TOWARDS A PROCESS-RESPONSE MODEL FOR CLIFFED COASTS: THE CASE OF NORTH-EAST YORKSHIRE

by

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VOLUME 1

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The research into coastal erosion in north-east Yorkshire, of which this thesis is the result, was instigated because initial reconnaissance by Mr. J. Palmer had revealed that the published work on the topic was partly in error. The conclusions reached during that preliminary study have now been made public (Eyre and Palmer, 1973). The research was made possible by the award of a Natural Environment Research Council Research Studentship. Mr. J. Palmer has been my supervisor and has made valuable criticisms of earlier drafts of this thesis. He has also supplied the map reproduced as Fig. 1.3.

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CONTENTS

VOLUME 1

DIAGRAMS, PHOTOGRAPHS AND TABLES

VOLUME 1

Chapter 3

Chapter 4

page

Chapter 5

VOLUME 2

Chapter 6

Chapter 7

ABSTRACT

Within the coastal supersystem there are the two main systems of the cliff and the foreshore and thirdly, but at a lower hierarchical level, the coastline system. The forms of and processes shaping each of these physical features are analysed quantitatively. Instrumented sites have been set up for the measurement of rates of erosion of the shore platform, of other foreshore features, and of the cliff foot over a longer period than has so far been possible. A section of cliff has also been instrumented.

An original technique for the analysis of coastline morphology is described. Bays that are fundamentally arcuate, triangular, or rectangular are associated with different extraneous factors, the first particularly with a bare cliff foot or a sand or pebble beach, the second with a boulder beach or geological heterogeneity and the third with glacial deposits.

The cliff consists of any combination of the elements termed the sandstone scarp, the bevel, and the marine-activated cliff. The bevel results from protection of the cliff foot by talus cones and boulder beaches. It is concluded that bevelled cliffs are in dynamic equilibrium though relaxation time is long, leading to continuous changes in form. A cliff consisting of the marine-activated element only is probably a steady-state feature and is associated with a bare cliff foot or one which has a sand or pebble beach.

The shore platform may include any combination of two elements, the ramp and the plane, the former being steeper than 2.5 degrees and shaped by the corrasion of the overlying debris. The sub-horizontality

of the plane is a product of secondary erosive processes - mainly expansion and contraction of the shale due to wetting and drying in tidal and intertidal periods.

The resistance of boulder beaches is increased if the boulders become imprisoned. Boulders partly embedded in the shore platform may remain perched when this feature is lowered. In the base of talus cones conglomerate can be formed in less than 200 years.

Therefore the nature of the cliff foot is the principal regulator in the coast supersystem but superficial deposits undergo erosion so this regulator and the supersystem continuously change. Measurements of erosion rates show that it is incorrect to hypothesise that some of the coastal landforms have been inherited from Pleistocene times.

CHAPTER 1

INTRODUCTION

Some Basic Definitions

This study is concerned with the geomorphology of a cliffed coast. Although terms such as "cliff", "shore platform", "foreshore", "coast" and "coastline" are in everyday usage, different meanings are often attached to them so that it is necessary to define them strictly for the purpose of the ensuing discussion. In view of the radically different processes which have been proposed for the genesis of many coastal landforms, these definitions are purely descriptive and have been designed primarily for use on the north-east Yorkshire coast alone. A hierarchical organisation of all the terms defined is presented as Fig. 1.1.

The term coast refers to the whole complex of features found bordering the sea and directly or indirectly produced by marine processes with the sea at that level. That area of land which forms the coast is composed of the cliff and foreshore and lies between the cliff top and the edge of the sea.

The cliff is the zone between the plane of marine erosion and the surface of sub-aerial erosion; in north-east Yorkshire it usually has an inclination greater than 40 degrees. The cliff top is the sharp break in slope between the cliff and the main land surface while the cliff foot is also a sharp junction where it is developed in solid rock. Where talus lies on the shore platform the cliff foot is less obvious and may arbitrarily be taken as the mean high water mark. The sandstone scarp is a near-vertical face which is intimately related to the outcrop of sandstone strata in the cliff. The bevel, a plane whose inclination is 40 to 50 degrees, may also cut across sandstones but it is usually developed on shales and lies above the marine activated cliff. This latter feature is a slope of more than 50 degrees and is being formed by the present sea which attacks its base. It should be noted

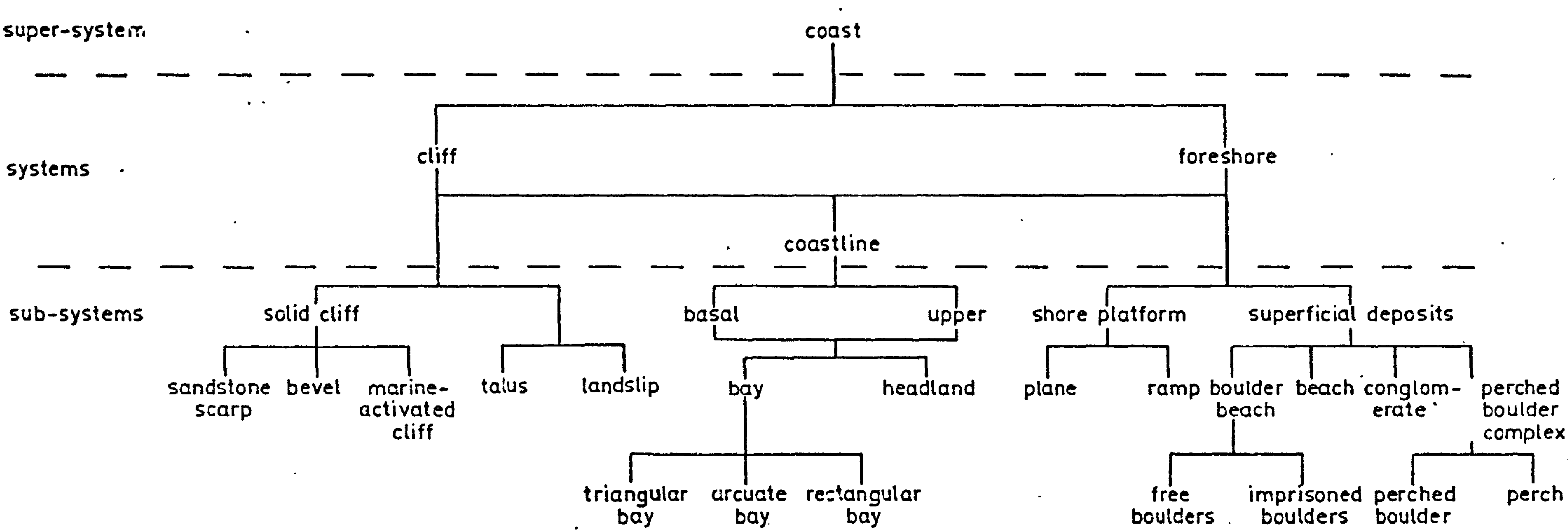

Fig.1·1 The hierarchical organisation of terms that the terms "activated" or "active" for this part of the cliff do not imply that the remainder, the bevel and sandstone scarp, are relict features. The term talus is used in its normal sense; talus is the accumulation product of individual falls of rock fragments and is in the form of single or coalescent cones. Landslips are different from talus in that large masses of rock slide on a few slip planes and rotational movement is sometimes involved. Landslips are few in the solid rock sections of the north-east Yorkshire cliff but are common in the zones where glacial material crops out.

The shape of the cliff in plan is referred to as the coastline. At a small scale the differences between the cliff foot and the cliff top are irrelevant but the large scale and detailed nature of this study demand that they be recognised. Hence, the cliff foot in plan is termed the basal coastline and the cliff top plan the upper coastline. Both these coastlines consist of bays and headlands (rectilinear sections are absent from the north-east Yorkshire coastline). Bays are those parts which are concave towards the sea while headlands are convex in this direction. In this study bays are classified according to their basic shapes (triangular, arcuate, or rectangular) but because of the infancy of the analytical technique, headlands have not been similarly categorised.

The foreshore is the complex of principally marine-influenced features; it includes the shore platform and any superficial deposits lying on it. The shore platform is an erosional feature developed in solid rock and exposed completely at mean low spring tides. It is essentially a low-angle feature bounded on the landward side by the cliff and on the seaward edge by the sea. It may consist of two features, the ramp, a slope of 2.5 to about 10 degrees near the cliff foot and the plane, a subhorizontal facet with an inclination less than 2.5 degrees and normally constituting most of the shore platform. There is inevitably some overlap between the terms "talus" and superficial deposits since a talus cone is usually eroded at its base by the sea to form a boulder beach. Some superficial deposits remain in one position for a very long time, e.g. perched boulders and conglomerate but, because they have once been moved, they are not part of the shore platform. On the other hand, hard concretions in the rock may become perched also, but since they are in situ they are considered to be part of the shore platform.

The Physical Setting of the Study Area

The British Isles lie in temperate latitudes and are subjected to the meteorological conditions produced by vigorous depressions. High winds are not uncommon and lead to stormy seas with great potential for erosion. Parts of Britain are still undergoing isostatic uplift (Valentin 1953) and it is generally held that the post-glacial eustatic rise of sea level is continuing (Schofield 1960, Shepard 1963, Mörner 1969). There is a general lack of land close to sea level and an absence of large river systems depositing much sediment. These factors help to explain the abundance of cliffs and erosional features around England and Wales.

The western coasts are formed mainly of resistant Palaeozoic metamorphosed sedimentary rocks and erosion is slight, for relict features produced during or before the last glaciation are common, for example in Cornwall and Devon (Arber 1949, Orme 1962), in Wales (Wood 1959), in Anglesey (Hopley 1963) and in the Isle of Man (Phillips 1970). In the east, cliffs are developed in softer rocks - late Palaeozoic and Mesozoic sediments north of Flamborough Head and Tertiary and Quaternary clays and tills in Holderness and East Anglia. In these last two areas erosion is very high being, for example 120m. on average between 1852 and 1952 in Holderness (Valentin 1971). This is because the rock is very susceptible to subaerial erosion, a high water content producing landslipping. Such coastlines have landforms which are very different from coasts of hard coherent rock where the cliffs are steep, landslipping is rare, and shore platforms exist. Therefore the coasts of southern and north-eastern England where Mesozoic rocks crop out are the most favourable areas for the study of littoral erosional landforms and processes in hard rock since it is in these places that erosion is sufficiently rapid to be measurable within a short period of less than three years. North-east Yorkshire between Ravenscar and Saltburn-on-Sea (Fig. 1.2) is ideal in a number of respects for such a study because geological variations such as rapid changes in rock type, pronounced bedding planes, and intense folding and faulting are rare. A more detailed knowledge of the geology of the area emphasises its homogeneity; a map of the solid geology is shown in Fig. 1.3.

The Geology of the Study Area

Following the marine transgression at the start of the Jurassic period, the deposition of the thin Rhaetic strata was followed by the quiet sedimentation of the Lower Lias muds and very fine sandstones (Rayner 1967). Only the upper half of this thick formation is exposed in north-east Yorkshire (Fig. 1.4a). Calcilutite nodules are few and though occasional pieces of coal are present there has never been any mining for soft jet.

Next was deposited the Sandy Series, a thin series of fine-grained sandstones, strata individually being up to three feet thick, alternating with beds of silt and a sparse admixture of ironstone nodules. The joint system in these rocks is not as dense as that in the Lias shales, and large blocks of rock are the result.

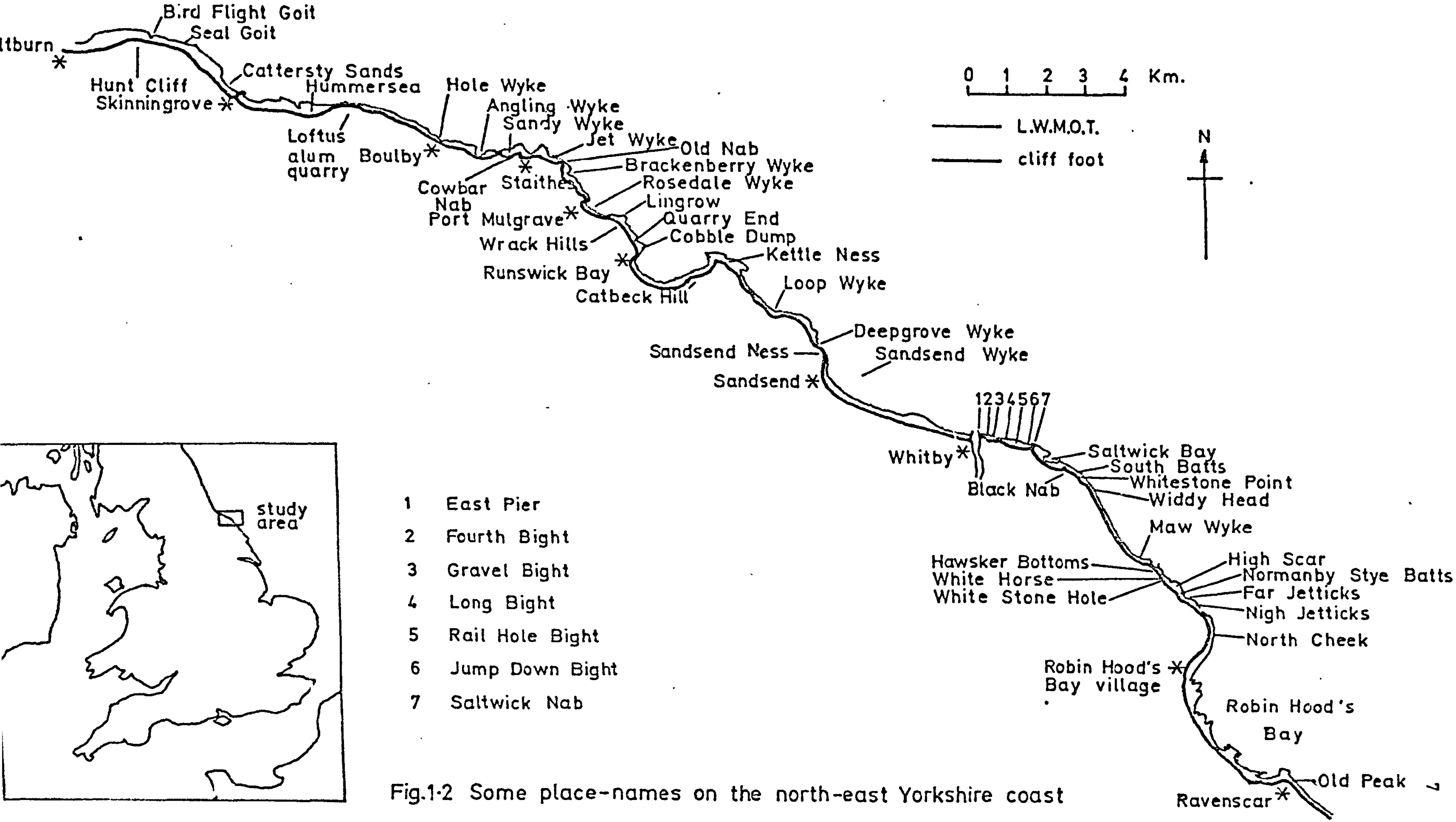

Fig.1·2 Some place-names on the north-east Yorkshire coast

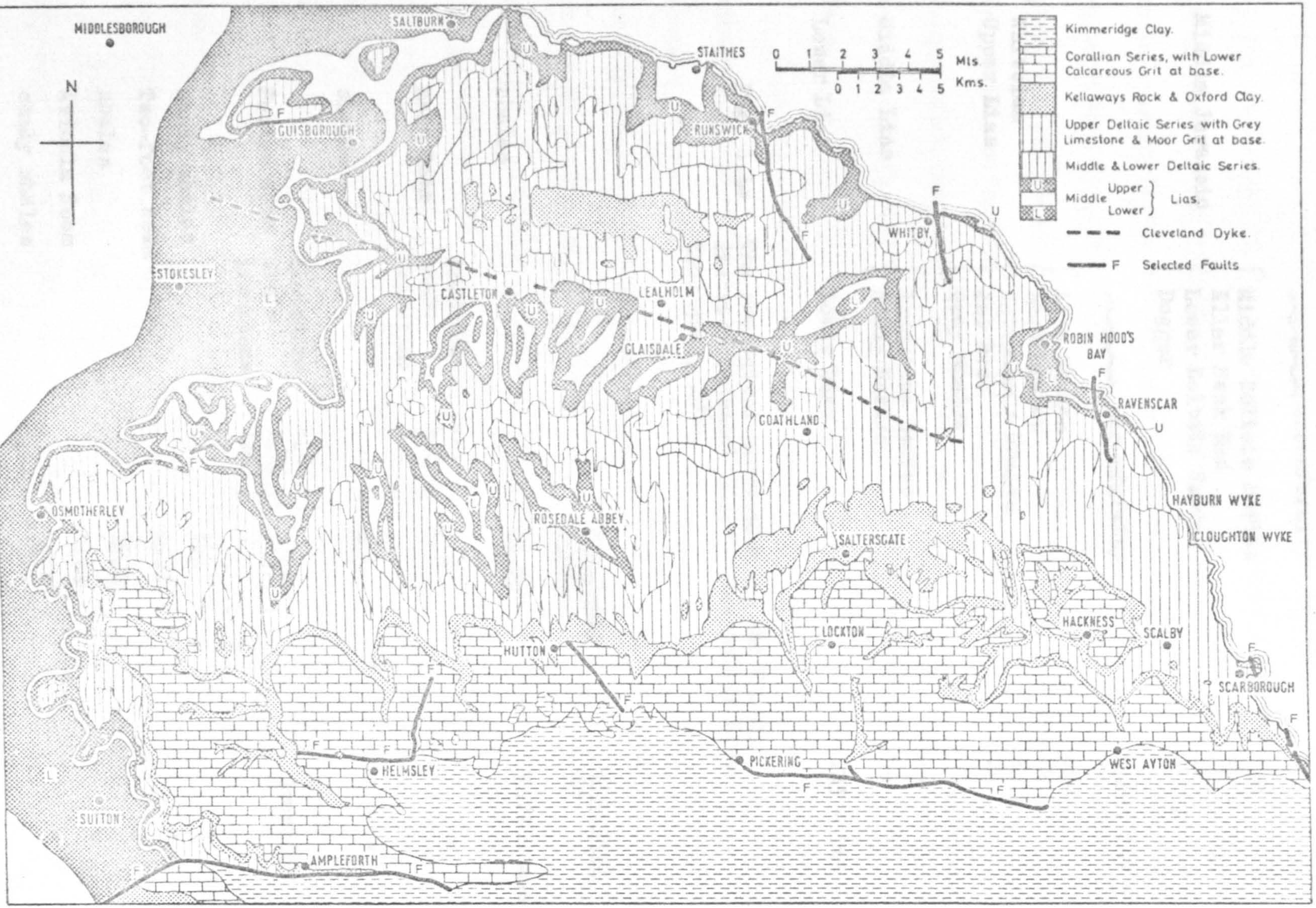

Fig. 1·3 The geology of north-east Yorkshire

Period	Name	Maximum thickness (feet)
Pleistocene	Glacial Deposits	0 to >200
	unconformity	
Middle Jurassic	Middle Deltaic Series	190
	Eller Beck Bed	12 - 20
	Lower Deltaic Series	103
	Dogger	0 - 8
	unconformity	about 149
Whitbian Upper Lias	Alum Shales	65
	Hard Shales	21
	Bituminous Shales	65.5
	Jet Rock	28
	Grey Shales	30
Middle Lias	Ironstone Series	93
	Sandy Series	54
Lower Lias	Lower Lias	703 - 944

Fig. 1.4a The geological succession in the Whitby district (stratal thicknesses mainly from Hemingway, 1958)

			Thickness (feet)	Measured at
shales			12.25	Kettleness
Main Seam	ironstone	1.7	6.7	"
	shale	2.0		
	ironstone	3.0		
shales			8.5	"
Pecten Seam	ironstone	0.5	3.58	Grosmont
	shale	1.25		
	ironstone	1.83		
sandy shales			3.5	"
Two-foot Seam			0.83	"
shales			25.0	"
Avicula Seam			0.83	"
sandy shales			31.5	"

Fig. 1.4b The Ironstone Series (after Hemingway, 1958)

Quieter sedimentation was resumed after deposition of the Sandy Series. Muds were laid down with thick beds of ironstone. Four of these seams (Fig. 1.4b) have been intensively worked in places especially in the north-west of the study area as they become thinner and increasingly split south-eastwards (Howarth 1955). A fuller account of the former industries on the north-east Yorkshire coast and their effects on landforms is given in Appendix I. The iron is in the form of siderite, chamosite and limonite in a matrix of calcite, opaline silica and clay. The seams are therefore extremely hard and can be broken only along the joints which transect them. Their resistance to erosion may have been a contributory factor in the formation of the promontory called Kettle Ness.

Deposition of muds continued throughout Upper Lias times in mainly anaerobic euxenic conditions which allowed the generation of a high oil content in the shales. Driftwood was compressed producing the high quality jet which was much sought after during the last century (Appendix I). Mining of jet was facilitated by the existence of a hard argillaceous limestone, the Top Jet Dogger, which formed the roofs of the adits. This bed is also resistant to erosion and may have been important in the formation of Saltwick Nab. The highest formation of the Upper Lias, the Alum Shales, is well suited to the production of alum because of its high pyrites content and low proportions of calcium and oil. The quarrying of this rock was a major industry at several places (Appendix I), the operations being aided, as with the rest of the Upper Lias shales, by the finely laminated bedding and close jointing.

Gentle uplift, folding and erosion during Yeovilian times was succeeded by the deposition of the Dogger, a tough siderite sandstone of remarkably uniform thickness throughout the study area. With an iron content of 20 to 24 per cent it weathers to a rusty brown and is very conspicuous in the cliff. It does not crop out on the shore platform which from Ravenscar to Saltburn consists of Liassic rocks only.

The succeeding medium-grained sandstones of the Lower Deltaic Series are often massive, lenticular channel sandstones which occasionally penetrate up to 20 feet into the Alum Shales. Between the beds and lenses of sandstone lie laminated micaceous yellow-brown silts and light-grey seat earths with the fossilised roots of plants in situ. Soft jet is found in these clays but there is no evidence of it having been mined in the cliff face. The sandstones and shales of the Eller Beck Bed and of the Middle Deltaic Series are very similar to the Lower Deltaic Series except that channel sandstones are not as common. All the Middle Jurassic strata, because of the structural competency of the sandstones, have joint systems which are less developed than those of the Lias shales.

In Oligocene/Miocene times, tectonic activity produced the series of gentle domes and basins and occasional faults found in the area (Versey 1948, Dingle 1971). The folding in Robin Hood's Bay is very evident from the arcuate pattern which the Lower Lias strata make on the shore platform. North-westwards, farther from the dome's centre, the strata dip at only 2.5 to 3 degrees until at Widdy Head, the Middle Deltaic Series is exposed in the cliff. A small basin has its centre beneath Whitby and in its limbs are subsidiary folds which bring the Dogger from +100 feet at Saltwick Nab to sea level at Long Bight, a distance of only half a mile. These are the steepest beds in the area but do not exceed five degrees. North-west of this point the strata again dip only gently so that the Jet Rock crops out in the cliff for all its length between Sandsend and Runswick Bay where one of the major faults of the area exists and gives rise to several small faults in Rosedale Wyke.

The final event of geological importance in the study area was the arrival of the Weichselian ice sheet. This laid down thick tills more than 200 feet deep in a number of pre-Weichselian valleys. However, these tills are thin or absent along most of the cliff top. At Robin Hood's Bay and from Whitby to Sandsend fluvioglacial sands and gravels up to 30 feet thick occur within the till. As along other British coasts where tills are exposed at sea level, erosion can be very rapid with the result that glacially plugged valleys now terminate in prominent bays, e.g. Runswick Bay.

From this brief account it can be concluded that the simple geology of north-east Yorkshire allows the development of landforms which are not greatly complicated by geological variations. Further, the unresistant nature of the shales permits erosion to be measured frequently.

Previous Work

Though geomorphological work in coastal areas has been considerable, it has tended to concentrate on beaches and the effects of constructive wave action. Research into the processes and effects of coastal erosion is relatively limited and studies employing quantitative techniques are especially scarce. Recent work on coastal cliffs has focused on the problem of the bevel which has often been thought to be a relict feature of periglacial origin. Such studies of cliff form include those by Agar (1960) in north-east Yorkshire; Arber (1949), Robson (1950) and Savigear (1962) in Cornwall and Devon; Hopley (1963) in Anglesey; Richards (1969) in the Isle of Skye; Orme (1962) in

Ireland; Fleming (1965) in the Auckland Islands; and Wood (1959) around Aberystwyth. Recent works dealing with the processes acting on marine cliffs include those of So (1966) on the soft London Clay cliffs of the Kent coast; of May (1964) in south-eastern England; and of Rudberg (1967) on the coast of Gotland, but no quantitative techniques have been used other than estimates of the rate of coastline erosion from the comparison of successive editions of plans. This long-established technique has also been used by Westgate (1957) in Durham but has found its most common application in the examination of rates of erosion on coastlines composed of soft rock such as tills and clays, e.g. Valentin (1971) in Holderness. Coastal erosion has also been estimated by Emery (1941) from dated inscriptions on cliffs and by Shepard and Grant (1949) from photographs.

Published works on shore platform morphology are more numerous. Early researchers were concerned with the recognition of different genetic types of shore platform, e.g. the Old Hat type due to sub-aerial weathering (Bartrum 1926), the storm wave platform of Bartrum (1935) and Edwards (1941), the spray erosion type (Ongley 1940), the water-levelling class of Wentworth (1938), and the type formed by solution (Wentworth 1939). In addition to the specific processes associated with these different sorts of platform, bio-erosion by rock-boring organisms (Healy 1968a) and gastropoda (Emery 1946), and salt crystallisation (Tricart 1959) are thought to be platform-generating processes. Discussion of all these processes has relied solely on observation and personal judgement except for a measurement of the rate of cliff foot recession by solution made in south-west Australia by Hodgkin (1964) and a wave tank experiment on erosion of solid rock by Sanders (1968). Several studies using measurements of shore platform morphology have been made, e.g. So (1965), Wood (1968) and Healy (1968b). Wright (1967) has proffered a classification of some shore platforms on the English Channel coast and in the northern part of the North Island, New Zealand, while Hills (1971) has classified the features which constitute the shore platform in southern Victoria, Australia.

Only recently have the characteristics of superficial deposits in an erosional environment been discussed. Shelley (1968) was the first to describe fitting or imprisoned boulders in any detail; perched boulders, which are a special form of these, have received only cursory attention (Hills 1970 and Bird 1969). In contrast there are very many papers (e.g. Russell 1959, 1960, 1962, 1963) dealing with beach rock which is principally found on retreating tropical sandy beaches and, hence, is not a common feature of erosional shores. A conglomerate allied in genesis to tropical beach rock is found in north-east Yorkshire but the characteristic cement of ferric compounds is unusual in low latitudes where calcium carbonate and aragonite predominate.

Many of the papers so far mentioned will be discussed in more detail later, but from this brief review it may be concluded that the study of erosional coasts is in an early stage of development. With recent advances in the direct measurement of the erosion of solid rock, the trend towards detailed quantitative studies of physical features and the development of computational techniques for the handling of the large quantities of data produced, the time is ripe for further research into the features produced by coastal erosion and the processes by which these are moulded.

The Objective of the Thesis

Several coastal studies, including the work of Agar (1960) in north-east Yorkshire, have suggested that wholly or partly bevelled cliffs are the result of weathering that followed the lowering of sea level at the onset of the Last Glaciation. It is recognised in this hypothesis that the active cliff is the result of post-glacial marine erosion and that it may occupy the whole cliff where there has been little resistance to erosion. The landward extension of the shore platform has been minor in post-glacial times and is identified as a steeper part of the shore platform which itself has undergone only slight lowering beyond the removal of a weathered mantle formed in periglacial times when the sea level was lower. Weathering did not, however, occur beneath boulders, which have consequently become perched. Patches of conglomerate were formed by the cementation of interglacial beaches under talus cones when the sea level dropped at the start of the Last Glaciation.

The alternative hypothesis has been outlined by Hemingway (in discussion of Agar 1960) and more fully by Eyre and Palmer (1973). It suggests that all these features have been formed since the Last Glaciation. The bevel is produced by weathering, or perhaps landslipping, when the cliff foot is protected by talus cones in the bases of which cementation occurs, forming patches of conglomerate from trapped beach and talus debris which are exposed when the cones are finally eroded. Any sufficiently large sandstone boulder which falls on to the shore platform becomes perched when the platform is subsequently lowered.

Obviously, the morphologies of the features found on this coast are adequately explained by either of these hypotheses. It is only when rates of landform changes are measured that the second one alone can be recognised as being valid. This theory still recognises that a number of features, e.g. the patches of conglomerate, are relict, in the sense that they are being destroyed, but other patches are also being formed. However, this theory has never been closely examined;

it has not been clear whether coastal features are steady-state phenomena, continuously and contemporaneously being destroyed and formed, or whether they are cyclic, being destroyed at one place and then later being formed again. It is recognised that present processes must be active enough to have created all the physical features visible today but few estimates of the rates of change of these features have been given nor, indeed, have specific processes been recognised as being important. Also, the evolution of the sea cliffs and the deposits at their foot have usually been examined in isolation from the other major components of the coast, namely the coastline and the shore platform.

The assemblage of coastal features can be regarded as a system, many features, as well as having their own courses of evolution, being affected by, and affecting, others. The objective of this thesis, therefore, is to synthesise a process-response model for the erosional solid-rock coast of north-east Yorkshire. The system is composed of three main subsystems: the cliff, the foreshore, and the coastline. The superficial deposits provide the regulator for these subsystems. In parts the system is in a nice adjustment, in others the features are undergoing rapid change relative to each other. It is necessary to describe the morphologies of the physical features and to establish relationships between them, as well as to show how and why they change and to give measurements of the rates of these changes wherever it has been possible to estimate them in the short duration of the study period. In fact, the latter half of this objective, the identification of processes and the measurement of rates of change receive most emphasis in this study because of our very elementary knowledge of them.

The Structure of the Thesis

Before the synthesis of the model can be achieved, analysis of the forms of the physical features and the processes acting on them must be carried out to rationalise the complexities found in nature. Each of the major physical features is discussed in turn, its morphology being examined first, followed by the processes which act on it. Objections to the hypothesis that some of the features are the result of the glacially-initiated eustatic fall in sea level are debated as they arise. The amount and nature of data for some of these features have necessitated that the two topics of form and rates-of-erosion be dealt with in separate chapters. Where two chapters have been necessary they should be regarded as a closely knit pair, e.g. the study of cliff form along the whole coast and the study of processes in detail at one site (Hawsker Bottoms). The major physical features discussed within this format are the cliff, the solid-rock cliff foot, the shore platform, the superficial deposits and the coastline, in that order. The first part of the final chapter gathers together the evidence which suggests that the hypothesis presented by Agar (1960) for some of the physical features of this coast is in error, and the relationships identified in the analyses of landforms are then synthesised into a coastal process-response model for north-east Yorkshire. The last chapter also outlines the wider relevance of the model to erosional coasts in general.

CHAPTER 2

THE MORPHOLOGY OF THE CLIFF

Introduction

The cross-sectional form of the cliff between Ravenscar and Saltburn varies considerably. Previous work by Agar (1960) indicates the existence of an upper morphological element, the bevel, which has an inclination of 30 to 40 degrees. In places it extends to the cliff foot though elsewhere it is truncated by the near-vertical marine cliff (the marine-activated cliff) which is retreating and is of recent origin. The sandstones of the Deltaic Series occasionally form a sub-vertical scarp above the bevel, termed the sandstone scarp.

This chapter examines the nature of cliff morphology in a quantitative objective way and, in so doing, verifies and extends Agar's analysis of the cliffs. The method of collecting and recording cliff form data is described first. A transformation of areal data was necessary to allow the analysis to be carried out. This manipulation is described next followed by the results of the analysis of cliff morphology. Of particular interest are the slope values of the various parts of the cliff since slope is the chief variable causing differences in cliff form. The reasons for variations in slope are examined by an analysis of its relationships with other factors such as geology, height above sea level, and nature of the foreshore. Thus, the cliff morphological system is analysed and certain common types of cliff are recognised. Although this analysis suggests that certain processes are responsible for the generation of particular morphological elements, these processes are not directly examined in this chapter but are analysed in Chapters 3 and 4. Finally, reasons for the frequencies of occurrence of different forms of the whole cliff in north-east Yorkshire are discussed.

The Construction of a Map of the Cliff and Foreshore

In recent years it has become possible to analyse the shape of the land surface by using the technique of morphological mapping. The basic assumption of this method is that the land surface can be divided into morphological units which are areas of uniform inclination (facets) or of uniform curvature (elements) (Savigear 1956), but for quantitative analysis it is necessary to assume that, at the scale adopted, the landscape can be divided into facets only (Doornkamp and King 1971, p. 129). The basic unit of landscape division is the drainage basin within which all slopes must be mapped (Doornkamp and King op. cit. p. 150; Gregory and Brown 1966). For cliff form analysis the basic unit is considered to be the full surface from the cliff foot to the cliff top.

The approach adopted in the present study is the same as that in morphological mapping; rectilinear morphological units (henceforth termed "units") which possess little variation in orientation are recognised and mapped. Normal maps are projections on to a horizontal surface; if such maps were used for cliff-mapping, the steepness of the cliff would make the area of the cliff on a map very small indeed - a vertical part of the cliff would be a single line and its area would be unmeasurable. Clearly, the maps must be projections of the cliff face on to a vertical plane. This is not a new idea, for views of the cliff showing geology are old-established (e.g. Phillips 1835) but morphological ones (e.g. Agar 1960, Pemberton 1966) are rare and they do not seem to have been so rigorously constructed as those used in this study. A vertical plane trending parallel to the general direction of the coastline is of little use since parts of the coastline lie at a high angle to this direction. The projection surface must be divided into segments which follow the detailed course of the coastline. On the c.1927 edition of the 1:2500

Ordnance Survey plans, the coastline between Ravenscar and Saltburn was divided into segments approximately one foot long (i.e. 758 metres) and a line was drawn parallel to the general trend of this segment of the coastline. Normals were drawn at each end of the line in the seaward direction. On successive straight segments of the coastline the projection surface lines joined each other and the normals were parallel. Corresponding lines were then drawn in exactly the same positions along the coast on the contoured O.S. maps of scale 1:10560. This allowed the fixing of points of known height on the cliff top on the larger-scale uncontoured plans. An orthogonal view of each segment of the cliff face could then be projected on to the lines following the general trend of the coastline. The vertical scale of these projected views was the same as the horizontal (i.e. 1:2500). Three of these projections for each coastal segment and the plan view of that segment were then placed on one sheet; this will be termed a "worksheet" since it was the form on which field data were put (a typical work sheet, though reduced in scale, is given in Fig. 2.1).[1]

When the cliff is vertical or the normals of a coastline segment are parallel to its neighbours, the cliff projection is bounded by vertical lines. However, when these conditions do not obtain, or when the actual direction of the coastline at the edge of the segment is not parallel to the projection surface, the cliff top, when viewed orthogonally, is not vertically above the true point at the foot of the cliff directly below it; this is because the cliff foot is nearer to the observer than is the cliff top. Therefore the edges of the projected view in this case are not vertical (nor even parallel) on the work sheet. This situation is also shown in Fig. 2.1.

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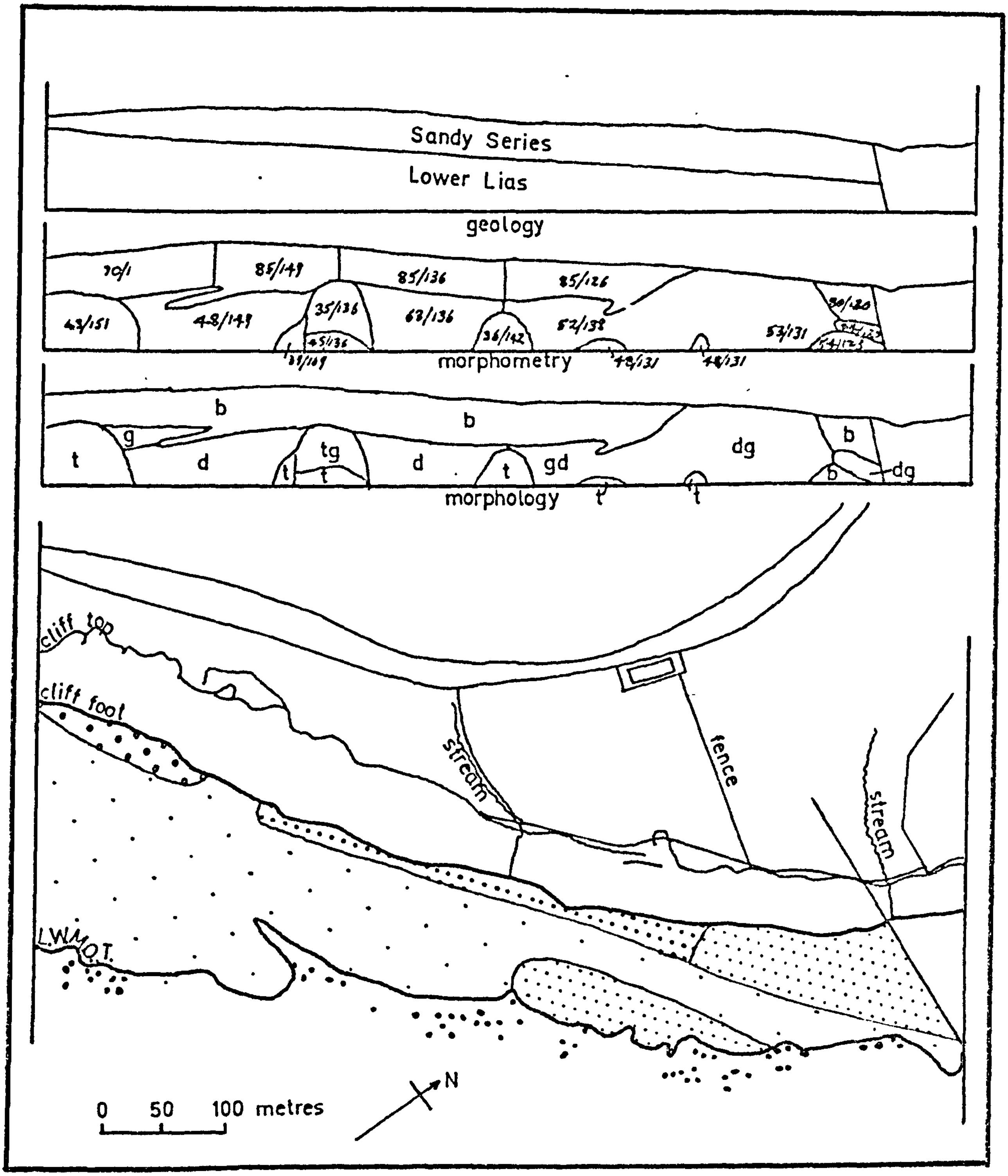
1. All worksheets are reproduced in Appendix V.



Key:

b bare rock exposed

d light cover of debris

g grass cover

t talus

morphometry format: slope/bearing

pebble beach

sparse boulders

medium density boulders

thick boulder cover

Fig. 2·1 Example of a worksheet (reduced in scale)

When normals to two adjacent projection surfaces diverge, e.g. at a large headland, their point of divergence is at the foot of the cliff and this leaves a wedge of foreshore excluded from the worksheet when these normals are taken as the edge of the worksheet. In this case the wedge is added to the sheet if the divergence of the normals is small; otherwise the length of the viewed cliff is reduced so that part of the cliff face is present on two worksheets.

Geological, Surficial and Foreshore Categories

The purpose of the worksheets was to record the geology, area, inclination, and surface characteristics of units on the cliff face and the distribution and type of superficial deposits lying on the shore platform.

The first projection on the worksheets records geological divisions which are as follows:

Glacial deposits
Middle Deltaic Series and Eller Beck Bed
Lower Deltaic Series and the Dogger
Alum Shales
Hard Shales
Bituminous Shales
Jet Rock Series
Grey Shales
Ironstone Series
Sandy Series
Lower Lias

In practice only a few points on each sheet had to be fixed with precision since the dip of the strata is small and the thicknesses of the divisions are constant so that interpolation of the boundaries between the geological divisions could then be done. The most conspicuous and, therefore, most easily mapped boundaries are those between the Dogger and Alum Shales, between the Sandy Series and the Ironstone Series, and between the Sandy Series and the Lower Lias.

The second projection records the morphometry of the cliff. The boundaries of units were drawn and the inclination of each unit and the orientation of the line of maximum slope written in the area delimited, using the format "slope/bearing" (e.g. $45^{\circ}/358^{\circ}$). The slope of the unit was measured with a clinometer fixed to a De Silva compass with which the orientation was measured, the magnetic bearing having been corrected for magnetic declination. The slope of cliff foot and accessible units could be measured directly. For those higher up the cliff, but of smaller angle than the unit below, a position could be found on the foreshore where the lower limit of the unit coincided with the upper boundary so that the unit was visible only as a line. By sighting on this line in the direction of maximum slope of the unit, its slope could be measured. If a unit had an inclination greater than the one below, its angle was measured either from the cliff top or by finding a position where a side view of the unit was available. If neither of these was possible, the angle had to be estimated by eye - estimated figures were enclosed in a ring on the worksheets and they were not used in any subsequent analysis that involved the inclinations of units.

The third cliff view, called morphology, depicts types of surface which were determined by field experience to be as follows:

1. bare - a unit with bare rock or with less than 50 per cent of its area covered with debris or vegetation.
2. light debris covering - the debris is usually shale fragments and it partially covers more than 50 per cent of the unit. The covering is said to be light because bare rock projects through it in many places.

3. thick debris covering - little bare rock penetrates the cover of unvegetated debris which is not continuous with any talus accumulation at the cliff foot.

4. vegetation - units which are covered with grass as well as bushes and bracken at some places.

5. talus - large conical accumulations of fallen material which are common at the cliff foot.

6. large boulders - such deposits usually lie at the foot of talus cones and are the residue of selective marine erosion.

7. slipped glacial material - this deposit was recognised west of Skinningrove where the till above the solid-rock cliff is thick and the cliff foot is reached by the sea only during very high tides and storms. Slipped till is usually easily removed by the sea.

8. cemented talus - this breccia may have a genetic connection with the conglomerate on the foreshore.

9. areas possibly modified by Man - this category was rarely used because such areas were mostly identified and excluded from the survey (see Appendix I).

Usually each unit corresponds with a particular type of surface but occasionally a unit may have several surface classes within it - such a unit was given a multiple surface-classification.

Categories of foreshore type used on the plans at the bases of the worksheets are as follows:

1. bare - areas with no inorganic cover except for very occasional boulders.

2. sand.

3. pebbles - pebbles are defined as being from sand size to 15.2cm in diameter.

4. occasional boulders - boulders from 2.7 to 18.2m apart.
5. medium density boulder cover - boulders which are touching or up to 2.7m apart.
6. thick boulder cover - boulders touching each other or piled up.
7. perched boulders - boulders, usually composed of Deltaic or Dogger Sandstone resting on shale plinths.
8. conglomerate - patches of cemented material on the shore platform.
9. areas modified by the activities of Man.

The Positioning of Boundaries

With practice it was easy to recognise the boundaries between adjacent cliff-face units in the field - they are best seen from the very foot of the cliff. The lateral positioning of these boundaries on the worksheets was a simple matter of correlating the variations in the line of the cliff top and the cliff foot with those shown on the plan of the foreshore. The seaward co-ordinates of points on the foreshore were fixed by pacing from the cliff foot. The vertical positioning of a point on the cliff is more difficult. When viewed from the base of the cliff a point half way up the cliff seems to be much nearer the top, because of perspective. The procedure adopted was to draw the boundary in approximately its true position and then to check that position when standing a long distance from that part of the cliff by the method of similar triangles, the long distance being required to reduce the effect of the actual slope of the cliff so that it could be considered to be vertical. A millimetre scale on a ruler held at arm's length was used to find the height of the point and of the cliff top above it. Knowing the height of the cliff on the worksheet at that point, the height of the point could be fixed with accuracy. (For example, if a point is 20mm and the cliff top is 30mm above the cliff foot on the ruler then, if the cliff at that point is 15mm high on the worksheet, the point is $\frac{20}{30} \times 15 = 10$mm from the cliff foot on the worksheet.) The boundary of a unit could then be drawn with considerable accuracy by interpolation between fixed points.

The limits of accuracy adopted for the fixing of points were $\pm$ 0.13cm (0.05 inch) (i.e. $\pm$ 3.66m (12 ft.) on the cliff). The lateral fixing of points should be within these limits but checks were necessary to determine the quality of the vertical fixes. A tacheometer was used to check the heights of 25 randomly selected points on the cliff. It was found that 80 per cent were within the stated limits and 60 per cent were within the limits $\pm$ 1.83m (6 ft). It is concluded, therefore, that the methods used in locating boundaries are sufficiently accurate for analytical results to be valid.

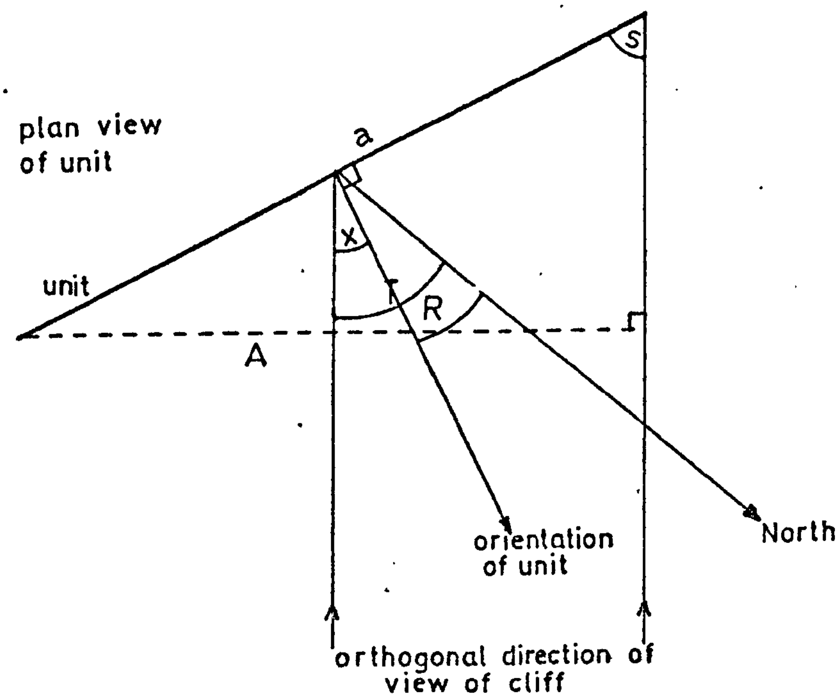
The Preparation of Field Data for Analysis

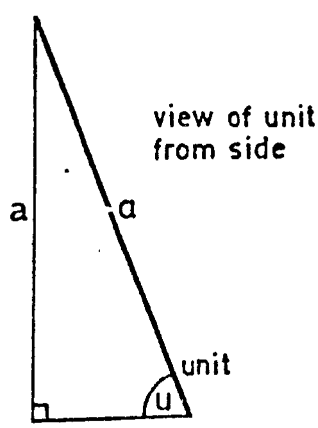
Data for most variables could be extracted and used for analysis without modification except, perhaps, multiplication by the scale factor. This was not so with the variable of ground area because a unit is not usually normal to the orthogonal direction of view in either the plan or the vertical sense. A plan view of a unit together with a view of it from one side is given in Fig. 2.2. Having measured the area of a unit on the worksheet by the method of counting graph-paper squares, the ground area is calculated from the equation:

$$\text{ground area} = \text{scale factor} \times \left(\frac{A}{\sin S \ \sin U}\right)$$

where $S = (90 - T) + R$

(for notation see Fig. 2.2)





a true area of unit
A measured area of unit
a measured area corrected for orientation
T angle between true North and orthogonal direction of view
R bearing of unit
S inclination of unit to orthogonal direction of view
U inclination of unit to the horizontal

Fig. 2·2 Geometrical representations of the corrections needed for unit areas

The Method of Analysis

The objective of this chapter has been described at the beginning; it is the identification of common elements of cliff form from units, the examination of relationships between units and other factors and, finally, the identification and description of frequently occurring types of cliff form. Unfortunately, the polymodal character of angle distributions with respect to any other variable and the nominal scale of measurement of some of the important variables (e.g. geological and surface classes) preclude the use of parametric statistical methods. Non-parametric techniques are most suited to such distributions (Siegel 1956), and in particular the χ^2 test has been much used for this analysis.

Following the testing for differences between distributions, the histograms can be examined to find the causes of differences, or similarities. Young (1961) has introduced the concepts of characteristic and limiting angles. The definitions of these used in this study are those given by Gregory and Brown (1966) which are more restricted than those of Young:

Characteristic angles are those angles which occur on a specific type of morphological unit under controlled conditions such as geology or orientation. Such angles are peaks or maxima on distributions and are separated by limiting angles.

Limiting angles are those angles which indicate the range of the distribution of a specific type of morphological unit under controlled conditions. Such angles are minima on distributions and are separated by at least one characteristic angle. The limiting angles of a whole distribution are those enclosing all values but in which no unit occurs.

The Characteristics of Units

Each unit has the following independent characteristics: orientation, shape, area, inclination, and height above the cliff foot. Orientation is mainly a result of coastal erosion in plan and, since it has no influence on inclination, the chief characteristic to be studied, it is not discussed further.

The shape of a unit is rather artificial since a unit has been defined as an area possessing little variation in orientation. Thus, if an area of the cliff which is curved in plan has a uniform inclination it will be divided into a number of units and the position of the lateral boundaries will be arbitrary. A high proportion of rectangular units results so the shape of units is considered no further in this study.

The areal characteristics of units developed on rock which is in situ are shown in Fig. 2.3a; it is a highly skewed, unimodal histogram with the peak being between 500 and 1000 sq.yds. (418 and 836m^2). Above 13000 sq.yds. (10868m^2) the occurrence of units is sporadic; the highest value being 41500 to 42000 sq.yds. (34700 to 35100m^2). The minor peaks in the distribution at 3500 to 4000 (2926 to 3344m^2) and 6000 to 6500 sq.yds. (5016 to 5434m^2) are probably due to chance.

The slope characteristics of all units are shown in Fig. 2.3b. This distribution is markedly bimodal with other small peaks also occurring. Adjacent classes vary considerably, suggesting slight operator bias. Gregory and Brown (1966) encountered this and ascribed it to the fact that small angular differences are minimised when measuring high-angle slopes. The bias can be eliminated by combining single-degree classes into classes of two degrees. This has been done for all subsequent examinations of slope variations.

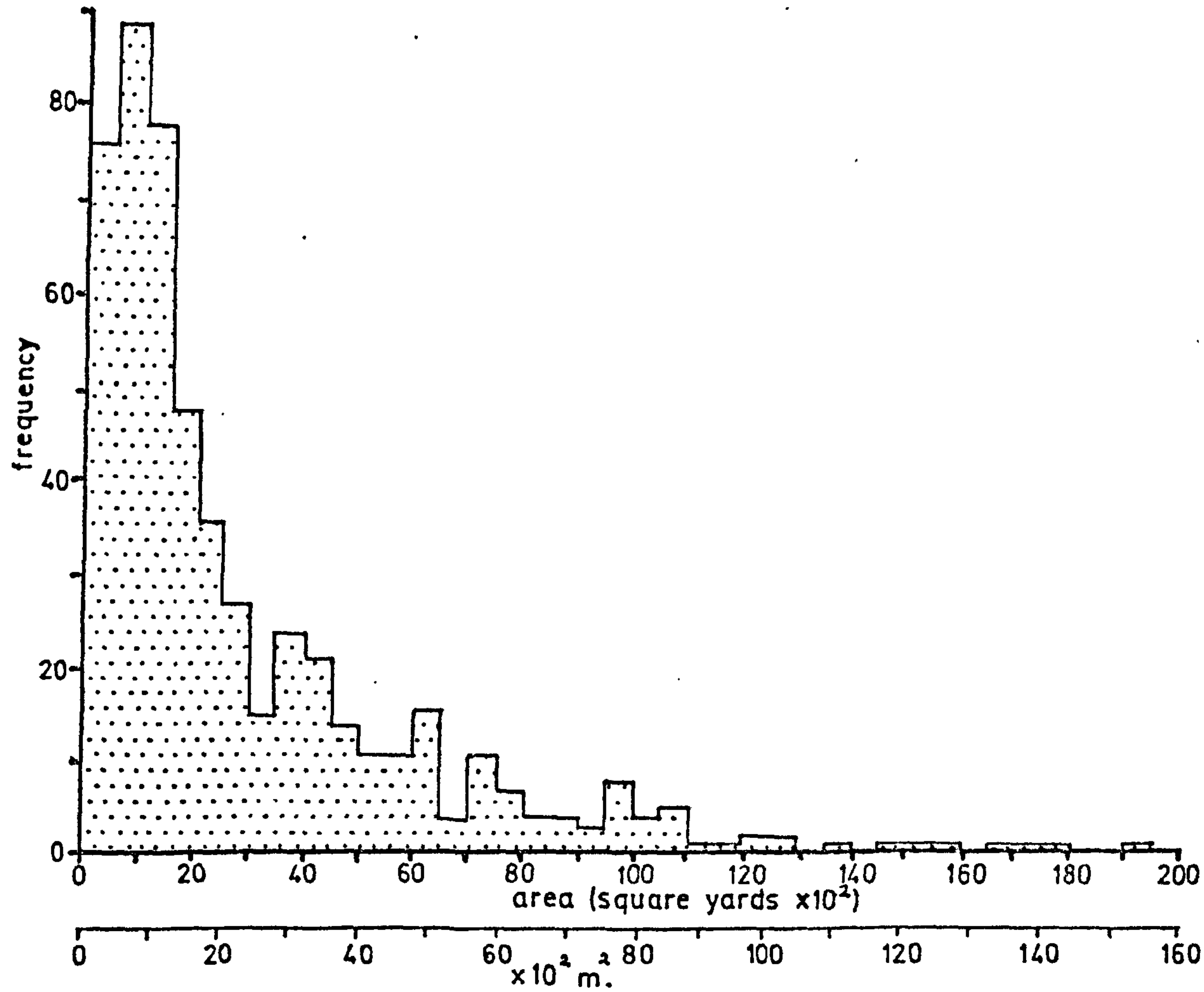


Fig. 2·3a Area histogram for solid units

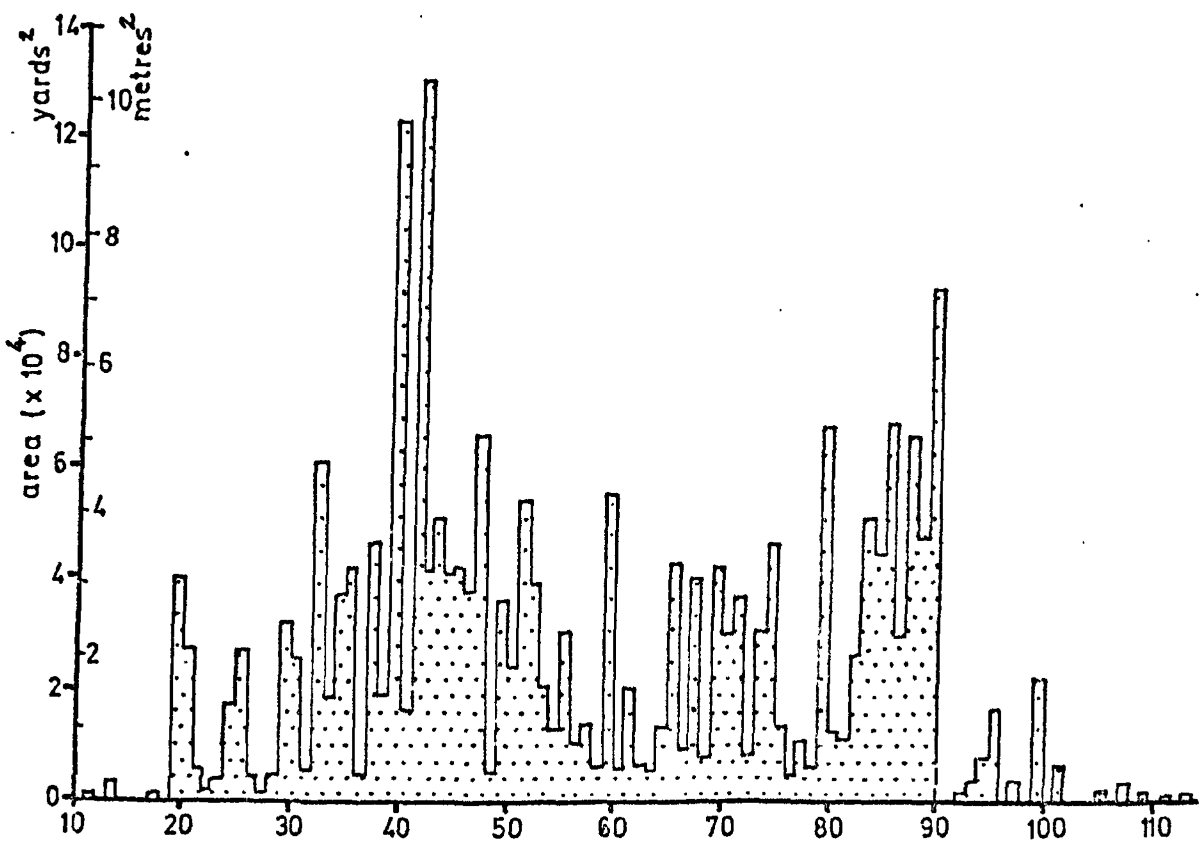


Fig. 2·3b Area-slope histogram of all units (one-degree classes)

The frequency-height distribution of units is given in Fig. 2.4a, the number of units having been counted at each 50ft. (15.25m) interval up the cliff face. There are more units at the 100ft. (30.5m) level than at any lower level because talus cones occupy much of the cliff foot and are often more than 50 ft. high. The diagram also reflects the total area of the cliff at different heights, i.e. only in one place does the mapped cliff exceed 325ft. (99.1m), and much of it is below 175ft. (53.4m).

Fig. 2.4b is the area-slope histogram of all units and is subdivided into parts determined by the geology of the units (solid rock, glacial deposits, and talus). The dominant characteristic of this distribution is its bimodality with peaks at 42 and 88 degrees. It is evident that the former characteristic angle is common both to the solid cliff where it is an erosional plane (the bevel) and to talus where it is the angle of rest of debris. The importance of this relationship to the maintenance of a specific angle for the bevel will become clearer in the next chapter. The major characteristic angle at 88 degrees and the one of less importance at about 70 degrees are both cut in solid rock. They represent the marine activated cliff and the sandstone scarp. Therefore, the relationships shown in this diagram are the result of a number of factors whose effects on unit characteristics (chiefly slope) need to be examined more closely. These variables are: geology, surface characteristics of units, height on the cliff, and foreshore characteristics.

The Influence of Geology on Unit Characteristics

The effects of geology on the characteristics of units are felt mainly through variations in lithology. On this basis, there are two groups of rocks, the Lias shales and the Middle Jurassic sandstones.

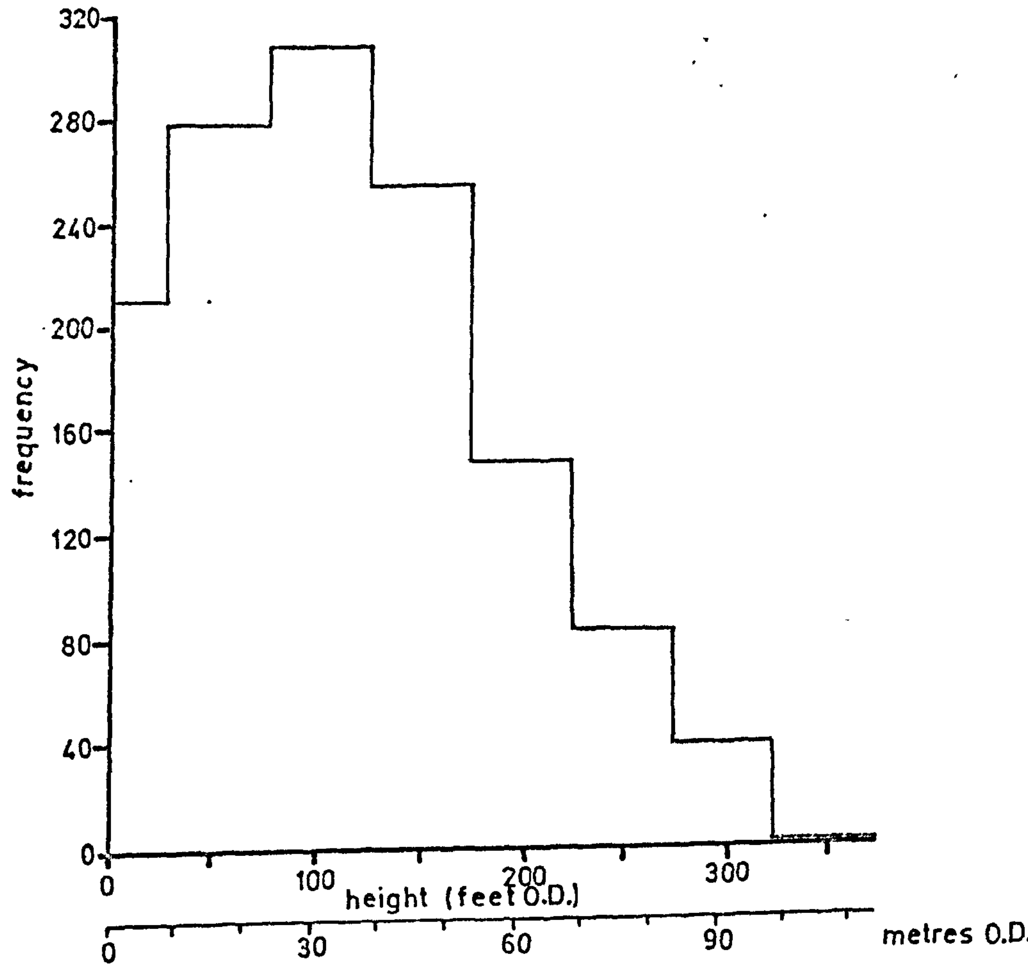


Fig.2·4a Frequency-height distribution of solid units

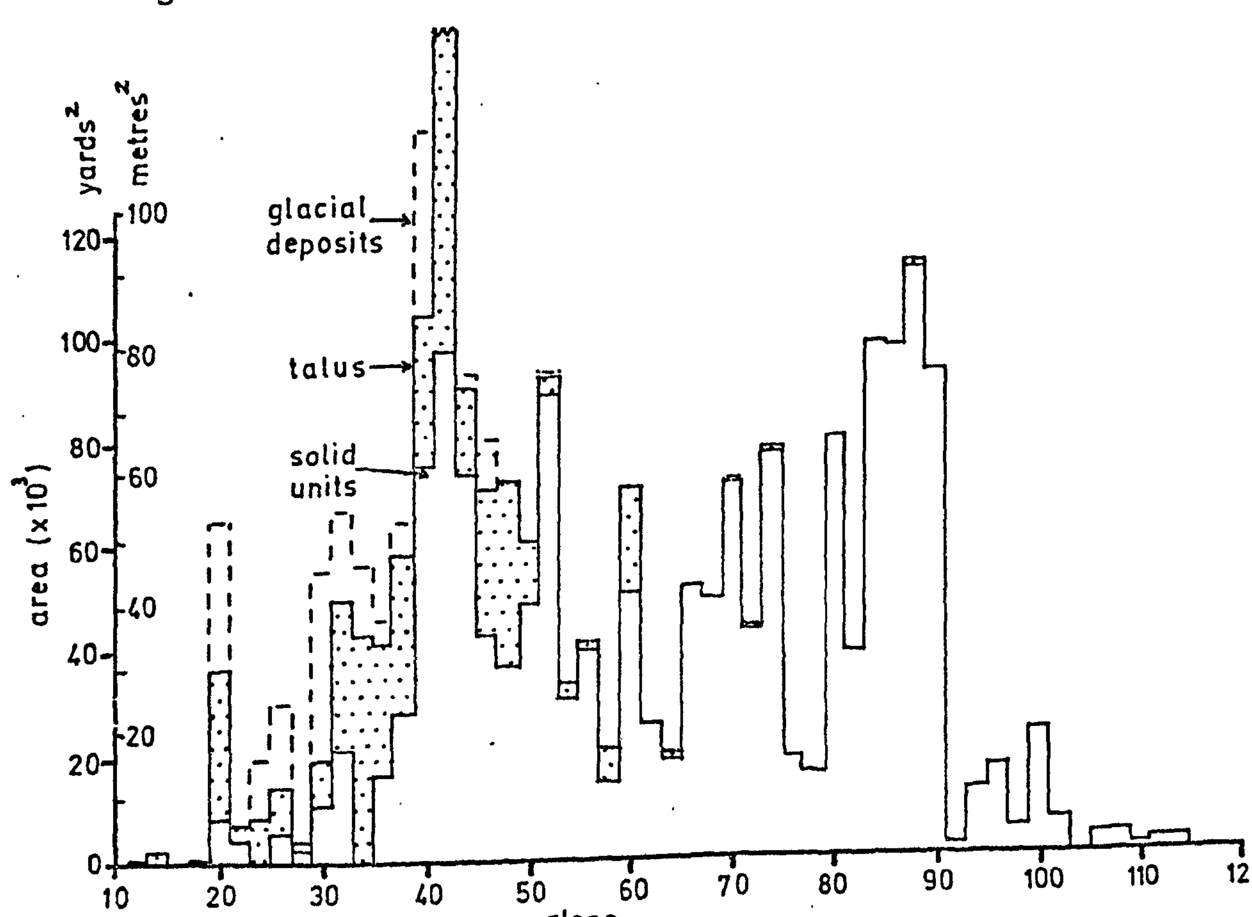


Fig.2·4b Area-slope histogram of all units

However, minor heterogeneity also occurs within these groupings so the influence of these on unit inclination needs to be examined. Because units frequently cross a number of geological divisions, all units developed on rock which is in situ (i.e. "solid units") were split into facets; a facet is defined here as that part of a unit developed on a specific geological division, a much more restricted use of the word "facet" than that usually adopted in morphometric analysis (Savigear 1956). This division of units into facets has no influence on the shape of the frequency-slope distribution (χ^2 = 7.638; 34 degrees of freedom; insignificant at 0.05 level) i.e. there is no change in the information contained in the data.

