Beach Development, Sediment Budget and Coastal Erosion at Holderness

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THE HOLDERNESS COAST

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SUMMARY

Complex relationships exist among offshore conditions, beach sediment transport and morphology, and till cliff erosion. Modelled and measured sediment transport rates established for the Holderness coast are similar to those on comparable coasts elsewhere. The direction of sediment drift depends on wave approach, and determining sediment transport rates, cliff composition and cliff retreat rates allows a sediment budget to be prepared. The beach response predicted by the sediment budget was confirmed by field observations, with budget surpluses and deficits coinciding with full and depleted beach profiles respectively. The area of deficit in the north of the study area was associated with the reduced sheltering effect of Flamborough Head on sediment drift.

At most profiles, especially those with a sediment deficit, high energy waves may remove the sand veneer completely, leaving the till platform exposed. These bare till patches which elsewhere have been called ords and have been regarded as unique, were thought, in the present study, to represent a normal beach response to limited sediment supply and prevailing offshore conditions.

Beach evolution was also modelled formally, the range of beach profiles exhibited on the Holderness coast being grouped into a number of distinct types, and evolution among them described and predicted by a first-order Markov model. This can be refined to provide different models for "winter" and "summer". Different modal types occur at different locations, and certain types of transitions between classes can be associated with particular ranges of wave conditions.

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Till cliff retreat at Holderness is extremely variable, both spatially and temporally, being influenced by beach level, energy conditions, cliff moisture content and the actions of man.

The sediment transport rates, cliff retreat data, sediment budget and beach behaviour model are all essential elements of a research programme currently being undertaken to find a cheap method of protecting this coast.

ACKNOWLEDGEMENTS

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CHAPTER 1 INTRODUCTION

In recent years various aspects of beach variability such as the inter-relationships between beach changes, back beach erosion and sediment budgets have been the objects of a great deal of research. For example, Sunamura and Horikawa (1977) investigated wave conditions, longshore sediment transport, till cliff erosion and beach morphology on the Pacific coast of Japan, and Harrison et al. (1965) produced formulae linking longshore currents, beach slope, sediment characteristics, and beach erosion or deposition. Allen (1980) produced a comprehensive analysis of beach erosion as a function of variations of the sediment budget of Sandy Hook, New Jersey, in which he investigated the beach sediment transport rates, a range of offshore conditions and the distribution of beach erosion; but most coastal studies have failed to tackle all aspects of the coastal system and have been confined to one or two of the elements involved. This is unfortunate as offshore conditions, patterns of sediment movement, changes in beach morphology and back beach erosion are inter-related, and the results of these inter-relationships may be summarised in a sediment budget. The present study aims to examine the processes of the main coastal sub-systems which govern beach behaviour, and in particular their interaction with the cliff erosion system.

The first part of this chapter will be devoted to describing the aims of the present research, experimental design and research procedure. This is followed by a literature review, a description of the study area and an outline of the thesis structure.

1.1 AIMS OF THE RESEARCH

The aim of this research is to explain the processes governing beach variability and its interaction with till cliff erosion. In order to fulfil this aim a general hypothesis was put forward, i.e.:

"that specific relationships exist among beach morphology, sediment transport processes and back beach till cliff erosion".

In order to assess the various processes governing beach variability, the following specific aims were defined:

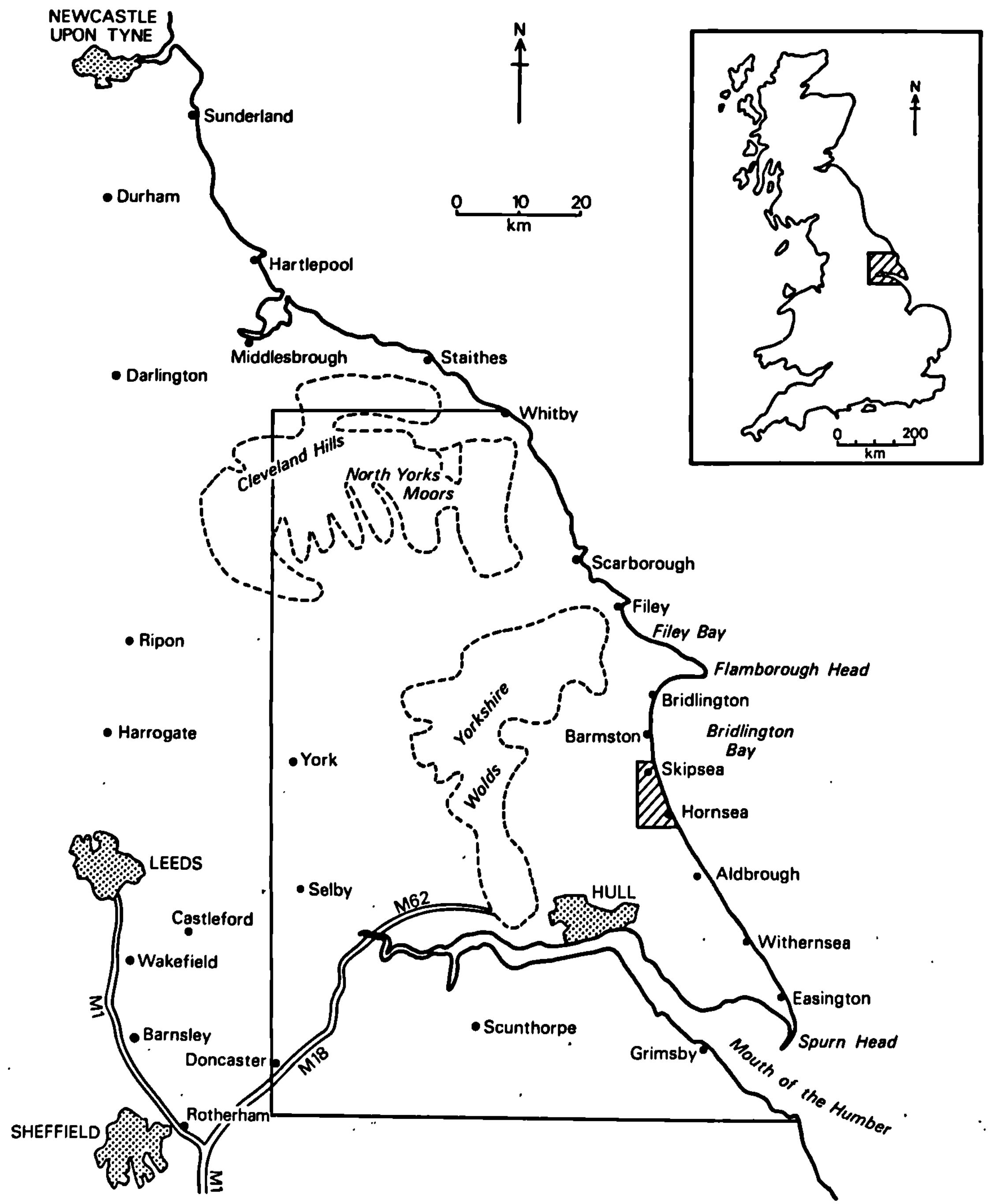
1. To establish the relationships between beach morphology and sediment transport processes,
2. To establish the relationships between these processes and intertidal and nearshore marine conditions,
3. To establish the relationships of beach morphology and wave conditions to the erosion of (till cliff) sediments and
4. To produce a probabilistic model for beach evolution.

A suitable field site for investigating these relationships is the till cliff coast of Holderness, North Humberside (Figure 1.1). Cliff erosion is rapid, the beach is highly dynamic and sufficient local archive data exist to allow the long-term sediment supply to the beach to be calculated.

In order to devise a suitable experimental scheme which would allow the four specific aims presented above to be fulfilled, a number of sub-hypotheses were formulated, on which the bulk of the experimental work was concentrated. These sub-hypotheses were:

1. That the rates and directions of sediment transport vary as a result of variations in nearshore marine conditions,
2. That variation in beach morphology is directly related to variations in sediment transport rates and directions,

Figure 1.1 Location of Holderness Coast and Field Area.



NEWCASTLE UPON TYNE
Sunderland
Durham
Hartlepool
Middlesbrough
Darlington
Staithes
Whitby
Cleveland Hills
North Yorks Moors
Scarborough
Filey
Filey Bay
Flamborough Head
Bridlington
Barmston
Bridlington Bay
Skipsea
Hornsea
Yorkshire Wolds
Ripon
Harrogate
York
Selby
LEEDS
Castleford
Wakefield
Barnsley
Doncaster
Rotherham
SHEFFIELD
M1
M62
M18
HULL
Aldbrough
Withernsea
Easington
Spurn Head
Scunthorpe
Grimsby
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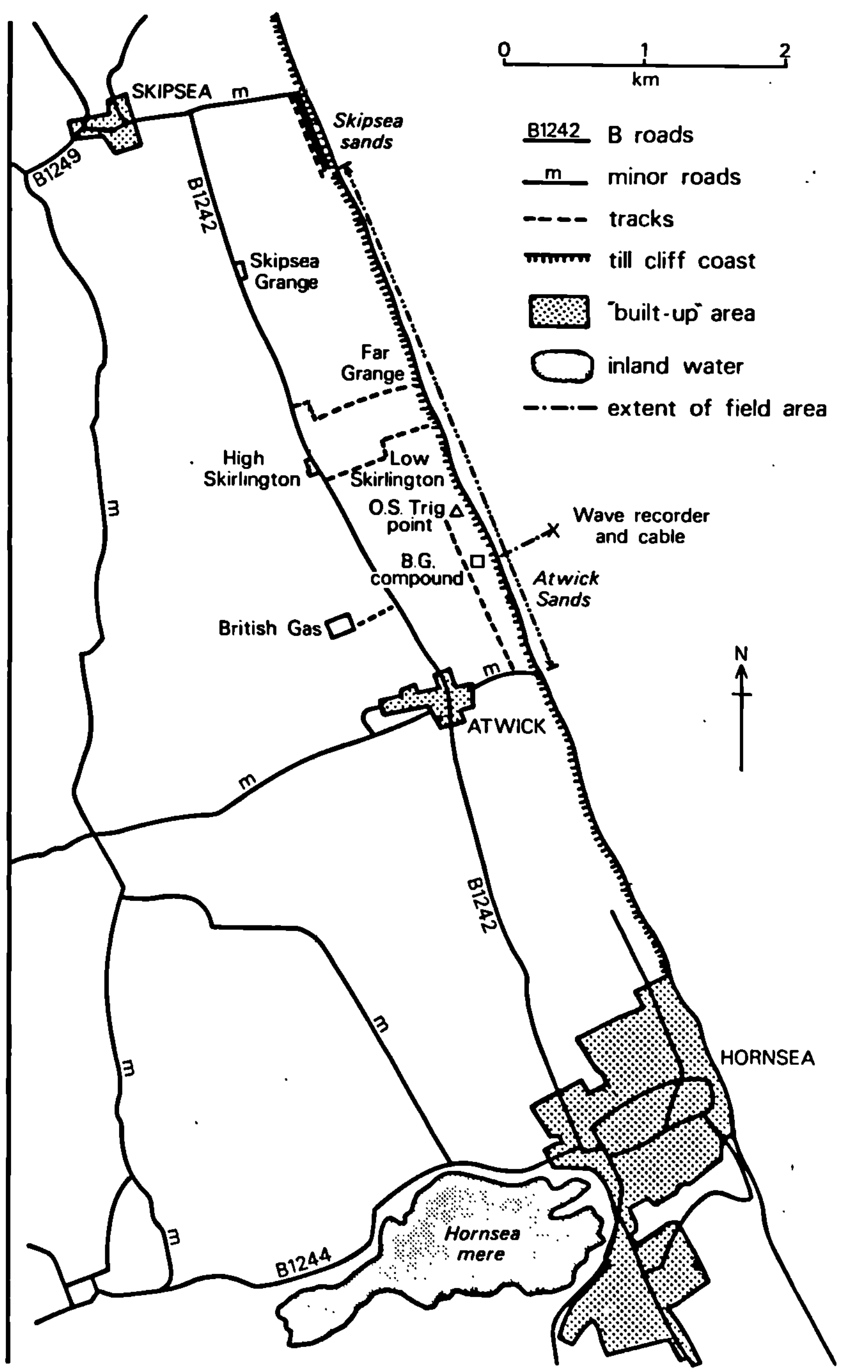


0 1 2
km
B1242 B roads
m minor roads
tracks
till cliff coast
"built-up" area
inland water
extent of field area
SKIPSEA
B1249
B1242
Skipsea sands
Skipsea Grange
Far Grange
High Skirlington
Low Skirlington
O.S. Trig point
Wave recorder and cable
B.G. compound
Atwick Sands
British Gas
ATWICK
N
HORNSEA
Hornsea mere
B1244
m

3. That theoretical models of sediment transport produce results which agree with those obtained in the field,
4. That throughout the year the beach profile may be represented by a range of specific beach types,
5. That beach geometry changes exhibit Markov properties, with evolutionary cycles expressed as probability functions based on previous beach states,
6. That the nature of beach evolution reflects prevailing offshore marine conditions and
7. That rates of till cliff erosion are influenced by beach morphology.

Experiments were designed to test these hypotheses, and a research procedure devised to produce the necessary data. It was recognised that before the hypotheses could be tested some smaller pilot studies and tests would be necessary to determine appropriate experimental methods, e.g. the best methods of surveying and of carrying out tracer experiments.

A suitable experimental design and research procedure, devised to fulfil the aims of the research and to test the hypotheses which were set up, is presented below.

1.2 EXPERIMENTAL DESIGN AND RESEARCH PROCEDURE

A study to investigate the relationships among offshore conditions, beach variability, sediment transport and shore erosion involves work in all three sub-systems of the coast, i.e. offshore, the beach and the cliff. The present study therefore concentrated on:

1. Variations in wave and tidal processes,
2. Variations in beach, sediment transport rates, sediment characteristics and morphology and

3. Variations in cliff retreat.

Wave and tidal processes were investigated over a relatively long period of time so that predictions of sediment movement rates could be made, and related to prevailing offshore conditions and particular beach states. On the beach it was necessary to monitor the profile at a number of fixed places along a stretch of coast for as long a time as possible. Thus comparisons could be made at different times and positions alongshore, and the continuous evolution of the beach examined. Regular sampling of beach material was required so that changes in sediment characteristics could be determined, ideally associated with specific offshore conditions and beach morphology. Actual measurements of sediment movement on the beach were required in order to compare them with those modelled using wave data. The most appropriate method was to conduct tracer experiments, on both the upper and lower beaches, so that sediment movement rates might be calculated. The effects of varying offshore conditions could be investigated by carrying out the experiments during different wave and tidal conditions.

Regular simultaneous sampling and monitoring of a number of variables over a fixed network in the three coastal sub-systems enabled a sediment budget to be derived, which could be tested against the relevant field data. Field tracer experiments could be used to calibrate sediment transport models and thus obtain a more accurate sediment budget. Tests were performed to determine whether significant correlations existed between various combinations of cliff erosion, beach morphology, sediment transport and offshore variables.

Many beach studies reported in the literature have relied upon rather limited data which were acquired inconsistently. The research procedure of the present study, however, included a systematic and comprehensive series of retreat measurements, profile surveys and tracer experiments. Each set of data could then be used to test more than one of the hypotheses put forward in Section 1.1, and combined, help to explain the processes and interactions in various coastal sub-systems.

Following a brief review of field techniques reported in the literature Chapter 2 will contain a description of the field methods adopted in the present study, appropriate to the experimental design and research procedure.

1.3 LITERATURE REVIEW

In order to understand previous coastal work and the various field and analytical techniques available it is necessary to conduct a literature review. This also helps to determine any gaps in the existing work.

The coastal geomorphological literature ranges from articles in the professional and academic press to pieces of more general appeal in national or local newspapers and magazines, which usually concentrate on particular problems in specific locations. Journals and books cover a wide range of research from descriptions of field studies and experiments, through the presentation of empirical and mathematical equations and models based on field and laboratory experiments, to accounts of almost entirely theoretical approaches based on physical laws.

This brief review contains five sections; firstly, a summary of the development of coastal research and its applications, followed by sections which are particularly relevant to the present research, covering studies of the offshore, beach and cliff zones and work on sediment budgets.

1.3 a COASTAL GEOMORPHOLOGY

An evaluation of the evolution of coastal geomorphology within the past few decades helps to place present work in perspective. The first publications (around the turn of the century) were almost purely descriptive, and in many cases were simply an inventory of coastal forms, with occasional suggestions for genesis, rarely based on experiments or long-term observations. Occasionally some morphological classification was attempted (Sheppard, 1912; Johnson, 1919). Such accounts were valuable as a starting point for studies which had a greater emphasis on coastal processes. As early as 1919, Johnson was investigating "Shore Processes and Shoreline Development", placing emphasis on offshore conditions. However, it was only after 1945 when coastal research had made some valuable contributions to the war effort (Williams, 1947) that there was a real move to link different processes and forms, in an attempt to study the "coastal process system" as a whole. This coincided with the "New Geography" of the post-war years. The processes and forms involved in coastal geomorphology were extremely complicated and poorly understood, and both were so variable in space and time that simple observations were no longer adequate for determining the relationships involved. There was an upsurge in quantification, and a desire arose to link variables by means of mathematical expressions, a task which was aided by computer applications. As Pethick (1984) points out, many of the first studies were actually conducted by engineers who responded to specific coastal problems by producing "predictive, deterministic models of coastal development" and some of the techniques were then adopted by coastal geomorphologists.

As a result of quantification in Geology and Physical Geography numerous statistics and mathematics books were published which had a bias towards the geological sciences (Krumbein and Graybill, 1965; Davis, 1973), while the literature concentrated on the application and use of particular statistical techniques e.g. Markov Chain Analysis (Krumbein, 1967; Sonu and James, 1973; Collins, 1975), Factor Analysis (Dal Cin, 1976), Polynomial Regression Analysis (Allen, 1975), multiple linear regression (Krumbein, 1961; Harrison and Krumbein, 1964) and Fournier Shape Analysis (Porter et al., 1979). It became apparent that the process-form links were not one-way deterministic relationships but inter-relationships, and it was convenient to represent them in the "general systems theory". This led to the consideration of sediment budgets which encompass the entire coastal system.

Several workers acknowledged the importance of scale in the coastal system (Wolman and Miller, 1960; Schwartz, 1968; Cambers, 1976). Relationships among processes and form may vary with scale; the large scale (space or time) effects may be an average of those at a much smaller scale. Three main time scales have been described; cyclic time (10^4 years), graded time (10^2 years) and steady time (10^{-1} year, i.e. just about a month). It is at the smaller scales that most geomorphological work must be carried out; frequent intensive spells of fieldwork and data gathering in different locations eventually build up a reservoir of information. As Wolman and Miller (1960) pointed out, the larger an event the less frequently it occurs and so the chances of not recording it are greater.

Continuing work thus enables the coastal zone as a whole to be studied and has coincided with an increased concern for the environment, heralded by a "coastal management" approach to problems. The emphasis on management has evolved within two decades from a position where engineering experience was used to "overcome" the effects of the sea, to one where working "with nature" rather than against it is advocated (e.g. Jolliffe, 1978; Clark, 1982). Management schemes may work more satisfactorily now that coastal geomorphologists have produced empirical and mathematical models which help to describe, explain and predict the various processes at work. This has been made possible by contributions from a large number of disciplines - geography, geology, engineering, meteorology, mathematics and biology (McLean, 1983). Refinements are continually being made to the existing techniques and theories, and new ones will no doubt be introduced.

1.3 b OFFSHORE WORK

Theory: Waves produce the most important energy source for beach development and sediment transport. Various summaries of wave equations have been published (Peregrine, 1972; CERC, 1975; Komar, 1976a); expressions vary both in complexity and in the degree to which they reflect reality, for waves before breaking, in deep water, and after breaking (in shallow water). The Admiralty Manual of Navigation (HMSO, 1955) gives relatively simple formulae for sea and swell waves and also for calculating wave energy from wave height. Two early classic wave theories were proposed by Airy and Stokes (summarised in CERC, 1975 and Komar, 1976a). The former developed a linear wave theory, and the latter a more advanced finite amplitude theory. cnoidal wave theory and solitary wave theory were later developed for use in shallow water (CERC, 1975). The conditions under which these wave theories are appropriate are shown in Komar (1976a), along with various linear wave parameters.

When waves enter shallow water they behave like a series of solitary waves and are refracted; a wave approaching the coast obliquely will change direction to become more parallel to the coast, and slow differentially as the water depth decreases. The associated change in wave height is governed by:

$$H = \frac{b_o}{b} \cdot H_o \qquad (1.1)$$

H = wave height

b = distance between wave rays (lines at 90^o to the wave crests)

$\frac{b_o}{b}$ = the refraction coefficient (Holmes, 1975)

o subscript indicates deep water conditions

The angles which the waves make with the shore is governed by Snells law:

$$\frac{\sin \alpha_1}{\sin \alpha_2} = \frac{c_1}{c_2} = \frac{L_1}{L_2} = \text{constant} \qquad (1.2)$$

α_1 α_2 = angles which two wave rays make with the coast

c_1 c_2 = speeds of wave crests

L_1 L_2 = wave lengths

As this refraction occurs energy is dissipated along the shore, although it is assumed that the energy between adjacent wave rays is constant. Wave rays can therefore be used to estimate the energy distribution alongshore. Where they converge there is a concentration of wave energy, whereas ray divergence implies energy dissipation.

Wave refraction patterns have been established graphically but their construction is time-consuming (Johnson et al., 1948). During the last decade or so it has become more usual to produce wave refraction patterns using computer programs which, from bathymetric depth grids of the sea area and deepwater wave parameters, track rays from deep water to breaking at the shore. Calculation of energy distributions along-shore is subsequently performed (Harrison and Wilson, 1964; Bryant, 1974; May and Tanner, 1975;

Abernethy et al., 1977; and Fico, 1978). Refraction patterns may also be deduced from good quality aerial photographs.

A vital aspect of refraction studies is the estimation of wave energy available at the shore for sediment movement, and many studies have presented formulae based both on theory and on laboratory and field experiments. These range from the relatively simple, e.g.

$$E = 41 H_0^2 T^2 \quad \text{(Phillips and Rollinson, 1971)} \quad (1.3)$$

and $$E = \frac{\rho g H^2 L}{8} \quad \text{(CERC, 1975)} \quad (1.4)$$

to the more complex,

$$P = (\rho g H^2/8)(L/T) \tanh \frac{2\pi d}{L} \cdot n \quad \text{(Sonu and Russell, 1966)} \quad (1.5)$$

where H_0 = deepwater wave height

E = wave energy

41 = constant; these vary widely among equations

g = acceleration due to gravity

d = water depth

T = wave period

P = wave power

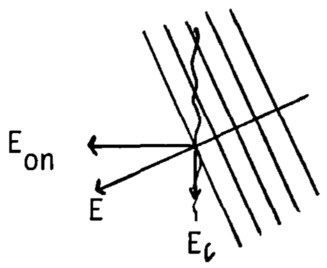
L = wavelength

ρ = density of water

$n = 1 + \frac{4\pi d}{L}$ (sin 4 d/L)

cgs units

Where waves approach the shore at an angle, longshore currents are set up, i.e. there is a net transfer of energy up or down the shore. The incident wave energy can be resolved into its perpendicular components (alongshore and at right angles to the shore):



$$E_\ell = \sin\alpha\ E \qquad (1.6)$$

$$E_{on} = \cos\alpha\ E$$

Komar (1976a) gave the longshore wave energy flux as;

$$P_\ell = EC_n \sin\alpha \cos\alpha \qquad EC_n = \text{wave energy flux} \qquad (1.7)$$

and other similar expressions for longshore wave power have been produced.

Longshore currents capable of moving sediment may also be induced by longshore variations in wave height. Longshore current velocities were predicted and described by Putnam et al. (1949), Inman and Quinn (1951), Nagai (1954) and Brebner and Kamphuis (1963), although a good summary appears in Sonu et al. (1966). Harrison et al. (1965) and Allen (1974) produced empirical equations for current velocities based on multiple regression of field measurements of wave (and beach) characteristics.

Wave theory is not as simple as some of the expressions presented might suggest. Ocean waves are made up of many trains of waves of different periods and heights (Silvester, 1959) - a wave spectrum. Waves within a fetch, i.e. where the generating winds are still blowing, are generated in several directions at once; swell waves have moved outside the generating area and are in a state of decay, spreading laterally and longitudinally, dispersing energy via long-crested waves.

Where real wave data are not available conditions have been hindcast from wind data; this means that providing suitable archive wind records exist, wave conditions can be calculated for any time in the past, perhaps coinciding with periods of fieldwork (CERC, 1975; Armon and McCann, 1977). Knowledge of the present sea state derived from wind information can be used to predict conditions at various intervals in the future, based on forecast winds. These forecast winds are obtained from a single source,e.g. the regional version of the complex Met-Office 10-level atmospheric prediction model (Golding, 1980). Wind direction at the coast is particularly important; where a wind is onshore, wave set up is greater and more work can be done. Offshore winds,however, tend to dampen wave heights, so less energy is available. Many beach studies have obtained hindcast wave data, including those of Fairchild (1966), Armon and McCann(1977), Nummedal and Stephen (1978), Greenwood and McGillivray (1978), Davidson-Arnott and Pollard (1980), and Nummedal et al. (1984). Meteorological conditions start a chain of processes which affect the coast, and knowledge of these processes leads to an understanding of sediment movement and beach behaviour.

Field measurements: The most important wave parameters to measure in the field, enabling the subsequent calculation of wave energy, power and sediment transport, are height, period and direction. Wave heights and periods have been measured using a variety of methods, including waves staff , pressure transducer wave recorders and simple visual estimations of waves passing posts of known height. Dugdale (1981) listed a number of methods for obtaining values of the critical parameters of height, direction and period; often wave direction poses the greatest problem. Currents have been monitored using static-fin current-meters, and also by tracing the passage of sea bed drifters (Phillips, 1968; Bartolini and Pranzini, 1977). However, there are still relatively few long, high quality records of offshore conditions.

1.3 c THE BEACH: SEDIMENT MOVEMENT

Theory: Work investigating sediment movement can be considered under three headings; firstly the principles of sediment movement, secondly, the studies which have derived or tested equations and models, and thirdly, work which is wholly or partly a description of field experiments and observations of changes in beach state, morphology or sediment characteristics. The second approach provides the expressions and models for calculating potential sediment movement for various marine conditions.

The theoretical approaches are based on wave energy expressions which have been developed to enable sediment movement to be calculated. Occasionally sediment transport by winds (Svasek and Terwindt, 1974) and turbulent tidal flow (Jolliffe, 1978) has been investigated, but most work has concentrated on wave-induced sediment transport. Bagnold (1963 etc.) did much theoretical work based on individual sediment grains or "elements". He produced equations for sediment transport rates, upon which Komar and many others based their work. Perhaps the most common expression of total sediment transport (I) is that presented by Komar (1976a) and Komar and Inman (1970):

$$I = 0.77\ (\tfrac{1}{2}\,\rho\, gH_b C_b)\ \sin\alpha_b\ \cos\alpha_b \qquad (1.8)$$

or

$$= 0.77\ EC_n\ \sin\alpha\ \cos\alpha$$

$$= 0.77\ P_\ell$$

g = acceleration due to gravity

ρ = density of water

H_b = wave height at breaking

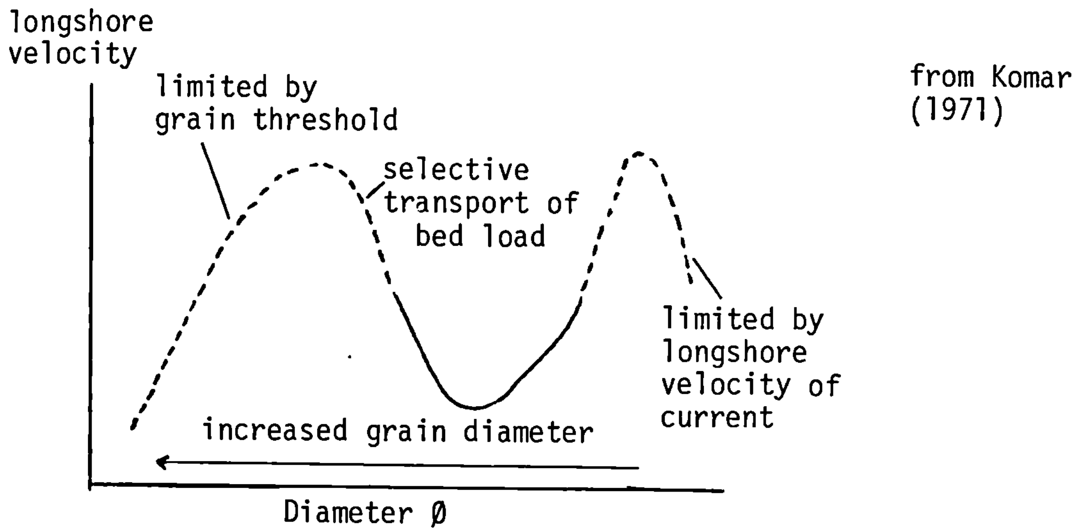
EC_n = wave energy flux

C_b = wave speed at breaking

α_b = angle which wave crests make with shore

P_ℓ = longshore wave power

Various workers have used the same basic equations but have modified the coefficients and constants to suit the study area, usually after carrying out some empirical tests (Appendix 2). Komar investigated the selective transport of different grain sizes and the way in which they are transported. He summarised his findings in a diagram:



Equations for calculating sediment transport may enable beach changes to be predicted (Lewis, 1931; Kidson and Carr, 1959; Thompson and Harlett, 1968; Price et al., 1973). They have been incorporated in models which describe beach behaviour, plan, volume, profile etc. (Tanner, 1971; May and Tanner, 1975; Greenwood and McGillivray, 1978; Holman and Bowen, 1982, etc.). The same expressions have also been used to help solve engineering problems, many connected with coastal defences (Hoyle and King, 1957; Williams, 1960; Willis and Price, 1975; CERC, 1975). Inevitably errors arise when using these equations (Section 4.2)

Some more specialised work has concentrated on specific elements of sediment transport, e.g. on the existence and possible effects of edge waves (Huntly and Bowen, 1975; Holman, 1983). Kirk (1975) studied the work done by surf and run-up on mixed sand and gravel beaches, while Waddell (1976) investigated relationships among swash characteristics and beach profile.

In contrast to the equations and models produced from theoretical work backed up by field measurements are the empirical equations which have been derived for longshore current velocity (Harrison, 1968) and sediment transport rates (Harrison et al., 1965). These are obtained by making numerous field measurements and performing multiple linear regression analysis upon them to determine the most influential independent variable. These equations should really only be applied to the site where the measurements were made, though they have been used elsewhere with adjusted co-efficients. For example, combinations of environmental variables such as deep water wave height, wave period, current velocity and beach slope are used to predict certain beach parameters like sediment deposition, beach erosion and longshore current velocity.

The cell approach to beach sediment studies of Tanner (1971) and May and Tanner (1975) assumes units of the beach to have closed sediment circulation patterns. These cells may not be immediately apparent in the field, and their existence may be revealed only by sediment studies; on the other hand they may form a physically obvious cell, e.g. a small bay. Depending upon energy distribution cells may be net "accumulators" or net "providers" of sediment relative to adjacent cells. Lowry and Carter (1982) used a wave refraction programme to delimit littoral power cells, which in turn were used to establish a pattern of sediment transport.

Numerous models devised to investigate and describe beach behaviour incorporate the equations mentioned above. For example, Davidson-Arnott (1981) simulated nearshore bar formation while Stapor and Murali (1978) and Vincent (1979) modelled longshore sand transport rates, and Fico (1978) investigated the influence of wave refraction on coastal geomorphology; Fox and Davis (1971) produced simulation models for storm cycles and beach erosion.

One branch of research has examined the evolution of beach form under a variety of conditions, and sometimes among a number of beach types. In contrast to most of the studies already described, which predict erosion or deposition, these incorporate sequences of specific beach forms which occur under specific related conditions. These models (Davis and Fox, 1972; Sonu and James, 1973; Sonu, 1973; Owens, 1977; Short, 1978, 1979; Wright et al., 1979, 1985; and Wright and Short, 1983) based on the monitoring of beach changes and associated wave conditions over many months and years, establish whether any patterns in behaviour exist.

In addition to studies which predict or describe sediment transport quantitatively, attempts have been made to measure sediment transport in the field.

Beach field techniques: Sediment transport has been measured using tracers, sediment traps (Bruun and Purpura, 1964), aerial photograph analysis (Allen, 1980) and beach profile surveys. Some of these will be considered in greater detail in later sections, but by far the most common field technique is the use of tracers. These experiments have varied widely in detail but the principles behind them are the same. Material as similar as possible to the natural beach material is "marked" in a way that makes it easily detectable, it is introduced to the beach and its progress monitored. This "marked" sample of the beach sediment population is assumed to behave identically to the background beach material. The methods of "marking" fall into three categories. Firstly there are radioactive tracers (Kidson et al., 1956; Kidson et al., 1958; Kidson and Carr, 1959; Crickmore and Lean, 1962; Bruun, 1962 etc.) where the received signal is proportional to tracer concentration. Radioactive tracers are rarely used now owing to numerous problems of safety during preparation and detection. Secondly, magnetic tracing has been attempted whereby the magnetism of natural beach material is artificially enhanced; detection involves the use of instruments similar to metal detectors. This technique is, however, in its infancy (Oldfield et al., 1981).

The most common tracer used now is beach material which is simply dyed or painted. Zenkovitch (1960), Jolliffe (1963), Newman (1964), Ingle (1966), Teleki (1966, 1967), Yasso (1966), Price (1968), Knoth and Nummedal (1978), Weatherill (1978) and Lees (1983) describe techniques for dying material, as well as methods of injection, sampling and data analysis. These experiments are easy and safe to carry out, and tracers have been used not only to investigate directions and rates of beach sediment transport but also to assess size and shape sorting (Caldwell, 1983).

Suspended sediment has been measured in the field using a variety of apparatus. Downing et al. (1981) and Brenninkmeyer (1976) described such instruments. More recently, suspended sediments have been estimated from remotely sensed imagery following calibration with field data (Curran et al., 1986). Such assessments of suspended sediment concentrations can be used to check the calibration of sediment budgets etc.

1.3 d CLIFF AND BACKBEACH EROSION

Compared with many topics in coastal geomorphology coastal erosion, including that of beaches and dunes as well as cliffs, has had widespread coverage, not only in the academic press but more generally. Quantitative treatment of the processes involved including modelling, has been carried out by Bruun (1954), Williams (1960), Komar (1976a), Sunamura (1977, 1981, 1982, 1983b) and many others. Other reports have been rather broad, covering large time scales (Kaufman and Pilkey, 1979), or even controversial (Pilkey et al., 1981; O'Brien, 1984). Some studies have concentrated on the engineering aspects of the problem and methods of protection (Minikin, 1952; HMSO, 1960; Willis and Price, 1975; Cambers et al., 1978, Clayton, 1980; U.S. Corps Engineers, 1981; Dean, 1983; Moore and Moore, 1983). Other publications have provided inventories of retreat rates for eroding areas (Poulson, 1840; HMSO, 1907, 1911; Bird and May, 1976; Bryan and Price, 1980; Dolan et al., 1983; Sunamura, 1983b).

Dossor (1955) and Sunamura (1983b) considered the mechanisms of cliff retreat and collapse whereby undermining proceeds until a slope fails. The mechanisms of unconsolidated cliff erosion were studied by Cambers (1973) and Bryan and Price (1980), who considered various forms of mass movement to be responsible, viz. landslides, water erosion, mudflows and wind erosion. Numerous studies on the Holderness coast have considered the retreat of glacial till cliffs (Thompson, 1923; Steers, 1948; Dossor, 1955; Phillips, 1962, 1963, 1964; Pringle, 1981, 1984, 1985; Valentin, 1971; Catt and Madgett, 1981; De Boer, 1972); these will be described in greater detail later.

Many models have thus been produced to predict and describe erosion but few studies explain how to prevent it! Williams (1960) listed the most common structures used to protect the coast; seawalls, revetments, groynes, breakwaters and jetties. Reports of the effectiveness and design of various defences are common in engineering literature (Silvester, 1959; Kemp, 1962; CERC, 1975). Unfortunately some erosion has started or has been exacerbated as a result of measures taken to protect beaches, and man's wider use of the coast has enhanced erosion (Komar, 1983b, 1983c).

A major problem has been balancing the need to defend a coast against the costs which would be incurred in doing so; would the capital invested be justified by the value of the land saved, or the money raised by having a full beach available for recreation? Valentin (1971) worked out that in 1957 for protection of the Holderness coast to be economical it would have to be effective for 10000 years!

Finally, there is the argument that in some areas erosion should be allowed to proceed unimpeded, at the same time providing a large scale sediment movement experiment. This point of view is often unpopular, particularly with the residents of the area, but it has become one of the criteria used by the Nature Conservancy Council to oppose engineering schemes on the coast (Carr, 1983).

1.3 e SEDIMENT BUDGETS

Many coastal studies have used the concept of "sediment budget". The amount of material leaving a coastal area, either directly off-shore or downdrift,is compared with the "sources", thus yielding the theoretical change in volume of the beach. This derived sediment budget is simply a way of describing the beach sediment system in terms of the possible sediment sources and sinks.
Komar (1976a) listed the elements of a sediment budget as:
Sources: estuaries, rivers, streams, cliff or dune erosion, wind transport, longshore drift of material, onshore drift of material and minor sources (biogenous deposition, hydrogenous deposition, artificial

beach nourishment, mining of beach sediments, solution and abrasion of the beach platform).

Sinks: longshore sediment drift out of beach section, offshore sediment movement into the nearshore and submarine canyons.

The balance between the material supplied by the sources and that lost through sinks constitutes the net sediment budget, and indicates the net erosion or deposition which will take place.

Shuisky and Schwartz (1983) presented the gains and losses in a simple expression:

$$\underbrace{A + d + Q + Q_t + E_a + K_{g'} + I}_{\text{sources}} \quad \text{v.} \quad \underbrace{0_s + 0_{ds} + E_a{}^1 + K_{gl}{}^1 + T_g + T_t + K_{red}}_{\text{sinks}} \qquad (1.9)$$

$$\Delta Q = \Sigma(\text{sources}) - \Sigma\ (\text{sinks})$$

when ΔQ = + ve; net sediment gain i.e. deposition

when ΔQ = - ve; net sediment loss i.e. erosion

Sources
- A - sediment eroded from cliff
- Q - fluvial sediment volume
- E_a - Aeolian material
- I - Volcanic contribution
- d - sediment eroded from platforms
- Q_t - biogenous material
- K_{gl} - sediment ice rafted into glaciers

Sinks
- 0_s - sediment deposited in formation of coastal features
- 0_{ds} - suspended sediment material carried out of area by currents
- $E_a{}^1$ - Aeolian transport away from the shore
- $K_{gl}{}^1$ - ice rafting away from the shore
- T_g - sediment loss to submarine canyons
- T_t - sediment removal via tidal currents
- K_{red} - loss due to disintegration by abrasion

The expression will be slightly different depending on local conditions.

Many practical studies of beach changes have involved surveying profiles over a period of time (Phillips, 1962, 1963, 1964; Craig-Smith, 1973; Scott, 1976; Williams, 1979; Davidson-Arnott and Pember, 1980). The differences in beach volume can be calculated from this, but not the absolute rates or direction of sediment transport.

Numerous studies have evaluated the elements of a sediment budget, usually in order to estimate beach changes, erosion or deposition, depletion or accretion and retreat or advance of the shoreline. These have included work by Davies (1974), Komar (1976a, 1983a, 1983b), Jarrett (1977), Sunamura and Horikawa (1977), Kureth (1978), Allen (1980), Shuisky and Schwartz (1983) and Dally and Dean (1984).

1.3 f SUMMARY

The above is a brief and selective review of the coastal geomorphology literature, particuarly that concerning sediment movement. It illustrates the scope of previous work and forms the background for new work.

It is apparent, however, that many individual studies reported in the literature have been rather specialised and of limited scope; they have tended to concentrate on one particular element of the coastal system and often on only one technique within a field. Though these are interesting it is when their findings are used in part of a wider study that their true value is realised. Relatively few workers have conducted experiments to investigate the processes, and interactions of processes, at work in the whole of the coastal system; many have concentrated their efforts on the beach, often producing values for longshore sediment movement in various locations and relating this to beach change. Though this has been done repeatedly, the changes among specific beach types have not been investigated rigorously or quantitatively; references are merely made to increases or decreases in beach volume. Sometimes actual values for changes in volume are mentioned but rarely are patterns of profile shape changes presented.

This literature review reveals that most studies have investigated beach behaviour under unusual conditions, e.g. beach profile changes during storms; comparatively few have included the periods of less dramatic conditions which prevail for much of the time. Beach evolution throughout the entire year is not generally considered.

A review of the available literature reveals that many studies are based on limited data. Often offshore data are collected in areas remote from the study site, and do not coincide with the study period. Frequently surrogate variables have been used, e.g. wind data to represent wave conditions, and some of the basic coastal theory describing wave energies and sediment movement includes assumptions which inevitably mean that they give only an approximate representation of reality.

In conclusion, coastal geomorphology as a whole would benefit from further investigation to reduce the many assumptions in certain theories, as well as from more comprehensive studies of the coastal system, both in terms of the area and time periods covered, and the use of better, more realistic data.

1.4 INTRODUCTION AND BACKGROUND TO THE HOLDERNESS COAST

Before describing the work carried out in this study it is essential to describe the Holderness coast in general, and the area chosen for fieldwork in particular. Following this is a more detailed section reviewing the erosion of the Holderness Coast, the subject which until recently was the sole preoccupation of many writers, and which still gives great cause for concern.

The Holderness coast provided a suitable site for studying beach processes because it is dynamic, and significant changes, including cliff erosion, can be measured within the duration of a typical research project. There was scope for obtaining good quality data from offshore, the beach and the cliff. Archive material existed allowing long term estimates of sediment supply from the cliff to be made, and it is easy to identify the various sources and sinks of beach material. On the coast as a whole man's intervention has been limited and many stretches reflect only natural processes. Variations in beach morphology and processes enabled inter-relationships in the coastal system to be investigated, and the slightly sheltered nature of the coast meant that although a wide range of offshore and beach contions exists, fieldwork was relatively easy and recording equipment functioned well.

1.4 a DESCRIPTION OF SITE

Before concentrating on the Holderness coast, its wider setting will be described briefly (Figure 1.1). The East Riding of Yorkshire (now included in North Humberside) approximately represents the northern end of the cretaceous lands of the English Plain (Brown, 1943). The Yorkshire wolds (hard chalk beds) extend in a crescentic curve from the Humber to the sea, rising to 244 m a.s.l. in places and ending in the white cliffs of Flamborough Head. To the north, the wolds slope steeply to the deposits of the old lake floor of the Vale of Pickering; to the west a narrow belt of Lias and Oolite limestone prolongs the slope of the wolds to the Triassic plains of the Vale of York. To the S.E. the wolds slope gently down to the plain of Holderness, a monotonous plain relieved by small hummocks and covering about 65 000 ha (Brown, 1943). Its chalk floor is covered with glacial material which is partly overlain by lacustrine and alluvial deposits. These glacial deposits form a low, virtually continuous line of cliffs averaging 14 m in height. In pre-glacial times an old sea extended to the foot of the wolds from Flamborough Head to Hessle leaving Holderness below sea level. The buried cliff can be seen running from Sewerby by way of Driffield, Beverley and Cottingham to Hessle (Catt and Penny, 1966).

Glacial deposits older than the last (Ipswichian) interglacial are widespread but the ages of various deposits are disputed. Since the last interglacial two distinct tills have been deposited, Skipsea Till formed mainly from the North Sea ice which was moving from East to West (indicated by preferred stone orientation), and Withernsea Till (or Purple Till) containing red Triassic material from the middle Tees valley. When ice in the Vale of York, Holderness and Lincolnshire Marsh melted it left a series of morainic ridges approximately parallel to the ice front, kettle holes and sinuous eskers. During the Holocene some glacial hollows filled with water as sea level rose; Hornsea Mere is an example of one which has remained filled. Others, e.g. Skipsea Whittow, dried up during the Flandrian, and this relict mere, now

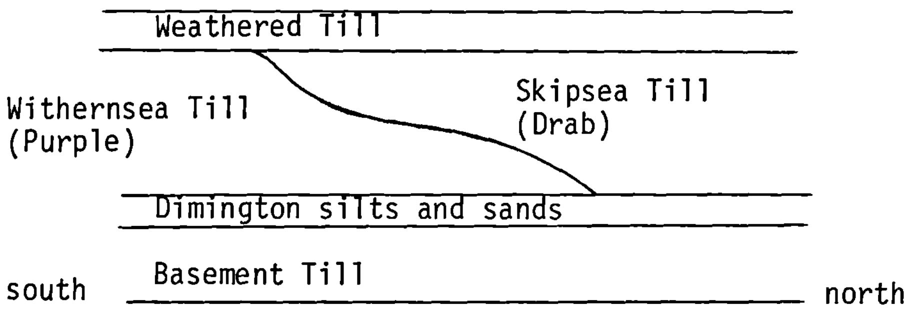
Plate 1.1 Skipsea Whittow.

Plate 1.2 Coastal Erosion Near Ulrome.

cut across by the cliff line (Plate 1.1) is rapidly disappearing. The cross-section is very impressive with large tree trunks and beech mast exposed in a peaty matrix overlying varied lacustrine clays.

The succession of the till cliff sections on the Holderness coast is seen in the sketch (Figure 1.2).

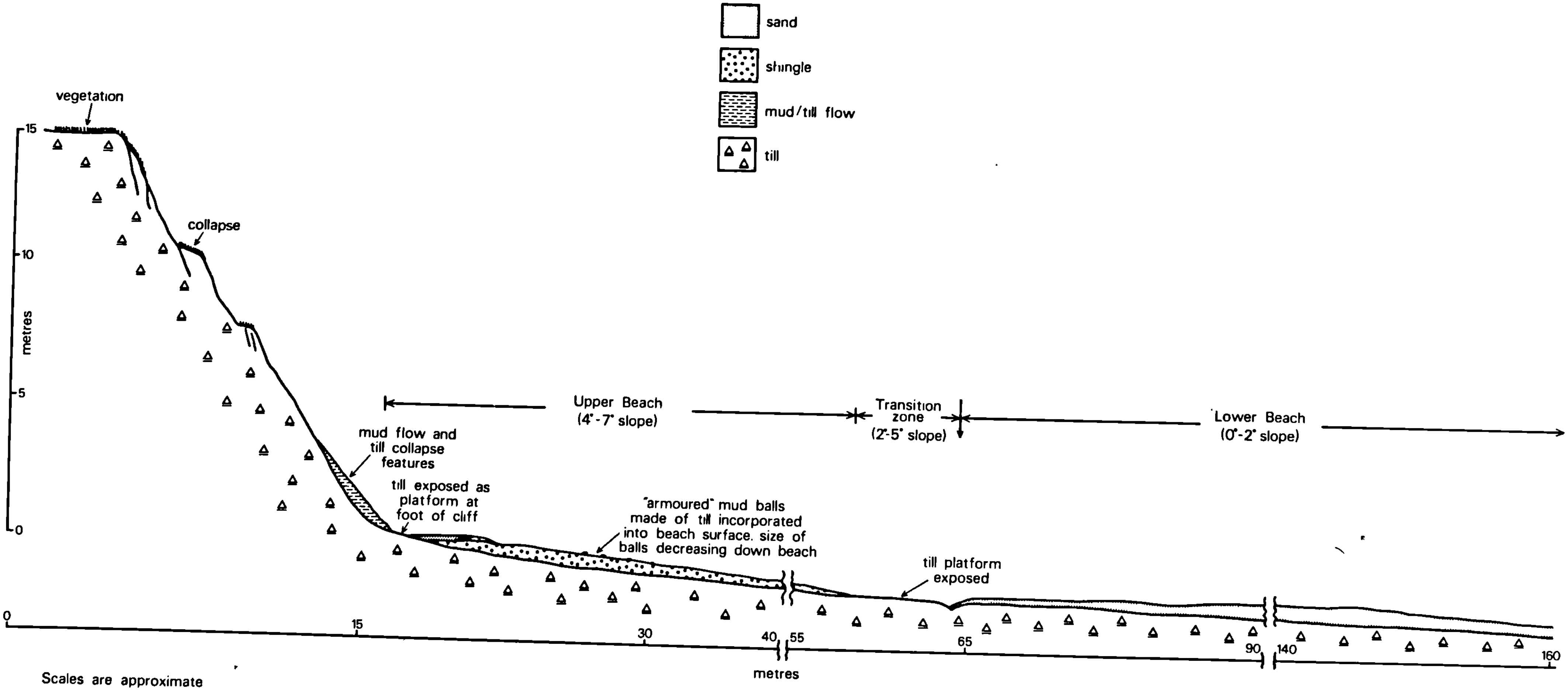
Figure 1.2 Till Succession on the Holderness Coast



A sandy beach now runs the whole length of the coast but its form changes alongshore (Pringle, 1981). In Bridlington Bay it is over 300 m wide at mean low water, and has a gentle overall gradient of about 1.5^{o}, and a well-developed ridge and runnel system. The beach is almost entirely sand and shell fragments. From Barmston to Spurn Head the beach is reported to have a characteristic form. In cross-section it can be divided into two parts, the upper part of which is composed of coarse sand and shingle. The water table intersects the beach towards the base of the upper beach, and above the lower beach which has a lower gradient and is of fine and medium sand (Phillips, 1962, 1964).

The stretch of coast on which field work was carried out in the present study is about 4 km long between Skipsea and Atwick

Figure 1.3 Stylised Section Through Cliff and Beach on the Holderness Coast.



sand
shingle
mud/till flow
till
vegetation
collapse
15
10
5
0
metres
mud flow and
till collapse
features
till exposed as
platform at
foot of cliff
Upper Beach
(4°-7° slope)
Transition
zone
(2°-5° slope)
Lower Beach
(0°-2° slope)
"armoured" mud balls
made of till incorporated
into beach surface. size of
balls decreasing down beach
till platform
exposed
0
15
30
40
55
65
90
140
160
metres
Scales are approximate

(Figure 1.1). The soft glacial till cliffs here range from 5 m to 20 m high and it appears that losses have averaged 1.5-2.0 m a year, though clearly in many places catastrophic cliff falls over 5 m wide have occurred.

The beach has some areas of shingle and prominent cusps, and exhibits a coarser seasonal beach crest. The upper beach slopes at about 4^{0} to 7^{0} and comprises a few millimetres of sand on coarser sand and shingle with a mean particle size of 2.6 mm This in turn lies on the till platform (Figure 1.3), which is periodically exposed to a varying extent alongshore. The gentler lower beach sloping at 0^{0}-2^{0} is of finer material (mean particle size of 0.26 mm). The beach is very dynamic and shows considerable variation in form throughout the year.

The prevailing winds are south-westerlies and the predominant direction of wave approach is from the E and, especially in winter, the NE; at Hornsea the respective fetches for the directions NE, E and SE are approximately 900 km , 450 km and 120 km. Thus potentially the greatest storm waves can build up from the NE. The tidal range in the area is 5.0 m at springs and 2.4 m at neaps. Table 1.1 shows the range of tide levels.

Table 1.1 Heights of Tides Source: HMSO 1982

MHWS	- 6.1 m	range:	5.6 - 6.6 m
MHWN	- 4.7 m	range:	4.4 - 5.0 m
MLWN	- 2.3 m	range:	1.2 - 2.7 m
MLWS	- 1.1 m	range:	0.4 - 1.7 m

At spring tides the cliff foot is washed regularly, even under low wave conditions.

The field site had to have easy access to both the cliff edge and the beach. Between Skipsea and Atwick it is easy to scramble up or down the cliff in a couple of places where tracks reach the cliff edge, and near the middle of this study area there is a steep boat ramp from the cliff top to the beach.

As the references in this section have indicated some work has been carried out on this coast in the past, indeed the cliff erosion has been reported for many centuries. The following section reviews this previous work, providing background information for the present study.

1.4 b COASTAL EROSION AND CLIFF RETREAT ON THE HOLDERNESS COAST

The land loss resulting from erosion of the soft Holderness cliffs has given cause for concern for hundreds of years. Sheppard (1912) estimated that a strip of land three miles wide has been removed since Roman times; he also published a map showing this reconstructed coast (Figure 1.4), though his figures have been disputed by Valentin (1971). A variety of rates for average retreat have been cited (Table 1.2) from 0.8 to 3.0 m per year depending upon location; however, observations of a single episode of erosion removing over 10 m have been made. The land loss is therefore extremely variable. The rapid retreat of the coast as a whole has had implications for the evolution of Spurn Head, which has completely reformed at least three times in the past 600 years (De Boer, 1964). The resulting coastline provides dramatic pictures of buildings perched perilously on the cliff edge, and of large cracks in the cliff top where material is starting to break away (Plates 1.2 and 1.3).

The rest of this section will review the accounts of erosion which already exist. In later sections, in Chapter 3, cliff-retreat rates obtained in the current study will be presented and a mean

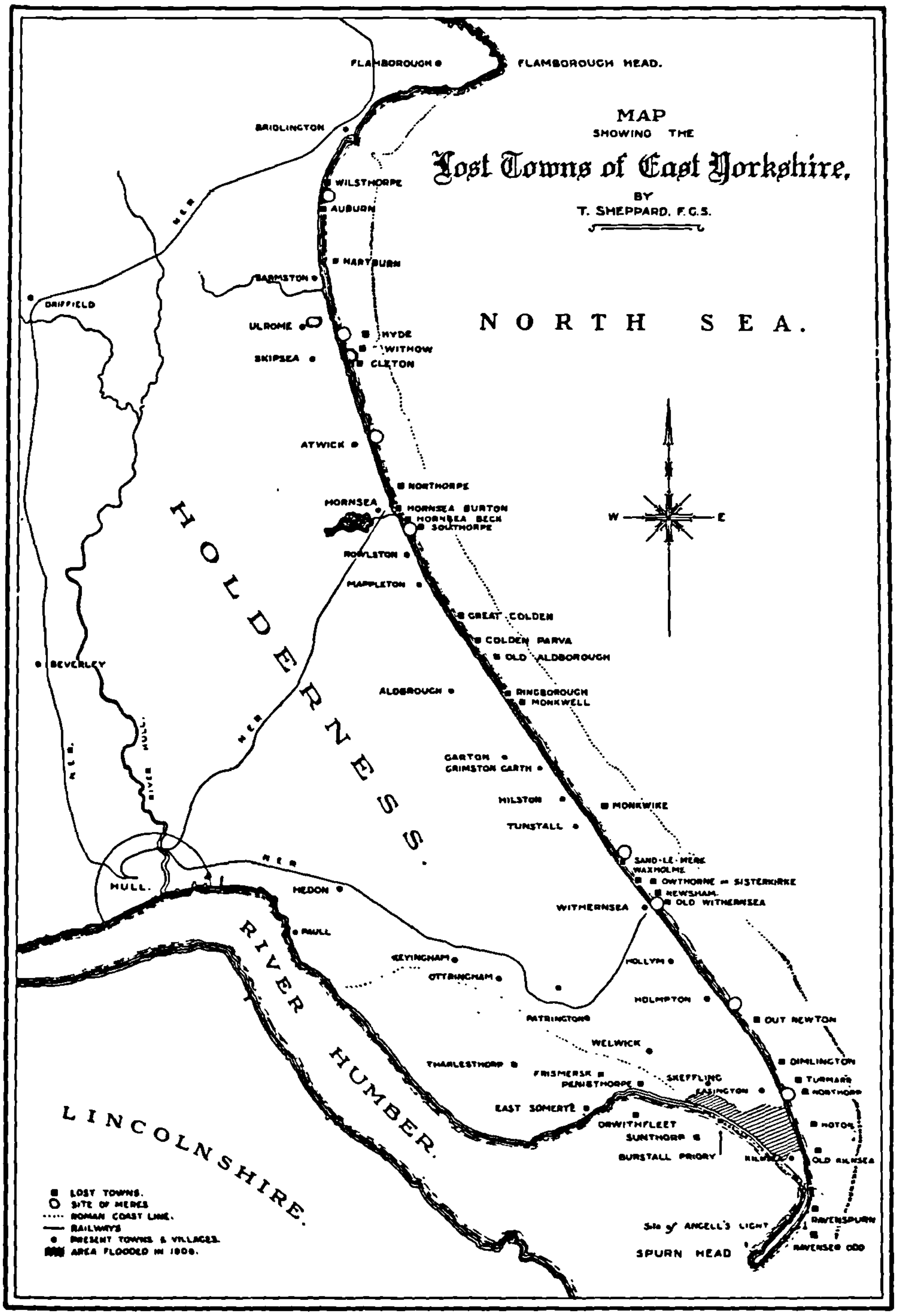

MAP
SHOWING THE
Lost Towns of East Yorkshire,
BY
T. SHEPPARD, F.G.S.
NORTH SEA.
HOLDERNESS.
RIVER HUMBER.
LINCOLNSHIRE.
FLAMBOROUGH
FLAMBOROUGH HEAD.
BRIDLINGTON
WILSTHORPE
AUBURN
HARTBURN
BARMSTON
DRIFFIELD
ULROME
HYDE
WITHOW
SKIPSEA
CLETON
ATWICK
NORTHORPE
HORNSEA
HORNSEA BURTON
HORNSEA BECK
SOUTHORPE
W
E
ROWLSTON
MAPPLETON
GREAT COLDEN
COLDEN PARVA
OLD ALDBOROUGH
BEVERLEY
ALDBROUGH
RINGBOROUGH
MONKWELL
GARTON
GRIMSTON GARTH
HILSTON
MONKWIKE
TUNSTALL
SAND-LE-MERE
WAXHOLME
OWTHORNE or SISTERKIRKE
NEWSHAM
OLD WITHERNSEA
WITHERNSEA
RIVER HULL
N.E.R.
HULL.
HEDON
PAULL
KEYINGHAM
OTTRINGHAM
HOLLYM
HOLMPTON
OUT NEWTON
PATRINGTON
WELWICK
DIMLINGTON
THARLESTHORP
FRISMERSK
PENISTHORPE
SKEFFLING
EASINGTON
TURMARR
NORTHORP
EAST SOMERTE
ORWITHFLEET
SUNTHORP
HOTON
BURSTALL PRIORY
KILNSEA
OLD KILNSEA
Site of ANGELL'S LIGHT
SPURN HEAD
RAVENSPURN
RAVENSER ODD
LOST TOWNS.
SITE OF MERES
ROMAN COAST LINE.
RAILWAYS
PRESENT TOWNS & VILLAGES.
AREA FLOODED IN 1906.

