium and Macoma were the dominant species but that Hydrobia was comparatively rare. Current sorting was less marked than in the surface shell-bed and almost all the valves were lying convex upwards. Mytilus valves transported from outside the area were present together with valves from deep burrowers. The fragment weight percentage of Macoma was greater than that of Cardium. These differences between surface and channel-floor shell-beds were used to show that a buried shell-bed had accumulated on a former channel-floor and not on the surface of the flats.

The composition of the shell-beds suggested that Cardium was the dominant species in the area and that individual cockles lived up to five years of age. The faunal composition indicated by the shell-beds differed from that of the actual living fauna in several important respects.

Experimental studies using dyed shells and valves of Cardium edule indicated that the directions of current transport are precisely defined, and that the directions of transport of complete shells were different from those of valves. In the experimental populations cockle valves in the 14 - 17 mm length range were preferentially removed as a result of current action. The gaps in the size-frequency distributions of Cardium valves from the shell-beds in this range probably indicate a preferential removal of valves by current action and not an absence of this size range in the original population.

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T A B L E S

TABLE 1 Values of Median and Mean-Grain Diameters in mms

Sample	Median	Mean	Mean - Median	Sample	Median	Mean	Mean - Median
1/1	0.059	0.084	25	2/4	0.088	0.092	4
1/2	0.053	0.059	6	2/5	0.078	0.075	-3
1/3	0.067	0.064	-3	2/6	0.070	0.068	-2
1/4	0.065	0.067	2	2/7	0.100	0.106	6
1/6	0.070	0.073	3	2/8	0.113	0.116	3
1/7	0.065	0.067	2	2/9	0.078	0.087	9
1/8	0.070	0.070	0	2/10	0.102	0.108	6
1/9	0.078	0.083	5	2/11	0.122	0.125	3
1/10	0.070	0.069	-1	2/12	0.107	0.116	9
1/11	0.074	0.072	-2	2/13	0.097	0.105	7
1/12	0.070	0.072	2	3/1	0.100	0.139	39
1/13	0.101	0.104	3	3/2	0.070	0.071	1
1/14	0.080	0.084	4	3/3	0.074	0.080	6
1/15	0.098	0.104	6	3/4	0.073	0.082	9
2/1	0.069	0.076	7	3/5	0.079	0.087	8
2/2	0.080	0.078	-2	3/6	0.078	0.086	8
2/3	0.078	0.082	4	3/7	0.178	0.174	-4

Contractions used in Tables 2 - 24

Liv - living
Sh - complete shells
LV - left valves
frag - fragment weight percentage

C.edul or C.ed - Cardium edule
M.balth - Macoma balthica
M.aren - Mya arenaria
S.plan - Scrobicularia plana
M.edul or M.ed - Mytilus edulis
T.tenuis - Tellina tenuis
H.ulv - Hydrobia ulvae
R.obt - Retusa obtusa

TABLE 2 Transect Data - Transect 1, Layer 1

CATEGORY	STATION														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
H.ulvae															
Liv	145	181	50	20	25	32	519	182	152	98	-	-	24	-	1
Sh	4	60	31	-	-	5	264	380	192	104	2	-	597	4	-
R.obtusa															
Sh	-	-	-	-	-	-	1	-	2	-	-	-	1	-	-
C.edule															
Liv	-	-	-	-	-	-	1	2	4	23	8	6	6	1	-
Sh	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-
LV	-	-	-	-	-	4	-	9	4	2	-	-	12	1	2
M.balthica															
Liv	6	9	20	8	1	10	36	43	30	25	9	11	3	2	2
Sh	-	4	2	-	-	12	6	6	-	-	-	-	-	-	-
LV	-	4	-	-	-	3	11	-	3	-	-	-	3	-	-
M.arenaria															
Liv	-	-	-	-	-	-	1	4	-	-	-	-	-	-	-

TABLE 3 Transect Data - Transect 1, Layer 2

CATEGORY	STATION														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
H.ulvae															
Sh	22	280	10	-	-	-	166	72	74	-	-	-	136	-	-
R.obtusa															
Sh.	-	-	-	-	-	-	-	-	5	-	-	-	4	-	-
C.edule															
Liv	-	-	-	-	-	-	-	-	-	2	-	2	2	-	-
Sh	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-
LV	-	2	-	-	-	-	21	8	36	4	-	-	10	-	4
S.plana															
Sh	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-
LV	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-
M.balthica															
Liv	10	28	14	12	28	7	19	10	22	13	4	10	3	1	1
Sh	-	12	2	1	2	-	7	-	-	-	-	-	-	-	-
LV	-	3	-	-	2	-	5	6	6	-	-	-	-	-	-
M.arenaria															
Liv	-	-	-	-	-	2	-	-	-	1	-	-	-	-	-

TABLE 4 Transect Data - Transect 1, Layer 3

CATEGORY	STATION														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
H.ulvae															
Sh	5	87	73	-	-	-	71	134	15	74	10	-	41	-	-
C.edule															
Liv	-	-	-	-	-	-	-	-	-	-	-	1	2	-	-
Sh	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-
LV	-	-	-	-	1	-	13	2	12	16	-	-	4	-	2
M.balthica															
Liv	3	2	-	1	3	-	-	1	-	5	2	3	1	-	-
Sh	-	9	2	-	-	-	-	-	-	-	-	-	-	-	-
LV	-	-	-	-	-	-	8	-	1	3	-	-	-	-	-
M.arenaria															
LV	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-

TABLE 5 Transect Data - Transect 1, Layer 4

CATEGORY	STATION														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
H.ulvae															
Sh	12	112	50	-	13	-	50	182	34	12	-	-	-	-	-
M.edulis															
LV	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-
C.edule															
LV	-	2	-	3	5	-	5	5	6	-	-	-	7	-	2
S.plana															
Liv	2	-	1	-	-	-	-	-	-	-	-	-	-	-	-
Sh	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-
M.balthica															
Liv	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-
Sh	-	1	4	-	-	-	-	-	-	-	-	4	-	-	-
LV	-	1	-	-	1	-	2	2	2	3	-	-	-	-	1

TABLE 6 Transect Data - Transect 1, Layer 5

CATEGORY	STATION														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
H.ulvae															
Sh	250	1100	132	-	-	192	166	960	18	263	-	-	64	-	-
C.edule															
Sh	-	-	-	-	-	5	-	-	-	4	3	-	-	-	-
LV	-	23	10	1	15	13	61	10	53	57	-	-	25	-	1
S.plana															
Liv	-	1	-	-	1	-	-	-	-	-	-	-	-	-	-
Sh	-	2	4	-	-	-	-	-	-	-	-	-	-	-	-
LV	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-
M.balthica															
Liv	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-
Sh	-	4	1	-	-	2	1	-	-	-	-	-	-	-	-
LV	-	47	1	2	1	1	3	6	1	3	2	-	-	-	-
M.arenaria															
Liv	-	-	-	-	2	-	2	1	-	-	-	-	-	-	-
LV	-	-	4	-	-	-	2	-	-	-	-	-	-	-	-
Balanus	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-

TABLE 7 Transect Data - Transect 2, Layer 1

CATEGORY	STATION												
	1	2	3	4	5	6	7	8	9	10	11	12	13
H.ulvae													
Spat	50	-	-	-	64	-	-	-	-	-	-	-	-
Liv	550	1	12	125	518	10	-	-	-	-	-	25	-
Sh	-	-	-	-	32	-	16	-	-	-	-	-	-
R.obtusa													
Liv	-	-	-	-	6	8	-	1	2	2	-	-	-
Sh	-	-	-	18	-	-	-	-	-	1	1	-	-
C.edule													
Spat	-	-	12	266	80	30	32	-	-	10	-	-	-
Liv	4	15	5	416	110	13	17	22	21	9	8	5	3
Sh	-	-	2	16	-	-	-	-	-	-	-	-	1
LV	1	1	4	165	4	-	-	-	-	19	3	2	-
M.balthica													
Spat	50	60	-	225	-	-	-	-	-	-	-	-	-
Liv	319	62	8	17	18	14	1	22	11	1	1	-	6
Sh	5	5	5	-	-	-	-	-	-	-	-	-	-
LV	1	4	-	26	-	-	-	1	-	1	-	-	-
T.tenuis													
Liv	-	-	-	-	-	-	-	-	-	1	-	-	-
M.arenaria													
Liv	19	2	-	-	-	-	-	-	-	-	-	-	-
LV	-	-	-	-	-	-	-	-	-	1	-	-	-

TABLE 8 Transect Date - Transect 2, Layer 2

CATEGORY	STATION												
	1	2	3	4	5	6	7	8	9	10	11	12	13
H.ulvae													
Sh	50	-	10		24	-	-	16	-	-	-	-	-
M.edulis													
LV	1	-	-	-	-	-	-	-	-	-	-	-	-
C.edule													
Liv	-	4	1	8	19	2	3	1	-	5	4	-	-
Sh	-	-	-	-	1	-	-	-	-	-	-	-	-
LV	1	-	-	12	-	1	1	-	2	19	2	9	3
M.balthica													
Liv	93	44	12	52	15	7	1	3	4	3	3	-	1
Sh	16	1	-	2	2	-	-	-	-	-	-	-	-
LV	5	-	-	-	-	-	-	-	-	-	-	-	-
T.tenuis													
Liv	-	-	-	-	-	-	1	-	-	-	-	1	-

TABLE 9 Transect Data - Transect 2, Layer 3

CATEGORY	STATION												
	1	2	3	4	5	6	7	8	9	10	11	12	13
H.ulvae													
Sh	96	24	-	-	10	-	-	-	-	-	32	-	96
M.edulis													
LV	4	-	-	-	-	-	-	-	-	-	-	-	-
C.edule													
Liv	-	-	-	4	5	-	-	1	1	-	1	-	-
Sh	1	2	2	-	1	1	1	-	-	-	-	1	-
LV	5	5	-	11	7	-	-	2	-	3	2	-	12
M.balthica													
Liv	18	62	10	15	7	2	2	4	1	3	1	-	1
Sh	2	5	2	-	-	-	-	-	-	-	-	-	-
LV	2	5	2	1	-	-	-	1	-	-	-	-	1
T.tenuis													
Liv	-	-	-	-	-	-	2	-	1	-	-	-	-

TABLE 10 Transect Data - Transect 2, Layer 4

CATEGORY	STATION												
	1	2	3	4	5	6	7	8	9	10	11	12	13
H.ulvae													
Sh	360	-	-	-	-	-	-	-	-	-	-	-	-
M.edulis													
LV	139	1	-	-	-	-	-	-	-	-	-	-	-
C.edule													
Sh	7	-	3	-	1	-	-	-	-	-	-	-	-
LV	50	9	3	1	9	-	-	-	-	-	3	2	10
M.balthica													
Liv	-	4	1	2	2	-	-	-	-	1	-	-	-
Sh	-	3	5	-	-	1	-	-	-	-	-	-	-
LV	22	4	-	-	1	-	1	-	-	-	-	-	1
T.tenuis													
Liv	-	-	-	-	-	-	2	2	1	-	-	-	-

TABLE 11 Transect Date - Transect 2, Layer 5

CATEGORY	STATION												
	1	2	3	4	5	6	7	8	9	10	11	12	13
H.ulvae													
Sh	6527	-	-	-	-	-	-	-	-	-	80	-	-
M.edulis													
LV	131	-	-	-	-	-	-	-	-	-	-	-	-
C.edule													
Sh	31	-	11	1	1	-	1	-	1	-	-	-	1
LV	146	9	15	4	33	-	-	3	3	7	27	4	10
S.plana													
LV	3	-	-	-	-	-	-	-	-	-	-	-	-
M.balthica													
Liv	-	2	-	-	-	2	-	-	-	1	-	-	-
Sh	12	4	7	-	-	1	-	-	-	-	-	-	-
LV	25	-	1	1	6	-	-	-	-	-	-	-	1
T.tenuis													
Liv	-	-	-	-	-	-	1	-	-	-	1	-	-
M.arenaria													
LV	1	1	-	-	-	-	-	-	-	-	-	-	-

