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Lockery, Andrew R. (1971) *Quaternary sea level change, Lake formation, and associated glacial events, with special reference to the lower tees basin*, Durham theses, Durham University. Available at Durham E-Theses Online: http://etheses.dur.ac.uk/8445/

QUATERNARY SEA LEVEL CHANGE, LAKE FORMATION, AND ASSOCIATED GLACIAL EVENTS, WITH SPECIAL REFERENCE TO THE LOWER TEES BASIN

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Dissertation presented for the degree of
Doctor of Philosophy
to the Department of Geography,
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August, 1970

Resubmitted in March 1971.

ABSTRACT

QUATERNARY SHORELINE CHANGES, LAKE FORMATIONS AND ASSOCIATED GLACIAL EVENTS, WITH SPECIAL REFERENCE TO THE LOWER TEES BASIN

The Thesis set out to fulfil two purposes:

1) To further the development of a methodology for the study of displaced shorelines.
2) To apply the methodology to the lower Tees Basin.

1) Methodology

An examination of previous work suggested that a methodology should encompass as many facets of a marine environment as possible to obtain best results. Three such facets were selected for detailed study, morphology, sedimentology, and fossil evidence, and the value of each was assessed on both theoretical and practical grounds.

It was concluded that the degree of differential warping exhibited by a terrace could indicate the origin of the feature. Similarly the particle size and mineralogy of a sand sized sediment may indicate its depositional environment. Although both of the above techniques were partially successful it was concluded that "in situ" fossil evidence provided the best means of identifying a displaced marine environment.

2) The Lower Tees Basin

The above methodology was applied to both the onshore and

offshore environments of the Tees Basin, and it appeared that there was no evidence for a late or post glacial sea level above O.D. Newlyn. In contrast, there was evidence for sealevels lower than present.

Summary

One may conclude that there were three areas in need of further study. All three could be applied to the methodological and regional aspects of the present study.

Firstly there was a definite need for improvements in the field of sedimentology. It was felt that a detailed survey of particle size, shape, and density groups within sand sized sediments would provide the best measure of environmental conditions.

Secondly, there was a very great need for further detailed studies of the offshore environment, whilst thirdly, there was a pressing need for an absolute chronology.

PREFACE

The author has always maintained an active interest in the sea and this thesis represents a desire to enhance man's understanding of this natural phenomenon.

Following graduation in 1966, two specific events combined to influence the choice of thesis topic. The Institute of British Geographers published a special number on "The Vertical Displacement of Shorelines in the British Isles," and the British Geomorphological Research Group held a stormy but stimulating seminar on this same topic. This publication, the seminar, and the remaining British works on the subject of sea level change all served to emphasise a concentration on the study of raised features and morphological evidence at the expense of submerged features and sedimentological evidence. Further perusal of previous work confirmed a basic need for a reliable methodology enabling all forms of displaced shorelines to be recognised and the thesis is dedicated primarily to fulfilling this need.

The enormity of this task became more apparent as research progressed and the selection of the Lower Tees Basin as the test region for the proposed methodology placed the necessary limitations on the scope of the thesis.

The Lower Tees was almost certainly glaciated during the

Würm Ice advance, (Beaumont, 1967), and although earlier events are discussed, the need to examine unmodified features and sediments effectively restricted the study to the period following the retreat of this ice sheet.

It was also acknowledged that factors other than sea level change had played significant roles in the morphological evolution of the Tees Basin and the inclusion of the words "lake formation and associated glacial events" in the thesis title not only reflected this recognition but further allowed for comparisons to be made between morphologically similar marine, lacustrine and ice stagnation features. Finally, the sheltered nature of the Tees Basin led to a greater emphasis being placed upon depositional features than might otherwise have been the case.

In concluding this preface, one must reiterate that every care was taken to avoid the possible pitfall of excessive regionalism. This would have obscured the prime aim of the thesis which is to promote a greater understanding of the mechanisms and consequent results of changes in sea level.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the assistance of the following persons :

Dr. P. Beaumont, for his thorough and conscientious supervision;

Professor W. B. Fisher, Head of the Geography Department at Durham, for permission to use the departmental equipment and facilities;

Dr. J. B. Sissons, for his helpful advice during the initial stages of the project;

Dr. D. J. Bellamy, University of Durham Botany Department, for the generous loan of marine equipment and personnel;

Denys Smith and Eddy Francis, of the Geological Survey, for readily supplying the geological evidence in existence;

Dr. J. E. Klovan, for assistance with computer analyses;

and last but not least, Valerie Lockery, for her willingness to assist in fieldwork and typing.

In addition, the author would like to acknowledge the considerable assistance of the following authorities:

Middlesborough Corporation
The Tees Water Board
The Tees Harbour Authorities
Hartlepool Corporation

Stockton Corporation

Billingham Corporation

Imperial Chemicals Industries

J. D. and D. M. Watson, Civil Engineers

The Geological Survey of Britain

The University of Winnipeg, Winnipeg, Manitoba

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SECTION 1

INTRODUCTION

CHAPTER 1

INTRODUCTION

> "The edge of the sea is a strange and beautiful place. All through the long history of the earth it has been an area of unrest where waves have broken heavily against the land, where the tides have pressed forward over the continents, receded and returned. For no two successive days is the shoreline precisely the same. Not only do the tides advance and retreat in their eternal rhythms but the level of the sea itself is never at rest. It rises or falls as the glaciers melt or grow, as the floor of the deep ocean basins shifts under its increasing load of sediments, or as the earth's crust along the continental margins warps up or down in adjustment to strain and tension. Today a little more land may belong to the sea, tomorrow a little less. Always the edge of the sea remains an elusive and indefinable boundary."
>
> —Rachel Carson, from "The Sea" (MacGibbon and Kee Ltd.)

This chapter is composed of two sections. The first explains the form of the thesis, whilst the second examines the causes of sea level change since the retreat of the last ice sheet, with special reference to Highland Britain.

PART I

The Form of the Thesis

The aim of the thesis is twofold. In the first place, an attempt is made to develop a methodology for the recognition of displaced shorelines, and secondly, to apply the methodology to the Lower Tees Basin. The text may be separated into four parts:

(1) Introduction
(2) Methods and results
(3) Interpretation of results
(4) Conclusion

Introduction

The introductory section examines the causes of late and post-glacial sea level change in Highland Britain with a view to determining the nature of displaced shorelines and the likelihood of their occurrence in the Lower Tees Basin. This chapter is followed by an examination of previous work in an attempt to summarise the existing methodologies and their application to the present study. In this examination a distinction is made between raised and submerged shorelines because of the environmental problems associated with underwater study. Further, justification is given for the choice of the Lower Tees as the test area for the proposed methodology. The area is described and previous work examined in order to assess the particular problems of study.

Methods and Results

This section likewise falls into three parts, examining in turn the morphological, sedimentological, and fossil faunal evidence which accumulated from field and laboratory investigations. Where applicable a distinction is again made between raised and submerged features.

Interpretation of Results

The concluding section discusses the significance of the thesis findings from both a regional and systematic viewpoint.

PART II

The Causes of Sea Level Change

One hopes that an understanding of the causes of sea level change will provide some guide as to the evidence one may expect to find in the research area, the Lower Tees Basin.

Isostasy

This term was first used by Dulton in 1889 to explain the theory of "crustal equilibrium." This theory relates to the balance which exists between the world's continental and oceanic crust. Any change in this balance, as a result of weight redistribution, such as the transference by erosion of sediment from an upland mass to a deltaic complex is matched by a crustal readjustment effected by the lateral flowage of sub-crustal magma (Bott, personal communication, 1968). By this process, therefore, coastal regions may be uplifted or downwarped and a relative change of sea level ensue.

Glacio-isostasy relates to the specific case of crustal equilibrium being disturbed by the retention of precipitation on land masses as snow and ice. For example, it was suggested by Lawson (1940) that ice one kilometre thick of density 0.917 added to the surface would be compensated by the removal in depth of 0.278 kilometres of rock of density 3.3. King (1966) summarised this process, stating that ice depressed the land surface by one quarter to one third of its own thickness. Although depression is greatest where the ice attains maximum thickness (normally the zone of ice accumulation) there is a critical threshold value which must be reached prior to any crustal deformation taking place. There appears to be little agreement concerning this value and estimates vary from an ice cap 200 miles in diameter to one ten times that value (Charlesworth, 1957). Nye (1969 personal communication) is of the opinion that ice thickness rather than area is critical but gives no precise figure, whilst Broeker (1966) supports the view that a 200-mile diameter ice cap would result in crustal deformation.

Crustal rebound takes place following the melting of this ice and consequent removal of its weight. It is generally agreed that the speed at which isostatic rebound takes place gradually diminishes as crustal equilibrium is reached such that adjustment may continue long after initial commencement (Fig. 1). One cannot determine without detailed geophysical measurements whether the rate of uplift decreases as smoothly as Fig. 1 would suggest. One should, however, note that some recent workers (Broeker, 1966; and Andrews, 1968) have recorded deviations in the curve of uplift coincident with variations in the rate of ice retreat (Fig. 2).

The Extent of Glacio-Isostatic Rebound in Britain

All existing diagrams of the limits of isostatic rebound are based on the elevation of raised shoreline features (Fig. 3). The zone encircled by the zero isobase does not delimit the total extent of uplift but rather the extent of uplift with reference to present Ordnance Datum. One can observe from Fig. 3 that the Lower Tees Basin lies in each case to the south of the zero isobase. The occurrence or non-occurrence of raised shorelines in the region could provide further evidence on the position of this isobase.

The Nature of Isostatically Displaced Shorelines

This section is included in an attempt to ascertain the morphological character of displaced shorelines and thus provide a guide to the ways in which one might determine their origin. It is restricted to the effect of isostatic rebound and does not include the influence of tidal range and the nature of the environment, both of which are examined in Chapter 4.

It is generally supposed that glacio-isostatic uplift will distort a once horizontal shoreline so that it will rise towards the centre of uplift. The degree of this tilt will usually increase towards the centre of uplift and with the length of time the shoreline is exposed to isostatic rebound. Thus, one may surmise that under similar conditions two synchronous shorelines could possess a similar degree of warping provided:

(1) they lie between the same isobases

(2) they possess a similar orientation with respect to the centre of uplift

It follows that shorelines which vary in distance and orientation from the centre of uplift could possess similar tilting but a very different date of origin. In concluding this section it is interesting to note that Sissons and Smith (1965) record a maximum tilt for a late glacial shoreline feature in the Firth of Forth of 6.93' per mile. This degree of differential uplift would be unlikely to occur in the Lower Tees which is some 100 miles further from the centre of uplift.

Eustasy

Eustatic theory recognises that world sea level change can result solely from changes in water level as opposed to land level. A detailed history of eustasy was provided by Smith (1966) and again, to avoid repetition the early development of the subject is omitted.

It is generally agreed that eustatic changes in sea level may arise as a result of the following processes acting alone or in unison.

(1) A change in the configuration of the oceanic basins as a result of tectonic forces.
(2) A change in water volume effected by salinity or temperature changes. (It is generally accepted that a world-wide rise in oceanic temperature of +1°C. would raise the water surface by 2 metres.)
(3) Glacio-eustasy.

Glacio-eustasy was first developed in 1842 by McClaren and relates to the initial lowering of sea level at the onset of glaciation as a result of the retention of runoff on the land masses as snow and ice, and the gradual rise of sea level as the major ice sheets retreated under the influence of the post-glacial climate. The particular aspects of glacio-eustatic theory which affect this study are:

(1) the amount of sea level lowering during the Würm glaciation

(2) the rate and amount of the late and post-glacial rise in sea level

(3) the interrelationships of eustasy and isostasy

The Amount of Sea Level Lowering During the Würm Glaciation

Most workers have recognised a pre-Würm sea level coincident or near coincident with that of the present day (Charlesworth, 1957).

The use of this basic assumption, together with formulae for the calculation of ice thicknesses (Donn, Farrand, and Ewing, 1962) has resulted in a variety of figures for the maximum amount of sea level lowering. Estimates vary between 328' and 525' (Donn et al) but a recent concensus of opinion by workers using C14 dating methods on sea bed materials, favours 375' (Curray, 1961; Shepard, 1963).

Despite the greater accuracy obtained by the use of C14 dating, one is forced to conclude that no positive agreement has yet been reached on the precise amount by which sea level was lowered during the Würm glaciation.

The Rate and Amount of Late and Post-Glacial Rise in Sea Level

Figs. 4 and 5 have been included to illustrate the wide range of opinion which exists in regard to the eustatic rise of sea level since the last ice age. A comparison of curves based on C14 dating does, however, clearly portray those areas in the time scale where disagreement exists.

Most investigations recognise a rapid rise in sea level during the late glacial period, interrupted by two falls consequent upon two readvances, and a less rapid rise in the post-glacial period levelling off after 5000 B.P. For convenient discussion, two periods can be distinguished (Fisk, 1955): 17000 to 6000 B.P., and 6000 B.P. to the present day.

17000 to 6000 B.P.

During this period sea level rose at an average rate of 25' per 1000 years (Shepard, 1963) and this general rise, with the possibility of occasional reversals, is supported by all those investigators using C14 dating.

6000 B.P. to Present

In contrast to the preceding period, a considerable degree of disagreement exists amongst workers for this time section. Fairbridge, 1961, following the lead of Daly, 1920, 1934, supported the existence of high stands of post-glacial sea level. He considered these to occur at approximately 1000, 2200, 2400, 3700, 4900 and 5700 B.P., with heights up to 12' above present.

Leblanc and Bernard, 1954, Fisk, 1959, Curray, 1960, 1961, Shepard, 1963, Bloom, 1963, Jelgersma, 1961, 1966, and Andrews, 1968, who worked in widely separated areas, all supported a constant sea level at the present height, during the past 5000 to 6000 years. Jelgersma (1961), in particular, who studied in the Netherlands, produced clear evidence that present sea level had not been exceeded in this zone of crustal submergence, as continuous growth has been experienced in coastal peat marshes.

Whilst the author agrees with workers in the Northern Hemisphere that no evidence exists for late and post-glacial eustatic sea levels above that of the present, there is some case for further study in the Southern Hemisphere where Fairbridge's conclusions are supported by Schofield, 1960, 1961, 1962, 1963, 1964.

The Interrelationships of Eustasy and Isostasy and the Likelihood of Late and Post-Glacial Shorelines Occurring in the Lower Tees Basin

It is the relationship between eustasy and isostasy that creates the major problems in Scandinavia, Britain, and the Lower Tees, specifically with regard to shoreline displacement.

Following the maximum extent of the Würm glaciation, there is evidence to suggest that a series of readvances interrupted the gradual retreat of the ice (Fig. 6); namely, the Scottish readvance, Lammermuir-Stranraer, Perth-Aberdeen, and Highland readvance (West, 1968), with each consecutive readvance encompassing a lesser area. The immediate effect of ice melt is the provision of meltwater for a eustatic rise in sea level, followed at a later date by the gradual commencement of crustal rebound.

It has been argued that the variability of the eustatic sea level rise and the rate of isostatic crustal rebound resulted in the numerous raised shorelines of the Firth of Forth (Sissons, 1962, 1963, 1964, 1965, 1966; Smith, 1965, 1966, 1968; Cullingford, 1966), North-West Scotland (McCann, 1962, 1963, 1964; Kirk, Rice, Synge, 1966), and North-East Ireland (Stephens, Synge, 1963, 1964, 1965, 1966).

It is possible that peripheral areas of the major ice sheets, not overrun by later readvances, underwent isostatic rebound whilst regions closer to the centre of the ice sheets remained ice covered, (providing the period of relaxation between initial deglaciation and the commencement of rebound is exceeded by the period between initial and total deglaciation). An absolute chronology for Würm retreat stages in Britain is far from complete owing to the absence of datable deposits. However, workers throughout the world all support a marked change in climate between 17000 to 15000 B.P., which is further supported by the evidence for a eustatic rise in sea level commencing at this time (Shepard, 1963; Curray, 1961; Fairbridge, 1961). The Perth readvance, which appears to have close relationships with the late glacial shorelines of the Firth of Forth (Sissons and Smith, 1965) is dated at not younger than 12000 B.P. Whilst this chronology is very tenuous indeed, it can be argued that isostatic uplift could take place during the intervening period of 3000 to 5000 years, between deglaciation of the peripheral and more central zones of the ice sheet. The critical factor is the amount of isostatic rebound which would take place. No C14 dates exist in the Lower Tees for periods prior to the Allerød (10851 ± 500 B.P., Blackburn, 1952) but it is almost certain that the area was ice free throughout all four late Würm readvances (West, 1968).

Between 17000 B.P. and 12000 B.P., Shepard (1963) records a eustatic rise in sea level of 180' and thus one can argue in favour of any isostatically uplifted shorelines either being later submerged by the continuing eustatic rise, or non-existent as a result of the eustatic rate being in excess of the isostatic rate at this time.

Proof of this hypothesis would necessitate the precise dates and maximum extents for each of the four major Würm readvances, plus an accurate date for deglaciation of the Lower Tees area. In addition, it requires a precise estimate of ice thickness in the Tees area and consequent isostatic rebound plus a definite figure for the relaxation period between deglaciation and commencement of uplift. This proof cannot be obtained within the economic and temporal bounds of this thesis but the absence of any evidence to suggest raised shorelines above present ordnance datum could support this hypothesis.

Tectonic Forces

Tectonic earth movements refer to endogenic crustal movements, all of which may influence sea level on a regional rather than a world scale. Excluding isostasy, which has already been discussed, only the tectonic downwarping of the southern North Sea basin can influence the present study.

Eight major works on this phenomenon by Dutch workers illustrate the considerable significance attached to negative changes of level along the low-lying coasts which form the southern boundary of the North Sea.

The amount of tectonic subsidence in the Netherlands has been approximated by the depth of marine pleistocene deposits, tide gauge readings and precision levelling (Jelgersma, 1961).

Variations in results suggest from 2 cm. per century (Benema, 1954) to as much as 12 cm. per century (Umbgrove, 1950). This maximum estimate by Umbgrove of 12 cm. per century compares favourably with that of Godwin (1941) who estimates a local downwarping of approximately 9 metres since 8000 B.P.

Whilst highly significant in the Netherlands and those sectors of East Anglia where coastal erosion is severe (Godwin, 1945; Green, 1961), it must be realised that the above tectonic movements have very little significance, if any, in the areas of Britain which underwent, or are undergoing, crustal rebound following the retreat of the last ice age.

In summary, one must, however, point out that tectonic forces are not as easily discounted in the major deltaic regions of the world as Fisk (1939, 1940, 1944) demonstrated for the Mississippi, or in the world's "mobile belts" such as Japan (Kaizuka, 1958, 1959) where there has been tectonic upwarping in the order of 300 metres.

