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

by

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CHAPTER 6

SUPERFICIAL DEPOSITS

Introduction

It has been shown in previous chapters that the morphology of the cliff can be related to the presence or absence of talus and superficial deposits on the shore platform and that sand, pebble and boulder beaches influence the production of ramps. It will be shown in Chapter 7 that the occurrence of superficial deposits also affects the morphological development of bays by modifying the rate of erosion of the cliff foot. In the present chapter, the nature and evolution of some of these superficial deposits are investigated.

Three major categories of deposits are considered here. Boulder beaches are usually composed of free boulders, i.e. boulders that simply rest against each other, but occasionally the blocks interlock or are embedded in the shore platform. The term "imprisoned" was first used by Baker (1959) to describe interlocking boulders at Cape Paterson in south-eastern Victoria. Other adjectives such as "fitting" and "fretting" (Hills 1970) have also been used to describe the same phenomenon. Detritus of any size which was formerly loose may also be stabilised for long periods by the deposition of cement, producing a conglomerate. The third type of superficial deposit is composed of blocks of resistant lithology (perched boulders) resting on pillars of shale, termed perches, which may be over a metre high or, exceptionally, over two metres. The bases of the perched boulders are partly embedded in the upper surfaces of the perches. The whole physical feature consisting of perched boulder and perch will be referred to as a perched boulder complex.

Very few studies have been made of any of these three categories of deposit. None has dealt with the characteristics of boulder beaches and only recently has the existence of the process of imprisoning been recognised[1]; it has been discussed briefly by three authors - Baker (1959), Shelley (1968, 1970) and Hills (1970, 1971). The formation of beach conglomerate is a much-studied process (e.g. Ginsburg 1953, Kaye 1959, Russell 1959, 1960, 1962, 1963) but the cement is usually calcium carbonate. Davies (1972, p. 116) has produced a diagram showing the distribution of such beach conglomerate; it is almost restricted to the tropics. The conglomerate of north-east Yorkshire is different in both nature and environment, so that few analogies can be drawn from the published literature. However, both Agar (1960) and Richards (1969) have concluded that cemented material on the coasts of north-east Yorkshire and Skye respectively are the result of the precipitation of compounds since the fall of sea level at the onset of the last Glacial period. The perching of boulders in a littoral environment has long been known; as early as 1903 Geikie gave an illustration of a large dolerite block resting on tuff at Largo, Fife. Hills (1971) has recently noted that fallen aeolianite blocks at Sorrento, in Victoria, Australia, lie on perches three to five inches high, but it is evident that the dominantly solutional environment with which he was concerned is radically different from the high energy coast of north-east Yorkshire. No other studies of perched boulders have been made except for the interpretation reached by Agar (1960) that in north-east Yorkshire the perches result from the weathering of the Eemian shore platform exposed between the boulders during the Last Glacial period. He considered that the weathered material has been removed by the sea in Post-Glacial times.

It is therefore the objective of this chapter to examine the characteristics of these three basic types of superficial deposit and to show how they have evolved. A subsidiary aim is to examine the

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[1] A passing reference was made to "grouted boulders" by Hemingway in 1950.

evidence for Agar's proposition that the perched boulder complexes and patches of conglomerate are basically the result of formerly operating processes.

Boulder Beaches

The Distribution of Boulder Beaches

The three categories of superficial deposit are closely related in their spatial occurrence to the lithology of the cliff immediately landwards. The thickest spreads of boulders lie between White Stone Hole and Whitestone Point, near Saltwick Bay, where a broad syncline ensures that almost the whole cliff is composed of the Lower and Middle Deltaic Series. The boulder beaches here are usually associated with talus cones. Elsewhere, there are no spreads of sandstone boulders where the Lower Deltaic Series do not crop out in the cliff. Hence, in Far Jetticks, north of Robin Hood's Bay, where Lias Shales constitute all the 300ft. (91.5m) cliff, there are no boulders. Similarly from Sandy Wyke near Staithes to Hole Wyke which is below Boulby the platform is almost bare, but west of this bay the boulder beach is thick where the Deltaic Series crops out on Boulby Cliff. However, such superficial deposits are not correlated with the Deltaic Series alone; large arenaceous blocks of rock which are not easily destroyed by wave action are also produced by the Sandy Series. Talus cones are not commonly associated with this series, though several do lie on the northern side of Robin Hood's Bay, and the associated boulder beaches are of only medium density. They exist also at Cowbar Nab, Staithes.

Although the existence of a boulder beach is related to lithology, its density is related to the two variables of the proportion of the cliff composed of resistant sandstone and to the thickness of the individual beds. Thus at Hawsker Bottoms the sandstone scarp is only about 7.5m high but a thick boulder beach and talus cones exist because the channel sandstone stratum alone is more than 4m thick. Between Whitby and Saltwick Nab the talus cones and boulder beaches are thicker wherever channel sandstones occur. In contrast, though the whole cliff in the bay south-east of Widdy Head is composed of Middle Jurassic rock, the thin arenaceous strata constitute only a quarter of its height and no talus cones exist; the landward half of the shore platform is covered by a pebble beach and the boulder beach on the rest is of only medium density.

The Nature of a Beach of Free Boulders

In order to examine the nature of a boulder beach, a belt transect 5m wide was delimited in a direction perpendicular to the coastline at Hawsker Bottoms (the site is marked with an asterisk in Fig. 3.1). The lengths of the principal axes, the orientation and dip of the long axis, the distance of the centre seaward from the datum line, and the lithology (Dogger or Lower Deltaic Sandstone) were noted for each boulder whose long axis was greater than 0.5m. The transect was 40m long and the characteristics of 171 boulders were measured.

The size distribution of the boulders is highly positively skewed there being 27.5 per cent less than 0.1cu.m. but only 17.0 per cent between 1.0 and 8.2cu.m. The 120 Lower Deltaic Sandstone boulders do not differ significantly in size from the blocks composed of the Dogger sandstone. A statistically significant difference exists at the 0.001 level ($\chi^2 = 38.074$; 3 degrees of freedom) between the shape distributions of the two lithological categories (Fig. 6.1a). The Dogger produces more prolate boulders and the Deltaic Sandstone more triaxial boulders than would be expected by the null hypothesis. This may be chiefly due

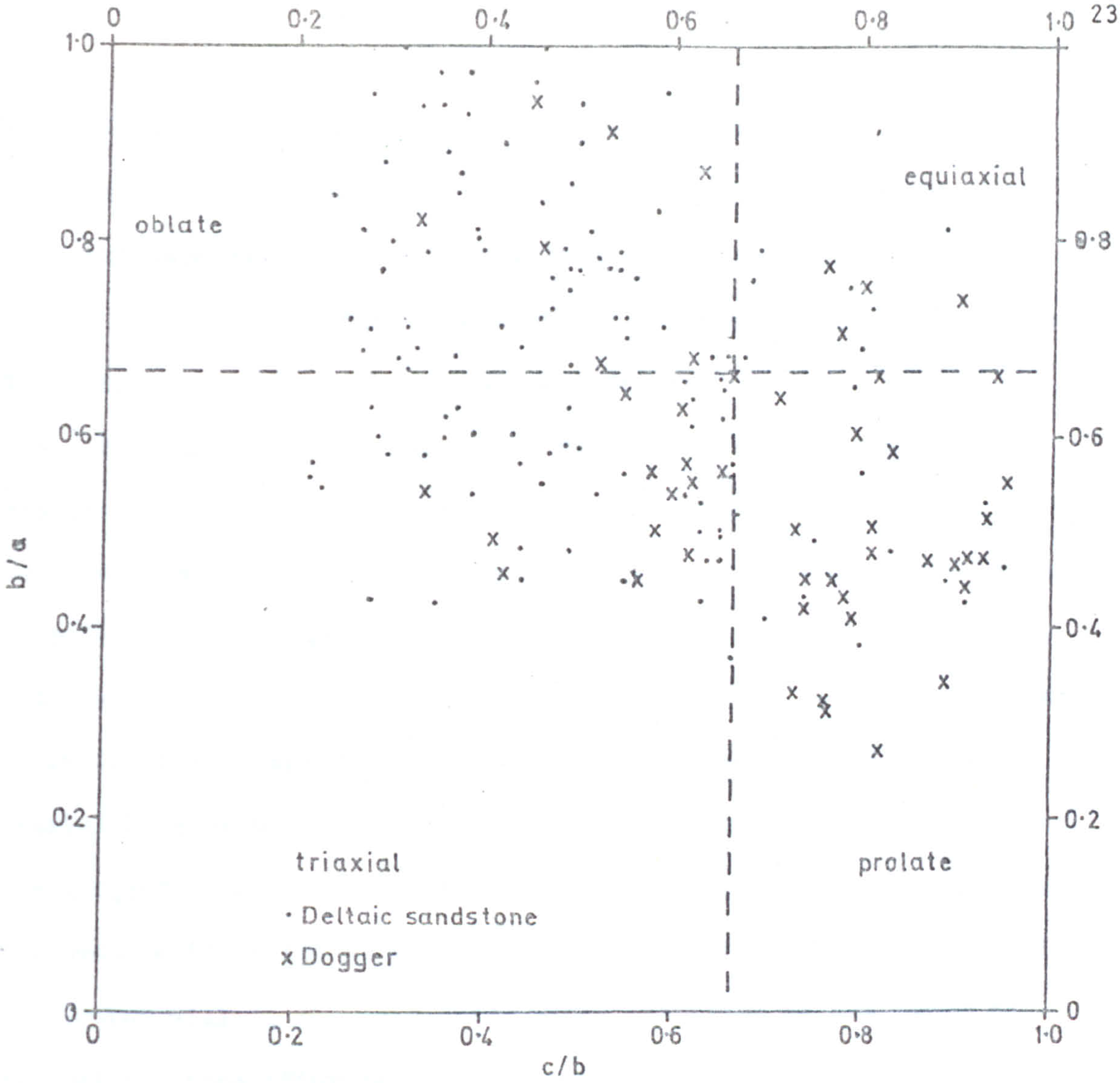

Fig. 6·1a Shape of boulders in the Hawsker Bottoms beach

Fig. 6·1b A boulder fractured during a storm to the thickness of the Dogger at Hawsker Bottoms (1.9m) and to the thinness of the Deltaic Sandstones in the scarp above the study area; and secondarily to different joint systems in the strata.

It is clear from Fig. 6.1a that the littoral environment imposes limits on the spectrum of possible boulder shapes. Thus few exist with a b/a axial ratio of less than 0.4 and none has a c/b ratio less than 0.2. The difference between these two values indicates that moderately triaxial boulders can remain unmodified in the beach but moderately prolate boulders cannot. In the case of two boulders of the same volume and b axis, one triaxial and one prolate with the b/a ratio of the former equal to the c/b ratio of the latter, the triaxial boulder will have the larger maximum cross-sectional area ab. This largest face is the one on which the boulder will preferentially rest because it is the most stable position. The larger this face is, the greater will be the cushioning effect provided by the water as the boulder drops after having been lifted by a wave. The probability that the boulder will be fractured will therefore be reduced. This cushioning effect must outweigh the opposite one of the thickness (c) of the triaxial boulder being less than that of the prolate block. During storms, boulders are lifted wholly or in part and, on being dropped, the confusion of boulders in a beach ensures that there is a high probability that the boulder will strike the corner of another. All the force generated during the fall is concentrated into a narrow zone or at a point by this corner so that there is a high chance of the impinging block being fractured. The results of this are obvious after each storm (Fig. 6.1b); large boulders can be found with fresh, angular fracture faces. Those boulders possessing a large surface area with respect to their volume will be most prone to this, i.e.

those less than or near the common limits for shape. The truncation of projections and corners of large boulders will then produce small blocks which can be lifted and moved more easily and, therefore, eroded quicker. In more equidimensional boulders, abrasion is likely to be important since these will be more difficult to lift as more pressure will be needed and as fewer protuberances will be available for fracturing. This trend toward more equant boulders is clear when Fig. 3.9a is compared with Fig. 6.1a.

The landward 10m of the transect were situated on the edge of a small talus cone while the rest was on the boulder beach proper where the blocks are covered at each high tide. The differences in the frequencies of Dogger and Deltaic sandstone boulders between the three ten-metre sections of this latter part are not significant at the 0.05 level ($\chi^2 = 0.122$; 2 degrees of freedom). However, of the 53 boulders in the talus section only one was composed of the Dogger. The differences between this section and the rest are significant at 0.001 ($\chi^2 = 27.936$; 3 degrees of freedom). This grouping of fallen boulders of the same lithology might be expected if Dogger blocks fall in rare large collapses of the sandstone scarp but is clearly in marked contrast to the even mixture of rock types in the beach. This may indicate that despite the numerous upward projections of boulders and their hemming in of each other, the sea is able to carry blocks to and fro, thus mixing them. It may also indicate that Dogger blocks persist longer in the beach because of the higher iron content and coarser grain size of the Dogger in comparison with the Deltaic sandstones.

There is no significant difference between the size distributions of the boulders in the four ten-metre sections. Nevertheless, in the field the absence of shale fragments and the paucity of boulders less than about 0.5m long in the seaward 30m of the corridor are in marked contrast to their abundance in the talus cone. Neither the shape characteristics of the measured boulders nor the dips of their long axes differ significantly seawards, though there is a strong tendency (significant at 0.10) for the dips of the boulders on the talus cone to be different from those in the rest of the corridor. As might be expected, the boulders on the talus cone tend to have higher inclinations than those in the true beach. The proportion of boulders with dips equal to or greater than 10 degrees in each of the ten-metre sections falls seawards as follows: 64.2 per cent, 59.5 per cent, 51.2 per cent, 36.8 per cent.

Hence it is concluded that in the erosion of a talus cone small particles are removed leaving boulders behind. These boulders tend to rest on their largest faces and are carried hither and thither while being moulded towards a spectrum of stable shapes and inclinations. Therefore the boulders become increasingly resistant to erosion.

The Nature of a Beach of Imprisoned Boulders

Wherever an expanse of boulders is described as sparse or of medium density, the blocks tend to be sub-angular or sub-rounded, due to abrasion between themselves or with the shore platform, and there is little impediment to movement. Imprisoning is therefore more common where blocks are piled up, and movement is restricted. The phenomenon has not been noticed with Sandy Series boulders possibly because the blocks are smaller and the beaches thinner. Imprisoning is especially common between White Stone Hole and Whitestone Point. At White Horse (east of Hawsker Bottoms), imprisoned boulders exist at heights of 1 to 2.5m above O.D. At Cobble Dump (north of Runswick) and South Batts (east of Saltwick Bay), imprisoned boulders which are cemented together occur at about the one metre level. It seems therefore that this phenomenon of imprisoning is best developed in the zone of maximum wave energy which lies above mean sea level. It is in this zone that the highest boulders can be agitated within the confined spaces allotted to them by their neighbours. At higher levels impinging waves are less frequent while below the optimum zone the higher frequency of wave action increases the rate of abrasion and fracturing of the boulders so that only the largest blocks will be imprisoned.

At White Horse, in a belt transect 5m wide aligned towards the sea, the parameters of all boulders greater than 0.5m long were noted if the lengths of all their three principal axes could be measured. 45 boulders above about one metre O.D. were found, they being either cemented together or overlying conglomerate. Below 1m O.D. 69 boulders were located in the corridor. Of the first group, in addition to many of them being cemented, 75.5 per cent are imprisoned while in the second, none are cemented and only 8.7 per cent interlock (the differences are extremely significant at the 0.001 level; $\chi^2 = 50.560$, one degree of freedom). This may be due to the different boulder size distributions exhibited by the two groups - these differences are also significant at the 0.001 level ($\chi^2 = 19.395$; 3 degrees of freedom), the boulders in the cemented area being much larger on average than the others. 51.1 per cent of the boulders in this group are bigger than 0.5cu.m. while only 18.8 per cent of the second group exceed this size. There are no significant differences in shape, lithology and orientation and dip of the long axes of the boulders in the two groups.

Each imprisoned boulder has both male and female components. Only the maximum male and female penetration of each boulder were considered in this study. Volume is likely to be the principal variable influencing the amount of penetration between boulders. However, the correlation coefficient ($r = -0.0349$) between the size and female component of each boulder completely fails to attain significance. On the other hand, the correlation coefficient between the male component and boulder size is significant at the 0.0005 level though only 43.10 per cent of the variation is explained by the equation:

$y = 3.5926 + 1.2595x$ where y = amount of male penetration (cm)
x = size of boulder (cu.m.)

Therefore, small boulders, although they can be moved more frequently than larger ones and might be expected to attain greater penetration, cannot do so because they are more likely to be moved so much that the imprisonment is destroyed. It is noteworthy that the agitation of a boulder causes it to dig into another rather than for it to become impaled on its neighbour, i.e. the male component is the result of agitation while the female is caused by the boulder remaining stationary with respect to its mate. The male component occurs at the primary corners of a boulder while the female is generally located in a face or at the junction of two faces.

It has been shown that imprisoning is related to the efficacy of marine energy through the variable of the size of the boulder. This is a different conclusion from that reached by Shelley (1968, 1970) who has ascribed the occurrence of imprisoned boulders in New Zealand to " . . . disruption by the crystallisation of salt and of ice . . . " though the solution of silicate minerals by micro-organisms is also thought to operate where the fitting interfaces remain damp. If these weathering processes are important in north-east Yorkshire it is difficult to see why the amount of penetration is related to boulder size. It would be necessary for adjacent boulders to be continuously moved together to maintain the close fit and it is not clear why erosion by salt and ice crystallisation should be more effective at the interface of two boulders, where air circulation is limited and there is likely to be permanent shadow, than on the rest of the boulders' surfaces where there are no such limitations. In addition, the weathering processes mentioned by Shelley should differ in effectiveness with lithological variations such as the degree of cementation. Moreover, the argument that fitting boulders are not found in rivers and therefore that agitation of the blocks is not the formative process in imprisoning is not valid because the turbulent flow in a river is essentially uni-directional while, in waves, water particles describe circular or oscillatory paths and waves themselves can be reflected with great force. It must be concluded, therefore, that abrasion is the main erosive process in the imprisoning of boulders, a fact tacitly assumed by Baker (1959) and briefly discussed by Hills (1970).

An attempt has been made to measure the rate at which imprisoned boulders abrade each other. The technique used is that employing pairs of stainless steel hexagonal set screws described earlier, each one of the pair being separated from its twin by the interface between the imprisoned boulders. The instrumentation area is the accumulation of large boulders which is the remnant of a talus cone at White Horse. Because the boulders are just as likely to be parted as to be forced closer together, and because the frequency of waves powerful enough to move the boulders must be very small, these instruments will have to remain in position for many years before any reliable erosion rates are obtained.

The Evolution of a Cuirass

It seems reasonable to suppose that, with time, most boulders in a small area could become imprisoned and the rate of mutual abrasion should diminish to a negligible amount. In this case the imprisoned boulders will form an impregnable cuirass which could remain for a very long time. However, there is a number of ways in which it can be destroyed; processes exist which attack either individual boulders or the whole cuirass. As in a beach composed of free boulders, wherever there is some movement, fracturing is probably the most important process. A special form of abrasion which is visible at a number of places at White Horse is best described as a pestle and mortar action (Fig. 6.2a). The mortar is a pot hole and the pestle is a single small boulder, usually less than 0.5m long. They are normally found where two or more imprisoned boulders have formed a depression in which the pestle becomes trapped. Agitation of it creates a hole in the boulders.

While fracturing, abrasion, and pestle-and-mortar action attack individuals or groups of boulders they are unlikely to be of great impartance in the destruction of a cuirass as a whole. This will be most effectively carried out, as at White Horse, by the corrasion of the shore platform itself which becomes lower than the buried, protected part and a riser is formed. The corrasion is produced by free boulders which cause the retreat of the riser(Fig. 6.2b) and undermine and break up the cuirass thus liberating the imprisoned boulders. Because of the intensive erosion at the points where their neighbours have abraded them, the released boulders have many projections which are easily broken off by fracturing. The boulders so produced are statistically significantly smaller than the imprisoned blocks (vide supra). Owing

Fig.6·2a A pestle and mortar

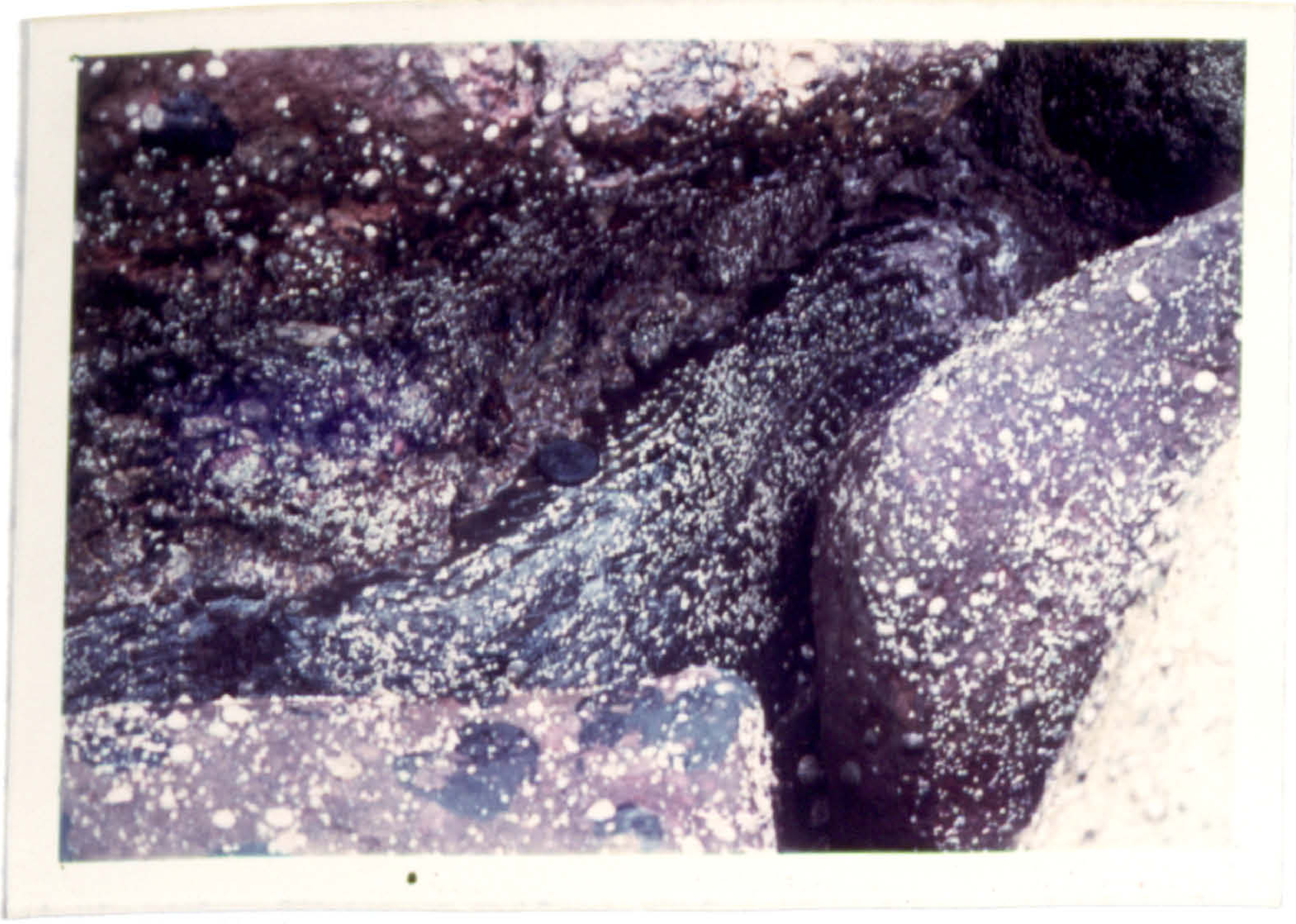

Fig.6·2b The shale perch beneath the White Horse boulder cuirass with free, eroding boulders in the foreground to the removal of much material during the imprisonment, releasing, and fracturing periods, the total volume of released rock is much less than before imprisonment occurred. Hence, these free boulders are more likely to remain free, though at White Horse six of the 69 boulders measured were still imprisoned. The freed boulders in turn are nearest to the shale perch and erode it further causing more of the cuirass to be destroyed. Should the free boulders be removed, e.g. by being transported around the cuirass to the cliff foot, the cuirass will remain for a long period. After the removal of the sandstone boulders by the action of the other processes described and by the force of highly destructive waves, a shale perch will remain which may be several metres in diameter and up to a metre high. Such a genesis may explain these features at, for example, White Stone Hole, South Batts, and Lingrow.

The Conglomerate

The Nature and Distribution of Conglomerate Patches

The conglomerate patches of the north-east Yorkshire coast can be found in many situations, e.g. at the heads of bays, in the bases of degraded talus cones and surmounting shale perches far from the cliff. Their composition is related to the proportions of rock types available at their time of formation and so can vary rapidly in small areas. Thus, part of the conglomerate patch at Cobble Dump (Fig. 5.12) has more than 75 per cent of its volume in the form of rounded shale blocks up to 40cm long while a few metres away sandstone boulders, iron nodules and fine grained matrix occur in equal proportions and no blocks of shale can be found. However, the dark red to brown colour of the matrix, the frequent red coating of cemented cobbles, and the leaching of the interiors of Dogger and Lower Deltaic Sandstone boulders to a light grey colour while very hard iron pans up to 0.5cm thick coat their surfaces, indicate that the common cementing agent is a ferric compound of iron.

The patches extend from High Scar (951075) in the south east to Seal Goit in the north west but, within this stretch of coast, they are absent from Old Nab near Staithes to Long Sand near Boulby Cliff. The locations of many patches are listed in Fig. 6.3 but many others exist. These sites are highly correlated with the outcrop of the Lower Deltaic Series in the cliff. Thus, from Saltburn to Seal Goit and from Far Jetticks to Ravenscar the cliff is composed of Lias rocks alone and cemented material is absent from the foreshore. Nevertheless, the Upper Lias shales are rich in iron (4 to 5 per cent on average according to Gad et al (1969)). The well jointed and laminated nature of these shales allows them to be broken into small fragments making the resulting debris highly permeable. Therefore, iron-rich solutions are easily formed. These shales may not be the only source of iron for the cementation of material, since above them lies the Dogger which is a coarse, highly ferruginous sandstone (20 to 24 per cent iron content - Hemingway 1958) which has been mined in the past as an iron ore. Its coarseness permits it to be highly permeable also.

Because of the great compositional variations, the conglomerate patches are classified in Fig. 6.3 on the basis of their environments. In numerous talus cones, reddening of the basal layers is common. The colour fades upwards giving way to a light grey hue characteristic of thoroughly weathered shale. Occasionally, e.g. at Quarry End, the reddened layer is in the middle of the talus section where material is coarser than that below. The basal debris in this case is probably

Location	Grid Ref.	(I)	(2)	(3)	(4)	(5)
Hunt Cliff	6972I7		X			
Hummersea	72520I			X		
Boulby West Cliff	733202		X			
Lingberry Hill	75III9		X			
Rockhole Hill	755I96		X			
Hole Wyke	762I92			X		
Brackenberry Wyke	793I82				X	X
" "	797I8I	X				
" "	798I80		X			
Port Mulgrave	798I86					X
High Lingrow	806I72		X			
" "	808I72		X			
Victoria Ironworks	8III66					X
Quarry End	8III65				X	
Cobble Dump	8I2I63		X			
Redscar Hole	822I56			X		
Kettle Ness	832I60					X
" "	836I60		X			
Lucky Dog Holes	839I57				X	
Holms Grove	84II54			X		
" "	84II54	X				
" "	843I42	X				
Loop Wyke	847I47				X	
Tell Green	85II47	X				
Keldhowe Point	854I46				X	
Overdale Wyke	856I43		X			
Deepgrove Wyke	857I42			X		
Sandsend	859I35				X	
Whitby East Pier	902II5		X			
Saltwick Bay	9I6II0					X
" "	9I7I09			X		X
Black Nab	92II07					X
" "	922I07					X
South Batts	925I06		X			
" "	927I05		X			
Ling Hill	930I0I				X	
Widdy Head	933094	X				
Pursglove Stye	947080				X	
" "	94708I		X			
White Horse	948079	X				
White Stone Hole	948078	X				
High Scar	95I076		X		X	

(I) Cemented material under boulder beach
(2) Cemented coarse-grained beach
(3) Cemented sand
(4) Cemented talus
(5) Cemented material associated with activities of Man

Fig.6.3 Locations and classification of some patches of cemented material impermeable or has a high water table allowing little permeation of iron-rich water to lower levels. These talus cones often occur at the foot of marine activated parts of the cliff and have surfaces with fresh shale fragments upon them indicating their youth. Only a few are listed in Fig. 6.3.

Because spreads of thick boulders are the degraded remnants of former talus cones, the patches of cemented material found in their bases are probably older than conglomerate exposed in talus cones. At White Horse, boulders are up to 8cu.m. in size and the formation of the cuirass of imprisoned blocks has added to their stability. Interestingly, however, a number of boulders which have cemented bases are also imprisoned. This suggests that the imprisonment occurred before deposition of the shaly material which forms the conglomerate matrix, i.e. that some of the boulders formed a boulder beach before a talus cone accumulated over them. This in turn implies that there has been a period when the amount of material falling from the cliff was small, then a period of intensive deposition followed by the present period when no shale falls on the area of the boulders.

Several patches of cemented material can be found resting on broad shale perches far from the cliff foot. The best examples are those already referred to at Cobble Dump and South Batts. In both these cases barnacles are common indicating the very low rates of erosion. As at White Horse many of the cemented boulders are also imprisoned. In addition, 20 erratics have been recognised at Cobble Dump and three at South Batts. All these rocks are extremely hard - much more so, in fact, than any of the local ones. They are all very well rounded and the maximum lengths are 32cm at Cobble Dump and 7cm at South Batts. They have clearly been subjected to prolonged corrasion in a beach environment following their transport to this coast. Similar erratics can be found in the present beach at Quarry End but no cobble beach now exists south of Black Nab.

At Cobble Dump, at the point marked with an asterisk in Fig. 5.12, there was found the internal cast of a limpet together with some of the shell. Though such shells are not common in the high energy environments of a cobble beach, the fossil is Patella vulgata Linné (Dr. J. R. Lewis, personal communication) an extremely common species at the present day in the intertidal zone of north-east Yorkshire.

The Rate of Cementation

It is clear from the presence of cemented cobbles beneath a number of modern beaches, e.g. about 3m east of Whitby East Pier, at the southern end of Brackenberry Wyke, and at High Scar, that the cementing process continues today. The protection from movement by waves has been afforded in these cases by overlying cobbles, while the source of iron compounds is the shale fragments that have fallen from the cliff and have been incorporated into the beach. At High Scar, the rounded cemented cobbles of a beach are overlain by partially cemented talus. No boulders have protected this site but it is high enough to be washed by waves only during severe storms, so a talus cone of small shale fragments has been sufficient to provide the necessary protection. All these sites occur at the feet of marine-activated sections of the cliff which are undoubtedly post-glacial in age. Indeed, the site at Whitby was landward of the cliff in 1816 (Chapter 8). Therefore, the rate of cementation is rapid. Even after the first major storm of winter has removed from the cliff foot at Hawsker Bottoms the material which has accumulated there during the preceding summer only, the rock surface is coated with a patina of iron. Also the weathering of the shale fragments is rapid, for those fragments which fall at the start of the accumulation period have been partially metamorphosed to mud by the end of it.

An estimate of the rate of cementation can be obtained from a consideration of the age of features which have been built or formed by Man and which are now associated with patches of conglomerate. There is no reason to think that the process is different or more rapid in these cases, except where indicated. The jet adits which were intensively exploited in the second half of the eighteenth century and abandoned by about 1900 (Raistrick 1966) have now collapsed and can be recognised only by their straight, cut sides and bases. They are best seen in White Stone Hole and between Sandsend and Kettle Ness. Their bases are frequently reddened and cemented by iron. This vanishes upwards indicating that the solid base of the adit has formed a perched water table in the debris where the iron compounds have consequently been deposited. These numerous examples are not listed in Fig. 6.3. The cementation is certainly not as strong as at Cobble Dump, but the available period for cementation has been less than 100 years.

During the quarrying of the Alum shales, the rock was broken into small fragments and piled into large heaps in layers alternating with brushwood. This was ignited and the heaps burnt, sometimes for many months aided by spontaneous combustion of the iron pyrites in the shales (Turton 1938; Chapman 1968b). The ash produced by this calcination is red and can be seen in most quarries as its sterility is too severe for the growth of vegetation. The ash was put through various washing processes to extract the alum and was then discarded. On the western side of Kettle Ness, some of these patches of burnt shale are cemented and show steep bedding due to the debris having been thrown over the cliff edge. In one of these patches a piece of wood was found and pieces of metal are common in others. Metal is particularly well cemented to rock fragments as it provides a richer source of iron than the rock. The actual output and periods of operation of the alum quarries are not well documented, but Chapman (1968b) has given approximate dates during which the following sites were exploited:

Sandsend	1600 - 1871
Saltwick	1649 - 1821
Boulby	1649 - 1871
Lingberry (Loftus)	1649 - 1863
Kettleness	1728 - 1871

This indicates that the canglomerate at Kettle Ness has formed during a maximum period of 242 years.

Tiny fragments of burnt shale commonly make up much of the sand in the beaches along the coast especially at deeper levels, e.g. at Saltwick Bay, from Whitby to Sandsend, at Kettleness Sand, Hole Wyke, and Hummersea. Following severe storms when the sand is combed down or after long periods of constructive wave action when it is pushed towards the cliff foot, small patches of cemented, partly burnt fragments can be found.

Small piers are associated with most alum quarries. These quays were built with local Deltaic sandstone or occasionally with Dogger, and were filled with debris if necessary. This interior is now cemented in all cases and even where the pier is only a few metres wide, e.g. east of Saltwick Nab, small patches of cemented material can be found. No records of the dates of these structures have been discovered though their proximities to the quarries indicate that they were built shortly after the initiation of operations. On the western side of Black Nab, however, there is a stone pier with a dated inscription recording its construction in 1766. The boulder bearing this date does not appear to be itself cemented as it lies on the surface but conglomerate is common around it. This consists in some places of unburnt shale (black), completely calcinated fragments (red) and those which have been ignited in part only (red and black). At Wrack Hills, Runswick, a small pier below the Victoria Ironworks (1856 to 1858) has a vertical piece of wood to which are cemented fragments of rock. Conglomerate can also be seen in the eroded base of the south-eastern pier at Port Mulgrave (built between 1850 and 1856 according to Chapman 1968a), but none is visible in the northern pier which was demolished in the storm surge of 1952. It is possible that the rate of cementation was increased by the storage of iron ore on the pier before it was loaded on to ships.

Although exact rates of cementation cannot be evaluated for all the above cases, it seems reasonable to conclude that they are of the order of one hundred to two hundred years. For much if not all of this period therefore the material being cemented must have been protected from movement and washing by waves either by a pier, a beach, or by a talus cone where there is a local source of Upper Lias shales from which the cement has been derived.

Perched Boulder Complexes

The Lingrow Perched Boulder Area

Blocks composed of sandstone and of the arenaceous members of the Sandy Series commonly rest on shale perches along the north-east Yorkshire coast. The largest area of perched boulders is at grid reference 48095171, which is midway between the village of Runswick Bay and Port Mulgrave. This locality will be termed the Lingrow perched boulder area since to the north lies the low-tide island Lingrow Knock, and to the west the hill High Lingrow. The large number of perched boulders in this area facilitates a statistical analysis of the dynamics of the perching process.

The Lingrow perched boulder area extends seawards (i.e. to the north-east) for more than 60m being bounded in this direction by unperched boulders and an extensive area of bare shore platform. Towards the land lies a boulder beach and behind that a large landslip called Wrack Hills. Eastwards the area merges into a boulder beach which occupies the whole foreshore, while to the west the shore platform is predominantly bare for 60m, though towards the sea this bare area gives way to a mélange of shale boulders typical of a locality where the shore platform has been mined for jet.

A detailed geological map of this area has been produced by Howarth (1962). The perched boulder area lies on the Grey Shales and its western edge is marked by the two parallel faults constituting the Runswick Bay Fault. This is one of the major dislocations of the district with a displacement of 30 to 40ft (Hemingway 1958). It downthrows to the west where Bituminous Shales crop out at the cliff foot. These faults coincide with the slip scar of the large back-tilted Wrack Hills landslip and it is evident that their presence has facilitated the occurrence of this landslip.

The Age of Wrack Hills and the Lingrow Perched Boulder Area

Because the landslip has moved eastwards, no Lower Deltaic sandstone now crops out on about 50m of the north-facing marine cliff (between points A and B in Fig. 6.4) to the west of the faults.

Fig. 6·4 Morphometric map of Wrack Hills

Seaward of this shale cliff, the shore platform is bare while seaward of the landslip in a northerly direction lies the perched boulder area. Therefore it is concluded that the perched boulder area was formed after the landslip.

Agar (1960) has stated that boulders lying on the shore platform during the Last Interglacial protected the shale beneath while weathering of the rock continued between them during the periods of lowered sea level in the periglacial phase before the advance of the ice of the Last Glaciation. The post-glacial seas have removed the weathered material leaving the boulders perched. In addition, Agar has noted that " . . . boulder clay overlies a slip - at Wrack Hills, Runswick." Therefore, before any meaningful investigation of the perched boulders can be made, it is necessary to examine this proposition that the landslip, and thus the sandstone boulders on the shore platform, pre-date the Last Glaciation.

Fig. 6.4 is a morphometric map of the northernmost two-thirds of Wrack Hills. The southern part of the cliff has been disfigured by an iron mine and blast furnace. At the cliff foot three large facets slope away from the sea providing a typical back slope. On the upper part of the cliff there are also two small facets which slope only very gently seawards and all facet boundaries are sharp. There is, therefore, no evidence of a smoothing of Wrack Hills by ice; on the contrary, the freshness of the land surface, with its distinct boundaries, indicates its youth.

Nor has the landslip been adjusted to present environmental conditions for a long period. Secondary landslips, unconnected with marine erosion, exist near the cliff top and are shown in Fig. 6.4 by the two low-angle facets. That they are secondary and post-glacial is shown by the presence of thin boulder clay on them while their steep slip planes behind have none. There is also a record of a landslip at the southern end of Wrack Hills. The Victoria Ironworks Co. built a blast furnace which opened in August 1856 at this site. The major landslip must have been present at this time otherwise the cliff would have been too steep to build on. However, on 22nd March 1858, a landslip occurred destroying much of the workings and they were abandoned (Chapman 1968b).

Glacially deposited material only one to two feet thick covers the whole of the surface landward of the cliff top. It is not surprising, therefore, that this material should also lie on Wrack Hills wherever slips have occurred. One to two feet of red clay containing quartzite, greywacke and other erratics forms the uppermost layer of the marine-eroded face of the landslip and is undoubtedly glacial till. Elsewhere, on the slip planes of the landslip, none of the characteristically red deposit can be seen. Fine-grained material, though of a light grey to dark yellow colour is visible in the eroded face between the blocks of sandstone. It was probably produced during the actual landslipping and, subsequently, by the weathering of shale and sandstone. A gully, up to 15 feet deep in places, transects the major slip plane in the upper part of Wrack Hills. No red clay and no erratics crop out in its sides; only shale breccia and the very pale weathered derivatives of shale are exposed above the in-situ shale. It is concluded, therefore, that neither the morphology nor the composition of the landslip indicate a pre-Last Glacial origin for Wrack Hills, and thus of the sandstone boulders derived from this landslip and now lying in the perched boulder area.

The age of this area is also indicated by the rate of erosion at the cliff foot. Assuming a pre-Last Glacial age this should be negligible, but comparison of the 1914 and 1928 editions of the O.S. 1:2500 plans shows a rate of about 43cm in 13 years on average. This implies that the cliff foot could have retreated from the present seaward limit of perched boulders in about 4000 years and from the low water mark of ordinary tides in about 7300 years, assuming a stable sea level and a constant erosion rate. However, M.E.M. sites just west of the faults have shown a maximum rate of erosion (at the head of the notch) of 6cm in one year. At this rate the above periods for coastline recession are reduced to approximately 2200 and 4000 years respectively. It is concluded, therefore, that both the landslip and the perched boulder area have been created in post-glacial times. In addition, it will be shown later that certain characteristics of the perched boulders are compatible with this inference only.

The Distribution of Perched Boulders

North of the Wrack Hills landslip there is a boulder beach which is about 45m wide. Measurements were made of the characteristics of the 83 boulders in a randomly chosen belt transect across this beach; each measured boulder had a long axis of at least 0.90m. A part of the perched boulder area seaward of this beach was delimited for this study and is shown in Fig. 6.5. The area measured 60m in the seaward direction and included the most landward perched boulder while the other edge was near the marine limit of perched boulders. The area was 27.7m wide and contained 114 perched boulders, the smallest of which was 0.90m in length. Five tall perched boulder complexes were also included near the south-west corner of the area. The characteristics

Fig. 6·5 Distribution of perched and free boulders at Lingrow of all unperched boulders whose long axes were at least 0.90m were also measured; there were 128 of these.

Differences in the frequencies of perched boulders in four equal sectors of the study area (Fig. 6.5) are significant at the 0.01 level of probability. There is a below average number of occurrences in the south-west sector and an excess in the north-east. This concentration might be due to chance variations in the geology of the part of the Lower Deltaic Series which produced these boulders. Although the paucity of perched boulders in the south-west sector might be attributable to the same cause, an additional factor could be the nature of the recession of the platform here (a contour map is given in Fig. 6.5). It has been noted previously that tightly packed boulders in a cuirass are highly resistant to erosion but may be undermined and broken up by the generation and retreat of a riser in the shore platform because of the action of free boulders. Such a feature is prominent in the south-west quarter and no perched boulders exist immediately in front of it. The riser becomes gentler and fades out to the east. To the west it is covered by boulders and is truncated by the faults where the Grey Shales are replaced by the resistant Top Jet Dogger and the soft Bituminous Shales.

It will also be noticed from Fig. 6.5 that in no sector are the perched boulders evenly distributed. They tend to occur in clusters and often prevent the movement of free boulders landwards. Only those boulders with long axes greater than 90cm are shown in this diagram so the trapping effect is greater than might be inferred from the map. The free boulders, in turn, influence the distribution of the perched boulders in two ways. A large free boulder that is prevented from moving landwards may become embedded and, eventually, perched. On the other hand, an accumulation of small, free boulders, where movement is impeded by perched boulders, may act as a saw, eating into the perches and toppling the boulders so that a swath of foreshore is produced which is bare of perched boulders.

The Characteristics of Perched Boulders

The characteristics of a boulder are important in determining whether it can become perched. Descriptions of these physical attributes (viz. size, shape, inclination and orientation) are given in turn together with assessments of their influence in the perching process. Because the coastline is retreating, perched boulders far from the cliff foot can be assumed to have a longer history than those near the cliff. The surface roughness of the foreshore makes it unlikely that rip currents are sufficiently strong at Lingrow to carry seawards boulders which are large enough to become perched. Movement of boulders landwards confuses any relationship between distance from the cliff and boulder age.

1. The Size of Boulders - The size of each boulder was estimated from the product of its three principal axes. Three samples of data exist (namely, perched and free boulders in the perched boulder area and those boulders in the boulder beach) and there are significant differences (at the 0.01 level) between each pair of size-frequency distributions. Perched boulders are on average the largest of the three types while those boulders found in the boulder beach are the smallest. This result implies that as the boulder beach retreats with the coastline, large boulders remain behind and become perched while most smaller ones are perched for only a short time, if at all, and generally form the population of free boulders. By comparing the percentage distributions for perched and free boulders and by adding the smaller value for each class it is concluded that 64.8 per cent of

the free boulders are sufficiently large to become perched. Similarly 37.9 per cent of those in the boulder beach are eligible to become perched but they have not been exposed long enough for this to have happened. The existence of bare perches indicates that some of the free boulders in the perched boulder area have been dislodged.

There is no correlation of perched boulder size with distance seawards but if those boulders larger than 3cu.m. are excluded, i.e. ones which are rarely moved, a relationship is revealed. The regression equation between mean boulder size (y) in 10m zones and distance seaward is

$$y = 1.5372 - 0.0107x \qquad (r = -0.8761)$$

Hence, perched boulders tend to become smaller seawards though very large ones still occur. Since the movement of boulders is predominantly landwards, this trend is unlikely to be the consequence of the transporting of small boulders towards the sea. Therefore the relationship must be the result of the increasing history and, thus, greater period available for the erosion of the boulders which are now perched. Such boulders are usually above the influence of corrasion by free boulders, so erosion can occur only when they are not perched. This will take the form of corrasion, or more effectively, fracturing especially during their dislodgement from the top of the perch. Very large boulders are likely to be dislodged very infrequently so that they show little reduction in size. As free boulders can be eroded constantly it is not surprising that most of them are less than one cubic metre in size and this parameter, except in the case of the largest boulders, shows no reduction towards the sea.