Differences between the frequency-slope distributions of the geological divisions are extremely significant at the 0.001 probability level (χ^2 = 186.126; 72 degrees of freedom). The areal outcrop of each division is shown in Fig. 2.5a, the differences between them being due to varying differences in their thicknesses as well as to differences in their length of outcrop on the coastline. It can also be seen from this diagram that while the frequency distribution roughly follows the areal one it differs considerably in some classes. The number of Lower and Middle Lias facets is under-represented compared with other divisions. This may be due to larger facets on these rocks, irrespective of division thicknesses.

The mean slope of facets on each division is shown in Fig. 2.5b. Four groups of broadly similar angular values can be discerned. The Lower and Middle Lias and the Grey Shales have facets with high angles, the value for the Sandy Series being 79 degrees, a higher angle than the shales in this group. It is not immediately apparent, however, why these shales should have higher mean angles than the Upper Lias rocks

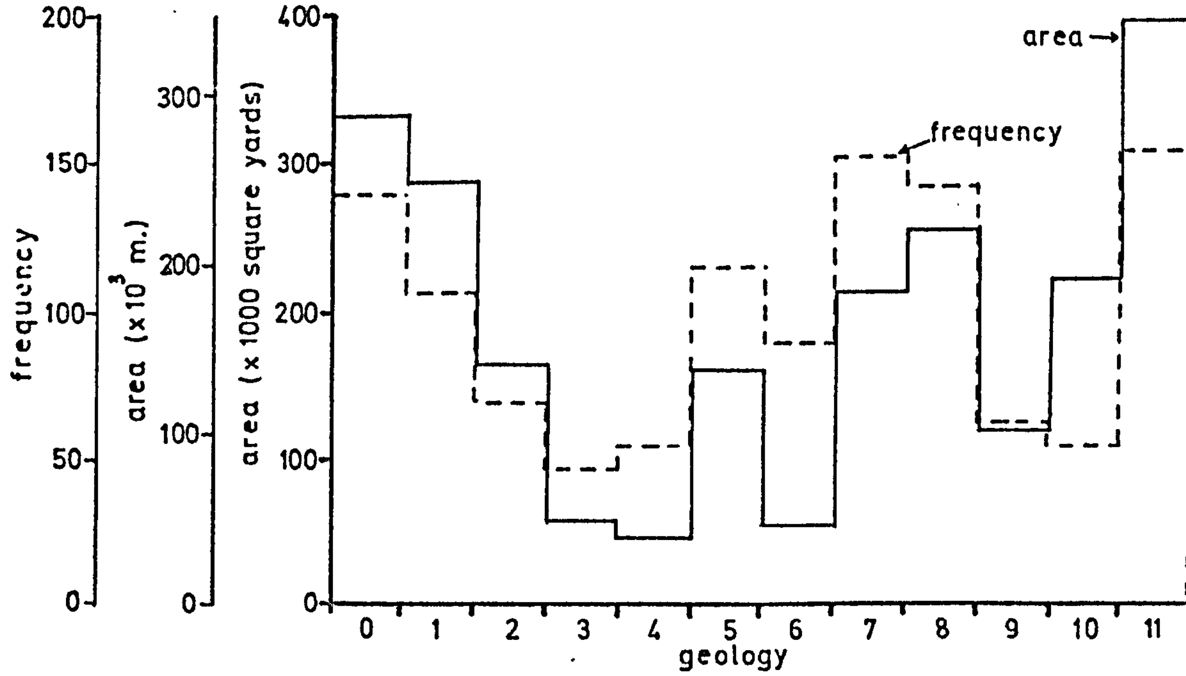


Fig.2·5a Areal outcrop and frequency of facets on each geological division

0	Lower Lias	6	Hard Shales
1	Sandy Series	7	Alum Shales
2	Ironstone Series	8	Lower Deltaic Series
3	Grey Shales	9	Middle Deltaic Series
4	Jet Rock	10	Glacial Deposits
5	Bituminous Shales	11	Talus

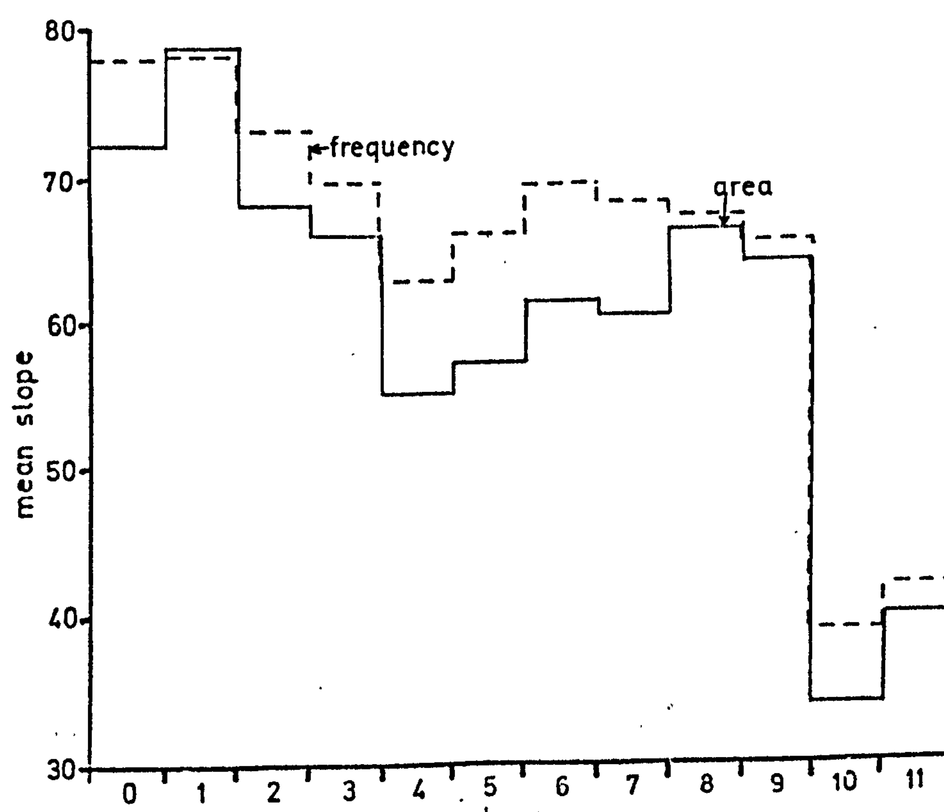


Fig.2·5b Mean slope of facets on each geological division unless it is because of their less laminated strata or because of factors which are not directly geological. The Upper Lias shales above the Grey Shales have mean angles of 55 to 61.5 degrees, the Jet Rock being the lowest. This is surprising since the Jet Rock is more massive than the other shales; in fact this low angle may be partly due to jet mining, the visual evidence of which has now been hidden or removed. The low slope of the Upper Lias shales would be compatible with a lowland subaerial milieu but high angles might be anticipated for a marine environment as shales should offer little resistance to the dominantly horizontal forces of marine erosion. In fact, the low angle on this group of rocks is due to the presence of the bevel which does not extend on to the lithologically similar Grey Shales or Ironstone Series. The third group in Fig. 2.5b is produced by the Lower and Middle Deltaic Series with average slopes of 66.5 and 64 degrees respectively. The massive nature of parts of these rocks might be expected to give these higher values because they are structurally competent. However, they are not as high as the angles in the first group; this dichotomy can again be explained by the existence of the bevel on parts of these rocks. The fourth group consists of the soft-rock glacial deposits with mean slope of 34 degrees and talus with mean surface inclination of 40 degrees. The mean angular values calculated using frequencies follow the areal mean slope values except for the Upper Lias group - this reflects the smaller facets developed on rocks of this group.

In detail, the significance of the effects of differences in geology on facet inclination are revealed by pairwise testing (with χ^2) of the frequency distribution of each, the results of which are summarised in Fig. 2.6a. Most divisions differ significantly from each of the others except for those belonging to the Upper Lias; all frequency-slope distributions of the Upper Lias are insignificantly different from each other and so can be grouped together. Therefore the geological categories used in this study are the Lower Lias, Sandy Series, Ironstone Series, Upper Lias, Lower Deltaic Series, Middle Deltaic Series and glacial deposits, together with the additional category of talus.

The table in Fig. 2.6b shows the mean slope values of these geological divisions together with the weighted mean angular values given by Gregory and Brown (1966) for these rocks in Eskdale. Though the actual angles differ markedly as befits their contrasted environments it is not obvious on the basis of geology alone that the rocks should differ relative to each other. The Spearman rank correlation coefficient is 0.7954 and this does not attain the critical value of 0.829 necessary for the two sets of data to be significantly correlated at the 0.05 level (using the one-tailed test for small samples). The most marked change in rank is by the Upper Lias. These unresistant shales have a high mean angle in Eskdale as might be expected in an upland area but their low inclination in the marine environment where they should offer little resistance to erosion must be attributed to factors which are not geological. Thus the bevel cannot be explained as a phenomenon related simply to geological factors.

The frequency-slope and area-slope distributions of each geological division are shown in Fig. 2.7, 2.8 and 2.9 with a summary of their characteristic and limiting angles in Fig. 2.10. Groups of characteristic angles can be discerned. Slopes of about 45 degrees occur on the Middle Jurassic rocks and extend on to the Upper Lias shales where the angles tend to be about 40 degrees; this correspondence

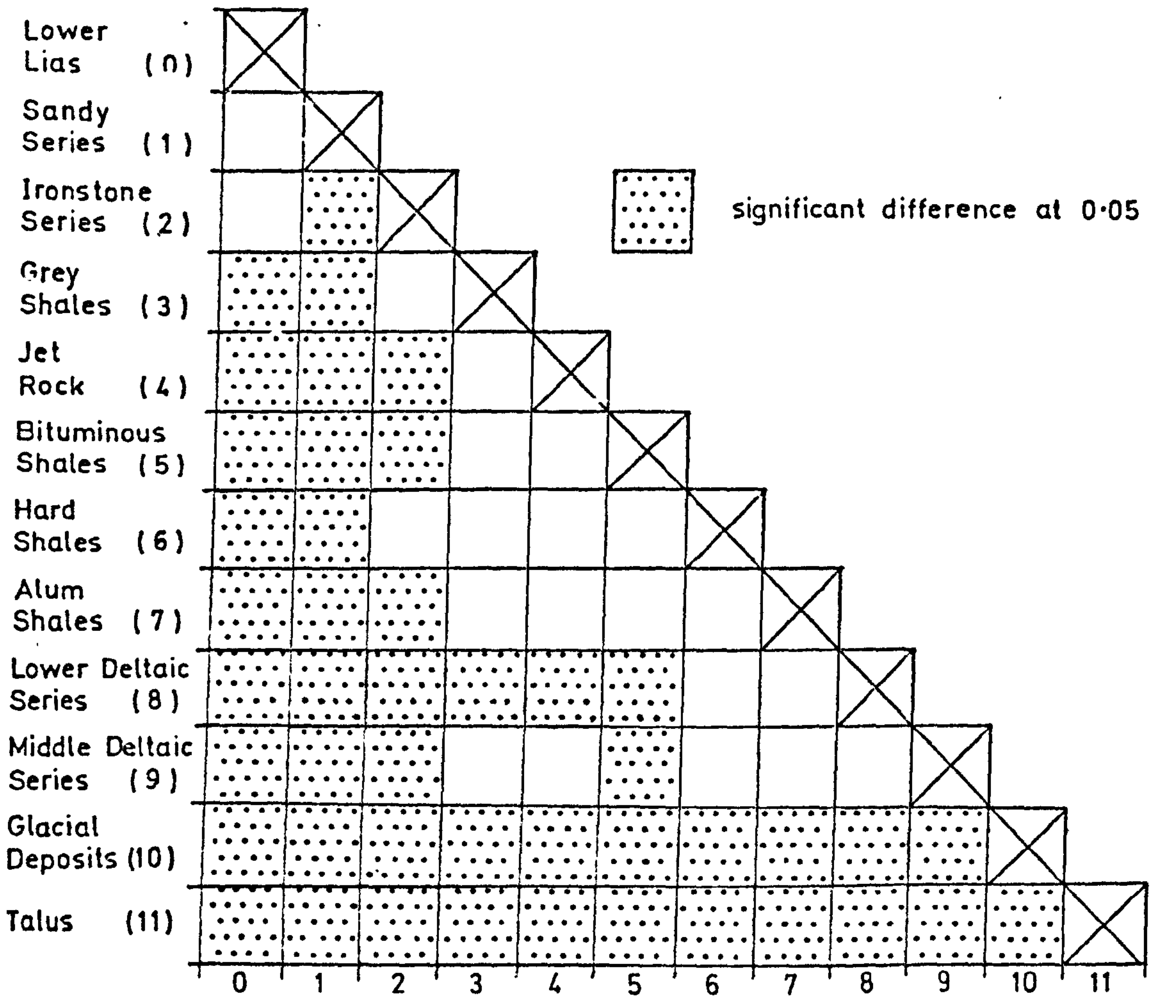


Fig.2·6a Results of pair-wise χ^2 tests on frequency-slope histograms of geological divisions

	Eskdale		North-east Yorkshire coast	
	weighted mean angle	rank	mean slope	rank
Middle Deltaic Series	5·03	5	64·1	5
Lower Deltaic Series	7·11	3	66·5	4
Upper Lias	9·32	1	59·9	6
Ironstone Series	4·59	6	68·0	3
Sandy Series	6·49	4	78·8	1
Lower Lias	8·72	2	72·1	2

Fig.2·6b Mean slopes in the sub-aerial and littoral environments

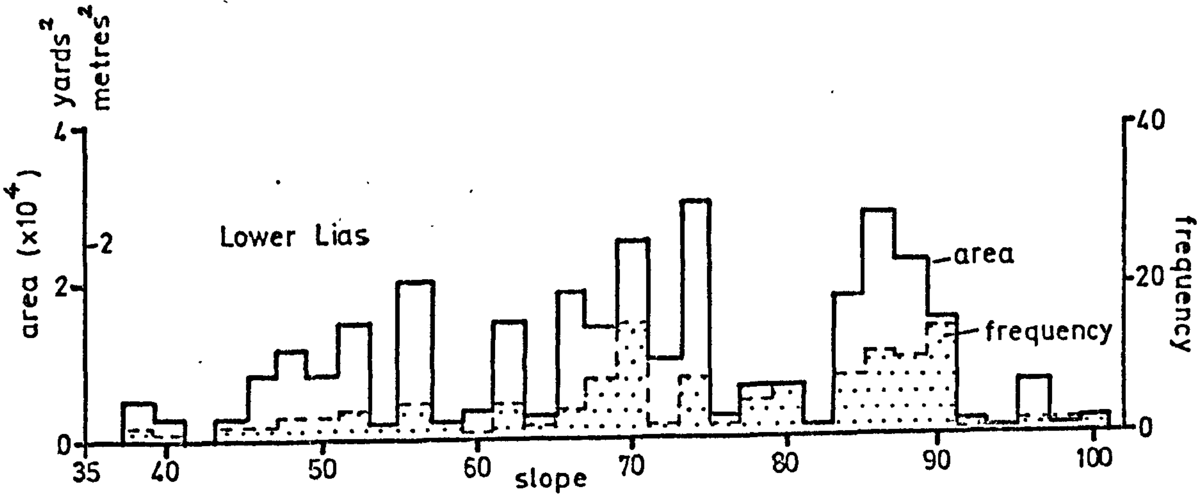


Fig.2·7a Slope histograms for the Lower Lias

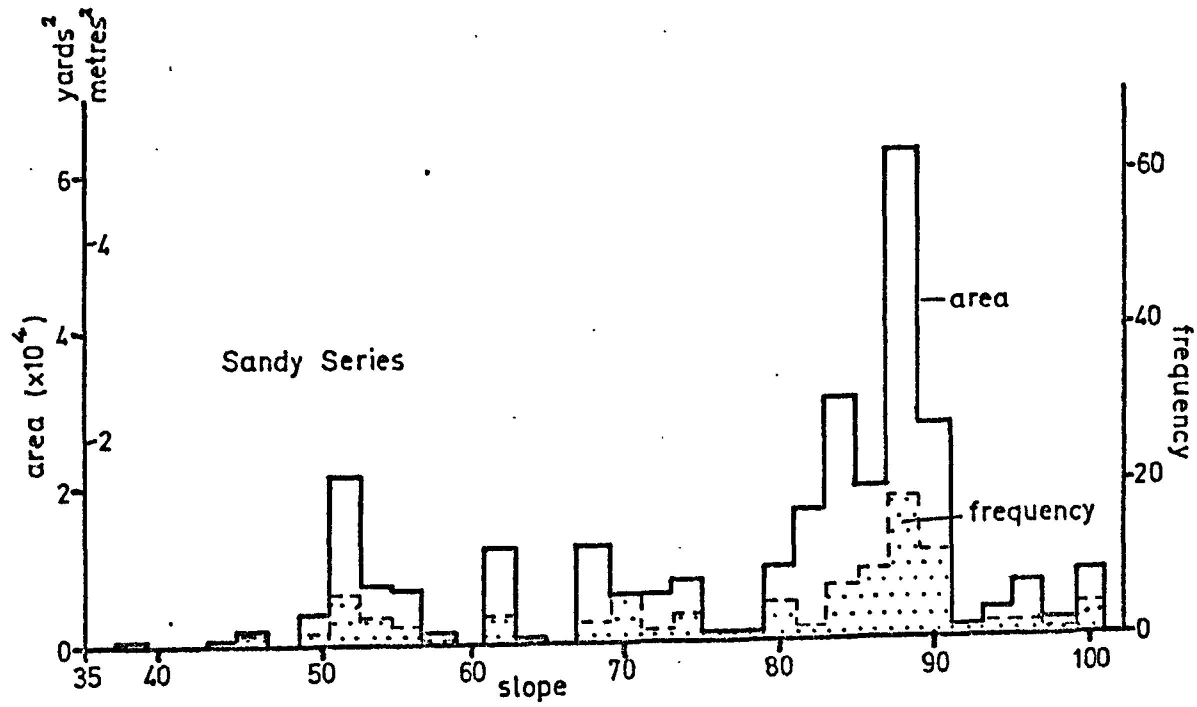


Fig.2·7b Slope histograms for the Sandy Series

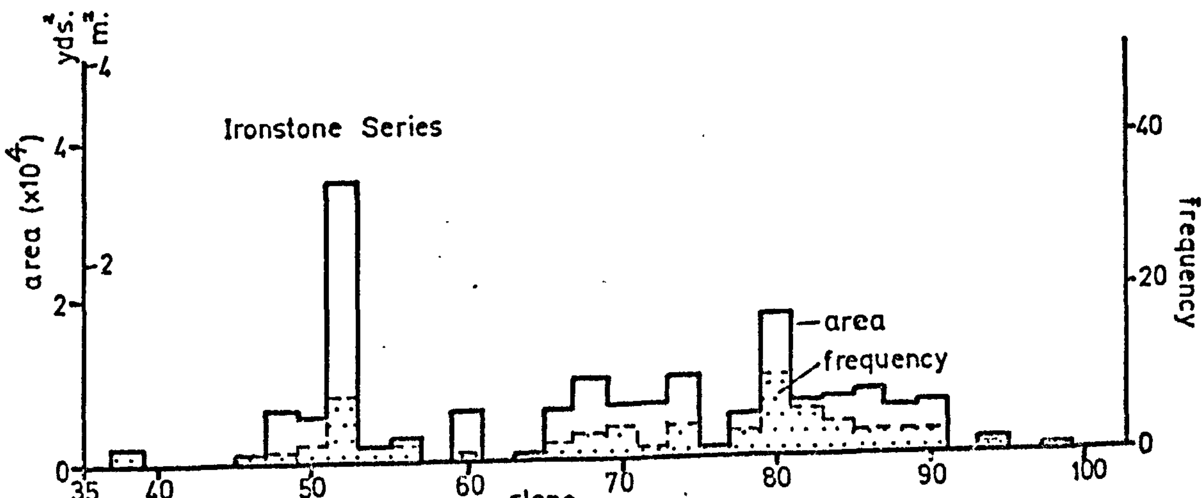


Fig.2·7c Slope histograms for the Ironstone Series

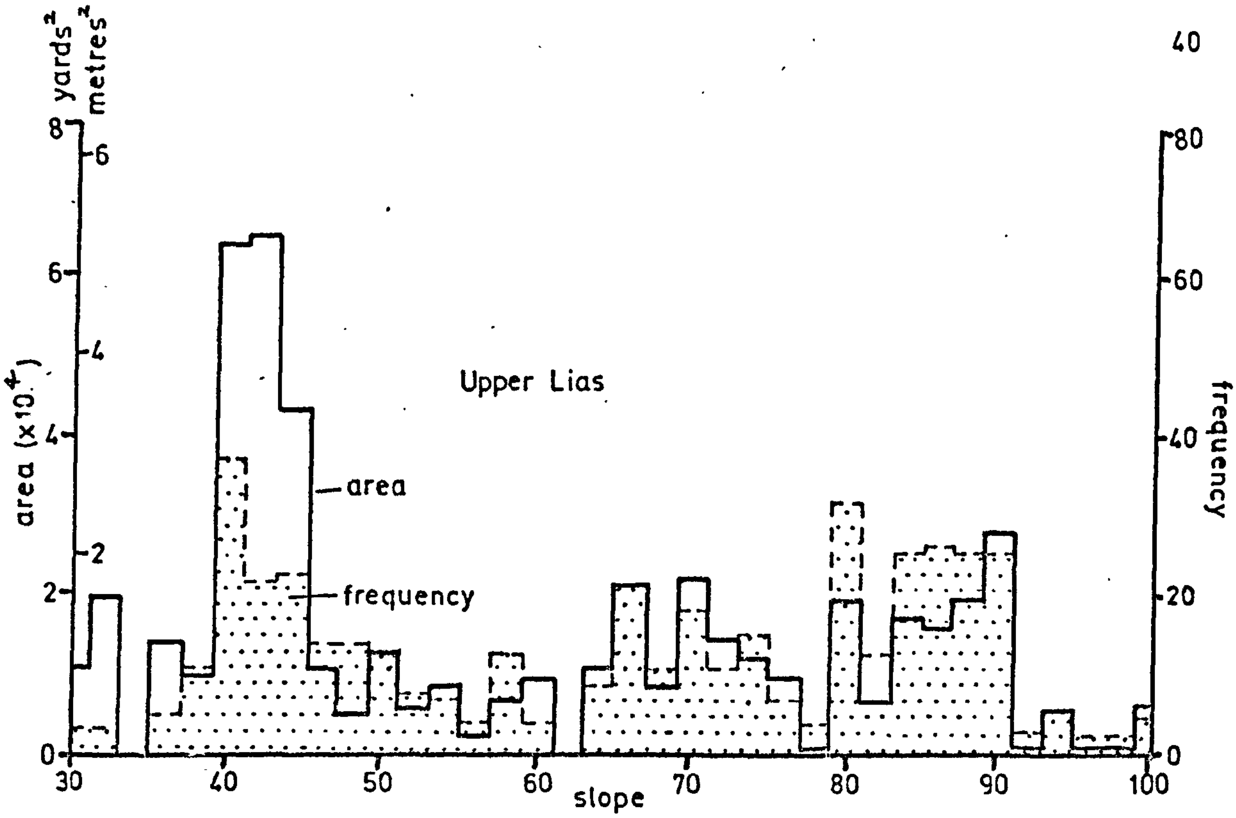


Fig.2·8a Slope histograms for the Upper Lias

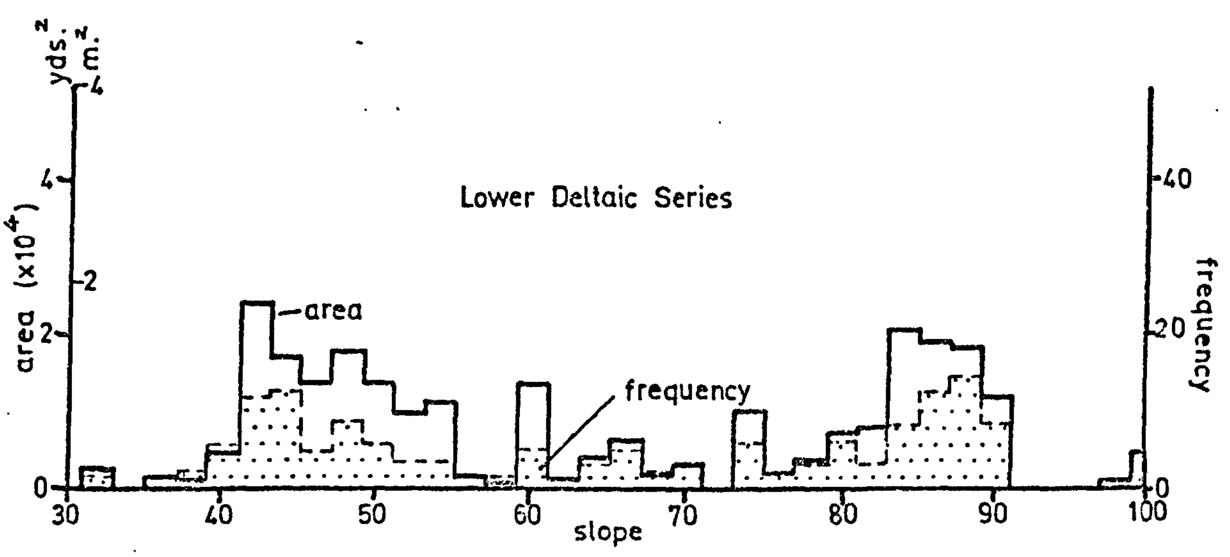


Fig.2·8b Slope histograms for the Lower Deltaic Series

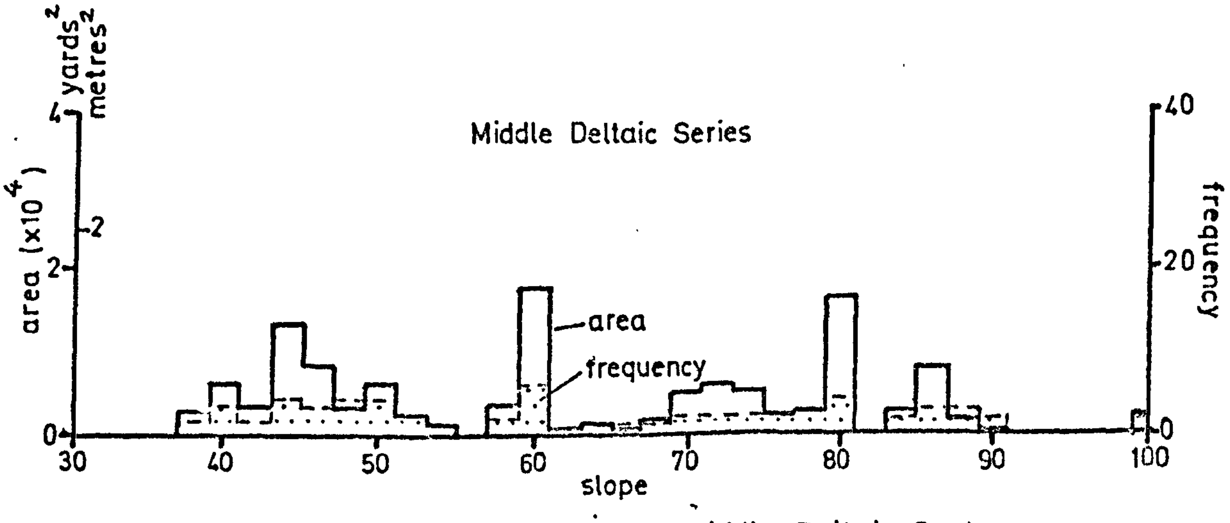


Fig.2·8c Slope histograms for the Middle Deltaic Series

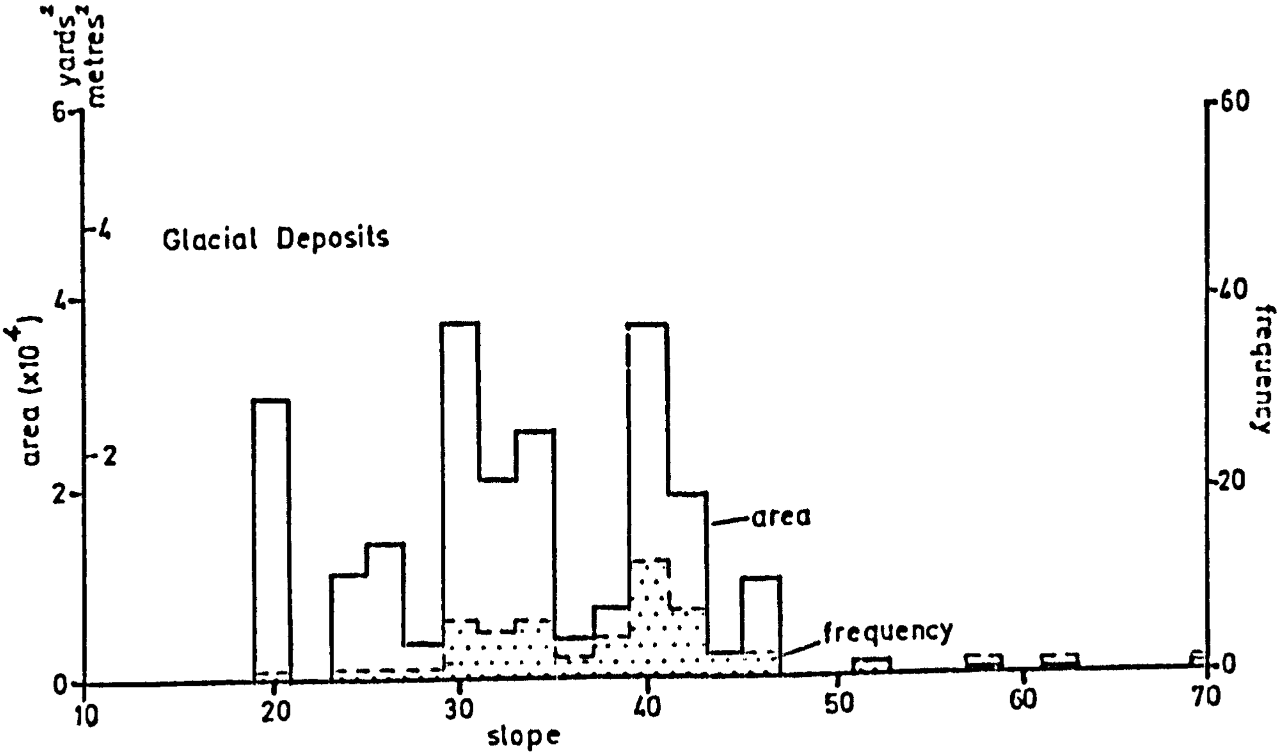


Fig. 2·9a Slope histograms for Glacial Deposits

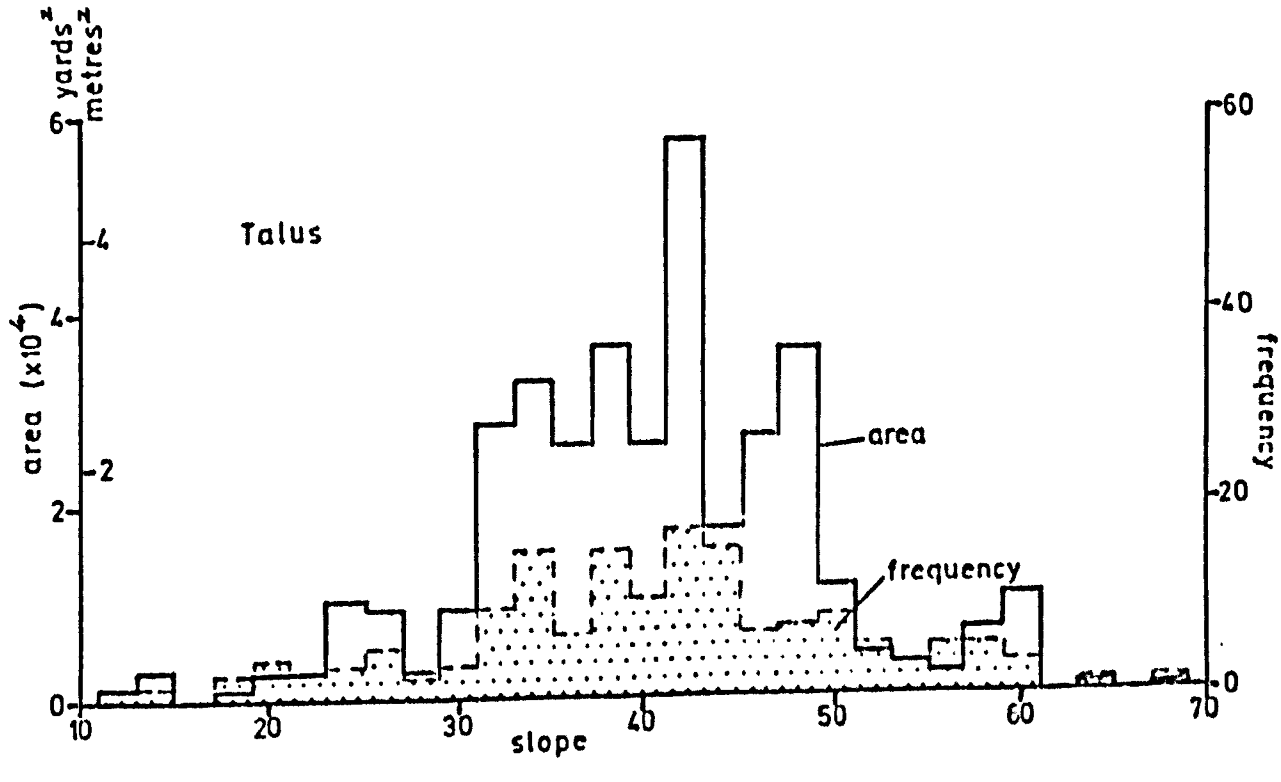


Fig. 2·9b Slope histograms for talus

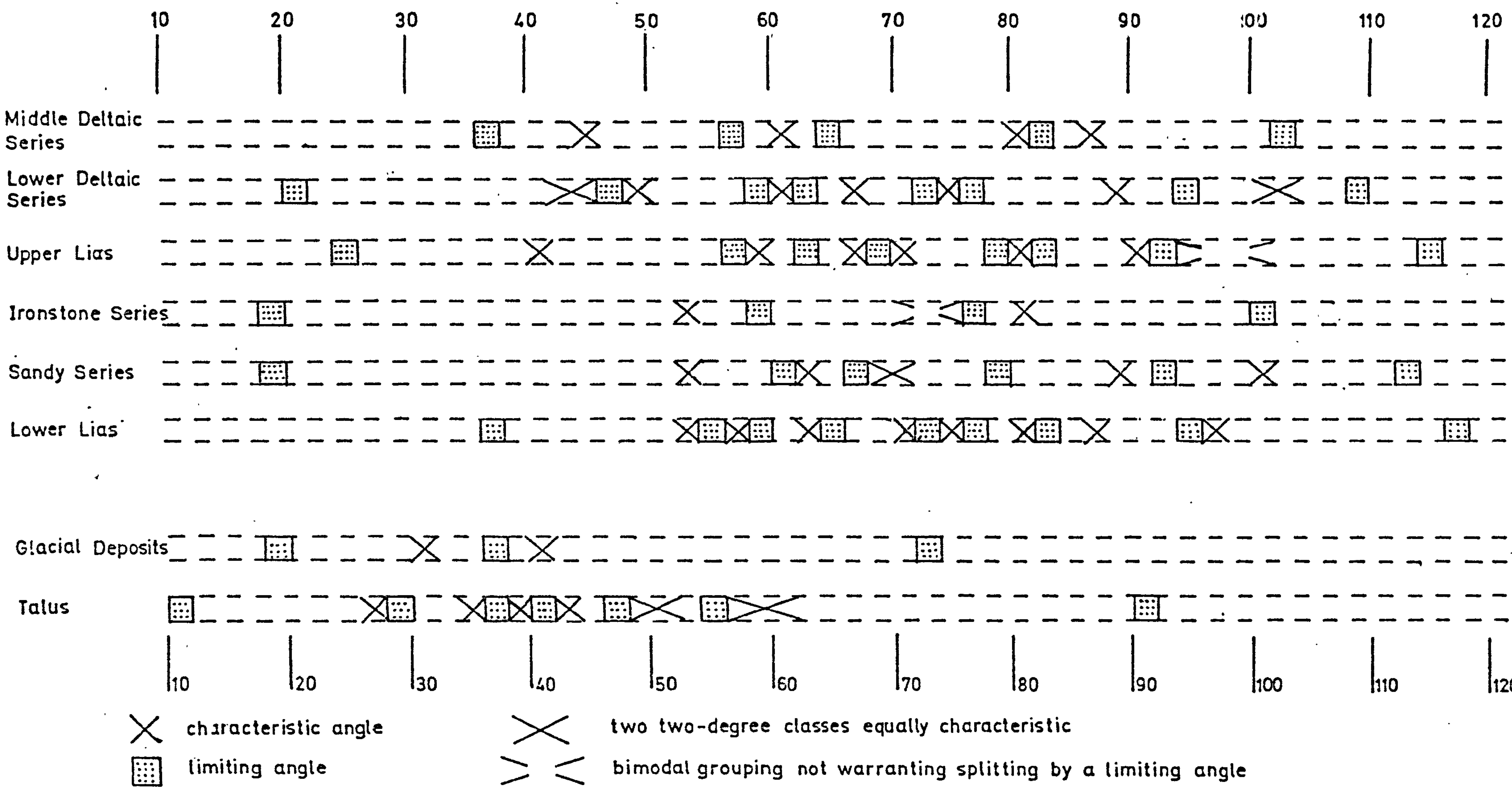


Fig.2·10 Characteristic and limiting slopes of the geological divisions of characteristic angles is surprising in view of the lithological differences. The same characteristic angles do not occur on other shales but a group of maxima exists at 34 to 43 degrees on talus cones. The lowest characteristic angles on the Lower and Middle Lias are at about 52 degrees; it may be that this angle is genetically related to the lower angle on the Upper Lias. The pattern of characteristic angles from 60 to 79 degrees in Fig. 2.10 is rather confused. The Upper Lias tends to follow the Middle Jurassic while the Lower Lias follows the Sandy Series. Characteristic angles of 80 and 81 degrees are present in four of the six divisions; this slope is the result of marine erosion. Similarly angles of 86 to 91 degrees, which are characteristic of five of the six divisions, being highest (90-91 degrees) on the least resistant to erosion, the Upper Lias. Overhangs, where the slope is greater than 92 degrees, have maxima in four of the divisions but show no tendency towards a common specific angle suggesting that the slope of the overhang depends greatly on the strength and fracture pattern of the particular rock. Well-developed overhangs caused by rapid marine erosion can be seen east of the East Pier at Whitby while some of those developed in structurally competent rocks are visible at Hawsker Bottoms.

The many small differences in the slope of facets due to small variations in geology are aggregated into more fundamental differences when the frequency distributions of the slopes of units are viewed in terms of the effects of the major differences between the Lias rocks and the Middle Jurassic strata. For this purpose units have been divided according to whether Middle Jurassic rocks crop out in the cliff (termed the "sandstone cliff" though most of it may be composed of Lias shales) or whether only Lias rocks are found there (termed the "shale cliff" although the Sandy Series strata are included). Units of 40 to 50 degrees are very important on the sandstone cliff (Fig. 2.11a) and it has already been shown that this angle is typical of the Upper Lias. Units of about 52 and 70 degrees characterise the shale cliff but the true bevel is absent. Clearly, then, the existence of the Deltaic Series is vital to the bevel. The characteristic angle of about 52 degrees on the Lower Lias of the shale cliff may be interpreted as meaning that the Lower Lias/Sandy Series association is analogous to the Upper Lias/Deltaic Series association.

It can be concluded, therefore, that the direct effects of lithology on the inclination of units are broadly what should be expected, shales being characterised by high angles because they are easily eroded by waves and sandstones also having high angles because they are not easily weathered and are structurally competent. It is the association of sandstones lying above shales which produces the anomalous angles characteristic of the bevel, a feature which is best developed on the Upper Lias shales. Because the reasons for this association are not clear at this stage of the analysis it is necessary to look at the other factors which can influence the slope of units.

The Surface Characteristics of Units

Most units are bare rock though the percentage varies according to geology, e.g. on the Lower Lias 89.0 per cent of facets are bare while on the Upper Lias this figure is only 60.9 per cent. There is a distinct correlation of surface class with slope on the Upper Lias (Fig. 2.11b). Vegetated facets are rare above 50 degrees at which point debris is the most common surface type. Bare facets are the norm on slopes above 70 degrees. Erosion of such surfaces is likely to be more severe than on those covered with debris because such a

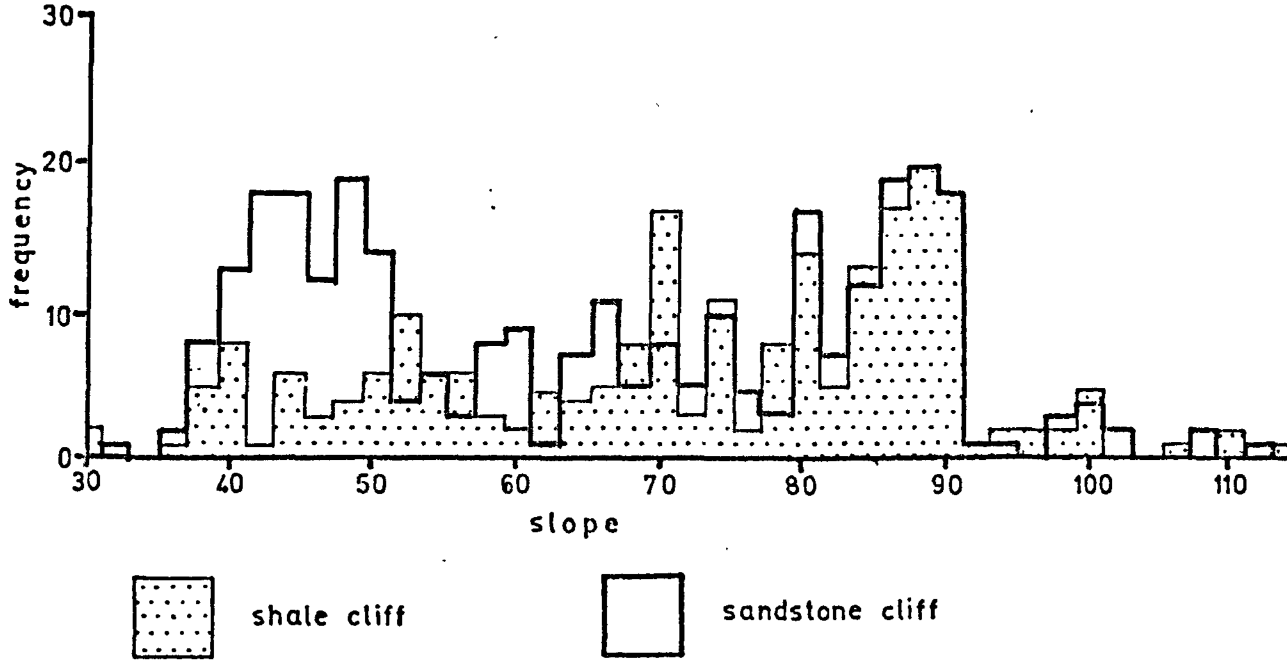


Fig.2·11a Slope histograms of units on the shale and sandstone cliffs

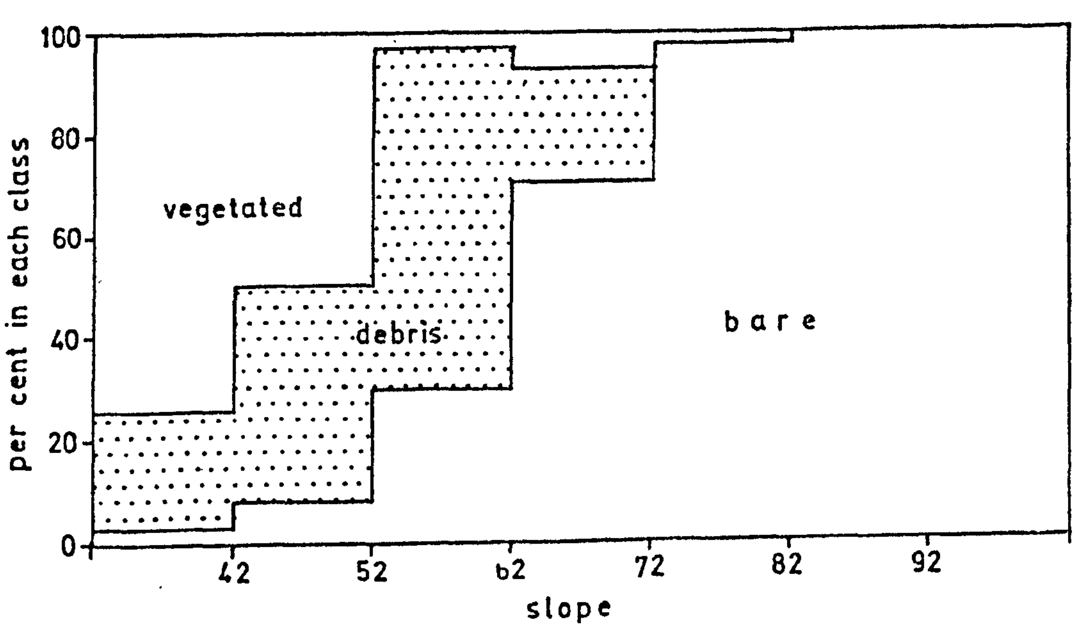


Fig. 2·11b Relationship between surface type and slope on the Upper Lias cover insulates the rock from subaerial forces such as wind and frost. Similarly, erosion on vegetated units is smaller than on debris-covered slopes because forces such as creep and rainwash have reduced effectiveness. Therefore the nature of the surface is important in determining the erosive processes.

The Influence on Units of their Height on the Cliff

Frequency-slope distributions of units for every interval of 50ft. (15.25m) up the solid rock cliff are given in Fig. 2.12. Although inclinations of about 40 degrees occur at low levels, slopes of 80 to 90 degrees predominate showing the importance of marine erosion. The lower slopes increase in proportion with height so that at the 100ft. (30.5m) level definite peaks occur at 40 to 50 degrees. Overhangs, being related to rapid erosion, follow the opposite trend, those at high levels being the result of massive sandstone strata. Therefore at the scale of the whole mapped cliff, marine erosion is pronounced below about 100ft. This is strongly shown by the table of χ^2 results in Fig. 2.13a; distributions below 100ft. are not significantly different from each other while those above this level do differ significantly from that at sea-level.

A more complicated picture is revealed when units are divided into those found on the shale and sandstone cliffs. On the latter, units at the cliff foot are significantly different (at 0.05 level) from those above 50ft. (Fig. 2.13b). Therefore the bevel is prominent above 50 ft. The shale cliff is very different in that only the slope distributions at 150 and 250 ft. (45.75 and 76.25m) differ significantly from those at 0 and 50ft. (Fig. 2.13c). This uniformity is a result of the steepness of this type of cliff throughout its height.

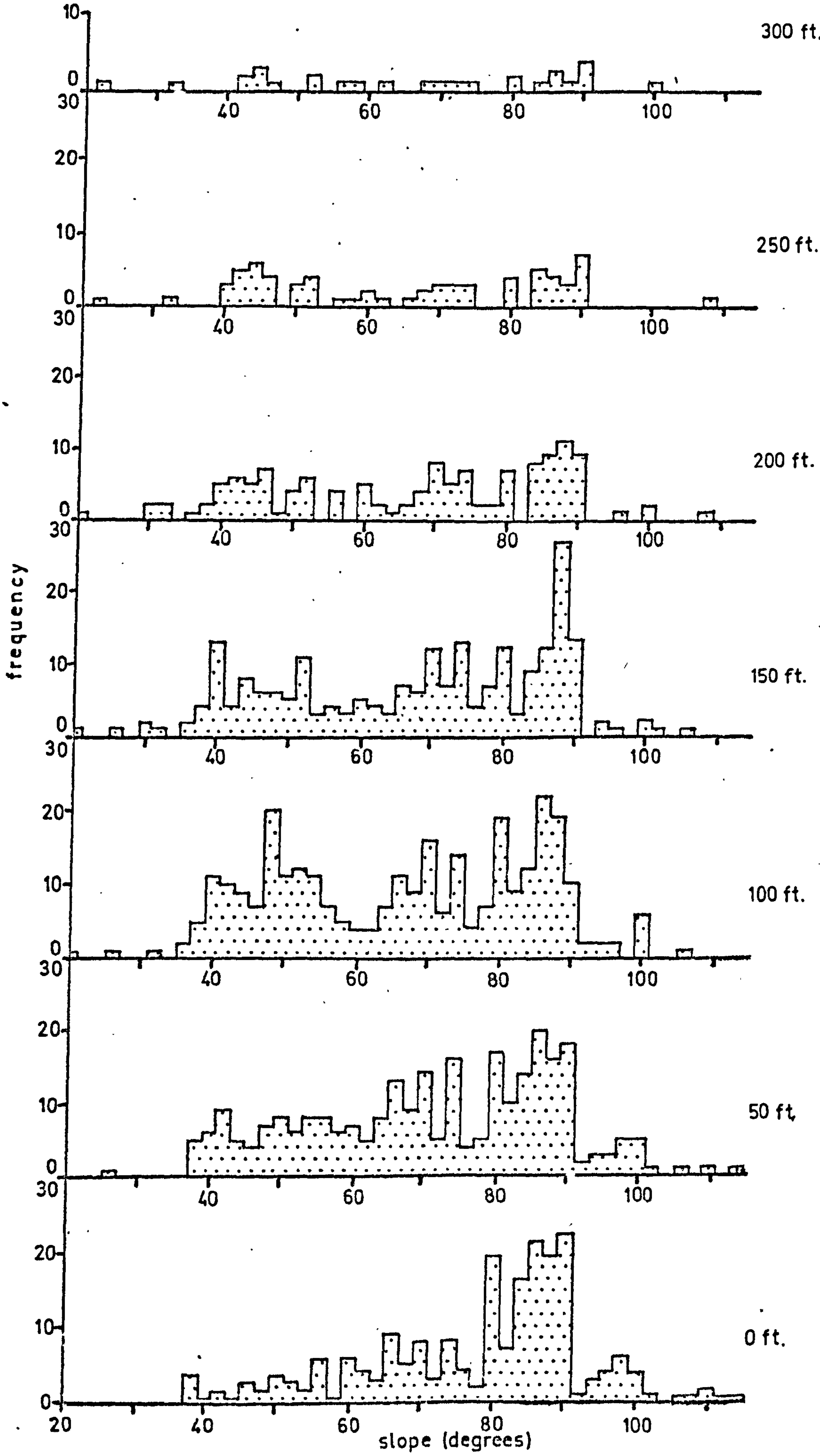


Fig. 2·12 Frequency of slopes of solid units at 50 ft. height intervals

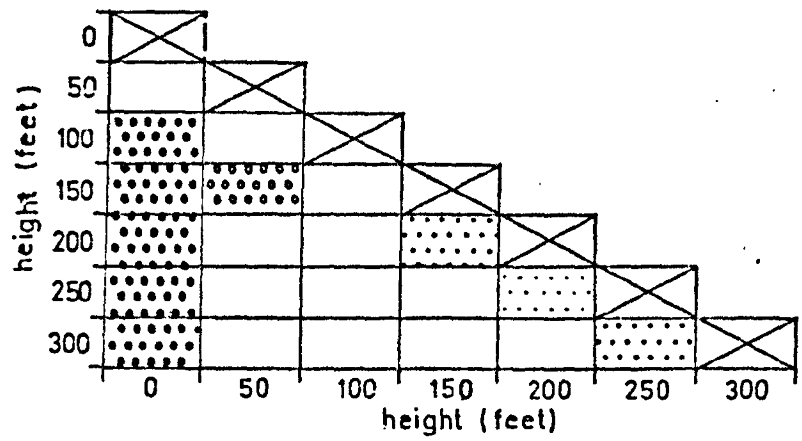


Fig. 2·13a Pair-wise χ^2 tests on frequency-slope histograms of units at 50 ft. intervals on the cliff

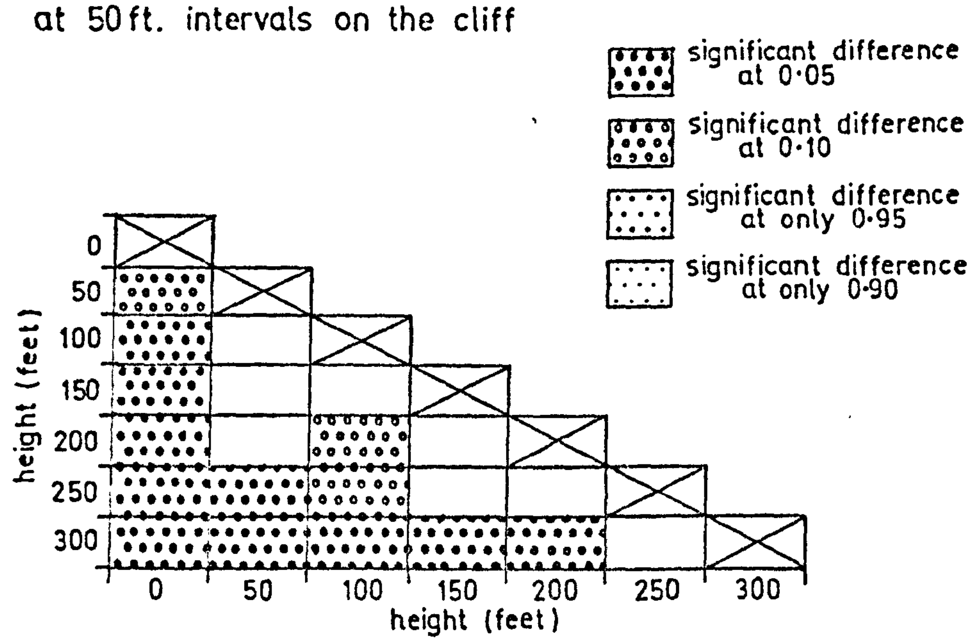


Fig. 2·13b Pair-wise χ^2 tests on frequency-slope histograms of units at 50 ft. intervals on the sandstone cliff

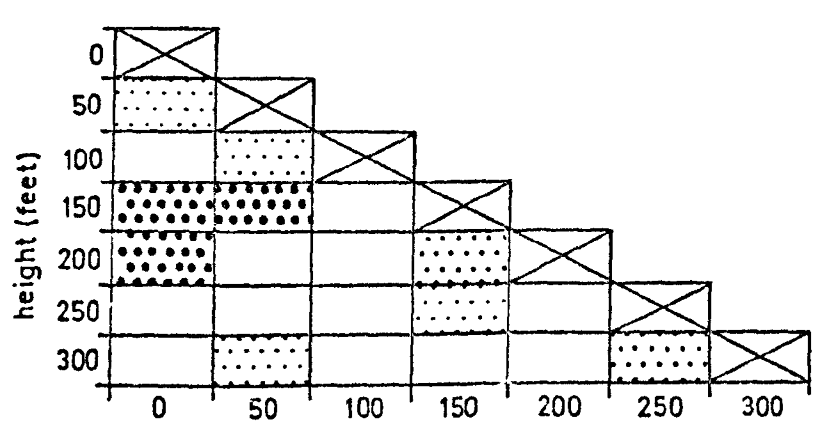


Fig. 2·13c Pair-wise χ^2 tests on frequency-slope histograms of units at 50 ft. intervals on the shale cliff

The frequency-area distributions of units at each 50ft. contour are shown in Fig. 2.14 and the results of pairwise χ^2 tests on those below 250ft. (76.25m) in Fig. 2.15a. The χ^2 test for all the distributions together reveals a significant difference between them at the 0.01 level ($\chi^2 = 74.421$; 64 degrees of freedom). Distributions below 100ft. (30.5m) are similar while the distributions at all heights differ from the one at 200ft (61m). Reference to Fig. 2.14 reveals that maxima of unit sizes occur at about 750 sq.yds. ($627m^2$), 2750 sq.yds. ($2300m^2$), 3750 sq.yds. ($3155m^2$) and 6250 sq. yds. ($5226m^2$). These are persistent up to 100ft. At 200ft. the major peak at 750 sq.yds. is overshadowed by a peak at 4250 sq.yds. ($3554m^2$). Small units become less important up the cliff and this is shown in Fig. 2.15b. This trend is due to the selective nature of marine erosion, the softest or most fractured parts of the strata being removed first. Higher up the cliff subaerial forces become more important and these are less influenced by geological variations.

The Influence of Foreshore Types on Unit Characteristics

Superficial deposits on the shore platform vary from very occasional boulders to large talus accumulations while extensive areas are completely bare. Since marine erosion of the cliff occurs at the cliff foot it might be supposed that differences in the types of foreshore at this point produce the most marked changes in cliff form. On the other hand, because this is the zone of most change through time since it is here that marine erosion is concentrated, the category of foreshore occupying most of the distance from the cliff to the sea ("the major foreshore type") might be more in phase with cliff form than the cliff foot foreshore type. Therefore it is necessary to examine the influence of foreshore type in each of these situations.

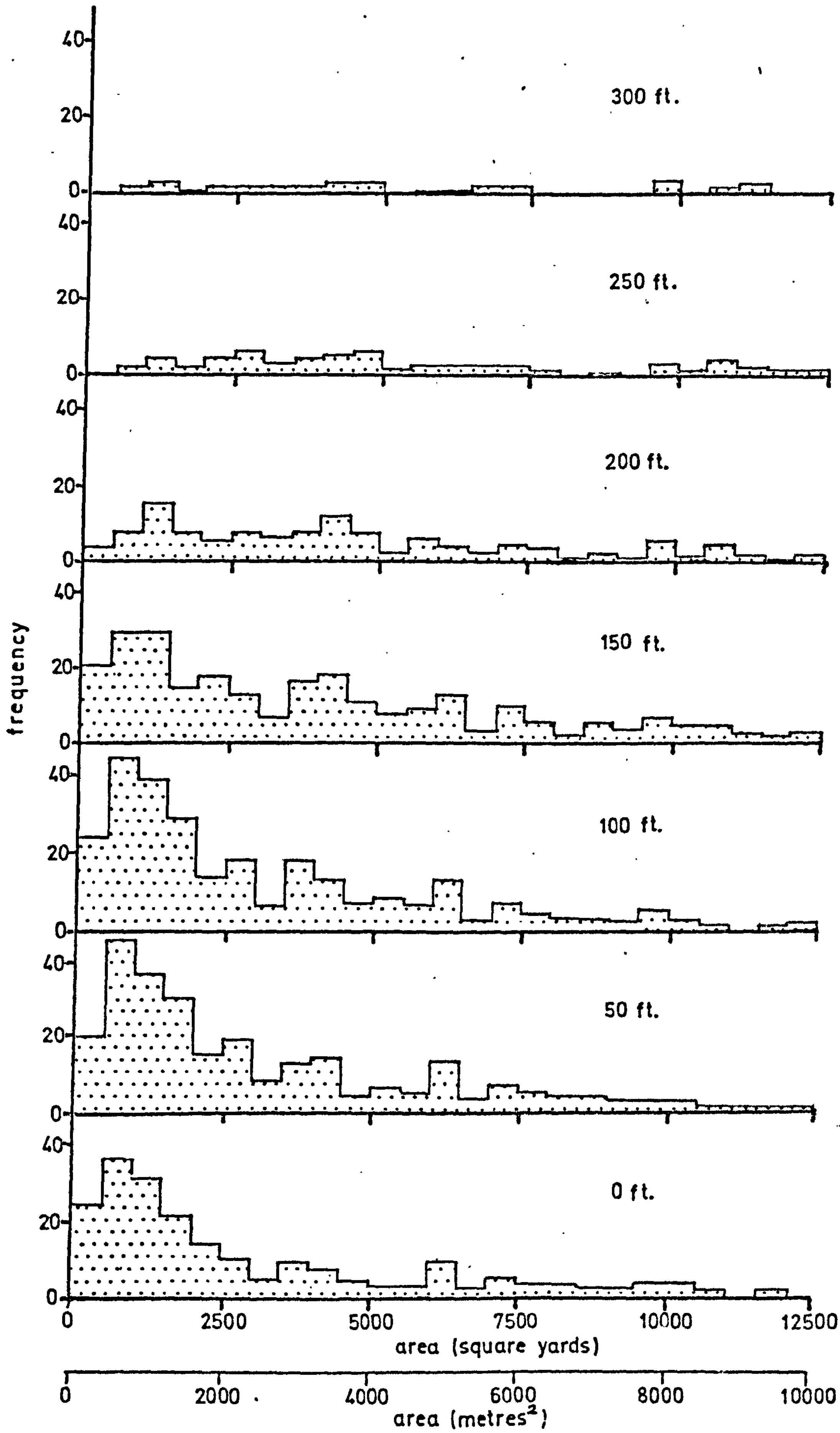


Fig. 2·14 Size-frequency of solid units at 50 ft. height intervals

height (feet)	0	50	100	150	200
0					
50 (15·2m)	6·024 16 0·99				
100 (30·5m.)	7·164 16 0·975	3·501 16 0·999			
150 (45·7m.)	19·886 16 0·25	18·502 16 0·30	11·150 16 0·80		
200 (61·0m.)	45·530 16 0·001	39·491 16 0·001	32·983 16 0·01	13·805 16 0·70	

Key: χ^2 value / degrees of freedom / significance level

Fig.2·15a Pair-wise χ^2 tests on frequency-area histograms of units at 50 ft. intervals

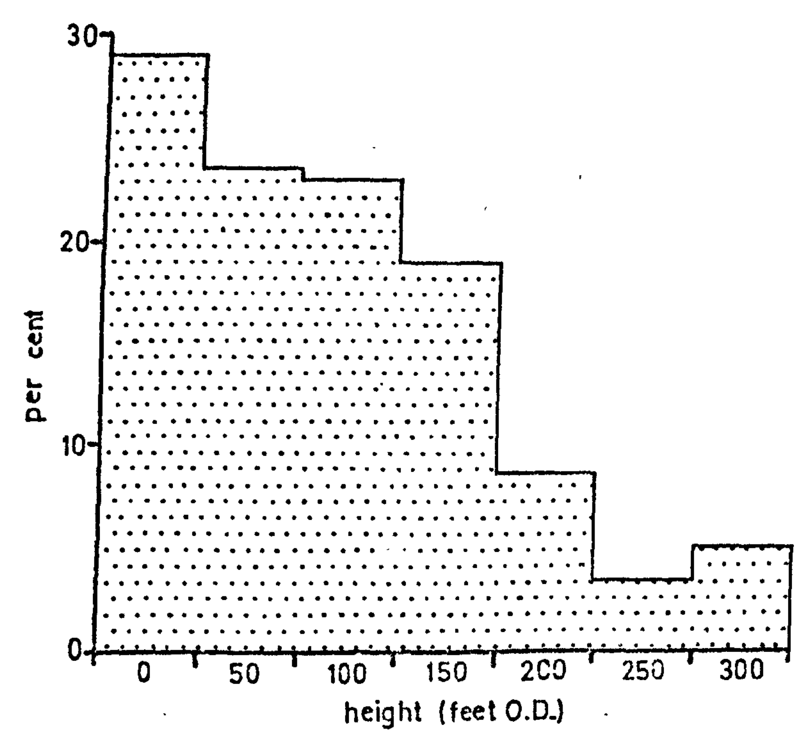


Fig.2·15b The proportional reduction of units less than 1000 yds.^{2} in area with height on the cliff

A bare platform (54 per cent) is the most common major foreshore type with areas of perched boulders (17 per cent) and thick boulders (15 per cent) the next most frequent. At the cliff foot talus (29 per cent) and thick boulders (21 per cent) are the most widespread while bare foreshore, sand and pebble beaches each occupy 10 per cent. Therefore one of the major differences between foreshore types at the foot of the cliff and those covering most of the platform is the dominance of extensive bare areas in the latter case. This indicates that the shore platform is swept clean by marine action; the distinct junction in many places between spreads of boulders at the cliff foot and extensive bare areas occupying the rest of the shore platform indicates that superficial material on the foreshore is pushed towards the cliff foot rather than carried seawards.

i. The influence of cliff-foot foreshore types - The type of foreshore at the very foot of the cliff lying in front of and vertically below every solid unit was noted. If more than one occurred the one fronting most of the unit was selected. Division of these units into those on the "shale cliff" and those on the "sandstone cliff" (as defined on page 43) yields Fig. 2.16a. Since all deposits are provided by fall from the cliff, differences reflect the size and type of material reaching the foreshore. From the shale cliff only shale boulders can fall; roughly equal proportions of medium density boulders, thick boulders, and talus result at the cliff foot. The material is easily broken up and no large proportion of thick immovable deposits can form with the result that a bare platform or beaches of sand or pebbles are common. In contrast, at the foot of the sandstone cliff the fall of large boulders of sandstone resistant to movement and erosion creates a high proportion of talus cones and thick boulders.