Table 1.2

Rates of Erosion on the Holderness Coast

Rate Quoted	Location	Source
1m/yr-2.75m/yr	Bridlington to Kilnsea	De Boer (1964)
6ft/yr (≑ 1.8m/yr)	Bridlington to Kilnsea	Phillips (1964)
1.2m/yr	Average rate for coast	Phillips (1966)
1.5m/yr	Near Hornsea	Valentin (1971)
1.4-1.68m/yr	South of Hornsea	Valentin (1971)
2.12m/yr	Withernsea	Valentin (1971)
1.2m/yr	Average	Valentin (1971)
2.75m/yr	Southern end of coast	De Boer (1964)
0.8-1.0m/yr	Barmston	De Boer (1972)
5ft10in/yr (= 1.78m/yr)	Average	Sheppard (1912)
6ft/yr (= 1.8m/yr)	Average	Thomson (1923)
3.14-4.37 ft/yr (= 0.96-1.33m/yr)	Skipsea to Hornsea	Thomson (1923)
3yd/yr (= 2.74m/yr)	Bridlington-Barmston	HMSO (1907)
1½-4yd/yr (= 1.37-3.66m/yr)	Barmston-Ulrome	HMSO (1907)
2yd/yr (= 1.8m/yr)	Ulrome-Skipsea	HMSO (1907)
2yd/yr (= 1.8m/yr)	Skipsea-Skirlington	HMSO (1907)
2½-3yd/yr (= 2.3-2.7m/yr)	Skirlington-Atwick	HMSO (1907)

Plate 1.3 Till Cliff Cracking.

Plate 1.4 Cliff Collapse.

value produced, allowing the volume of material supplied to the beach to be calculated.

The earliest accounts of erosion on Holderness (Poulson, 1840; Sheppard, 1912) and later works on early erosion (Allison, 1984; Thomson, 1923) are almost entirely concerned with describing the land and property losses incurred, and occasionally give retreat rates: these values seem to have been recorded most frequently by local clergymen. The concern expressed for this and other coasts was reflected in the setting up of a Royal Commission in 1906 to investigate the problem. Interest was sustained with the publication of Thomson's article in 1923. Since the second world war further work has been carried out on the coast, and in contrast has concentrated less on mere description. Repeated measurements were still taken from old maps and in the field but attention was paid increasingly to the processes involved.

Research is still proceeding on this coast, and the local newspapers report the efforts being made to enter a third phase, i.e. preventing or substantially reducing the erosion.

Early Reports

Local concern and agitation over land loss by coastal erosion is by no means new. In 1797, for example, the township of Withernsea (the buildings of which have now disappeared) contained 811 acres (328 ha), but by 1852 this had been reduced to 746 acres (302 ha) (Allison, 1984); in the late eighteenth century nothing but a few houses along the cliff remained of Medieval Withernsea. Near Easington at least, in the 1770s property owners were liable to maintain their own "protective works".

Further north erosion is reported by Poulson (1840). Of Atwick he says:

"(a) village situated immediately contiguous to the German Ocean suffers greatly from its encroachments".

Barmston, according to its vicar, was suffering erosion of 1½ yards (1.37 m) a year at around this time. Earlier still at an

"Inquisition taken at Hedon on 10 January 1400 ... the Abbot and convent of Meaux, having sustained great losses, ... by the inroads of the ocean, represented their case to the King and Parliament petitioning for a reasonable deduction in their assessments" (Allison, 1984).

In 1609 there was a similar "inquisition" at Hornsea where 38 houses and 80 yards (73.15 m) of land had been lost in 50 years. Sheppard (1912) calculated that over 2500 acres (9112 ha) would have been lost from Holderness since 1086, representing an area of 83 $miles^2$ (215 km^2). He traced the depopulation and eventual destruction of many villages (Figure 1.4), while noting that other settlements had moved steadily westward, the original sites now being well out to sea.

In the second half of the nineteenth century erosion was dramatically reduced at a number of places along the coast, e.g. Bridlington, Hornsea, Withernsea and Aldbrough, following the construction of sea defences, usually a sea wall and a series of groynes.

The Royal Commission of 1906

The setting up of the Royal Commission on Coast Erosion in 1906 was a significant point in the history of erosion in Britain. It not only recognised and sought to describe the rates and distribution of erosion, but inquired into its causes, and into methods and costs of reducing its effects. It should be noted that, as well as investigating erosion, its remit included a consideration of the reclamation of tidal lands, and was later extended to cover afforestation.

Originally the work of the commission fell into four sections. It was to "Inquire and Report:

1. As to the encoachment of the sea on various parts of the coast of the United Kingdom, and the damage which has been, or is likely to be, caused thereby; and what measures are desirable for the prevention of such damage.
2. Whether any further powers should be conferred upon local authorities and owners of property with a view to the adoption of effective and systematic schemes for the protection of the coast, and the banks of the tidal rivers.
3. Whether any alteration of the law is desirable as regards the management and control of the foreshore.
4. Whether further facilities should be given for the reclamation of tidal lands".

Three volumes of evidence and reports were published from 1907 to 1911 (MHSO, 1907, 1909, 1911). The first (1907) report which contained evidence concerning England and Wales also dealt with ownership of, and responsibility for, the shore. Areas recognised as suffering particuarly included Yorkshire (Bridlington to Kilnsea), Norfolk, Suffolk, Essex, Kent and Sussex. The causes of erosion were also examined, and the costs and effectiveness of various protection schemes, including the additional rates which were levied to finance them, were considered. Much information was gleaned from replies to letters the commission sent to councils of all coastal counties in England and Wales, which listed the "information desired"; this included sites of erosion, measurements, opinions as to the cause of erosion and works undertaken etc. The second report

(1909) dealt mainly with afforestation. Volume III, the final report, included the evidence concerning Scotland, as well as sections on the sources of beach material and a summary of the amount of land lost in various places.

The commissioners concluded that whilst most erosion occurred on the open coast, accretion tended to occur in sheltered estuarine environments, and that the removal of shingle etc.in the past had aggravated erosion: in fact more land had been gained by accretion than had been lost by erosion. They recommended a change in administration to reduce the difficulties which were experienced when shore protection work was undertaken. Care must be taken to construct schemes suitable for each individual area, with expert scientific and engineering advice being sought.

The commissioners' summing up is interesting; they saw no case for making grants from public funds in aid of sea defence. They went further:

"We cannot see that there is any ground for the contention that sea defence is a national service; it is true that there is serious erosion in places but this erosion does not effect the nation at large".

The Royal Commission in at least recognising the problem of coastal erosion on behalf of the government, and in making an attempt to discover its causes, paved the way for further "process" work on the Holderness, and other similar, coasts. Most of the Holderness work was concentrated on the area south of Hornsea, especially on Spurn Head at the southern end.

Recent Research

To establish retreat rates previous studies have used old maps; some of the reported values are included in Table 1.2.

According to Valentin (1971) more than 1000000m^3 of cliff material is lost each year, a mass of over 210 x 10^6 tonnes during the past century. The general retreat is often composed of a number of small "jumps"; the cliff loses a metre or so every few months, or even ten metres or more once in four or five years, rather than steadily retreating a few centimetres a month.

Various studies have suggested causes for cliff erosion and factors which influence it; some of these are mentioned below, along with observations made in the field. Cambers (1973) gives the actual mechanisms of erosion as landslides, water erosion, mudflows and wind erosion. The relative importance of these actually depends on the following factors:

1. Beach Level - Where the beach is "combed down", often during periods of stormy weather, the cliffs are less well protected and waves may wash against them for longer, removing material from the base of the cliff: this undermining proceeds until the till above collapses onto the beach (plate 1.4). At severely depleted sections of beach, some of which form "ords" (Pringle, 1981, 1984, 1985), even during neap tides the cliff may be exposed to wave attack and thus erode more rapidly than the stretches on either side. According to Pringle (1985) a migrating ord (exposed till platform) may take three years to pass a certain point on the cliff, meanwhile allowing enhanced erosion to occur.
2. Tide and wave conditions - Whether the sea can reach the cliffs depends on a combination of beach level and water level. Normally on Holderness when the beach is full the cliff is only attacked directly by waves at high water on Spring tides, but on lower stretches it may be liable to attack

on all high tides. During periods of low atmospheric pressure and storm surges the general water level will rise and the duration of wave attack on the cliff will be greater. During high energy wave conditions water may crash against the cliff over halfway up, often hurling shingle against the till to leave a pitted surface. Portions of the cliff may be washed away completely. The protection afforded to a section of coast will also influence the wave conditions.

Changes in sea level not associated with the tide have been put forward by Valentin (1971) to explain variations in retreat over a period of about 100 years; however, the south of Holderness is sinking at 15 mm per 100 years relative to the north (Valentin, 1971), so the effects in the past 100 to 400 years have been small.

3. Geology - On Holderness the clayey cliff material can often liquefy if it is subjected to high rain fall or field drain effluent, and may flow down the cliff and out onto the beach. At Barmston bungalows had been built on a lens of silts in a till hollow which ran parallel to the coast (De Boer, 1972). After becoming thinner and thinner the outer limb of till was breached and the silt flowed onto the beach taking the bungalows with it!

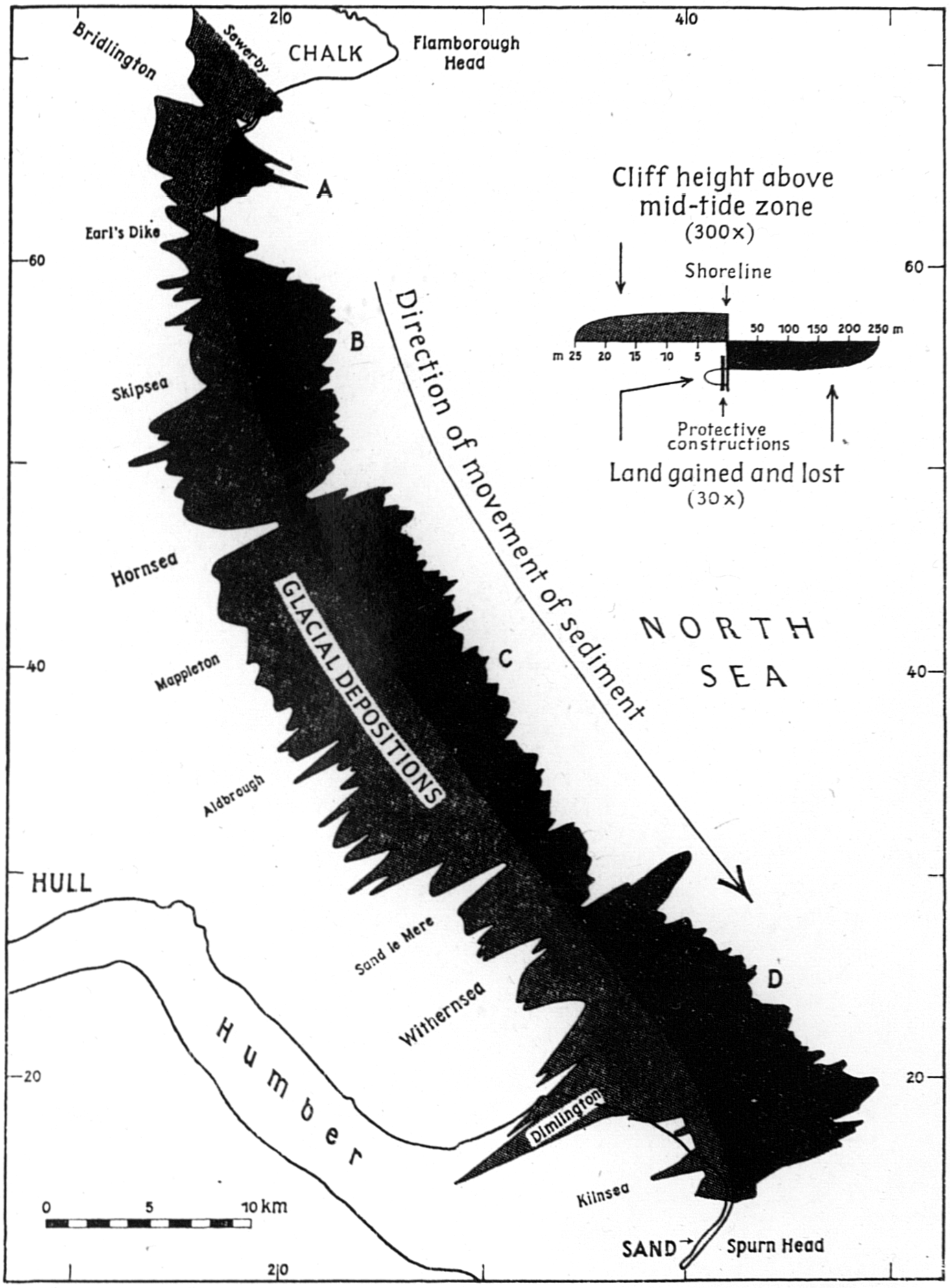
The strength of the till, its resistance to wave action and mudflow formation will depend upon its sand-silt-clay composition, and its internal physical properties. Sunamura (1982) produced a predictive model for wave-induced cliff erosion which took into account the mechanical strength of the cliff material, related to its lithology, jointing, faulting and stratification, as well as the strength of the wave attack.

4. Cliff Height - Valentin (1971) found that the rate of erosion of cliffs decreased with an increase in their height, but pointed out that differences may be a result of varying degrees of exposure to attack. His evidence, in the form of Figure 1.5, would not, except at a few locations, seem to bear this out.

5. Cliff Moisture Content - During very wet periods mudflows can form which transfer material very rapidly onto the beach. Water in the cliff may also serve to lubricate cracks, shear planes or bedding planes which are already present.

During the period of the present research the influence of many of the factors mentioned above was observed in the field. The effect of moisture on the cliff is particularly important, especially the pattern of periods of wet and dry weather. A prolonged dry spell followed by heavy rain can produce quite dramatic losses of cliff material, just as large as any produced by high energy wave attack during winter storms. The effects of desiccation were observed during the very dry summer of 1984 when the till dried out forming cracks which became enlarged. In time, no doubt, the seaward portions would have collapsed onto the beach. However, heavy rain entered the cracks, washed supporting material away and as a result sections of cliff up to 8 m wide were removed within a very short space of time. In winter freezing of interstitial water may loosen the surface layers of sediment on the cliff; these particles may, on thawing, cascade onto the beach. Frost action may also enlarge bigger cracks which have become filled with water. The influence of moisture was observed again at many field junctions where drains or ditches reached the cliff edge. The till is removed very rapidly causing large indentations landward (Plate 1.5).

Figure 1.5 Cliff Height and Coastal Retreat on the Holderness Coast, 1850-1950. From Valentin (1971)



Bridlington
Sewerby
CHALK
Flamborough Head
A
Earl's Dike
B
Skipsea
Hornsea
GLACIAL DEPOSITIONS
Mappleton
Aldbrough
C
Direction of movement of sediment
NORTH SEA
HULL
Sand le Mere
Withernsea
D
Humber
Dimlington
Kilnsea
SAND
Spurn Head
0 5 10 km
Cliff height above mid-tide zone
(300x)
Shoreline
m 25 20 15 10 5
50 100 150 200 250 m
Protective constructions
Land gained and lost
(30x)
20
40
60

In the past consideration has also been given to the costs of various erosion prevention schemes. It would be extremely costly to fill in the gaps between existing protected stretches, always assuming that this was deemed necessary or desirable in the first place. In 1950 the cost of achieving protection of the entire Holderness coast would have been £10.6 M, whilst the value of land lost each year was only £1040 (Valentin, 1971). The probable cost of protecting the coast now would be £150 M to £200 M, or even more. Over the years there have been some rather alarmist predictions, such as Hornsea and Skipsea becoming peninsula towns.

Despite the huge expense involved, a large number of local people believe that something should be done about the problem. The local press (The Bridlington Free Press) periodically produces features on the problems of erosion along the coast, usually in winter when some new collapse or land loss has occurred. More frequently, it reports the latest committee meetings on Coastal Erosion and on the fate of various applications for financial help. In December 1946 the Press reported that the matter of erosion was to be raised in parliament, and in February of the following year that the government had agreed to give assistance to local authorities. By 1969 there were calls for a Coastal Protection Order along the whole coast with various schemes being suggested, ranging from the usual sea walls to the more unorthodox idea of introducing artificial seaweed offshore. In the early 1970s it was realised that there was an urgent need for research; at the same time all the coastal parishes joined forces to fight erosion, and some individuals put forward their own schemes.

In 1978 a Coastal Action Group sent out a questionnaire to investigate local views on the subject, including what were felt to

Plate 1.5 Accelerated Erosion at Field Drain.

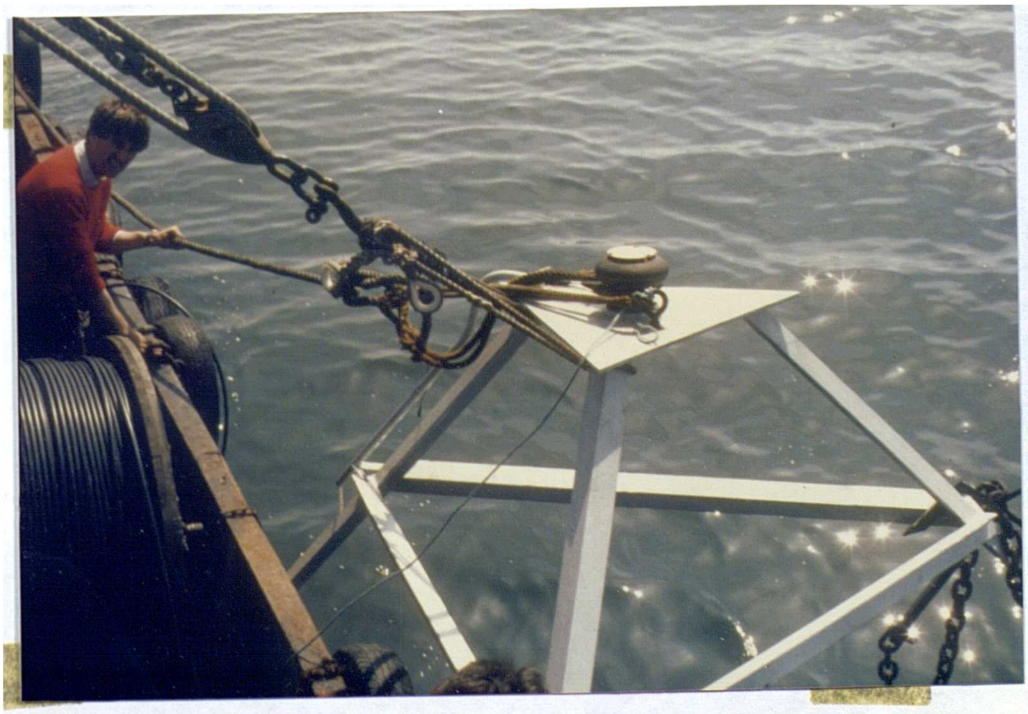


Plate 2.1 Installation of Wave Recorder.

be the main causes of erosion. Most people apparently regarded the coastline as a national asset, and felt that its defence must be paid for from national funds, in contrast to the findings of the Royal Commission in 1911. The most favoured types of defence were sea walls, groynes, cliff/land drainage, and revetments. Various petitions and appeals for money have been presented to the Westminster and European parliaments, usually in vain. In 1982 £5000 was given to Manchester University to carry out a study on the area, and in the same year the Humberside Joint Advisory Committee on Coastal Protection was formed, representing Humberside County Council and Holderness and East Yorkshire Borough Councils. It hoped to obtain money from the EEC to set up a large scale investigation into the problem and in 1984 produced a publicity brochure outlining the aims, which are to find cheaper methods of coastal protection and to coordinate various interested parties. The proposed project will cost around £750 000 and the Joint Advisory Committee, hoping that both the UK government and the EEC might be persuaded to make a contribution, believes that five pilot schemes could be tested and evaluated by 1991.

Research is still being carried out on the coast, based at Sheffield, Hull and Lancaster Universities, and local concern continues to run high.

1.5 OUTLINE OF THESIS

The results of the present research are presented in the five chapters of this thesis.

The introductory Chapter 1 sets out the aims of the research and explains the experimental design and procedure. It also includes a literature review which considers briefly a number of relevant topics, as well as drawing attention to areas of the available literature which will not be dealt with in great detail later. The topics covered are the general development of coastal geomorphology, work which has been carried out offshore, on beaches, and in connection with cliff erosion, and finally the concept of sediment budgets. A background to the field site follows the literature review - this covers the physiography and geomorphology of the area and includes a general description of the beach, as well as a fairly detailed account of publications about, and previous work carried out along, the coast.

After presenting a summary of the fieldwork timetable, Chapter 2 explains in detail the various field methods used. The field methods, in common with the contents of Chapters 3 and 4, and dealt with in three sections - those used in the offshore zone for the measurement of waves and currents, on the beach in surveying, tracer experiments and sediment work, and on the cliff, where archive and survey data were used to produce retreat rates and the sediment composition of the till was established.

The data analysis is described and the results presented in Chapter 3. Results from offshore include modelled sediment transport rates from wave data, and sediment movement by tidal currents. Analysis and results from the beach profile work include the determination of beach types, beach evolution, the preparation of probability matrices and testing for Markov properties among the beach transitions. Sediment properties and their variations are dealt with and results of tracer experiments presented. The rates of cliff retreat are reported and a final section describes the sediment budget, which incorporates results obtained from each of the coastal sub-systems.

Chapter 4 comprises an interpretation and discussion of results and the associated implications for the whole coastal system. Four main sections are presented dealing with offshore, beach, cliff and sediment budget work. Each section considers the results obtained on Holderness in the light of work carried out elsewhere, i.e. they are put into a world-wide perspective. The beach section is once again sub-divided to deal separately with profile evolution, sediment characteristics and sediment transport rates from tracer experiments. Chapter 5 presents the conclusions drawn from this research, tying together results from each sub-system and considering whether the initial hypotheses should be upheld or rejected. Ways in which the field methods and analysis could be improved are discussed, suggestions for further work made and an assessment of the general applicability of the techniques and models presented.

The appendices follow Chapter 5.

CHAPTER 2 METHODS

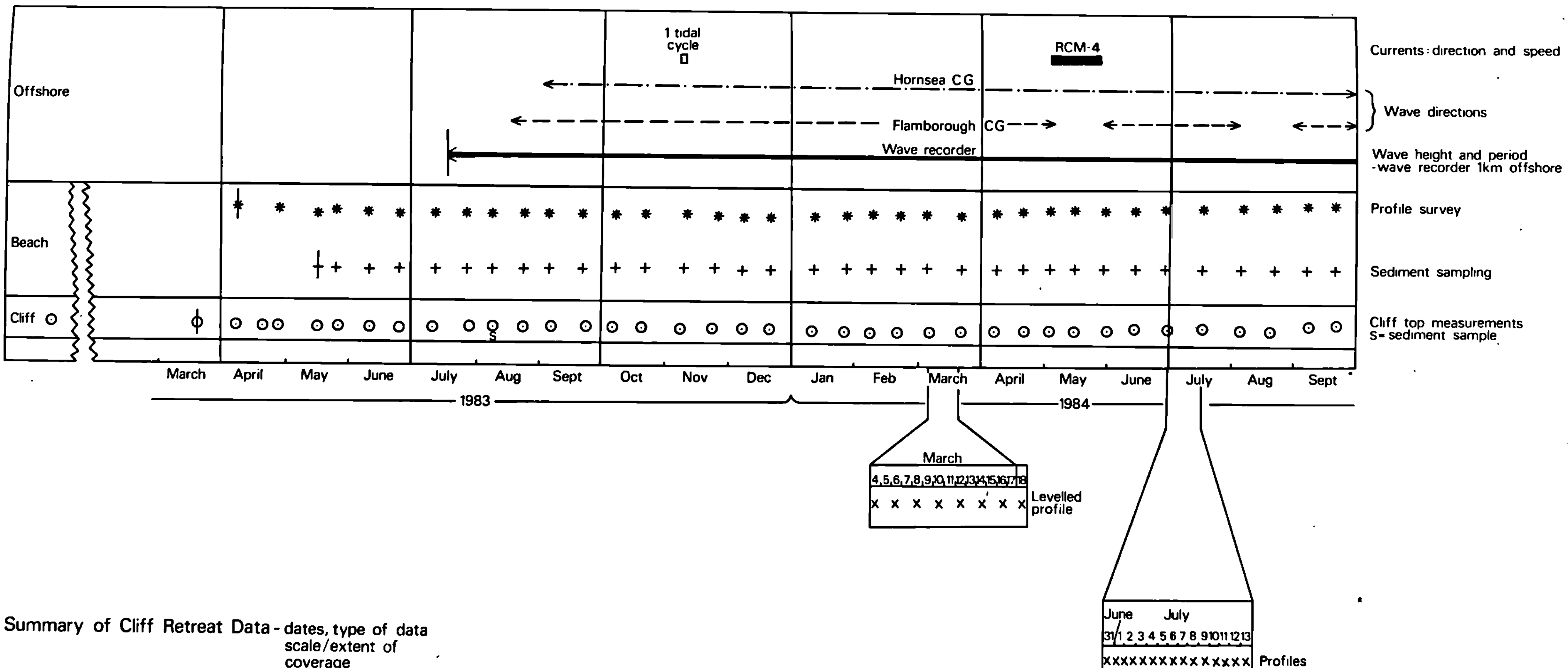
This chapter describes the field procedures and laboratory methods adopted in the current research. After presenting a field-work timetable, the methods will be described in three sections relating to work in the offshore zone, on the beach, and on the cliff.

2.1 TIMETABLE OF FIELD MEASUREMENTS (Figure 2.1)

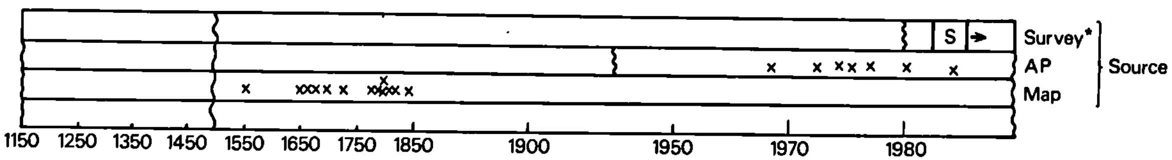
Preliminary reconaissance visits to the coast took place in October and December 1982 and determined a suitable location at which to carry out fieldwork where access to the cliff and beach was easy, where the beach surface was free from artificial structures or debris and where there was scope for identifying reference points. During the first three months of 1983 measurements were made and investigations carried out within the chosen field site to find suitable profile locations and cliff top temporary benchmarks on which to base the entire beach survey network. In March 1983 the chosen temporary bench marks were marked and surveyed into the Ordnance Survey grid - a triangulation point was chosen as one of the temporary benchmarks. On the first spring tide in April (6/4/83) the first of 55 beach surveys was carried out. Sediment samples were taken at the same time, and at each survey point the nature of the beach material noted; the final survey was on 26/9/84. During these 18 months two periods of more intensive surveying were undertaken. From 4/3/84 to 18/3/84 inclusive the beach profiles were levelled on alternate days and from 30/6/84 to 13/7/84 inclusive the beach profiles were surveyed every day. Other beach work included tracer experiments, also carried out during the first

Figure 2.1 Timetable of Field Measurements.

Summary of Field Data Collection



Summary of Cliff Retreat Data - dates, type of data scale/extent of coverage



* Fortnightly until Sept. 1984 then once every 2-3 months

two weeks of July 1984.

From July 1983, when a wave recorder was installed 1 km offshore from the field site, a continuous record of wave height and period taken for a 12 minute sample every three hours was available. To supplement these wave data, observers recorded the direction of wave approach either once or twice a day. The wave recorder was left in place but the observers were relieved of their duties in October 1984. A record of wind speed and direction is also available for the same period, measured less than 1 km inland from the field site.

A second set of offshore data comprised current measurements for two recording periods; the first on 5/11/83 was a pilot study conducted 500 m from the shore and lasted for not quite a full, tidal cycle. The second experiment,in May 1984, using a remote recording current meter installed 1 km offshore involved the measurement of direction and velocity for 25 days. Some limited suspended sediment data are available, recorded both in the field and from aerial photographs in June 1984.

Measurements of cliff retreat commenced in April 1983 and continued at fortnightly intervals until September 1984. Since then distances have been recorded every 2-3 months; altogether retreat data are available from maps and aerial photographs from 1557 onwards.

2.2 THE OFFSHORE ZONE

There are two main topics considered in the offshore sub-system; the first is the methods used for modelling potential sediment movement rates using measured wave data and a wave refraction computer program. The wave data were from two sources, published data from Dowsing light vessel and a record from a pressure transducer wave recorder (plate 2.1) installed 1 km offshore from the field site. The second involves an assessment of the effects of tidal currents.

2.2 a WAVE REFRACTION

In any study of coastal sediment movement and calculation of sediment budgets, it is essential to examine the distribution of wave energy alongshore, and hence the potential sediment movement which is possible. It is important to emphasise that such a value is a potential one either because of limited sediment availability or because it is too coarse to be moved.

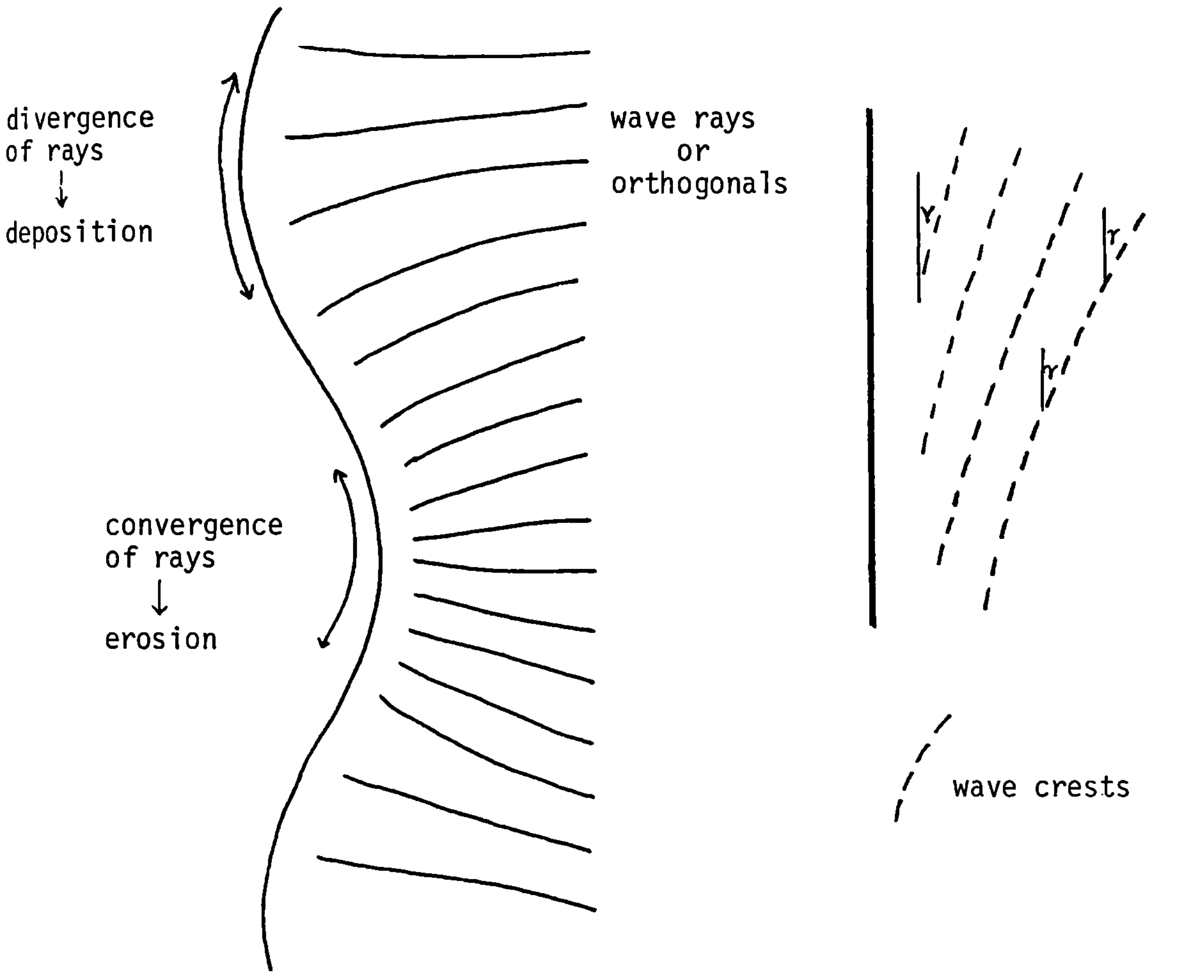
It is necessary to consider the alongshore distribution of wave energy. As waves approach the shore they encounter gradually decreasing water depths, slow down and undergo refraction. If waves approach the coast at an angle to the isobaths the wave crests bend to become more nearly parallel to the sea bed contours. Wave rays, or orthogonals, may be drawn perpendicular to the wave crests, and in perfect conditions the energy between adjacent wave rays is assumed to be constant. If the orthogonals converge towards the coast then there is a concentration of energy, higher potential sediment movement and erosion relative to neighbouring areas may proceed. If, however, orthogonals diverge, then energy is less concentrated, a reduced potential sediment movement is sustained and net deposition is possible (Figure 2.2).

Wave Refraction Calculation

Wave refraction patterns can be obtained in a number of ways - graphically, in a semi-computerised manner, and from a comprehensive computer program.

SHEFFIELD
UNIVERSITY
LIBRARY

Figure 2.2 Wave Refraction and its Effects.



divergence of rays ⟶ deposition

convergence of rays ⟶ erosion

γ decreases as the shore is approached

a. Graphical method. This involves drawing repeated refraction steps for a wave approaching the coast. Johnson et al. (1948) explained the principles involved in greater detail, gave the appropriate formulae for describing wave behaviour, and listed the assumptions involved. This very laborious procedure produces a diagram showing the pattern of wave crests, on which wave orthogonals can be drawn. It was considered that this method would be too time-consuming for the present study; superior methods exist which provide more useful information for the calculation of wave energy flux.

Wave refraction patterns can be extracted from aerial photographs provided that they have adequate overlap, and that the resolution is such that individual wave crests can be discerned. Though potentially quicker, this method could not be used in the present study; the aerial photographs available did not exist for different prevailing conditions, and the quality was poor.

b. Semi-computerised refraction. Harrison and Wilson (1964) developed a slightly more advanced method by integrating graphical techniques with some limited computer applications. Following the preparation of a depth grid and the selection of wave parameters, a series of computer programs is used to determine water depths, wave veolocities and ultimately ray curvature, for a sequence of points along a wave ray. This again is too slow a procedure, and the results have limited applications.

c. Computation of wave refraction. Several computer-programs are now available which perform all of the steps mentioned above, and indeed go on to calculate a number of useful parameters, including the wave energy flux alongshore. Such programs have been produced by Abernethy et al. (1977), who presented two programs, Dobson whose version was used by Armon and McCann (1977), FICO (1978) and Allen (1981).

The program chosen for use in this project was a slightly adapted version of WAVENRG (May 1974) which had been altered already by Orford (P. Comm.). This was most suited to the computer facilities available, though in practice it took some time and effort to get it working. The program determines the changes in wave characteristics as rays shoal across the sea bed and break. The basic "inputs" fall into two categories:

1. The bathymetry - this comprises a grid of (x,y) coordinates with a depth assigned to each one, derived from an Admiralty chart.
2. Wave characteristics - including deepwater wave height, period and direction of propagation, as well as the coordinates of the assumed starting points.

In the program wave direction and phase velocity are recomputed at short intervals along the ray. The wave height at breaking is a function of the wave power which remains after dissipation by shoaling, refraction and friction. The energy that is lost on breaking becomes available to do work on the bottom, moving sediment and generating heat.

A brief summary of some important elements of the program follows, whilst details of the input to, equations incorporated in, and output from, the program are in appendix 2.1.

<u>Elements of the program:</u> The original program (May 1974) was translated into Fortran 77, and a number of sub-routines altered to allow it to run in Sheffield. The main program explains various aspects of the procedure and goes on to read the data from a file; it then calls the first sub-routine, RAYN. RAYN calls the other sub-

routines which in turn determine the depth at a point of interest along the ray, the distance to the next point, the slope, the wave energy density and wave height etc. When the wave length to depth ratio indicates that the wave breaks, the routine is terminated and breaker line parameters calculated; the formulae used are given in appendix 2.1. Then a new wave ray is begun. Data are stored in two results files, one of which is a series of coordinates of points along the generated wave rays. To replace some sub-routines presented by May (1974), a new plotting program was created for drawing the shore line and the wave rays from the first results file.

The second results file comprises a repetition of the input data (valuable for checking and for presenting a comprehensive set of information) followed by a section which plots the iterative refraction of a wave ray along its route to the shore by presenting a list of variables. Details of the output variables are presented in appendix 2.1. For each ray a list of breaker parameters is presented, the most important of which are:

a. Total breaker power P_b

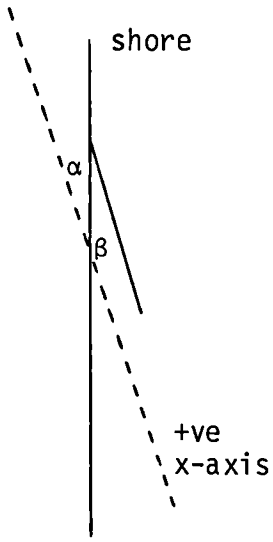
b. Effective shore-parallel component of breaker power P_l

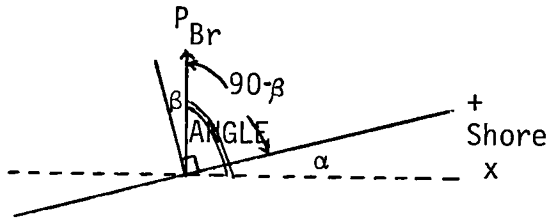
c. Mean longshore current velocity (Komar, 1971).

In this study a slight modification had to be made to all the results: the specifications for the program stipulated that the x-axis of the bathymetric grid should be parallel to the coast. This is all very well where the coast is relatively straight but on Holderness there is a steady curve so that at either end the orientations are quite different, particularly when Flamborough Head is approached.

To overcome difficulties arising from this changing orientation the shore was divided into stretches each of which could be regarded as being straight. The angle α which each stretch makes with the grid's positive x-axis was determined (the values are given in appendix 2.2). In order to obtain the true longshore energy component, the angle which the wave ray makes with the perpendicular to the shore, i.e. β, needs to be calculated - Figure 2.3.

Figure 2.3 Determination of β





$$180 = -\alpha + \text{ANGLE} + \beta + 90$$

$$\beta = 90 + \alpha - \text{ANGLE} \quad (2.1)$$

α = angle between shore and x-axis

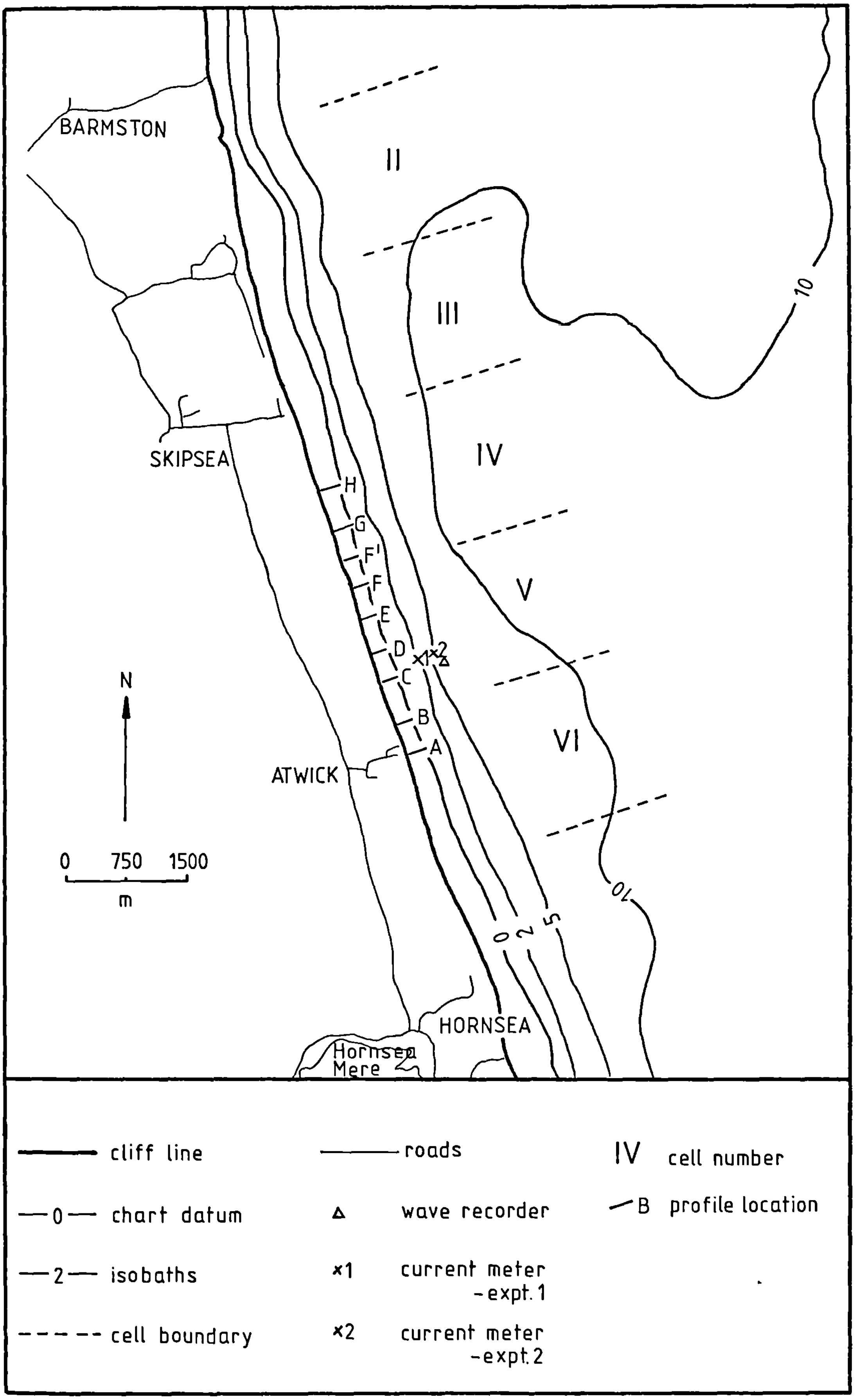
ANGLE = angle between incoming ray and the positive x-axis from program

β = angle between vector of net energy and longshore direction

β is then used to obtain the new values of P_l.

There are a number of general assumptions built into the program, and others which are specific to this study. May (1974) pointed out that the occurrence of spurious values for wave energy requires results to be smoothed. A reason for local fluctuations in longshore wave power along the coast is that the sea bed, a continuous surface, is represented in the program by a series of intersecting planes. Each time the ray crosses one of the boundaries (joining points on depth grid) it must readjust to the new slope; if this occurs just before breaking, the necessary

Figure 2.4 Northern Holderness showing Bathymetry, Beach Cells, Profile Locations and Instrument Positions.



BARMSTON
SKIPSEA
ATWICK
HORNSEA
Hornsea Mere
II
III
IV
V
VI
10
0
2
5
H
G
F'
F
E
D
C
B
A
×1
×2
N
0 750 1500
m
cliff line
chart datum
isobaths
cell boundary
roads
wave recorder
current meter -expt. 1
current meter -expt. 2
cell number
profile location

adjustment may not have been achieved in the time available. Consequently, the P_ℓ values may be either too low or too high.

Further assumptions are that the use of linear wave theory is valid, that no significant energy losses occur due to internal friction, and that energy dissipation under waves is similar to that in rivers, tidal flow and winds. Results obtained from the program would have differed slightly if some other existing expressions for wave energy had been incorporated. The value for the coefficient of friction is assumed by May (1974) to be 0.03 for conditions similar to those on the Holderness coast, so this value was adopted in the present study.

This section has described the method of obtaining values for longshore wave power. Section 3.1 a will describe its application on the Holderness coast, explain the derivation of resultant longshore wave power and sediment movement rates for various coastal cells (Figure 2.4) and present the results obtained on that coast.

2.2 b CURRENT METER EXPERIMENTS

In addition to wave-induced sediment movement, there is potential for net sediment transport resulting from the action of residual tidal currents. In an attempt to determine the currents likely to occur on Holderness and the types of sediment they might move, current velocities and directions were measured close to the wave recorder site (Figure 2.4). As the tide ebbs and flows currents are generated in northerly and southerly directions respectively, changing direction following the turn of the tide. In order to establish whether velocities were high enough to entrain and transport sediments, and whether any residual current existed, an experiment was carried out over one tidal cycle. Once it had been

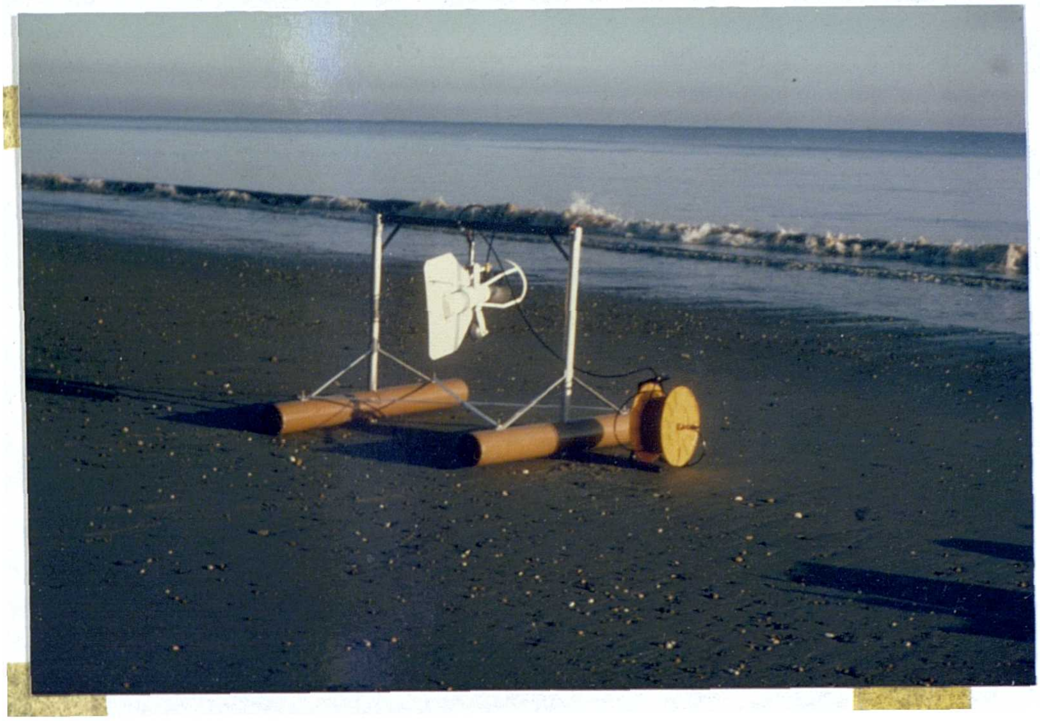


Plate 2.2 Current Meter Equipment - Experiment 1.

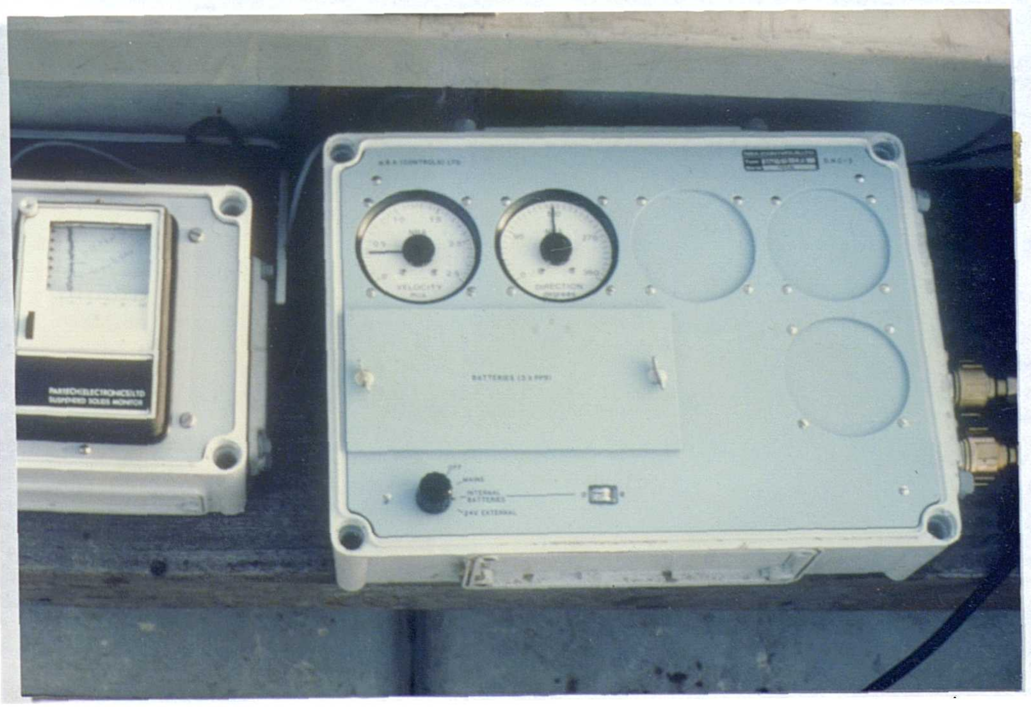


Plate 2.3 Current Meter Recording Equipment - Experiment 1.

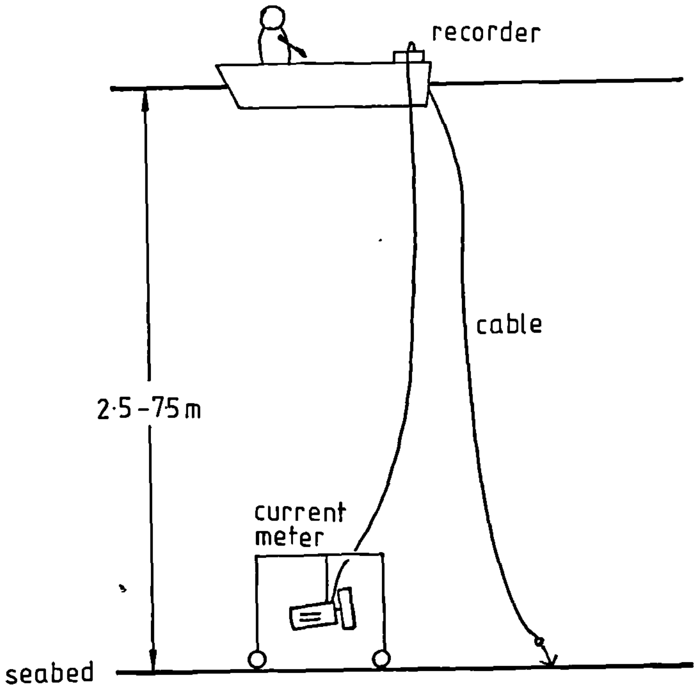
established that sufficient velocities were likely, and the probable maximum velocity had been obtained, a second more comprehensive experiment was set up to quantify currents. Thus two experiments using different instruments were carried out to measure currents.

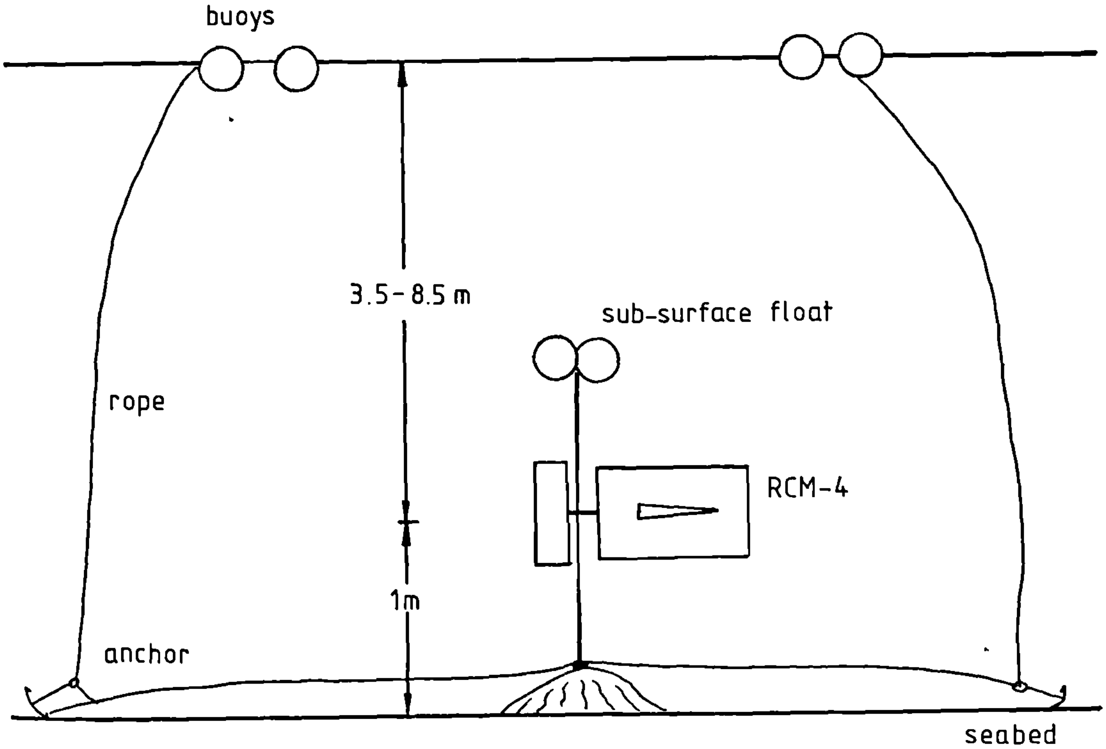
Experiment 1 - Direct Reading

The first experiment was carried out approximately 500 m from the shore in about 5 m of water on 5 November 1983, and lasted for almost ten hours over low tide. The meter used for measuring current speed and direction was a direct reading DNC-3 supplied by NBA (Controls) Limited via the NERC equipment pool (Plate 2.2). It was suspended from a framework which rested on thesea bed, and was connected to recording equipment in a boat moored above (Figure 2.5). The velocity output was connected to a pen recorder and to a moving needle meter; the direction was displayed only on a dial. Values were noted from these instruments as they were recorded, for direction, and for velocity in order to calibrate and check the scale on the pen-recorder chart. The recording equipment can be seen in Plate 2.3. During this experiment the sea surface was calm.