2. <u>The Shape of Boulders</u> - Zingg diagrams for perched boulders, free boulders and boulders in the boulder beach are shown in Figs. 6.6a,

6.6b and 6.7a respectively. All but one (i.e. 0.9 per cent) of the points for perched boulders lie within the limiting ratios of c/b = 0.250 and b/a = 0.375, values which are very close to the limiting ratios found for the boulder beach at Hawsker Bottoms (Fig. 6.1a). Only 4.8 per cent of boulders in the beach have shapes that fall outside these limits. This indicates that shape is not important initially in determining whether a boulder can become perched. However, 15.6 per cent of the free boulders lie outside the limits and most of these are oblate, i.e. the c-axis is small relative to the other two. Boulders rest on their largest (i.e. ab) face because it is the position of greatest stability. Corrasion of this face by movement of the boulder over the shore platform reduces the length of the c-axis thus producing smaller c/b ratios for free boulders in the perched boulder areas than for those boulders still trapped in the boulder beach. Boulders with low c/b ratios also exert the least vertical pressures so sliding is easier than for other shapes. In contrast, equiaxial boulders exert the most vertical pressure and also have the least surface area relative to their volume with the result that the greatest wave pressure per unit of mass must be applied to initiate movement.

3. The Inclination of Boulders - The inclination of boulders, which is the angle of their long axes to the horizontal in the direction of dip, has little influence on their development. There is no statistically significant difference between the frequency distributions of the dips of boulders in the boulder beach, of the perched, and of the free boulders. All categories have a high frequency at less than 10 degrees (68.8 per cent of free and 61.3 per cent of perched boulders, and 56.6 per cent of those in the boulder beach). Therefore, most boulders have been moved into stable positions by the sea before perching occurs.

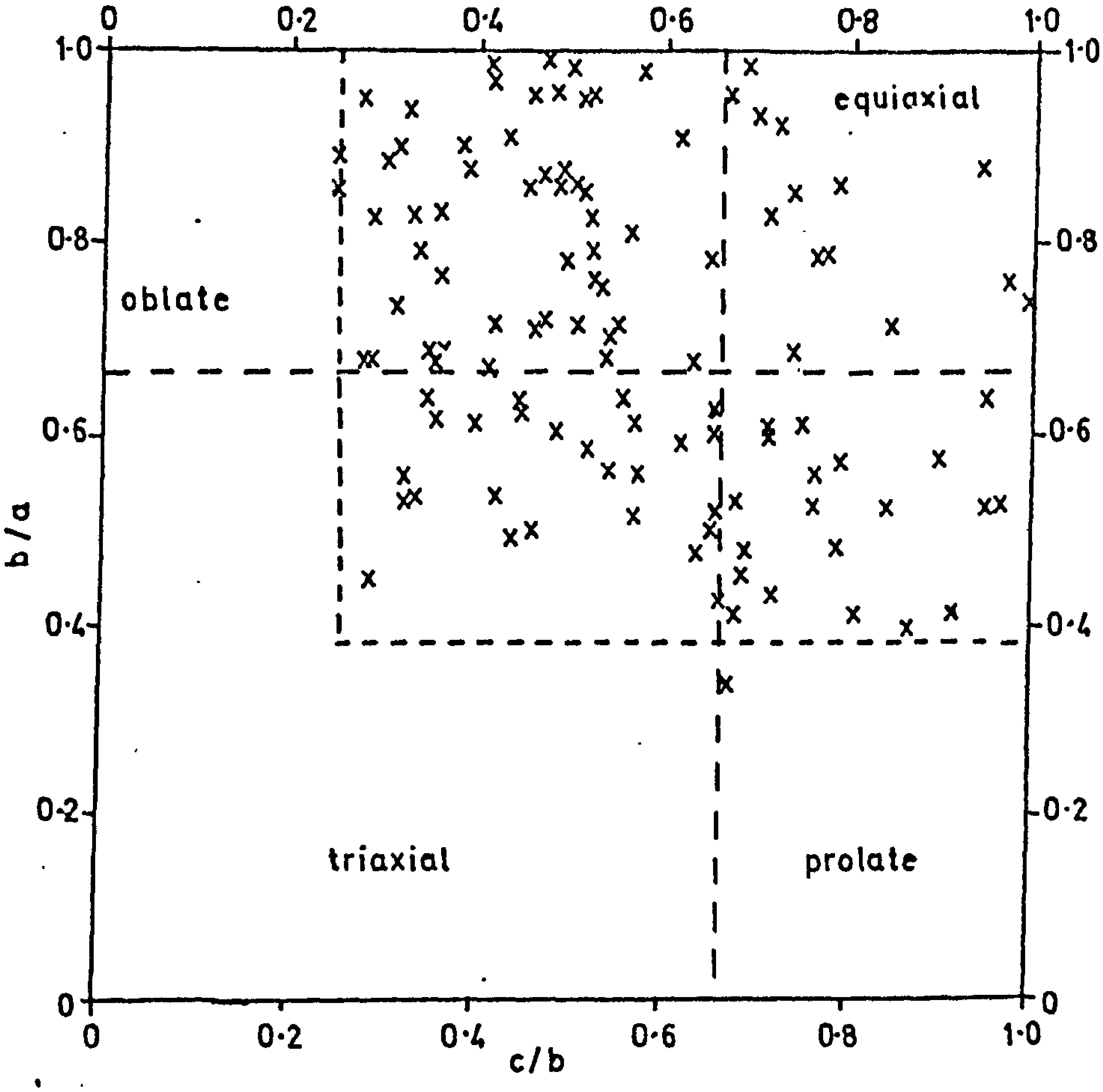

Fig. 6·6a Zingg diagram for perched boulders

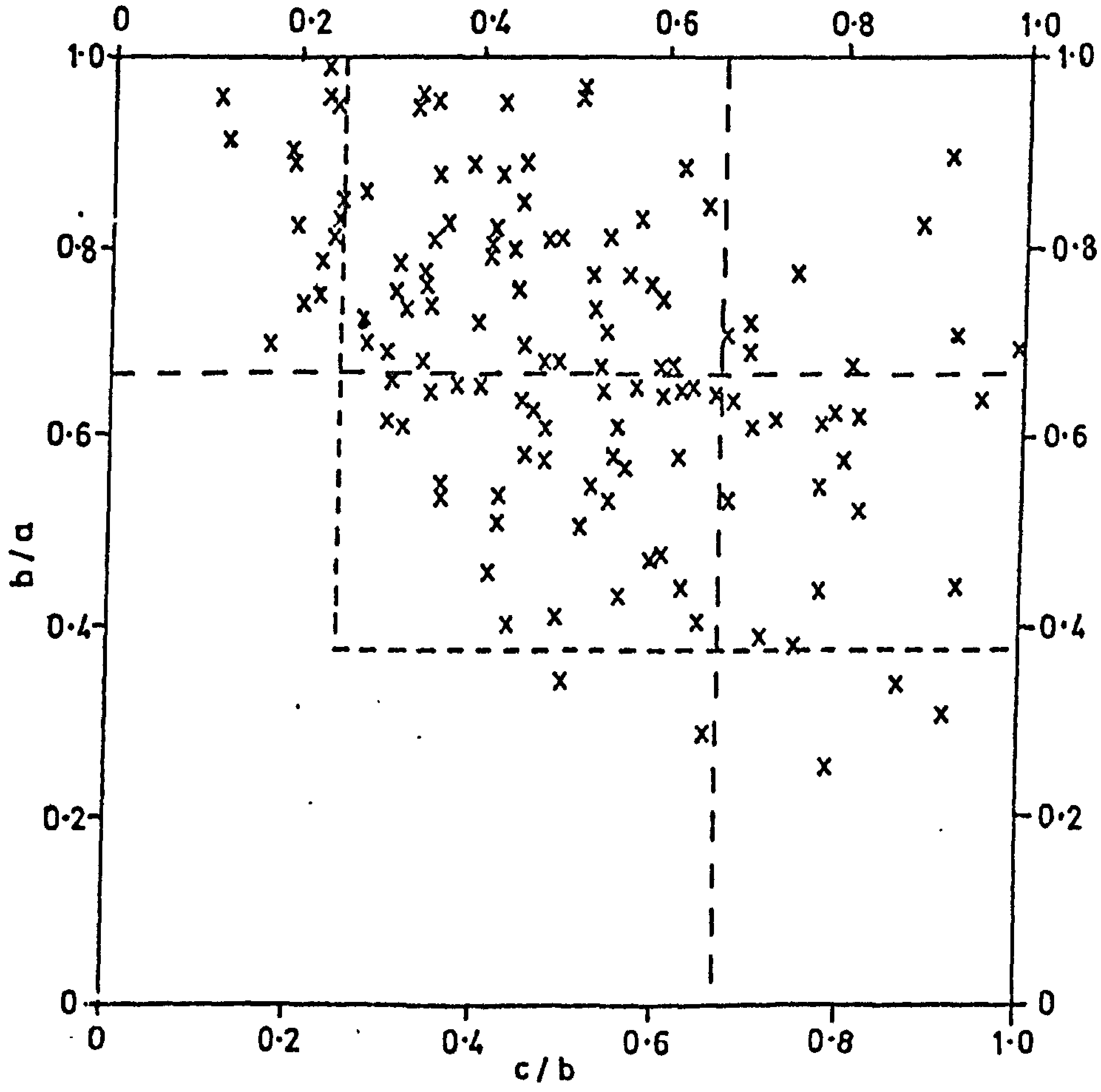

Fig. 6·6b Zingg diagram for free boulders

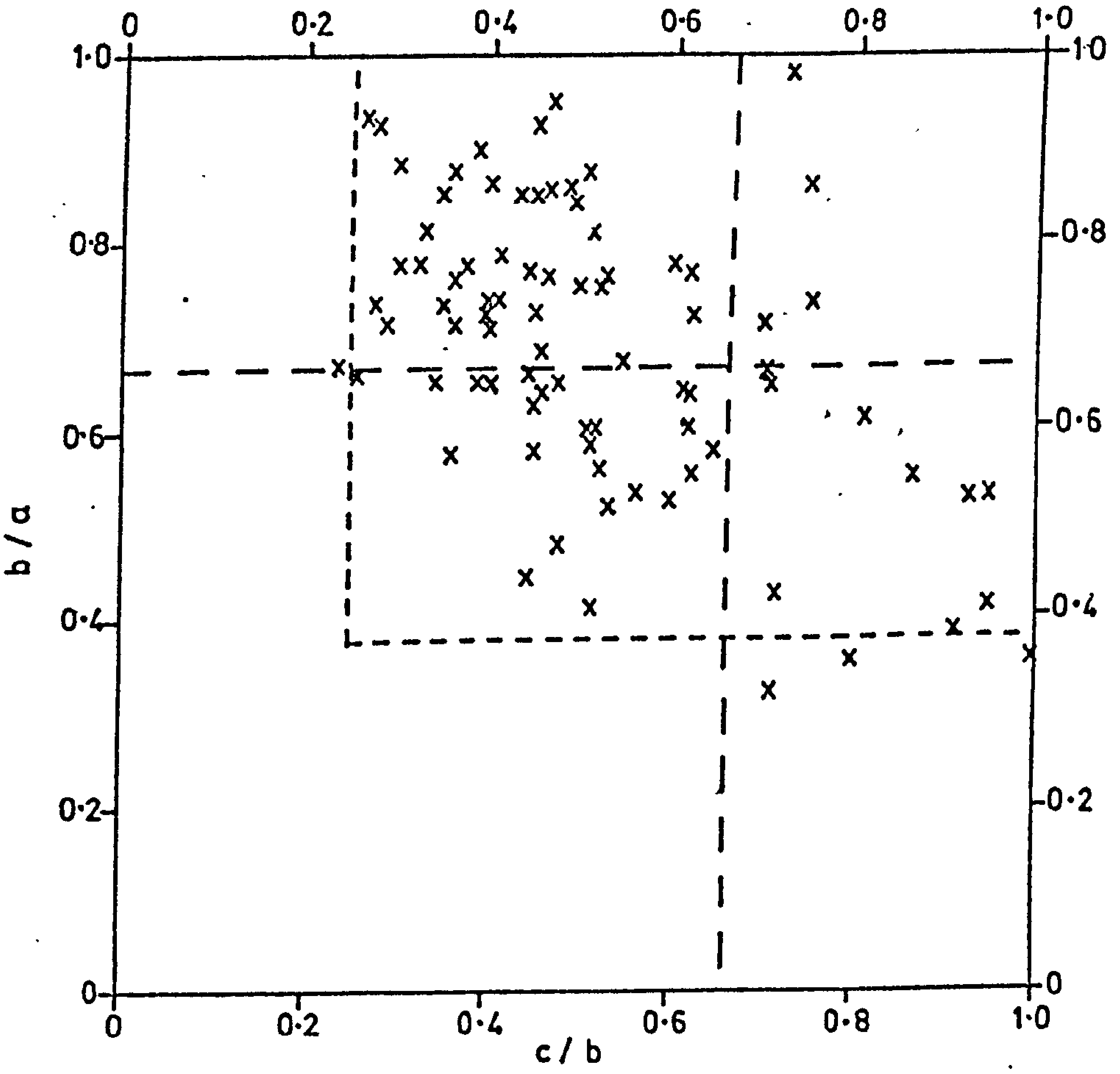

Fig. 6·7a Zingg diagram for boulders in the boulder beach

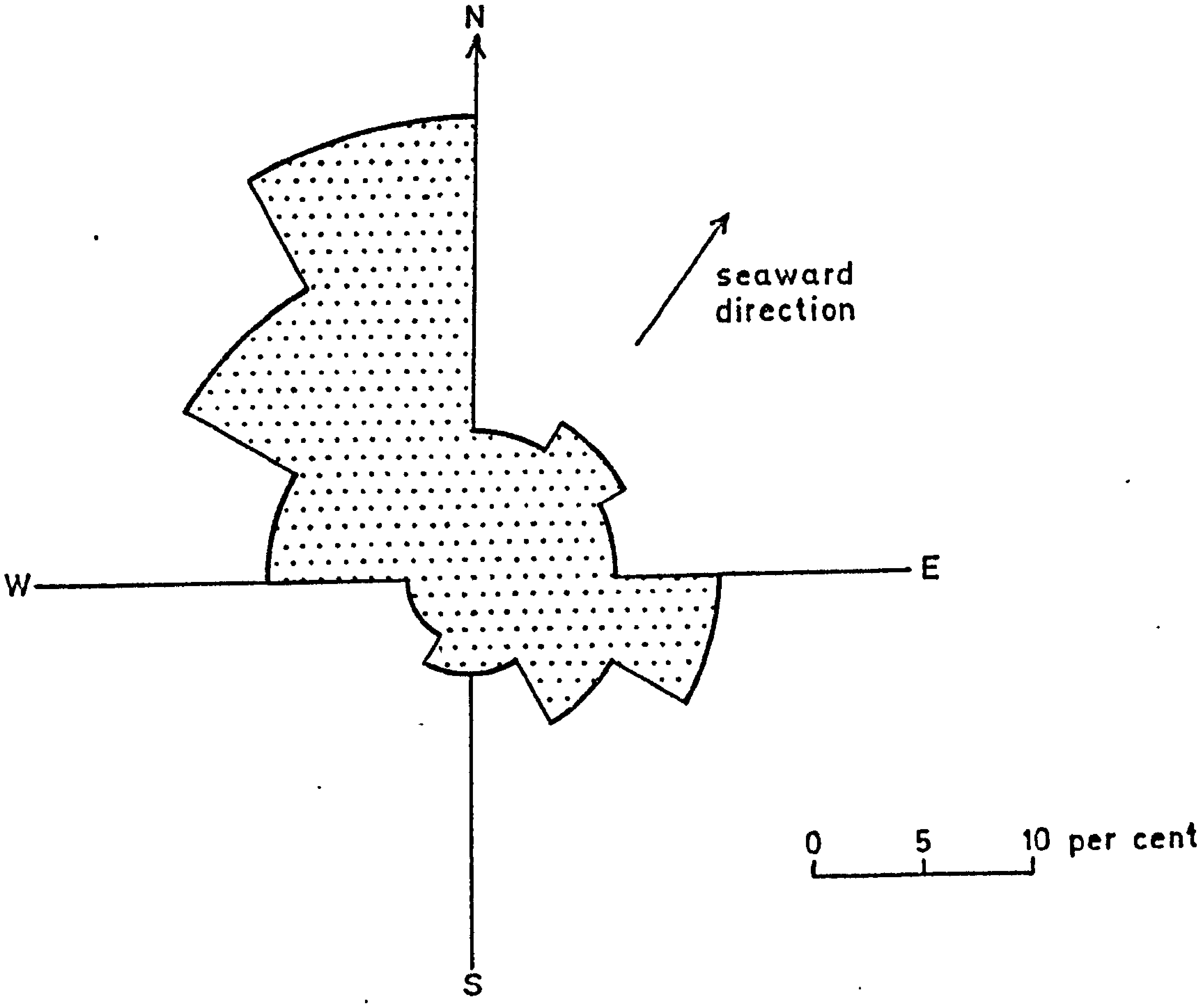

Fig. 6·7b The orientation of perched boulders

4. The Orientation of Boulders - Orientation from true north was measured in the direction of dip of the long axis. A rose diagram for the perched boulders is given in Fig. 6.7b from which it can be seen that a large proportion (62 per cent) are orientated at more than 45 degrees to the seaward direction. This implies that a favourable orientation for perched boulders is with the intermediate (ac) cross-section facing the direction of wave attack. It is not clear why this is so but the distinct modality of the rose diagram suggests that the orientation of the boulder is an important factor in the perching process.

The Embedding of Boulders

Although a boulder's physical characteristics influence, to a greater or lesser extent, its ability to become perched and to resist dislodgement by waves, it is doubtful whether any smooth boulder resting on the top of a perch would stay in position for long. All the perched boulders at Lingrow are embedded in their shale perches. Embedding is probably dependent on the roundness (i.e. smoothness) of the boulder as well as on the hydrodynamic factors (e.g. size and shape), influencing the ease with which it can be vibrated by impinging waves. Unfortunately, the amount of embedding cannot be measured with accuracy because the maximum penetration of the shale may be in the centre of the perch in most cases. Thus it may be the crudity of the data in this study which has not allowed the identification of significant correlations between the amount of embedding and other variables. However, this lack of relationships may have also been caused if the process is most active at its commencement, the rate of embedding then decreasing to a negligible amount because only larger and larger waves are able to vibrate the boulder as it becomes more tightly embedded. Nevertheless, waves of great magnitude are more likely to dislodge the boulder than to embed it further. A decreasing rate of embedding may also hide a positive correlation between this process and boulder size. Although this relationship might still hold for very large boulders they are unlikely to become perched because the Grey Shales are not structurally competent to withstand the forces involved. The two biggest boulders at Lingrow (but not in the study area) each of which is about 20cu.m. in volume, do not rest on perches but are deeply embedded in the shore platform for perhaps this reason.

Roundness is important in embedding because secondary corners allow the mass of the boulder to exert more pressure on parts of the shale beneath than can a smooth surface. Therefore embedding can take place at a higher rate. Also, once some embedding has occurred, an irregular surface has a greater area than a smooth one producing more friction and increasing the resistance of the boulder to dislodgement. Roundness is very difficult to quantify; for this study, boulders were subjectively classified according to the categories suggested and depicted by Pettijohn (1957).

Almost all perched boulders are extremely angular but the narrowness and sharpness of the secondary corners suggest that the surface roughness has been produced after the perching of the boulder. This roughening may be by weathering of sand grains due to salt crystallisation and to sub-aerial weathering processes, any variations in the degree of cementation of the rock being etched out. It is probable, however, that most of the roughening is carried out by limpets during their scraping of the rock surface in search of their algal food. Limpets can be found perfectly fitting depressions half a centimetre or more deep. This secondary roughening gives dislodged boulders a high probability of becoming embedded in the shore platform once again, the necessary first stage in the process of perching.

M.E.M. units have been established at eleven sites on two of the perched boulders at Lingrow in an attempt to measure the rates of erosion. The total measurement period of seventeen months is thought to be inadequate for differences in rates due to lithological and environmental variations to have become apparent. The mean erosion rate for the units for the period 7 November 1970 to 18 April 1972 was 8.7×10^{-3} inches, the range being 1.0×10^{-3} to 19.0×10^{-3} inches.

Though surface roughness as extreme as that exhibited by the perched boulders is not common in the population of free boulders, 36.7 per cent of them were still classified as angular with 33.6 per cent sub-angular and 27.4 per cent sub-rounded. The high proportion in this last class is due to the considerable corrasion wrought by the free boulders upon each other. It is also high in the boulder beach (33.8 per cent) while 48.2 per cent of these boulders are sub-angular. It is concluded, therefore, that despite the higher degree of roundness of non-perched boulders, over 65 per cent of them are sub-angular or angular and are probably capable of becoming easily embedded in the shore platform, assuming other factors are also favourable.

The Morphology of Perches

Perches exist solely because of the protection given to the shore platform by embedded boulders. 88.2 per cent of perches have the same orientation as their incumbent boulder, and one-third of those where the directions are not the same occur in clusters with one perch merging into the next. 49.5 per cent of the perches have areas greater than or equal to that of the boulder but less than 1.5 times. Only 1.7 per cent have areas less than the horizontal area of the boulder.

The ratios of the respective principal axes of perches and their perched boulders do not yield the same frequency distributions. The differences are significant at the 0.05 level, the number of occurrences of the ratio of width of perch to width of boulder exceeding 1.7 being higher than the occurrences above the same value for length of perch to length of the boulder. This means that the lengths of the perches tend to be shorter than their widths measured relative to the corresponding parameters of the boulders. This anomaly is probably due to the truncation of perches by joints, there being a greater chance of joints passing through the long axis than the short axis. In fact, almost all perches have been affected in parts by the quarrying of joint-bounded blocks.

Together with six vertical profiles down which M.E.M. units were installed, profiles were traced from those parts of fourteen different perches where no blocks have been quarried. The tracings were made using the flexicurve technique described in Chapter 4. The upper end of each profile is at the boulder/perch junction while the lower extremity is the easily recognisable sharp change in gradient at the shore platform which is almost horizontal. In Fig. 6.8 scale reductions of the profiles are superimposed with their lowest points at a common origin. The profiles fall for much, if not all, their lengths into a narrow band, the mean angle being about 16.5 degrees. This indicates that the forms of perches in section, in contrast to their shapes in plan, are due to the characteristics of impinging waves and to some extent to the nature of the shale in which they are developed, rather than to the properties of their perched boulders. In the highest parts of the tallest perches the surfaces gradually steepen, sometimes to verticality; the reason for this will be discussed later.

Fig. 6·8 Profiles of perches

The Development of Perches

The top of each perch has been reduced unevenly by the embedding of its boulder so the height of the perch can be only approximated by measuring the distance between the highest visible point of the perch and the general level of the shore platform which has a very low angle in most of the study area (about 0.6 degrees). A scatter diagram of the maximum height of each perch plotted against its distance seaward of the datum line is given in Fig. 6.9, those points where the platform slopes sharply having been omitted. It is apparent that over short distances the heights of perches vary considerably. Certainly there is no evidence for a constant perch height as would be required if the perches were created by the weathering of the inter-perch shale in periglacial times. In order to explain the marked fluctuations in perch height it is concluded that the perches vary in age.

The scatter of points in Fig. 6.9 reflects the influence of two chronological variables as well as many other factors. Distance from the datum line is a measure of the period during which the perched boulder has been available for perching and, therefore, may indicate the number of cycles of perching through which it has passed. The height of the perch on which the boulder rests shows the length of time during which the perched boulder has been in its present cycle. At the datum line perched boulder complexes are just beginning to form. As far as 21m, the heights of the highest perches increase. Complexes with smaller perches may be in a later cycle if the boulders are small or they may have been initiated later. At 21m the highest perch is found and there is a marked discontinuity in maximum perch height. From this point to 34m this parameter again increases; this is the second cycle of perching. The pattern is repeated from 35m seawards where the third cycle occurs. The height of the very tallest perches (at 21m, 34m and 51m) in each cycle decreases steadily, perhaps due to the reduction of

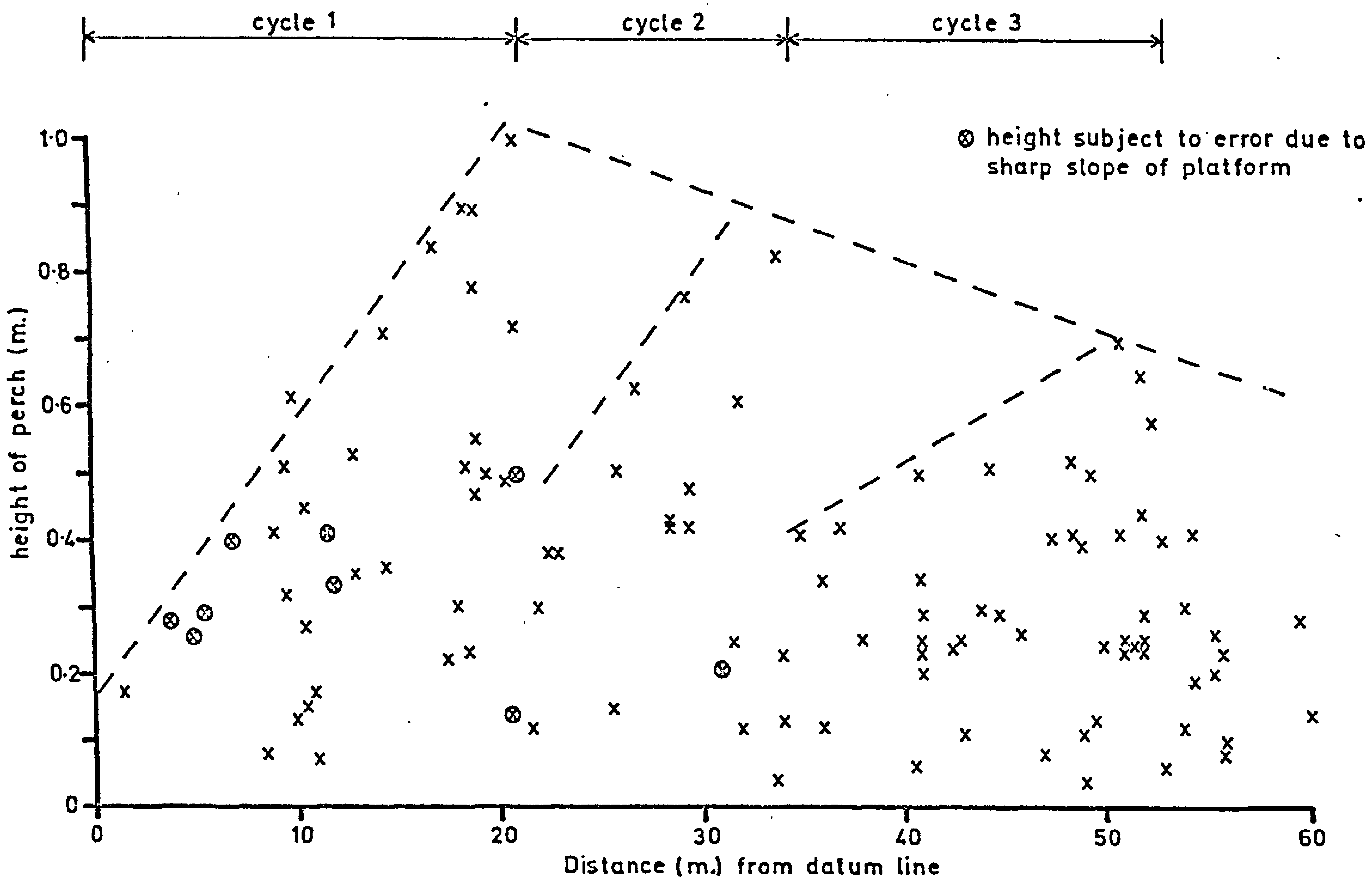

Fig.6·9 Variation in perch height seawards boulder size with age, the reduction taking place during the periods of dislodgement.

It is not immediately clear why, with all other factors being favourable, a maximum perch height should exist. The ratio of the height of the perch to half the length of its base is the tangent of its angle of slope. The correlation coefficient (0.7524) between this variable (y in degrees) and the height of the perch (x in metres), which can be interpreted as the length of the present perching cycle, is significant at a level higher than 0.001. The regression equation is:

$$y = 7.4098 + 28.5129x$$

This indicates that, as the perch grows higher, its base, though growing areally, becomes relatively smaller. Such a tendency will probably make the whole perch and its boulder more unstable as its centre of gravity will be lifted.

Apart from some small lowering of the highest point of a perch by the embedding of its boulder, this upper extremity is static, the perch increasing in height by the erosion of the surrounding shore platform. In Fig. 6.10 fourteen vertical profiles of perches are superimposed with their highest points at a common origin. As the height of a perch is correlated with its age, these sections can be viewed as a developmental sequence. Excluding the three smallest profiles (numbers 1, 2 and 3), pro tempore, the positions of the lowest ends of the remaining profiles are described by the equation:

$$y = 0.4832x - 4.4179 \qquad \text{(NB. the position of the origin)}$$

The correlation coefficient (0.8083) is significant at the 0.005 level. This best-fit line makes an angle of 25.80 degrees with the horizontal; if the deviant points 13 and 14 are excluded, the line has a slope of 37.95 degrees. Thus a unit lowering of the shore platform produces a horizontal extension of the perch by a distance of about 1.3 to 2.0

Fig. 6·10 Developmental sequence of perch profiles units. The above equation implies that just after its initiation, the horizontal length of a profile down the perch will be 9cm, or 31cm if points 13 and 14 are disregarded, values which are difficult to explain. A better model postulates that the lowest point of a perch profile follows a path at about 16.5 degrees to the horizontal (thus including points 1, 2 and 3) until it is about 20cm below the level of the top of the perch (stage 3 in Fig. 6.11a). During this period the actual perch surface is lowered very little; after this, the point follows a path of 25 to 38 degrees and the surface of the profile is lowered in a parallel rectilinear fashion (stages 4 and 5 in Fig. 6.11a). As the lowest point of the profile follows the 25 to 38 degree path, the maintenance of a segment of the profile at about 16.5 degrees necessitates a similarly angled path for a point near the upper extremity of this segment. Since the highest point of the perch is fixed, the amount of embedding of the boulder with respect to the height of the perch being negligible, a steeply inclined surface is produced in the highest part of the perch. If the c.16.5 degree segment extends in length this upper part will be even steeper. It is probable that, as the perch grows in height, the 16.5 degree segment will evolve to a slightly lower gradient and, in fact, the whole profile becomes more concave with age. Such a form does not exist in the cases of profiles 13 and 14, perhaps because of geological factors.

The means whereby the shale is eroded to form perches are indicated by M.E.M. data. The tall perch marked A in Fig. 6.5 is up to 92cm high; a photograph of it forms Fig. 6.11b. Five M.E.M. units were installed down the side and one on the shore platform facing Port Mulgrave on 13th November 1970 and six down the side and one on the shore platform facing Runswick Bay on 8th November 1970. A small perch,

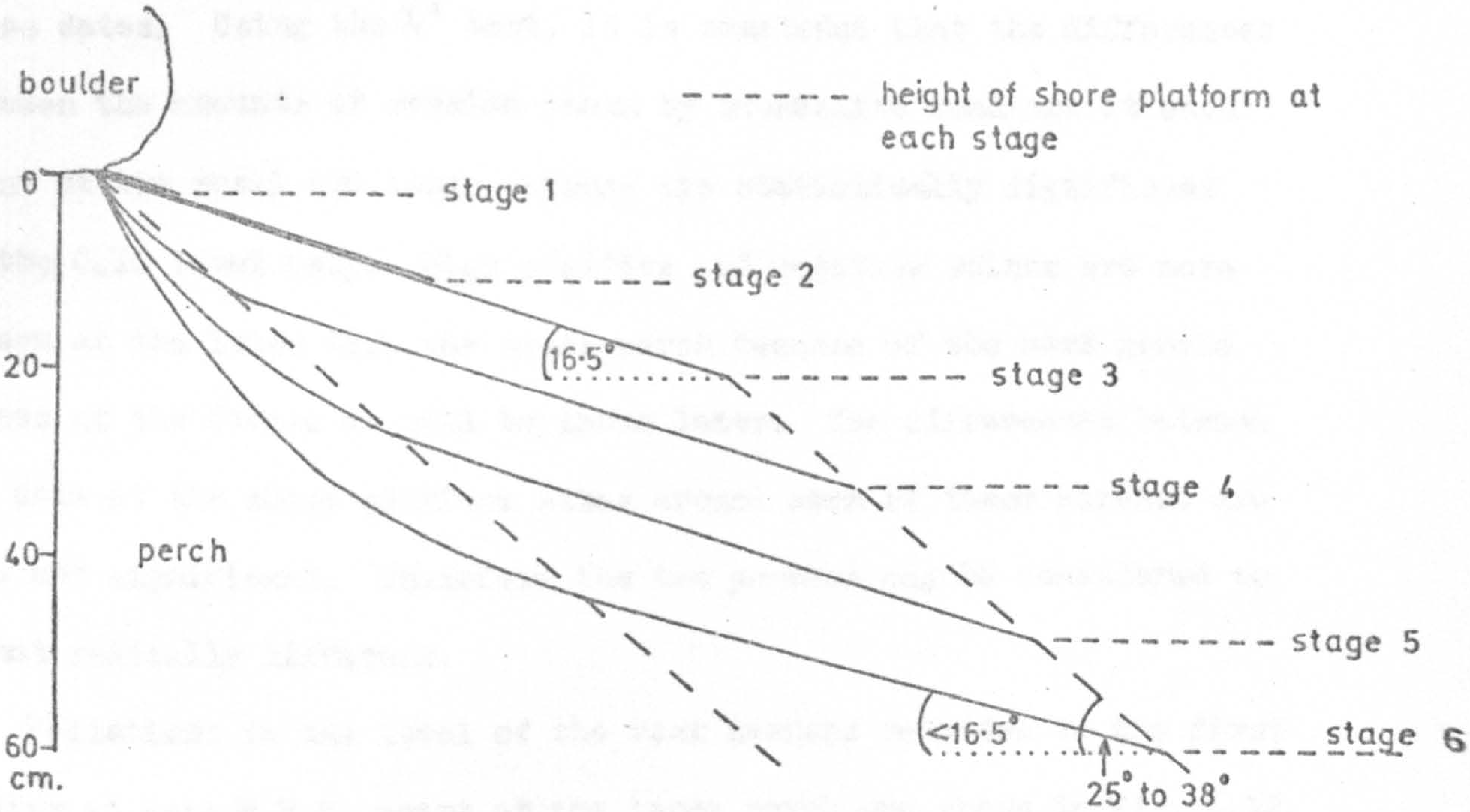

Fig. 6·11a A model for the development of the perch profile

Fig. 6·11b The perched boulder complex marked A in Fig. 6·5 not in the study area shown in Fig. 6.5, was also instrumented on these dates. Using the χ^2 test, it is concluded that the differences between the amounts of erosion shown by successive readings at each point at the small and large perches are statistically significant at the 0.10 level only. High positive and negative values are more common at the large than the small perch because of the more gentle slopes at the former as will be shown later. The differences between the data at the shore platform sites around each of these perches are also not significant. Therefore the two perches may be considered to be not radically different.

Variations in the level of the rock surface relative to the first reading at each M.E.M. point at the large perch are shown in Fig. 6.12. Some points, for example at units 4, 8, 11 and 13, show little variation, but at others sharp changes occurred in the readings during the study period. At a number of points, e.g. 2A, 5A, 10A, 10B, 10C, 12A and 12B, erosion readings are alternately positive and negative (this is particularly so of 12B). The amplitudes of these movements preclude the possibility of their being due to measurement errors. The only explanation for this erratic behaviour is that the shale laminae on which the readings are taken were being knocked up and down by waves. Though the perch is far from a sandy beach the platform, especially in summer when the sea is at its calmest, is often covered with a thin layer of fine-grained mud. This mud, on being thrown into suspension, may easily become trapped beneath uplifted laminae causing them to remain wedged up. It is possible that the amplitude of oscillation increases with time until the fragment of shale is freed from the perch. Points 9A and 9B are obvious examples of the erosion of shale fragments from the perch, the erosion at each of these points being over 0.4 inches. However, because of the brevity of the measurement period in relation to

Fig. 6·12 Erosion readings at perch A

the average rates of perch erosion, it is not easy to say in other cases whether apparent erosion of, say, 50×10^{-3} inches is the result of the removal of a shale fragment or just a major downward knocking of it. It is interesting that at points 12A and 12B, once at least one fragment was removed, others were quickly eroded from below in subsequent erosion periods. Differences between the summer and winter M.E.M. data are not significant but, as almost all perches have been partly deformed by the removal of joint-bounded blocks, erosion of perches is probably highest during winter.

The spatial variation of erosion is rather diverse since the M.E.M. points in each unit are sufficiently far apart to be concerned with different shale fragments and since the period of erosion measurements was comparatively short. The variability is reduced to some extent by averaging the three values of total erosion in each unit. The resulting figures for the large perch are shown in Fig. 6.13; because of the tiny amount of erosion compared with the size of the perch it has been necessary to use two scales in this diagram. The erosion of the low-angled part of each profile is much greater than that of the high-angled section. Excluding units 1 and 7 which are on the shore platform, the equation

$y = 58.05 - 363.0x^{-1}$ where y = mean erosion/unit ($\times 10^{-3}$ inch/year)

x = angle of surface of unit

explains 97.89 per cent of the variation and is extremely significant at the 0.001 level but use of the reciprocal transformation skews the data with respect to both variables to such an extent that this exact relationship is viewed as tentative, though points representing the mean erosion at five of the seven units on the small perch conform closely to the regression line also. It seems logical, however, that

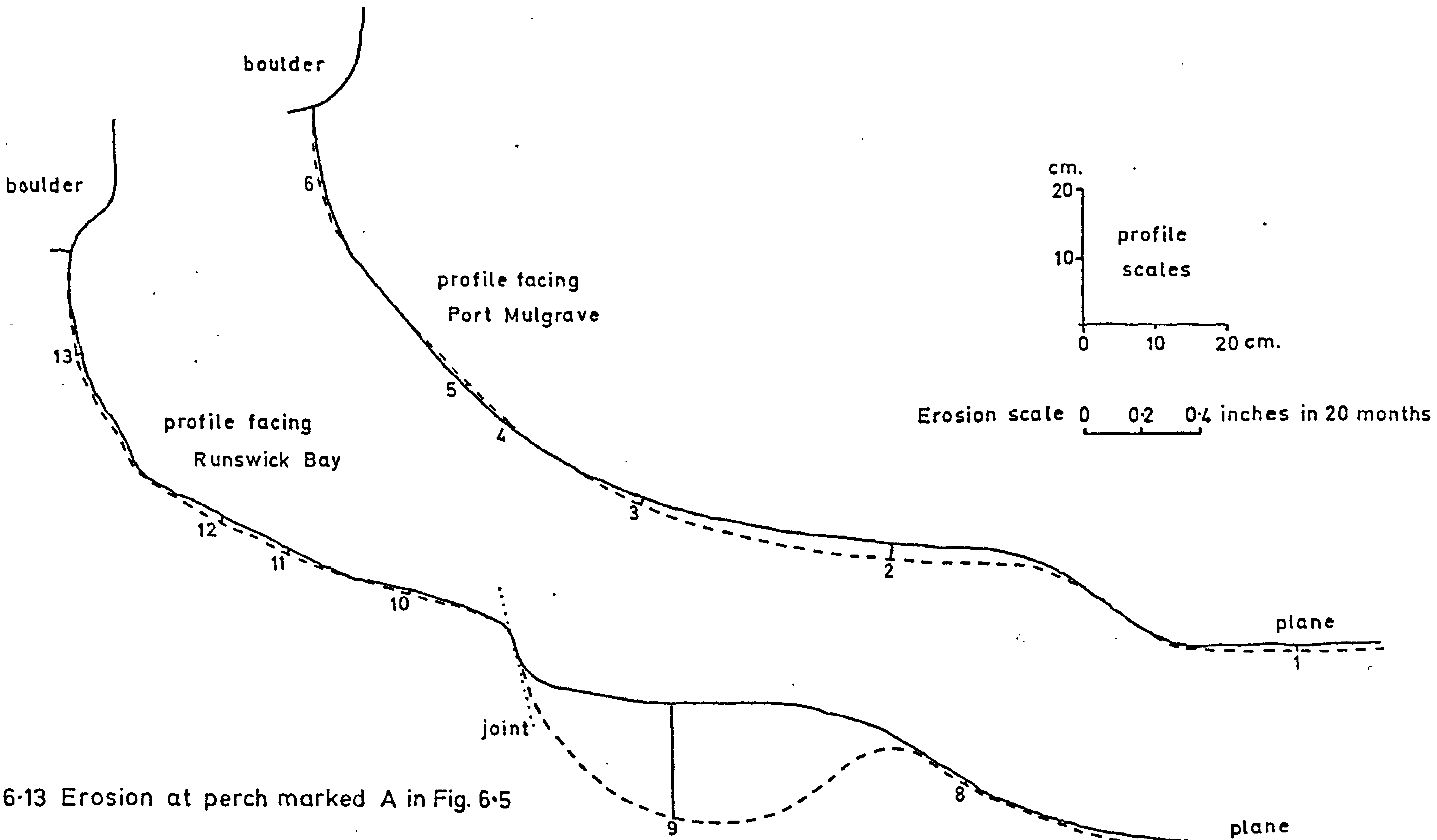

Fig. 6·13 Erosion at perch marked A in Fig. 6·5 erosion should be highest on low-angled surfaces since the shale laminae which split into fragments are almost horizontal. On such surfaces, the fragments cannot be held in position by partly overlying fragments as they can if they crop out on a steep surface. This may explain the maintenance of a segment inclined at about 16.5 degrees on most profiles. Another factor is important, however; on the rather gentle slope on the boulder side of the joint which cuts the Runswick Bay flank of the large perch, erosion has been negligible. This may be due to the brevity of the measurement period or to the fact that the exposed joint plane is smooth so the ability of waves to get under and lift up shale fragments is much reduced. On the other hand, the sharp slopes leading down from the gentle inclines on each side of the perch are rough with the result that the projecting corners concentrate wave energy towards the cracks between the laminae. The low amounts of erosion at the units (1 and 7) on the shore platform are attributed to the low slope of this landform which inhibits the drying of the shale and thus the expansion-contraction process discussed in Chapter 5. Small values of erosion which, nevertheless, are higher than might be expected from the relationship given above have also been registered for the highest units (6 and 13) at each side of the large perch. If these values are not due to error it is difficult to see how they could have been produced since corrasion is most unlikely and quarrying must be negligible on such steep surfaces. It might be that some of this erosion is done by limpets. Biogenic erosion has been advocated as a process in the formation of shore platforms by Emery (1946), McLean (1967) and Healy (1968a).

Conclusions

This chapter has shown that the three main categories of superficial deposit on the shore platform in north-east Yorkshire may each follow a discrete path of evolution. Thus free boulders in a boulder beach may become imprisoned, perhaps forming a cuirass which is eventually broken up allowing the boulders, though considerably modified, to become free once more. The components of a beach may become cemented and when they are liberated from the conglomerate they may be far seaward of the new cliff foot. Boulders may also become perched, only to be dislodged from their shale pedestals at some later date.

However, these three classes of phenomena are also interlinked. Boulders initially become perched because they are constrained in their abilities to move laterally by their neighbours. In time they become embedded in the shore platform and no longer require this impediment to movement. Therefore perched boulders are rarely seen near the cliff foot; they are most frequent towards the seaward edges of boulder beaches where there are also fewer free boulders available to corrade and destroy the shale perches. Perched boulders are, therefore, the residues of a boulder beach which has passed landwards with the recession of the cliff foot. Destruction of the perches may allow the freed boulders to be swept landwards to rejoin the boulder beach, or new perches may be formed.