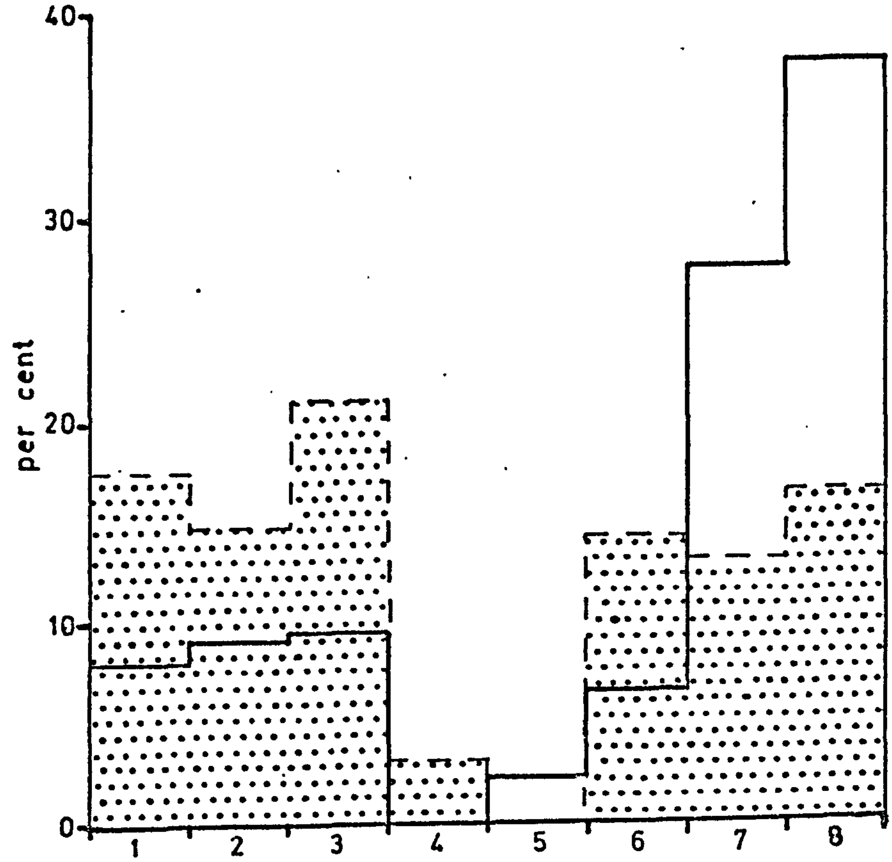


Fig. 2·16a Proportions of foreshore types at the foot of the sandstone and shale cliffs

shale cliff

sandstone cliff

1 bare foreshore
2 sand beach
3 pebble beach
4 occasional boulders
5 perched boulders
6 medium density boulders
7 thick boulders
8 talus

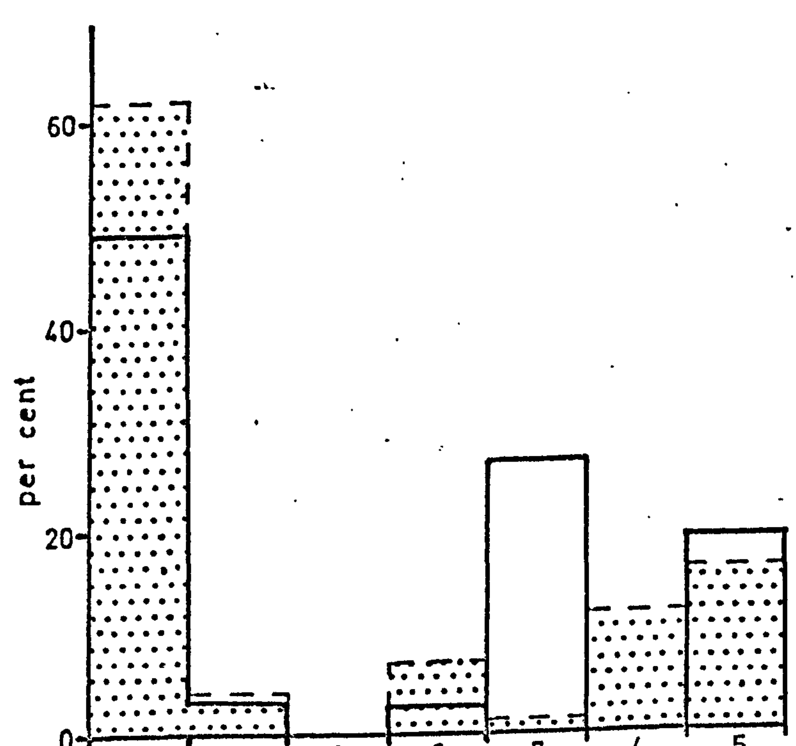


Fig. 2·16b Proportions of major foreshore types

Significant differences that exist between the frequency-slope distributions of units with the cliff foot type held constant and the units divided between those on the shale and the sandstone cliffs, are those developed behind thick boulders and talus (differences are significant at the 0.01 and 0.02 levels of probability respectively). The histograms for these are given in Fig. 2.17. The bevel is evident on the sandstone cliff behind both talus and thick boulders. The latter has a peak at 52 degrees on the shale cliff, the same characteristic angle as that noted for the Lower Lias and Sandy Series since these are the major constituents of the shale cliff. The association of this peak with thick boulders at the cliff foot supports the proposition that it may be analogous to the bevel on the Upper Lias.

The characteristic angle at 48 degrees on the talus distribution in Fig. 2.17 is higher than the one at 44 degrees on the thick boulder histogram for the sandstone cliff, implying that the former, in fact, provides the cliff with less protection from marine erosion. However, all units with angles less than 50 degrees are likely to be the product of subaerial erosion. Thus the difference must be explained in terms of age; the slope of a unit is being reduced continuously while the talus at the cliff foot is also being degraded so that the gentlest bevel is likely to occur just before being destroyed by marine erosion, i.e. when only piles of boulders remain of the former talus cones.

ii. <u>The influence of major foreshore types</u> - A bare foreshore is very common in front of both sandstone and shale cliffs (Fig. 2.16b). Thick boulders occupying most of the foreshore are confined to the sandstone cliff, and in particular from Maw Wyke to Whitestone Point. Perched boulders, which are usually of low density, are equally important seaward of both types of cliff. Therefore a large proportion of the

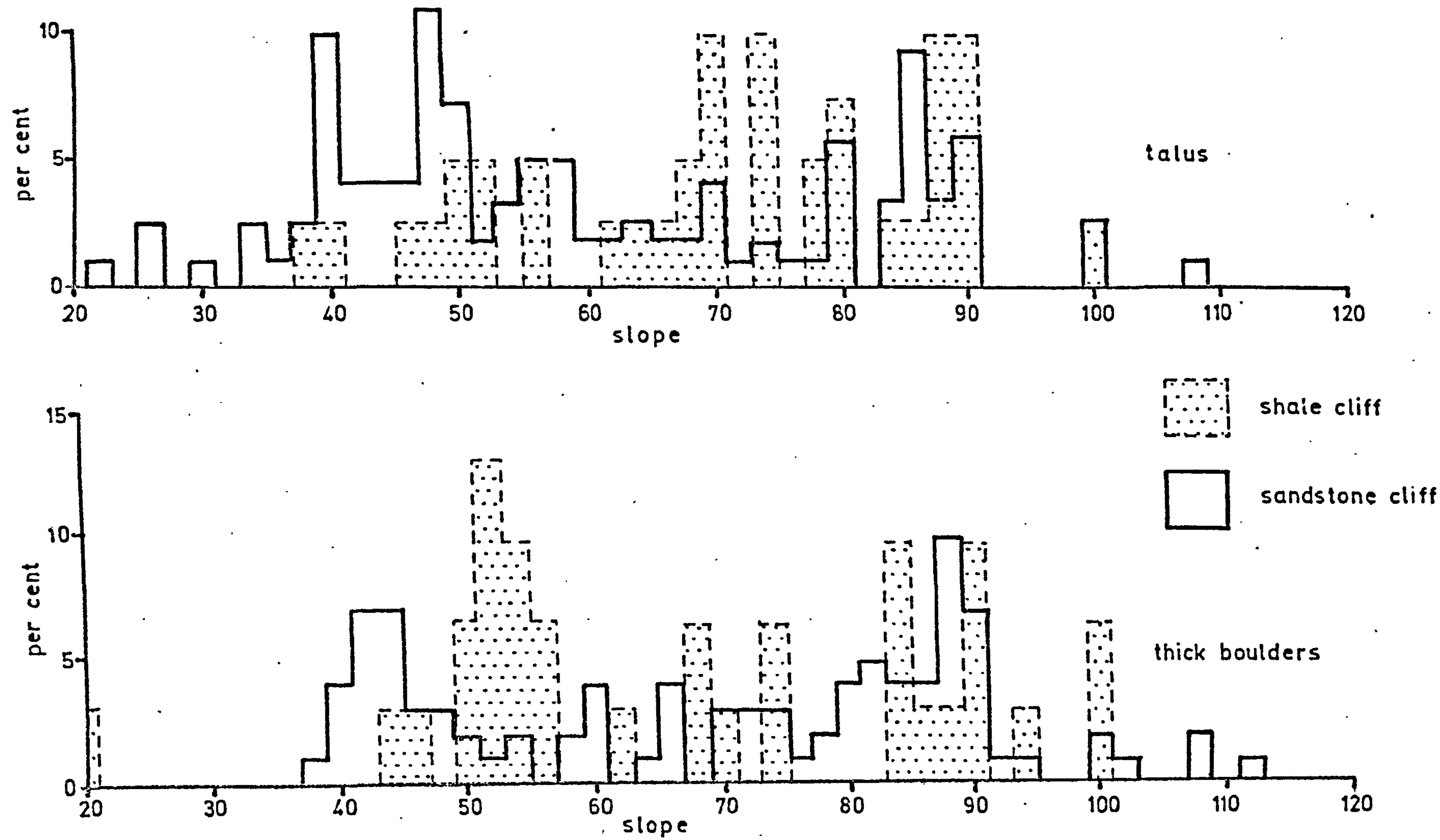


Fig.2·17 Slope histograms of units on the sandstone and shale cliffs with talus and thick boulders at the cliff foot shore platform is covered by no or scanty deposits in front of both the sandstone and the shale cliffs. This is the reason for the fact that no statistically significant differences exist between the frequency-slope distributions of units classified according to major foreshore type other than between the distribution for a bare foreshore and those for medium density boulders and thick boulders. It can be concluded that unit frequency-slope distributions are better correlated with cliff foot foreshore type than with the major foreshore type.

Summary of the Characteristics of Cliff Morphological Elements

This chapter, rather than looking at small stretches of coast, has considered the whole population of cliff units and has thus minimised the dangers of subjectivity. The analysis has confirmed the importance of the morphological elements of cliff form in north-east Yorkshire which were first recognised by Agar (1960).

The marine-activated cliff is an element which is well developed at the foot of those parts of the cliff where no talus exists. The units are small (mainly smaller than 2000 sq.yds. ($1672m^2$)) because marine erosion exploits minor geological heterogeneity. The units are also sub-vertical with inclinations most frequently 80 to 90 degrees. This element is typically developed in shale which, with its intensive jointing system and unresistant rock, is unable to withstand marine erosion. Overhangs are, therefore, common at low levels. Neither is the debris produced by this erosion sufficiently massive to impede further erosion for long; the iron seams of the Ironstone Series and the calcilutite nodules of the Upper Lias forming only small pebble and cobble beaches while shale fragments are rapidly broken up and removed.

The sandstone scarp similarly reflects the nature of the rock it is cut into. The Middle Jurassic rocks do not crop out at the cliff foot between Ravenscar and Saltburn so no units on this geological division are directly eroded by marine action. The resistance of these sandstones and the wide spacing of the joints permit units to be steep (65 to 90 degrees) sometimes with overhangs. Where there is a considerable proportion of shales in the Deltaic Series as south of Widdy Head, the slope of the cliff is as low as 70 degrees. The debris resulting from erosion of this morphological element is large and, the rock also being resistant to erosion, thick boulder beaches and large talus cones are produced.

The bevel is, perhaps, the most interesting landform from the point of view of morphology because it seems to be anomalous. Its slope is 40 to 50 degrees and yet it is mainly cut in Upper Lias shales. The Grey Shales and shales of the Ironstone Series, though lithologically and structurally very similar, do not bear this landform and so it is concluded that the cause lies in the association between soft shales and a capping of sandstones. A poor imitation of this exists in the Lower Lias shales/Sandy Series association but, because the latter is only a thin group and the strata are more argillaceous than the Deltaic sandstone, the typical slopes of units on the shales are 50 to 60 degrees (e.g. on the northern side of Robin Hood's Bay). The true bevel is associated with thick spreads of boulders on the shore platform and with talus cones, its slope being slightly greater where talus exists at the cliff foot than where it can be attacked by the sea. This allows the postulate to be made that talus, because it prevents erosion of the in-situ rock at the cliff foot, allows the upper part of the cliff to be weathered back. Where there is much sandstone in the cliff this is likely to be a slow process but where arenaceous strata merely cap the cliff, the shale below is easily eroded and a bevel is formed. This element attains its lowest slope just before being destroyed by marine action but by this time the cover of vegetation will have reduced the rate of reduction of slope to a negligible figure. A corollary arising from this postulate is that the bevel will be most quickly and best developed where there is just sufficient capping of sandstone at the cliff top to produce a talus cone which can resist marine erosion for the minimum period necessary for bevel formation.

Types of Cliff Form

Several common associations of cliff morphological elements are found in north-east Yorkshire. Of the seven possible combinations of these elements (Fig. 2.18) all but one depend on the presence of sandstone at the cliff top. The exception ((c) in Fig. 2.18) is the case where the whole cliff is composed of Lias shales. The marine-activated cliff extends to the cliff top and the cliff is sub-vertical throughout its height. In Far Jetticks this type of cliff is over 300ft (91.5m) high with only a small cobble beach at its base. This simple cliff form is found along most of the coast within the study area north-west of Staithes and south-east of Far Jetticks wherever Middle Jurassic rocks do not exist in the cliff.

The second type of cliff ((b) in Fig. 2.18) in which the bevel extends from the cliff foot to the cliff top is not found in the study area because contradictory properties are needed for its existence. On the one hand, individual sandstone strata must be thin with considerable thicknesses of shale between them to allow the bevel to be cut across them and to preclude the formation of a sandstone scarp. On

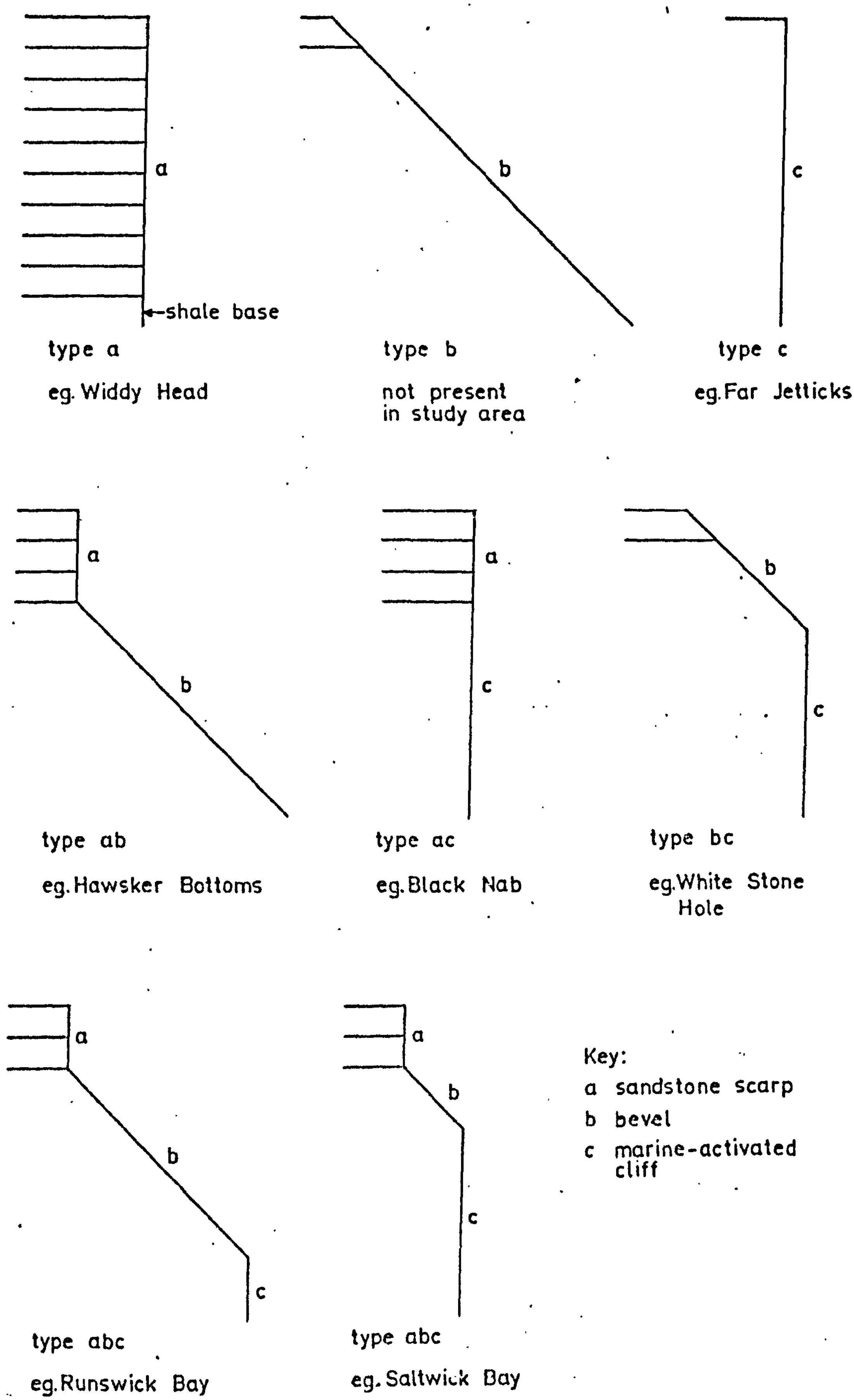


Fig. 2·18 Types of cliff form

the other hand the sandstones must be massive enough to form large talus cones at the cliff foot so that marine erosion of the solid rock is prevented.

The third type of cliff ((a) in Fig. 2.18) exists between Maw Wyke and Widdy Head. Here is found the thickest exposure of Middle Jurassic strata in the cliffs of the study area and Lias shales exist only at the very foot of the cliff which is usually covered by large talus cones containing enormous boulders. The cliff is not vertical but has slopes from 65 to 85 degrees.

All three types of cliff in which two morphological elements occur can be found in north-east Yorkshire. The best example of type (ab) (Fig. 2.18) is at Hawsker Bottoms, a location studied in more detail in the next chapter. The fall of blocks of sandstone from the scarp over a long period has formed talus which protects the base of the bevel from marine erosion. The same category of cliff exists at Wrack Hills but here the sandstone has fallen in one large landslip whose slip plane now forms the bevel (this landslip is discussed in more detail in Chapter 6).

Examples of type (ac) cliff form exist in many places in the study area, e.g. at Hawsker Bottoms, Black Nab, and Jump Down Bight. The bevel is not present for one of two reasons. Either sandstones are found only at the cliff top and, therefore, the quantity of massive debris reaching the cliff foot is insufficient to protect it, or, though Middle Jurassic strata occupy a substantial part of the cliff, individual beds are thin with thick shales between them, so the size of debris reaching the cliff foot is too small to impede marine erosion for long. This latter case is found south of Widdy Head and at Long Bight.

The third class of two-element cliff form (bc) is the type most usually referred to as a bevelled cliff or slope-over-wall cliff in other areas, e.g. in Cornwall and Devon, as a sandstone scarp is not present in these areas. However, this class is uncommon in north-east Yorkshire because, as in type (b), it requires contradictory factors - sandstone strata to be sufficiently thin to allow the cutting of the bevel across them and yet massive enough to permit the formation of the bevel through the creation of a talus cone. Nevertheless, there is an excellent example of this cliff type around White Stone Hole. It must be concluded that here massive channel sandstones, now exposed nearby at Hawsker Bottoms, once occurred at the cliff top producing large talus cones and consequently a bevel. With the wearing back of the cliff top which this demands, the channel sandstones have been removed and the bevel has extended upwards across the thin sandstones now exposed in only a few places at the cliff top.

Examples of cliffs where all three elements of form are present are many. This class (abc) is the most common where Middle Jurassic strata are found in the upper half of the cliff. The proportion of the cliff occupied by each element varies widely. Between Black Nab and Whitestone Point the bevel is very narrow and in places is pinched out completely between the other two elements. In contrast, just north of Runswick Bay village the marine-activated cliff is only small and most of the cliff is formed by the bevel while on the southern side of Maw Wyke over half the cliff is formed by the sandstone scarp. Therefore type (abc) can be considered to be intermediate between classes (ab) and (ac) in a sequence based on the amount of marine erosion.

So far the discussion on the morphology of the cliff has tacitly assumed that all types of cliff form in the study area are the result of processes operating in post-glacial times. This chapter has shown that the diversity of cliff form per se can be explained in this way. It remains to be shown in the next chapter, whether the sub-aerial processes causing removal of rock from the cliffs are sufficiently active to conform with this model and whether there is any valid evidence for Agar's (1960) hypothesis for the genesis of the bevel.

CHAPTER 3

THE CLIFF AT HAWSKER BOTTOMS

Introduction

It has been suggested in Chapter 2 that certain processes and combinations of processes may account for the various classes of cliff form found in north-east Yorkshire, but the nature and rates of operation of these processes were not studied directly. Therefore the purpose of this chapter is to identify the sub-aerial processes which cause erosion of each morphological element of the cliff, to show how these processes affect the detailed morphology of each element and how they are themselves affected by changes in form, and to examine the influence of the elements on each other.

There are only three accessible sites on the north-east Yorkshire coast where the three components of the cliff, the marine-activated cliff, the bevel, and the sandstone scarp, exist together. Of the three possibilities, at Runswick Bay, at Saltwick Bay and at Hawsker Bottoms, the last was considered to be the most suitable because it is the least visited by tourists. A morphological map of the site is reproduced in Fig. 3.1. The section of cliff studied is 288m. long and rises to approximately 90m. (270 ft.) above Ordnance Datum. Because the strata (Bituminous Shales to Lower Deltaic Series) dip gently at less than 3 degrees to the north-west, few geological complications influence the cliff's morphology. The bevel extends to the cliff foot in the northern half of the study area (cliff type (ab)) while south of this all three elements of cliff morphology are present (cliff type (abc)). Near the southern end the bevel is so narrow that the cliff can be classified almost as type (ac). More detailed descriptions of the morphological elements are given as each is treated in turn, beginning with the marine-activated cliff, and followed by the bevel and, finally, the sandstone scarp. The methods for measuring rates of

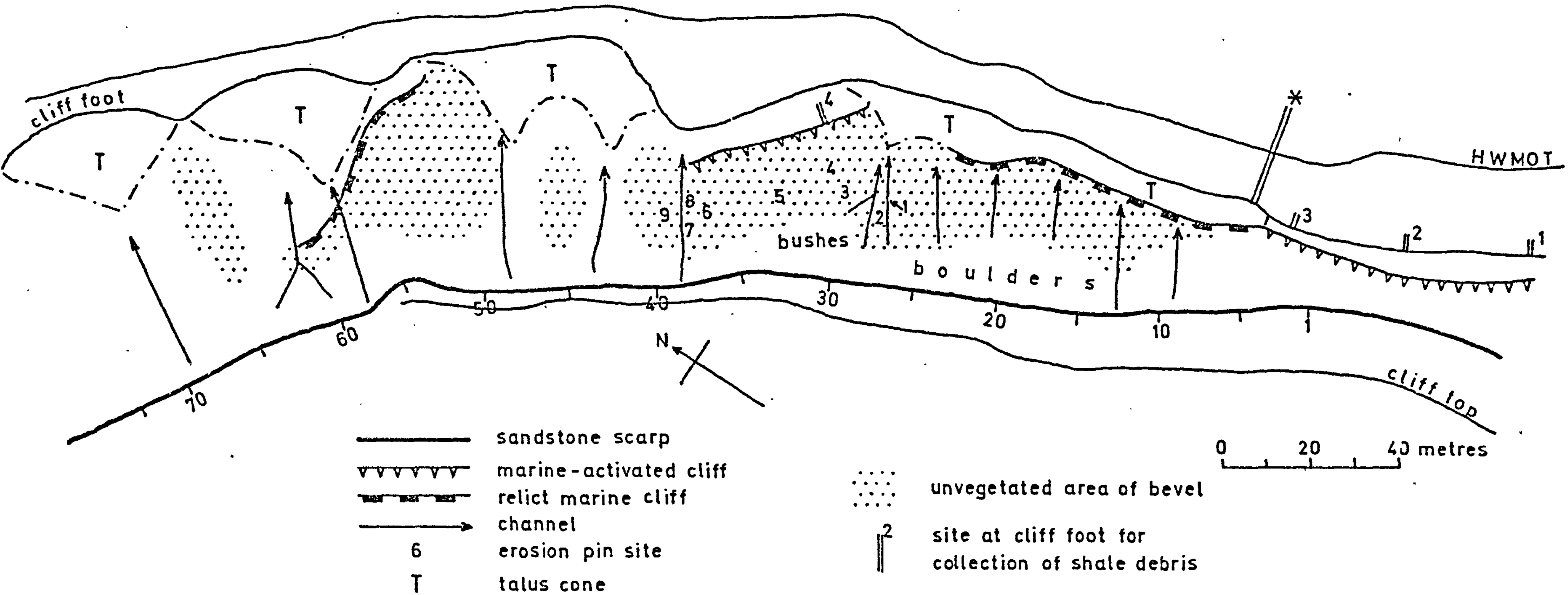


Fig. 3·1 Morphological map of Hawsker Bottoms cliff erosion on each element are also described in the relevant section, together with discussions of the natures of the erosive processes. All data concerning erosion rates at Hawsker Bottoms are listed in Appendix III.

The Marine-Activated Cliff

The Collection of Data

Sections of marine-activated cliff exist in the centre and southern parts of the study area at Hawsker Bottoms. The latter part is the largest and its height increases southwards gradually pinching out the bevel above it (Fig. 3.2a). Although two small areas of the southern marine-activated cliff are almost vertical, the slope of most of this element is about 75 degrees and the exposed shale is unweathered because the fall of particles is almost continuous. In addition to several other sets of joints, the Upper Lias strata are transected by a major set of joints which runs in a direction parallel to the coastline, a condition which probably enhances the rate of erosion. The altitude of the cliff foot is high (3 to 4m. above sea level) and so is reached by waves only during high spring tides and during storms. This fact allows a wedge of shale debris to accumulate at the cliff foot during summer but each winter, storms being more frequent, the cliff foot is washed clean several times.

In order to be able to identify the processes causing erosion of the marine-activated cliff it is necessary to be able to measure the amount of debris falling from it. The altitude of the cliff foot allowed the setting up of a simple method for the collection of this debris. Four points along the cliff foot (which are marked in Fig. 3.1) were selected and, at each site, two lines of paint were drawn 1m. apart

Fig.3·2a The southern part of the Hawsker Bottoms cliff

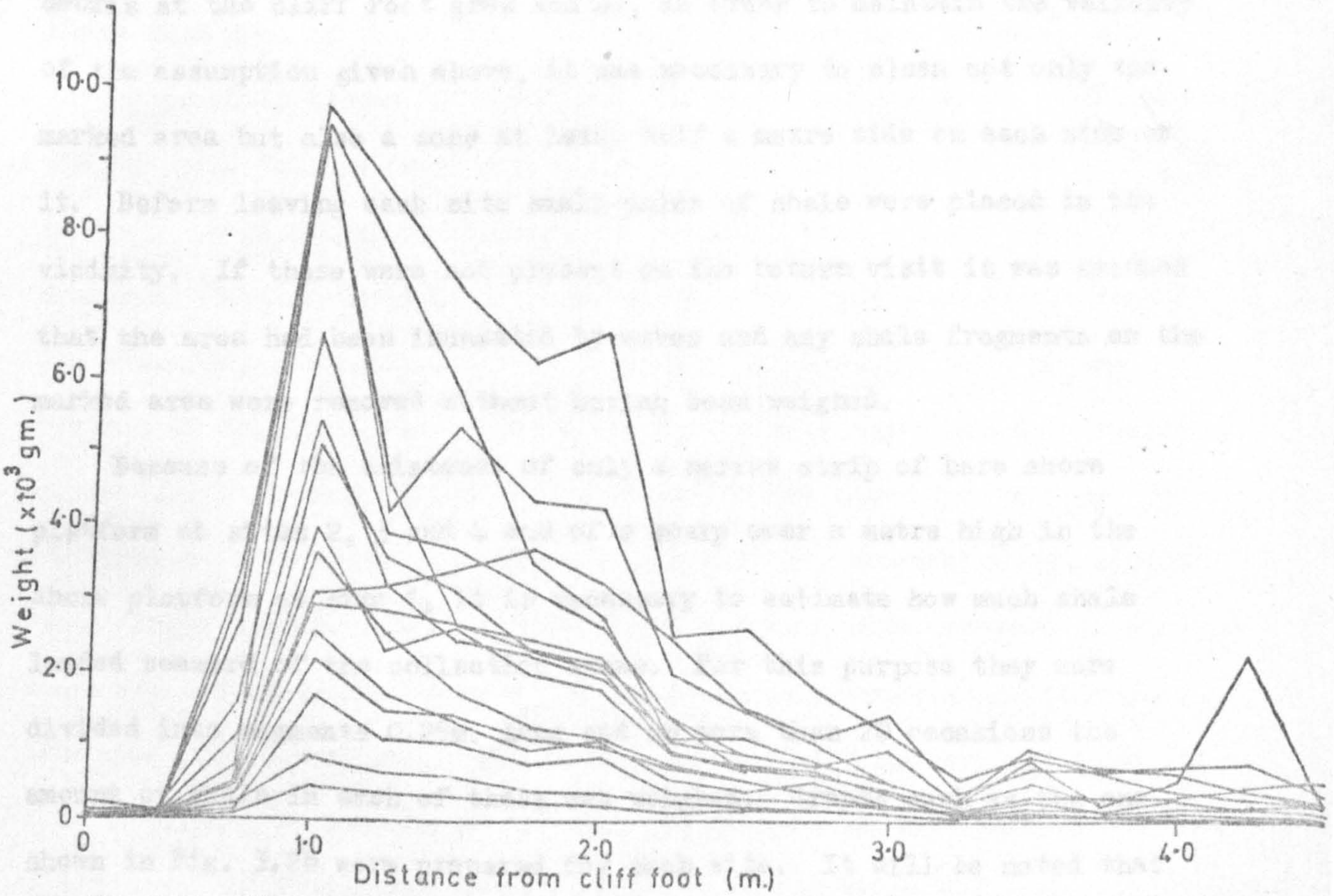


Fig.3·2b Distribution of fallen shale debris at site 2 in a direction perpendicular to the cliff. Assuming that the weight of shale fragments bouncing out of these marked areas on hitting the shore platform was equal to the amount bouncing into them, the quantity of debris accumulating in each area is the amount which fell from a strip of cliff 1m. wide extending to the cliff top, including fragments of sandstone from the sandstone scarp and shale and sandstone particles from the bevel. During the nine-month period from 26th April 1971 to 13th January 1972 the amount of shale at sites 1, 2 and 3 was weighed as often as possible (usually every day except at weekends). At site 4 the quantity was so small that only one reading was made each week totalling 33 in all. At sites 1, 2 and 3 the numbers of readings obtained are 97, 105 and 107 respectively. All visible pieces of sandstone were picked out before the shale was weighed and were taken back to the laboratory for weighing. As summer progressed the amount of debris at the cliff foot grew and so, in order to maintain the validity of the assumption given above, it was necessary to clean not only the marked area but also a zone at least half a metre wide on each side of it. Before leaving each site small piles of shale were placed in the vicinity. If these were not present on the return visit it was assumed that the area had been inundated by waves and any shale fragments on the marked area were removed without having been weighed.

Because of the existence of only a narrow strip of bare shore platform at sites 2, 3 and 4 and of a scarp over a metre high in the shore platform at site 1, it is necessary to estimate how much shale landed seaward of the collection areas. For this purpose they were divided into segments 0.25m. long and on more than 20 occasions the amount of shale in each of these was weighed. Graphs such as the one shown in Fig. 3.2b were prepared for each site. It will be noted that the proportion of debris in the final quarter-metre is small. In fact for sites 1, 2 and 3 the mean percentages of the total weights of shale which fell in the end quarters are 0.35 per cent, 0.80 per cent and 0.32 per cent. At site 4 the marked area was 3m. long but almost all the detritus fell into the first metre. It is concluded therefore that only negligible amounts of shale fell seawards of the collecting areas.

Factors Influencing the Fall of Debris

At each site the amount of debris varied by several orders of magnitude. For instance, at site 2 the range of weights for periods of one day is from 85 to 18140 gm. and at site 3 it is from 150 to 26480 gm. The bevel at these two sites is small so the amount of shale falling from this element can be considered to be negligible compared with that derived from the marine-activated cliff. Indeed, direct observation shows that most of the debris falls directly from this element; small blocks of shale become detached from the rock face and break into numerous pieces while falling down this steep slope with the result that a shower of small shale fragments cascades to the cliff foot. There is also a continual fall of individual fragments from the bare rock face. Very few fragments are retained by small ledges in the cliff face so the arrival of debris in the marked areas can be directly related to erosion of the cliff at sites 2 and 3. At the other two sites screes also contribute fragments to the collecting areas and, therefore, complicate this simple relationship. Nevertheless, the four sites respond to the same erosive processes as is shown by the Kendall coefficient of concordance (0.6794) which is significant at the 0.001 probability level (χ^2 = 38.046; 14 degrees of freedom) using one-week data periods. This coefficient is equivalent to an averaged pairwise Spearmans rank correlation coefficient of 0.5725.

Meteorological data are collected eight times each day at the coastguard station on Whitby East Cliff which is 6km. (3.7 miles) to the north-west. The data used in this analysis are for 9 a.m. Variables which were thought to be important are rainfall, maximum air temperature, air temperature range, and minimum concrete temperature, all of which are values for the preceding 24 hours, and wind speed and the amount of cloud which are parameters for 9 a.m. The last variable is a measure of the amount of direct insolation on the cliff at Hawsker Bottoms which, being north-east facing, receives only early morning sunlight.

At site 2, 67 of the erosion periods were about one day long. Simple (zero order) correlation between the amount of shale (standardised by using the variable of mean weight/hour) and the environmental factors showed that none of these is significant. However, using the data for only those one-day periods when rain fell, the important variable of cloud cover is revealed. The correlation coefficient (-0.4626) is significant at the 0.025 level but the amount of explained variation (21.4%) is low, the regression equation being

$$y = 561.37 - 52.09x$$

where y = mean weight (gm) of shale/hour

x = cloud cover (octals)

Therefore, the most significant process for one-day erosion periods is wetting-and-drying. At site 3 no significant relationship exists. Hence, for short measurement periods, the importance of randomness is great; no short-term variations in environmental factors have much influence on the amount of debris falling from the marine-activated cliff except, perhaps, the one of wetting-and-drying.

By considering longer periods the effects of short-term randomness are reduced. Sequential erosion periods were grouped into longer ones, preferably of 14 days. Thirteen such periods resulted for site 2 and

14 for site 3. Again to standardise the data, values were averaged to give the mean daily value of each variable. An additional variable, ("elapsed time") the number of days that had elapsed from 1st May 1971 to the last day of the erosion period, was included in this analysis (1st May was chosen because it was only four days before the first erosion period).

For the data relating to site 2, the best multiple regression equations were calculated for successively more variables. The most important one in the set is elapsed time, the equation

$$y = 16031.39 - 57.94x_1$$

where y = weight (gms)/day

x_1 = elapsed time

explaining 39.44% of the variation in weights and the correlation coefficient (-0.6280) is significant at the 0.01 level. Addition of the next most important variable, that of cloud cover, increases the explained variation by 6.8% but the total is not significantly greater than that supplied by the first equation. Indeed, inclusion of all other variables, though increasing the amount of explained variation to 70.39% yields an insignificant F-ratio. Therefore elapsed time is by far the most important variable at site 2, though randomness is considerable.

At site 3, this is again the most important parameter explaining 42.98% of the variation in measured weights. However, addition of the cloud cover variable increases this figure to 71.40% which is significant at the 0.05 level. The resulting equation is

$$y = 21130.32 - 30.51x_1 - 1987.73x_2$$

where y = weight (gms)/day of shale

x_1 = elapsed time (days)

x_2 = mean cloud cover (octals/day)

Addition of the other five variables increases the coefficient of determination to only 0.7868 which is not significant. The data for site 3 show less randomness than those at site 2 but the analyses are in agreement on the two most important variables. The influence of cloud cover can again be interpreted as a wetting-and-drying phenomenon but it is interesting that it seems to operate over long cycles as well as the diurnal effect noted earlier.

That elapsed time is such an important variable is an unexpected conclusion. This parameter has a negative effect on the weight of shale falling from the cliff, i.e. the longer the time which elapsed after 1st May the smaller was the amount of debris at the cliff foot. Since the total measurement period for these two-week data periods ran from May 1971 to mid-January 1972, this trend implies that some process operated before May that weakened the shale to a certain depth such that detachment of shale particles was at first easy and thereafter became progressively more difficult. The obvious process which is as time-localised as this is freezing. At Whitby Coastguard Station air frosts were recorded in the winters of 1968/69, 1969/70 and 1970/71 on 40, 55 and 23 occasions respectively. More importantly, minimum temperatures of less than 0°C were recorded on concrete (which gives a closer approximation to rock temperatures) on 56, 73 and 33 occasions, i.e. the rock surface may be below freezing point 37% more times than is the air. Temperatures on a concrete surface have been measured at Whitby since December 1968; the frequency distribution of temperatures below freezing point on concrete according to month and averaged for the winters 1968/69 and 1969/70 together with the distribution for 1970/71 are:

Month:	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June
Mean Frequency (1968/70):	0	>6	14	8.5	14.5	13.5	8	0	0
Frequency (1970/71):	0	2	4	8	7	9	2	1	0

It will be noted that during the winter (1970/71) preceding the period of measurement, the number of rock frosts was much lower than the average in most months of 1968/69 and 1969/70. Despite this, the fall of shale was considerable during the following summer. It can be postulated, therefore, that following a more normal (i.e. more severe) winter than that of 1970/71 more shale falls than the amount recorded in the summer of 1971. Thus, the effect of freeze-thaw on erosion of the marine activated cliff is probably more important than the data indicate.

The rock frosts cause freezing of water in cracks between shale laminae, producing a loosening of the whole face of the marine-activated cliff. Shale laminae are cracked with the result that small fragments and small blocks of shale are easily detached from the cliff face by other sub-aerial erosive processes such as wetting-and-drying during the rest of the year. Detachment of large joint-bounded blocks of shale is rare; these are recognisable because the debris resulting from them is larger than the normal shale fragments. The contrast in sizes is exemplified in the photograph in Fig. 3.3a. Field experience indicates that these large blocks fall only after particularly heavy rainfall. It may be that the rainwater collects in open joints and its weight pushes the blocks outwards. Lubrication of joint and bedding planes should also aid their displacement.

As noted earlier, the data collected at the other two sites are not representative of the marine-activated cliff alone. Above site 1, where there is no bevel or sandstone scarp, a small scree intercepts a small proportion of falls of shale and discharges small amounts at other times when no rock has been detached from the cliff. Debris falling at site 4 is derived mainly from the bevel because the marine-activated cliff is small. At site 1 no zero-order correlation coefficient is significantly greater than zero but at the first order the best equation involves the

Fig.3·3a Accumulations of shale fragments at the cliff foot looking towards the cliff

Fig.3·3b Active channels on the bevel looking down to the beach variables of mean wind speed and mean maximum air temperature, the amount of explained variation being 65.79%. These parameters are, of course, not the same as those which are significant at sites 2 and 3. The importance of wind implies that shale fragments at this site can be easily dislodged and the fact that air temperature is also influential indicates that more shale falls when it is dry because frictional forces between contiguous shale fragments are reduced. Clearly wetting-and-drying is not the most effective process here. However, the fourth order equation is also significant at the 0.01 level (explained variation = 99.06%), the regression coefficient of each variable being significant at the 0.05 level.

$$y = -2883.39+368.77x_1-577.13x_2-10.14x_3-842.66x_4+558.04x_5$$

where y = mean weight of shale/day (gms)

x_1 = mean wind speed (kts)

x_2 = mean cloud cover (octals)

x_3 = time elapsed since 1st May 1971 (days)

x_4 = mean rainfall/day (mm)

x_5 = mean minimum concrete temperature ($^{\circ}C$)

Mean maximum temperature is not present in this relationship but there is a zero order correlation coefficient of 0.8648 between it and mean minimum concrete temperature. It will be noted that in this equation the wetting-and-drying variable of cloud cover and the length of time since the commencement of data collection are again present as they were at the other two sites. These variables are indicative of direct fall from the cliff face while wind speed and minimum concrete temperature probably represent the processes which are important on the scree slope and on any detached fragments lying on ledges higher up the cliff. The negative effect of the rainfall parameter on the amount of shale falling supports this conclusion. No higher order equation than the fourth is significant.

At site 4 the amount of fallen shale in the marked area was weighed only once each week. These data were subjected to multiple correlation and regression analysis using the same eight predictor variables as above. However, no correlation coefficient higher than the zero order is significant at the 0.05 level. At the lowest order only that which uses mean maximum temperature is significant though the equation

$$y = 54.37x - 262.37 \qquad \text{where } y = \text{mean weight of shale/day (gm)}$$
$$x = \text{mean maximum temperature } (^{\circ}C)$$

explains only 20.29% of the variation in y. This, perhaps, indicates that the bevel above the site, being bare of vegetation over a considerable area and covered by loose shale fragments, is contributing most to the shale which was found in the marked area and acts like the scree slope at site 1. In other words, the small marine-activated cliff at this site is being eroded very little.

The Bevel

Morphology of the Bevel

In detail, the bevel at Hawsker Bottoms is not a simple inclined plane. Its constituent parts can be seen in the morphological map in Fig. 3.1. The bevel is transected by channels, some of which expose bare rock and are active while others are choked with debris covered by vegetation. The best examples of the former are shown in Fig. 3.3b. They are about 1.2m deep and at their bases lies a talus cone which is low enough to be attacked by waves throughout most of its height during storms. Therefore there is a continuous washing of debris down the channels to the talus cone from where it is removed by waves. The upper ends of these two channels are sharp for they are undermining part of a spread of large boulders which have fallen from the sandstone scarp.

However, most of the detritus in the channels is shale which has been dislodged from the bare slopes on each side. Almost all channels, other than those eating into the area of boulders, terminate at the sandstone scarp whose foot is lower at these points. It is usual for the Upper Lias shales to be exposed here and, having little resistance, they are quickly eroded and the scarp is undermined. Some other channels (e.g. in Fig. 3.4a) are very shallow and are clearly not active because they are choked with debris and vegetation. Such channels occur where the talus at the foot of the cliff is sufficiently high and resistant not to be eroded by waves in their upper parts. Hence debris falling into these channels cannot be flushed downwards. However, it is still possible for the ridges to be eroded because they are higher. They become less pronounced and the whole ridge-channel complex of the bevel is smoothed out. Eventually these subdued ridges may become covered with scree which, in turn, allows the growth of vegetation and erosion of the bevel will be reduced to a minimum. However, because of the high slope of the bevel (about 45°) and the existence of terracettes, plant cover is not usually complete. Erosion may continue on the risers between such features (Fig. 3.4b) but these small screes become vegetated in time also.

An interesting morphological feature at Hawsker Bottoms is shown in Fig. 3.5a. A vertical scarp cut into the Upper Lias is fronted by a large, vegetated talus cone. This scarp was formerly a marine-activated cliff but the growth of the talus cone has isolated it from the sea. It is now being dissected from above by deep channels while the removal of shale from its face continues. It is therefore a relict marine cliff which is being destroyed and may eventually be transformed into a typical section of the bevel. Another section of marine cliff fronted by talus cones exists between sites 3 and 4. This part is relict in the sense that the sea can no longer reach it but whether or not it also will be

Fig. 3·4a Channels choked with debris

Fig.3·4b Erosion of a riser

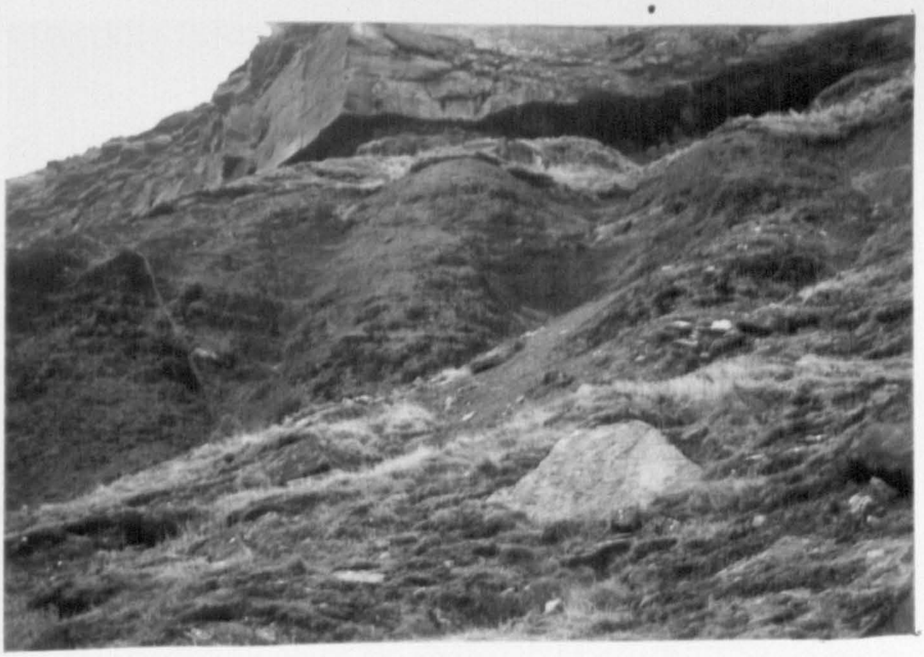


Fig.3·5a A relict marine-activated cliff now undergoing degradation

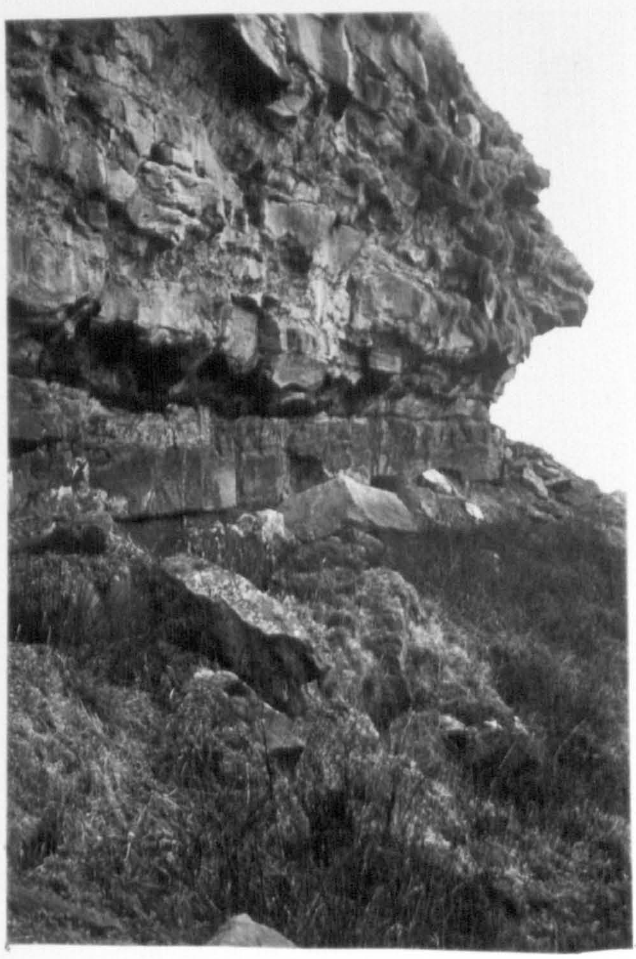


Fig.3·5b An overhang of the sandstone scarp destroyed and become part of the bevel will depend on the permanence of the talus cones which protect it. This in turn will depend upon the rate of supply of resistant sandstone blocks from above relative to the destruction of them by marine action.

Erosive Processes on the Bevel

Before the amounts of shale collected in the four marked areas at the foot of the cliff were weighed, all sandstone particles were picked out. These fragments which are small, their modal size class being from 2.6 to 6.9 mm in diameter, were originally derived from the sandstone scarp but have probably rested for some time on the bevel, as is shown by their frequently rough weathered surfaces. Above site 2 the bevel is very narrow and so this assumption might be weak but it is certainly true for site 4. The bevel immediately in front of the sandstone scarp at this point is covered with nettles and small bushes and so particles falling from it are unlikely to reach the cliff foot at once. Moreover, almost all particles collected at site 4 had rough weathered surfaces and were often well-rounded indicating that they had rested on the bevel for a considerable period. Therefore, if the quantities of sandstone collected at the cliff foot sites can be assumed to be proportional to the amounts of shale which fell during the same periods, the weights of sandstone are indicative of the erosive processes on those parts of the bevel above the collecting areas.

The conclusions reached rely on the additional assumption that all sandstone particles were picked out of the piles of debris. Certainly very small specks could not be seen but their total weight is likely to be negligible since their volumes, and therefore their weights, are proportional to the third power of their diameters. Fortunately, the contrasts in surface texture and colour between black shale fragments and the fawn-yellow sandstones and silts are obvious with the result that a very high percentage of the total weight of these particles must have been extracted from the debris.

There is no bevel above site 1 because it is at a corner in the cliff. The sandstone fragments collected here, which were rare, must have been blown on to the marked area while dropping from the cliff.

At site 2 multiple correlation and regression, employing the same environmental variables as in the previous section of this chapter and utilising data which were averaged over fortnightly periods, reveals that the best single variable is rainfall explaining 74.13% of the variation. However, the best equation, which increases this figure to 87.23% (significant at 0.01 level), is

$$y = 21.79 + 4.96x_1 - 13.65x_2 + 12.68x_3$$

where y = mean weight of sandstone/day

x_1 = mean maximum air temperature

x_2 = mean air-temperature range

x_3 = mean rainfall/day

Because the two air temperature parameters have a zero-order correlation coefficient of 0.9057 they can be considered as one variable measuring the dryness of the air and, therefore, of the debris lying on the bevel. The drier this detritus is, the more will fall because of reduced friction between the fragments. The rainfall variable must be interpreted as the effectiveness of water in the washing of fragments off the bevel.

No relationship is statistically significant for the sandstone data collected at site 3. This results from the fall of a large sandstone block weighing about 58,650 gm between 18th August and 2nd September 1971. The clean surface of it indicated that it had probably not been resting on the bevel but had broken off the scarp immediately before its fall. The weight of sandstone for this one erosion period (15 days) is thirteen times the total weight of all other periods combined (158 days).

At site 4 only one variable, that of maximum air temperature, is important but it explains only 28.83% of the variance in sandstone weights; the equation is

$y = 2.42x - 24.64$ where y = mean weight of sandstone/day
x = mean maximum air temperature

This variable, the dryness of the debris, is probably important at all sites therefore. However, it is curious that rainfall is not equally influential. In fact this may be due to the thickness of debris on the bevel. At site 2 the bevel is narrow, steep and the debris on it thin, so runoff occurs immediately. At site 4 rainwater quickly percolates below the surface of the thick debris so that runoff is rare. It is interesting that neither wetting-and-drying nor elapsed time are important variables in the erosion of the bevel.

Retreat of the Bevel

Although the preceding analysis has exposed the nature of the principal erosive processes on the bevel it has not been able to provide an estimate of the rate of erosion since shale particles from the bevel are indistinguishable from those derived from the marine-activated cliff. Several workers (e.g. Schumm 1956 a and b, Bridges and Harding 1971, Imeson 1970) have been able to measure erosion and accretion at the surface by the vertical insertion of pieces of wire or nails which had been passed through washers. This washer provides a point of reference from which to measure to the top of the wire or nail. By rusting the washer also forms an effective bond with the soil.

Several lines of pieces of galvanised wire running in the direction of maximum slope were established at Hawsker Bottoms; their positions are marked in Fig. 3.1. The sites are in the south-eastern part of the study area because other sites were destroyed by vandals before any readings could be taken. The pieces of wire were placed normal to the bevel surface since measurements in the vertical direction would overestimate the actual rate of erosion. Wires were also arranged in arrays in a few places. The period covered by the measurements cited here is from May 1971 to July 1972.

At site 4, eleven of the 27 erosion pins were not provided with washers so that the effects of these could be examined. The Mann-Whitney U test (Siegel, 1956) reveals that, at the 0.025 significance level, there was less erosion around the pins with washers than around the other pins. In fact the former sample showed a mean accretion of 6.8mm while the other witnessed mean erosion of 2.2mm. Because the measurement period was short it might be that the differences are due to temporary fluctuations; four of the washers were deeply covered at one time by a tongue of fine debris about 20mm thick. Nevertheless it is difficult to believe that the washers do not reduce erosion to some extent. Also, it was not infrequently noted that the erosion pin itself arrested the passage of shale fragments down the bevel. For this reason two readings were taken at each erosion pin, one on the up-slope side and one on the down-slope side. The amount of erosion at the pin is then the mean of two measurements. It seems that more research is needed into the operation of the erosion-pin technique to assess its accuracy and consistency.

The erosion pins constituting site 1 are located down the thalweg of the channel shown on the right in the photograph in Fig. 3.3b. Because it was evident in the field that these pins were retarding much material being washed down the channel, the erosion measurements are not reliable and, therefore, are not used.

Erosion readings at site 2 do not have the same inaccuracies as those at site 1, since site 2 runs down the ridge shown in Fig. 3.3b and retardation of shale fragments is much less common. The correlation coefficient (-0.1664) relating the amount of erosion (whose mean is -2.60mm, i.e. 2.6mm of accretion) to height on the cliff is not significant at the 0.05 level. This may be due either to the brevity of the measurement period or to the fact that the bevel is undergoing parallel retreat rather than steepening or flattening. Until more data can be collected, the former alternative must be preferred since net accretion is indicated. An insignificant correlation coefficient (-0.1234) for site 9 is interpreted in the same way.

In detail, the variability in erosion rates can be partly related to local factors. At site 3 some of the erosion pins are situated in grassed areas while others are in areas with no vegetation. A Mann-Whitney U test on these samples reveals that erosion is significantly smaller (at 0.05 level) in the latter areas, 11 of which are undergoing accretion. There is a significant correlation (-0.4612) between erosion and vertical distance from the uppermost pin, a trend resulting from the fact that the upper part of the profile is grassed while the lower part is scree. Net accretion was also experienced by most pins on the scree slope (mean angle = 36.3 degrees) at site 4 (mean accretion at 25 pins = 3.56mm in 14 months) and by all pins (mean accretion = 10.78mm) at site 5 where the surface is slightly steeper (mean inclination = 40.89 degrees). In the same period site 6 suffered 2.83mm of accretion, site 7 3.4mm and site 8 5.0 mm. These averages hide the variability of erosion as some pins showed erosion consistently while others suffered continuous accretion. The high frequency of sites showing net accretion can be attributed to the fact that a unit amount of erosion of solid rock at one point caused by the removal of several shale fragments will lead to more than one unit of accretion at another if all the fragments are deposited there because of the large air spaces between them. This point raises the question of whether erosion and accretion rates measured with the erosion pin technique where the debris is as coarse as it is at Hawsker Bottoms can be compared at all. Certainly, to obtain reliable estimates of the rate of erosion of the bevel, measurements must be taken over a longer period than was possible for this study.

Seasonal variations in erosion rates are often important. At site 2 erosion is significantly greater (at the 0.05 probability level) in winter than summer (using the Wilcoxon matched-pairs signed ranks test). Since most of this site is composed of bare shale it is probable that winter frosts are the main agency for the liberation of fragments just as they are on the marine-activated cliff. The same regime exists at site 4 but as this is a scree slope it is difficult to rationalise this fact. The other sites show more erosion in summer than winter, perhaps because they act merely as the recipients of material removed from locations where winter erosion is high. The summer regime sites are generally scree slopes. Therefore these conclusions agree well with those inferred for the marine-activated cliff.

The Sandstone Scarp

Composition of the Scarp

The sub-vertical scarp forming the highest part of the Hawsker Bottoms cliff is present solely because of the cropping out of sandstone strata of the basal Lower Deltaic Series and of the Dogger Sandstone. In the study area this scarp is about 7.5m high, but because the rocks dip to the north-west it becomes smaller and finally disappears at the head of White Stone Hole where only the bevel lies above the marine-activated cliff. Towards Maw Wyke the scarp occupies more and more of the total cliff with the result that the bevel is gradually pinched out from above.

It is impossible to give a detailed account of the strata exposed in the scarp since only the lowest two or three metres of it are accessible; a qualitative account must therefore suffice. At the corner marked 55 in Fig. 3.1 all the Dogger (about 1.9m thick) is exposed. Overlying it is 1.05m of shale, coal and seat earth and above this is the thickest sandstone stratum in the scarp. This bed, which is about 5m thick, is undoubtedly a channel infill for it thins rapidly on each side. To the north-west, sandy shales and seat earths thicken as this layer thins so that at point 72 they are 2.8m thick. South-eastward of the channel sandstone the Dogger is buried and sandstones continue to constitute most of the scarp though the beds are separated by thin sandy shales. The Dogger reappears near the point marked 35 in Fig. 3.1. A view of the scarp south-east of this point is shown in Fig. 3.5b where sandstones and shales are roughly equal in proportion. Continuing in the same direction, the Dogger again becomes hidden and thick contiguous sandstones make up 4m at the foot of the scarp. At the southern end of the study area the Dogger reappears.

The structure of the exposed strata is very simple, there being no folds to complicate their low dip. The only fault was probably sub-contemporaneous with deposition; it cuts the shales and seat earths near point 65 with a throw of less than a metre. Joints are fairly well developed in the sandstones but are not obvious in the shales as these crumble easily. The sandstones are generally cut into fairly large cuboidal blocks by these joints (Fig. 3.6a). Small peaks in the frequency distribution of joint directions occur at 285 degrees and 355 degrees which are at a considerable angle to the direction of the coastline. Also joints parallel to the rock surface can be seen in several places producing thin sheets of rock rather than cuboidal blocks.

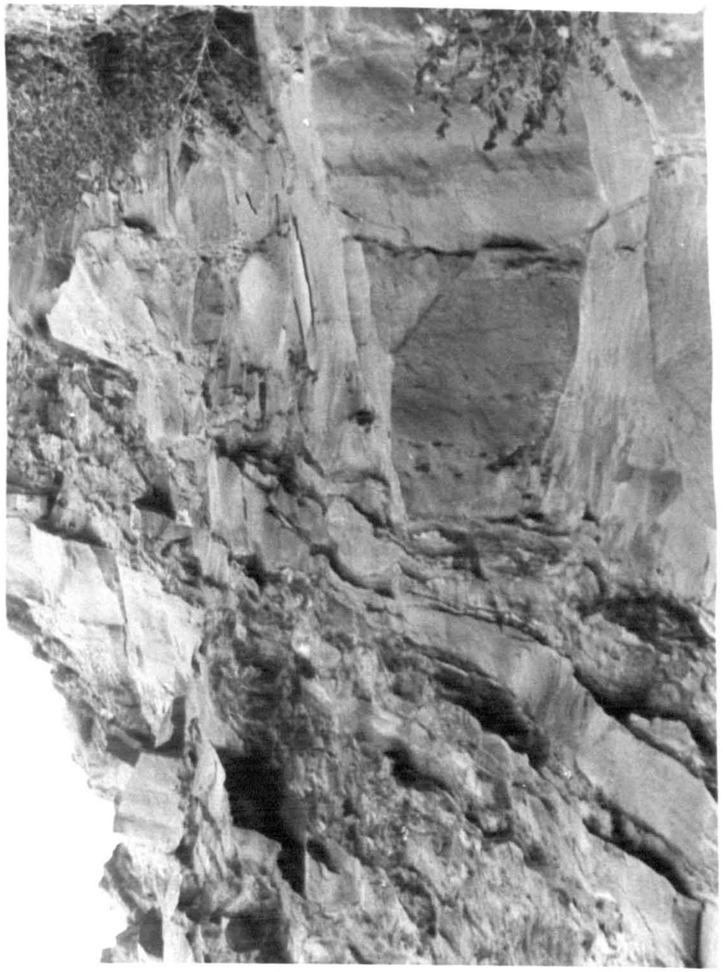


Fig.3·6a Joint systems in the sandstone scarp

Fig.3·6b A collapsed section of the sandstone scarp

Morphology of the Scarp

The main feature of the morphology of the scarp is the amount of overhang, i.e. the horizontal distance over which protrusions of rock are unsupported from below. For example, that part shown in Fig. 3.5b clearly has a large overhang while other parts have very little. Measurements were made at approximately four-metre intervals, some of the points being shown in Fig. 3.1; these locations were marked with paint to allow measurements to be made in several years' time. A four-metre levelling staff was positioned vertically using a spirit level and, by sighting along it, the staff was placed exactly under the tip of the overhang at that point along the scarp. The horizontal distance from the staff to the basal resistant stratum was then measured. The Dogger or sandstone bed forming this basal stratum is often undermined also; the amount of this overhang has been added on in the shaded areas of Fig. 3.7 to give the total size of the overhang.

The amount of overhang varies from zero to 4.4m, the mean being 1.6m. Five zones can be recognised according to the amount of overhang. The first, at the south-eastern end of the study area, has more than the average amount and there is strong undermining of the basal stratum, the Dogger. The bevel fronting this part is very narrow because of the rapid retreat of the marine-activated cliff. The second zone has little overhang and the foot of the scarp is above the Dogger because of a large accumulation of sandstone blocks and debris which have fallen from the scarp. A view of this section is given in Fig. 3.6b. The third zone is in complete contrast to this; the overhang is very pronounced (Fig. 3.5b) and the Dogger is exposed and undermined in part. The bevel here descends almost to the cliff foot. The fourth zone is very like the second with little overhang and the Dogger is covered. Large amounts of debris lie at the cliff foot to where the bevel extends.