Compaction

Again, Dutch investigations dominate the literature because of the close proximity of their country to sea level, the considerable thickness of sedimentary structures and the long term risks concerning their reclamation prospects.

Sediment compaction is caused by load consolidation as a function of time, and by changes in hydrological condition (Jelgersma, 1961). Wiggers (1954) examined the susceptibility of different rock types to compaction, concluding that the following factors were significant.

(i) Grain density-- i.e., the density of constituent particles

(ii) Bulk density--the density of the dry rock; that is, the rock plus pore space free of liquids

(iii) Natural density--the density of the rock with pore space water filled

(iv) Porousity--the percentage of total rock volume occupied by pores,

$$\% \text{ pore space} = 100 \left(1 - \frac{\text{bulk density}}{\text{grain density}}\right)$$

(v) Void ratio--the ratio of voids to volume of solid particles in a rock. If porousity is p and the void ratio is ε, then

$$= \frac{p}{100 - p} \qquad \text{and } p = \frac{100\,\varepsilon}{1 - \varepsilon}$$

Compaction, therefore, expressed as the % reduction of rock volume may be represented by the following equations:

$$\frac{\varepsilon_1 - \varepsilon_2}{1 - \varepsilon_1} \qquad \text{or by} \qquad \frac{p_1 - p_2}{100 - p_2}$$

where ε_1 = initial void ratio

ε_2 = final void ratio

p_1 = initial porousity

p_2 = final porousity

Wiggers notes that sand exhibits less susceptibility to compaction than clays, but it is especially significant to note that Van Veen, Van Straaten, and Pannekoek (1954) are in agreement that peat can undergo compaction to the order of 65% to 95% of its original volume. The significance of this situation is immediately apparent when one realises the importance attached to the relative levels of coastal peat bands with regard to the chronological reconstruction of the post-glacial eustatic sea level rise. Reid (1913), Godwin (1943), Godwin, Suggate, and Willis (1958), Curray (1961), and Churchill (1965) all make use of submerged coastal peats in their relative or absolute chronologies of sea level change. Jelgersma (1961) was first to minimise this complication by sampling only at the base of peat beds.

In summary, whilst one may accept the base level of the lowest peat bed in a submerged sequence as reasonably accurate, any significance attached to the depth of subsequent submerged peat beds higher up the stratigraphical column must allow for compaction. The presence of two submerged peat layers in the research area and their significance with regard to compaction and sea level change is discussed in Chapter 3.

Summary

It would appear from the foregoing discussion that the respective amounts of crustal rebound and eustatic sea level rise control the likelihood of late and post-glacial raised shorelines occurring in the Lower Tees Basin.

There is a general concensus of opinion that the eustatic rise of sea level totalled 375 feet. Kendall (1902), Raistrick (1931), and Agar (1954), all support an ice thickness in the Tees of approximately 1000' (based on erratics found on the north face of the Clevelands).

If one accepts that crustal depression equals 1/4 to 1/3 of the total ice thickness then it is probable that displaced shorelines will only occur below present sea level in the Lower Tees Basin. Certainly, the existing isobase diagrams (Fig. 3) which show the extent of crustal rebound above present Ordnance Datum, confirm that the Lower Tees lies south of the zero isobase.

CHAPTER 2

PREVIOUS WORK

An Appraisal of Techniques for the Initial Recognition and Chronology of Displaced Shorelines

In order to assess the validity of the conclusions drawn in Chapter 1 it is essential that there should be no mistaken identification of shoreline remnants. This chapter, therefore, sets out to examine and assess the methodologies of earlier investigations.

RAISED SHORELINES

World Studies Based Primarily on Morphological Evidence

In all, 264 works were examined in this section and one was able to distinguish between those using a descriptive, and an analytical approach.

Descriptive Studies

Field identification of terrace features was used as a major technique in the third century B.C. when the existence of terraces parallel to existing sea level suggested to Aristotle the likely hypothesis that they were of marine origin. This association of coastal terraces with past sea levels has dominated the literature well into the twentieth century. However, the following examples have been selected from widely separated areas, in order to avoid needless repetition.

Cooke, in a series of articles (1951, 1952, 1958), recognised the existence of a series of terraces on the Maryland coast (Atlantic seaboard, U. S. A.), between 215 and 6 feet above present sea level. On the basis of their heights above sea level they were correlated with other shoreline features, notably in Florida (Cooke, 1945) and automatically presumed to be marine. Hack (1955) later proved that the three terraces above 100 feet were non-marine.

Wengert (1951), working in Frobisher Bay, Baffin Island (Eastern Arctic Canada), recognised elevated strand lines definitely to a height of 900' and possibly to 1400'. Particularly with regard to the higher terraces (above 500') his evidence was solely morphological and out of harmony with the conclusions of later works (Løken, 1962, 1965; Andrews, 1968).

Only a limited selection of Soviet work was available for study, but Federov (1943, 1948) exhibited similar faults as investigators elsewhere in the world when he used only the position of terraces bordering the Caspian to support a marine hypothesis. He did, however, introduce supporting stratigraphical evidence for his hypothesis in 1952.

In the above investigations the methodology amounted to field observation and consequent deductions based very largely on the premise that the most obvious hypothesis, with regard to origin, is the correct hypothesis. A terrace remnant may develop in one of the following ways:

(1) Fluvial origin
(2) Structurally controlled erosion or bedding plane surfaces
(3) Marginal drainage channels peripheral to an ice sheet
(4) Lacustrinal terraces
(5) Man-made terraces
(6) Marine origin

In summary, whilst some of the alternate hypotheses could be ruled out almost immediately, as irrelevant to a particular environment, one must acknowledge, from this preliminary survey, that a composite approach incorporating morphological, stratigraphical, and faunal evidence could eliminate some of the errors exhibited by previous works. A descriptive morphological approach has the very real advantage of leading the researcher to those features worthy of further investigation. It is questionable whether the morphological character of a displaced shoreline is sufficiently distinctive to allow genetic speculation.

Analytical Studies

The term "analytical" is used here to indicate some form of measurement over and above the allocation of spot heights. Methodologies may be divided into those using surveying techniques, those using quasi-statistical or morphometric techniques, and those employing sophisticated statistical and/or computer methods.

Surveying Techniques

It would appear from the literature that surveying as a technique for the study of raised marine features was largely developed in Fennoscandia and has not been as widely used elsewhere. The advantages of precise surveying techniques may be tabulated as follows:

(1) It allows for the accurate measurement of shoreline heights.

(2) It enables a more detailed appraisal of the nature of uplift in cases where differential isostatic or tectonic forces are suspected.

(3) It enables, in some cases, the differentiation of shorelines from fluvial terraces on the degree of tilting.

Outside Fennoscandia, Leverett and Taylor (1915) recognised the numerous raised shorelines of the Great Lakes by completing levelled profiles along the terraces, so determining the existence of warping upwards toward the centre of ice accumulation. Johnson (1946) completed a similar survey of the shorelines of Glacial Lake Agassiz (Manitoba, Canada) and both investigations recognised irregularities in the warped profile of the shorelines.

In Fennoscandia, Witting had already produced a detailed contour map of the extent and amount of post-glacial uplift by 1918, and the frequency with which precise levellings were completed enabled continuing rates of uplift to be estimated by the variation in height of fundamental bench marks between successive levellings (Bergsten, 1930; Gutenberg, 1941; Heiskanen, 1964).

Gillsberg (1952) and Sauramo (1939, 1955) completed detailed levellings along terraces and concluded, as did Leverett, Taylor, and Johnson (op. cit.), that uplift was not a simple updoming but incorporated anti-clinal and "hinge" line flexures.

From the above work one learns that the use of precise levelling, hand levels, or aneroid barometers, to determine whether terraces exhibit variations from the horizontal, was not used in the "initial identification" of shorelines but did enable the nature of isostatic rebound to be determined after identification.

The introduction of morphometric techniques (hypsometric curve, area height analysis) assists identification only as a preliminary analysis to suggest areas where field work might prove profitable. Photogrammetrical techniques, with an error of ± 10 inches may be similarly classified, whilst computer studies, notably trend surface analysis, are best utilized after precise levels have been completed to assess significant trends in uplift (Andrews, 1968).

In conclusion, morphological study, whether descriptive or analytical, has the obvious advantage that it leads the investigator to a feature which could be of marine origin. But, genetic conclusions cannot be drawn solely from this evidence.

World Studies Based Primarily on Sedimentological Studies

A total of two hundred and fourteen investigations have been reviewed to provide the statistics for this section. A similar distinction is made between descriptive and analytical studies.

Descriptive Studies

The majority of sedimentological work on raised shorelines falls into this category. The degree of description varies from cursory reference to "terrace deposits" (Jahns, 1954) to detailed stratigraphical examinations (Oaks and Coch, 1963; Jahn, 1959). The following examples, however, have been selected to illustrate the very varied nature of the deposits described as raised marine.

Coarse Sediments

Lipps (1964), Coats (1956), Crawford (1963), Schlanger and Brookhart (1955) all recognised raised marine boulder deposits on the Californian, West Alaskan, Southern Australian, and West Caroline Islands coasts respectively.

Fine Deposits

At the other end of the sedimentological size scale, Upson (1954) described a raised marine clay in coastal Maine, whilst Gadd (1960) recognised a similar highly fossiliferous deposit from the brackish Champlain Sea. Hickox (1962) describes an estuarine clay 65' above sea level around the Bay of Fundy and a similar deposit is recognised by Lee (1957) in New Brunswick. The dominance of these fine grained deposits in land-sheltered ice protected low energy environments and estuarine conditions, is further supported by the joint work of Mackay, Matthews and MacNeish (1961) in the Yukon, Sjors (1959) in the Hudson Bay, Miller and Drobrovolnye (1959) in Alaska, Cadilla (1960) in Puerto Rico, Derjatora (1960) in the White Sea, Dyvyetov and Losyev (1964) in the Caspian, and Wyllie (1957) in North-East Greenland. The latter worker, emphasising the inadequacy of sedimentological evidence alone, recognised that the N.E. Greenland terraces could be of marine or lacustrine origin.

Sands and Gravels

The extremes of the sedimentological size scale include only 10% of the recognised raised marine deposits incorporated in this survey. The remaining 90% is subdivided as follows:

50%—sand
25%—gravel
25%—sand + gravel

It is also worthy of note that 72% of these works citing marine deposits as evidence of raised shorelines support their conclusions with faunal evidence.

It is perhaps significant that gravel terraces predominate on exposed coasts and sand terraces on more sheltered coasts, where the local rock breaks down to sand size particles, and close to a large river where excess sediment is available.

However, despite these conclusions, one must emphasise that sedimentological evidence alone is insufficient to justify a marine hypothesis as fluvial, fluvio-glacial, lacustrine, and marine deposits are frequently indistinguishable from one another on visual and often on analytical grounds only.

Analytical Studies

During the twentieth century sedimentological work has become increasingly analytical in the fields of mineral identification, particle size, shape, density and recognition of depositional environments. This work has, however, concentrated primarily on present day sediments and environments such that detailed analytical studies on "fossil" environments are by comparison exceedingly rare. The following investigations are examined as representative of studies which assist the recognition of raised marine sediments.

Cayeux (1941) recognised the link between past and present sedimentary environments and Laursen (1950) in Western Greenland carried out a detailed petrographic study of highly fossiliferous raised marine deposits in an attempt to provide a list of characteristics by which such a deposit may be recognised.

Shukeri and Phillip (1956), investigating raised features in the Egyptian Mediterranean coast, attempted to correlate the raised fossiliferous deposits with the Nile River terraces on the basis of heavy mineral similarities. In so doing the authors provided one example of the heavy mineral content of raised marine deposits.

McKee (1957), using a slightly different approach, attempted to provide a key to the recognition of depositional environments by listing the structural characteristics of sediments. For example, beach sediments exhibited low bedding angles and long even surfaces of foreshore laminae, whilst dune sediments exhibited more steeply dipping cross-bedded strata. The problem with this approach is the subjective nature of the assessment and the occurrence of similar structures in different environments, as with lacustrine and marine.

Claridge (1961) returned to mineralogical considerations when providing a detailed mineralogy of wind-blown raised sands in New Zealand. Neiheisel (1962), working in Georgia, provided a further guide to the heavy mineral content of some Recent and Pleistocene sands.

Colquohoun (1962), in South Carolina, described in detail the sea cliff, beach, lagoon, bar and shelf deposits in an attempt to find diagnostic properties. It was not until 1964, however, that Shepard, produced the first co-ordinated attempt to enlist all the possible characteristics of depositional environments recognised in present day deposits, which might assist in the identification of 'fossil' marine deposits.

Shepard gave the following list of diagnostic properties of depositional environments. Dune sands are distinguished by a greater percentage of heavy minerals, a greater rounding of particles, a total absence of mica, and a high silt content. Fluvial sands particularly contain a high percentage of mica; beach sands, a greater abundance of shell fragments; whilst near shore sediments characteristically contain an appreciable amount of silt and very fine sand, sorting is rather worse than on beaches. In addition, the sediments of the near shore zone are more negatively skewed because of the abundance of relatively large shell fragments and less erosion of the large foraminifera. Shepard further suggested that clay minerals in the finer grained sediments gave some indication of environment, but proved inconsistent, whilst the orientation of grains proved helpful in some environments.

One must point out that the above properties are by no means wholly reliable and are dependant upon the consistency of several variables (Chapter 5).

Supplementing Shepard's work, Middleton (1965) further developed the ideas of McKee (op. cit.) and Colquohoun (op. cit.), in his work on primary sedimentary structures and their hydrodynamic interpretation.

Sames (1966) applied the study of roundness and shape of pebbles to both present and ancient deposits and was partially able to distinguish between environments. However, despite all these works on various depositional environments it was not until 1967 that an attempt met with any success.

Chappell (1967) was able to identify raised Pleistocene beach and dune sediments by a comparison of the sediments with those of the present day. The results of particle size analyses were subjected to Friedman's (1961) formulae for the calculation of moment measures and a 95% separation between beach and dune environments achieved when skewness values were plotted against grain size frequency.

Most recently in these studies King and Buckley (1968) succeeded in procuring a meaningful environmental classification from roundness and shape measurements of pebbles in Baffin Island. Mean size alone differentiated between deltas, eskers, and ice contact features, whilst roundness proved most distinctive of the three aspects of stone shape.

So far only sand and gravel deposits have been considered in any detail, although Shepard (op. cit.) did mention that in some instances clay minerals are environmentally diagnostic. Pratt (1963) (unpublished Ph.D. thesis, University of California), in his detailed investigation into the origins and nature of glauconite confirmed the earlier views of Gallagher (1935), Cloud (1955), and Keith and Degens (1959), that the presence of this mineral was indicative of a marine origin or at very least indicative of post genetic subjection of the sediment to marine conditions as would result from land being inundated by the eustatic rise of sea level prior to isostatic recovery.

In summary, despite a wealth of descriptive stratigraphies, there have been very few applications of detailed sedimentological analyses to the study of possible raised marine deposits. Techniques are available, as the above works testify, to allow a detailed environmental assessment of the complete sediment size range and one of the major aims of this thesis must be to carry out such analyses.

World Studies Based Primarily on Fossil, Faunal and Floral Evidence with Additional Reference to Absolute and Relative Chronologies

Over six hundred investigations were examined from the literature citing fossil, faunal, or floral evidence as proof of high sea levels. This greatly increased number of works, over and above both morphological and stratigraphical evidence, is indication in itself of the greater reliability of such evidence. It is true to say that only fossil, faunal, or floral evidence can be accepted as indication of a higher sea level, without support. The evidence may be grouped as follows:

	Percentage of Total Works Examined	
(1)	Mammals and fish	0.02%
(2)	Shell and coral	76 %
(3)	Diatoms, ostracoda, radiolaria, foraminifera	23.98%

and in the forthcoming section, each of the above three sections is examined with regard to acceptability and problems.

Mammals and Fish

The rare discovery of semi-fossilised fish in Littorina clay approximately 6,000 years old and in late glacial clay approximately 13,500 years old, by Nybelin (1946) on the East Swedish coast is accepted proof of a higher sea level than present. Similarly the occurrence of whale bones on the west coast of Sweden, 104 meters above present sea level, embedded in a gravel deposit, is quoted by Bjorsjo (1953) as clear evidence of a marine level. The finding of similar bones in Spitzbergen (Birkenmayer, 1958) at 5 to 8 meters above sea level, must be regarded as suspect owing to their association with artifacts of the 17th century whaling community. It is likely that carcasses would be dragged some height above mean sea level by this community.

It is then the rapid decomposition of fish and the rarity of whale bone finds which provides the major restriction to their use as marine indicators.

Shells and Corals

Several hundred occurrences of fossil molluscs and corals are recorded in the literature. In most cases they may be accepted as being in situ and, therefore, representative of higher sea levels. Exceptions to this rule may be recorded when only isolated shells are found, when the distribution of shells is irregular, or in a river terrace such that an archaeological origin might be suspected, or when the deposit in which they occur is not in situ; glacial till or fluvio-glacial deposits, for example. One must further accept that sea birds transport shells inland as does man when fertilising coastal areas with seaweed. Emerson (1960), working in Baja, California, clearly illustrates these problems when a series of shell deposits gave a C14 date of 100 ± 80 B.P. A closer inspection revealed that the deposits were shell mounds from human inhabitation. In addition, an experiment was carried out by the present author on the north-west coast of Scotland where numerous small bivalves coated in red paint were placed at HWM in an onshore gale with wind speed gusting to 68 mph. These bivalves travelled up the beach to heights 20' to 30' above mean sea level. If this experiment is to be accepted, in some instances wind transport may give rise to incorrect conclusions.

These problems apart, the occurrence of a mollusc or coral assemblage in raised deposits, can indicate, in addition to marine conditions, the temperature, clarity, salinity, and depth of the water. For example, Addicott (1963, 1964), working in California and south-west Oregon, discovered a molluscan fauna on a wave cut terrace 22 feet above present sea level. The assemblage suggested moderately shallow water and near shore conditions with a slightly cooler average water temperature than present.

Valentine (1956) exhibited even greater precision when stating that Californian marine terraces contain fauna indicative of shallow water conditions (not exceeding 5 fathoms) within 1/2 mile of the shore, and a greater seasonal temperature change than at present.

Thomas (1963) described a 150-foot terrace with fresh water fauna, supporting the existence of an ancient high level delta of the Colorado River when sea level was at least 100 feet above present.

It must be remembered, however, that such precise environmental classifications are dependant upon the assumption that molluscs have not adapted to different environments since the Pleistocene. Valentine (1955) argues that such adaptations have taken place, thus lessening the validity of environmental zoning. The evidence for this conclusion is based primarily on the occurrence, in present faunal assemblages, of species not found together in the Pleistocene. It is possible, however, that this situation reflects a transitional stage in climate amelioration and Valentine's conclusions must, therefore, be regarded as only tentative.