Those conglomerate patches that are most resistant to erosion contain imprisoned boulders. Also the longer the time period during which the conglomerate remains unwashed by the sea, the greater will be the degree of cementation. The best protection for a talus cone is afforded by a beach of large boulders which can be moved little by impinging waves and which exert much friction on them. Areas of cemented material are, therefore, the result of favourable conditions on both the foreshore, which controls the erosive power of waves at the cliff foot, and on the cliff from where the rate of fall of material determines whether accumulation of talus can occur.

It is concluded, therefore, that the initial nature of the boulder beach has considerable influence on its own development. The probability is small that imprisoned or perched boulders will evolve from a beach of free boulders with low density, the category of boulder beach which is the most common in north-east Yorkshire.

CHAPTER 7

A CARTOGRAPHICAL ANALYSIS OF THE COASTLINE

Introduction

It has been shown in previous chapters that the character of the cliff and shore platform varies in section at different points along the coastline. The reasons for these variations are partly geological and partly due to differing erosional conditions at the cliff foot. Although the discussion so far has been mainly concerned with morphology in the vertical plane the shape of the coast also alters in the third dimension. Of the two coastlines defined in the first chapter, "upper" and "basal", the one produced directly by marine erosion is the one of primary interest. Hence, wherever the term "coastline" is used in the present chapter, it refers to the "basal coastline".

At the smallest scale the coastline between Ravenscar and Saltburn forms a protrusion into the North Sea but, since this is related to the pattern of major tectonic domes and basins, it probably has little relevance to the coastal erosion system. At the other extreme, the minutest crenelations of the coastline are related to the fracture patterns of the rock and are also unlikely to have much influence on the system under investigation. Hence it is the objective of this chapter to examine the morphology and development of the coastline at intermediate scales in order to discover the major influences causing variations in form. Of special interest is the importance of the nature of the cliff foot, since this is deemed to be significant to the development of other physical features.

Even a brief look at any map of a coastline shows that it is very sinuous. The coastline is indented by very many small bays and these can occur within larger ones. In addition, the size and shape of both bays and headlands are varied. In order to rationalise this variation it is necessary first to delimit objectively the features which constitute the coastline and then to quantify their characteristics.

The conceptual model used for this analysis recognises that headlands and bays alternate along the coastline and together constitute the whole of it. A bay is defined as a segment of coastline which is concave to the sea while a headland is convex in this direction. One of the properties of such a bay is that lines drawn normal to its outline converge seawards while normals to a headland diverge seawards. These properties allow the practical subdivision of any coastline. However, because of the infancy of the analytical technique only bays have been examined in great detail in this study.

The Spacing of the Normals

The spacing of the normals is of crucial importance to the order of the feature being defined ("order" refers to the degree of generalisation of the coastline). Fig. 7.1a illustrates a headland HG protruding perpendicularly by half a unit distance from the section of coastline FG. A chord of length x (denoting the separation of normals) is laid from the tip of the headland at H to some point between F and G. As x varies, the angle α changes and the graph in Fig. 7.1b results. This graph is assymptotic to the X-axis indicating that with increasing x the influence of the headland on normal orientation becomes markedly reduced and is small after the x value of about three units, i.e. separation of the normals six times the length of the headland. Therefore, in order to include small coastline features, the separation of the normals must be small. They must also be equally spaced, otherwise headlands of the same size would influence their osientation differently.

For the present study, the separation of the normals was two-tenths of an inch and they were drawn on Ordnance Survey Third Edition 1:2500 County Series plans of <u>circa</u> 1927. However, for the coastline

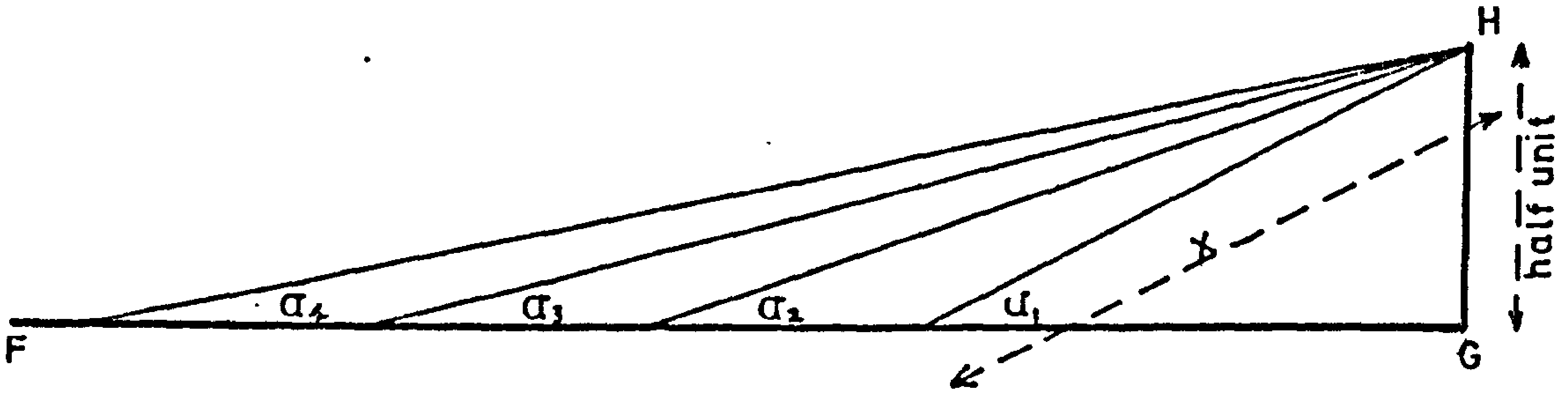

Fig.7·1a Variation in normal-orientation with spacing

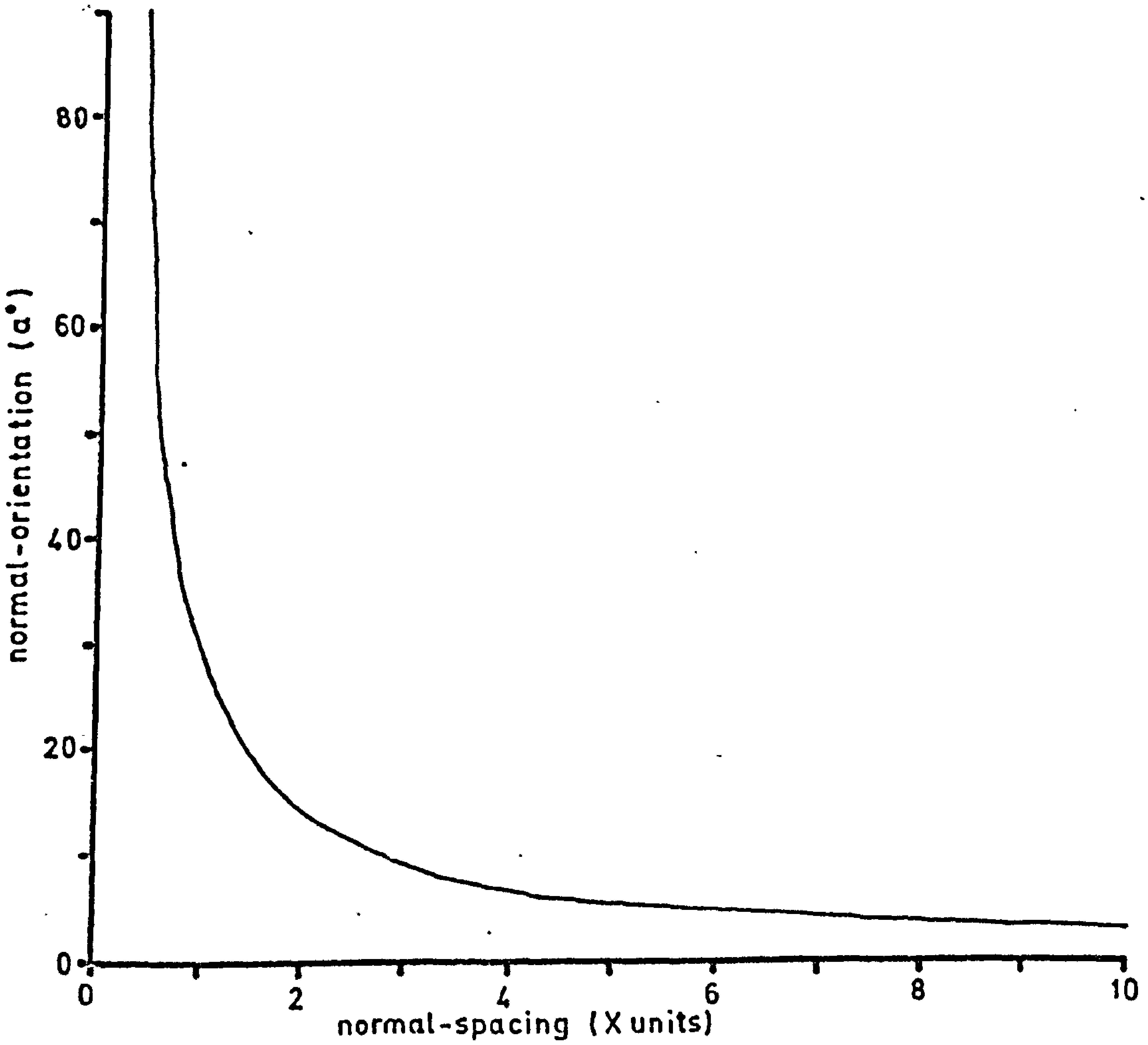

Fig.7·1b Relationship between normal-orientation and spacing between Whitby West Pier and Sandsend the First Edition (circa 1895) plans were used because the coastline was less changed by Man-made features such as sea walls at that time. The chosen spacing means that headlands and bays less than about seven feet long or wide have little influence on the orientation of the normals; features larger than 42 feet have total control.

The practical method of normal-construction was to place copies of the plans (on tracing paper) over graph paper with lines one-tenth of an inch apart. A point on the coastline was placed over a line-intersection on the graph paper and the tracing paper was manoeuvred until a point on the coastline lay over a line-intersection two-tenths of an inch in a straight line from the first. A line was then drawn perpendicular to the line joining these two points and half way between them by tracing the line on the graph paper which was situated below this point on the tracing paper. The position of the first normal was randomly selected. Where the mouth of a large stream interrupts the continuity of the coastline a random point was chosen to start the construction of normals on the other side of the stream.

The Ordering of Bays

Fig. 7.2 illustrates a section of the north-east Yorkshire coastline which has been cartographically dissected into bays and headlands. It is plain that the bays at points T, U, V, W, X, Y and Z may be combined into the much larger bay called Deepgrove Wyke. This bay is said to have a higher order than its constituent bays.

The method of coastline analysis already described can be extended so that the assignment of order values can take place on an objective basis. It has been shown that by increasing the separation

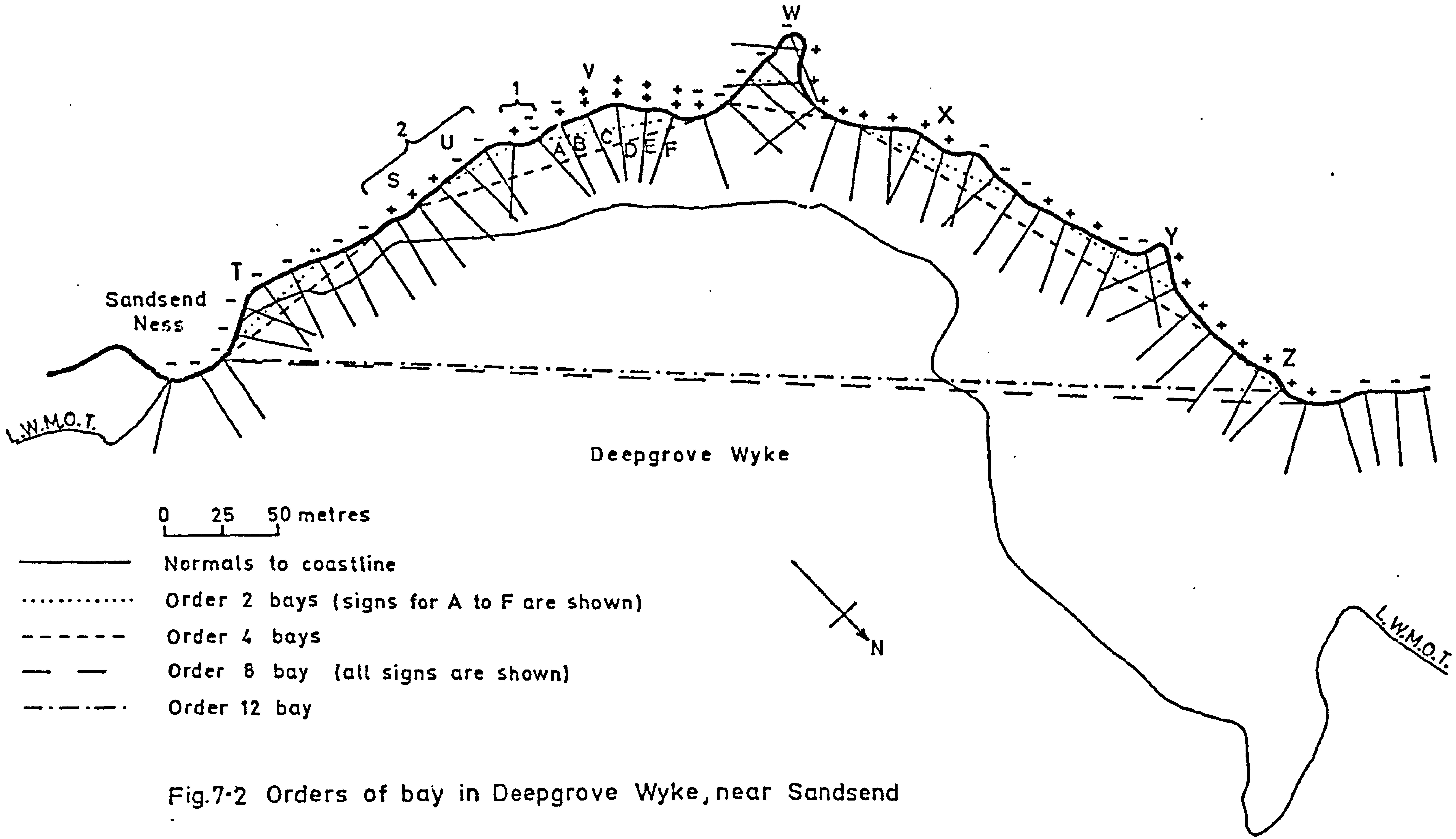

Fig.7·2 Orders of bay in Deepgrove Wyke, near Sandsend of normals minor detail contributes less and less to the orientation of these lines. Therefore, normals with wider spacing delimit bays and headlands of higher order. Such bays may contain headlands of smaller order, and similarly a high order headland may contain low order bays. This is because the low order features have become insignificant at the higher scale of generalisation being considered. Hence, in a high order bay most normals still converge seawards.

Bays defined by the comparison of the orientations of normals drawn two-tenths of an inch apart are termed first order bays. Bays of order 2 may be defined by the comparison of the outer two normals of double pairs of normals drawn two-tenths of an inch apart, e.g. by the comparison of normals A and C in Fig. 7.2 - these two converge and so the section of coastline between them is a bay section of order 2. A plus sign is drawn at the base of the leading normal (C) to indicate convergence of the pair. The next double pair of normals (B and C, and C and D) is then taken and B and D are compared - these also indicate a bay and another plus is drawn. The procedure is repeated using running double-pairs for the whole coastline. Similarly, for bays of order 3, triple pairs of normals are taken, e.g. A and B, B and C, C and D in Fig. 7.2, and the outermost normals are compared (A and D in this case). Diverging normals are marked by minus signs.

The normals to the coastline having been drawn and the pairs of normals appropriate to the order being considered having been compared for convergence and divergence, the following procedural steps are used to identify bays and headlands:

1. A run (i.e. a sequence) of plus signs is found. Since a run may consist of any number of pluses, it might be possible (incorrectly) to identify a coastline as consisting of one high order bay because the

orientation of the normals is determined by minor features. It is therefore necessary to use only runs longer than some value proportional to the order being considered. In the present study the value of 25 per cent was adopted, and so to identify order 20 bays runs of five or more pluses were found, for order 16 bays runs of four or more pluses and so on. For orders 2 and 4 the minimum length of a run was two signs.

2. Having found a run of pluses of at least the requisite minimum length, e.g. for order 8 at the point V in Fig. 7.2, successive pairs of runs of pluses and minuses are compared and if the former is longer than the latter the pair is combined with the run first identified. If the runs are equal the next pair is considered. For example, going towards Sandsend Ness in Fig. 7.2 from the run at point V, the next negative run consists of one sign and the next plus run also totals one. Hence, these two runs (pair 1) are equal and it is necessary to compare the next pair (2). The first run of minus signs (at U) is of length 2 and the next plus run (at point S) is 3. Therefore, the crenelations in the coastline between this run and point V which have produced diverging pairs of normals, and thus minus signs, are deemed to be insignificant at order 8 and this section of coastline is part of a bay. From point S towards Sandsend Ness the run of minuses is more than eight in length. This indicates that the limiting normal of the bay is the eighth from the last plus sign in the run at S. This is because pairs of normals were compared for convergence successively in a westerly direction and the plus or minus sign for the pair was drawn at the base of the leading normal. Going away from Sandsend Ness, from the run at point V, pairs of plus and minus runs are compared until the western limit of Deepgrove Wyke is identified.

3. Having identified the limits of the bay a line is drawn between them to indicate the presence of this landform.

The procedure is repeated to find other bays of the same order and of other orders. Indeed, the limit to the order of bay or headland to be defined is reached only when the outermost normals of the pairs of normals are those at each end of the coastline being examined, e.g. in the present study 3,628 normals were drawn between Old Peak at Ravenscar and Saltburn so that the highest order feature recognisable would be of order 3628 and would be a headland. Exactly the same procedure as that outlined for bays can be used for the identification of headlands except that runs of minus signs will be considered. There will be an overlapping of features equal to the order multiplied by the normal spacing, e.g. in order 8 bays a length of coastline 8 x $^2/_{10}$ inch overlaps at each end of the bay with the headlands separating it from adjacent bays. To separate the features completely the mid point of this overlap may be used as the boundary; this modification was not used in the present study.

Where the mouth of a stream interrupts the coastline, a line is drawn between the end points of the lowest order bays identified on the marine-eroded coastline. Normals are then drawn to this straight line. This means that the influence of the river mouth is eliminated and yet ensures that rivers flow into bays which they generally do. In north-east Yorkshire only four river mouths had to be dealt with in this way.

An Alternative Ordering Procedure

The use of the method described above for the identification of bays and headlands requires that only one set of normals, two-tenths of an inch apart, need be drawn along the coastline. An alternative and, perhaps, more logical procedure to define (say) bays of order 2 would be to draw normals 2 x $^2/10$ inch apart along the coastline. For bays of order 3, normals 3 x $^2/10$ inch apart are drawn and so on for higher orders. This method clearly involves much more work than the procedure adopted here. In addition, it is not a modus operandi which can be easily developed for use on a computer as can the present method. Nor are longer runs of like signs developed so it is still necessary to amalgamate short runs which are less than some arbitrary minimum with runs that are longer than this figure. For these reasons, this alternative method of ordering is considered no further.

Coastline Parameters

Bays and headlands possess several characteristics. Width is defined as the length of the chord joining the lateral points (1 and 3 in Fig. 7.3a). The length of a bay is the length of the longest perpendicular from the chord to the coastline. The area is then the space enclosed by the chord and the coastline; it was measured in this study with a polar planimeter. The orientation of a bay is the deviation from true North of the perpendicular to the chord. Bay shape can be measured in a number of different ways. The ratio of length to width is termed kurtosis while the ratio (less than 1.0) of the lengths of the eastern and western segments of the chord provides a measure of the skewness of a bay. The shape of a bay can also be compared with basic geometrical forms by calculation of the ratio of the area of the bay to the area of the geometrical figure fitted through the points numbered 1, 2 and 3 in Fig. 7.3a. In this study three such ratios have been derived; they are the circular area ratio (CAR), the triangular area ratio (TAR) and the rectangular area ratio (RAR).

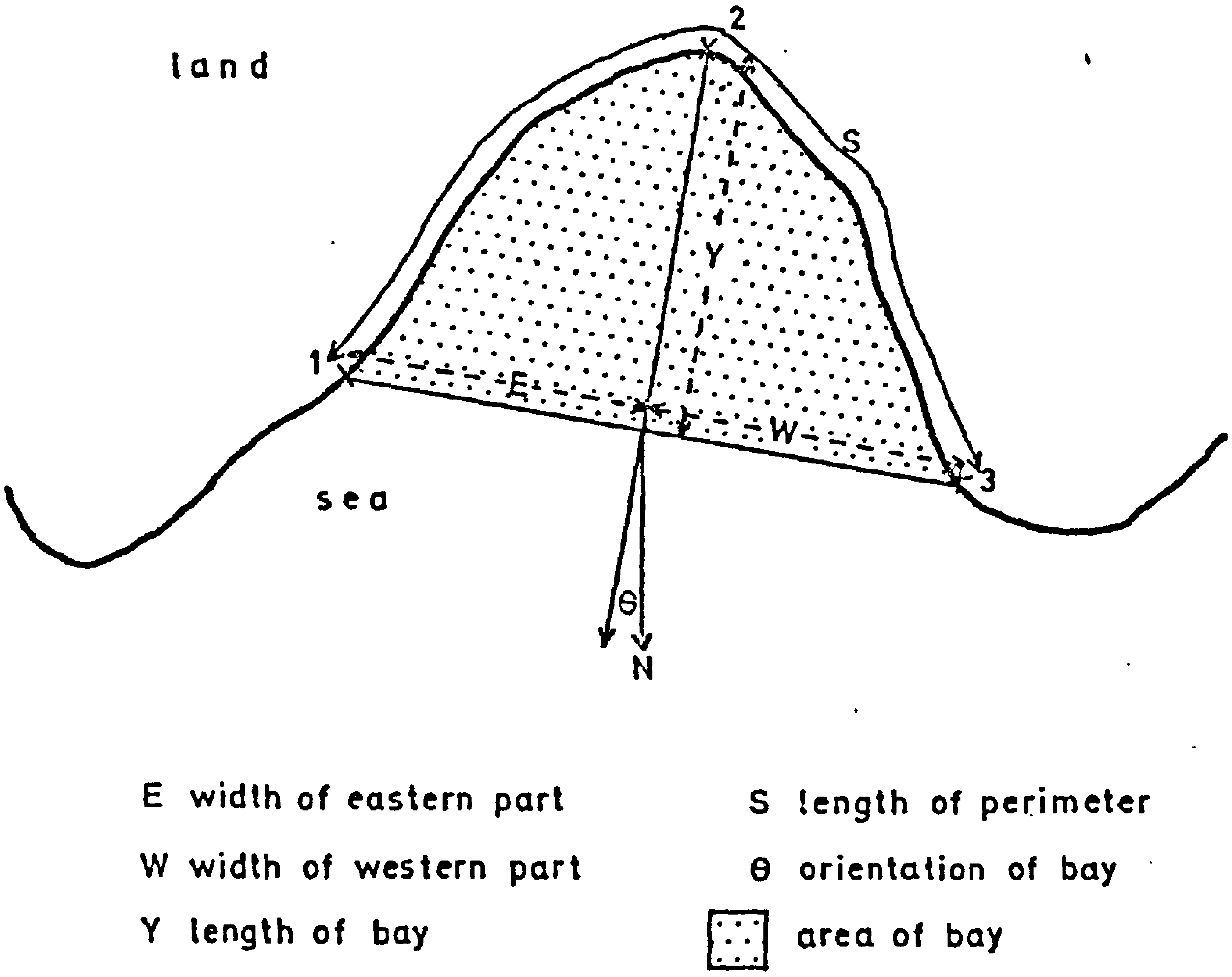

Fig. 7·3a Actual bay parameters

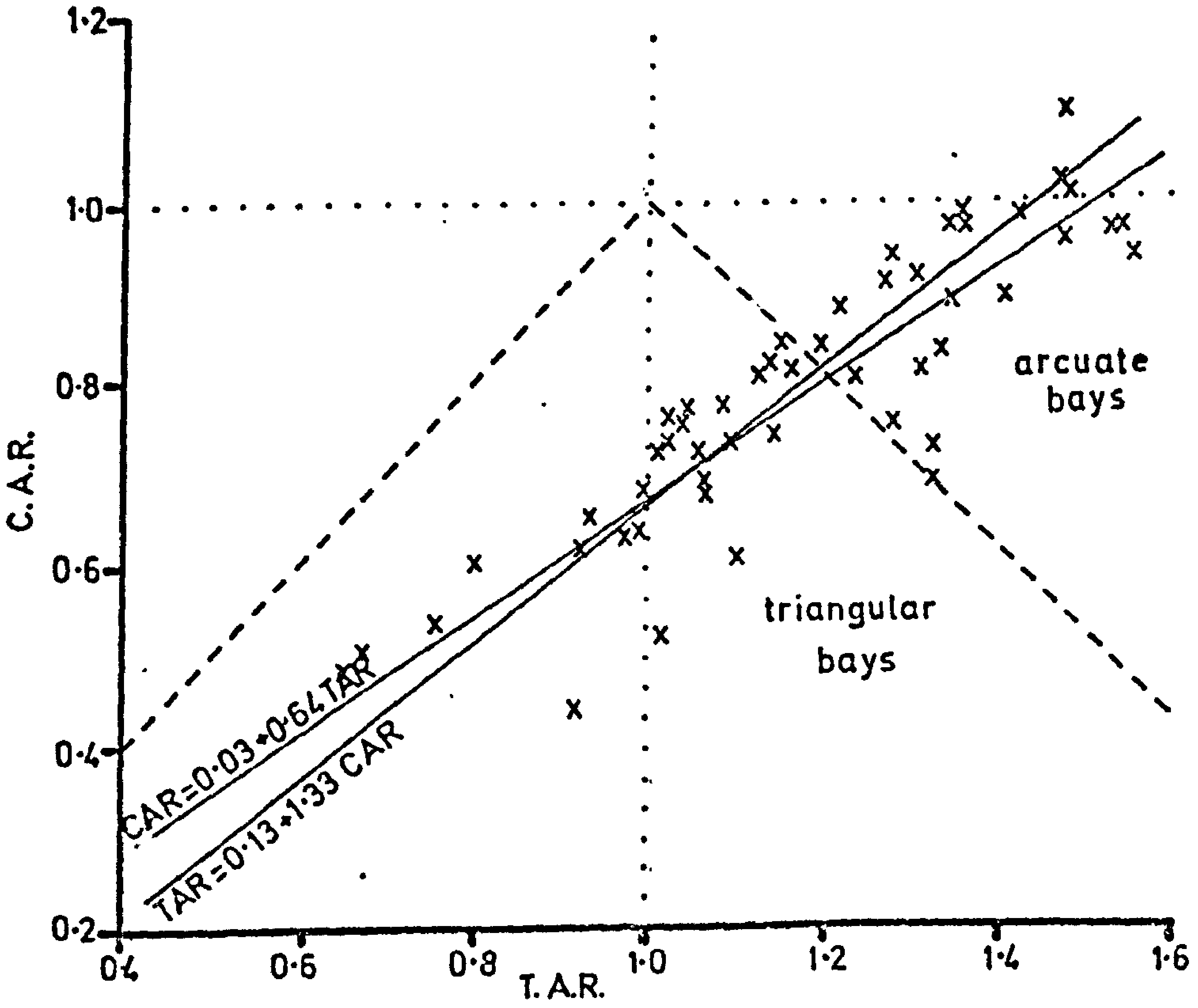

Fig. 7·3b Relationship between C.A.R. and T.A.R.

Having calculated the triangular (TAR), circular (CAR) and rectangular (RAR) ratios for each bay, the ratio nearest to 1.000 ascribes that bay to that basic shape (bays in which the CAR is nearest to 1.000 are termed arcuate rather than circular bays). These three ratios are, of course, closely related, in particular, the rectangular ratio being always double the triangular ratio. The relation of these two to the circular ratio is slightly more variable. A scatter diagram of CAR values plotted against TAR values for order 16 bays is shown in Fig. 7.3b and it is basically the same for other orders. The relevant equations for the relationship are:

$$y = 0.0304 + 0.6421x$$

$$(r^2 = 85.10\%;\ \text{significant at } 0.001)$$

$$x = 0.1279 + 1.3262y$$

where y = CAR and x = TAR

For most of this study the CAR parameter is used since the circularity of a bay is of more interest than its triangularity.

The Meaning of "Order"

Before discussing the form and development of bays in north-east Yorkshire it is necessary to examine more closely the meaning of "order". By using the procedure already outlined for the delimitation of bays it is possible to state that bays at a certain order are parts of the coastline with a fixed value of complexity. With increasing order, greater generalisation is achieved so that, for instance, a headland at one order may become incorporated into a bay at higher orders. For this to happen the bay must be larger than the lower-order landforms that it contains so there should be a correlation between bay area and order. This relationship is shown in Fig. 7.4a where the mean area of all bays at each order is plotted against order. The curve is paraboloid:

$$y = 2.7912 + 0.3232x^2 \quad (r^2 = 99.80\%;\ \text{significant at } 0.001)$$

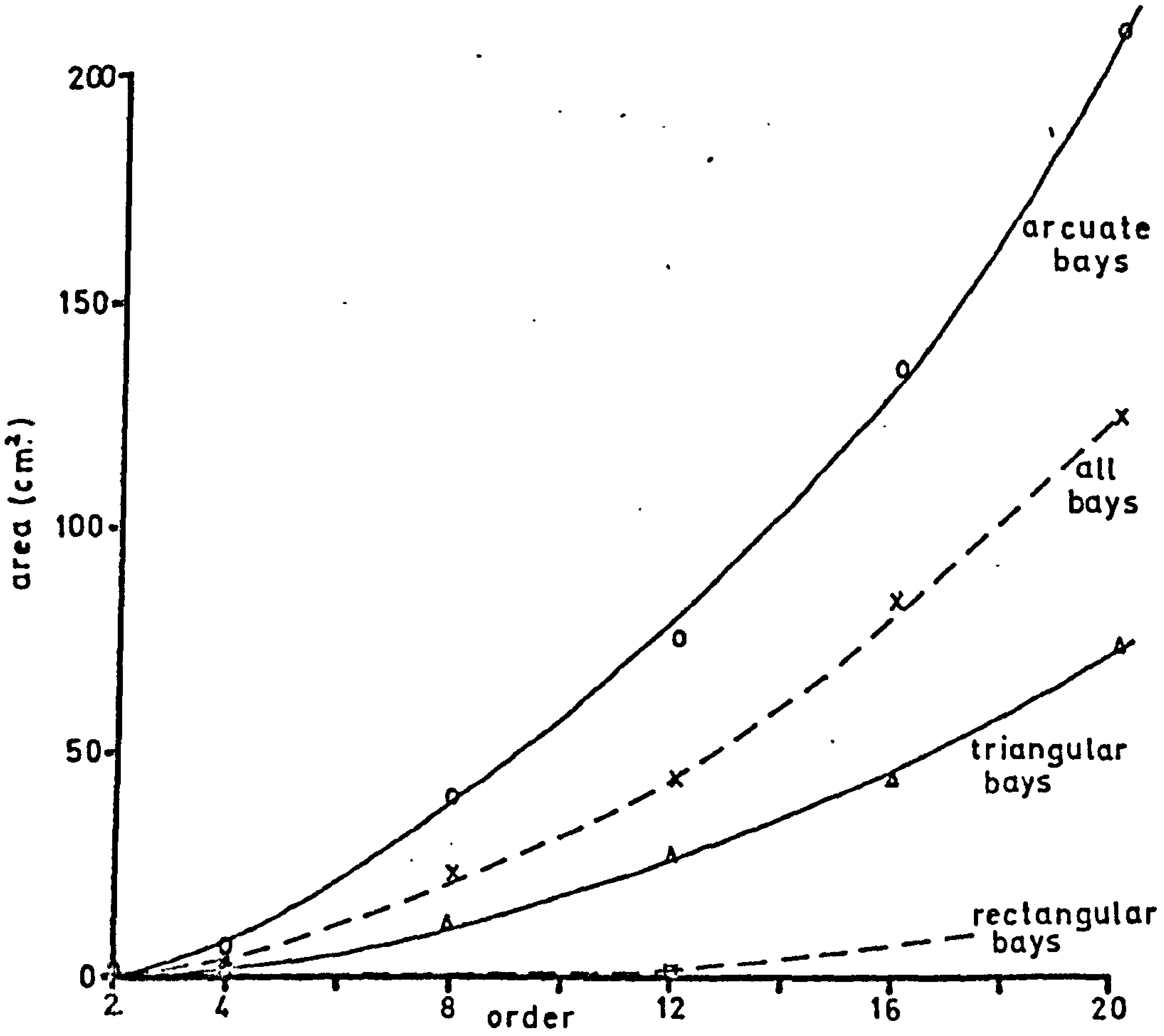

Fig. 7·4 a Mean area of bays at each order

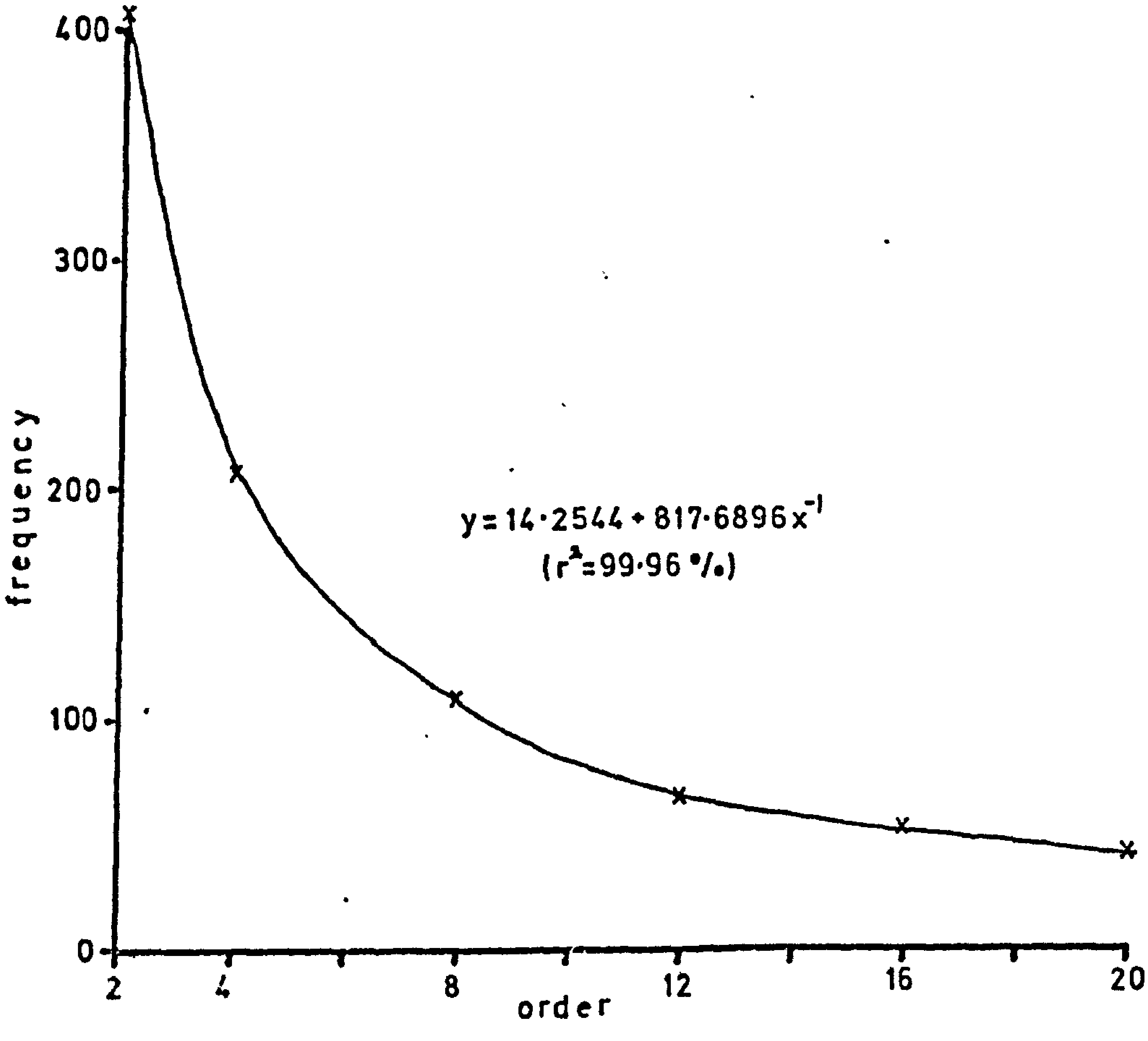

Fig. 7·4 b Relationship between order and frequency

However, it is different for each basic shape of bay; the regression equations are:

for arcuate bays: $y = 1.5986 + 0.5301x^2$ ($r^2 = 99.84\%$; significant at 0.001)

for triangular bays: $y = 0.1860x^2 - 0.0540$ ($r^2 = 99.70$; significant at 0.001)

for rectangular bays: insufficient data

The reason for these differences will be discussed later. It can be concluded therefore that the order of a bay is closely related to its area as well as to the degree of generalisation of the coastline. If it can be assumed that area is a chronological parameter, order can be similarly described; this assumption is the ergodic hypothesis (Chorley and Kennedy 1971, p. 277). For it to be strictly valid all the bays at each order should grow at the same rate. The next chapter will show that data for this subject are not particularly reliable since they cover a period of only 34 years for the whole coastline. Within a few years it will be possible to have data for about 74 years but even this is probably too short since "retreat at the same rate" must be viewed in relation to some time scale allowing short-term variations to eventually cancel out. Therefore there is no way in which to test the ergodic hypothesis. However, the general uniformity of the shales being eroded in north-east Yorkshire suggests that the geological conditions are conducive to the hypothesis. Hence it is, perhaps, wisest to regard area as being only loosely correlated with time.

At times, order may be unpredictable, yielding a smaller bay than one at the same site of lower order, e.g. orders 8 and 12 bays in Fig. 7.2; these differences may be due to very localised variations in normal-orientation and, in any case, are rare. Despite such small imperfections, the method is consistent in its task of generalisation.

In Fig. 7.4b the number of identified bays (excluding those with negligible area) is plotted against order. The equation for the curve is:

$$y = 14.2544 + 817.6896\ x^{-1} \quad (r^2 = 99.96\%;\ \text{significant at } 0.001)$$

The fall in the number of bays is very rapid at low orders, but decreases at higher orders. Since area and order are closely correlated, but the former is the easier variable to understand, area will be usually used in this study in preference to order. The differences in relationships with other variables are small, e.g. slightly curvilinear graphs replacing rectilinear ones and vice versa.

The Morphology and Development of Bays

The forms of bays vary in a continuum centred around some average CAR value which depends on the order of the bay. A scatter diagram (Fig. 7.5a) of CAR plotted against area for each bay of order 4 reveals that arcuate bays differ from the other two types in their size as well as their shape. The distinguishing parameter of triangular and rectangular bays is morphology but for arcuate bays, size is more important.

The three basic forms of bay also vary in proportion at each order (Fig. 7.5b). Arcuate bays are approximately constant at 40 per cent of all bays at each order. Rectangular bays, the most common form at order 2, diminish rapidly in number to zero at order 8 while, conversely, triangular bays increase in proportion until above order 8 they are constant at about 60 per cent of bays. This implies that basic shapes remain constant with increase in area above order 8, i.e. that changes in shape are most severe in the early stages of development.

This point can be more closely examined by a plot of CAR against the mean area of bays at each order (Fig. 7.6a). Rectangular bays

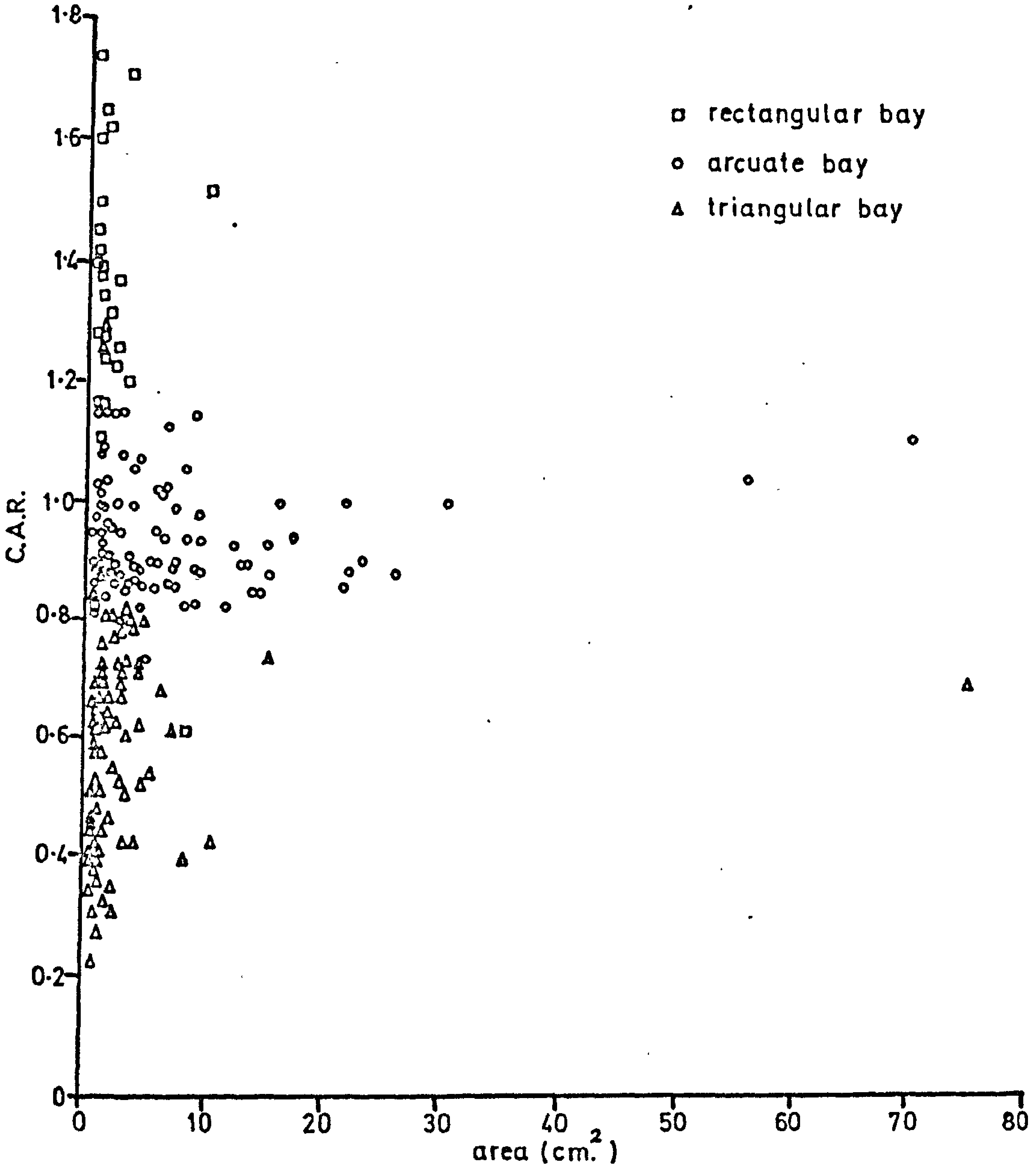

Fig.7·5a Scatter diagram of area plotted against C.A.R. for order 4 bays

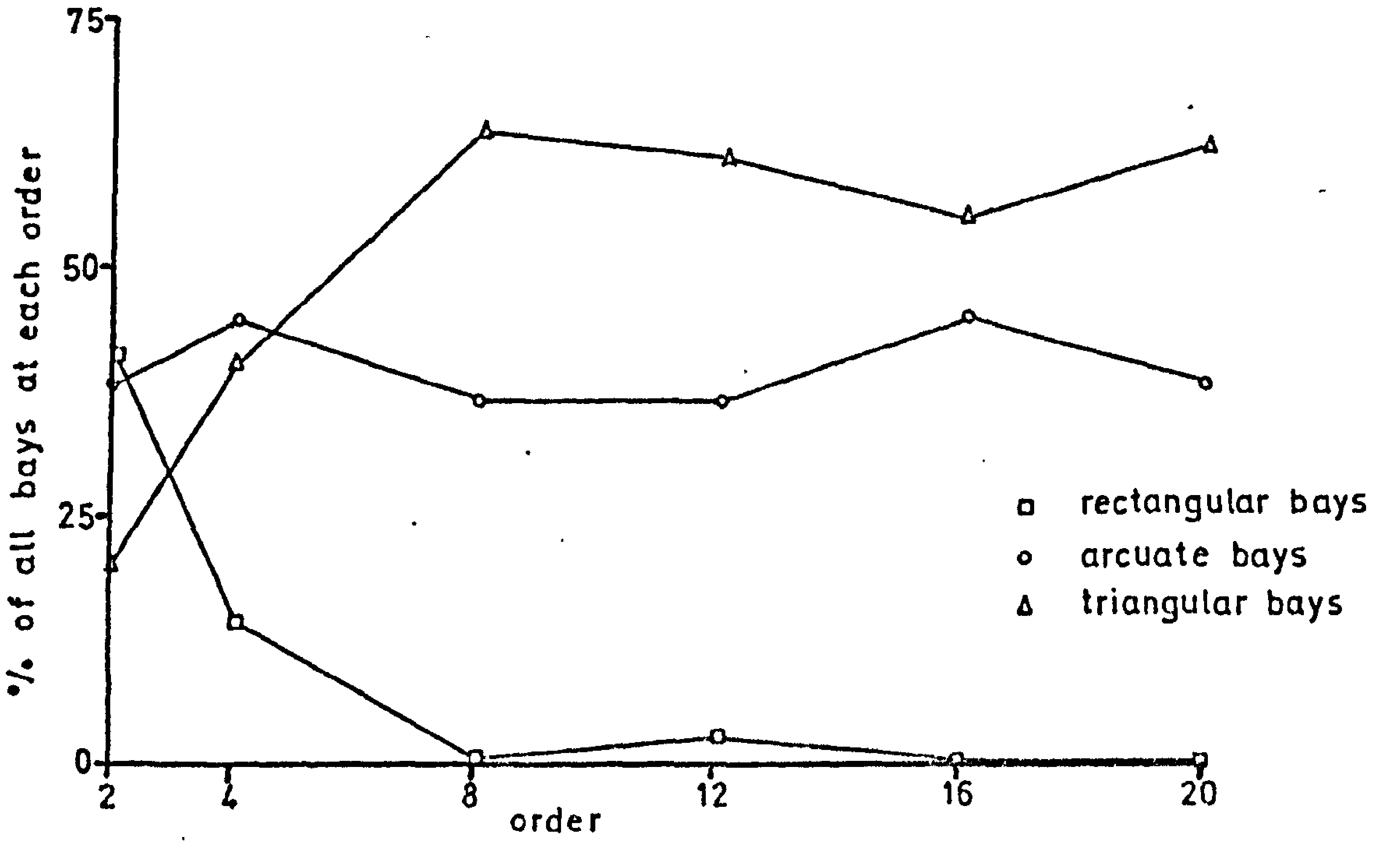

Fig.7·5b Relative proportions of basic shapes at each order rapidly become arcuate. Arcuate bays become more triangular initially but their shape stabilises at order 8 at a CAR value of 0.900 and is remarkably constant from then onwards. The precise evolution of triangular bays is not as clear. It is possible that they show a tendency toward circularity as shown in the diagram, but the linear correlation between CAR and area for these bays leads to only 5.13 per cent explained variation which is significant at the 0.70 level only. Hence, these bays are rather randomly distributed with respect to these two variables.