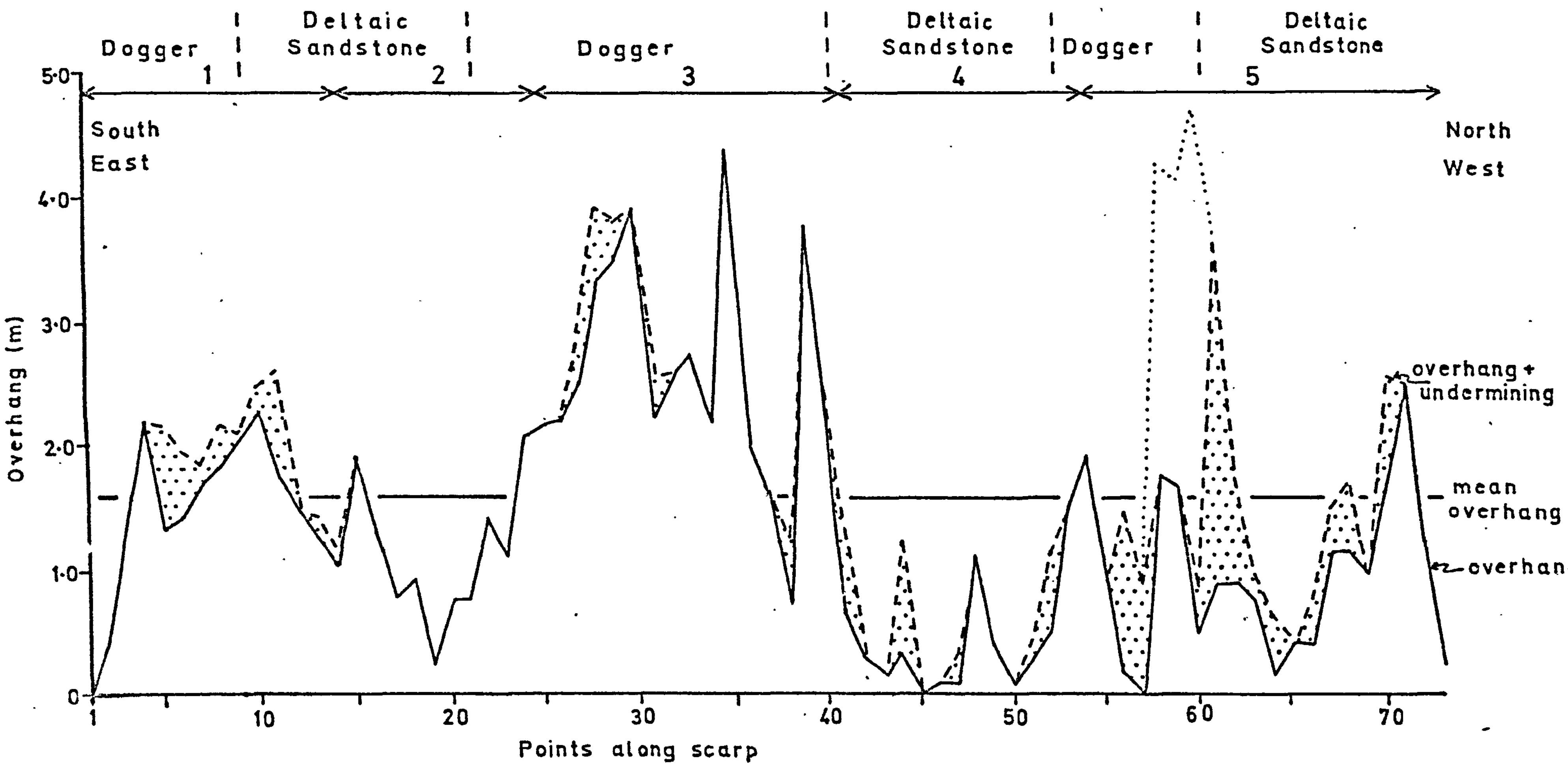


Fig. 3·7 Size of the sandstone scarp overhang

The fifth zone is heterogeneous containing small and very large overhangs. Part of this section lies behind the relict marine-activated cliff described earlier. The scarp contains thick shales and seat earths here which have been preferentially weathered out producing the maximum overhang not at the foot of the scarp but above the Dogger (these measurements are shown by the dotted line in Fig. 3.7). From the preceding description it can be concluded that large overhangs can be correlated with those parts of the scarp where the Dogger is exposed. Indeed, a Mann-Whitney U test on the overhang data classified according to whether the Dogger or Lower Deltaic sandstone is exposed at the foot of the scarp shows that measurements in the former sample are extremely significantly larger (significance level of less than 0.00003). This implies that the bevel is eroded and exposes the Dogger leading to the undermining of this because no resistant strata occur below it. Eventually, the overhang having become greater than the rocks can bear, the scarp collapses and the overhang is destroyed.

It is not clear whether collapses occur instantaneously as large falls (which appears to have happened in Fig. 3.6b) or protractedly as falls of individual blocks. Since these operations are merely the two ends of a continuum it is likely that both can take place. The process leading to the fall of individual boulders and the growth of the overhang can be seen in several of its stages near point 30 along the scarp in Fig. 3.1. Scattered boulders occur in front of this part of the scarp. The photograph in Fig. 3.8a is a closer view of the Dogger bed at its base. Undermining of the block by the weathering and washing out of shale has been severe enough to leave it unsupported and it has broken away. The bed above it is now left without support and eventually a block may fall from this also. Washing of weathered shale from beneath the Dogger continues and the overhang grows in this way until the structural

Fig.3·8a Undermining of the Dogger

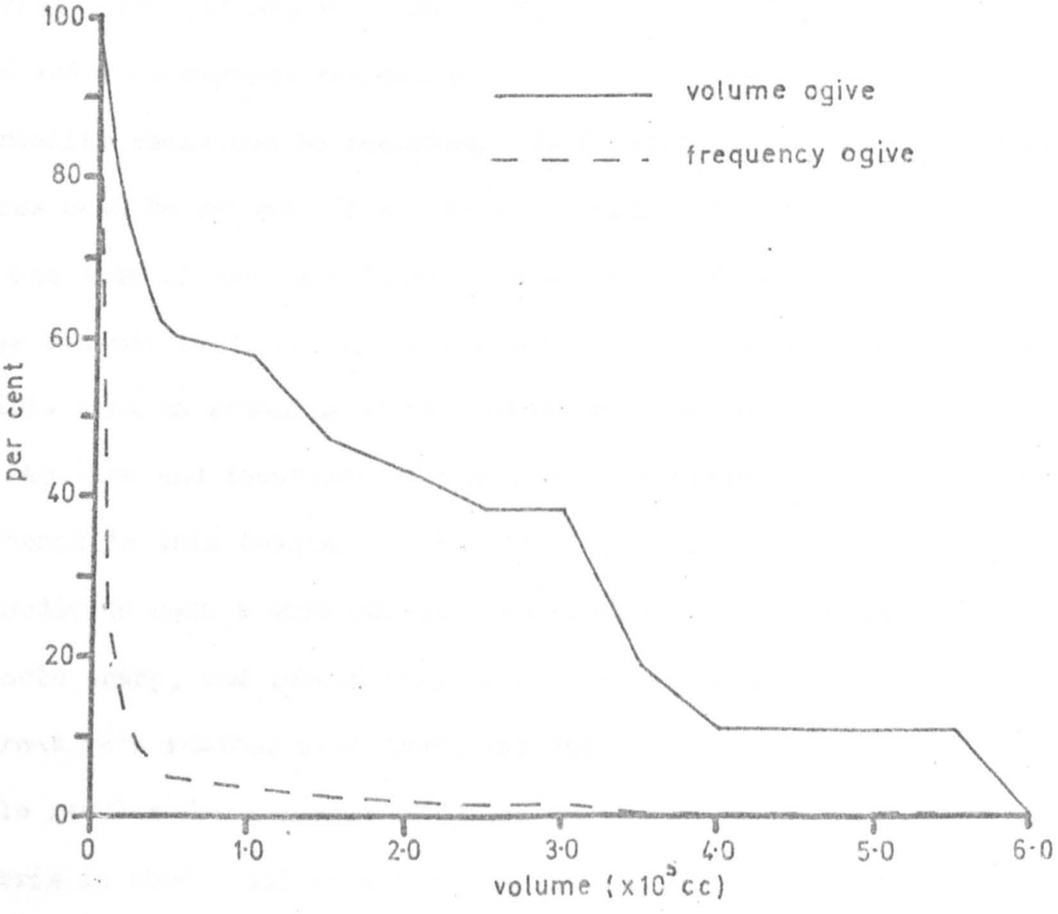


Fig.3·8 b Size distribution of sandstone boulders which fell between 17/11/71 and 15/8/72 strength of the Deltaic sandstones is exceeded and a large collapse occurs. Some of the debris may be retained at the top of the bevel (as in Fig. 3.6b) and this raises the base of the sandstone scarp so that renewed growth of the overhang is impeded until the debris is removed by creep or undermining by channels on the bevel.

The Rate of Retreat of the Sandstone Scarp

Procedures have been set up to allow the measurement of the rates at which joints are widening in the accessible part of the scarp, the lowest two metres. The technique used was to bore a hole at each side of a joint and to insert a half-inch diameter rawltamp into each. Stainless steel hexagonal set screws were then screwed into these and fixed with araldite. Measurements between the outermost and innermost points of these pairs of screws with vernier callipers were made and subsequent widening of the joints could then be recorded. Unfortunately the initial installations were destroyed by vandals. Rawltamps were replaced and measurements retaken but the screws were removed so that such vandalism could not be repeated. In future, before taking a reading, the screws must be screwed in as far as possible and then loosened slightly so that one side of one is in line with one side of the other. The distances between the inner and outer points can then be measured. It is probable that no widening of the joints will be measurable for several years. The data and locations of the sites are given in the volume of data appended to this thesis.

In order to gain a more reliable assessment of the rate of recession of the whole scarp, and secondarily to examine spatial variations in this retreat rate another experiment was set up which will also not give dependable results for a number of years because of the slow rate at which debris is shed. All accessible sandstone blocks more than 25cm in length lying on the bevel were marked with a spot of blue paint. Any fallen from the cliff since this experiment began (on 17th November 1971) can now be recognised. Another characteristic of such new blocks will be their relatively clean surfaces. In addition all those sandstone masses which have reached a talus cone were marked with spots of yellow paint so that it will be possible to calculate the rate at which blue-painted blocks move from the bevel to the cones as well as to find the proportion reaching the cones without resting for long on the bevel. The areas of yellow and blue painted rocks are shown in Fig. 3.10.

Before 15th August 1972, a period of 272 days, 269 blocks more than 25cm long fell from the scarp. The three principal axes, the position on the bevel and the lithology were recorded for each boulder and each was given a spot of pink paint. (These data are also reproduced in the appended volume of data.) The product of the three axes gives the approximate volume of each block. The size-frequency distribution is extremely skewed and is presented as an ogive in Fig. 3.8b, together with the size-volume cumulative frequency curve. It will be noted from these curves that only 5 per cent of the boulders account for 60 per cent of the total recorded volume of sandstone which fell. Five per cent represents only 13 boulders each of which is more than $5 \times 10^4 cm^3$, the biggest being $5.5 \times 10^5 cm^3$. It is apparent from this diagram that the total volume of those blocks smaller than $1000 cm^3$ is probably of negligible importance compared with the amount of sandstone measured. This justifies the choice of 25cm (at first sight a high figure) as the minimum length of each measured block. The shapes of the newly fallen blocks are shown in the Zingg diagram of Fig. 3.9a. Few are equiaxial or prolate, the dominant oblate and triaxial forms reflecting the influence of bedding planes. The thirteen largest blocks (which are distinctively marked in this diagram) have the same distribution as the rest. The spatial arrangement of all the blocks is shown in the

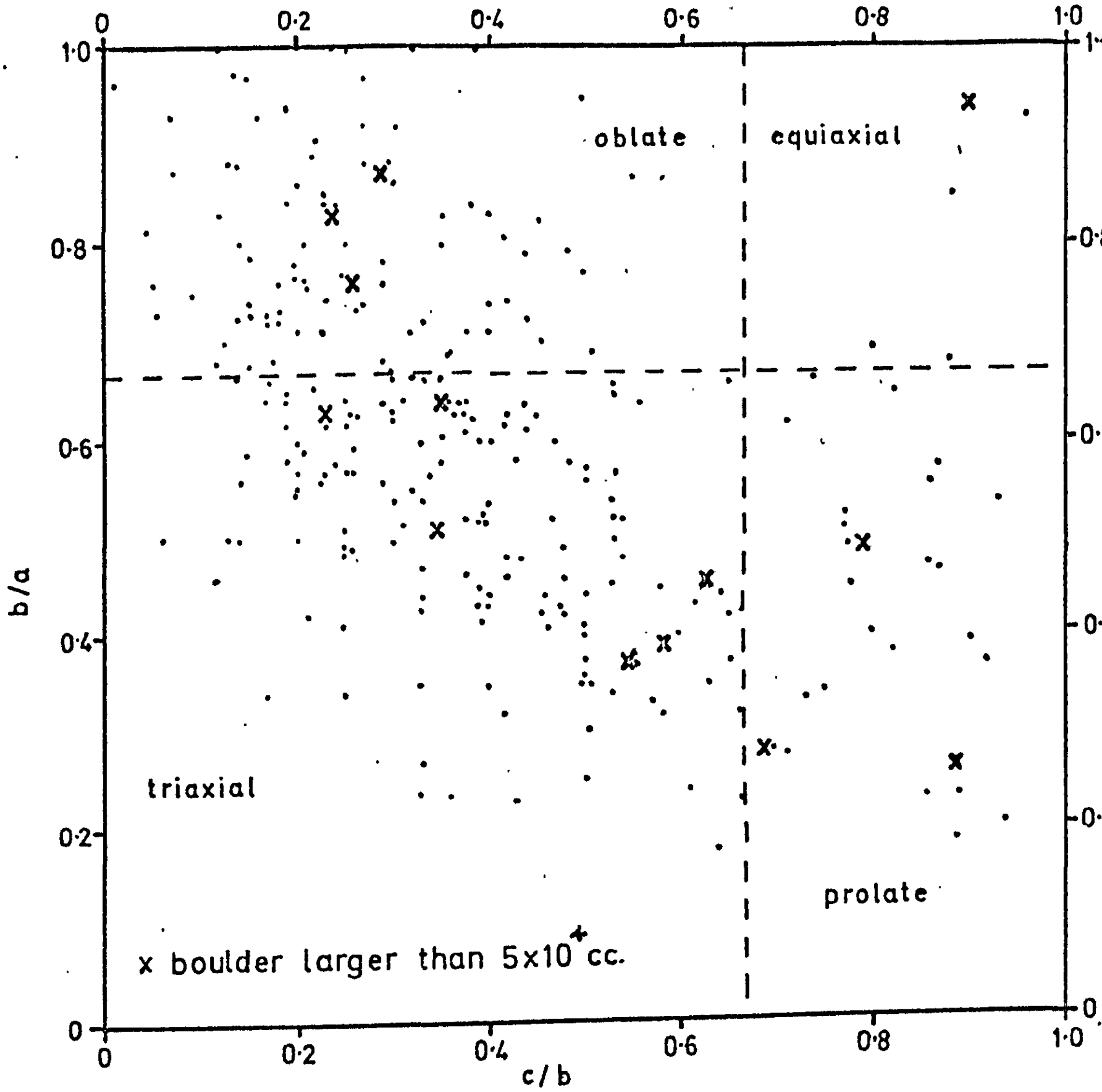


Fig. 3·9a Zingg diagram for the shape of newly fallen boulders

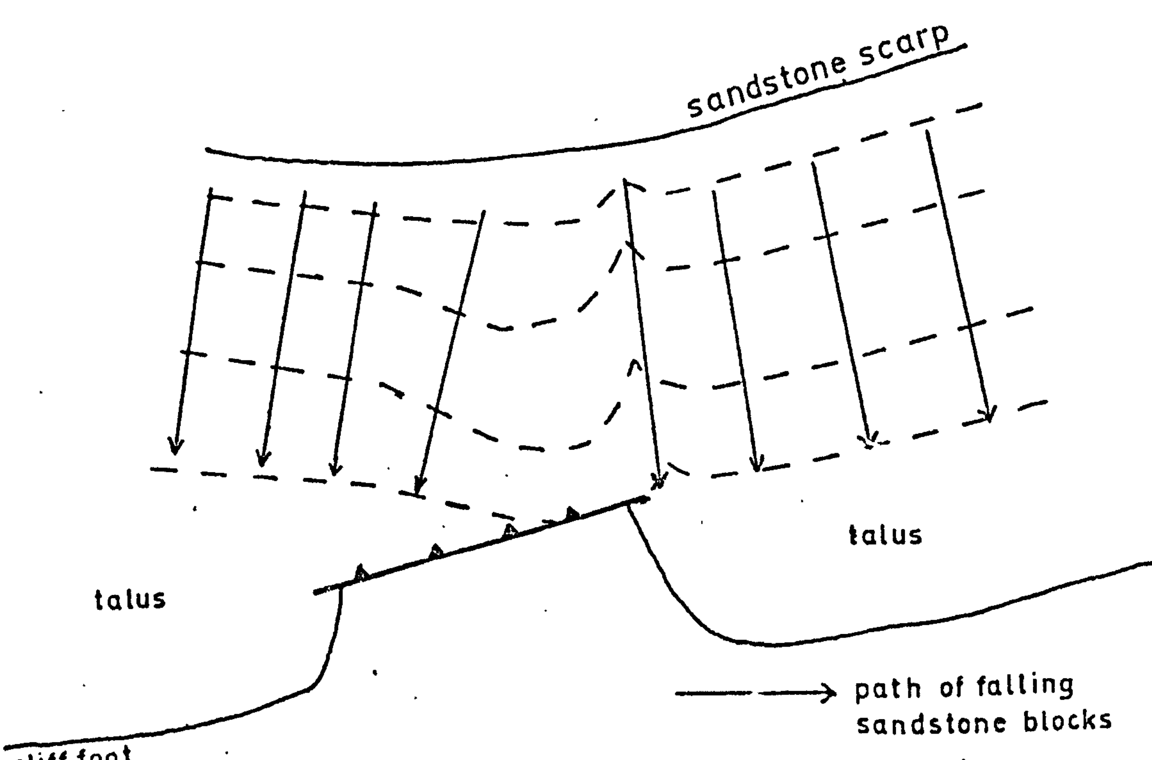


Fig. 3·9b The preservation of a marine activated cliff at a corner following diagram (Fig. 3.10). Most are clustered into three main zones and it seemed evident in the field that the members of each group had fallen at the same time as a larger mass which broke up on landing. Most of the blocks did not travel far down the bevel though there was some sorting with the large blocks sliding, or possibly rolling, farther. These would have more momentum than smaller sizes and would, therefore, require friction to last longer. Because of the brevity of the measurement period it is not possible to examine the conditions which favour post-depositional movements to the foot of the cliff. Two of the clusters occur where the bevel extends to low levels. The fall at the north-western end of the scarp may also be correlated with above-average overhang at that point but at the other location there is very little net overhang though the fall probably happened because of the development of a subsidiary one in the scarp. The south-eastern fall was also at a site with above-average overhang. It is too early to conclude that the scarp is being eroded differentially in plan but it does seem safe to conclude that it is being actively eroded. Indeed, assuming a mean height for the scarp of 7.5m and extrapolating the figure to give an annual rate, the mean erosion of the studied scarp was 0.3015cm/ cm^2/year. This is undoubtedly a gross underestimate of the long term average because, as Fig. 3.8b shows, infrequent falls of large boulders are the main form of scarp retreat and it has been shown that these large boulders fall in abrupt collapses of the scarp. The period of observation has been inadequate so far to include such falls.

Conclusion

Agar (1960, p. 416) has stated that "This upper zone (the bevel plus the sandstone scarp) gives the impression of great antiquity. It must have taken a very long time to weather back to its present angle,

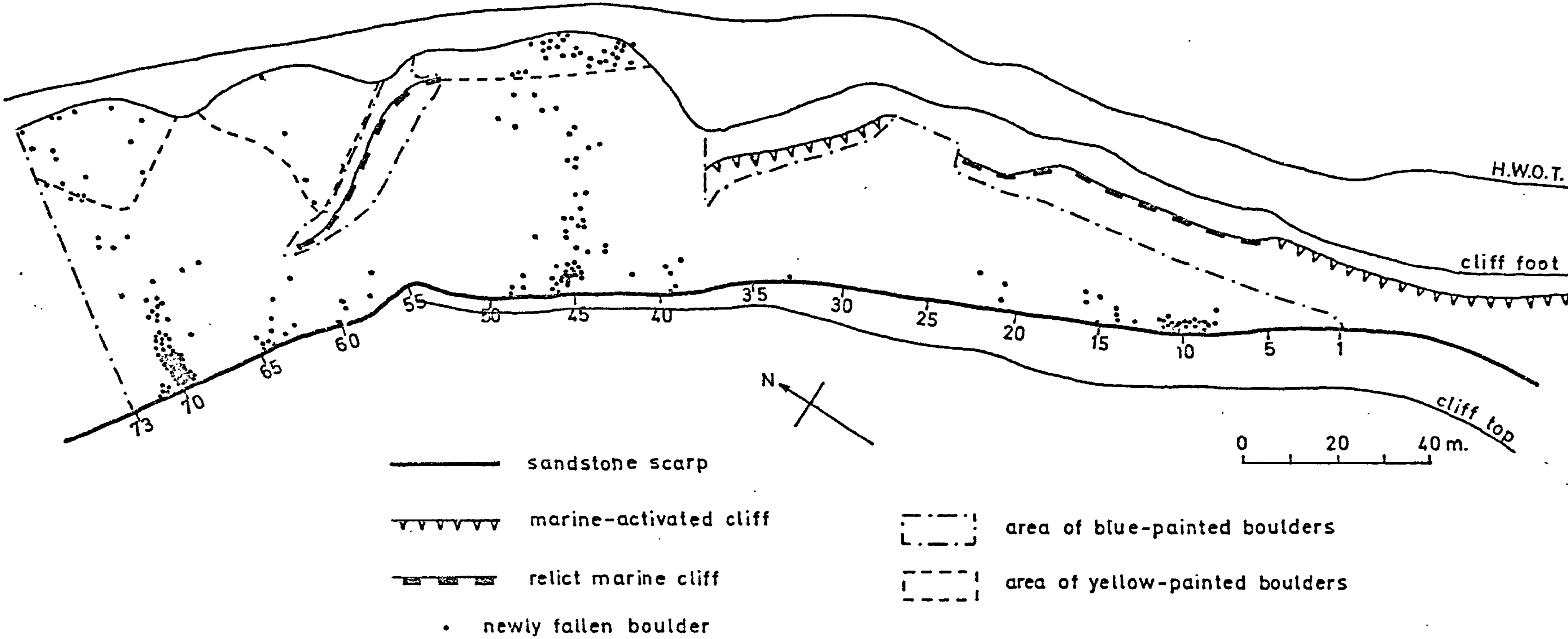


Fig. 3·10 Distribution of newly fallen sandstone boulders and this weathering rate is now so small that it is not measurable. It is considered that this upper zone has not altered greatly in angle or position during the whole of post-glacial time." In view of the data presented here this statement must be refuted. The sandstone scarp is being actively eroded by the fall of individual boulders and by the collapse of overhangs. It has been shown that overhangs are small where the Dogger is not exposed but, when the head of a channel crossing the bevel reaches the scarp the base of this feature is lowered. Thus the Dogger is exposed and a large overhang is developed because the Upper Lias shales are weathered and washed out from beneath the resistant basal stratum. Channels are active on the bevel only if the talus cones at their bases are eroded. Debris moves into the channels from adjacent ridges because of gravity, frictional forces being reduced when the shale fragments are dry. Where talus cones are large and resistant to erosion due to the great number and large size of sandstone boulders contained in them, the channels above the cones become choked with debris and covered with vegetation. Ridges between the channels are eroded by freeze-thaw action until they too are overwhelmed with debris and become vegetated. Therefore, the rate of erosion of both the bevel and the sandstone scarp and, indeed, the very existence of the bevel, are a function of the protection from marine erosion provided by talus cones at the base of the cliff.

Where a marine-activated cliff exists, the chief sub-aerial erosive process acting on it is winter freeze-thaw. Wetting-and-drying throughout the year also causes shale to be detached from the cliff. During heavy rainfall the accumulation of water in open joints can force large blocks of shale from the face of the marine-activated cliff. These processes, therefore, cause rapid erosion of this element. However, unless the cliff foot retreats at approximately the same rate, these sub-aerial processes also lead to the degrading of this steep section of the cliff. The relict marine-activated cliff which is now fronted by a large talus cone near the north-western end of the study area is an example of this degradation. Its slope is being reduced by sub-aerial processes while it is being dissected from above by channels in the bevel. Clearly, therefore, the absence of a resistant talus cone is fundamental to the preservation of a marine-activated cliff while its presence is necessary for the maintenance of the bevel. These contradictory properties of the two morphological elements imply that where both are found in a cliff (as in type (abc)) there has recently been a change in the type of cliff foot, e.g. a resistant talus cone has ceased to give its former high degree of protection to the cliff foot because it has itself been eroded. No true estimates of the time scale involved in these changes can be given here but indications of the minimum period needed for the formation of patches of conglomerate in the bases of talus cones are described in Chapter 6.

This discussion has intimated that, except during periods of change in cliff form, the bevel and the marine-activated cliff are mutually exclusive morphological elements. However, at first sight there do seem to be exceptions to this general model. At site 4, the small marine-activated cliff is receding only slowly and, its cliff foot being high, it is rarely reached by the sea. Despite this and the considerable weathering of the surface shale, its slope is 81 degrees which does not imply that it is being degraded. Therefore, this small section of cliff seems to be a steady state feature. There is no apparent reason why talus cones of sandstone debris should not have accumulated at this point just as they have to the north-west and south-east where the protection of the cliff foot has been such that no marine-activated cliff has been formed. However, this section of cliff at site 4 is situated at a corner to where no detritus can fall because it moves down the maximum slope of the bevel towards the talus cones at each side (Fig. 3.9b). Therefore the cliff at this point is better described as a moribund than as a steady state feature; it is not a contradiction of the general model presented here but is, rather, a situation where local circumstances have radically slowed down the rates of change of the morphological elements.

CHAPTER 4

THE SOLID-ROCK CLIFF FOOT

Introduction

The erosive action of the sea can be likened to a saw eating horizontally into the edge of the land. The zone in which direct removal of rock is most active is very limited and occurs at the foot of the cliff. As was shown in Chapter 3, it is clearly this process that maintains the steepness of the marine-activated cliff and, indeed, of the whole cliff. Therefore as the role of erosion at the cliff foot is so important, this physical feature is treated by itself in this chapter. Variations in morphology and in rates of erosion give some indications of the processes which have shaped the cliff foot while the processes themselves are also of interest as their relative importance might be expected to vary in different littoral environments. The first two topics are examined by the visual comparison of vertical profiles of the cliff foot recorded at a number of points along the coastline, and by data obtained from micro-erosion meter (M.E.M.) installations (see Appendix II for a critical appraisal of this technique and a description of the instrument used in this study). It is then necessary to give a brief discussion of the marine conditions off this coast, followed by a closer study of the erosive processes in a small bay near Whitby.

Cliff Foot Morphology - Initial Considerations

The cliff foot is defined as that part of the cliff which comes into direct contact with the sea. The influence of the waves should, therefore, be visible in the distinctive morphology of this part of the cliff. Unfortunately there are no clear edges to the feature and so it is difficult to delimit; it merges gradually into the main parts of the cliff and the shore platform. The upper and lower points of the cliff foot must be considered as arbitrary so that any attempt to measure and analyse the dimensions of it would be prone to much subjective error. In this study, the extremities of the solid rock cliff foot when viewed in cross-section, are about one to two metres from the junction of the cliff and the shore platform.

Wherever there is a notch the cliff foot is more easily recognisable. This type is not common in north-east Yorkshire. Apparently it is prevalent on coasts formed of limestone. Takenaga (1968) has examined such notches in considerable detail in the Ryukyu Islands and has offered a nomenclature for their classification. Notches, developed in calcareous aeolianite in Victoria, Australia, have been described by Hills (1971) while Hodgkin (1964) has estimated accurately the rate of limestone solution and, thus, the speed of notch recession at Point Peron in Western Australia. Sanders (1968) has carried out a wave tank experiment to simulate cliff erosion by waves.

The Recording of the Cliff Foot Profiles

The technique used to record the vertical profile of the cliff foot is a simpler version of that employed by Pemberton (1971). It involves the use of the flexible curve - a piece of laminated plastic which can bend in two dimensions only. Such a curve, about 1.75m long was placed vertically on the surface of the cliff foot and moulded to the rock surface. The horizontal and vertical distances between the upper and lower points were then noted by using two long rules and a spirit level. Next the curve was carried to a large piece of paper, care being taken to ensure that it did not bend further. Measurement of the straight line distance between the end points of the curve when it was in contact with the rock allowed the separation of these two points to be checked when the curve was on the paper. The outline of the rock surface was then traced directly on to the paper. Reduction of this outline to a more convenient smaller scale and orientation of it with respect to the vertical were done later using tracing graph paper. This method is probably accurate to only about ± 2cm but it is quick and easy to use. Maximum error occurs where the rock surface changes direction sharply since the curve rounds these off.

The points at which the cliff foot was recorded were the landward limits of the shore platform profiles which were measured for this study. The sampling design adopted for the location of these is described in Chapter 5. In the field the actual sites of the cliff foot sections were marked with much yellow paint in order to allow major changes in morphology to be measured at a later date by the recording of another profile. Of the 51 points selected for platform profiles, the solid rock cliff foot was hidden at 16 and sections were not recorded at a further two. However, three profiles were made at the sites where the cliff foot was instrumented to measure the smaller rates of erosion and two were recorded for platform profile number 7.

A Classification of Cliff Foot Profiles

The cliff foot in north-east Yorkshire can be classified according to two variables - the influence of joint planes and the roughness of the rock surface. These give three broad categories of cliff foot:

type 1 - the incidence of whole or eroded joint planes and/or bedding planes is high and the rock surface is rough

type 2 - joint planes do not appear to be important and the rock surface is smooth type 3 - an intermediate class between the first two categories where the existence of joints and/or bedding planes seems to be unimportant but the rock surface is rough due to protruding shale laminae.

These classes will be discussed in turn and tentative estimates of the rates of erosion at exemplary sites given.

Type 1 Cliff Foot - This category is the most common, involving 19 of the 37 profiles; an example is shown in Fig. 4.1a. Corners are generally sharp and adjacent segments of the profiles occur at high angles to each other. As the Lias is well jointed throughout, the segments are short. Lithological differences between contiguous strata are small so that bedding planes are not well developed. Therefore horizontal segments of the cliff foot profile are subordinate to those which are vertical, or nearly so, which follow joints. The profile segments, though on a large scale rectilinear due to the presence of joint planes are, in detail, intensely pocked. On vertical surfaces fragments of bedding laminae have been quarried out leaving pits of the order of 0.5cm in vertical and landward dimensions and 1.5cm in the direction parallel to the coastline. This pocking can occur only when there is direct exposure to wave attack. Thus the removal of a joint-bounded block exposes perfectly smooth rock surfaces even though sea water may have reached them along the opened joints before the erosion occurred. Such new surfaces may also be recognised by their ochreous coatings of iron compounds. These are removed within a few months leaving the natural grey colour of the shales, but in the case of the profile E2 depicted in Fig. 4.1a an iron stained surface has existed for three years at least and the pocking is not yet well

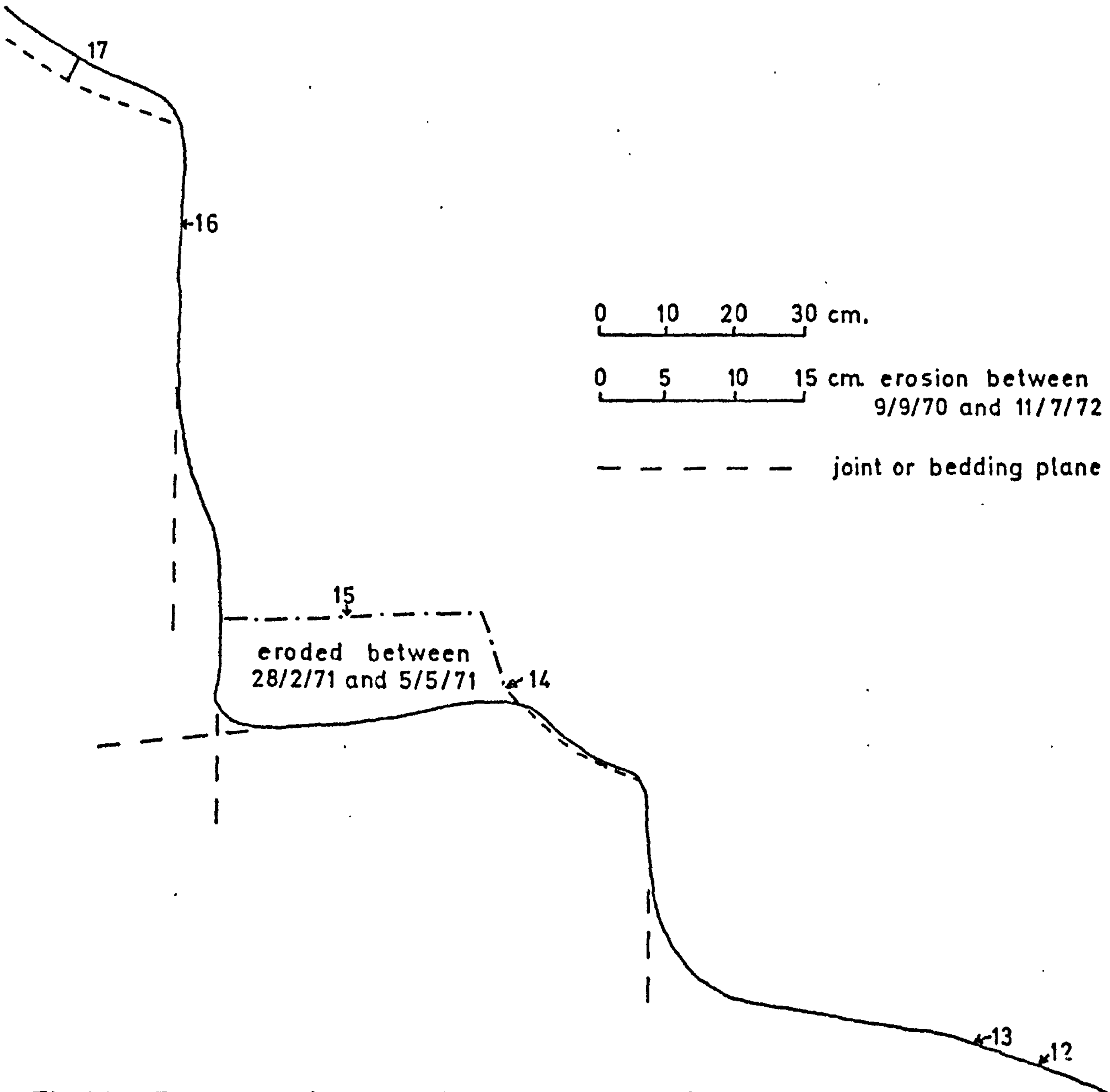


Fig.4·1a Example of type 1 cliff foot : profile E2

	9/9/70–31/10/70	31/10/70–5/1/71	5/1/71–28/2/71	28/2/71–5/5/71	5/5/71–7/7/71	7/7/71–6/10/71	6/10/71–20/4/72	20/4/72–11/7/72
	summer	winter	winter	winter	summer	summer	winter	summer
A	35·0	6·6	0·4	-0·5	24·0	46·0	7·7	13·4
B	36·3	-0·3	0·7	1·1	40·6	37·5	2·8	34·5
C	39·2	0·0	0·7	12·1	26·5	25·1	14·9	18·4

Fig. 4·1b Erosion rates ($\times 10^{-4}$ inch/day) at unit 17, profile E2 developed. At a site at Fourth Bight near Whitby an intensely roughened surface took less than a year to develop. The size of laminae will influence the speed with which this small scale quarrying can occur and the erosional environment may be of some importance.

On low-angle segments of the cliff foot profile, which are usually bedding planes, removal of a block of rock also leaves a smooth surface which becomes shattered into small polygons about one centimetre in diameter (e.g. as in Fig. 5.7a). This shattering may be due to the impact of waves on the single lamina forming the rock surface; it may be compared loosely with the effect of breaking a car windscreen. Again the thickness of the lamina will influence the rate at which the initially smooth surface is destroyed.

If there is lithological heterogeneity at the cliff foot this is picked out by the sea. It is not common in north-east Yorkshire, but where an ironstone seam or the Top Jet Dogger crops out the cliff foot lies on its upper surface, joint planes once again forming the vertical elements.

The predominance of joint planes in this category of cliff foot profile indicates that erosion is primarily by quarrying. Repeated recordings of profiles at exactly the same site have supported this conclusion. Unfortunately, at six locations the paint had been removed rendering the construction of new profiles impossible. Of the remaining 12, three showed erosion. At P26 (Fig. 4.2) near Widdy Head, the first profile, taken in August 1971, showed that a block of shale was being eroded; it had been moved 6cm seawards. On the next profile, made in August 1972, this block had been removed completely, together with many blocks from below it. Evidently, once this one block had been eroded by horizontal movement the joint plane constituting most of the profile

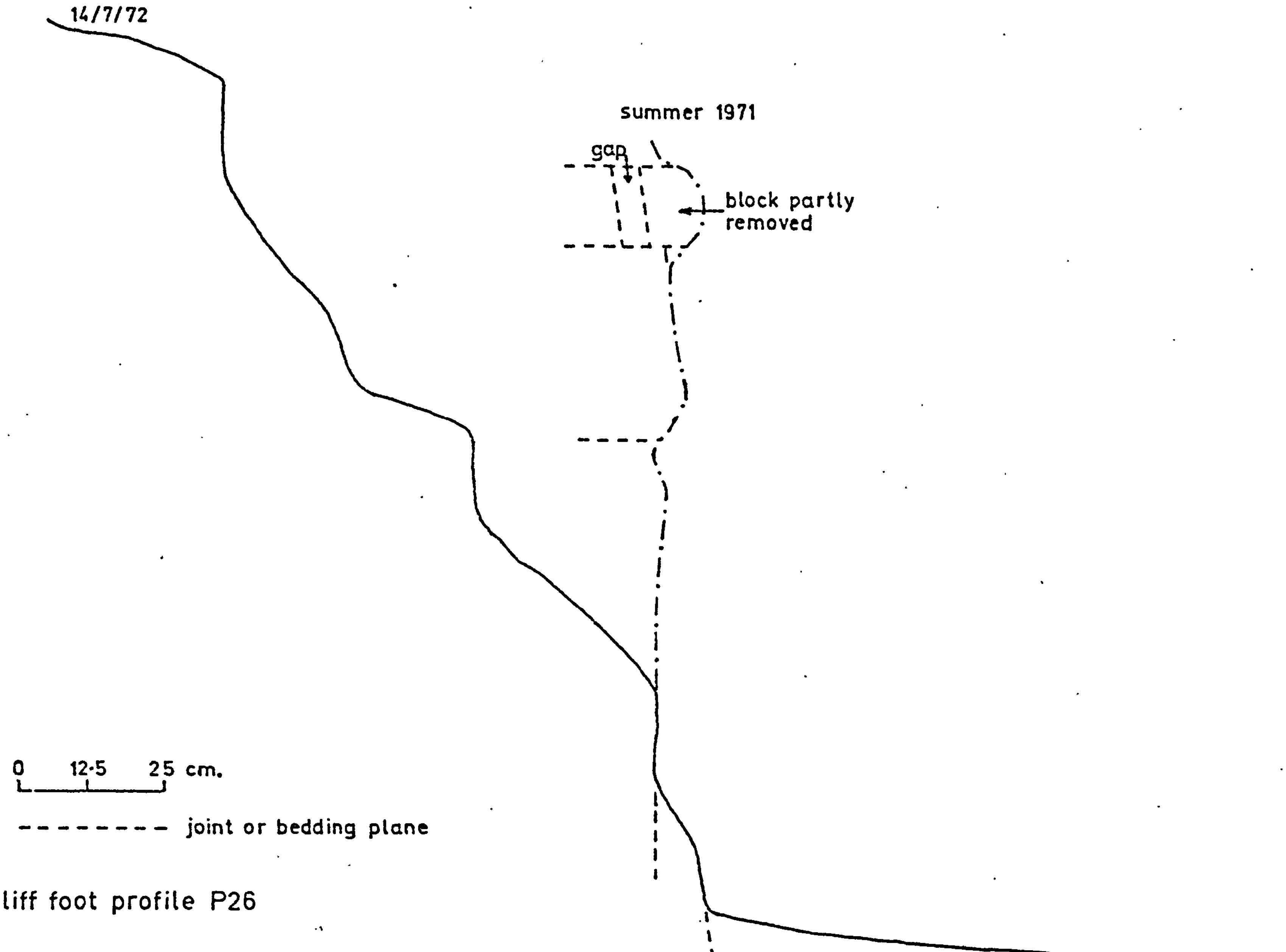


Fig.4·2 Cliff foot profile P26

had been punctured and further blocks could be removed easily because they were not constricted in the vertical dimension. It is possible that this rapid erosion will continue until another major vertical joint plane is encountered. This means that erosion will be negligible for a long period followed by a short space of intense erosion after which the cycle begins again. On the western side of Saltwick Bay erosion has been less spectacular. Micro-erosion meter (M.E.M.) units were installed here in September 1970 to measure the small rates of erosion overlooked by the crude flexicurve technique. Data from these units have been standardised to the amount of erosion/year in Fig. 4.1a because some units have been removed while others have not. The diagram indicates that the amount of erosion at the vertical joint planes is negligible. At unit 15, sited on a bedding plane, it was also very small but at unit 17 it has been considerable. At this latter site the surface seems to have evolved from a projecting corner. The almost horizontal bedding laminae form a staircase, a condition favourable to erosion. Little hindrance to lifting of the laminae by waves is provided by overlying laminae and the surface roughness itself creates much small scale turbulence in the waves which is also conducive to erosion. The erosion at this M.E.M. site averages 0.601 inches/year. However, this figure does not reveal the inherent variability of the erosion rates; these are tabulated in Fig. 4.1b for the periods between the dates shown. It will be shown later that the stormy season in the North Sea falls in the winter half of the year running from November to April inclusive. Division of the erosion rates according to whether they fall in this period or in summer and use of the Mann-Whitney U test reveals that the summer erosion rates are easily significantly larger at the 0.001 probability level than those for winter. This result is most surprising in view of the reduced erosive power of waves in summer. However, it must be remembered that the erosion at unit 17 is of laminae fragments only and this does not imply that most of the total erosion of this cliff foot is carried out during this season. A possible reason for this apparent anomaly will be discussed in Chapter 5.

The type of erosion occurring at unit 17 is fairly continuous in comparison with the erosion of blocks of rock; only one of these was removed at this site during the 22 months of observations. Nevertheless, the quantity of rock eroded in this one action was greater than the total erosion of laminae at the cliff foot. The short period of this study has been insufficient to allow the evaluation of true erosion rates by this large scale quarrying but the abundance of joint faces indicates that its frequency precludes the establishment of small scale continuous quarrying of laminae as a more important process in the total removal of rock. It is noteworthy that the erosion of this block took place during the stormy season.

In the study area, the only rock formation at sea-level which does not have intensely developed joint systems is the Sandy Series. A cliff foot profile (P10) (Fig. 4.3) in this series at Cowbar Nab again shows that bedding and joint planes are important. However, erosion is probably much slower because the rock is more massive and harder than the Lias Shales. At this location a thin bed of softer, more argillaceous rock is being eroded preferentially leaving the thick arenaceous bed above it hanging. Eventually, the undermining will cause this stratum to break. On removal of the liberated block undermining will be resumed and the cycle will be repeated.

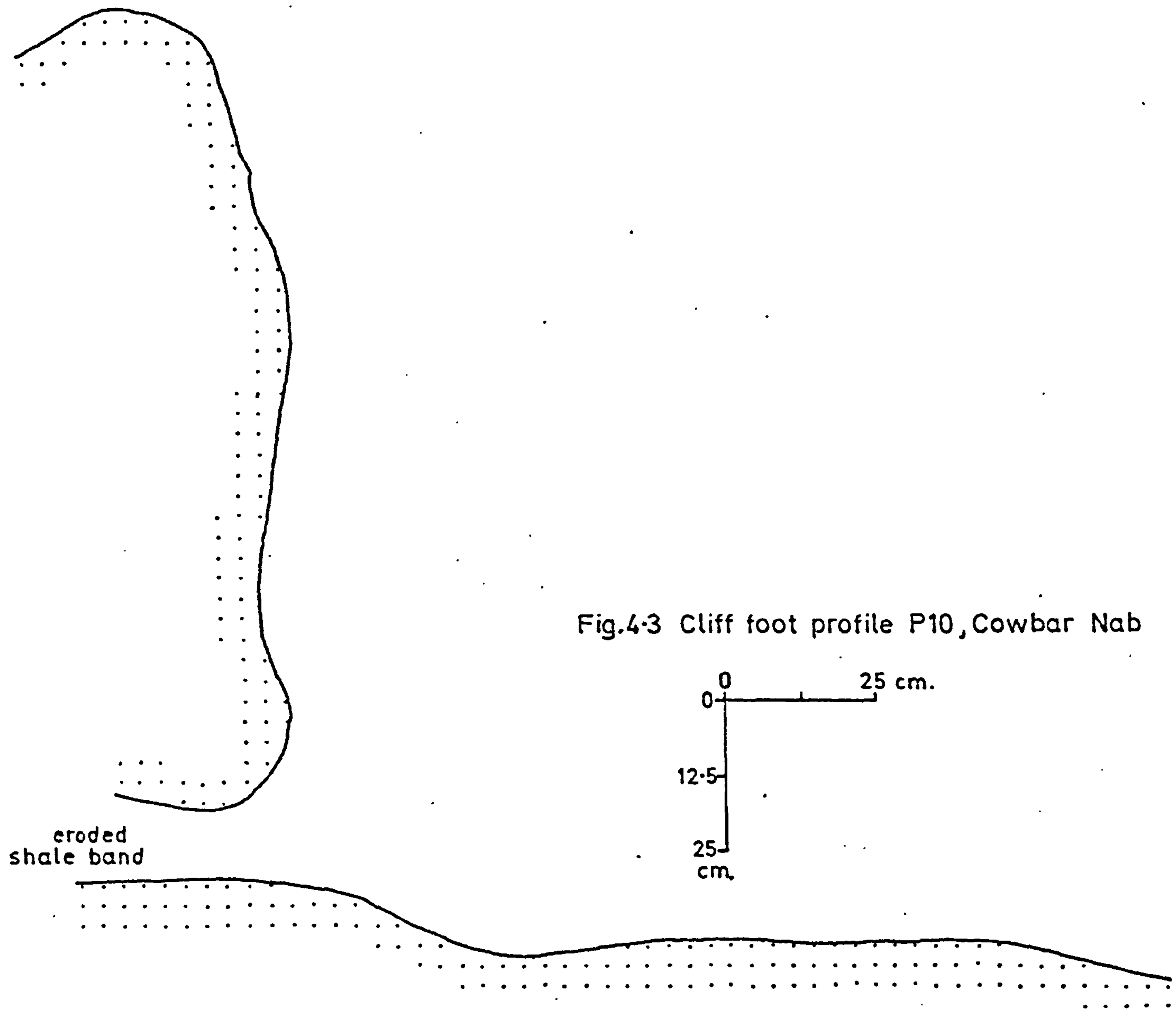


Fig.4·3 Cliff foot profile P10, Cowbar Nab

Type 2 Cliff Foot - Eight of the 37 cliff foot profiles have been classified in this group in which the profile has few joints and the rock surface is smooth. The profile is basically a curve and the term "notch" may be used to describe most of the members of this group. This feature which in calcareous rocks is due to solution (Hodgkin 1964, Hills 1971) has a different genesis in north-east Yorkshire. In every case a beach of mobile superficial deposits, varying in grain size from sand to cobbles, lies in front of these sites.

The general form of the profiles is best described by Takenaga's (1968) term "bow-shaped" i.e. the vertical dimension is much more important than the horizontal. The roof slope is not well developed as the undercutting is small (usually less than 0.5m) except where a more resistant stratum crops out, e.g. profile 50 in Fig. 4.4. The retreat point tends to be low, i.e. the vertical dimension of the roof slope is greater than that of the foot slope, because it is intimately related to the mean level of the surface of the beach. Projections which disrupt the curve of a profile (e.g. P51 in Fig. 4.5) are due to mainly lithological vagaries and secondarily to the existence of bedding and joint planes.

The smoothest part of the rock surface is on the footslope where the rock is frequently in contact with the beach. In the profile in Fig. 4.6 the surface is smooth up to about unit 16. Above this it is increasingly pocked until at unit 17 there is little evidence of the effect of the beach, the surface being composed of angular shale laminae and is partly covered by green algae. This indicates that the influence of the beach is severely restricted vertically. Reference to Fig. 4.6 reveals that the erosion was greatest at unit 14 (3.467 inch/year) and diminishes both upwards and seawards from this.

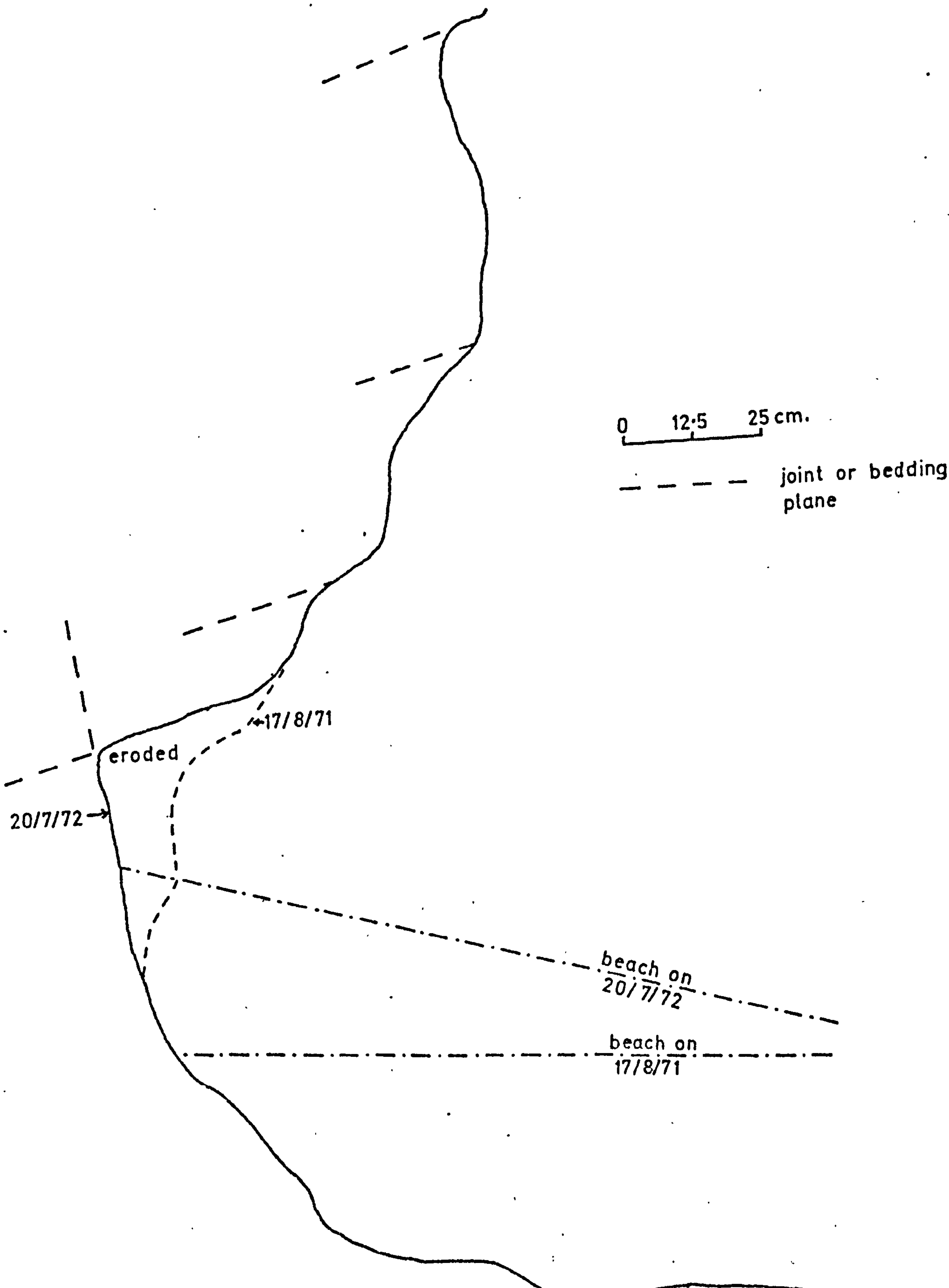


Fig.4·4 Example of type 2 cliff foot: profile P50

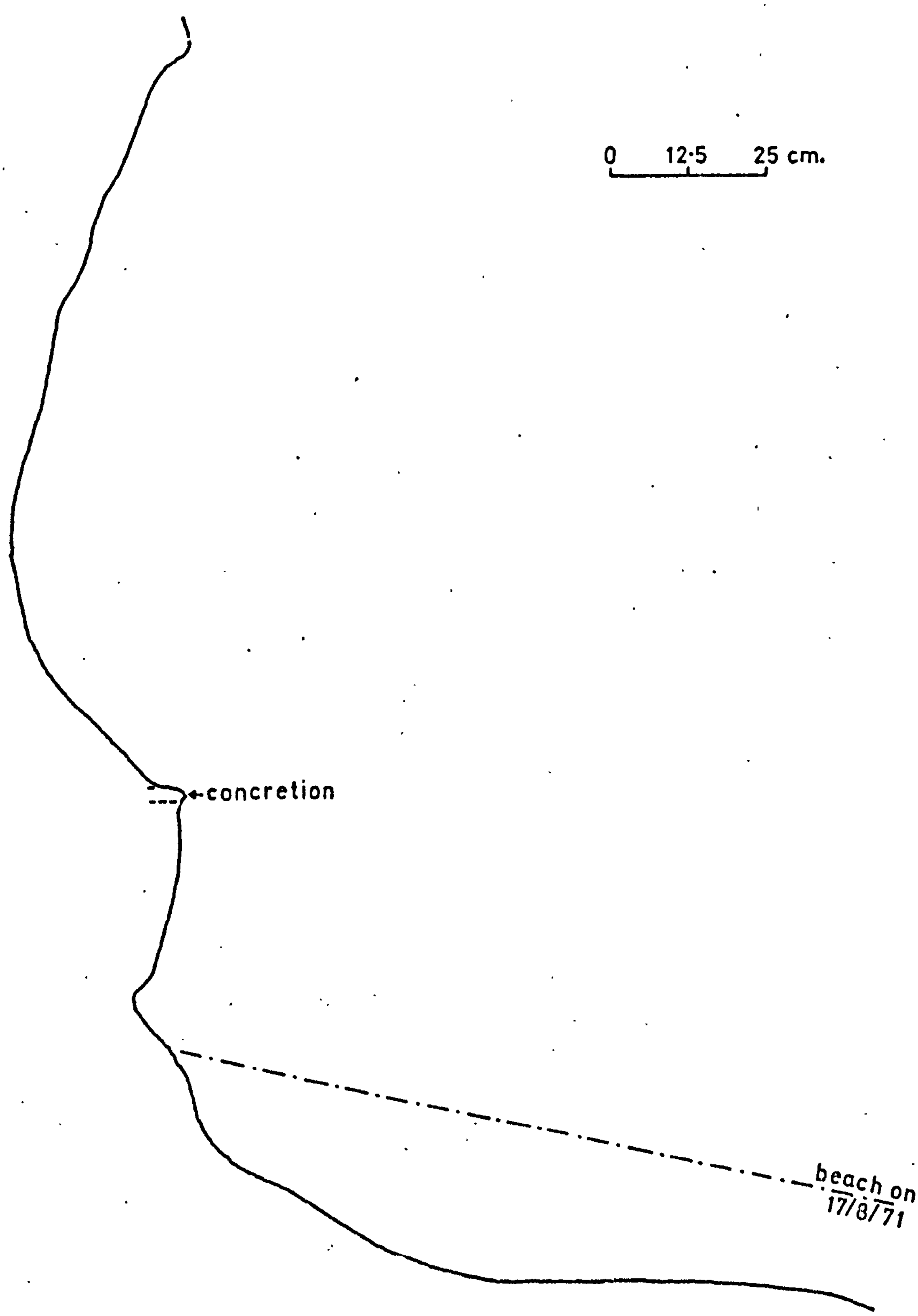


Fig. 4·5 Cliff foot profile P51, Robin Hood's Bay

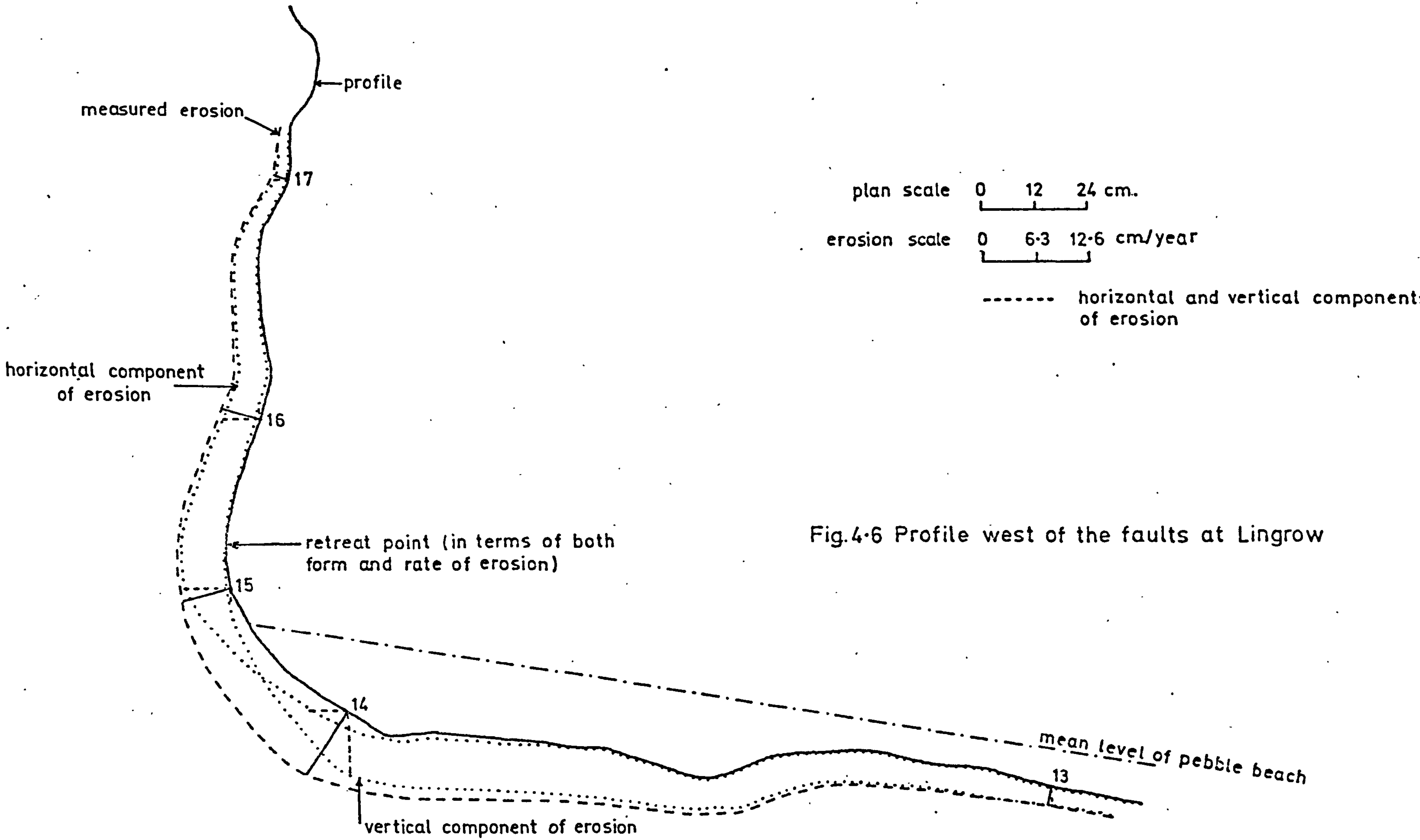


Fig.4·6 Profile west of the faults at Lingrow

However, these figures must be used with care for they imply that the point of maximum erosion is no longer in phase with the retreat point of the notch. Computation of the horizontal and vertical components of the erosion vectors shows that in fact the retreat point is the site of greatest landward erosion while unit 14 is the position at which downwearing is at a maximum. At units 14 and 16 the amounts of erosion shown in Fig. 4.6 are smaller than those which actually occurred because the sites were removed by quarrying. It is inferred by use of the Mann-Whitney U test that at unit 13 the summer erosion rates just fail to be significantly larger at the 0.05 probability level than those for winter periods. At unit 14 the differences between the rates for each season are not significant indicating that erosion by the beach is continuous varying little in intensity throughout the year. At units 15 and 16, however, the winter rates are stochastically larger at the 0.01 and 0.05 levels respectively. The former site is on average just above the surface of the pebble beach while the latter is far above. Pebbles are more likely to be driven to these higher points in winter when waves are larger. Moreover, it has already been noted that differences in the surface characteristics indicate variations in the relative importance of processes with height. At unit 17 erosion rates are extremely low except for occasional periods of high erosion which show the importance of the quarrying of laminae or simply the influence of the falling of small pieces of rock from the overhanging roof slope. Despite the implication from the smoothness of the surface near the beach that quarrying is unimportant at this level the process is able to operate near or even below the beach surface. The block eroded from profile 50 (Fig. 4.4) testifies to this while a large block was removed at beach level from the cliff foot shown in Fig. 4.6.

Type 3 Cliff Foot - The intensity of joint development in north-east Yorkshire has allowed very few cliff foot profiles to develop without the complications of these structural planes. Therefore, this third group includes profiles intermediate between types 1 and 2. Ten of the 37 profiles were classified in it of which one could not be accurately relocated subsequently. Two of the remaining nine showed measurable erosion. The profiles are simple curves (Fig. 4.7), near-vertical parts being rare. At several places pronounced notches occur but in all cases the surfaces are composed of angular shale laminae. In the example shown in Fig. 4.8 a bedding plane is important as the retreat point is following it. The instrumented profile shown in Fig. 4.9 is in Whitby Harbour. Though a sand beach occurs in front of it, the sand seems to remain below the notch whose superficial laminae are angular. Erosion has been roughly uniform at the sites varying from 0.364 inch/year at unit 12 to 1.390 inch/year at unit 13. Mann-Whitney U tests on the data from each unit reveal that there is no significant difference between erosion rates in winter and summer at the 0.05 probability level. However, grouping of all the data from the profile (units 11 to 14 inclusive) produces the conclusion that summer erosion is the greater at 0.0107 probability. This is the same apparent anomaly as that encountered at unit 17 on the profile in Saltwick Bay; both sites have the same surface characteristics and, therefore, the same processes are thought to operate. A notch is formed in members of this group only where the vertical range of the cliff foot over which waves strike is limited. Thus in Whitby Harbour the piers reduce the size of the waves while at profile 20, which is between Rail Hole Bight and Long Bight, near Whitby, there is an area of boulders in front of the cliff which must also reduce the vigour of incoming waves.