Experiment 2 - Remote Reading

The second experiment required a remote, i.e. internally recording, current meter - an Aanderaa Instruments RCM4 (Plate 2.4). It was installed approximately 1 km from the shore, a few metres away from the wave recorder (Figure 2.4), from 9 May 1984 to 4 June 1984 over two neap and two spring tides. The current speed and direction were recorded on magnetic tape within the instrument. In order to determine when a certain current velocity was achieved, it was important to switch the tape on and off at precisely known times. This procedure was carried out in the


recorder
cable
2·5 - 7·5 m
current meter
seabed


buoys
3.5 - 8.5 m
sub-surface float
rope
RCM-4
1m
anchor
seabed

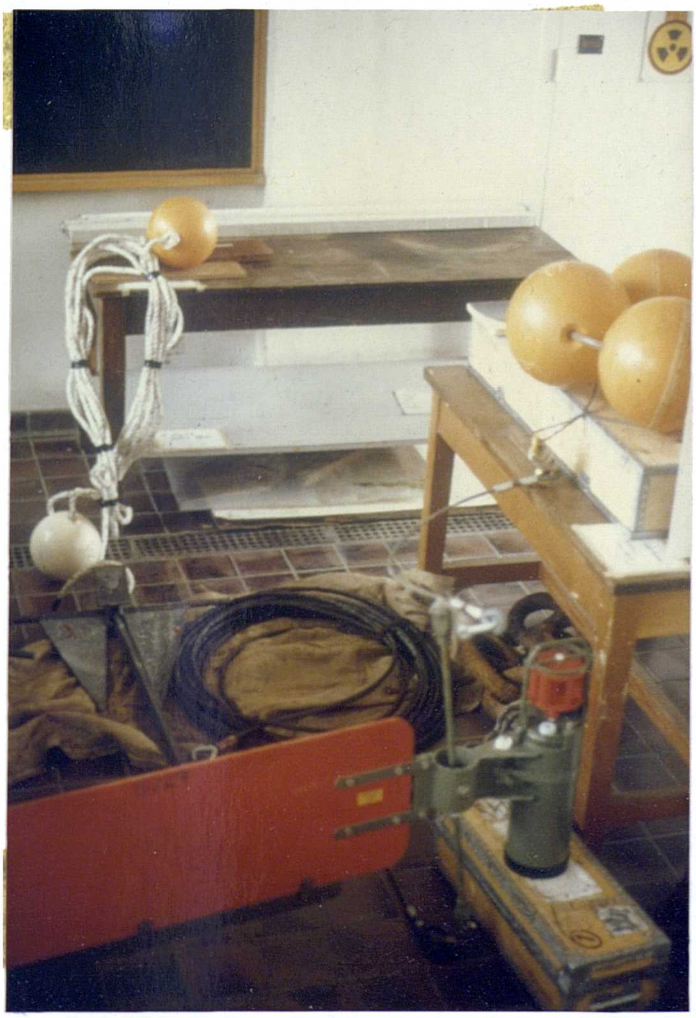


Plate 2.4 Current Meter Equipment - Experiment 2.

Plate 2.5 Tracer Sand on Beach.

laboratory, synchronised with the speaking clock and the time at which the meter was placed in the water noted. Figure 2.6 shows the configuration of the equipment, which was launched from a small boat; the configuration is one recommended by MAFF (Baxter and Bedwell, 1972).

The meter site had a mean water depth of 7 m with a tidal range of 5 m (i.e. $\pm$ 2.5 m); the meter itself was suspended about 1 m. above the sand and gravel bed. The maximum expected current was around 0.50 ms^{-1}. These data had been supplied to NERC Research Vessel Services, from whom the equipment was borrowed, so that the meter could be calibrated correctly. The sample interval was to be 10 minutes; thus every ten minutes the current velocity and direction were determined, and recorded on magnetic tape. At the end of the recording period the tape was returned to NERC for the data to be read onto 9-channel tape. During this experiment the sea surface varied from calm to having waves up to 1.5 m high.

Section 2.2 has thus described how the field data from the offshore zone were obtained.

2.3 THE BEACH

The second major section describing the methods used in this study considers those used in the beach sub-system; firstly survey work carried out on beach profiles, then analysis of sediment characteristics, and finally tracer experiments to determine beach sediment movement.

2.3 a BEACH PROFILE WORK

Many workers have undertaken studies to investigate the evolution and behaviour of beach profiles, the way they vary both along the shore and through time.

Regular measurements of beach morphology provide data which enable patterns of beach change to be modelled formally, and allow changes in the beach sediment budget to be established. The present study involved monitoring beach profiles along the Atwick to Skipsea field site over an 18-month period from April 1983 to September 1984. It was decided that an ideal longshore spacing for the monitored profiles would be about 500 m. Cliff top points which could be used as temporary bench marks for beach surveys had to be established; one potential problem was the relocation and identification of these points from the foot of the cliff. Fence posts and the remains of war time pill boxes proved to be most useful for this purpose, but owing to their positions the intervals between adjacent benchmarks were not exactly 500 m. One of the temporary benchmarks (TBM) was actually an Ordnance Survey triangulation point of known position and altitude, so all the other benchmarks were surveyed into this by tacheometry; it was the altitude of these selected points which was of interest for determining the heights of the beach. The location of the TBMs and their surveyed heights are given in Table 2.1. Nine TBMs associated with suitable profile locations were chosen along the cliff top, a to h (f' was decided upon after the others; hence its odd nomenclature).

Surveying was undertaken at each spring tide so that the maximum exposed profile length could be measured. A number of constraints had to be borne in mind when deciding upon a suitable

Table 2.1 Description, Grid Coordinates and Altitude of Benchmarks

See Figure 2.7 for location

<u>Profile A</u> 19675105

End of coast road from Atwick. Northern-most post of road barrier - marked with paint

15.597 m a.s.l

<u>Profile B</u> 19465128

Field gate post opposite pill box on lane to gas station. Yellow paint

17.607 m a.s.l

<u>Profile C</u> 19295196

SE corner of outer fence round British Gas compound.

15.122 m a.s.l

<u>Profile D</u> 19175221

O.S. trig point north of two pill boxes

22.04 m a.s.l

<u>Profile E</u> 19085259

Nail driven into wooden sleeper on base of winch at southern end of High Skirlington caravan site

15.856 m a.s.l

<u>Profile F</u> 1891307

Landward fence post at boundary between High Skirlington and Far Grange caravan sites. Painted.

16.056 m a.s.l

<u>Profile F'</u> 18775330

Post with tap nearest to slipway/ramp at Far Grange caravan site. Nail put in post.

15.041 m a.s l

<u>Profile G</u> 18705367

North side of pill box door - paint. Ground level measured.

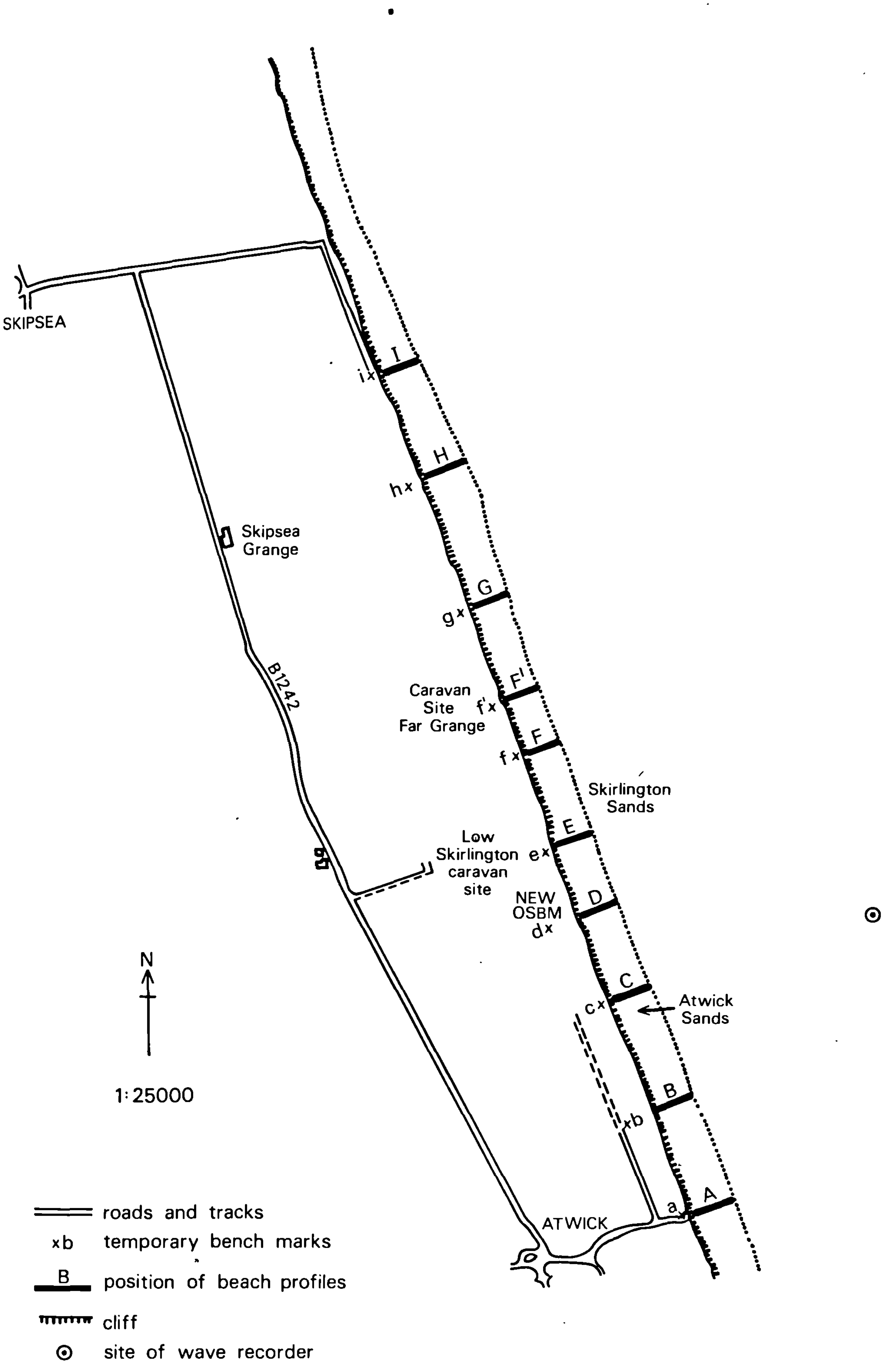
16.961 m a.s.l

<u>Profile H</u> 18515432

Old pill box foundations and pillars. Corner of raised section of floor (painted)

11.071 m a.s.l

Figure 2.7 Field Site showing Surveyed Beach Profile Locations and Low Water Mark (dotted line).



SKIPSEA
Skipsea Grange
B1242
Caravan Site Far Grange
Low Skirlington caravan site
Skirlington Sands
NEW OSBM
Atwick Sands
ATWICK
I
H
G
F'
F
E
D
C
B
A
i×
h×
g×
f'×
f×
e×
d×
c×
×b
a
N
1:25000
roads and tracks
×b temporary bench marks
B position of beach profiles
cliff
site of wave recorder

method of survey:

1. The surveying would often have to be carried out by one person.
2. Time would be limited if a reasonable length of beach profile was to be measured. A 2½ hour period spanning low tide would be best, during which time nine profiles spread over a distance of 4 km would be surveyed.
3. The equipment had to be easily portable for one person.

The need for a rapid one-"man" technique meant that some accuracy would be sacrificed. It was decided that most surveys would use Abney levels, and ranging poles with the surveyor's eye-level marked on them. Distances down the beach were measured by the surveyor alone. The beach was surveyed by placing ranging poles at obvious breaks of slope, then measuring the distances between them and the angle of the beach slope. This procedure was carried out to the water's edge. During a more intensive period of fieldwork the profiles were surveyed using a Watts autoset level. To obtain the height of the top of the beach, from which all the other points could be determined, some method of linking it to the cliff top temporary benchmarks was required. After experimenting with a number of techniques a relatively simple method was adopted. Pegs were inserted into the lower cliff-face at each profile location, and were surveyed into the TBM network by tacheometry. This method had been rejected at first as it was thought that the pegs would not remain in the cliff-face for long enough; these fears proved to be greatly exaggerated, and the scheme worked well. At many profiles the 300 mm steel pegs remained in place for many months; when pegs did fall out or were removed between surveys, a new peg was inserted as soon as its absence was discovered, and was surveyed into the TBM as soon as possible. The altitude of each peg was thus known, so that at each survey the height of the peg above the top of the beach was measured to obtain the altitude of the beach. Beach measurements were filled in on booking sheets and the time of survey noted so that the exact state of the tide could be determined afterwards. The peg to beach-top heights were recorded, and for each survey leg the nature of the beach material was noted.

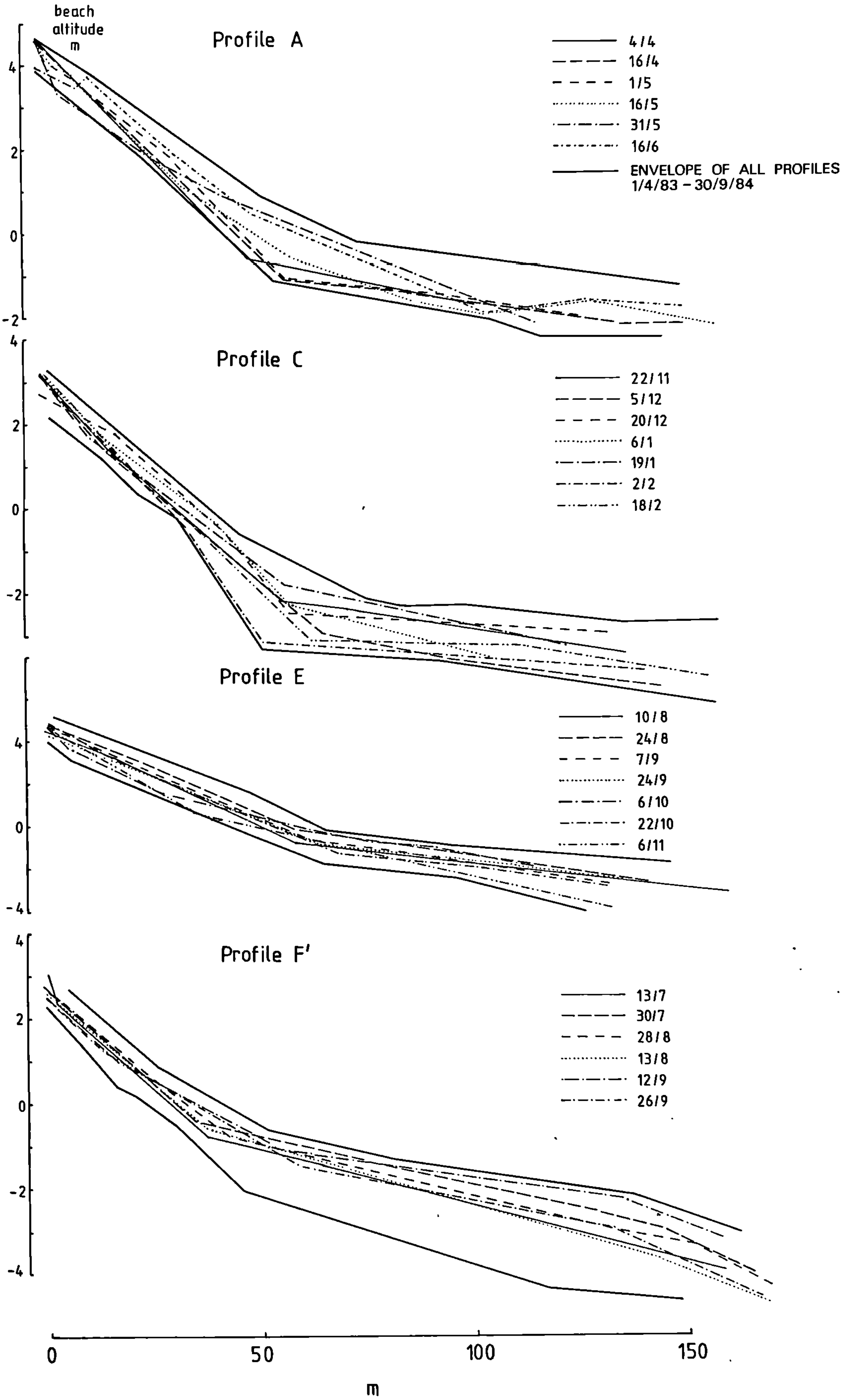
In the laboratory survey data were converted to beach coordinates. A PET computer program was used to calculate the coordinates of all survey points from the beach-top (x,y) coordinates and the angles and lengths of the various beach sections. A second program calculated the cross-sectional area under the profile, both to the minimum beach height for a particular profile on a certain date, and to an arbitrary basal datum for a profile which could remain at a fixed level throughout the 18 months. However, the absolute areas under profiles of significantly different lengths could still not be compared with total validity, despite the arbitrary datum being defined. It would not be satisfactory to place a similar arbitrary limit for the plan position of the seaward limit of the beach. Beach profiles were subsequently plotted; examples are shown in Figure 2.8 and Appendix 2.3.

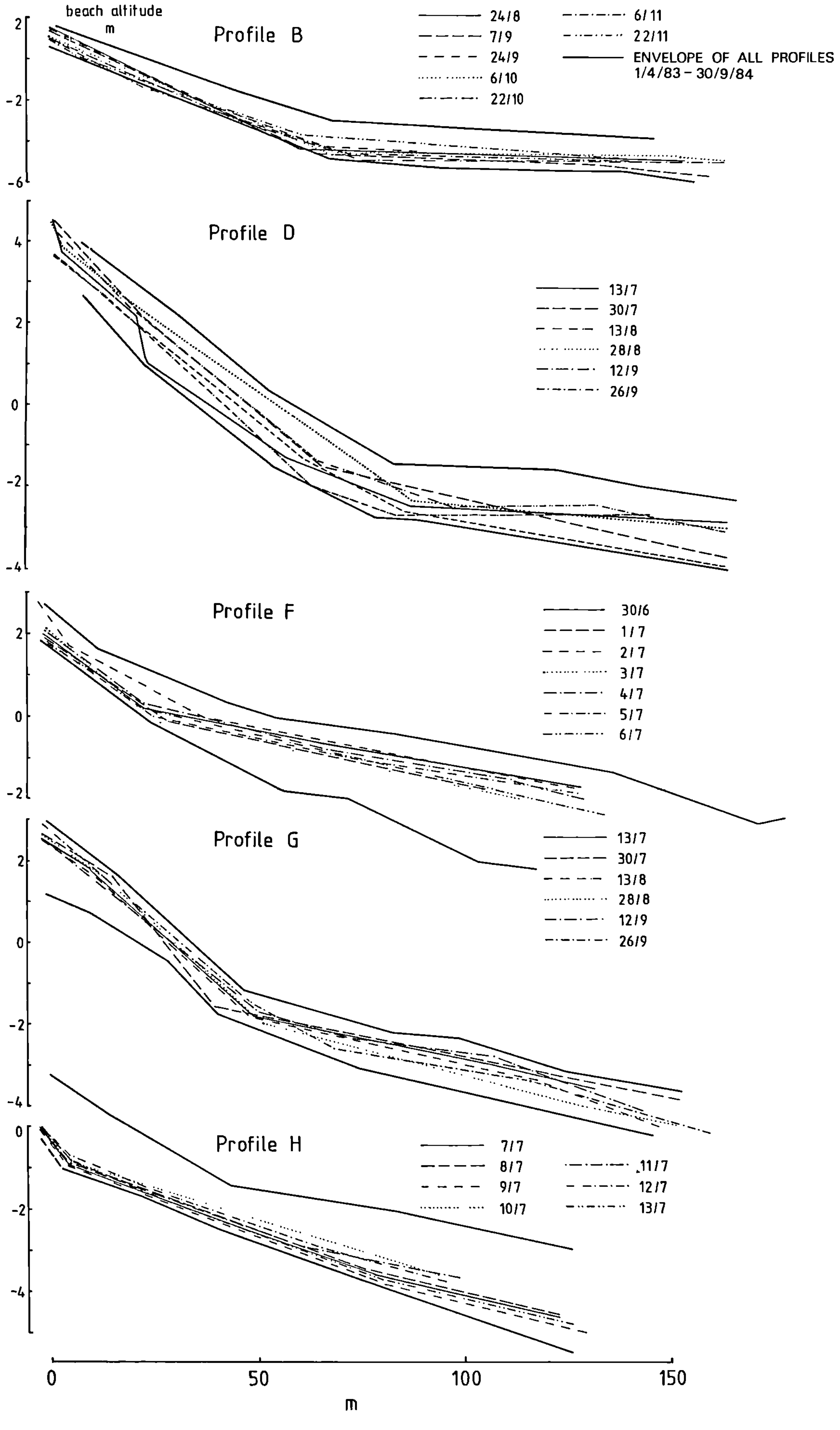
The nine beach profiles, A, B, C, D, E, F, F', G and H were surveyed at each spring tide (roughly fortnightly) for eighteen months. During this time there were two periods of intensive and detailed work. From 4 March to 18 March 1984 the profiles were quickset levelled on alternate days by a team of student surveyors. In spite of rather unsocial hours and occasional gathering gloom the surveys were conducted at low tide. The other period of

Figure 2.8 Examples of surveyed beach morphology, Profiles A, C, E and F^1;

B, D, F, G and H overleaf

The boundary lines describe the complete range of beach profiles from October 1983 to September 1984 inclusive.


beach altitude m
Profile A
4/4
16/4
1/5
16/5
31/5
16/6
ENVELOPE OF ALL PROFILES 1/4/83 – 30/9/84
Profile C
22/11
5/12
20/12
6/1
19/1
2/2
18/2
Profile E
10/8
24/8
7/9
24/9
6/10
22/10
6/11
Profile F'
13/7
30/7
28/8
13/8
12/9
26/9
0
50
100
150
m



beach altitude
m
Profile B
24/8
7/9
24/9
6/10
22/10
6/11
22/11
ENVELOPE OF ALL PROFILES
1/4/83 – 30/9/84
Profile D
13/7
30/7
13/8
28/8
12/9
26/9
Profile F
30/6
1/7
2/7
3/7
4/7
5/7
6/7
Profile G
13/7
30/7
13/8
28/8
12/9
26/9
Profile H
7/7
8/7
9/7
10/7
11/7
12/7
13/7
2
-2
-6
4
0
-4
0
50
100
150
m

intensive field surveys was from 30 June to 13 July 1984, when the profiles were surveyed every day. This time the Abney level was used as only limited help was available. The 18 month-long survey period produced 495 beach profiles measured on 55 days.

2.3 b BEACH SEDIMENTS

Part of the object of the work carried out on the beach was to investigate its sediment composition and to describe the variation of these sediments, both over a period of time, and along the beach. This is essential if the beach system is to be understood; beach composition might be expected to change as its morphology and the prevailing offshore conditions vary. The nature and behaviour of the beach is investigated before being interpreted in the light of prevailing offshore conditions (Section 4.2 b). A knowledge of sediment characteristics is also useful for determining the amount of movement likely to occur under various energy conditions.

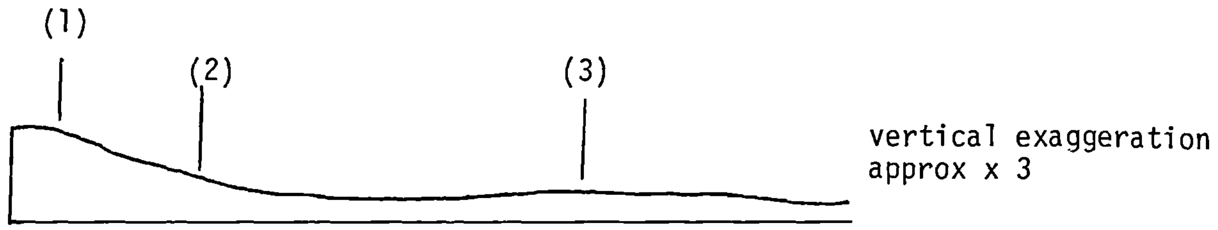
This section describes the sediment sampling scheme and the methods of laboratory analysis used to determine the sediment characteristics.

Methods

Sediment samples were collected over an 18 month period from April 1983 to September 1984, the dates of sampling coinciding with those of the profile surveys. Four of the surveyed profiles were sampled at each date, viz profiles A, D, F' and H, being approximately 1.25 km apart. Usually three batches of sediment were extracted from each profile, though when no beach crest was discernible only two samples were taken. The sample sites (Figure 2.9) were:

1. On the beach crest,
2. In the middle of the upper beach and
3. In the middle of the lower beach

Figure 2.9 Sediment Sampling Positions on the Beach Profile.



1. beach crest
2. upper beach
3. lower beach

Towards the north of the field site, from F onwards it was often difficult to determine exactly where the upper beach ended and the lower beach began. The sample sizes ranged from 1.5 to 3.0 kg.

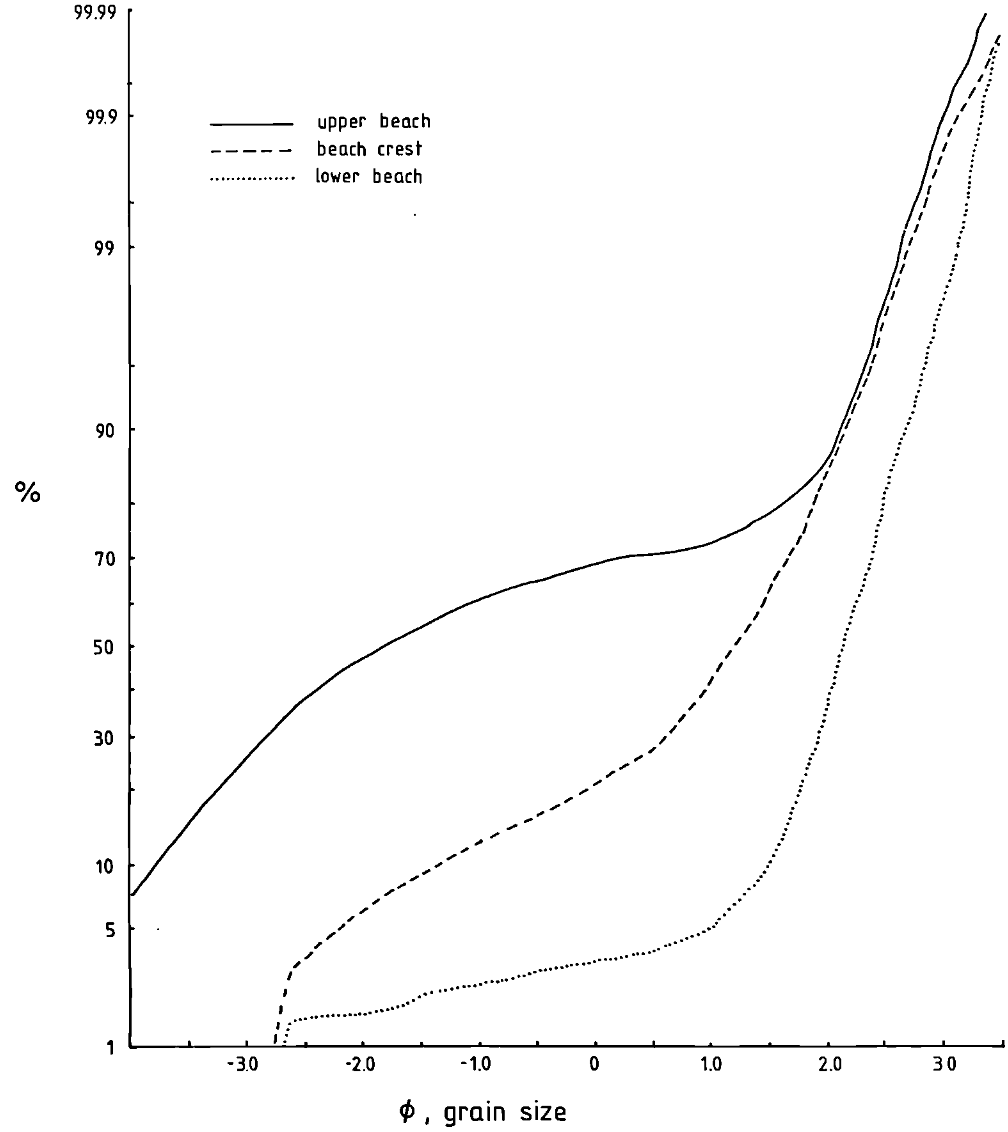
All samples were taken back to the laboratory, washed, dried, and sieved through a nest of sieves at ½ ø (0.5ø) intervals from -4.5ø (22.4 mm) to 3.0ø (0.125 mm). This enabled the particle size distribution of each sample to be dertermined. The percentages of material retained in each sieve were then plotted on ordinary graph paper, and the cumulative percentages on arithmetic probability paper (Figures 2.10 a and b). The cumulative graphs provided data for calculating certain descriptive statistics, namely the median grain size, mean grain size, skewness, sorting

Figure 2.10 Beach Particle Size Distribution.

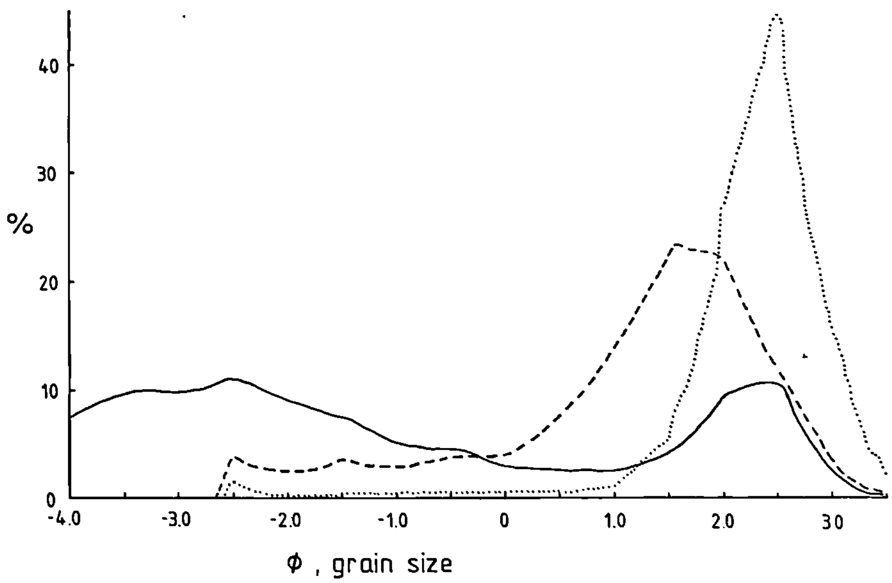
(a) Example of Cumulative Percentage Frequency Curve for ½ phi intervals: Profile D, 13/7/84.

ø	
< -4.5	coarse gravel
-4.5 - -3.25	medium gravel
-3.25 - -1.0	fine gravel
-1.0 - 0.75	coarse sand
0.75 - 2.25	medium sand
2.25 - 4.25	fine sand

(b) Example of Particle Size Percentage Graph for ½ phi intervals: Profile D, 13/7/84



99.99
99.9
99
90
70
50
30
10
5
1
%
upper beach
beach crest
lower beach
-3.0
-2.0
-1.0
0
1.0
2.0
3.0
Φ , grain size



40
30
20
10
0
%
-4.0
-3.0
-2.0
-1.0
0
1.0
2.0
3.0
Φ , grain size

and kurtosis. The formulae used were (Briggs 1977):

$$\text{Median} = \phi 50 \quad (2.2)$$

$$\text{Mean} = \frac{\phi 75 + \phi 50 + \phi 25}{3} \quad (2.3)$$

$\phi 50$ = the ϕ value at which the cumulative curve crosses the 50% value

(See Figure 2.10 a)

$$\text{skewness} = \frac{\phi 84 - \phi 50}{\phi 84 - \phi 16} - \frac{\phi 50 - \phi 10}{\phi 90 - \phi 10} \quad (2.4)$$

$$\text{sorting} = \frac{\phi 84 - \phi 16}{2} \quad (2.5)$$

$$\text{kurtosis} = \frac{\phi 90 - \phi 10}{1.9\,(\phi 75 - \phi 25)} \quad (2.6)$$

Eventually it was decided that only two statistics would be used in the analysis, mean grain size being the main one, with sorting of secondary importance. It should be remembered that each statistic is just one way of describing the bulk characteristics of a sediment population. The mean particle size calculated may not be present in a sample, but is produced because of a high percentage of larger and smaller grains. Similarly, the means of two samples may be fairly close together, but the associated cumulative percentage plots can differ widely. It is important not to draw too many conclusions from these mean values, and always to bear in mind the original grain size distribution.

Analysis

1. Mean Particle Size: The first step in establishing the nature of the beach sediments was to consider how the mean particle size varied throughout a 17-month period. For each profile, A, D, F' and H, a plot was produced showing the mean particle size at three positions down the beach for each sample date. Curves were

drawn showing the pattern of change for each beach position.

The second investigation was into the variation of mean particle size alongshore. For this the data were handled in two 6-month batches, October 1983 to March 1984 and April 1984 to September 1984. The mean sediment size of each upper and lower beach sample during the six months was plotted at the appropriate position along the beach. The calculated mean of these values was then added to the diagram.

2. Sorting: A similar procedure was carried out using the values for sediment sorting instead of those for mean particle size. Firstly the sequence of sorting on the upper and lower beaches throughout the 16 month period was plotted.

Finally the variation of sorting alongshore was investigated by plotting all upper beach and lower beach sorting values for for a six month period at the appropriate location along the beach; the mean sorting over the six months was calculated and added to the figure.

2.3 c TRACER EXPERIMENTS

Predictions of sediment movement from mathematical and computer models are useful but it is often necessary to test their reliability against field observations. Some means of following moving sediments was required, and the solution was to label particles so that they could be recognised later. In the past various methods have been used to do this; some have involved introducing "foreign" material to the beach, while others have adapted existing material.

Tracer experiments are necessary to obtain an indication of the direction and rate of sediment movement, and may allow sediment budgets to be calculated if the experiments are at a sufficiently large scale, i.e. are repeated at intervals along a coast.

Previous Work and Techniques

Tracer experiments of two main types have been carried out, those which require a sensor for detection, e.g. radioactive and magnetic tracers, and those using dyes or visible tracers. There are certain characteristics (mentioned later) which a good tracer must possess, and workers have found it most satisfactory to adapt the native beach sediments, either by dying or irradiating them so that the resulting tracer behaves identically to the background material.

Radioactive tracers, where beach material is "tagged" with a radioactive isotope, are re-introduced to the beach, which is later scanned with a Geiger counter or similar instrument. The strength of the returned signal reflects the concentration and distribution of tracer. Kidson and Carr (1959) have described radioactive pebble experiments, and Crickmore and Lean (1962) those using sand, while experiments with silts are explained by Bruun (1962).

Tracer experiments using dyed material are most common now for a number of reasons, not least of which is the safety factor; permission to inject radio-isotopes into public beaches is difficult to obtain. Most coarser sediments (sand size and above) can be dyed, and because they are particularly easy to identify under ultraviolet light and can be identified in low concentrations, fluorescent tracers have been widely used. Their use has been well-documented; Lean and Crickmore (1966) and Price (1968) considered their dispersion, and Knoth and Nummedal (1978) concentrated on the possible differences between tracers and native sand. Teleki (1966, 1967) tested dying techniques and developed equipment for tracer analysis, while Newman (1964), Yasso (1966) and Weatherill (1978) concentrated on the preparation of tracers. The quantities of tracer used in experiments has varied from many tonnes to just a few kilogrammes (Ingle, 1966), usually injected by simply dumping it on the beach surface. Its distribution is usually determined by sampling the active beach layer, and then counting the number of coloured grains in each sample under ultraviolet light in the laboratory. Good tracers can be produced from native beach material as dying sand particles only increases their radius by 300 nm (3×10^{-7}m) (Jolliffe, 1963).

Relatively new and untried tracer techniques include using sediments in which the natural magnetism can be artificially enhanced, and also using pulverised coal as a fine tracer.

Tracer Properties

Table 2.2 lists the advantages and disadvantages of the two main tracer methods, i.e. radioactive and fluorescent tracers. It was evident that the only possible method which could be used in this study was fluorescent tracing, and it is useful to summarise the properties which the tracer had to possess.

1. The coating had to be of a minimal and uniform thickness allowing the tracer to reproduce the hydraulic behaviour of the native material, e.g. have the same shape, hardness, grain size and specific weight.
2. The coating had to be resistant to abrasion and not fade or lose its UV fluorescent properties over a short period of time.
3. The tracer had to be easily detectable in small concentrations (1 in 10^6), if not in the field, at least under UV light in the laboratory.

Table 2.2 Advantages and Disadvantages of Tracer Techniques

Radioactive Tracers

Advantages

1. Detection is non-extractive, i.e. laboratory analysis is unnecessary
2. Detection can be done remotely
3. Suitable for tracing fines - silts, clays
4. More suitable for deep water work
5. Radioactive "tags" do not affect the hydraulic characteristics of material

Disadvantages

1. Severe safety problems in preparation, injection and presence on the beach
2. Permission for use is virtually impossible to obtain
3. Material has to be removed from the beach (if identical properties are required), transported, treated, transported again and re-injected
4. Artificial materials containing traceable isotopes are rarely hydrodynamically equivalent to native sediments
5. If coating or drilling techniques are not used then naturally occurring grains must contain a radioactive isotope
6. They are very expensive

Fluorescent Tracers

Advantages

1. Safe for use in field; some hazards may be encountered in preparation, but are insignificant compared with other methods
2. Rapid dispersal - no permanent beach changes
   Large scale economical commercial preparation is possible
4. Different colours are available for distinguishing different experiments
5. Most larger particles can be dyed
6. Preparation is relatively easy
7. Solubility of binding medium can be adjusted
8. Hydraulic properties unaffected
9. Samples need not be analysed immediately after collection
10. They are cheap

Disadvantages

1. Sand experiments generally require extraction of samples and laboratory analysis
2. Extractive sampling dilutes the tracer; in practice this is insignificant
3. Material usually has to be removed from the beach, transported, dyed, transported again and replaced, taking time and increasing the cost

The durability of tracers used in this experiment was tested by leaving a number of pebbles, which generally suffer the greatest abrasion, in water in a rotating drum for several days. Despite repeated collisions the pebbles were still noticeably dyed, whether coated with fluorescent or ordinary gloss paint; only odd spots of paint had been removed. The sand did not fade or lose its fluorescent activity and grains were easily detectable in low concentrations during laboratory analysis. The tracers produced in the present study were thinly and uniformly coated and any blemishes on the pebbles could be removed easily.

Fluorescent Tracer Experiment

Preparation of Sand

Partly owing to the high cost of commercially available dyed sand, but mainly to ensure that the experiments were as rigorous as possible, it was decided not to use artificial tracers, but to dye sand and pebbles from the study beach. It was decided to carry out three experiments, one on the upper beach using pebbles (over -.45 ø, 22.4 mm), and two on the lower beach using very much finer material. The lower beach experiments would be conducted under contrasting conditions but within a relatively short space of time, so different coloured tracers were required. The methods of tracer preparation will be described, followed by an account of the field experiments. Finally the techniques for laboratory analysis and determination of sediment movement rates will be presented.

The method used for dying was that described by Weatherill (1978), chosen because the equipment that he had used could be borrowed from the University of Aberdeen. The paint used for coating was from the "Dayglo brushing system" and was available in a range of "intense" colours. For manufacturers and suppliers see Appendix 2.4. One experiment used green (Flash Green) sand, the other Sunset Orange. The resin required to make the paint adhere to the grains and render it resistant to abrasion is Bettle Resin BE 610 (supplier in Appendix 2.4), and to ensure proper mixing a solvent, xylene, was used. The coating process must be undertaken with care, preferably outdoors. The "recipe" for producing dyed sand is in Appendix 2.5.

The equipment used for the coating has been called a "Throtnungler" and was developed in New Zealand. It comprises a revolving drum and a device for blowing hot air into it. Plate 2.5 shows an example of the dyed sand produced and used in the present study.

Preparation of Pebbles

Pebbles were collected from the upper beach (4.5 ø or 22.4 mm) and were painted by hand. Various methods were tried but the most effective one was to hold the pebble in a pair of tongs and dip it into a bath of thinned paint. The paints used were Sunset Orange and Rocket Red fluorescent and ordinary "daffodil yellow" gloss (See Plate 2.6). The pebbles were then baked in an oven to ensure that the paint was thoroughly dried and hardened.

Sand Experiment - Field Procedure

a. Injection - It was decided that a reasonable quantity of sand to use in each experiment would be 75 kg. Obviously larger quantities would have given a greater return but this had to be weighed against the time taken to dye the sand, and the ease with which it could be carried down to the beach. The sand was depositied in a line perpendicular to the shore next to a marker stake driven into the beach. Detergent was then sprinkled over the sand, and the

Plate 2.6 Tracer Pebbles on Beach.

Plate 2.7 Tracer Sand after the Passage of the First Few Waves Following Injection.

tracer wetted with sea water. Plates 2.5 and 2.7 show the tracer after injection, and the effects of the first few waves passing over it.

b. Sampling - A grid sampling scheme was adopted, the final dimensions of which could only be settled in the field. So that all the tracer particles had a chance of being recovered the 2.5 cm thick active beach layer was sampled; using a 7.2 cm diameter corer to give a reasonable sample volume. A sample network was staked out on the beach and the extracted cores placed in labelled polythene bags. Sampling was undertaken once every two tides, i.e. every 25 hours.

The dimensions of the sample framework depended upon where coloured sediment was observed in the field. In the first experiment samples were taken on four days following injection - the tracer was laid down on 1 July 1982 and sampling carried out on 2, 3, 4 and 5 July. On 2 July a 20 m x 25 m grid was sampled at 5 m intervals. Most of the grid was to the south of the injection point, a result of observing the wave direction, the initial movement of tracer and of quickly scanning the samples for tracer grains. The same basic network, extended by 5 m south of the injection point, was sampled on 3, 4 and 5 July. Figure 2.11 a shows this framework. After 5 July the return of tracer was considered to be too low to continue the sampling.

Tracer dispersion in the second (green) experiment was much slower and therefore the initial grid was smaller. The injection was on 7 July at 7.30 am and after one tide the patch of green was so distinct that nine cores were taken at 2.5 m intervals (Figure 2.11 b). On 8 July when the sediment could still be seen as a

Figure 2.11 Sampling Framework for Tracer Experiment.

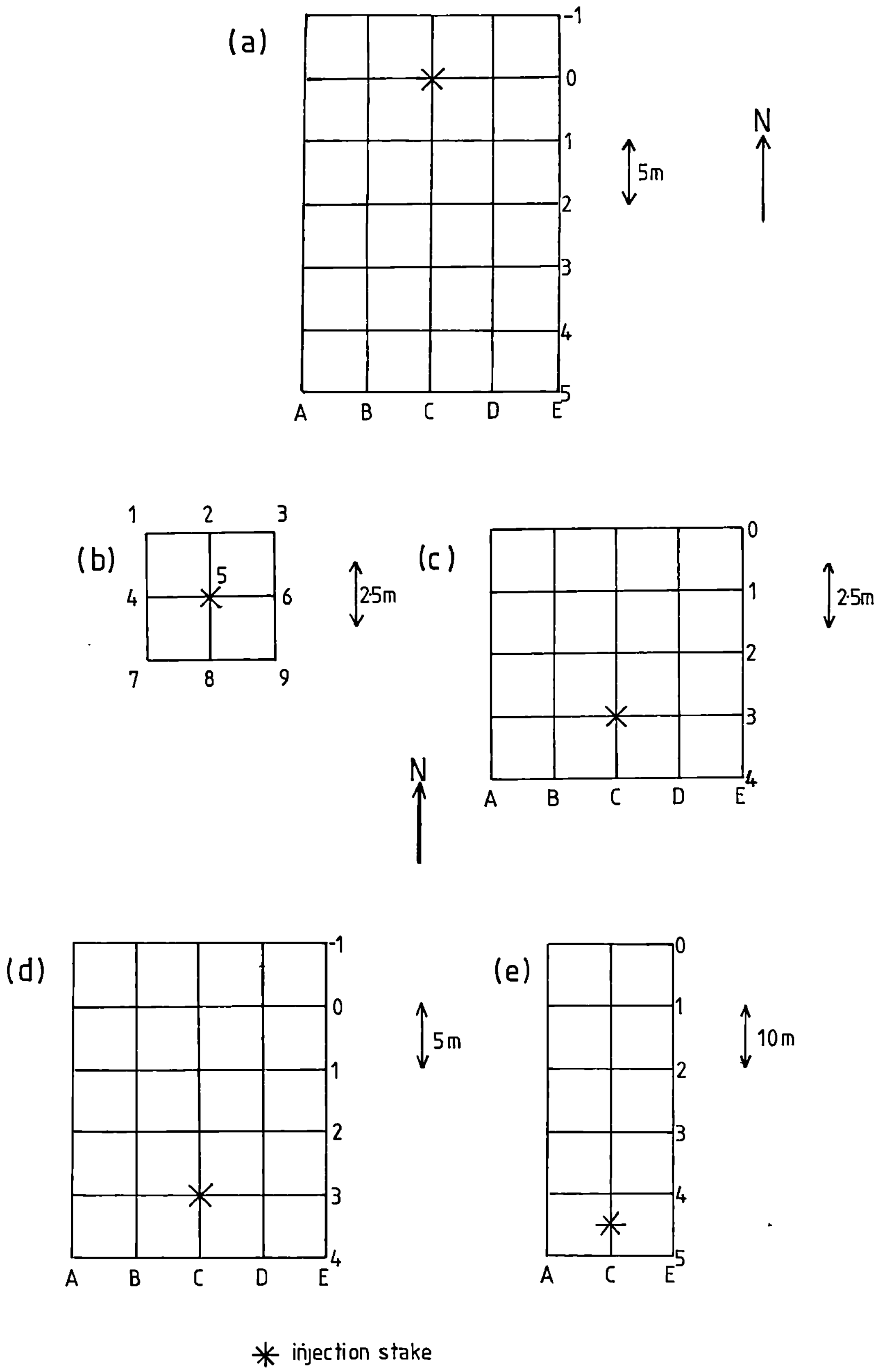
a Experiment 1, 2/7/84-5/7/84 inclusive

b Experiment 2, 7/7/84

c Experiment 2, 8/7/84

d Experiment 2, 9/7/84-12/7/84 inclusive

d Experiment 2, 13/7/84


(a)
-1
0
1
2
3
4
5
A B C D E
5m
N
(b)
1 2 3
4 5 6
7 8 9
2·5m
(c)
0
1
2
3
4
A B C D E
2·5m
N
(d)
-1
0
1
2
3
4
A B C D E
5m
(e)
0
1
2
3
4
5
A C E
10 m
injection stake

"shadow" on the beach surface extending northwards from the stake, a 10 m x 10 m grid was sampled at 25 m intervals (Figure 2.11 c). On 9, 10, 11 and 12 July a 20 m x 25 m grid was sampled at 5 m intervals (Figure 2.11 d). Finally a 20 m x 25 m rectangle was sampled every 10 m on 13 July (Figure 2.11 e). All these grids were nested so that the smaller ones fitted exactly inside the larger ones, and the sample points on the larger grids coincided with ones on the smaller grids.

Pebble Experiment - Field Procedure

a. Injection - Because of the time involved in painting the pebbles the experiment was rather limited in terms of the number used. An injection sample size of 750 was chosen - a mixture of 3 colours which was totally arbitrary. The pebbles were dumped on the beach at dusk on a rising tide so that they were exposed (presenting a temptation to "beachcombers") for as short a time as possible. Despite this it is felt that a number of pebbles were removed "by human intervention". Plate 2.6 shows the pebbles deposited on the beach and Plate 2.8 shows them after the passage of just one wave. Some of the smaller pebbles moved over 6 m southwards along the beach.

b. Sampling - Sampling in this experiment was non-extractive, i.e. all measurements were made in the field, and the sampled pebbles were left in place. Sampling was carried out at intervals of two tides, the entire upper beach being examined up to 300 m from the (known) injection point. When a pebble was found its position - distance and bearing from the injection point - was noted.
The lengths of its three axes and degree of rounding were also recorded. The return of the pebbles was very poor; a great deal of burial appeared to have occurred and a layer of finer sand was

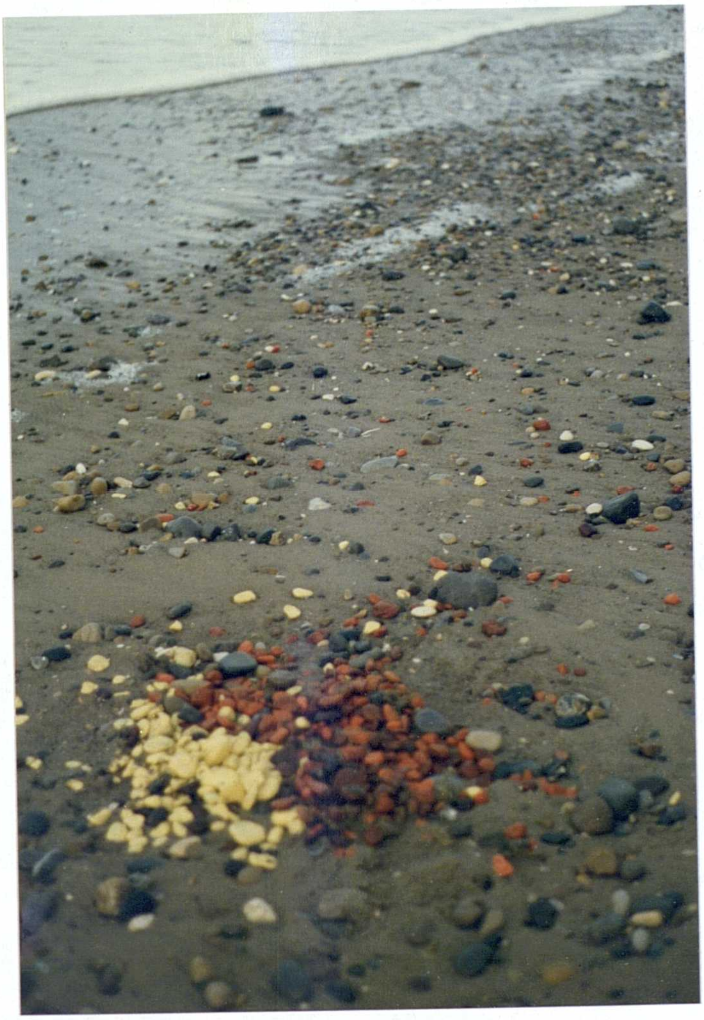


Plate 2.8 Tracer Pebbles after the Passage of One Wave.

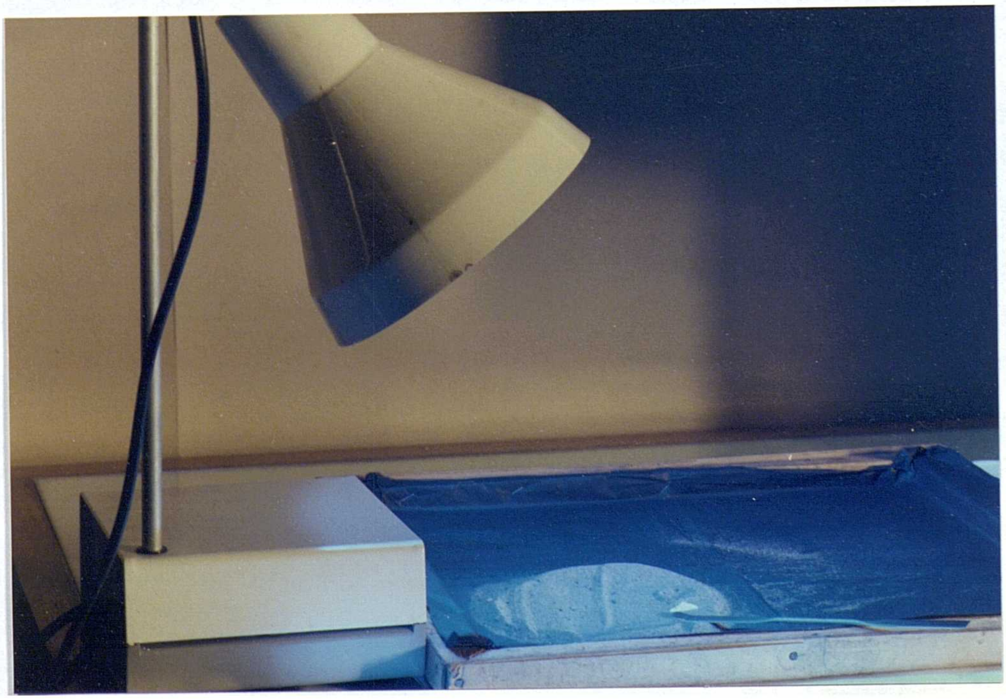


Plate 2.9 Fluorescent Tracer Grain Counting Equipment.

deposited on top of a predominantly pebbly patch. Injection took place on 30 June 1984 and the maximum number of pebbles recovered on any of the succeeding six days was 18.

Sand Experiment - Laboratory Analysis

In the laboratory each sample (over 300 in all) was washed in warm water to remove salt and so prevent aggregation of the grains, and was then wet-sieved through a 63 μm sieve to remove fines. The samples were dried and weighed. The next procedure was to count the number of fluorescent grains, and it was decided that systematic analysis of alternate samples would be adequate (those chosen will be seen in the results section - 3.2 c). The time taken to count each sampled depended upon how many coloured grains were present, the colour of the grains (the green tracer was easier to see) and the experience of the "counter". Care had to be taken only to count the dyed fluorescent grains, i.e. orange or green, not any which occurred naturally.

Fluorescent grains in the low concentrations present in the beach samples could only be identified satisfactorily under ultra-violet light (wavelength approximately 365 nm). A large black tray was placed under the UV light (Plate 2.9) and the sample emptied onto it. Then small quantities of sand were sprinkled, no more than one grain thick, onto a smaller tray which was held close under the lamp and the grains counted using a hand trip counter. This was repeated until a quarter of the whole sample had been scanned. It was then weighed, enabling the number of grains in the whole sample to be determined as well as the overall concentration of fluorescent grains per gramme of sand.

The grain concentrations were plotted on a "map" or plan of the sample network and isolines of concentration interpolated enabling the gradual movement alongshore to be seen. A method which has traditionally been used to determine directions and rates of movement is the centroid method. For each day (i.e. sample period) the coordinates of the centroid of grain concentration were calculated using the following formulae (Blackley, 1980):

$$\bar{x} = \frac{\sum_{i=1}^{m} C_i x_i}{\sum_{i=1}^{m} C_i} \qquad \bar{y} = \frac{\sum_{i=1}^{m} C_i y_i}{\sum_{i=1}^{m} C_i} \qquad (2.7)$$

$\bar{x}$ = x coordinate of centroid

$\bar{y}$ = y coordinate of centroid

$\sum_{i=1}^{m}$ = sum from 1 to i=M when M = number of sample points

C_i = concentration of tracer grains at the point whose coordinates are (x_i, y_i)

The centroid was then marked on the beach plan, and by comparing the plots for consecutive days the general movement of sand was observed and the speed of the centroid movement alongshore calculated.

The longshore sediment transport rate was calculated from:

$$Q_s = \bar{V}_c \times W \times d \quad \text{(from Knoth and Nummedal, 1978)} \qquad (2.8)$$

where Q_s = longshore sediment transport rate in m^3/day

$\bar{V}_c$ = speed of centroid movement ("advection rate") in m/day

W = width of sediment movement in m

d = depth of sediment movement in m

The results obtained from these experiments are presented in Section 3.2 c.

2.4 THE CLIFF

To complete the study of the shore system it is necessary to examine the cliff. The aim of this part of the study is to investigate the retreat of the coast since the production of the earliest maps, establishing average rates for this retreat and investigating its spatial and temporal variations. The volume of sediment contributed by the cliff to the beach is used in the production of a sediment budget, and is derived both from the rate of cliff retreat and from the cliff height and composition.

2.4 a METHODS OF DETERMINING CLIFF RETREAT

This section describes how rates of cliff retreat were obtained in the present study. A selection of maps published from 1557 onwards was used to make measurements of coastal recession; these included a number of different editions of the Ordnance Survey (O.S.) 1in and 1:50000 maps. Seven sets of aerial photographs were acquired, from which further measurements were taken. A list of sources appears in Table 2.3. Finally, measurements were taken in the field at the same locations as the surveyed beach profiles as well as at some intermediate points which provided a more dense network of values. Field measurements were made once a fortnight from spring 1983 until September 1984, and thereafter at intervals of two or three months.