It is unlikely that most bays will have the same basic shape and follow only one of the three paths described throughout their evolution. Fig. 7.5b shows that the fall in the proportion of rectangular bays up to order 8 is matched by a corresponding rise in the percentage of triangular bays. Hence, some rectangular bays will become arcuate while most, together with some that were originally arcuate, will become triangular. It is clear, however, that above order 8 basic shapes change little, although Fig. 7.6a does show that arcuate bays grow much larger than triangular bays.

The ways in which bays grow in size are indicated by Fig. 7.6b. The kurtosis of arcuate bays increases with area, the rate of increase diminishing slightly as development proceeds. The relationship is formulated by the regression equation:

$$y = 0.1395 + 0.005689\sqrt{x} \qquad (r^2 = 98.43\%;\ \text{significant at } 0.001)$$

Therefore, these bays do not develop at the same rate around their perimeter; their lengths increase faster than their widths. It was shown in Chapter 4 that Fourth Bight also lengthens much faster than it is widened owing to the orientation of its sides with respect to the direction of wave attack. The importance of orientation must be substantial in bigger bays but erosion at their heads will also be enhanced

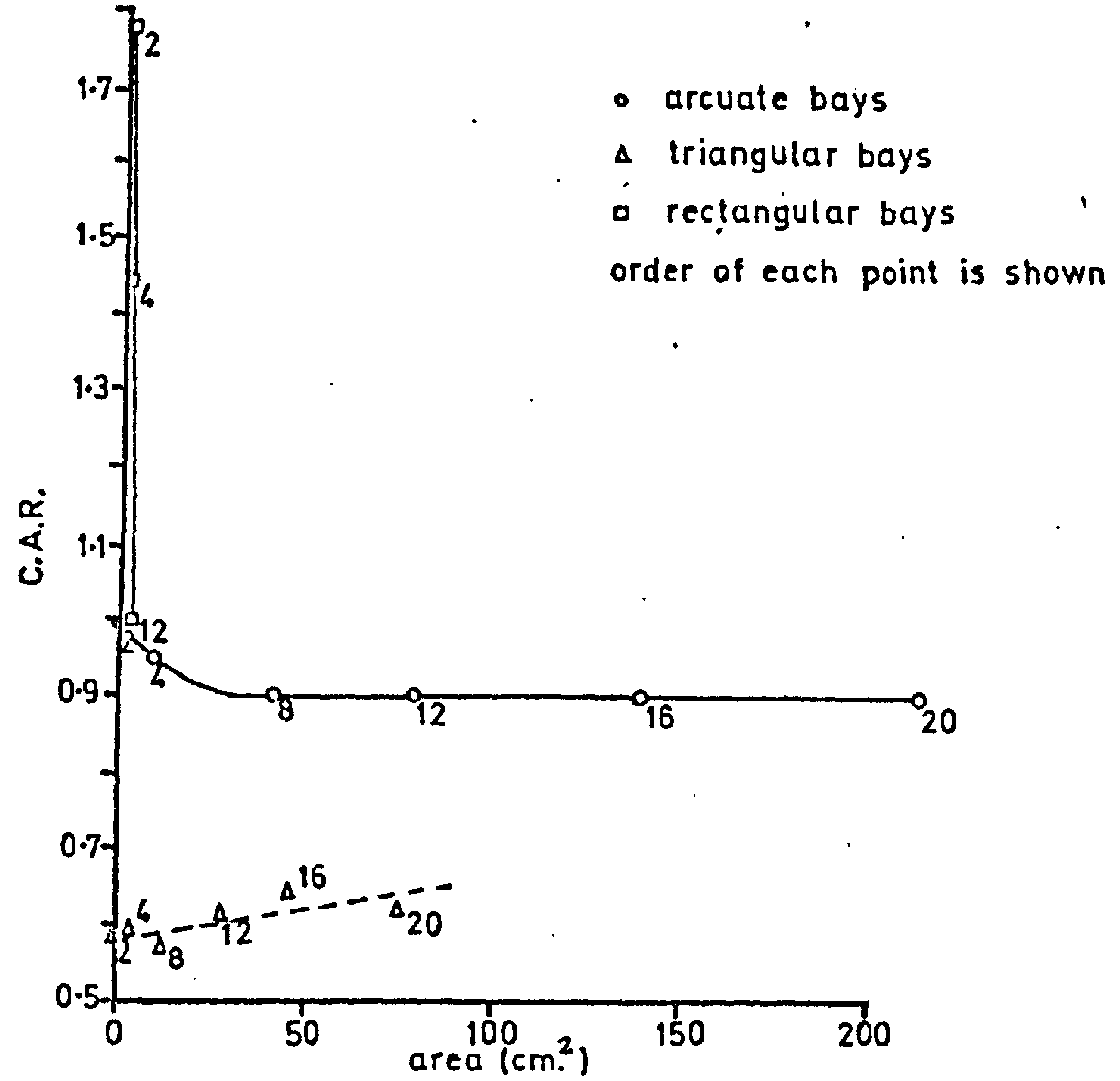

Fig. 7·6a Relationship between mean C.A.R. and mean area

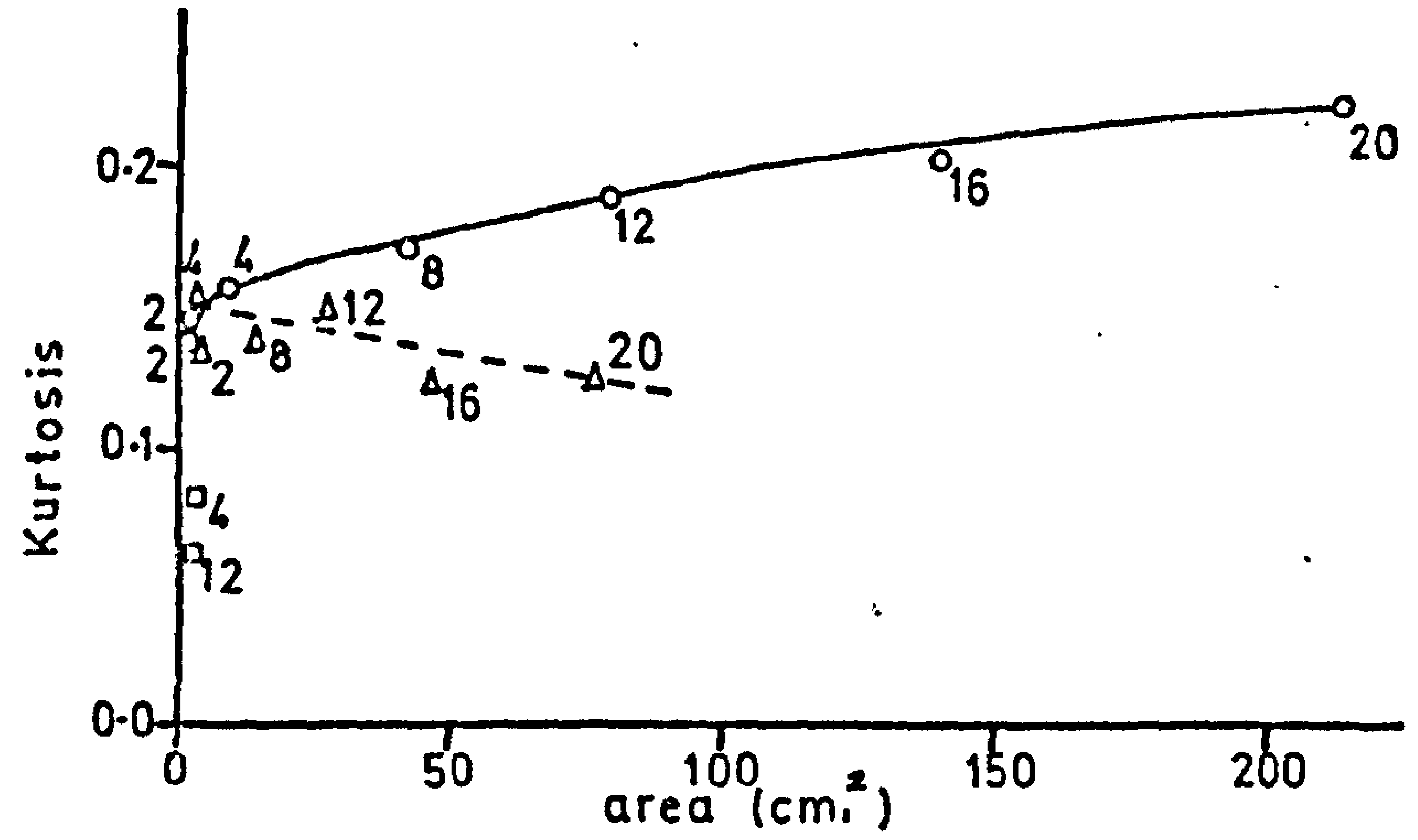

Fig. 7·6b Relationship between mean kurtosis and mean area

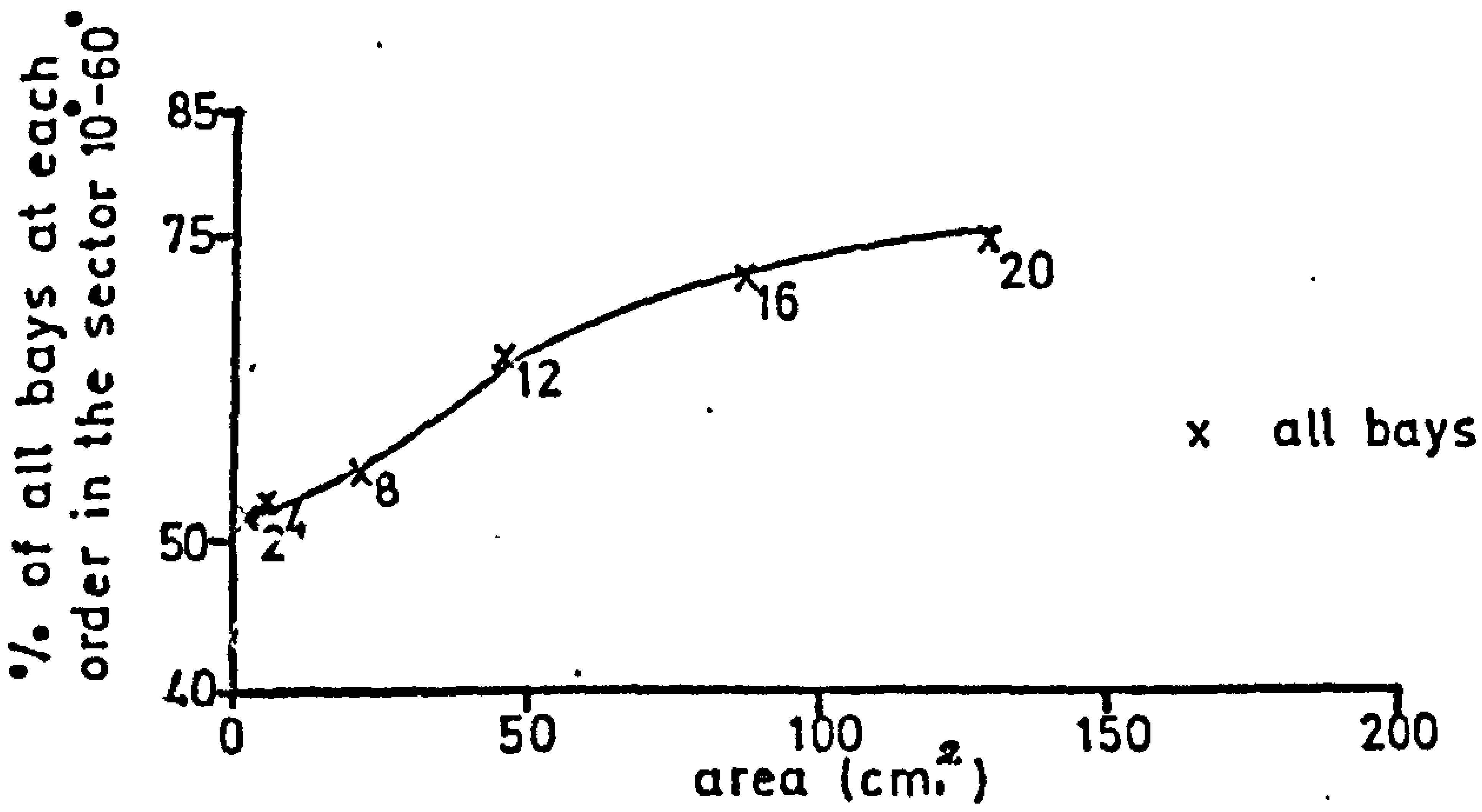

Fig. 7·6c Relationship between mean orientation and mean area of all bays by small pebble beaches. Because wave refraction is increasingly possible in larger bays, the differences in rates of erosion around their perimeters are reduced and the rate of increase of kurtosis also diminishes.

At all orders the kurtosis of arcuate bays is higher than that of triangular bays. This explains the fact that arcuate bays are larger on average than others at each order. There is a slight trend for the kurtosis of triangular bays to decrease with increased size but the correlation coefficient ($r = -0.7028$) is not significant at the 0.05 level ($t = 1.9758$; degrees of freedom = 4). Hence the slight tendency that exists is for these bays to widen faster than they are lengthened i.e. the angle made by their sides at the head of the bay increases with increase in size. The frequency distributions of kurtosis values for these and for arcuate bays become increasingly different with higher order and the difference becomes statistically significant (at the 0.05 level) at order 16. The differences between the histograms for rectangular bays and for the other two basic shapes are significant at order 4. The kurtosis of rectangular bays decreases very quickly with increase in area implying that those bays which remain rectangular simply fail to develop; the reason for this is geological as will be shown later.

The mean skewness of each basic type of bay at each order shows no consistent trend with increase in area. At order 2, the frequency distribution of triangular bays is evenly spread throughout the range of skewness values (0.0 to 1.0). At order 4 there is a small mode at 0.25 but at higher orders the spread is again fairly even. Arcuate bays, however, show a strong mode so that up to, and including, order 8 there is a significant difference (at 0.01) between these distributions and those for triangular bays. The mode is at 0.65 at order 2 and 0.75 at order 4. With higher orders the mode disappears and the spread of values is even. Rectangular bays differ significantly (at 0.005) from arcuate bays because of their strong mode at 0.95. The mode at order 4 is at 0.75 and the differences from arcuate bays are not significant though from triangular bays they are statistically significant at the 0.02 level. Since the exact point on the bay perimeter marking the head of the bay is probably subject to chance variations in geology and as the kurtosis of all bays is low, i.e. they are more than five times wider than long, it is not surprising that skewness shows little correlation with increase in area.

The orientation of bays has some effect on their morphological development. A frequency distribution (Fig. 7.7) of order 2 bays is an indication of the orientation of the whole coastline. It is normally distributed about the bearing 25 degrees from grid north and 99.25 per cent of the bays occur within the 210 degree sector from 310 to 160 degrees. The coastline from Saltburn to Old Peak is about 38km long so that refraction of waves usually reduces the importance of orientation. However, it has been shown that the north-east Yorkshire coast is attuned more to storm conditions than to those which are most frequent, storms from the sector between north and north-east being the most important. It may be coincidence that 52 per cent of the bays at order 2 lie within the sector 10 to 60 degrees but the proportion of bays increases by 21.8 per cent in the sector with higher orders and Fig. 7.7 shows that the most distinct modes at orders 8, 12 and 20 are in the sectors 10 to 30 degrees. The percentage of bays in the 10 to 60 degree sector is plotted against the mean area of the bays at each order in Fig. 7.6c. The proportion of bays rises with area but from order 12 onwards the

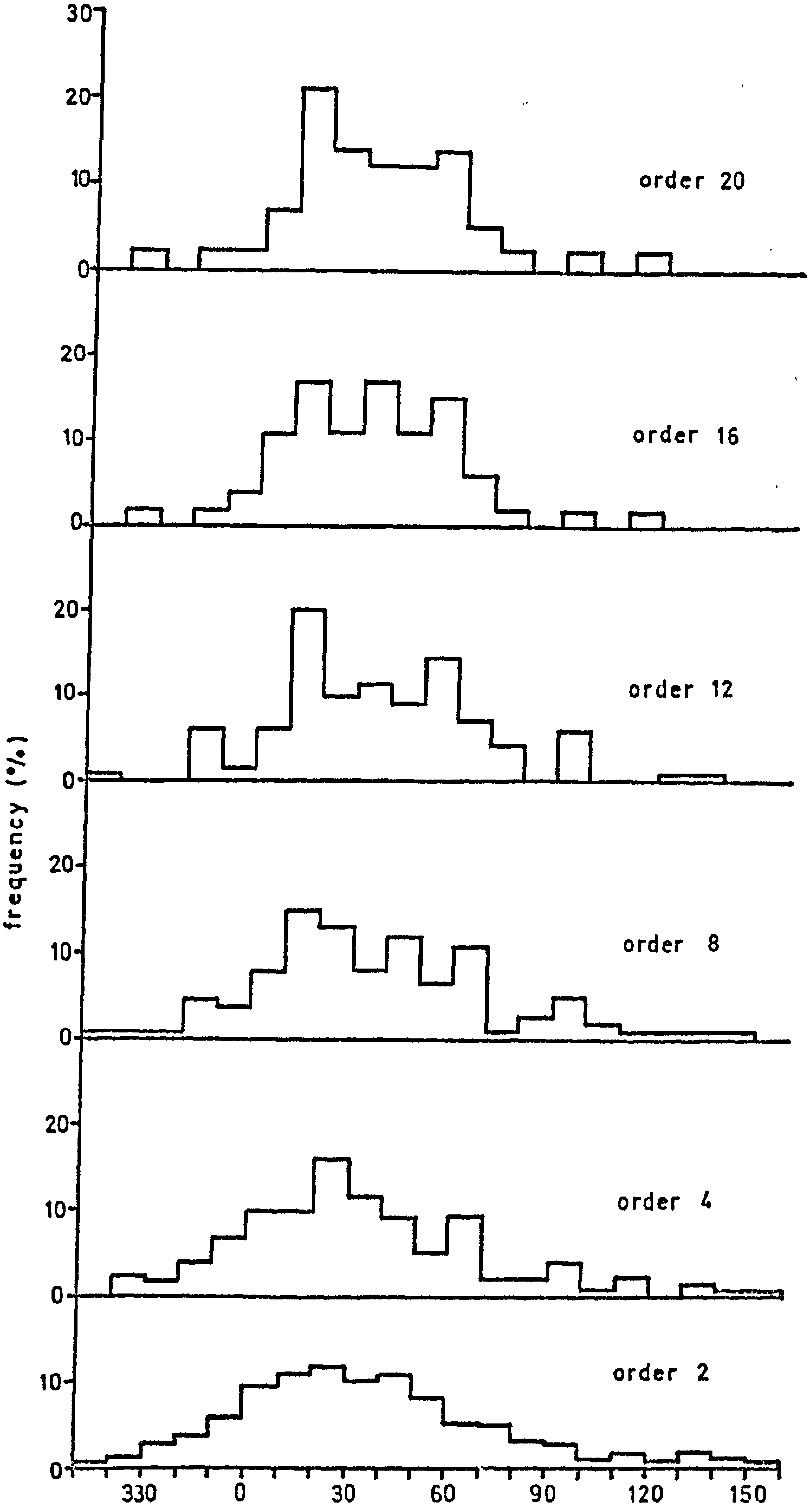

Fig. 7·7 Orientation of bays at each order rate of increase diminishes. Therefore, at low orders, when bay shape and area (of arcuate bays) change most rapidly, their orientation tends to swing towards the sector from which the most vigorous waves come. Lewis (1938) on the Bristol Channel coast, Arber (1940) in Cornwall and Devon, and Schou (1952) in Denmark have also shown, by various methods, that bays become orientated perpendicularly to the direction from which the most vigorous waves travel. Hence, it is concluded that storms are important in shaping the coastline, as well as many other features, in north-east Yorkshire.

It has become clear in this discussion of bay morphology and development that arcuate bays differ in many respects from bays which are basically triangular. It seems pertinent to examine the proposition that environmental factors such as geological and cliff-foot conditions are important in influencing the form and development of bays. Since geological variations are obscured to some extent by certain types of cliff foot, e.g. talus, the importance of the nature of the cliff foot will be investigated first.

The Influence of Cliff Foot Type

Three categories of cliff foot are recognised for this study:

1. "beach" cliff foot - this includes those parts of the basal coastline which are bare and those where easily movable superficial deposits such as sand and pebbles rest.
2. boulder beaches - the bare cliff foot can be reached by the waves only after crossing areas of boulders of medium or high density (the meanings of these terms are given in Chapter 2).
3. talus - in this category the solid rock at the foot of the cliff is hidden by talus cones. These cones in turn are usually surrounded by thick spreads of large boulders.

The length of coastline fronted by each type of cliff foot in each bay was calculated and the most important type was used to characterise the whole coastline in that bay. Again, the three basic morphological classes of bay react in different ways to the same factors. Arcuate bays are most common on sections of the coastline where the cliff foot is "beach" (Fig. 7.8 a). This is due to the fact that this category of cliff foot is the most common. Hence the absolute values of proportions in Figs. 7.8 a and b are irrelevant in this discussion of the influence of cliff foot type on bay development. However, this factor is most important as is shown by the trends of the relationships. Arcuate bays are able to grow unhindered where the cliff foot is "beach". The best-fit regression equation (excluding data for order 12 which deviates strongly) is:

$$y = 49.2149 + 9.6624x^{\frac{1}{4}} \quad (r^2 = 95.18 \text{ per cent; significant at } 0.005)$$

The increase in the proportion of bays is most rapid at orders 2 and 4 confirming the conclusion reached earlier that shape changes most rapidly in the very early stages of bay development. Boulder beaches impede this development considerably so that the proportion of arcuate bays falls; the equation is

$$y = 18.3782 - 0.0317x \quad (r^2 = 83.16 \text{ per cent; significant at } 0.05)$$

Talus further accentuates the decline in proportion so that at order 20 no arcuate bays exist where talus constitutes most of the coastline. This relationship is expressed formally as:

$$y = 21.5332 - 1.4685\sqrt{x} \quad (r^2 = 99.68 \text{ per cent; significant at } 0.001)$$

Again changes are most rapid at low orders.

There is a trend for the proportion of triangular bays to fall with increasing bay size where the cliff foot is "beach" but the scatter

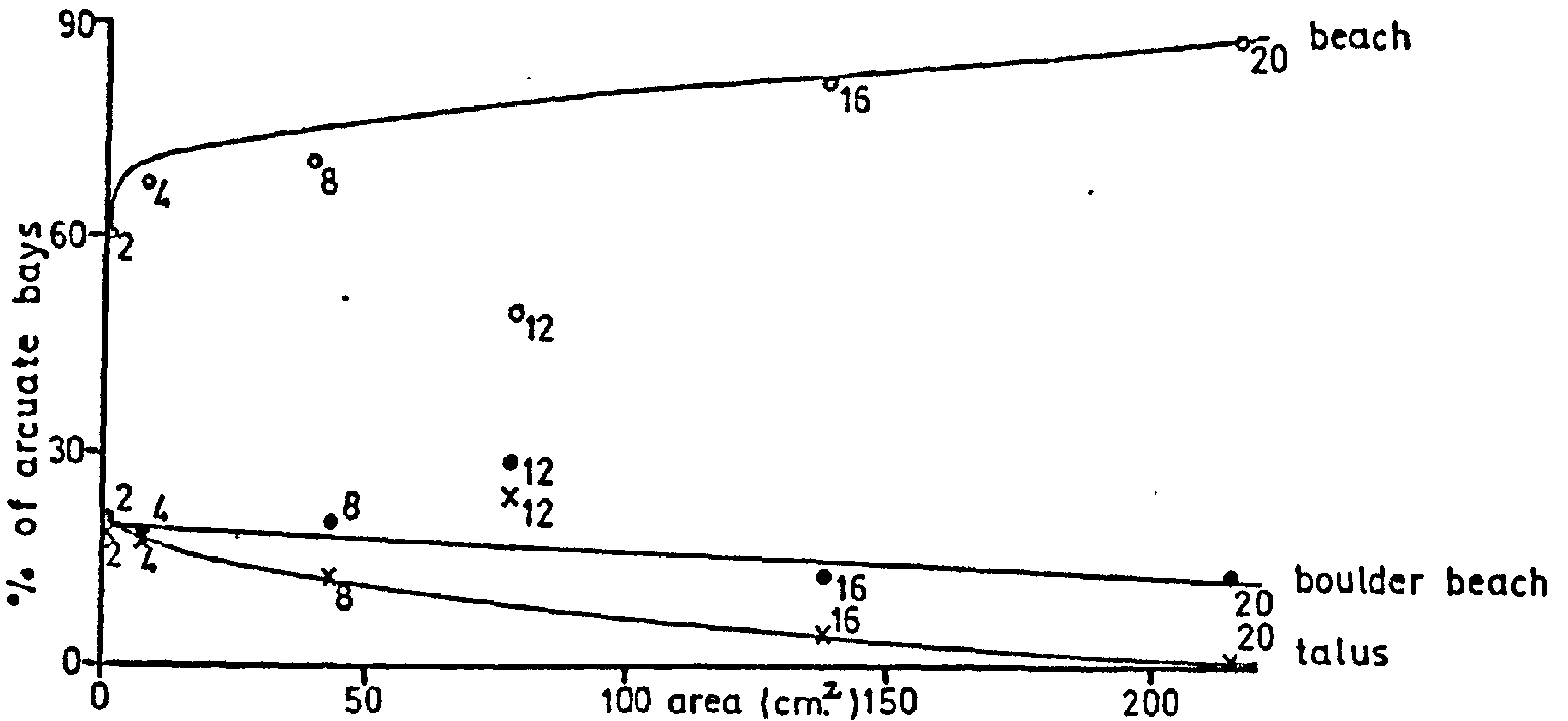

Fig.7·8 a Influence of cliff foot foreshore type on the number of arcuate bays

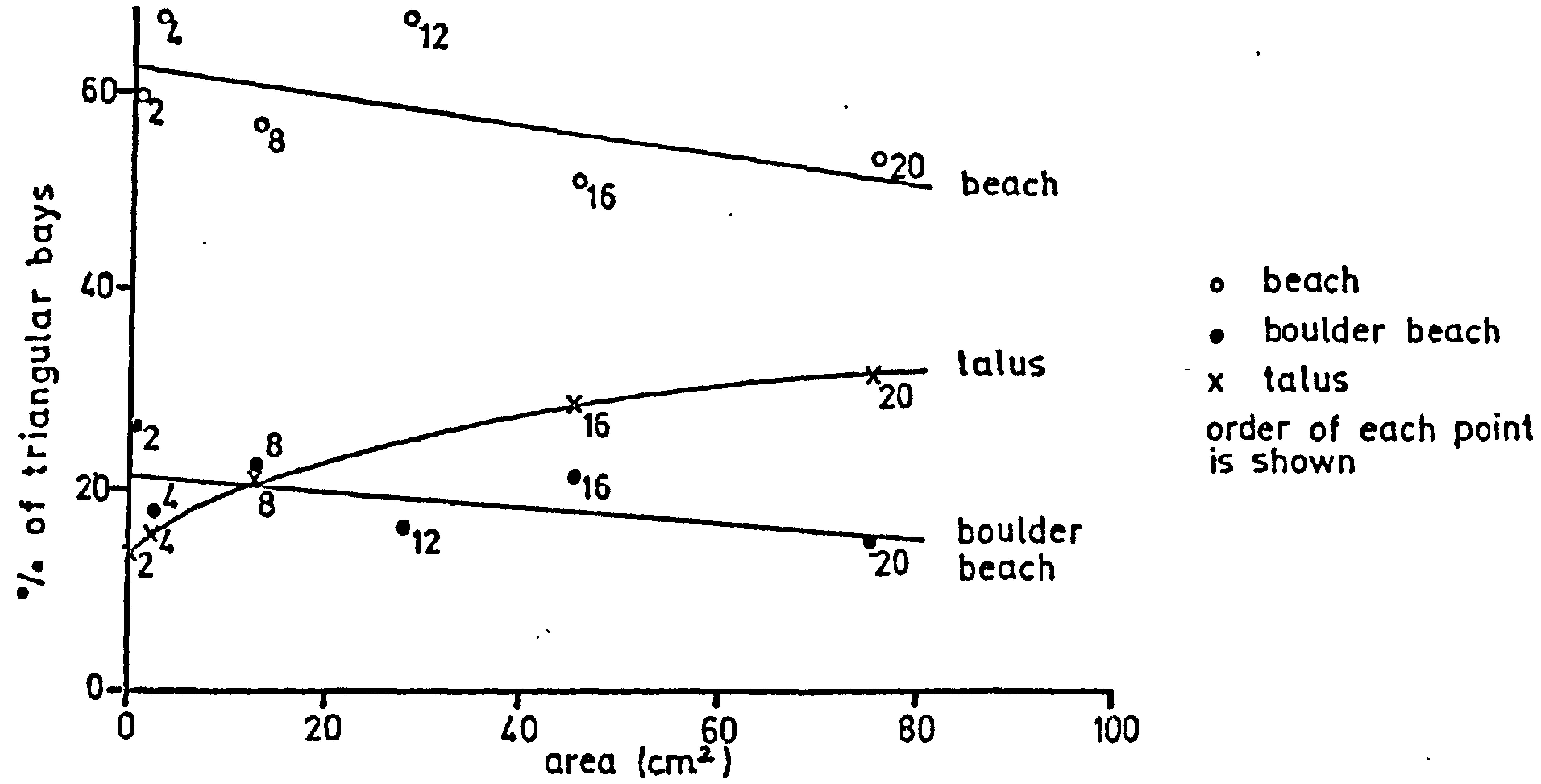

Fig.7·8 b Influence of cliff foot foreshore type on the number of triangular bays

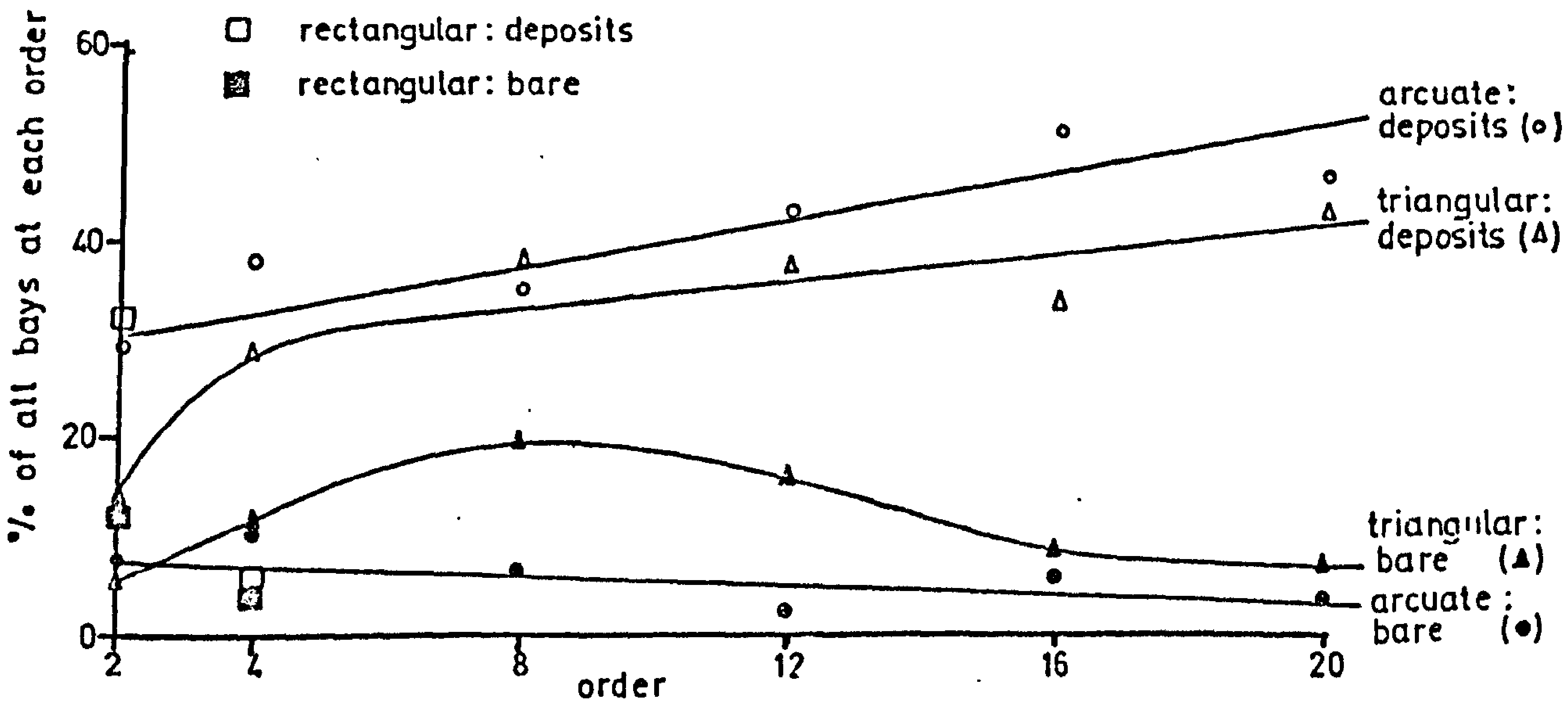

Fig.7·8 c Relative importance of cliff foot foreshore types in the development of each basic shape of bay of points is considerable so that the correlation coefficient is not significant at the 0.05 level. Again boulder beaches seem to impede an increase in the proportion of bays but this trend also is not significant at the 0.05 level. Talus, however, leads to a rapid increase in the proportion of triangular bays with increases in order and area. The best-fit equation is:

$$y = 6.4538 + 8.1121x^{\frac{1}{4}} \quad (r^2 = 99.04 \text{ per cent; significant at } 0.001)$$

The increase is most rapid at low orders. Talus is an increasingly important characteristic of triangular bays as they grow in size, and yet the proportion of bays in this category is lower at each order than that where the cliff foot is "beach". This is partly due to the different sorts of cliff foot included in this category. Division of arcuate and triangular bays into groups where the cliff foot is truly bare and where superficial deposits occur yields Fig. 7.8 c. Most bays contain sand or pebble beaches and the proportion increases with area. Arcuate bays with a predominantly bare cliff foot are not common and decrease in proportion with greater size. This implies that arcuate bays tend to have beaches in them which encourage their development. However, a high proportion of triangular bays also contain beaches. The relationship for bare triangular bays is most interesting and suggests that, initially, the absence of a beach encourages the production of triangular bays by the exploitation of rock weaknesses. However, as the bays grow in size, there is a greater tendency for material which is being transported by longshore movement from outside the bay and for debris falling from the cliff itself to become trapped in the bay. When the bay is sufficiently large for this to occur (order 8) it is also too large for its basic shape to be greatly altered by the increased erosion which the presence of the beach allows. Thus, the formation of arcuate bays is encouraged by few geological variations and by the existence of a beach while triangular bays develop where there are structural or lithological weaknesses and/or where the cliff foot is bare and secondarily where the cliff foot is formed by talus cones. These eliminate erosion of the solid rock leading to the deformation of the initial bay morphology since erosion will continue where the cliff foot is not so protected.

The presence of talus, and secondarily, boulder beaches at the cliff foot seems to be conducive to the development of rectangular bays while, where the coastline is bare, there is a rapid reduction in the number of them with increasing order, probably because they develop into arcuate forms. The data for rectangular bays are insufficient, however, for confident generalisation.

The forms and morphological development of both arcuate and triangular bays are profoundly influenced by the type of cliff foot. Arcuate bays, where the cliff foot is "beach" have high circularity and this is maintained after a small initial fall as they grow in area (Fig. 7. 9 a). The relationship is described by the equation:

$$y = 1.0551 - 0.0725x^{\frac{1}{6}} \quad (r^2 = 84.57 \text{ per cent; significant at } 0.01)$$

Boulder beaches hinder erosion to a considerable extent so that bays of the same order as those where the cliff foot is bare are both smaller and, as they grow, their circularity drops sharply according to the equation:

$$y = 1.1331 - 0.1335x^{\frac{1}{4}} \quad (r^2 = 93.43 \text{ per cent; significant at } 0.005)$$

Those arcuate bays where the cliff foot is composed mainly of talus show a similar trend but the bays are usually even smaller and the fall in circularity is more rapid. Excluding the point for order 16

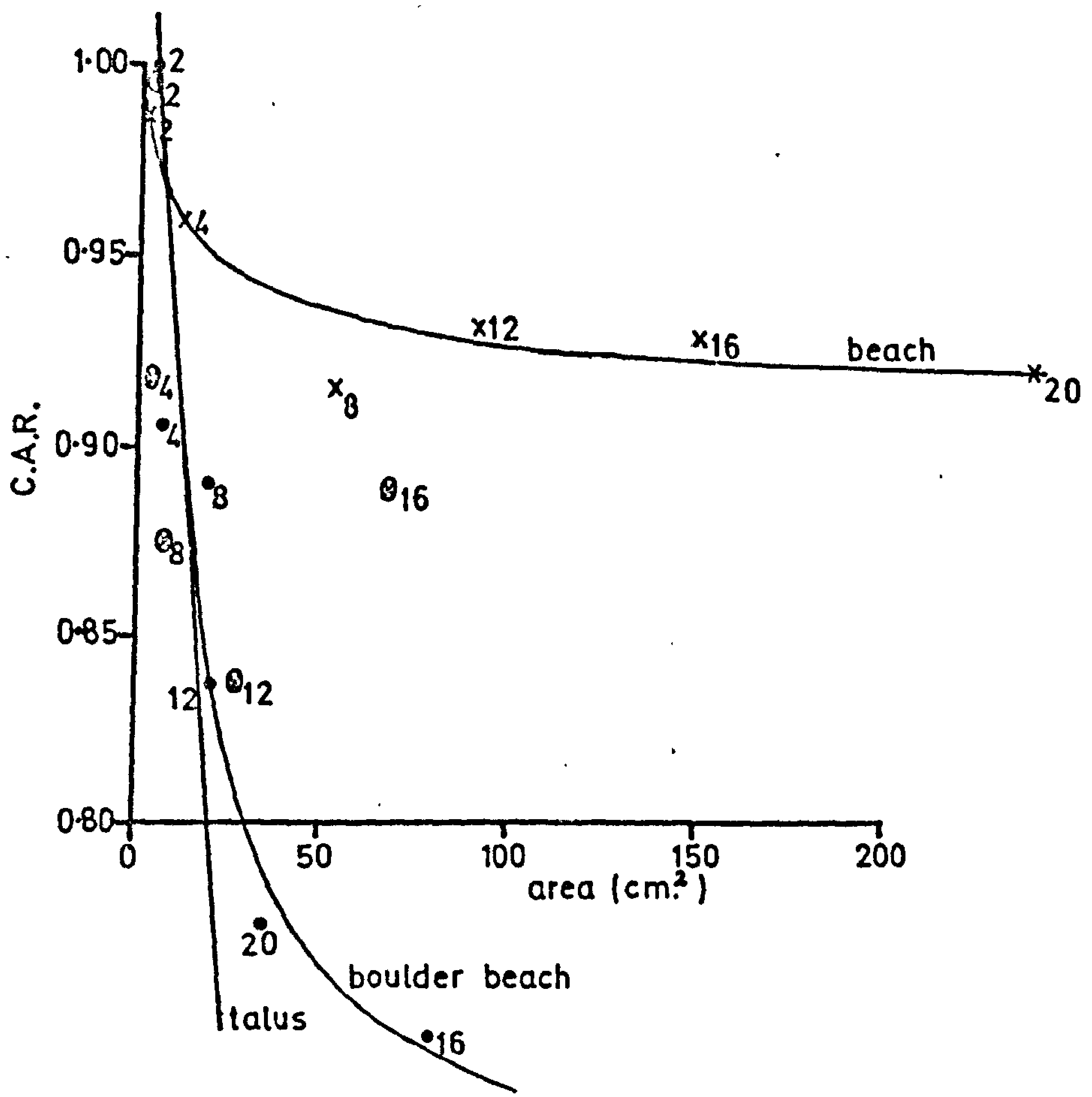

Fig.7·9a The influence of cliff foot type on the morphological development of arcuate bays

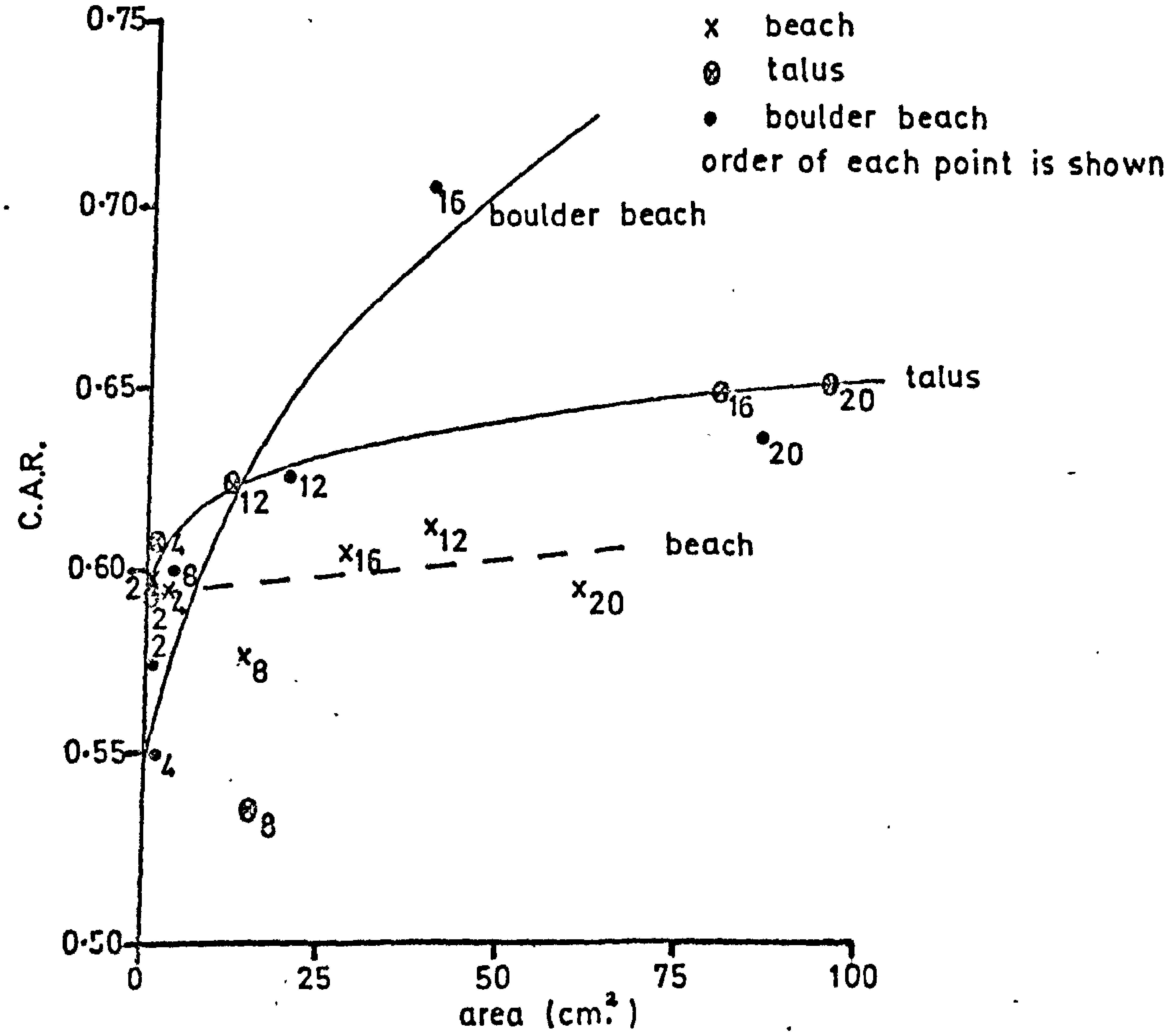

Fig.7·9b The influence of cliff foot type on the morphological development of triangular bays which deviates strongly from the trend, the equation is:

$$y = 1.7788 - 0.7773x^{\frac{1}{8}} \quad (r^2 = 91.91 \text{ per cent; significant at } 0.05)$$

Therefore, arcuate bays which do not have the "beach" type at the cliff foot become increasingly triangular as they develop.