TABLE 12 Transect Data - Transect 3, Layer 1

CATEGORY	STATION							
	1	2	3	4	5	6	7	8
H.ulvae								
Spat	-	710	144	224	25	-	-	-
Liv	138	361	256	168	-	-	-	-
Sh	10	356	192	38	25	-	10	-
R.obtusa								
Liv	-	-	-	-	2	-	-	-
Sh	1	2	-	-	-	-	-	-
M.edulis								
Spat	24	30	8	128	-	30	10	-
LV	11	7	-	2	-	-	-	-
C.edule								
Spat	288	80	20	48	-	20	10	-
Liv	58	73	61	6	4	-	-	-
Sh	3	12	4	1	1	-	2	-
LV	36	70	12	13	-	2	-	-
M.balthica								
Spat	772	410	168	96	25	-	-	-
Liv	111	31	168	125	7	-	-	2
Sh	4	20	-	-	-	-	-	-
LV	4	29	-	2	1	-	-	-
M.arenaria								
Spat	-	8	8	16	-	-	-	-
LV	-	-	1	-	-	-	-	-
Balanus	26	26	3	-	-	-	-	-

TABLE 13 Transect Data - Transect 3, Layer 2

CATEGORY	STATION							
	1	2	3	4	5	6	7	8
H.ulvae								
Sh	37	681	7	36	-	10	-	-
M.edulis								
LV	11	-	-	2	-	-	-	-
C.edule								
Liv	-	7	2	5	-	-	-	-
Sh	3	4	-	1	-	-	-	-
LV	59	90	1	9	-	-	2	-
M.balthica								
Liv	89	105	44	61	9	2	-	-
Sh	27	4	2	-	-	-	-	-
LV	23	38	2	5	-	1	2	-
M.arenaria								
LV	-	-	1	1	-	-	-	-
Balanus	56	33	-	11	-	1	2	-

TABLE 14 Transect Data - Transect 3, Layer 3

CATEGORY	STATION							
	1	2	3	4	5	6	7	8
H.ulvae								
Sh	112	1256	20	224	-	-	16	-
M.edulis								
LV	5	2	1	12	-	-	-	-
C.edule								
Liv	-	-	1	-	-	-	-	-
Sh	-	5	-	3	-	-	-	-
LV	31	109	7	156	1	-	3	-
M.balthica								
Liv	6	26	28	72	2	5	-	-
Sh	3	6	-	-	-	-	-	-
LV	23	10	1	22	-	-	1	-
T.tenuis								
Liv	-	-	-	-	-	5	-	-
M.arenaria								
LV	-	-	1	1	-	-	-	1
Balanus	46	16	-	-	-	-	-	-

TABLE 15 Transect Data - Transect 3, Layer 4

CATEGORY	STATION							
	1	2	3	4	5	6	7	8
H.ulvae								
Sh	1232	1644	134	336	-	-	-	-
R.obtusa								
Sh	-	1	-	-	-	-	-	-
M.edulis								
LV	-	3	3	10	-	-	-	-
C.edule								
Sh	-	4	2	9	-	-	-	-
LV	53	103	15	112	-	-	1	-
M.balthica								
Liv	1	-	11	68	-	-	-	-
Sh	-	1	-	-	-	-	-	-
LV	63	36	-	18	1	-	1	1
T.tenuis								
Liv	-	-	-	-	-	2	-	-
M.arenaria								
LV	-	-	2	3	-	-	-	-
Balanus	143	11	1	5	-	-	-	-

TABLE 16 Transect Data - Transect 3, Layer 5

CATEGORY	STATION							
	1	2	3	4	5	6	7	8
H.ulvae								
Sh	11394	9686	1944	1067	-	-	533	-
R.obtusa								
Sh	36	16	-	-	-	-	10	-
M.edulis								
LV	-	16	3	-	-	-	-	-
C.edule								
Sh	-	42	4	1	1	-	-	-
LV	102	175	37	32	1	-	3	9
M.balthica								
Liv	-	-	25	-	1	-	-	-
Sh	-	9	2	-	-	-	-	-
LV	392	165	42	13	-	-	8	-
M.arenaria								
LV	-	3	7	-	-	-	-	-
Balanus	1956	462	18	-	-	-	-	1

TABLE 17 Comparative Densities of Hydrobia Ulvae

AUTHOR	LOCALITY	HABITAT	DETAILS OF SAMPLE	DENSITY PER SQUARE METRE
STOPFORD 1951	Dee Estuary Cheshire	Muddy sand	Average Density Sept-Oct. 1946	12,500
REES 1940	Bristol Channel nr.Cardiff	Muddy sand towards LWM	Highest Density on Transect Aug.-Sept. 1937	18,100
	" " "	Mud, upper mud flat	Transect Aug.-Sept. "	1,100
SPOONER & MOORE 1940	Tamar Estuary	Mud, upper mud flat	Max.Density Transect 1937	35,000
	" " St.John's Lake	Mud flat	" "	13,800
	" " " "	Mud flat	Feb. 10th Transect 1937	10,890
BEANLAND 1940	Dovey Estuary	Mud flat	Nov-Dec 1925 Av.Density	20,000
	" "	Mud flat	Nov-Dec 1926 Max.Density	44,200
SMIDT 1951	Fano. Denmark	Soft Wadden	Max.Density Sept. 1946	192,000
	" "	Sand Wadden	Max.Density July 1947	440,000
	Nordby "	Soft mud	Max.Density June 1947	640,000
THAMDRUP 1935	Skalling, Denmark	Wide sandy mud flat	Max. Density	60,000
	" "	Wide muddy sand flat	Max.onTransect March 1934	46,000
	" "	" " "	" " " July 1932	37,000
	" "	" " "	" " " July 1933	24,500
	" "	" " "	" " " Aug. 1934	15,300
NICOL 1935	Aberlady Bay, Firth of Forth	Estuarine mud	-	32,500
		Estuarine mud	-	8,930
WILSON 1965	Carse Bay, Solway Firth	Upper mud flat	Station Site Oct.1961	4,650
		" " "	" " Sept.1962	9,320
		" " "	" " Mar. 1963	5,670
		" " "	" " Aug. 1963	2,470
		Sand at edge of upper mud flat	" " Mar. 1963	9,210
		Sand at edge of upper mud flat	" " Aug. 1963	5,500

TABLE 18 Comparative Densities (Number per square metre) from Mud Flats in Different Areas

Range is given (where quoted)

LOCALITY	Danish Wadden Sea Skalling	Danish Wadden Sea Fanø	Tamar Estuary St.John's Lake	Exe Estuary	Bristol Channel	Dovey Estuary	Dee Estuary	Mersey Estuary Dingle Bay	North Bay Kyle Scotnish	Budle Bay Northumberland	Firth of Forth Tynninghame	Solway Firth Carse Mud Flats
AUTHORITY	THAMDRUP 1935	SMIDT 1951	SPOONER & MOORE 1940	HOLME 1949	REES 1940	BEANLAND[3] 1940	STOPFORD[2] 1951	FRASER 1932	RAYMONT 1955	BRADY 1943	STEPHEN 1930	WILSON 1965
Hydrobia ulvae	15,000-46,000	61,000 640,000*	4,000-13,800	364-16,480	1,100-18,100	4,336-12,277	1,400-1,840	no quantitative data	6,021-9,809	-	-	2,470-9,320
Mytilus edulis	rare[1]	rare[1]	5[1]-24[1]	1[1]- 6[1] 4 - 24	-	-	24[1]	-	-	-	-	5[1]
Cardium edule	2,000-3,000	90-430 7,000* 22,000*	51-174	8-60	-	-	-	5-6	80 1,000*	-	-	40*-800*
Macoma balthica	300-1,000	100-700 5,900*-16,000*	12-76	24	140-800	11-118	196-640	1,030-3,071	250	4-102	156	25-1,350 60*-2,960*
Scrobicularia plana	20-60	-	4-138	32-156	rare	-	12	1 -	150-330	-	136	10-20
Mya arenaria	5-20	100*-43,000*	-	-	-	-	24-112	11-200	rare	-	16	10-20 190*

* 0-Group

1 Juveniles

2 Corrected from square feet

3 Corrected from $\frac{1}{4}$ square metre

TABLE 19 Comparative Densities (Number per square metre) from Sand Flats in Different Areas

Range is given (where quoted)

LOCALITY	Exe Estuary	Dovey Estuary	Dee Estuary	Budle Bay Northumberland	Aberlady Bay Firth of Forth	Carse Sands Solway Firth
AUTHORITY	HOLME 1949	BEANLAND[2] 1940	STOPFORD[1] 1952	BRADY 1943	STEPHEN 1929	WILSON 1965
Hydrobia ulvae	10 - 148	270 - 11,168	40 - 80	-	-	980 - 1,820
Retusa obtusa	-	-	-	-	-	20 - 80
Cardium edule	4 - 8 16*- 48*	43 - 624	-	12 - 36	2 - 32	50*- 140*
Macoma balthica	4 - 20	43 - 559	48 - 52	20 - 28	3 - 89	30 - 90
Tellina tenuis	20 - 88	1	-	4 - 62	1 - 8	20 - 70
Mya arenaria	-	-	-	-	-	1 - 10

* O-Group

1 Corrected from square feet

2 Corrected from $\frac{1}{4}$ square metre

TABLE 20 Surface Shell-Bed Data

SAMPLE	C.edule			M.balthica			M.arenaria		S.plana		H.ulvae	Total Frag.
	Sh	LV	Frag	Sh	LV	Frag	LV	Frag	LV	Frag		
A	-	105	40.1	12	28	23.0	2	59.7	-	100	940	39.4
B	-	127	38.3	13	31	17.1	-	100	-	-	690	36.2
C	-	247	30.7	13	60	9.9	2	41.2	-	100	925	29.8
D	-	124	51.5	14	27	17.8	-	100	1	17.8	281	48.2
E	-	104	49.6	13	26	14.3	1	3.8	-	-	437	45.1
F	1	70	49.2	15	29	13.3	1	85.7	-	-	562	45.4
G	-	96	45.2	9	34	6.3	-	-	-	-	312	30.8
H	-	163	38.7	17	43	18.3	-	--	-	100	375	36.4
I	-	90	41.5	17	35	11.4	1	33.3	-	-	80	39.9
J	-	48	19.4	10	16	11.1	-	-	-	-	565	18.5
K	-	25	38.8	3	7	14.8	-	100	-	-	250	34.0
L	-	32	38.0	5	20	10.8	-	-	-	-	175	35.4
Average												
A - I	-	112	-	14	35	-	-		-	-	622	-
J - L	-	35	-	6	14	-	-		-	-	330	-
Average Frag Wt%			40.1			14.0		43.6				36.6

TABLE 21 Shallow Channel-Floor Shell-Bed

SAMPLE	C.edule			M.balthica			M.edulis		M.arenaria		S.plana		H.ulvae	Total Frag.
	Sh	LV	Frag	Sh	LV	Frag	LV	Frag	LV	Frag	LV	Frag		
A	-	4	48.5	32	81	27.3	1	43.5	4	43.9	19	34.0	1,061	32.3
B	-	5	41.7	46	118	27.7	-	100	8	19.5	25	25.3	742	26.6
Average	-	5	45.1	39	100	27.5	-	71.7	6	31.7	22	28.6	901	29.4

TABLE 22 Carse Gut Shell-Bed Data

SAMPLE	C.edule			M.balthica			M.edulis		M.arenaria		S.plana		H.ulvae	Total Frag.
	Sh.	LV	Frag	Sh.	LV	Frag	LV	Frag	LV	Frag	LV	Frag		
A	-	61	15.2	-	19	41.1	26	49.9	1	4.3	-	-	28	31.1
B	-	82	23.0	2	30	40.9	46	50.1	-	58.5	-	-	24	45.2
C	-	81	13.3	4	20	38.4	15	63.8	1	34.8	-	100	32	32.1
D	-	34	24.6	5	13	43.2	2	89.7	-	37.8	-	100	8	42.4
E	-	72	50.5	3	15	43.9	13	74.8	1	-	-	100	20	38.0
F	1	74	19.6	-	19	28.9	19	74.6	-	67.5	-	-	20	42.5
Average	-	67	24.4	2	20	32.1	20	67.2	-	33.8	-	100		38.6