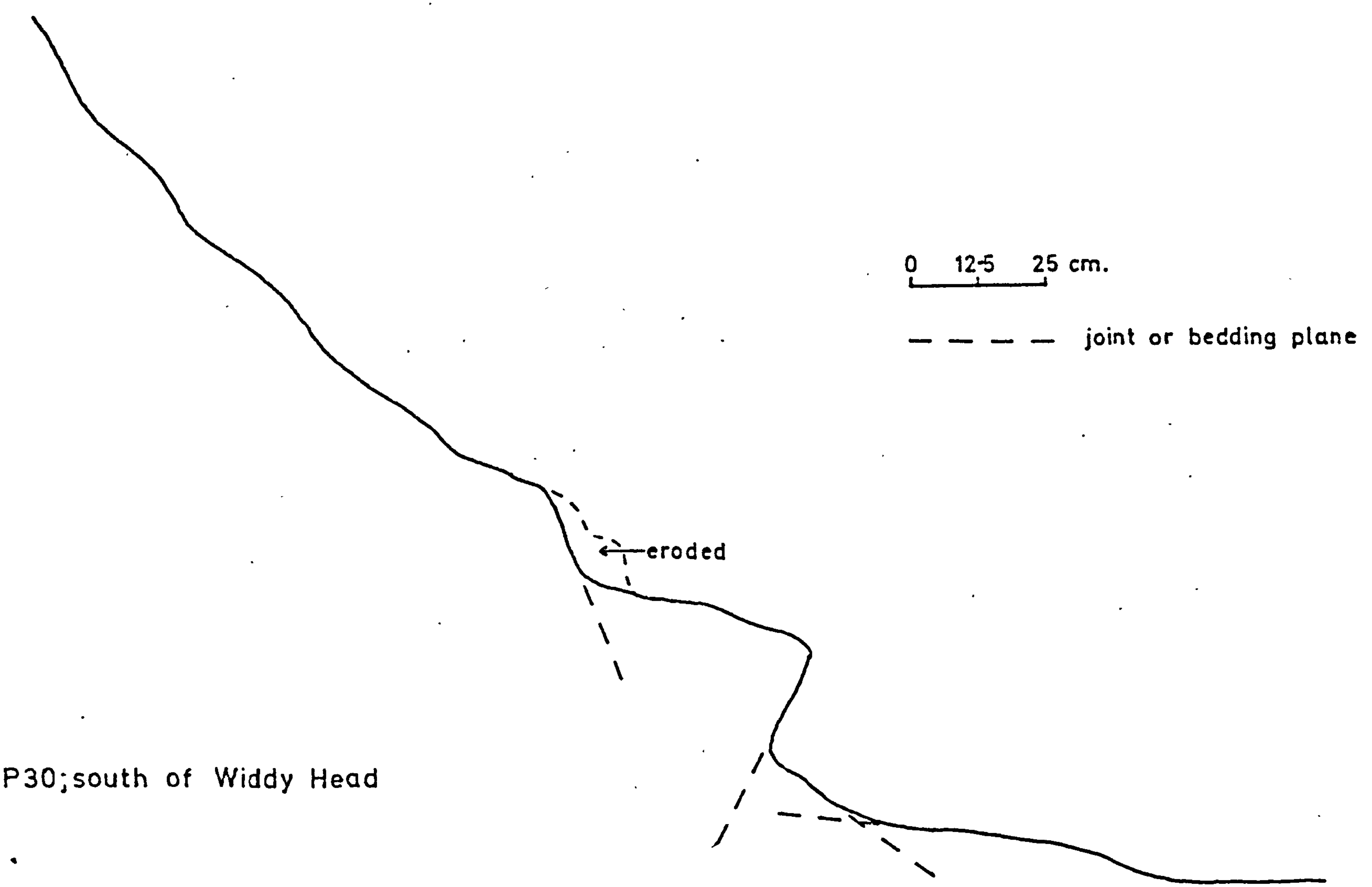


Fig. 4·7 Profile P30; south of Widdy Head

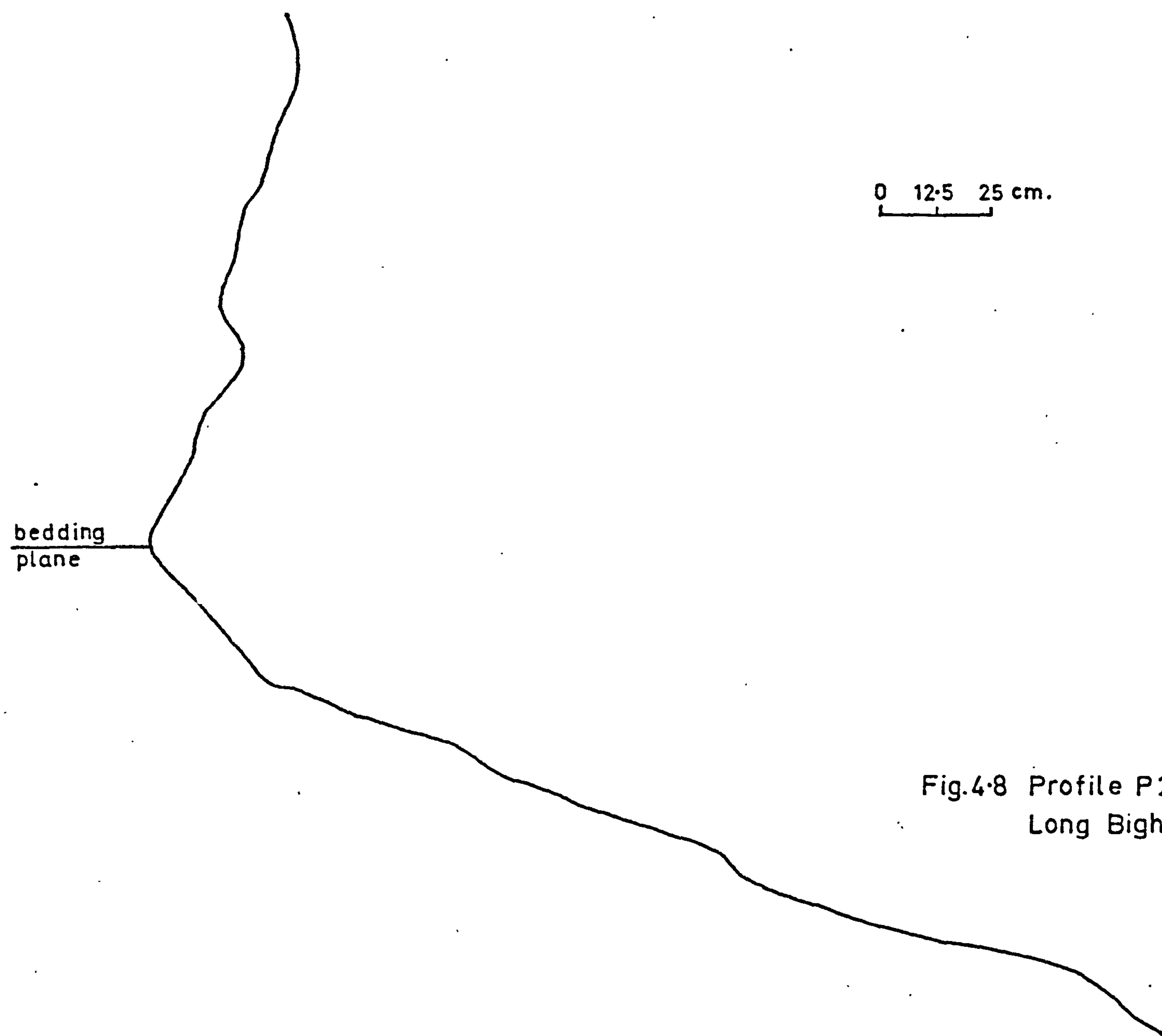


Fig.4·8 Profile P20: at the headland between Long Bight and Rail Hole Bight

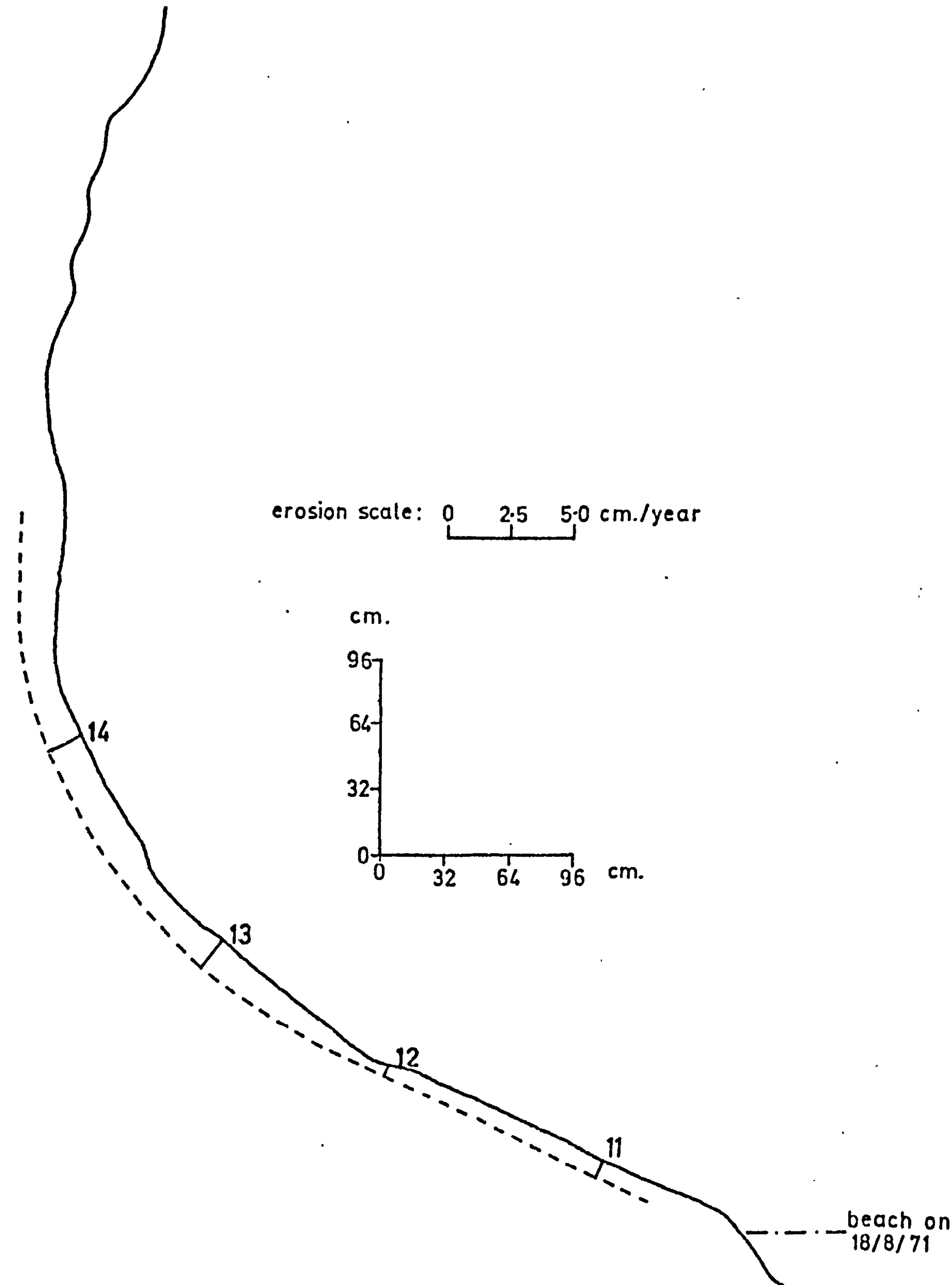


Fig.4·9 Profile E5,Whitby harbour

It is apparent from this discussion of cliff foot morphology that the structural characteristics of rocks, particularly the density of joint planes and the occurrence of well-developed bedding planes, play a considerable part in the form of this feature. Nevertheless, the environment is also important as a beach smooths the rock surface and often produces a notch. Rather than replacing the erosive processes which operate at the cliff foot in a non-beach environment, such superficial deposits add new ones and so the erosion rate is much higher wherever a beach occurs. Thus for type 1 and type 3 cliff foot profiles changes due to erosion were noted in 25 per cent and 22 per cent respectively while 40 per cent of those included in type 2 suffered measurable wear.

The objective of the rest of this chapter is to examine in more detail the erosional processes characteristic of a beach environment and to assess their relative contributions to the total amount of erosion wrought. However, it is first necessary to examine briefly the marine conditions at Whitby which are taken to be typical of the whole study area.

Marine Conditions at Whitby

In the absence of instrumental data on wave size, frequency and direction off the north-east Yorkshire coast, it is necessary to examine marine conditions indirectly by analysing the strength, frequency and direction of the winds. Since waves are produced by friction between the wind and the surface of the sea there is a direct relationship between the two. Hence wave size is dependent on the force, duration and fetch of the wind.

Schou (1952) has shown that the force (on the Beaufort Scale) and duration (or frequency) of the wind may be combined into a vector, the Direction Resultant of Wind Work (D.R.W.). This vector is directly related to the orientation of parts of the Danish coastline since its direction is the direction from which waves do most work. The coastline, therefore, becomes orientated normal to the vector.

At the coastguard station on the east cliff at Whitby the direction and speed of the wind are measured eight times per day. Data for the period May 1965 to December 1970 were used to calculate the D.R.W. s. All readings for each day were used because of the possible correlation of wind direction with time of day during the summer months (especially August) - the result of diurnal land and sea breezes. Mean frequency wind roses for each month and the mean monthly D.R.W. are given in Figs. 4.10, 4.11 and 4.12. The importance of winds from the south-west quarter is obvious and these are especially prevalent in the months of September to March inclusive because of the more intense development of depressions in winter. The mean D.R.W. for these months is seaward and so the most frequent winds have little effect on the production of waves which can erode the north-east Yorkshire coast. In the months April to August inclusive sea-winds are much more common and the mean D.R.W.s for July and August actually trend landwards on the generalised coastline north-west of Widdy Head. The percentage frequency of landward winds at Whitby for each month is shown in Fig. 4.13a. For most months winds blow from the sea for 30 to 35 per cent of the time with the peak (47.8 per cent) in April and minima in January (21.8 per cent) and October (15.6 per cent). Hence, it might be concluded that littoral erosion is fairly constant throughout the year. However,

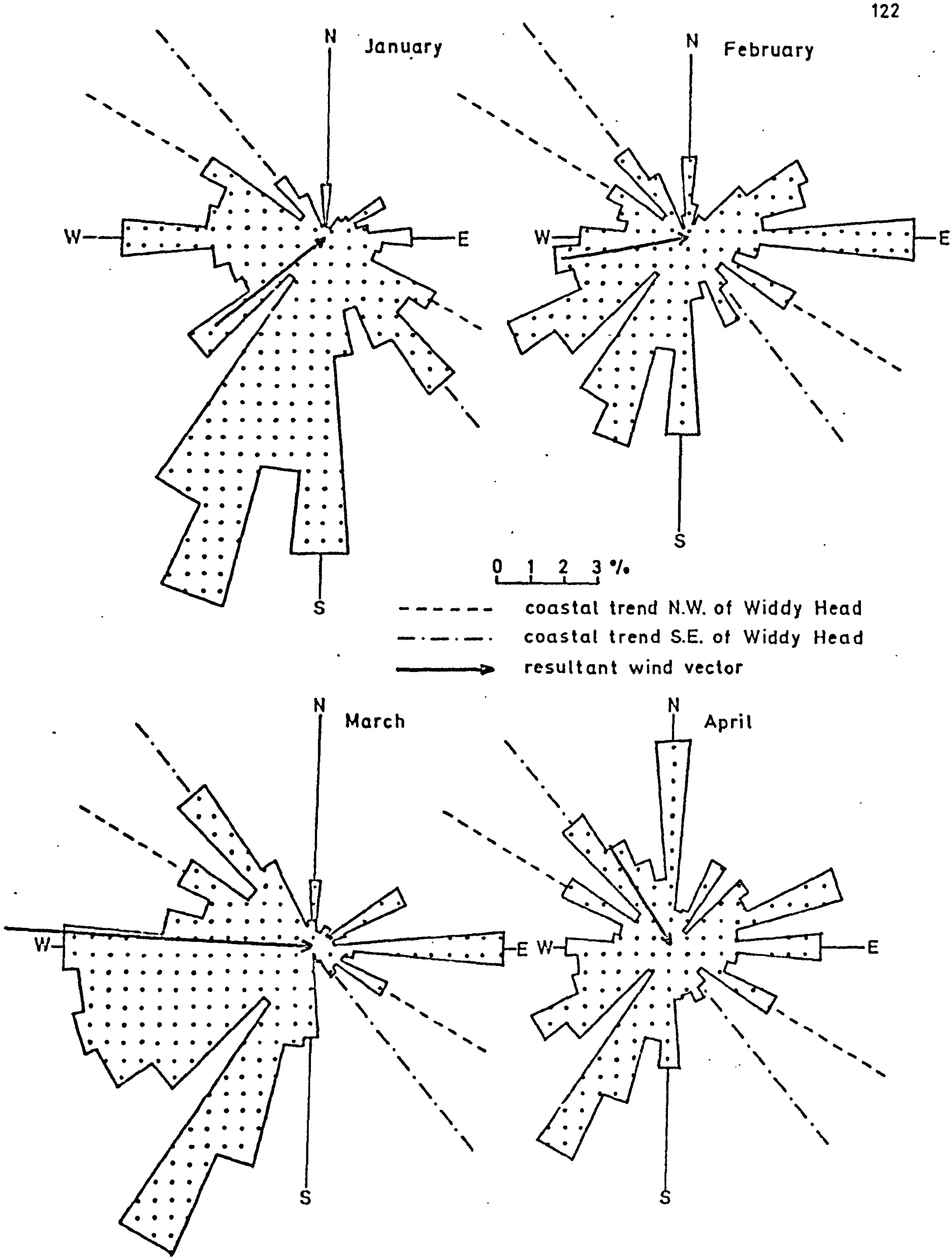


Fig. 4·10 Monthly wind roses for Whitby

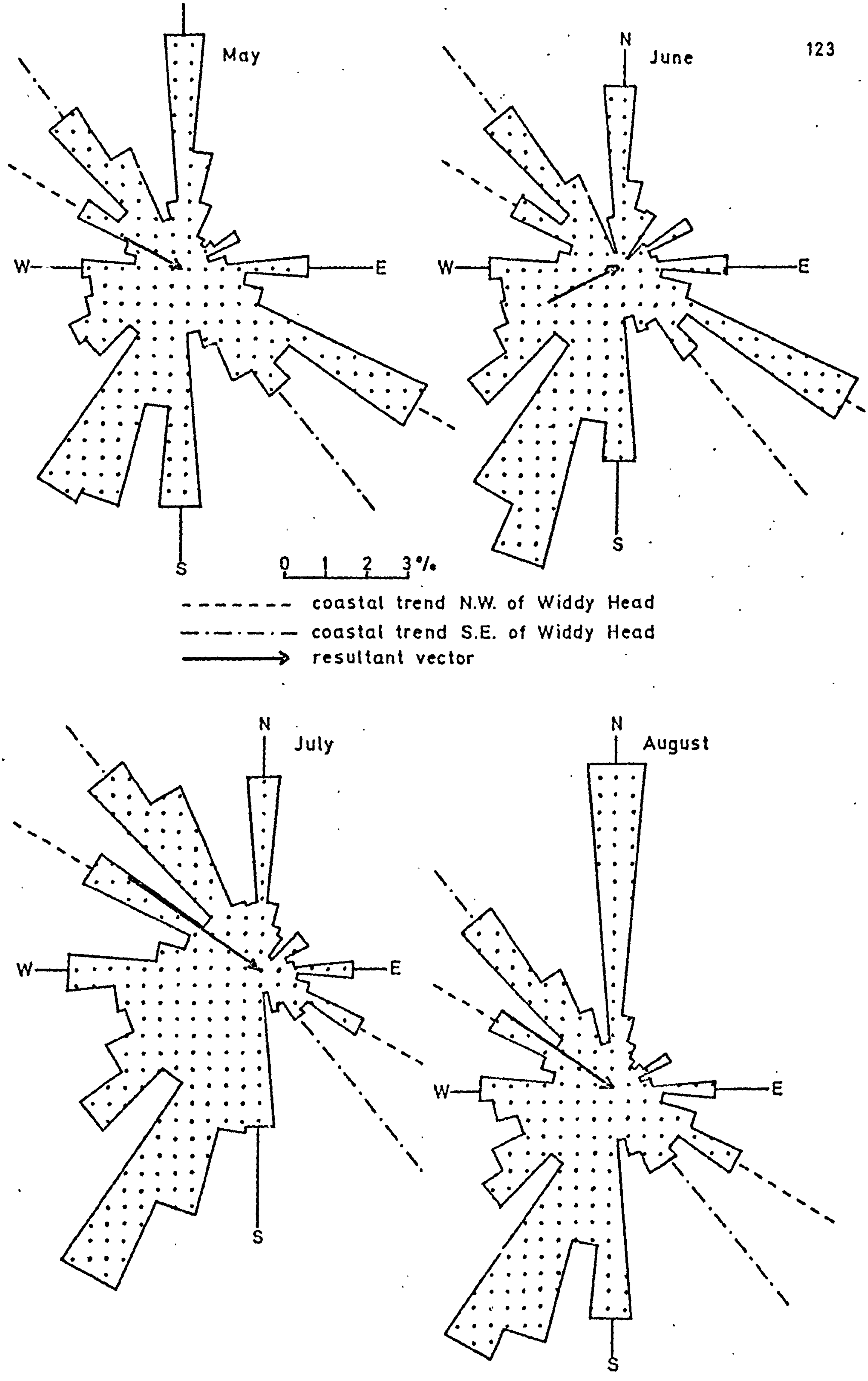


Fig. 4·11 Monthly wind roses for Whitby

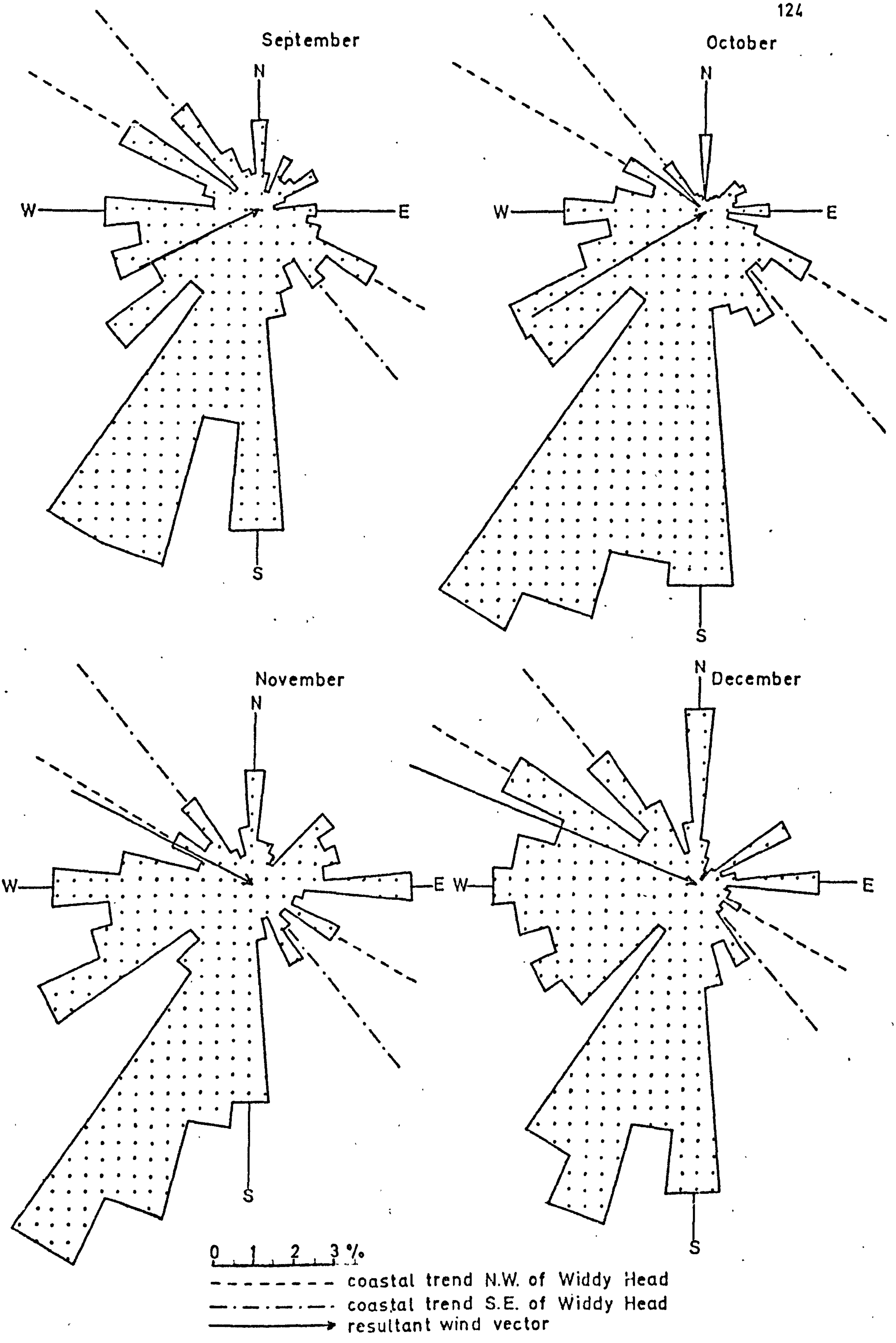


Fig. 4·12 Wind roses for Whitby

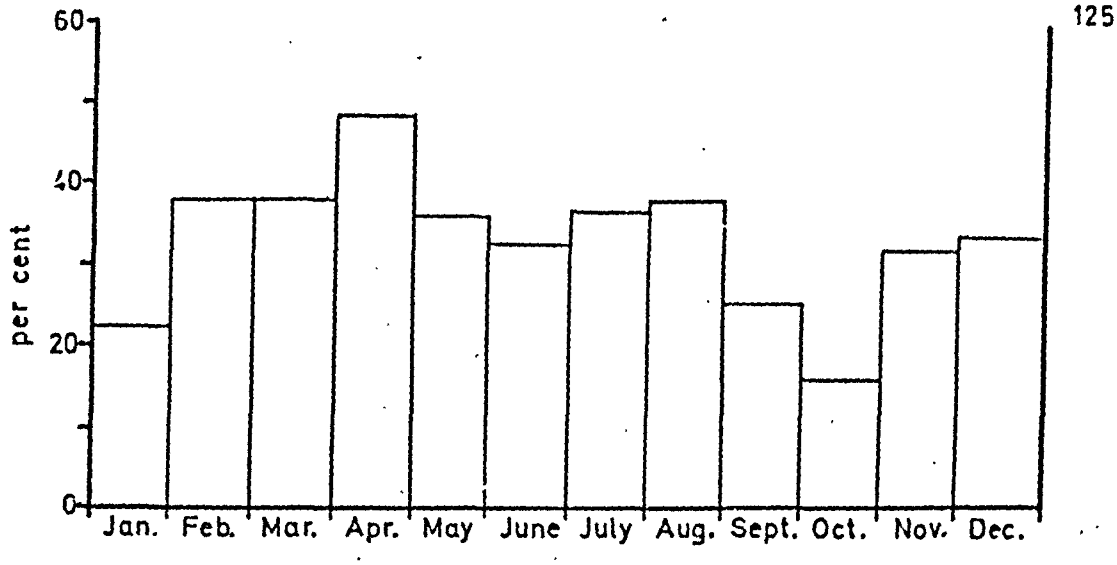


Fig. 4·13a Frequency of onshore winds at Whitby

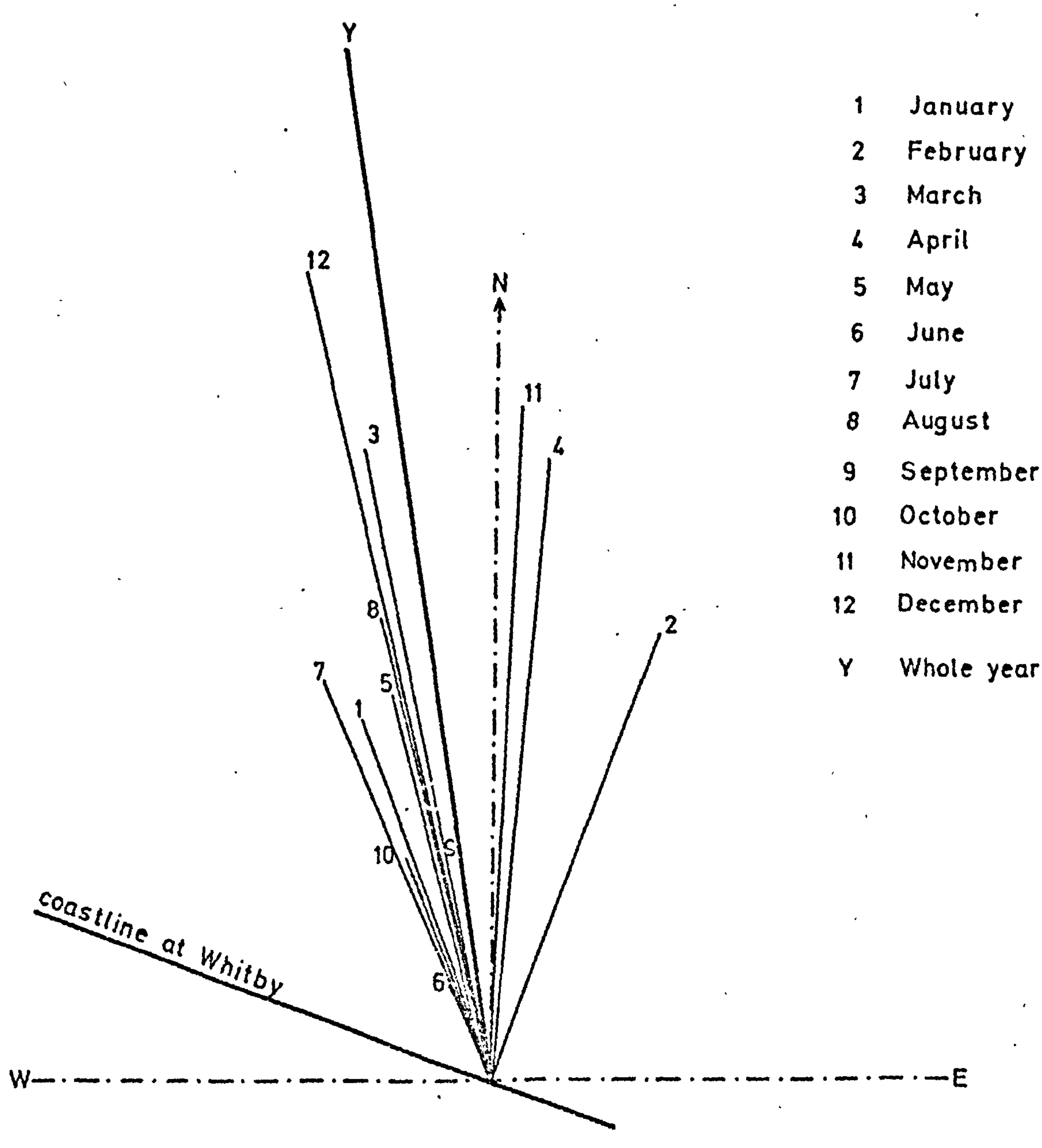


Fig. 4·13b Landward mean monthly wind vectors at Whitby the strength of the sea winds, and hence the size of the waves they produce, must also be considered. Fig. 4.14 shows the landward component at Whitby of the mean monthly D.R.W. April, November and December are the months when the strongest effective winds blow and thus when the most erosive waves occur. The winter months are more important than the summer except for July and August. These two months are at the height of summer when the land is warmest thus producing the strongest diurnal land and sea breezes. The short duration of such sea breezes precludes the generation of large waves. Hence it can be concluded that strongly erosive waves are most likely to be produced during the winter half of the year (1st November to 30 April) and especially during the seasons of change - November to December and February to April.

Because the mean monthly landward D.R.W.s are in the sector north-west to north-east (Fig. 4.13b) it is unlikely that fetch will have much influence on wave generation. This sector, and especially that part between north and north-east is the direction in which the North Sea opens into the Atlantic and the Norwegian Sea. The landward D.R.W.s for April and November are not only two of the three largest (Fig. 4.14a) but also occur in the north to north-east sector so that large waves in these months are especially probable.

Though no instrumental data on wave parameters exist, subjective assessments of the state of the sea are made by coastguards at the South Gare breakwater for the Tees and Hartlepool Port Authority. The "state of the sea" is essentially an indication of wave height since it is made on the Beaufort Scale (Fig. 4.15); the relationship between sea-state values (x) and mean wave height (feet), calculated from the data given in Fig. 4.15, is given by the equation

$$y = 0.5624x^2$$

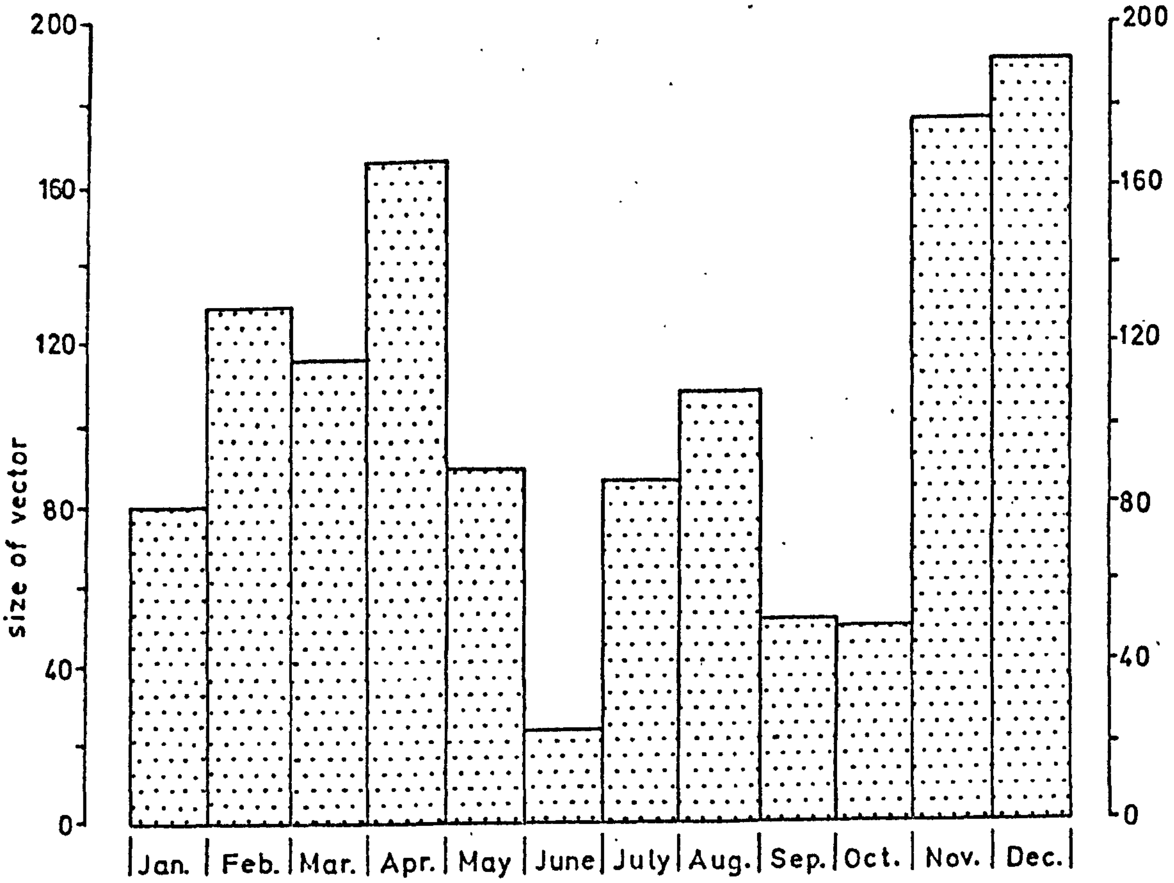


Fig. 4·14a Component of landward mean monthly wind vectors at 20 degrees

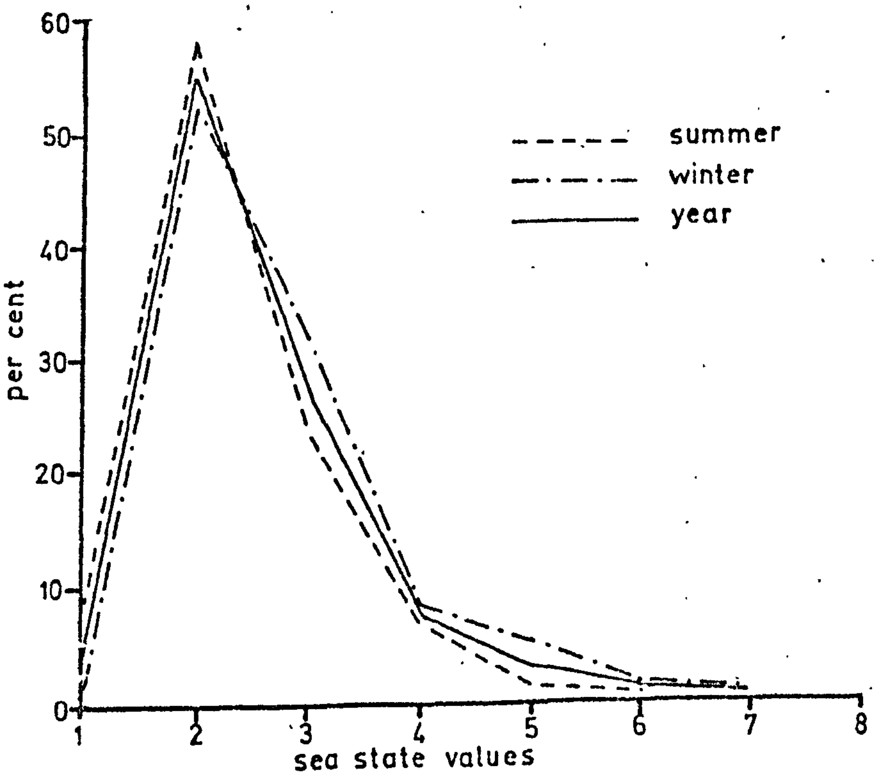


Fig. 4·14b Frequency distribution of sea state values

Sea state value	Mean wave height (ft)	Description of sea surface	Beaufort wind no.	name of wind	Wind speed(kt)
0	-	Sea like a mirror	0	calm	<1
1	$\frac{1}{2}$	Ripples with appearance of scales are formed, without foam crests	1	light air	1-3
2	1	Small wavelets still short but more pronounced, crests have a glassy appearance but do not break	2	light breeze	4-6
2	$2\frac{1}{2}$	Large wavelets, crests begin to break; foam of glassy appearance. Perhaps scattered white horses	3	gentle breeze	7-10
3	5	Small waves becoming larger; fairly frequent white horses	4	moderate breeze	11-15
4	9	Moderate waves with more pronounced long form; many white horses; chance of some spray	5	fresh breeze	16-20
5	14	Large waves begin to form; white crests more extensive everywhere; probably some spray	6	strong breeze	21-26
6	19	Sea heps up; white foam from breaking waves begins to be blown in streaks; some spindrift	7	moderate gale	27-33
7	25	Moderately high waves of great length; spindrift; foam blown in well-marked streaks	8	fresh gale	34-40
8	31	High waves; dense streaks of foam; sea begins to roll; spray affects visibility	9	strong gale	41-47
8	37	Very high waves with long overhanging crests; resulting foam in great patches is blown in dense white streaks; surface of sea has white appearance; heavy rolling; visibility affected	10	whole gale	48-55

Fig.4.15 The scale of sea state values derived from the Beaufort scale of wind (nautical) (from Strahler, 1963)

The estimations are probably consistent, despite the subjectivity involved, because the members of the coastguard service have a long and intimate knowledge of the sea. Nevertheless, it does not follow that wave conditions at South Gare are the same as those at Whitby. The Spearman rank correlation coefficient for a random sample of 150 pairs of wave values from South Gare and landward daily D.R.W.s at Whitby is 0.4791 which is highly significant at the 0.001 significance level. The amount of explained variation (22.95 per cent) is low but is due to the fact that seaward-blowing winds do not have a large damping influence on wave height near the coast because the fetch is negligible. The absence of this damping influence is supported by the lack of correlation between wave values and the D.R.W.s on those days when the wind blew to seaward. The correlation coefficient for wave values and landward winds is 0.7108 so the amount of explained variation is 50.52 per cent, a value sufficiently high to allow the conclusion that wave conditions at South Gare are very similar to those at Whitby. Therefore the South Gare wave data can be used for Whitby also.

The frequency of sea state (wave) values for the year 1971 is given in Fig. 4.14b. There are two readings per day; those occasional ones which were not taken have been interpolated and assigned to the nearest half value and then the total for each half value has been divided between the adjacent whole values. Fig. 4.14b shows a log-normal relationship with the most frequent sea-state (55 per cent) being of value 2. When the distribution is split between winter (November to April inclusive) and summer months, the two distributions differ significantly at the 0.001 probability level using the χ^2 test. The differences lie mainly in the tails of the distributions;

values of 1 are much more common in summer and those of 5, 6 and 7 in winter. This corroborates the conclusion reached from the examination of wind conditions that the year can be divided into two parts, winter being the period of storms.

<u>The M.E.M. Sites at Fourth Bight, Whitby</u>

In order to examine the processes by which the cliff foot is eroded in a beach environment, 14 M.E.M. units were established around a small, unnamed bay to the west of Gravel Bight which is about 100m east of the East Pier at Whitby. The instrumented bay will henceforth be called Fourth Bight since it is the fourth bight from the pier. It will be shown in Chapter 8 that this small section of coastline has suffered a mean rate of erosion of 0.54 feet/year (0.16m/year) for 156 years. Also, Fourth Bight has a sandy beach which is present throughout the year, except for very short periods after the material has been carried into Gravel Bight. Hence it can be assumed that corrasion is operating in addition to quarrying so that the site provides an opportunity to examine the relative importance of these processes.

Fourth Bight is approximately 36m wide and 25m deep from front to back (Fig. 4.16). Its western headland projects seawards of the beach for all but very short periods during the year. As the eastern headland of Gravel Bight also cuts off the beach, the deposit in Gravel Bight and Fourth Bight is considered to be a true pocket beach with little addition of material by longshore movement. Being in an erosional environment, it is present only because of the existence of headlands to east and west of it. The head of Fourth Bight consists of two small triangular bights each of which has a small fault at its head. Strictly speaking, since the cliff overhangs, these two small bights are caves.

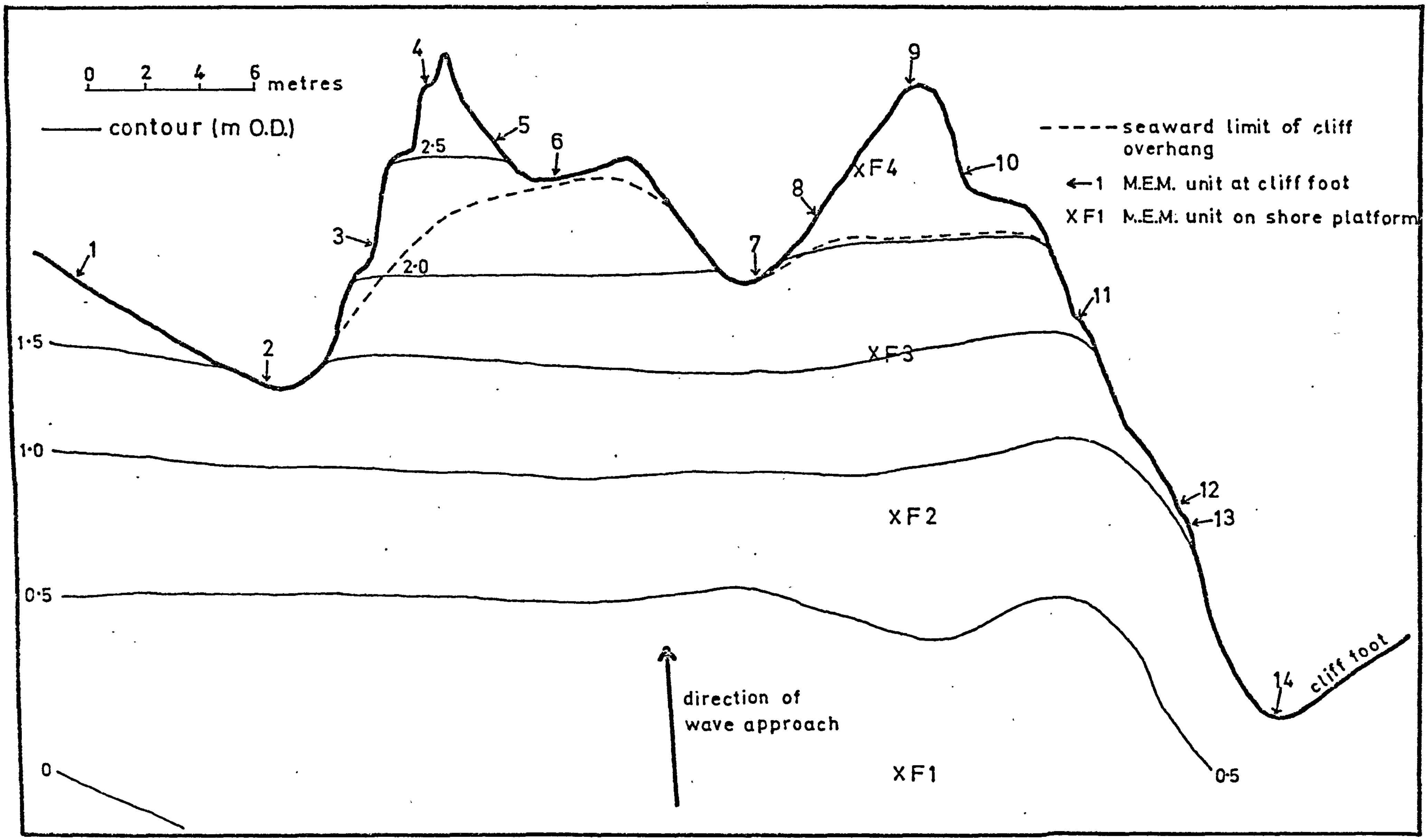


Fig. 4·16 The location of M.E.M. units at Fourth Bight, Whitby

The M.E.M. sites are shown in Fig. 4.16. All are on near-vertical surfaces and are 30 to 60cm above the shore platform but, because this slopes upwards to the landward side, the sites are not at the same height above sea level. The lowest are sites 12 and 13 (1.210 and 1.134m O.D. respectively) and the highest are sites 4, 5 and 9 (3.105m, 2.899m and 2.705m O.D. respectively). They are all situated in strata of the Alum Shale Series (beds no. 53 and 55 of Howarth (1962)).

The sites are at about the surface of the beach, whose level fluctuates according to sea state. The material is coarse sand to small pebble size (i.e. up to about 1cm in diameter), but there is a very rapid transition to cobble and boulder sizes between sites 1 and 2 so that the former is fronted by cobbles from 1 to 10cm in diameter. Site 14, being on the tip of the western headland, has never had a beach in front of it and so corrasion is unlikely; this site and perhaps site 1 are therefore in a different environment from the others.

Erosion readings were collected at approximately weekly intervals between 6th January 1971 and 10th January 1972. Each period between successive erosion readings will be termed an "erosion period". The data are susceptible to multivariate analysis, the causal variables being sea state and beach conditions. Because of the tidal nature of the North Sea and the varied height of the M.E.M. sites above sea level, it is necessary to include a variable for the period during which the sea is in contact with each site. Other variables, such as geological factors, cannot be measured but will be discussed later.

Modifications to the Data

Erosion Data - At each M.E.M. unit three erosion readings were taken. These were averaged for the analysis to reduce variation in the erosion readings possibly caused by small geological vagaries. It is unlikely that short-term variations over such small areas reflect long-term changes (the three points at which the readings are taken are only 7.5cm apart).

Data for the Period of Water Contact - The tidal curve for the River Tees Entrance (and for Whitby) follows a simple sinusoidal path. The mean springs range is 15.1ft. and the mean neap tide range 7.3ft. (Admiralty Tide Tables, 1971) though the range may be over 20ft. and under 4ft. at extreme values. It is possible to calculate the theoretical period of water contact at a point using this curve, given the range (R) of the tide which is recorded in the Admiralty Tide Tables. The height (x) of the point above low water is then found and the ratio x/R calculated. This ratio is found on the tidal curve and the period of water contact read off. It is necessary to do these calculations for increments of only half a foot except for tides whose highest levels are less than a foot above the M.E.M. site in which case the period of water contact for increments of a tenth of a foot of the height of high tide are calculated. The resulting relationships between the period of water contact (hours) and the height of the high point of the tide is shown in Fig. 4.17a for each site. The graphs are paraboloid and all have the same form. Site 4 is, theoretically, never touched by the water since spring tides reaching a height of 3.0m O.D. are rare. For each site a table of the period of water contact for each 0.1ft. increment of the height of high tide was prepared from the graphs in Fig. 4.17a. The period of water contact

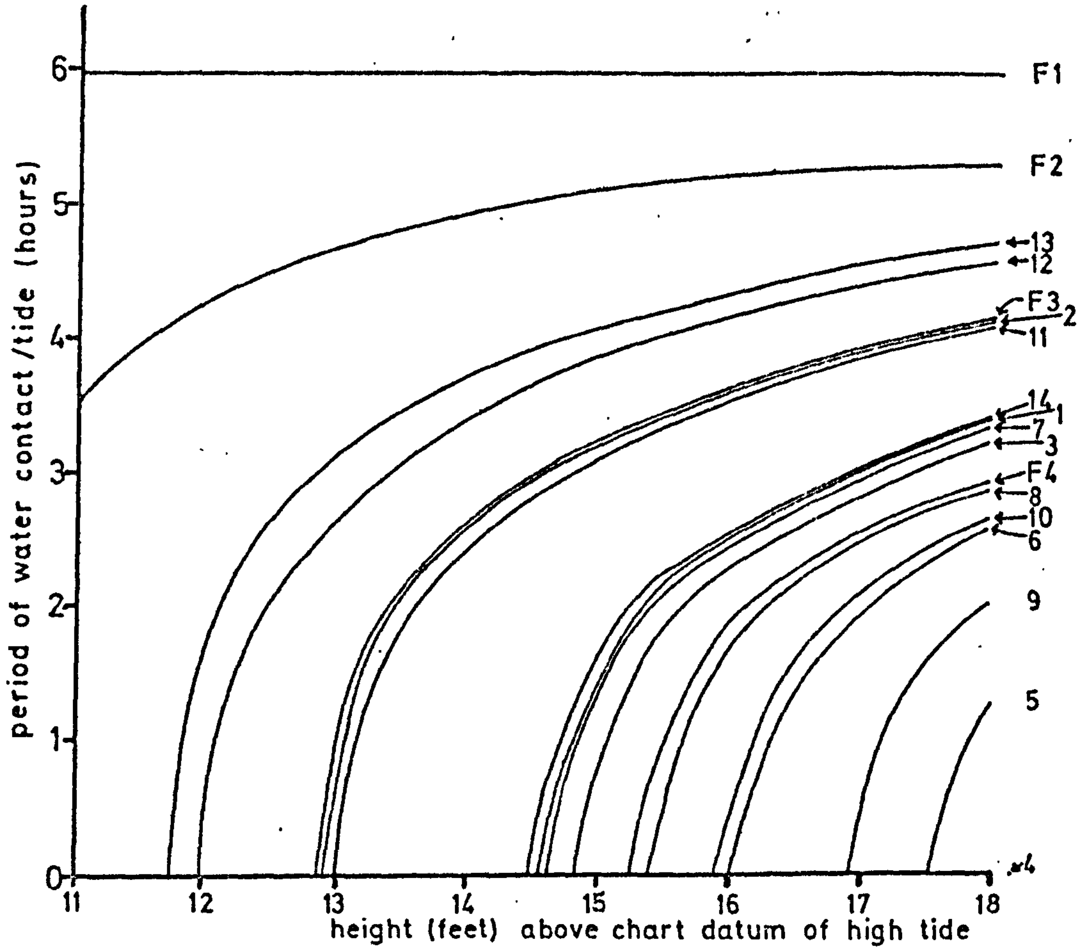


Fig.4·17a Relationship between period of water contact and height of high tide for each MEM site

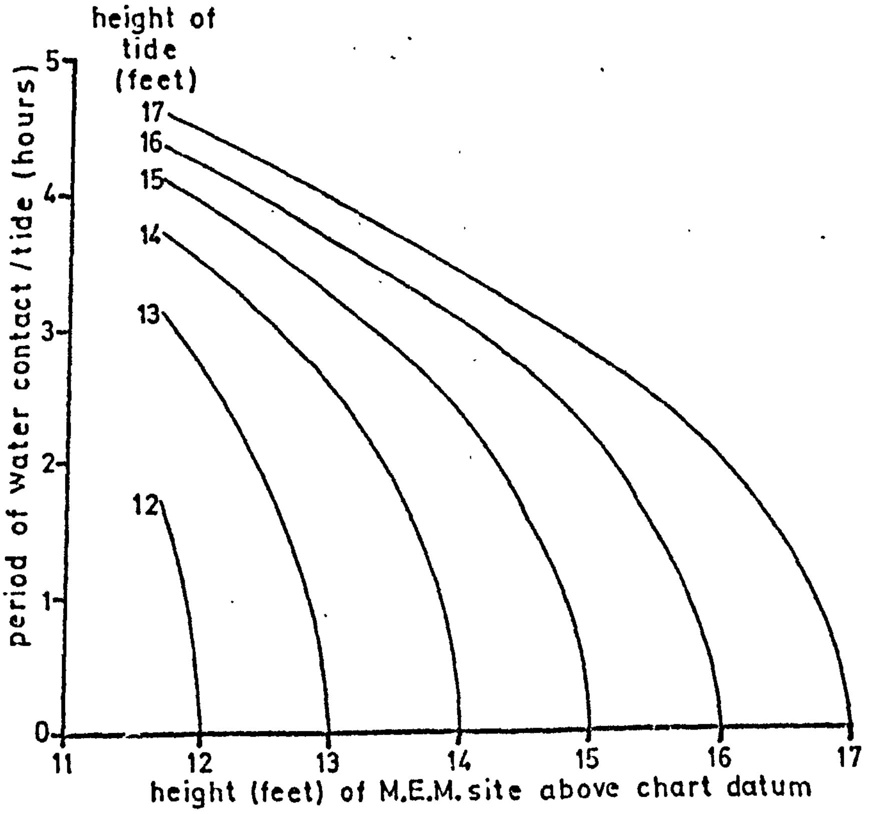


Fig. 4·17b Relationship between period of water contact and height of M.E.M. site was then summed for each erosion period if the site was uncovered by sand for the whole of the period. (The average number of tides in each erosion period was 16.7.) Covering of the M.E.M. site by the beach shortens the period of water contact. After adding the average thickness of this cover for an erosion period to the height of the site it is possible to interpolate the period of contact for the site from Fig. 4.17a, assuming that once the sand over the site is covered with water, erosion at the site is started i.e. that the sand in contact with the rock is moved. However, Fig. 4.17b shows that interpolation must involve some inaccuracy since the period of water contact is not linearly correlated with height above chart datum (A.C.D.) (which is 8ft. below Ordnance Datum). The relationship between the period of water contact (y) and the variables of height of high tide (ACD) (x_1) and height above chart datum (x_2) using a paraboloid equation is:

$$y^2 = 7.99 + 3.93x_1 - 4.43x_2$$

Though this equation explains 95.9 per cent of the variation, the standard error of estimate is 1.29 hours. The error is severe for tides covering a site by less than one foot. Therefore estimation of periods of water contact when the sites are covered by sand for part of the erosion period was done by interpolation from Fig. 4.17a.

Data for Sea State - Since two estimates of sea state are made at South Gare each day and there are usually two tides per day, one value of sea state was used for each high tide. The scale of sea state values is a power function, small changes in the state of the sea when it is little disturbed being more important on the scale than equivalent changes during, say, a storm. It is not obvious, however, that the erosive power of waves is linearly correlated with sea state values. Site 3 was randomly chosen from the population of sites 2 to 13 inclusive. Multiple regression analyses were repeated with successively higher values of n up to 6 using the equation:

$$\log_{10}E = a+b_1\log_{10}(\sum^{k} W^{n})+b_2\log_{10}(\sum^{k} T)+b_3\log_{10}D$$

where E = erosion during erosion period

W = wave value/tide

T = period of water contact/tide

D = mean height of site above beach during erosion period

k = number of high tides during erosion period

a, b_1, b_2, b_3 = constants

The amount of explained variation for each analysis is shown graphically in Fig. 4.18a. Above n = 2 the explained variation increases by just over 1 per cent only, the maximum being at n = 5. Therefore, above n = 2 the term $(\log_{10}(\sum^{k} W^{n}))$ acts almost as a constant. The reason for this is not clear but may be because the erosive power of large waves is increasingly influenced not only by their magnitude but, for instance, by the way they break. Also, the orientation of site 3 is at a large angle from the direction of wave attack so that the true relationship between erosion and wave power may not operate. Repetition of analyses with increasing values of n for site 2 reveal that here n = 2 is the optimum power (Fig. 4.18a) but again there is a difference of only 3 per cent between n = 2 and n = 6. For subsequent analyses of erosion data at other sites the power n = 5 was used.

Data for Beach Conditions - The position of the surface of the beach with respect to each M.E.M. site in Fourth Bight is very variable

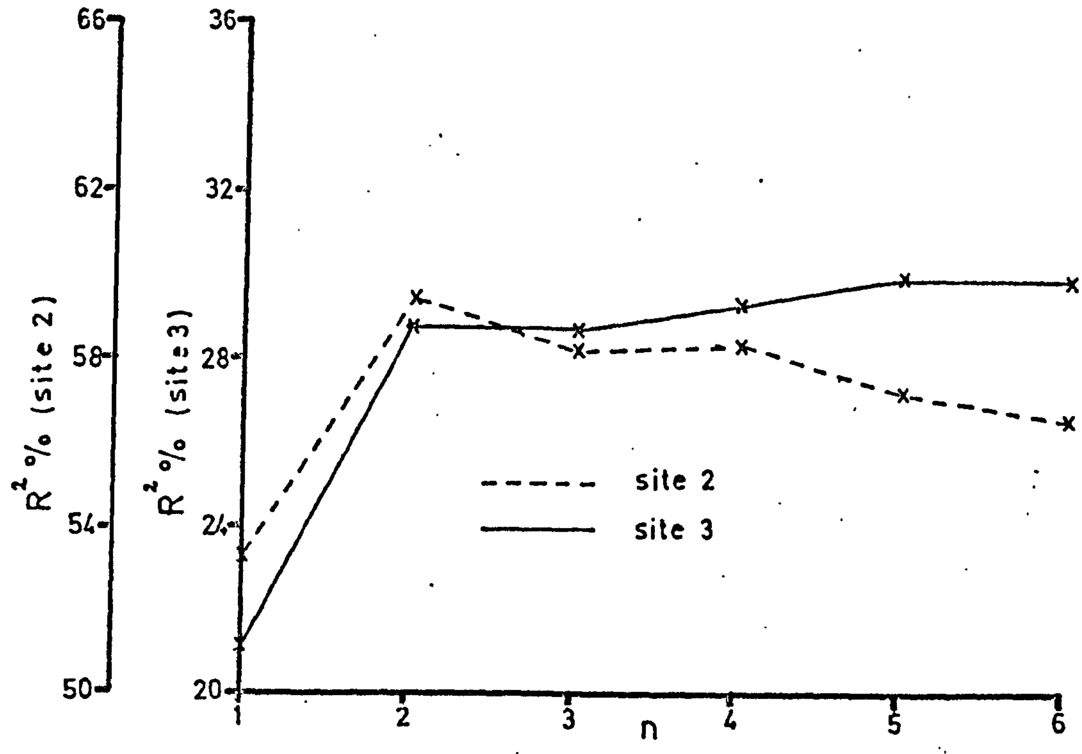


Fig. 4·18a Relationship between n and amount of explained variation

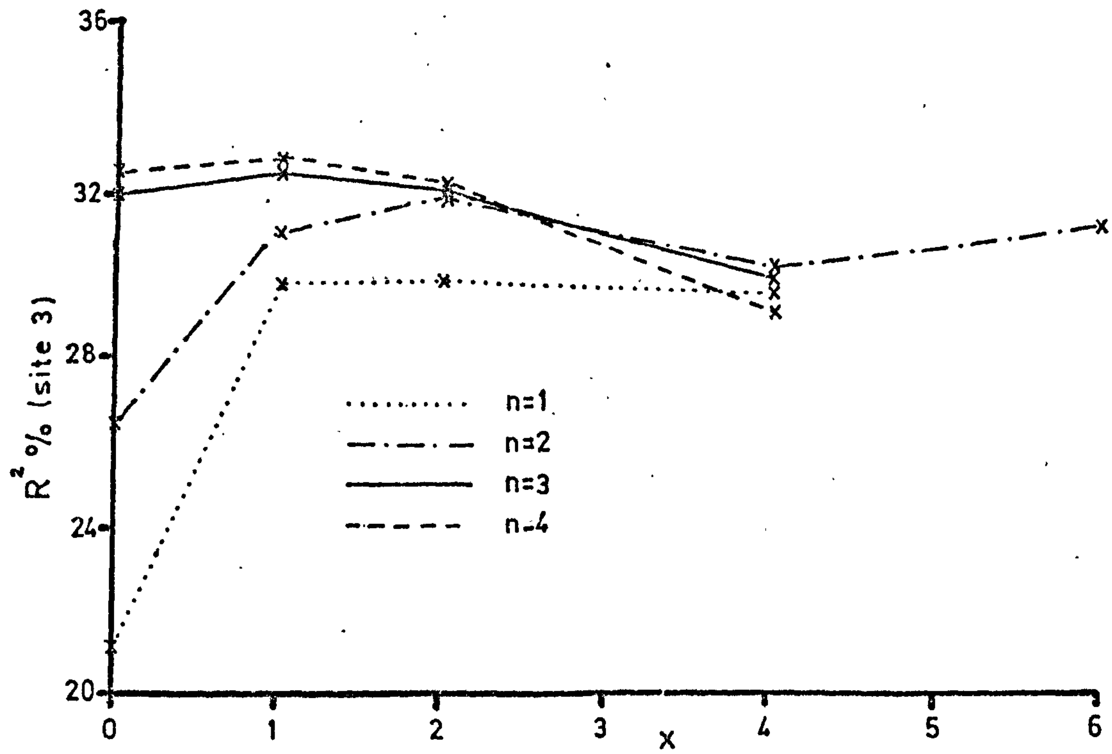


Fig.4·18b Relationship between x,n and explained variation according to the state of the sea. After a storm the beach is combed down and during periods of calm the sand is pushed towards the foot of the cliff. However, the direction of wave attack is also most important, the shore platform beneath the sand being laid bare occasionally after the beach has been carried into Gravel Bight.

The height of each erosion stud above the beach surface was measured to the nearest inch at the end of each erosion period and the mean height of the site above the beach surface then found. Site 14 had no beach in front of it for all but the last two erosion periods which were excluded from the analysis, and it showed very little erosion during this time. It might be inferred that the rate of erosion decreases with height above the beach surface. With increasing depth below this level, the sand must provide the rock surface with increasing protection. Hence it can be concluded that erosion is proportional to some power of the height of the M.E.M. site above the beach. It is not clear, however, that erosion should be a maximum at the surface of the beach and not at some higher or lower level. Therefore, multiple regression analyses were repeated for site 3 with successively higher values of the terms x and n using the equation:

$$\log_{10}E = a+b_1\log_{10}(\sum^{k}(W)^5)+b_2\log_{10}(\sum^{k}T)+b_3\log_{10}(D+x)^n$$

where the terms are the same as those given above.

The results of these analyses are given in Fig. 4.18b. The amount of explained variation is at a maximum with x = 1 and decreases with higher values. It is also maximum with n = 4 so that the optimum equation for analysis is:

$$\log_{10}E = a+b_1\log_{10}(\sum^{k}(W)^5)+b_2\log_{10}(\sum^{k}T)+b_3\log_{10}(D+1.0)^4$$

The Influence of On-Site Variables

The Amount of Explained Variation - Multiple regression analyses for each M.E.M. site were carried out using the above equation which incorporates the on-site variables, i.e. those which change with time. The results of these are summarised in the table in Fig. 4.19. The correlation coefficient for site 14 is not significant at the 0.05 level - this site underwent very little erosion during the year. In contrast the correlation coefficient for site 11 is insignificant because of the small number of degrees of freedom, a result of the extremely rapid erosion rate at this point (2.877 inches in 154 tides) which necessitated its abandonment; more will be said about this anomalous case later. The lack of significance of the correlation coefficient for site 10 is difficult to explain - it may be partly due to its orientation and to the very high erosion rate of 0.8723 inches in erosion period 25.