<u>Mapping the Coast</u>

Maps to show coastal change over time were produced by converting a selection of maps of different dates to a common scale using a mechanical projector. Three maps were produced covering a variety of dates and areas. The first map was drawn to a scale of 1:100000 and had the cliff top from Bridlington to Spurn Head plotted from five maps dating from 1557 to 1976. The second map, at 1:50000, showed

Table 2.3 Sources used to obtain Cliff Retreat Rates

Pre-1850 maps

Date	Compiler/ Author	Given Scale	Calculated Scale	Area Covered
1557	Saxton	-	1:285333	Whole coast
1648	Blaen	1:158400	1:190080	Whole coast
1652	Jansson	1:100000	1:233333	" "
1672	Blome	1:316800	1:388182	" "
1695	Mordern	1:181029	1:220103	" "
1725	Moll	1:316800	1:347154	" "
1777	Kitchen	1:150000	1:189778	" "
1785	Bowen	1:150000	1:176885	" "
1786	Tuke	1:95040	1:94260	" "
1787	Cary	1:421294	1:412162	" "
?1795	Bowle	1:372965	1:344355	" " may be 1695
1806	Baker	1:487680	1:484127	" "
1829	Bryant	1:63360	1:62761	Bridlington to Aldbrough
1843	Greenwood	1:206326	1:191480	Whole coast

Ordnance Survey Maps 1850 onwards

Date Published	Surveyed	Revised	Scale	Date for plotting	Edition
1858	1849-52		1:63360	1850	1st
1912	"	1904/12	1:63360	1912	3rd
1929	"	1924/29	1:63360	1929	Popular
1962/8	1960	1960/68	1:63360	1968	7th
1979	1951-69	1972/76	1:50000	1976	2nd series

nb - revisions assumed to include major coastal changes

Aerial Photographs

Date	Source	Scale	Coverage
May 1968	JARIC*	1:36000	Barmston - Hornsea
June 1972	O.S.	1:14000	N of Atwick - N of Nornsea
May 1974	O.S.	1:7500	Southfield Ho. - Atwick
July 1975	O.S	1:32585	Ulrome - N of Nornsea
July 1977	Meridian	1:10000	Barmston - Hornsea
May 1980	M.O.D.*	1:50000	Ulrome - Hornsea
June 1984	NERC ^	1:6600	Southfield Ho. - N of Hornsea

*Ministry of Defence   O.S. Ordnance Survey   ^NERC MSS 84 flights

Field Measurements

Fortnightly August 1983 - December 1984 +⟶ covering coast from Skipsea to Atwick the area from north of Skipsea to just south of Hornsea for five dates from 1834 to 1976, again based on maps. Finally a 1:10000 map of the field site was produced from aerial photographs, showing the cliff line in 1968, 1972, 1977, 1980 and 1984.

Retreat Graphs

The second method of investigating retreat was, instead of mapping the position of the cliff at various dates, to take measurements from certain known points to the edge of the cliff. This gives a clearer, but more selective, indication of rates of retreat. The results were then plotted on graphs, a small sample of which will be presented.

The graphs were prepared in three ways:

1. From map data,
2. From aerial photography and
3. From field measurements.

1. Retreat rates from maps: For the entire coast from Bridlington to Kilnsea, or that section of coast covered by each map, recognisable points were chosen at intervals of approximately 2 km ; usually these were churches or cross-roads which would have been landmarks for early map-makers, and therefore more likely to be accurately plotted. Occasionally the reference point had to be changed when a feature disappeared. It was recognised in advance of measuring that the earliest maps, and indeed many of the pre-O.S. maps, contain inaccuracies. As pointed out by the Royal Commission on Coast Erosion (HMSO, 1907), between certain dates portions of land actually appear to have been gained!! It is unfortunate that not even the positions on the first map are known precisely. The shortest distance to the cliff top at each point was measured under magnification and

recorded. For each point along the coast a plot of time against distance to the cliff edge was prepared from 1557 to 1976. For the period of O.S. coverage (1850 onwards) intermediate points were measured, providing figures for land loss at 1 km intervals. The gradients of the "best-fit" lines, subsequently inserted, yield an estimate of the rate of retreat. These graphs show the retreat at particular places over a period of time; the next step was to investigate retreat along the shore. For a particular time period the amount of land lost, and the rate of loss, at each point down the coast was plotted; this was carried out for a number of different time periods, and a final graph presented showing the changes between 1850 and 1968 for comparison with a simialar diagram produced by Valentin (1971). From this, average rates of retreat were calculated.

2. Retreat rates from aerial photographs: A similar procedure was undertaken using aerial photographs. The measurements, however, represented retreat over a much shorter time, and were taken at more frequent intervals along the shore from Barmston to Hornsea. The interval on either side of the field site was approximately 0.5 km , while between Skipsea and Atwick it was around 325 m. Again, the "best fit" lines were inserted and the mean rates calculated. These rates were plotted on a graph of distance alongshore against retreat rate.

3. Retreat rates from field measurements: In the field the temporary benchmarks used for establishing the heights of the beach profile pegs were used as the reference points for measuring purposes, though occasionally wooden pegs were inserted at more convenient locations. In addition to these, another nine intermediate "benchmarks" (some

purpose-built ones thoughtfully provided by the caravan site owner!! - Plate 2.10) were chosen in the area covered by High Skirlington and Far Grange Caravan sites. At these 18 locations measurements were taken with a tape in a straight line to the cliff edge once a fortnight; a plot of time against against distance to the edge was prepared. Following this the average retreat rate was calculated at each point and plotted against distance alongshore; the mean value alongshore was then calculated.

This chapter has described the fieldwork undertaken in the present study. The first section set out the timetable of field-work, and the following three sections contained explanations of the particular methods used in the various experiments in each of the coastal sub-systems. Chapter 3 will present the results obtained from these experiments.

Plate 2.10 A Benchmark!

CHAPTER 3 ANALYSIS AND RESULTS

This chapter presents the data analysis and results obtained from the experiments which were described in Chapter 2. They are presented in four sections, the first three of which deal in turn with the three coastal systems, i.e. the offshore zone, the beach and the cliff. These sections aim to establish modelled sediment transport rates, and to measure current velocities and associated sediment movement: a description of the morphological and sedimentological evolution of the beach and the measurement of sediment transport on the beach are also required. Cliff retreat rates will be produced in order to determine the amount of sediment being supplied to the cliff. Finally, a sediment budget based on the results of the work in all three sub-systems is calculated and presented.

3.1 THE OFFSHORE ZONE

3.1 a MODELLED SEDIMENT TRANSPORT RATES FROM WAVE DATA

Sections 2.2 a in Chapter 2 dealt with wave refraction and the chosen program in fairly general terms. This section describes how the refraction program WAVEJB.F77, a variation on WAVENRG, was applied in the Holderness study and presents the results obtained from it. The aim is to produce sediment transport rates for different prevailing offshore conditions, values for seasonal and annual sediment transport in each of a number of beach cells and a figure for overall net sediment transport.

The approach adopted involved two separate experiments being carried out; the first set of test data, using a larger, coarser depth matrix (Grid 1), was designed to give a general impression of wave refraction patterns and wave energy conditions in the area. The second experiment was designed to investigate more detailed refraction closer inshore using a more dense depth matrix (Grid 2). In each case the longshore wave power P_{ℓ}, results from the program are weighted to reflect wave conditions which were either obtained from published records or measured in the field.

General Holderness Refraction

Each experiment may be considered in three sections - the wave data used, the refraction and the conversion to sediment movement rates. Finally, the sediment movement results are presented.

Wave data: The first "run" of the program used data extracted from published records from the Dowsing Light Vessel, which is anchored approximately 40 km due east of Spurn Head (Draper, 1976). The data used were % exceedence of H_s, the significant wave height (which is the mean height of the highest one third of waves), H_{max}, the most probable height of the highest wave occurring during a recording interval, and the frequency of wave periods. Each of these was summarised for winter (January, February and March), spring (April, May and June), summer (July, August and September) and autumn (October, November and December) for the year May 1970 to May 1971. Wave direction data for the same period, also from Dowsning, were obtained from the Meteorological Office, with further information being extracted from the relevant section of "Ocean Wave Statistics" (Hogben and Lumb, 1967).

Representative conditions were extracted from the published statistics as follows: it was assumed that the "H_s exceeded for 70% of the time", $H_{s\ 70}$ represented low to medium energy conditions, and that "H_s exceeded for 30% of the time" $H_{s\ 30}$ represented medium to high energy. It was decided that in order to reflect mean conditions "70% exceedence" heights would prevail for 65% of the time and 30% exceedence for 35% of the time. The modal wave period which had the greatest percentage of occurences within ± 1 second of it, regarded as being representative of the general conditions, was extracted from the Dowsing data for each season. Table 3.1 summarises the representative conditions.

Table 3.1. Wave Conditions for General Refraction

		Wave height Low/Medium energy	Wave height Medium/High energy
Winter	T = 5s	H_{s70} = 1.0 m	H_{s30} = 1.6 m
Spring	T = 5s	H_{s70} = 0.8 m	H_{s30} = 1.4 m
Summer	T = 5s	H_{s70} = 0.8 m	H_{s30} = 1.3 m
Autumn	T = 5s	H_{s70} = 1.2 m	H_{s30} = 2.2 m

Future weighting of P_{ℓ} values would use the 35%/65% allocation mentioned above. This, however, would not take into account a greater proportion of higher or lower energy waves from a certain direction and a second method of analysing wave data was thus used. From "Ocean Wave Statistics" (Hogben and Lumb, 1967), the overall (all directions) H_{s70} and H_{s30} values for the area were obtained, as well as the percentage of time for which they were sustained from the N.E., E., and S.E. Thus the percentage of high/medium energy and medium/low energy from each of the directions was known. Dowsing data had already established typical heights for these energy conditions (Table 3.1 above).

The total proportion of waves from each of the directions N.E., E. and S.E. was extracted from a record of swell wave directions and wind directions at Dowsing for the year May 1970-May 1971. Twelve readings were presented for each day and the information extracted as follows:

1. Two representative wave directions were taken for each day, one for 0-12 GMT, the other for 1201-2359; this corresponds to the number of field readings per day supplied by one of the coast-guards on the Holderness coast, i.e. the same resolution was used for later comparison.
2. Where waves at Dowsing were from the western half of the compass they were assumed to have had a limited influence on this east-facing coast, and the swell direction of the previous 24 hours (the time taken for a wave at Dowsing to reach the shore) was assumed to have been dominant for half a day. Only half a day is allocated as the remainder is considered to be calm to allow for the dampening effects of offshore winds. If many days of westerly winds occurred, then apart from the one day before an easterly wind (N.N.E. to S.S.E.) was re established, calm conditions were assumed.
3. Only approximately one half of waves from the north and south contribute energy to the study area, so half of the northerly waves were allocated to the N.E. frequencies and half of the southerly ones to the S.E. The remaining waves were allocated to the previous days swell direction as above. Thus,for the whole year directions of wave approach were assigned to each day, these were added up for each season and the percentage occurrence calculated (Table 3.2 a)

Table 3.2 Wave Directions by season for General Refraction

a. Proportion of waves by direction and season - Dowsing Data

	N.E.	E.	S.E.	Calm
Winter	25%	15%	20.56%	39.44%
Spring	39.56%	22.53%	12.64%	25.27%
Summer	16.85%	9.78%	23.37%	50%
Autumn	16.30%	14.13%	16.85%	52.72%

b. Proportion of low/medium and medium/high energy waves from each direction, by season - Ocean Wave Statistics

	N.E.		E.		S.E.	
	L/M %	M/H %	L/M %	M/H %	L/M %	M/H
Winter	66.44	28.86	78.08	21.92	71.51	28.49
Spring	72.49	27.51	65.55	34.45	70.16	29.84
Summer	80.10	19.90	75.73	24.27	73.15	26.85
Autumn	83.56	16.44	82.52	17.48	75.38	24.62

L/M = Low to medium energy M/H = medium to high energy

These then are the 2 sets of direction data which will be used later to allocate the results of the refraction program.

Refraction of waves: A bathymetric grid (Grid 1) covering 40-45 km of coast and extending a similar distance offshore was constructed from Admirality charts (Nos. 121 and 129, 1974 revised 1982). Depths were recorded every 750 m , these points constituting the corners of the grid units. The rays were started away from the margins of the grid about 37 km from the shore to avoid edge effects.

Wave refraction was carried out for the representative seasonal periods and for each of the low/medium and medium/high energy conditions shown in Table 3.1, from each direction of approach, i.e. N.E., E. and S.E.. Figure 3.1 shows a represenative example of a refraction diagram from the N.E. and E. Total wave power, longshore wave power and wave direction were produced.

The correction for coastal orientation (see Section 2.2 a) was applied and the angle of wave approach to the shore re-calculated;

$$\beta = 90 + \alpha - \text{ANGLE} \qquad (3.1)$$

α = angle between shore and positive x-axis of the grid at point of interest (Appendix 2.2)

ANGLE = angle between incoming rays and the positive x-axis from the refraction results

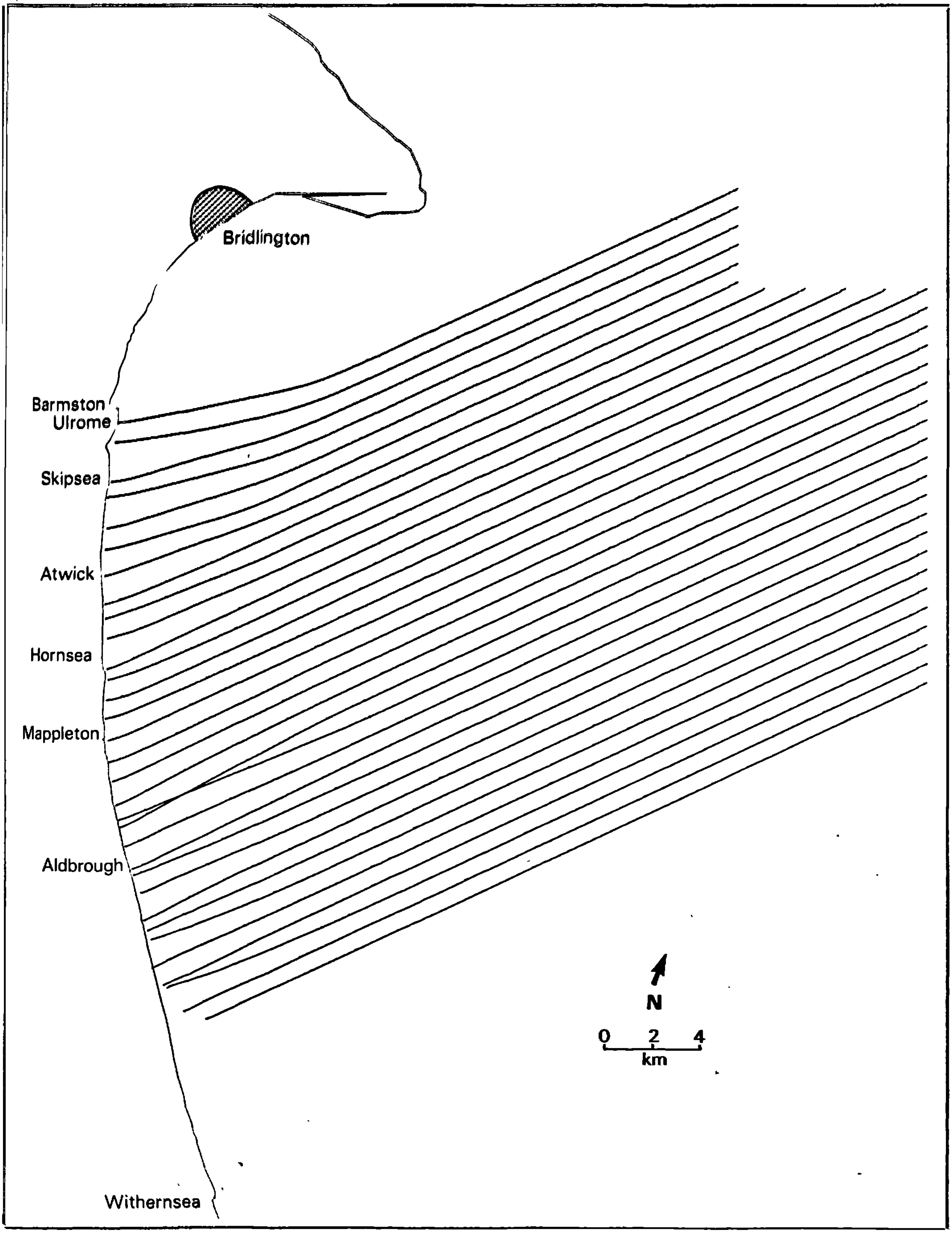
β = angle between vector of net energy and longshore direction

Figure 3.1 Diagrams of General Refraction.

a. Waves from the N.E.

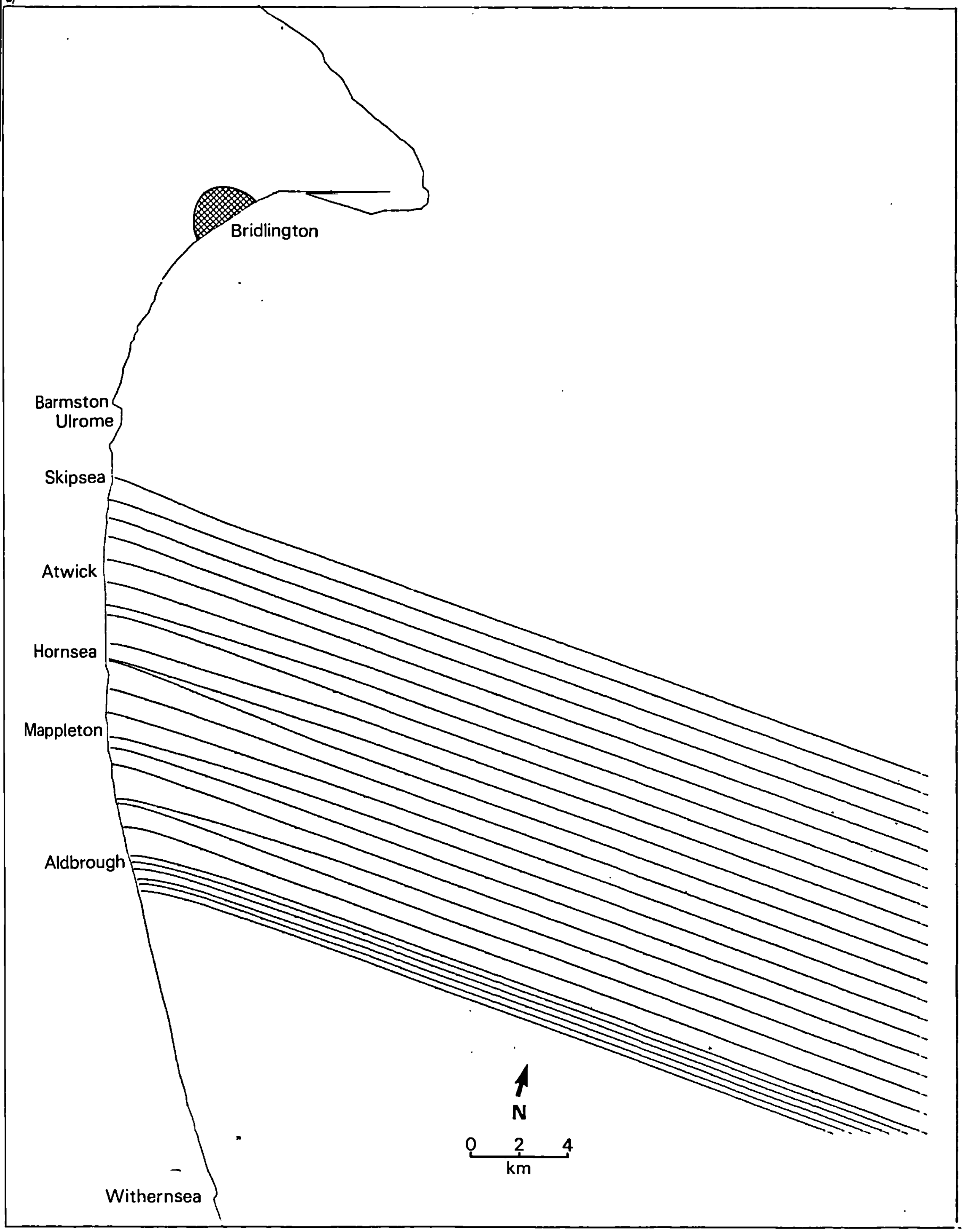
b. Waves from the E.

(a)



Bridlington
Barmston
Ulrome
Skipsea
Atwick
Hornsea
Mappleton
Aldbrough
Withernsea
N
0 2 4
km

(b)



Bridlington
Barmston
Ulrome
Skipsea
Atwick
Hornsea
Mappleton
Aldbrough
Withernsea
N
0 2 4
km

When β is positive this indicates a northwards net energy flux and sediment movement; a negative β indicates southwards movement. From the corrected β value and the total wave power P from refraction, the longshore component of wave power or energy flux, P_ℓ, can be calculated.

$$P_\ell = P \sin\beta \cos\beta \quad \text{from Komar (1976a)} \qquad (3.2)$$

The coast was then divided into a number of "cells" each comprising the equivalent of 5 units on the depth grid, i.e. 3.75 km long, and the mean P_ℓ calculated for each cell. (Table 3.3). Cell "e" represents the field site covered by cells (iv) and (v) in Figure 2.4. The P_ℓ values were then allocated according to the proportions of different conditions obtained from the wave data. Two sets of results were calculated - firstly making the assumption that from each direction 65% of waves were low/medium energy and 35% medium/high energy. The overall proportions of directions are those in Table 3.2 a. Secondly, the data from the Ocean Wave Statistics were used, which allowed for different proportions of lower and higher energy from each direction (Table 3.1 b).

The general equation for calculating the resultant longshore wave power using the 65%/35% allocation (Table 3.2 a) is;

$$P_{\ell R} = \%N.E.\ P_{\ell NE} + \%E.\ P_{\ell E} + \%S.E.\ P_{\ell SE} + \%calm\ P_{\ell calm} \qquad (3.3)$$

where $P_{\ell R}$ = resultant longshore wave energy flux, $JS^{-1}m^{-1}$

$$P_{\ell NE} \text{ etc.} \equiv \%\ \text{low/medium energy waves} \times P_{\ell \ell m_{NE}} + \%\ \text{medium/high energy waves} \times P_{\ell mh_{NE}} \qquad (3.4)$$

($P_{\ell \ell m_{NE}}$ = longshore power of low/medium energy waves from N.E.)

Table 3.3 P_{ℓ} values from General Refraction ($Jm^{-1}s^{-1}$)

cell		d	e	f	g	h	i
Winter							
NE	$P_{\ell\ell m}$	-128.98	-299.38	-287.31	-229.88	-172.44	-184.97
	$P_{\ell mh}$	-428.20	-871.54	-788.14	-823.66	-540.88	-377.85
E	$P_{\ell\ell m}$	+137.27	+174.99	+268.94	+286.85	+265.31	+214.87
	$P_{\ell mh}$	+612.55	+614.20	+841.81	+918.79	+1092.56	+854.47
SE	$P_{\ell\ell m}$	+363.66	+482.74	+623.29	+460.29	+297.29	+518.47
	$P_{\ell mh}$	+1225.84	+1411.63	+1587.03	+1260.70	+934.37	+1184.82
Spring							
NE	$P_{\ell\ell m}$	-67.35	-181.70	-149.22	-135.52	- 87.74	-100.98
	$P_{\ell mh}$	-361.13	-669.53	-684.86	-586.78	-389.93	-436.84
E	$P_{\ell\ell m}$	+105.92	+ 98.11	+158.67	+141.76	+206.54	+117.91
	$P_{\ell mh}$	+441.82	+425.15	+603.02	+660.08	+840.84	+547.15
SE	$P_{\ell\ell m}$	+269.01	+3.9.69	+319.69	+284.16	+176.83	+349.70
	$P_{\ell mh}$	+1028.56	+509.60	+1129.08	+936.08	+742.65	+1023.81
Summer							
NE	$P_{\ell\ell m}$	- 67.35	-181.70	-149.22	-135.52	- 87.74	-100.98
	$P_{\ell mh}$	-232.34	-537.76	-510.12	-444.94	-354.36	-356.78
E	$P_{\ell\ell m}$	+105.92	+ 98.11	+158.67	+141.76	+205.54	+117.91
	$P_{\ell mh}$	+372.19	+359.06	+515.88	+549.17	+701.62	+497.20
SE	$P_{\ell\ell m}$	+269.01	+319.69	+391.50	+284.17	+176.83	+349.70
	$P_{\ell mh}$	+700.90	+898.62	+1033.56	+798.84	+564.12	+813.02
Autumn							
NE	$P_{\ell\ell m}$	-209.80	-465.60	-444.05	-389.80	-259.32	-270.15
	$P_{\ell mh}$	-854.43	-1909.80	-1948.18	-1840.06	-1271.65	-1270.73
E	$P_{\ell\ell m}$	+306.22	+290.92	+424.03	+455.59	+566.04	+365.66
	$P_{\ell mh}$	+1269.17	+1409.60	+1807.12	+2084.33	+2400.79	+1964.51
SE	$P_{\ell\ell m}$	+631.47	+716.64	+936.58	+706.92	+477.27	+743.79
	$P_{\ell mh}$	+3110.17	+1844.24	+2746.86	+2699.68	+2652.46	+2199.90

$P_{\ell\ell m}$ = longshore wave power for low/medium energy conditions
$P_{\ell mh}$ = longshore wave power for medium/high energy conditions
-ve = alongshore power component towards the south

% NE = % of waves from the north-east

The specific equation for winter would be:

$$P_{\ell R} = 25\% \, (65\% \, P_{\ell \ell m_{NE}} + 35\% \, P_{\ell mh_{NE}}) + 15\% \, (65\% \, P_{\ell \ell m_{E}} + 35\% \, P_{\ell mh_{E}}) + 20.56\% \, (65\% \, P_{\ell \ell m_{SE}} + 35\% \, P_{\ell mh_{SE}}) + 0 \qquad (3.5)$$

Using ocean wave statistic proportions of low/medium and medium/high energy gives similar equations but the percentages of $P_{\ell \ell m}$ and $P_{\ell mh}$ vary from season to season. For example in winter the formula would be:

$$P_{\ell R} = 25\% \, (66.44\% \, P_{\ell \ell m_{NE}} + 28.86\% \, P_{\ell mh_{NE}}) + 15\% \, (78.08\% \, P_{\ell \ell m_{E}} + 21.92\% \, P_{\ell mh_{E}}) + 20.56\% \, (71.51\% \, P_{\ell \ell m_{SE}} + 28.49\% \, P_{\ell mh_{SE}}) \qquad (3.6)$$

All eight equations are listed in Appendix 3.1.

Potential sediment movement: The analysis described in the previous sections resulted in a (mean) $P_{\ell R}$ value for each cell in each season. (Table 3.4). A negative value indicates a movement towards the south, and a positive one movement towards the north. The potential sediment movement induced by the incident wave energy can then be calculated. Two equations were chosen, mainly because they had been derived for sandy beaches. The first equation was that presented by Allen (1981):

$$S_{\ell} = 40.6618 \, P_{\ell} \qquad (3.7)$$

Where S_{ℓ} is the longshore sediment transport rate in yd^3/day

P_{ℓ} is longshore wave power in ft-lb-s

(both per m length of beach)

When converted to SI units this becomes:

Table 3.4 Sediment Movement from General Wave Refraction

Season	Cell / Parameter	d DG	d OWS	e DG	e OWS	f DG	f OWS	g DG	g OWS	h DG	h OWS	i DG	i OWS
A Winter	$P_{\ell R}$ $Jm^{-1}s^{-1}$	121.87	131.28	90.49	98.59	152.27	159.94	156.10	124.00	124.60	127.08	157.23	160.98
	$\overline{Q_\ell}$ m^3/day	$3.14x10^2$	$3.37x10^2$	$2.32x10^2$	$2.53x10^2$	$3.9x10^2$	$4.11x10^2$	$4.01x10^2$	$3.18x10^2$	$3.2x10^2$	$3.27x10^2$	$4.04x10^2$	$4.14x10^2$
	$\overline{Q_\ell}$ m^3/season	$2.82x10^4$	$3.04x10^4$	$2.09x10^4$	$2.28x10^4$	$3.52x10^4$	$3.70x10^4$	$2.60x10^4$	$2.86x10^4$	$2.88x10^4$	$2.94x10^4$	$3.64x10^4$	$3.72x10^4$
B Spring	$P_{\ell R}$ $Jm^{-1}s^{-1}$	50.64	53.97	-42.73	-29.91	19.74	30.24	21.48	29.96	67.38	71.86	47.99	53.00
	$\overline{Q_\ell}$ m^3/day	$1.30x10^2$	$1.39x10^2$	$-1.10x10^2$	$-0.77x10^2$	$0.51x10^2$	$0.78x10^2$	$0.55x10^2$	$0.77x10^2$	$1.73x10^2$	$1.85x10^2$	$0.51x10^2$	$1.36x10^2$
	$\overline{Q_\ell}$ m^3/season	$1.18x10^4$	$1.26x10^4$	$-1.00x10^4$	$-0.70x10^4$	$0.46x10^4$	$0.71x10^4$	$0.50x10^4$	$0.70x10^4$	$1.58x10^4$	$1.68x10^4$	$1.12x10^4$	$1.24x10^4$
C Summer	$P_{\ell R}$ $Jm^{-1}s^{-1}$	96.58	89.82	66.57	61.99	125.32	118.54	95.24	89.02	79.64	73.86	112.03	105.74
	$\overline{Q_\ell}$ m^3/day	$2.48x10^2$	$2.31x10^2$	$1.71x10^2$	$1.59x10^2$	$3.22x10^2$	$3.04x10^2$	$2.44x10^2$	$2.29x10^2$	$2.04x10^2$	$1.90x10^2$	$2.88x10^2$	$2.72x10^2$
	$\overline{Q_\ell}$ m^3/season	$2.28x10^4$	$2.12x10^4$	$1.57x10^4$	$1.46x10^4$	$2.96x10^4$	$2.80x10^4$	$2.30x10^4$	$2.10x10^4$	$1.88x10^4$	$1.74x10^4$	$2.64x10^4$	$2.50x10^4$
D Autumn	$P_{\ell R}$ $Jm^{-1}s^{-1}$	272.50	24.11	125.4	121.68	234.71	214.30	235.29	203.98	279.45	226.56	240.82	205.49
	$\overline{Q_\ell}$ m^3/day	$7.00x10^2$	$6.20x10^2$	$3.22x10^2$	$3.12x10^2$	$6.03x10^2$	$5.55x10^2$	$6.04x10^2$	$5.24x10^2$	$7.18x10^2$	$5.82x10^2$	$6.19x10^2$	$5.28x10^2$
	$\overline{Q_\ell}$ m^3/season	$6.44x10^4$	$5.7x10^4$	$2.96x10^4$	$2.88x10^4$	$5.55x10^4$	$5.06x10^4$	$5.56x10^4$	$4.82x10^4$	$6.60x10^4$	$5.36x10^4$	$5.70x10^4$	$4.86x10^4$
E Year	Total $\overline{Q_\ell}$ m^3	$12.72x10^4$	$12.12x10^4$	$5.62x10^4$	$5.92x10^4$	$12.49x10^4$	$12.29x10^4$	$11.96x10^4$	$10.48x10^4$	$12.94x10^4$	$11.72x10^4$	$13.10x10^4$	$12.32x10^4$

Key: $\overline{Q_\ell}$ = sediment transport rate; P_{1R} = resultant longshore wave power; DG = 65%/35% energy allocation; cell "e" is Field site
OWS = ocean wave statistics energy allocation; -ve = southwards drift; +ve = northwards drift.

$$S_\ell = 2.05 \times 10^{-5} P_\ell \qquad S_\ell \text{ in } m^3s^{-1},\ P_\ell \text{ in } Jm^{-1}s^{-1} \qquad (3.8)$$
$$= 1.77\ P_\ell \qquad S_\ell \text{ in } m^3/\text{day}$$

The second formula is that of Vincent (1979) where the SI form for calculating Q, the longshore sediment transport rate,is:

$$Q = 3.9 \times 10^{-5} P_\ell \qquad Q \text{ in } m^3s^{-1},\ P_\ell \text{ in } Jm^{-1}s^{-1} \qquad (3.9)$$
$$= 3.37\ P_\ell \qquad Q \text{ in } m^3/\text{day}$$

It was decided that the mean of the results of equations 3.8 and 3.9 would provide a representative value of sediment movement on a sandy beach. This quantity was designated $\overline{Q}_\ell$, and the equivalent equations for calculating the daily and seasonal transport rates are:

$$\overline{Q}_\ell = 2.57\ P_\ell \qquad \overline{Q}_\ell \text{ in } m^3/\text{day},\ P_\ell \text{ in } Jm^{-1}s^{-1} \qquad (3.10)$$
$$= \chi P_\ell \qquad \overline{Q}_\ell \text{ in } m^3/\text{season} \qquad \chi = 231.30 \text{ in winter}$$
$$\chi = 233.87 \text{ in spring}$$
$$\chi = 236.44 \text{ in summer and autumn}$$

Daily, seasonal and annual $\overline{Q}_\ell$ values were calculated from the $P_{\ell R}$ values obtained from both the 65%/35% and ocean wave statistic allocations of energy,and the results are presented in Table 3.4 (A-E).The errors involved in such calculations will be discussed in Section 4.2

Results

From the Dowsing winter data the positive resultant P_ℓ value for each cell indicates a movement of sediment towards the north (contrary to previous results obtained on this coast). In Table 3.4 A the $P_{\ell R}$ values range from 90Js^{-1} per metre length of beach (Jm^{-1}s^{-1}) to 157 Jm^{-1}s^{-1}; the variation does not seem to exhibit any definite longshore trend, though there may be a slightly increased rate in the south. This produces a mean sediment transport ranging from 2.32 x 10^2 m^3/day to 4.04 x 10^2 m^3/day per metre length of beach, though it must be remembered that direction could not be matched up with specific waves at Dowsing.

For the case where the ocean wave statistics data were used to allocate the proportions of higher and lower energy waves by directions, the results show slightly higher $P_{\ell R}$ values; consequently sediment movement varied from 2.53 x 10^2 m^3/day to 4.14 x 10^2 m^3/day, but the direction of movement remained constant.

In spring (Table 3.4 B) all but one of the cells gave positive $P_{\ell R}$ values (the one negative value might have been excluded by smoothing). Spring values were very much lower than winter; the standard energy allocation yielded mean sediment movement rates from -1.10 x $10^2 m^3$/day to 1.73 x $10^2 m^{/}$/day (both per metre length of beach). When higher and lower energy conditions were allocated according to the ocean wave statistic (OWS) data the northwards trend was greater, -0.77 x 10^2 m^3/day to 1.85 x 10^2 m^3/day.

Summer values (Table 3.4 C) again indicate a movement towards the north, greater than that in spring. This time, however, the appropriate allocation of higher and lower energy waves from each direction leads to a reduction in rates. The standard allocation of energies (65% low/medium energy and 35% medium/high energy from each direction) gives rates of movement from 1.71 x 10^2 m^3/day to 3.22 x 10^2 m^3/day. Under the OWS transformation the equivalent values are 1.59 x 10^2 m^3/day to 3.04 x 10^2 m^3/day.

Autumn values (Table 3.4 D) without specific energy allocation by direction range from 2.96 x 10^2 m^3/day to 6.60 x 10^2 m^3/day, reduced to 3.12 x 10^2 m^3/day to 5.82 x $10^2 m^3$/day when the OWS proportions were used; movement is still in a northwards direction.

Summary results are presented for the year as a whole (Table 3.4 E) showing a net movement towards the north, the annual mean over all cells being approximately 11.0 x 10^4 m^3.

Field Site Refraction

This "run" set out to investigate in more detail the wave energy distribution, and hence sediment movement, along a smaller section of the Holderness coast which included the field site (cell "e" in the general experiment). This time the wave data used had been measured within the field site, and were of very high quality.

Wave data: This second set of wave data was obtained from a wave recorder (IOS Pressure Type Recorder - type 5255, see Plate 2.1) installed 1 km offshore from the field site (Figure 2.4). These data comprised H_s (significant wave height), T (wave period) and tidal level, for a 12 minute sample in each three hour period. The H_s and T values are plotted on a graph of the whole month. Another diagram comprises a plot of the percentage exceedence of significant wave height values, and a third shows the percentage occurrence of wave periods. The wave height and period record for September 1983 to September 1984 obtained from the wave recorder is shown in Appendix 3.2). Wave directions were recorded once or twice a day by the coastguards at Flamborough Head and Hornsea. These directions were entered on the wave recorder graph. This is the longest continuous record available for this, and indeed most other, areas.

In order to allocate correctly the results from the refraction program the frequency of occurrence of N.E., E. and S.E. waves and the proportions of high, medium and low energy within each of these classes must be known. These data were dealt with on a monthly basis and a frequency table drawn up for wave height and direction - see Figure 3.2a for an example of the January 1984 waves, and directions from the Hornsea coastguard. Similar tables were prepared for Hornsea and Flamborough Head directions for each month.

When directions were given as N.N.E., E.N.E., E.S.E. and S.S.E. they were assigned equally to the directions on either side, i.e.

Figure 3.2 Frequency of Wave Heights by Direction for Field site Refraction: January 1984, Hornsea direction data.

(a)

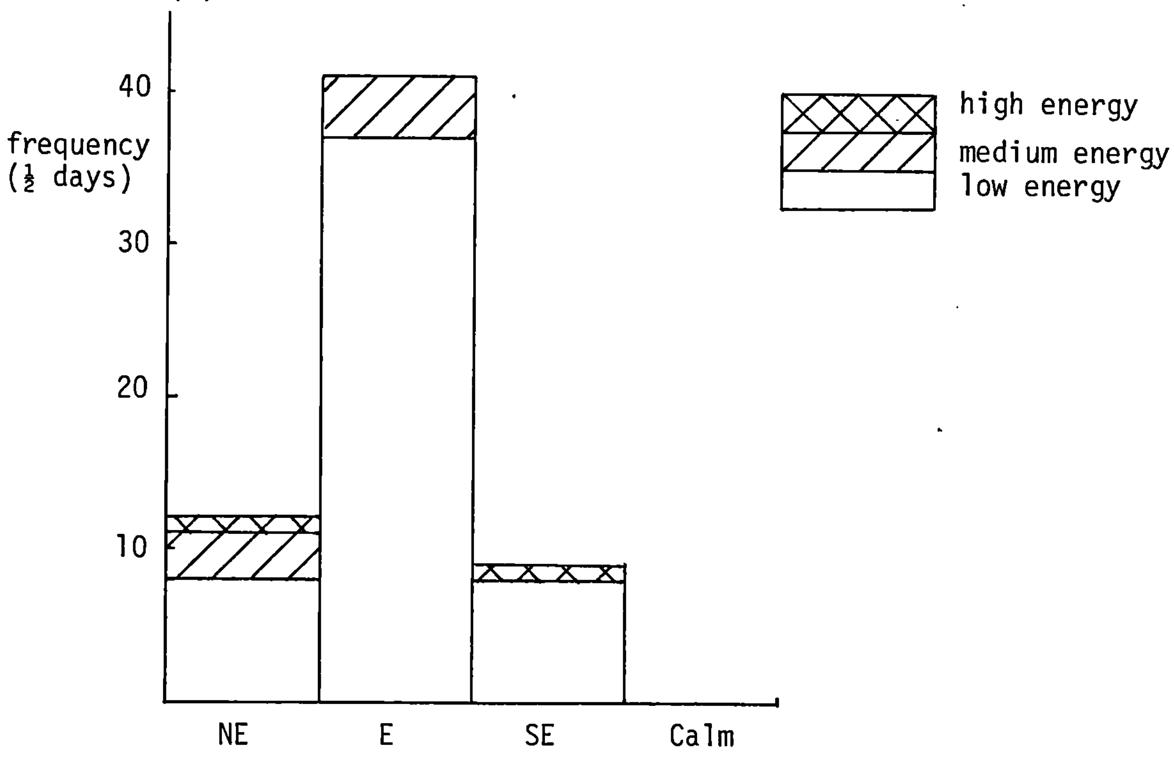
Wave Height (m)	NE	E	SE
0-0.25		10	3
0.26-0.5	5	17	
0.51.0.75	2	8	2
0.76-1.00	1	2	1
1.01-1.25	1	1	
1.26-1.50	1	2	1
1.51-1.75		1	1
1.76-2.00	1		
2.01-2.25			
2.26-2.50			
2.51-2.75	1		
2.76-3.00			
3.01-3.25			1
Totals	12	41	9

T = 62

3.22% high energy ($H > 2m.$)
14.52% medium energy ($1m < H \leqslant 2m.$)
82.26% low energy ($H \leqslant 1m.$)

19.35% from NE
66.13% from E
14.52% from SE

(b)



N., N.E., E., S.E. and S. For Flamborough data N. and S. directions occasionally occur, one quarter of these occurrences were assigned to the N.E. or S.E., the rest were regarded as being insignificant for the study beach and were excluded, as were directions from the western half of the compass. For this reason the Hornsea directions were preferred in the final calculation of sediment movement, and also because they were measured closer to the field site and would thus reflect the conditions at the Atwick wave recorder site, 3 km to the north, better. "Calm" conditions prevailed when waves were less than 0.05 m high and were regarded as being insignificant in terms of sediment movement.

The data were then plotted on a histogram (e.g. Figure 3.2 b), and the percentage of time for which the waves from each direction possessed high, medium and low energy evaluated. These percentages were aggregated to give seasonal values (Table 3.5).

Refraction and derivation of $P_{\ell R}$: A similar procedure was adopted to that used in the general Holderness run. The wave data had been recorded much closer to the shore and a smaller more dense grid was used (Grid 2), with units of side 375 m Bathymetry was extracted from the same Admiralty charts and the starting points of the rays were set at three cell widths from the shore (1125 m), the wave data having been recorded at about 1000m from the coast.

Once again wave approach directions from the N.E., E. and S.E. were considered, and the practice of aggregating data over a three-month-long season was repeated. For each season a representative wave period was selected (the one which occurred most frequently and had the greatest percentage of occurrences within $\pm$ 1 second of it). Wave heights of 0.5 m , 1.5 m and 2.5 m were chosen to represent

Table 3.5 Percentage of N.E., E. and S.E. waves by season, and Percentage of high, medium and low energy waves by direction and season for field site refraction

HE = high energy ME = medium energy LE = low energy

Season			Direction N.E.	E.	S.E.
Winter	Overall %		24.49	63.78	10.59
	% energy by direction	HE	4.11	--	5.55
		ME	11.00	13.85	--
		LE	84.89	86.15	94.45
Spring	Overall %		28.93	34.32	5.72
	% energy by direction	HE	--	--	--
		ME	11.76	1.67	--
		LE	88.24	98.33	100
Summer	Overall %		24.03	35.48	2.71
	% energy by direction	HE	--	--	--
		ME	3.17	4.44	--
		LE	96.83	95.56	100
Autumn	Overall %		36.08	45.16	13.96
	% energy by direction		1.67	1.20	--
			16.67	6.02	7.69
			81.67	92.77	92.31

low, medium and high energy conditions in the ranges 0-1.0 m , 1.01 m -2.0 m and over 2.0 m. The wave refraction program was then used for each combination, i.e. a maximum of 36 runs; four seasons having different periods, each of which had three directions of approach for each of its three wave heights. The wave periods were 7.0s for winter, 7.5s for spring, 8.5s for summer and 9.5s for autumn.

The resulting P_ℓ values were corrected for shore orientation as explained before, and again mean values calculated for cells of 5 units on the bathymetric grid, i.e. 1.875 km ; these cells can be seen in Figure 2.4. The results for P_ℓ are shown in Table 3.6.

Table 3.6 P_l Values from Field Site Refraction ($Jm^{-1}S^{-1}$)

Key; LE, ME, HE = low, medium and high energy waves; • later altered by smoothing; -ve = southwards drift; +ve = northwards drift; na = not applicable

Cell		(ii)	(iii)	(iv)	(v)	(vi)	(vii)
Winter							
NE	HE	-7647.01•	-6035.43	-6572.50	-5297.42	-4778.79•	-4868.50
	ME	-2390.27	-1562.50	-1871.14	-1514.86	-1451.44•	-1226.35
	LE	- 193.85	- 91.32	- 132.86	- 101.88•	- 28.02•	- 76.06
E	HE	4062.15	4452.47	3322.38	2692.24	4059.42	4655.79
	ME	1250.42	1034.80•	859.34	873.14•	1189.46•	1002.73
	LE	110.16	75.84	52.60	99.32•	123.80•	39.20•
SE	HE	7733.91	9128.49	7156.41	6291.76•	5023.31•	6774.89
	ME	2639.46	2524.99	2151.95	1981.20	1826.39	1828.88
	LE	208.88	166.10	170.66	147.98•	180.87•	121.11
Spring							
NE	HE	na	na	na	na	na	na
	ME	-1556.01	-1742.12	-1931.67	-1582.99	-1524.78	-1255.49•
	LE	- 178.03	- 107.56	- 138.45	- 112.12	- 30.19	- 82.90
E	HE	na	na	na	na	na	na
	ME	679.46	1110.53	899.60	1195.86	2185.75•	1042.89
	LE	- 8.03•	83.80	52.81	7.63•	302.22	40.32
SE	HE	na	na	na	na	na	na
	ME	na	na	na	na	na	na
	LE	200.21	181.13	177.81	202.68•	187.46	132.90
Summer							
NE	HE	-8811.75	-6962.57	-7552.22	-6113.75	-5436.46	-5625.80
	ME	-2737.31	-1829.78	-2152.90	-1706.96	-2571.75•	-1424.46•
	LE	- 230.17	- 108.89	- 156.10	- 127.36•	- 36.93	- 99.80
E	HE	4612.85	4653.74	3868.66	2859.45	4686.74•	5496.11
	ME	1470.44	1266.49•	991.64	981.14	1358.20	1192.17
	LE	132.20	55.11•	60.30	43.10	145.32•	49.86
SE	HE	8951.64	10098.08	7998.98	6554.24	6760.91	7716.63
	ME	2643.06	2989.53	2443.75	2229.22	1596.90	2186.98
	LE	195.61	207.15	192.81	161.68•	130.98•	154.02
Autumn							
NE	HE	-10103.50•	-7728.82	-8229.57	-6776.99	-6578.36•	-6012.09
	ME	-3003.56	-2098.95	-2376.24	-1958.26	-1863.44•	1577.73 •
	LE	- 256.28•	- 121.68	- 173.35	- 121.59•	+ 45.32•	- 117.00
E	HE	5015.08	5053.95•	4247.52	3777.11•	6400.08•	6285.56•
	ME	1640.45	1430.36	1110.07	865.90	1588.13	1344.37
	LE	147.47	106.40	68.59•	139.79	160.37•	55.76•
SE	HE	7834.55	1049.50	8707.69	6564.42	7334.00	8423.74
	ME	2637.70	3407.79	2658.51	2950.81	1772.01•	2445.40
	LE	199.31	233.16	210.39	198.96	123.47•	174.59

The wave refraction diagrams were plotted, three examples of which are presented in Figure 3.3

The proportions of wave energy from the different directions and the overall proportions of these directions, shown in Table 3.5, were used to produce resultant P_ℓ values for each cell in each season. These results are presented in Table 3.7. The general formula used to calculate them is:

$$P_{\ell R} = \%NE\,(\%HE_{NE}P_{\ell HN} + \%\,ME_{NE}P_{\ell MN} + \%\,LE_{NE}P_{\ell LN}) + \%E\,(\%HE_{E}P_{\ell HE} + \%ME_{E}P_{\ell ME} + \%LE_{E}P_{\ell LE}) + \%SE\,(\%HE_{SE}P_{\ell HS} + \%ME_{SE}P_{\ell MS} + \%LE_{SE}P_{\ell LS}) \qquad (3.11)$$

Where $P_{\ell R}$ = resultant longshore power

$\%NE, \%E, \%SE$ = % of time for which waves from each direction prevail

$\%HE_{NE}$ etc = % of time for which NE waves possess high energy (HE)

$P_{\ell HN}, P_{\ell LE}$ etc = longshore wave power for (1) high energy waves from the NE and (2) low energy waves from the E etc, obtained from refraction results.

Table 3.7 $P_{\ell R}$ values from Field Site Data ($Jm^{-1}s^{-1}$)

Cell	(ii)	(iii)	(iv)	(v)	(vi)	(vii)
Season			⊢ Field Site	⊣		
Winter	55.67	81.51	19.76	68.17	127.67	63.95
Spring	- 85.77	-41.75	- 67.93	- 61.48	54.36	- 37.41
Summer	- 1.15	4.97	- 13.58	- 8.19	46.03	5.78
Autumn	-129.48	-31.18	-106.00	-134.55	-10.02	22.87

+ve northwards drift; -ve southwards drift

Additional Weighting of Wave Power

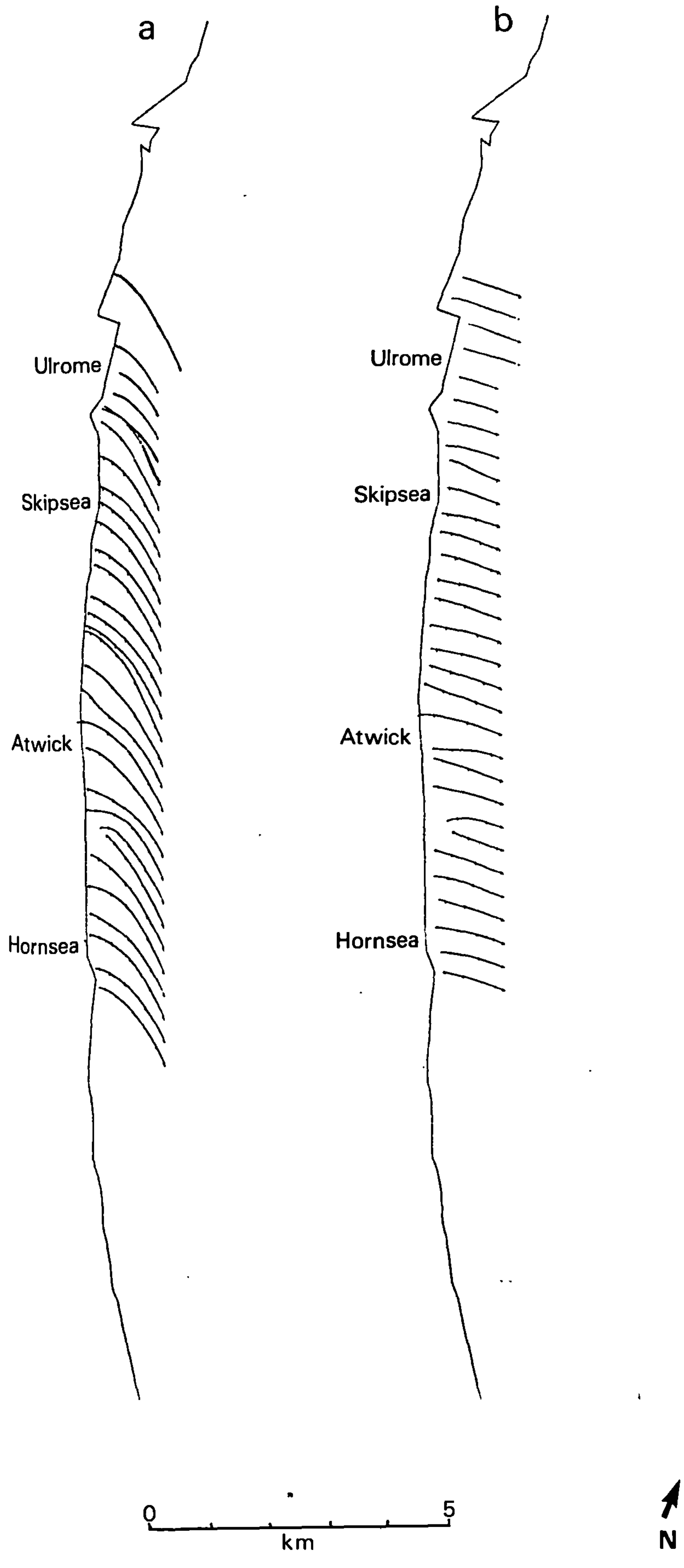
It was not until all the $P_{\ell R}$ calculations had been carried out that it became apparent that some modifications were necessary. The H_s values of 0.5 m , 1.5 m , and 2.5 m seemed to involve a certain

Figure 3.3 Diagrams of Field Site Refraction.

a Waves from the S.E.

b Waves from the E.

c Waves from the N.E.


a
b
c
Ulrome
Skipsea
Atwick
Hornsea
Ulrome
Skipsea
Atwick
Hornsea
Ulrome
Skipsea
Atwick
Hornsea
0
5
km
N

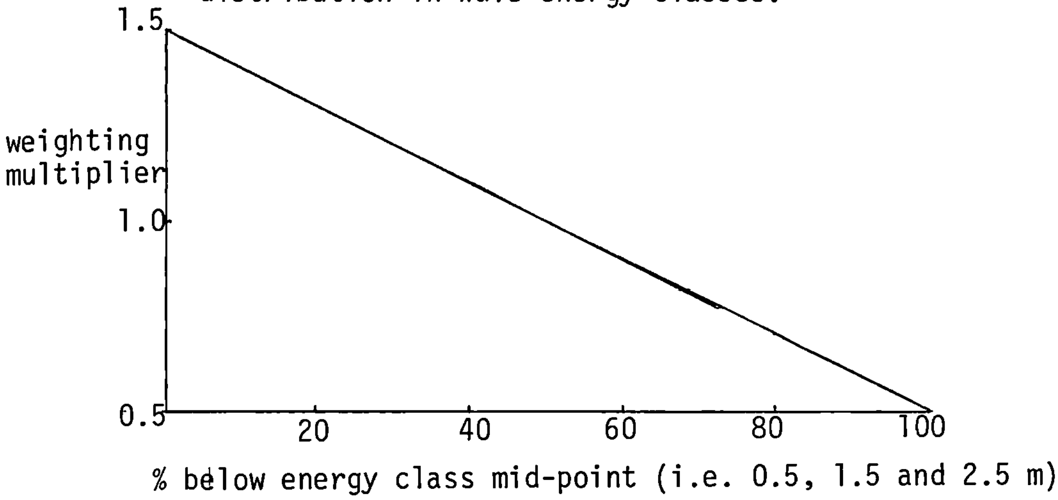
amount of bias; using these values as mid-points of the energy classes having heights 0.0-1.0 m , 1.01-2.0 m and >2.0 m, it had been assumed that a normal or at least symmetrical frequency distribution existed. It transpired after a year's data had been collected that this was not the case (e.g. Table 3.8). Some sort of weighting system had to be applied. For each season and for each direction of wave approach a wave height tally table was plotted for 0.25 m intervals, and a weighting derived to obtain more representative wave energies. Table 3.8 shows an example of a tally table for winter, those for the other seasons are in Appendix 3.3. If 50% of observations were above the mid-value, then no adjustment was

Table 3.8 Tally Table showing Asymmetry of Wave Height Frequencies

Winter	NE waves		E waves		SE waves	
Wave height (m)	frequency		frequency		frequency	
0.0-0.25	7	total = 38	31	total = 99	9	total = 16
0.26-0.50	10	% < .5 m	46	% < .5 m	1	% < .5 m
0.51-0.75	10	= 45	15	= 78	4	= 62.5
0.76-1.00	11		7		2	
1.01-1.25	1	total = 5	8	total = 16		total = 2
1.26-1.50	2	% < 1.5 m	6	% < 1.5 m	1	% < 1.5 m
1.51-1.75	0	= 60	2	= 87.5		= 50
1.76-2.00	2					
2.01-2.25		total = 2				
2.26-2.50	1	% < 2.5				
2.51-2.75	1	= 50				
2.76-3.00						

necessary and the weighting was 1.0. If more than 50% fell below the mid-point wave height then the representative wave height used was too high and consequently the P_L values too large. A weighting of less than 1.0 was applied to the previous percentage value. The weightings were obtained from the curve in Figure 3.4.

Figure 3.4 Weighting "Curve" to compensate for skewed frequency distribution in wave energy classes.



The following formula gives an example of the application of this weighting to P_{ℓ} values for waves from the N.E.

$$P_{\ell NE} = WV_{2.5} \times \%HE_{NE} \times P_{\ell HN} + WV_{1.5} \times \%ME_{NE} \times P_{\ell MN} + WV_{0.5} \times \%\,LE_{NE} \times P_{\ell LN} \quad (3.12)$$

$WV_{2.5}$ = weighting for 2.5 m (high energy) waves

$\%HE_{NE}$ = % of high energy waves from the N.E.

$P_{\ell HN}$ = longshore component of wave power for high energy waves from the N.E.

For winter this becomes:

$$P_{\ell NE} = 1.0 \times 4.11\% \times P_{\ell HN} + 0.9 \times 11.0\% \times P_{\ell MN} + 1.05 \times 84.89\% \times P_{\ell LN}$$

$$= 4.11\%\ P_{\ell HN} + 9.90\%\ P_{\ell MN} + 89.13\%\ P_{\ell LN} \quad (3.13)$$

The corresponding equations for the other directions and seasons are in Appendix 3.4.