TABLE 23 Buried Shell-Bed Data

SAMPLE	C.edule			M.balthica			M.edulis		M.arenaria		S.plana		H.ulvae	Total
	Sh	LV	Frag	Sh	LV	Frag	LV	Frag	LV	Frag	LV	Frag		Frag.
A	-	90	30.0	13	27	24.3	31	50.9	-	93.6	-	-	52	39.3
B	-	145	25.2	29	52	34.8	12	72.9	1	94.9	-	63.0	63	43.5
C	-	164	30.4	18	60	29.8	7	90.7	-	97.2	-	-	24	36.0
D	-	182	24.5	41	64	25.7	4	87.5	-	100	-	-	252	40.1
E	-	160	22.7	17	54	29.5	2	95.5	-	100	-	-	56	35.9
F	1	276	27.2	17	96	25.1	5	94.1	1	96.6	-	-	98	47.2
G	-	709	19.7	23	177	30.0	10	93.6	3	80.0	-	--	140	31.6
H	3	814	29.6	18	304	40.0	4	96.5	3	90.6	1	22.2	1,688	43.4
I/1	-	69	18.5	11	35	35.1	5	71.6	-	100	-	-	70	30.9
I/2	-	130	36.7	4	37	37.7	-	97.1	-	100	-	-	112	47.2
I/3	-	120	23.8	1	36	57.0	2	82.9	-	-	-	-	98	42.1
I/4	1	141	27.3	1	37	45.7	3	70.5	-	100	-	100	42	40.7
J	-	1,305	28.2	12	424	28.3	28	93.9	8	95.6	1	82.2	900	48.5
K/1	[illegible]	69	21.0	9	52	37.6	2	84.8	1	13.0	-	-	140	34.1
K/2	1	112	68.1	1	45	64.6	-	96.8	1	41.5	-	-	63	70.8
K/3	-	97	29.0	1	42	53.0	1	84.1	-	100	-	-	154	41.8
K/4	-	199	23.3	-	41	60.5	2	96.8	1	90.2	-	-	133	36.9
K/5	-	133	36.8	-	33	49.5	2	96.2	1	96.1	-	-	70	52.2
L	-	764	24.0	6	209	36.3	9	89.4	2	93.6	-	-	518	37.8
M/1	-	100	33.0	-	50	47.7	1	97.0	1	34.8	-	-	91	41.0
M/2	1	97	38.5	1	33	50.0	2	97.1	-	100	-	-	21	49.1
M/3	-	122	28.7	-	27	54.4	1	98.7	-	59.9	-	-	147	37.6
M/4	-	75	35.9	-	9	46.5	-	100	-	100	-	100	42	41.4
M/5	-	73	45.1	-	16	47.5	-	100	-	100	-	[illegible]	63	51.5
N	-	129	47.8	6	72	36.9	2	93.0	-	93.0	-	100	320	53.8
O	1	52	33.6	3	63	24.3	1	97.8	1	73.4	-	-	143	41.8
Average	-	-	31.8	-	-	40.4	-	-	-	82.4	-	-	-	42.9

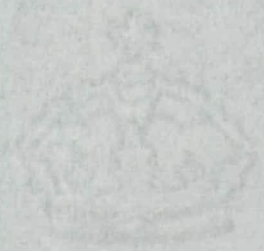
TABLE 24 Composition and Percentage Recovery of Residual Populations

Population	Category	Valve size range in mm 10 - 14	14 - 17	17 - 23	23 - 28	28 - 32	Over 32	shells
A	Laid	100	200	150	100	25	3	50
	Rec	69	106	110	92	25	3	0
	% Rec	69	53	73.3	92	100	100	0
B	Laid	100	200	150	100	25	3	50
	Rec	55	56	74	67	23	3	0
	% Rec	55	28	49.4	67	92	100	0
C	Laid	100	200	150	100	25	3	100
	Rec	41	66	98	68	25	3	14
	% Rec	41	33	65.3	68	100	100	14
D	Laid	100	200	150	100	25	3	100
	Rec	0	1	2	7	2	2	0
	% Rec	0	0.5	1.3	7	8	66.6	0
E	Laid	100	200	150	100	25	3	50
	Rec	3	21	21	39	22	3	0
	% Rec	3	11	14	39	88	100	0
F	Laid	100	200	150	100	25	3	50
	Rec	86	67	88	46	25	3	0
	% Rec	86	33.3	58.6	46	100	100	0

PLATES

PLATE 1.

a. Coastal erosion of '25 foot' raised beach south of Carsethorn.



b. Section through '25 foot' raised beach exposed by coastal erosion 400 metres south of Carsethorn. Details are given on p. 10.

a

b

PLATE 2.

a. Galvanised steel sampling frame a surface area of 1/10th square metre.

b. Sampling frame in position with the flange flush with the sediment surface.

a

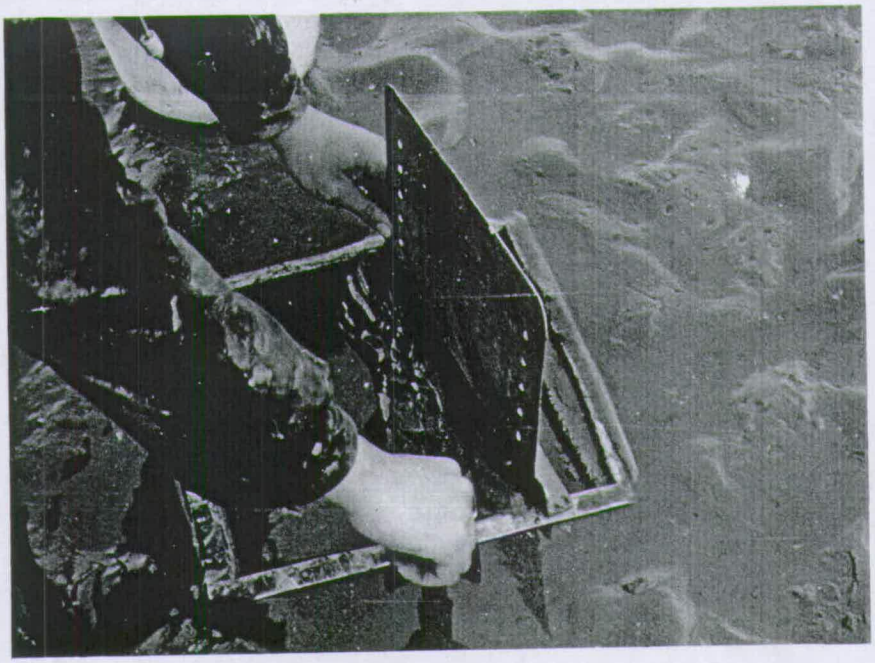
b

PLATE 3.

a. Removal of layer of sediment using a trowel. The accurate depth of each layer is insured by the bar of angle iron fitted to the flat plate at the appropriate level.

b. Sampling frame after the removal of layers 1, 2, 3 and 4.

a



b

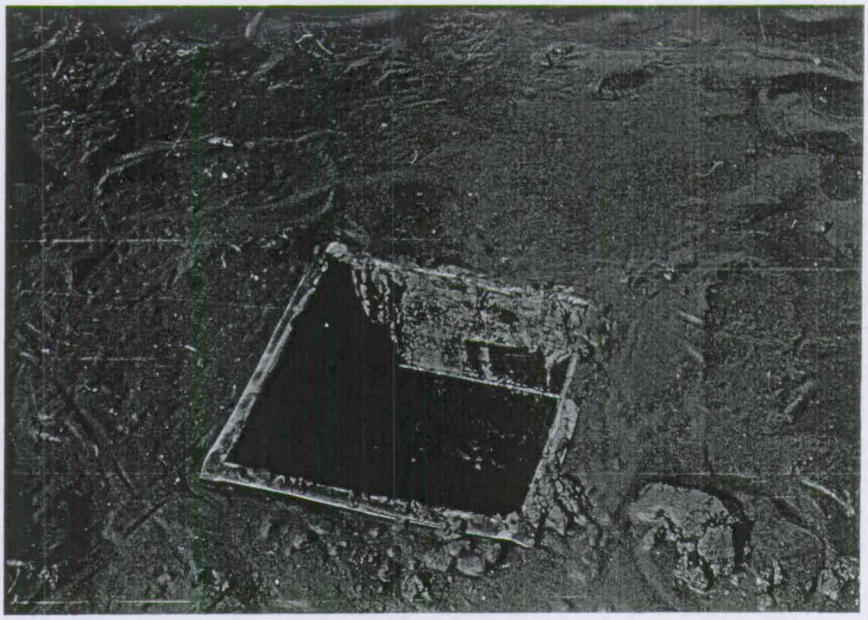
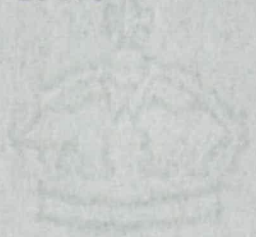


PLATE 4.

a. Waterlogged tree trunk stranded on the sand flats at Locality 14, 31st March 1963.



b. Waterlogged tree trunk stranded on the sand flats at Locality 14, 9th April 1964.

a

b

PLATE 6.

Panorama of megaripples taken from Locality 15.

20th September 1962.

Note interconnected pools of water in the megaripple troughs.

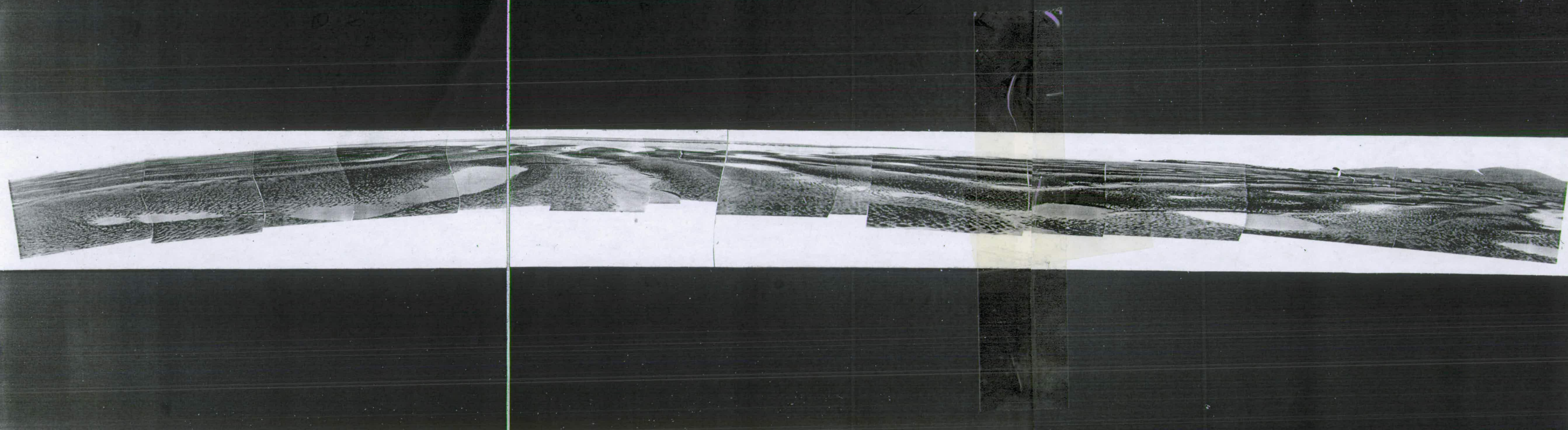
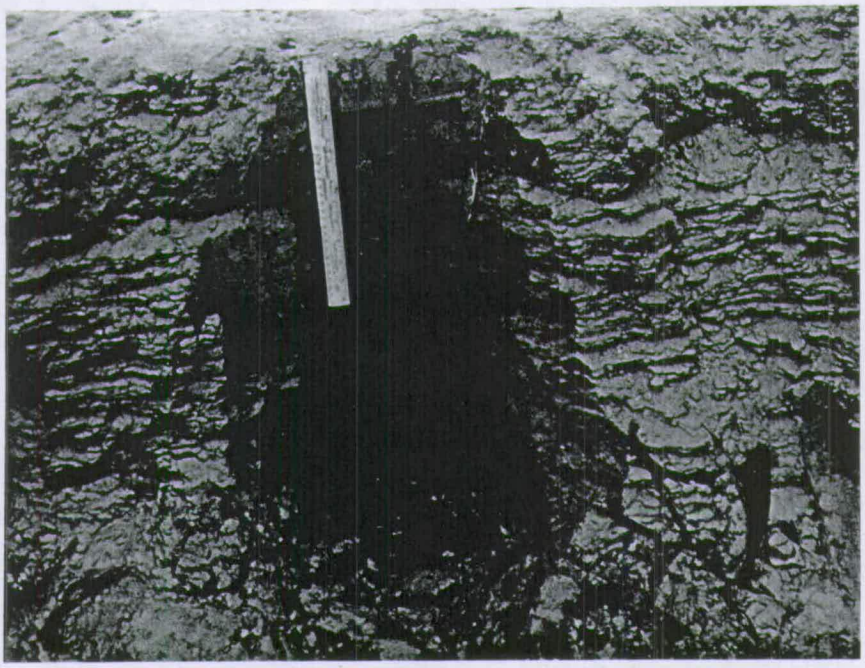