As with other variables, the relationships between mean CAR and mean area at each order for different types of cliff foot in triangular bays are not as clear as they are for arcuate bays. Thus there is only a slight trend for "beach" triangular bays to become more circular and the scatter of points is large. The correlation of shape with size for bays lined with talus (Fig. 7.9 b) is statistically significant (at 0.001) if the point for order 8 is excluded, the regression equation being:

$$y = 0.6760 + 0.0253x^{\frac{1}{4}} \quad (r^2 = 98.29 \text{ per cent})$$

Hence, these triangular bays initially become more circular but their shapes tend to stabilise at a CAR value of about 0.67. Triangular bays fringed with boulder beaches rapidly become more arcuate; excluding the point for order 20, the equation:

$$y = 0.5384 + 0.0242x^{\frac{1}{2}}$$

explains 89.49 per cent of the variation and is significant at the 0.02 level, while if the point for order 16 is excluded and that for order 20 included, the equation

$$y = 0.4725 + 0.0973x^{\frac{1}{4}}$$

explains only 77.02 per cent of the variation and the correlation coefficient is not significant at the 0.05 level. It is most interesting that these triangular bays seem to develop towards circularity while those which are arcuate with the same type of cliff foot become increasingly triangular. This suggests that the basic shapes of bays can change when they are fringed with boulder beaches if initially triangular or when the cliff foot is not the "beach" type if arcuate.

Therefore the nature of the cliff foot is very important to the morphology of bays.

The type of cliff foot also affects the areal growth of bays. The relationships for arcuate bays between mean kurtosis and mean area for each type of cliff foot at each order are shown in Fig. 7.10a. The curvilinear affinity between the two variables for bays with a "beach" cliff foot is expressed by the equation:

$$y = 0.1422 + 0.005657x^{\frac{1}{2}} \quad (r^2 = 99.10 \text{ per cent; significant at } 0.001)$$

The rate of increase of length relative to width diminishes with increase in area and the same tendency exists for bays with boulders at the cliff foot though the gradient of the relationship is lower indicating some impedance of wave action. The equation is:

$$y = 0.1502 + 0.0005224x \quad (r^2 = 69.19 \text{ per cent; significant at } 0.05)$$

The correlation coefficient for those bays lined with talus cones is not significant.

The strongly negative correlation (Fig. 7.10b) between mean kurtosis and mean area (excluding the data for order 12) for those triangular bays where the cliff foot is "beach" just fails to attain significance at the 0.05 level though 73.89 per cent of the variation is explained by the equation:

$$y = 0.1562 - 0.0003612x$$

The correlation coefficients for the other two types of cliff foot in triangular bays are not statistically significant.

This discussion of the influence of cliff foot type on the form and development of bays has revealed that the very different characters of arcuate and triangular bays can be correlated with the category of cliff foot to a considerable degree. Several of the relationships for

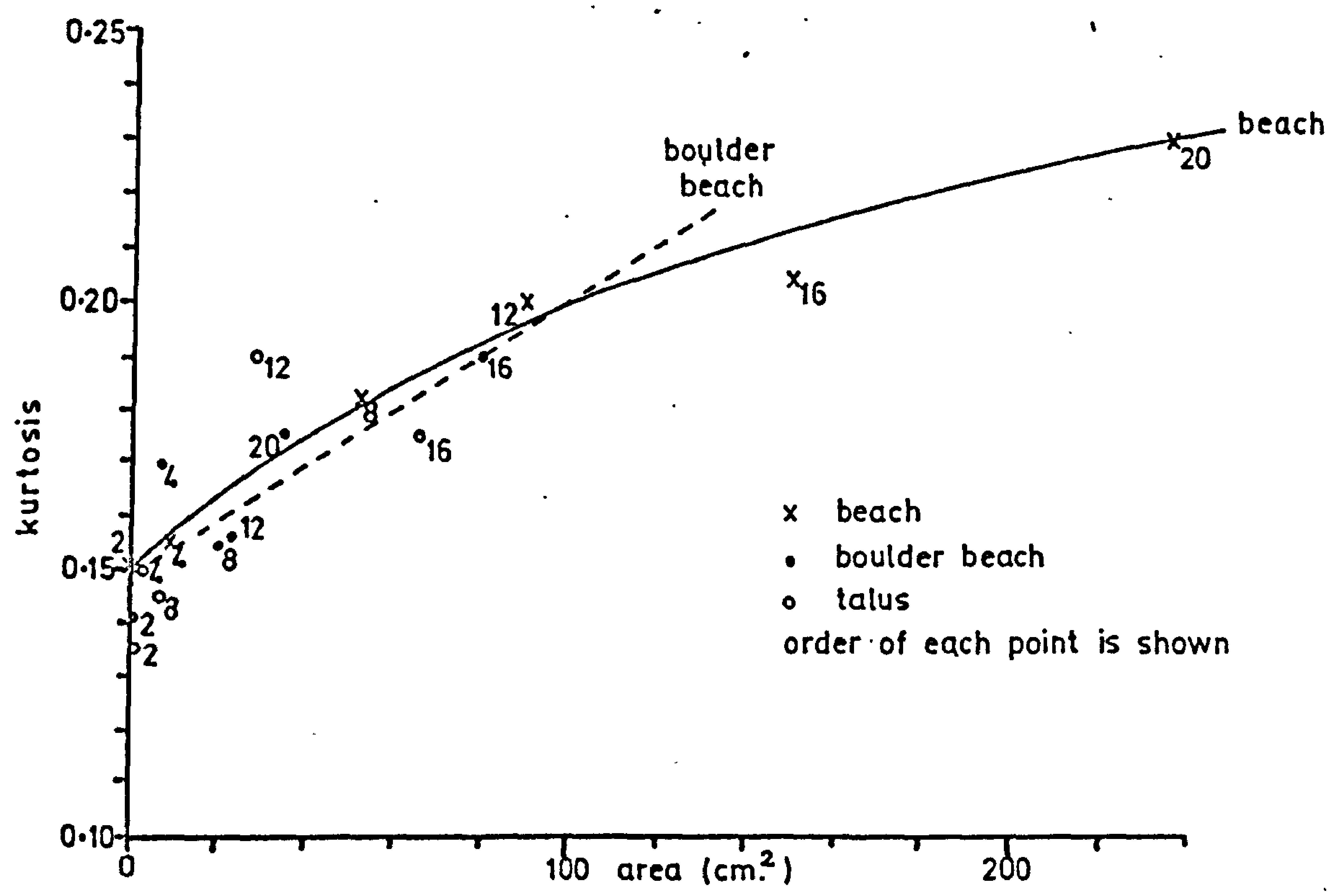

Fig.7·10a The influence of cliff foot foreshore type on the kurtic development of arcuate bays

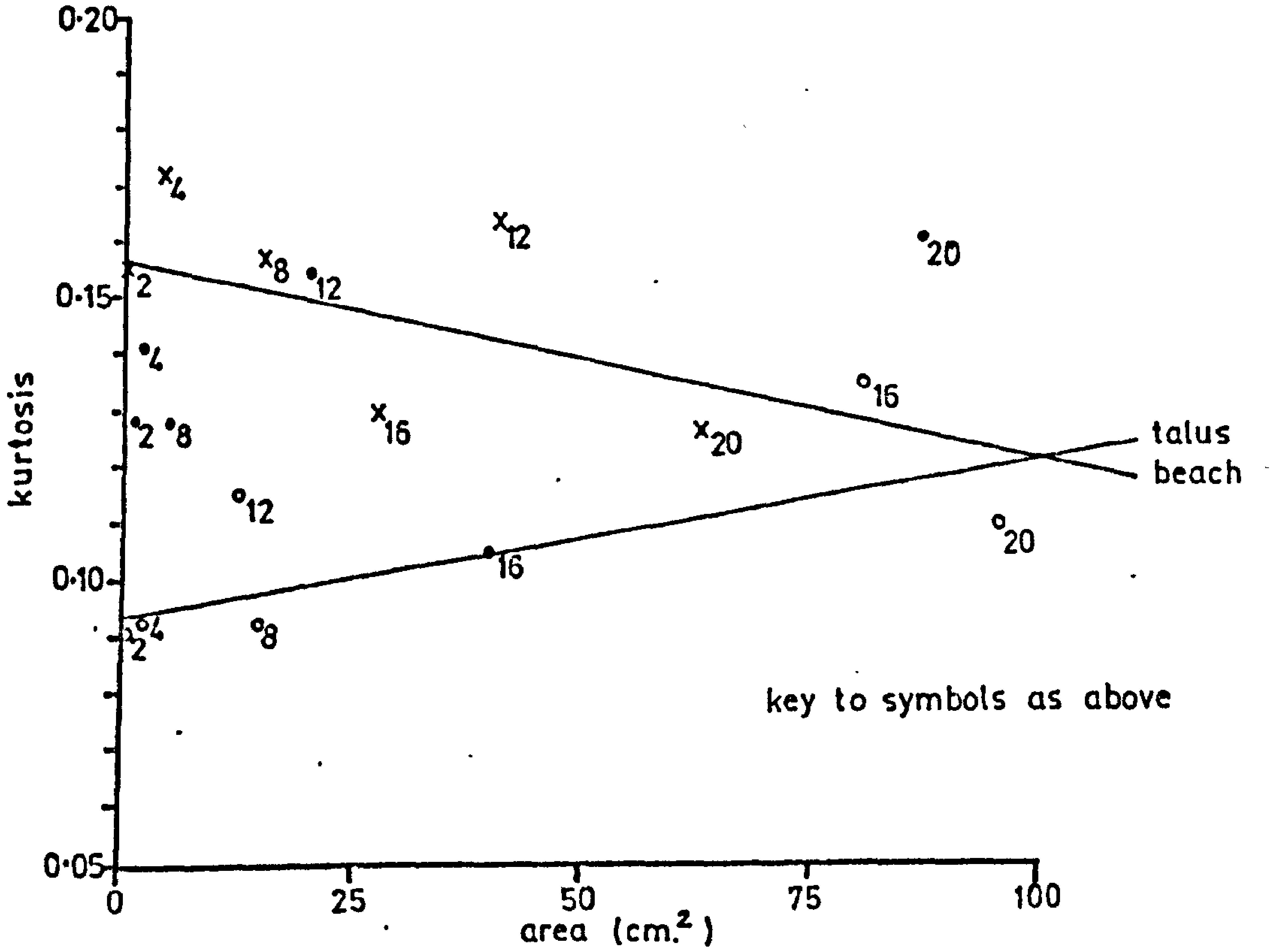

Fig.7·10b The influence of cliff foot foreshore type on the kurtic development of triangular bays triangular bays would perhaps have been more certain if the degrees of freedom had been higher. Certainly the exclusion of points which deviate markedly from a trend is not very satisfactory if complete objectivity is being aimed at. Such relationships must be considered to be tentative. Geological factors have been shown to be important in several instances and so it is necessary to examine the influence of these.

The Influence of Geology

Although the outcrop of different rock types influences marine erosion indirectly through the production of different types of cliff-foot superficial deposit, it is the direct influence of geology which is of interest here. This influence is created by the varied resistance of the rocks to marine erosion either because of fundamental lithological differences, e.g. the contrast between glacial deposits and sandstone, or structural variations of which joint systems are the most important component in north-east Yorkshire. The influence of geology will be examined only in those bays where the cliff foot is the "beach" type in order to minimise the influence of the type of the cliff foot. The five geological subdivisions derived in Chapter 2, namely Lower Lias, Sandy Series, Ironstone Series, Upper Lias, and glacial deposits, are used in this analysis. Where more than one subdivision crops out in a bay, the bay is assigned to the subdivision with the largest outcrop.

There is a strong tendency for certain shapes of bay to be developed in certain geological types. The frequency distributions of basic forms of bays at order 2 in each geological category excluding the Sandy Series for which the frequencies are too small, are significantly different at the 0.05 level. The Lower Lias shows an anomalously low frequency of triangular bays, and the Ironstone Series has a high count of arcuate bays and a low one of rectangular bays while glacial deposits have a very low frequency for arcuate bays and a high one for rectangular bays. These differences are due to geological variations. Thus the Lower Lias, with no intensive joint systems, has comparatively few triangular bays, the soft shales of the Ironstone Series allow arcuate bays to predominate and rectangular bays to be under-represented. Glacial deposits, which produce mud flows and rotary slumps, allow parts of the coastline to be pushed seaward very unevenly and are conducive to the existence of rectangular bays. At order 4, however, there is no significant difference between the frequencies of triangular and arcuate bays in each geological category, i.e. the influence of geology is reduced.

The proportions of arcuate and triangular bays at each order existing on the geological types are plotted against their mean areas in Figs. 7.11a and b respectively. It must be emphasised that the relationships pictured in these diagrams are tentative owing to the small frequencies of bays in each category at middle and high orders - indeed in some cases the frequency is zero. Hence, points which seem to deviate markedly from general trends have been ignored in plotting the relationships. For these reasons no statistical analysis has been attempted. It is clear, nevertheless, that different lithologies react in different ways. The variation of proportions between geological types is a manifestation of the extents of their outcrops and, therefore, is not relevant. However, the variations in the trends shown are pertinent to the discussion. In Fig. 7.11a each geological type has a peak in its trend which represents the point in its development when the coastline formed by that rock type is most indented, i.e. when lateral lithological and structural differences are at their most extreme. The differences between the Ironstone Series and the rest are the greatest. This series

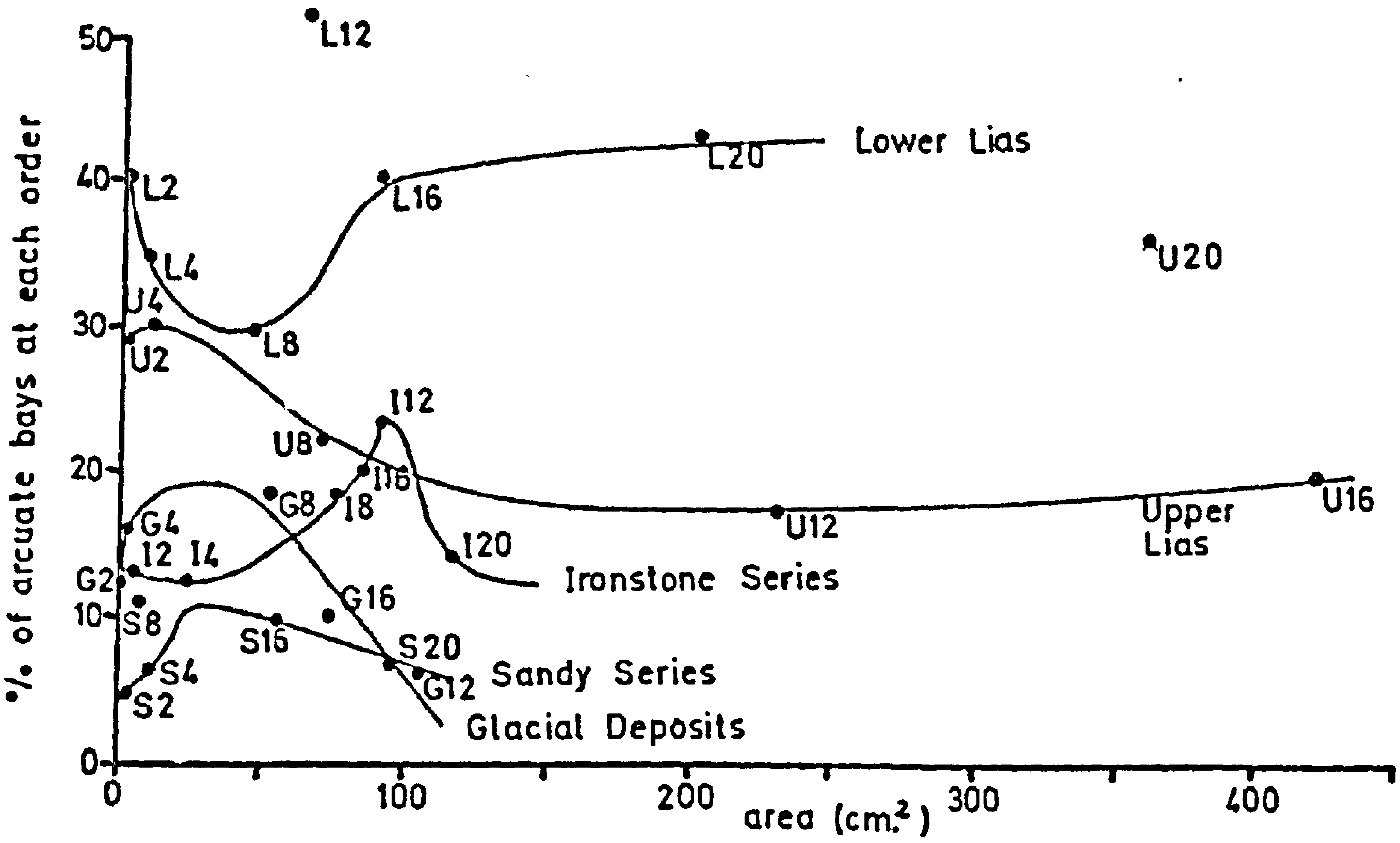

Fig.7·11 a The influence of geology on the numerical development of arcuate bays

G Glacial Deposits
U Upper Lias
I Ironstone Series
S Sandy Series
L Lower Lias
order of each point is shown

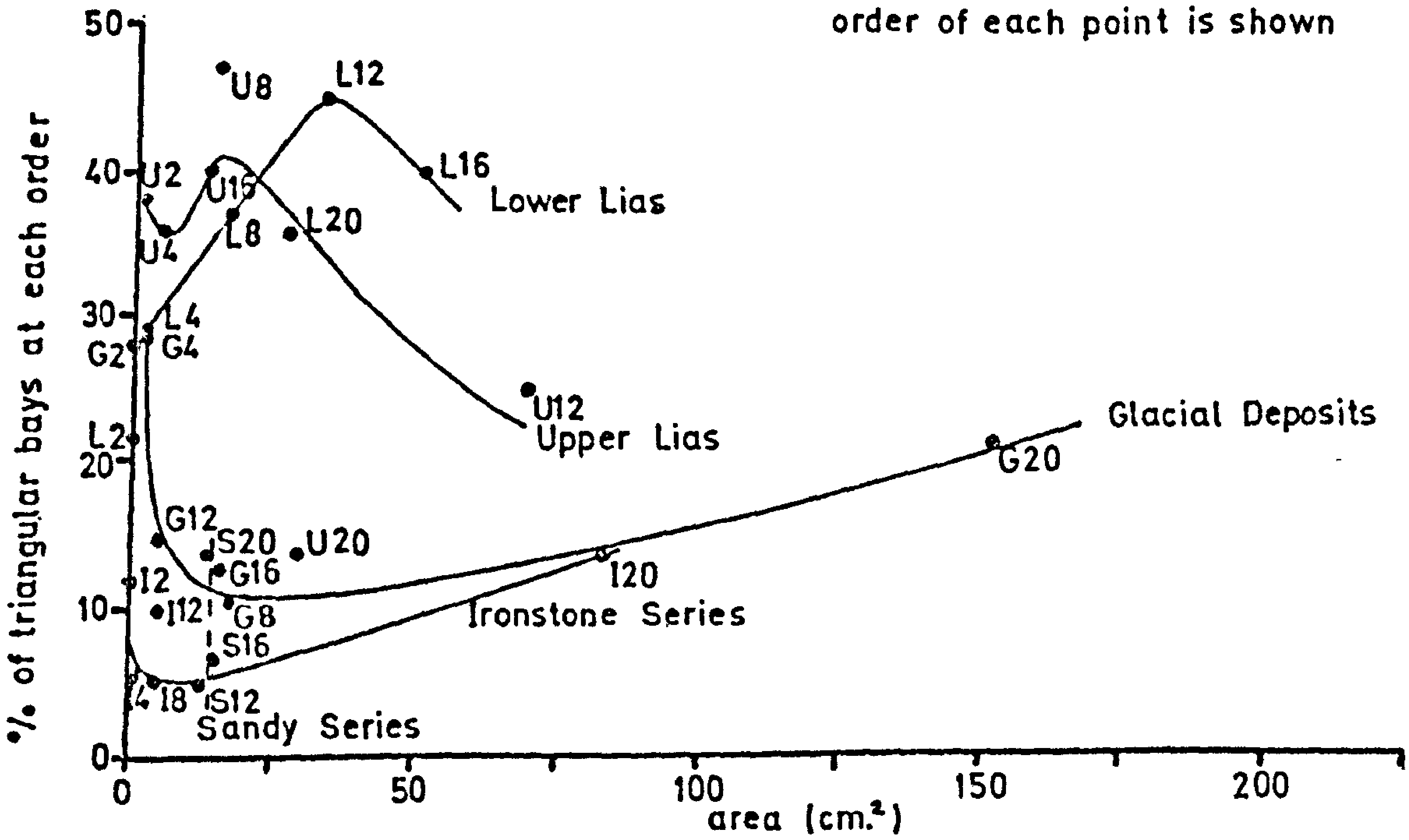

Fig.7·11b The influence of geology on the numerical development of triangular bays has thick beds of soft shale separated by sporadic seams of thin hard ironstone which allow large arcuate bays to develop between them. The other geological types do not have this lithological contrast.

Peaks also occur in the relationships in Fig. 7.11b but in all cases they occur in smaller bays especially in the cases of the Ironstone Series and glacial deposits. These two classes, generally having little resistance to erosion, allow large bays to develop rapidly so that their proportions initially drop but later rise.

Where the cliff foot is the "beach" type the morphological development of bays is controlled by geology alone (Figs. 7.12a and b). Again, the trends shown in these diagrams are tentative. The Upper Lias and the Ironstone Series have the most consistently circular arcuate bays. Both the Lower Lias and glacial deposits produce arcuate bays which initially become more triangular but the rate of decrease in circularity diminishes with increased size. Bays in the Sandy Series become triangular.

Triangular Upper Lias bays become more circular while those developed in the Ironstone Series and the Lower Lias soon attain stable forms. The shapes of triangular Sandy Series bays seem to have no relationship with area while bays in glacial deposits seem to become very triangular.

In summary, it can be concluded that the effects of geology on bay morphology are varied. Changes in shape on each type of rock are most rapid while the bays are small. The geological categories can be ranked according to the degree of circularity of both their arcuate and their triangular bays in the following order:

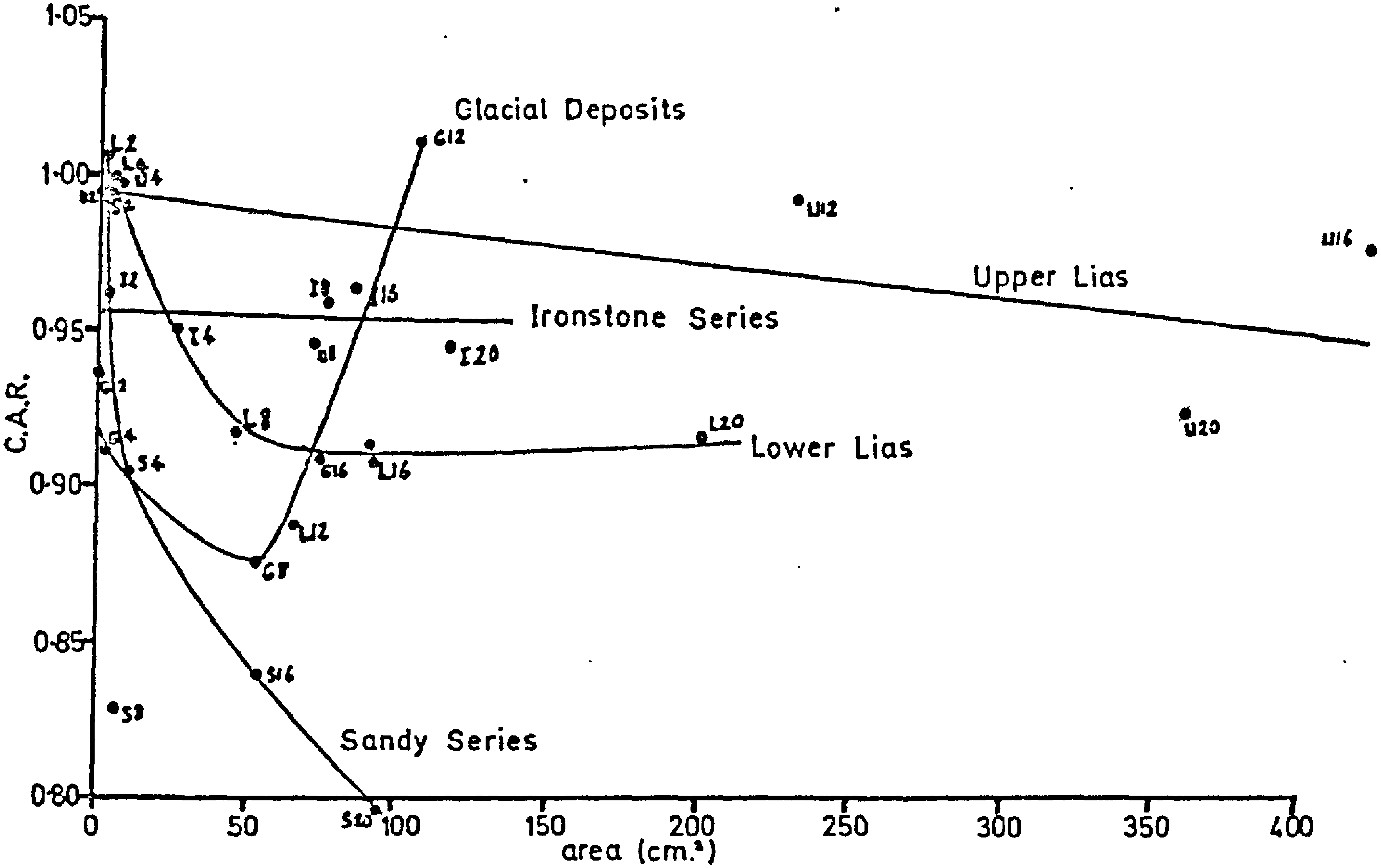

Fig.7·12a The influence of geology on the morphological development of arcuate bays

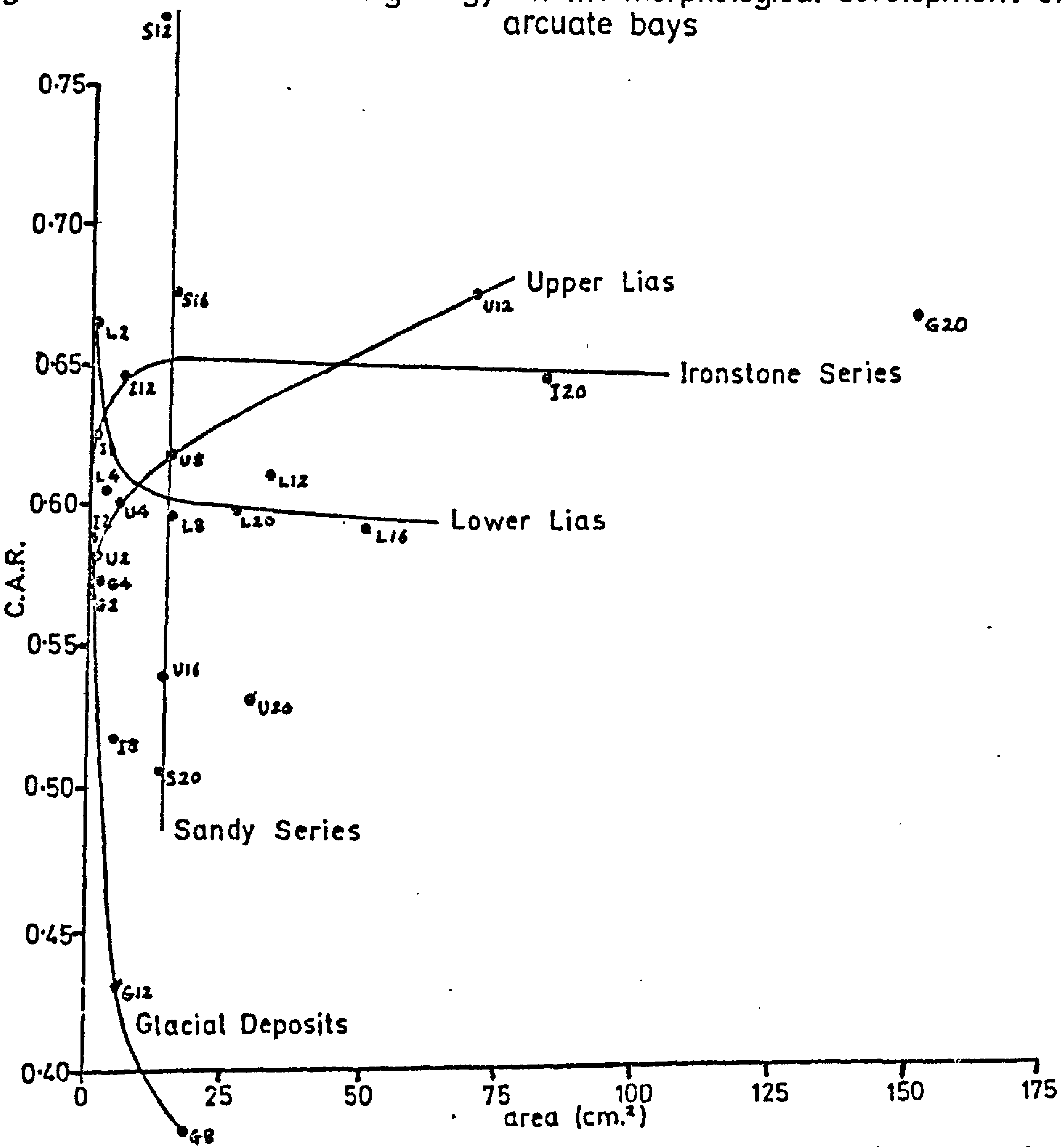

Fig.7·12b The influence of geology on the morphological development of triangular bays

1. Upper Lias
2. Ironstone Series
3. Lower Lias
4. Glacial deposits
5. Sandy Series

Geology also has marked effects on the relationships between kurtosis and the size of bays (Figs. 7.13a and b). There are few deviant points in these diagrams so that the trends are more reliable than the preceding ones. The geological types can be grouped into two classes according to their effects on the kurtosis of arcuate bays. In the first class (Sandy Series, Ironstone Series and Upper Lias) bays, as they grow in size, become more highly kurtic. In the second class (Lower Lias and glacial deposits) a peak in kurtosis is attained when the average size of bay is about 50 sq.cm. (on the 1:2500 plans, i.e. 0.03125 sq.km.) and then there is a rapid fall in kurtosis. This second class of bays also has lower values of kurtosis at almost all times than bays in the first class. The differences are due to the ability of the rocks to produce headlands. Thus the Lower Lias and glacial deposits, being relatively uniform and unresistant, are eroded at fairly uniform rates along their outcrop so that only small headlands (and bays) develop. The Sandy Series is the most resistant lithology at the cliff foot, yielding large headlands and small bays which are most likely to develop along lines of weakness and in the softer argillaceous strata of the Series. Similarly the ironstone seams of the Ironstone Series yield headlands. It is variations in the intensity of joint systems which leads to headland development in the Upper Lias since, despite its considerable thickness, it is relatively uniform lithologically.

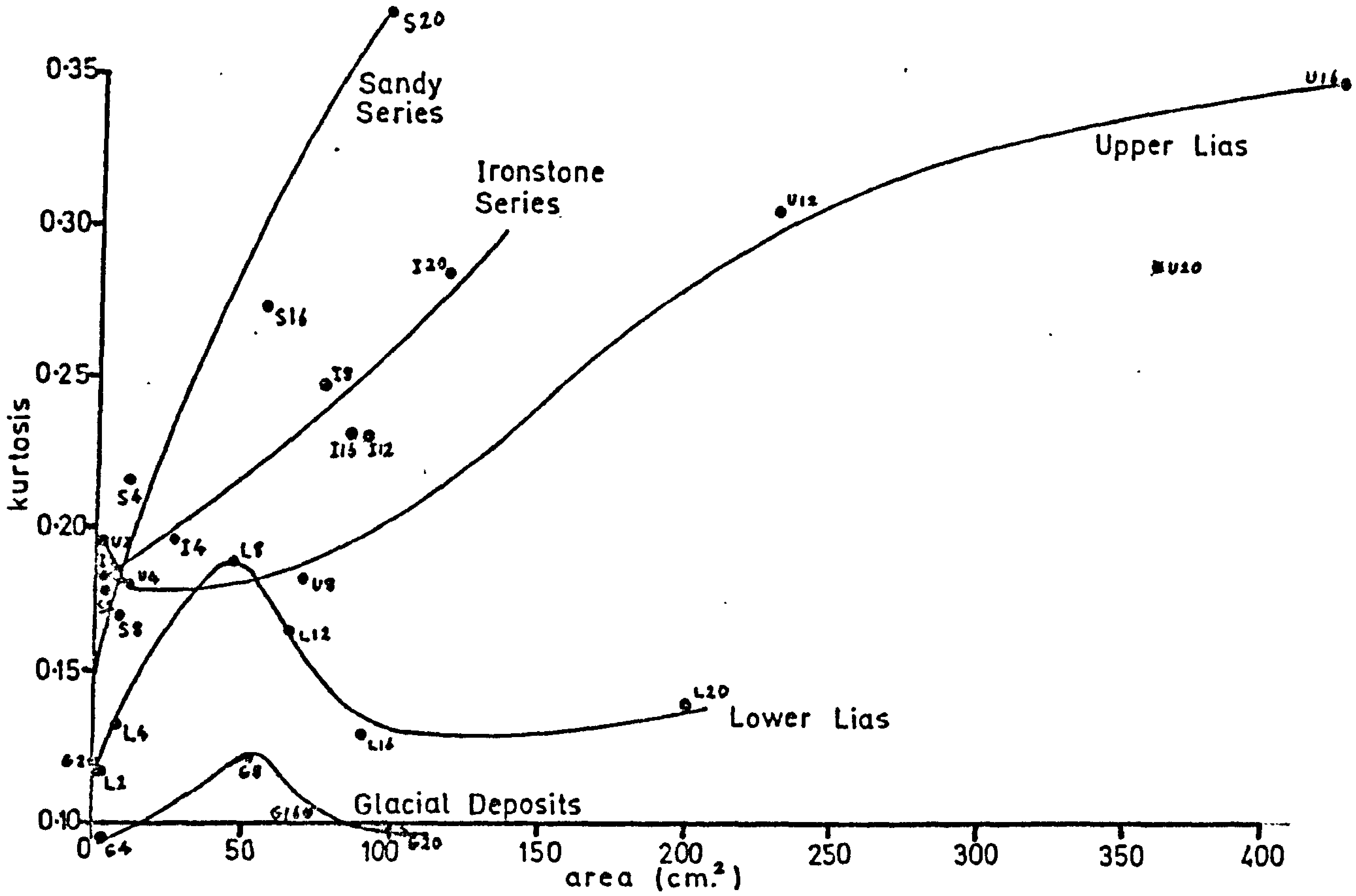

Fig.7·13a The influence of geology on the kurtic development of arcuate bays

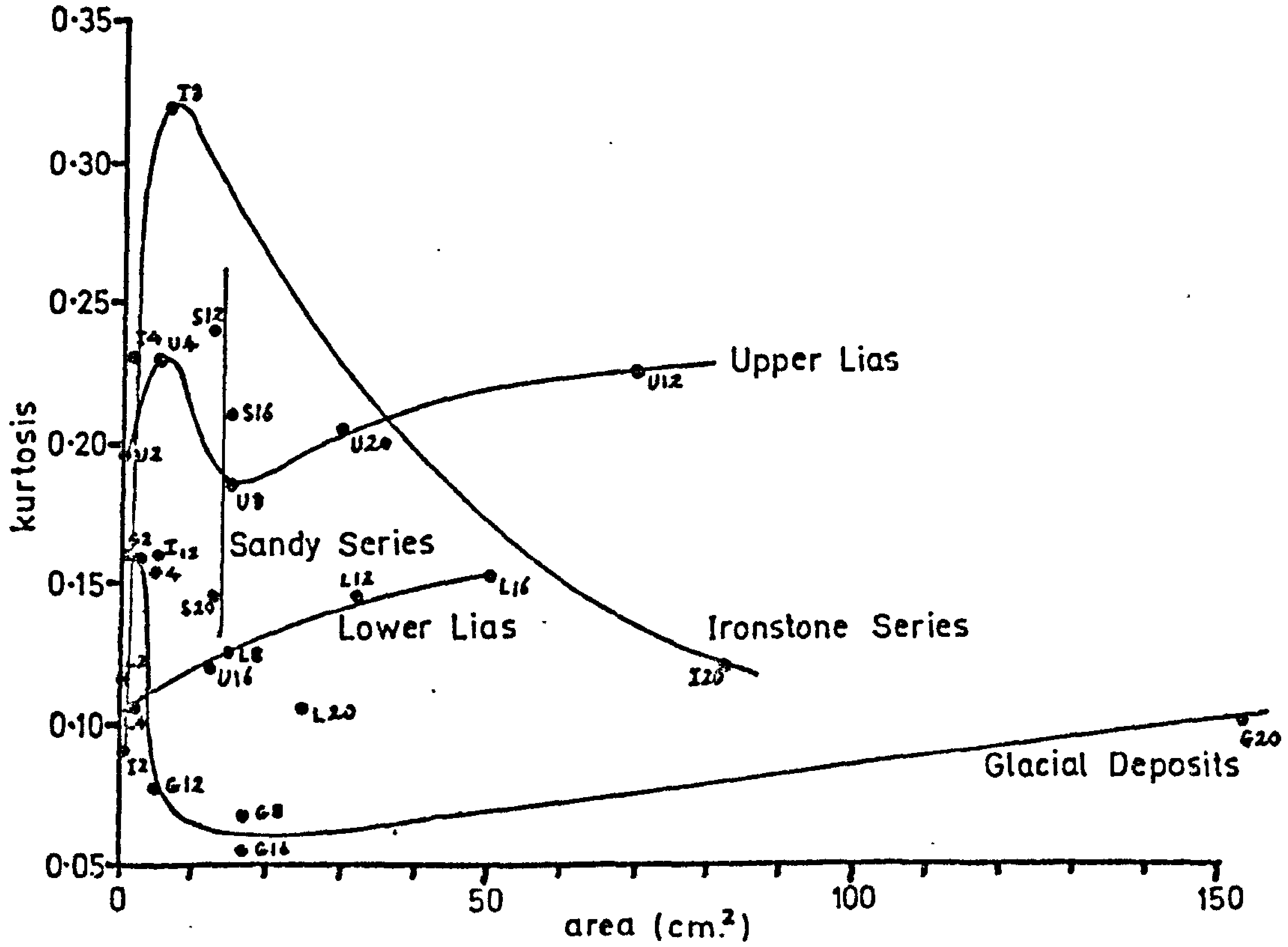

Fig.7·13b The influence of geology on the kurtic development of triangular bays

The relationships between kurtosis and area for triangular bays are similar to the second class defined for arcuate bays in that three of the five graphs have peaks, maximum kurtosis being reached early. Exploitation of weaknesses in the rock can proceed only to a certain depth depending on the nature of the weakness and the size of the bay, after which erosion of the bay is more uniform around its perimeter. The kurtosis of triangular Sandy Series bays is unrelated to area while in Lower Lias bays kurtosis increases at a diminishing rate.

The Location of Coastline Features

The most prominent headlands on the north-east Yorkshire coast are formed in the most resistant rocks, e.g. the ironstone seams at Old Peak, Normanby Stye Batts, Kettle Ness, and Old Nab, and the Sandy Series at Castle Chamber and Cowbar Nab. Conversely, the most conspicuous bays are cut into the least resistant lithology, the glacial deposits. They occur at Robin Hood's Bay, Saltwick Bay, Sandsend Wyke, Runswick Bay and at Skinningrove. Other prominent bays are bounded on one or both sides by headlands where resistant strata crop out, e.g. Far Jetticks is cut in shales of the Ironstone Series but to the south lie the Sandy Series and to the north ironstone seams. There seem to be few bays which have been eroded because of weakening of the rock by faulting but some examples are Staithes Wyke and Rosedale Wyke (Howarth 1955 and 1962 respectively has produced maps of these faults).

Despite these obvious correlations between resistance to erosion and the existence of coastline features, many exceptions to this relationship exist. There are no faults at Maw Wyke which is, perhaps, related to the thick boulder beaches that lie at each side of it though not at its head. Similarly, bays exist between Maw Wyke and Whitestone Point which are not obviously correlated with geological variations but perhaps with the superficial deposits on the foreshore. Many other small features (i.e. up to about order 8) are not obviously due to geological factors.

The influence of Man on the shape of the coastline has been limited. Saltwick Nab and Black Nab have alum quarries cut into them at low levels and iron mining has altered the shape of Kettle Ness and Old Nab a little, but these are isolated instances. With the construction of sea walls, especially where glacial deposits crop out, e.g. between Whitby and Sandsend and at the village of Robin Hood's Bay, this influence might be expected to increase.

The coastline features of high order are associated, therefore, with geological factors. Nevertheless, it has been shown that the influence of the type of cliff foot is most important in both the morphological and the areal developments of bays. It is concluded that the location of coastline features is a product of geological variables but that their development, especially at low orders, and the location of small bays and headlands are highly influenced by the type of cliff foot.