Following this adjustment the direction frequencies were applied as before to give a new resultant $P_{\ell R}$. The post-weighting P_{ℓ} values can be seen in the top rows of the seasonal results in Table 3.10.

Table 3.9 Sediment Transport: Field Site Data, before weighting or smoothing

Season	Cell / Parameter	(ii)	(iii)	(iv)	(v)	(vi)	(vii)
Winter	$P_{\ell R}$ $Jm^{-1}s^{-1}$	150.25	208.63	109.02	121.02	236.10	216.29
	$\overline{Q}_{\ell}$ m^3/day	38.61x10	53.62x10	28.02x10	31.10x10	60.68x10	55.58x10
	$\overline{Q}_{\ell}$ m^3/season	34.73×10^3	48.22×10^3	25.20×10^3	27.97×10^3	54.58×10^3	50.00×10^3
Spring	$P_{\ell R}$ $Jm^{-1}s^{-1}$	-85.77	-41.75	-67.93	-61.48	54.36	-37.41
	$\overline{Q}_{\ell}$ m^3/day	-22.04x10	-10.73x10	-17.46x10	-15.80x10	13.97x10	-9.62x10
	$\overline{Q}_{\ell}$ m^3/season	-20.06×10^3	-9.76×10^3	-15.88×10^3	-14.38×10^3	12.72×10^3	-8.75×10^3
Summer	$P_{\ell R}$ $Jm^{-1}s^{-1}$	-1.15	4.97	-13.58	-8.19	46.03	5.78
	$\overline{Q}_{\ell}$ m^3/day	-0.29x10	1.28x10	-3.49x10	-2.10x10	11.83x10	1.48x10
	$\overline{Q}_{\ell}$ m^3/season	-0.28×10^3	1.18×10^3	-3.2×10^3	-1.94×10^3	10.88×10^3	1.36×10^3
Autumn	$P_{\ell R}$ $Jm^{-1}s^{-1}$	-129.48	-31.18	-106.00	-34.55	-10.02	-22.87
	$\overline{Q}_{\ell}$ m^3/day	-33.28x10	-8.02x10	-27.24x10	-8.88x10	-2.58x10	-5.88x10
	$\overline{Q}_{\ell}$ m^3/season	-30.61×10^3	-7.38×10^3	-25.06×10^3	-8.16×10^3	-2.37×10^3	-5.40×10^3

Key: -ve southwards drift; +ve northwards drift

$\overline{Q}_{\ell}$ = sediment transport rate

Table 3.10 Sediment Transport: Field Site Data, after weighting

Season	Cell / Parameter	(ii)	(iii)	(iv)	(v)	(vi)	(vii)
Winter	$P_{\ell R}$ $Jm^{-1}s^{-1}$	-8.70	40.44	-9.10	16.14	51.32	34.68
	$\overline{Q}_{\ell}$ m^3/day	-2.24x10	10.90x10	-2.33x10	4.15x10	13.18x10	8.92x10
	$\overline{Q}_{\ell}$ m^3/season	-2.01×10^3	9.81×10^3	-2.10×10^3	3.74×10^3	11.86×10^3	8.02×10^3
Spring	$P_{\ell R}$ $Jm^{-1}s^{-1}$	-62.35	-30.72	-48.32	-41.03	34.21	-25.93
	$\overline{Q}_{\ell}$ m^3/day	-16.02x10	-7.98x10	-12.42x10	-10.54x10	8.80x10	-6.66x10
	$\overline{Q}_{\ell}$ m^3/season	-14.58×10^3	-7.18×10^3	-11.30×10^3	-9.6×10^3	8.00×10^3	-6.06×10^3
Summer	$P_{\ell R}$ $Jm^{-1}s^{-1}$	-22.21	-10.09	-22.72	-18.03	16.46	-7.70
	$\overline{Q}_{\ell}$ m^3/day	-5.70x10	-2.59x10	-5.84x10	-4.64x10	4.23x10	-1.98x10
	$\overline{Q}_{\ell}$ m^3/season	-5.26×10^3	-2.38×10^3	-5.37×10^3	-4.26×10^3	3.89×10^3	-1.82×10^3
Autumn	$P_{\ell R}$ $Jm^{-1}s^{-1}$	-57.85	7.67	-45.64	-2.42	47.57	17.01
	$\overline{Q}_{\ell}$ m^3/day	-15.12x10	1.97x10	-11.73x10	-0.62x10	12.22x10	4.37x10
	$\overline{Q}_{\ell}$ m^3/season	-13.91×10^3	1.82×10^3	-10.75×10^3	-0.57×10^3	11.24×10^3	4.02×10^3

Key: -ve southwards drift; +ve northwards drift

$\overline{Q}_{\ell}$ = sediment transport rate

Table 3.11 Sediment Transport: Field Site Data, after Weighting and Smoothing

Season	Cell / Parameter	(ii)	(iii)	(iv)	(v)	(vi)	(vii)
Winter	$P_{\ell R}$ $Jm^{-1}s^{-1}$	-3.66	55.20	-9.10	39.69	81.95	36.03
	$\overline{Q}_\ell$ m^3/day	-0.94x10	14.18x10	-2.34x10	10.20x10	21.06x10	9.26x10
	$\overline{Q}_\ell$ m^3/season	$-0.84x10^3$	$12.76x10^3$	$-2.10x10^3$	$9.18x10^3$	$18.94x10^3$	$8.33x10^3$
Spring	$P_{\ell R}$ $Jm^{-1}s^{-1}$	-47.40	-30.72	-48.32	-35.77	32.99	-29.09
	$\overline{Q}_\ell$ m^3/day	-12.18x10	-7.9x10	-12.42x10	-9.19x10	8.48x10	-7.48x10
	$\overline{Q}_\ell$ m^3/season	$-11.11x10^3$	$-7.18x10^3$	$-11.30x10^3$	$-8.36x10^3$	$7.72x10^3$	$-6.80x10^3$
Summer	$P_{\ell R}$ $Jm^{-1}s^{-1}$	-22.21	-0.02	-22.72	-15.28	13.68	-9.77
	$\overline{Q}_\ell$ m^3/day	-5.7x10	-0.005x10	-5.84x10	-3.92x10	3.52x10	-2.51x10
	$\overline{Q}_\ell$ m^3/season	$-5.26x10^3$	$-0.005x10^3$	$-5.37x10^3$	$-3.62x10^3$	$3.24x10^3$	$-2.31x10^3$
Autumn	$P_{\ell R}$ $Jm^{-1}s^{-1}$	-48.22	3.63	-40.11	-1.51	25.10	12.34
	$\overline{Q}_\ell$ m^3/day	-12.39x10	0.93x10	-10.31x10	-0.39x10	6.45x10	3.17x10
	$\overline{Q}_\ell$ m^3/season	$-11.40x10^3$	$0.86x10^3$	$-9.48x10^3$	$-0.36x10^3$	$5.94x10^3$	$2.92x10^3$
Year	$\overline{Q}_\ell$ total, m^3	$-28.60x10^3$	$6.44x10^3$	$-28.25x10^3$	$-3.16x10^3$	$35.83x10^3$	$2.13x10^3$

Key: -ve southwards drift; +ve northwards drift

$\overline{Q}_\ell$ = sediment transport rate

Smoothing: After this weighting had been carried out it was realised that the initial data required smoothing to remove some obviously spurious extreme values generated because of limitations of the refraction program. When P_l values were plotted alongshore the spurious results were identified and replaced with average values, although in practice relatively few (fewer than one in six, on average) occurred. After smoothing, the P_{lR} values were re-calculated and can be seen at the top of the seasonal sections of Table 3.11. Thus final values for P_{lR} were established and all that remained was to convert them into sediment transport rates.

Potential Sediment Movement

Sediment transport rates, $\overline{Q}_l$, were obtained from P_{lR} values in the same way as for the general Holderness refraction, using equation (3.10). Owing to the order in which the weighting and smoothing were carried out, sediment transport rates were produced before both weighting for the bias within the wave height classes or smoothing (Table 3.9), after weighting but before the smoothing (Table 3.10), and finally, after both corrections had been applied (Table 3.11). This enabled the effects of these adjustments to be assessed.

Results

Comparing the three sets of results produced in the field site refraction, those before weighting and smoothing (Table 3.9), those after weighting only (Table 3.10) and those after both operations (Table 3.11), it can be seen that weighting reduced net transport in spring and autumn (i.e. movement had been over-estimated originally). In winter the northwards movements were reduced while southwards movements were increased. In summer too, values were increased in a southwards direction. Generally high energy waves had been overestimated, particularly from the east and south-east.

Smoothing had the following effects:

Winter: In some cases a greater northwards movement was recorded as a result of replacing very large negative values with less extreme ones.

Spring: A general but slight decrease in the volume of sediment transported.

Summer: A slight reduction of $P_{\ell R}$ in some cells, otherwise no difference.

Autumn: Reduced sediment movement, i.e. ironed out extremes.

Thus smoothing had the general effect of removing extremes in the data, in either direction - positive or negative.

The following summary of results applies only to those obtained after both weighting and smoothing had been carried out (Table 3.11).

Autumn results indicate a southwards drift in half of the cells and a smaller northwards drift in the rest; the mean drift over the area (per metre length of beach) is $-2.09 \times 10\ m^3$/day, i.e. towards the south. The range is from $-12.39 \times 10\ m^3$/day to $+ 6.45 \times 10\ m^3$/day. The cells which exhibit a southward drift are well distributed across the area. Skipsea, at the northern most end of the field site, falls at the junction of cells (iii) and (iv), thus the field area is contained in cells (iv) and (v).

Winter exhibits a southwards drift in only two cells with a mean of $8.57 \times 10\ m^3$/day towards the north. This could be caused by a period of high energy waves from the S.E. The values range from $-2.34 \times 10\ m^3$/day to $21.06 \times 10\ m^3$/day and the cells which exhibit a movement towards the north tend to occur at the southern end of the modelled coast.

In Spring all but one cell records a southwards drift of quite large quantities from -7.48 x 10 m^3/day to -12.42x 10 m^3/day (per metre length of beach). There seems to be no obvious change in the volume transported alongshore.

Summer values indicate a smaller southwards movement, again in all but one cell (the same one as was encountered in spring). This time sediment movement rates varied from -0.005 x 10 m^3/day to -5.84 x 10 m^3/day.

For the whole year a mean movement over all cells of -2.8 x 10^3 m^3 was recorded, though there is a net northward movement in some cells, e.g. in the cells immediately to the north and south of the Atwick to Skipsea field site.

Comparison of General Holderness and Field Site Results (Tables 3.4 and 3.11)

The first apparent difference is that the Dowsing data, almost without exception, give a net sediment transport towards the north, whereas, though locally and seasonally variable, the wave recorder refraction indicates a net southwards drift. It can only be assumed that either the wave data from 1970/71 were atypical or, more likely, that invalid assumptions were made in allocating directions. Waves from the west recorded at Dowsing were ignored although they may have had a dampening effect on waves from the east. Wave data from more directly offshore from the field site would have been more satisfactory. Waves at Dowsing may have been influenced by local bathymetry and conditions which are not sustained 25 km or more to the north and in the nearshore zone. The wave record, especially for direction, is probably an abstraction of a very complex wave climate.

The sizes of the $P_{\ell R}$ values for the General Holderness refraction from the Dowsing data are very much larger than those of the Field site refraction from wave recorder data, in all seasons but spring. This is presumably a result of over-estimating the high energy waves in the Dowsing data, of a much longer refraction procedure and of generally less detailed data. There is less opportunity for errors to accumulate in the smaller scale run of the program. This serves to emphasise just how vital it is to understand the nature and quality of the data fed into a wave refraction,or any other,program.

Besides the increased accuracy as a result of the shorter operation of the refraction program in the field site experiment, the high quality, comprehensive data which were available from the "on-site" wave recorder meant that the results would be much more reliable than those produced in many other sediment transport and refraction studies. An important feature of the experimental method was that sediment transport rates were calculated seasonally, allowing comparisons among the seasons to be made and times of particular importance for sediment movement to be identified.

The field site data thus provided a more realistic and accurate estimate of field conditions, and it is these results which will be used in subsequent sections.

The field site wave data, the wave refraction procedure and sediment transport equations have thus provided a set of modelled potential sediment movement values which exhibit a great deal of variability, both among the cells, and from season to season. These variations will be interpreted in Chapter 4 (4.1 a).

3.1 b CURRENT METER EXPERIMENTS

In Chapter 2 the methods of obtaining current measurements, both in the pilot experiment over almost one tidal cycle, and the longer 3½ week experiment, were described. This section describes the analysis of the current data and presents the results of both experiments.

Data Preparation - Experiment 1 - No preparation was required as data were recorded directly on a paper chart.

Data Preparation - Experiment 2

The data on the 9-channel tape which was returned from processing had to be converted into "real" figures as a first step to obtaining the desired current characteristics. The maximum current was required, as well as the frequency of occurrence of currents from various directions, and of various velocities. Finally, and most importantly, the residual flow over a 24 hour tidal cycle and the mean residual flow over the entire period were required; it is these results which enable the estimation of potential sediment movement as a result of tidal currents. Such currents, though measured 1 km offshore, will also prevail further inshore, and are important in redistributing wave-transported sediments.

The data on the 9-channel tape were read into a computer data file ready to be manipulated into a more useful form. The following procedure was carried out, the steps of which were included in the program CMMANIT.F77, compiled for the purpose. Appendix 3.5 explains how the various steps in the manipulation were carried out.

1. The mean direction associated with the average velocity recorded over the 10-minute sample period was calculated.
2. Mean direction values on the tape were converted to directions relative to grid north.

3. Current velocity data, which depended upon instrument calibration, were converted to true values giving results in cm/s.

These procedures resulted in a series of velocity measurements and associated current directions.

4. The next step was to resolve the current velocity into its components in a north-south (v) and east-west (u) direction

$$v = S \cos (GD) \qquad (3.14)$$

$$u = S \sin (GD) \qquad (3.15)$$

Where GD = direction relative to grid north

S = velocity

5. Frequencies of currents flowing in various directions and with different velocities were obtained.
6. A similar count was carried out for the frequency of N-S component velocities. This direction component is dominant on the Holderness coast.
7. Finally the daily residual flow was calculated over two tidal cycles.

<u>Results</u>

<u>Experiment 1</u>

The current velocities and directions recorded in the test experiment are shown in Figure 3.5. The plot of current direction is just long enough to reveal the bi-modal nature of the record, the current being predominantly towards 180^o but changing to 360^o following the turn of the tide.

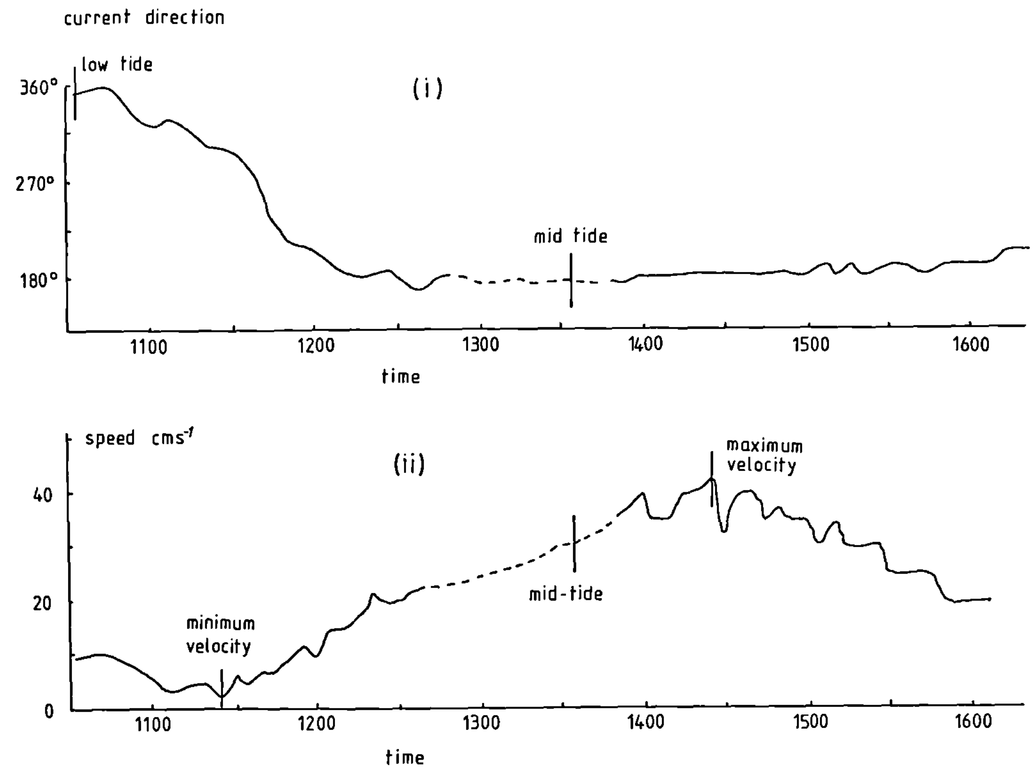
The minimum current speed was 0.05 ms^{-1}, occurring just after low tide; the maximum value, recorded 2½ hours before high tide, was 0.45 ms^{-1} and the mean based on five minute samples between 1030 hrs and 1625 hrs was 0.21 ms^{-1}. These velocities enabled estimates of possible maximum currents to be made so that the remote meter used in experiment 2 could be properly calibrated. There was little point in working out the residual flow as the sample was biased, taking place during a rising tide. The grade of sediment capable of being entrained by these currents and the corresponding maximum grades which can be maintained in motion are shown in Table 3.12.

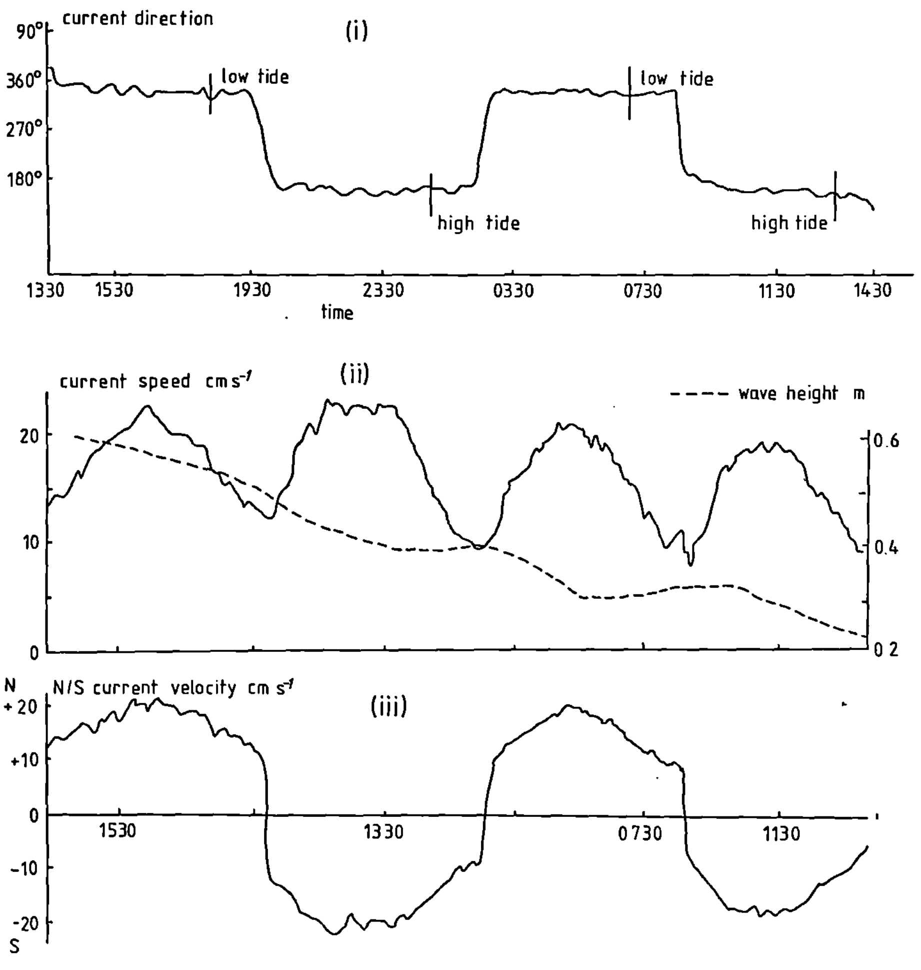
Table 3.12 Minimum, Mean and Maximum Recorded Current Velocities and their Associated Critical Sediment Entrainment and Suspension Grades.

Velocity (ms^{-1})		Entrainment Grades	Suspension Grades
0.05	minimum current	--	< 2Ø, 250μm
0.21	mean current	3-1 Ø, 125-500μm	<-1.4Ø, 2700μm
0.45	maximum current	5.5--1.4Ø, 23-2700μm	<-2.6Ø, 5800μm

In experiment 1 velocities of .35 ms^{-1} or greater were only recorded for approximately 70 minutes (11.86% of the time) while the velocity only dropped below .15 ms^{-1} for 16.95% of the time. From the velocity plot against time (Figure 3.5 ii) it can be seen that there is potential for greatest sediment movement in the mid-tide period, i.e. when the tide is in full ebb or flow.

It is important to consider the calibre of material actually present in an area. The bulk of the material may be moved by relatively weak currents; any higher velocities may just increase the net quantities moved, not alter their size composition. Conversely a stretch of beach or area of sea bed may be so coarse that movement will only take place at very high velocities. (Tidal current velocities will be enhanced by currents induced by waves). It is thus important to remember that sediment movement as a result of tidal currents usually operates in addition to wave-induced longshore drift. Experiment 1 was carried out in calm conditions in order that wave effects would be negligible.


current direction
low tide
(i)
360°
270°
180°
mid tide
1100
1200
1300
1400
1500
1600
time
speed cms⁻¹
(ii)
maximum velocity
40
20
0
mid-tide
minimum velocity
time


current direction
(i)
90°
360°
270°
180°
low tide
high tide
1330
1530
1930
2330
0330
0730
1130
1430
time
current speed cms⁻¹
(ii)
---- wave height m
20
10
0
0.6
0.4
0 2
N
N/S current velocity cm s⁻¹
(iii)
+20
+10
0
-10
-20
S
1530
1330
0730
1130

Current action inshore: If similar current velocities to those measured 500 m from the shore were recorded over the inshore area, then it is worth considering which grades of sediment could potentially be moved. The sediment sizes given are only rough guides. Table 3.13, based on the mean sediment size in the study area, shows what current velocities would be required to move material on the lower and upper beach.

Table 3.13 Potential sediment movement by tidal currents on the upper and lower beach

Profile	A	D	F'	H
lower beach mean particle size	1.75 Ø	1.9 Ø	1.5 Ø	1.25 Ø
Velocity required ms^{-1}				
- for entrainment	0.20	0.20	0.20	0.20
- for suspension	0.022	0.020	0.025	0.026
% of time moved	likely to be moved at all times. If originally at rest would move for 18.6% of record			
Upper beach mean particle size	-1.75 Ø	-1.5 Ø	-1.0 Ø	-1.0 Ø
Velocity required ms^{-1}				
- for entrainment	0.60	0.50	0.35	0.35
- for suspension	0.25	0.20	0.15	0.15
% of time moved	Would not move during this tidal cycle			

Once again it is not totally satisfactory to consider only the mean particle size, it might be more important to know when the extreme sizes will be moved. Much of the finer upper beach material would actually be entrained, while the few pebbles larger than -4.5 Ø would require velocities of 2 ms^{-1} to move them.

The main object of this first experiment was to provide a general idea of conditions in the field area in preparation for the second longer experiment.

Experiment 2

The second experiment produced a much longer record of current velocities and direction, comprising a number of cycles like that monitored in experiment 1. Figure 3.6 shows the changes in current direction, total speed and north-south components of velocity over one tidal cycle from 1.30 p.m. on 9/5/84 to 2.20 p.m. on 10/5/84. Once again minimum velocities are found as the current direction changes - about 1¼ to 1½ hours after low and high tides.

For the whole 25-day period of the experiment a histogram of frequency of net current from each direction (at 10^{o} intervals) showed the strong bi-modal nature of the results, with the two dominant opposing directions corresponding to periods of ebb and flow. 35.27% of the readings fall between 150^{o} and 170^{o}, and 45.07% between 140^{o} and 180^{o}: from the opposite direction (south to north) 44.22% and 35.40% fall between 320^{o} and 360^{o}, and 330^{o} and 350^{o} respectively. The histogram may be seen in Appendix 3.6 (i).

Histograms of net current velocity and resultant velocity in a north-south direction (Appendices 3.6 (ii) and 3.6 (iii)) revealed that the modal net velocity was between 0.15 and 0.20 ms^{-1}, and that in a N-S direction too, the modal velocity in each direction was in the range 0.15-0.20 ms^{-1}. At the upper end of the range this would entrain grains of 1-3 Ø (1.25-500 μm), and sustain the transport of suspended grains of -1.0 Ø to -2.0 Ø (2000-4000 μm) or smaller.

After the tide turns sediment movement is reversed; the overall effect will be to transport sediment first in one direction and then in the other. The relative strengths of the northerly and southerly currents, and the times for which different velocities are sustained, will determine whether there is a residual current in either direction, and hence overall sediment movement in one direction or the other. The same provisos apply to the movement of different grades of sediment. If there is a period of very high current velocity in one direction large particles may be entrained but when the tide reverses the mean velocity may be lower and transport greater quantities of moderate-sized material in the opposite direction; velocities high enough to move the large material back may not be achieved. Thus, a residual velocity in one direction does not rule out the possibility of net movement of a particular grade of material in the other. Where material is fairly uniform on the sea bed this effect is not as important and in this study the residual current will represent the capacity for net transport of sand for a particular day. The greater the velocity, the greater the amount of sand which can be moved. It can be seen in Figure 3.6(ii) that as the wave height fell so did the net current velocity.

Residual currents are frequently calculated in marine studies, usually over a 24 hr 50 minute tidal cycle. The residual currents in this study can be seen in Figure 3.7. It is apparent that on some days there would have been a net sediment movement in one direction, and on others in the opposite direction. During this experiment calm conditions did not prevail throughout, so there would be some wave-induced current present: when wave heights and approach directions are superimposed on the record (Figure 3.7) it can be seen that the currents towards the south were more common during wave approach from the N.E. and E.N.E., and that the magnitude of the velocity residual is greater during periods of higher waves. Currents may be significantly higher during stormy periods. The residual movement of most material during this experiment would be towards the south. Depending upon whether there is a spring or neap tide, different velocities may be achieved.

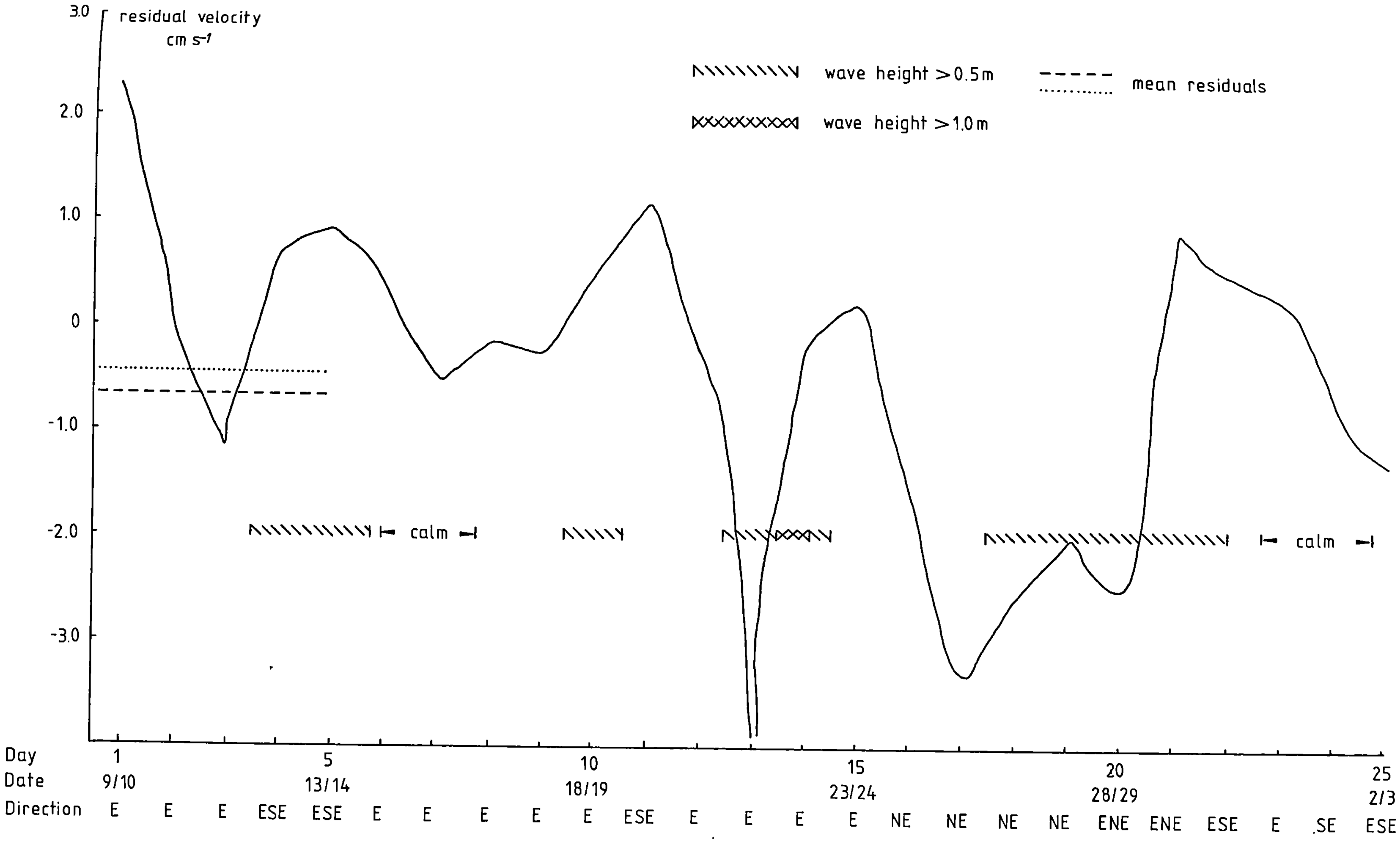
It is difficult to separate wave and tidal currents; however, two calm periods occurred during the experiment when wave-induced currents would have been minimal. Residual values less than 0.5 cm s^{-1}

Figure 3.7 Daily Residual Currents, Experiment 2; 9/5/84-3/6/84.

broken line = mean residual current -0.651 cms^{-1}

dotted line = mean residual excluding most extreme value in each direction -0.458 cms^{-1}

directions of wave approach appear at the foot of the diagram


residual velocity
cm s-1
3.0
2.0
1.0
0
-1.0
-2.0
-3.0
wave height >0.5m
wave height >1.0m
mean residuals
calm
calm
Day
Date
Direction
1
9/10
5
13/14
10
18/19
15
23/24
20
28/29
25
2/3
E E E ESE ESE E E E E E ESE E E E E NE NE NE NE ENE ENE ESE E SE ESE

(0.005 ms^{-1}) occurred during this time suggesting that for the rest of the time values in excess of this may represent the effect of waves.

Table 3.14 indicates the maximum velocity achieved in each direction for each day. If these were similar then there would be little difference in the grade of material moved in each direction, and the residual would be directly reflected by transport direction and rate. On most days during this period the maximum current was slightly higher in a negative direction, i.e. towards the south, the same direction as the overall mean residual for the entire period.

Table 3.14 Maximum Northwards (+ve) and Southwards (-ve) Current Velocities and Associated Sediment Entrainment

Day	Max +ve Current (ms^{-1})	sediment entrained (Ø)	Max -ve Current (ms^{-1})	Sediment entrained (Ø)
1	21.655	3.5-0.8	-22.306	3.5-0.8
2	21.880	3.5-0.8	-23.318	0.1-3.9
3	28.010	-0.2-0.5	-29.618	-0.2-0.5
4	30.113	-0.3-4.75	-32.627	-0.6-5.0
5	30.181	-0.3-4.75	-29.043	-0.2-0.5
6	23.739	-0.6-5.0	-32.111	-0.6-5.0
7	29.040	-0.2-0.5	-33.302	-0.6-5.0
8	30.066	-0.3-4.75	-31.123	-0.75-4.8
9	27.350	-0.2-0.5	-31.031	-0.75-4.8
10	34.724	-0.8-5.2	-32.460	-0.6-5.0
11	27.204	-0.2-0.5	-25.989	0-4.5
12	23.676	-0.1-3.9	-25.030	0-4.5
13	28.484	-0.2-0.5	-31.658	-0.75-4.8
14	23.477	0.1-3.9	-27.705	-0.2-0.5
15	18.745	2.0	-18.513	2.0
16	18.925	2.0	-25.691	0-4.5
17	21.373	3.5-0.8	-24.748	0-4.5
18	25.297	0-4.5	-27.958	-0.2-0.5
19	23.253	0.1-3.9	-28.564	-0.2-0.5
20	27.632	-0.2-0.5	-31.929	-0.6-5.0
21	27.301	-0.2-0.5	-28.484	-0.2-0.5
22	29.847	-0.3-4.75	-27.586	-0.2-0.5
23	28.152	-0.2-0.5	-29.413	-0.2-0.5
24	27.649	-0.2-0.5	-28.140	-0.2-0.5
25	28.447	-0.2-0.5	-30.477	-0.3-4.75

The differences were not large enough to result in a significantly segregated sediment movement. These velocities, capable of moving sediment between 4.6 Ø and -0.5 Ø at the extremes, contrast with the modal values in each direction, capable of entraining 1 Ø-3 Ø sized particles and maintaining the motion of those under -0.5 Ø to -1.5 Ø. From a comparison of Tables 3.13 and 3.14 it is apparent that the mean particle size on the upper beach would not be moved by any maximum current value in either a northwards or southwards direction.

The current velocities obtained in experiments 1 and 2 enabled the types of sediment grades moved on this coast to be established, the relative velocities generated by the ebb and flow tides to be determined and the contribution of tidal as opposed to wave-induced currents estimated. These results will be interpreted in Chapter 4, assessing the contribution of tidal current-induced sediment transport in comparison to wave-induced sediment transport.

Section 3.1 has thus evaluated the potential sediment movement resulting from both tidal and wave action. The results will be interpreted in Section 4.1 and used in sediment budget investigations (Sections 3.4 and 4.4).

3.2 THE BEACH

This section describes the data analysis for, and the results of, the investigations of the beach sub-system. Firstly, the beach profile work will be considered, followed by the results of beach sediment analysis, and finally beach sediment transport rates obtained from tracer experiments will be presented.

3.2 a BEACH PROFILE WORK

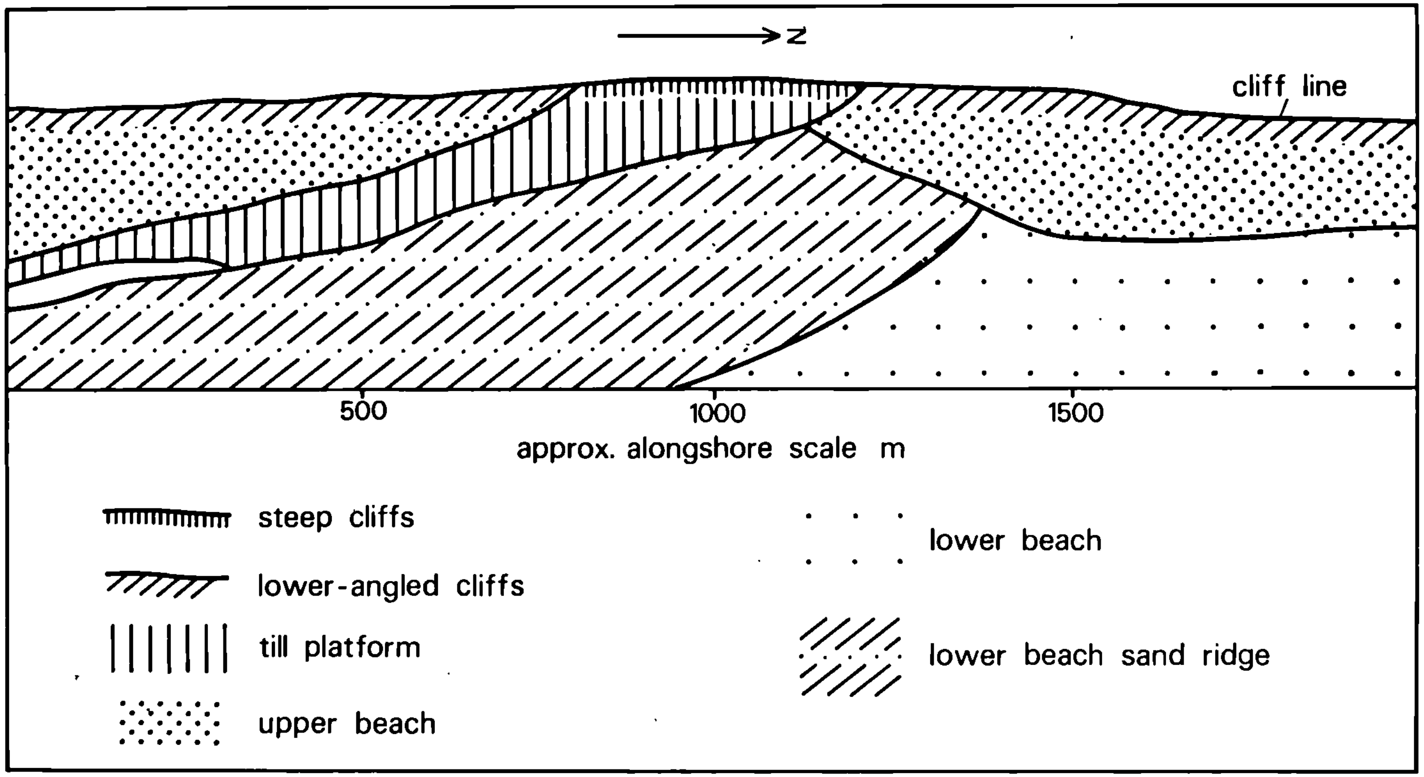
Before describing the way in which beach profile evolution was investigated it is useful to describe the nature of the beach and its behaviour in qualitative terms. A detailed description of the field area appears in Chapter 1 (Section 1.4). Along much of the Holderness coast the sandy beach has distinctive upper and lower beaches, sloping at an average of 4^o-7^o and 0^o-2^o respectively. The upper beach frequently exhibits prominent cusps, particularly in winter, while the lower beach sometimes comprises one or two low amplitude bars; there is often a narrow runnel or channel at, or close to, the junction between the upper and lower beach. This junction changes its position both alongshore and throughout the year. Towards the north of Holderness this distinct upper and lower beach system breaks down; the upper region of the beach becomes gentler and the seaward portion steeper. The breakdown occurs within the Atwick to Skipsea field site around profiles G and H (Figure 2.7).

Periodically some areas of beach are stripped of sediment, exposing the underlying till platform (Plate 3.1). Sometimes the stripping is transient, the result of a particularly violent storm, e.g. May 1984, but often during winter the upper beach zone is bare for a few months, particularly at profiles E, F and F'. These areas can be likened to, and may indeed be, the "ords" described by Phillips (1962, 1964)/Pringle (1981, 1984, 1985). However, they do not exhibit all the characteristics described by Phillips/Pringle (Figure 3.8), e.g. the oblique form of the till patch across the beach which is a function of ord migration, with the sandy portions on either margin merging into incipient oblique bars offshore. These

Plate 3.1 Till Platform Exposed.

Plate 3.2 Low Amplitude Bar Oblique to the Shore.

Figure 3.8 Characteristic Plan of an "Ord" according to Pringle (1985).


N
cliff line
500
1000
1500
approx. alongshore scale m
steep cliffs
lower-angled cliffs
till platform
upper beach
lower beach
lower beach sand ridge

welded bars are observed in the field site (Plate 3.2) but are not obviously associated with exposed till patches. The till exposures at the northern end of the Holderness coast do not seem a great deal lower than the adjacent sections of beach, the change in elevation is almost imperceptible and the veneer of sand on the adjacent stretches must be very thin. The patches are less extensive than the 1-2 km long ords reported further south, usually being less than 500 m alongshore; in common with the instances described by Pringle, however, the lower beach was always full and well developed. Ords were reported as migrating at 0.5 km / year (Pringle, 1985). On the field site the centre of distribution of smaller areas of exposed till on a generally depleted section of beach migrated around 650 m in 15-18 months - a similar rate to the ords. Further details of the exposed till areas may be seen in Section 4.2. (iv).

The behaviour of the beach proved difficult to describe and this was one of the main reasons why the following more formal approach of Markov analysis was attempted. Frequently, however, it was possible to observe the beach responding to wave conditions in the traditional manner reported in the literature; higher energy and storm conditions lead to a combing down of the upper beach and a build up of the lower beach and offshore zone, i.e. a transfer of material offshore. During quiescent conditions the reverse happens with a general movement of material onshore. At other times the beach response is not as easily discerned and the changes are subtle. A more detailed description and interpretation of general beach behaviour is found in Section 4.2. (iv).

The aim of the following work was to find out whether the sequence or development of beach profiles could be described by some formal model. Fieldwork had provided 513 profiles covering nine locations, each of which was surveyed 57 times (2 during reconnaissance). Were the changes in the profiles among various characteristic types random? or could they be described, for instance, by a Markov model as they had been in previous studies? Did certain profile shapes occur with a greater frequency than others? Sonu and James (1973), in a rather theoretically based study, had described beach changes in terms of a 1st order Markov model.

Markov models, frequently used in geography and geology, are conceptual devices for describing and analysing the nature of changes which involve transitions from one state to another or movement between locations (Collins, 1975).

In the present study, the first step was to classify beach profiles and secondly derive the transitions among the classes, i.e. the beach evolution was determined. These data were then summarised in matrices which formed the basis of the Markov model and could be tested for Markov properties. This model might then be used to predict future beach changes. Six months worth of data were used to produce the initial model which was then tested using data from a second six-month period.

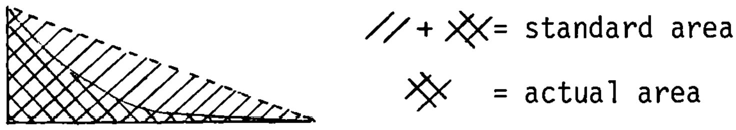
3.2 a (i) Classification of Profiles

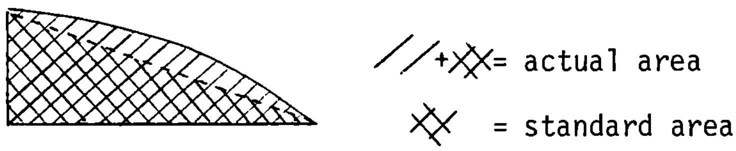
In order to test rigorously whether beach morphology did behave in a specific way the surveyed profiles had to be classified into representative beach types according to shape: Markov models describe transitions among specific states so it was necessary to determine them. Previous workers have produced classifications by eye, but it was felt that with a total of more than 500 profile surveys over 18 months it would be difficult to be totally consistent in allocating profiles to classes; it would also have been difficult to differentiate among various types from the sets of plotted profiles. It was considered desirable therefore to have a quantitative method of classifying the profiles based upon measurable variables. Cluster analysis seemed to provide an adequate method of classification as long as suitable profile descriptors were used. Cluster analysis produces a classification for a number of individuals (beach profiles in this example) based on the similarities among a series of variables measured for each individual. The computer package CLUSTAN carries out this operation and is described in detail by Wishart (1978).

A list of variables which might adequately describe beach shape was prepared and a range of some theoretical beach shapes drawn-up to test whether the clustering program grouped those of a similar shape together. Many of the theoretical shapes were never observed in practice, and also happened to be the ones which required the most time-consuming calculation of variables. For example, linear regression expressions were used to describe profiles which might, according to other combinations of variables, appear to be linear when they were in fact convex or concave. Within the population of plotted profiles only one or two were of this type and so regression calculations were considered unnecessary.

As most of the beach profiles had distinct upper and lower beaches it was decided that variables should be included which described each of these separately, as well as indices describing the beach as a whole. Thirteen variables were originally chosen to describe the theoretical beach shapes. These variables were:

V1 - A measure of upper beach convexity/concavity; actual area (AA) under the upper beach divided by a "standard area" (SA) which assumed a linear beach having the same two end points.





A convex beach will give a V1 value >1, while a concave one will have a V1 value < 1.

V2 - a measure of lower beach convexity/concavity. Again, the actual area was divided by the standard area.

V3 - The distance from the top of the beach (cliff foot) at which the junction of the upper and lower beach occurs, expressed as a percentage of the total beach length.

V4 - V1/V2 (comparison of upper and lower beach convexity)

V5 - Volume under the actual profile (upper and lower beach) taken to an arbitrary minimum basal datum.

V6 - Angle between upper and lower beach at their junction.

Variables V7-V13 were curve properties obtained from a set of three possible linear regression expressions which describe each profile. Clustan tests on 22 profiles were run using various combinations of variables and the resulting clusters compared with the actual plots of the test profiles by eye to determine which combination of variables had produced the most realistic grouping. These tests revealed the redundancy of V7-V13; they had provided refinements describing certain profile shapes which were not encountered in this study. Runs which had used a large number of variables did not seem to distinguish very well between convex and concave upper beaches, a feature of the profile regarded as being important, especially as beach development was to be studied. V7-V13 were replaced by three new variables reflecting the gradients of the beach profile; this was regarded as being important, bearing in mind the lower overall beach gradients in the north of the study area and the lack of distinction between the upper and lower beaches there. The new variables were:

V'7 - overall gradient of upper beach (straight line)

V'8 - overall gradient of lower beach

V'9 - V'7/V'8

Five more tests were run on the 22 beach cases as follows:

(a) V1, V2, V3, V4, V'7, V'8, V'9

(b) V1, V2, V3, V4, V'9

(c) V1, V2, V4, V'9

(d) V1, V2, V3, V4, V'7, V'8

(e) V1, V2, V4, V'7, V'8

Comparisons of the resulting clusters revealed that runs (a), (c) and (e) were the most consistent. It was decided to use either the (a) or (e) combination of variables as they had virtually identical results. Combination (e) was chosen as it required less calculation.

The variables used were thus:

V1 - calculated from AA - actual area of upper beach

SA - standard area of upper beach

V2 - calculated from AA - actual area of lower beach

SA - standard area of lower beach

V3 - calculated from V1 and V2

V4 - upper beach gradient

V5 - lower beach gradient.

These were all calculated from the beach profile coordinates using computer programs. "HALF BEACH AREAS" produced the actual area under either the upper or lower beach from the relevant coordinates (distance along beach and beach elevation); "STANDARD AREAS" produced the standard (straight line) area and gradient of the relevant beach section from the coordinates of each end of that section.

These variables were then calculated for six months of real profile data obtained from the surveys of 4/4/84 to 26/9/84 inclusive. This included a period of more intensive field work from 31/6 to 13/7: the total number of profiles was 225.

The next decision to be made was how many clusters, i.e. classes of beach profile, were required. When ten clusters were generated 96.5% of profiles fell into six of the designated clusters. The remaining 8 individuals were divided among four clusters, two having three cases each. This was regarded as satisfactory and the eight profiles left over from the six large clusters were grouped in a seventh, miscellaneous cluster. "CLUSTAN" revealed that the six clusters were all quite distinct and that the next "fusion of categories" would involve linking profile sets which had greater differences between them than those which had already been linked. see dendrogram links in Appendix 3.7a
From the results of the CLUSTAN package mean profile shapes for each type were drawn. For each cluster (profile type) the mean and standard deviation were given for each variable. These values would be used in the future to determine the classes of other profiles.

Figure 3.9 a Mean Beach Types from Cluster Analysis.

nb vertical scale does not represent absolute beach altitude; X and Y-type profiles will be referred to later (Section 3.2 a (v)).

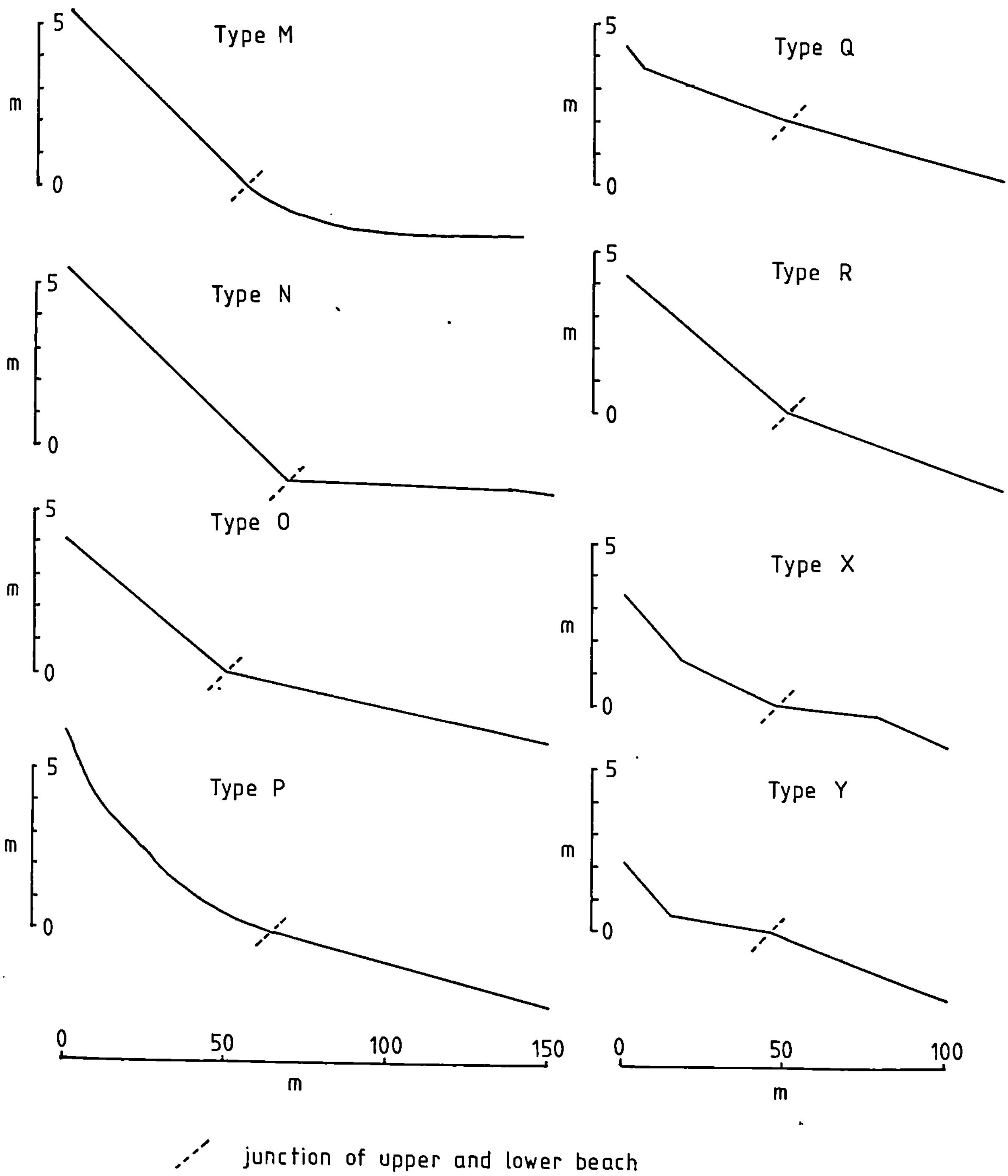

Type M
Type N
Type O
Type P
Type Q
Type R
Type X
Type Y
m
5
0
0
50
100
150
0
50
100
junction of upper and lower beach

Figure 3.9b Characteristics of Type Profiles

M-Type		V1	V2	V3	V4	V5
	Mean	.9928	.7118	1.5434	.0975	.0173
	S.D.	.0769	.2103	.5954	.0105	.0042

linear upper beach, concave lower beach
Eg 1= 140 m U/L = 55 m

N-Type		V1	V2	V3	V4	V5
	Mean	.9725	1.3727	.7829	.0932	.0069
	S.D.	.0698	.4578	.2741	.0070	.0035

linear upper beach, convex lower beach
Eg 1 = 170m U/L = 70 m

O-Type		V1	V2	V3	V4	V5
	Mean	.9717	1.0016	.9980	.0811	.0213
	S.D.	.0846	.1617	.1965	.0036	.0047

linear upper beach, linear lower beach
Eg 1 = 170 m U/L = 50 m

P-Type		V1	V2	V3	V4	V5
	Mean	.7487	.9853	.7703	.1039	.0245
	S.D.	.0817	.0957	.1399	.0110	.0057

very concave upper beach, linear lower beach
Eg 1 = 190 m U/L = 60 m

Q-Type		V1	V2	V3	V4	V5
	Mean	.8542	1.0007	.8664	.0467	.0272
	S.D.	.1485	.1848	.1619	.0140	.0074

less concave upper beach, linear lower beach
Eg 1 = 130 m U/L = 50 m

R-Type		V1	V2	V3	V4	V5
	Mean	1.0266	.9892	1.0492	.0851	.0355
	S.D.	.0380	.1198	.1570	.0074	.0068

linear upper beach, linear lower beach - smaller ΔU/L gradient
Eg 1 = 150 m U/L = 50 m

X-Type		V1	V2	V3	V4	V5
	Mean	.7690	1.436	. 545	.0729	.0233
	S.D.	.0523	.0026	.0775	.2227	.0077

concave upper beach, convex lower beach
Eg 1 = 90-110 m U/L = 47 m

Y-Type		V1	V2	V3	V4	V5
	Mean	. 501	1.002	. 500	.0490	.0385
	S.D.	.0707	.0320	.0707	.0100	.0075

extremely concave upper beach, linear lower beach
Eg 1 = 100 m U/L 42-45 m

Mean = mean of variable over all individuals in cluster
S.D. = standard deviation of variable over all individuals in cluster
Eg 1 = Typical beach profile length (m)
U/L = distance from cliff foot to junction of upper and lower beach (m)

nb linear - <3% difference between AA and SA; all but one in fact differ by <1%

The profile types revealed by clustering were designated M, N, O, P, Q, R and S Types, the last representing the miscellaneous cluster. The mean profiles M-R are shown in Figure 3.9 a., along with a description of the profiles and the means and standard deviations of the variables (Figure 3.9 b). Profiles X and Y, derived for a second period, will be referred to later (Section 3.2 a (iv)).

A histogram of the overall frequencies observed is shown in Figure 3.10, as well as the frequencies observed at the individual survey locations along the beach (Profiles A-H). It is evident that a particular type profile may be more common at certain locations. For example, M, N and O types dominate profiles A to F and M and N types are most numerous at profiles A to E. P, Q and R types dominate profiles F' to H.