PLATE 7.

a. Ridge formed on the crest of a flood megaripple by the ebbing tide. The pen is on the down current face of the ridge. Note the asymmetrical ripples on both faces of the megaripple.

b. Early-stage megaripples on the sand flats, 30th March 1963.

a



b

PLATE 8.

a. Asymmetrical ripples near Station 2/13 formed by the ebb tide. Note the frequent bifurcation of the ripple crests.

b. Longitudinal ripples developed on the crests of asymmetrical ebb ripples, east bank of Channel C.

a

b

PLATE 9.

a. Superposed ripples with parallel crests, sand flats near Locality 17.

b. Superposed ripples with sub-parallel crests.

a

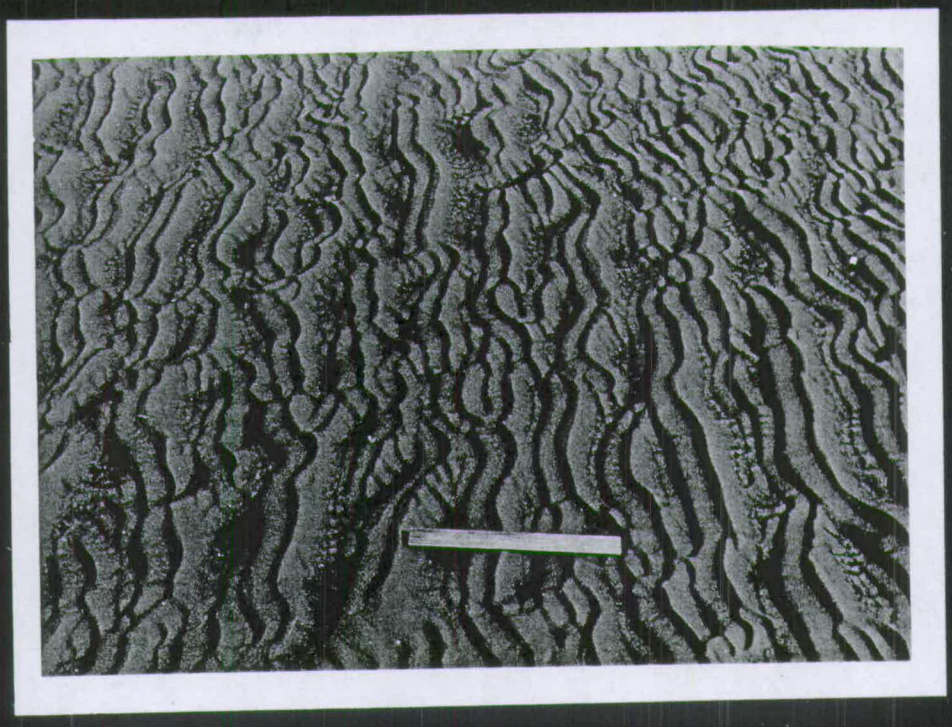
b

PLATE 10.

a. Superposed ripples with crests at right angles, slope on west bank of Channel C.

b. Interference ripples with a regular rectangular pattern, sand flats near Station 1/10.

a



b

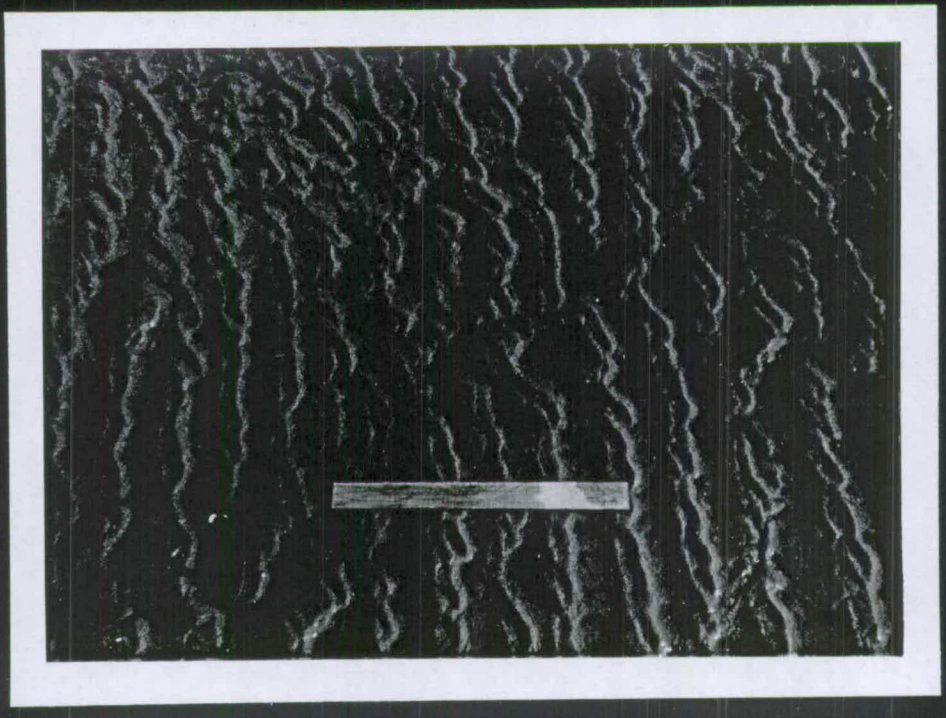


PLATE 11.

a. Interference ripples with an irregular polygonal pattern, sand flats near Station 1/10.

b. Flattened interference ripples towards the margin of the interference ripple zone on the sand flats near Station 1/10.

a

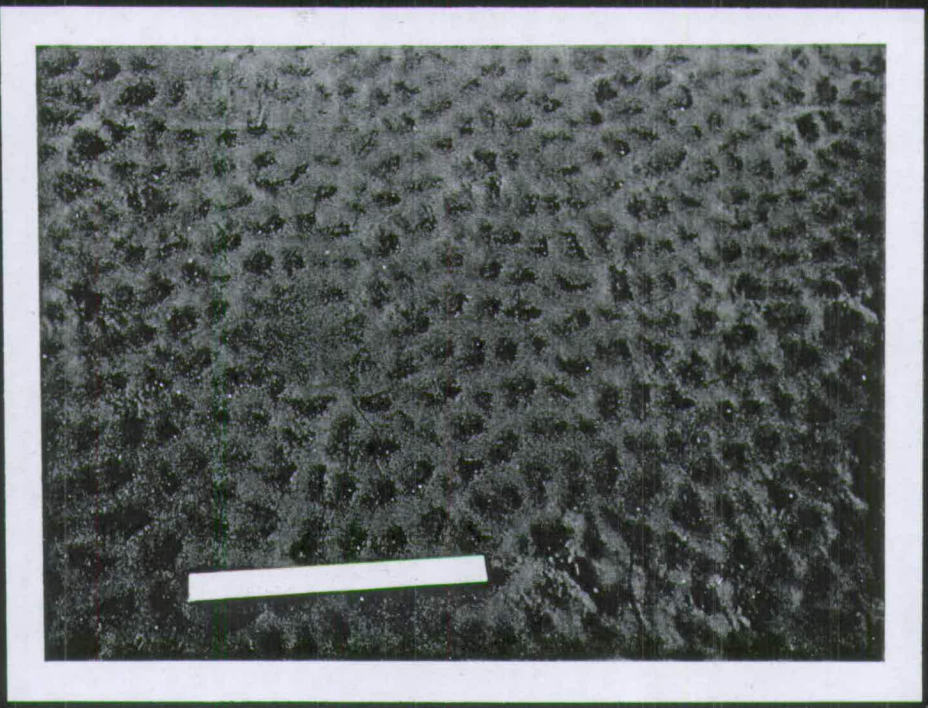
b

PLATE 18.

a. Lingoid ripples on the floor of Channel G near Locality 14.

b. Braided rill marks formed by water draining from the sand flats into the channel at low tide, west bank of Channel G at Locality 21.

a



b

PLATE 13.

a. Incomplete mud cracks on the silt flats on the east bank of the Carse Gut at Locality 4.

b. Incomplete mud cracks on the silt flats at Locality 4 re-exposed by the lowering of the bank associated with the infilling of the pre-March 1964 course of the Carse Gut. The more resistant mud lining the cracks now stands out as a positive feature.

a

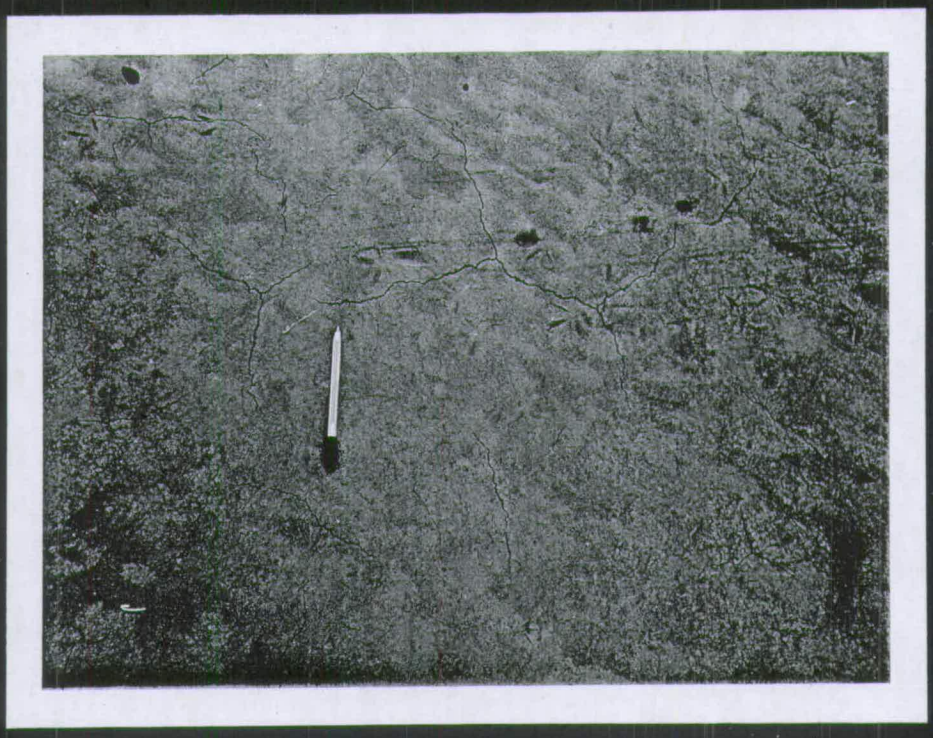
b

PLATE 14.

a. Ridged erosion pools, sand flats at Locality 13. 30th March 1963.

b. Cuspate margin at the southern end of a ridged erosion pool showing the prominent low ridge. Note the numerous Polydora tubes exposed behind the ridge.

a



b

PLATE 15.

a. Shallow troughs on the upper mud flat near Locality 2 formed by rain driven across the flat during the storm on 2nd April 1962. The troughs are parallel to the direction of the wind.

b. Segregation of organic matter towards the edges of the troughs and of silt and clay in the centre. Note the tendency for the rain pits on the intervening ridges to coalesce forming small ridges at right angles to the wind direction. 2nd April 1962.

a

b

PLATE 16.

a. Storm erosion gully on the edge of the upper mud flat. A lump of sediment has been torn out of the right bank by the swiftly moving water giving the bank a ragged appearance. 2nd April 1962.

b. Sand volcano showing three phases of eruption. The third phase produced a symmetrical cone. Note the concentration of organic matter on lower slopes of the volcano. The end of the eruption is marked by the appearance of the small satellite cones.

a

b

PLATE 17.

a. Group of sand volcanoes showing the presence of well defined craters in only 25% of the cones.

b. Group of sand volcanoes where the organic matter on the lower slopes of adjacent cones has coalesced.