Marine Micro Fossils

Molluscs occur most frequently in sand deposits and to some extent in gravels, whilst more delicate micro fossils are best preserved in less abrasive clay sediments, although still occurring to a lesser extent in sands. As with corals and molluscs, it is possible for transported fossils to mislead the investigator.

Stainforth (1952) produced evidence suggesting that turbidity currents were responsible for the occurrence of shallow water arenaceous foraminifera at considerable depths. A similar problem was experienced by Emery and Terry (1956) off the southern Californian coast when coral algae were discovered in a core at 2,670' below present sea level, 2,170' below what is considered its normal living depth.

Despite such hazards, valuable insight into Pleistocene conditions has been gained from diatom and foraminiferal studies. Numerous works exist on foraminiferal zonation, notably McGill and Loranger (1961), Phleger (1960), Stainforth (1952), and Ladd (editor) (1957), and the following investigations illustrate their application.

Gadd (1960), working in Quebec, was able to recognise the existence of Brackish water conditions in the Champlain Sea, thus confirming earlier conjectural writings on its marine nature. Bandy (1953) recognised the existence of cool, shallow water conditions during the formation of some Californian raised terraces, whilst Kincaird (1957) recognised shallow water bay or estuarine conditions near Seattle. Tinoco (1958) suggested shallow, clear, warm water at Rio de Janeiro during the formation of raised terraces, whilst Feyling-Hanssen (1964), in south-east Norway, was able to discern the slow change from Arctic to Boreal conditions from changing foraminiferal assemblages.

Summary

These three types of faunal evidence are of great significance in the initial recognition of raised marine features. In each case the technique for collection demands field researches, with only microfossils demanding laboratory methods in addition. In this latter case, the techniques for the concentration of microfossils from a sediment sample are amply discussed in works by Kornicker, Phleger, and Brady (op. cit.) and involve simple flotation in alcohol or carbon tetrachloride. It may be concluded that without faunal evidence great difficulty in proving a suspected marine origin, for either a deposit or terrace feature, will result. A detailed search for such fossil remains must be included within the scope of this thesis.

Chronology

Absolute Pleistocene dating relies heavily on the radioactive isotope dating techniques, especially C14. The reliance of C14 on the occurrence of organic remains has led to the inclusion of this section alongside faunal studies.

The incorporation of shell, bone, or wood in a sediment permits the allocation of a C14 date and it is by this means that detailed graphs of the eustatic rise of sea level during the last 25,000 years have been constructed (Jelgersma, 1961; Fairbridge, 1961; Shepard, 1963; Schofield, 1964).

The introduction of absolute dating has in fact made three important contributions to the study of sea level change:

(1) It has enabled the course of mean sea level to be accurately plotted during the late and post glacial period.

(2) In any one locality it has confirmed that the highest raised shoreline is frequently the oldest.

(3) In several different localities it has proved that similarities in height are of no significance in correlative studies if differential uplift has taken place.

The specific example of "Tephrochronology" or dating by means of a widely occurring easily recognisable volcanic ash or tuff layer is worthy of mention as a highly successful technique in the few areas of the world where glaciation and vulcanicity occurred in unison (Auer, 1950, 1959, South America; and Thorarinsson, 1955, Iceland).

The relative and absolute chronologies and associated environmental discoveries, developed from palynological studies are also recognised but discussed in greater detail in the later section on submerged features, where these studies have provided highly significant data.

It is concluded that chronological data has greatly assisted the clarification of the history of sea level change.

World Studies on Submerged Shorelines

The majority of investigations of displaced shorelines have been instigated by the occurrence above sea level of clearly distinguishable terrace and faunal remains. This factor is a reflection of the obvious difficulties of environmental access encountered by "Man" in his attempts to study submerged shorelines. The following section examines those investigations carried out to date in an attempt to assess the problems and significant conclusions which have come to light. A subdivision of investigations on the basis of morphology, sedimentology, and faunal and floral evidence is again used.

Morphological Studies

Initial morphological studies on submerged shorelines owe their origin to the hydrographic surveys completed to safeguard shipping during the nineteenth and twentieth centuries, but more detailed oceanographic surveys in the twentieth century have added considerably to the documentation of submerged terrace features. In this brief review, the greater majority of available works have been examined, not only in an attempt to determine dominant shoreline patterns but also to assess the nature and validity of the methodology.

Whilst there is a general agreement of views regarding morphological evidence for the maximum lowering of the Pleistocene sea level as being between 300' and 450' (Emery, 1962; Coats et al, 1961; Cooke, 1952; Fray and Emery, 1962; Richards and Craig, 1963; Vedder and Norris, 1961) it is noticeable from the literature that investigations off Soviet coastlines and off the Norwegian coast record terrace features at considerable depths:

Soviet Conclusions

(1)	Ganeshin and Chemekov (1960)	-1,500' terrace,	Soviet Far East
(2)	Kulikov and Martinov (1961)	-1,500'	Kara Sea
(3)	Lakukov (1954)	-1,500'	Soviet Arctic Basin

Kulikov and Martinov (op. cit.) support their conclusions with evidence of submerged river valleys continuing from present sea level to this great depth, and further suggest that it dates from the maximum Riss glaciation 110,000 B.P.

Norwegian Evidence

(1) Evers in 1962 recognised a -600' terrace

(2) Whilst Holtedahl (1955) recognised a terrace at -710' O.D.

It seems difficult to reconcile these conflicting results with regard to maximum levels of sea level lowering. One can only suggest that the continuing development of precise dating techniques will enable the distinction to be made between Riss and Würm associated features.

Despite the world wide distribution of terrace features, no attempt is made to correlate levels owing to the facts brought to light in the previous section on "Chronology." In fact the effects of differential uplift and tilting of submerged terraces is recognised by Rikhter et al (1961) in the Caspian, Dannstedt (1948) in the Baltic, and Baczyk (1963) in Polish waters.

In almost all cases, investigations made use of echo sounding equipment. The investigations of Federov and Leontin (1953) in the Caspian using self-contained underwater breathing apparatus and the work of Ewing, Le Pichon and Ewing (1963), using a sparker sub-bottom survey to prove the existence of Pleistocene terrace features buried beneath recent littoral facies, provide two alternative approaches, whilst several workers, notably on the Atlantic coast of the U. S. A. use the grade of buried river valleys to predict the level of lower sea levels.

One must, in summary, criticise, not the method, but the accuracy of later interpretations. Goreau (1961), investigating the continental shelf, provides one alternative hypothesis when suggesting that of the five terraces observed, the lowest at 200' is not a submerged shoreline but rather a fault scarp feature. The occurrence of submerged terrace features has a similar value as raised terraces in that it leads the worker to an area where further investigations might bear fruit.

Sedimentological Studies

Compared with morphological investigations which constitute 58% of the studies which were examined, sedimentological investigations make up only 18%. A two-fold division may be made between those investigations which recognise the existence of terrestrial deposits below sea level, and those which recognise shallow water marine deposits at depths well below their zone of formation.

Terrestrial Sediments Below Sea Level

Caldenius and Linnman (1949), in a borehole sample from southern Sweden, recognise a late glacial lacustrine clay overlain by marine deposits at -38 feet O.D. whilst Blanc, Segre, and Tongiorgi (1953) record terrestrial sediments to 310 feet below present sea level in the Mediterranean. Harrison (1962) recognised in Chesapeake Bay, Virginia, the occurrence of a sub-aerial erosion surface of Pleistocene age corresponding with the base of buried channels extending to depths in excess of 300 feet. Bloom (1963), working in coastal Maine, recognised the occurrence of glacio-fluvial deposits covered by marine clay to depths of 70 feet below present sea level whilst Boillot (1964) is unique in his description of periglacially frost shattered pebbles, on the bed of the English Channel, as evidence of a lower sea level in immediate post glacial time. Finally, Doeglas (1950) recognised, partly on the basis of submarine morphology and partly on the evidence of particle size curves, the existence of river and dune sands at -15 meters and -25 to -30 meters below present sea level in the Mediterranean.

Marine Sediments of a Character Inconsistent with Their Present Environment

Suggate (1958) recognised a sequence of marine estuarine and fluviatile deposits extending down to -200' O.D. off Christ Church, New Zealand, whilst Emery and Niino (1963) recognised relict beach deposits on the continental shelf off Thailand. Fray and Ewing (1963), working on the Argentinian shelf, discovered in bore hold cores, remnants of beach sediments at -390' O.D. Some years previously Clements and Dana (1944) had used similar evidence to support the occurrence of a shoreline at -150 fathoms on the Californian shelf. Wimberley (1955) recognised a similar coarse grained deposit at -40 fathoms in Scripps Canyon off La Jolla, California. Completing this sequence, Shepard (1956) and Shepard and Moore (1965) recognised the occurrence of "bay" deposits at -80' off the central Texas coast.

In view of the considerable difficulties experienced by sedimentologists, trying to define characteristics of present-day beach deposits (Folk, review article, 1966), hypotheses based on the recognition of submerged beach deposits must be regarded with scepticism if no other supporting evidence is available. Turbidity offshore and tidal currents are all documented as carrying large amounts of sediment seawards (Stainforth, 1952, op. cit.) and transportation should be acknowledged as an alternate hypothesis.

Fossil, Faunal, and Floral Evidence in Support of Sea Levels Lower than Present

As in the above section, one can distinguish between out-of-character marine fossils and terrestrial species below present sea level.

Terrestrial Species Below Present Sea Level

One of the earliest evidences cited in support of sea level change was the "submerged forest" and peat which frequently occurs intertidally or just below low water mark. Such deposits have been observed in many localities on world coasts and C14 dates vary from 3,000 B.P. to 8,000 B.P. with a marked concentration between 6,000 and 7,000 B.P. The following works include examples of such findings together with remains from greater depths.

Bradley (1953) in coastal Maine records the existence of tree stumps 3 to 5 feet below ordnance datum and dated at 4000 B.P. whilst Harrison (1962) in Virginia records two peat beds at 42 and 93 feet below sea level together with a further bed at -30 feet O.D. at Churchland, west of Norfolk (U. S. A.). Kaye and Barghoorn (1964) similarly record peat beds at -70 feet (10,000 B.P.) and -2 feet (3000 B.P.) off Boston (Massachusetts) whilst Dutch workers record numerous peats along the north European coast (summarised and dated by Jelgersma, 1961, op. cit.). Churchill (1959), in the

Swan River district, Perth, Western Australia, recognised peat beds at -68' O.D. dated at 9850 B.P., whilst Te Punga (1954) discovered wood remains in a bore hole core at -150 feet and dated at 9900 B.P. near Palmerston North, New Zealand. Avnimelech (1950) discovered "elephas" bones at -36 meters on the Israelian shelf near Yavneh, but perhaps the most significant discovery was that made by Brodie (1955) off South Island, New Zealand, of a peat bed at -450 feet O.D. and considered by him to be of Pleistocene age.

These submerged organic deposits are of considerable value in the assessment of sea level change providing two precautions are observed. Firstly, the problem of compaction in peat (Wiggers, 1954, op. cit.) can lead to false levels, and secondly, care must be taken to determine whether the peat was formed at or near sea level. With regard to this second case, Dutch workers (Geol. en Mijnb, 1954, symposium) record the gradual transition from peat to estuarine fossiliferous muds and argue in favour of peat formation in these cases being a function of the rising water table accompanying the rise in sea level.

Marine Species of a Character Inconsistent with Their Present Environment

It is important to note that the conclusions drawn from the evidence presented in this section relied upon the basic assumption that faunas have maintained similar environmental limits during the last 50,000 years.

McKee (1956) records truncated shallow water coral reefs at 10 to 12 fathoms, 14 to 17 fathoms, and 25 to 27 fathoms in the Caroline Islands Oceania, arguing that their truncation results from the increasing rate of sea level rise out-pacing their growth rate. Fairbridge and Stewart (1960) in Melanesia recognise a similar relict coral reef at 10 to 15 fathoms; and Keble in the Bass Strait (1947), one at -276 feet O.D.

Richards and Craig (1963) support the earlier mentioned conclusions of Fray and Ewing (1963) in their recognition of a -390' shoreline by the discovery of a cold shallow water mollusc assemblage in a core at that depth. Shepard (1960) recognised at -40' O.D. relict near shore and shallow bay micro-organisms in the north-western sector of the Gulf of Mexico; whilst Parker and Curray (1956), Gould and Stewart (1955), and Jordan (1952) similarly recognised the occurrence of both submerged relict corals and a preponderance of Pleistocene shallow water foraminifera at depths between 50 and 20 fathoms.

In summary it is worthy of note that all the information included in this section was the result of dredge and core sampling from a surface vessel. There follows a brief summary of conclusions regarding world studies of displaced shorelines.

Summary

The following conclusions may be drawn as a result of this survey of previous work:

(1) Morphological studies constitute the initial stage of research and guide investigations to areas where further studies are justified.

(2) Descriptive sedimentological studies emphasise the wide range of sediments making up beach deposits, but it is felt that fluvial, fluvio-glacial, lacustrine and marine deposits are frequently visually indistinguishable from one another, thus questioning the validity of marine hypotheses based solely on such evidence.

(3) Analytical sedimentological studies on raised marine sediments have not made maximum use of existing techniques developed on present day sediments. Techniques are available to allow a detailed environmental assessment of the complete sediment size range and should be attempted in shoreline studies.

(4) The value of fossil, faunal, and floral evidence is paramount when supporting a marine hypothesis and as such a detailed search for evidence must be undertaken.

(5) A brief section on chronology lists three contributions of absolute dating to shoreline studies.

With regard to submerged studies similar conclusions are drawn with the exception of sediment studies when doubt is cast on the accuracy of environmental studies on submerged deposits because of sampling problems and the possibility of post depositional reworking.

In general terms a two-fold criticism is levied on previous literature:

(1) There is a strong tendency towards descriptive studies as opposed to sounder analytical approaches.

(2) Marine hypotheses are too frequently postulated when evidence is only circumstantial.

The following brief summary examines British literature primarily to determine whether there are methodological differences or weaknesses.

Previous Work in the British Isles

Raised Shorelines

Studies Based Primarily on Morphological Evidence

Descriptive Studies

From Smith's (1965) examination of early British work it is clear that morphology was not a major factor in the initial recognition of raised marine features. An article in "The Scotsman" (1834) discussed the significance of raised shell beds near Barrowstowness (Grangemouth) and Murchison (1837), similarly described shell beds in south-west England, as suggestive of higher sea levels than present. Nor do early descriptions of terrace features rely solely upon morphological evidence when suggesting a marine hypothesis as Geikie (1861) and Jamieson

(1865, 1882) demonstrated. Jamieson, in the latter of the above articles, recognised correctly that raised marine terraces in glaciated areas were frequently warped as a result of glacio-isostatic crustal rebound. Despite this early arrival at a correct and logical conclusion in the study of Quaternary shorelines, the only work between that date and 1962, which recognised this uneven uplift and furthered its comprehension, was that of Wright (1914) whose "isokinetic theory" explained the interrelationship of crustal rebound and the eustatic rise of sea level. There was instead a series of works frequently supporting a marine hypothesis for raised terraces and erosion surfaces.

Green (1946) describes ten terraces in the region of Bournemouth, ranging between 330 feet and 33 feet above sea level, and in a later article (1949) recognises eleven terraces between 1,150 feet and 12 feet above sea level in the Dart Valley (Devon) and correlates these with post oligocene high sea levels. Brown (1952) discusses the morphological evidence in favour of a 600-foot shoreline in Wales, whilst Burnaby (1950) recognised a raised platform 10 to 15 feet above sea level on the north Norfolk coast. Davies (1958, 1960, 1963) recognised sixteen terraces between 20 feet and 1,000 feet above sea level in Ireland but does acknowledge that there is no evidence to confirm a marine origin.

Analytical Studies

A major criticism, voiced by Sissons (1962) and later by Smith (1965) was the lack of precise levels for these terraces. Authors were criticised for the use of aneroid barometers with a 4 to 5 foot working error (Donner, 1959, 1963; King and Wheeler, 1963); for employing the elevation of non-significant parts of terraces (Donner, 1963) and subsequent use of this measure to calculate the height and tilt of shorelines; and thirdly, the use of O.D. Liverpool, high water mark, and the upper limit of Balanus Balanoids as opposed to O.D. Newlyn (McCann, 1961, 1963).

This highly significant article by Sissons (op. cit.) supporting Jamieson's original conclusions of 1882, met with criticism from Earp, Read, and Francis (1963) of the Scottish Geological Survey, who supported the well established 100' 50' 25' horizontal classification but Sissons (1963) produced precisely levelled profiles of recognised raised shorelines to confirm his 1962 conclusions.

The result of this brief interchange stimulated renewed interest in raised shorelines and was followed first by a series of articles—Sissons and Smith (1965), Stephens (1963), Synge and Stephens (1965), Jardine (1963, 1964), concentrating on the shorelines of upland Britain; secondly, by the publication of a "Special number on the Vertical Displacement of Shorelines in Highland Britain" (1966)(Inst. Brit. Geog.); and more recently still, by further articles by individual workers, Jardine (1967), Smith (1968), and

Smith, Sissons, and Cullingford (1969).

The result of this spate of publication with regard to the advancement of morphological studies was the recognition by Smith, Cullingford, and Sissons of a series of shorelines far greater in number than was previously suspected along the north and south sides of the Firth of Forth, each distinguished on the basis of its different height above sea level.

This marks a significant development in morphological studies. The original work by Sissons (op. cit.) involved recognised shoreline features containing marine faunal evidence. In the more recent work, terrace features formed in a variety of deposits were levelled and on the basis of this evidence alone identified as shorelines or fluvio-glacial terraces. Fluvio-glacial features possessed gradients 30 to 40 feet per mile whilst tilted shorelines did not exceed 10 feet per mile. Sissons and Smith (1965) do qualify the above evidence stating that fluvio-glacial terraces are predominantly of gravel, and raised beaches predominantly sand, silt, and clay.

The question arises as to whether one can distinguish between shorelines and fluvio-glacial terraces solely on the degree of warping. Sissons and Smith together with Cullingford clearly support such a conclusion and Sissons and Smith (1965)(page 155), observe a "raised shoreline terrace" merging imperceptibly with a fluvio-glacial terrace as the sediments gradually become coarser and the angle of warping steeper. Similar terraces, however, described by Gresswell (1952) in the Mersey Valley at 8, 15, 20, and 35 feet above normal river level, are considered by Simpson (1958), to represent changes in load to volume ratio in the river and not variations in sea level.