Conclusions

The new method of cartographical coastline analysis described in the first half of this chapter has allowed significant relationships to be identified not only in the evolution of the shape and area of bays but also between these variables and different environmental factors. Most bays, after attaining order 8, maintain their forms while growing in size by lengthening if arcuate or possibly by widening if triangular.

The development of arcuate bays is favoured by geological uniformity and by the presence of a beach; these bays are larger than those which are triangular. The existence of lithological or structural contrasts, the absence of a beach, or the occurrence of talus cones all favour the generation of triangular bays. The detailed evolution of bays is also controlled by the properties of the rocks into which they are cut.

These basic shapes can be changed, especially at low orders when evolution is towards the attainment of stable arcuate or triangular forms. At orders greater than 8, boulder beaches encourage the conversion of bays of one basic form into bays with a different basic morphology. This property of boulder beaches, which is also possessed by talus cones when they fringe arcuate bays, indicates that cliff foot type can act as a regulator in the evolution of bay morphology. Of course, the cliff foot type is itself subject to geological factors, e.g. no talus cones are generated where glacial deposits form the whole cliff and the "beach" type is more common where the cliff is composed wholly of Lower Lias or the Ironstone Series than it is where the Sandy Series or the Deltaic Sandstones crop out in it. The regulating action of boulder beaches and talus is due to their ability to impede erosion of the solid-rock-cliff foot. Erosion is rapid where they do not occur, leading to the indentation and deformation of arcuate bays. In triangular bays protection of the head of the bay allows erosion to be maintained along the sides, and particularly the central areas of the sides, so that the bay may become more arcuate. Alternatively, protection of the lateral end points of the bay allows the bay head to be widened by a sand or pebble beach, if it is present, so that greater circularity is again achieved. Since widening of the mouth of the bay is hindered in this case, lengthening will also be impeded. However, as well as coastline features, the type of cliff foot also evolves with the addition or removal of material so that bay development is also subject to the length of time over which a particular cliff foot exists.

Although this chapter has been concerned with the form and development of the north-east Yorkshire coastline, the rate of retreat of this feature has not been discussed. This topic is the subject of the next chapter.

CHAPTER 8

THE RETREAT OF THE COASTLINE

Introduction

This chapter treats solely those changes in the coastline for which there are cartographic and instrumental data; changes in the form of the coastline due to variations in sea level during post-glacial time are not analysed. It is possible to estimate rates of erosion at certain points along the coast by other means. Scattered through literature dealing with the study area are references to the loss of a few houses here and a few there. Thus, mention is made of the loss of 16 houses at Staithes (Mee 1942, p. 228), of the catastrophic landslip at Runswick in about 1700 when very many houses were destroyed (Fletcher 1901, p. 312; Wheeler 1902, p. 217), of the loss of 130 dwellings at Whitby on 24th December 1787 (Fletcher 1901, p. 332; Young 1817, p. 502), and of the demise of 193 houses at Robin Hood's Bay in the 202 years up to 1970 (Sunday Times, 4th March 1973). Unfortunately, however, such accounts relate only to very short sections of the coastline which may not be typical of the whole coast. The data available for the study of the whole coastline are rather scanty, being limited to the various Ordnance Survey plans produced at different dates and to the measurements taken in the short period of study in the area using the M.E.M. technique.

The Comparison of Ordnance Survey Plans

The comparison of Ordnance Survey plans of different editions is an established technique in the evaluation of the rate of coastline retreat. Some recent examples, using 1:10560 plans, are by So (1966), Wood (1968) and Trenhaile (1969), and using 1:2500 plans, by Westgate (1957). Despite their inherent inaccuracies these plans are generally the only source of data covering a fairly long period of time for the whole coast.

Assuming a plotting accuracy of 0.01 inch (0.025cm) on 1:10560 and 1:2500 O.S. plans (probably an optimistic figure), the minimum amount of retreat necessary before it is revealed by the comparison of two plans is 2.64m (8.80 feet) and 0.625m (2.08 feet) respectively. On a coast such as that in north-east Yorkshire where the main rocks are hard, i.e. they are neither glacial nor alluvial material, the erosion rate is probably low necessitating the use of the largest scale plan available over the longest possible time period. For this reason 1:2500 plans have been used for this study. The first edition was in c.1894-'96 (surveyed in 1893) with revisions in c.1914-'15 and in c. 1927. Publications after this date were patchy. A new edition was scheduled for the late 1930s and early 1940s but was interrupted by the war, so that only a few plans termed "the provisional edition" were published in c.1938. A complete national grid and metrically based edition is now in course of publication but, for the study area, only a few have been issued; they were surveyed in about 1967. This means that for some parts of the coastline (Saltburn to Skinningrove, Port Mulgrave to Lingrow, and Sandsend Ness to Saltwick Bay) changes can be traced for a period of approximately 74 years, while for others the record lasts for only about 34 years.

In the use of surveyed plans certain sources of inaccuracy must be borne in mind. Carr (1962) has categorised these into three types: technical accuracy, cartographic misrepresentation, and changes subsequent to publication. By 1893 errors due to inadequate instruments and techniques were negligible but this consideration precluded the use of the many large scale tithe award plans dating from the fifth and sixth decades of the nineteenth century.

The second source of error is more serious. Four lines generally constitute the coastline, these being the low-water mark (L.W.M.) and high-water mark (H.W.M.) of ordinary tides, the cliff foot, where this is not coincident with the H.W.M., and the cliff top. The low slope of the foreshore, the limited intertidal period, and variations in sea level from predicted heights are probably so important collectively that the L.W.M. cannot be relied upon. This line is almost exactly the same on the 1927 revision as on the 1893 edition, implying that it was not considered at all in the revision. However, the current national grid series representation of it is very different in many places, even where a shore platform exists and erosion is likely to have been small. Therefore the L.W.M. is worthless as an indication of change even though it has occasionally been used (e.g. So 1963, Trenhaile 1969). The H.W.M. is probably closer to reality because along much of the coastline it coincides with a definite physical feature, the cliff foot. Wherever the two do not coincide the latter is marked as a dotted line, which is probably quite accurate. More reliable still is the position of the cliff top since this is always accessible and is economically important. However, there are problems of delimitation in the surveying of the cliff foot and cliff top. Where talus occurs at the base, the position of the cliff foot is not obvious, especially if debris also covers the shore platform. Similarly, where the cliff top is a change in slope rather than a break, the actual location of the cliff top is difficult to identify. Fortunately, glacial deposits, which are prone to landslipping, are common on the cliff top and a distinct cliff edge results when a slip occurs. Under the heading of cartographic misrepresentation is also included the problem of the extent of revisions made in 1927. Where erosion had been obvious, e.g. in the glacial deposits south of the village of Robin Hood's Bay, resurveying was carried out, but where any changes were small or not obvious, e.g. where a talus cone had been eroded or had increased in area, it is simply not known whether such alterations were recorded.

The third source of inaccuracy is also of great importance; it is produced by non-uniform expansion and contraction of the paper on which the surveys had been printed. Also included in this category are errors due to the copying of plans for this study (photostats and tracings were used). Invariably, when two plans of the same area are compared by making some inland details coincide, the cliff foot and cliff top lines vary markedly although it is quite obvious that the morphologies of these two lines had changed very little in the intervening period.

Despite these inaccuracies, valid data concerning coastline changes can still be gleaned. By considering small areas of coast, distortion of the paper becomes unimportant. Therefore the basal coastline was divided into segments with a straight-line distance of 8cm (i.e. 200m on the ground). Perpendiculars to the coastline then defined the upper coastline also - this was usually 8cm long but where the coast is convex seawards it was less and where convex landwards more. While the cliff foot can either retreat or advance, the cliff top can only retreat. This allows each 1927 or 1967 plan to be accurately positioned over the corresponding one for 1893, with regard only to the 8cm segment under consideration, using the upper coastline. Differences between the two plans were recorded on the later one and then the two were adjusted to give the best fit for the next coastline segment.

The nature and amount of coastal erosion determine the means by which this is measured. Thus where a coast has receded fairly uniformly it is valid to measure the distance between the successive coastlines at selected points. However, where coastal changes are small and sporadic it is much more important to use all the data available. In so doing there is a greater probability that apparent coastal changes which in fact are due to inaccuracies will cancel out, especially when the data are derived from many plans. In order to obtain the whole population of changes it is necessary to measure the areal size of them, not the variations in one direction only. It was found, in the present study, that because of the smallness of the areas, the polar planimeter technique was too inaccurate, and so areas were measured by counting millimetre squares when the plans were superimposed on graph paper. The total area of change was calculated for both the basal and upper coastlines in each 200m segment. These areal data are not internally consistent because of the varied lengths of coastline in the segments. Therefore they were standardised by dividing by the length of coastline which was evaluated by means of a map measurer. The resultant figure (in metres) is the average movement of the coastline in each 200m segment; it will be given the units metre/metre (of coastline) in order to denote that it is a mean, not a point measurement. Such data as these averages are not meaningful as point measurements of erosion, but are eminently suitable for other purposes because the influence of inaccuracies is minimised and all the available information in the plans is used.

The dangers of using point estimates of erosion from O.S. plans are illustrated by a comparison of such estimates with rates measured by the M.E.M. and other techniques at the same points. However, certain reservations about the M.E.M. data must be borne in mind. Firstly, these measurements represent a period of less than two years and so may not be close to the true long-term averages. Secondly, it must be assumed that long-term erosion rates have not altered substantially as the M.E.M. data are not contemporaneous with the O.S. data. Finally, it has already been noted that the M.E.M. erosion measurements are minima because true erosion is underestimated where a unit is removed by quarrying. Mean erosion rates per year calculated from O.S. point measurements and from M.E.M. data are presented in the table in Fig. 8.1. The pairs of values which roughly agree are indicated. It is plain from this table that there is no correlation between the two sets of data. Rightly, within the limits of accuracy, no erosion is discernible from the O.S. plans of White Stone Hole, and yet estimates for the Rail Hole Bight and Jump Down Bight sections are greater than the M.E.M. data. No erosion can be recognised on the O.S. plans of Fourth Bight and yet the M.E.M. readings for this part are substantial. Corroborative evidence of the high rates here is provided by measurements carried out by Young (1817, p. 776) in 1816. The distance was 680 feet from the outer edge of the north buttresses of the transept of Whitby Abbey measured in a line with the middle of the transept to the edge of the cliff, a point which is above Gravel Bight. By 1972 the distance from the westernmost buttress was 580.58 feet and from the easternmost 610.67 feet. Hence, mean erosion was 84.38 feet or 0.5409 feet/year (0.1649m/year). This figure is not far from some of the rates recorded with the M.E.M. bearing in mind that these are minima and that Young's measurement was for the cliff top. This indicates that the cliff has receded in a parallel fashion. Young (p. 776) also measured the distance " . . . from the middle of the

Location	M.E.M. technique		O.S. 1:2500 plans		Remarks
	Unit No.	Estimate (m/yr)	Period of record	Estimate (m/yr)	
Lingrow	15	0.0471	1893-1967	0.0676	pair agree
Fourth Bight	1	0.1290	"	0.0	
"	2	0.1975	"	0.0	
"	3	0.0556	"	0.0	
"	4	0.0581	"	0.0	
"	5	0.0486	"	0.0	
"	6	0.0528	"	0.0	
"	7	0.1106	"	0.0	
"	8	0.0473	"	0.0	
"	9	0.0735	"	0.0	
"	10	0.1177	"	0.0	
"	12	0.0966	"	0.0	
"	13	0.0088	"	0.0	pair agree
"	14	0.0015	"	0.0338	
Rail Hole Bight	1	0.0028	"	0.0507	
"	2	0.0111	"	0.1014	
"	3	0.0077	"	0.0	pair agree
"	4	0.0001	"	0.0676	
"	5	0.0033	"	0.0676	
"	6	0.0000	"	0.0507	
Jump Down Bight	7	0.0126	"	0.0	pair agree
"	8	0.0020	"	0.0	pair agree
"	9	0.0097	"	0.0169	
"	10	0.0466	"	0.0	
"	11	-0.0002	"	0.0169	
"	12	0.0001	"	0.0676	
"	13	0.0001	"	0.0676	
Saltwick Bay	14	>0.0881	"	0.0169	
White Horse	4	0.0240	1893-1927	0.0	pair agree
White Stone Hole	8	0.0000	"	0.0	pair agree
"	11	>0.0419	"	0.0	pair agree
"	12	>0.0266	"	0.0	pair agree

Fig. 8.1 A comparison of O.S. point and M.E.M. erosion rate estimates

outer court gate in front of Mrs. Cholmley's hall to the verge of the cliff, taken in a line with the cross" to be 714 feet. In 1972 the distance was 600 feet indicating cliff top erosion of 114 feet (i.e. 0.7308 ft/year or 0.2227m/year). This may be compared with the O.S. estimate of only 0.08013m/year for the basal coastline and zero for the cliff top at this point and the mean O.S. estimates for the sections of basal and upper coastlines from the East Pier to Fourth Bight of 0.0664m/year and zero respectively. Clearly great care must be taken when using erosion data derived from O.S. plans, especially those of hard rock coasts such as north-east Yorkshire where a considerable proportion of estimated rates of erosion may be due to errors. On coasts where erosion is rapid, e.g. Holderness, such errors can probably be disregarded and point measurements of erosion can be made.

The Factors Influencing Erosion; 1893-1927 Data

The spatial variations of erosion of both the basal and upper coastlines are depicted in Fig. 8.2. The points represent the mean erosion (metres/metre) in the 200m segments of coastline and, therefore, the greater variations which would have resulted from the graphing of point measurements of erosion have been smoothed out to some extent. Most points for the upper coastline are zero but high readings also occur. This pattern indicates that erosion of the cliff top is usually small but when it does occur it may be large because big landslips or, in the case of glacial material, rotary slumps, are the principal mode of removal. Nevertheless it must be remembered that individual fragments continually fall from the cliff face but that the changes produced by these are not sufficient to have been recorded on the O.S. plans.

Variations in the basal coastline are more severe. Small amplitude positive and negative movements are the norm, but many of these are

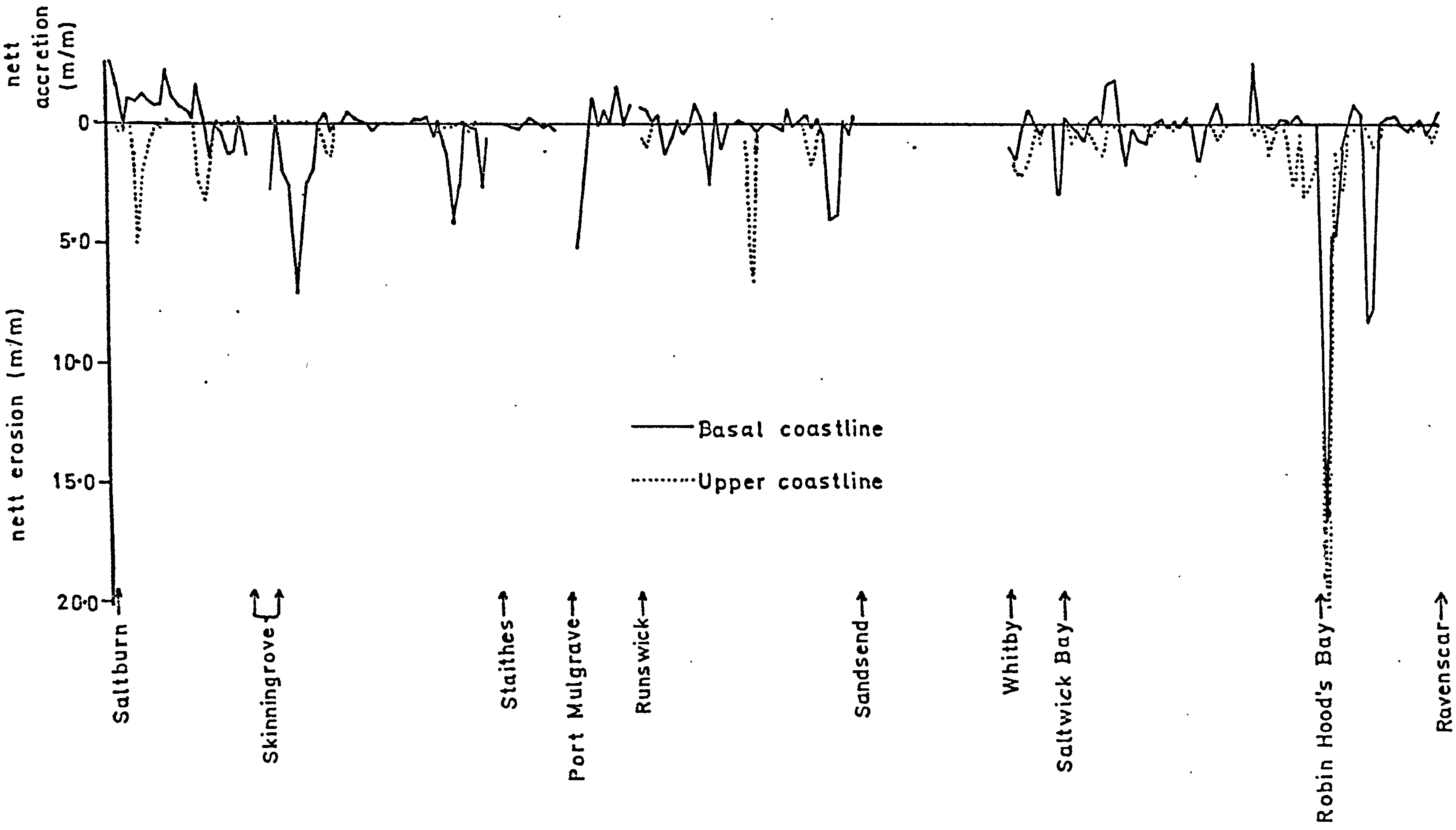

Fig. 8·2 Spatial variation of coastline erosion : 1893 - 1927 undoubtedly due to the various sources of inaccuracy. Despite this, significant erosion and accretion can be identified at a number of places, even if the figure of 0.6m is selected as the lower limit of real movements. There is no apparent correlation of either basal or upper coastline erosion with position, nor is there a coincidence of marked cliff foot erosion with pronounced cliff top erosion, except just south of Robin Hood's Bay where glacial deposits constitute the whole cliff. Neither is there any apparent correlation of high upper coastline erosion with high accretion at the cliff foot, a situation which should obtain if large falls of debris took place during the period. Of course, such falls would have to extend to the cliff top to have been recorded. Therefore it seems that accretion at the cliff foot has been caused by the fall of material from the cliff face leaving the cliff top unaffected. It is possible that talus cones were formed in the inter-survey periods but were swept away before the next survey was made. Hence comparison of plans does not show all the movements that have occurred in the basal coastline.

A number of factors may be important in governing the rate of coastline erosion; geology, nature of the cliff foot, amount of wave energy, and height of the base of the cliff are some of these. Information on only the first two factors is available for most of the study area. Considering only those parts of the coast where no talus cones exist, from the use of the Kruskal-Wallis one-way analysis of variance test on the three samples based on geology (Lower Lias, Ironstone Series, and Upper Lias) for which sufficient data can be gathered, it is concluded that there is no significant difference in erosion rates at the 0.05 significance level. The respective means for these samples are 0.6280, -0.0945 and 0.6750 m/m, the negative sign indicating net accretion in the 200m coastal segment during the 34 years. This result is not surprising in view of the fact that these geological divisions are dominantly shale. Grouping of these categories into one sample allows a comparison of cliff foot erosion rates on shale and those on glacial material. It might be expected that rates for the latter class should be significantly greater than those of the former and, indeed, this is confirmed at the 0.05 level by the Mann-Whitney U test. The mean erosion rate for glacial material is 0.08465m/m/year while that for shale is 0.01667m/m/year.

The same statistical test was used to assess the significance of differences in erosion rates due to the presence or absence of talus at the cliff foot, the data for those parts of the basal coastline where glacial deposits are exposed having been excluded. Since debris cones are usually composed of resistant material and the influence of marine quarrying is negligible because they are too permeable, erosion should be smaller than in those parts of the basal coastline where no talus exists. This hypothesis is substantiated by the test at a significance level of greater than 0.0158, the mean erosion rate for the sections of coastline fronted by talus being -0.0190m/m (i.e. net accretion) and for the other category 0.6098m/m during the period 1893 to 1927.

Variations in erosion rates of the upper coastline may also be attributed to geological factors. Differences between the data for those coastline segments where either the Ironstone Series or the Upper Lias cap the cliff and those where the Lower Deltaic Series strata occupy this position are not significant. It may be argued, perhaps with some justification, that this merely reflects the inadequacy of the data. There is no doubt, however, that erosion rates wherever glacial material (0.0243m/m/year) caps the solid cliff are greater than elsewhere (0.0067m/m/year), the significance level being greater than 0.0012.

Comparisons can be made between the rates of erosion of basal and upper coastlines of each segment but it must be remembered that the data are for only 34 years and, therefore, extrapolation to a longer period is dangerous. A chi-square test on the frequency of segments where the cliff became gentler during the period (due to cliff foot accretion, cliff top erosion or both) and on the frequency of segments where the cliff became steeper reveals that there is significant variation from randomness. 92 segments had a slightly gentler cliff and 55 a steeper one by 1927 (those parts of the cliff where quarries exist were excluded). This might be expected in view of the conclusions reached previously that the erosion of glacial deposits is much more rapid than that of shale and that glacial material is common at the cliff top. However, where the Quaternary deposits cap the cliff, the difference between the number of gentler-cliff segments (49) and that of steeper-cliff segments (32) is not significant at the 0.05 level. The corollary of this result is that the tendency toward a gentler cliff must occur where there is no capping of till. This hypothesis is confirmed when the data are tested; 41 segments underwent a widening of the upper and basal coastlines in the 34-year period while only 23 sections of cliff were steepened. These tendencies are not caused by different cliff foot conditions (i.e. the presence or absence of talus cones). This conclusion prompts an examination of the means by which the cliff sections are developing towards lower angles; is the basal coastline moving seaward while the upper coastline is moving landward or is the cliff top retreating faster than the cliff foot? The frequency of segments falling into the first category is 27 and the number in the latter 14 but the χ^2 test (χ^2 calculated = 3.512; one degree of freedom) shows that these differences are not significantly different from random at the 0.05 level though they are at the 0.10 level. This implies that there may have been a slight tendency in the first quarter of this century for more lower angled cliffs to develop from the growth of talus cones than from the rate of cliff top retreat to be greater than the rate of cliff foot recession.

The method of coastline analysis described in the previous chapter provides a means of examining whether bays are being eroded more rapidly than headlands although the sizes of bays were overemphasised at the expense of headlands. Only order 16 bays have been considered for this study. Each 200m coastline segment was classified according to whether most of its length formed part of a bay or a headland. The mean basal-coastline erosion of all segments that are parts of bays was 0.4588m/m in the 34 year period while the headland segments suffered net accretion of 0.2305m/m. The data of the former sample are significantly larger than those of the latter at a significance level of greater than 0.0087. It could be argued that the differences are due to the ease with which glacial deposits are eroded since these always occur in bays. However, exclusion of these data does not change the conclusion, though the significance level is slightly reduced to 0.0125 (one-tail). Clearly, therefore, the bays were being eroded faster than the headlands. This conclusion might imply that the parts of the cliff in bays may have steepened while those at headlands have become gentler. However, the χ^2 test on the frequency data for this two-by-two case shows that any differences are not significant at the 0.05 probability level.

Factors Influencing Erosion: 1893-1967 Data

The same procedures were used to gather data for the period 1893-1967 as for the shorter period; the spatial distribution of erosion is shown in Fig. 8.3. Unfortunately, the small size of the sample (64 segments) to some extent nullifies the advantage of being representative of a longer time period. In order to allow comparisons to be made between the short term (1893-1927) and long term (1893-1967) erosion rates, the coastline segments used for the gathering of data are exactly the same in both cases.

Erosion during the period 1927-1967 was calculated in order to compare the erosion rates with those for the previous interval. The Wilcoxon matched-pairs signed-ranks test on the sample of 57 segments for which basal-coastline data for the two periods are available shows that the differences are extremely significant (at a level of greater than 0.0006). The mean erosion per year in 1893-1927 was 1.2230×10^{-3}m/m while in 1927-1967 it was 8.8875×10^{-2}m/m. The same conclusion is reached for the upper coastline, the level of significance being 0.0018 and the respective mean amounts of erosion 1.2342×10^{-2} m/m/year and 4.3849×10^{-2}m/m/year. These results may be compared with that derived by So (1963) who concluded that maximum foreshore development occurred before 1939 and found an apparent correlation between erosion and the number of major storms. Assuming the same storms were important off the Yorkshire coast, the 1893-1927 period had four (1897, 1907, 1916 and 1921) and the 1927-1967 period experienced seven (1928, 1936, 1938, 1942, 1943, 1949 and 1953). Using the "Calendar of Historic Weather Events" compiled by Lamb (1964) and excluding those gales blowing from the south and south-west, there were ten major storms in the former period and nineteen in the latter. A correlation between erosion and storms is therefore implied.

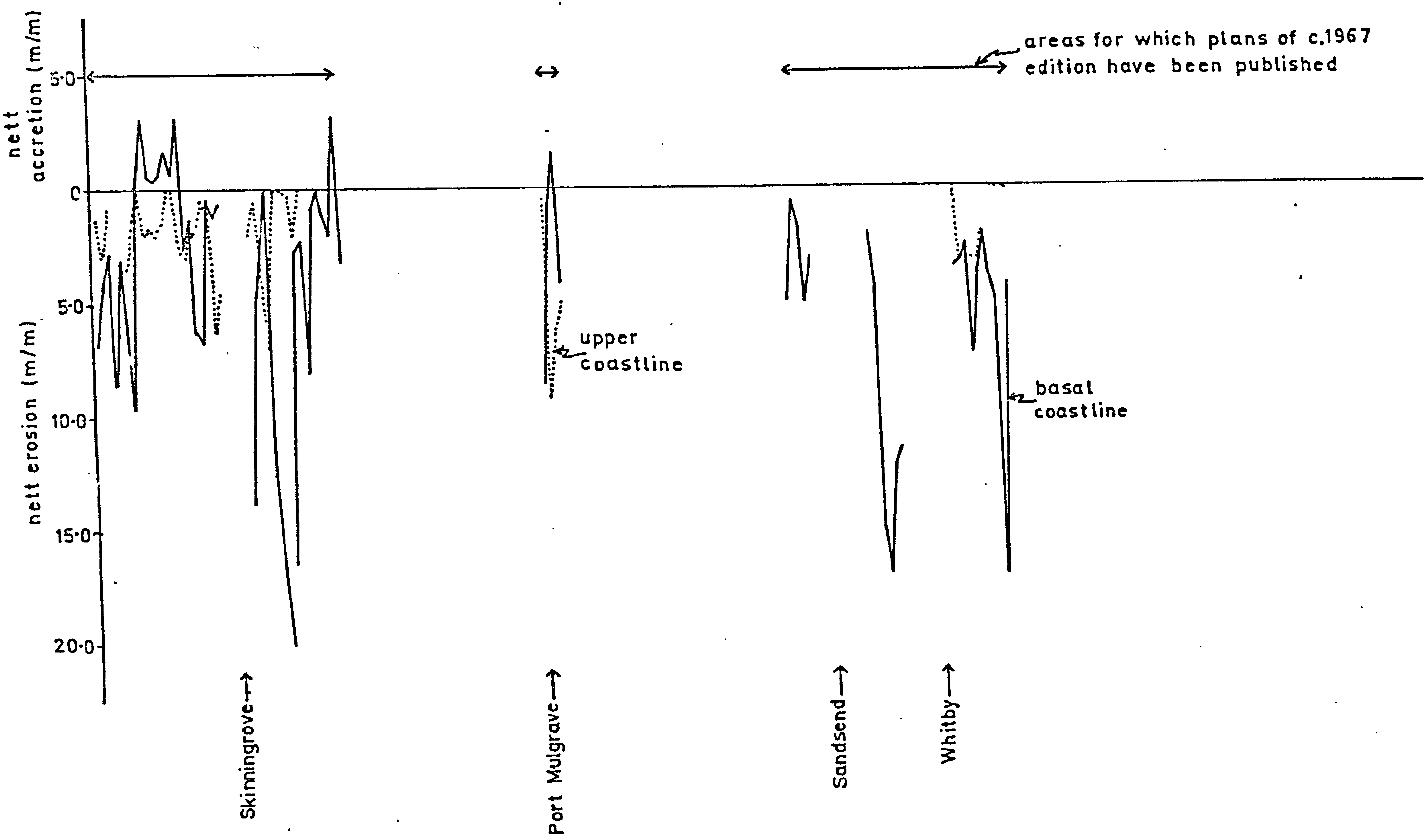

Fig. 8·3 Spatial variation of erosion:1893-1967

In Fig. 8.3 it can be seen that only eleven segments (17.2 per cent of the total) over the long term show either no erosion or net accretion whereas the corresponding figure for the first quarter of the century is 63.1 per cent implying that talus cones are temporary features or, at least, that they may undergo considerable erosion.

Over the longer time interval of 1893-1967 the conclusion reached previously, in the analysis of the 1893-1927 data, that the divisions of the Lias shales do not have significantly different influences on the rate of erosion is partly confirmed (there are no long term observations for the Ironstone Series), the mean amounts of erosion for the Lower and Upper Lias being 7.0060m/m and 3.8967m/m. However, grouping of these data (mean erosion = 5.6241 m/m) and comparing them by means of the Mann-Whitney U test with values of erosion for glacial deposits (mean = 9.9200m/m) yields the unexpected conclusion that there is no significant difference (actual significance level = 0.0869). This implies either that the sample size (eight) for the latter category was too small, or that, over the longer period of 74 years, differences in erosion rates between the two lithologies were unimportant. Clearly more data for the 1893 to 1967 period are needed to resolve this dilemma.

The conclusions inferred in the short-period study concerning environmental influences on erosion rates are confirmed by the second set of data. Erosion wherever the cliff foot is free of talus cones (mean = 5.6241m/m) is greater than where such accumulations can be found (mean erosion = 2.3114m/m) at a significance level of 0.0036. Moreover, erosion in bays (mean = 5.3592m/m) is more pronounced than at headlands (mean = 1.5682m/m), a conclusion significant at the 0.0136 level.

There is no correlation between the movements of the upper and basal coastlines, an inference made also from the 1893-1927 data. However, while the number of coastline segments in which the cliff became gentler was significantly greater than randomness allows, from the data available for 1893-1967 it is concluded that cliff sections becoming gentler (24) are just as common as those (18) where the opposite trend occurred. Also, no differences are significant when these frequencies are subdivided into categories based on either location (bay/headland) or state of the cliff foot (talus/no talus). Nevertheless in the latter case the calculated value of χ^2 (3.650) is significant at the 0.10 level implying that there is a tendency for the cliff to become gentler by cliff top erosion or cliff foot accretion where it is fronted by talus.

Coastline Recession: M.E.M. Data

An analysis of the factors which are important in marine erosion at the cliff foot based on M.E.M. data has been described in Chapter 4. A model for the evolution of the basal coastline near Fourth Bight was also presented in that chapter. Additional M.E.M. data bearing on the problem of coastline recession were provided by the instrumentation of Rail Hole Bight and Jump Down Bight, two bays to the west of Saltwick Nab. The locations of the M.E.M. units are shown in Fig. 8.4 together with the mean erosion per year for each. The measurement period was from 12th January 1971 to 11th July 1972. The diagram shows that there has been more erosion on the western sides of the bays than on the eastern. This does not reflect some regional tendency but is solely due to conditions in the immediate vicinity of each site. Thus, seaward of sites 5, 6 and 13 there are no deposits of sediment and erosion is very low. Units 3, 9, 11 and 12 are respectively about 2.4, 4, 2 and

Fig.8·4 Erosion rates at M.E.M. units in Rail Hole and Jump Down Bights

3 feet above pebble beaches and, therefore, usually out of range of large particles thrown into suspension or moved by waves with the result that erosion is fairly low although beach surfaces are very variable and if built up for a short time (as at unit 9), erosion is increased. Boulders are found seaward of units 1, 2, 4, 7 and 8 and erosion is variable. At the first, the rock surface is minutely jagged allowing shale laminae to be easily broken off while the last of these units was covered for about two-thirds of the eighteen months by a small talus cone of shale debris with the result that erosion was low. The highest erosion rate was recorded at unit 10 which is located at the surface of a pebble beach and, therefore, at the point of maximum erosion. These results emphasise the fact that erosion at any point along the coastline is very much controlled by the immediate environmental conditions, particularly distance from a beach.

Five erosion readings were made at all but units 8 and 13; two erosion periods fell during winter seasons and three during summers. Summation of the readings and division by the number of days allows the mean erosion per day during summer to be compared with the equivalent figure for winter. The respective means for these seasons are 0.56×10^{-3} inch/day and 1.31×10^{-3} inch/day; the differences between the two samples are significantly different at a level of 0.0250 using the Wilcoxon matched-pair signed-ranks test. This conclusion supports the results of Chapter 4 where it was shown that at the cliff foot winter erosion is generally dominant while over most of the shore platform and at some cliff foot sites where no beach exists, summer processes are probably more important.

Conclusions

It has not been possible to examine all facets of coastline retreat in this chapter because of the inadequacy of the data. Those measurements done with the M.E.M. technique are more accurate than the O.S. data but can only be considered as minimum rates. Also they are scanty and probably do not represent adequate lengths of time for great confidence. Nevertheless, the available data have illustrated some broad relationships and it has been possible to calculate mean erosion rates because errors in the collection of the data were minimised.

The main conclusions of this chapter support the findings of earlier chapters. Erosion of the cliff foot where this is bare does not vary according to the geological division of the shale. The conclusions regarding the erosion of glacial material at the cliff foot are equivocal since the rate of retreat was significantly higher than at the shale cliff foot in the 1893 to 1927 period but not in the longer period of 1893 to 1967. However, the effect of talus cones on erosion is pronounced as they themselves suffer little marine erosion while the solid rock cliffs behind them undergo none. The growth of talus cones is thought to be the reason for the development of more lower angled, than steeper, cliffs in the pre-1927 period. The rate of retreat of the basal coastline is greatest in the bays, an indication that the headlands on this coast are not yet sufficiently protrusive to shelter the bays. Once more, M.E.M. data affirm the conclusions reached earlier in this study that erosion at a point is highly dependent on local environmental conditions. The great influence of the type of superficial deposit at the cliff foot on rates of retreat (of the coastline in this case) is again shown by this chapter.

CHAPTER 9

A PROCESS-RESPONSE MODEL FOR THE NORTH-EAST YORKSHIRE COAST

Introduction

The many relationships which have been explored in the preceding chapters point to the fact that the physical features of the north-east Yorkshire coast are related dynamically, a change in one producing changes in others. The numerous measurements of erosion rates have shown that the features are changing at the present day, i.e. that the system is active, not partly moribund. This latter interpretation as formulated by Agar (1960) is the current one for this coast and, indeed, wherever bevelled cliffs are found similar explanations have usually been promulgated and are still accepted. Therefore, before any process-response model can be presented it is necessary to summarise the evidence which refutes the hypothesis that certain physical features on the north-east Yorkshire coast are relict.

The Evidence for Relict Landforms

The established hypothesis can be best illustrated in the form of the "diagram of stages of coastal development" compiled by Agar (op.cit. p. 423) which is reproduced here as Fig. 9.1a. The sequence of events has been summarised by that author (p. 424) in the following passage:

"1. Eemian Interglacial - Recession of the cliff line from about present L.W.M.M.T. (Low Water Mark Medium Tides) to seventy feet from present cliff by cutting of the lower foreshore zone during phases when the sea was near present level. The larger sandstone boulders falling from the Lower Deltaic Series and Sandy Series remained on the foreshore, and tended to embed themselves into the shale when rocked by waves. Small intermittent sand and gravel beaches.

"2. Onset of Würm Glaciation - Lowering of sea-level caused cessation of coast erosion. The abandoned foreshore was subjected to weathering, soil formation and growth of vegetation

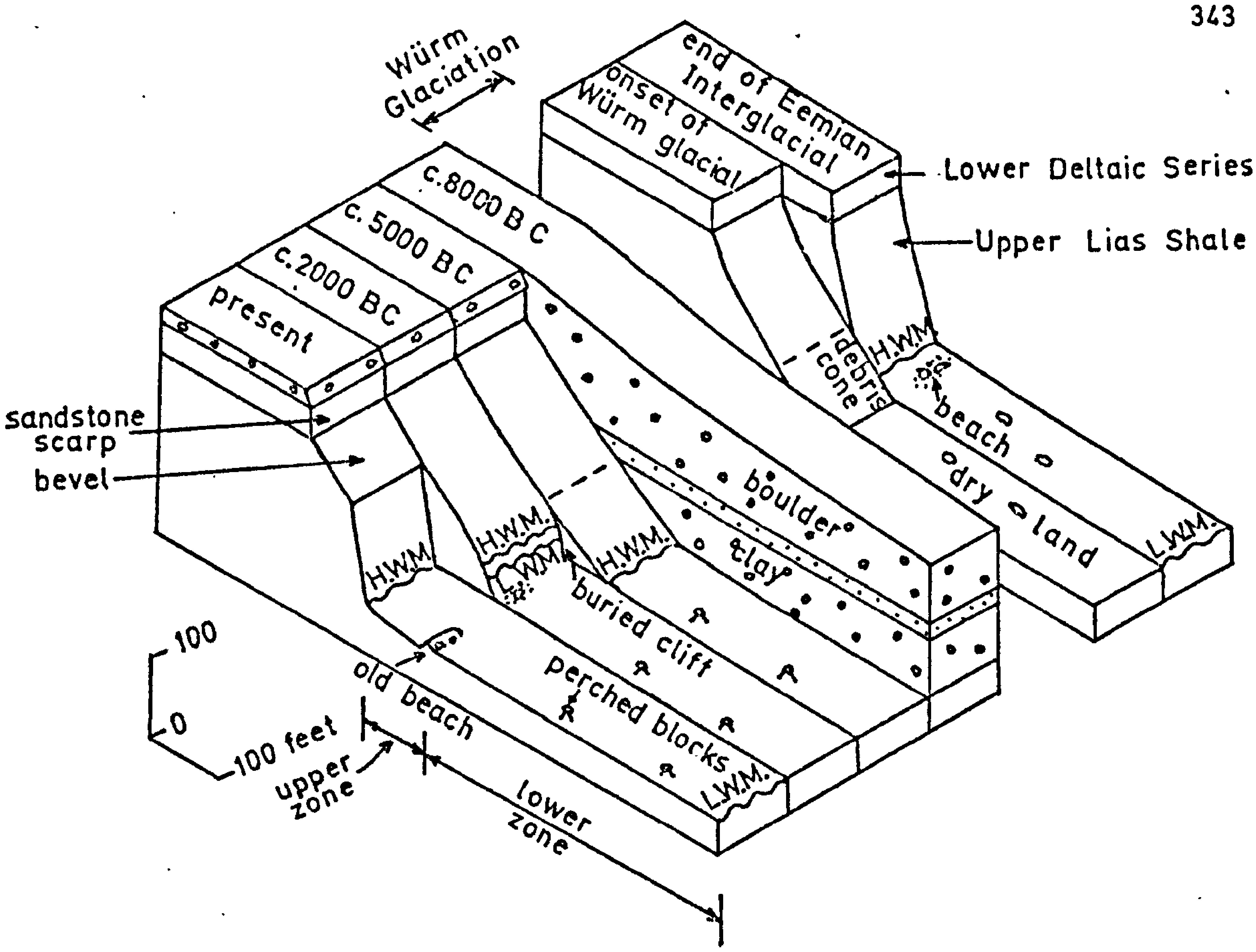

Fig.9·1a Stages of coastal development (after Agar, 1960)

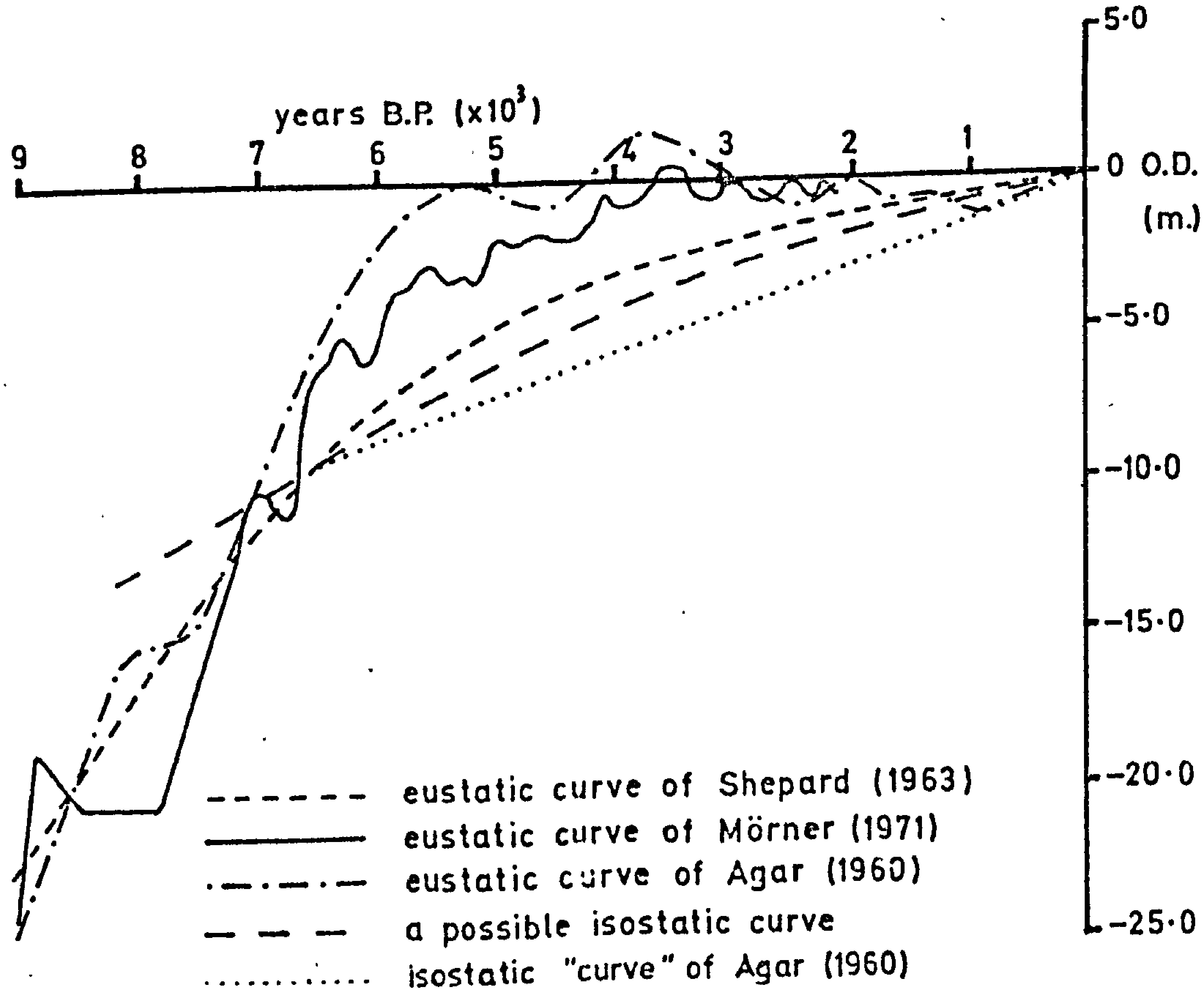

Fig.9·1b Isostatic and eustatic curves for north-east Yorkshire but the shale under the sandstone boulders was protected. The cliff top weathered back, with a debris cone that filled the cliff notch resulting . . . The landslips are probably mostly of this date.

"3. Würm Glaciation - The growth of ice-fields, but with little movement here in the basal layers as the sandstone blocks in the old foreshore were left in place; deposits of glacial drift occurred in phases. A low sea-level, starting to rise in late-glacial times (see Fig. 9.1b). Late-glacial initiation of narrow stream gorges in glacial drift.

"4. Post-glacial period - Sea-level continuing to rise rapidly to -16 feet O.D. clearing the glacial drift with its forest cover off the shale platform and leaving a residue of gravel and sand on the sea-bed. No appreciable erosion of solid rock.

"5. Pause in rise of sea-level between -16 feet O.D. and -10 feet O.D. with formation of peat bed in alluvium of Tees Estuary. Clearance of glacial drift off lower zone of foreshore, including weathered shale surface, leaving sandstone boulders perched.