a

b

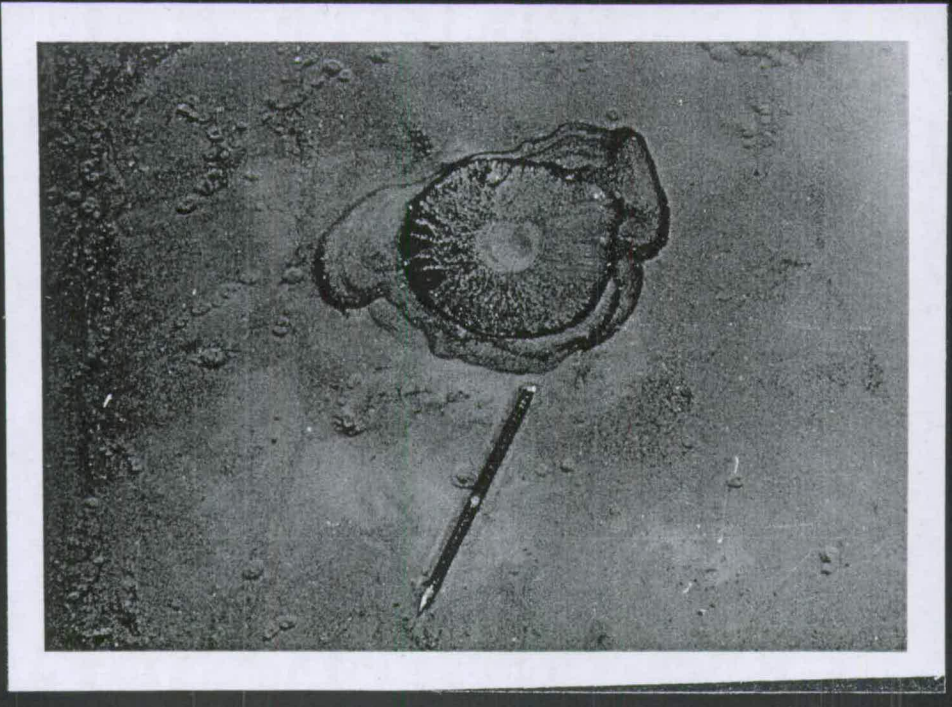


PLATE 18.

a. Sub-concentric ring fractures and associated subsidence in the non-thixotropic sand round the area of eruption.

b. Vertical section through a sand volcano showing minor faulting and upwarping of the organic layers adjacent to the feeder.

a

b

PLATE 19.

a. Young *Mytilus edulis* attached to a hydroid colony.

b. *Chrysaora hysoscella* individual.

a

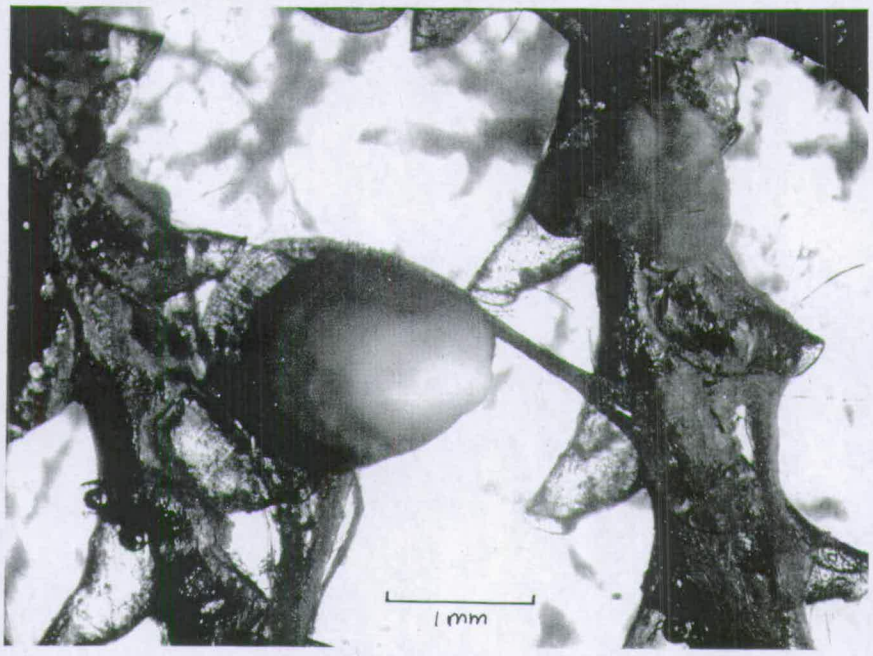
b

PLATE 20.

a. Numerous Pleurobrachia pileus individuals trapped in ripple troughs on the lower mud flat. 16th August 1962.

b. Nereis diversicolor burrows in peat block from the lower mud flat near Locality 3.

a



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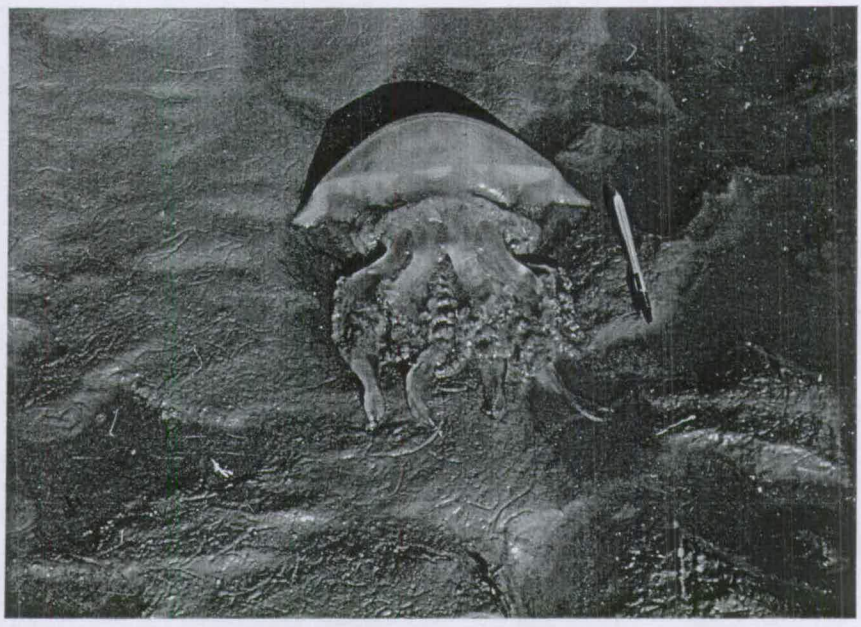


PLATE 21.

a. Numerous Polydora ciliata tubes exposed by the formation of the ridged erosion pools (see Plate 14b).

b. Arenicola marina nursery area at the foot of the beach at Borron Point 2000 metres south of Carsethorn. 26th September 1962.

a

b

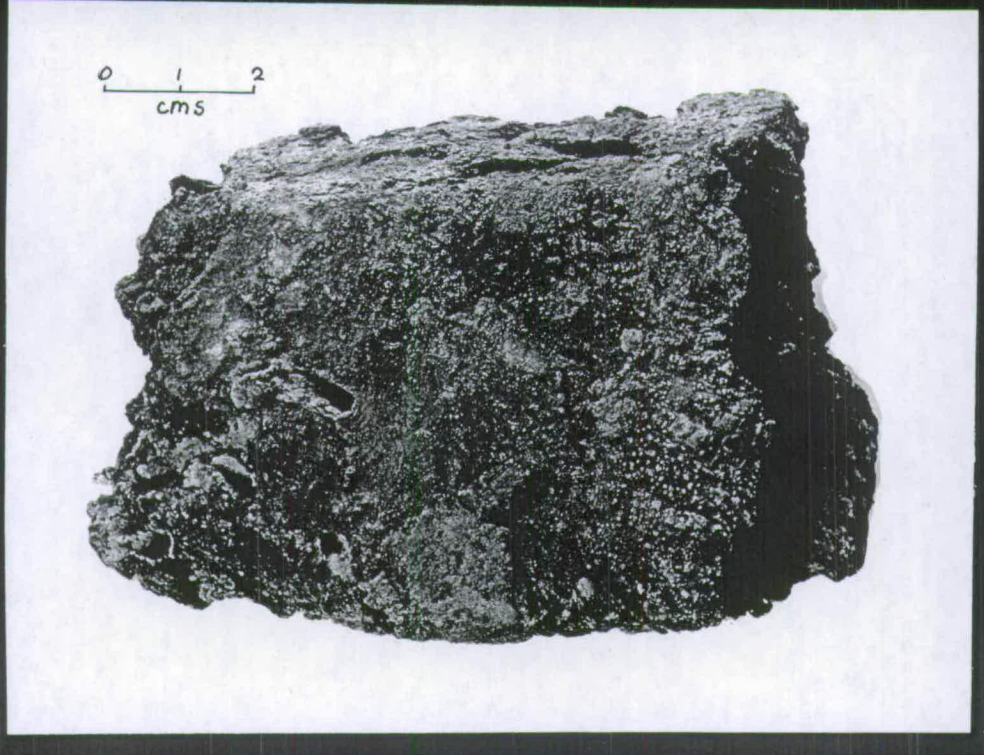


PLATE 22.

a. Arenicola marina nursery area on the upper mud flat at Locality 1 containing juvenile worms from spring 1964 spawning. Note that the lines of castings are confined to the wet areas on either side of the raised areas.

b. Cobbles on the lower beach near Locality 1 colonised by Elminius modestus and Balanus balanoides. The large white barnacles are B. balanoides, and they are surrounded by E. modestus.

a

b

PLATE 23.

a. Tree stump stranded on upper mud flat at Locality 1 colonised by Elminius modestus and Littorina littorea. The Littorina are confined to the sheltered cleft. The vertical and steeply sloping parts of the stump are colonised by Elminius.

b. Accumulation of hundreds of dead Corophium volutator individuals in an old footprint on the upper mud flats. August 1963.

a

b

PLATE 24.

a. Corophium volutator trails lower mud flat near Locality 3. The details of the trail are best seen on the crests of the ripples where the sediment is drier. The detail is lost in the ripple troughs where the sediment is damp.

b. High concentrations of Hydrobia ulvae on the banks of a small shallow channel on the upper mud flat.

a

b

PLATE 25.

a. Hydrobia ulvae spiral feeding trail, sand flats near west bank of Channel G.

b. Hydrobia ulvae and Macoma balthica trails, west bank Channel B.

a

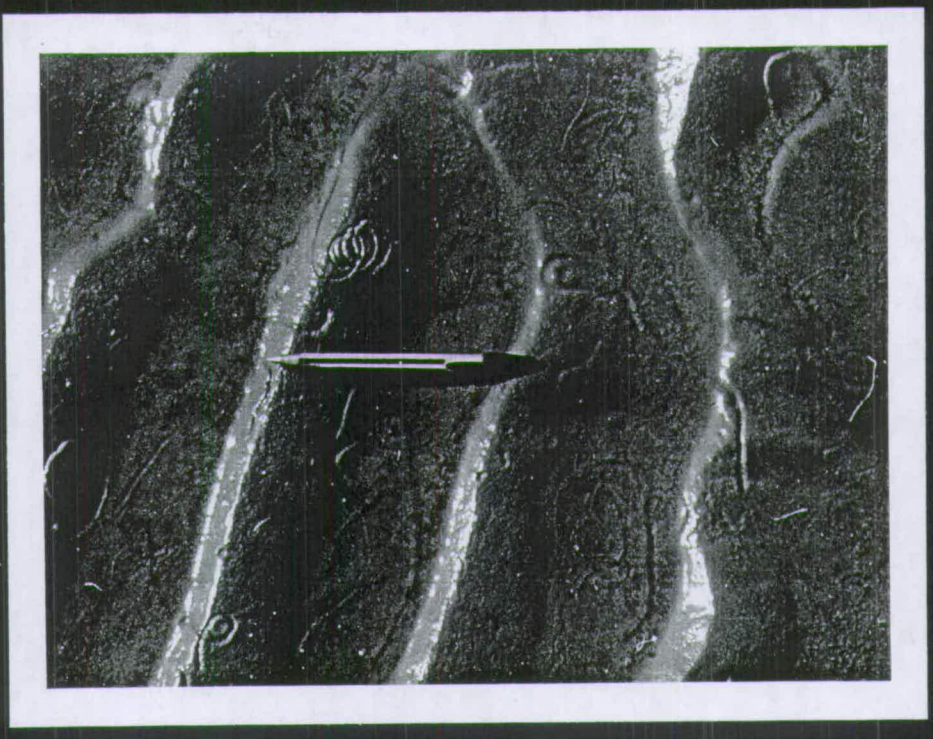
b

PLATE 26.

a. Retusa obtusa trail, sand flats near Station 2/11.

b. Small Enteromorpha compressa filaments on sand flats near Station 1/9 at the stage of growth seen in late March.

a



b

PLATE 27.

a. Enteromorpha mounds on the sand flats near Station 1/9 at the stage of growth seen in late summer.

b. Mytilus edulis spat attached to Enteromorpha filaments. Specimen was collected from an Enteromorpha mound in September.

a

b

PLATE 28.