Whilst the evolution of morphological studies centred on this work in the Firth of Forth, other investigations, by Stephens, Synge, Jardine, McCann, Kirk, Rice, Walton, Ritchie, Orme, Smith, J. S., King, and Wheeler (1966), made reference to morphological features in highland Britain recognising in most cases evidence of warping.

It is concluded that morphological evidence for the recognition of raised shoreline features has been used as genetic proof of a marine hypothesis in Britain; a method not attempted elsewhere. An examination and assessment of this technique is incorporated in Chapter 4.

Studies Based Primarily on Sedimentological Evidence

Descriptive Studies

The literature emphasises only one significant difference between world and British studies using sedimentary evidence. This is the very rare use of sedimentary evidence alone as an indication of a raised shoreline. The majority of investigations incorporate morphological, sedimentary and faunal evidence: attention frequently being first drawn to the deposit by its environmentally displaced faunal content and terrace location. Of the exceptions, the following are particularly significant.

Sparks (1953), working in the Weymouth lowlands, recognised the existence of post Pliocene terraces overlain by gravels. These gravels, however, did not contain a marine fauna and their character suggested a solifluction deposit. Sissons (1966), with the aid of numerous shallow boreholes, recognised buried shorelines beneath the coarse clay deposits of the Firth of Forth. His evidence, in support of a marine hypothesis for these terraces, includes a gravel layer of supposed marine origin, and making up the surface deposit of the buried steps, overlain by a thin peat layer which Newey (1966) records as representative of salt marsh conditions in their lower parts. The investigation contained sufficient accurately levelled borehole sitings to enable the tilt of these buried terraces to be calculated (1.3 feet and 0.4 feet per mile). This tilting, as with the sub-aerial shoreline features in the Firth of Forth, is considered to result from post glacial crustal rebound. Downing (1959), however, in a note on the Crag deposits in Norfolk, describes lower Pleistocene estuarine clays, on top of the Crag, as dipping east from +20' O.D. at Norwich to -20 feet O.D. at South Burlingham and -60 feet O.D. near Sea Palling (an eastward dip of approximately 2 feet per mile).

This dip must be presumed to reflect either the estuarine gradient at the time of deposition, or post depositional subsidence in the southern North Sea basin, the latter possibly being more likely (West, 1963).

In summary, as with world studies, shoreline features may include deposits representative of the whole sedimentary size range although more recent raised shorelines tend to be composed of finer sediments (Sands, silts, and clays).

Analytical Studies

Analytical studies of raised marine deposits have rarely been attempted in Britain although D. Kemp (University of Edinburgh) is at present engaged in such work.

McCann (1961) examined supposed raised beach gravels at Corran, Loch Linnhe, and Loch Etwe and was able to prove by orientation analyses on long axes of pebbles that a fluvio-glacial origin in a late glacial ice dammed lake was in fact correct. This technique may be added to those used in world studies, by King and Wheeler (1966, op. cit.), as a significant test of gravel genesis.

Studies Based Primarily on Faunal and Floral Evidence

Because of the composite nature of most evidence supporting marine hypotheses mention has already been made of faunal and floral supporting evidence. Again, as in world studies, fossil organic evidence, in support of a marine hypotheses, carries more weight than morphological and sedimentological data.

Whale and seal skeletons, molluscs, ostracoda, foraminifera, and saltmarsh peat deposits are all cited as evidence of raised marine shorelines. The works included in this section, however, relate only to those investigations interpreting conditions from the organic remnants.

Anderson (1947) recognised cold water ostracoda and mollusc species in the "100 foot" beach clays of Scotland, whilst MacGregor and MacGregor (1948) supported this view and further stated that the "25 foot" beach was dominated by temperate species. Similarly, Van de Vlerk (1950) recognised in the foraminifera of the Crag deposits of Norfolk an increase in Arctic species, when compared with present day assemblages.

Submerged Shorelines

Morphological Studies

Heezen, Tharp, and Ewing (1959), in their detailed study of the North Atlantic, recognised at 70 to 100 fathoms, persistent bench features, too continuous to be explained as structural benches or as a result of faulting, which it was suggested were formed by Pleistocene eustatic sea levels.

On a more local scale Cooper (1948) recognised a distinct submerged ancient cliff near Plymouth, its foot at 22 fathoms O.D. Flinn (1964) used detailed echo soundings in a survey of the near shore shelf off the Shetlands on which a series of benches were recognised, the most distinct being at 40 to 45 fathoms. Hawkins (1962) recognised submerged benches associated with the Bristol Avon at -23 feet and -50 feet.

Several investigations cite the grade of buried river channels as evidence of lower sea levels. McFarlane (1955) recognised the drowned channels of the Erne, Tawe, and Torridge in Devon and suggested a sea level of -150' O.D. at the time of their formation. Robinson, 1952, described in detail the character and channels of the North Sea bed, and suggested a sea level 140' to 160' below present. Stephens (1958) recognised similar buried channel features in Belfast and Strangford Loughs.

Sedimentological Studies

The identification of marine sediments at depths greater than that of their formation does not appear to have been used by British workers but several records exist of terrestrially formed sediments below present sea level.

Mitchell (1963) interpreted four ridges on the floor of the Irish Sea, as moraines. Stride (1959) describes the Dogger Bank (North Sea) as a large moraine on the basis of seismic and core sample evidence and in an article with Bowers (1961) suggests two hollows in the floor of the Irish Sea were fresh water lakes during deglaciation.

Fossil, Faunal, and Floral Evidence

Reid (1913) produced a book listing known levels and sites of submerged peat and forest beds. These were later dated by Godwin, Willis, and Suggate (1945, 1958, 1961) and more recently by Churchill (1965).

This latter work concentrating solely on those deposits occurring just below present sea level and all dated between 6000 and 7000 B.P., thus supporting the evidence in favour of a slowly continuing eustatic rise of sea level since that date.

Flinn (op. cit.) recognised peat below sea level in the Shetlands down to -38 feet O.D., whilst Ritchie (1966) in the Uists discovered submerged peat beds down to -6 feet O.D. Stephens (1958) similarly recognised peat deposits off the Ards Peninsula, N. E. Ireland, whilst a most interesting and significant discovery of peat beds in the Dogger Bank is discussed in some detail by Stride (op. cit.).

Summary

Should further information on British shorelines be required, the reader is referred to two relevant publications:

(1) Stephens and Synge, 1966, "Pleistocene Shorelines," in Dury, G., Editor, Essays in Geomorphology.

(2) Inst. Brit. Geog., Special No. 39, 1966, Vertical Displacement of British Shorelines.

From this section on Britain it is suggested that the following techniques are worthy of inclusion in any attempt to finalise a methodology for the initial recognition of displaced shorelines:

(1) Detailed morphological levelling may have genetic properties (Sissons, personal communication).

(2) Orientation analyses may distinguish between beach and deltaic deposits (McCann, 1961).

(3) A search for buried terraces beneath marine transgressive deposits (Sissons, personal communication).

CHAPTER 3

THE LOWER TEES BASIN

In the previous two chapters the problems associated with the causes of sea level change and those associated with methodologies for the initial recognition of displaced shorelines, have been examined and discussed. The Lower Tees has been chosen as the area in which to test the various hypotheses and methodologies put forward. The chapter will discuss the reasons for this choice, the general physiography and stratigraphy of the Tees, and the nature of previous work. In addition to sea level change the glacial history of the region is discussed in some detail in view of the close interrelationships of the two phenomena.

The Choice of Area

In addition to its proximity to the University of Durham, and consequent ease of access, the Lower Tees (Fig. 7) was particularly suitable for this study.

Firstly, an examination of Fig.3 which shows the zero isobases of late and post glacial uplift, as demonstrated by the tilt of existing raised shorelines, suggests that the Tees basin is close to this position. The occurrence or non-occurrence of raised shorelines in the area could, therefore, considerably assist the accurate positioning of this isobase. In relation to the above statement there is evidence in previous work (Agar, 1954) for the existence of sea levels both above and below that of present, in the Tees area, ranging from + 82' O.D. to -160' O.D. Should the occurrence of raised shorelines be proven the following subjects should be examined:

(1) The amount, timing, and nature of post glacial crustal rebound as discussed in Chapter 1 must be re-examined.

(2) The relative influence of the various ice sheets, Lake District, Scottish, and Scandinavian, which converged on the Tees (Raistrick, 1931) might be assessed from the direction of tilt of such features.

(3) Dateable shoreline features cut into surface deposits could determine more accurately the deglaciation chronology of the area.

Physiography and Stratigraphy

Physiography (Fig. 8a, 8b)

The Lower Tees Basin, especially below the 100-foot contour, is almost devoid of relief, a characteristic which contrasts strongly with the steep, scarp slope of the Cleveland Hills to the south and the hummocky, glacial topography to the north and west.

This low-lying plain extends 16 miles inland, gradually diminishing in width from 14 miles at the coast to 4 miles at Egglescliffe, and is partially dissected by the incised tributaries of the Tees; on the northern side, by the Billingham Beck, and on the south, by the River Leven, Ormesby, and Middlebecks. Apart from these easily distinguished breaks, this lack of relief is important in the study of sea level change as it permits the easy recognition of any widely occurring break of slope, such as might indicate a potential marine limit. With reference to Fig. 19 it becomes clear that any advantage to be gained from this morphology is very largely obliterated by the combined effects of industrial and urban expansion together with 18th and 19th century coastal reclamation. Rapid urban development continued apace throughout the period of research and it was against this background of rapid destruction of the landscape that morphological study was pursued.

Stratigraphy

This section deals only with a description of the depositional sequence in the research area; interpretations are not attempted at this stage.

The protective form of the Tees estuary, itself a reflection of solid geology, ensured a depositional environment on an otherwise erosional coastline (Agar, 1960), and has resulted in the preservation of a suite of detrital and organic deposits bearing evidence to past environments. This natural aid to stratigraphical study, together with the provision of innumerable borehole and excavation records from urban and industrial developments, clearly demonstrates the particular value of such study in the Tees basin.

This wealth of information has, however, rather than simplified comprehension of the stratigraphical sequence, confirmed and emphasised its complexity, and resulted in several different interpretations of the stratigraphical history.

Barrow (1888), of the geological survey, was first to study the area in any detail but the resulting map was not accompanied by a memoir and the recognition of two boulder clays separated by sands and gravels was thus without interpretation.

Carruthers (1939, 1946, 1953) introduced the "undermelt hypothesis." This hypothesis supported a single ice sheet melting from the base and resulting in a complex series of shear clays, laminated clays, sands, gravels, and boulder clays.

More recently Smith and Francis (1967), of the geological survey, resurveyed part of the northern sector of the research area and recognised the following stratigraphy:

Prismatic clay
Tees Laminated clay
Morainic drift and upper gravels
Middle sands--upper
--lower
Lower boulder clay
Lower gravels

Loess

Scandinavian drift

Fissure deposits

Their work related primarily to the area immediately north of the Tees Basin and the only detailed study of the Lower Tees was made by Agar (1954), whose years in the region as a civil engineer allowed him access to a wealth of constructional information and enabled him to produce the following stratigraphy:

Recent	Blown sand
	Marine warp
	Brown alluvium
	Marine sand of raised beaches
	Peat and forest bed of estuary
	Grey alluvium
Late Glacial	Marginal sand
	Laminated clay
Glacial	Red boulder clay
	Dark boulder clay
	Sand
	Drab boulder clay
	Gravel

Agar also recognised the occurrence of buried peat in several of the Tees tributary streams dating from Zone VIIb of the palynological sequence, and occasionally containing fresh water shells. It may prove significant to note that these peat beds are restricted to the tributaries of the Billingham beck and the beck itself on the north side of the Tees.

Summary

From this brief survey of stratigraphies there would appear to be little general agreement between the Tees basin and surrounding areas. Many deposits are aerially discontinuous and several laminated clays, red Tees clay, and coastal peats occur only in the Tees Basin (Fig. 1L). Several investigations have attempted to interpret the complex sequence of deposits, particularly with regard to glacial history and sea level change and the coming section is devoted to further examination of these two topics.

Glacial History and Chronology

Beaumont (unpublished Ph.D.)(1967) provided a detailed summary of glacial research in Northern England and in County Durham in particular. Part of this work has since been published (1968) and in order to avoid unnecessary repetition the following account deals primarily with works related to the Lower Tees Basin, but does make reference to surrounding regions where necessary.

The Tees Basin has, to some extent, been avoided by workers because of the complexity of the stratigraphical sequence and the early realization (Goodchild, 1875) that the area's history was complicated by the confluence of three major ice sheets (Lake District, Scottish, and Scandinavian). Kendall (1902) discussed in detail the glacial history of the Northern Cleveland Hills, and recognised evidence in favour of Goodchild's earlier conclusion that the first ice to reach the Tees Basin had originated in the Lake District, entered the Tees via the Stainmore Pass, and flowed out to sea beyond the present coast line. Kendall further discussed the possibility of the Scandinavian ice sheet reaching the British coast but concluded that this was unlikely owing to the intervention of a third ice sheet travelling down the coast from the Cheviots.

This early recognition of three ice sheets which influenced the glacial history of the Tees provides the basis upon which a greater understanding of the chronology of events must be established.

Whilst Woolacott (1905) further supported Kendall's assertion that evidence for three distinct ice sheets existed in the Tees Basin, it was not until 1915 that Trechmann brought to light proof of the close proximity of the Scandinavian ice sheet by the discovery of a pure Scandinavian suite of erratics in till at Warren House Gill on the Durham coast. Beaumont (op. cit.) points out that both Trechmann and Lamplugh (1907), the latter working in Holderness, were in agreement that the Scandinavian ice not only reached Britain but did so before local ice reached the east coast and in addition that it represented a separate earlier period of glaciation. Trechmann (1919) described in detail a "loess" like deposit overlying the Scandinavian drift which he felt confirmed a period of climatic amelioration followed by its deposition. Trechmann further contributed to the understanding of glacial history in North-East England when on the basis of erratic distribution he emphasised his view that the Scottish ice had not extended far inland because of the influence of the Pennine and Lake District ice sheets. Woolacott (1921) summarised the state of knowledge of glacial history in County Durham supporting a four-fold glacial sequence, notably different from earlier work in his separation of Cheviot from Scottish ice:

(4) Cheviot

(3) Lake District

(2) Scottish Ice

(1) Scandinavian

A further difference is his placement of the Scottish Ice at an earlier date than the Lake District advance. Raistrick (1931) corrected this statement in favour of the following sequence of events in agreement with the conclusions of Kendall and Goodchild:

(3) Cheviot-Scottish

(2) Lake District

(1) Scandinavian

He noted that the Cheviot ice was sandwiched between the other two ice sheets but was able to force its way south at a later stage encircling the Cleveland Hills (Fig. 12).

What is not clear in Raistrick's account is whether he accepts Trechmann's theory on the existence of an inter-glacial period between the deposition of the Scandinavian drift and the local drifts. Certainly his own theory demands the presence of the Scandinavian ice sheet close offshore in order to divert the Cheviot ice south.

Carruthers (1939, 1946, 1953), in marked contrast to earlier investigations, stated that there was no evidence to support more than one glaciation in County Durham. All the deposits were, he stated, the result of basal melting of stagnant ice. Agar (1954), working solely in the Lower Tees, recognised three boulder clays which he correlates with the Hessle, Purple, and Drab of Holderness. No Scandinavian deposits are recorded, whilst most recently Smith, in Smith and Francis (1967) came to the conclusion that eastern Durham showed clear evidence of three glaciations, whilst western Durham showed evidence for only one.

It may be summarised that although three deposits exist, containing different erratic suites, there is no faunal, floral, or depositional evidence available to allow an absolute chronology of events to be established.

Evidence in favour of an inter-glacial period between the deposition of the Scandinavian drift and local drifts, is sedimentary in nature and by no means conclusive, whilst a recent find of an inter-glacial peat erratic in till at Hutton Henry, County Durham (Beaumont, Turner, and Ward, 1969) demonstrates only that the inter-glacial existed prior to its inclusion in the till sheet.

Catt and Penny (1968) recently dated the Dimlington moss, which underlies the Holderness sequence, at 18,500 ± 400 B.P., thus clearly supporting a late Würm origin for all deposits above the Basement till and possibly supporting Carruthers' contention that evidence for only one glaciation exists in much of County Durham.

In summary, although agreement is reached on a relative chronology based on the law of superimposition, the absolute chronology in County Durham is far from complete.

Deglaciation in the Tees

Although Agar (1954) provides for a comparison of events with those of County Durham, his investigation does not emphasise the details of deglaciation in the Tees. The following works are examined with a view to rectifying this shortcoming.

Elgee (1908) recognised the existence of an ice stream from the north holding up small lakes along its margin during its retreat across the Stokesley plain immediately south and west of the Tees Basin.

Fawcett (1916), in a study of the Tees and its tributaries, recognised that the laminated clay of the Lower Tees Basin (Fig. 11) was of lacustrine origin. The clay deposit extended to 250 feet above sea level and was related to a supposed 400-foot water level.

These two investigations by Elgee and Fawcett suggested a pattern of events resembling closely the stages of deglaciation suggested by Raistrick (1931)(Fig.12). It may also be significant to note that the ice sheet occuping the Tees Basin retreated down slope and would be capable of blocking the natural drainage to give rise to these lacustrine features. The situation might be paralleled by conditions in Central Canada (Elson, 1956) which gave rise to the enormous glacial Lake Agassiz, again as a result of a down slope ice dam.

The conclusions of this pioneer work in the Tees were supported and added to by Gayner and Melmore (1934) and Radge (1939). Both investigations supported the existence of a late glacial lake but Radge made a further distinction between the marginal lakes recognised by Elgee up to 400 feet O.D., and the lowland basin lake which was associated with the deposition of the laminated clay beds.

Best (1954), in support of Radge (op. cit.) noted that the basin lake in the Tees was clearly delimited by the laminated clay deposit and more particularly by a fringing beach at approximately 75 feet O.D.

Summary

On the above evidence the deglaciation of the Tees basin was dominated by lacustrine conditions, in turn a reflection of the down slope direction of ice retreat. Alternative proposals have been made notably by Agar who suggested that a marine origin for the laminated clay could not be overlooked, and by Carruthers, who, in keeping with his undermelt hypothesis, supported a subglacial origin as a "shear clay." A shear clay is similar to a laminated clay in appearance, but the laminae result from supersaturated clay particles becoming aligned parallel to one another as a result of ice pressures.

Sea Level Change

Prior to an examination of evidence supporting changes of level in the Lower Tees Basin, it is necessary to note the work of Harrison (1921). Harrison, in a detailed study of the Tees marshes, records the chronology of estuarine reclamation practised between 1740 and the twentieth century. His reproduction of a chart by Hewitt (1832) gives a clear indication of the original position of the coastline (Fig. 16) and of the zone in which any evidence for higher sea levels must be doubly checked.