Of the remaining sites, the amount of variation explained by the variables is between 20.5 and 57.3 per cent. Even this maximum value is low; the possible reasons for this are many:

1. The quality of the data:

   (a) the period of water contact is a theoretical variable based on the average tidal and meteorological conditions at Teesmouth. The lack of accuracy of this parameter is indicated by site 4 which recorded erosion of 2.0297 inches in 595 tides and yet should never have been wetted by the sea. Higher sea levels can be produced by strong onshore winds and even by unusually low or high barometric pressure (34mb change of pressure gives a height change of one foot (Admiralty Tide Tables, 1971)).

unit number	R^2%	signif. level	standard error	intercept	wave variable (2)				period of water contact variable (3)				beach variable (4)				number of observations
					$r_{12\cdot34}$	t	signif. level	b_2	$r_{13\cdot24}$	t	signif. level	b_3	$r_{14\cdot23}$	t	signif. level	b_4	
1	39·5	(0·01)	0·5665	-5·1987	0·5461	3·779	(0·001)	0·7278	0·2205	1·189	(0·25)	0·2776	0·2346	1·155	(0·30)	0·9475	31
2	57·3	(0·01)	0·2571	-0·2226	0·6515	4·773	(0·001)	0·3964	0·4666	2·962	(0·01)	0·5059	0·1368	0·641	(0·60)	0·0822	32
3	32·8	(0·01)	0·5117	1·6401	0·4884	3·304	(0·005)	0·5477	0·1001	1·092	(0·30)	0·1911	-0·2671	-1·715	(0·10)	-0·6155	34
4	29·2	(0·01)	0·4798	0·5858	0·4715	2·708	(0·02)	0·4030	-	-	-	-	-0·3666	-1·800	(0·10)	-0·1197	36
5	40·3	(0·01)	0·4993	0·7746	0·4697	2·893	(0·01)	0·4217	0·3121	0·968	(0·40)	2·2023	-0·5028	-2·264	(0·05)	-0·2682	39
6	26·5	(0·025)	0·5048	-0·3980	0·4957	3·189	(0·005)	0·4873	0·1167	0·933	(0·40)	0·1835	-0·1742	0·101	(0·95)	0·0142	37
7	27·2	(0·05)	0·5866	-0·4897	0·4231	2·686	(0·02)	0·5473	0·2420	1·789	(0·10)	0·4149	-0·1337	-0·121	(0·95)	-0·0151	30
8	34·9	(0·01)	0·5481	0·5248	0·4885	3·296	(0·005)	0·4892	0·3423	2·309	(0·05)	0·3982	-0·1345	-0·477	(0·70)	-0·0428	37
9	20·5	(0·05)	0·6424	-5·0368	0·2953	1·844	(0·10)	0·3362	0·2609	1·617	(0·20)	5·6690	0·2510	1·480	(0·20)	0·9599	38
10	16·4	(>0·10)	0·5631	0·7612	0·2501	1·681	(0·20)	0·2661	0·3042	1·995	(0·10)	0·3939	0·0120	0·111	(0·95)	0·0202	37
11	59·9	(>0·10)	0·3269	-0·7217	0·6451	0·540	(0·70)	0·1941	0·7580	1·072	(0·40)	1·3990	0·2931	0·192	(0·90)	0·0929	9
12	56·9	(0·01)	0·5786	2·2519	0·4367	2·371	(0·025)	0·4013	0·1749	1·198	(0·25)	0·6746	-0·6596	-5·453	(0·001)	-0·8557	38
13	43·6	(0·01)	0·3762	0·1710	0·3678	0·339	(0·80)	0·0438	0·4086	2·582	(0·02)	1·2217	-0·4636	-2·817	(0·01)	-0·3914	26
14	4·3	(>0·10)	0·2734	0·7300	0·1683	0·914	(0·40)	0·0705	-0·1409	-0·726	(0·50)	-0·0668	-	-	-	-	38

Fig.4·19 Results of multiple regression and correlation analyses of M.E.M. units at Fourth Bight

Changes in sea level of 2 to 3 feet may occur several times in a normal year in the North Sea and, of course, lower sea levels than those predicted also occur.

(b) The wave data are by no means ideal - it would have been necessary to install a wave gauge very near the sites but the probability of vandalism would have been great.

(c) It is possible that the beach in Fourth Bight is very susceptible to change so the parameter indicating its level has less meaning than is at first apparent.

2. Randomness is introduced by the varying erosive power of waves of the same size. This may be created by the way in which the wave breaks, impedance of it by the reflection of the preceding wave, direction of wave attack, etc.

3. Geological variations - the density, orientation and openness of joints must control erosion by quarrying processes and these structural properties vary spatially and temporally as erosion proceeds.

4. The existence of a number of erosion processes, e.g. quarrying and corrasion, with different intensities and frequencies. Because the capacity of an erosion site is governed by the depth of the studs below the rock surface, M.E.M. sites preferentially do not measure very high erosion rates. The various types and scales of erosion will be discussed in some detail later.

The amount of explained variation at each site is plotted against height above ordnance datum in Fig. 4.20a, the non-significant analyses

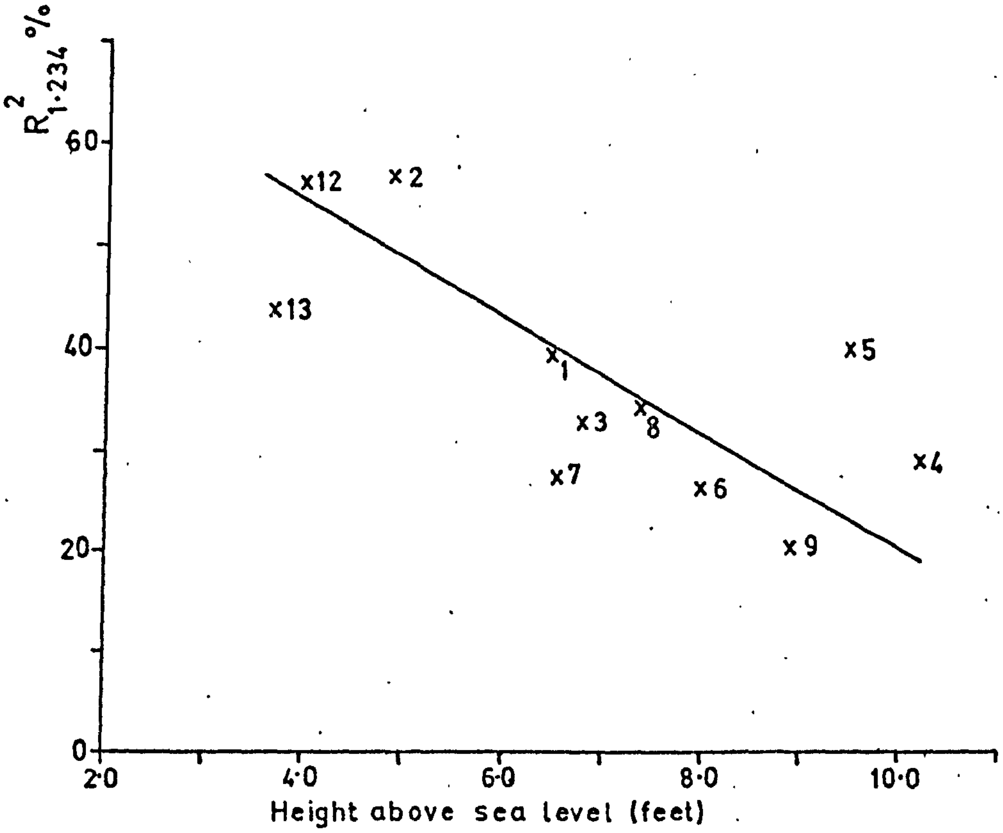


Fig. 4·20a The relationship between explained variation and height above sea level

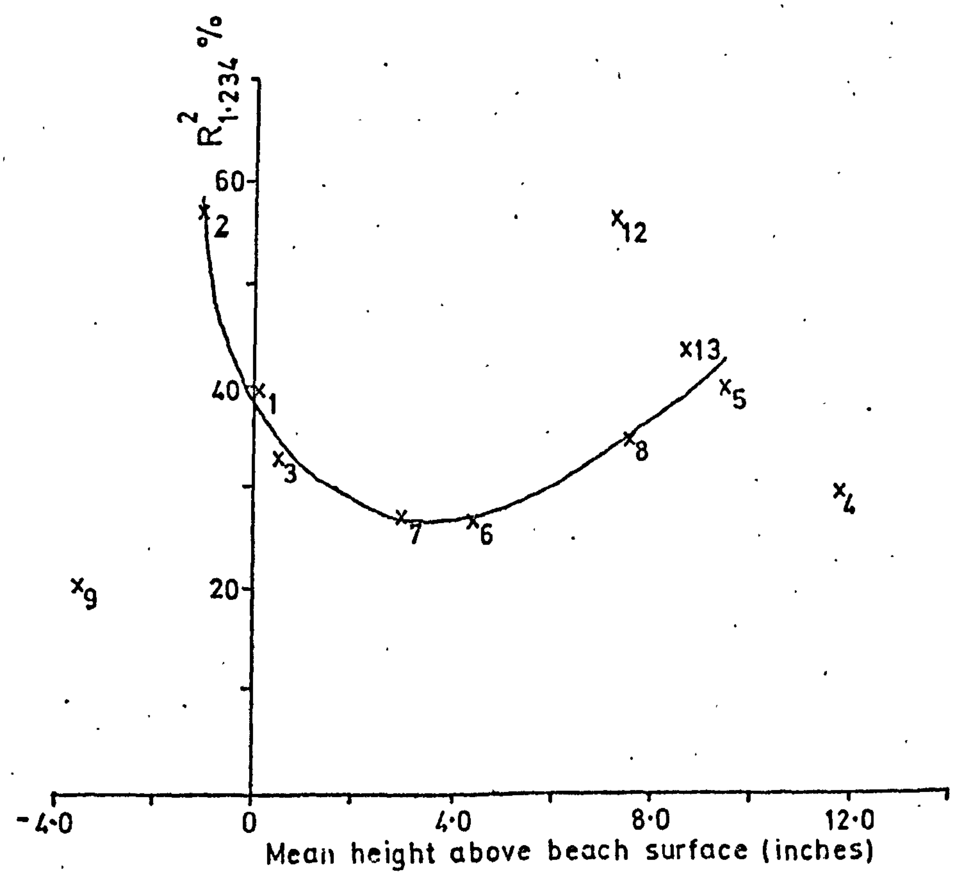


Fig. 4·20b The relationship between explained variation and mean height above the actual surface of the beach being omitted. Generally, the variables used explain less of the variation with increasing height. This may be due to the increasing inadequacy of the variable for the period of water contact and to the increasing randomness of erosion at higher sites. Explained variation at each site is plotted against the mean height of the site above the beach and a suggested curvilinear relationship is given in Fig. 4.20b. Sites 4, 9 and 12 clearly do not conform to this relationship but the others fit remarkably well. Again, the randomness of erosion due to different erosive processes may be the cause of the variations in $R^2_{1.234}$.

The Sea State Variable - Indications of the relative importance of the on-site variables are given by simple correlations between them and erosion. The values of these and the t values of the significance of each variable in the regression are given in Fig. 4.19. The wave variable is the most significant of the three at all sites except numbers 12 and 13. The relative importance of the variables is better shown by their standardised partial regression coefficients (or β coefficients) (Fig. 4.21a) - the non-significant analyses are omitted. Again it is clear that the wave variable has the most important direct, positive effect at all sites except numbers 12 and 13; the orientation of the latter is at a very large angle to the direction of wave attack. Other variables are of only minor importance in contributing to erosion and indeed, at many sites as Fig. 4.19 shows, they are frequently not significant.

The wave variable is not uniformly important at all sites as is shown by a comparison of β-coefficients of different sites (Fig. 4.21b). This diagram is very like Fig. 4.20a because the wave variable is the

unit number	wave variable	period of water contact variable	beach variable
1	0·5668	0·1918	0·1859
2	0·5959	0·3719	0·0797
3	0·4976	0·1640	−0·2570
4	0·4080	——	−0·2711
5	0·3903	0·1443	−0·3466
6	0·5033	0·1415	0·0161
7	0·4626	0·3050	−0·0209
8	0·4677	0·3247	−0·0423
9	0·2824	0·2475	0·2268
12	0·2902	0·1458	−0·6314
13	0·0622	0·4483	−0·4955

Fig. 4·21a Standardised partial regression coefficients of significant analyses

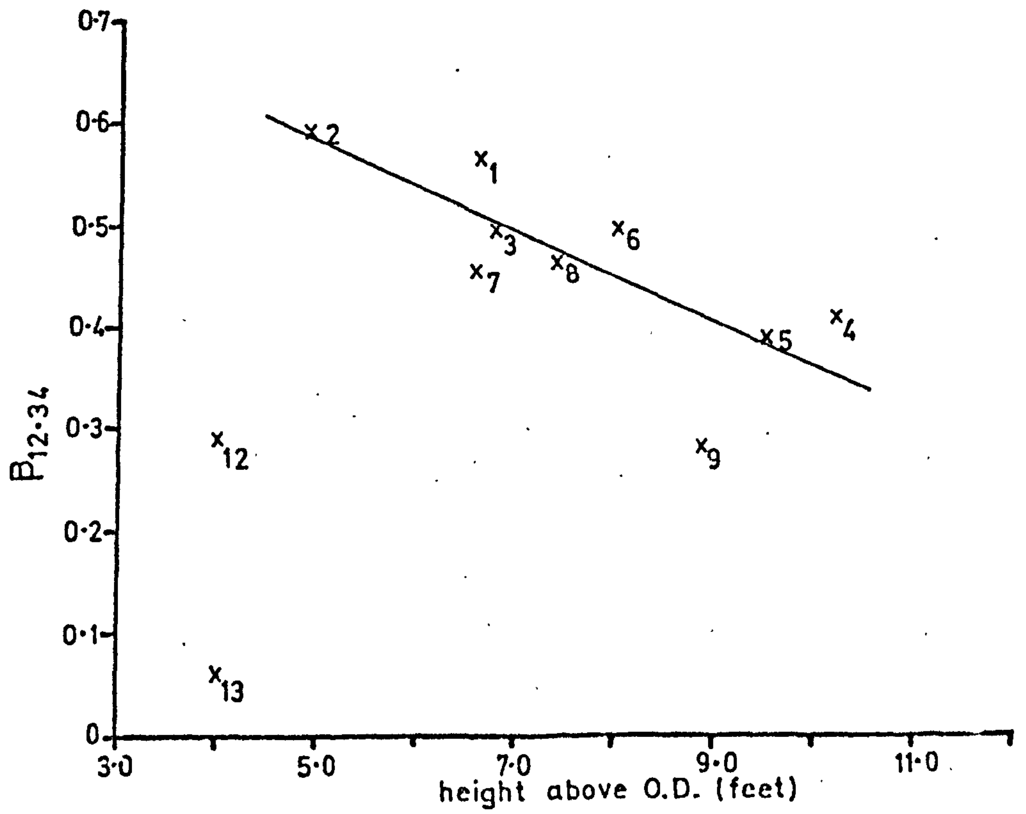


Fig. 4·21b Variation of the influence of the wave variable with height above O.D.

most important in explaining the variation in erosion. The influence of sea-state drops gradually with height above sea level, i.e. randomness increases with height, probably because the period of water contact decreases with height, and high storm seas are proportionately more frequent. Sites 12 and 13, at the sides of Fourth Bight, deviate markedly from the general trend. The correlation coefficient between $\beta_{12.34}$ and height above sea-level (in feet), excluding these two sites and site 3 (also at the side of the bight) is significant at the 0.025 level, explaining 60.39 per cent of the variation, the regression equation being

$$y = 0.8068 - 0.0448x$$

It has been shown that the maximum amount of explained variation is attained with the variable term $\log_{10}(\sum^{k} (W)^5)$. This implies that erosion is proportional to the fifth power of the sea state value - the relationship is shown in Fig. 4.22a. By superimposing this on a graph of the frequency of sea state values, a relationship depicting the total amount of work done at each state of the sea is produced (Fig. 4.22b). It is clear from this diagram that sea states of value 5 do most work despite the fact that seas of value 2 are by far the most common. However, it has been noted that the explained variation at site 3 is reduced by only 1 per cent if n = 2 in the wave variable. Fig. 4.22b shows that seas of value 3 do the most work if erosion is proportional to this power. In spite of the uncertainty of the best value for n it can be concluded that the most common seas are not the most important for erosion. With n = 5, Fig. 4.23a shows that 80 per cent of the work is done in only 14 per cent of the time (with n = 2, this increases to 58 per cent of the time). This supports the conclusion that it is storm seas which erode most actively and, in turn, that the

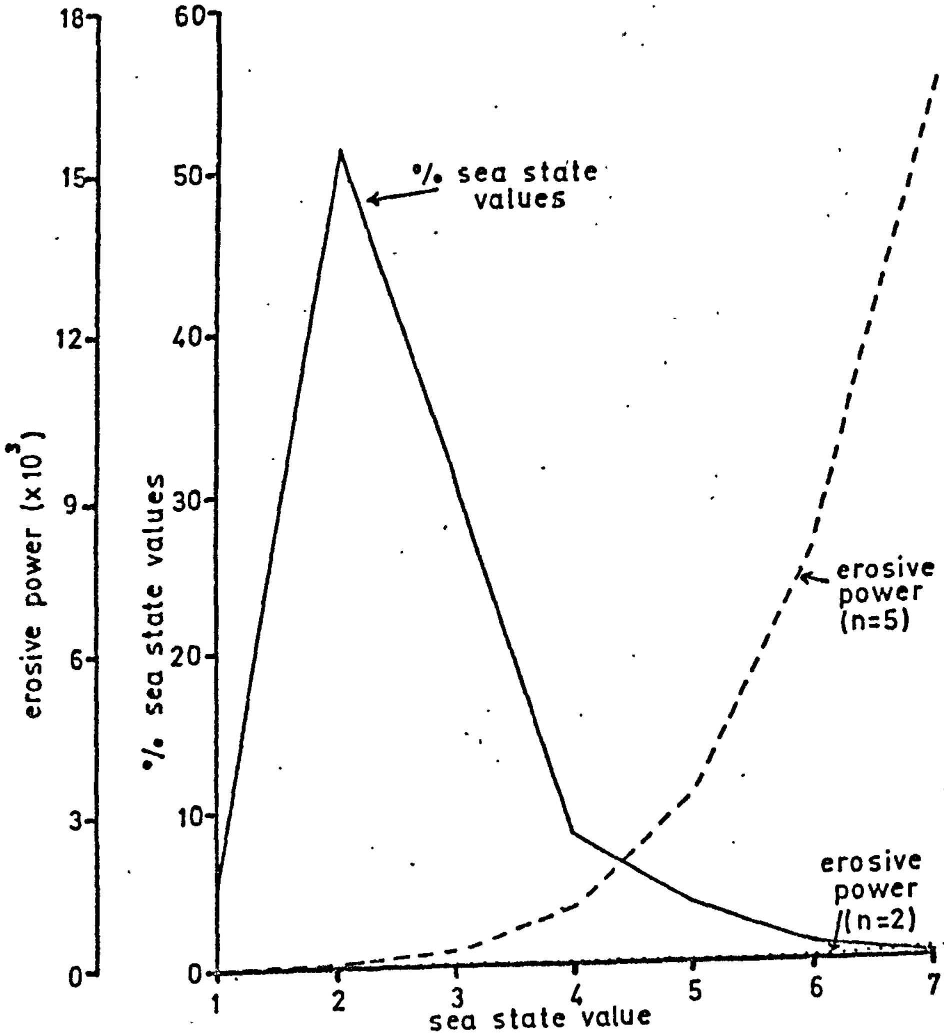


Fig. 4·22a Frequency of sea state values compared with their erosive powers

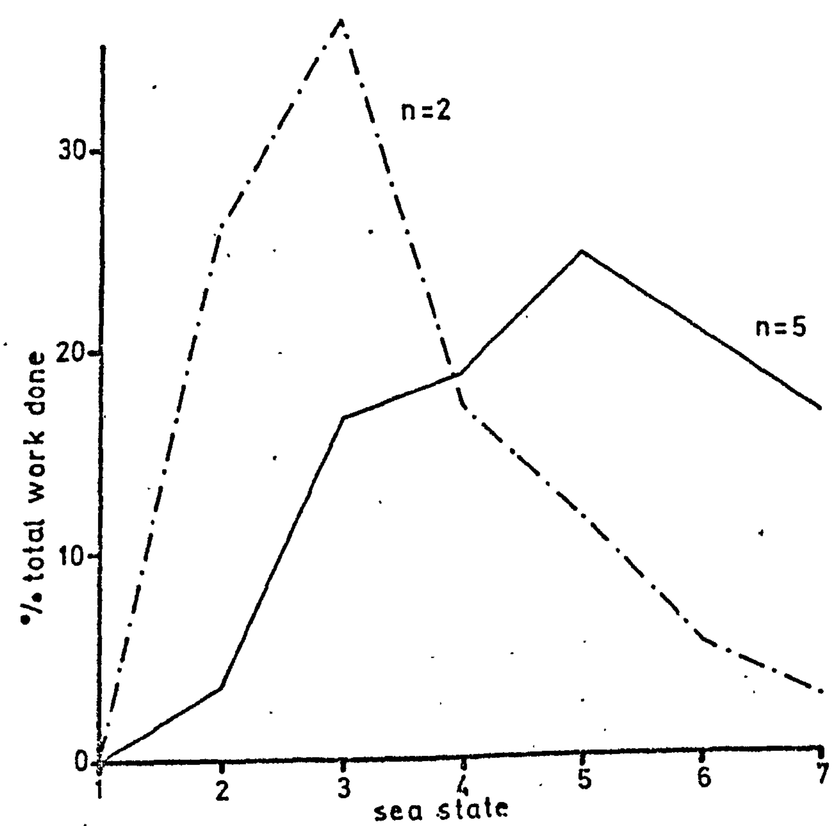


Fig. 4·22b Work done by each value of sea state

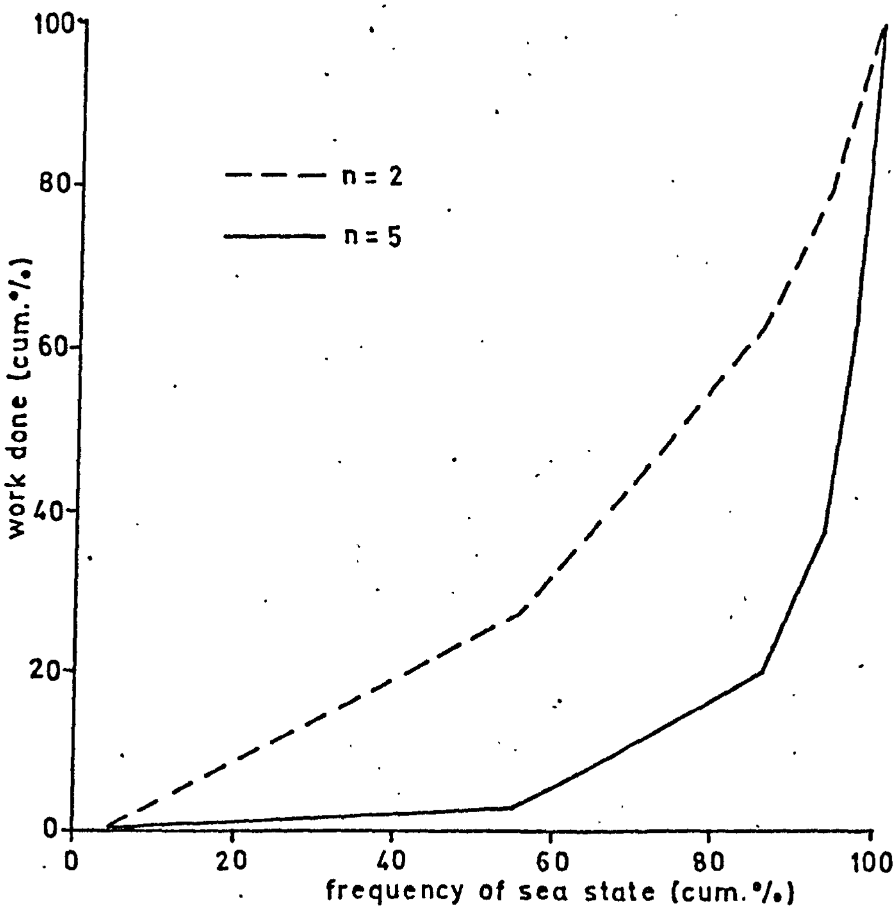


Fig. 4·23a Cumulative work done

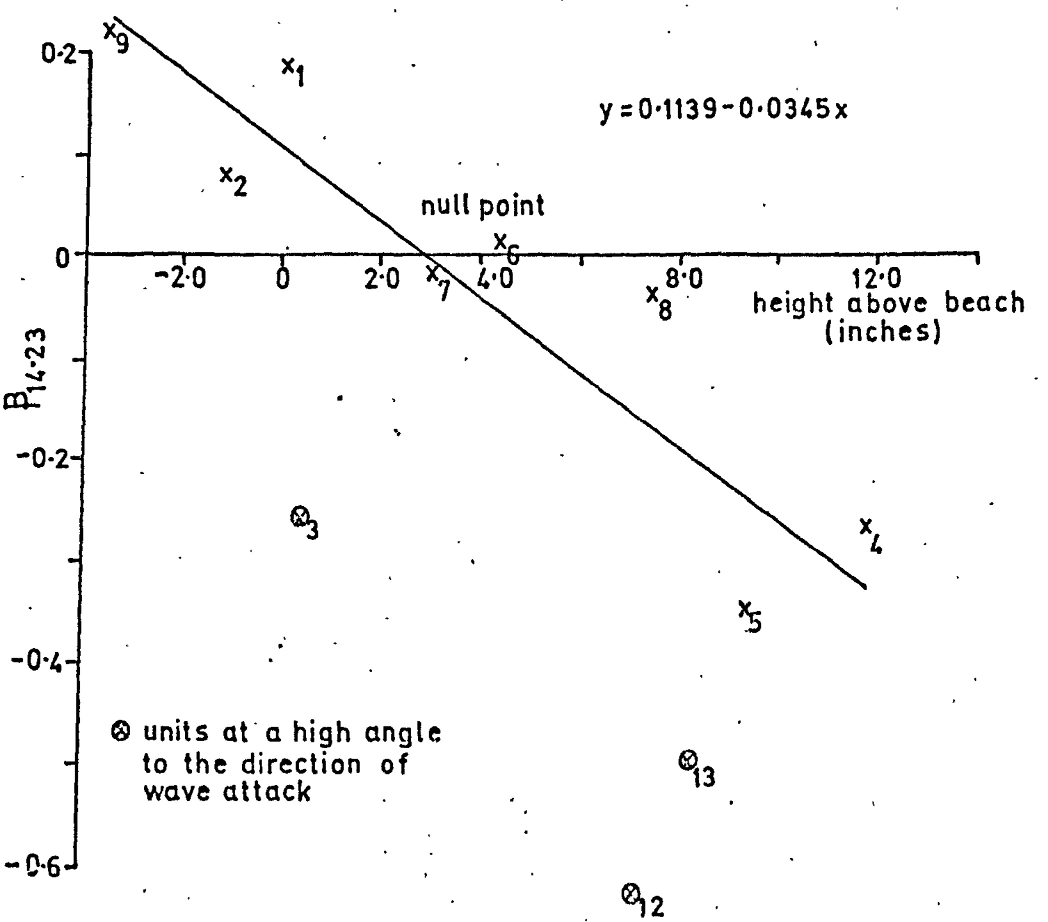


Fig. 4·23b Variation of the influence of the sand variable with height above the actual surface of the beach morphology of the cliff foot is in equilibrium with storm conditions and not with normal (i.e. most frequently occurring) states of the sea. The erosion of site 4 attests to this since this unit is, theoretically, never in contact with the sea.

The Time Variable - The table in Fig. 4.21a shows that the variable for the period of water contact is in 8 out of 10 cases only one third to one half as important as the wave variable in directly affecting erosion. At site 13 the time variable is the more important probably because of the orientation of the site. The influence of this variable shows no trend with the height of the site above either sea level or the mean surface of the beach. The correlation of erosion with period of water contact in each erosion period is significant at the 0.05 level at sites 2, 8 and 13 only.

The Beach Variable - The partial regression coefficient of the distance of the site from the "real" surface of the beach (i.e. one inch below the "actual" surface) is statistically significant at sites 5, 12 and 13; at sites 6, 7 and 10 it is completely insignificant. This does not, however, invalidate an investigation into possible trends of the β-coefficient. At seven of the eleven sites where the multiple regression analysis was significant, the beach variable has a negative influence on the erosion rate, it being significantly important at the sites (5, 12 and 13) where it reaches its highest absolute values. The negative influence implies that increased distance from the real beach surface increasingly inhibits the ability of waves to erode. At sites 1, 2, 6 and 9 the beach variable affects erosion positively. Fig. 4.23b is a scatter diagram of $\beta_{14.23}$ plotted against the mean height of each site above the actual surface of the beach. The position of the null point shows that the beach has a positive effect on erosion only when the site is (on average) buried or less than three to four inches above the actual surface of the beach. This must be the limiting height to which large quantities of sand are thrown into suspension in the waves. It might be postulated that below a level of about five inches (i.e. a mirror image of 4 inches above actual surface + 1 inch beneath) below the actual surface of the beach, the increasingly protective action of the sand again produces a negative effect on erosion; however, no data exist to substantiate this inference. A strongly negative relationship exists between increased height above the beach and the effect of the beach. Interestingly, at the sites (numbers 3, 12 and 13) orientated at considerable angles from the direction of wave attack, the influence of the beach is very much increased in a negative direction, probably because these sites do not receive the full impact of sand propelled by the waves. The correlation coefficient between β(y) and mean height above the beach (x) for all sites but these three is significant at the 0.05 level, 56.33 per cent of the variation being explained by the regression equation:

$$y = 0.1139 - 0.0345x$$

The null point of sand influence when calculated from this equation is at a level of 3.301 inches above the actual surface of the beach.

The importance of the level of the beach in determining the rate of erosion can be seen in Fig. 4.24 in which the mean erosion/tide at each site is plotted against the mean height of the site above the actual beach surface. Though the scatter is considerable with some sites orientated at high angles to the direction of wave attack again deviating most markedly, there is a definite trend for erosion to increase towards a level of one inch below the sand surface both from

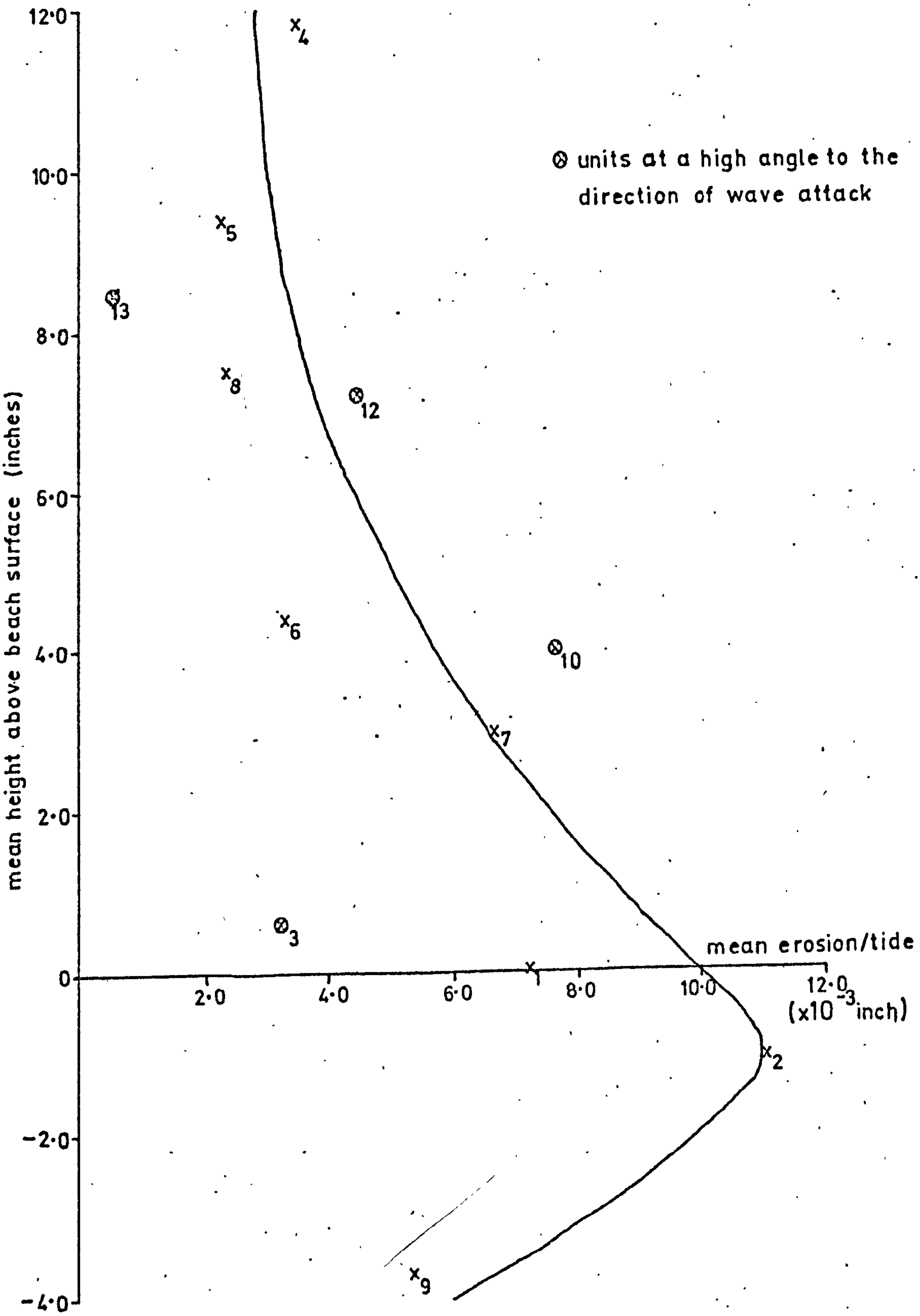


Fig. 4·24 The relationship between the rate of erosion and height above the surface of the beach above and below this point. (Erosion at unit 1 is lower than it should be because it is fronted by cobbles.) This conclusion clearly differs from that of the multiple regression analysis in which the beach variable at most sites is insignificant. This is because the multivariate analysis considered short-term (i.e. weekly) variations in the level of the beach while the conclusion just reached uses data referring to a longer period (a year) over which the weekly variations in the level of the beach are negligible in toto.

The Between-Site Variables

Of the main between-site variables which could be chosen for inclusion in analysis such as the mean grain size of the sand fronting each site, hardness of the rock at the site, and joint spacing, most are difficult to quantify. Those selected were:

1. height of the site above ordnance datum
2. mean height of the site above the beach
3. the angle between the orientation of the site and the direction of wave approach.

The height (H) parameter (measured in feet) is equivalent, to some extent, to the period of water contact used in the temporal analysis. Use of both variables is impractical because of multi-colinearity.

The mean height of the site above the beach is the mean of the data for all erosion periods at each site. A similar variable to that used in the temporal analyses, i.e. $(D+1.0)^4$ was used.

It has already been noted that in Fig. 4.23b the influence of the beach variable is much reduced at sites along the sides of Fourth Bight. The direction of wave approach was found by drawing a line perpendicular to the shore platform contours shown in Fig. 4.16; this orientation is thus a mean value. It is unlikely that erosion is directly proportional to the angle (α) between the direction of wave attack and the orientation of the site since the magnitude of a unit vector will decrease according to the cosine of this angle as the angle increases. Therefore the cosine of the angle was used. A variable for wave values was not included since this varies temporally but not spatially.

Hence, the estimating equation used for analysis was:

$$E = a+b_1H+b_2(D+1.0)^4+b_3\cos\alpha$$

where E = mean erosion/tide for each site

a, b_1, b_2, b_3 = constants

Each set of data refers to one site, sites 10, 11 and 14, the correlation coefficients of which were not significant in the temporal analyses being omitted.

The Between-Site Analysis

Though 52.8 per cent of the variation was explained by using the three independent variables listed above, the total of only 11 cases used in the analysis meant that the correlation coefficient was significant at the 0.10 level only. The variable for mean height above the beach being the most insignificant the exclusion of it and repeat of the analysis using the other two independent variables increased the explained variation to 54.22 per cent and allowed the correlation coefficient (0.7363) to be accepted as significant at the 0.05 level. The fact that the beach variable is insignificant indicates that when expressed in the same way as in the temporal analysis it is unimportant. Of the other two variables, the orientation parameter is by far the most important (β coefficient = 0.7600) and its t value is significant at the 0.02 level. The variable for height above sea level has a β coefficient of -0.4509 but its t value is significant at the 0.20 level only. It seems therefore that the slight influence which height above sea level might have on erosion is negative. The simple correlation coefficient (0.6029) between mean erosion/tide and the cosine of the angle (α) between site orientation and direction of wave attack is significant at the 0.001 level such that the equation

$$E = 6.2268\cos\alpha - 3.1039$$

explains 36.35 per cent of the variation.

Fig. 4.24 indicates that the beach variable might be better expressed in linear form and so the analysis was repeated, excluding site 9. The regression equation

$$E = 3.5946 - 0.2556H - 0.4085D + 6.2489\cos\alpha$$

explains 81.52 per cent of the variation and the correlation coefficient is significant at the 0.025 level. However, the regression coefficient for the term for height above sea level is not significant. A repeat of the analysis using the two remaining independent variables reveals that the equation

$$E = 2.6117 - 0.4597D + 5.5959\cos\alpha$$

explains 79.10 per cent of the variation. The correlation coefficient is significant at 0.01; the regression coefficient for height above the beach is significant at 0.005 (β-coefficient = -0.6586) and that for orientation at 0.02 (β-coefficient = 0.5229). It can be concluded that the former variable is the more important. The linear form of the beach variable is different from the power function variable in the temporal analysis; this is a result of the movement of the beach surface about a mean position.

Erosion in Plan at Fourth Bight

The importance of the orientation of the M.E.M. site in influencing erosion has been shown in the last section and is also clear from Fig. 4.25 which depicts the projected amount of erosion for one year at Fourth Bight. Clearly at site 14 erosion has been negligible despite its optimum orientation to wave attack; this is due to the absence of a beach in front of it. At sites 2 and 7 which have similar positions to 14 as they are at the tips of headlands, erosion has been much more severe as it has also at sites 4 and 9 which are at the heads of the bight. At sites orientated away from the direction of wave attack erosion has been much less though when measured in the direction of wave attack it is much more constant. Sites 11 and 12 were located so that they did not lie parallel to the western side of the bight but site 13 was situated like this. Site 11 illustrates the hazards of extrapolation since the two-foot thick sliver of rock between the bight and one of the series of major joints forming the western side of Fourth Bight was rapidly eroded but the rock then exposed at the joint was worn very little. The only major anomaly to the correlation of erosion with orientation is at site 10 - this is probably due to very local conditions.

Fig. 4.25 indicates that Fourth Bight is being extended headwards much more rapidly than sideways so that the headland to the west of it whose tip is not being eroded at its base (site 14) because of the lack of beach is being made longer and longer and slightly narrower. A number of these headlands exists east of Whitby East pier. A few feet above site 14, three blocks of rock were eroded during the year of observation while at the headland nearest the East Pier the tip is receding at a level of about five feet above the shore platform.

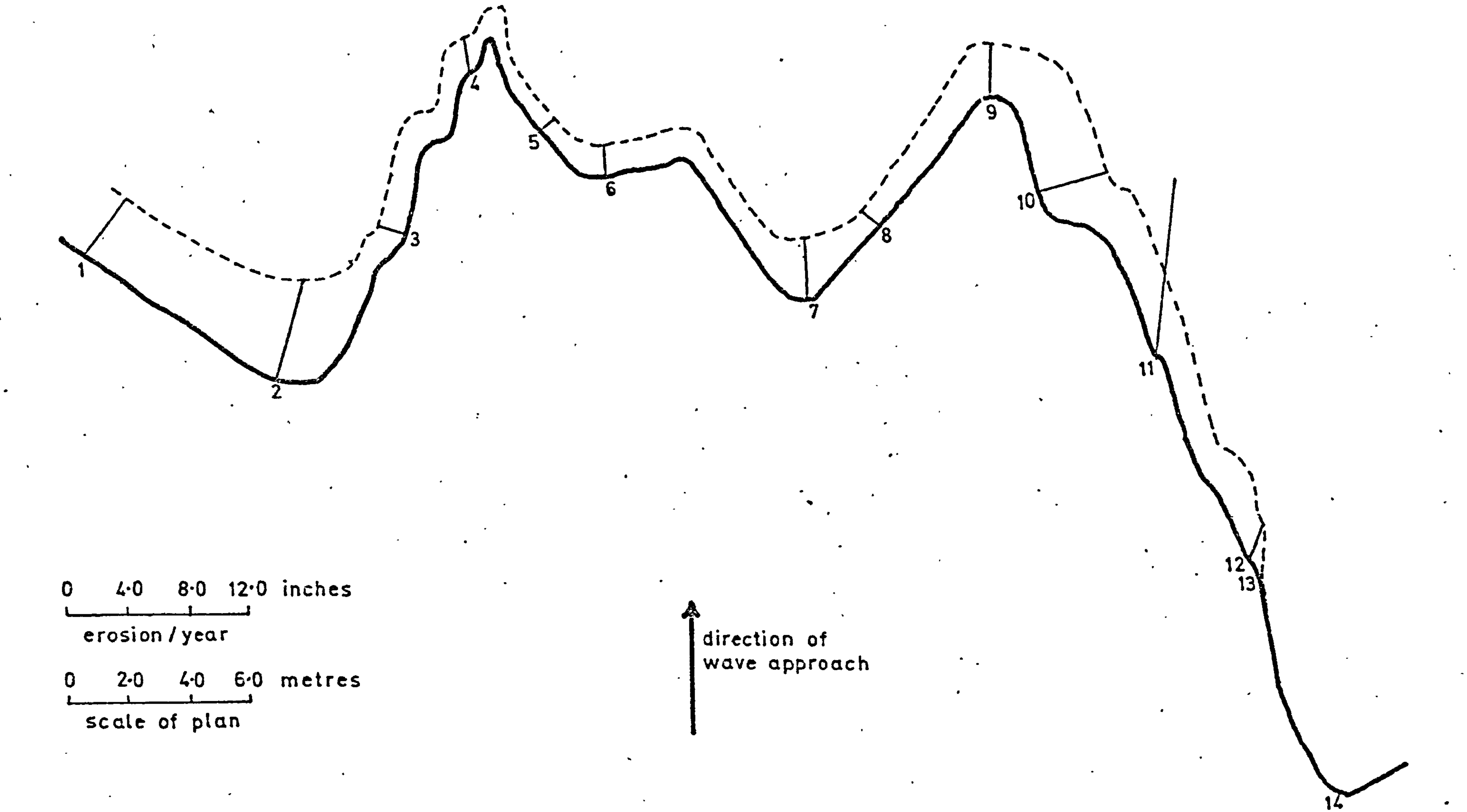


Fig. 4·25 The rates of erosion in plan at Fourth Bight

Between this headland and Fourth Bight lies a stump of rock two to three feet high separated from the headland behind by a pebble beach. A model for the plan erosion of this stretch of coastline might, therefore, be postulated as follows:

1. the bights extend landwards and the tips of the headlands between become increasingly isolated from the beaches in the bight.
2. erosion by quarrying, which is linked with storms and, therefore, high seas proceeds at a high level on the headlands.
3. eventually the horizontal high-level erosion intersects the sloping ramp of the bight and the beach can then erode the tip of the headland.
4. the headland can then recede at about the same rate as the bight but a stump of rock is left seaward of it.

The applicability of this model depends on the existence of small bights with active beaches; these features are certainly not common on the north-east Yorkshire coast.

Corrasion and Quarrying

Although the nature and influence of variables governing erosion have been discussed in some detail, little has been said of the actual nature and relative importance of the erosive processes. The Alum Shales of Fourth Bight are probably little affected by solution compared with physical erosive processes of which quarrying and corrasion are the major constituents. Hydraulic quarrying is the lifting out of joint-bounded blocks of rock by the pressure transmitted from waves into the water filling the joints. Pneumatic quarrying is similar but the pressure is exerted by pockets of air which become compressed to very high pressures in the joints for very short periods when a wave meets the rock surface; data concerning these shock pressures have been reproduced by King (1972, p. 451). The data collected at Fourth Bight do not allow the results of these two allied processes to be differentiated and so the process of erosion of blocks of rock will be termed "quarrying". Corrasion is a fundamentally different process; it is the rubbing of the surface of the rock with material carried by the waves. Hence, corrasion produces a uniform amount of erosion over a wide area of the rock surface while quarrying generates spatially very varied erosion rates. It is possible that these two processes are, in fact, the two extremes of a continuum since large pieces of beach material, when thrown against a rock surface, may knock pieces off it as well as rub the surface. This knocking off (abrasion) is not distinguishable from small-scale quarrying.

It has been shown that the beach variable in the analysis of on-site and between-site variables has considerable influence on erosion only within a narrow band about 4 inches above and 4 inches below the real surface of the beach. This erosion might well be due to corrasion while erosion at higher levels is the result of quarrying. The coarse sand to small pebble grade of the beach in Fourth Bight reduces the importance of abrasion without being too fine to reduce corrasion. Hence it can be assumed that the two processes, corrasion and quarrying, operate in Fourth Bight.

The Relative Importance of Erosive Processes

As three readings were taken with the M.E.M. at each unit, it is possible to derive the coefficient of variation of erosion values for each unit for each period of erosion. Corrasion, being the rubbing of the rock surface, should yield spatially uniform erosion (that is, uniform over an area whose diameter is only 7.5cm) and a low coefficient of variation. In contrast, quarrying produces localised erosion by the removal of joint-bounded blocks of rock and, thus, should be characterised by a high coefficient of variation. The histogram of these coefficients at the 14 M.E.M. units in Fourth Bight is shown in Fig. 4.26. This distribution is bimodal with peaks at 0.25 and 0.675 and a minimum frequency at 0.575 which can be assumed to be the discontinuity between the range of coefficient values characteristic of corrasion and that associated with quarrying. Negative values are also indicative of quarrying.

The histograms of values of erosion/tide associated with corrasion and quarrying (at all units except number 14) are shown in Fig. 4.27a. Small rates of erosion are the norm especially for quarrying; this is due to the removal of fragments of shale laminae from the cliff foot. Where no corrasion occurs (i.e. where there is no beach) this type of quarrying produces the rough rock surface with a micro-relief of 1 to 2cm typical of the class 1 cliff foot. For higher values of the rate of erosion, quarrying is carried out by the removal of joint-bounded blocks of rock. It should be noted that this process is more important than the data indicate because the removal of blocks can destroy M.E.M. units rendering impossible measurement of the amount of erosion. Fig. 4.27a implies that corrasion is a more active process than quarrying; in fact the 58.3 per cent of observations attributed to corrasion account for 63.1 per cent of the total work.

It was shown previously that corrasion is largely confined to a zone less than 4 inches above the beach surface. This furnishes a test of the validity of the value of 0.575 used to distinguish between

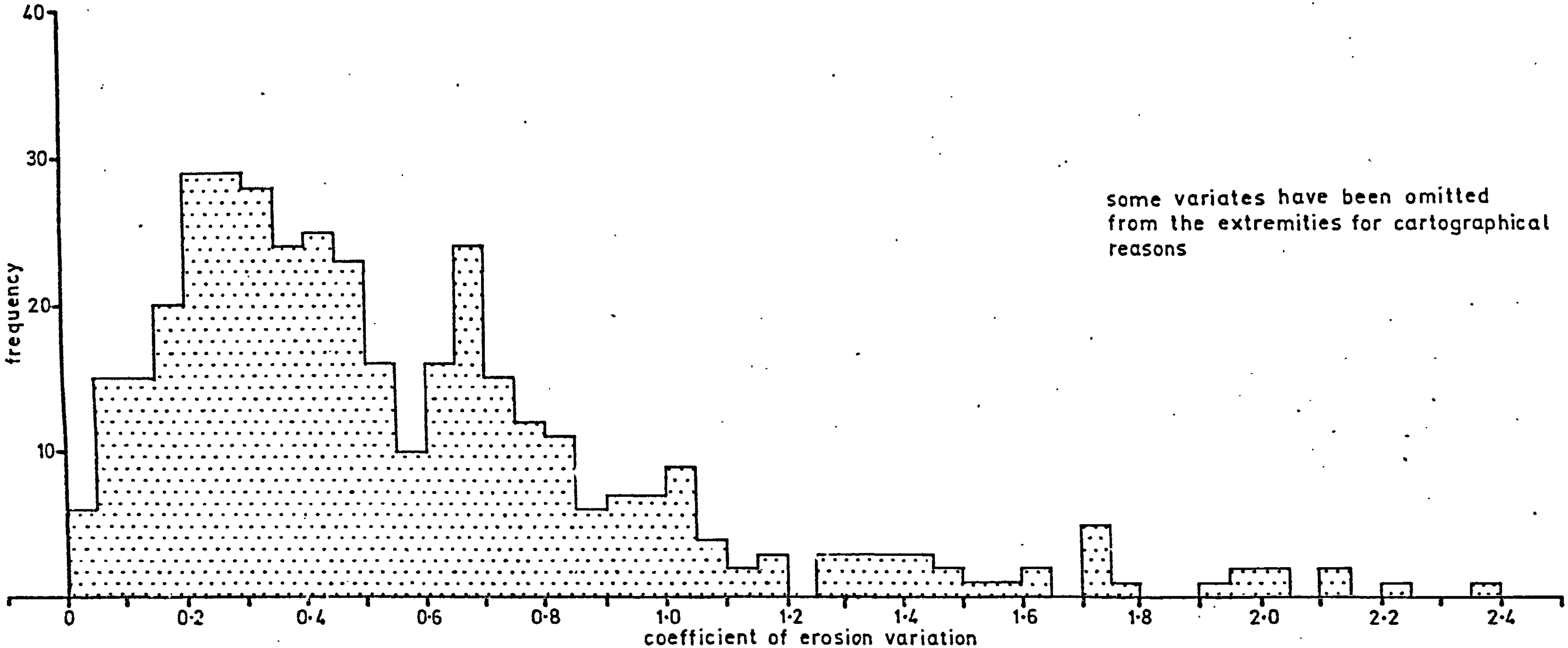


Fig. 4·26 Histogram of values of the coefficient of erosion variation

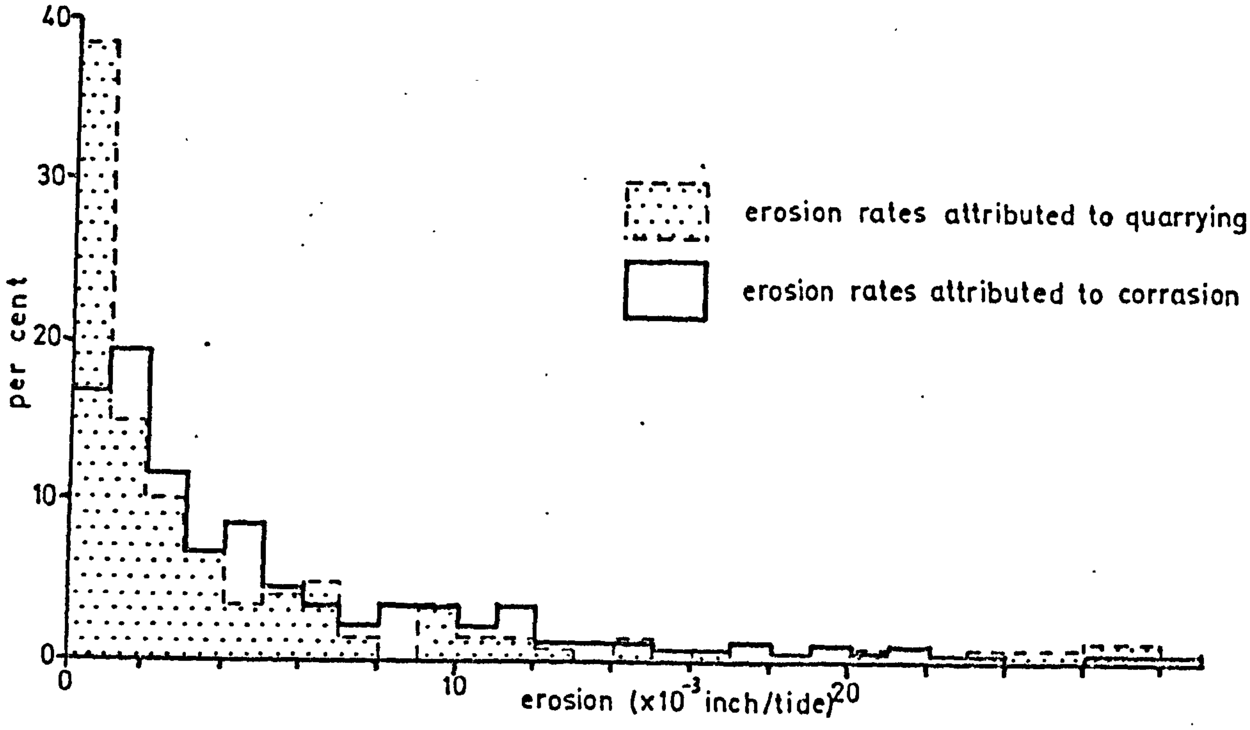


Fig.4·27a Histograms of erosion rates attributed to corrasion and quarrying

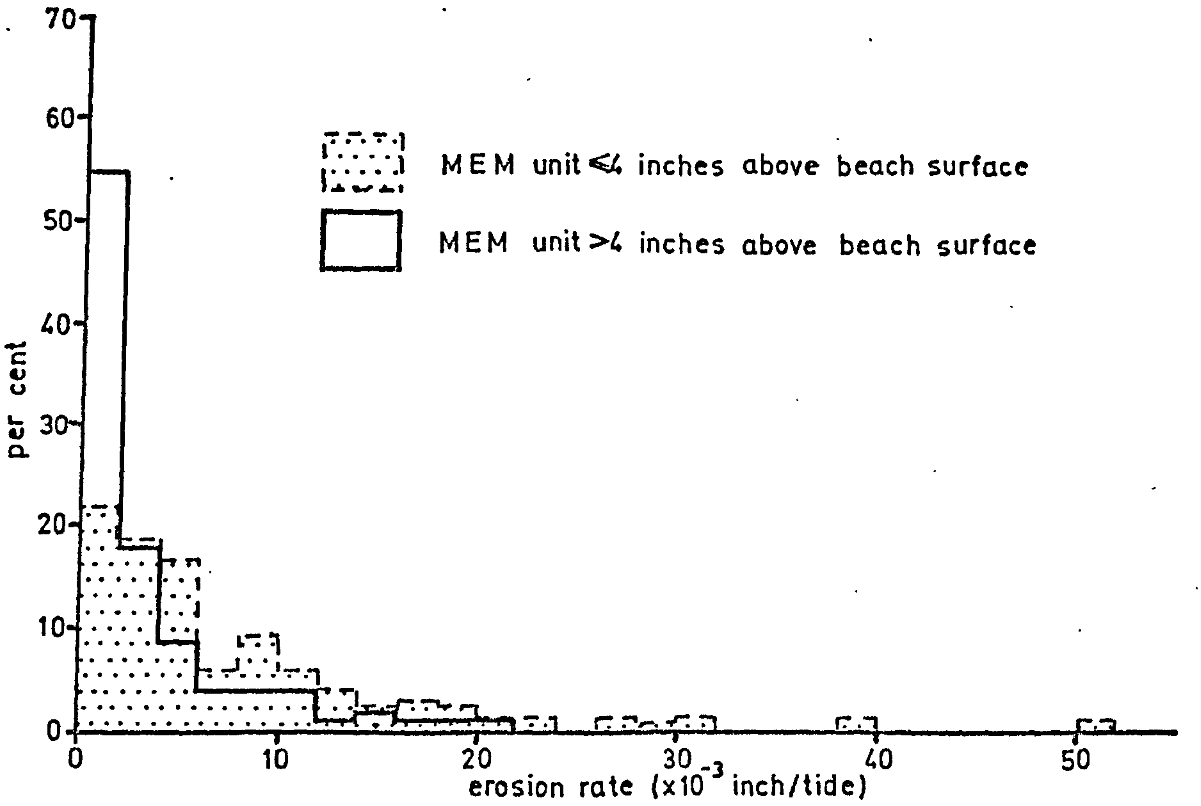


Fig.4·27b Erosion rates attributed to corrasion classified according to height of MEM unit above beach surface corrasion and quarrying. The histograms in Fig. 4.27b show the frequency of values for mean erosion/tide when the erosive process has been judged to be corrasion, the histograms representing those periods when the M.E.M. unit was above or below the level of 4 inches. The distributions are significantly different at the 0.001 level ($\chi^2 = 30.693$; 5 degrees of freedom). 56.1 per cent of the erosion values deemed to be due to corrasion represent periods when the M.E.M. unit was higher than 4 inches above the beach surface. However, 55 per cent of these values indicate negligible erosion and the whole sample of values shows significantly smaller erosion than does the sample of values when the M.E.M. unit was below the 4-inch level. Many of the variates in the supra-four inch category may have been falsely classified because it was possible to measure the height of the beach only when M.E.M. readings were taken. Therefore, it is concluded that Fig. 4.27b supports the contention that the coefficient of variation value of 0.575 is a diagnostic value.

Classification of values of erosion rates attributed to quarrying on the basis of the position of the M.E.M. unit relative to a height of 4 inches above the beach surface produces the histograms shown in Fig. 4.28a. It is evident from this that quarrying is more severe below this level than above it; the difference is significant at the 0.0021 level using the Mann-Whitney U test. This result is surprising for it might be postulated that quarrying should be little affected by the presence of a beach or even that the beach should inhibit the process since it may reduce the hydraulic and pneumatic pressures exerted by waves. Given a block of rock or fragment of a shale lamina which has been partly moved so that the joints or cracks around it are open, there is an equal probability that the block will be pushed back

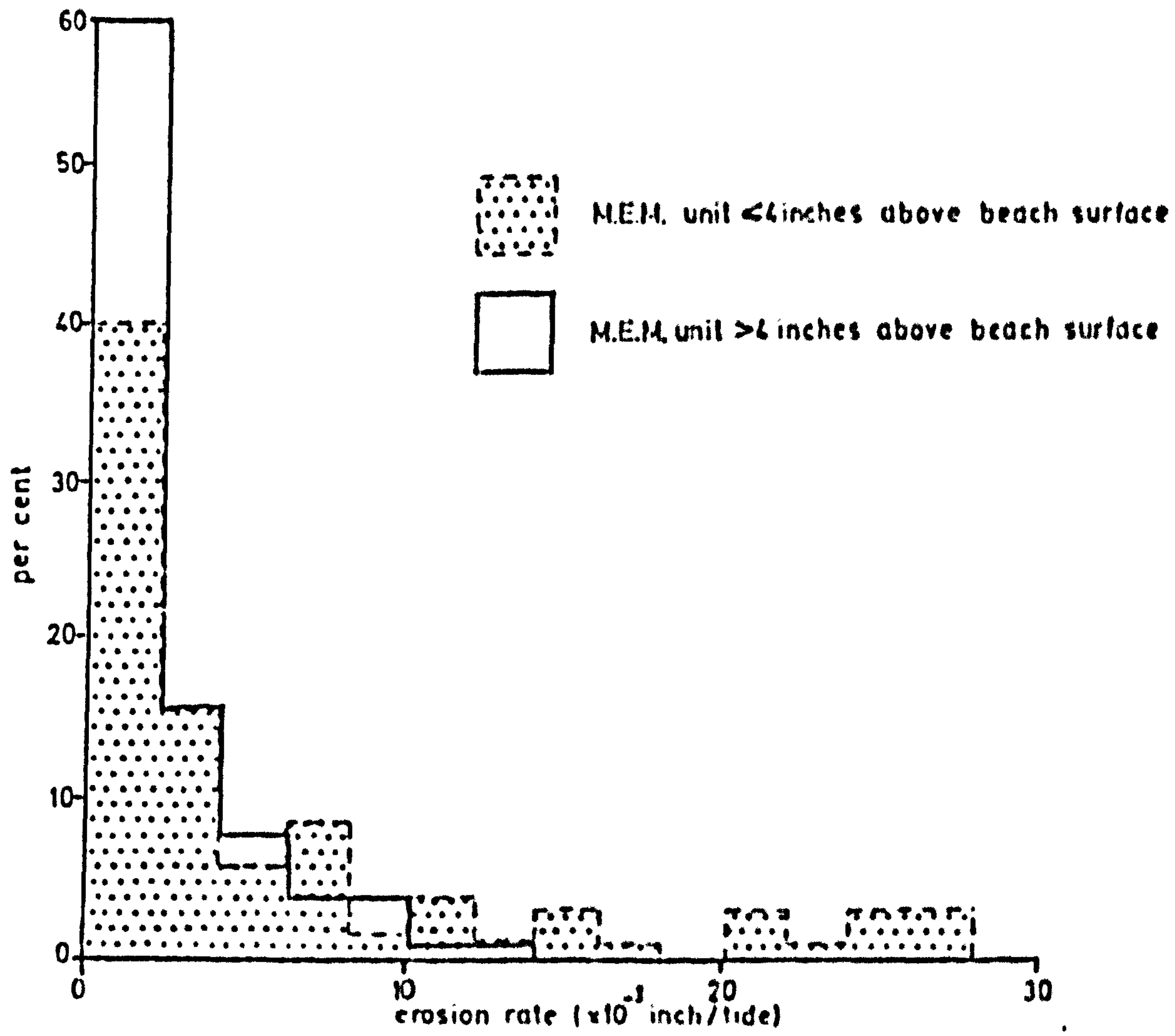


Fig.4·28a Erosion rates attributed to quarrying classified according to height of M.E.M. unit above the beach surface

	per cent frequency	total erosion (x10 inch/tide)	per cent erosion	mean erosion (x10 inch/tide)	efficiency relative to quarrying
corrasion	58·3	1365·492	63·1	5·987	1·43
wedging	16·4	385·173	17·8	6·018	1·44
quarrying	25·3	412·887	19·1	4·171	1·00

Fig.4·28b Importance of erosive processes in Fourth Bight into the cliff as there is that the joints will be opened further. However, if some obstruction such as sand in the joints prevents any movement of the block back to its original site probability will be biased towards outward movement and thus the rate of erosion will be enhanced. This process, a type of hydraulic or pneumatic quarrying involving the presence of comminuted debris, will be termed "wedging".

Wedging is believed to have been responsible for the very high erosion rates experienced by unit 11. In a period of only 154 tides, 2.877 inches of rock were removed at this point, a rate 3.9 times the mean for the other sites (excluding unit 14). At unit 11 the Alum Shales were intensely fractured due to the proximity of the major vertical joint which is one of a series forming the western side of Fourth Bight.

From the foregoing discussion it is possible to conclude that three processes operate at Fourth Bight: corrasion, quarrying, and wedging. The erosion values can be attributed to these processes by the following diagnostic parameters:

corrasion - coefficient of variation less than 0.575 and greater than 0.0

quarrying - coefficient of variation greater than 0.575 and M.E.M. unit more than 4 inches above the beach surface

wedging - coefficient of variation greater than 0.575 and M.E.M. unit less than 4 inches above the beach surface

On this basis it is possible to assess the relative importance of each process at the M.E.M. units (Fig. 4.28b). However, it is not possible to show the relative importance of each erosive process in

Fourth Bight as a whole since many more M.E.M. units would be needed. The dominance of corrasion, with respect to the total amount of work done, is clear from Fig. 4.28b, but the three processes vary little in importance when the mean work done during each occurrence of the process is calculated. (The estimates for wedging and quarrying are probably too low because the M.E.M. cannot measure erosion when the unit is destroyed by the removal of a large piece of rock.) Therefore, the dominance of corrasion is due to the frequency with which it acts rather than to its intensity. Not only does the presence of a beach allow corrasion to operate at the cliff foot, but also wedging can take the place of ordinary quarrying. Assuming an index figure of 1.00 for the effectiveness of quarrying, the index for the efficiency of wedging is 1.44 and for corrasion it is 1.43. This means that a cliff foot where a beach exists suffers an erosion rate of 2.87 units while the cliff foot with no beach, where only quarrying can operate, has an erosion rate of 1.00 units.