a. Living Cardium edule eroded out of the surface layer by strong winds. Note depressions from which the shells have been lifted by the wind. Sand flat near Station 2/11.

b. Scrobicularia plana trail, upper mud flat near Locality 1.

a

b

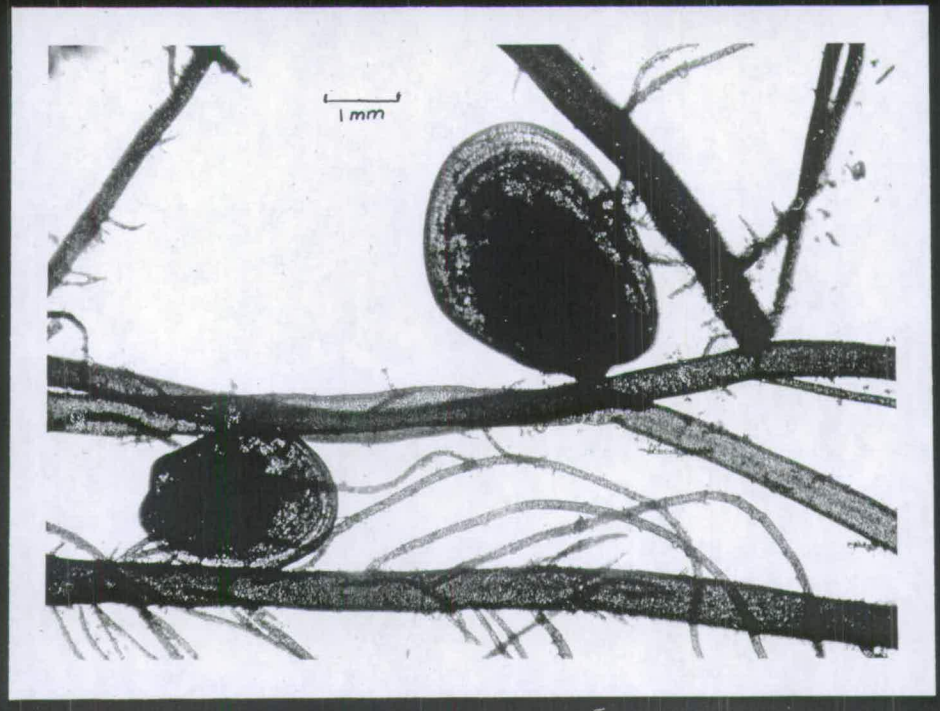


PLATE 29.

a. Macoma balthica trail in fairly dry sand. Note the ridge crossed by smaller transverse ridges marking successive positions of the anterior margin of the shell.

b. Dead Mya arenaria shells in their living position exposed on the east bank of the Carse Gut at Locality 11.

a

b

PLATE 30.

a. Group of Mya arenaria shells showing a preferred orientation roughly at right angles to the bank of the Carse Gut.

b. Polychaete U-burrow in the sediment filling a dead Mya arenaria shell.

a

b

PLATE 31.

a. Young Macoma balthica and Cardium edule living in the sediment filling a dead Mya arenaria shell.

b. Carcinus maenas individualin the protected environment of a dead Mya arenaria shell.

a

b

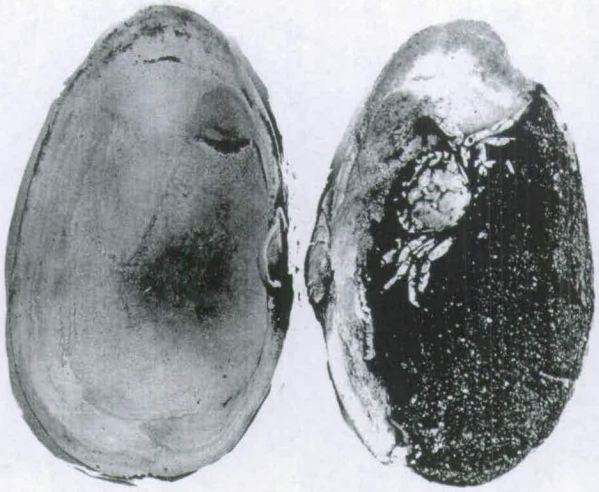
PLATE 32.

a. *Mytilus* valve in dead *Mya arenaria* shell.

b. *Mya* shell with part of the right valve broken by an Oystercatcher. Sand flats near Locality 20.

0 1 2 3 4
cms

a



0 1 2 3
cms

b

PLATE 33.

a. Beak mark made by oystercatcher attacking a *Mya arenaria*. The mark is enlarged by the bird rotating its head from side to side. Sand flats near Locality 80.

b. Crop 'coprolite' consisting of numerous *Macoma* fragments, upper mud flat at Locality 9.

a

b

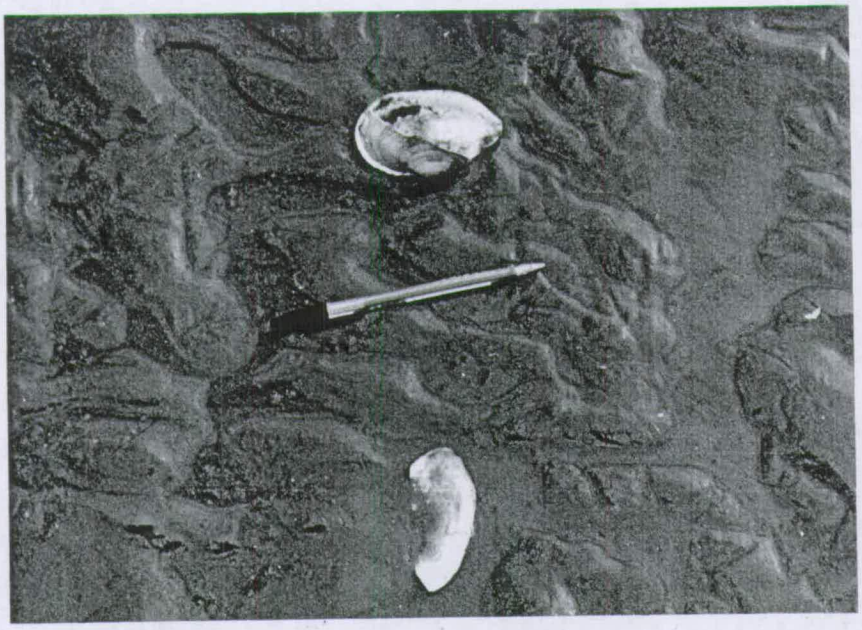


PLATE 34.

a. 'Helminthoid' trace on upper mud flat formed by a bird sweeping the sediment surface with its beak as it moves forwards.

b. Valve Fragmentation Patterns.

A. Posterior portions of broken Mytilus edulis valves. The inner nacreous layer has become detached.

B. Umbo and hinge area of Mytilus valves showing the loss of parts of the calcitic layer exposing the nacreous layer.

C. Cardium edule valve with the central portion lost.

D. Cardium valves broken along a rib furrow.

a

b

PLATE 35.

Characteristic Shell Fragments.

a. A. Part of crenulate margin of C. edule with 1 rib.

B. " " " " " " " 2 ribs.

C. " " " " " " " 3 ribs.

D. Lateral tooth of C. edule.

F. Umbo and cardinal teeth of C.edule.

E. Fragments of the prismatic and nacreous layer of M. edulis.

b. A. Macoma balthica fragments from a 'crop coprolite'.

B. Macoma crescent fragments.

C. Umbonal parts of Macoma valves attached by a strong ligament.

D. Scrobicularia plana crescent fragments.

E. Part of chondrophore of Mya arenaria.

F. Chondrophore, umbo and dorsal margin of Mya arenaria left valve.

a

b

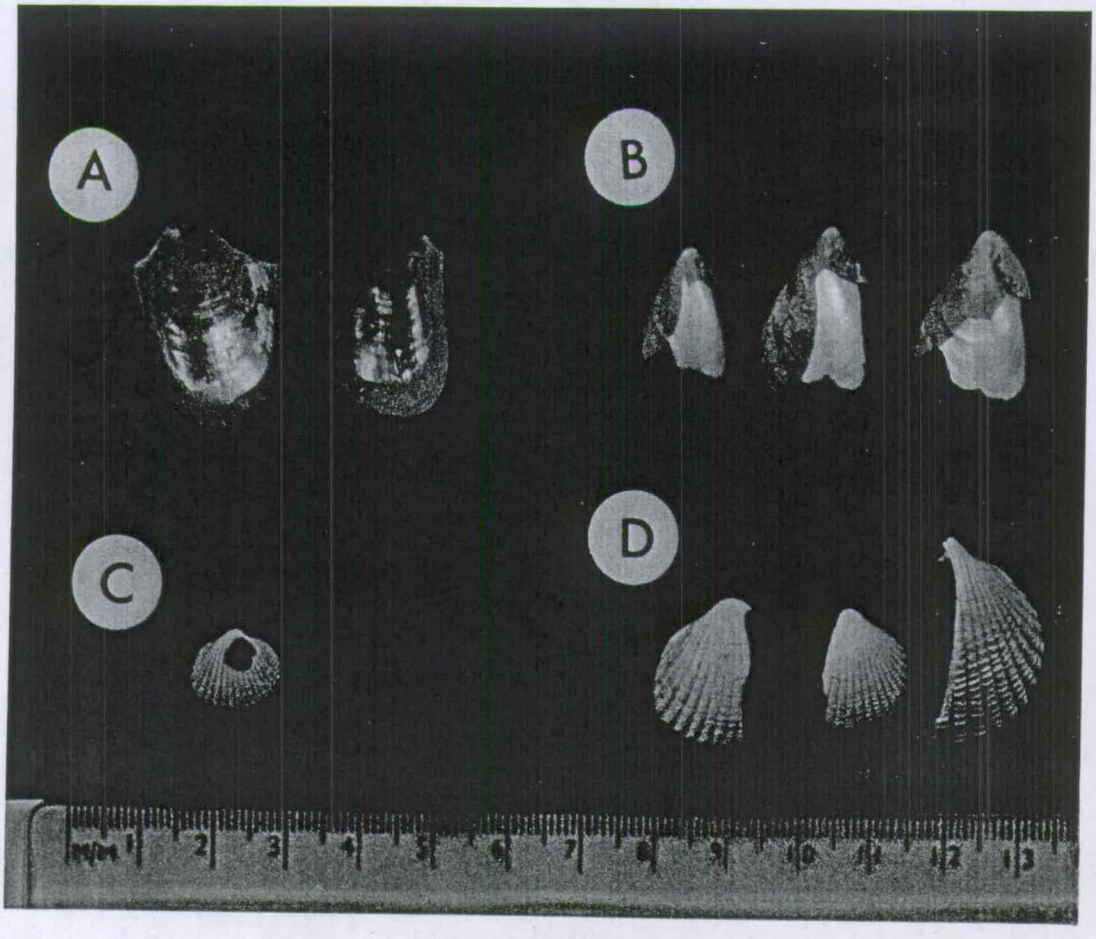
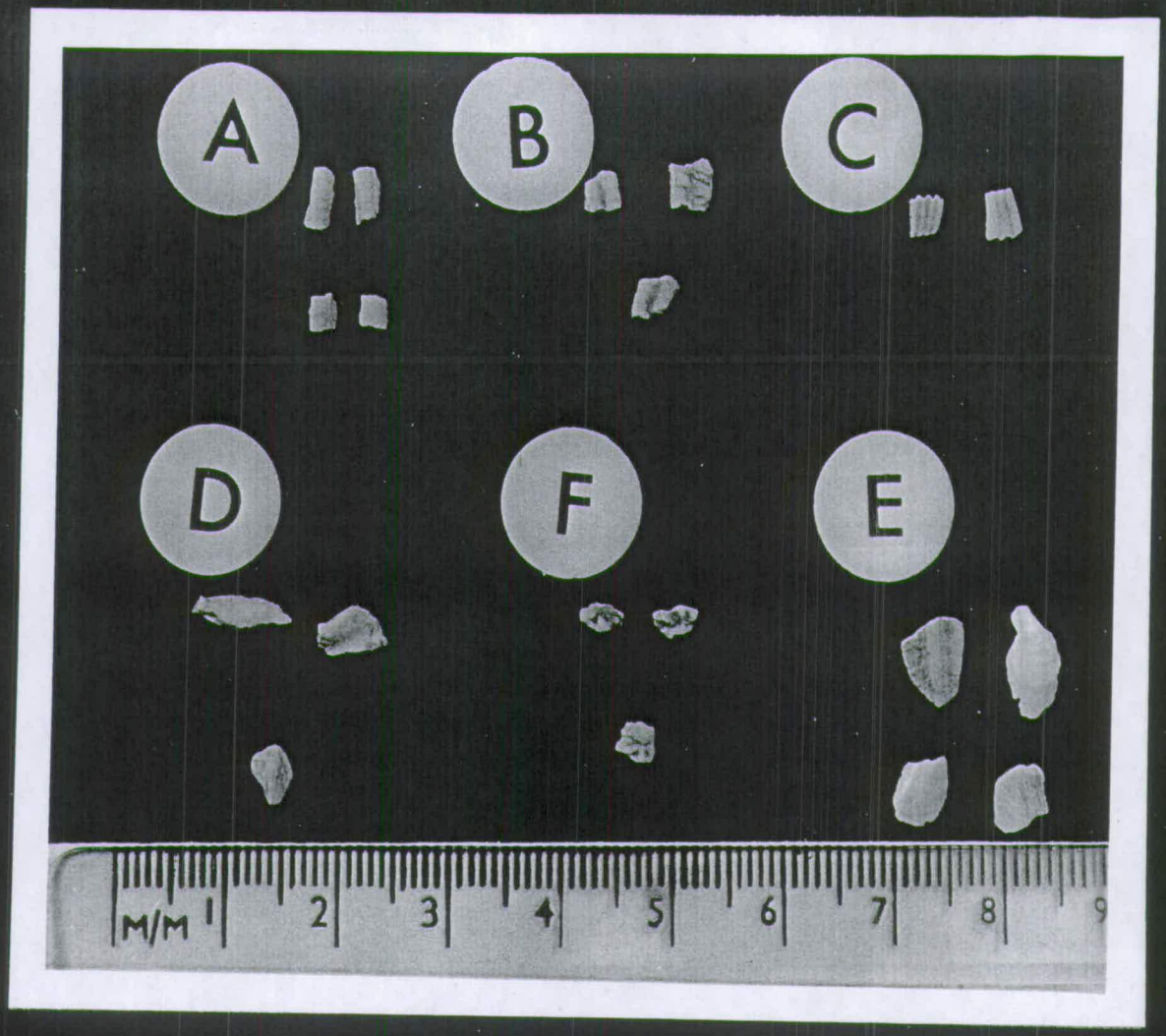