Tute (1883) was first to notice the occurrence of marine deposits above present sea level in the Tees basin. He described the occurrence of a bed of sandy clay containing many shells of Rissoa ulva with broken mussel and cockle shells and the vertebrae of fishes at Warrenby, a new village near Coatham on the eastern outskirts of Redcar. The land surface was 14 feet above High Water Mark and he concluded that the coast had been raised some 20 to 25 feet since the deposition of these faunal remains. Tute described the upper layers of the deposit extending into a peaty material overlain in turn by brown clay. There is little doubt that the deposit was in situ, but an examination of Harrison's study confirmed that it lay within the reclaimed zone, and that its present height above mean sea level reflects this reclamation.

Veitch (1883) discussed the significance of several indicators of displaced sea levels notably on the south side of the Tees Basin. He recognised the buried channel of the Tees to a depth of 98' below O.D. and the implication that it was graded to a sea level well below -100 feet O.D. His description of the submerged peat beds on both northern and southern sides of the estuary similarly supports the existence of a sea level below present. It was noted that the maximum depth at which peat is recognised was -30' O.D. Veitch's most significant contribution, however, was the recognition, at Saltburn, of a band of alluvial sand containing innumerable shell fragments (*Purpura*, *Litorina litoraea*, *Trochus cinerarius*, *Natica globosa*, *Lachesis minima*, and *Cypraea Europaea*). The deposit unconformably overlies glacial drift and is 35 feet above High Water Mark, thus supporting a mean sea level 41 to 46 feet above present O.D. Veitch did acknowledge the presence of an ancient kitchen midden associated with the deposit containing the shell fragments but did not consider the possibility that the two occurrences were related.

Fox (1886) recorded a submerged deposit 30 feet below O.D. at Whitby 18 miles south of the Tees, but containing similar organic remains as the Tees submerged peats, and further supporting the continuing rise of sea level since 8000 B.P. (The Tees peat was dated using C14 at between 8100 and 8700 ± 180 B.P. (Smith and Francis, 1967).

Barrow (1888) re-examined the Saltburn beach discussed by Veitch. It was noted that although all the shells found in the raised deposit occurred on the present beach, a number of shells on the present beach did not occur in the raised deposit. On this evidence, Barrow suggested the existence of different conditions during the deposition of the present beach and the raised deposit.

Barrow further described the occurrence of shells (Tellina balthica) in sands and gravels near Guisborough 400 to 600 feet above sea level, but did not suggest a raised marine origin.

Some years passed before further reference to displaced shorelines occurred in the literature.

Woolacott (1920) discovered a gravel bed in the cliffs at Easington, 10 miles north of Hartlepool, rich in marine fauna and approximately 80 feet above O.D. Woolacott originally considered a late or post glacial origin but Trechmann (1947) demonstrated that the fauna was from a warm temperate environment and a C14 date of greater than 38000 B.P. by Smith (Geological Survey) confirmed his view that it represented an inter-glacial or inter-stadial high sea level.

Anderson (1939, 1940) described a series of meltwater channels and fluvio glacial deposits graded to a height of 190 feet O.D. and noted bench features at 140' and 100' O.D. in northern Durham and southern Northumberland. He postulated that there was considerable evidence to support late glacial sea levels at these heights but the lack of marine faunal remains would appear to testify against a marine origin (Beaumont, 1967).

Radge (1939), although not greatly concerned with sea level change, noted that the buried Tees Valley was graded to a depth of 160 feet below O.D. supporting a sea level at that depth.

More recently Agar (1954) recognised in the Lower Tees two raised sea levels, one at 41 feet O.D. and the other at 82' O.D. The upper level is distinguished by yellow sands marginal to the laminated clay, on both northern and southern sides of the Tees, and yet overlying it. No organic or shell remains are found nor does the shoreline form a well defined surface feature. The 41-foot level, similar in elevation to that at Saltburn, is recognised on the south side of the Tees in the form of a buried notch in the underlying deposits of the Middle beck bed, infilled with a yellow sand, containing randomly distributed shells (*Mytilis edulis*, *Cardium edule*). Agar considered that it was related to the Scottish 25' beach and noted notches at a similar height (40' to 45') on the sides of the Billingham beck north of the Tees.

Since the publication of this work by Agar the geological survey re-mapped the northern area and Smith and Francis (1967) in the accompanying memoir devote a small section to a discussion of evidence for sea level change.

Most significant is their recognition of ground interpreted as a "Terrace of Marine Warp" (Fig. 12) upon which Hartlepool is situated. The feature is essentially erosional, cut in Magnesian Limestone which is overlain by Upper Boulder Clay with marine deposits occurring only in small patches and consisting of brown to grey clay plus small rounded stones. This so-called marine deposit consisted of reworked material from the underlying drift and graded imperceptibly into it. The terrace consists of a series of ill defined sub-terraces distinguished by slight changes of slope. North of Hartlepool it is between 500 and 600 yards wide but it extends southwards into the Tees where it reaches two miles in width and grades at its seaward end into recent alluvial flats at 12 feet O.D.

Smith and Gaunt (op. cit.) define this terrace as the northward extension of Agar's 82-foot shoreline but note further that Agar's 41-foot shoreline does not exist in the area mapped.

Also identified are the older "marine" planations at 140 and 95 feet O.D. Redistributed drift is recognised on their surface but no marine remnants are in evidence. Similar features are recognised near Hartlepool between 80 feet and 110 feet.

Gaunt (in Smith and Francis, 1967) described a sand and gravel ridge 300 to 400 yards wide trending north-south between Threston and Greatham, curving west-south-west at its southern end (Fig. 1f). The ridge lies at the inland edge of the earlier described terrace of marine warp and is interpreted by Gaunt as a raised storm beach. In detail the ridge is composed primarily of sand and "pea" gravel but contains medium-sized gravel also. Morphologically, it is steeper sloped on the western inland side in the north, becoming symmetrical further south. Bedding is described as dipping eastwards or horizontal with graded bedding at several localities. Very few shell fragments occur and the ridge is observed to drop in altitude in a southerly and south-westerly direction. This latter characteristic leads Gaunt to suggest that the ridge gradually changes from a storm beach in the north to an offshore bar in the south.

Finally, in the memoir Gaunt and Smith precisely locate the submerged peat at Hartlepool as occurring between -35' O.D. and + 12' O.D.

Summary

It would appear from the above account that there is abundant evidence in support of displaced shorelines in the Lower Tees.

Submerged Shorelines

(1) The buried valley of the Tees is graded to minus 160 feet O.D., supporting a shoreline at or below that level in immediate post glacial time.

(2) Terrestrial peat beds dated 8100 to 8700 ± 180 B.P., occurring up to 35 feet below O.D., support a level at least 40 feet below O.D. (Smith and Francis, 1967).

Raised Shorelines

(1) A marine deposit containing contemporary fauna is described at 20' O.D. near Redcar.

(2) A marine deposit containing shells is described at 41' O.D. near Saltburn.

(3) A marine sand with shell fragments is similarly recorded at 41' O.D. in the Middle Beck valley.

(4) A marginal sand deposit is recognised at 82' O.D. (no faunal remains) north and south of the Tees.

(5) A terrace of marine warp backed by a raised storm beach is recognised at 80' near Hartlepool. It is observed to lose height in a southerly and south-westerly direction.

(6) Planation surfaces, considered marine, are recognised at 95', 140', and 190' O.D.

All the above mentioned features are considered to be late or post glacial in age. One example only of a beach of interglacial age is recognised at Easington and is C14 dated as older than 38000 years B.P.

In general terms, both raised and submerged features are recognised in the Lower Tees all of which are considered to post date the last glaciation. Despite the occurrence of the Easington Beach, therefore, it seems likely that investigation will be confined primarily to the post-glacial period. With regard to the conclusions drawn in Chapter 2 it is significant to note that a wide variety of evidence is used to support marine hypotheses.

SECTION 2

MORPHOLOGY

METHODS AND RESULTS

CHAPTER 4

TERRESTRIAL MORPHOLOGY AND THE RECOGNITION OF RAISED SHORELINES

This chapter sets out to examine and test the validity of morphological evidence as a means of identifying raised shorelines. Two general observations were made in the previous section:

(1) That morphological evidence constitutes the initial stage of research and locates features which are worthy of additional study.

(2) That terraces in the Firth of Forth were identified as either marine or fluvio-glacial, on their deviation from the horizontal. Precise levelling proved that fluvio-glacial terraces possessed a steeper gradient.

These two observations explain the division of the chapter into two parts; the first, a preliminary morphological survey, and the second, a more detailed look at previse levelling to ascertain whether it can be applied to the Lower Tees as a means of identifying raised shorelines.

Preliminary Morphological Survey

The object of this preliminary investigation was to determine those areas where more detailed morphological studies might prove the existence of a shoreline terrace remnant. The investigation was approached in three ways:

(1) Morphometric studies

(2) Aerial photography

(3) Field observation

Morphometric Studies and Morphological Considerations

A detailed bench mark cover was essential before levelling could commence. The Ordnance Survey provide bench mark lists at 10/- per kilometre square or the alternative of personal extraction from their offices at £10.10s. per day. In both cases cost was exhorbitant and use was consequently made of 6" and 25" maps. These were checked and added to by extraction from Stockton, Billingham, Middlesbrough, and Hartlepool Borough Engineers' offices. A comprehensive cover was thus amassed although further problems were encountered in the field as a result of bench mark eradication through road widening, decay of objects upon which the bench mark was imprinted and other developments. In cases where several bench marks were missing a circular net of levelled heights was completed from the nearest known bench mark to a suitable point on which to carve a temporary bench mark. These bench marks, together with spot heights, were used to construct a base map of the area with a 10' contour interval on a scale 6" to 1 mile. Thirty profiles at right angles to the contours were constructed (Fig. 13). Fig. 14 shows some of the profiles and clear terrace features are indicated. Field observations, however, demonstrated the inadequacy of form line maps based on the above data as the terrace features were non-existent. It is thus felt that work based on form line analysis, short of photogrammetric standards, would be valueless in the recognition of terrace remnants, or minor erosion surfaces in areas of gentle relief. This conclusion agrees with Clarke and Orrell (1961) who comment on the high level of subjectivity in morphometric analyses.

Aerial Photography

The Lower Tees is covered by several aerial surveys; the most recent and best in quality was completed in 1966 for the Tees-side development board. Using a stereoscopic viewer, some isolated breaks of slope were recognised but frequently the breaks of slope were too gradual to stand out clearly.

Field Observation

The need for permission from the farming populace for access to their land allowed a thorough, field-by-field survey to be completed. Even where the farmer refused to allow access to his land it was possible to recognise breaks of slope whilst in the process of asking.

Thus, it was by this time-consuming and yet invaluable field survey alone that terrace remnants were first noted. Fig. 15 shows the location of these features which were later levelled.

Precise Levelling

The purpose of precise levelling is to determine the exact height of a terrace remnant above O.D. and at the same time to determine the degree of warping if the area has been subject to differential uplift.

Sissons (1962, op. cit.) demonstrated in the Firth of Forth that raised shorelines dipped away from the centre of uplift. This dip was normally between 2 and 3 feet per mile, although Sissons and Smith (1965, op. cit.) did record one feature with a gradient of 6.93' per mile. This relatively gentle dip was contrasted with a gradient of 15 feet to 40 feet per mile for fluvio-glacial terraces.

Differentiation appears relatively simple at first, but to apply the technique to the Lower Tees necessitates allowances for a whole range of variables and differences between the two areas.

As was explained in Chapter 1, the Lower Tees lies closer to the periphery of the area subjected to isostatic uplift and any deformation of shorelines would be minimal when compared with those of the Firth of Forth.

Secondly, the predominantly east-west orientation of terraces in the Lower Tees results in a different alignment to those of the Firth of Forth with respect to the centre of uplift.

Thirdly, the Lower Tees was deglaciated at an earlier date than the Firth of Forth and consequently features are not as fresh.

Fourthly, it seems probable from the evidence in Chapter 3 that the Tees was deglaciated from west to east in a down slope direction. The consequent blockage of natural drainage would almost certainly have led to the formation of proglacial lakes which in turn would leave relict shorelines indistinguishable from marine shorelines on morphological evidence alone.

Also, there is the added problem of confusion between estuarine river terraces and a raised shoreline. The present Lower Tees flood plain dips eastwards during its last 20 miles at an average gradient of 1.25' per mile. The influence of tidal range on a raised shoreline would similarly result in a gentle easterly dip.

Thus, of the two aims of precise levelling, it appears that any dip obtained would be meaningless.

The height above sea level of the terrace remnants shown in Fig. 12 could indicate a common level or alternatively a series of apparently unrelated levels. Even in this field, the value of morphological data may be suspect. Sediment compaction may have resulted in differential subsidence, later erosion may have removed a variable amount of sediment, or alternatively fluvial deposition may have shrouded the original morphology of a terrace.

In two examples, Middle Burn Toft (NZ 457279) and Middleton St. George (NZ 355140), fourteen feet of alluvial deposition and up to 30 feet of channel erosion have respectively influenced and modified the original terrace form.

Thus, although a detailed list of levelled heights is provided in the appendices the only value the survey possesses is to demonstrate the approximate height of terraces and to determine whether there does appear to be a marked level at any height, or in particular at the heights referred to by Agar (1954, op. cit.) as raised marine levels. No genetic classification is possible. The various terraces are plotted on graphs (Figs. 15, 16, 17, 18)19,) and the data, along with the sediments on which the terraces are formed, is summarised in tabular form (Table 83).

Interpretation and Summary

The survey located 43 terrace remnants in the Lower Tees Basin. From Table 83 the only common characteristic appears to be the discontinuity and short length of the terraces. No general terrace levels were noted throughout the Tees Basin, although on the south side of the present river there does appear to be a consistent level between 76' and 84' O.D., the approximate height of Agar's (1954, op. cit.) late glacial marine shoreline, and coincident with the margin of the laminated clay deposit which occupies the lower portion of the research area.

All one can suggest at this stage is that four hypotheses may explain the origin of the terraces.

N.B. All Tables are recorded by Page numbers.

(1) Late and post glacial run-off

(2) Sub-glacial meltwater

(3) Lacustrine shorelines

(4) Marine shorelines

Further explanation depends upon the inclusion of sedimentary and fossil faunal evidence.

It should be mentioned, as a postscript, that a sequence of sub-surface contour maps were constructed using the multitude of borehole records available in the Lower Tees. In all, three weeks were spent collecting and collating this evidence and it was noted that no clearly distinguishable terraces existed beneath the laminated clay. These maps have not been included in the thesis, partly because of the negative results, but more especially because the Geological Survey did not wish to have its work duplicated. The maps will, however, appear in the memoir which is being prepared by the Geological Survey.

TABLE SHOWING MORPHOLOGICAL DATA RESULTING FROM FIELD SURVEYS AND PRECISE LEVELLING

Location	(Feet O.D.) Height	Length	Sediment
Saltburn NZ667215	16'	1,758'	Alluvium (floodplain)
Windy Hill Farm NZ652218	133'	400'	Red Stony Boulder clay
Cliff Top, Saltburn to Marske	131' to 95'	1,950'	Red Stony Boulder clay
Ox Close Farm NZ651211	141' to 170'	3,340'	Red clay, some stones, some evidence of water sorting
Fell Briggs NZ613210	156'	1,300'	Red clay, sand and silt lenses
Turners House NZ601210	84'	10,000'	Patchy occurrence, sand interbedded with clay
Black's Bridge NZ621215	47'	2,630'	Laminated clay with five sand layers
Kirkleatham Farm NZ595207	55'	870'	Laminated clay
Broadway Farm NZ560205	80'	3,100'	Coarse dirty sand
Town Farm NZ582207	93'	2,410'	Reddish-brown washed till
Lackenby Hall NZ565195	76'	1,130'	Red-brown stony clay
Normanby High Farm NZ535195	50'	1,390'	Laminated clay
Spencer Beck Farm NZ540180	100'	1,260'	Sandy deposit, clay rich with depth
Coulby Manor NZ496154	106'	890'	Red stony clay plus sand lenses
Sandy Flat Farm NZ493158	99'	3,800'	Clean yellow sand
Stainsby Hall Farm NZ471152	77'	1,640'	Clean, and medium-grained sand
High Leven NZ450123	122'	2,920'	Silty sand
Barwick Farm NZ432146	76'	120'	Pockets of sand on laminated clay
Leven Mouth Farm NZ435122	118'	4,240'	Unbedded sand
Howe Hill Cottages NZ355110	78'	2,050'	Red stony clay plus some gravel
Hill House NZ354102	122'	2,210'	Sand
Girsby Grange NZ385086	144'	2,910'	Sand interbedded with laminated silty clay
Old School NZ358094	133'	1,060'	Fine silty clay
Low Entercommon NZ335060	174'	1,050'	Sand and silt
Low Hail Farm NZ309097	134'	1,250'	Laminated clay
Garden House NZ303106	119'	950'	Red-brown stony clay
Hurworth Moor NZ315121	131'	820'	Red-brown stony clay
Middleton St. George NZ355140	132'	10,600'	Reworked, washed, red-brown till
Long Newton NZ380162	115'	10,400'	Red-brown stony clay (washed)
Elton NZ401174	106'	3,750'	Red clay, upper layers washed
Coatham Stob NZ405162	94'	640'	Sand
Coatham Stob NZ405162	80'	1,200'	Sand
N. Edge Stockton NZ445225	59'	350'	Sand
Howden Hall NZ415225	132'	1,130'	Resorted till
Warren House Farm NZ437254	111'	2,150'	Red stony clay
Woodside NZ436273	176'	1,750'	Red-brown stony clay
Wolviston NZ454258	109'	10,000'	Washed red stony clay
Marsh House NZ461256	59'	1,385'	Laminated clay
Middle Burn Toft NZ457279	53'	580'	Alluvium
Middle Burn Toft NZ457279	73'	600'	Brown alluvium
Claxton NZ476287	61'	1,200'	Brown alluvium
Cowpen Bewley NZ483247	30'	150'	Laminated clay
Throston Grange NZ492341	60'	3,150'	Washed boulder clay

CHAPTER 5

SUB-AQUEOUS MORPHOLOGY

Purpose of the Study

So many of the problems of British Quaternary history stem from the inability to envisage Britain as anything but an Island. In view of the accepted lowering of sea level during the Würm glaciation (Shepard, 1963) it is almost certain that Britain was then part of the European continent. It is also probable that many of the answers to unsolved problems of east coast glaciation, such as the westward extent of the Scandinavian ice sheet, and the chronology of Würm events, lie buried beneath the waters of the North Sea.