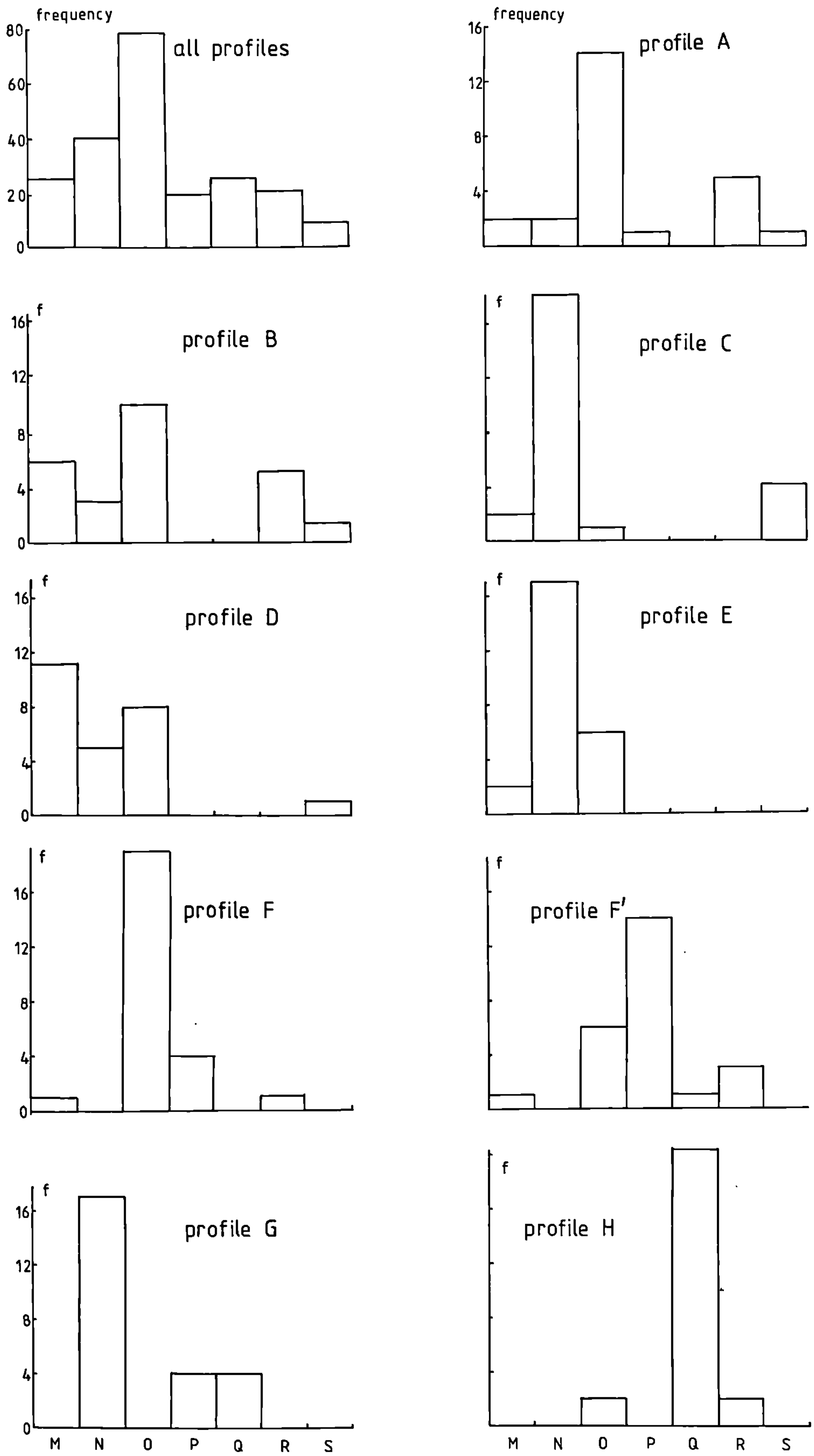
2.3 a (ii) Sequence of Beach Profile Transitions

For each profile location along the beach (A to H) the sequence of classified profile types was listed from 4/4/84 to 26/9/84. The frequency of each type of individual transition was noted for that beach location for three distinct data sets:

1. Bulk - all transitions together
2. Fortnightly - 4/4/84 to 31/6/84 and 13/7/84 to 26/9/ 84 inclusive
3. Daily - 30/6/84 to 13/7/84 inclusive.

These three data sets were considered separately because it was thought that it would be more rigorous to separate the 14 days of continuous surveys, which would include variations within one tidal cycles, from the fortnightly data, which involved changes among the same stages in a number of tidal cycles. The inclusion of

Figure 3.10 Frequency of Beach Profile Types, April 1984 to September 1984; overall and by beach profile location.



frequency
80
60
40
20
0
all profiles
frequency
16
12
8
4
profile A
f
16
12
8
4
0
profile B
f
profile C
f
16
12
8
4
0
profile D
f
profile E
f
16
12
8
4
0
profile F
f
profile F′
f
16
12
8
4
0
profile G
f
profile H
M N O P Q R S
M N O P Q R S

the bulk data would test whether this separation was necessary. (Eventually it became apparent that the Bulk approach was perfectly adequate and this alone was adopted when a winter model was finally presented.) The transitions and frequencies for Profile A are shown in Figure 3.11.

Figure 3.11 Transitions For Profile A from 4/4/84 to 26/9/84

M — N — N — 0 — P — 0 — 0̲

0̲ — R — R — 0 — 0 — 0 — R — daily

— 0 — 0 — 0 — 0 — 0 — S — R̲

R̲ — M — R — 0 — 0 — 0

0̲ these two profile types represent the same day i.e. at the beginning or end of the intensive daily surveys. Likewise for R̲

Frequency of Transitions

Bulk

M-N	1	R-0	3
N-N	1	0-S	1
N-0	1	S-R	1
0-P	1	R-M	1
P-0	1	M-R	1
0-R	2	0-0	9
R-R	1		

Fortnightly

M-N	1	0-0	3
N-N	1	0-R	1
N-0	1	R-M	1
0-P	1	M-R	1
P-0	1	R-0	1

Daily (July)

0-R	2
R-R	1
R-0	2
0-0	6
0-S	1
S-R	1

Transitions for the other profiles can be seen in Appendix 3.7b

3.2 a (iii) Frequency and Probability Matrices

For all profiles the transitions of each type were added up and the totals placed in a frequency transition matrix (Figures 3.12 a-3.14 a). From these, the corresponding probability transition matrices could be derived, each cell value being divided by the row total, i.e. in the probability transition matrices each of the rows adds up to one. The probability transition matrices for the bulk, fortnightly and daily (July) samples can be seen in Figures 3.12 b-3.14 b.

One of the original purposes of this exercise was to determine whether any patterns govern beach development; simply by scanning

	M	N	O	P	Q	R	S	Total
M	10	4	8			2		24
N	3	31	8				3	45
O	6	5	48	6	2	5	3	75
P	1		6	10		2		19
Q			1	1	20	2	1	25
R	1		10	1		8		20
S	1	3	1			1	1	8
								216

Figure 3.12 a Frequency Transition Matrix: bulk data

	M	N	O	P	Q	R	S
M	.42	.17	.33			.08	
N	.07	.69	.18				.06
O	.08	.07	.64	.08	.03	.07	.03
P	.05		.32	.53		.10	
Q			.04	.04	.80	.08	.04
R	.05		.50	.05		.40	
S	.12	.38	.12		.13	.12	.13

Figure 3.12 b Probability Transition Matrix: bulk data

	M	N	O	P	Q	R	S	Total
M	3	2	4			1		10
N	2	14	6				1	23
O	2	4	29	2	1	3	1	42
P			2	3		2		7
Q			1		10	2		13
R	1		6	1		3		11
S		1	1					2
								108

Figure 3.13 a Frequency Transition Matrix: fortnightly data

	M	N	O	P	Q	R	S
M	.30	.20	.40			.10	
N	.09	.61	.26				.04
O	.05	.10	.69	.05	.02	.07	.02
P			.29	.43		.28	
Q			.08		.77	.15	
R	.09		.54	.10		.27	
S		.50	.50				

Figure 3.13 b Probability Transition Matrix: fortnightly data

	M	N	O	P	Q	R	S	Total
M	8	2	4			1		15
N	1	19	2				2	24
O	4	1	21	4	1	3	3	37
P	1		4	7				12
Q				1	11		1	13
R			4	1		5		10
S	1	2			1	1	1	6
								117

Figure 3.14 a Frequency Transition Matrix: daily (July) data

	M	N	O	P	Q	R	S
M	.53	.13	.27			.07	
N	.04	.79	.09				.08
O	.11	.03	.57	.11	.03	.08	.07
P	.08		.34	.58			
Q				.08	.85		.07
R			.40	.10		.50	
S	.17	.33			.17	.17	.16

Figure 3.14 b Probability Transition Matrix: daily (July) data

the transition probability matrices certain transitions are observed to occur more frequently than others. For example, the diagonal of the matrix M — M, N — N etc. has relatively large numbers in its cells: in the bulk matrix (Figure 3.12 b) M — M has a probability of .42 and N — N, .69, i.e. 69% of the time an N-type profile will be followed by an N-type profile. The large diagonal values reflect a certain inertia or stability in the system, i.e. the profile is likely to exhibit the same type. There seem to be fewer instances of transitions between M, N or O types and Q, R or S types. For a certain profile location the most likely transition can be determined.

The overall probability transition matrix can be used to predict transitions from an existing set of frequencies for profile types by matrix multiplication. If a certain location on the beach exhibits a certain frequency of profile types over a period of time, then it is possible to predict by matrix multiplication the frequency of occurrence of these profile types for the next time period.

Analysis of Transitions

It is desirable to test the beach profile transitions and transition probabilities for three properties:

1. Whether the transitions exhibit Markov properties, i.e. is it valid to use the probability matrix to predict changes from one time to the next?
2. Whether the beach transitions are uniform through time (i.e. within the 6 months).
3. Whether the beach transitions are uniform over the length of the beach.

Testing 2 and 3 means finding out whether for data subsets (e.g. a specific location or specific time peridd), the bulk, fortnightly, or daily probability matrix predicts what is actually observed to happen, i.e. do the beaches in the south behave differently to the overall average predictions for the entire beach? This does not mean that the same types of transitions must occur in the north and the south but that, given the profile types that are already exhibited, the matrix predicts adequately the next set of profile types. Similarly, this means finding out whether the predictions for one time period are significantly different than for any other.

3.2 a (iv) Markov Model and Testing

Testing for Markov Properties

Previous workers have suggested that beach profile transitions behave in a way which can be described by a Markov Chain. A summary of the principles involved is given in Appendix 3.8. The most important property exhibited by a 1st order Markov sequence is that the state of the system at time t_2 depends only upon the state of the system at time t_1, and is not influenced by the state at t_0 or before, i.e. transitions are not influenced by any state except the immediately preceding one.

The hypothesis that the study beach profiles exhibited Markov transition properties was tested, i.e. that the beach type at t_2 was independent of beach types at all times except t_1. In order to do this, a number of t_0 — t_1 — t_2 transitions from the field data was examined. The first set considered was that where the beach was type N at t_1, the second set where type O was observed at t_1. A table of the corresponding t_0 and t_2 frequencies was constructed. To achieve large enough values in the table a simple choice of N or ≠ N was used in the first instance, then N, O or ≠ N or O in the second, all for the t_1 = N test.

Eg

	Sub-set A	Sub-set B
$t_1 = N$		
	$t_2 = N$	$t_2 \neq N$
$t_0 = N$	(2) 3	(4) 9
$t_0 \neq N$	(6) 11	(12) 1

If Markov properties are exhibited by the data then the proportions of the two data subsets A and B (i.e. the state at time t_2) should not be significantly different, i.e. the state at t_0 should not influence the proportions of N and ≠ N at t_2. The figures in brackets show an example where there is no memory in the system. If the state at t_0 did have an influence on the system at t_2 the proportions of N and ≠ N would differ (depending upon the t_0 state). The unbracketed figures show how "memory" might affect the figures; the two data subsets are significantly different.

A simple method of testing for differences between sets of data is the chi squared (χ^2) test. Observed transitions of the relevant types were extracted from the profile sequences and the expected values obtained as usual, (row total x column total/grand total). Then $\frac{(O-E)^2}{E}$ was calculated for each cell of the table and the total of all of these values obtained. O represents the observed value and E the expected. The total value was then compared with the values given in statistical tables (Neave, 1981). If a significant difference existed between the two data sets, i.e. $t_2 = N$ and $t_2 \neq N$ then the $\Sigma \frac{(O-E)^2}{E}$ value would exceed the values given in the tables for a variety of significance levels. In order that the χ^2 test may be strictly applicable the expected frequency should always be greater than 5.; however, even when many data were grouped this was not always achieved. It was thought, however, that the method would still be quite adequate for this application.

The following results were obtained for the two test cases of t_1 = N and t_1 = 0:

1 a. For t_1 = N and t_0 and t_2 classes of N and ≠ N

$\chi^2 = 1.167$ table value (1%) = 6.635 (degrees of freedom = 1)

$\chi^2 <$ table value

∴ no significant difference exists between t_2 = N and t_2 ≠ N data

∴ Transitions exhibit Markov properties at 1% level of significance.

b. For t_1 = N and t_0 and t_2 classes of N, 0 and ≠ N or 0

$\chi^2 = 5.317$ table value (1%) = 13.277 (degrees of freedom = 4)

∴ no significant differences exist among N, 0 and ≠ N or 0

∴ Transitions exhibit Markov properties at 1% level of significance.

2 a. For t_1 = 0 and t_0 and t_2 classes of 0 and ≠ 0

$\chi^2 = 4.438$ table value (1%) = 6.635 (degrees of freedom = 1)

∴ no significant difference between t_2 = 0 and t_2 ≠ 0

∴ Transitions exhibit Markov properties.

b. For t_1 = 0 and t_0 and t_2 classes of 0, N and ≠ 0 or N

$\chi^2 = 12.936$ table value (1%) = 13.277 (degrees of freedom = 4)

∴ no significant differences among N, 0 and ≠ 0 or N

∴ Transitions exhibit Markov properties.

Testing for Homogeneity of Transitions along the Beach

For each profile location the frequency of each profile type was recorded over the period 4/4/84 to 10/9/84 inclusive, and placed in a matrix. The matrix for profile A was

$$\begin{bmatrix} 2 & 2 & 13 & 1 & 0 & 5 & 1 \end{bmatrix}$$

i.e. 2 M-types, 2 N-types, 13 O-types etc. This was multiplied by the probability transition matrix to give the predicted number for each type.

[2.44 3.01 12.28 1.82 0.52 3.29 .64]

A comparison was then made with the observed frequency after transitions had operated, i.e. the frequency from 16/4 to 26/9 inclusive. From field observations of the sequence at Profile A, this was:

[1 2 14 1 0 5 1]

Obviously the observed and predicted results did not agree exactly - observed frequencies only occurred in whole numbers. Bearing this in mind the variations seem relatively minor: that is, profile A did not seem to behave significantly differently from the general behaviour of the beach as described by the probability transition matrix.

In order to find out exactly which transitions among profiles (as opposed to the overall resultant frequency of profile types) were predicted compared with those which actually occurred, two transition matrices were prepared. The first was a prediction obtained by multiplying each original frequency by each of the probabilities in the corresponding row of the large probability transition matrix - Table 3.15.

Table 3.15 "Predicted" transitions for Profile A

frequency matrix X P = Probability Matrix

frequency matrix							
2	.42	.17	.33			.08	
2	.07	.69	.18				.06
13	.08	.07	.64	.08	.03	.07	.03
1	.05		.32	.53		.10	
0			.04	.04	.80	.08	.04
5	.05		.50	.05		.40	
1	.12	.38	.12		.13	.12	.13

The predicted number of each type of transition becomes

.84	.34	.66			.16	
.14	1.38	.36				.12
1.04	.91	8.32	1.04	.39	.91	.39
.05		.32	.53		.10	
.25		2.5	.25		2.0	
.12	.38	.12		.13	.12	.13

This first matrix was then compared with a second matrix (Table 3.16) containing the observed frequencies for the various transitions.

Table 3.16 Observed transitions for Profile A

	1					1
	1	1				
		9	1		2	1
		1				
1		3			1	
					1	

The procedure was repeated for all nine profile locations and for the three sample periods and probability matrices, i.e. bulk, fortnightly and daily (July). Overall, the predictions using the three matrices differed little, only occasional disparities were seen. Appendix 3.9 contains the predicted frequencies of types and transitions and the corresponding observed frequencies of types and transitions produced from the bulk matrix multiplication.

In order to assess more satisfactorily how well the predictions coincided with observed values for each profile, a more rigorous method of comparison was required. A suitable method involved using the Poisson distribution curve since the frequencies predicted were not large enough for the normal curve to be used. The Poisson curves give the probability of actually obtaining a certain observed value, given a particular predicted mean value. This predicted mean is regarded as being at the centre of the Poisson distribution curve; the value of the predicted mean for testing is that predicted by the probability transition matrix for a certain transition.

Many of the predicted values agreed very well with the observed values so were ignored for the purposes of the test. The largest discrepancies between predicted and observed transition frequencies were examined in the light of the Poisson curve, with the aid of a

Computer program. Predicted values (the means of the distribution) were entered into the program and the corresponding curve produced: the observed value was fed in, and the program calculated the probability of obtaining a value either $\geqslant$ (greater than or equal to) or $\leqslant$ (less than or equal to) this value, under the specified curve. Interest was always in obtaining a value more extreme than, or equal to, the observed value. If the observed frequency for a transition was greater than that predicted then the probability of obtaining that value or greater was required. If, however, the observed value was less than predicted then the probability of obtaining this frequency or lower was required. It is important to remember that it was only the observations which showed the greatest departure from the predictions that were treated in this way; the rest were in reasonable agreement showing that no one particular profile was predicted less well than the rest. Appendix 3.10 gives the results of comparisons of the bulk predictions with the Poisson curve.

If the probability was greater than .32 the observed value was regarded as being within about one standard deviation of the predicted mean, i.e. the difference was fairly insignificant. If the probability was greater than .10 it was also considered to represent a relatively insignificant difference, i.e. there was a 1 in 10 chance of this value or one more extreme occurring with the specified predicted value. Below .10 the chances of occurrence were regarded as too small; the predicted and observed values were significantly different (though at a probability of .05 it would be only just outside approximately 2 standard deviations of the predicted mean). For values below .01 the prediction was inadequate - unhomogeneous behaviour could be occurring, depending upon how often these small probability values occurred for a data sub-set.

There are inevitably problems when using predictions for low frequencies, the actual value must be either 0 or 1 so the variations are understandable. It would be interesting, though extremely laborious, to experiment with a very much larger data set where the predicted frequency values for individual transitions would be much larger.

Of the 77 transitions which it was thought might have been incorrectly predicted, 5.7% of all transitions, none fell into the < 0.01 probability class, 5 between 0.01 and 0.05, and 7 between 0.05 and 0.10. The remainder, likely to occur with a one in ten chance or greater, were not regarded as indicating a section of beach behaving in a significantly different way to the rest. Table 3.17 shows the instances where the predicted and recorded values were significantly different.

Table 3.17 Occurrences of erroneous predictions - worst examples

Probability	Profile & Matrix used	Transition	Predicted value	Observed value
0.01-0.05	B bulk	N — O	.54	5
	B daily	N — O	.18	2
	D daily	O — M	.33	2
	E bulk	O — N	.35	2
	H bulk	O — Q	.03	1
0.05-.10	C bulk	N — R	1.08	3
	C daily	N — O	2.6	0
	D bulk	M — M	4.2	8
	F daily	O — P	.88	3
	F' bulk	O — P	.40	2
	G daily	O — O	6.84	11
	H fortnightly	O — Q	0.02	1

Thus, no one profile location suffered particularly from erroneous predictions and therefore the transitions described by the matrices are spatially homogeneous.

Test of Homogeneity of Transitions over Time

To test whether any particular time period varied significantly from the prediction based on the bulk matrix, a similar procedure to that described for variation along the beach was undertaken.

The data were divided into two-month periods, and the same procedure as before carried out, i.e. the total frequency of beach types from 4/4/84 to 16/5/84 inclusive, for all profiles, was multiplied by the probability transition matrix (bulk and fortnightly) to give predicted frequencies. Then the individual transition frequencies making up this overall change were calculated as before. These were compared with the observed frequencies for the period 16/4 to 31/5. This produced the values for April and May; the same procedure was carried out for June and July, and for August and September. Similarly, using the bulk and daily (July) probability matrices both the first and second weeks in July were investigated to determine whether they behaved in a similar way to the beach over the entire six months. Table 3.18 contains an example of the results, for August and September.

Table 3.18 Predicted frequencies and transitions for August and September

$[4 \; 6 \; 17 \; - \; 4 \; 5 \; -]$ X P bulk = [3.71 6.01 15.94 1.77 3.71 3.83 1.03]
Observed = [3 4 22 - 3 4 -]
X $P_{F'ly}$ = [3.04 6.16 17.91 1.35 3.42 3.54 0.58]

bulk matrix

1.68	.68	1.32			.32	
.42	4.14	1.08				.36
1.36	1.19	10.88	1.36	.51	1.19	.51
		.16	.16	3.2	.32	.16
.25		2.5			2.0	

fortnightly matrix

1.2	.8	1.6			.40	
.54	3.66	1.56				.24
.85	1.7	11.73	.85	.34	1.19	.34
		.32		3.08	.60	
.45		2.7	.50		1.35	

observed

1		2				
2	2	2				
	2	13			2	
		1		3		
		4			1	

No two-month period seemed from a brief scan of the resulting matrices to be predicted or represented significantly worse than any of the others. However, in the second week of July the "diagonal" values, representing a static profile type, were consistently underestimated. This also tended to happen for certain transitions, e.g. 0 — 0, in other months. The second week of July saw predominantly calm offshore conditions and a relatively inactive beach, i.e. one in which the profile type remained the same.

The predicted and observed values in the 2-month or week-long transition matrices were compared, and the same procedure as before followed with the Poisson curve. This time none of the "suspect" transitions fell below .01 or between .01 and .05, and the probability value for only one transition lay between .05 and .10. This was the R — R prediction during April and May which had a predicted mean of .40 and a recorded frequency of 2. Of the remaining 49 transitions which were tested for significant differences, 21 had probabilities greater than .33 and 28 had probabilities between .10 and .33. These values indicate a good prediction of profile type over time, with no one period showing extreme results. The numbers in these probability classes seemed to be fairly evenly distributed among the periods with the exception of April and May where none of the suspects were over .32, i.e. the April and May period was predicted slightly less well than the remaining periods, perhaps reflecting more variable conditions (there were storms during May). This difference is not regarded as being very significant.

Conclusions from Six Months of Data

From the six months of data 4/4/84 to 26/9/84, the transition probability matrix constructed allowed predictions of future conditions to be made, it having been established that:

1. The transitions among beach types were Markovian, i.e. exhibited no "memory effects".
2. The transitions predicted by the bulk probability transition matrix agreed fairly well with the behaviour within data sub-sets.
3. The transitions are generally homogeneous, both spatially and temporally.

3.2 a (v) Prediction of Beach Development using the Markov Model

The next step was to try to use the "summer" matrix derived for April to September 1984 to predict the transitions which would occur during a completely different six-month "winter" period from October 1983 to March 1984. These predictions were then compared with what was actually observed to determine their quality. It was decided that if the predictions were poor, as might be expected if "winter" conditions resulted in different behaviour, then a new probability transition matrix would be created based on these "winter" data. Two predictive models would then exist covering the whole year. A set of hypotheses was set up regarding the changes which might be observed between these "winter" and "summer" predictive matrices:

1. In "winter" the profile would be more variable,reflecting more variable, and rougher, wave conditions.
2. Fewer static periods would be observed in "winter".
3. 1. and 2. above mean that the diagonal values of a "winter" probability transition matrix would be smaller than those of a "summer" one.

The data for this new six month period would have to be checked for Markov properties. (Bearing in mind that the first six months exhibited such properties it would be expected that behaviour during this period would be similar. In fact if the beach did turn out to be more variable the Markov properties might be expected to be more marked - periods of one persistant beach type, might be mis-interpreted as some indication of inertial memory.) Again tests for spatial and temporal homogeneity would have to be undertaken to determine whether a particular location or time period exhibited behaviour significantly different from the general behaviour of the entire system.

Assigning beach types to new 6-months data: The first step in testing the original matrix model was to assign the various profiles at certain dates to the existing profile types, remembering the possibility of new profile types existing as a result of conditions which did not prevail during 4/84 to 9/84 , i.e. the period for which type profiles were derived.

The five variables V1-V5 were calculated for each survey profile for the period 6/10/83 to 18/3/84 and the profiles assigned to the most similar suitable profile. There were a number of profiles which seemed not to fit satisfactorily into any of the existing categories. The S-type category, which already contained 3 profiles with a convex upper beach and concave lower beach, could accommodate other similar profiles. Two new type profiles, X and Y, were added (Figure 3.9 a and b), which could eventually be built into another matrix.

If the original probability transition matrix was to be used then clearly these "new" or anomalous profiles would also have to be assigned to the nearest existing profile type, (the original matrix could only predict within this range of 7 types).

All the profiles having been assigned to a type, the sequences of transitions for each profile were obtained as for the first six months. The frequency of occurrence of the various profile types at each location, and overall totals, were plotted (Figure 3.15), and as for 4/84 to 9/84 M, N and O-type profiles dominated the A-E profile locations, and P, O, Q and S those from F to H; i.e. in the north (F to H) the beach had gentler upper beaches and steeper lower beaches compared with the south, reflecting the less distinct upper and lower beach . In the south the upper beaches tended to be more nearly linear and the lower beach more variable - convex, concave or linear. In the north the upper beach tended to be less "full", i.e. concave, with a linear lower beach. This reflects the thinner sand cover and more frequent exposures of till mentioned in the opening of this section (3.2 a).

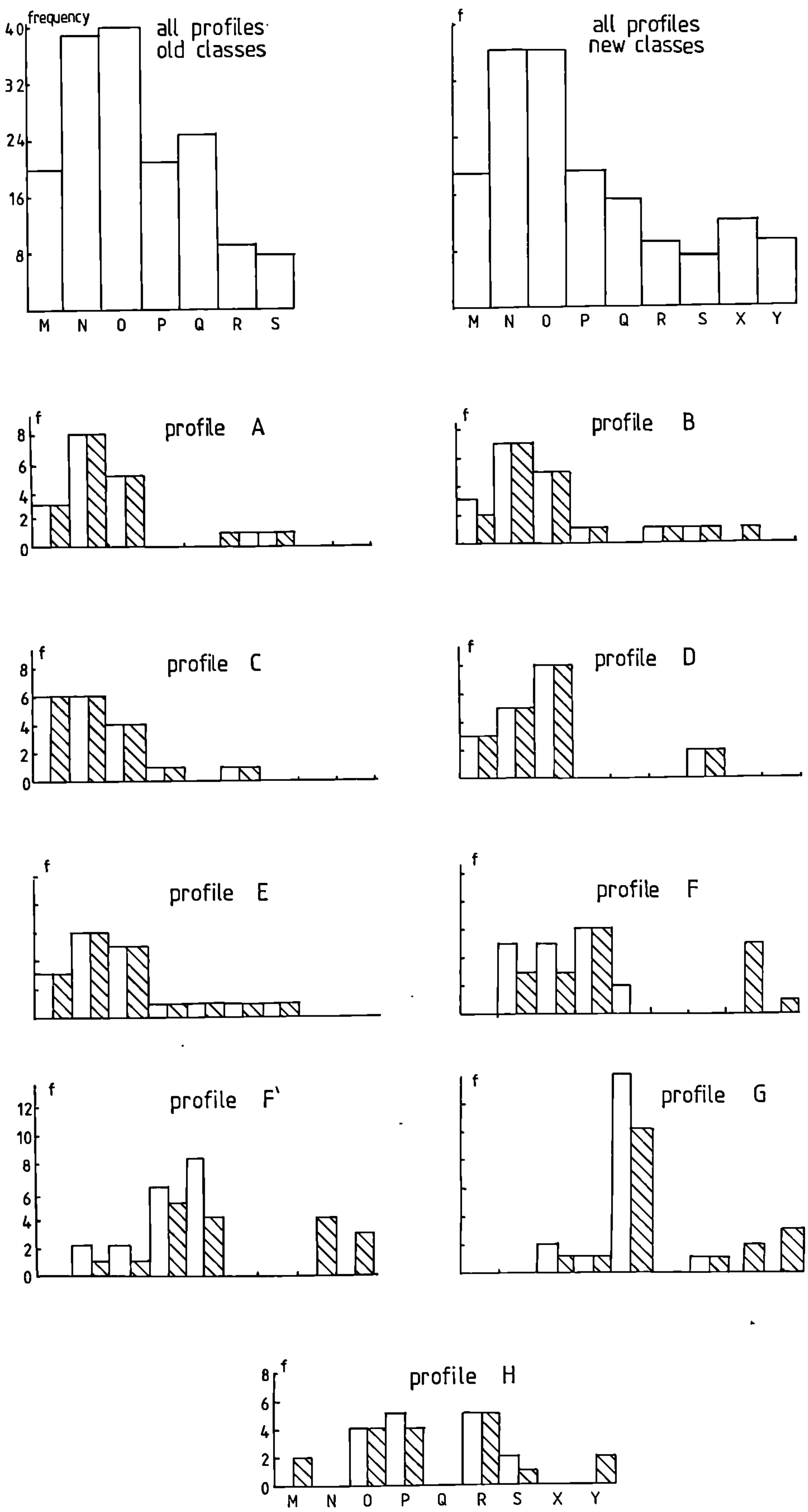
Table3.19 shows the frequency of the different profile types during the two six-month periods.

Table 3.19 Frequency of profile types - 4/84 to 9/84 and 10/83 to 3/84

Profile type	4/4/84 - 26/9/84 frequency	%	6/10/83 - 18/3/84 (new system) frequency	%
M	25	11.11	19	11.73
N	45	20.00	36	22.22
O	83	36.89	36	22.22
P	19	8.44	19	11.73
Q	25	11.11	15	9.26
R	20	8.89	9	5.56
S	8	3.56	7	4.32
X	-		12	7.40
Y	-		9	5.56
Total	225	100	162	100

It shows that there is only one major difference in type occurrence, apart from the introduction of X and Y types. This major change is the reduction from nearly 37% to 22% of the presence of O-type profiles; all the others are within 2 or 3% of the corresponding

Figure 3.15 Frequency of Beach Profile Types, October 1983 to March 1984 -
overall and by location, according to existing and "new" (diagonal shading) classifications.


frequency
40
32
24
16
8
all profiles
old classes
M N O P Q R S
f
all profiles
new classes
M N O P Q R S X Y
profile A
profile B
profile C
profile D
profile E
profile F
profile F'
12
10
profile G
profile H
8
6
4
2
0
M N O P Q R S X Y

value for the other time period. This O-type profile exhibits a linear upper beach and linear lower beach and is more common in "summer" (April to September). The frequencies of all the transitions for each profile for both the "old" and "new" classifications were compiled. During this second period there was again a two-week spell of more intensive surveying. From 4/3/84 to 18/3/84 inclusive the beach profiles were levelled every other day.

The same procedure as before was carried out, the 4/84 to 9/84 probability transition matrix being used to predict the total frequency of type profiles for the second six months, both for different time periods and for different locations. These results, which were truly predictions, were then compared with the observed frequency distribution so that the quality of beach profile prediction could be assessed, not just whether a particular subset exhibited unrepresentative behaviour.

Agreements between the predicted and observed frequencies proved to be fairly strong, differing only by one or two occurrences in all cases. However, the quality of predictions was not quite as good as in the first experiment. The worst predictions were, not surprisingly, for profile locations F', G and H where the new profiles X and Y occur, yet no allowance for their presence could be made under this scheme. The predictions for A-E were reasonable, though generally the transition matrices were less well predicted than the absolute distribution of types. In other words, the individual transitions involved in achieving that distribution would appear to differ slightly from those predicted.

A comparison of the predicted and observed transition matrices during this six-month period (10/83 to 3/84) revealed that certain transitions occurred more often than the 3/84 to 9/84 matrix predicted, while others occurred less frequently. There is a general tendency for the diagonal elements, transitions indicating the profile remaining the same type, to be overestimated, though they do still just dominate at most locations. This reflected a greater variability of beach shape from October to March, the transitions perhaps occurring more rapidly, and therefore when surveyed, with greater apparent frequency. In other areas of the table, away from the diagonals, there was a corresponding underestimation of frequency.

Table 3.20 summarises the principal increases or decreases from the expected values for each existing profile type. In terms of profile types, the "winter" period exhibits a greater variability and also a greater tendency for the upper beach to remain linear or to become more concave, i.e. lose material; this is provided that there is no great change in overall altitude. The lower beach, however, has a tendency to gain material; this indicates a movement of material from the upper to the lower beach, a general combing down or levelling out of the beach. It should be emphasised that this does not occur all the time, just with greater frequency than before.

The predicted and observed transition frequencies were subjected to the Poisson curve comparison procedure. A slightly poorer agreement, i.e. lower probabilities, was observed than for the "predictions" using the 4/84 to 9/84 matrix on the 4/84 to 9/84 data. Of the observations which appeared to be unreasonable, for a given predicted mean, more were in the $<.05$ probability class (5 of 34 "suspect" predictions instead of 3 in 38).

Similarly, the 4/83 to 9/84 matrix was used to predict the transitions that would be observed during different two-month periods. Again, the overall predicted frequencies of beach types were fairly

Table 3.20 Increased and decreased frequency of transitions

Increased f in 10/83 to 3/84	Decreased f in 10/83 to 3/84	Increase in transitions from	Decrease in transitions from
M — N	M — O	linear UB + concave LB — linear UB + convex LB	linear UB + concave LB — linear UB + linear LB
N — M	N — N	linear UB + convex LB — linear UB + concave LB	linear UB + convex LB — linear UB + convex LB
O — N	O — O	linear UB + linear LB (steep) — linear UB + convex LB	linear UB + linear LB (steep) — linear UB + linear LB (steep)
P — Q	P — P	v. concave UB + linear LB — less concave UB + linear LB	v. concave UB + linear LB — v concave UB + linear LB
Q — P	Q — Q	less concave UB + linear LB — v. concave UB + linear LB	less concave UB + linear LB — less concave UB + linear LB
R — O	R — R	linear UB + linear LB (gentle) — linear UB + linear LB (steep)	linear UB + linear LB (gentle) — linear UB + linear LB (gentle)

f = frequency UB = upper beach LB = lower beach good, allowing for the inevitable overestimation of O-types and underestimation of N-types. The values predicted for February and March were noticeably worse, and once again the individual transitions tested against Poisson curves were less well predicted, 5 of 18 "suspect" transitions having probabilities $< .05$. Likewise the prediction for the fortnight of intensive surveying in March was not particularly good.

Thus the results of predicting 10/83 to 3/84 profile transitions using a probability transition matrix derived from 4/84 - 9/84 data had some flaws; the two periods had slightly different behaviour. The use of the probability transition matrix for 4/84 to 9/84 would be sufficient to obtain an estimate of the frequency of profile types from an existing frequency distribution, but the individual transitions would probably not reflect reality very well. Thus to refine the predictions for a "winter" period it was decided to create a new probability transition matrix from the 10/83 to 3/83 data, incorporating the new profiles, X and Y.

3.2 a (vi) A Specific Winter Model

The new frequency matrix and probability transition matrix can be seen in Figure 3.16. It was desirable to test the data for true Markov behaviour, and again to see whether the transitions were homogeneous over the length of the beach and throughout the six-month period. A chi-squared test was carried out as for the first six-month period and revealed that the beach did exhibit first order Markov behaviour (figures significant at the 5% level).

New frequencies of profile types and new transition matrices were "predicted" using the "winter" probability transition matrix, P_w, for each profile location, and for each of the two-month periods. The results for each profile seemed to be reasonably similar to what

Figure 3.16

	M	N	O	P	Q	R	S	X	Y	Total
M	6	6	3	1		1				17
N	7	13	4	1		1	4	3		33
O	4	7	14	4	1	5				35
P	1	2	5	6	2			1	2	19
Q			1	2	7		1		2	13
R	1		3			1	1		2	8
S		3	2		1		1			7
X		3	1	1	1			4	2	12
Y				1	2	1		4	1	9

a Frequency Transition Matrix, October 1983 to March 1984

	M	N	O	P	Q	R	S	X	Y
M	.35	.35	.18	.06		.06			
N	.21	.40	.12	.03		.03	.12	.09	
O	.11	.20	.40	.12	.03	.14			
P	.05	.11	.26	.32	.11			.05	.10
Q			.08	.15	.54		.08		.15
R	.12		.38			.13	.12		.25
S		.43	.29		.14		.14		
X		.25	.08	.08	.09			.33	.17
Y				.11	.22	.11		.45	.11

b Probability Transition Matrix, October 1983 to March 1984 was predicted from overall beach behaviour. Not unexpectedly the observed transitions were closer to the predicted ones than they had been when prediction was carried out using the original (4/83-9/84) matrix. Inevitably there was still some deviation from expected values for profiles F', G and H. This probably reflects the critical beach zone where the beach profile changes from having distinct upper and lower beaches, in the south, to having a more gentle overall gradient with a less marked upper/lower beach junction, in the north.

The Poisson test for homogeneity over the length of the beach revealed much closer values for observed and predicted transition frequencies. For A, B, C and D profiles, of 13 "suspect" values only one was between .05 and .10, the rest being over .10. For profiles E to H, only 4 of 26 "suspect" transitions were below .10. All profiles and transitions on the beach were described equally well by this matrix. The corresponding results for different time periods also indicated a much better agreement than when the original probability matrix was used, especially for February and March. For all the periods only three transitions had associated probabilities less than .10.

This better prediction is not surprising as the matrix could now incorporate all profile types satisfactorily. It describes more accurately the behaviour, along the entire length and for different time periods within the six months, than did the first matrix.

<u>Summary</u>

It is important to note that in most instances the overall frequencies throughout the year, i.e. the numbers of each beach type that would occur, were quite well predicted by the original matrix. The importance of the "predictions" for limited parts of the data set lies in the fact that they illustrate homogeneous behaviour along the beach given the initial profile type. Different transitions occur in the north from those in the south because different profile types predominate, but all of these changes/transitions can be described by just one matrix.

The two matrices describe behaviour adequately over set time periods but judging from these matrices there is some seasonal variation in terms of the transitions which go to make up the overall behaviour. The first matrix might be termed a "summer" matrix, the second a "winter" one. Comparison of the two bulk matrices confirms earlier observations; the "winter" matrix diagonal values are smaller than those in the "summer" one, while those off the diagonals have an increased chance of occurring. Notably there are increases in M—N, N—M, O—M and O—N, confirming the observations recorded in Table 3.20.

Conclusions

The studies detailed above enable the following conclusions regarding beach behaviour to be made.

1. It exhibits Markov properties.
2. It can be described by a probability transition matrix or matrices.
3. The transitions involved, as described by the transition probability matrix, are homogeneous along the length of the beach.
4. The transitions involved, as described by the relevant matrix or matrices, are temporally uniform, though more variability is encountered than in 3 above.
5. The probability matrix or matrices can be used to predict beach changes and the nature of the beach in the future.

Possible refinements would involve specific matrices for different times of year.

6. Certain transitions are observed to occur with slightly different frequencies in "summer" and "winter".

It is important to compare wave conditions with various profile transitions which occur, for example are certain transitions associated with particular wave energy conditions? The following hypotheses might be advanced:

1. Higher energy conditions will lead to a combing down of the upper beach and a build up of the lower beach.
2. Calm conditions will lead to a build up of the upper beach or will maintain a linear profile of increased volume.
3. Long periods of calm or similar conditions will produce little change in beach profiles.

This section has established that the field site beach exhibits 1st order Markov behaviour, which can be expressed in terms of a probability transition matrix model which describes and predicts behaviour uniformly, both spatially and temporally. Though one model gives adequate prediction for the whole year, it is more satisfactory to present two models - one for winter, the other for summer. Beach behaviour thus established will be analysed in respect of offshore conditions in a later section, 4.2 a (iv).

3.2 b BEACH SEDIMENTS

The previous section dealt with the characteristics and behaviour of beach profile shape. In this section the results of experiments designed to establish the characteristics and behaviour of sediment composition are presented. These data will be interpreted later (Section 4.2 b) when the sedimentary response of the beach to wave conditions is investigated.

Mean Particle Size

Figure 3.17 shows, for profile A, a plot of upper beach and lower beach mean particle size from May 1983 to September 1984; also shown is the curve for the beach crest. The mean size of the lower beach material is remarkably constant, around 2Ø (0.25 mm), considerably smaller than that of the upper beach, the mean of which fluctuates rather more. A steady -1.0 Ø to -1.5 Ø is observed during the summer of 1983,then a fairly uniform increase in grain size to around -3.0 Ø (8 mm) in March 1984, reflecting the coarsening of the upper beach during winter. There follows a dramatic decrease in size, and for three months the value fluctuates between -2.0 Ø (4 mm) and 0 Ø (1 mm). From July/August onwards the variation is not nearly as great. There is a slight, probably insignificant, tendency for the lower beach to coarsen as the upper beach becomes finer, and vice versa.

The plot for profile D is presented in Figure 3.18. Again, with the exception of two samples, the lower beach mean particle size in constant at around 2.0 Ø. The upper beach coarsens slightly during the '83/'84 winter, but is finer during early January. Overall, the record is much more variable, fluctuating between -2.0 Ø and 0.0 Ø. There are signs of finer sediments dominating from mid-July 1984 onwards. From a comparison of the two curves, there is no obvious relationship between the upper and lower beach sediments.

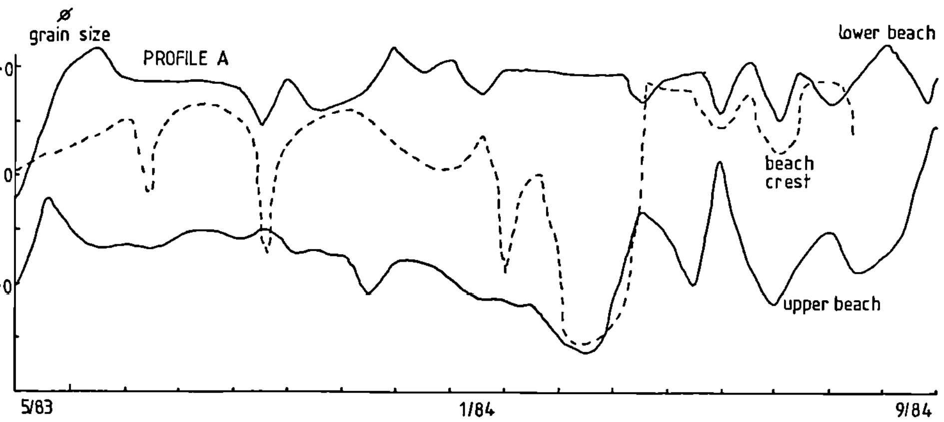
Figure 3.19 demonstrates the pattern of mean particle size for profile F'. The lower beach sediment is more variable; for much of the year the mean size is around 1.5 to 2.0 Ø but is considerably coarser in November and February, yet only slightly coarser than "normal" during December and January. The upper beach is

Figure 3.17 Mean Particle Size of upper and lower beach and beach crest.
Profile A, May 1983 to September 1984.

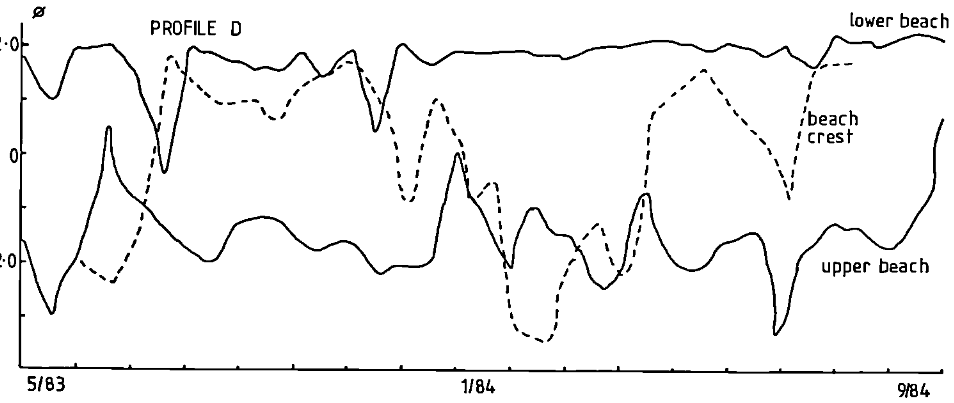
Figure 3.18 Mean Particle Size of upper and lower beach and beach crest.
Profile D, May 1983 to September 1984.

Figure 3.19 Mean Particle Size of upper and lower beach and beach crest.
Profile F', May 1983 to September 1984.

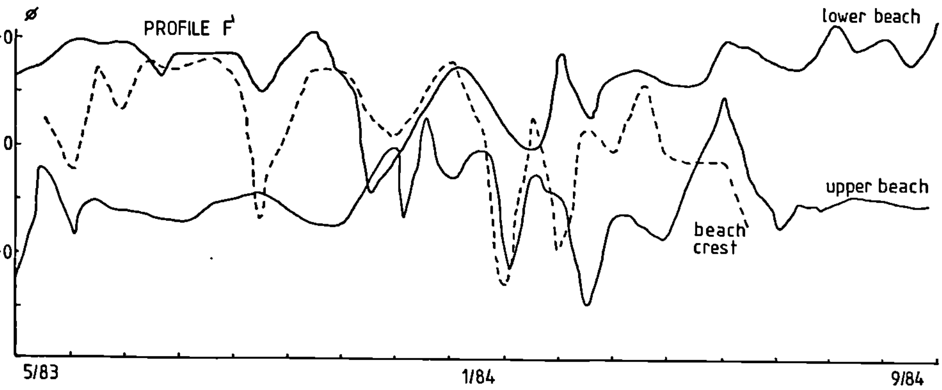
Figure 3.20 Mean Particle Size of upper and lower beach.
Profile H, May 1983 to September 1984.



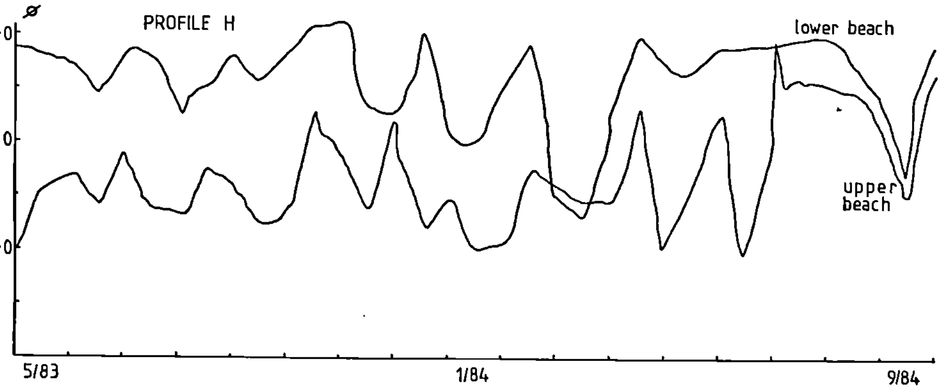
ø
grain size
PROFILE A
lower beach
beach crest
upper beach
2·0
0
-2·0
5/83
1/84
9/84



ø
PROFILE D
lower beach
beach crest
upper beach
2·0
0
-2·0
5/83
1/84
9/84



ø
PROFILE F
lower beach
upper beach
beach crest
2·0
0
-2·0
5/83
1/84
9/84



ø
PROFILE H
lower beach
upper beach
2·0
0
-2·0
5/83
1/84
9/84

about -1.5 Ø for most of 1983, becoming finer briefly in December before coarsening steadily until the end of April 1984, after which it remains around -1.0 Ø. The most noticeable feature of this figure is its cluttered nature. The values for the upper beach and lower beach are much closer together than for profiles D and A; the curves actually cross at the end of November. The upper and lower beaches are thus becoming less sedimentologically distinct. This feature has been noticed before in other beach variables, e.g. the profile shapes show a less distinct break of slope at the junction of the upper beach and the lower beach. A similarly less distinct pattern is seen in Figure 3.20 which represents the results for profile H. Here the two curves intersect in two places. The lower beach is again much more variable than at A or D, the mean particle size being around 1-2 Ø from May 1983 until November 1983. There follows a coarsening trend (with fluctuations) until April/May 1984 and, apart from a coarse episode in early September, the value remains around 1.75 Ø. The upper beach too exhibits a coarsening from December until the end of March 1984, after which the record is extremely variable.

Beach crest behaviour: Before moving on to consider variation of mean particle size alongshore, rather than throughout the year, something will be said about the nature of the beach crest. Sometimes it comprises material similar to that on the upper beach while at others it is much finer - more like the material on the lower beach. When it is finer it is composed of a mass of undisturbed fine sand on top of the beach. Often, especially during low spring tides and calm conditions, this may be untouched by waves or spray for up to a month.

At profile A during the summer months (until November 1983) the beach crest is only slightly coarser than the lower beach material; in the field this is represented by a mass of dry sand piled up beneath the cliff. From November onwards the mean particle size increases until by March it is very similar to the material on the upper beach. This represents the period when the finer sands at the top of the beach are removed, the combing down of the beach to a "winter" profile according to traditional beach models. During April there is a rapid decrease in the grain size of the beach crest as the sand "berm" is restored; this position is maintained throughout the summer.

The beach crest curve of profile D (Figure 3.18) exhibits the same pattern as at Profile A, though at times its fluctuations are greater. After a relatively coarse period lasting until August 1983, the beach crest has a similar composition to the lower beach (1.0 Ø to 2.0 Ø). There is a steady increase in particle size until March/April, by which time the mean grade is between -1.0 Ø and -2.0 Ø. The crest is extremely coarse in February (-3.0 Ø) when it appears to have been created by pebbles and coarse gravel being thrown up the beach (Plate 3.3). In spring and summer the crest material becomes finer as less coarse material is deposited at the top of the beach.

Figure 3.19 shows the behaviour of the beach crest sediments at profile F'. Here, in keeping with the general breakdown of the upper beach/lower beach pattern, the picture is more confused. The crest composition fluctuates between coarse and fine sediments though there is an overall increase in size during January, February and March.

Plate 3.3 Coarse Beach Crest.

Plate 3.4 Underminded Pill-box near Profile G.

Figure 3.21 Mean Particle Size Variation Alongshore.

a. April 1984 to September 1984

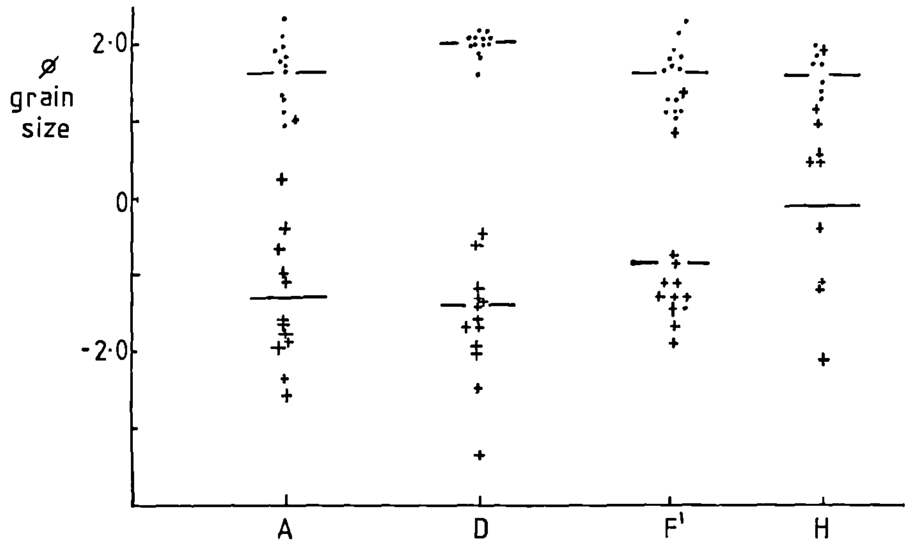
b. October 1983 to March 1984

+ = upper beach

• = lower beach

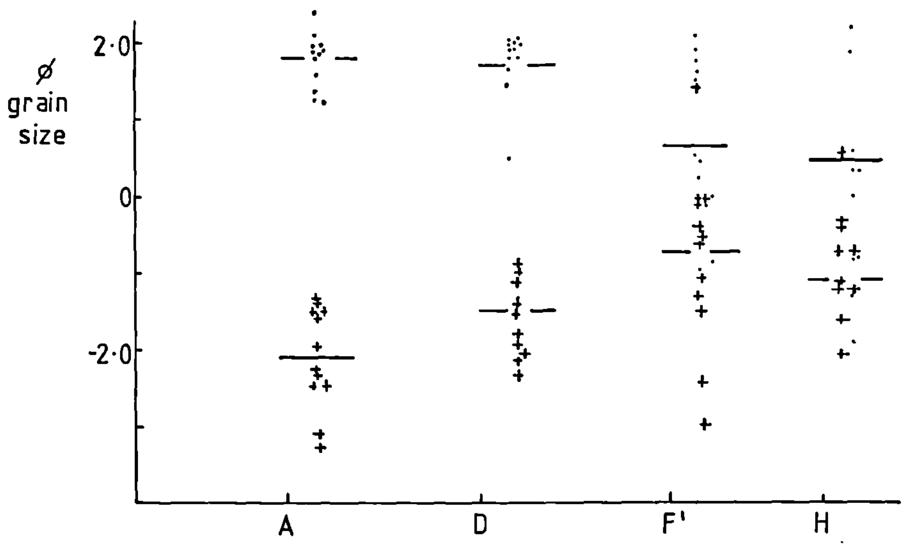
$\overline{UB}$ = mean of upper beach mean particle size

$\overline{LB}$ = mean of lower beach mean particle size



(a)

Profile A $\overline{UB}$=-1·22 $\overline{LB}$= 1·66
Profile D $\overline{UB}$=-1·33 $\overline{LB}$= 2·09
Profile F' $\overline{UB}$=-0·73 $\overline{LB}$= 1·72
Profile H $\overline{UB}$=-0·11 $\overline{LB}$= 1·58



(b)

Profile A $\overline{UB}$= -2·09 $\overline{LB}$=1·76
Profile D $\overline{UB}$= - 1·48 $\overline{LB}$=1·74
Profile F' $\overline{UB}$= - 0·69 $\overline{LB}$=0·69
Profile H $\overline{UB}$= - 1·01 $\overline{LB}$=0·50

No beach crest plot is shown for profile H because for most of the time no distinct crest exists. Here, as far as profile shape is concerned, the upper and lower beaches are virtually indistinguishable. It is difficult to determine where the junction occurs, though there is some variation in sediment composition down the beach. This may be an incipient ord but there is no evidence of local sediment variations associated with such beach depressions.

Variations alongshore: A certain amount of longshore variation could be observed in the results presented above for temporal variation. Figure 3.21 shows the mean sediment grain size at the various profile sites alongshore, for two periods, April to September 1984 (Figure 3.21 a) and October 1983 to March 1984 (Figure 3.21 b). The division was made as much for clarity as for drawing attention to any differing trends in winter and summer. The mean values for the six-month periods are marked on the diagram but it should be remembered that they may represent a wide range of values. Few observations can be made from these diagrams. The main one, once again, is the increased simiłarity of the upper and lower beaches from south to north; the upper beach becomes finer towards the north while the lower beach coarsens.

Sorting

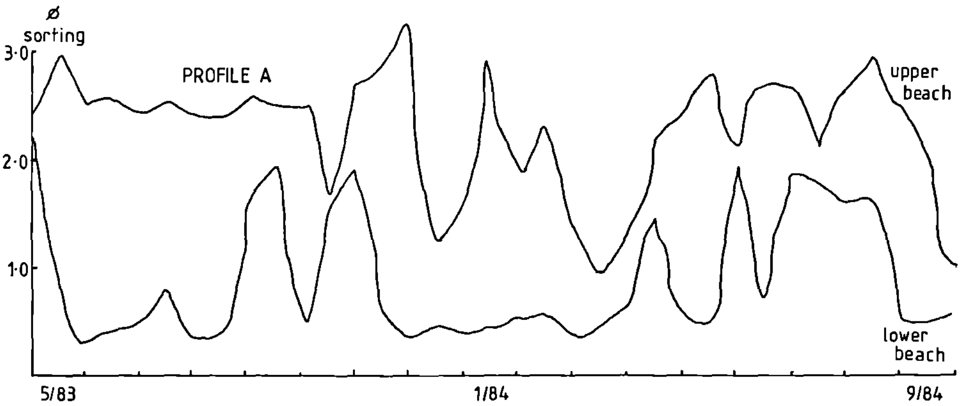
The second index used to describe the beach sediment characteristics was sorting (see Table 3.21 for the sorting scale). Figure 3.22 shows the plot of sorting of the upper and lower beach material at profile A, over the 17-month sampling period. The sorting of the upper beach was, as would be expected for coarser sediments, poorer than for the lower beach. The traces are too variable to draw any definite conclusion from the data; sorting appears to be slightly

Figure 3.22 Sorting of upper and lower beach sediments. Profile A, May 1983 to September 1984.

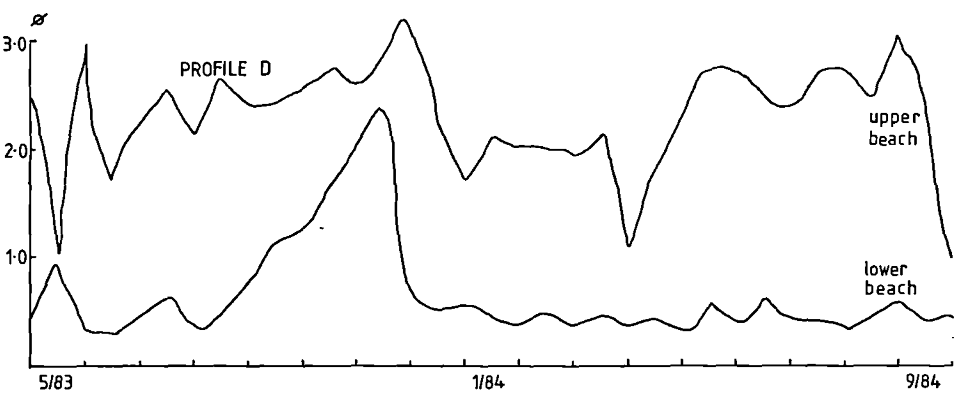
Figure 3.23 Sorting of upper and lower beach sediments. Profile D, May 1983 to September 1984.

Figure 3.24 Sorting of upper and lower beach sediments. Profile F', May 1983 to September 1984.