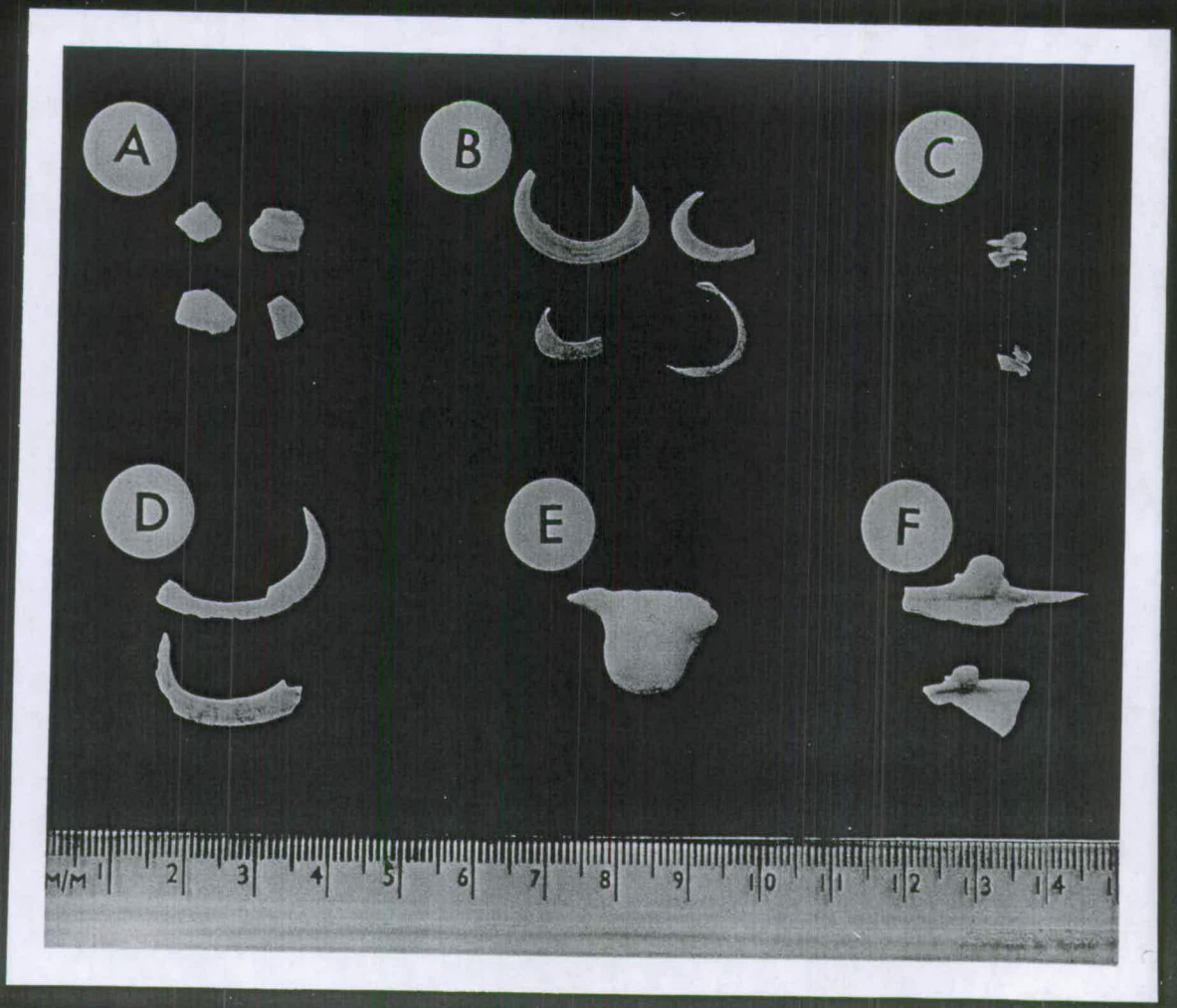
PLATE 36.

a. Modiola modiolus valve with attached seaweed, Carse Gut Flood Channel near Locality 3.

b. Laminated blocks lying in the soft mud at the foot of the east bank of the Carse Gut at Locality 4. Note the high angle of the lamination in the fallen blocks.



a



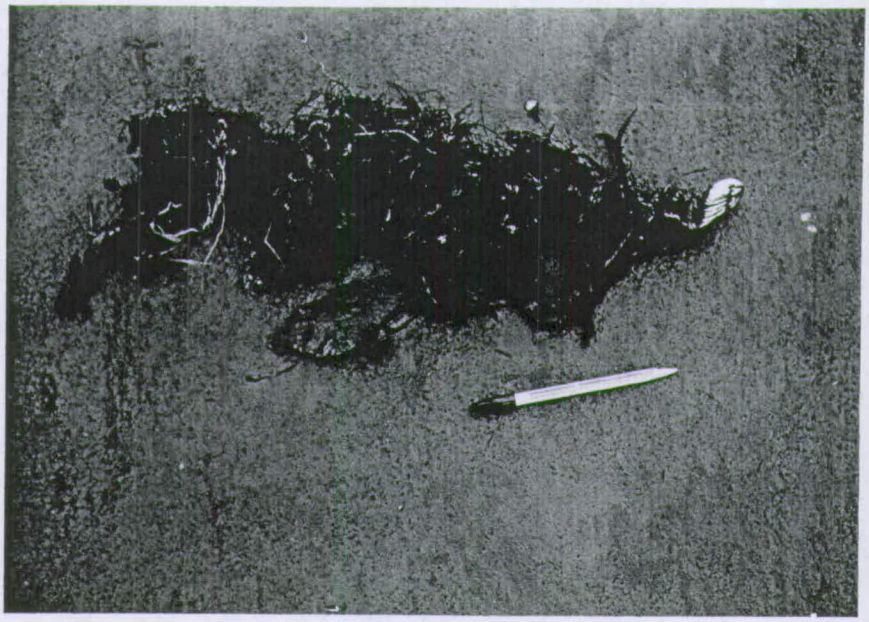
b

PLATE 37.

a. Terrace erosion, west bank of Channel B.

b. Edge of terrace showing prominent clay laminae and the development of a small secondary terrace.

a



b

PLATE 38.

a. Irregular terrace erosion and isolated terraced areas associated with small temporary drainage channels. West bank of River Nith Channel near Station 1/16.

b. Rapid Reworking During Storms

Cane inserted at edge of receding east bank of the Carse Gut at Locality 12. Note undercut block falling into the Carse Gut.

4.04 p.m., 12th September 1962.

a

b

PLATE 39.

Rapid Reworking During Storms.

a. Cane now 2.3 metres from edge of bank. Note fallen blocks at foot of vertical bank.
4.54 p.m., 12th September 1962.

b. Cane now 2.5 metres from edge of bank. Note black anaerobic zone 2-5 cms below the surface.
6.14 p.m., 12th September 1962.

a

b

PLATE 40.

Rapid Reworking During Storms

a. Active undercutting taking place along the total length of the bank at Locality 12.
7.04 p.m. , 12th September 1962.

b. Grading of east bank of the Carse Gut at Locality 12 after two high tides. Note the resistant terrace formed by the anaerobic layer.
4.04 p.m., 13th September 1962.

a

b

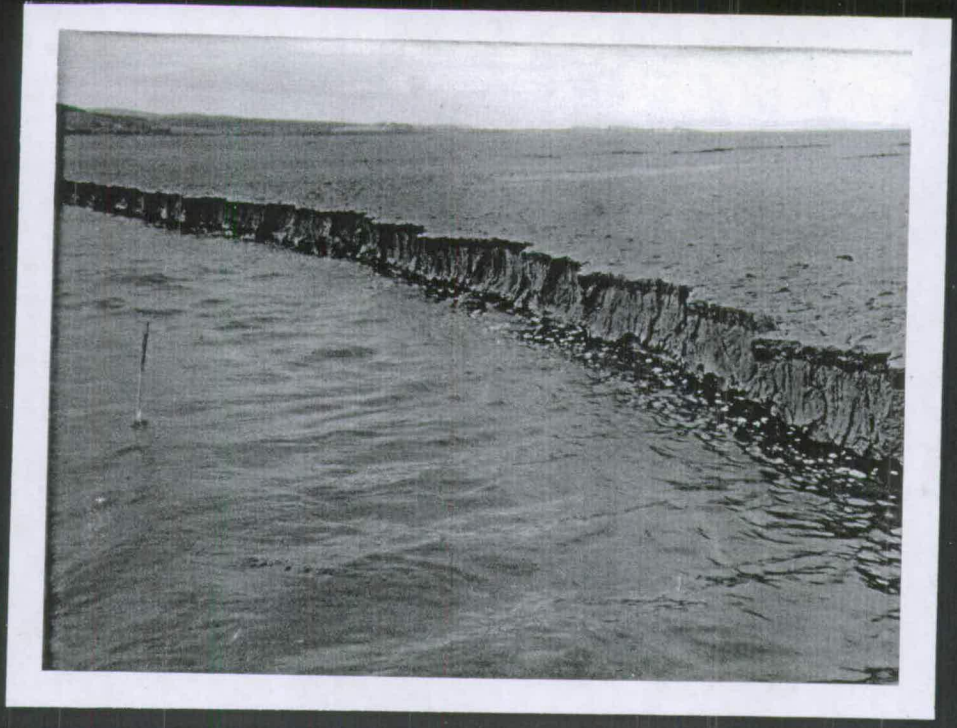


PLATE 41.