Apart from these general considerations Sissons (1967, personal communication) considers that the tilting of the late and post glacial shorelines recognised on the east coast of Scotland, is sufficient to place them below present ordnance datum well to the north of the Tees Basin. Certainly there is definite evidence of terrestrial deposits and shallow water shell bands at depth off the Tees coastline. If, therefore, the topic of Quaternary sea level change is to be fully understood, the sub-aqueous environment must be explored. This is especially true in the peripheral areas of glaciation, where the eustatic rise of sea level is offset by only a limited amount of crustal rebound. Thus, there is an obvious need for an underwater survey and the choice of area and detailed aims are discussed in the coming section.

Aims of Survey and Choice of Area

The prime aim of the sub-aquatic survey was to determine the degree to which the submerged glacial landscape had been modified by post glacial marine processes and to discover whether offshore terraces exist, which represent sea levels lower than present.

In Chapter 2, reference was made to several articles (Gill, D. G., 1960, Australia; Fairbridge, 1948, 1953; Uchupi, E., 1961, Pacific Coast, U. S. A.; Cuerda, 1960, Spain), acknowledging the existence of terraces below present sea level and which date from the post glacial eustatic rise of sea level.

Unlike the terrestrial survey outlined in the previous chapter, which was largely restricted to the Lower Tees, the sub-aquatic survey was extended north of the Tees Bay into Scotland. The reason for the extension reflected the author's belief that any terraces found may rise northward towards the centre of rebound. A terrace which was only recognised in the Tees Bay could have several origins, but if it were recognised over an extended distance, one could possibly determine the degree of warping. It was also hoped that the shorelines of the Firth of Forth might be traced after they dipped beneath O.D. Newlyn.

For economic reasons the survey was limited to a zone extending three miles offshore and to a depth of 180'. This depth of 180' was chosen for three reasons:

(1) It was the maximum depth to which the author was prepared to dive to check the validity of soundings.

(2) The buried valley of the Tees extends to this depth (Radge, 1939).

(3) It marks the maximum calibration of the most accurate echo-sounding equipment which could be afforded.

The choice of methods, and problems which emerged, are discussed in the light of these controls.

Methods Chosen and Problems Encountered

Several echo-sounding devices were tested and the ferrograph "Inshore Graphic" sounder proved superior in both accuracy and quality of result. The major problems with regard to the survey are discussed below.

(1) Survey errors: (a) Instrumental and Operator
    (b) Surface water conditions
    (c) State of the tide

(2) Navigation errors

Description of the Instrument

The "Inshore Graphic" sounder operates on the principle common to all echo sounders, that the velocity of sound waves in water is sensibly constant. A pulse of sound energy is triggered by a rotating arm, carrying a pen, at the moment it passes the zero position on the recording paper. This sound wave takes approximately 1/40th of a second to make the two-way trip from sounder to sea bed and back in 60 feet of water. (See Fig. 29)

Instrumental Errors

(1) Reference Plane

All readings are related to the position of the transducer below the water surface. This depth, which is a constant, must be allowed for when calculating the absolute depth at any given location.

(2) Variation in Velocity of Sound

The velocity of sound in water is not constant. It can vary as a function of two factors, temperature and salinity. For any fixed velocity, depth will appear greatest in cold fresh water and least in very warm, salty water. The theoretical difference between these two extremes could conceivably exceed 5% but in the Tees estuary and Firth of Forth salinity and temperature differences account for only a 2% error. Even so, a sudden change in salinity as occurs under estuarine conditions could give the impression of a small step in the sea bed. Where visibility permitted scuba divers investigated any recorded changes in sea bed topography.

(3) Speed of Stylus Rotation

This third error is a function of the constancy of speed of the rotating stylus. The most frequent variation resulted from water getting in the drive mechanism causing the drive belt to slip. A second possible variation could be failing battery voltage. To prevent this latter, frequent hydrometer checks were taken to determine the battery charge and a replacement battery used as necessary. The problem of drive belt slippage was also solved quite easily by sealing the face of the sounder with waterproof adhesive tape.

Surface Water Conditions

In excessive swell and heavy seas the oscillations of the ocean surface are transferred to the chart making interpretation difficult. Providing a swell was uniform in terms of wave height and length, charts were easily interpreted. Soundings were not, however, attempted in choppy seas with variable wave height and length.

State of the Tide

To obtain the absolute depth relative to O.D. Newlyn, it was necessary to determine the state of the tide. The elapsed time of the cruise was noted and the state of the tide computed from the nearest tide gauge records.

The following table summarises the effect of the errors discussed:

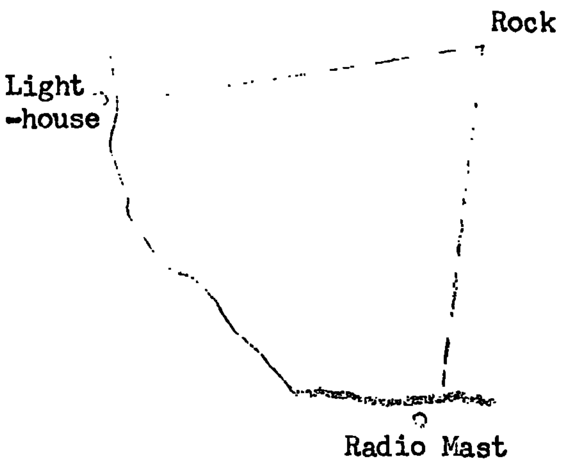
TABLE OF ERRORS

State of the Tide	Surface Conditions	Reference Plain	Sound Velocity	Speed of Stylus Rotation
± 0.5'	± 2'	+ 0.5'	2%	0.05%

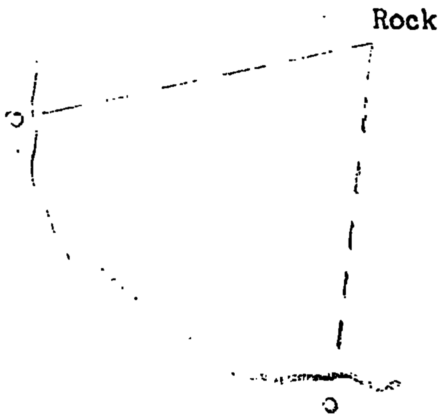
Total error in	20' water	± 3.6'
	60' water	± 4.2'
	100' water	± 5 '
	160' water	± 6.2'

Navigation Errors

To determine the precise location of a traverse and the position of any change in bottom gradient, a sextant was used in preference to a navigation compass because of the much greater accuracy which can be obtained. Horizontal angulation was checked for accuracy against an aerial photograph of known scale, and the maximum error recorded.



A. Charted Position of Rock.



B. Air Photo on Same Scale.

Seventeen tests using the air photo comparison showed positions up to 30' in error at one mile distance from the shore and 120 feet in error at three miles distance from the shore.

Summary

One may conclude that in terms of horizontal and vertical accuracy the aquatic survey cannot compare favourably with terrestrial levelling of visible features. There is, however, no doubt that significant changes in gradient and depth are visible on recordings and it was found that 80% of the recorded changes were valid when checked by divers.

Method of Approach

After determining the feasibility and accuracy of the survey methods, use was made of a Royal Navy inshore rescue craft to complete numerous traverses at right angles to the sea bed contours. In all, 71 days were spent at sea, 45 of which were devoted solely to echo-sounding. A detailed map showing one-foot contour intervals was constructed for the Tees Bay, but elsewhere the time involvement and the detail necessary made this task impossible. Fig. 21 shows the location of all traverses but detailed profiles from each area are only shown if there is evidence of a change in bottom gradient. In all cases use was made of Admiralty and commercial soundings to supplement the coverage. (Fig. 27)

Results

A five-fold division of the area was used, for ease of study:

(1) Tees Bay (Fig. 22)
(2) Tees Bay to Tynemouth (Fig. 23)
(3) Tynemouth to Berwick (Fig. 24)
(4) Berwick and the Firth of Forth (Fig. 25)
(5) Firth of Forth to Stonehaven (Fig. 26)

(1) Tees Bay

The results of detailed soundings in the Tees Bay are portrayed in Fig. 27 using a one-foot contour interval. One can immediately observe that no significant change of gradient exists between O.D. Newlyn and a depth of 108 feet. The existence of both valleys and spurs transverse to the coastline was noted but the cause of these features was not apparent. At a depth of 70 feet several mounds were identified, their position coinciding with the area of "rough around" identified by fishermen and in which were found sharp granite "erratics." Perusal of documentary records, coupled with diver investigation, confirmed that many of these features represented ballast dumps.

Fig. 29, whilst illustrating a typical sounding in the Tees Bay, also indicates a slight lessening of the bottom gradient at -70' O.D. west-north-west of Hartlepool. This feature was recognised to the north of Hartlepool but not to the south which suggests that the depositional environment prevailing in the bay had successfully obliterated any evidence which may have existed. Evidence from the channel of the Tees and from probes by scuba divers indicated at least 8' to 9' and in one instance 37' of recent sandy deposits overlying boulder clay.

In Fig. 28 profiles transverse to the coastline indicate that two changes of gradient exist within the Tees Bay, at -70' and -180' respectively (latter recognised from Admiralty soundings). It is sufficient to note, at this stage, that these features exist. The degree of accuracy of the soundings is inadequate to determine whether the gradient change maintains a constant depth.

(2) Tees Bay to Tynemouth

Many of the detailed soundings in this area were derived from commercial surveys completed by Wimpey and by Land and Marine Contractors Ltd. Some use was also made of detailed Admiralty soundings in the area immediately offshore from Tynemouth. For convenience the results of soundings in this area are examined in three groups:

(i) Sunderland-Seaham

(ii) Souter Point

(iii) Tynemouth

(i) Sunderland-Seaham

Fig. 29 shows a detailed contour map of the sea bed completed by "Wimpey" whilst surveying the sea bed in search of commercially exploitable gravel deposits. Two levels were of interest at -90' and -135' respectively. In both instances divers noted coarse sand on the sea bed.

(ii) Souter Point

Solid rock which crops out at the coast was noted to a depth of -85' by divers. At that depth it was covered with a veneer of medium to fine sand. Soundings showed a gradual drop to -18' where a distinct wave cut platform exists. A second platform was noted at -110' and a third, at -170'. It was possible to determine that the shallowest platform was cut in solid rock, but in the latter two cases sand and silt made up the bottom deposits.

(iii) Tynemouth

Two very detailed surveys completed by Land and Marine Contractors Ltd. were available for examination; one, to the north of the navigable channel, and one, to the south (see Figs. 31, 30). It is perhaps significant to note that the southern area has a more uniform gradient. This in turn is a reflection of excessive sedimentary deposition from the River Tyne. In the northern section the contours of the sea bed are not masked by recent deposition and a change of gradient in the sea bed was noted at -50' O.D. with others at -70' and -80' O.D. Divers noted a wide variety of deposits on the sea bed in this area and it was concluded that the sea bed surface resembled the late glacial landscape more closely than in other areas.

Admiralty Soundings

In the areas between these detailed surveys Admiralty charts recorded the following features of interest:

(i) A change in bottom gradient at -68' to -72' between Hartlepool and Sunderland.

(ii) A similar feature at approximately -70' north of Sunderland.

Admiralty, commercial, and the current soundings suggest that a widely occurring terrace feature exists at a depth of approximately -70'. In the Tees Bay its absence may be explained by the strong depositional environment which could have led to its obliteration.

(3) Tynemouth to Berwick

The evidence compiled for this region comes predominantly from Admiralty sources, supplemented by work completed during the present study and by the Dove Marine Laboratory (Newcastle University). (Fig. 24 depicts the precise location of traverses.)

In addition, two terrace levels were noted from Admiralty soundings at -180' and -276'. The latter marks the existence of a very extensive level. Soundings from the Dove Marine Laboratory (Fig. 32) do not, however, confirm the existence of these two levels east of Blyth.

Detailed inshore sounding of the Farne Islands and Berwick recognised two levels at -58' O.D. and -84' O.D., and it is particularly interesting to note that these two levels can be traced northward to St. Abbs Head where they occur at -44' and -80' O.D.

It would seem likely that these two levels are wave cut platforms. No evidence exists to suggest that they are of pleistocene age, particularly as they are etched into solid rock at St. Abbs, not glacial deposits. Also at St. Abbs two deeper levels were recognised at -126' and -180' O.D.

(4) Berwick and the Firth of Forth

This area was of particular significance in view of the many raised shoreline features along the shores of the Firth. As in the case in the Tees, however, excessive deposition from the estuary has successfully obliterated any evidence of submerged levels in shallow water. Two levels were noted at depth, at -126' and -186' respectively, along the southern shore of the Firth between St. Abbs Head and North Berwick. Again, there was no evidence that they were etched into glacial deposits.

(5) Firth of Forth to Stonehaven

It was originally intended to terminate the offshore survey at the Firth of Forth, but the singular lack of success in finding submerged shallow water terraces led to the completion of a series of traverses in St. Andrews Bay.

In the bay only one level was noted between -42' and -54' O.D. This level was obviously of post pleistocene origin since it was cut in boulder clay and covered with a discontinuous layer of recent sandy deposits. Further north, Admiralty soundings recorded a very distinct terrace at -162' O.D. although in this instance it was not possible to determine the nature of the deposit.

Summary and Interpretation (Fig 33)

In summary, these results have been fairly satisfactory insofar as they did give indications of several submerged terraces. The major ones were found at -20' O.D., -40' O.D., -70', -80', -126' O.D., -180', and -276' O.D., but were too discontinuous to allow east coast correlations.

Some occurred quite widely whilst others were recognised in only one or two traverses. A major problem was the inability to determine the existence of any terrace remnants in the areas of recent deposition. One would expect terraces to be preserved more readily in these depositional environments and both the Tees Bay and the Firth of Forth were in this category. In order to combat this situation attempts were made to obtain seismic soundings in these two areas. The following section outlines the problems encountered in this attempt and discusses the significance of the results.

Seismic Soundings

(1) Method and cost

(2) Existing surveys

(3) J. D. and D. M. Watson

Equipment

The "sparker" system for obtaining underwater geological information is a modified seismic reflection technique. In essence, the main differences between the Ferrograph sounder, used in the previous section, and the "sparker" are increased sensitivity and power (see Fig. 34). It is possible, using this method, to distinguish between sand, gravel, boulder clay, and solid rock. Thus, any terrace cut in glacial clays and later obliterated by recent deposition will show up on the chart recorder.

The complexity of the equipment, its size, and the necessity of a large power generator, make its use impossible in any ship smaller than a 30-foot fishing vessel. The Natural Environment Research Council does possess such a vessel equipped with sparker equipment. The author was unfortunately unable to obtain its use. The reason given (a just one) was that the vessel was designed for deep sea oceanography and was in great demand for such work which was carried out by research teams studying many aspects of the ocean environment. Had the author's own work been part of a team project it would have been possible to make use of the vessel; as it was, the return from a single project did not justify the time or cost involved.

A second possibility, the "Alexander Meek," a converted fishing vessel operated by the Dove Marine Laboratory, was available at a nominal cost of £50 per day. Permission was obtained to use this vessel in conjunction with the Sparker belonging to the Geophysics Department at Durham. Both the vessel and the equipment were in almost constant use and although careful arrangements were made, technical faults prevented their use as the vessel and the equipment were not available simultaneously.

Two sources having proved negative, the major oil companies and consultant engineers were contacted to determine if they would allow the perusal of their records pertaining to the research area. Despite some detailed negotiations with George Wimpey and Co. Ltd., and the Shell Oil Company, neither would agree, for security reasons, to allow examination of their records.

A fourth possibility, that of hiring a commercial company to complete the survey, was investigated but rejected in view of the cost (£200 per day).

Following these failures the author learnt in December 1967 of a proposed sparker survey to be carried out in the Tees Bay, at the request of a committee representing the five Teesside Local Authorities by J. D. and D. M. Watson Ltd., Chartered Civil Engineers. The nature of their work was to present a report regarding the feasibility and economics of a sewage system for Teesmouth and entailed a considerable amount of work on flow measurement, offshore currents, and their effects on effluent distribution.

An aqualung sampling survey of existing sedimentary environments in the Tees Bay had already been completed as part of this thesis, and after discussion with a representative of the company, this data on sub-surface currents and sediment distribution was exchanged for the Sparker records. The following section examines the results of four "Sparker" traverses in the Tees Bay (see Fig. 22). For convenience each traverse is considered separately.

PROFILE 1 Trending East-North-East from the Coast Between Marske and Redcar

Extending approximately three miles out to sea and to a depth of -106' O.D., this southernmost profile is unique amongst the four as the chart shows no evidence of glacial deposits between the bedrock and a thin, discontinuous veneer of recent sand deposits (Fig. 35). The surface of the bedrock is seen to be most irregular and contains no evidence of any marine planation.

PROFILE 2 East-North-East from the Coast Midway Between West Scar Rocks and the South Gare Lighthouse (Fig. 36)

The profile shows two minor terraces at -25' and -35' O.D. cut into the sandy deposits on the sea bed. Whilst these have, in themselves, very little significance, it would appear from the profile that they might be related to a similar pair of terraces in the underlying boulder clay. This relationship is not easy to determine as the features in the sand do not correspond precisely in either location or depth to the underlying boulder clay terraces which occur at -28' and -38' O.D. respectively. (A further terrace is noted at -49' O.D. etched in bedrock.)

The following laboratory experiment was set up to determine whether the two sand terraces might be related to the two features etched in the underlying boulder clay. (Fig. 37)

A clay deposit was moulded into the shape of two terraces, in a glass tank 2'x3'x10", roughly proportional in size and relative location to those cut in the Tees Bay boulder clay. The tank was filled with water to a depth of 8" and at 12-hour intervals a 50-gram sample of deflocculated clay was added to the water and allowed to settle. Care was taken to use alternative red and grey clay samples and it is most interesting to note the result. The gradual sedimentation of the clay resulted in a layer of uniform thickness paralleling the moulded clay surface. The position of the break of slope was displaced towards the deeper water. One may, therefore, suggest that the sand terraces are reflections of the underlying boulder clay topography. No further conclusions can be drawn from this profile other than to note that the terrace notched in the bedrock could be of preglacial origin, whilst those notched in boulder clay must date to late or post glacial time. Genesis can not be determined from morphological evidence alone.

PROFILE 3 East-North-East from a Point One Mile South of the South Gare Lighthouse (Fig. 38)

The most significant occurrence in this profile was the recognition of a large buried valley, presumably that of the Tees, cut into the boulder clay beneath the sand layer. The presence of this valley indicates that sea level must have been lower than at present during the lifespan of the valley. Two valleyside terraces are noted and may indicate other baselevels during the eustatic rise of sea level. The valley is located 1¼ miles offshore in 35' of water, whilst its bed and terraces are recorded at -87' O.D., -66' O.D., and -45' O.D. respectively.