"6. Continuing rapid rise in sea-level, passing present level. Erosion of debris cone from most of old cliff foot and start of slow erosion on face of solid cliff.

"7. Maximum sea-level about thirty feet above present, then fluctuations gradually approaching present level. Slow erosion of solid cliff at successively lower levels above present upper foreshore zone.

"8. About A.D.1000 to present time - Sea-level remaining near present level. Slow downward erosion of lower foreshore zone resulting in increased height of boulder perches. Outflanking and erosion of old beach conglomerate. Recession of cliff foot notch, forming present upper foreshore zone and lower zone of cliff face."

This whole argument is based on a number of observations and deductions which can be listed as follows:

1. that the perched boulders have become perched as a result of the periglacial weathering of the surrounding shore platform.
2. that the cementation of debris, now found in patches on the shore platform and in eroded talus cones at the cliff foot, is such a slow process that it cannot have been carried out in post-glacial time.
3. that "this upper zone (the bevel and sandstone scarp) gives the impression of great antiquity. It must have taken a very long time to weather back to its present angle, and this weathering rate is now so small that it is not measurable" (Agar 1960, p. 416).
4. that the sea-level on the north-east Yorkshire coast has fluctuated as shown in Fig. 9.1b.

The hypothesis that perched boulders have resulted from the weathering of shale in the inter-perch areas while the sea-level was very much lower than now implies that all the shale perches must be of the same height, unless the original shore platform on which the boulders rested was incredibly uneven - a state seen nowhere today. At Lingrow, Fig. 6.9 shows that there is certainly no such constancy of perch heights seawards. M.E.M. data furnish the evidence for the conclusion that the perches could have formed in post-glacial times. While it is true that the rates of erosion on the shore platform between the perches at Lingrow are very low (mean = 3.3×10^{-3} inch/year), they are still adequate. From the relationship shown in Fig. 9.2 which employs the Lingrow M.E.M. data and disregards the distinct threshold in erosion rates at the ramp/plane junction, it can be seen that the lower the shore platform is below the level of maximum marine erosion (which is above mean sea level) the lower is the erosion rate. Also, work by Bradley (1958) has shown that in the Santa Cruz area of California there is a level at less than thirty feet (9m) beneath the surface of the sea below which pyroxene sand grains are not abraded. This inverse relationship between depth and erosion rates being true, extrapolation of mean erosion measurements to calculate the time necessary to produce perches of given heights must be gross overestimates. Nevertheless, the generation of a perch 0.5m high with an erosion rate of 3.3×10^{-3} inch/year would take 5965 years. Undoubtedly, wherever the many small free boulders are found in the Lingrow area, the rate of erosion is higher. No M.E.M. measurements were made at these places but at White Horse where free boulders also occur and the level of the shore platform is similarly well below sea level, the recorded rate at unit 11 was 39.2×10^{-3} inch/year. At this rate, a 0.5m perch could be formed in only 502 years. Therefore it can be concluded that the rate of erosion of the shore platform is sufficient to have allowed the production of perched boulders during post-glacial times.

Agar (1960, p. 414) has stated with reference to the patches of conglomerate resting on the shore platform, that "these features are

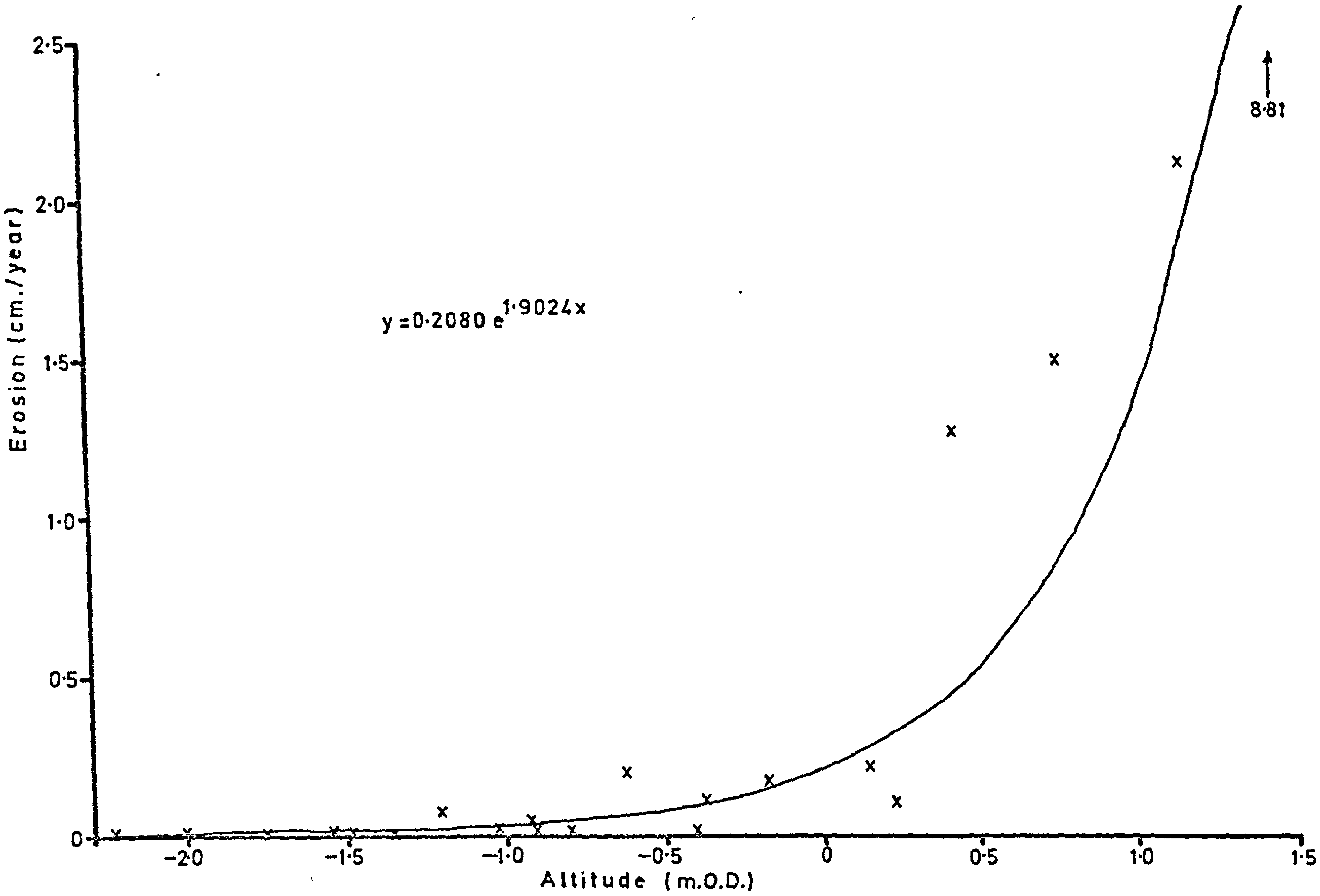

Fig. 9·2 Relationship between erosion rate and altitude on the Lingrow shore platform an important key to the sequence of events". The table in Fig. 6.3 showing their locations illustrates that there are many more than the sixteen conglomerate patches and six "ancient cliff notches" listed by that author (p. 415 and p. 417). It has been shown clearly in Chapter 6 that the cementation of debris can occur within periods of 200 years. Except for special localities such as the southern pier of Port Mulgrave where iron ore was stored in piles before shipment[1] there is no evidence that cementing processes in artificially produced situations such as piers and jet adits are different from those operating in natural talus cones. The only preconditions to conglomerate formation are that there be sufficiently long-lasting protection by massive debris and that there be a high proportion of the pyritous Upper Lias shale. The "ancient cliff notches" which have been equated with the fossiliferous Ipswichian interglacial buried beach at Sewerby (Agar, op.cit. p. 417) can, therefore, be reinterpreted merely as parts of the recent cliff foot which have been covered by accumulations of talus and subsequently eroded revealing cemented material. There is no reason why beach material should not be covered by such features and later become cemented also. The existence of many glacial erratics in the conglomerate areas of South Batts and Cobble Dump proves the occurrence of a glacial period before their formation. It is true that the erratics are very resistant lithologies and are well rounded but a considerable period (about 10,000 years (West 1968, p. 181)) has elapsed since the Weichselian glaciation ended. It has been estimated that the Eemian Interglacial lasted for about 30,000 years (95000 to 65000 B.P.) (West, op.cit., p. 181) so it seems unlikely that so many erratics, even of great hardness, could survive for such a long time in the active erosive conditions of the beach environment; certainly, there are very few erratics in the Sewerby beach. No Old Drift is

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[1] Iron ore was not stored on the northern pier and no conglomerate can be found here.

preserved on the north-east Yorkshire cliffs so the erratics probably came from the New Drift. In addition it has already been noted that there is a patch of cemented beach and talus material on the eastern side of White Stone Hole at the very foot of an active marine cliff whose angle is about 70 degrees and, therefore, is undoubtedly modern. In conclusion, it can be stated that the patches of conglomerate are not relict but are fairly young features.

If the sandstone scarp is of great antiquity, its age should be reflected in the degree of weathering of its surface. At Hawsker Bottoms, as almost everywhere else, the faces are smooth and planar being exposed joint planes. Surficial roughness and differential weathering of the arenaceous strata of the Deltaic Series can be seen only at Saltwick Bay and at Runswick in places where the rock at the western sides of the buried interglacial valleys have been stripped of their glacial deposits. At the latter site the old appearance may also have been aided by variations in the degree of cementation of the rock. It is surely improbable that overhangs of the sandstone scarp which are very common could have survived the whole of the Weichselian glaciation and post-glacial time especially as the sandstone scarp, being at the top of the cliff, would be at the point where, if the glaciers carried out any erosion at all, erosion would be most severe. The length of time during which detailed observations have been undertaken at Hawsker Bottoms is small but during that period the erosion of sandstone averaged 3.015×10^{-2}m/year, a minimum figure as pieces below 25cm in length were not measured and no very infrequent large collapses were included in the study period. The weathering rate does not, therefore, seem to be small. Thin glacial deposits cap the cliff at Hawsker Bottoms and yet they are not found on the bevel. The large landslip at Wrack Hills with its fresh morphology and only secondary glacial material does not support an Ipswichian inception either. Measurements of the rate of erosion on the bevel at Hawsker Bottoms are certainly not reliable. Nevertheless, the high rates of accretion at some points indicate that, where there is no vegetation, denudational processes are active. The converse must also be true; in the channels, especially the two shown in Fig. 3.3b and on the bare inter-channel areas, erosion is too rapid to allow a cover of loose debris to form and thus prohibiting the colonisation of such areas by plants. Even in partially vegetated areas the erosion of risers between the small terracettes on this 45 degree slope must be considerable. Therefore it is concluded that the bevel and the sandstone scarp are landforms which are being actively eroded at the present day.

The reconstruction of the post-glacial history of sea-level changes in north-east Yorkshire is extremely difficult because of the paucity of data. It is known that the area is now being inundated at a rate which is of the order of 1mm.yr^{-1} (Valentin 1953) to 1.5mm.yr^{-1} (Sissons 1967) because of the global eustatic sea-level rise, but that it is isostatically stable (Valentin, op.cit.) being the hinge around which Britain is tilting. Despite this, the widespread cover of glacial deposits implies the presence of an ice sheet up to 305m (1000ft) thick (Gregory 1965) and the necessary corollary that isostatic readjustment has occurred in post-glacial time, this being exponential, not linear, in form (Brotchie and Silvester 1969).

Local evidence for former sea-levels is not indisputable. It is unfortunate that the raised beach at 9m O.D. (30ft) described by Barrow (1888) can no longer be found because Veitch (1882) identified it as a kitchen midden noting that the evidence for this was destroyed during his investigations. The recognition of a raised beach at 6 to 12.5m O.D.

(20 to 41 ft) near Middlesbrough (Agar 1954) is also based on tenuous evidence for both Mytilus edulis and Cardium edule are edible species and if not part of a kitchen midden could easily have been dropped by gulls. Clearly sedimentological analysis of this " . . . clean yellow sand with the washed appearance of a beach . . . " is necessary before it can be firmly identified as such. Fluvioglacial sands are common in the tills of north-east Yorkshire and contain fragile objects (e.g. pieces of jet) which may have been picked up from the sea floor; even fossils are known in the Basement Till at Dimlington in Holderness (Catt and Penny 1966, p. 380). Moreover, Westgate (1957) has concluded from his study of the Durham coast that it is possible for fines to be washed from boulder clay at the water table leaving a coarser residue. The only other possible raised beach is the mass of sand described briefly by Hemingway (1958). It lies on the eastern side of Whitby harbour at 4.3 to 7.3m O.D. (14 to 24 ft), but that author did not speculate on its mode of origin. Oak trees have been found between -6.4 and -1.8m O.D. (-21 to -6 ft) at Larpool viaduct, Whitby (Hemingway 1958) and an extensive peat bed occurs between -1.8m O.D. (-6ft) and O.D. in the Tees estuary, at Redcar, and at West Hartlepool (Agar 1954). Churchill (1965) has used this latter group of deposits to examine the displacement of the 6500 B.P. sea-level. In summary, therefore, only a few incontrovertible facts seem to exist; these are that the sea-level 6500 years ago was approximately the same as or slightly lower than today's and that isostatic uplift is now zero.

Eustatic curves published by Mörner (1969, 1971) and Shepard (1963) are shown in Fig. 9.1b together with that compiled by Agar (1960) based on the data whose validity has been discussed above. Mörner's curve is probably the better of the first two since it was evolved in the

North Sea region.

A straight line through the point for 6500 B.P. and the present day represents the lowest possible position of a point on land now at sea-level since the isostatic curve is exponential; such a curve with zero slope for the present is also shown in the diagram. It is clear from this that the sea-level could not have risen above the present sea-level by more than 2.5m (8ft) (Shepard), 5.5m (19ft) (Mörner), or 7.5m (25ft) (Agar). (Agar's dating of the Tees peat at 7000 B.P. increases these heights to about 3.5m, 6.5m and 8.5m respectively.) However, these levels do not preclude the possibility of erosion during the whole of this time period. The mean tidal ranges at Whitby and Teesmouth are about 3.4m (11.2ft) (4.6m (15.1ft) mean springs and 2.2m (7.2ft) mean neaps). Also Bradley (1958) has shown that pyroxene grains off the coast of California become rounded at depths down to 9m (30ft). This fact and the large tidal range in north-east Yorkshire ensure that even with the highly conservative assumptions used for the level of the land for the period since 6500 B.P., the sea could easily have continued to erode the cliff foot throughout this period no matter whose eustatic curve is used.

The important conclusion that variations in sea-level have not been an important constraint on erosion in north-east Yorkshire enhances the probability that all landforms on this coast are the result of post-glacial forces. The shore platform attains widths of over 305m (1000ft) in several places, e.g. in Saltwick Bay, White Stone Hole, and Robin Hood's Bay. Assuming an erosion rate of 0.183m.yr^{-1} (0.6ft.yr^{-1}) which is the mean of the three 156-year rates at Whitby East Cliff where the pebble beaches facilitate high erosion rates, the period needed to push back the cliff by 305m is 600 years. Employing the mean of the non-random sample of 32 M.E.M. erosion rates at the cliff foot (0.0413m.yr^{-1}) (Fig. 8.1) the time needed is 7385 years, while using the mean erosion rate calculated from comparison of Ordnance Survey 1:2500 plans of the c.1893 and c.1967 editions it is 4013 years. Hence, it is possible that the extreme seaward parts of sections of the shore platform could have been inherited from earlier features. This inference accords with those by So (1965) for the Kent coast and Trenhaile (1972) for the Vale of Glamorgan, both areas where extensive shore platforms exist in unresistant hard rock comparable with the Yorkshire Lias shales. It does not mean, however, that ancient landforms have been preserved. For, just as Tertiary erosion surfaces in the subaerial environment have been dissected to form hills which are essentially the result of more recent processes, so some of the most seaward parts of the modern shore platform may have evolved from some older platform at a slightly higher level.

The Cliff System

The hierarchical organisation of terms shown in Fig. 1.1 can be used also to show the pattern of nested supersystems, systems, subsystems and so on. The highest order is the single supersystem, the coast which embraces all the features which are being or have been produced by the present sea level. At the second hierarchical level, two major systems (the cliff and the foreshore) exist. The coastline is considered as a system here also though it is at a lower hierarchical level and is common to both major systems. It is by a consideration of these three systems that the most important analytical results of the previous chapters will be synthesised into a process-response model for the north-east Yorkshire coast.

The cliff system may itself consist of any number of subsystems up to a total of three (Fig. 9.3). It may be a marine activated cliff alone as in Far Jetticks or a combination of the other three elements as at Hawsker Bottoms. Being subject to the force of gravity at all times, the flow of mass is always downward and all but small amounts of energy act in the same way, the exception being the energy provided by wind. This uni-directional property of the cliff system means that there is no direct feedback of energy or mass from low subsystems to higher ones, though indirect feedback is possible as will be described later. Energy is input directly into every subsystem; in the higher two, the sandstone scarp and the bevel, energy is derived from only the sub-aerial system in the form of the sun's energy, of rain, and of wind. The lowest two subsystems receive in addition the energy which is unused by the foreshore system. These two subsystems are, however, mutually exclusive since the occurrence of a talus cone at the cliff foot precludes the maintenance of a marine-activated cliff.

Each subsystem is structurally simple usually containing only one regulator within it and a number of stores. In order to give the general case, Fig. 9.3 includes a dichotomised regulator of the "presence-or-absence" type before the entry of mass and energy into each subsystem. The sandstone scarp is the first in the chain and is the simplest. Energy falling on it acts on the in-situ rock and most is expended as frictional heat (entropy). Productive work is done only if the threshold of rock strength is overcome causing blocks of rock to cascade into the next subsystem. The sandstone scarp has no facilities to store the debris it produces, the only energy remaining in it being the potential energy of the strata which on release of a block of rock is partly expended as frictional heat during the arresting of motion as the block falls to the bevel or the cliff foot.

Fig.9·3 The cliff cascading system
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The bevel acts as the temporary store for much of the output from the sandstone scarp subsystem but if the total energy of the falling block is sufficient it will pass straight through the subsystem to the talus cone or to the foreshore system. Therefore, there is a threshold regulator in the bevel subsystem which governs the destination of falling sandstone debris; this regulator is the amount of momentum needed to overcome the friction of the bevel. Friction depends on the roughness, slope, and length of the bevel. This subsystem gains energy from the subaerial system also and this does work on the shale which constitutes the feature. Again only if the threshold of rock strength is overcome will productive work be done. The debris may not be output from the subsystem immediately but is stored on the surface of the bevel. It was shown in Chapter 3 that the specific variables of subaerial energy which are important in causing output from this store are wind velocity and air temperature which reduces inter-fragment friction and thus enhances the rate of creep while the washing of material from the bevel is important in some places also.

The fate of debris output from the sandstone scarp and bevel subsystems is determined by the important regulator of the presence or absence of a talus cone at the cliff foot. If this feature does not exist the detritus is immediately input to the foreshore system unless it is intercepted by small screes in the marine-activated cliff - probably a rare occurrence. Therefore most of the output from the higher subsystems by-passes the marine-activated cliff whose output is derived from its own store of rock which is released as in the other subsystems if the critical threshold of rock strength is exceeded by the sub-aerial energy. This is most potent in the form of freeze-thaw and wetting-and-drying. Because the base of the marine-activated cliff is also part of the foreshore system erosion is usually rapid.

As with the other subsystems debris may cascade straight through the talus cone subsystem unless friction is greater than momentum. This subsystem's principal function is as the chief store of debris for the cliff system as a whole. Gravity is much less important causing only slight creep to lower levels and the permeability of the material causes sub-aerial energy to be relatively unimportant compared with the major source of incoming energy which is from the foreshore system.

The cliff morphological system is pictured in Fig. 9.4. Many of the relationships have been shown statistically or were described in Chapters 2 and 3. Where possible, the direction of causality and the sign of the relationship are given. Very many variables can be recognised but only those central to the argument are shown. Within the sandstone scarp subsystem, the thicknesses of the sandstone strata, the ratio of sandstone to shale, the resistance of the sandstone strata to sub-aerial weathering, and the intensity of joints are geological variables and are fundamentally responsible for the very existence of the scarp. The parameters of interest in scarp morphology are the amount of overhang and the height of the base of the scarp which are negatively related. The former is also negatively correlated with the geological variables the most important of which, in the general case, is probably the intensity of jointing, but at Hawsker Bottoms it is the ratio of the amount of sandstone to shale, a variable itself related positively to the thickness of the sandstone strata, since the scarp is of constant height here.

The exact slope of the bevel is probably a function of the resistance of the shale to erosion but in north-east Yorkshire there is little variation in this parameter. The most important variable in this

Fig.9·4 The cliff morphological system

subsystem is channel activity for it influences both the superficial characteristics such as the degree of vegetation cover and the depth of debris as well as micromorphological features such as the amount of dissection of the in-situ rock of the bevel.

The geometrical variables of height and width of the talus cones are related to the resistance of the feature to marine erosion in a positive sense for if little material is removed, the cone is built up by accretion from above. Its resistance to erosion is principally a result of the size and proportion of sandstone debris of which it is composed.

Only a few variables are responsible for the characteristics of the marine-activated cliff. Its steep slope is permitted by the structural strength of the rock (i.e. its resistance to subaerial erosion) a factor determined by the properties of the jointing system and to the lithological characteristics. Where a bevel and marine-activated cliff occur the height range of the former is inversely related to the height of the latter.

The relationships between the subsystems are of much interest in understanding the cliff system as a whole. Perhaps the most striking thing about Fig. 9.4 is the independence of the marine-activated cliff subsystem. This reflects the fact that it is a product of different energy flows from the rest of the cliff. The remainder of the cliff system shows many relationships between subsystems. Most importantly, several of them form part of a large negative feedback loop which involves all three subsystems. The more intense the jointing of the sandstone strata, the smaller the overhang and the size of the sandstone fragments that are eroded. Small sandstone blocks lead to low resistance of the talus cone to marine erosion and in turn to a small talus cone. The size of cones is also positively related to the thickness of sandstone strata and to the proportion of sandstone in the cone. Small cones do not extend far up the cliff and so allow material to be removed from channels on the bevel thus allowing greater channel activity and a lowering of the base of the sandstone scarp. Once this base is below the Dogger Sandstone undermining of this stratum is rapid producing an overhang and increasing the flow of sandstone debris to the talus cone to counteract the small size of the blocks. It is important to note that this last link in the loop is a component of the cascading system which shows that the whole system can be best understood by a process-response model. While the constituents of this loop are equally important, the one most prone to changes and, therefore, the one most critical to the loop, is the resistance of the talus cone since it is the one most influenced by conditions external to the cliff system. Therefore the resistance of the talus cone can be regarded as the regulator for the cliff system.

By combining the cliff cascading and morphological systems a process-response model results. The essential features of this are shown diagrammatically in Fig. 9.5. The two systems are linked by common properties, such as the debris resting on the bevel being the store for the bevel cascading subsystem and the morphological properties of talus cone height and width combine to form the store for the whole cliff system. Similarly the regulators of the bevel and talus cone cascading subsystems are the critical levels of friction necessary to bring falling debris to a standstill; such levels are determined by morphological properties such as surface micro-relief, slope, and length of the feature and whether the surface is vegetated or not.

The important point about the nature of the cliff process-response model is that the flow of energy is opposed by the direction of causality of the morphological variables. Thus, should the debris flow be increased, for instance by changed geological conditions in the scarp, the store of debris at the cliff foot is also increased. This may lead

Fig.9·5 Essential characteristics of the cliff process-response system to increased resistance of the talus core to marine erosion and the clogging of the channels transecting the bevel. Hence, erosion of the foot of the sandstone scarp is reduced and the rate of debris supply lowered. It is clear, therefore, that these three subsystems form an open system which attains dynamic equilibrium (Abrahams 1968) if unaffected by external forces. The marine-activated cliff subsystem is alien to this state of equilibrium and is the result of interference from the second system, the foreshore.

The Foreshore System

The foreshore cascading system is fundamentally different from that of the cliff. The major source of energy is derived from the marine system and is input first into one subsystem whose output cascades into the next and so on. Sub-aerial energy enters all subsystems but is of negligible importance except in the case of the plane. As in the cliff system there is one main direction in which mass moves but the relatively small influence of gravity allows the feedback of some debris from one subsystem to the next. Either or both of the components of the shore platform may be present and so in Fig. 9.6 a presence-or-absence regulator is positioned before the entrance of mass and energy into each.

Wave energy on the plane is reduced mainly by friction with the solid rock which is eroded by the quarrying of fragments of shale laminae. Friction is increased where perched boulder complexes or conglomerate occur. Other superficial debris is sparse but where it does exist, if some critical value of energy is exceeded, abrasion of both the debris and the plane occur. Comminuted and dissolved material is returned to the marine system. Sub-aerial forces, especially in the form of wetting-and-drying, as shown in Chapter 5, are important leading to the release of shale laminae.

Fig.9·6 The foreshore cascading system

Little wave energy is expended in friction with the bottom and with debris, so much remains to be input to the next subsystem (if it exists), that of the ramp. Friction is greatly increased if there is a cover of boulders but an admixture of small boulders allows productive work to be done at lower thresholds of wave energy than on the plane. The suspended and dissolved material resulting from abrasion is removed. Debris from the plane may be swept into this subsystem whose debris in turn cascades into one of two alternatives which provides the next link in the chain.

As in the cliff system, the regulator determining which of two subsystems is the final one of the series is the presence or absence of a talus cone. If the bare rock of the cliff foot is exposed a pebble or sand beach may also exist. The efficiency of wave energy is greatly increased by these particles when thrown into suspension with the result that much quarried and abraded debris is removed from the solid-rock store. This debris may be fed back into the beach store or possibly into the ramp or even plane subsystems if strong rip currents are generated. The occurrence of a talus cone at the cliff foot enables a boulder beach to extend to that point. There is much friction both between the water and the rock and within the water itself because of the generation of extreme turbulence. Feedback of large blocks to earlier parts of the foreshore system from a boulder beach is unlikely.

The foreshore morphological system is very simple (Fig. 9.7). The plane's parameters of slope and height of the landward edge (which may be the cliff foot) are almost invariate and the width of the plane is probably inversely related to the resistance of the rock to erosion in the general case. In contrast, the slope of the ramp varies considerably, being influenced by the resistance of the overlying

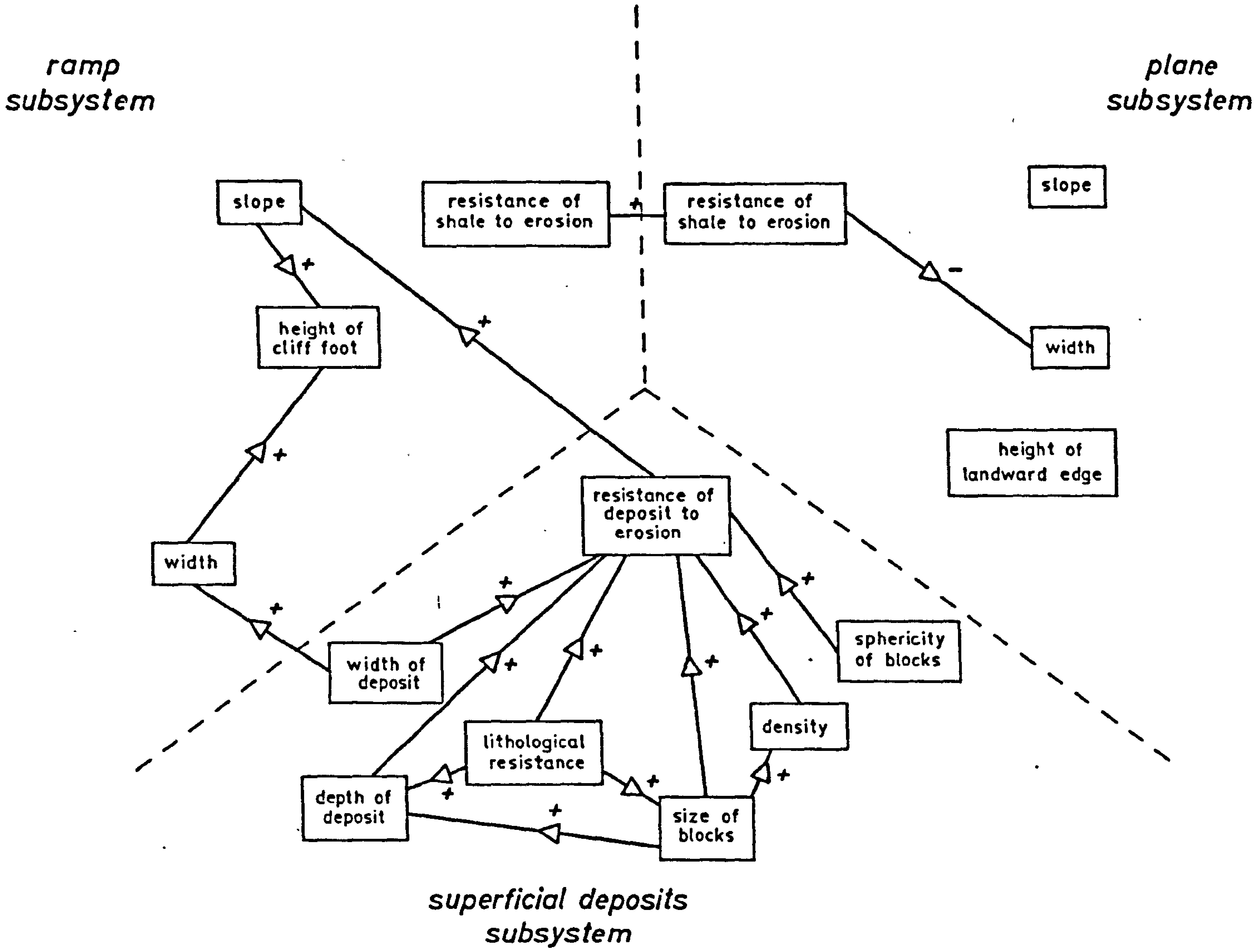


Fig.9·7 The foreshore morphological system debris to erosion, a property which is chiefly controlled by the size of the individual boulders. The resistance of the superficial deposits to erosion is also, by way of the slope of the ramp, the main determinant of the height of the cliff foot.

Few relationships seem to exist in the foreshore morphological system perhaps because of the small geological contrasts in north-east Yorkshire. The plane subsystem is isolated from the other two because its principal distinguishing feature, its low slope, is not chiefly the result of erosion by waves. The subsystems of the ramp and superficial deposits are closely interrelated and are the product of the interaction between the marine and cliff systems. There is no feedback between the morphological subsystems, which suggests that the physical properties of the foreshore may be better described by a process-response model since the characteristics of the energy and mass flows may be all-important.

The essential features of the foreshore process-response system are shown in Fig. 9.8. The amount of wave energy leaving the plane sub-system is reduced in some measure depending on the morphological properties of the subsystem. Both wave energy and sub-aerial energy tend to lower the inclination of the plane, thus reducing the amount of friction. This, therefore, is a positive reaction and may explain the very small range of characteristic angles possessed by the plane. In contrast, widening of this feature leads to increased friction and a lowering of the quantity of wave energy reaching the next subsystem. As the plane is being lowered continuously, width can operate as a regulator of wave energy only if the sub-aerial energy is inefficient (e.g. in hard rock) and if the plane is very wide. With the geologically recent rise in sea level such conditions have not yet been attained.

Fig.9·8 Essential characteristics of the foreshore process-response system

However, various estimates of the maximum width which can be eroded by the sea at one level have been made, e.g. Bradley (1958) - 0.3 miles (536m); King (1963) - 4000 feet (1220m).

The ramp is usually covered with loose debris which must be agitated before a significant amount of work is done. This means that the hydrodynamic characteristics of the debris are most important, the chief one of which is the size of the fragments. Work is done on the shale constituting the ramp only if wave energy is greater than some critical level above which wave energy and movement of the debris are positively related. The important thing in this process-response subsystem is, therefore, the size of the overlying debris. However, this is being continuously reduced, permitting more wave energy to reach the cliff foot. This means that no self-regulatory property exists within the ramp subsystem nor even within the foreshore system as a whole. Hence, energy is always available for the erosion of the cliff foot. This is especially true where no boulder beach lies on the shore platform. The rate of erosion of the cliff foot then depends on the immediately local conditions which determine which erosive processes will operate and, therefore, which critical thresholds are important.

The Coastline System

The coastline cascading system (Fig. 9.9a) is simple compared with the others. Energy output from the foreshore system is input to either the bay or to the headland subsystem and is spent in overcoming friction or in doing work in the form of abrasion or quarrying. Debris is input from the cliff system and thus by pushing the coastline seaward, increases the store of mass. Because the coastline is taken to be the cliff foot, it is unlikely that much detritus is put into this store from the foreshore system by the essentially horizontally acting forces of waves.

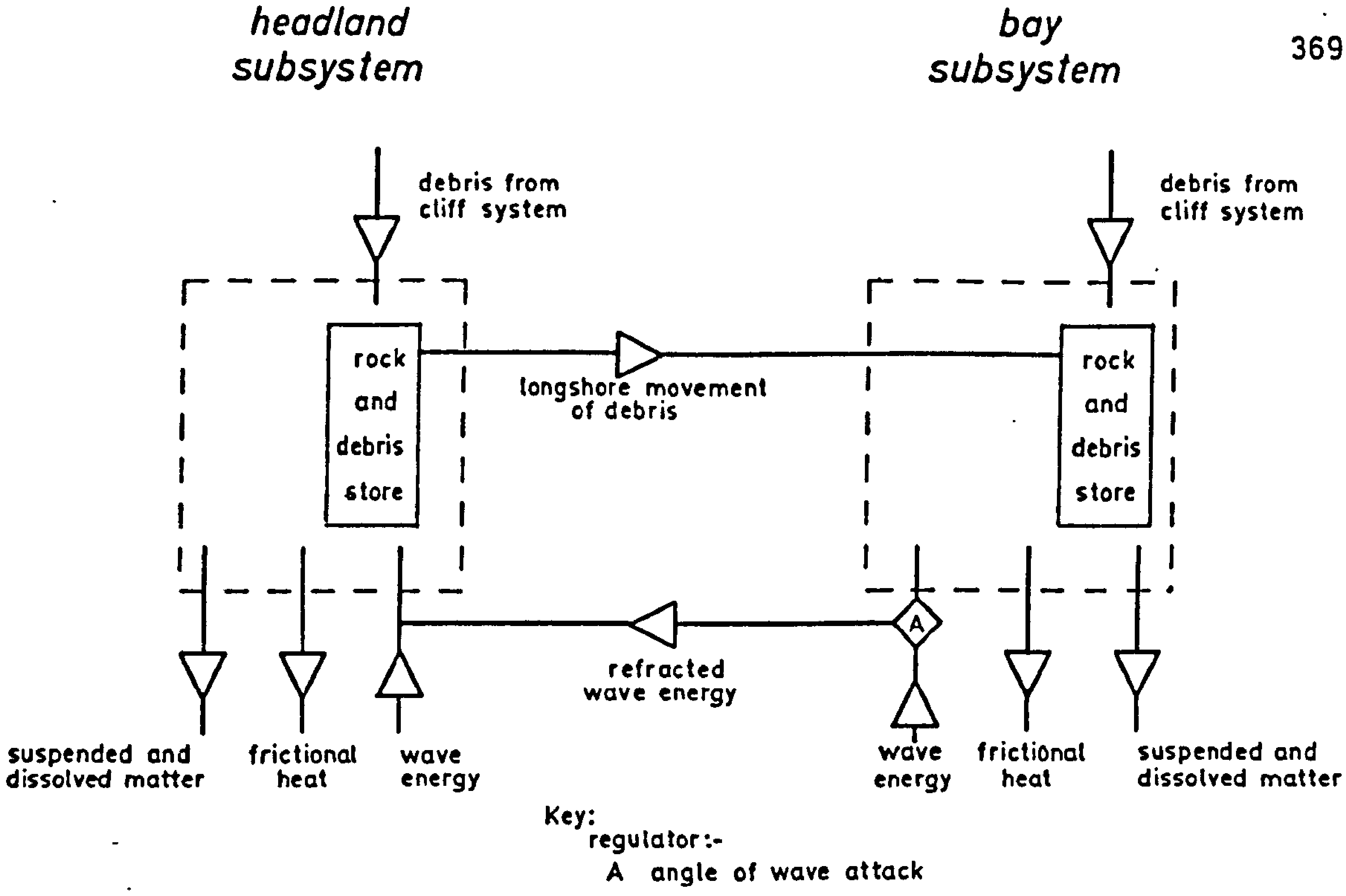


Fig.9·9a The coastline cascading system

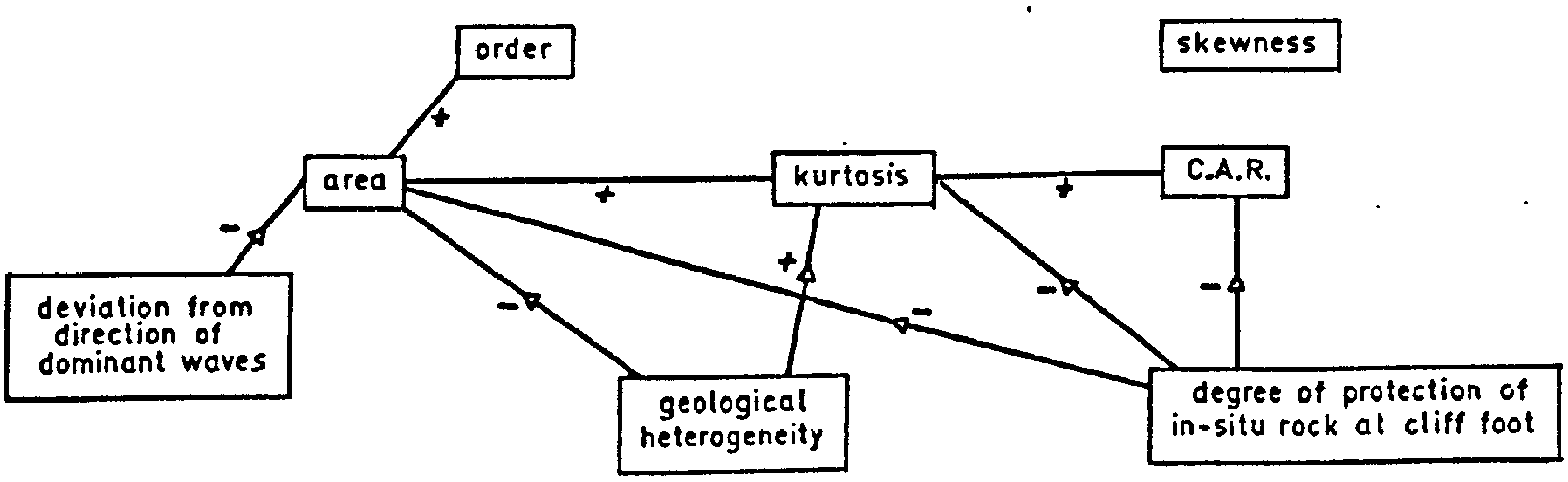


Fig.9·9b The arcuate bay morphological system

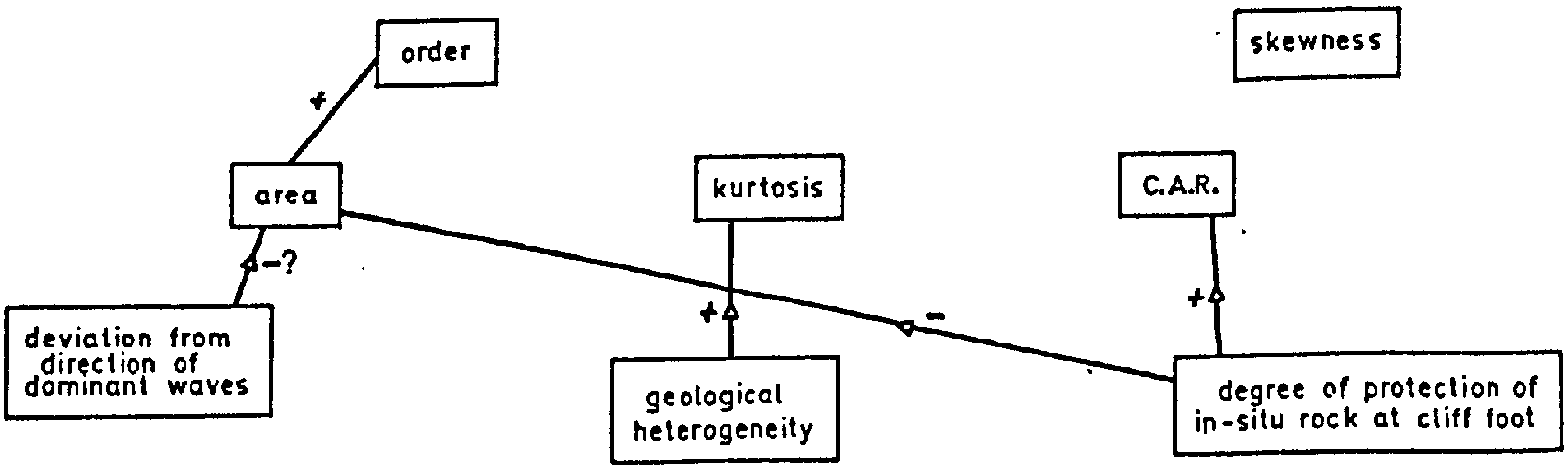


Fig.9·9c The triangular bay morphological system

These forces, especially during storms, are the principal means by which material is output from the system. Output is mainly in the form of suspended material which is swept seawards.

Owing to the arrangement of the subsystems and their inputs, the passage of debris and energy from one to the next is probably not great in north-east Yorkshire. The direction of wave attack is the regulator for this interaction. A non-normal direction to the coastline ensures that energy is first influenced by the headland system which exerts friction and reduces the total energy. However, the more acute the angle of wave attack to the coastline, the greater is the component of energy parallel to it and thus the more debris is carried into the bay subsystem from the store of the headland subsystem.

The morphological systems are pictured in Fig. 9.9b. Because of the crudeness and novelty of the technique, the analysis of headland morphometry has not yet been attempted so no relationships are shown for this landform. It is clear from this diagram that more correlations exist between the parameters for arcuate bays than for those which are basically triangular. This suggests that the former have a nicer state of internal adjustment than the latter and, therefore, that the arcuate bays give more evidence of being in dynamic equilibrium. The reason for this has been shown in Chapter 7; it is that triangular bays are more closely related to those parts of the basal coastline where talus cones exist than are arcuate bays. Indeed, the relationship between circularity and degree of protection of the cliff foot for arcuate bays is positive, while it is negative for triangular bays. Another regulator which was indicated in that chapter was that the development of the latter type of bay is encouraged by structural variations on the rock. Without knowledge of the headland morphological system there seems to be little point in trying to synthesise a coastline process-response model.