The relative importance of each erosive process which is implied by Fig. 4.28b cannot be applied to specific points at the cliff foot. It has been shown that corrasion is confined to a narrow zone, but its importance within this zone has not yet been estimated. Fig. 4.29a shows the proportion of erosion readings at each site which are attributed to corrasion. The suggested relationship agrees with the fact that corrasion is much reduced above a level of 4 inches above the beach - another confirmation that 0.575 is a diagnostic value of the coefficient of variation. The fact that more than 40 per cent of readings above the 4-inch level are also attributed to corrasion must be ascribed to the rapid variation in the level of the beach. It has already been shown that the amounts of erosion shown by these readings

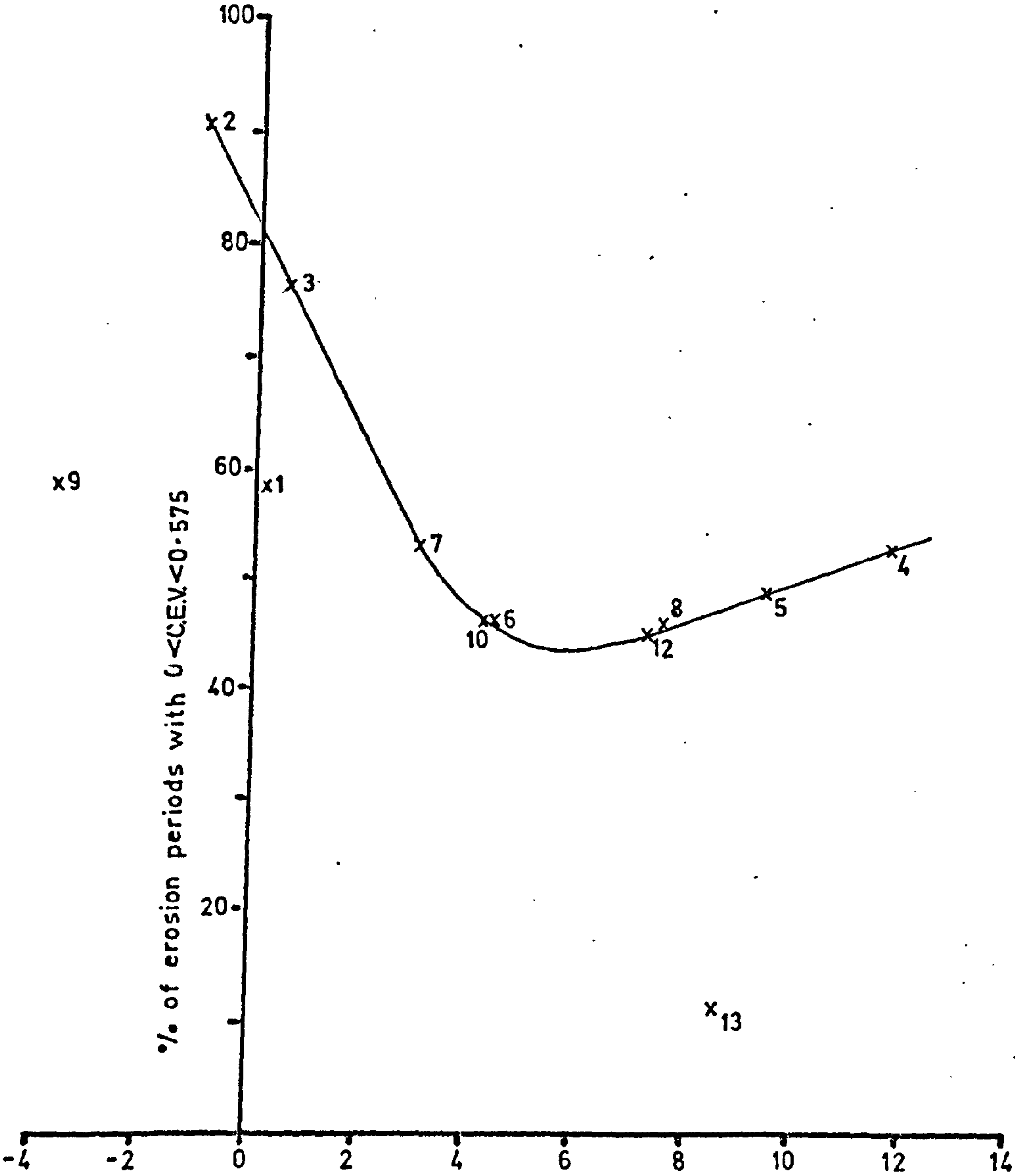


Fig. 4·29a Relationship between proportion of erosion periods with 0<C.E.V.<0·575 and mean height above beach surface

Unit no.	1	2	3	4	5	6	7
P (E)	0·0885	0·0037	0·0418	0·0166	0·0034	0·3156	0·0052
P (S)	0·2981	0·0294	0·1469	0·0721	0·0007	0·0019	0·0505

Unit no.	8	9	10	11	12	13	14
P (E)	0·0038	0·0823	0·0314	winter data only	0·0096	0·0823	0·2420
P (S)	0·0838	0·0001	0·0011		0·0047	0·0968	no beach

——— significant difference at 0·05 probability level

- - - - significant difference at 0·10 probability level

P(E) probability under H_0 that mean erosion/tide is greater in winter than summer

P(S) probability under H_0 that M.E.M. is nearer, or farther below, beach surface in winter than summer

Fig. 4·29b Test results for the seasonality of erosion rates are negligible. The paucity of data below the level of 1 inch below the beach does not permit the relationship to be examined in this region. It should continue to rise until all erosion is done by corrasion. The data provided by site 9 do not agree with this speculation but the height of this site above sea level (2.7m) and its cover of debris allowed erosion to take place less frequently than if it had been lower or had been nearer the beach surface.

Seasonal Variations of Erosion

Seasonal variations in the level of the beach may be expected to lead to seasonal variations in erosion rates. Values for mean erosion/tide at each unit were divided according to whether they fell in the winter (1st November to 30th April) or summer half of the year. Mann-Whitney U tests on the data for each unit using the hypothesis, alternative to the null one, that erosion in winter is greater than that in summer are summarised in Fig. 4.29b. At eight of the thirteen cliff foot units (at unit 10 all readings were in winter) this hypothesis was accepted at the 0.05 probability level and strong trends (significant at 0.10) occur at another three. The explanation for these results can be found in the behaviour of the beach. At six of the twelve points along the cliff foot (unit 14 had no beach in front of it) the M.E.M. unit was significantly nearer or below the beach surface during winter than during summer while at four more the differences become significant at the 0.10 level. These results imply, therefore, that the effect of increased wave action at the cliff foot is felt directly partly through its greater energy and, perhaps more importantly, indirectly by way of its influence on the level of the beach. It is clear also that the beach at the cliff foot is built up during winter and combed down during summer. This may be due to the increased frequency of waves which transport sand from Gravel Bight into Fourth Bight during winter.

Conclusions

Because of the importance of wedging and corrasion, both processes needing the presence of a beach of sand or pebbles, it is not surprising that the number of cliff foot profiles showing measurable change in the type 2 category was double that in the first and third classes. As quarrying, the main erosional process in the non-beach environment, is much less constrained in its vertical range than other processes, the incidence of notches in these last two groups is low; they occur only under the special circumstances of very few joints transecting the rock where a well-developed bedding plane is to be found.

Notch-formation is greatly enhanced wherever a beach of sand or pebbles lies at the foot of the cliff. The localisation of intense wedging and corrasion to within about four inches of the beach surface leads to rapid erosion in this narrow band. Variations in the level of the beach surface allow the band to move a little way above or below the mean position of the beach surface. This produces an increase in the vertical range of the notch and a reduction in its landward dimension compared with values for these directions which would be created by a static beach surface. Where the rock is well jointed it is probable that the overhanging roof slope of the notch cannot form because blocks of rock easily fall and quarrying is highly effective.

In addition to elucidating the nature of erosive processes, the study of Fourth Bight has provided the important conclusion that the morphology of not only the cliff but also the forms of possibly many other littoral features are attuned not to those marine conditions which are most frequent but to those which do most work; in other words to the storms which occur only a few times each year.

CHAPTER 5

SHORE PLATFORM MORPHOLOGY AND DEVELOPMENT

Introduction

The shore platform is one of the principal features of a cliffed coast. It is present throughout the study area in north-east Yorkshire except where interglacial valleys filled with boulder clay cut across it in the major bays at Robin Hood's Bay, Saltwick Bay, Sandsend Wyke, Runswick Bay and Skinningrove Wyke. At these points there are sandy beaches. Elsewhere the platform may be partly covered by sand or, more usually, by boulders varying in density from the very sporadic to thick piles. Indeed, in several areas, the shale across which the platform is cut cannot be seen at all because of the overburden of boulders or sand.

These and other environmental conditions lead to considerable variation in the morphology of the platform. Because of the strong influence of geology on platform morphology, workers in other areas have usually disregarded the effects of superficial deposits. Except for the studies by Hills (1971, 1972), no attempt has been made to analyse individual profiles in order to identify elements common to most profiles. While the genesis of platforms has been attributed to many different processes, there have been few attempts to measure the rates of erosion produced by them. It is against this background of few quantitative analyses of form, processes, and erosion rates that this chapter is set. The chief variables which govern the morphology of a shore platform are described first, particular emphasis being placed on the characteristic gradients which exist. Classes of platform are then recognised based on combinations of elements of characteristic slopes. The processes which produce the morphological elements are examined next. In several places in north-east Yorkshire relict platform surfaces have been preserved beneath patches of conglomerate. The differences in morphology between these relict portions and the modern platform show how the platform has changed in form over a long period. Short term changes measured by the M.E.M. technique during a period of 19 months are also examined. The chapter concludes with the presentation of a model for changes in platform profiles.

The Width of the Shore Platform

One of the chief parameters which determines the morphology of the shore platform is its width. For the study of this parameter the seaward limit of the platform is taken to be the mean low water mark of ordinary tides (LWMOT) which is shown on the O.S. 1:2500 plans. The landward edge is the foot of the cliff which may or may not coincide with the mean high water mark of ordinary tides. The LWMOT on the O.S. plans is probably not calculated and surveyed accurately but in view of the width of the platform, errors in its position are likely to be relatively small.

The width on O.S. 1:2500 plans of c.1927 was measured at 51 points along the coastline between Robin Hood's Bay and Boulby Cliff. The position of each point was determined by a stratified random sampling procedure described later in this chapter. The variable was measured along the line perpendicular to the general coastline. Where the LWMOT, due to its sinuosity or to the fact that low tide islands occur, cuts the line at several points, the measurement was made to the most seaward intersection.

The 51 widths were classified according to the rock type of the platform using the geological divisions derived in Chapter 2 (Lower Lias, Sandy Series, Ironstone Series and Upper Lias). The rock types can be ranked as in Fig. 5.1a according to the mean width of the platform cut into them. The differences in platform widths between the Lower Lias and the Ironstone Series are not significantly different but for all other pairs either statistical significance is attained at the 0.05 level or a strong trend exists which may be deemed to be significant at the 0.10 level. Therefore platform width seems to be correlated with rock type. However, the ranking of the Upper Lias in the fourth position is surprising in view of its unresistant nature when compared, for instance, with the Sandy Series. The high standard deviation for the Upper Lias implies that the platform is wide in parts but that in others it is narrow. The similarly high figure for the Lower Lias can be interpreted in the same way, though the coefficient of variation shows that its variability is only half of that experienced by the Upper Lias. Reasons for the great variation in platform width on these two rock types can be found in the nature of the superficial deposits.

In the Upper Lias, the platform seaward of the cliff foot where this is a talus cone[1] (mean width = 59m) is significantly smaller than that where the cliff foot is bare (or has a beach) (mean = 123.3m) or where it has a boulder beach[2] (mean = 116.5m) at the 0.01 and 0.047 levels respectively (Fig. 5.1b). Differences between the samples of widths of these last two categories (bare or boulder beach cliff foot) are not significantly different.

On the Lower Lias, the three cliff foot categories which can be recognised because there is a sufficient number in each, are bare, beach-covered, and boulder-beach covered. Platform widths in the second of these (mean = 228.8m) are significantly greater than in the first (mean = 154.5m) at the 0.05 level perhaps because of the increased amount of erosion which can be done by a beach. Similarly, the second

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1. talus cones have boulder beaches at their feet.
2. in the boulder beach category, there is no talus at the cliff foot.

Rank	Geological class	Mean platform width (metres)	Standard deviation	Coefficient of variation
I	Lower Lias	I9I.5	7I.5	37.3%
2	Ironstone Series	I89.0	29.3	I5.5%
3	Sandy Series	I30.0	44.8	34.5%
4	Upper Lias	92.5	62.8	67.9%

Lower Lias platform widths are greater than Sandy Series and Upper Lias widths at 0.05 and 0.0002 significance levels respectively

Ironstone Series platform widths are greater than Upper Lias widths at 0.00I8 significance level

No other pairs are significantly different at the 0.05 significance level

Fig.5.Ia The ranking of rock type according to shore platform width

Geol.	Cliff foot type	mean width (m)		Cliff foot type	mean width (m)
Upper Lias	bare or sandy beach	I23.3	widths are greater than	talus	59.0
Upper Lias	boulder beach	II6.5	" " " "	talus	59.0
Lower Lias	sandy beach	228.8	" " " "	bare	I54.5
Lower Lias	sandy beach	228.8	" " " "	boulder beach	II5.0

Differences are significant at 0.05 level of probability

No other pairs are significantly different

Fig.5.Ib Results of pair-wise Mann-Whitney U tests on shore platform widths classified according to cliff foot type

class is significantly greater than that in which the cliff foot has a boulder beach (mean = 115m) at the 0.025 level. Differences between the bare and boulder beach widths are not significant, probably because of the low number of values in each.

It is concluded from these analyses that although rock type is important, the type of foreshore wields very considerable influence on platform width. This parameter achieves its maximum where there is a beach at the cliff foot. Where the platform is bare it is wider than where a boulder beach exists. The narrowest parts of the shore platform have talus cones at the cliff foot in addition to boulder beaches on the rest of the platform.

Several workers (e.g. Edwards 1941, Trenhaile 1969) have noted that the higher the cliff, the narrower is the shore platform because increased cliff height yields more material to be eroded from the surface of the platform and, therefore, reduces the vigour of wave attack on the cliff face. Such a situation will only occur, however, if the transporting capacity of the waves is always fully used. This is manifestly not so as breaking waves are usually transparent indicating that at least their suspended load is small. On the north-east Yorkshire coast the correlation between platform width and cliff height is not significant. However, classification of the former values according to whether the cliff behind is less than or greater than (or equal to) 200ft (61m) which is the approximate median value, and use of the Mann-Whitney U test, reveal that the latter class of platform widths is almost significantly smaller than the former at the 0.05 level (actual probability = 0.0559). This result which appears to substantiate Edwards's tenet on a broad scale (though not in detail as the lack of correlation illustrates) is probably generated by two allied factors. Firstly, there is a strong trend ($\chi^2 = 3.329$; significant at 0.10) for the cliff where over 200ft high to have Middle Jurassic Sandstones cropping out in it while, where the cliff is less than 200ft, it tends to be composed of Lias shales only. This implies that both the wide platform and low cliff are due to the unresistant nature of the shale, i.e. they are each directly related to the rock type and thus indirectly rather than directly to each other. Similarly the narrow shore platform and high cliff are only indirectly related because they are each directly influenced by the more resistant rock. Since the Middle Jurassic rocks do not crop out on the shore platform the sandstones are influential because of the large size of the debris which forms the foreshore. The frequency distributions of platform widths where the cliff is $<$ 200ft and $\geqslant$ 200 ft subdivided according to the type of foreshore (bare or boulder covered) are significantly different at the 0.05 level ($\chi^2 = 4.643$; 1 degree of freedom) because a bare shore platform is more associated with parts of the cliff which are less than 200ft high and a boulder beach foreshore with cliffs greater than 200ft. The conclusion is reached, therefore, that the strong tendency for cliff height to be inversely related to platform width is not a cause-and-effect association since each variable is directly or indirectly, through the nature of foreshore superficial deposits, controlled by geology.

The Measurement of Platform Gradient

Because of the low gradient of most of the shore platform and the thick cover of superficial deposits in some places, its gradient cannot be measured by the areal morphometric techniques which are commonly used in landform analysis since they rely on the identification by eye of facets of uniform slope. Similarly, the low angles do not allow the recognition of measured lengths by eye as a small change in angle may be significant to the morphology of the feature. This means that the technique of slope profile construction evolved by Savigear (1956, 1965) and Young (1964, 1971) could not be used for this study. A more objective method allied to that invented by Pitty (1969, 1970) was employed instead. A straight-edged metal rule one metre long was placed successively on the profile across the shore platform and its inclination measured with an Abney level fitted to a spirit level. This technique has the disadvantage that measured lengths are constant. If a sudden change of slope occurs the angle of the measured length is a compromise which does not exist in reality. While this inaccuracy might not be great on a long hillslope where changes in angle are not usually sudden anyway, on the shore platform which has a vertical range of only a few metres such error may be important. Therefore a measured length of one metre was used except where there was a marked change in slope. This was judged to occur if the seaward end of the straight-edge was over 4cm above the rock surface. In this case the measured length was shorter than a metre. If the two ends were in contact with the rock while part of the rule was at least 4cm above the surface, the measured length was broken into smaller parts conforming more closely to the inclination of the surface. Because of the smoothness of this, inaccuracy due to micro-relief is believed to be small. Readings on the abney level were taken to the nearest 10 minutes but the maximum tolerance of 4cm means that this was unnecessarily accurate as this limit is equivalent to 2.3 degrees. Therefore the inclinations of measured lengths were taken to the nearest degree in the analysis.

This technique could be used for the measurement of profiles only where the platform is bare or where beaches of sand or cobbles could be dug through. At other places where this was not possible only the bare part of the shore platform was measured in this way. The remaining parts of such profiles were surveyed using an automatic level. Wherever the shale platform was hidden by large boulders except for a few points along the profile or about one metre on each side, surveying was the only technique which could be employed. Surveyed profiles have been used to assess shore platform morphology by a number of workers, e.g. So (1963), Everard et al (1964), Wright (1967), Healy (1968b), Phillips (1969) and Trenhaile (1969, 1972). However, if detailed analysis of profiles is to be carried out this method is inadequate because the location of points where readings are made is purely subjective and the calculation of gradient between successive points smooths out variations in the slope.

The area from which profiles were drawn was restricted by two considerations. Firstly, just as the cliff has been exploited in the past for various raw materials which Man has found useful, so the shore platform has been treated in a similar fashion. The areas where the platform is not natural are usually associated with workings in the cliff and are generally obvious in the field (see Appendix I). Secondly because it is possible to measure the profile on the low parts of the platform only one or two hours on each side of low tide, the problem of ease of access was most important. Hence these two factors necessitated that the area from which profiles were drawn was limited to the stretches of coast at Staithes (between Boulby and Jet Wyke), at Runswick Bay (Cobble Dump to Catbeck Hill), and from Whitby to Stoupe Beck at Robin Hood's Bay though small areas in these tracts of coast had also to be excluded.

The location of platform profiles was determined using a stratified random sampling procedure. On the basis of an initial reconnaissance it was noted that wherever the Sandy Series crops out the platform is more structurally controlled than elsewhere. On the Lias Shales structural conditions seemed to be important in only isolated places. It was also noted that the platform tends to be wide and very gently sloping where no superficial deposits occur and steep and narrow where the cover is dense. The strata in the sampling procedure were therefore the two basic geological divisions and, secondarily, the two types of foreshore which were distinguished as more or less than 50 per cent of the platform being covered by boulders (the selection of sites for platform profiles was carried out after the survey of foreshore type which has been reported in Chapter 2.)

Having located on a plan a random point for each of the four categories, the rest were found by stepping off appropriate distances so that the total number of profiles was 50 and the whole stretch of suitable platform was considered. This procedure is likely to introduce less autocorrelation between profiles than would the use of locations found by employing random numbers for each site. Fifty-one profiles were actually selected in order to locate one in the smallest class (Sandy Series and mainly covered by deposits). The grid references for these profiles are given in the table in Fig. 5.2.

The locations were found as accurately as possible in the field. The landward end of each profile is the cliff foot. Because this feature is rounded, except where the quarrying of joint-bounded blocks has occurred, the exact end of the profile could not be identified.

profile number	approx. grid ref.	% platform surveyed	% elements / measured lengths	% segments / measured lengths	% best units / measured lengths
I	7595I936	74.4	72.4	46.I	42.I
2	7607I920	80.6	72.6	52.I	46.2
3	7642I9I0	78.2	58.3	27.5	25.0
4	7670I900	72.4	67.6	26.I	24.3
5	7700I882	I06.7	73.7	46.2	40.9
6	7740I88I	96.9	58.5	22.8	2I.I
7	7746I832	I25.3	55.2	26.2	24.I
8	7793I883	94.8	65.9	28.8	28.0
9	7800I892	76.4	65.I	24.6	22.2
I0	782II905	97.4	63.6	46.7	4I.I
II	7866I886	77.5	7I.9	67.6	57.6
I2	7900I87I	I02.3	67.0	42.0	36.0
I3	8II3I623	99.3			
I4	8II2I6I8	99.9			
I5	8I45I547	0			
I6	8I70I543	I0I.2	65.0	36.3	32.5
I7	82I3I547	I05.5	70.2	55.8	44.7
I8	9039II45	73.6	75.0	48.I	44.2
I9	9063II36	26.6	76.5	70.6	64.7
20	9088II33	86.8	62.7	35.3	30.4
2I	9II5II23	69.8	68.3	34.6	32.7
22	9I96I068	62.7	63.5	32.4	25.7
23	9285I0I9	0			
24	9303I002	0			
25	93170975	0			
26	93270952	8I.3	64.4	6I.0	52.5
27	934309I8	5I.2			
28	93540892	0			
29	93660868	77.2			
30	9387085I	52.3			
3I	94000844	85.8			
32	94290826	89.9			
33	945I08II	77.I			
34	94640804	64.4			
35	94850769	57.6	67.9	37.5	32.I
36	95070752	99.9	73.7	4I.5	32.2
37	95I20730	I06.I	67.2	46.0	40.7
38	953207I0	67.I	69.6	42.4	36.0
39	9558070I	73.6	64.5	47.6	4I.9
40	95720687	45.2	7I.0	70.I	58.9
4I	95860680	0			
42	95900677	55.8	8I.8	52.3	50.0
43	95970636	68.0	62.7	6I.2	53.7
44	95960627	0			
45	95880602	II9.2	72.I	64.0	56.8
46	95580570	64.I	69.0	54.8	48.8
47	95440564	87.6	7I.8	54.2	47.5
48	95350538	65.2	70.I	30.8	29.I
49	952905I2	8I.6	7I.5	I3.I	II.5
50	95640385	72.4	68.3	42.5	38.2
5I	95770359	68.2	73.6	60.9	58.6

Fig.5.2 Data on platform profiles subjected to best units analysis

However, this inaccuracy affects only the first measured length and so is unimportant. Of more concern is the direction in which the profile should run. There are two alternatives - either down the maximum gradient of the shore platform or in a direction perpendicular to the general coastline, i.e. the general coastline over a distance of about 100m on each side of the selected location. In the former case the profile will often not be in a straight line though it might be argued that this is the path which a wave follows. However, large waves are not greatly affected by small changes in water depth over the small distance seaward of the cliff that is on the shore platform. Also, changes in the direction of maximum slope may be produced by the cropping out of strata. For these reasons it is thought that the second alternative for the direction of the profile is the better one. Fortunately differences between the two alternatives seem to be very small in the study area at all locations except for the two shown in Fig. 5.3; even here the differences are minor when the whole platform is considered.

In the field the line of the profile was marked with string. The slope was recorded using the procedure described earlier wherever the platform was bare or deposits could be dug through to expose the platform. The ends of each profile were marked with paint as were other points where deposits overlay the rock as it was necessary to return to survey[1] the covered part of the platform. Because of the tides, it was frequently not possible to measure the most seaward part of each profile. However, since the largest variation in gradient is at the landward end where changes in foreshore type are most common, these missing parts are unlikely to affect the conclusions reached. The proportion of each profile which was surveyed by the two techniques

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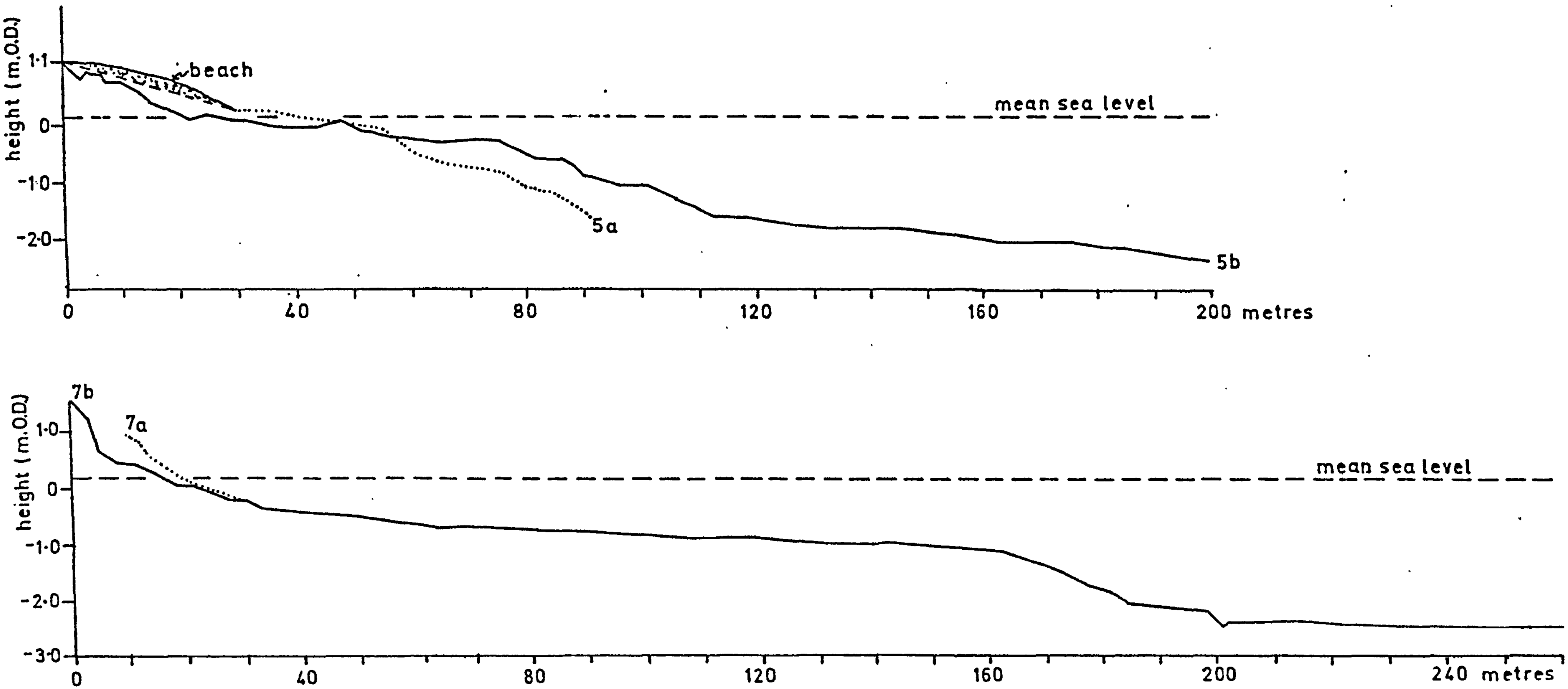
1. All altitudes were measured relative to Ordnance Datum using Bench Marks.



Profiles 5a and 7a are in the direction of maximum slope of the platform

Profiles 5b and 7b are in directs normal to the generalised coastline

Fig. 5·3 Platform profiles constructed according to different principles is given in the table in Fig. 5.2 from which it will be noted that a high percentage of the widths of most of the profiles was surveyed. Seven profiles (numbers 15, 23, 24, 25, 28, 41 and 44) could not be measured by either method because very few parts of the shale platform were exposed.

The Analysis of Platform Gradient

For each profile, the inclinations of the measured lengths having been rounded to the nearest degree, adjacent measured lengths with the same angle were combined. These modified values were then subjected to best units analysis (Young 1971), a procedure for the division of a profile into rectilinear, convex and concave units, each unit containing adjacent modified measured lengths which differ only within specified limits of the coefficient of variation. Because of the shortness (commonly only one or two metres) of most modified measured lengths and their low inclinations, in this study, the high figure of 50 per cent was selected as the maximum value for the coefficients of variation of both angle and curvature. Concerning the choice of a figure, Young (1971, p. 9) has noted that " . . . there is no mathematical reason for selecting the same values since the properties concerned are dissimilar". However, it seems to be possible to gain some idea of whether segments or elements are important in a profile by choosing the same number for both coefficients. Each profile was divided in turn into best segments, best elements and best units. The ratio of the number of units to the number of modified measured lengths is given in percentage terms in the table in Fig. 5.2. The lower is the figure for a profile, the fewer units there are, i.e. the more successful has been the generalisation procedure. The mean proportion of units when the 35 profiles are divided into elements is 68.3 per cent with a range of 55.2 to 81.8 per cent. The corresponding figures for segments are 44.3 per cent and 13.1 to 70.6 per cent. When the profiles are reduced to best units (i.e. segments and elements) 39.2 per cent is the mean and the range is 11.5 to 64.7 per cent, which numbers are little different from those for segments. It is concluded, therefore, that elements (i.e. curvilinear units) are of little importance in shore platform profiles at this scale of generalisation. Although more generalisation is achieved by including elements in best units analysis the improvement is small compared with the operational difficulties of comparing profiles in which both types of unit have been included. Hence, the ensuing discussion is confined to the consideration of profiles which have been divided into best segments only.

The percentage figure for each profile derived from the ratio of the number of best segments to the number of modified measured lengths is an indication of the amount of micro-relief on that profile. Thus the lower the ratio, the smoother is the rock surface. Small variations in surface relief result from geological factors and fall into three broad categories:

1. The cropping out of well-defined strata with different responses to erosion produce stepped (e.g. profile 10) or scarp-and-vale topography (e.g. profile 51) depending on the dip of the strata. The importance of dip is evident when the ratios for profiles 1 to 9 in the Lower Lias at Staithes (dip of 2 degrees to the south-east) are compared with those (profiles 43 to 51) for Robin Hood's Bay, where the Lower Lias dips at 5 degrees or more. The Mann-Whitney U test on

the two samples of data allows the conclusion to be drawn, at the 0.025 significance level, (bearing in mind the fact that parts of the profiles could not be measured) that the ratios for profiles near Staithes are smaller than those for the Robin Hood's Bay profiles i.e. the lower the dip of the beds, the smoother is the shore platform. Differential erosion of the shore platform is also produced by lithological contrasts, e.g. where isolated iron and calcareous nodules crop out.

2. A second source of micro-relief is provided by the nature of exposed bedding planes. This factor is particularly important where iron seams with their undulating surfaces constitute much of the rock surface (e.g. profiles 36 and 42) (Fig. 5.4).

3. A type of micro-relief is characteristic of the platform where the more arenaceous strata of the Sandy Series crop out. Being resistant to erosion except perhaps along their sub-vertical joint planes, water draining off this rock is concentrated and preferentially erodes the joints. The result is a series of runnels often half a metre deep running seaward and apparently very similar in form to runnels found on sub-aerial Carboniferous Limestone pavements. Curious, very small erosional features only two or three centimetres high also exist along much of the north side of Robin Hood's Bay. Fragments of shale remain as tiny ridges wherever joints transect the surface while the interiors of joint-bounded blocks are eroded to a deeper level. Therefore, there seems to have been some induration of the rock adjacent to the joint planes. Similar, though much larger, features in arkosic sandstone have been described by Hills (1971, p. 169 and photos 11 and 12).

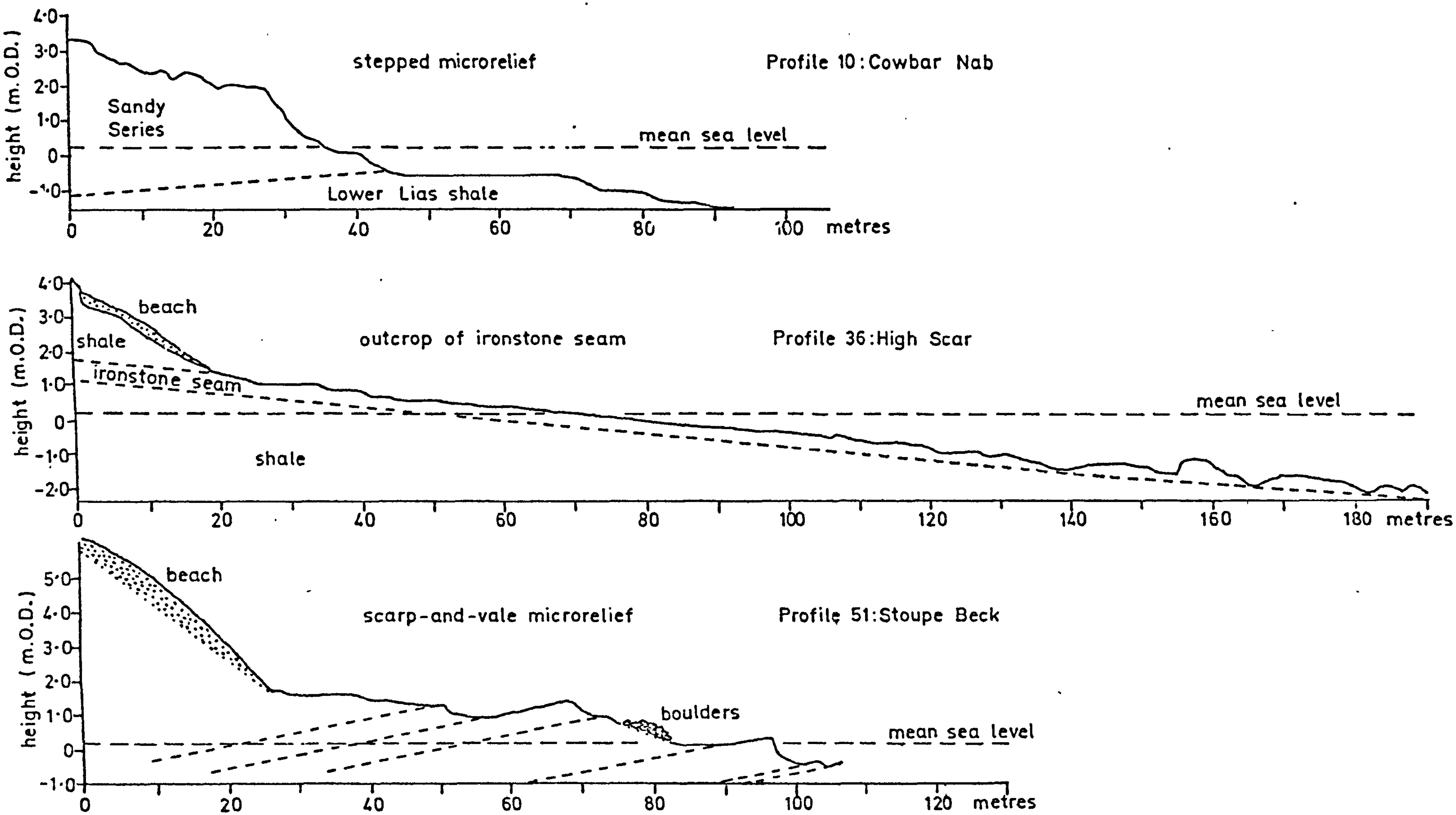


Fig. 5·4 Some platform profiles controlled by structure

Because all segments resulting from best segments analysis have the same accuracy (i.e. the same amount of generalisation) it is possible to assess the importance of different slope values in each profile. The total length of segments in each degree class in each profile was calculated and then the characteristic angle or angles associated with each one found. In order to be objective it was necessary to draw up rules for the recognition of these. All characteristic angles are represented by more than five metres of the profile, and more than one class interval of one degree separates characteristic angles. All those identified are shown in Fig. 5.5, those which were measured by levelling being distinctively shown, since they are not as accurate as those deduced for the more objectively measured profiles.

The number of characteristic angles in each class interval is given on the bottom line of Fig. 5.5. Peaks at 1 and 6 degrees in this frequency distribution represent specific features of the population of platform gradients. A third part of the histogram can also be identified - the region of negative values i.e. where the inclination of the platform profile is away from the sea, a feature due solely to the exposure of resistant strata, usually iron seams, although pronounced bedding planes between silty and shale beds are the reason in the case of profiles 11, 18, 47 and 51. The influence of such strata is confined to only part of the profile, other characteristic angles usually developing near the cliff foot. Negative angles can also be produced by the sporadic quarrying of blocks of rock, but the lengths of segments at these angles are small and the inclinations vary so that characteristic angles do not result. Strata dipping towards the sea can produce characteristic angles similar to

profile number	angle -3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	profile classification
1				X							X						2
2					X				X								2
3					X					L			X				2
4				X						L							2
5					X												1
6					X						L						2
7				X													1
8				X					X								4
9					X							X					2
10					X									X			4
11			X							X							4
12					X												1
13					L												
14				L							L						2
15																	
16		X			X												1
17		X			X			X									2
18	X			X													1
* 19					X												
* 20					X												
* 21					X				X								
* 22					X												
23																	
24																	
25																	
26				X				X									2
27																L	3
28																	
29											L						3
30										L							3
31					L						L						2
32					L			L									2
33					L						L						2
34					L			L									2
35				X					X								2
36					X				X								4
37				X						X							2
38						X							X				2
39					X			X			X						2
40					X					X			X				2
41																	
42							X										4
43						X				X							2
44																	
45				X			X					X					2
* 46					X												
47	X			X					X								2
48					X												1
49					X					L							2
50				X						X							2
51			X				L										4
Total	2	2	2	12	24	2	3	5	6	9	7	2	3	1	0	1	

X characteristic angle derived from best segments analysis
L characteristic angle derived from levelling of profiles
* denotes that profile could not be measured in cliff foot area
1 plane only; 2 ramp & plane; 3 ramp only; 4 structural control

Fig.5.5 Characteristic angles of shore platform profiles those produced for other reasons, e.g. profiles 36 and 42 rest on single ironstone seams throughout much of their lengths. Structural control in other profiles is minor because the Lias rocks vary little in composition and bedding planes are not pronounced, except in the Sandy Series. This geological division is represented by profiles 10, 11, 40 and 41 (no shore platform visible). Their characteristic angles at about 1 degree are caused by the cropping out of bedding planes and, in profile 10, the angle at 10 degrees is the result of undulations of this plane.

The very sharp peak in the number of characteristic angles at 1 degree indicates that this inclination is common to most profiles. The limiting angles of this feature (henceforth termed the "plane") are at -0.5 and 2.5 degrees implying that the potential amplitude of variation of it is very small. In contrast, the range of values of the second group of characteristic angles is from 2.5 to about 15.5 degrees with its peak at 6 degrees. Clearly the controlling variables for this feature (the "ramp") are much less restrictive than are those for the plane. The term "ramp" has often been used in the past (e.g. Hills 1949, 1971; Edwards 1951 and Healy 1968b), but in this study it is employed theoretically to denote any part of a profile which yields a high characteristic angle. In practice, because of the simple morphology of the platform in the study area, the meaning of the term ramp in this study is the same as that employed by Hills. It is possible to classify the profiles according to the occurrence of characteristic angles. For this categorisation, those profiles are not considered where the platform is not visible as a whole (15, 23, 24, 25, 28, 41 and 44) or, in part, at the cliff foot (13, 19, 20, 21, 22 and 46). The categories are:

1. only the plane is present (e.g. Fig. 5.15b).
2. both the plane and the ramp occur (e.g. Fig. 5.15c).
3. only the ramp exists.
4. those profiles deemed to be controlled by structural or lithological factors.

The classification of each eligible profile is shown in Fig. 5.5. The members of the third class were all measured by levelling because of the very thick cover of boulders throughout their lengths; they are located between Maw Wyke and Widdy Head. Profile 35[1] should perhaps also be in this group since the characteristic angle at 0 degrees is due to many short segments at this angle, though a true plane does exist, being visible at low spring tides. The occurrence of deposits on the platform near the cliff foot for profiles in the other classes is not so well correlated with a high characteristic angle. However, the Fisher exact probability test reveals that profiles in the second class do tend to have deposits near the cliff foot while profiles in the first class are bare in this region, the probability of occurrence of the observed frequencies under the null hypothesis being 0.0054 (one-tail). In other words, it is concluded that the presence of deposits at the cliff foot will lead to the development of a ramp. This association suggests that the deposits provide the shore platform with some protection and, perhaps, that once these have been removed, the segment will disappear. Certainly, no major segments at this angle were observed without debris on them. The incessant sweeping of such material landwards by the sea and the rain of debris from the cliff will maintain such angles near the cliff foot. Because areas covered by boulders tend to merge into the bare area seaward of them, the change in platform inclination is not obvious. However,

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1. Profile 35 is near the profile shown in Fig. 5.16b.

pebbles and sand are easily transportable and, therefore, always occur at the cliff foot where they are held in position by the cliff. The seaward edges of such beaches are sharp and continuous, with the result that the junction between the ramp and plane is also obvious. The profiles in Fig. 5.5, where the ramp is due solely to the presence of such a beach, are numbers 3, 4, 6, 14, 38, 49 and 50. A similar feature developed under a cobble beach occurs on the Sandy Series of profile 40.

It can be hypothesised that the exact angle at which the ramp occurs will depend upon the amount of protection from erosion afforded by the overlying deposits. Thus the range in characteristic angles is broad. Although this model seems to be intuitively correct, use of the Kruskal-Wallis one-way analysis of variance to test for significant differences in ramp angle between the three samples identified according to type of superficial deposit (beach, medium density boulders, and thick boulders) yielded the conclusion that the differences are not significant. This result is likely to be affected by the accuracy of angular measurements where the platform is rarely visible and by the subjective nature of the assessments "medium density boulders" and "thick boulders".

The Height of the Shore Platform

The height of the shore platform is the third major parameter constituting its morphology. Because the cliff foot is often curved rather than angular the exact height of the landward edge is difficult to define - an approximate measurement is the best that can be obtained. The altitudes of the cliff foot for many profiles are shown in Fig. 5.6 as crosses. From this diagram have been excluded those cases where

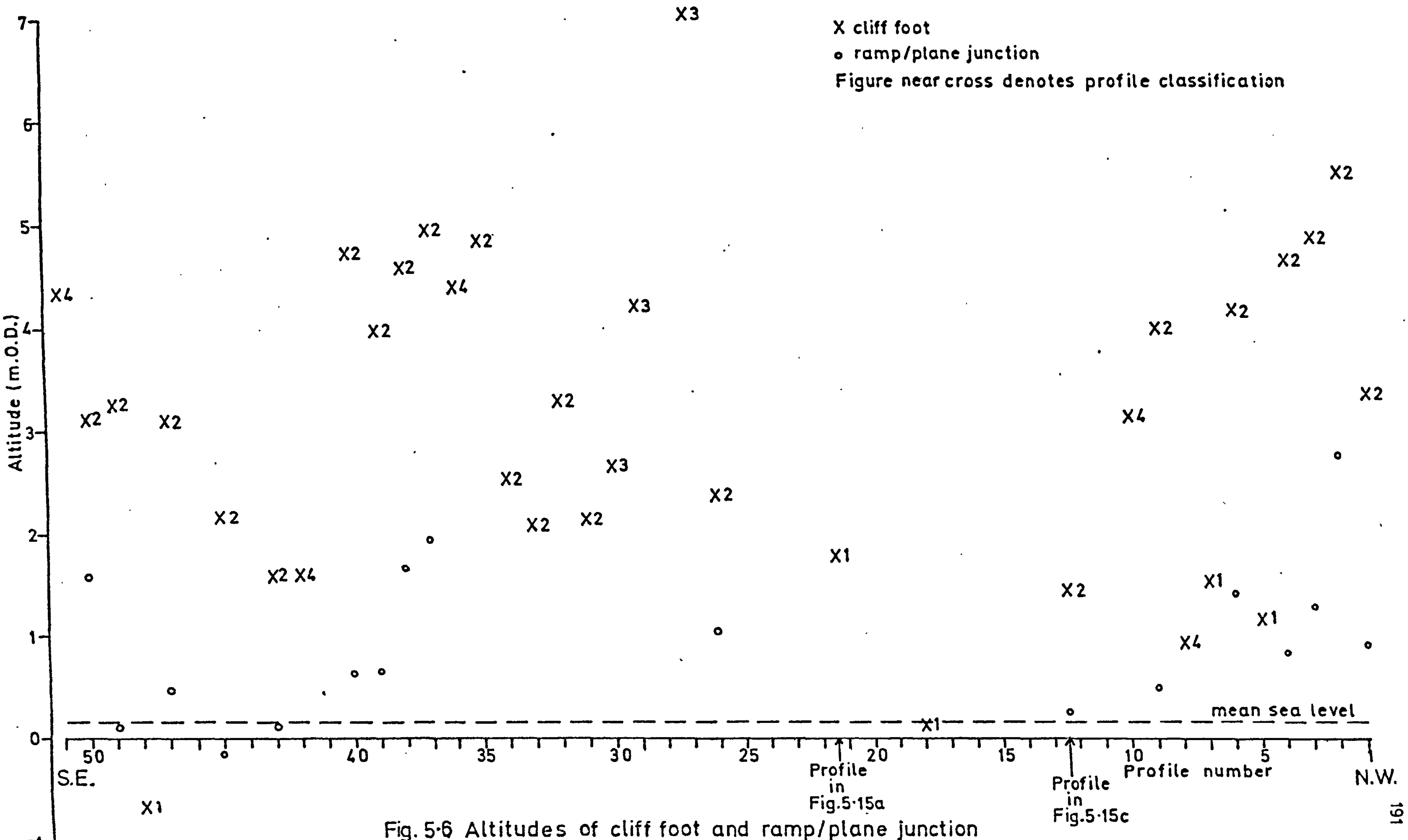


Fig. 5·6 Altitudes of cliff foot and ramp/plane junction the cliff foot cannot be defined at all (numbers 19 to 25 inclusive, 28, 41, 44 and 46) and some (numbers 11 to 17) which were, unfortunately, not measured. Heights for the M.E.M. profiles at Saltwick Bay and Lingrow have been included. It should be noted also that the cliff foot was difficult to identify in profiles 27 to 34, though points for these have been included. The scatter of values is great, ranging from 7.1 to —0.67m O.D. There is no obvious correlation with geology, unlike the case noted by Trenhaile (1969) in South Wales, because lithological and structural contrasts on the north-east Yorkshire coast are small. Some order is discernible when the classification of each profile is noted. Points falling in class 4 which are influenced by geology and are, therefore, likely to show randomness, can be disregarded. Those in classes 2 and 3 which include a ramp in at least part of their profile fall mostly into the upper part of the diagram above about 2m O.D. while all those in class 1 are below this height. The Fisher exact probability test shows that the distribution of points about the two-metre level has a (two-tail) probability of occurrence of 0.0003. Hence it is possible to conclude that the existence of a ramp causes the cliff foot to be higher.

The height of the ramp/plane junction is also included in the scatter diagram in Fig. 5.6. Of course, it has been possible to do this only for profiles in the second class; those of this type which were measured by levelling have been excluded because it is not possible to fix the junction accurately. The junction is usually obvious in the field and so its height was measured directly. Wherever it was not, the objective method used to measure platform gradient allowed it to be found easily by simple trigonometry. All but one of these junctions are below the level of 2mO.D., i.e. they are in the same range of heights as the cliff foot where there is no ramp. This suggests that a profile in category 1 can develop into a class 2 type simply by the development of a ramp at its landward end. This is substantiated by a significant correlation ($r = 0.7959$) between the height range (x) of the ramp (in metres) and the altitude (y) of the cliff foot, the regression equation

$$y = 0.6995 + 1.0937x$$

explaining 63.4 per cent of the variation. There is no correlation between the height range of the ramp and the altitude of its lowest point. This means that the ramp, while extending upwards, does not simultaneously extend downwards, for example, by the formation of a gutter between the ramp and plane. The non-significant correlation also implies that the landward end of the plane does not increase in altitude during the extension of the ramp upwards and landwards.

The preceding discussion has shown that the plane is a landform with a very restricted range of variation in gradient and in the height of its landward point. These characteristics are in marked contrast to those of the ramp whose slope is varied while the altitude of the landward point also has a wide range of variability. To gain a fuller understanding of the reasons for these contrasts between the ramp and plane it is necessary to examine the erosive processes which are characteristic of each.

Erosive Processes on Bare Shore Platforms: A Brief Review of Published Works

Papers dealing with the erosion of bare shore platforms have ascribed their genesis to a veritable plethora of processes with usually little substantive evidence to support any of them. Most seem to be intuitively plausible as means of at least modifying micro-relief on platforms.

The earliest workers (De La Beche 1839; Ramsey, 1846; Lyell 1865) firmly believed in the ability of mechanical marine erosion to plane land on a continental scale. Later the existence of shore platforms (the "Old Hat" type) in very sheltered waters, where the rock is impermeable and easily weathered, was attributed by Bartrum (1916, 1926, 1952) to the weathering of overlying rock, this process being ineffective below the permanent water table which is at sea level. Waves then serve merely as agents of debris removal. Subsequently it was recognised (Bartrum 1938; Bartrum and Turner 1928) that sub-aerial processes could modify and lower benches originally cut by wave action by means of alternate wetting and drying and the resultant crystallisation of salts. However, some writers (e.g. Edwards 1941, 1951, 1958; and Jutson 1939, 1950) continued to emphasise that all processes other than storm wave action are of negligible or only minor importance. In contrast Hills (1949, 1971) has consistently maintained that wave erosion produces a ramp sloping seaward and that modification of this ramp to a platform surface (i.e. plane) is brought about by subsequent processes of which the most important is water level weathering. This term was originally used by Wentworth (1938) to describe a collection of specific processes acting at water level in pools in weathered palagonite tuff on the island of Oahu. It was described by him as " . . . a physical process, perhaps akin to the slacking of shales when exposed to water and with rock pressure released. Surface tension phenomena and colloidal dilatation behaviours may enter into the process. Also salt from the brine may crystallise giving break-up of the rock". It therefore seems to be just another name for sub-aerial weathering though with the added connotation of particular effectiveness around the edges of pools and thus of acting in a horizontal plane rather than the downward direction normally associated with sub-aerial weathering. It was clearly intended by the author to be thought of not as an additional process to the ensemble of processes already recognised, such as salt crystallisation and hydration, but as a group or generic term. In the same paper Wentworth noted that solution benching, ramp abrasion and wave quarrying were as important on the shores of Oahu as water level weathering. Other processes that have been assigned important roles in the genesis of platforms include salt crystallisation (Tricart 1959), spray erosion (Ongley 1940) and rock-boring and rock-browsing organisms (Healy 1968a). The dominant process on coasts composed of calcareous rocks has long been recognised to be solution (e.g. Hills 1971; Hodgkin 1964; Wentworth 1939), although So (1965) has stressed the efficacy of storm wave erosion in the chalk of Kent. Scarp recession, by the undermining of well-defined limestone strata along softer beds is the most effective process on the coast of the Vale of Glamorgan (Trenhaile 1969). In fact, this is the most important method of erosion on all lithologies in South Wales except on the homogeneous Triassic rocks where quarrying predominates. Many secondary processes have modified the rock surface to form small features of little importance in the formation of the platform as a whole. These processes include the solution of rock to form hollows, spray erosion giving micro-solutional hollows, potholing and organic action.

It may be concluded from this brief résumé of published works that for storm wave environments, such as those around the coast of Britain, most writers agree that erosion and the formation of shore platforms are the result of the action of these marine forces. There is also general acceptance of the tenet that secondary processes subsequently operate on this planar area, although the relative importance of these with respect to wave action or to each other is less clear. The different effects which secondary processes can have on varied lithologies have also been dealt with only cursorily. In environments such as very sheltered bays these secondary processes may become dominant. It is perhaps noteworthy that they have been discussed mostly in studies on Australasian shores where, as Davies (1964) has pointed out, the marine environment is radically different from that found around Britain in that swell is much better developed.

Erosive Processes on the North-East Yorkshire Shore Platform

In addition to the many individual M.E.M. units established in lines across the platform to study its recession in section, units were emplaced on the western side of Saltwick Bay to measure the variations in erosion rates over small areas. The mosaic (equivalent to the term "array" of High and Hanna (1970)) of M.E.M. units at the cliff foot (mosaic B) supplied 78 readings for each erosion period, and the other (mosaic A) which was about 40m from the cliff foot provided 81. Both lie on strata of the Bituminous Shales but their surfaces are very different. The photograph of mosaic B in Fig. 5.7a shows that this is composed of shale laminae which have been cracked into polygons only 1.5cm in diameter. These are probably produced by the shattering of the surficial laminae by impinging waves (the smooth fresh rock surface can be seen in the lower right hand corner of this photograph where someone attempted to chisel out an M.E.M. stud). The corners of the laminae are generally sub-rounded perhaps because of suspended sediment carried by the waves in this bay, the beach being only about 100m away, although it never covered the mosaic during the study period and probably never does. Erosion at this cliff foot

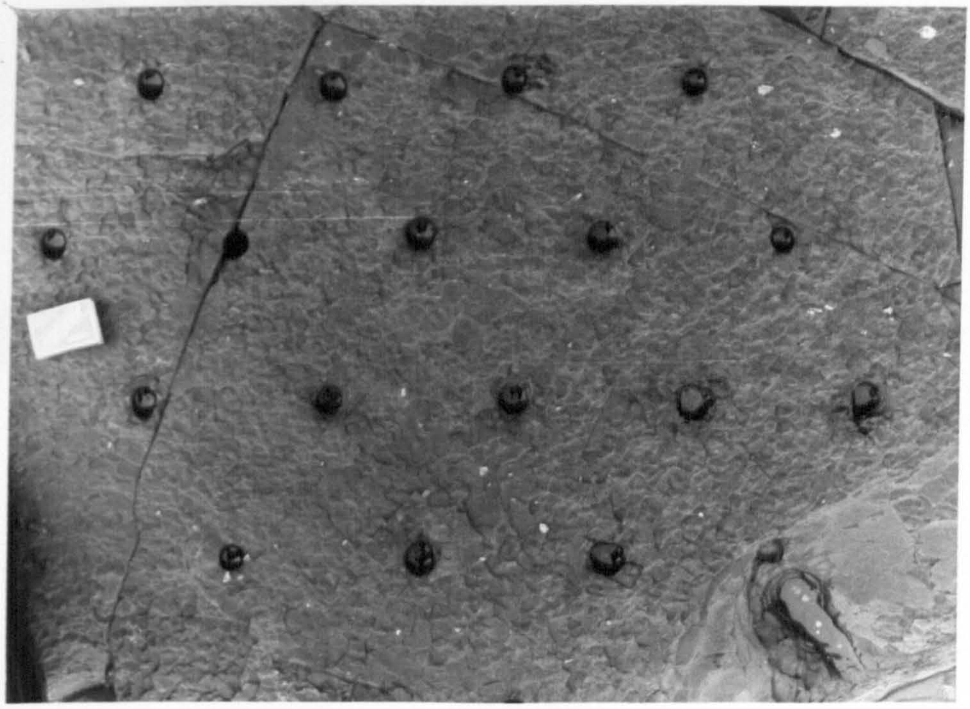


Fig.5·7a Mosaic B, at the cliff foot in Saltwick Bay

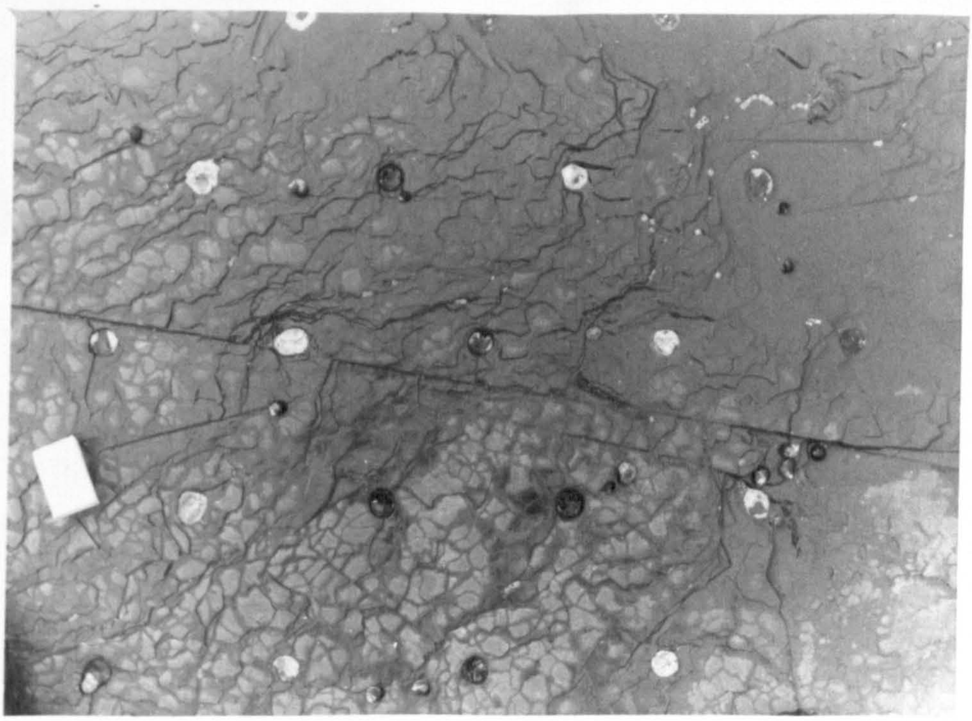


Fig.5·7b Mosaic A, on the plane in Saltwick Bay area is undoubtedly dominated by quarrying, as is shown by the number of large blocks of shale removed during the period of observation. No doubt the block on which most of the mosaic lies will be removed in the not too distant future in a similar way. It is noteworthy that this rock surface, because of its slopes and height above the main shore platform, is able to dry out during most intertidal periods. At mosaic A (Fig. 5.7b) this is much less possible as the surrounding area has a very low gradient and it is on the main shore platform. Fragments of shale laminae are here larger than at mosaic B, probably because passing waves cannot exert shock pressures on the near-horizontal surface below them. Erosion in the area of this mosaic is certainly not wrought by quarrying of blocks of shale, since no pits can be found. However, this does not invalidate the possibility that quarrying occurs through the erosion of fragments of shale laminae.

The mean erosion/year at mosaic B is 0.266 inches, while at mosaic A it averages 0.041 inches/year. The samples are evidently significantly different statistically since only the highest two values of mosaic A exceed the lowest value for mosaic B. This need not, however, imply that different processes are at work at the two sites. The shape of the frequency curve for A suggests that erosion has been sporadic and the modal value is zero; in other words, erosion is carried out by infrequent independent events in the form of the removal of fragments of shale rather than as whole layers. At mosaic B, erosion being 6.5 times more rapid and therefore more continuous, a normal frequency distribution results with the modal value (about 0.250 inch/year) centred at a value determined by the frequency of removal and the average thickness of shale laminae.

The season during which most erosion occurs gives some indication of the means by which laminae fragments are detached from the surface, since it has already been shown that quarrying is the result of vigorous waves which are most frequent in winter. Of the seven erosion periods, four were from the winter season and three were from summer. The mean erosion/day was calculated for each measurement point. Use of the χ^2 test furnishes the conclusion that erosion at A in summer (mean = 1.52×10^{-4} inch/day) is significantly greater than that in winter (mean = 0.56×10^{-4} inch/day) with extreme confidence ($\chi^2 = 39.427$; 10 degrees of freedom; significant at 0.0005). At mosaic B, summer erosion (mean/day = 16.31×10^{-4} inches) is even more different from that occurring in winter (mean = 2.66×10^{-4} inch/day) ($\chi^2 = 290.917$; 5 degrees of freedom; significant at 0.0005). This certainly suggests that erosion by the quarrying of laminae is ineffective compared with processes operating in summer. It might, however, be argued that the drying out of the cracks between laminae in summer allows the occupation of them by air. The impact of even a small summer wave on this might create considerable erosion because of the high pressures which can be generated by pneumatic quarrying, i.e. the change from hydraulic quarrying more than compensates for the reduced size of waves. In Whitby Harbour, waves, though not eliminated, are very much reduced in height. The Mann-Whitney U test applied to values of mean erosion/year at six units on the shore platform in the harbour reveals that these are not significantly different from equivalent erosion rates at mosaic A. Further, there is a probability of only 0.1114 that the two samples are not different, i.e. they are drawn from the same population. This in turn indicates that erosion by waves is insignificant at mosaic A and therefore, perhaps, at mosaic B also.

The spatial distribution of erosion rates is of some interest as it allows their randomness to be assessed. In Fig. 5.8a an isopleth map of values of erosion/year at each point in mosaic A is given. Marked erosion greater than 0.060 inch/year is sporadic. At five points no erosion occurred during the nineteen-month period and, indeed, these points suffered net negative erosion, i.e. the rock surface was raised. This may be the result of measurement error or of an upward expansion of the rock due to weathering. Visual comparison of Fig. 5.8a with the crude contour map given in Fig. 5.8b reveals that the area of largest erosion is also the lowest region of the mosaic. The Spearman rank correlation coefficient (r = -0.4250) between mean erosion/year for each unit and its mean height is significant at the 0.025 level but the amount of explained variation (18.06 per cent) is small. The negative relationship is not indicative of wave action which would be expected to be greatest at higher points. It can be concluded from a number of arguments, therefore, that other processes predominate at this site. The weakness of the negative correlation between erosion and height may be due to the fact that the existence of pools, or at least of near-horizontal areas whither drainage is slow, depends on the slope of the rock surface outside the area of the mosaic. Reference to the photograph in Fig. 5.7b shows that the lowest area is able to dry out while in the centre and upper right the mosaic remains damp for considerably longer because of the existence of a shallow pool to the right. In this case, the presence of a pool seems to be inhibiting erosion rather than promoting it. The drying out of inter-pool areas leads to erosion and to a reduction in their height which may explain the remarkable flatness of the shore platform.