In addition to the valley, the surface of this upper layer of boulder clay also shows evidence of planation when compared with the more irregular surface of the lower boulder clay which is similarly recorded in the profile. Bedrock in this profile is notably deeper than in the previous profiles and shows no evidence of planation.

In summary, the most significant evidence provided by this profile is the confirmation of the existence of a low sea level indicated by the presence of a river valley cut into the boulder clay surface to a depth of -87' O.D. It is probably that this valley extends beyond the point where it crosses the profile but this extent cannot be determined from the above evidence.

PROFILE 4 North-North-East from the North Gare Lighthouse (Fig. 39)

This profile indicated a sandy sea bed with almost perfect grading interrupted only by a small break at -29.5' O.D. It is possible that this break reflects some irregularity in the underlying glacial deposits not portrayed by the record. The most interesting evidence shown by this profile, however, relates to glaciation and the presence of three distinct layers of boulder clay. Even more interesting, each layer exhibits several valley forms some of which show evidence of terracing. It may be possible that each boulder clay layer was separated by a period of sub-aerial weathering and erosion. Beaumont (personal communication) recognised evidence for a marked weathering profile on a boulder clay found approximately 36' beneath sea level, near Seaton Carew (NZ 536272).

Summary of Findings from Seismic Profiling

Although few in number, the following valuable pieces of evidence have emerged from the seismic profiles.

(1) A river valley extending beyond the existing coastline indicative of a lower sea level than present.

(2) Terraces on the side slopes of this and other valley forms, possibly indicating the existence of several base levels during the eustatic rise of sea level.

(3) The recognition of terraces cut in the buried boulder clay surface, possibly indicating a lower sea level at -28' O.D. and -38' O.D.

(4) Confirmation of bore hole records, indicating the presence of several layers of boulder clay beneath the sea bed.

(5) Acceptance of the possibility that irregularities in the sandy sea bed deposits may reflect similar irregularities in the underlying deposits.

General Summary Relating to the Sea Bed Survey

One concludes that both seismic and sea bed profiles are valuable means of locating terrace forms. The accuracy of the sounding equipment does not match the onshore survey and nor does the method of execution (at right angles to the contours) match the efficiency of levelling along the contours parallel to the break of slope. This problem, with the offshore survey, of constantly searching for a sea bed break of slope, invisible from the surface, was to some extent alleviated by the continued use of divers to confirm suspected changes of gradient.

The major interpretational problem is, however, common to both the terrestrial and marine survey. In neither case is it possible to determine the origin of the terrace without supporting evidence. Many hypotheses can be entertained with equal merits and few, if any, can be discounted on morphological grounds alone. One should re-iterate, therefore, the conclusion drawn in Chapter 4, that morphological surveys of this nature cannot be described as morphogenetic. Supporting evidence, in the case of the sea bed survey may take the form of shallow water faunal evidence or "beach sorted" sediments.

A further criticism of both surveys is that no absolute chronological evidence emerges from morphological studies. The most significant conclusion to emanate from this section on terrestrial and aquatic morphological surveys, is to emphasise the importance and relevance to the thesis of the forthcoming sections on sedimentology and fossil, faunal chronology evidence.

CHAPTER 6

DEPOSITIONAL ENVIRONMENTS: PREVIOUS WORK AND METHODS OF RECOGNITION

This chapter examines the different characteristics of a sediment which have been used to determine its depositional environment. Some attempt is made to assess the weaknesses of each characteristic and technique to determine its value to the present study.

Introductory Statement

With notable exceptions, the majority of work on the recognition of a depositional environment has been completed by geologists working outside the British Isles. These workers have assumed that a sorting agent (wind, wave action, running water, gravity settling) is capable of depositing sedimentary particles of different sizes, shapes, and densities, in such a way that the dominance of these respective agents will be reflected in the nature and structure of a deposit. The fact that no universal characteristics have been identified testifies to the complexity of the problem and as an introduction to the topic the work of F. P. Shepard is reviewed.

Shepard (1964) made the only attempt to examine the criteria in modern sediments useful in recognising ancient sedimentary environments. Much depends on the basic assumption that the present is the key to the past and diagenic processes have in many localities successfully prevented environmental recognition. The following table of environmentally significant characteristics summarises Shepard's work:

A. Dune sand may be distinguished from a beach sand by:
    (1) Greater roundness
    (2) Greater number of heavy minerals
    (3) Higher silt content
    (4) Smaller shell content
    (5) Aeolian cross bedding

B. Beach sands are distinguished from shallow water deposits by:
    (1) Lower silt content
    (2) Better sorting
    (3) Greater rounding

C. Lagoon and estuarine deposits are distinguished from shallow shelf deposits by:
    (1) Scarcity or absence of glauconite
    (2) Presence of sandy clays, low in silt

D. Marine delta facies are identified by:
    (1) Abundant laminations

E. Glacial marginal deposits can be differentiated from marine deposits of the same depth range by the presence of numerous scattered stones, mostly angular, and often striated.

F. Deep water sands differ from shallow water sands as they contain:

(1) More numerous alternations between sand and mud

(2) A sharp lower boundary of the sand layers

(3) The graded nature of the sand beds

(4) The differences between shallow and deep water ripple marks

The above classification was adopted for the study of the following characteristics in this thesis:

(1) Particle size and sorting

(2) Particle shape

(3) Particle density

(4) Particle composition

(5) Surface texture of particles

(6) Sedimentary structures

Four vital problems are common to all six topics, and these must be discussed before attempting any work in this field. They are:

(1) Sample collection

(2) Methods of analysis

(3) Presentation of results

(4) Interpretation of results

Only the latter three are discussed in this chapter as the first is sufficiently important to warrant a separate chapter.

Particle Size Analysis

Methods

Methods of analysis in particle size studies vary with the nature of the sample and in particular with the range of grain size it exhibits. The standard method for gravel and sand sized fractions involves dry or wet sieving through a nest of sieves of successively finer mesh. The weight of sample retained on each sieve is weighed and recorded after fifteen minutes on an automatic sieve shaker.

There are several errors involved in this technique, the solution of which provide for improved analysis. The Institute of Chemical Engineers (1947) noted that experimental error is related to three factors:

(1) The accuracy of the sieve mesh
(2) Variations in the shape of grains
(3) Variations in the time the sample is sieved

The accuracy of the sieve mesh can be checked under the microscope against a micrometer but the shape of the grains cannot be accounted for. Of the three, the latter is most easily controlled and several workers have suggested a time period which allows an accurate result.

Another error which has only recently been acknowledged (Folk, 1966) relates to the size range between the sieves; that is, if ten sieves are used, then the size range is divided into ten

GRAIN SIZE SCALES FOR SEDIMENTS

The grade scale most commonly used for sediments is the Wentworth (1922) scale which is a logarithmic scale in that each grade limit is twice as large as the next smaller grade limit. The scale starting at 1mm and changing by a fixed ratio of 2 was introduced by J.A. Udden (1898), who also named the sand grades we use today. However, Udden drew the gravel/sand boundary at 1mm and used differentterms in the gravel and mud divisions. For more detailed work, sieves have been constructed at intervals 2/2 and 4/2. The Ø (phi) scale, devised by Krumbein, is a much more convenient way of presenting data than if the values are expressed in millimeters, and is used almost entirely in recent work.

U.S. Standard Sieve Mesh #		Millimeters	Microns	Phi (Ø)	Wentworth Size Class
		4096		-12	
		1024		-10	Boulder (-8 to -12Ø)
Use		256		- 8	Cobble (-6 to - 8Ø)
wire		64		- 6	
squares		16		- 4	Pebble (-2 to - 6Ø)
5		4		- 2	
6		3.36		- 1.75	
7		2.83		- 1.5	Granule
8		2.38		- 1.25	
10		2.00		- 1.0	
12		1.68		- 0.75	
14		1.41		- 0.5	Very coarse sand
16		1.19		- 0.25	
18		1.00		- 0.0	
20		0.84		0 0.25	
25		0.71		0.5	Coarse sand
30		0.59		0.75	
35	1/2	0.50	500	1.0	
40		0.42	420	1.25	
45		0.35	350	1.5	Medium sand
50		0.30	300	1.75	
60	1/4	0.25	250	2.0	
70		0.210	210	2.25	
80		0.177	177	2.5	Fine sand
100		0.149	149	2.75	
120	1/8	0.125	125	3.0	
140		0.105	105	3.25	
170		0.088	88	3.5	Very fine sand
200		0.074	74	3.75	
230	1/16	0.0625	62.5	4.0	
270		0.053	53	4.25	
325		0.044	44	4.5	Coarse silt
		0.037	37	4.75	
	1/32	0.031	31	5.0	
	1/64	0.0156	15.6	6.0	Medium silt
Analyzed	1/128	0.0078	7.8	7.0	Fine silt
by	1/256	0.0039	3.9	8.0	Very fine silt
		0.0020	2.0	9.0	
Pipette		0.00098	0.98	10.0	
		0.00049	0.49	11.0	Clay
or		0.00024	0.24	12.0	
		0.00012	0.12	13.0	
Hydrometer		0.00006	0.06	14.0	

classes. Any increase in the number of sieves within the extreme range of the sample size will obviously improve the accuracy of the technique. Folk (1966) stated that the gap between sieves should not exceed 0.25ø units[1] if the results are required for genetic predictions, although Moiola and Weiser (1968) were successful with a 0.5ø sieve separation.

Two methods of analysis are available for finer sediments, the Andreasan pipette and hydrometer analysis. The methods are similar insofar as both involve the gradual settling in water of a sample suspension maintained at a constant temperature. In the hydrometer method the density of the suspension is recorded at specific time intervals, whilst in the pipette method a sample of the suspension is siphoned off and the weight of sediment is recorded by evaporating the water. Of the two, the pipette method is subject to fewer experimental errors; ± 1.58% as compared with ± 1.75% for the hydrometer technique (Reineck, 1967).

Although the pipette method was available during the latter months of research the present study used the hydrometer method throughout for comparative consistency.[2]

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[1] A ø (phi) unit is the negative logarithm to the base 2 of the mean diameter, of grain size, in millimeters.

[2] Detailed outlines of the methods of analysis are included in the Appendices.

Presentation of Results

A variety of graphical and statistical techniques have been applied to the results of particle size analyses in order to display the differences between sample populations. Although the most recent trend has been towards the increased use of computers and consequently more complex statistical analyses, there are still different schools of thought concerning the merits of graphical and statistical presentations. This section compares these methods and progresses from the least to the greatest level of sophistication.

Graphical Analysis

Fig. 40 portrays the most common graphical presentation.

(1) The histogram and arithmetic graph.

These two methods were amongst the first to be used (Udden, 1898, 1914) and allow for the easy recognition of:

(i) The modal grain size

(ii) The presence of a bimodal distribution

(iii) Negative or positive skew

(iv) The concentration of grain sizes into a central group (peakedness)

(v) The range of grain sizes present

One must remember that visual appraisal can only be relative and where differences between samples are slight the visual method rapidly becomes ineffective. Doeglas (1946, 1955, 1962), one of the pioneers of recent advances in sedimentology, argues, with some success, that if the difference between two particle size graphs is not readily visible in a graph, then statistics which are based on percentile readings from the graph will be ineffective. Certainly during the current work one could frequently recognise a depositional environment from the shape of the graph.

(2) The Triangular Graph.

In many ways the triangular graph is less sensitive than the simple bar graph. Its prime use is to indicate the ratio of sand, silt, and clay. One can quickly demonstrate this by referring back to page 112 and Folk's (op. cit.) statement that 0.25ϕ should be the maximum gap between sieves. All that is required for the triangular graph are three sieves.

Plumley and Davis (1956) adapted the triangular diagram to estimate the median, mean, standard deviation and skewness of sediments, from a three-component plot of sand, silt, and clay percentages. The method is not suitable for detailed environmental study as it lacks the necessary degree of precision.

(3) The Three- or Four-Cycle Semi-Logarithmic Graph and the Arithmetic Probability Graph.

It is commonly acknowledged that the grain size distribution of a sediment approximates to the log-normal. Udden (1914, op. cit.) was first to recognise this property and made extensive use of this graph. However, the semi-logarithmic graph was largely superceded in the 1930's by the use of the arithmetic probability graph.

Krumbein and Pettijohn (1938, p. 228) outline the value of the probability scale:

(i) The normal distribution plots as a straight line.

(ii) Drawing errors are thus reduced.

(iii) Any deviation from a normal distribution is immediately recognised.

(iv) The end members of the size distribution are exaggerated. As they represent the extreme range of the sorting agent they frequently provide the most sensitive environmental indicators.

(v) The probability scale should not be used for analysing samples which cannot include the end members. For example, boulder clay size analyses cannot be plotted on this paper. A cumulative plot would present a false picture if the coarsest 10% and finest 5% were omitted from the analysis.

The use of the probability scale evolved in conjunction with phi (ϕ) units. The phi unit was in turn developed specifically as a statistical device to permit the direct application of conventional statistics to sedimentary data.[1]

One may conclude this brief synopsis by referring to the close relationships between graphical and statistical studies. In particular, the ϕ probability plot allows one to observe, bimodality, peakedness, and skewness. Folk (1966, op. cit.) further mentions the value of graphical presentations in detecting experimental weighing errors and faulty sieves. Even more important, it is often possible to detect genetic relationships which are not readily observed from statistics.

Statistical Analysis of Grain Size Data

Statistical analyses emerged from the desire to test the significance of differences between sediment size populations. Before discussing the different procedures one should note that statistical tests rely on a representative sample and an accurate method of processing to ensure valid results. The statistical method inherits all sampling and processing errors involved in obtaining the data, as well as its own level of significance (70% to 99% as the case may be).

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[1] $\phi = -\log_2 \xi$ where ξ = diameter of the grain in millimeters.

For convenience the methods, used to date, can be reviewed under three headings:

(1) Intercept statistics

(2) Moment measures

(3) Computer analyses

(1) Intercept Statistics.

The mean, median, mode, and standard deviation were first used by Udden (1898) and were of little or no value for distinguishing between environments of deposition. It was primarily to improve the situation that led Krumbein (1937) to make use of moment measures.

(2) Moment Measures.

These statistics, which relate to the arithmetic mean, standard deviation, skewness, and kurtosis of a frequency curve were later elaborated upon in a series of articles by Inman (1952), Folk and Ward (1957), Friedman (1961, 1967), McCammon (1962), Chappell (1967), and Moiola and Weiser (1968). Some of these articles test the parameters whilst others attempt to improve upon them, and it is the latter which merits discussion in this section.

Inman (1952, op. cit.) used percentiles to compute his results and the main weakness lay in the selection of too few percentile values.

Folk and Ward (1957) improved upon Inman's work by using the following formulae:

Arithmetic Mean $$M_2 = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

Standard Deviation $$\sigma_1 = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

Skewness $$Sk_1 = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} - \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$$

Kurtosis $$K_G = \frac{\phi 95 - \phi 5}{2.44(\phi 75 - \phi 25)}$$

These formulae have been used by many workers with varying degrees of success. The best means of differentiating between environments was achieved when skewness was plotted against kurtosis or mean size against standard deviation. The students "t" test was used as a probability check and values greater than 0.05 were not accepted.

Friedman (1961, 1967) developed the following formulae in preference to the graphical approach:

Mean $$\bar{x}\phi = \frac{1}{100} \sum fm\phi$$

f = frequency of different grain size grades present

$m\phi$ = mid-point of each grain size grade in ϕ values

Standard Deviation $\sigma\phi \quad \frac{\sqrt{\sum f(m\phi - \bar{x}\phi)^2}}{100}$

Skewness $a_3\phi = \frac{1}{100}\,\sigma_\phi^{-3} \sum f(m\phi - \bar{x}\phi)^3$

Kurtosis $a_4\phi = \frac{1}{100}\,\sigma_\phi^{-4} \sum f(m\phi - \bar{x}\phi)^4$

Chappell (1967) noted that a separation between beach and dune sands was 70% successful using Folk and Ward's formulae for skewness and 95% successful using Friedman's. (Fig 41)

McCammon (1962) also noticed limitations in the work of Folk and Ward and suggested the following improvements for the calculation of the mean and standard deviation:

97% efficient $M_2 = \frac{\phi 5 + \phi 25 + \phi 35 + \phi 45 + \phi 55 + \phi 65 + \phi 75 + \phi 85 + \phi 95}{10}$

87% efficient St.Dev. $= \frac{\phi 70 + \phi 80 + \phi 90 + \phi 97 - \phi 3 - \phi 10 - \phi 20 - \phi 30}{9.1}$

McCammon's 97% and 87% efficiency levels may be compared with 88% and 79% levels for Folk and Ward's formulae. It has been argued that the low improvement did not warrant the extra calculation (Folk, 1966) but the present writer would strongly maintain that any improvement is worthwhile, especially when one considers the pre-existing sampling and processing errors which are inherited by the statistical data.

The most recent improvement was introduced by Kane and Hubert (1963) who used a computer to eliminate errors which result from using only some parts of the size frequency curve. The present study makes use of this programme not only because it eliminates this error, but also because it is considerably quicker and allows a much greater number of samples to be analysed.

In summary, one should remember that many statistical tests are used to compare populations (Chi square, Kolmogorov-Smirnov, students' 't' test, and analysis of variance). This section has been concerned only with those statistics which provide the data for the above tests.

(3) Computer Analyses.

In the previous section the computer enabled moment measures to be calculated with greater accuracy and much greater efficiency than other methods. The same is true of more refined and more complex statistical studies.

The following section outlines the major computer techniques which have been adapted to sedimentology, and, in particular, appraises the programmes selected for use in the thesis.

(i) Factor and Vector Analysis.

Factor analysis was used by Spearman (1904), but only began to resemble modern factor analysis in the nineteen-thirties. Thurstone (1947) was responsible for popularising multiple factor analysis, which has since proved suitable for geological data.

The principle concern of factor analysis is to simplify a group of variables to determine the underlying causes or factors responsible for the co-efficients observed in a similarity matrix (Imbrie and Van Andel, 1964). Two types of factor analysis are currently in favour, "R" mode, and "Q" mode:

"R" Mode		"Q" Mode	
(1)	r-matrix	(1)	Cos θ matrix
(2)	Initial factor matrix	(2)	Initial factor matrix
(3)	Rotated factor matrix	(3)	Rotated factor matrix
(4)	Oblique vector resolution	(4)	Oblique vector resolutio

Most published studies involve only steps (1) to (3); once the fourth step is included, the programme ceases to be factor analysis and becomes vector analysis. With specific reference to grain size data, Visher (1965) and Klovan (1966) use "Q" mode factor analysis to determine the primary variables controlling deposition.