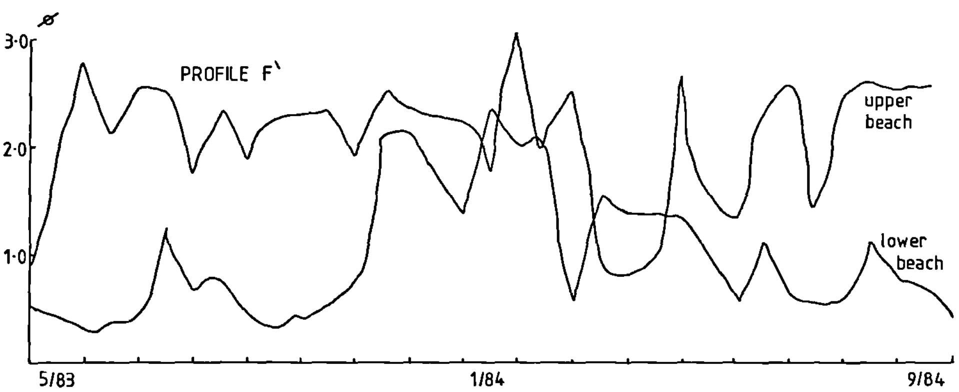
Figure 3.25 Sorting of upper and lower beach sediments. Profile H, May 1983 to September 1984.



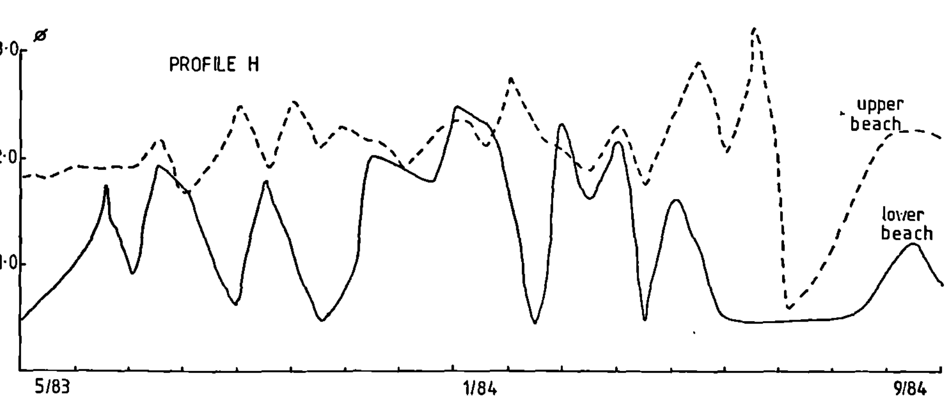
Ø
sorting
3·0
2·0
1·0
PROFILE A
upper beach
lower beach
5/83
1/84
9/84



Ø
3·0
2·0
1·0
PROFILE D
upper beach
lower beach
5/83
1/84
9/84



Ø
3·0
2·0
1·0
PROFILE F'
upper beach
lower beach
5/83
1/84
9/84



Ø
3·0
2·0
1·0
PROFILE H
upper beach
lower beach
5/83
1/84
9/84

better on the upper beach during the winter (December to March), while the lower beach for most of the time is fairly well sorted.

Table 3.21 Sorting Values (Ø) from Briggs (1977)

Very well sorted	<0.35
Well sorted	0.35-0.50
Moderately well sorted	0.50-0.70
Moderately sorted	0.70-1.00
Poorly sorted	1.00-2.00
Very poorly sorted	2.00-4.00
Extremely poorly sorted	>4.00

Figure 3.23 shows the same type of record for profile D. Apart from a period of poor sorting in the late autumn of 1983 the lower beach sediments are well sorted, while the upper beach sediments fluctuate widely with an increase in sorting during the spring.

The traces for profile F' (Figure 3.24) are somewhat confused, with a decrease in sorting of the lower beach material in winter (October/November to February), and an increase in upper beach sorting in March and April. With the exception of this period, lower beach sorting was much better than upper beach sorting.

Figure 3.25 illustrates the large variation in sorting at profile H, the sorting on the upper beach being marginally worse than on the lower beach, though sometimes the difference is extremely small. Here, yet again, the distinction between the upper and lower beach is breaking down.

Variation alongshore: Figure 3.26 (a and b) shows the patterns of sediment sorting alongshore. The distinction between the two data sets (upper beach and lower beach) decreases from profile A in the south to profile H in the north, with little contrast between the patterns in a and b (April to September and October to March). The igure 3.26 Sorting Variation Alongshore.

a. April 1984 to September 1984

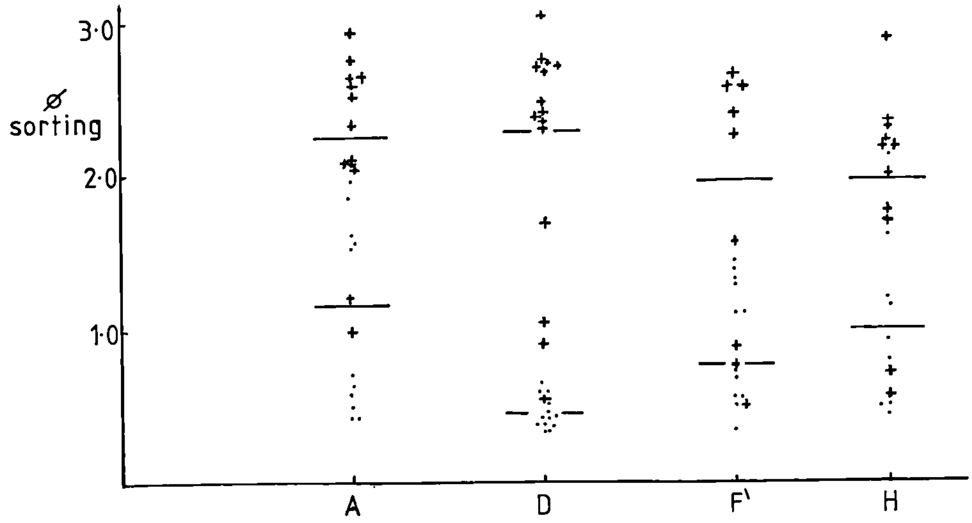
b. October 1983 to March 1984

+ = upper beach

• = lower beach

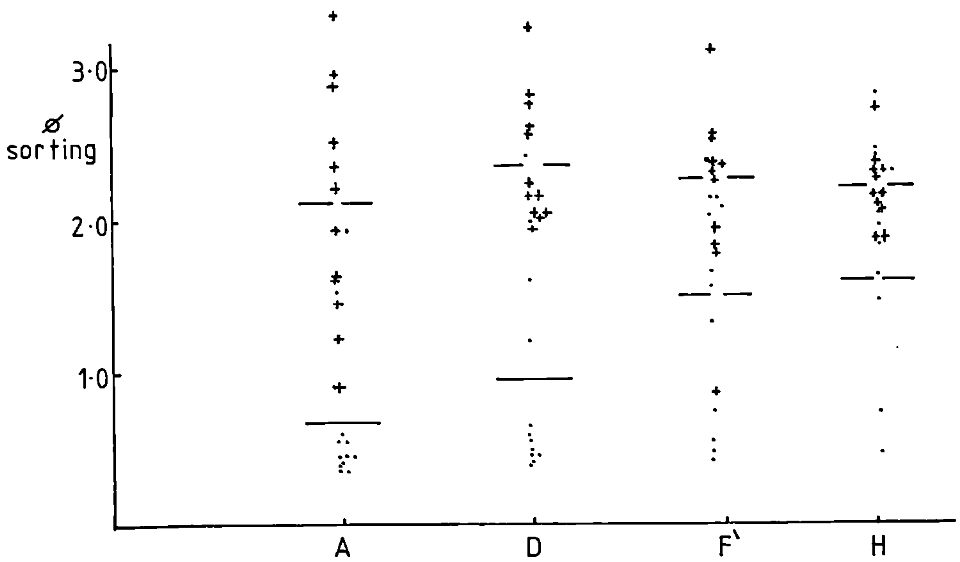
$\overline{UB}$ = mean of upper beach sorting

$\overline{LB}$ = mean of lower beach sorting



(a)

Profile A $\overline{UB}$= 2·25 $\overline{LB}$=1·15
Profile D $\overline{UB}$= 2·28 $\overline{LB}$=0·44
Profile F' $\overline{UB}$= 1·95 $\overline{LB}$=0·76
Profile H $\overline{UB}$= 1·98 $\overline{LB}$=1·00



(b)

Profile A $\overline{UB}$=2·11 $\overline{LB}$=0·66
Profile D $\overline{UB}$=2·35 $\overline{LB}$=0·93
Profile F' $\overline{UB}$=2·34 $\overline{LB}$=1·46
Profile H $\overline{UB}$=2·19 $\overline{LB}$=1·58

convergence of mean sorting values is brought about by a steady decrease in sorting on the lower beach from south to north, while on the upper beach the value remains much the same.

Before concluding the section on sediment characteristics a few additional points will be made. The first is that frequently towards the northern end of the field site very little or no sediment was present on parts, and very rarely the whole, of the upper beach. There the till platform was exposed. These sections can be likened to, and indeed may even make up part of, the "ords" described by Phillips (1962, 1964) and Pringle (1981, 1984, 1985); they are discussed in more detail in the sections dealing with beach profile evolution and general beach behaviour, (sections 3.2 a and 4.2 a).

Changes in sediment characteristics alongshore may well reflect the influence which Flamborough Head exerts on the coast, an influence which decreases from north to south and has been associated with other patterns of behaviour, e.g. beach profile shape, sediment movement and cliff retreat. Finally, the most likely direct cause of sediment characteristics varying is wave height (i.e. wave energy available at the shore). The influence of wave height is investigated in section 4.2 b.

The results from this section on beach sediments may be summarised as follows:

1. The upper beach material is generally much coarser (-0.5 Ø to -3.0 Ø) than that of the lower beach (0.0 Ø to 2.0 Ø), though there is considerable variation, depending upon location.
2. Upper beach material tends to coarsen during the winter, and become finer in summer. The lower beach is less variable overall.

3. Beach crest material during "summer" resembles finer, lower beach material, but during "winter" is often composed of coarse material resembling that of the upper beach.
4. These patterns in mean particle size break down in the north of the field site where variability is greater. The upper beach becomes progressively finer towards profile H. The lower beach is coarser at the northern end of the beach, particularly in winter.
5. Sorting values of upper beach material are greater than those of the lower beach, indicating poorer sorting, but are extremely variable. At some profiles, sorting appears to be better in winter.
6. Upper beach sorting remains fairly constant alongshore (2-2.5 Ø) with perhaps a slight decrease towards the north. The sorting index of the lower beach material increases northwards from 0.7 to 1.5 Ø, i.e. the lower beach in the north is less well sorted and the upper beach/lower beach pattern breaks down.

3.2 c SEDIMENT TRANSPORT RATES FROM TRACER EXPERIMENTS

Potential sediment movement was presented in an earlier section; it now remains to investigate the rates of sediment transport observed on the beach. Section 2.3 c contained a description of the field and analytical techniques used in the tracer experiments which were carried out to determine real sediment transport rates. In this section the results are presented for the two sand tracer experiments conducted under contrasting wave conditions, and for the pebble experiment. A later section (4.2 c (iii)) will compare the modelled and measured rates.

Table 3.22 Tracer Concentrations

A 2/7/84

Sample location	Weight (g)	Fluorescent* grains	Concentration grains/g
A-1	110.21	41.1	0.37
A0	141.26	198.8	1.41
A2	133.69	290.1	21.70
A4	146.71	1859.4	12.67
C-1	133.57	32.0	0.24
C0	111.80	2264.8	20.26
C2	154.14	3746.2	24.30
C4	149.26	1261.9	8.45
E-1	166.11	5.1	0.03
E0	148.83	39.5	0.27
E2	152.96	190.8	1.25
E4	156.30	422.1	2.70

B 3/7/84

Sample location	Weight (g)	Fluorescent* grains	Concentration grains/g
A-1	154.95	16.8	0.11
A0	149.61	14.4	0.10
A2	184.88	876.3	4.74
A4	163.24	540.9	3.31
A5	139.73	1166.6	8.35
C-1	163.83	37.8	0.23
C0	176.51	1126.2	6.38
C2	148.84	262.9	1.77
C4	145.82	186.1	1.28
C5	173.87	471.4	2.71
E-1	177.34	31.92	0.18
E0	214.21	60.4	0.28
E2	100.03	33.2	0.33
E4	173.92	97.4	0.56
E5	145.07	149.7	1.03

C 4/7/84

Sample location	Weight (g)	Fluorescent* grains	Concentration grains/g
A-1	166.95	16.9	0.10
A0	124.34	20.9	0.17
A2	200.28	302.3	1.51
A4	147.61	185.8	1.26
A5	138.45	258.8	1.87
C-1	148.70	16.1	0.11
C0	171.38	38.0	0.22
C2	154.34	129.4	0.84
C4	160.28	311.2	1.94
C5	185.72	418.8	2.26
E-1	126.63	24.5	0.19
E0	153.79	3.3	0.02
E2	161.52	59.9	0.37
E4	138.46	47.0	0.34
E5	154.09	29.4	0.19

D 5/7/84

Sample location	Weight (g)	Fluorescent* grains	Concentration grains/g
A-1	173.36	3.2	0.02
A0	206.85	29.4	0.14
A2	169.66	569.7	3.36
A4	156.00	429.8	2.76
A5	163.82	208.1	1.27
C-1	155.02	7.8	0.05
C0	125.56	12.7	0.10
C2	140.42	119.7	0.85
C4	131.21	81.5	0.62
C5	154.95	116.1	0.75
E-1	178.20	28.0	0.16
E0	149.20	12.4	0.08
E2	161.10	41.5	0.26
E4	118.45	68.3	0.58
E5	190.17	37.5	0.20

* Extrapolated from quarter-sized samples

Table 3.22 continued

E 8/7/84

Sample location	Weight (g)	Fluorescent* grains	Concentration grains/g
A0	154.92	2356	15.21
A2	187.03	2162	11.56
A4	202.90	219	1.08
B0	162.75	4730	29.06
C0	183.43	8543	46.57
C2	163.73	62645	382.61
C4	174.10	3312	19.03
E0	184.75	7274	39.37
E2	178.81	10746	60.10
E4	161.07	1497	9.92

F 9/7/84

Sample location	Weight (g)	Fluorescent* grains	Concentration grains/g
A-1	121.71	647	5.31
A1	164.59	820	4.98
A3	148.72	165	1.11
A4	148.65	37.9	0.25
C-1	139.30	43	0.31
C1	165.91	288	17.40
C3	157.84	323	2.05
C4	152.64	43	0.28
E-1	163.53	876	5.36
E1	183.32	2248	12.26
E3	153.66	1182	7.69
E4	171.79	81	0.47

G 10/7/84

Sample location	Weight (g)	Fluorescent* grains	Concentration grains/g
A-1	215.73	1171	5.43
A1	160.37	1365	8.51
A3	189.57	95	0.50
A4	192.15	52	0.27
C-1	208.85	5432	26.01
C1	184.85	12648	68.42
C3	193.10	19897	103.04
C4	184.93	660	3.57
E-1	190.58	200	1.05
E1	202.42	364	1.80
E3	179.02	256	1.43
E4	171.26	42	0.25

H 11/7/84

Sample location	Weight (g)	Fluorescent* grains	Concentration grains/g
A-1	175.97	2321	13.19
A1	152.71	2501	16.38
A3	185.88	132	0.71
A4	162.88	50	0.31
C-1	161.91	6234	38.50
C1	155.37	11581	74.54
C3	135.31	15775	116.58
C4	166.05	194	1.17
E-1	120.27	319	2.65
E1	185.99	1285	6.91
E3	149.60	115	0.77
E4	149.22	13	0.09

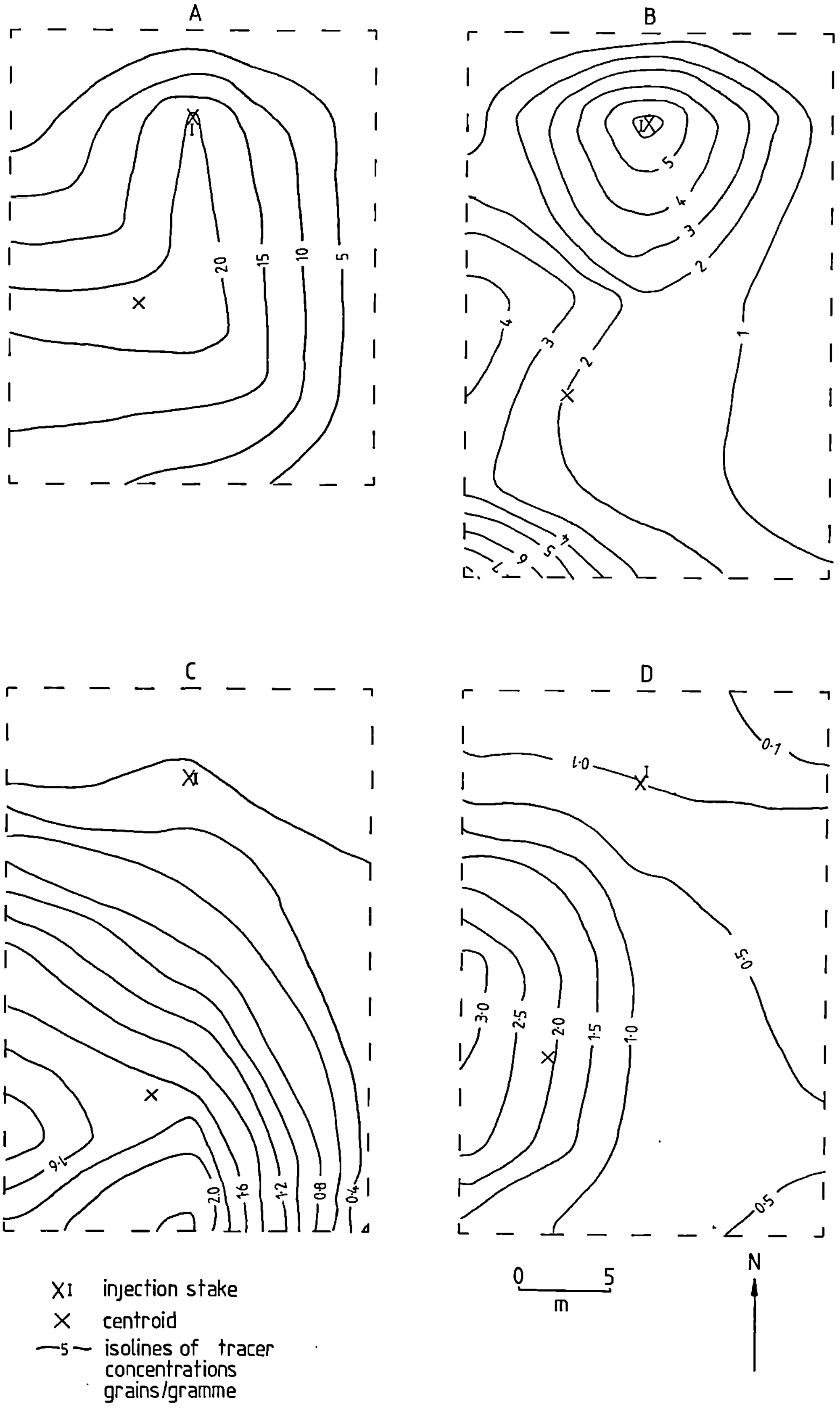
Table 3.22 Continued

I 12/7/84 Sample location	Weight (g)	Fluorescent* grains	Concentration grains/g	J 13/7/84 Sample location	Weight (g)	Fluorescent* grains	Concentration grains/g
A-1	146.54	3712	25.33	AX0	144.57	1241	8.58
A1	155.00	1088	7.02	AX2	181.70	9	0.05
A3	155.20	22	0.14	AX4	143.03	267	1.87
A4	145.27	13	0.09	AX5	170.65	40	0.23
C-1	174.26	11279	64.72	CX0	161.50	2125	13.16
C1	146.57	17966	122.58	CX2	142.72	5755	40.32
C3	158.32	237	1.49	CX4	141.10	11028	78.16
C4	155.07	53	0.34	CX5	149.43	104	0.70
E-1	161.03	2673	16.60	EX0	151.74	1472	9.70
E1	156.78	1742	11.11	EX2	164.40	1687	10.26
E3	111.01	15	0.13	EX4	125.81	523	4.16
E4	186.87	10	0.05	EX5	150.20	50	0.33

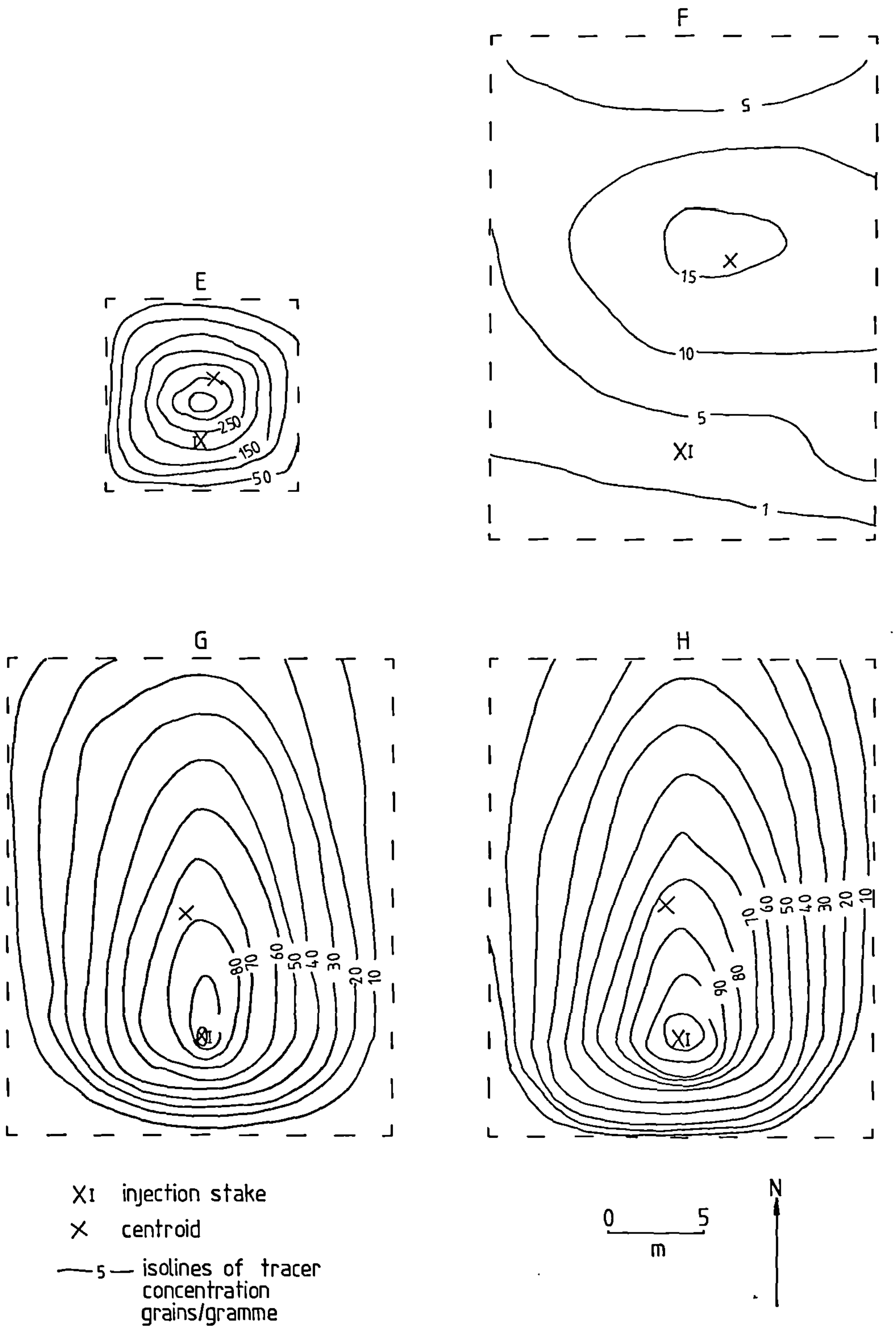
Figure 3.27 A-J Isolines of Tracer Concentration

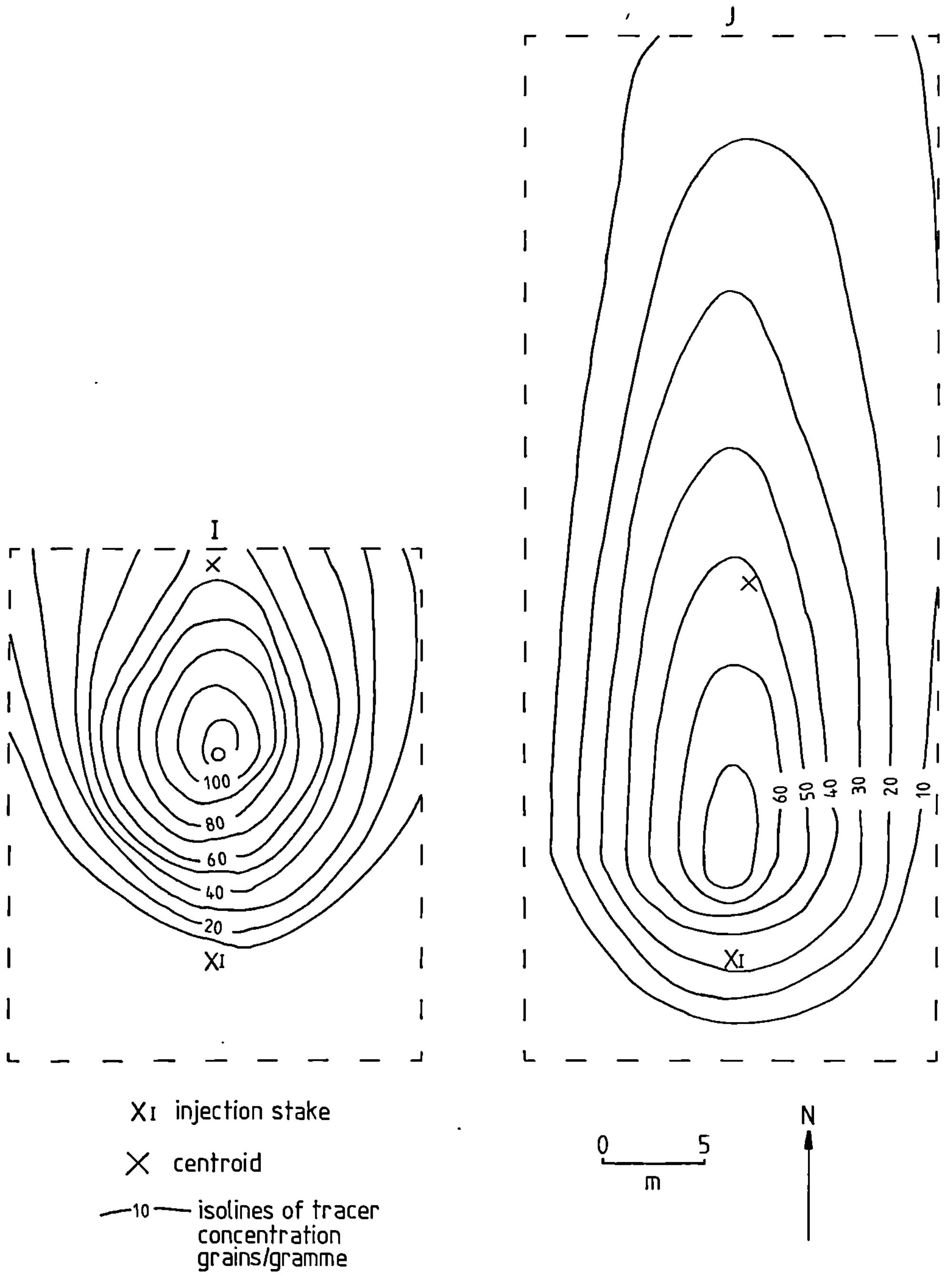
2/7/84-5/7/84 and 8/7/84-13/7/84.

A -	Experiment 1	2/7/84
B -	"	3/7/84
C -	"	4/7/84
D -	"	5/7/84
E -	Experiment 2	8/7/84
F	"	9/7/84
G	"	10/7/84
H	"	11/7/84
I	"	12/7/84
J	"	13/7/84



A
20
15
10
5
B
5
4
3
2
1
4
3
2
C
1·6
2·0
1·6
1·2
0·8
0·4
D
1·0
0·1
0·5
3·0
2·5
2·0
1·5
1·0
0·5
XI injection stake
X centroid
—5— isolines of tracer concentrations grains/gramme
0 5
m
N


E
250
150
50
F
5
15
10
5
XI
1
G
80
70
60
50
40
30
20
10
XI
H
70
60
50
40
30
20
10
90
80
XI
XI injection stake
X centroid
—5— isolines of tracer concentration grains/gramme
0 5
m
N



I
100
80
60
40
20
XI
J
60
50
40
30
20
10
XI
XI injection stake
centroid
10 isolines of tracer concentration grains/gramme
0
5
m
N

Sand Tracer Experiments - Results

The concentration of fluorescent sand tracer in each sample extracted from the beach is presented in Tables 3.22 A-J. These values were entered on a diagram of the sample grid and isolines of concentration drawn in between the points. These can be seen in Figures 3.27 A-J. The centroid of concentration for each day was calculated (according to the method shown in Section 2.3 b) and the results plotted on a plan of the beach for each experiment (Figure 3.28). The rate of centroid travel, $\bar{V}c$, was then calculated for each sampling interval, followed by the calculation of volume sediment transport, Qs:

$$Qs = \bar{V}c \times W \times d \qquad (3.16)$$

The active layer (d) was approximately 3.5 cm thick, from observations during both experiments, and an active lower beach width (W) of 120 m was assumed.

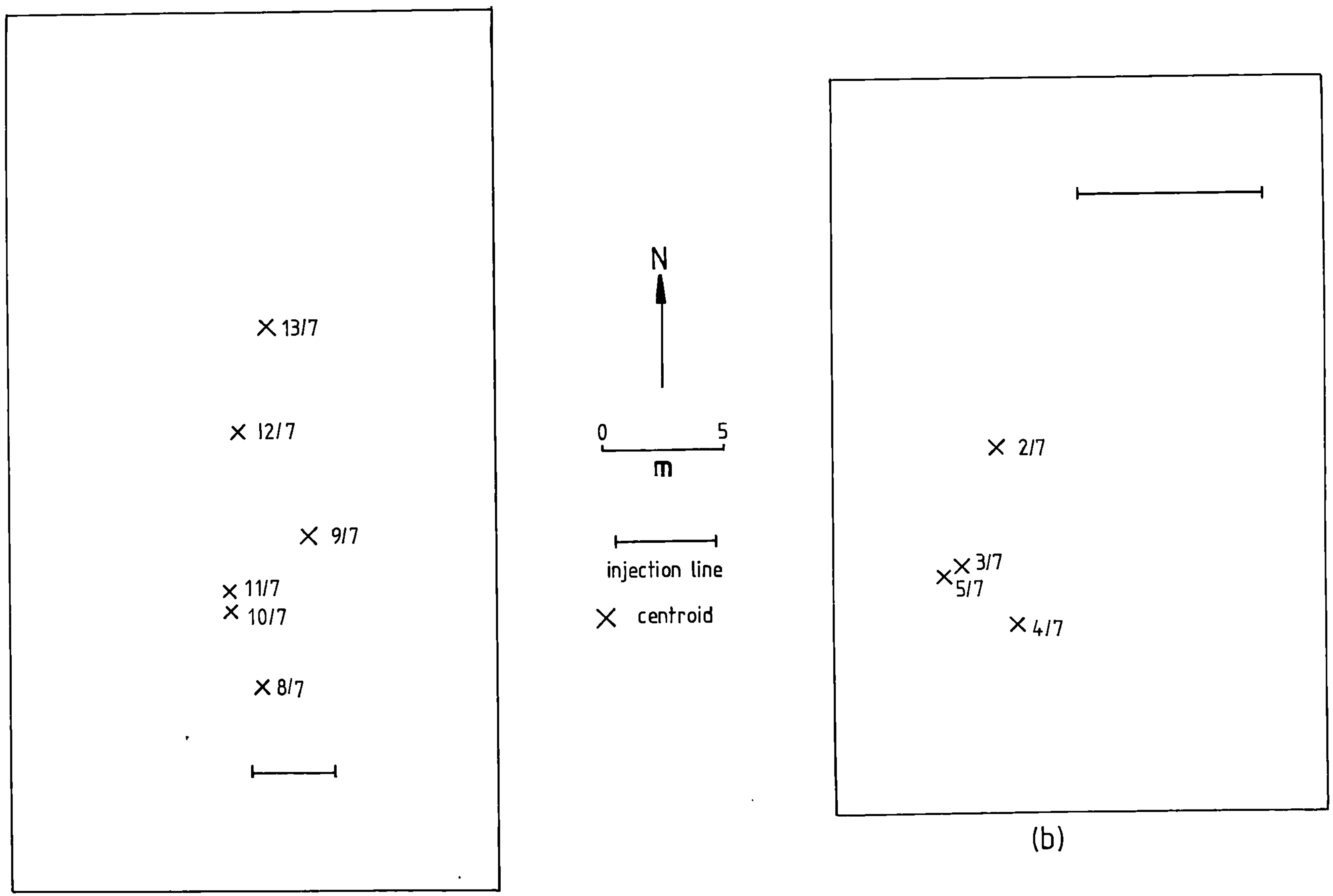
Experiment 1 (1 - 5 July)

During this experiment wave approach was predominantly from the N.E.; relatively rough conditions prevailed at first (waves of $H_o \doteqdot 0.70$ m) causing rapid tracer dispersal. By the end of the sampling period H_o was 0.30 m. Table 3.23 shows the coordinates of centroid positions for experiment 1. Over the 4-day sampling period the plotted centroids revealed a movement towards the south, relfecting the wave approach direction (Figures 3.27 A-D and 3.28 b). The reversal in centroid travel direction from 4/7/84 to 5/7/84 reflects a change in wave direction when the waves were from the E.N.E.

Figure 3.28 Centroids of Tracer Concentration.

a. Experiment 2 8/7-13/7 (i.e. 8 – 13 July)

b. Experiment 1 2/7-5/7 (i.e. 2 – 5 July)



(a)

(b)

Table 3.23 X and Y coordinates of tracer centroids
Experiment 1

date	X	Y
2/7	15.10	13.41
3/7	20.08	14.58
4/7	25.92	12.68
5/7	20.65	15.60

The returned concentrations of fluorescent grains were not particularly high owing to the small quantities injected and the rapid dispersal. Table 3.24 summarises the results of centroid movement and sediment transport.

Table 3.24 Rates of centroid movement and sediment transport
Experiment 1

dates	centroid travel (m/day)	Qs (m^3/day)
1/7-2/7	12.96	55.44
2/7-3/7	5.04	21.16
3/7-4/7	3.12	13.11
4/7-5/7	-3.36	-14.12

-ve indicates a movement towards the north

Experiment 2 (7 — 13 July)

Wave approach during this experiment was between 96^o and 133^o and conditions were calm ($H_o \leqslant 0.05$ m). Under these conditions tracer dispersal was slower than for experiment 1 (after two tides a shadow of coloured sand could still be seen on the beach), and higher tracer concentrations were observed. Consequently sampling was continued for six days. Table 3.25 shows the coordinates of the concentration centroids which, when plotted (Figures 3.27 E-J and 3.28 a), reveal a movement towards the north; there is no significant constant movement either up or down the beach profile. The one reversal in general movement reflects a temporary change in wave approach.

Figure 3.29 Distribution and Mean Daily Displacement of Tracer Pebbles.

Boat ramp at profile F'

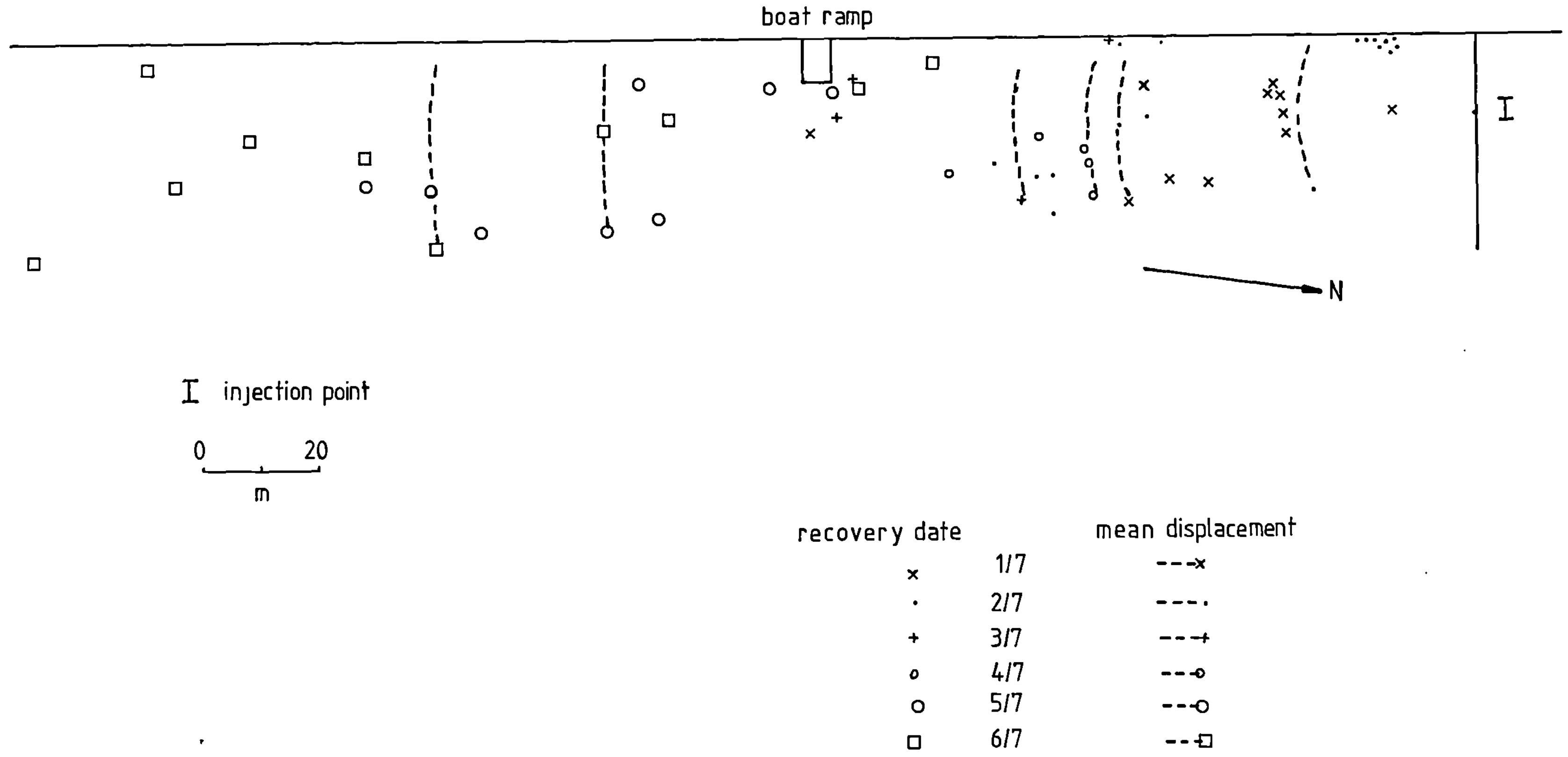

boat ramp
N
injection point
0
20
m
recovery date
mean displacement
1/7
2/7
3/7
4/7
5/7
6/7

Table 3.25 X and Y coordinates of centroid
Experiment 2

date	X	Y
8/7	5.82	4.45
9/7	14.76	7.54
10/7	11.43	10.46
11/7	12.32	10.74
12/7	19.17	10.19
13/7	23.52	9.20

Table 3.26 summarises the velocity of centroid movement and the equivalent sediment transport, Qs.

Table 3.26 Rates of centroid movement and sediment transport
Experiment 2

dates	centroid travel (m/day)	Qs (m^3/day)
7/7-8/7	3.6	15.12
8/7-9/7	0.82	3.42
9/7-10/7	-4.32	-18.15
10/7-11/7	.84	3.52
11/7-12/7	6.36	26.72
12/7-13/7	4.32	18.15

-ve indicates a movement towards the south

These observed sediment transport results will be compared with modelled rates (Section 3.1 a) in a later section (4.2 c (iii)).

Pebble Experiment - results

The retrieval rates of the painted pebbles were very disappointing but not altogether unexpected. When the pebbles were placed on the beach on 30 June the first wave which washed over them caused some to move over 6 m down coast (Plate 2.8 in Chapter 2). Thus many pebbles may have been moved great distances during one day. The pebbles which were recovered tended to have moved up the beach, and were presumably "stranded" there. It had been hoped to use the pebble axis measurements to determine whether any particular pebble shapes were moved preferentially, but the low recovery rate

Table 3.27 Pebble experiment - distances travelled and sediment transport

date	average distance travelled (m)	average velocity (m/day)	velocity - based on daily travel (m/day)	average projected volume transport (m^3/day)
1/7	63	63.0	63.0	189.0
2/7	31.67	15.8	-31.3	45.0
3/7	80.67	26.9	49	80.7
4/7	67.37	16.8	-13.3	50.4
5/7	151.07	30.2	83.7	90.6
6/7	183.72	30.6	32.6	91.8

-ve indicates movement towards the north prevented this. The movement was towards the south but it was difficult to calculate velocity and volume of travel. Figure 3.29 shows the distribution of the recovered pebbles.

By 1 July (i.e. after one day) the most distant recovered pebble was 92 m south of the injection point. The corresponding maximum distances for the 2, 3, 4, 5 and 6 July were 63 m, 89 m, 73 m, 191 m, and 226 m, the last of these indicating an average speed of 33.62 m/day. The average recovery distances for each day were calculated and, with average speeds from the time of injection, are shown in Table 3.27. Also included is a projected volume based on an upper beach width of 60 m, and a depth of disturbance of 5 cm.

Very little information other than direction of movement and a rough idea of the velocity of some pebbles can be gleaned from these limited results; the sediment transport rate is tentative.

Summary of Results

The sand sediment transport rates obtained in the first experiment, under N.E. waves from 0.2-0.7 m high, varied from 13.11 to 54.44 m^3/day; drift was mainly towards the south. The direction changes as waves altered to approach from the S.E. The second experiment which coincided with waves from the S.E. and heights of less than 0.1 m produced sediment transport rates from 3.4 to 26.7 m^3/day. Direction of movement was predominantly towards the north. Thus sediment transport in either direction alongshore is possible on this stretch of the Holderness coast. During the summer season a maximum of about 12000 m^3 of sediment might be moved. Extrapolations can be made from these summer results to produce an annual rate; a maximum might be around 90000 m^3 (winter rates are roughly double those in spring and autumn, which in turn are twice summer rates). It must be pointed out however, that these are total results in once direction not net results of component movement in opposing directions, such as those produced from the modelled potential rates. The pebble experiment results are extremely tentative, and indicate that rates of up to 200 m^3 of sediment a day might be achieved.

These measured sediment transport rates will be compared with modelled rates in Section 4.2 c (iii).

3.3 THE CLIFF

The cliff is an important element of the coastal system, particularly on the Holderness coast where the cliffs are eroding rapidly and supplying material to sustain a beach in front of them. It is therefore a very important sediment source for inclusion in the sediment budget. This section is divided into two parts, the first establishes the rates at which the Holderness cliffs are retreating (Section 3.3 a) and the second uses these rates and other field data to determine the volume of material supplied to the beach as a result of this cliff retreat.

3.3 a CLIFF RETREAT

The aim of this section is to establish the position of the till cliff, and hence the beach, over a number of years; this enables the rates of coastal recession to be determined and, as this is an important source of beach sediment, ultimately the volume of material being supplied to the beach to be calculated. Spatial and temporal variations in retreat are identified and mean rates presented. The methods of establishing retreat rates were described in Section 2.4 a and the results are now presented.

Mapping Coastal Retreat

Figures 3.30, 3.31 and 3.32 show maps of the coastline drawn at 1:100000 1:50000 and 1:10000 respectively, extracted from maps and aerial photographs. The 1:100000 map (Figue 3.30) shows the retreat along the entire coast from 1557 to 1976; since 1834 there has been no retreat at Bridlington, Hornsea, Withernsea etc., where sea defences have been erected. Figure 3.31 shows a selection of cliff lines since 1834. A progressive retreat of the cliff can be seen, though the variation in distances between these lines on both figures reflects the temporal and spatial variations in retreat. At some points adjacent lines cross; this is more common for the earlier lines and reflects inaccuracies in the original maps, or a lack of attention in bringing the coastline up to date.

Figure 3.32, produced from aerial photographs, again shows variations in retreat rates; it too exhibits areas where adjacent coastlines cross. This reflects the fact that on aerial photographs the scale varies slightly between the centre and the margins, even when the aircraft was perfectly level. Where a tilt was introduced then the variation between the centre and the edges is even more marked, and presented problems in matching up the same features on on different sets of photographs.

In spite of these problems the three maps do illustrate the erosion and land loss being suffered on this coast.

Retreat Graphs

Measurements from three sources, maps, aerial photographs and field measurements, were used to produce a series of graphs showing "distance to the cliff edge" from a series of known points, both alongshore and over a period of time, according to the methods described in Chapter 2 (2.4 a). The variations in gradient between

Figure 3.30 Cliff Retreat from Bridlington to Spurn Head, 1557 to 1976.

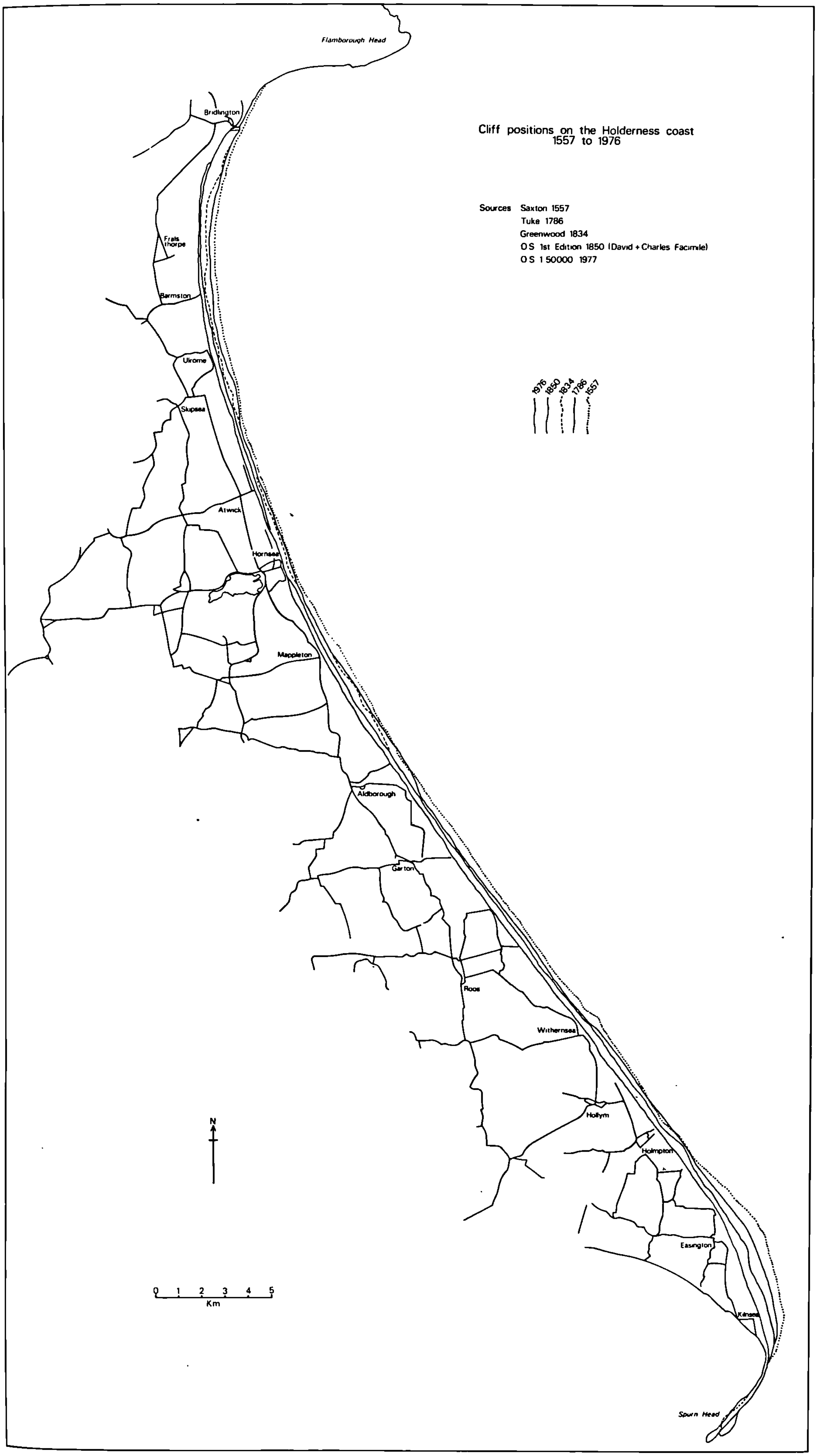

Cliff positions on the Holderness coast
1557 to 1976
Sources Saxton 1557
Tuke 1786
Greenwood 1834
O S 1st Edition 1850 (David + Charles Facimile)
O S 1 50000 1977
1976
1850
1834
1786
1557
Flamborough Head
Bridlington
Fraisthorpe
Barmston
Ulrome
Skipsea
Atwick
Hornsea
Mappleton
Aldborough
Garton
Roos
Withernsea
Hollym
Holmpton
Easington
Kilnsea
Spurn Head
N
0 1 2 3 4 5
Km

Figure 3.31 Cliff Retreat from Barmston to Mappleton,1834-1976.

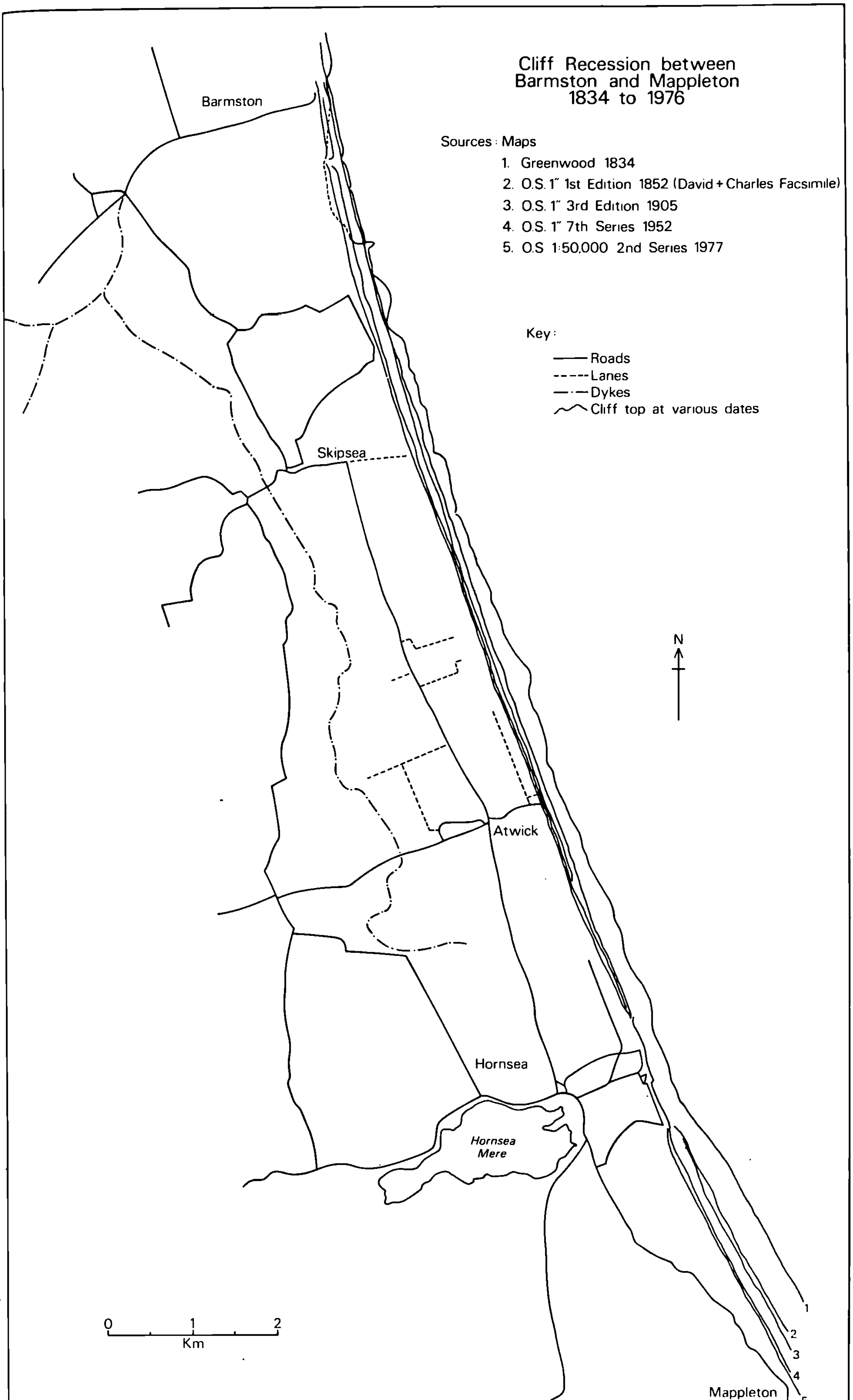
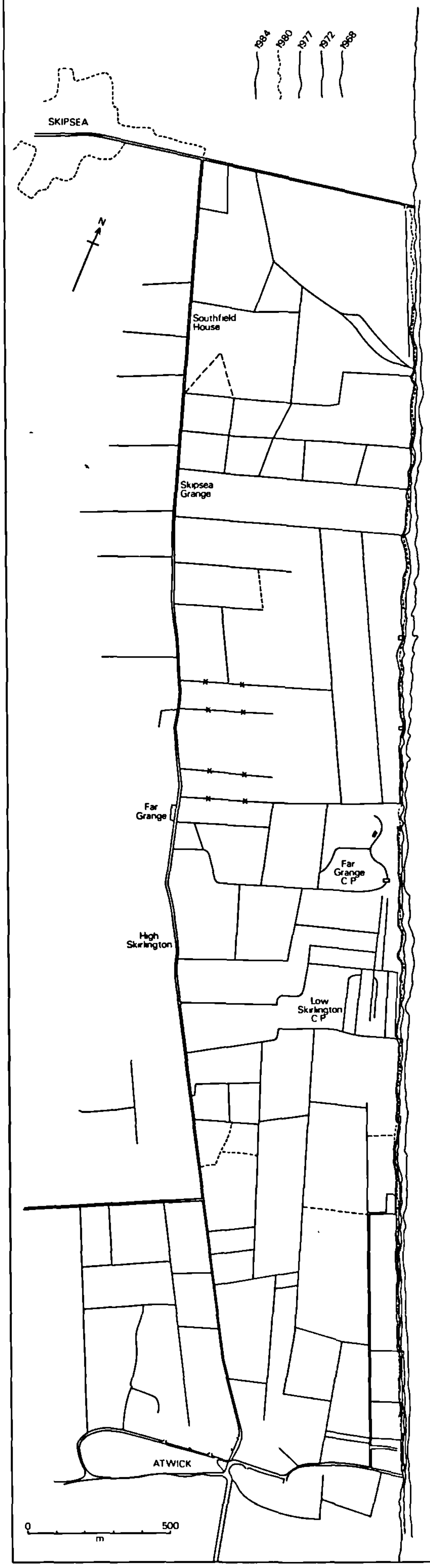

Cliff Recession between
Barmston and Mappleton
1834 to 1976
Sources: Maps
1. Greenwood 1834
2. O.S. 1" 1st Edition 1852 (David + Charles Facsimile)
3. O.S. 1" 3rd Edition 1905
4. O.S. 1" 7th Series 1952
5. O.S 1:50,000 2nd Series 1977
Key:
Roads
Lanes
Dykes
Cliff top at various dates
Barmston
Skipsea
Atwick
Hornsea
Hornsea Mere
Mappleton
N
0
1
2
Km
1
2
3
4
5

Figure 3.32 Cliff Retreat on Field Site, 1968 to 1984.

Cliff position between Skipsea and Atwick
1968 to 1984

Sources 31 5 68 Aerial Photographs RAF 4326 0040 - 0042
14 6 72 O S 72 158 001
4 7 77 Meridian Air Maps 22 77 181 183, 185, 187
19 5 80 V RAF 5609 263, 264
16 6 84 NERC MSS 84



adjacent points on the graphs emphasise the temporal variation of retreat rates, whilst the "best-fit" line provides an indication of the mean rate of retreat. The results produced from each source will be presented in turn.