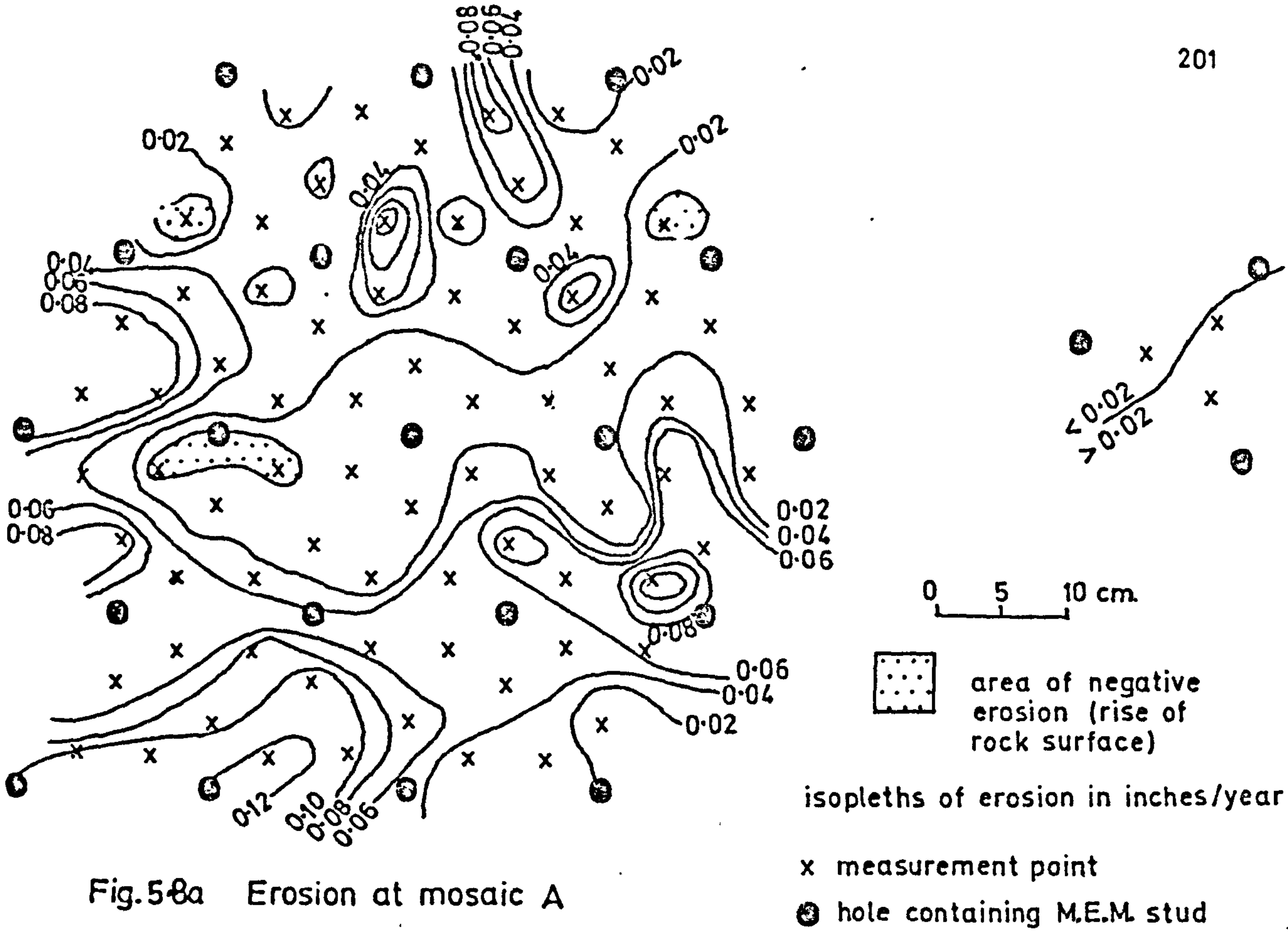


Fig. 5·8a Erosion at mosaic A

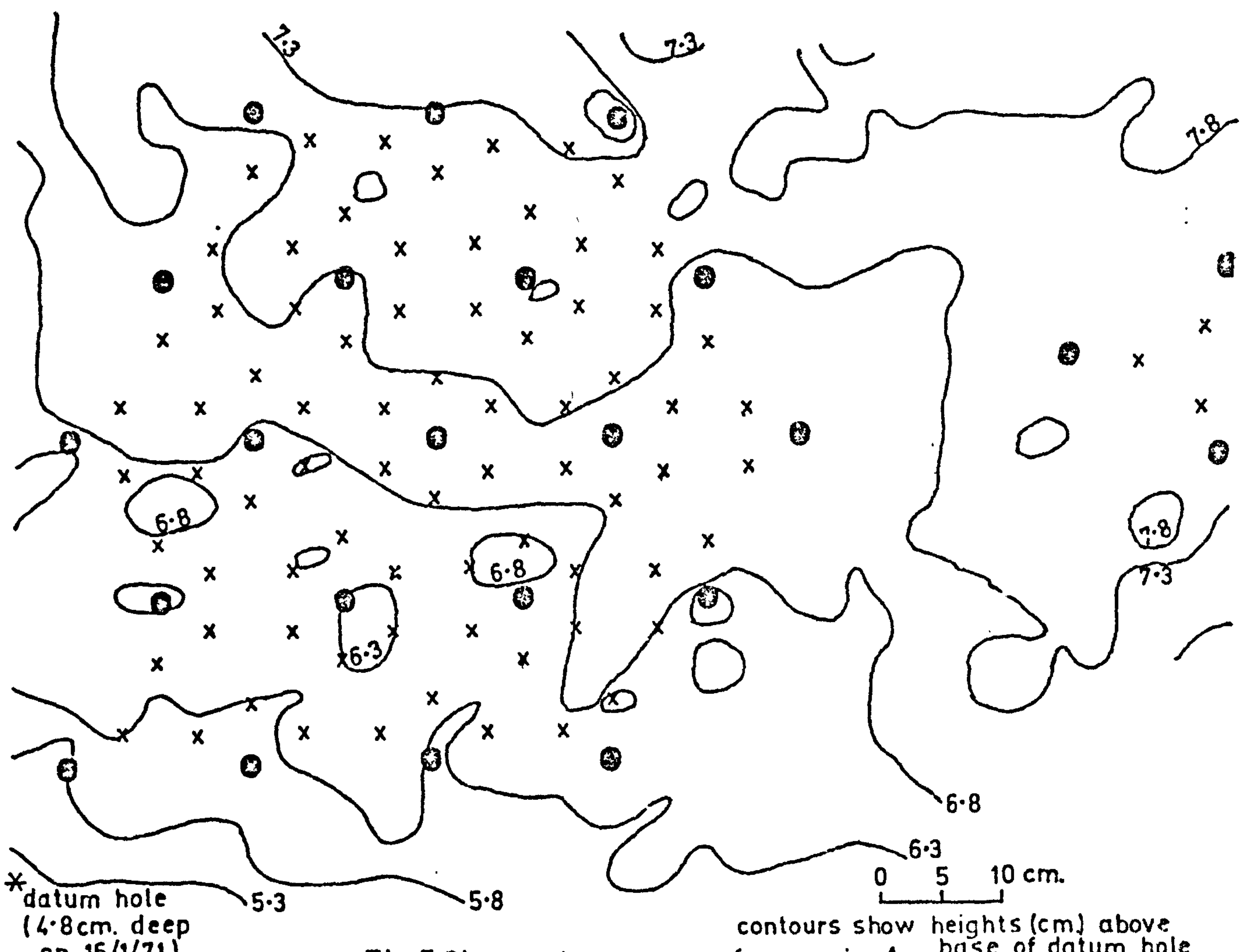


Fig. 5·8b Contour map of mosaic A

The crystallisation of salt in cracks may be able to free pieces of shale from the bedrock. Rings of salt crystals have been noticed around pools on hot days during summer but they are not common. Nevertheless a narrow crack would need only a small, hardly-visible crystal to widen it farther. This process requires the salt to become more concentrated as the water filling the crack evaporates. This reduction in the volume of water may itself lead to the freeing of a shale flake initially circumscribed by cracks produced by wave impact since the forces of surface tension will be reduced. A third, and unlikely, possibility is that drying and heating during the inter-tidal period followed by inundation by the incoming tide may lead to a sudden cooling and thus contraction of the rock, the surface having been heated to high temperatures by direct insolation on the dark grey (and therefore highly heat-absorbent) rock. Probably the most important process causing break-up of the rock is expansion and contraction. Drying causes a contraction of the shale to a small depth if the heat of the day is sufficient; wetting of the surface then allows the clay molecules to absorb water between their lattices and thus to expand. This will occur upwards toward the main free surface and outward to fill the cracks between fragments. The movements so engendered free the shale laminae from the laminae beneath them. This process is thought to be highly important because four large blocks of Alum shale each about 25Kg in weight were allowed to dry at room temperature for more than four months. They were then put in a field and after only a fortnight had all been reduced to piles of small fragments. Gad et al (1969), in their work on the geochemistry of the Upper Lias, have noted that "the clay fractions all contain approximately equal amounts of kaolinite, mica and swelling minerals (vermiculite and/or montmorillonite) with a little chlorite (less than 5 per cent)" (p. 109). This means that more than 17.5 per cent of the Bituminous Shales is composed of swelling minerals, and no division of the Upper Lias shales has less than 16 per cent. The amount of expansion which these shales undergo is considerable. Grim (1968) records that vermiculite contracts from a fully hydrated 14.81Å phase to complete contraction at 9.02Å (op.cit., p. 110), there being a large water loss below 100°C in terms of weight (ibid. p. 330) and, further, that "water is instantly regained on cooling at temperatures below 550°C" (ibid. p. 331). Grim gives little information on the behaviour of montmorillonite (smectite) at normal temperatures but the limits of cell height are 9.6Å (ibid. p. 78) and 21.4Å . No data are available for the relationship between water loss and temperature at less than 100°C but extrapolating from his figure 9.4 (p. 283) it appears to be very rapid. Water adsorption on calcium montmorillonite is more than 200 per cent in 1000 minutes while on sodium montmorillonite it is 750 per cent in 1000 minutes. It is concluded, therefore, that the most important erosive process at mosaic A is hydration and desiccation causing expansion and contraction of the rock.

These non-marine erosive processes, especially wetting-and-drying, may be dominant at mosaic B also. The greater height of this allows the rock surface longer to dry out during intertidal periods when cloud cover precludes direct insolation and when the site is in the shadow of the cliff. However, being at the cliff foot where waves expend most of their force, pneumatic quarrying may be more important. The pattern of erosion at this site is not correlated with height but comparison of Fig. 5.9a with Fig. 5.9b shows that erosion has been low on the plateau-like central and seaward parts of the mosaic and higher

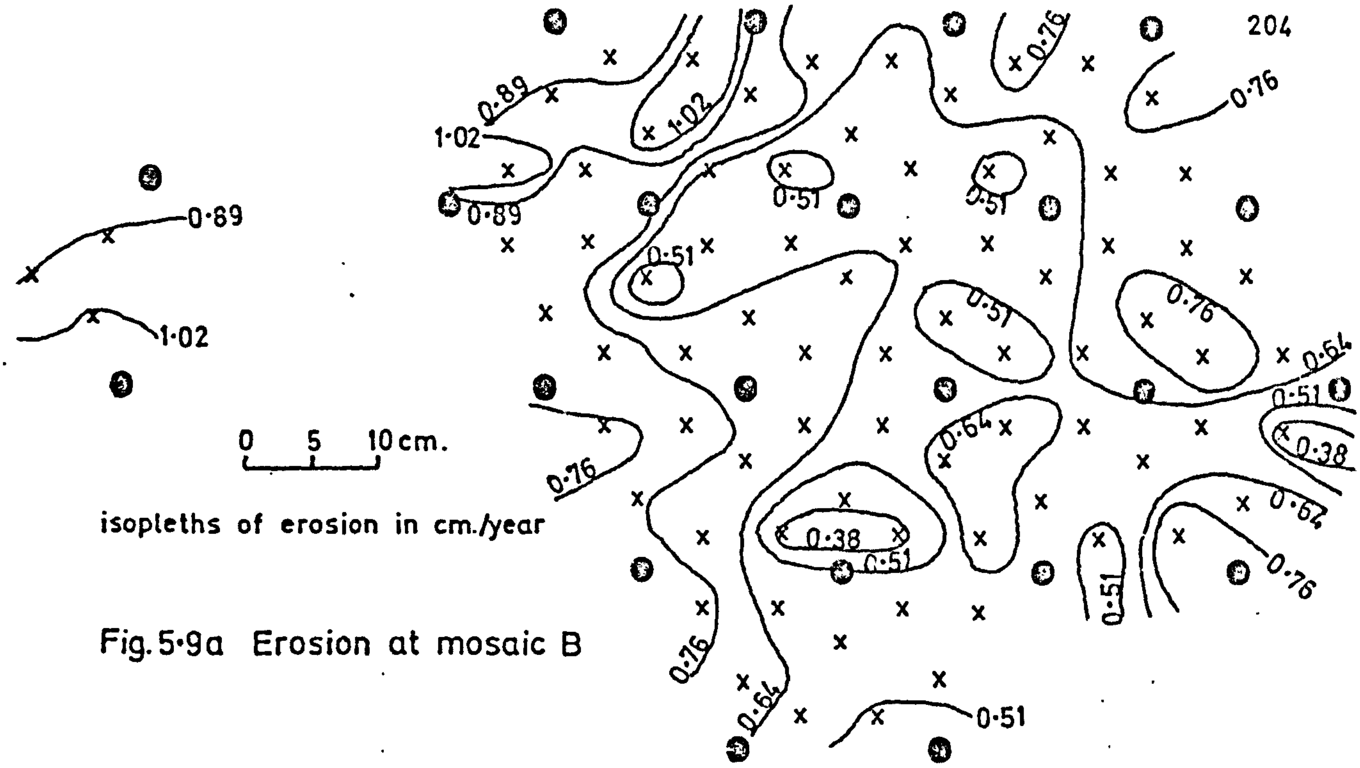


Fig. 5·9a Erosion at mosaic B

● hole containing M.E.M. stud   x measurement point

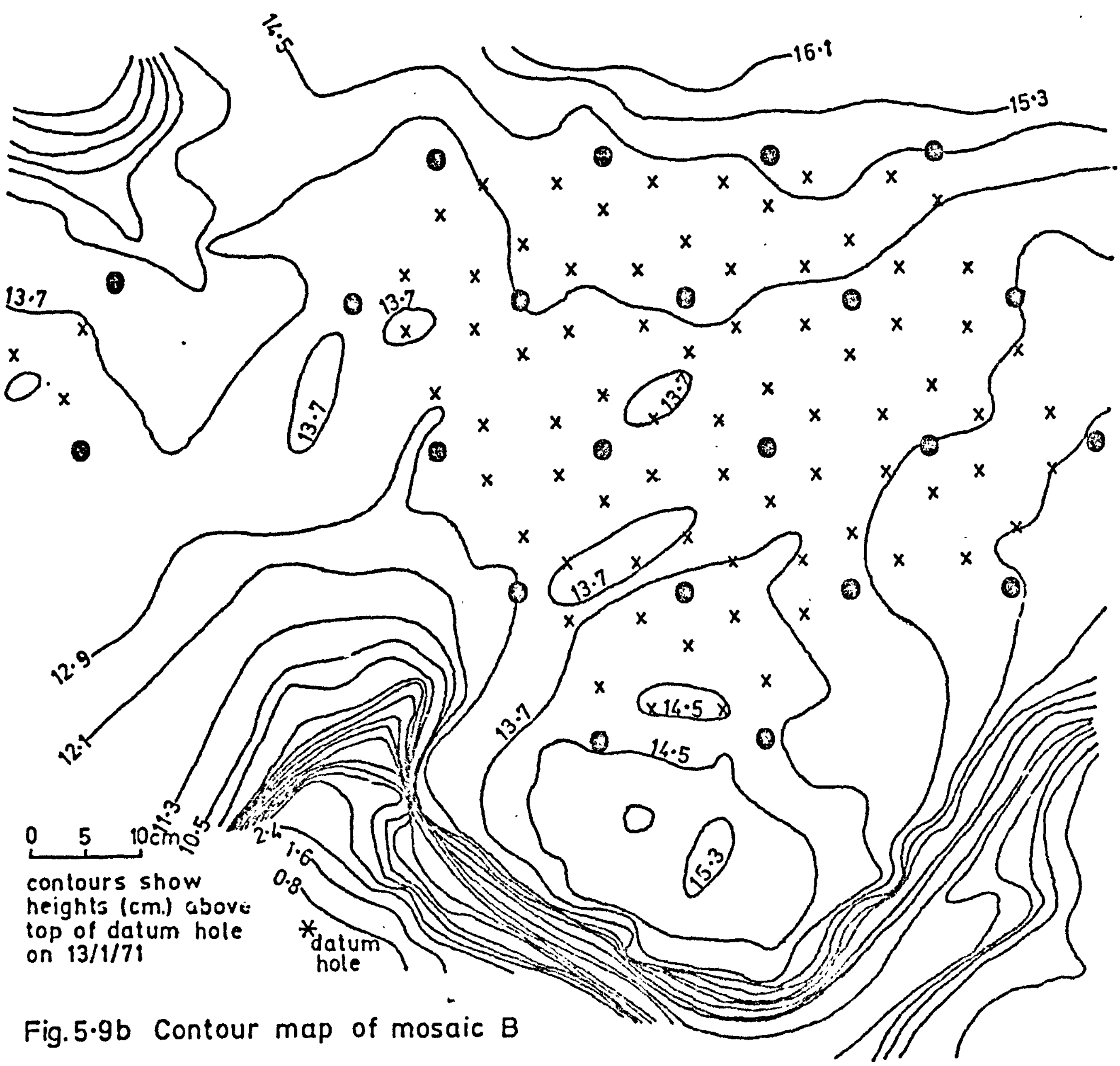


Fig. 5·9b Contour map of mosaic B

on the relatively steeper slopes around. The area of low erosion may result from slower drainage and, therefore, longer drying time. Alternatively it may be due to protection by the small hillock seaward of the mosaic from horizontal forces exerted by waves. Certainly where this hillock and its precipitous seaward edge (due to the presence of a joint plane) do not exist, around the re-entrant to the left, erosion is greater. This tendency for increased erosion on the relatively steeper slopes is a common feature of both mosaics. The greater exposure of the surface areas of both the individual rock fragments and their surrounding, initially water-filled, cracks may be a contributory factor in this.

Therefore it can be concluded that secondary processes dominate erosion at mosaic A and it is probable that one of these involving the expansion and contraction of fragments due to wetting and drying is pre-eminent. It may well be that it is the chief secondary process at mosaic B but more research needs to be done into these processes, preferably in the limited environments possible in the laboratory where, for instance, salt crystallisation could be excluded.

The Influence of Beach Characteristics on Erosion Rates

M.E.M. units have been established beneath five types of superficial deposit in order to examine variations in erosion rates due to the main variables of particle size and depth of deposits. The positions of the erosion sites and the mean values of erosion standardised to a period of 365 days at each point are tabulated in Fig. 5.10a. It is immediately apparent from this that erosion (mean = 0.0219 inch) at the White Horse units is very small relative to that at other sites. Large boulders, commonly over a metre long, provide considerable protection to the shore platform owing to their immobility. At units

Location	White Stone Hole (I)		Lingrow (2)		Fourth Bight (3)		White Stone Hole (4)		White Horse (5)	
Deposit	cobble beach		pebble beach		sand and pebble beach		shale fragments		large boulders	
	unit		unit		unit		unit		unit	
	2	0.I8I0	II	0.50I6	FI	0.4874	3	0.II49	6	0.0573
	3	0.3854	I2	0.5900	F2	0.3242	4	0.I289	7	0.026I
	4	0.3862	I3	0.8370	F3	0.3953	5	0.05I5	8	0.00II
	5	0.4I37			F4	0.6845	6	0.02I0	9	0.0063
	6	0.I920					7	0.0500	I0	0.00I4
	7	0.3776							II	0.0392
	8	0.5836								
	9	0.2I76								
	I0	0.II2I								

Fig.5.10a Variation in erosion rates (inch/year) with type of superficial deposit

site 2 rates are higher than site I rates at 0.0I0 significance level
" 2 " " " " " 4 " " 0.0I8 " "
" 2 " " " " " 5 " " 0.0I2 " "
" 3 " " " " " 4 " " 0.008 " "
" 3 " " " " " 5 " " 0.005 " "
" I " " " " " 4 " " 0.0I0 " "
" I " " " " " 5 " " 0.00I " "
" 4 " " " " " 5 " " 0.04I " "
" I " no different from " 3 " " 0.050 " "
" 2 " no different from " 3 " " 0.050 " "

Fig.5.10b Results of pair-wise Mann-Whitney U tests on erosion rates

Location	Type of beach	Erosion rate (inch/year)	Rank
Lingrow	thin ; pebbles	0.6429	I
Fourth Bight	thick ; sand and small pebbles	0.4729	2
White Stone Hole	cobbles	0.3I66	3
White Stone Hole	thick ; shale fragments	0.0733	4
White Horse	large boulders	0.02I9	5

Fig.5.10c The ranking of sites according to erosion rates

6 and 11 erosion is higher because small, more easily agitated boulders have occasionally lain on the units. Erosion (mean = 0.0733 inches/year) beneath the beach composed of shale fragments at White Stone Hole is more than three times higher. The particles are less than about 3cm in diameter, the beach being up to about 0.65m thick although this varies, as with all easily moulded beaches, according to wave conditions. The highest erosion at this site was experienced by units 3 and 4 which lie near the seaward edge of the beach and are occasionally not covered by it at all, i.e. they are in the zone of most frequent sediment movement. These variations imply that the depth of the beach may be an important variable determining erosion rates at this site. It is probable that differences in erosion rates between the units at Lingrow (near Runswick) (mean = 0.6429 inch/year) and beneath the beach at Fourth Bight (mean = 0.4729 inch/year) are mainly the result of the differences in beach depths. At the former site, the beach was up to 25cm deep but usually only about 5cm, the pebbles being smaller than approximately 3cm in diameter, while at the latter site the beach is composed mainly of sand and pebbles up to one centimetre in diameter with depths of less than 47cm. At White Stone Hole, the cobble beach contains some boulders with long axes over a metre but the average cobble diameter is nearer 15cm and the depth of the beach is similar.

Results of pair-wise Mann-Whitney U tests on the mean erosion/year for each unit at these sites are listed in Fig. 5.10b. These imply that the M.E.M. sites can be ranked in a statistically significant order, as shown in Fig. 5.10c, according to the amount of erosion experienced by them.

The thickness of the beach is the most important differentiating factor between the first and second sites. The larger mean grain size of the cobble beach at the third is almost equivalent in its inhibiting effect on erosion to the greater depth of the beach in Fourth Bight. The impotence of the beach of shale fragments is probably due to the softness of the constituent grains. It is concluded that grain size is basically important in determining the rate of erosion even though the Spearman rank correlation coefficient ($r_s = -0.500$) is not significant at the 0.05 level, perhaps because of the low degrees of freedom. This statistic ($r_s = -0.817$) is also not quite significant at the 0.05 level for the variables of beach thickness and erosion, mainly due to the fact that it is not really meaningful to describe a M.E.M. unit as being bare when it is surrounded, but not covered, by boulders more than a metre high which can provide complete protection from the forces of waves.

The factors of grain size and beach depth are also shown to be important from the temporal variations of erosion rates. In winter, the period of increased wave activity, erosion is significantly larger than in summer at the 0.0162 probability level at the White Stone Hole cobble site. At Fourth Bight, however, although at units F1, F2 and F3 both erosion and sand depth are not significantly different in winter from those in summer, at F4 erosion is greater in summer at the 0.01 level. This is because the beach at this unit is significantly deeper (at the 0.025 level) in winter than in summer. Nevertheless, approximately the same relative amount of erosion occurs at each unit at this site as is shown by the Kendall coefficient of concordance (0.4658) which is significant at the 0.02 level. This means that the amount of erosion is determined basically by wave size. As at Fourth Bight, there is a strong tendency (significant at 0.0606) for erosion to be more severe in summer than winter at the Lingrow site, and again the depth of the beach in winter (mean = 8cm) is significantly greater at the 0.01 level than that in summer (mean = 6cm). These two variables of sand depth and erosion tend to be related at Fourth Bight such that the Spearman correlation coefficient for units F3 (r_s = -0.2724) and F4 (r_s = -0.3381) are significantly greater than zero at the 0.10 level. The low amounts of explained variation (7.42 and 11.43 per cent respectively) and weak strengths of the associations are, perhaps, due to the fact that sand depth could be measured only on the days when M.E.M. readings were taken and thus are manifestations of poor data rather than poor relationships. These poor correlations were also evident when multiple regression analyses were carried out employing the variables of sand depth, wave values, the theoretical period of contact with sea water and the amount of erosion. Much more research into the influence of a beach on erosion of the shore platform needs to be done. It might be carried out best by using wave tank experiments.

Having recognised the two elements into which shore platform morphology can be analysed and having discussed the erosive processes typical of each element it is now necessary to show how these elements change with respect to each other, i.e. to show the influence of their specific processes on the morphology of the shore platform. This objective is fulfilled by the analysis of both long and short term changes in a few profiles.

The Development of the Shore Platform: Long-Term Changes

In many places in the study area lie patches of conglomerate which are much more resistant to erosion than the surrounding shale and so protect the underlying rock and the parts of the ancient shore platforms on which they rest. Several patches are isolated from the cliff foot, though their constituent boulders must once have fallen from the cliff. Differences between the sections of preserved platform and the modern profile, therefore, offer indications of changes in platform profiles over long time periods.

Two areas of conglomerate patches were chosen for close study. They are at Cobble Dump, near Runswick Bay, and at South Batts, near Saltwick Bay. Large-scale plans of them are shown in Figs. 5.11 and 5.12 together with interpolated contours of the sub-conglomerate platform surface. The contours in both plans have fairly simple trends, a fact which facilitates the construction of representative profiles down the maximum slopes of the relict surfaces. These profiles, together with profiles of the modern shore platform in the immediate areas, are presented in Fig. 5.13. It can be noted, firstly, that the relict sections have concave profiles which suggests that they were near the cliff foot when they were buried. The actual distances from the cliff foot at which they lay, when erosion of them ceased, can be calculated by two different methods.

The first technique uses the fact that the cliff landward of the South Batts conglomerate has a bevel. A line extrapolated down the direction of maximum slope intercepts the modern shore platform 39.5m landward of the most landward point on the relict platform. This intercept should mark the approximate position of the cliff foot during formation of the bevel. Of course, this method is based on the assumption

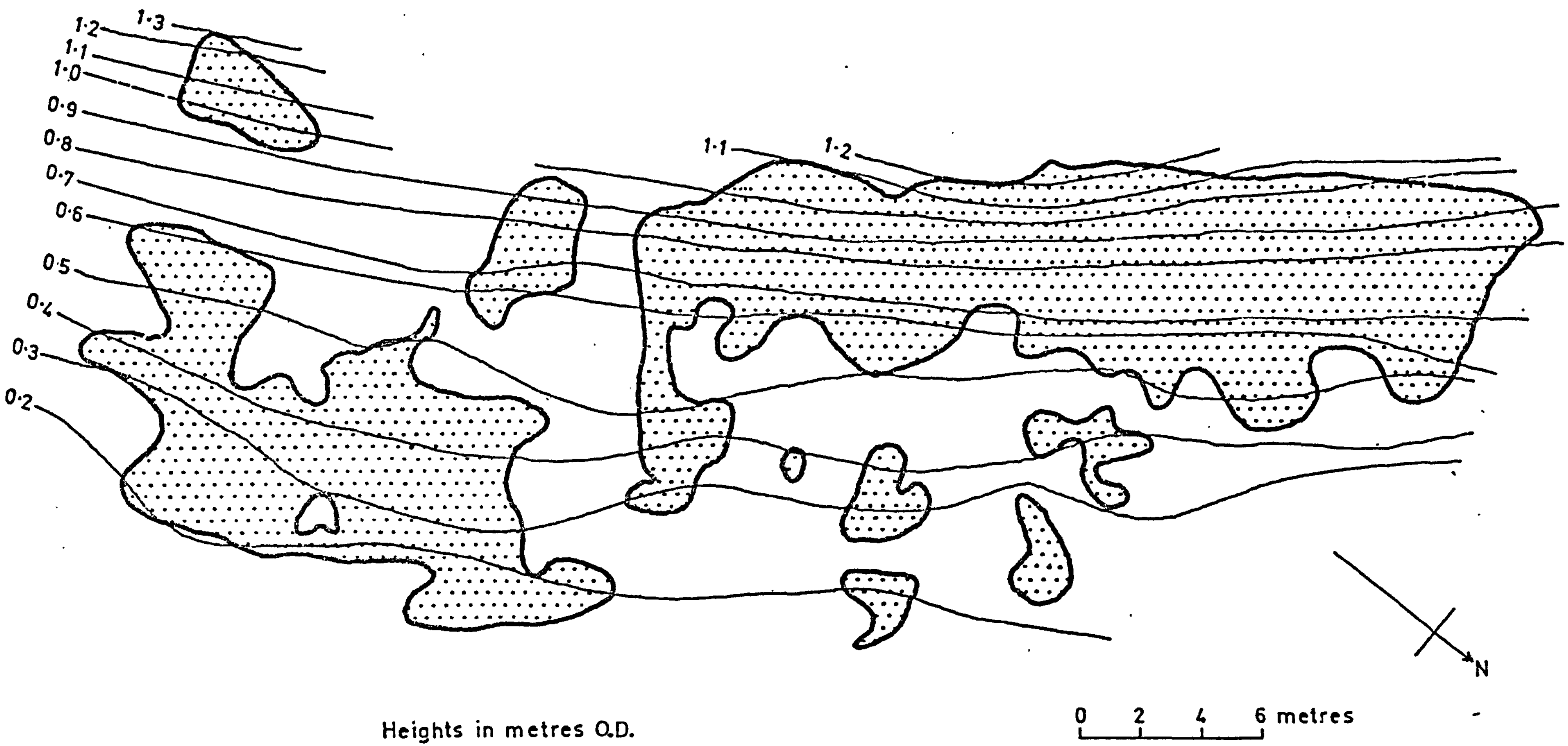


Fig. 5·11 South Batts conglomerate area with interpolated contours of sub-conglomerate base

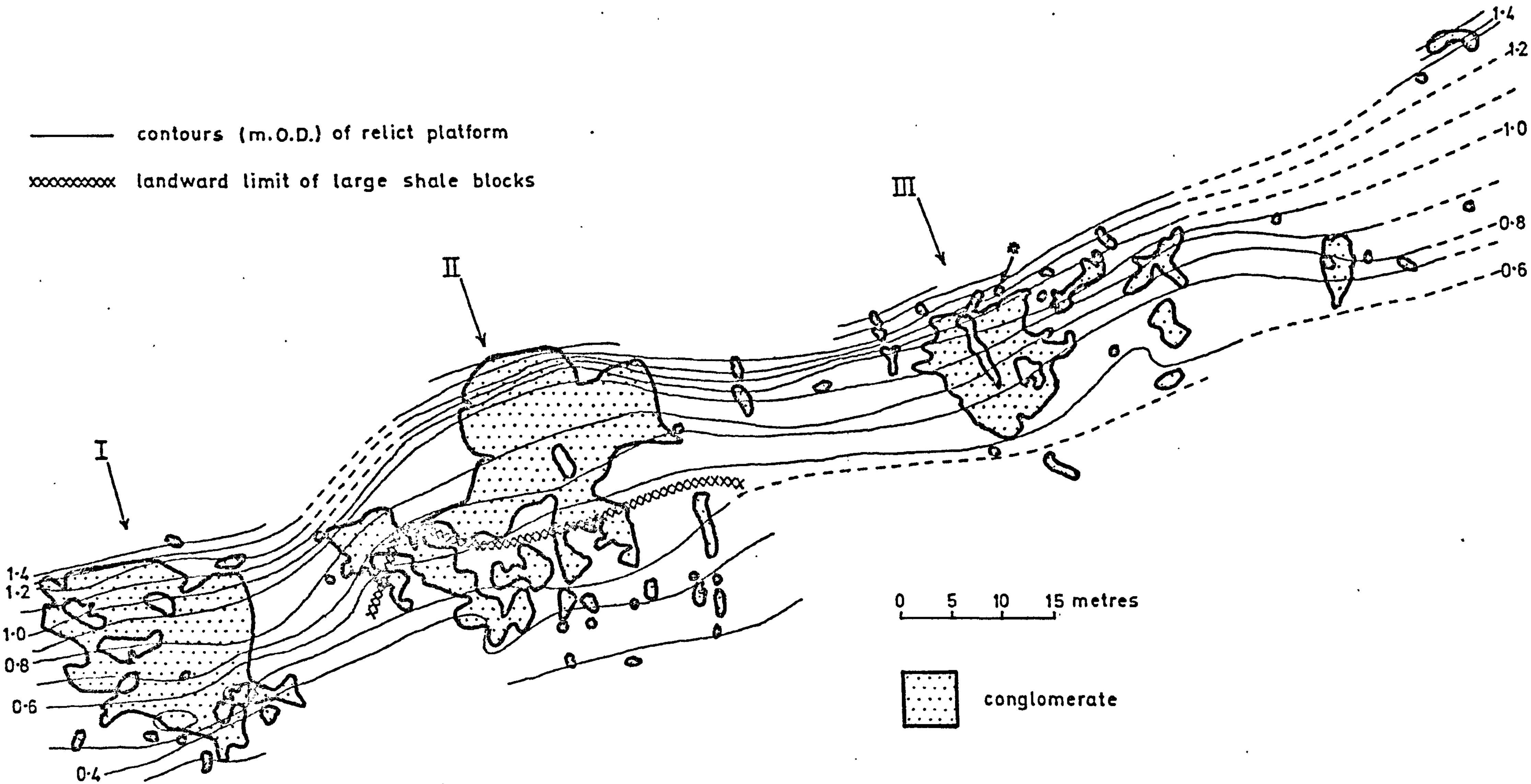


Fig. 5·12 Cobble Dump conglomerate area with interpolated contours of sub-conglomerate base

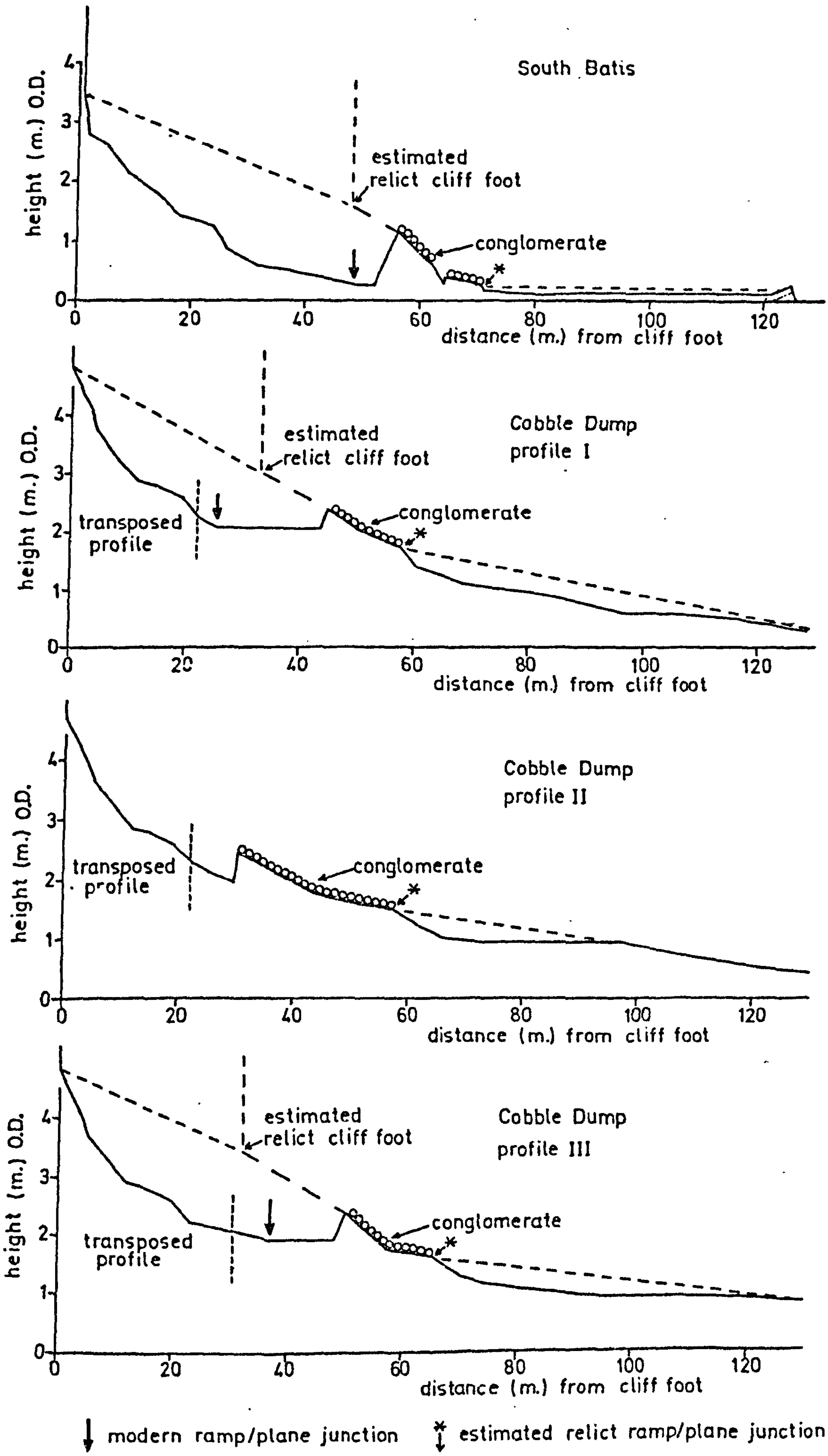


Fig.5·13 Platform profiles at South Batts and Cobble Dump that the bevel and conglomerate began to form at the same time, an assumption which seems valid since both phenomena need considerable time to form and both need the presence of a resistant talus cone.

The second technique for the location of the ancient cliff foot which was contemporaneous with the relict platform uses only the information contained in the profile of this feature. The relationship between the angle of the tangent to points on the relict profile and the height of these points above O.D. is almost rectilinear (Fig. 5.14a). Assuming that the cliff foot can be defined as having been reached when the angle attains 90 degrees, and that the profile landward of that part which remains continued to increase in angle at the same rate (i.e. that no rectilinear segment existed to upset the trend), extrapolation of the relationship shown in this diagram yields the figure of 1.58 $\pm$ 0.20m (with 95 per cent confidence) for the height of the cliff foot at South Batts. When the angle of the relict profile at various points is plotted against distance from its most landward point, extrapolation shows that the cliff foot was 8.06 $\pm$ 3.00m (with 95 per cent confidence) from this most landward point. This figure is much smaller than the estimate for the foot of the bevel. The lack of agreement may be reconciled if either the relict platform actually predates the bevel, or the bevel was not rectilinear in profile but concave. This latter alternative would permit the two landforms to be contemporaneous. It is also possible that the bevel might have retreated parallel to itself or that it has been steepened subsequently during the period of marine erosion at the cliff foot.

The same procedures as those described above were used for the three conglomerate patches at Cobble Dump. The distances obtained from extrapolation of the bevel are 15.8m, 10.4m and 20.1m from the landward points of the preserved platform profiles. Because it has

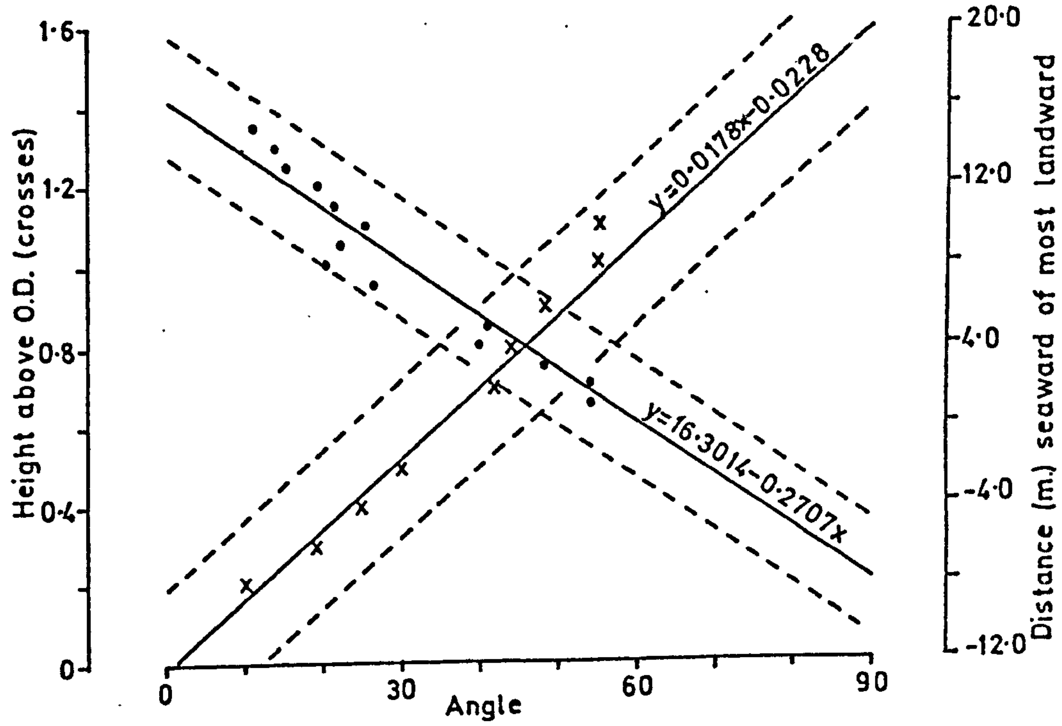


Fig. 5·14a Extrapolation of relict profile at South Batts

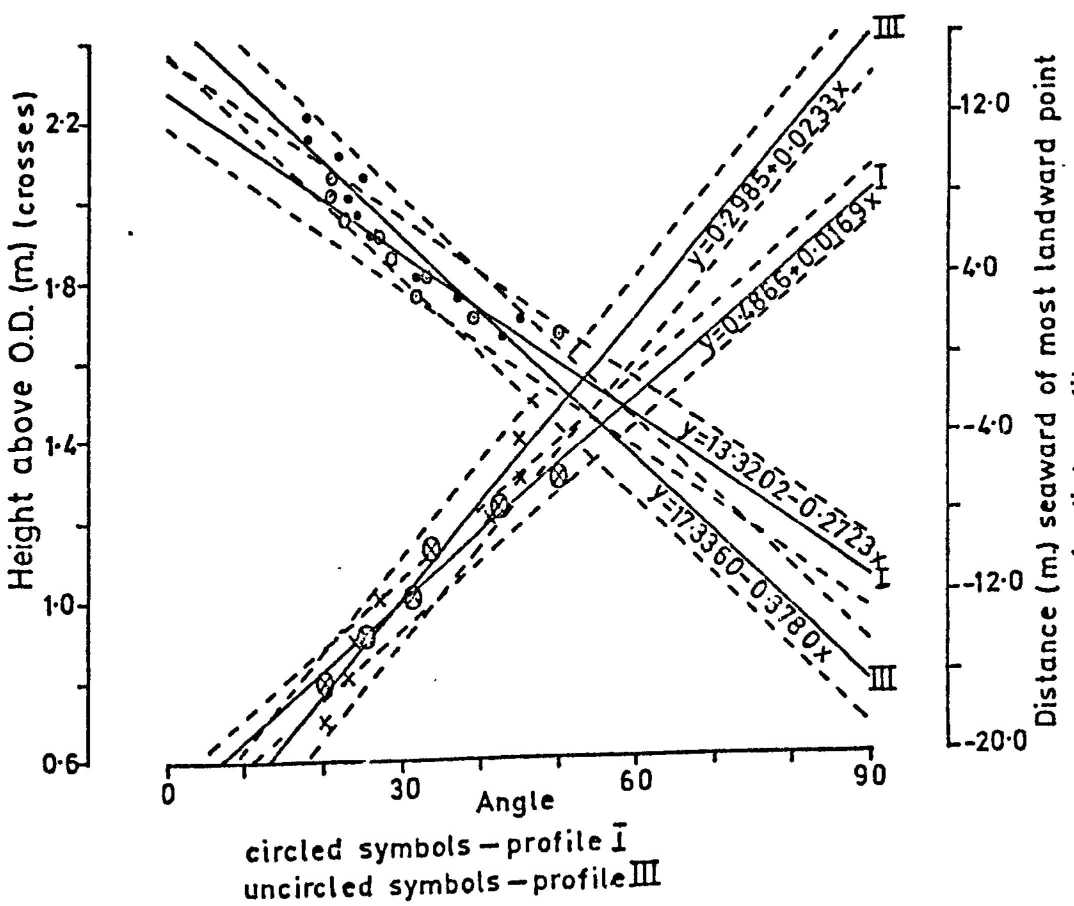


Fig. 5·14b Extrapolation of relict profiles at Cobble Dump been assumed that the bevel has remained in its original position and has retained its slope, these estimates may be too large. The method of extrapolation of profiles of the relict platform could be used only for profiles I and III; irregularities in profile II prohibited the fitting of a significant regression line. The heights of the ancient cliff foot are estimated to have been at 2.01 ± 0.06m and 2.40 ± 0.10m O.D. for profiles I and III respectively and their positions at 11.19m ± 1.75m and 16.68 ± 2.10m from the most landward points of the relict profiles. These distances agree well with the estimates from the extrapolation of the bevel.

Of the two methods of estimating the cliff foot position, the second derived from the extrapolation of the fossil profile is probably the more reliable as it employs the fewest assumptions. Further deductions about the changes in profile morphology, made from these estimates, are shown in Fig. 5.13. At South Batts the cliff foot has risen by 1.8m while it has retreated 47m following a path whose inclination is 2.2 degrees. The relict section of platform is classed as a ramp since it exceeds the limiting angle of 2.5 degrees. The upper extremity of the reconstructed ramp is the estimated cliff foot and the lower is taken to be the point 70m from the modern cliff foot and 0.02m above sea level where the fossil profile meets the modern plane. Comparing the ancient ramp with the modern one it is clear that the ramp has retreated with the cliff foot and that it has extended as the cliff foot has risen. The junction of the modern ramp and plane is marked in the diagram and is obvious in the field because of the change in angle and in the littoral flora. The mean angle of the ancient ramp (measured between the two defined end points) is

3.48 degrees and that of the modern ramp is 3.77 degrees. These changes are negligible, i.e. the ramp has maintained its angle as it has retreated and extended. The plane (the sub-horizontal segment of the platform) has retained its angle and extended horizontally by about 33m. In contrast to this large horizontal change, the fact that the seaward edge of the sub-conglomerate platform is only 10cm above the modern plane implies that this element has been lowered only a very little during the same period. It must be noted that the junction of the modern plane and ramp lies directly below the inferred position of the ancient cliff foot; as no reason can be deduced for this it is regarded as coincidence.

The relict profiles at Cobble Dump have to be compared with the modern profile (in the cliff foot area) about 100m to the south because of the lack of exposure of the cliff foot in the immediate area; the portion of this distant profile used for comparison is marked in Fig. 5.13. In profile I the cliff foot has risen 1.8m and retreated by 33.5m, which is equivalent to an angle of 3.0 degrees. The modern ramp/plane junction is marked in the diagram; the mean angle of the ramp is 6.47 degrees. It is difficult to see where the foot of the fossil ramp should lie but if it is as marked in the diagram, the ramp was angled at 3.27 degrees. Hence, as the ramp has retreated it has become steeper and has extended, though its foot seems to have risen slightly also, by 0.4m. The modern plane has a mean inclination of about 1.0 degrees and, as at South Batts, it has been lowered very little, the maximum having been 30cm.

The same deductions can be made for profile III (again using for comparison the part of the profile to the south). The cliff foot here seems to have risen by 1.4m and retreated by 32m, distances which produce an angle of 2.4 degrees. The modern ramp has an angle of 6.47 degrees and the relict 3.13 degrees, again indicating that the ramp has steepened as it has retreated and extended. The foot of the ramp has risen about 0.65m while the plane has been considerably widened and has been lowered by less than 30cm.

The Development of the Shore Platform: Short-Term Changes

Changes in shore platform profiles over the short period of (usually) November 1970 to July 1972 have been measured by the M.E.M. technique. The profiles, showing also the amount of erosion at each unit, are presented in Figs. 5.15 and 5.16. (The exact erosion rates standardised to a period of one year are given in the table in Fig. 5.17a). The vertical exaggeration (x 10) of the profiles and the much larger scale used for the erosion measurements should be borne in mind when viewing these diagrams. The angle of 2.5 degrees, the limiting angle between the two characteristic platform features, the ramp and the plane, is shown on each profile diagram also.

Fig. 5.15a shows the whole profile of the broad platform on the western side of Saltwick Bay; it is terminated seawards by a line of perched wheelstone doggers which are at the edge of a narrow area that has been mined for jet. Only a quarter of this profile nearest the cliff has been instrumented - this section is presented in enlarged form as the profile in Fig. 5.15b. The whole profile is classed as a plane since no characteristic angle over 2.5 degrees is present. It is apparent that erosion is very low (less than 0.1cm/year) at all units except for those at the very foot of the cliff (unit 9 is 1.1m from the cliff foot). Some of the distal units even show negative erosion, possibly due to hydration of the shale. Marked erosion is limited to the zone at the cliff foot where all the energy of impinging waves is expended. The mean erosion/year for the whole plane is 0.190cm

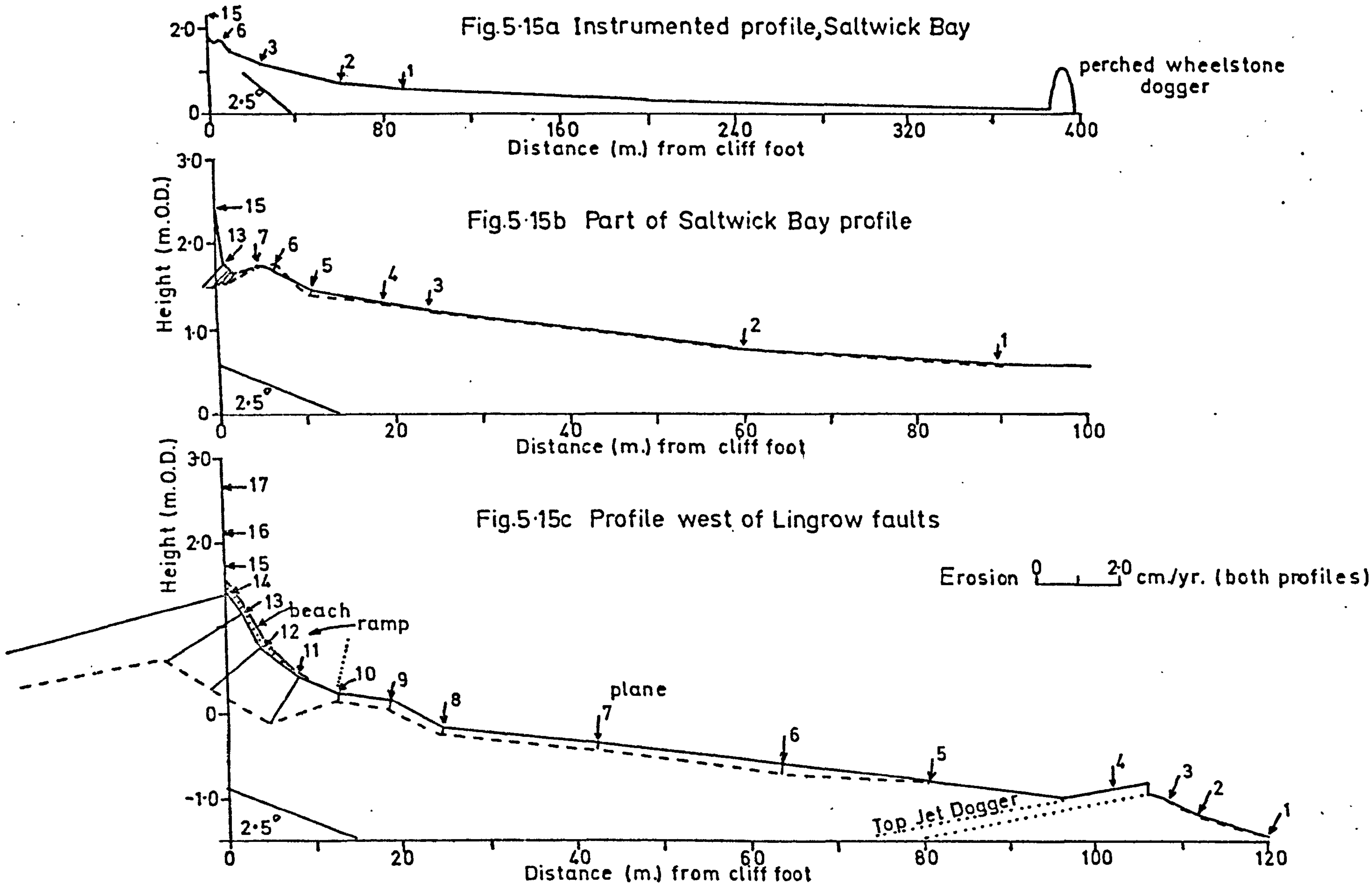


Fig.5·15a Instrumented profile, Saltwick Bay

Fig.5·15b Part of Saltwick Bay profile

Fig.5·15c Profile west of Lingrow faults

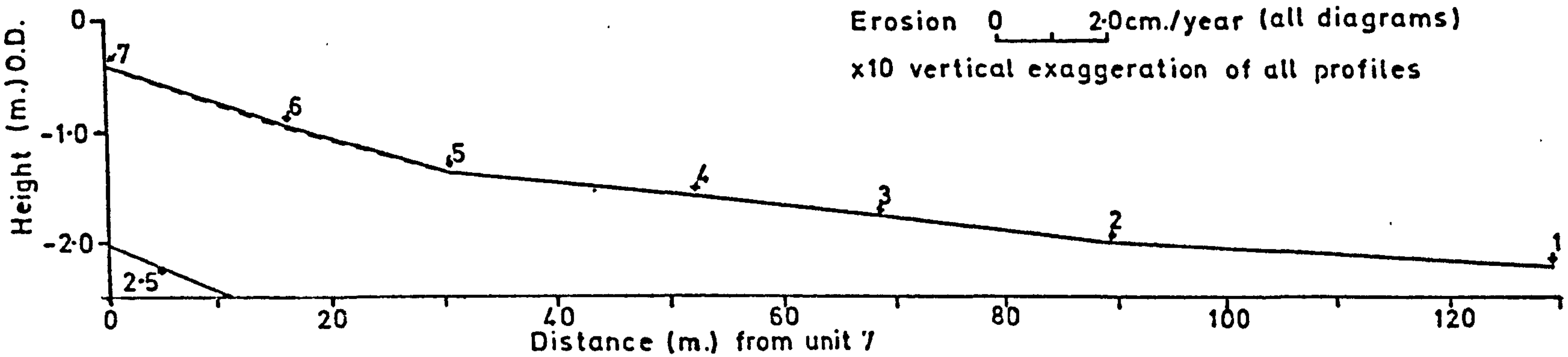


Fig. 5·16a Instrumented profile east of Lingrow faults

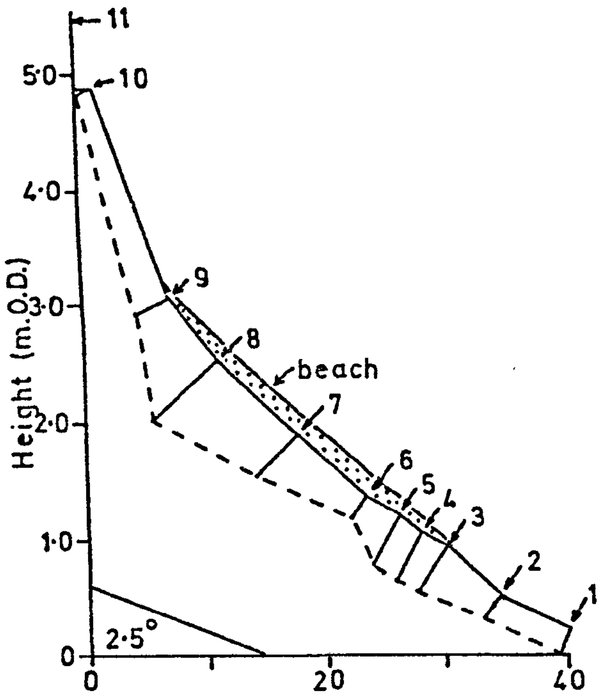


Fig. 5·16b Cobble beach profile, White Stone Hole

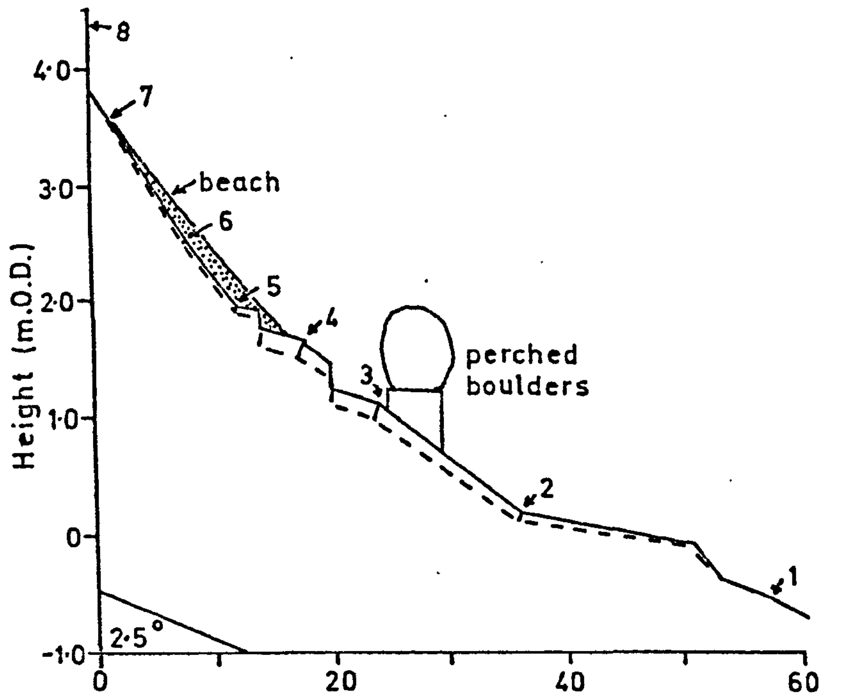


Fig. 5·16 c Shale beach profile, White Stone Hole but this figure conceals the facts that the mean of units 1 to 8 is 0.011cm and that of units 9 to 13 is 0.476cm. Such big differences are also evident between the two M.E.M. mosaics discussed earlier; mosaic B at the cliff foot suffers 0.676cm of erosion per year while mosaic A which is far from the cliff undergoes only 0.105cm. Therefore erosion on the plane is not uniform but appears to vary more in the direction normal to the coastline than in a direction parallel to it.

Fig. 5.15c shows the profile of the unmined part of the platform west of the parallel faults at Lingrow (near Runswick Bay). This profile comprises a ramp and a plane, the seaward end of which is irregular because of the outcrop of the Top Jet Dogger. Units 1 to 10 inclusive, which are on the plane, have a mean erosion of 0.092cm/year, a value which lies within the range of values for the Saltwick Bay plane. Fig. 5.16a shows most of the visible profile on the eastern side of the Lingrow faults. The mean erosion here is 0.011cm/year. Although these two Lingrow profiles are separated by only about 100m, erosion on the western side of the faults is much the greater. The rock type on this side is mainly the Bituminous Shales and on the other the Grey Shales. However, the differences in erosion rates are probably due more to the different altitudes of the profiles than to geological factors.

The differences in erosion rates between the ramp (mean = 3.427cm/year) and the plane of Fig. 5.15c are very pronounced; the rate at unit 11 is twelve times that at unit 10. This is because the former has the pebble beach lying on it. Erosion increases towards the cliff foot so that at unit 14, at the base of the cliff foot, it is 8.806cm/year. The ramp is therefore retreating rapidly and is probably becoming gentler. The ramp is also extending because its upper point is retreating faster than its base. The fact that the beach is thin (less than 10cm usually) implies that the inflow of the resistant debris which constitutes it is slow. Hence, as the ramp becomes gentler and wider the beach is swept forward as the cliff foot recedes and so the lowest parts of the ramp will be progressively exposed. This may explain the slopes at units 8, 9 and 10 which are steeper than those on the main plane.

The profiles shown in Figs. 5.16b and c are developed on shales of the Jet Rock Series. They are classified as ramps throughout. In their highest parts they are overlain by beaches; in the former the beach is composed of calcareous nodules and small sandstone boulders and in the latter the beach is made of small shale fragments. Erosion along the cobble beach profile, even where there is no beach, is greater than anywhere on a plane. However, erosion is highest where the beach is; in both profiles, but especially Fig. 5.16c, erosion decreases away from the lower edge of the beach. Erosion is highest at this edge of the shale beach and not at its centre because it is quite thick, only the upper few centimetres being agitated when inundated. The differences between the rates of erosion on these two profiles have already been attributed to the different types and thicknesses of beach material (the mean erosion at units along the cobble beach profile is 0.782cm/year and along the other is 0.151cm/year). There is a trend in each profile for erosion to decrease towards the cliff foot from the beach despite the smaller depths of this. Such a trend is in marked contrast to the rapid increase in erosion in this direction at Lingrow. It is undoubtedly due to the great height above sea level of the cliff foot in White Stone Hole. The sea reaches this point only at the highest spring tides and during storms, so quarrying of blocks of rock is likely to be a more important process than corrasion at these heights. As noted previously, the M.E.M. technique is not suitable for the measurement of quarrying of large blocks. Therefore it is concluded that erosion over a long period may be as rapid at the cliff foot as it is beneath the beach. It is not possible to say whether the cliff foot in this bay is rising as it retreats; in view of its present altitude this is unlikely. Therefore the ramp is probably retreating in a sub-parallel fashion.

Conclusions

This chapter has shown that the platform consists of either a plane, a ramp, or both of these landforms, when it is not influenced by structural factors. The plane usually forms most of the shore platform. It is a sub-horizontal element with a gradient of less than 2.5 degrees and there is little variation in slope. Although its existence must be fundamentally attributed to marine erosion since this process causes the cliff foot to retreat, M.E.M. measurements have made it clear that the dominant erosive process is expansion and contraction of the shale due to wetting during high tides and drying in the intertidal periods. The higher temperatures of summer make this season the one of maximum erosion. The inhibition of expansion and contraction where pools lie on the surface produces the characteristic flatness of the plane. Erosion rates are very low being of the order of 0.01 to 0.10cm/year.

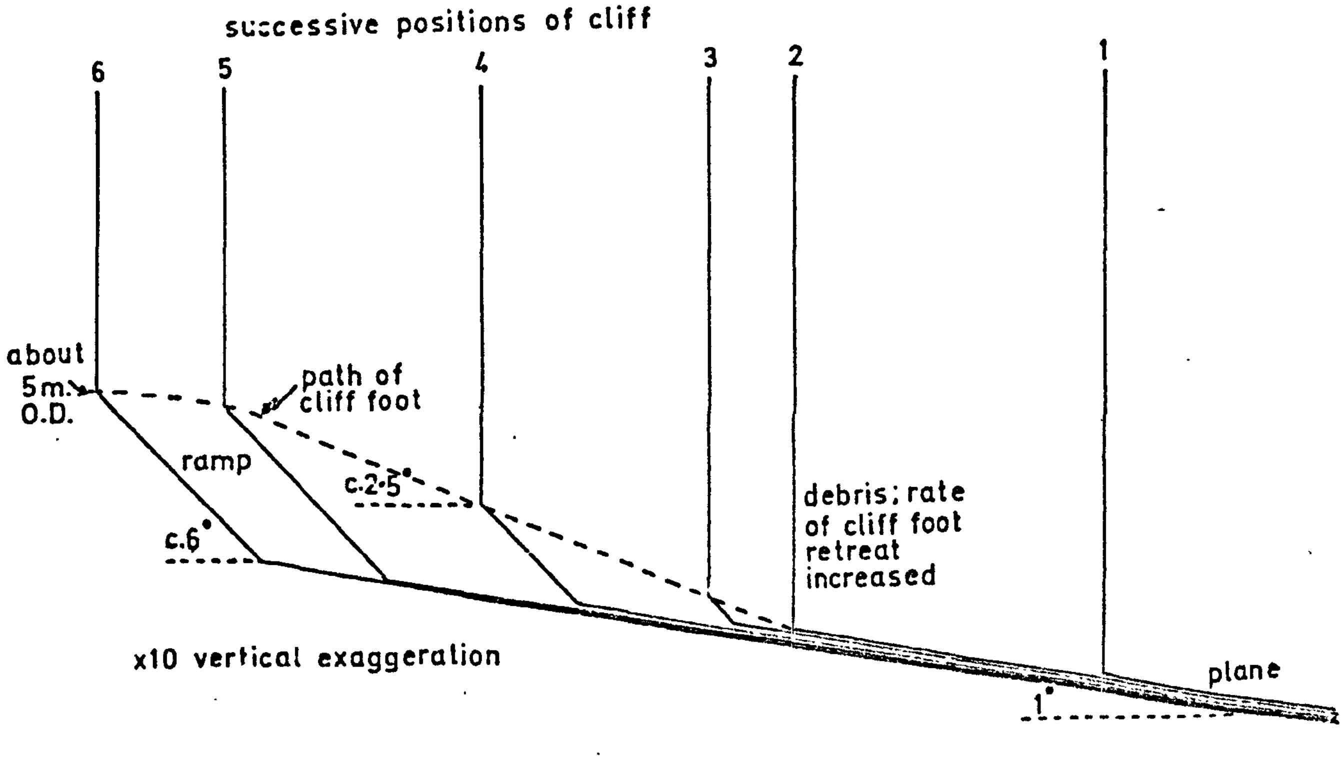
The ramp is found only at the cliff foot and is at least partly covered by deposits ranging in particle size from sand to boulders. The characteristic angle of the ramp is 6 degrees but the slope does vary. Erosion is by corrasion and the season at which this is a maximum is usually winter though variations in the thickness of the beach can make summer the more important season.

A model for the development of a platform consisting of a ramp and a plane is shown in Fig. 5.17b. Initially (stage 1), the plane constitutes the whole platform. The cliff foot is low and erosion at this point is slow because only quarrying can operate. An influx of debris to the cliff foot may rapidly change this situation. If the debris is not too massive to impede erosion it allows the erosion rate to be doubled because corrasion and wedging as well as quarrying are now the erosive processes. Cutting of the ramp is also initiated (stage 3). Erosion of this landform is at a rate which is of the order of 0.15 to 3.5cm/year depending on the grain size and thickness of the beach material. The altitude of the cliff foot is simultaneously increased. The path described by the cliff foot as it retreats is inclined at about 2 degrees to the horizontal. However, when it achieves a height of 4 to 5m O.D. it is probable that the cliff foot no longer rises as it retreats (stage 6). Unless material is constantly being added to the beach the lower end of the ramp becomes exposed because the overburden of debris is continuously retreating with the cliff foot and is being worn away. Therefore the lower, exposed parts of the ramp increasingly come under the influence of secondary erosive processes and are gradually worn down to become part of the plane. Should the rate of replacement of beach material be reduced, for instance, by fewer falls of resistant boulders from the cliff, the ramp will be reduced in size as the plane encroaches on it. On the other hand, if so much debris accumulates on the ramp that erosion of the cliff foot is substantially reduced, the landforms will become static. This

unit number	Lingrow (Fig. 5·15c)	Lingrow (Fig. 5·16a)	White Stone Hole (Fig. 5·16c)	White Stone Hole (Fig. 5·16b)	Saltwick Bay (Fig. 5·15b)
1	6·6	7·6	16·3	509·5	42·2
2	74·4	15·0	110·7	459·7	−11·9
3	19·3	0·0	291·8	978·9	0·0
4	10·7	10·2	327·4	980·9	75·4
5	11·2	−3·6	131·1	1050·8	93·0
6	201·7	40·6	53·3	487·7	−186·2
7	110·2	9·1	127·0	959·1	−21·6
8	172·5			1482·1	94·5
9	216·4			622·0	294·6
10	100·1			284·7	424·2
11	1274·3				297·9
12	1498·9				626·9
13	2127·5				734·6
14	8806·2				

Fig. 5·17a Erosion rates ($\times 10^{-3}$ cm./year) at M.E.M. units

Fig. 5·17b The development of a shore platform



situation can be seen between Maw Wyke and Widdy Head where erosion is so slow that the platform consists of a ramp element only. It can be concluded, therefore, that superficial deposits have great influence on the morphology of the shore platform.