Rapid Reworking During Storms.

a. Deep narrow clefts along planes of weakness formed by ebb waters draining off the flats. East bank, Carse Gut at Locality 12. 13th September 1962.

b. Abandoned storm course of Carse Gut past Locality 12. The position of the bank is marked by the resistant terrace formed by the anaerobic zone. 22nd September 1962.

a

b

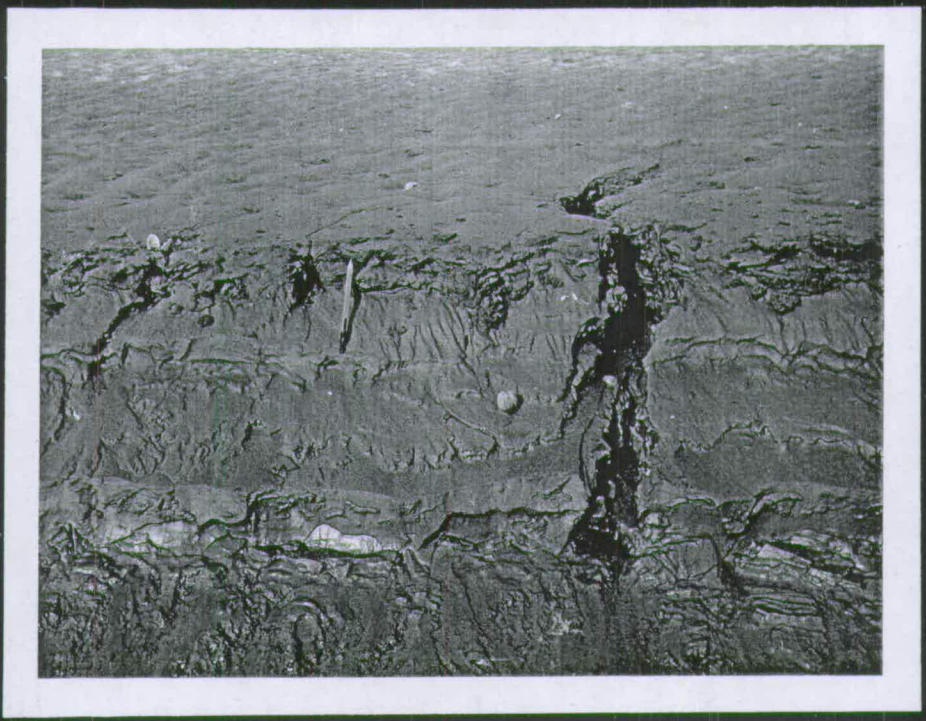
PLATE 42.

Rapid Reworking During Storms

a. Minor tributary draining the flats to the east of the Carse Gut.
4.30 p.m., 12th September 1968.

b. 'Hanging valley' of the minor tributary formed by the recession of the east bank of the Carse Gut.
6.05 p.m., 12th September 1962.

a



b

PLATE 43.

Rapid Reworking During Storms.

a. Delta formed at mouth of minor tributary associated with the grading of the east bank of the Carse Gut at Locality 12.
13th September 1962.

b. Enlargement of delta at mouth of minor tributary onto the floor of the abandoned storm course of the Carse Gut.
22nd September 1962.

a

b

PLATE 44.

Rapid Reworking During Storms

a. Living Mya arenaria exposed in the vertical face of the receding east bank of the Carse Gut at Locality 12.
12th September 1962.

b. Dead Mya arenaria individuals reworked from the east bank of the Carse Gut lying on the soft mud at the foot of the bank. The siphons point upstream.
13th September 1962.

a

b

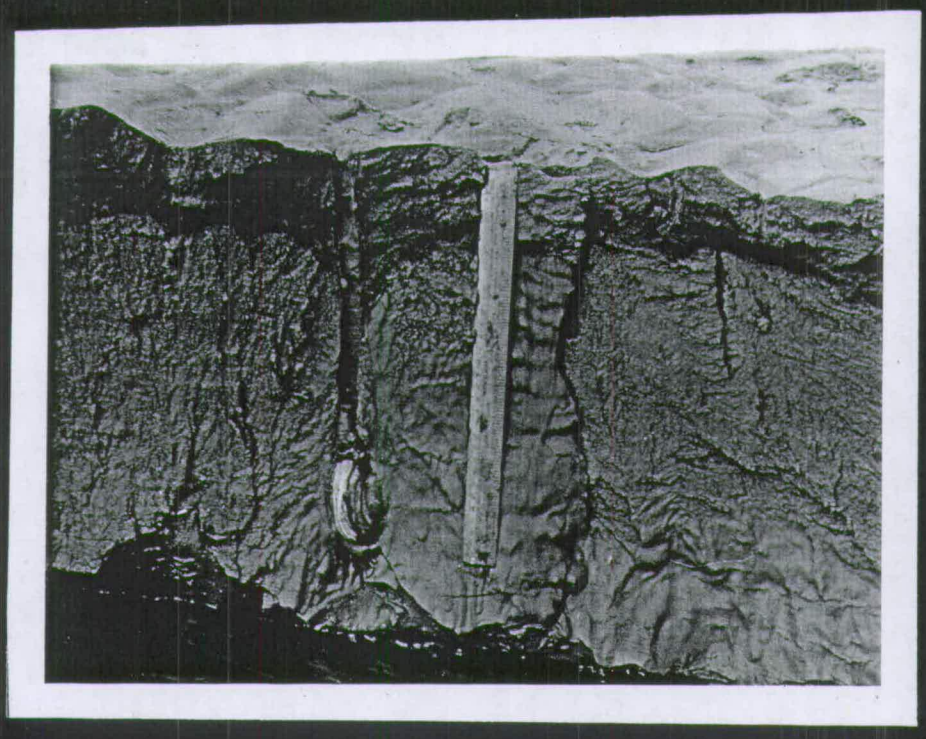
PLATE 45.

Rapid Reworking During Storms

a. Living Arenicola marina exposed in the vertical face of the receding east bank of the Carse Gut at Locality 12.
12th September 1962.

b. Resistant mucilage-bound tail tube of Arenicola marina exposed during the grading of the east bank of the Carse Gut at Locality 12. The tube is 5cms. in height.
13th September 1962.

a



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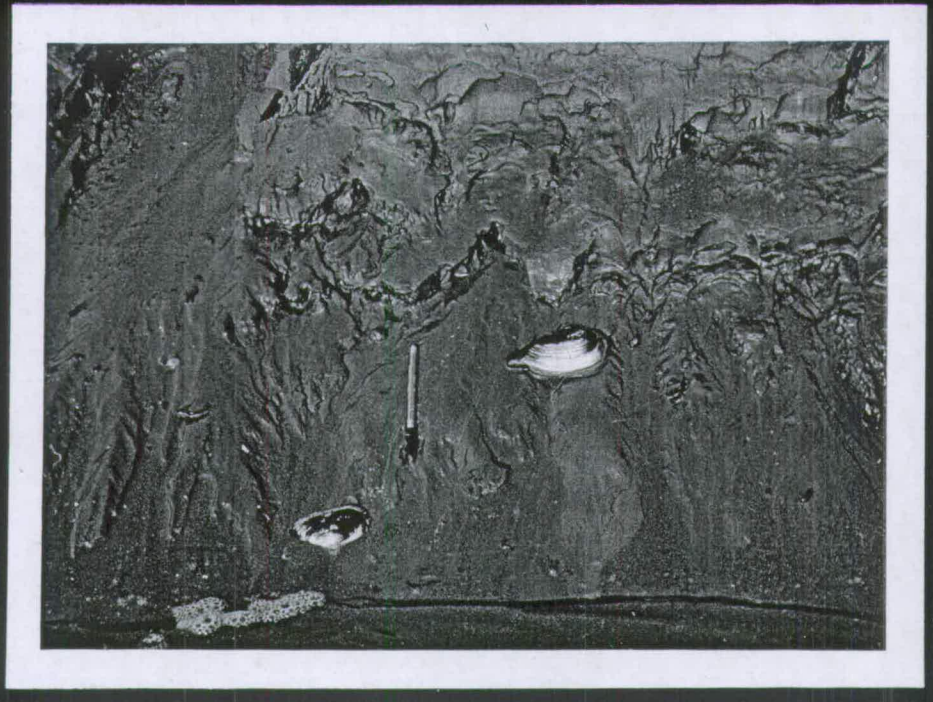
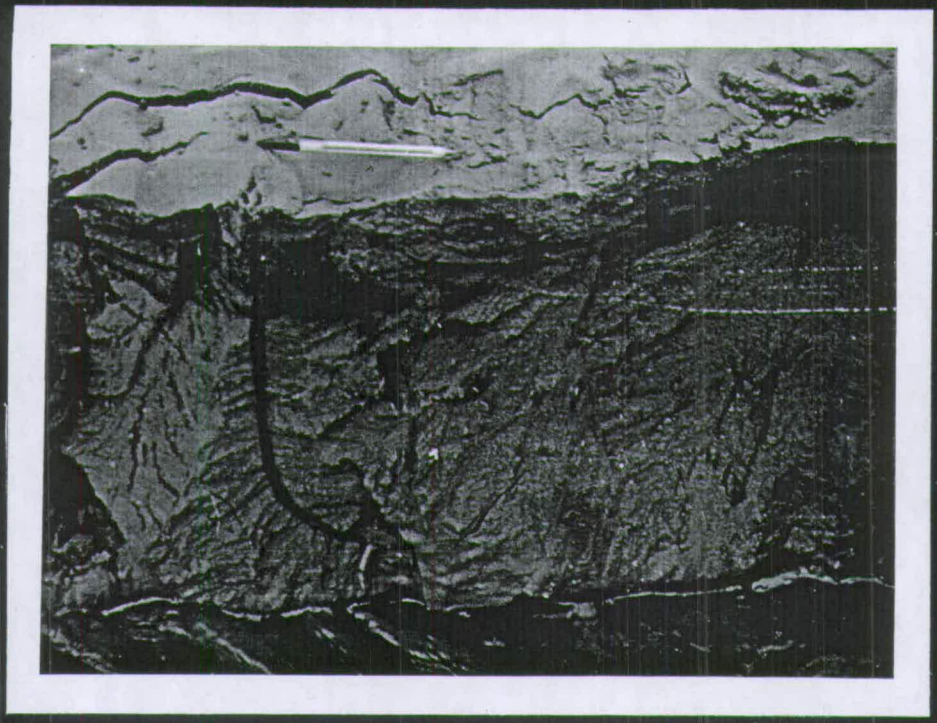


PLATE 46.

a. Growth of new meander in the Carse Gut at Locality 11 looking northwest, 9th August 1963. Note development of small drainage channels on the new bank. The two stakes mark the September 1962 position of the east bank of the Carse Gut.

b. Growth of new meander in the Carse Gut at Locality 11 looking southeast, 13th September 1963. A small portion of the new bank has been cut off and a small island formed.

a



b

PLATE 47.

a. Panorama of Carse Gut Flood Channel and the small tributary draining the lower mud flat.
4th January 1964.

b. Panorama of the new course of the Carse Gut along the former flood channel. Note the small drainage channel marking the former course of the Carse Gut.
8th April 1964.

a

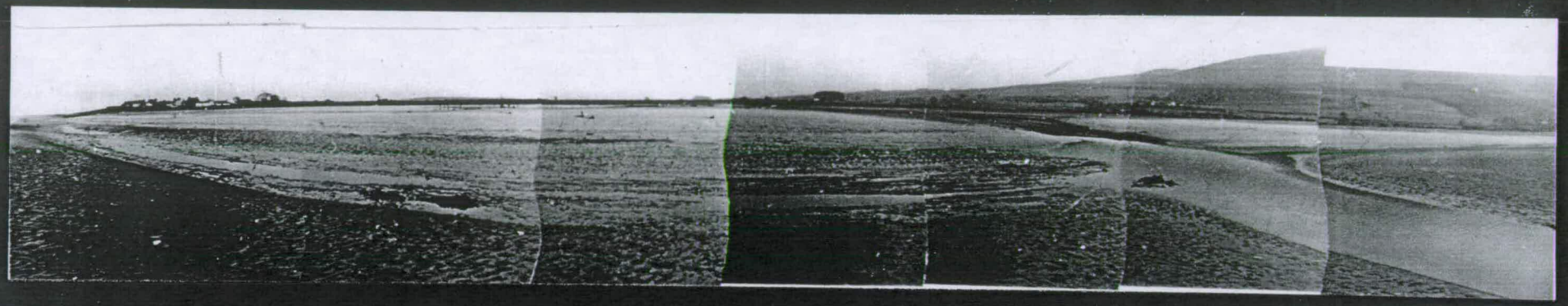
b

PLATE 48.

a. Former course of Carse Gut past Locality 11 looking southeast. The old channel is marked by the pools of water. Note remains of the former west bank. 8th April 1964.

b. Gully formed by the enlargement of the valley of a small channel by a waterfall. The 'fall maker' is a resistant band of organic debris. Upper mud flat at Locality 8, 15th September 1962.

a



b

PLATE 49.

a. Surface shell-bed near east bank of Channel D. Note the *Cardium edule* valves lying concave upwards.

b. Shallow channel-floor shell-bed on upper mud flat near Station 1/2.

a

b

PLATE 50.

Former channel-floor shell-bed exposed in the receding east bank of the Carse Gut at Locality 4.