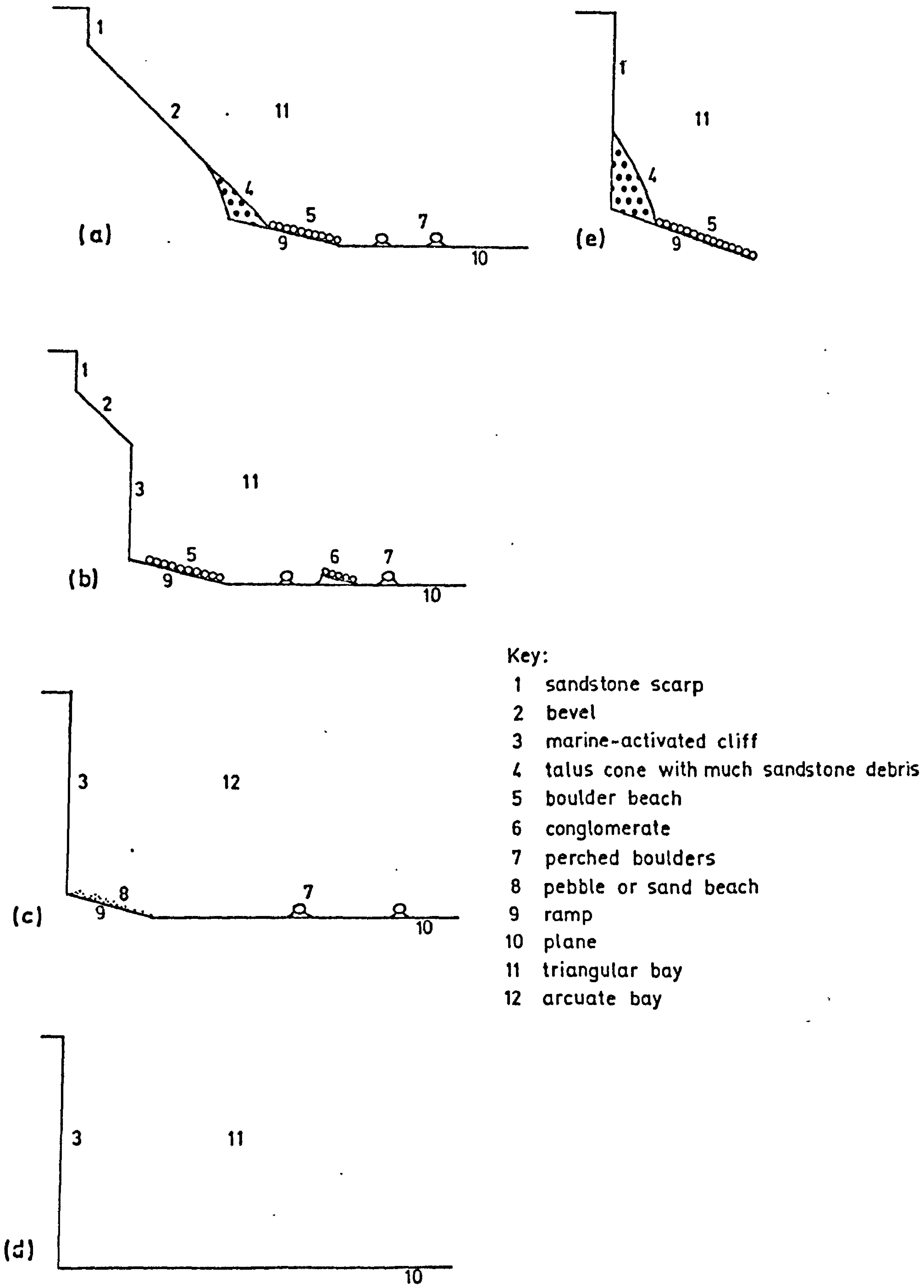
Change in the Systems

It has been shown that the tendency of the cliff system is toward a state of dynamic equilibrium, while the foreshore system requires a very long relaxation time to attain this state, a condition which has not yet been achieved, nor is likely to be until the sea-level remains constant. The unused wave energy reaching the cliff foot either does work (i.e. erosion) or is converted into friction. The latter is the usual case where boulders occur and where the cliff foot is bare unless some critical threshold is passed when, for instance, a boulder is moved and abraded, or a joint-bounded block of rock is quarried from the cliff foot. Such critical levels of energy are attained in storms but they are reduced if the waves are armed with pebbles or sand. Because the energy is confined to the narrow vertical zone at the cliff foot it has a much more noticeable effect on the morphology of the cliff than does an equivalent amount of subaerial energy spread over the rest of the cliff. With the aid of gravity, this effect is seen as the marine-activated cliff. Shale debris raining from this feature is easily abraded and transported away from the cliff foot allowing erosion to continue. However, large landslips of shale increase friction on the waves as well as presenting physical barriers to erosion. Large amounts of sandstone debris are even more resistant to erosion and may cut off the marine-activated cliff subsystem from its source of energy so that it will be subjected to subaerial forces only and, in time, will be erased. The cliff foot, therefore, is the battleground between the cliff and foreshore systems. Its nature determines the form of the cliff, the shore platform, and even the morphology of the bays. This indicates that relationships between the constituent parts of the supersystem are indirect, being always connected by this variable. Thus a bevel and a ramp are often associated but only because of the existence of a boulder beach.

Similarly, a cliff fully occupied by the marine-activated element is often associated with a shore platform where the plane is the most important element; this relationship requires no deposits at the cliff foot or only a pebble or sand beach. Clearly, the nature of the cliff foot is the regulator for the whole coastal process-response supersystem. Wherever a bevelled cliff exists the cliff foot in the form of a talus cone is also the temporary store for debris eroded from the cliff and in course of being removed from the supersystem.

Hence, it can be concluded that any changes in this regulator due to changing internal conditions (e.g. lateral variations in cliff geology) or external conditions (such as increased storminess or varying sea-levels) produce changes in the whole supersystem. However, it is more likely that the observable differences in form on the north-east Yorkshire coast are due to the long relaxation time of the cliff system. Erosion of the cliff foot, and inception of a marine-activated cliff can probably progress for a long time and much of the bevel be destroyed before the output of sandstone debris is increased sufficiently to reduce cliff foot erosion. In fact there is probably an over-reduction so that at each site along the coastline there is a continuous oscillation about some condition which is optimum for that particular geological and marine environment. Where the cliff is composed of the marine-activated element alone such oscillations are rapid causing little change in morphology. Where part of the cliff is composed of Middle Jurassic rocks the oscillations are longer and the morphological changes obvious. However, where almost the whole cliff is made up of sandstones, as between Maw Wyke and Widdy Head, the resistance of the rock to erosion is such that the oscillations are very long with the result that very steep cliffs are fronted by large talus cones.

Some of the very different assemblages of forms are shown in Fig. 9.10 but many other combinations also exist. In diagram (a), erosion at the cliff foot is reduced to negligible proportions by the boulder beach and talus cone and the full bevel has been allowed to develop. The best example of this assemblage is seen at Hawsker Bottoms. The second diagram in Fig. 9.10 is one in which cliff form is being radically altered, the talus cone having been reduced to a boulder beach, the bevel being destroyed and the output of sandstone debris not yet sufficient to arrest the growth of the marine-activated cliff. It is unlikely that cliff forms such as this are features in a steady state, i.e., the bevel and sandstone scarp being eroded in a parallel rectilinear fashion at the same rate as the marine-activated cliff is advancing landwards, because output from the sub-aerial cliff system is not as continuous as erosion in the foreshore system. Examples of assemblages such as this can be seen at White Stone Hole, South Batts, Saltwick Bay and Runswick Bay. The two diagrams (c) and (d) in Fig. 9.10 are situations where no or very little sandstone exists in the cliff to provide the necessary regulator for the coastal supersystem. Erosion continues unabated except for small talus cones made of shale which have little effect on morphology. The supply of small fragments of resistant debris allows erosion to be enhanced by the formation of a small beach. These assemblages are found for instance from Robin Hood's Bay to Far Jetticks and north of Staithes. In contrast, diagram (e) in Fig. 9.10 shows the assemblage of landforms fronting a cliff composed mostly of sandstone, e.g. at Widdy Head. Erosion is slow due to the thick boulder beaches which cover the narrow shore platform and to the large talus cones which protect the cliff foot.



Key:

1	sandstone scarp
2	bevel
3	marine-activated cliff
4	talus cone with much sandstone debris
5	boulder beach
6	conglomerate
7	perched boulders
8	pebble or sand beach
9	ramp
10	plane
11	triangular bay
12	arcuate bay

Fig.9·10 Some assemblages of landforms on the north-east Yorkshire coast

The Wider Relevance of the Process-Response Model

The relatively unresistant nature of the Lias shales in north-east Yorkshire compared with other hard rocks allows coastal features to develop quickly with little adulteration of the ideal forms by geological variations. This means that the process-response model presented here should be applicable to all erosional hard rock coasts where there is considerable tidal range and storm waves are dominant. Usually, however, the debris derived from the cliff is not of sufficient size to act as an effective regulator or, if it is, the rock forming the cliff is so resistant that it takes a very long time to weather down to a bevel. The marine-activated cliff is therefore the most common type of cliff.

Nevertheless, many examples of bevelled cliffs have been recorded. For example, they have been described in Cornwall and Devon (Arber 1949, 1951; Robson 1950; Wilson 1952), in the Inner Hebrides (Richards 1969), in Wales (Challinor 1931; Wood 1959; Hopley 1963), in France (Watson and Watson 1970), and in the Auckland Islands (Fleming 1965). Evidence for the periglacial origin of these features is certainly strong and in view of the fact that the rocks are very resistant to weathering this explanation must be accepted although in the case of the Isle of Skye (Richards 1969), where the cliffs are developed in Lias Shales, this interpretation may not be correct. The generation of the bevel on sea cliffs in North Cornwall has also been associated with the exposure of fault planes (Wilson 1952) and Savigear (1952) has used the Flandrian extension of the Pendine sand spit in South Wales to show how the Old Red Sandstone cliffs have been degraded to form slopes of about 32 degrees. It must be concluded, therefore, that bevels are equifinal forms; in other words, different environmental conditions can produce the same feature. Similarly, perched boulders can be produced by marine erosion of the surrounding shore platform and by its solution by marine and/or subaerial media. Therefore, while the model applies to the indisputably modern features of any coast, the origins of some features must be examined closely in the area under consideration.

Conclusions

Much remains to be investigated in the coast supersystem. Most of our knowledge is concerned with the morphometry of the cliff and foreshore systems, but even this needs to be increased by more refined methods and by studies of many different areas. Our understanding of the coastline system is rudimentary, for no techniques have been available for its analysis; the method described in this study certainly needs to be improved. Despite the shortcomings of the morphological aspects of the science of coastal geomorphology, there is no doubt that the greatest need is for more research into energy and mass flows in order that budgets and levels of critical thresholds can be evaluated. These flows necessitate the measurement of the frequency of action and the efficiency of processes and the monitoring of resultant changes in morphology. Such studies need to operate over long periods in order to obtain reliable data which are not greatly influenced by short-term and random variations. The instrumented sites on the cliff at Hawsker Bottoms and on the shore platform in several other places in north-east Yorkshire are intended for this purpose but many other locations are needed on other coasts.

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APPENDIX I

THE INFLUENCE OF MAN ON THE NORTH-EAST YORKSHIRE COAST

The rocks forming the coastline between Ravenscar and Saltburn have provided the raw materials for a number of industries in the past. The extraction of the rock has markedly changed the form of the cliff along several parts of the coastline and much rock has also been removed from the shore platform in various places. These industries and their effects will be described in turn working up the geological succession. The sites of each industry are marked in Fig. I.1.

The Ironstone Industry

The geological basis of this industry has already been noted. The most southerly exposure of the ironstone seams is in Far Jetticks, one mile north of Robin Hood's Bay. The Main Seam here consists of three thin ironstones totalling 13 inches in thickness and divided by shales which total 5 ft. 6 in. (Hemingway 1958). This is the only ironstone outcrop where there is no evidence that the seams have ever been worked for the thickest does not exceed nine inches (Howarth 1955).

The ironstone is mainly exposed north-westwards of Kettle Ness and has been intensively worked. Though several shiploads of ore were taken before 1838 exploitation on a serious basis started in that year with the workings of the Main Seam on the foreshore at Kettle Ness (until c. 1842) (Chapman, undated) and at Brackenberry Wyke (Bewick 1861). Mining was carried out only during the summer months, the period when the sea was calm enough for ships to be beached and loaded directly. The clean foreshore and sharp faces of the Main Seam outcrops indicate the activities of the Wylam Iron Company at Kettle Ness. In Brackenberry Wyke the workings are even more obvious. A scarp in the ironstone seams faces the land and its top is about four feet above the shale-cobble-strewn floor of the hole dug during the

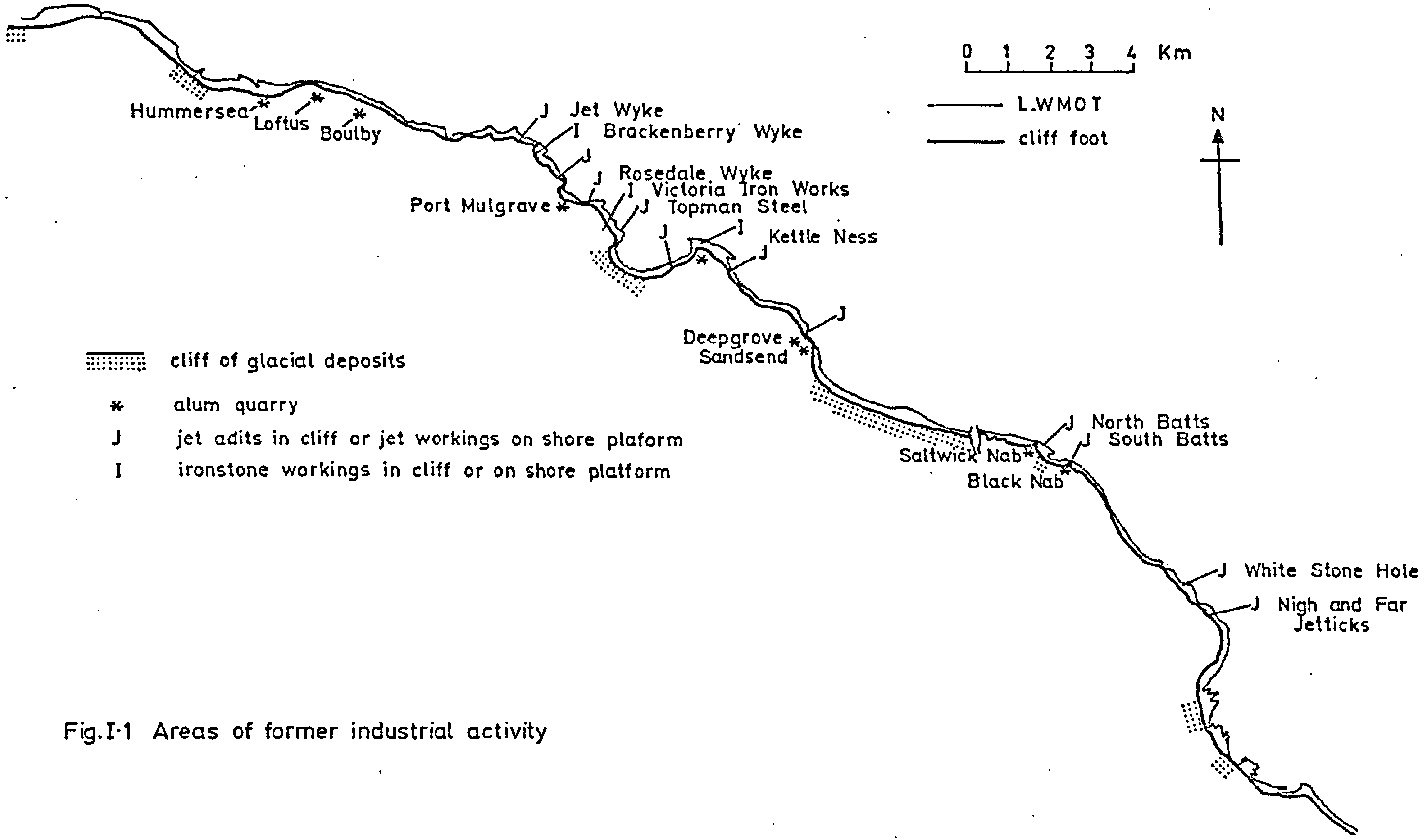


Fig.I·1 Areas of former industrial activity exploitation. The miners had difficulties with the filling of the hole with water and a deep channel was dug from the hole through the searp to relieve it. In this bay also a number of adits were sunk into the cliff to extract the ore. Most of these workings were made by Messrs. Palmer of Jarrow from the early 1850s onward. Nearby at Port Mulgrave the Main Seam was exploited from 1854 to 1860 by a drift and shaft, the seam being 10 ft. below sea level and 8 ft. thick here. Total output from this mine and the workings in Brackenberry Wyke was about 23,500 tons/year and Port Mulgrave itself was built to ship the ore to Jarrow.

Half a mile away the Victoria Ironworks Co. worked the Dogger, from August 1856 to 22nd March 1858, by means of a quarry north of Runswick at Wrack Hills, the stone being sent to the blast furnaces below the mine and thence exported via a small pier on the foreshore. These ironworks were destroyed by a landslide and the project was abandoned only about 100 tons of pig iron having been produced.

A shaft was sunk at Kettleness from 1910 to 1915 to test the quality of the Dogger but proved worthless. Other abandoned ironstone workings can be found near the top of the cliff at Boulby and on Huntcliff east of Saltburn.

The Jet Industry

Jet has been regarded as a semi-precious stone since prehistoric times (Elgee 1930). The jet industry really began in 1800 with the making of jet ornaments for visitors. By 1850 there were more than 50 jet workshops and in the peak year of 1873 200 workshops employed about 1500 men in the whole trade. Adits were opened at the foot of the cliff between Sandsend and the head of Runswick Bay, between Port Mulgrave and Penny Nab east of Staithes, on the cliff top between

Boulby and Skinningrove, on the cliff top between Nigh and Far Jetticks north of Robin Hood's Bay and near the base of the cliff at White Stone Hole. Also, adits were sunk into the cliff face by men dangling on the ends of ropes tied to secure posts on the cliff top (Head 1836). Thus it may be that the Jet Rock, wherever it is exposed, has been mined, the remains of the drifts often having been removed by later erosion. It is unlikely that the mines had much influence on the form of the whole cliff; they were holes only about 10 ft. high and up to 6 ft. wide. The roof was usually the tough Top Jet Dogger and the vertical range of mining was severely limited by the occurrence of the jet. Mining was by hand because explosives cracked the "planks" of jet, and so the adits penetrate only a short way into the cliff.

Mining was also carried out wherever the Jet Rock crops out on the foreshore. The characteristic evidence of such activities is a litter of shale boulders up to two or three feet in diameter with no common orientation, the areas often being bounded on at least one side by the Top Jet Dogger. Frequently, also, Whale Stones, a type of concretion found in these strata (Howarth 1962) are found resting in situ on shale pedestals (Fig. I.2a); these were left by the miners because, as noted in Chapter One, the jet was found only between these concretions. There is a line of Whale Stones on shale pedestals at Topman Steel, north of Runswick. Mined areas other than this one occur from Lingrow Knock to the east side of Rosedale Wyke, north of Port Mulgrave, and from Whitby to White Stone Point. The author has found no evidence of the mining on the shore platform at Hawsker Bottoms which was noted by Hemingway (1958).

Fig.I·2a Whalestone concretions left perched by jet mining

Fig.I·2b Apparent bevel produced by small scale alum quarrying

The Alum Industry

In contrast to the many small mines which provided jet, the alum shale was quarried in a few very large pits. Alum is a chemically complicated potassium aluminium sulphate (Raistrick 1966) and is important in the tanning and cloth-dyeing industries.

The first quarries were opened in north-east Yorkshire in 1604 and the industry continued until the mid-nineteenth century (Chapman 1968b). The Alum Shale was quarried, broken up and piled in alternating layers with brushwood into large heaps which were then set alight to calcine the shale. The high pyrites content of the Alum Shales aided combustion but it was sometimes found necessary to encourage it by the provision of a flue - this was the purpose of some tunnels dug into the solid rock, e.g. on the west side of Black Nab and at Kettle Ness. The burned shale was then leached in water, treated with an alkaline liquor and the liquid so prepared then concentrated by repeated boilings and crystallisations. By 1805 alum output was 6000 tons/year, one ton of alum being obtained from 50 tons of shale. In addition to the burnt-shale waste, any overburden (often the Dogger and basal beds of the Lower Deltaic Series) had to be removed, usually by throwing it on to the foreshore to be removed by the sea.

Alum quarries on the coast exist at Black Nab, Saltwick Nab, Sandsend Ness, Kettle Ness, possibly Port Mulgrave, and on Boulby and Hummersea cliffs. Associated with these quarries there are often remains of the alum house where the alum was refined. Such houses exist at the head of Saltwick Bay (this house served both the Black Nab and Saltwick Nab quarries), at Sandsend, on the west side of Kettle Ness, on the top and at the foot of the cliff at Boulby and at the cliff foot at Hummersea. In addition piers and even harbours were built to moor ships. Small piers built with blocks of Deltaic Sandstone occur on the foreshore on both sides of Black Nab, east of Saltwick Nab, west of Kettle Ness, and at Hummersea. Also wooden piles, possibly the remains of piers, exist on the foreshore east of Saltwick Nab, at Boulby and on the east side of Rosedale Wyke though these last may have been connected with the storage of iron ore before its shipment from Port Mulgrave. The small piers in Saltwick Bay were probably superseded by the construction of the small harbour at the head of the bay.

These large alum quarries are easily recognisable; they are great scars up to 100 ft. or more deep and cover several acres, often with piles of shale in them and always with patches of bare ground where the shale is a bright orangey-red - the result of the burning of the shale. The miners seem to have preferred to site their excavations on promontories, perhaps because of the greater exposure and therefore better calcining of the shale that would result.

However, along the length of Rosedale Wyke, there is a series of small excavations in the Alum Shales of the cliff. These are associated with the wooden piles already mentioned (Fig. I.2b), and a cross section through a scree which rests on a terrace cut in the cliff is visible. It is unlikely that the small scallops in the cliff above are of natural origin since they are visible nowhere else and are probably the result of alum quarrying which was only short-lived.

The Cementstone Industry

The use of the concretions in the Cementstone Shales, which constitute the upper 19 ft. of the Alum Shales, for the manufacture of various types of cement began in 1856 (Richardson, Stevenson and

Clapham 1863). The industry was never large since only about one ton of cementstone could be extracted from 60 tons of shale. Quarrying for the concretions was done mainly at the Sandsend alum quarry until about 1880 and then at Deepgrove until 1936.

Other Industries

All other industries have been of minor importance and have had little effect on the form of the cliff or foreshore.

Fossils - The Upper Lias is extremely rich in fossils, especially ammonites. In the nineteenth century the carving of *snakes' heads* on these for sale to tourists was a lucrative occupation. Large numbers of Dactylioceras commune (J. Sowerby) were obtained from the nodules of a bed in the Alum Shales which formerly cropped out on the shore platform in Rail Hole Bight (Howarth 1962). Fossil-hunting may also be the reason for the abnormally low level of the platform in Jump Down Bight.

Building Stone - The massive channel sandstones of the Lower Deltaic Series provide an easily worked building stone. There are very few quarries on the cliff but a tiny one exists on the East Cliff at Whitby and the large but shallow quarry at Port Mulgrave may have been used to provide the stone for the construction of the port. It is possible that sandstone boulders formerly lying on the shore platform east of Whitby East Pier were removed as building stone.

Conclusions

It is evident that the activities of Man have been considerable on the north-east Yorkshire coast. However, quarries for alum are few and mines and pits for the winning of ironstone are usually concentrated in accessible areas. Jet mining is probably the only industry to have been practised wherever suitable rock is exposed but the effects of this industry on cliff-form have been small.

APPENDIX II

THE MICRO-EROSION METER IN A LITTORAL ENVIRONMENT

The micro-erosion meter technique has been developed recently to measure directly the rate of erosion of solid rock. The basic principles of the technique have been described by High and Hanna (1970) and High (1971).

Briefly, the micro-erosion meter (M.E.M.) consists of a triangular base plate with a leg near each corner and a pillar placed off-centre on the upper surface. To this pillar is attached an engineers' dial gauge whose probe passes through a hole in the base plate so that its tip can rest on the rock surface. Exact relocation of the measurement point on the rock surface is achieved by use of the Kelvin Clamp Principle, the M.E.M. resting on three metal studs emplaced in the rock.

Modifications to the Apparatus

The M.E.M. constructed for use in the present study has a number of modifications. A detailed scale-drawing of it is given in Fig. II.1. The adaptations are as follows:

1. The M.E.M. is made wholly of stainless steel because of the great corrosive power of the sea. The steel specification is EN58B.
2. The erosion capacity of the instrument was increased to, theoretically, four inches with measurements in increments of one thousandth of an inch. This was to allow for the fact that erosion is rapid in this environment. In practice it was found that because of difficulties in the installation and cleaning of studs deeper than about 2.5 inches below the rock surface, this last figure is the actual erosion capacity of the M.E.M. The extra 1.5 inches is not totally wasted capacity, however, because this space allows the operator's

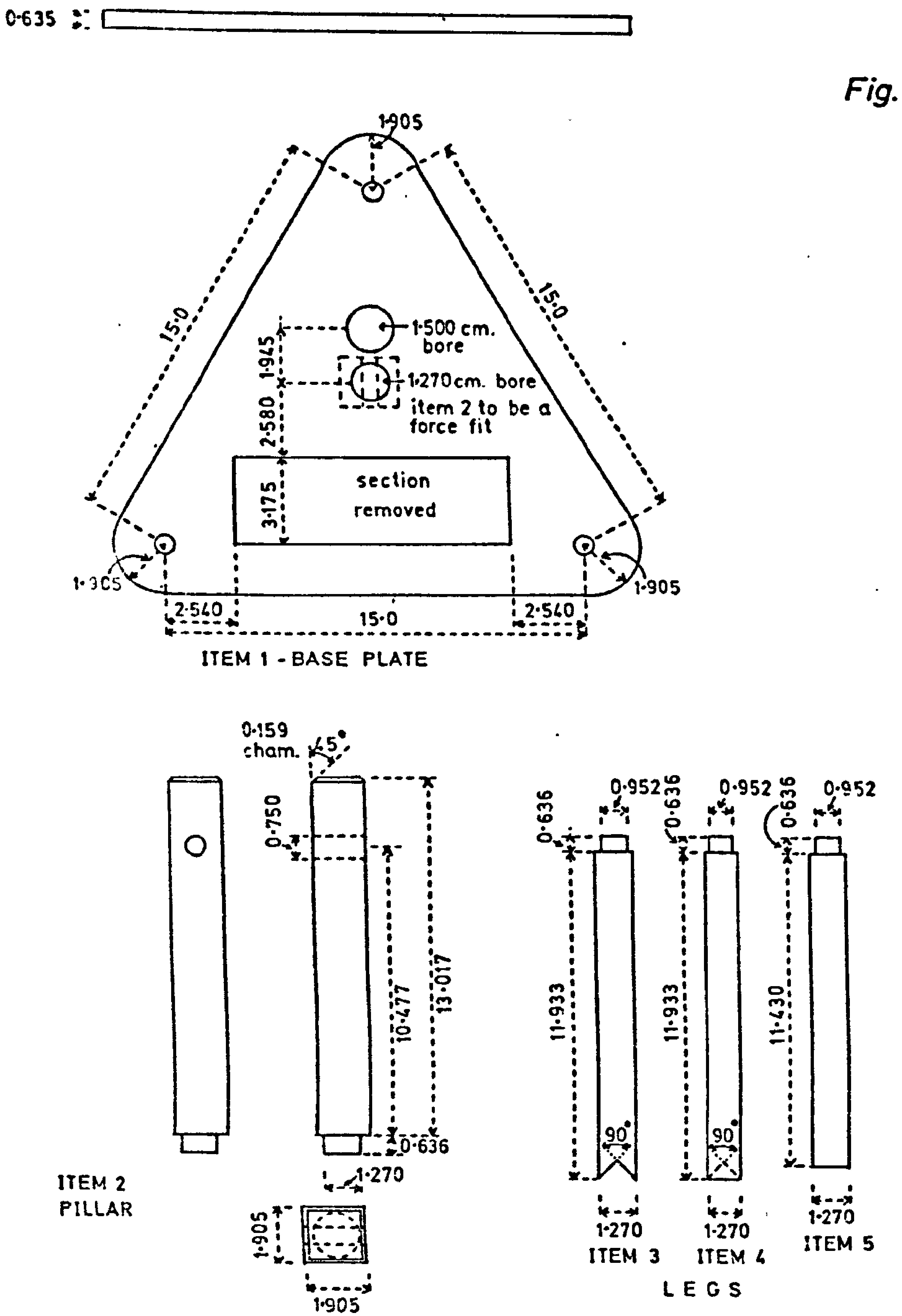
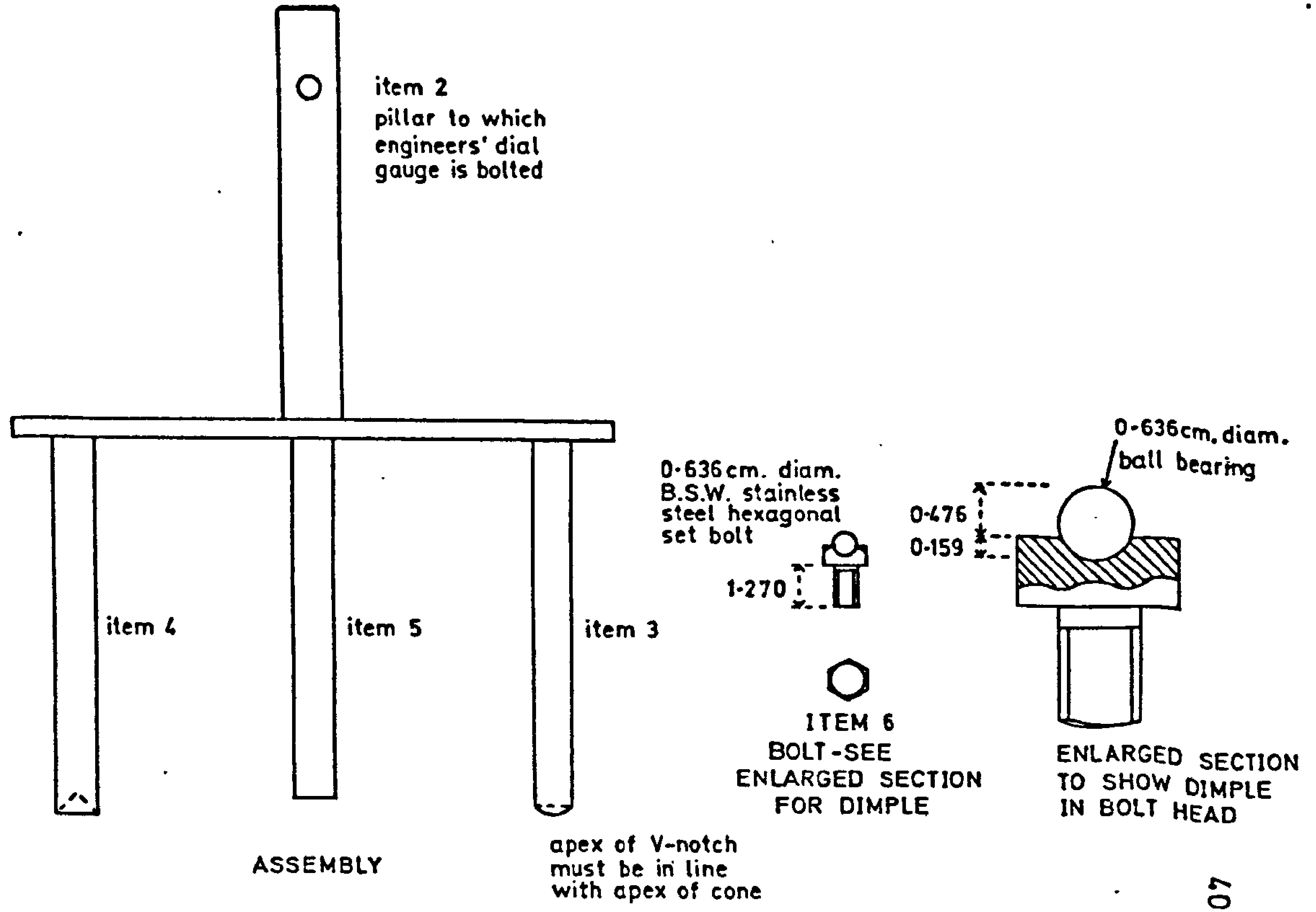


Fig. II·1 Specifications for the tripod of the micro-erosionmeter

All measurements are in centimetres
The legs and pillar must be located within fine limits at 90° to the base plate
Legs to be rivetted on the upper side of the base plate
Pillar to be rivetted on the lower side of the base plate
Item 1 - base plate
Item 2 - pillar
Item 3 - leg (V-notch)
Item 4 - leg (cone dimple)
Item 5 - leg (flat end)
Item 6 - stud



hand to hold the probe and to lower it gently on to the rock surface since no probe-lowering mechanism was affixed to the dial gauge. Also, when the rock has a hump on its surface between the studs, the probe may register between 2.5 and 4 inches.

3. The tip of the probe is hemispherical, not pointed - this reduces damage to the rock surface, a problem which could have been important on the soft shales of north-east Yorkshire.
4. It was thought wise to ensure that the legs were fixed firmly in the base plate and so, in addition to the pressure fitting, the tops of the legs were riveted.
5. In the experience of Mr. Max Pemberton of the Geography Department at Leeds the standard M.E.M. did not rest tightly on studs placed in vertical or highly inclined rock surfaces. To alleviate this problem the angles of the cone and wedge in the bases of two of the legs were reduced from 120 degrees to 90 degrees.
6. The standard instrument has legs 4 to 5 cm. long. There is an error inherent in the use of legs with the same length because the base of only the flat leg rests on the top of the stud. Therefore, with the tops of the studs at a horizontal rock surface the instrument will be tilted, the error being proportional to the depth of the depressions in the feet of the two legs. Fig. II.2 shows this situation using a 90-degree depression. Readings are underestimated by an amount which can be calculated from a formula derived as follows:

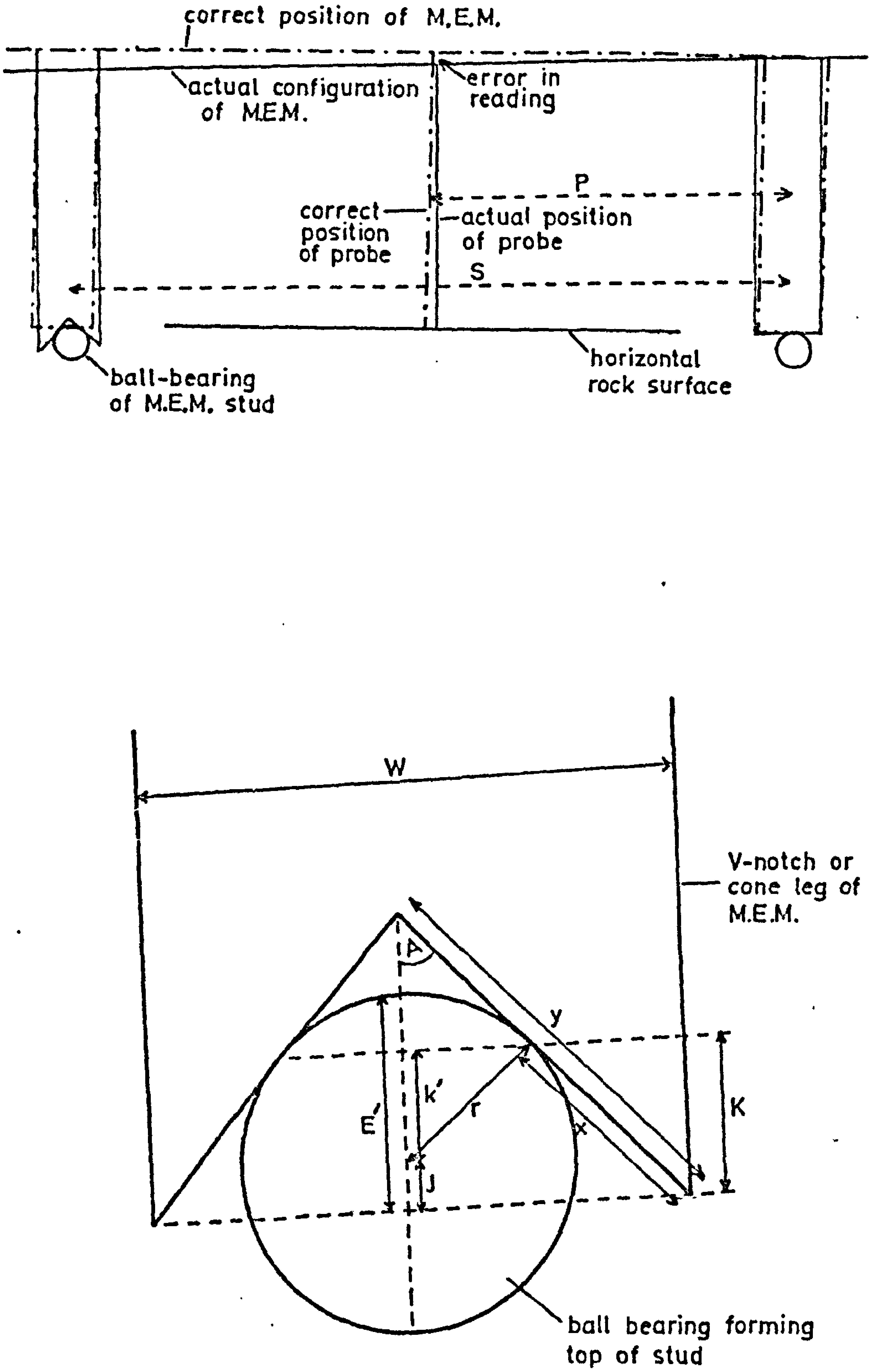


Fig.II·2 Errors in the design of the M.E.M. described by High and Hanna (1970)

$y = \dfrac{w}{2\sin A}$ where w = diameter of legs
A = half the angle of the cone or V-notch

$y - x = r \cot A$ where r = radius of ball bearing

$$x = y - r \cot A$$

$$k = y \cos A - r \cos A \cot A$$

$$= \frac{w \cos A}{2 \sin A} - r \cos A \cot A$$

$$k' = r \cos (90 - A)$$

$$j = k - k' = \frac{w}{2} \cot A - r \cos A \cot A - r \sin A$$

$$E' = r + j$$

$$= r + 0.5\, w \cot A - r \cos A \cot A - r \sin A$$

Therefore, error in readings $= \dfrac{pr}{s}(1 - \cos A \cot A - \sin A) + \dfrac{pw}{2s} \cot A$

where p = distance of the probe from the centre of the leg with the flat base

s = distance of the flat leg from the line joining the other two legs

$$\text{error} = \underline{\frac{pr}{s}(1 - \operatorname{cosec} A) + \frac{pw}{2s} \cot A}$$

In the case of an instrument constructed according to the dimensions suggested by High and Hanna (op. cit.) with $w = 0.5$ inch, $A = 60$ degrees, $r = 0.125$ inch, and the ratio p/s about 0.3938, the error amounts to 0.04923 inch. This may seem small, but if the gauge is deemed to read to an accuracy of 10^{-3} inch, the readings are underestimated by what is clearly a very large and significant amount. Fortunately, as the error is constant for all readings the amount of erosion measured is unaffected. However, the tilting gives rise to another error which is variable. Both can be eliminated by making the leg with the flat base shorter than the other two by an amount which can be evaluated from the relationship:

$$\text{correction} = r(1 - \operatorname{cosec} A) + 0.5w \cot A$$

With the tilting of the probe from normality to the rock surface by an angle B, each successive reading at the same site through time is overestimated by an amount proportional to the amount of actual erosion. Assuming that the rock surface undergoes parallel recession, this error is formulated as follows:

$$\text{error} = E(1 - \cos B)$$

where E = measured erosion

In the case of an erosion meter whose legs are the same length and has a probe measuring a maximum apparent erosion of one inch the error amounts to 3.0×10^{-4} inch. This is clearly very minor indicating that this source of error may be disregarded unless the instrument is able to measure a larger amount of erosion. Therefore the total inaccuracy in readings due solely to the design of the micro-erosion meter is usually a constant and is eliminated when the erosion is calculated from them.

Other error is introduced if the studs are not installed in a plane parallel to the plane of the rock surface. Where this is smooth and planar the author has found the use of a tyre-tread depth-gauge helpful to ensure that the tops of the studs are the same distance below the surface. However, where it is rough and the plane is not obvious, subjective judgement is the best which can be achieved.

7. In the standard M.E.M. the probe projects for half its length below the feet of the instrument. This aids the siting of the instrument on hummocky and sharply concave surfaces. Because such surfaces should be avoided due to the errors they produce and because of the great danger of knocking the end of the probe if it were to protrude two inches past the feet of the legs, the gauge was positioned on the pillar so that its tip lay about half an inch above the feet of the legs and so was protected by them.

8. The M.E.M. was provided with a handle, a rectangular hole cut in the base plate, because the instrument had to be carried long distances over rough terrain. It was also protected by a stout, close-fitting wooden box which was carried over the shoulder. The feet of the instrument were placed in holes in a bakelite plate which fitted in the base of the box. The holes in the plate were made conical so that, on its reverse side, the holes form a very tight fit when the legs are placed in them. Hence, should any damage be done to the legs, the feet may be replaced in exactly their former positions relative to each other. In this case it would be doubtful whether any readings taken after the event could be validly compared with those taken before.

9. It is necessary to have some means of measuring variations in readings which may be caused by the instrument being knocked sharply or even by a particle of dirt getting into the dial gauge. A strong datum was made by fixing two sets of studs into a piece of concrete paving stone. To produce a smooth surface a piece of glass was cemented with Araldite to the surface between one set of studs. Between the other set was

fixed a piece of glass on another piece of paving stone which in turn was glued to the first. The whole datum therefore is made of materials with low coefficients of expansion and allows the checking of readings at two bands within the range of the instrument at about 0.5 and 2.0 inches. Regular checks of the instrument have revealed no significant change in its readings.

10. The studs on which the instrument rests are usually made by cementing stainless steel ball bearings to stainless steel set screws with Araldite. Tests showed that this glue corrodes in sea-water so the studs were made by brazing the two parts with Eutectrod 1601 FC. After brazing, the ball bearings had to be cleaned and polished.

The Technique for the Emplacement of Studs

The M.E.M. site having been chosen on a smooth, flat surface, three holes three-quarters of an inch wide and equally spaced were bored with a hand drill. The use of a template to locate accurately the positions of the holes, as advocated by High and Hanna (1970), was found to be unsatisfactory, perhaps because of the length of the legs, and so the M.E.M. itself had to be employed. The depth of the holes depends on the location of the site but it was found that none should be less than about an inch to prevent vandalism. Holes about half an inch deep and a quarter of an inch wide were bored for the rawltamps in the centres of the bases of the bigger holes. Powdered shale produced by the drilling was removed with a scooped spatula. The rawltamps are best put into the holes by sliding them down a wire to prevent them turning over. The studs were screwed in using a brace after the rawltamps had been hammered with the special rawltamp caulking tool.

Because of the depth of the studs and, more especially, the difficulty of boring the rawltamp hole in the exact centre of the base of the larger hole, it was often found that the M.E.M. did not rest on them properly as its feet were touching the sides of the holes. The lower parts of the holes had to be widened with a hammer and cold chisel when this happened. (It is easily tested for, because on pressing the M.E.M. the reading on the dial gauge changes markedly.)

To prevent sediment filling the holes they were filled with plasticine. This also prohibits any eddying of the seawater on the surface caused by the presence of the holes and any quarrying of the studs by the sea. Black plasticine was found to be especially good for camouflaging the holes; vandalism was considerable at first on some sites. On the other hand, brightly coloured plasticine enables sites located on featureless parts of the shore platform and on remote sections of the cliff to be found quickly.

The Technique for Taking Readings

1. The rock surface is gently washed using a wash bottle.
2. The plug of plasticine is removed using the spatula. By freeing the plug from the walls of the hole first it can usually be lifted out in one piece and this eliminates the possibility of damage being done to the uppermost shale laminae around the hole.
3. Any water in the bottom of the hole is sucked out using the plastic wash bottle.
4. The stud is then rubbed with a fingertip to ensure that no dirt is sticking to it - a cloth is unreliable for this.
5. The feet of the M.E.M. are placed on the studs in the order cone foot, wedge foot, flat foot, and the probe is allowed to descend to the rock surface.

6. The reading on the dial is noted to the nearest one thousandth of an inch. The naming of studs follows the method used by Pemberton (1971) which is more succinct than that of High and Hanna (1970). Each site is given a number and each stud a letter, and the reading corresponding to that stud is made when the flat-footed leg of the M.E.M. rests on that stud. In a mosaic, which is a number of sites, one stud may occur in a number of sites but it keeps the letter. In the present study lettering was from the corner of the site nearest the cliff, seaward and from left to right, facing the cliff. For sites on vertical surfaces lettering was from left to right and top to bottom. Sites on the platform were numbered from the sea towards the cliff and for those at the cliff foot numbering was towards the path leading down to the shore.
7. Steps numbered 5 and 6 are repeated with the M.E.M. differently orientated on the site, the feet and tip of the probe having been checked for dirt after being lifted off the studs.
8. Each reading at the site is then checked and checked again if necessary until the readings are constant; it is incorrect to use average readings since some may be affected by dirt. Two checks are usually the maximum necessary.
9. The plasticine plugs must be replaced in the holes.

M.E.M. Sites and Erosion Data

Maps of the locations of M.E.M. sites and configurations of studs at each site on the north-east Yorkshire coast together with all M.E.M. readings collected during the study period form Appendix IV.