1. Map measurements to determine retreat rates:

The graphs of time against "distance to the edge" indicate a considerable land loss over the past 400 years. The apparent increases in distance to the edge between some dates reflect map inaccuracies, map scale errors (despite the scales for each pre-O.S. map being recalculated based on a known distance) and inaccuracies in making the measurements on the maps, even though these were often checked.

Figure 3.33 (a-f) shows examples of the plots of time against distance from 1557 to 1980, the last figure was taken from aerial photographs but was included in this section to bring the graphs up to date. The reference points of the locations are:

Figure 3.33 a Ulrome Church
b Skipsea Junction
c Atwick
d Mappleton
e Holmpton
f Easington

Variations in retreat throughout this time can be seen by the departure of points from the best-fit line, especially from 1850 onwards when map errors should be very much less. Before that date the large variation will be predominantly a function of original map errors. There is no guarantee that the date of publication was close to the date of survey, or even that the order of publication is the same as the order of surveying.

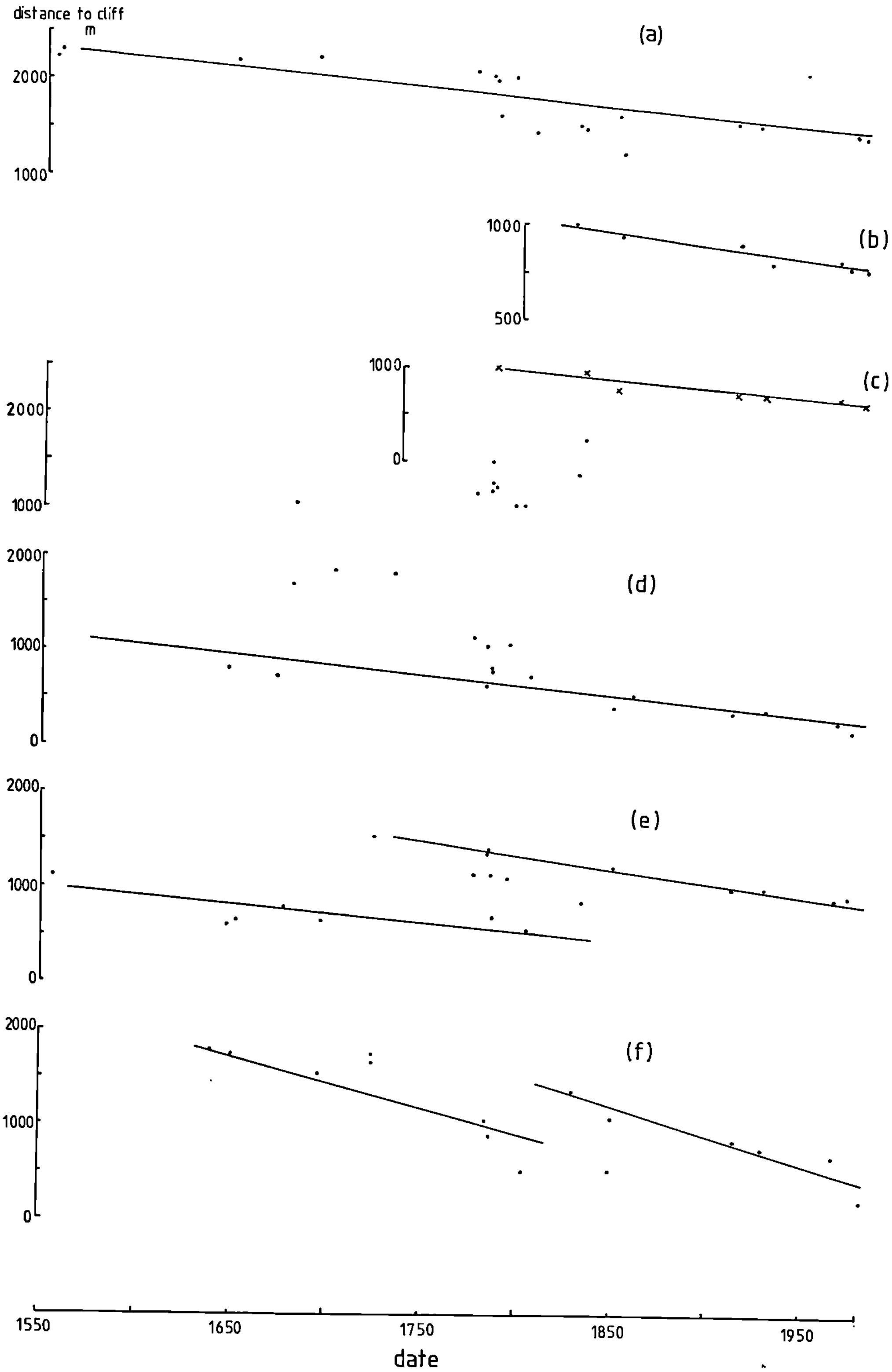
Figure 3.33 a-f Cliff Retreat from Maps, 1557-1980.

Distance to cliff edge from:

a - Ulrome Church
b - Skipsea Road Junction
c - Atwick Church (.) and crossroads (X)
d - Mappleton Church
e - Holmpton Church, then road junction
f - Easington Church, then crossroads

gradient of "best-fit" line represents mean retreat rate.

The best-fit lines on this figure have been added by eye and are purely indicative of the approximate retreat rates, and general variation of retreat. The scale of the diagrams render them unsuitable for showing errors.



distance to cliff
m
(a)
2000
1000
(b)
1000
500
(c)
2000
1000
1000
0
(d)
2000
1000
0
(e)
2000
1000
0
(f)
2000
1000
0
1550
1650
1750
1850
1950
date

Figures 3.34 a and b show examples of the graphs designed to illustrate cliff retreat alongshore; the time periods shown here are 1850 to 1912 and 1912 to 1968, the results for earlier periods were rather unreliable. Figure 3.34 a indicates a retreat rate of between 0.5 and 1.75 m/yr between Bridlington and Hornsea, then no losses at Hornsea where the shore is protected. Low rates prevail near Aldbrough, then from Withernsea to Holmpton rates are extraordinarily high - 3.5 m/yr to over 6.0 m/yr. At the high cliffs in the Dimlington area lower rates were recorded with an increase to 2.2 to 2.9 m/yr at Easington and Kilnsea. It is this southern end of the coast which is most exposed to north-easterly and easterly waves, and is affected by refraction effects. The period from 1912 to 1968 (Figure 3.34 b) shows rates of 1.75-2.0 m/yr between Ulrome and Skipsea, then around 1.0-1.25 m/yr from there to Atwick; south of Hornsea retreat rates of 1.5-2.5 m/yr are recorded.

Figures 3.34 a and b were combined to give values for total retreat between 1850 and 1968; these were then plotted on a map (Figure 3.35 a) for comparison with a similar figure produced by Valentin (1971) for the period 1850 to 1950 (this is shown on the overlay Figure 3.35 b). Figure 3.35 a shows a similar pattern to 3.35 b, with the lowest rates coinciding with areas of protection and increased erosion being observed towards the south. The overall mean retreat rate from map work is 1.34 m/yr increasing to over 3m/yr in the south.

Map measurements were made to at least ± 0.25 mm (± 12.5 m on the ground), sufficiently accurate for the time period concerned. O.S. maps, though not totally accurate, were more reliable than archive maps; most new editions of the O.S. maps did not involve re-surveying the coastline, only ammendments in the form of minor

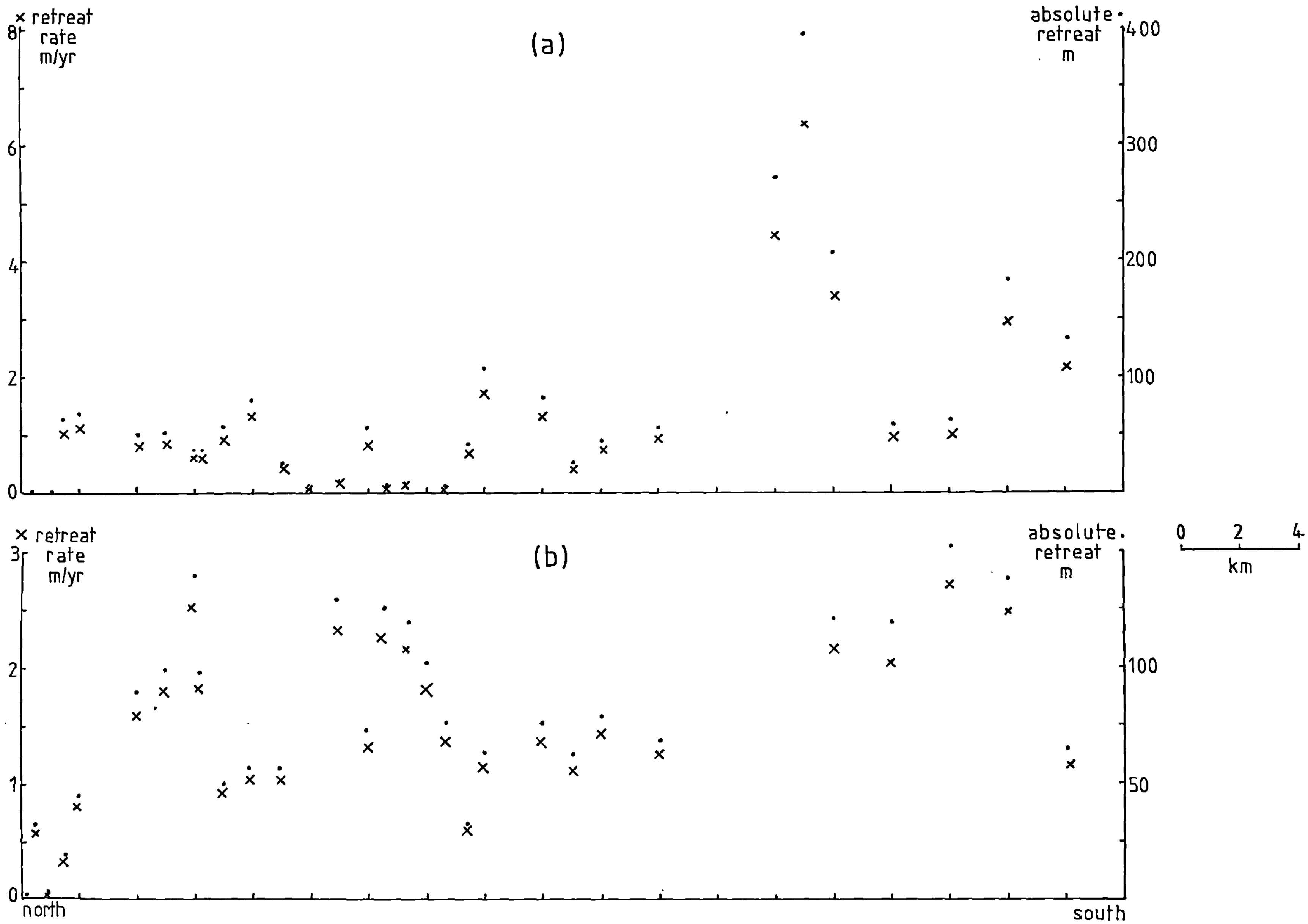
Figure 3.34 Variation in Retreat Alongshore.

Retreat Rate (×) and Absolute Retreat (•)

a 1850-1912

b 1912-1968

nb - different vertical scales

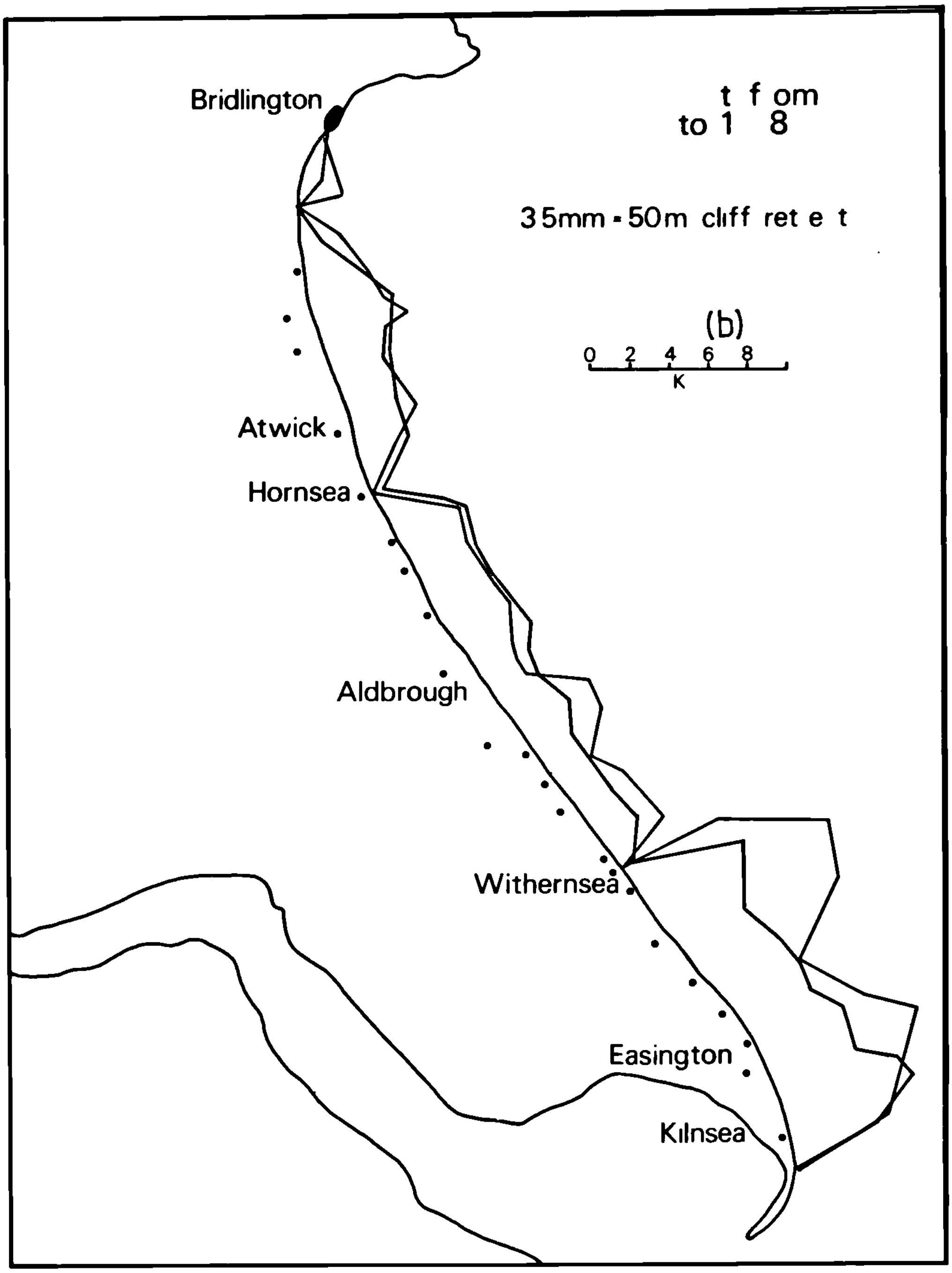


(a)
× retreat rate m/yr
absolute retreat m •
8
6
4
2
0
400
300
200
100
(b)
× retreat rate m/yr
absolute retreat m •
3
2
1
0
100
50
north
south
0
2
4
km

Figure 3.35 Cliff Retreat on Holderness.

a Retreat from 1850 to 1968; results of present study.

b Overlay showing retreat from 1850 to 1950 from Valentin (1971).


Bridlington
t f om
to 1 8
35mm - 50m cliff ret e t
(b)
0 2 4 6 8
K
Atwick
Hornsea
Aldbrough
Withernsea
Easington
Kilnsea

changes, but it was not clear just what these minor changes were.

2. Aerial Photograph measurements to determine retreat rates

Figure 3.36 a-e shows graphs of distance against time for a selection of sample points:

Figure 3.36 a Atwick
b Southfield House
c Field boundary S. of Skipsea Grange
d High Skirlington Caravan Site entrance
e Skipsea Grange.

Once again rates of retreat are variable, individual points departing from the best-fit line. The average retreat rate at each location is shown in Figure 3.37, varying from just over 4 m/yr (5 m in a couple of extreme cases) to no retreat at Hornsea. From Southfield House to High Skirlington there is a high but decreasing retreat, values falling between 2.0 and 4.0 m/yr. South of High Skirlington rates rarely rise above 3.0 m/yr and are often around 2.0 m/yr. The average retreat rate along this coast measured from aerial photographs for the period 1968 to 1984 is 2.5 m/yr, a more rapid rate than along much of the coast and for other time periods. The photographs used ranged from 1:6600 to 1:50000; on the largest scale measurements could be made to the nearest 1.5 m , whereas at the smallest scale, accuracy is ± 12.5 m.

3. Field measurements to determine retreat rates

Figure 3.38 a-f shows the time against distance plots for a selection of locations from field data. The locations are:

Figure 3.38 a Profile C
b extra a
c extra b
d 3rd bench (extra f)
e 2nd bench (extra g)

Figure 3.36 Cliff Retreat from Aerial Photographs, 1968-1984.
Distance to cliff edge from:

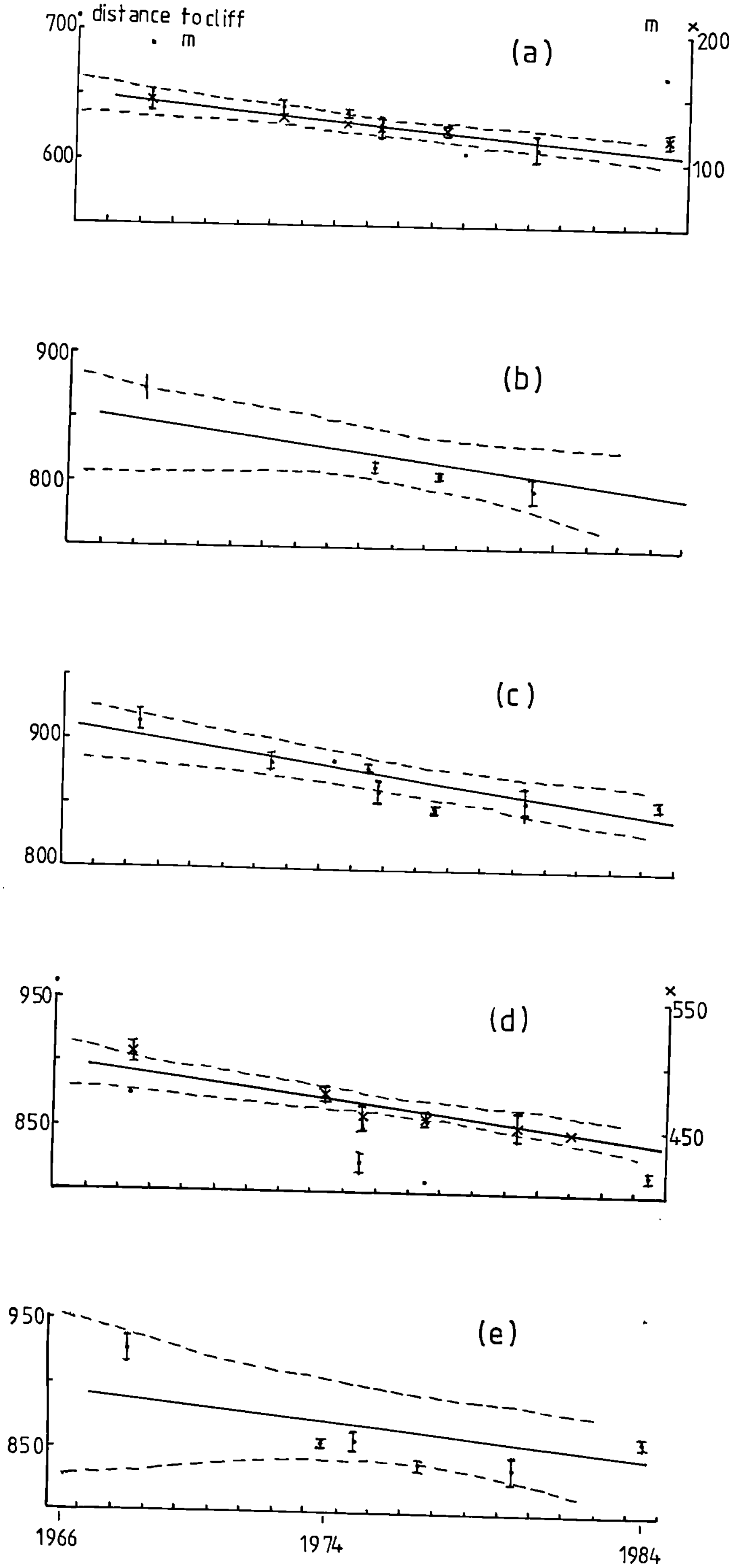
a Atwick, crossroads (.), road to gas station (X)
b Southfield House
c Field boundary south of Skipsea Grange
d High Skirlington Caravan Site, entrance (.), buidling (X)
e Skipsea Grange

The Regression lines which describe retreat are:

a $y = -1.49\ x + 644$ $r_{xy} = -0.884$, $t = 2.776$
b $y = -6.32\ x + 879$ $r_{xy} = -0.976$, $t = 4.303$
c $y = -2.91\ x + 910$ $r_{xy} = -0.871$, $t = 2.44$
d $y = -4.30\ x + 911$ $r_{xy} = -0.901$, $t = 2.776$
e $y = -4.33\ x + 907$ $r_{xy} = -0.735$, $t = 2.776$

Where y = distance to cliff (m), x = years post 1966, and the gradient represents the rate of retreat, all correlations significant to the 95% level.

The error bars show the estimated error involved in measurement from the photographs. The confidence limits at the 95% significance level are shown by the dashed line. These are relatively large, indicating the highly variable retreat of the cliff, in time and space. As no direct causal relationship is involved, these diagrams are most useful for showing the trends in retreat, and the rate at particular times. The errors invovled in determining cliff retreat are discussed in greater detail in Chapter 5 (5.3 e).



distance to cliff
m
m
(a)
700
600
200
100
(b)
900
800
(c)
900
800
(d)
950
850
550
450
(e)
950
850
1966
1974
1984

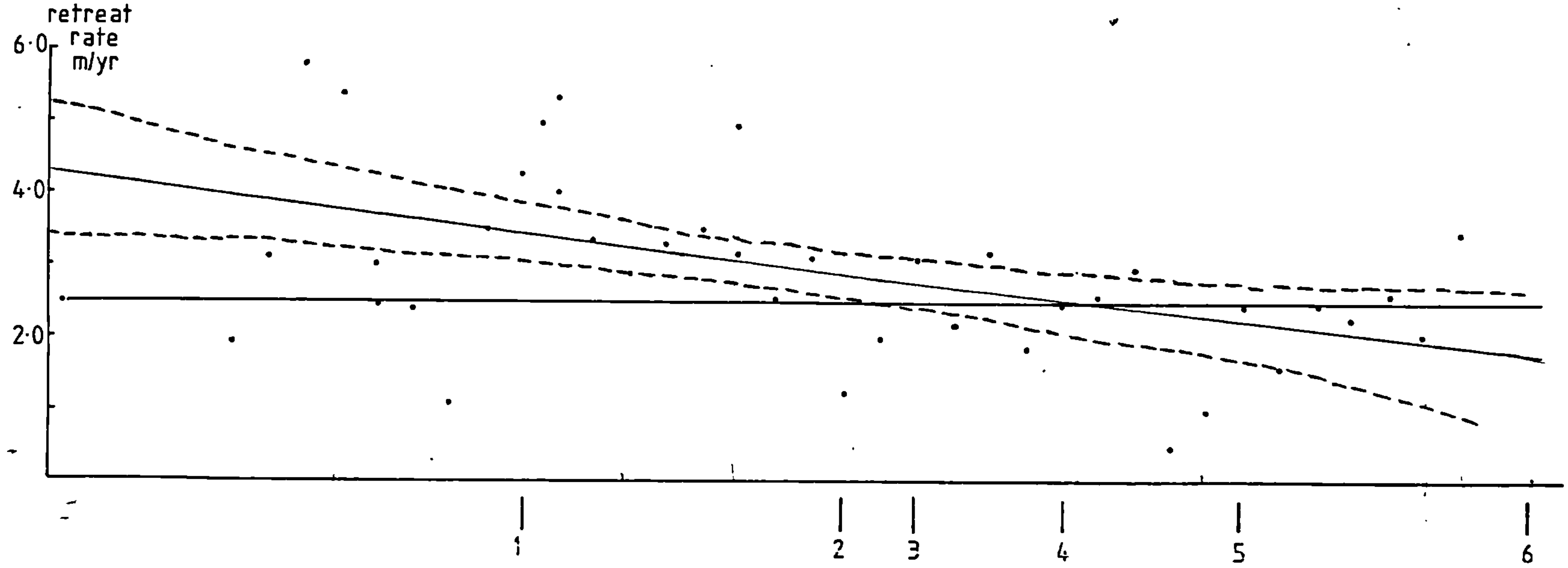
Figure 3.37 Variation in Retreat Rate Alongshore from Aerial Photographs, 1968-1984.
Solid line - mean retreat = 2.5 m/yr
coastal locations
1 Southfield House
2 Far Grange Caravan Site
3 High Skirlington Caravan Site
4 Gas Station
5 Atwick
6 Hornsea

The regression line describing the retreat rate alongshore is:

$y = -0.002\,x + 4.42 \quad r_{xy} = -0.516, \quad t = 2.02$

Where x = distance s of Ulrome (m)
y = retreat rate per year (m), correlation significant at the 95% confidence limits on the figure.

Although there may be no very significant causal relationship between the two variables along the coast, this expression is a guide to the variation in retreat. At this spatial scale a decrease in retreat rate down-shore was observed. This is a function of the position of the section of coast. The northern section coincides with the section of beach at the margin of Flamborough Head's influence, while the southern section, well outside this influence, has a beach which is fuller and experiences waves from a wider sector.


retreat rate m/yr
6·0
4·0
2·0
1
2
3
4
5
6

f profile G

Figure 3.38 a shows the retreat at profile C from August 1983 to September 1984 to be only a few centimetres; from early 1984 there is an increase in distance coinciding with the dumping of material on the cliff top. Figure 3.38 b shows a slight but steady retreat of the cliff. Figure 3.38 c shows the graph for a point only 100-150 m away from that shown in Figure 3.38 b; here the retreat is slightly more rapid but fairly constant. In contrast, Figures 3.38 d, e and f show much more rapid though variable erosion - up to 4.5 m lost during the 16 month period. Losses of up to 8 or 10 m were observed between the points at which measurements were taken. Figures 3.38 d-f show periods of steady or no retreat interspersed with one or more sudden and rapid cliff retreats. Generally these periods of sudden retreat were in September 1983, December 1983 and June 1984; these periods coincide with losses at some other locations, presumably when conditions favoured cliff collapse.

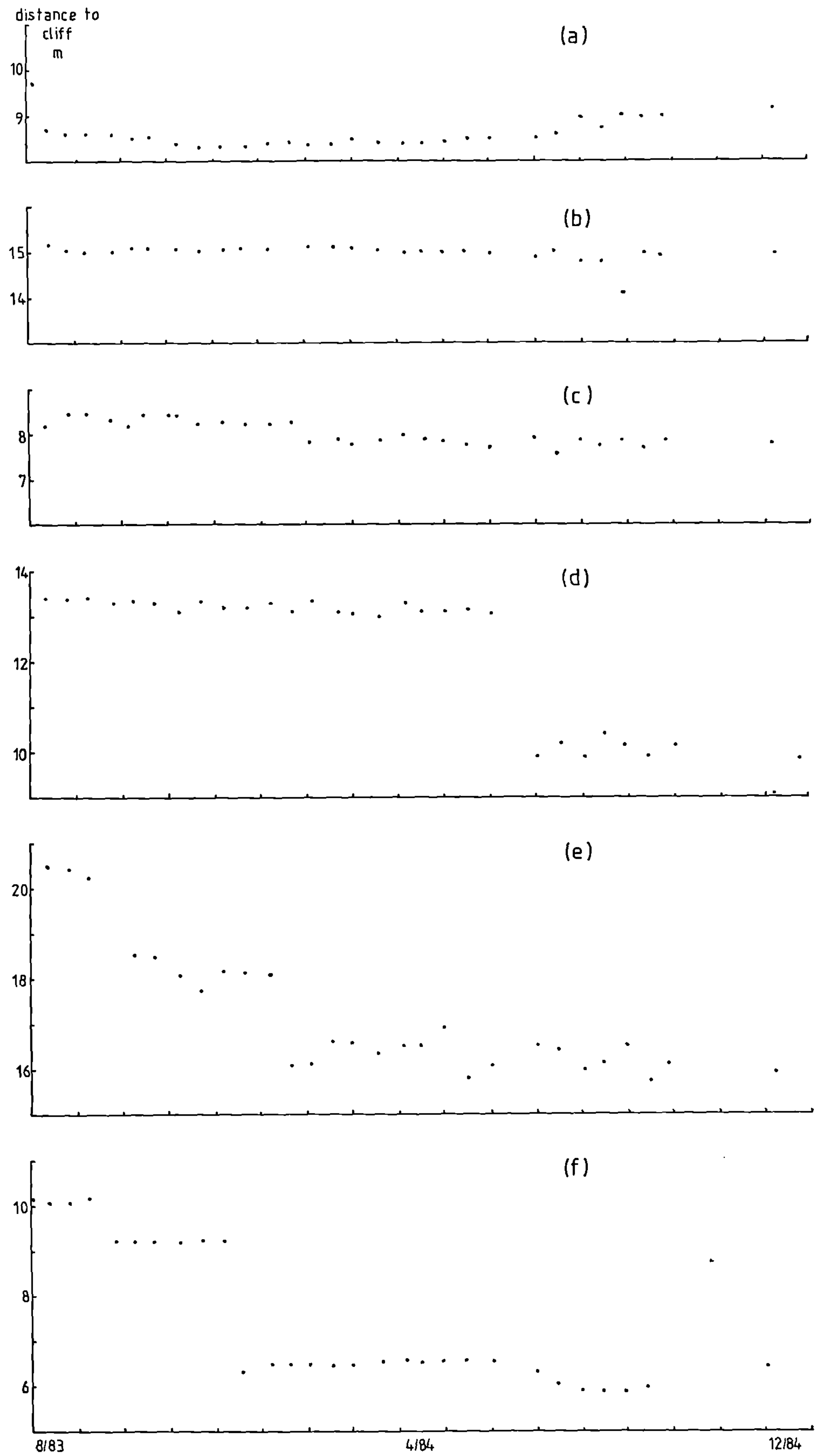
Overall, Figure 3.38 illustrates the extreme variability of cliff retreat; some locations may remain virtually inactive for years (b), others may exhibit a steady decline in distance to the edge (c), while elsewhere the retreat may be a series of "jumps" of a few metres. Man's intervention also adds to the variation (a). All of these types of behaviour can be observed within a few hundred metres of one another, emphasising the danger of relying on mean retreat rates at the small scale. Cliff top property will not "approach" the cliff edge steadily as overnight a few metres of land may be lost: on the two caravan sites within the field area vans are periodically moved away from the cliff, though some get perilously close to the edge before this happens. On the other hand, areas of cliff which might have been expected to collapse long ago are still in place. For

Figure 3.38 Cliff Retreat from Field Measurements, August 1983 to December 1984.

Distance to cliff edge from:

a Profile C
b extra a
c extra b
d 3rd bench (extra f)
e 2nd bench (extra g)
f Profile G

In this case the errors involved in field measurement are more significant, and important, especially as determining retreat rate is a step in calculating the sediment budget. Many more data, obtained over a longer period, would be required to determine a meaningful regression expression.


distance to cliff m
(a)
10
9
(b)
15
14
(c)
8
7
(d)
14
12
10
(e)
20
18
16
(f)
10
8
6
8/83
4/84
12/84

example, the pill box near profile D has been perched precariously on the edge, with very nearly half of it actually overhanging, for at least 2½ to 3 years (Plate 3.4).

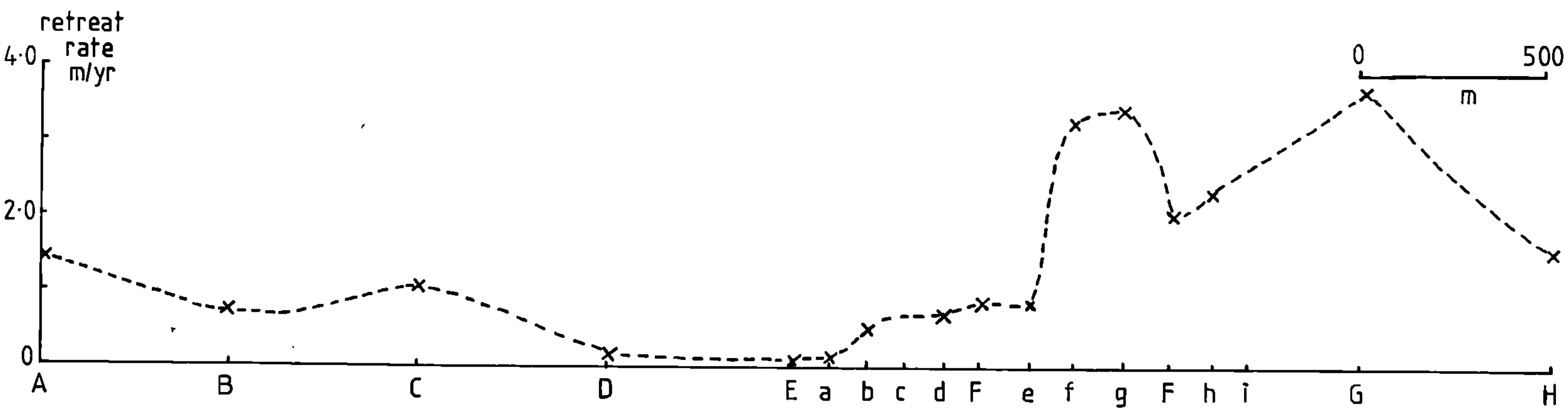
Figure 3.39 shows the variation in retreat rate alongshore; in the northern half of the field area from profile E/4th bench northwards the rates may be up to three times greater than in the south. There is thus, at this short time scale, an even greater variation in retreat alongshore. The average rate of retreat for this stretch of coast based on field measurements is 1.52 m/year.

Even these field measurements are not without errors and discrepancies; at certain points "gains" are observed, albeit small ones These are, except in extraordinary circumstances, clearly erroneous. Measurements may not have been made to exactly the same point on the cliff edge - a deviation of 0.5 m along the cliff may easily account for errors of 5-10 cm in the measurements perpendicular to the cliff. Larger errors of around 50 cm can arise during strong winds, measurements being "wind-assisted" when it was impossible to hold the tape taut. In general values are accurate to $\pm$ 0.05 m.

Accuracy of sources

Off all the different methods of establishing distances to the edge of the cliff, field measurement is the most accurate, but is only practical over a limited area and time. The next most reliable method in this study was to use the O.S. maps, though the measuring errors could have been reduced if all series had been available at 6" to 1 mile or 1:10000. Aerial photographs are potentially extremely accurate as the exact date of "survey" is known; however, over such a relatively short time period and at such a variety of scales they posed problems of accuracy and also of representing overall trends. The least reliable means of establishing distances was by taking

Figure 3.39 Variation in Retreat Rate Alongshore from Field Measurements, August 1983 to December 1984. Overall mean retreat = 1.52 m/yr



retreat rate m/yr
4·0
2·0
0
A
B
C
D
E
a
b
c
d
F
e
f
g
F
h
i
G
H
0
500
m

measurements from old maps of uncertain and variable scale. For example two adjacent distances were measured on three of the older maps and compared with the 1:50000 1976 map which was assumed to be correct. On the 1672 map the scales over the two distances were 1:305333 and 1:434524, on the 1786 map they were 1:90261 and 1:92328 and on the 1834 one 1:95432 and 1:87222. On many maps the coast itself seemed to have been drawn in as a rather arbitrary line. Despite these errors the general trends in retreat are easily seen. The various maps, and the graphs in particular, have shown how variable cliff retreat is, both alongshore and over a period of time.

Summary of Cliff Retreat

The general trend over the whole coast if for cliff retreat rates to increase from north to south. Bridlington Bay, in the north, is relatively sheltered, while rapid retreat is observed near Easington and Kilnsea where the coast is much more exposed. As the scale over which retreat measurements are obtained decreases the variability of erosion increases. The mean retreat rate from mapped data over the past 100 years is 1.34 m/yr, while from aerial photographs between 1968 and 1984 it is 2.5 m/yr. Accurate field measurements during the past two years have produced a mean rate of 1.52 m/yr. Table 3.28 summarises the retreat rates used in a subsequent section to calculate the volume of material supplied to the beach.

Table 3.28 Retreat rates for the field site from field measurements

Location	A	B	C	D	E*	F*	F'*	G	H
Average retreat rate m/yr	1.45	0.70	1.55	0.18	0.30	0.90	3.00	3.65	1.55

*intermediate locations taken into account.

Because of the variety of data used it was not possible to determine whether erosion is accelerating or slowing down on this coast. Many more, very accurate, long-term data would be required to establish the pattern.

3.3 b SUPPLY OF SEDIMENT FROM THE CLIFF TO THE BEACH

One of the purposes of determining the rate of cliff retreat in the previous section was to enable an estimation of the sediment supply from the cliff to the beach to be made. Valentin (1971) estimated that a total of 1 million m^3 a year is lost from the cliff.

The present study produced an average annual retreat of 1.34 m between 1850 and 1968 (excluding protected areas). Assuming that the till platform profile has remained constant over this time, that the average cliff height along the coast is 14.0 m and that the coast from Bridlington to Kilnsea (excluding protected areas) is 55 km, then the volume lost in 118 years is:

$$V = ((H \times r \times 118) + Pe) \times L \qquad (3.17)$$

where V = Volume lost Pe = contribution from platform erosion*

H = cliff height L = length of coast

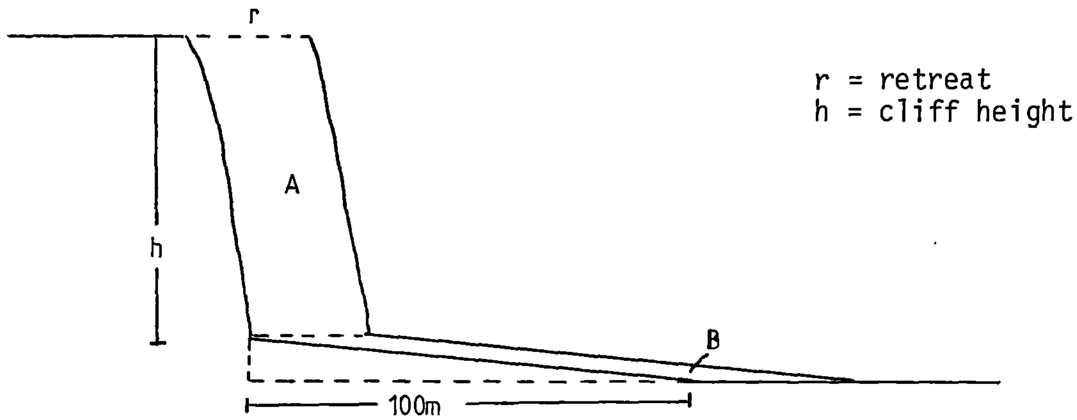
r = retreat rate

* Figure 3.40 shows the calculation of the platform contribution.

This method of calculating the volume of material lost assumes parallel retreat of the cliff and shore platform which would, for retreat rates of 1.5-3.0 m/yr, produce an annual depression at any point on the till surface of 0.08-0.16 m. It is possible that in certain places, e.g. where the beach is especially depleted like an ord, increased local lowering of the till platform may occur.

From 1850 to 1968, $1.67 \times 10^8 m^3$ of cliff material was supplied at an average rate of 1.4 million m^3 ($1.4 \times 10^6 m^3$) each year. Not all of this material is compatible with the natural beach material; much of it comprises very fine silts and clays which will be lost offshore.

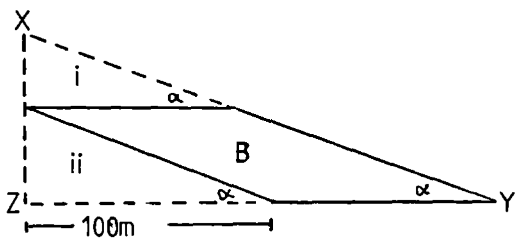
Figure 3.40 Area Calculations for Cliff Retreat



Assume (1) parallel retreat of cliff and till platform
(2) till slopes at 3^{o} for 100 m., - this is the base of any erosion
(3) Sea level has remained constant

Amount of Material Removed = A + B

$$A = r \times h$$



Area B = Area xyz - (Area i + Area ii)

$$\text{Area xyz} = \tfrac{1}{2}\left(\frac{100 + r}{\cos\alpha}\right) \times (100 + r) \times \sin\alpha$$

$$\text{Area i} = \tfrac{1}{2}\left(\frac{r}{\cos\alpha}\right) \times (r) \times \sin\alpha$$

$$\text{Area ii} = \tfrac{1}{2}\left(\frac{100}{\cos\alpha}\right) \times 100 \times \sin\alpha$$

In order to determine the amount of sand present, i.e. material capable of being retained on the beach, a series of till samples was taken from the cliff, along the field site, and sediment analysis yielded the proportion of sand, silt and clay. The percentage of sand recorded varied from 22.7% to 39.38% with a mean value of 33.70% and a standard deviation of 5.01%. Separate samples were taken from the top and bottom of the cliff but showed little difference: the samples taken from near the top had a mean of 32.16% and a standard deviation of 4.96% (n=9) while those taken near the foot had a mean of 35.24% and a standard deviation of 4.57%.

Assuming that 33% of the cliff material may be incorporated into the beach, then along the entire coast 462,000 m^3 of sand is being supplied to the beach, or 8.4 m^3 per metre length of beach per year. This supplements the material supplied to an area of beach from the updrift side and helps to compensate for the loss of material downdrift. As the retreat rate is not constant, so the supply of material from the cliff will vary alongshore.

For the field site it was decided to establish the variation in sediment supplied from the cliff to the beach. Each survey profile, coinciding with locations of retreat measurement and sediment sampling, was considered to be near the middle of a sediment "unit". The unit boundaries were places half way between profiles, and it was assumed that the conditions at each profile extended throughout the "unit". It was thus possible to take variations in cliff height, retreat rate and cliff composition into account. For the two end profiles, A and H, the boundaries were placed so that A and H were exactly in the centre. Table 3.29 shows the relevant figures for material supplied, and once again illustrates the variability of this sediment source to the beach. The amount of sand supplied annually ranges from 350 m^3 supplied to the cell around profile D to 12473.8 m^3 around profile G.

In concluding this section, it can be repeated that cliff retreat rates vary over time and alongshore, resulting in a variable supply of material to the beach, approximately a third of which can actually be incorporated into the beach.

Section 4.4 uses the retreat rates and sediment supply rates produced to establish a sediment budget.

3.4 SEDIMENT BUDGET

The previous three sections have produced results from each of the three coastal sub-systems including modelled potential sediment transport rates from offshore data, measured sediment transport rates on the beach and sediment supply from the cliff. In this section sediment budget calculations are presented. The importance of a sediment budget lies in its ability to identify and quantify the sediment sources and sinks of an area, and to summarise and predict beach change.

A potential sediment budget was prepared for the Holderness field site; in common with previous studies the supply from various sources was determined, and balanced against the material removed. The sources and sinks for each cell along this stretch of coast are:

sources - eroding cliffs and platform	sinks - alongshore sediment transport
- alongshore sediment transport	- (offshore sediment transport)
- (onshore sediment transport)	

In practice the onshore/offshore components of sediment movement could be included for only part of the section of coast which was modelled.

Onshore-Offshore Movement of Sediment

Most qualitative studies have ignored onshore-offshore movement of sediment in the presentation of sediment budgets: the wave refraction program used to calculate potential sediment movement in the present study was incapable of calculating the volume of sediment moved perpendicular to the shore. Indeed, it was almost impossible to find any quantitative determination of this movement. Most studies had deduced net effects from a change in beach profiles; however, changes in beach elevation also depend upon supply of material from the cliff and removal of material offshore.

Hardisty (1984) and Hardisty *et al.* (1984) produced expressions which would enable an estimate of sediment transport to be made. However, these depend upon some knowledge of post-breaking conditions; the present study produced only breaking and pre-breaking data. The simplest of these equations for calculating the onshore and offshore sediment movement required the swash and backwash velocities:

$$J_{in} = \frac{K_1 U_{in}^3 t_{in}}{(i + s)} \qquad J_{ex} = \frac{K_2 U_{ex}^3 t_{ex}}{(i - s)} \qquad (3.18)$$

J_{in} is onshore sediment transfer

K_1 and K_2 are empirical constants which may vary with grain size

U_{in} is swash velocity

t_{in} is duration of swash

t_{ex} is duration of backwash

J_{ex} is offshore sediment transfer

i is tangent of the angle of internal friction of the material 0.6 for quartz sand

s is tangent of beach slope

U_{ex} is backwash velocity

These expressions would be of little use in the present study for the following reasons:

1. They are potential rates (there is no means of checking them),
2. They assume that a deep beach layer is present to act as a sediment supplier, which on the Holderness coast is not the case,
3. They do not take into account material moved to or from the area seaward of the breaker zone.
4. The total energy at breaking is known in the present study but the losses on the surface are not. It might be possible to determine the material which can be suspended at breaking but the sediment entrained afterwards is unknown.
5. Tracer experiments revealed the predominant sediment movement in the area to be alongshore (section 3.2 c).

Morphological evidence may give an indication of the likely direction of net transfer. Beach profiles indicated a transfer of material back and forth between the upper and lower beach depending upon wave conditions (3.2 a and 4.2 a (iv)). Grab samples taken seaward of the breaker zone reveal the bed to be composed cf either till or coarse sands, gravels and cobbles, which are presumably derived from washed till. The absence of large quantities of sand suggests that there is little material offshore which could, under favourable conditions, be transferred offshore. Some material may be provided by small oblique bars which extend a short distance into the offshore zone and waves breaking on these bars may allow further movement offshore. Any material which is removed offshore would not remain there for very long but may be transported alongshore under tidal currents or moved further out to sea. Pringle (1985) reported no net onshore movement of material on this coast; further north in Bridlington Bay there may be movement towards the shore from offshore sand banks.

Plate 3.5 Suspended Sediment Plume.

Table 3.29 Calculation of Sand Supply to the beach from cliff retreat

Cell centred on profile	A	B	C	D	E	F	F'	G	H
Length of cell (m)	470	485	442.5	350	365	332.5	332.5	500	585
Average annual retreat rate (m)	1.45	0.70	1.55	0.18	0.3*	0.9*	3.0*	3.65	1.55
Height of cliff (m)	12.19	14.32	13.73	17.65	12.80	14.61	13.10	14.41	8.34
Cliff height x retreat (m^2)	17.68	10.02	21.28	3.18	3.84	13.15	39.30	52.60	12.93
Contribution from till platform (m^2)	7.59	3.65	8.12	0.94	1.57	4.72	15.72	19.13	8.12
Total volume of sediment lost (m^3)	1187.90	6629.99	13009.50	1442.00	1974.65	5941.78	18294.15	35865.00	12314.25
% sand in cliff	34.38	36.86	28.22	24.27	37.85	33.86	35.52	34.78	32.54
Volume of sand supplied to beach (m^3)	4083.28	2443.80	3671.28	349.97	747.40	2011.88	6498.08	12473.85	3995.97

* Taking into account retreat at intermediate points

There is obviously a considerable loss of fine material offshore; huge plumes of suspended sediment extend out to sea even during calm conditions (Plate 3.5). Probably some sand and shingle is removed. Offshore too and, during stormy weather in particular, the upper beach has been completely removed. Some of this material must be moved well out to sea where it eludes any influences which might return it to the beach.

Although the onshore-offshore component of sediment transport can only be measured for part of the coast, it has been excluded from some of the sediment exchange calculations. However, for part of the coast the surveying of beach profiles enables a full budget to be calculated.

Calculation of Sediment Exchanges and the Sediment Budget

The budget prepared is a potential one in which the alongshore sediment transport has been modelled rather than measured in the field. Sediment supply and removal rates alongshore are obtained from the sediment transport model (Section 3.1 a); it is assumed that the annual average amount of material moving in a cell is also the amount which will leave that cell in a year, and that the amount of material entering a cell will be that moving in the updrift cell in the previous year. The supply of material from the cliffs to each of the profiles is obtained from cliff retreat rates and sediment analysis of cliff composition (Table 3.29). The sediment analysis determines the precentage of cliff material which can be incorporated into the beach. The rest is assumed to be lost offshore.

Tables 3.30 and 3.31 summarise the data needed to calculate the sediment exchanges of the beach cells. Table 3.30 shows the supply from the cliff (derived from Table 3.29) and Table 3.31 shows sediment transport rates in, and sediment supply to, each cell (from Table 3.11). The cells are those used in the sediment transport model (Figure 2.4).

Table 3.30 Summary of sediment volume supply from the cliff

North Cell	(ii)	(iii)	(iv)	(v)	(vi)	South (vii)
cliff height (m)	7	8.5	detailed data in table 3 section 3.3		17	15
retreat rate (m/yr)	1.34	1.34			1.34	1.34
cell length (m)	1875	1875			1875	1875
contribution from platform (m^2)	6.2	6.2			6.2	6.2
volume supplied - total (m^3)	29212.5	32981.2			54337.5	49312.5
% age sand	33	33			33	33
Volume available to beach (m^3)	9640.1	10883.8	24987.6	11374.83	17931.4	16273.1

Table 3.31 Sediment transport and supply to beach cell

Cell	(ii)	(iii)	(iv)	(v)	(vi)	(vii)
sediment transport rate m^3/yr	-28605	+6440	-28250	-3155	+35830	+21400
sediment entering (m^3/yr)	? 6440	28605	0	35830 28250	3155 21400	?
sediment leaving (m^3/yr)	28605	6440	28250	3155	35830	21400

+ or - = movement to N. or S.

N.B. Where double figures occur in alongshore supply columns, the supply to that beach cell enters from both ends of the cell. This applies to Table 3.30 and subsequent tables involving longshore supply.

Table 3.32 Sediment Exchanges

Cell	(ii)	(iii)	(iv)	(v)	(vi)	(vii)
alongshore supply (m^3/yr)	x 6440	28605	0	35830 28250	3155 21400	y
alongshore removal (m^3/yr)	-28605	-6440	-28250	-3155	-35830	-21400
cliff supply (m^3/yr)	9640	10883.8	24987.6	11374.8	17931	16273.1
net change ΔV (m^3/yr)	x-12525	+33048.8	-3262.4	+72299.8	+6656	y-5126.9
equivalent beach level change (m)						
width - 150 m	$\frac{x-12525}{281250}$	0.118	-0.012	0.257	0.024	$\frac{y-5126.9}{281250}$
- 200 m	$\frac{x-12525}{375000}$	0.088	-0.08	0.193	0.018	$\frac{y-5126.9}{37500}$

In Table 3.32 the amount of material leaving a cell alongshore has been subtracted from that entering it from alongshore. For cells (ii), (iii), (vi) and (vii) the supply of cliff material is obtained from the average cliff retreat rate of 1.34 m/yr (Section 3.3 a), the height of the cliff along that section of coast, and an average value for the percentage of sand in the cliff. For cells (iv) and (v) which coincide with the field site between Skipsea and Atwick the sediment supply is calculated from more detailed field measurements and sediment analysis (Table 3.29).

The final elements of this table indicate the elevation or depression of the beach surface, assuming that the change in volume is distributed evenly over the whole beach, and assuming that there are no net onshore or offshore sediment transfers. The changes in volume of the beach cells range from +72300 m^3/yr to -3262 m^3/yr which may lead to a change in beach elevation, for a beach width of 150 m, of about 1 cm to 25 cm. The implications of these exchanges will be considered in the interpretation section, 4.4 a. Although the onshore-offshore exchanges were thought to be minimal this cannot be guaranteed, and therefore Table 3.32 represents only part of the picture. For the field site, cells (iv) and (v), from field observations, it was possible to calculate the actual change in beach volume over one year and this allows a complete budget to be presented. The difference between this measured change in volume and that predicted from the modelled sediment transport and cliff/platform supply represents the unknown onshore or offshore movement.

Table 3.33 a shows the areas under the profiles in August/ September 1983 and 1984. A correction had to be applied to the shorter of the survey profiles so that the areas were for profiles of an equivalent length. The observed increases or decreases are shown, and the average for each cell is presented. This was converted to a volume change by multiplying by the length of the cell (1875 m). Table 3.33b shows the difference between the modelled and observed changes over the year and hence the net onshore or offshore transfer of material. The changes in elevation which these volumes represent are also shown (for a 150 m wide beach). Temporal changes in beach volume are discussed in greater detail in Section 4.2 a (iv).

The net transfer of material offshore is relatively large. In cell (iv), in the north of the field site, the net offshore transfer of material is approximately 3 times greater than the net longshore sediment transport in either direction. However, at any instant it may be very much smaller than the longshore movement; these figures are aggregated to give net annual transport. Sediment tracer experiments suggested that under some conditions the net offshore transfer is negligible. Because of the sheltering effect of Flamborough Head, cell (iv) is limited in terms of its sediment supply from the north, and therefore its longshore supply is comparatively small. In cell (v), in the south of the field area, the net offshore movement is considerably less than the supply from either direction alongshore (approximately one third to one half). The offshore movement in the north is much greater than in the south, judging from the figures in Figure 3.33 b; this may be a result of the lower beach in the north allowing a greater proportion of waves to reach upper beach material and remove it; more cliff material will be moved directly. This section was depleted markedly between September 1983 and September 1984.

The size of offshore movement serves to emphasise that when the future behaviour is considered, it is not satisfactory merely to use longshore sediment transport to predict beach behaviour. In establishing a true budget, either the elevation/depression of the beach must be known or a reliable estimate of sediment transfer perpendicular to the beach should be available. The importance of producing a wave refraction model which incorporates onshore/offshore transfer of material is mentioned again later.

Sediment tracer experiments did not provide data adequate enough to calculate a budget since this requires experiments to be carried out at other locations along the beach. However, the tracer results do indicate that modelled rates for longshore sediment movement are realistic and therefore may form the basis of a crude calibration of the budget (Sections 3.1 a, 3.2 c and 4.2 a). In practice the modelled and measured values were so similar over this short timescale that no calibration weighting was applied.

Table 3.33a Mean Areas Under Beach Profiles (m^2) to Arbitrary Basal Datum and Corrected for a uniformly long Beach Profile; August/September 1983 and August/September 1984

	Profile								
	A	B	C	D	E	F	F'	G	H
1984	417.6	798.2	696.4	700.8	487.4	618.4	610.2	759.3	468.8
1983	393.8	389.3	575.5	712.1	715.2	529.5	593.7	508.8	458.8
1984 corrected	417.6	804.2	696.4	700.8	487.4	618.4	610.2	759.3	468.8
1983 corrected	401.3	389.3	644.5	787.0	735.0	557.5	679.5	557.7	864.4
Δ Area	+16.3	+414.9	+51.9	-86.2	-247.6	+60.9	-69.3	+201.6	-395.6
			cell (v)				Cell (iv)		
Mean Δ Area (m^2) for cell			+29.86				-50.60		
Δ Volume in cell (m^3)			+55987.5				-94875.0		

Table 3.33b Calculation of Difference Between Modelled ΔV (from Table 3.32) and Observed ΔV (from Table 3.33b) to Estimate Onshore or Offshore Sediment Movement

	Cell			
	South	(v)	(iv)	North
Modelled ΔV (m^3)		+72299.8	-3262.4	
Observed ΔV (m^3)		+55987.5	-94875.0	
Difference (m^3)		16312.3	91612.6	
Direction		offshore	offshore	
Equivalent volume transport per tide (m^3)		22.4	125.8	
Mean change in beach elevation per tide (m)		8.0×10^{-5}	4.5×10^{-5}	

In this chapter the results of experiments carried out in the various coastal sub-systems, i.e. the offshore zone, the beach and the cliff, have been presented, along with the relevant statistical analysis. Modelled sediment transport rates were derived from offshore data, and current measurements allowed the nature of sediment movements under tidal currents to be assessed. After some general beach observations had been made two (winter and summer) probabilistic models of beach evolution were presented which described and predicted beach transitions along the field site and throughout the year.
The seasonal and longshore trends of sediment characteristics were recognised and tracer experiments enabled measured sediment transport rates to be presented. A sediment budget was then prepared for a section of the Holderness coast using the results presented in previous sections. All of these results will be interpreted in Chapter 4, and will be compared with the results of similar experiments carried out elsewhere by other workers.