Briefly, the rationale behind the technique is as follows. A sample of clastic sediment may be considered as a vector in N dimensional space, where N is the number of size grades into which the sample has been divided. The position of the sample in

N space is determined by the amount of sediment in each of these size fractions (Solohub, 1967).

One measure of similarity between any two samples is the cosine of the angle between the two sample vectors. Imbrie and Purdy (1962) defined this similarity co-efficient and noted that its value ranges from 0.0 indicating complete dissimilarity to 1.0 indicating perfect similarity between samples. "Q" mode factor analysis specifically evaluates relationships between sample vectors based on N variables. Klovan (op. cit.) applied "Q" mode analysis to 69 samples from Barataria Bay (Krumbein and Aberdeen, 1937) and recognised three differing types of energy responsible for their characteristics. These were wind-wave energy, current energy, and gravitational energy. It was felt that the relative importance of these three factors determines the characteristics of a sediment.

Klovan (op. cit.) further ascribed the following advantages to the technique.

(1) It makes use of the entire spectrum of the grain size distribution.

(2) Arbitrary statistical descriptions are not required and hence analytical methods can be more objective.

(3) No "a priori" knowledge is required of the environmental and geographical location of the sample.

One must acknowledge that factor analysis is superior to the descriptive statistical methods already discussed. A possible weakness may be its reliance only on particle size data. The present study will encompass shape, density, composition, and surface texture, as well as size analysis and by incorporating all these variables into the analysis one may achieve a greater degree of environmental separation.

(ii) Discriminant Function Analysis.

Discriminant function analysis is designed to determine a series of lines along which previously established groups of samples can be separated (Sevon, 1966). Each suite of similar samples may be thought of as forming a cluster of sample points in multi-dimensional space (Solohub, 1967). The maximum number of discriminant functions for a particular problem is the lesser of the two numbers G-1 and N (where G is the number of groups and N is the number of variables measured for each sample).

The scores for a sample are the co-ordinates of the sample point along the discriminant functions. After results have been computed "unknown" samples may be assigned to the group to which they show the most similarity. This degree of similarity depends on:

(1) The dispersion of the group in discriminant space

(2) The distance, in discriminant space, between the sample and the group.

The results of factor analysis may be subjected to this analysis to determine the level of separation between factor loadings (Klovan and Billings, 1967). In this way, a more refined solution is obtained, and one to which degrees of probability can be assigned. If Chi square is used a value of 0.00 indicates that an "unknown" sample conforms precisely with a group whilst larger values indicate that the sample is less similar to the group.

(iii) Trend Surface Analysis.

It is perfectly feasible to map values from sediment analyses. The use of trend surface analysis, however, will reduce the level of subjectivity and may improve the level of interpretation.

The statistical base of trend surface analysis is discussed in detail by Whitten (1959, 1961) and Peikert (1963). In essence, it is a form of generalised three-dimensional mapping (two map co-ordinates plus a third dimension which represents the values of the variable) which effectively eliminates local variations or "noise." In this way a trend can be determined which might otherwise have remained unnoticed.

Apart from general trends the recognition of residuals may be highly significant. Andrews (1968) demonstrated the value of residuals when explaining the pattern of glacio-isostatic rebound in Northern Canada. In fact, trend surface analysis may be applied to any mappable data and it is used on a variety of sedimentary results in an effort to discover meaningful trends.

Interpretation

Two schools of thought have emerged in the interpretation of particle size analyses. In the first, source material and natural breakdown supposedly control the size frequency range, and in the second, sorting agents are considered responsible for size characteristics.

Although there is strong evidence in favour of source material controlling the basic character of sediments (Geer and Yancey, 1938; Aleva, 1956; Tanner, 1958) this does not prevent sorting agents from modifying the basic curve and producing environmental characteristics. The influence of source material is, nevertheless, critical to the success of the present study. It is the author's belief that one of the reasons for a lack of success in the search for a universal characteristic of a particular environment has been the failure to realise that source material is not a constant. It is much more likely that environmental differences will emerge when the source of sediment is restricted. This would explain why local studies have achieved a successful environmental classification when studies incorporating a wider sample area have failed (Mason and Folk, 1958; Moiola and Weiser, 1968).

One must, in conclusion, support Sevon (1965) in his belief that no single textural parameter can be successful and state further that it is doubtful if a single sediment characteristic—e.g., particle size—can possibly differentiate between environments formed essentially of similar source material. The same composite methodology which is being applied to displaced shorelines is equally necessary in the study of sediments.

Particle Shape and Roundness

No sedimentary characteristics have been studied as much as particle size analysis but particle shape has warranted considerable attention as an environmental indicator. It is certainly more difficult and tedious to obtain satisfactory particle shape measurements and previous works fall into two groups--objective and subjective. Each approach will be discussed in turn to indicate its relative merits.

Objective

Krumbein (1941) determined the sphericity of particles by using the formula $\sqrt[3]{bc/a^2}$ where "a" is the length of the long axis, and "b" and "c" the length of the intermediate and short axes. The result gives the cube root of the ratio of the stone volume to that of a circumscribed sphere. Zingg (1935) defined shape by setting up four distinct classes. Each class was determined by the ratio of the b/a and c/b stone axes.

TABLE SHOWING ZINGG'S CLASSIFICATION OF PARTICLE SHAPE

I_2	b/a	$>$	2/3	c/b	$<$	disc
II_2	b/a	$>$	2/3	c/b	$>$	sphere
III_2	b/a	$<$	2/3	c/b	$<$	blade
IV_2	b/a	$<$	2/3	c/b	$>$	rod

King and Buckley (1968) note that a graphic representation of sphericity is obtained by plotting b/a on the "y" axis and c/b on the "x" axis. The relative position of any point on the graph determines its Zingg class.

Cailleux (1945) produced a method for determining roundness which provides a better means of recognising environmental differences. Roundness is calculated from the formula 2 R/a x 1000, where R is the minimum radius of curvature in the principle plane and "a" is the long axis. In a sphere 2R is equal to "a" so that the roundness value is 1000. Cailleux further suggested a flatness formula: a + b x 100/2c. The result increases with flatness and may exceed 1000 in rock with a slaty clearage.

Cailleux's formulae were used, in the present study, on particles greater than sand size. This choice was partially influenced by the recent study of arctic pebble assemblages completed by King and Buckley (op. cit.), which uses Cailleux's approach.

<u>Subjective</u>

Subjective techniques for analysing particle roundness arose as a result of the tedious, time consuming nature of precise measurement. Krumbein (1941, op. cit.) developed a rapid technique for the analysis of roundness where particles were compared with a chart showing ten grades of increasing roundness. Rapidity is a major advantage when it allows the measurement of very much larger, more numerous, and hence more representative samples.

Thus, an objective technique is used for shape measurements and a subjective approach is chosen for roundness. The loss of accuracy in the latter choice is compensated for by the larger number of samples. In both instances, highly significant results were obtained by separating the sample into size grades and comparing shape and roundness with size. In the current work the data is presented in tabular form, in preference to a graphical approach, and differences between samples are tested statistically.

Interpretation

Cleavage, matrix structure, joint pattern and composition have always been recognised as the major factors influencing rock breakdown and resultant shape. In this way, shale, grey wacke, schist, and slate may be equated with disc-shaped pebbles, and the more granular species, sandstone, granite, with a shape approximating to an oblate spheroid.

Thus, a similar problem arises to that of particle size—the relative influence of source material and sorting agent. An appraisal of previous work would suggest that roundness studies which reflected the rate of abrasion had greater environmental application than shape. One can also determine that both characteristics are most effective in a limited lithology.

Surface Texture of Particles.

Very little previous work has used surface texture as a guide to provenance although some electron microscope work has been completed (Porter,1962; Bird and Freeman,1962.) In the current work two more primitive methods were tested as it was not possible to use an electron microscope. For practical reasons analysis was restricted to the sand size fraction.

Firstly,the degree of polish emitted by grains under direct light was subjectively evaluated. This proved to be exceedingly inaccurate if all samples were not compared simoultaneously. The following technique is suggested to introduce objectivity.

(1) Mineral grains from each size fraction were placed on black, opaque plastic.

(2) The degree of reflected light was recorded with a Weston Mark IV light meter.

(3) Before each period of work the light meter was calibrated by recording the degree of reflected light from a plain dark surface.

(4) This process was aided by the use of a rheostat controlled lamp.

(5) The light meter was clamped at 45°, two inches above the grains.

The meter recorded light variation at ASA 100 from 1.6 to 25.0 on the light scale with maximum polish giving the highest reading. One precautio taken was to eliminate all minerals but quartz to prevent the percentage of mafic minerals from influencing the result.

All results were presented in tabular form and similarities tested with comparative statistics.

Particle Density

It has been proved in laboratory tests, and later confirmed in the field, that sorting agents are sensitive to grain density differences (Leliansky, 1955; Bagnold, 1954, 1956; King, 1954). This fact has led to speculation that particle density differences should occur in various depositional environments. Studies have been completed which differentiate between environments on this basis, notably by Bradley (1957), White and Williams (1967), and Hand (1967). Several methods are available for the separation of light from heavy minerals and their relative merits are discussed in the following section.

Methods of Separation

(1) Flotation.

Rogers and Powell (1958) explain, in detail, the flotation technique:

(i) A 15-gram sample is crushed with a mortar and pestle.

(ii) Dispersal is achieved by boiling in NaOH for 20 minutes.

(iii) Clay is removed by allowing the sediment to settle in water for 2.5 minutes.

(iv) The sample is dried, then boiled for 20 minutes in a 20 ml. solution of concentrated HCl containing 10 grams of Stannous Chloride to remove calcite and iron oxide. Both of these minerals hinder bromoform separation.

(v) The remaining residue is floated in bromoform to separate the light from the heavy minerals.

This approach is unsatisfactory for three reasons if the aim is to differentiate between environments. Firstly, the destruction of some light minerals prevents later mineralogical studies of the light fraction. Secondly, the time period involved makes quantity sampling impossible and, thirdly, a fifteen-gram sample is too small to be representative of the true population.

A modified approach (Rogers and Adams, 1959) uses a 50-gram sample and involves sieving into size fractions. Each size fraction is separately centrifuged in bromoform for 5 minutes at 2500 rpm. This technique is more rapid and more representative in its sample size. Bradley (1957) emphasised the necessity for a 5-hour flotation period to obtain accurate separation. Although this time is a maximum, it does emphasise the problems of a multi-sample approach.

(2) Electro-Magnetic.

An alternative separation technique for sand size particles is provided by the S. G. Frantz Isodynamic separator. This unit is primarily a large electro magnet.

Minerals which respond to the magnetic attraction are drawn to one side and separation is effected in a matter of seconds. It should be noted that by varying the angle of the side slope one can separate a greater number of minerals. One should also note that not all heavy minerals are magnetic.

The experimental procedure is as follows:

(i) A 100-gram sample is sieved into size fractions.

(ii) The 72, 100, 150, and 200 mesh fractions are washed to remove dust.

(iii) A hand magnet is used to remove magnetite and pyrotite, as both could block the electro-magnet.

(iv) The size fractions are each passed through the magnetic field twice to ensure a perfect separation.

(v) The finer size grades took longer to run but did not exceed 200 seconds. On the other hand, a coarse sample may only take 7 seconds.

(vi) Variations in the % magnetic minerals can be recorded between samples from different environments and also between the different size fractions of a single sample.

The Isodynamic separator is used primarily to separate specific minerals. It has not been adopted for the precise purpose of environmental determinism. The results of the analysis are presented in tabular form and the weight percentages recorded alongside such key low density indicators as shell and coal fragments. In brief, density studies are a form of abbreviated mineralogy and the following section examines the value of a more detailed mineral count.

Interpretation

Allen (1948) observed that it was invalid to compare modern and ancient heavy mineral assemblages as the heavy minerals are more susceptible to weathering than the more common light minerals. This observation was supported by a 500% decrease in heavy minerals towards the surface of a weathered profile in Illinois.

Bradley (1957), who worked on present-day coastal environments, noted that it was possible to distinguish heavy mineral zones on Mustang Island, Texas.

(1)	Barner Island sediments	0.45% heavy minerals
(2)	Gulf sediments	0.04% heavy minerals
(3)	Beach sediments	0.34% heavy minerals

Sub-aerial sediments in the same locality contained 0.36% heavy minerals. Bradley's conclusions are, however, of only local significance as the availability of heavy minerals partially controls the ratio of heavy to light minerals. It is interesting to note that he explains the greater concentration of heavy minerals in sub-aerial deposits as a result of wind action. The percentage of heavy minerals is always greater in wind blown rather than water lain deposits, either as a result of the greater roundness of heavy minerals, or by the selective removal of light minerals.

Carrol (1957) argued against the environmental control of heavy mineral content, as he observed that the heavy mineral content of river sands in different tributaries of the same basin varied as a function of source material.

Poole (1958) compared heavy mineral suites statistically and observed four distinct zonations in San Antonio and Mesquite Bays on the Central Texas coast. Rogers and Adams (1959) further recognised that local environmental conditions could create very marked differences in the heavy mineral content of coastal sand deposits.

In the same year Andel cast further doubts on the environmental significance of heavy mineral counts by suggesting that availability, weathering, abrasion, and post depositional solution outweigh selective sorting in the control of heavy mineral concentration.

Martin and Long (1960) analysed numerous beach and dune sands whilst prospecting for commercially exploitable concentrations of heavy minerals. The results of their work, in South Island, New Zealand, showed no discernable difference between the two environments. De Graafe and Woensdregt (1963), who worked in north-west Spain, similarly noted that the percentage of heavy minerals in beach sands reflected the proximity of igneous rocks. This conclusion casts further doubts on the value of heavy minerals in the recognition of a depositional environment.

Imbre and Van Andel (1964) used vector analysis to demonstrate that heavy mineral distribution in the Gulf of California is explicable in terms of coastal currents and energy zones. Bruckner and Morgan (1964) confirmed this conclusion on the continental shelf off Accra, Ghana.

Hand (1967) demonstrated the value of settling velocity experiments as a means of distinguishing between beach and dune sands. A plot of the delta value[1] indicated that the heavy minerals in dune sands settled faster than those in beach sands. White and Williams (1967) completed similar experiments on fluvial sediments. They quote Ruhkin (1937): "differences in the mean grain size of minerals of different densities in a

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[1] Delta value = log median settling velocity of a mineral minus the log median velocity of associated quartz against the log median quartz velocity.

sample is a more sensitive indicator of environmental processes than the overall distribution." The reader should bear this quotation in mind as it proved very true of sediments in the Tees Basin.

In summary, a similar situation exists, as with other properties, whereby source material and sorting agent are alternately favoured as the controlling agent in heavy mineral concentration. It is perhaps significant to note the recent success of settling velocities as a means of distinguishing between two environments. It is felt that this technique is simply a refinement of heavy mineral content and in the present study heavy mineral separations are completed from the different size fractions to demonstrate and test their value as a means of recognising a depositional environment.

Particle Composition

A detailed mineralogy of a sample may indicate provenance but is more likely to reflect source material. Both microscopic and macroscopic examinations were completed to determine whether sorting agents could produce mineralogical differences, given similar source material. Not all minerals were identified, especially as the deposits were predominantly sand size and contained a high percentage of rock fragments. Thus, the following categories were used:

Sandstone

Limestone

Quartz

Mica

Heavy minerals (as a group)

Coal

Igneous and metamorphic rock fragments

Shell fragments

Beaumont (1967) noticed that the ratio of rock fragments to mineral grains frequently explained the shape of boulder clay particle size curves. This same ratio may prove useful as an environmental indicator. Results are presented in grains per thousand and comparisons made between known environments.

Particle Orientation

Orientation studies may be applied to gravel, sand and clay particles. In the current work only gravel orientation was attempted as it was not necessary to discover the orientation of clay particles and not possible to examine that of unconsolidated sands. Potter and Pettijohn (1963) summarise the technique for gravel orientation.

(1) The long axes of at least 100 pebbles must be analysed.

(2) These may be taken from a horizontal or vertical section.

(3) The results may be presented on polar graph paper.

In previous work the choice of a vertical or horizontal section has not received a great deal of attention. Kirby (1967) chose a horizontal section whilst Beaumont (op. cit.) chose a vertical section. From the present study it was demonstrated that the orientation fabric altered as successive layers were deposited. This was particularly true of fluvio-glacial deposits which were laid down in a braided, deltaic environment. For this reason a horizontal section was preferred.

Sedimentary Structures

Sedimentary structures have been described in the literature at considerable length. Recent works of note include those of Middleton (1965), Bagnold (1954), and McKee (1966), Van Straaten (1954, 1964), Krumbein (1956), and Potter and Pettijohn (1963). These workers deal respectively with fluvial, aeolian, deltaic, tidal mud flats, and beach environments.

Included under the general heading of structures are: ripples, cross-bedding, laminations, and folds; and two approaches to their identification may be recognised. In the first, different structures are noted in recent sediments of known origin. In the second, this classificatory approach is foresaken in favour of a genetic one, which attempts to understand the dynamics of structure formation. Middleton (1965, op. cit.) summarised progress in these two fields as: "encouraging, but of continual disappointment to geologists who seek clear cut answers to the problems of environmental interpretation." The absence of flumes and back up facilities resulted in the first method being used. Emphasis was placed on structural assemblages as the possible key to environmental interpretation, rather than individual structures.

Other Approaches

Other methods for recognising a depositional environment have been attempted with varying success. Pratt (1962, unpublished Ph.D. thesis, University of Southern California) studied the origin and distribution of glauconite and confirmed the belief that this mineral is formed only under marine conditions and is very unstable once exposed to the air. If one was to analyse the clay mineral content of a sediment and discover non-detrital glauconite, a marine origin may be assumed.

Link (1967) recognised three depositional environments --deltaic, mid-bay, and bay marginal--in northern Port Phillip Bay, Victoria, Australia. The environments were recognised by depth, sediment structures, carbonate and organic content, light and heavy mineral content, geochemistry, and faunal content. For example, the deltaic environment was characterised by 4% sand, 55% silt, 41% clay, thin laminations, abundance of plant fragments, and very low carbonate content.

By comparison the mid-bay environment contained a much higher carbonate and organic content and the bay marginal a much higher sand content. The essential value of the Link approach is not its obvious success, but rather its composite nature. One must draw on a wide variety of characteristics to support any proposed environmental zonation. This work by Link (ibid.) serves to emphasise not only the value of a composite approach but also to stress the need for a similar approach in the present study.

Summary

It is universally true that no technique for the recognition of depositional environments has yet proved sufficiently sensitive to succeed in this task. This lack of success has arisen despite a sound understanding of hydrodynamic principles and may be explained either by a lack of understanding of the sorting agents, or by attempts to find a universally acceptable approach rather than one which is regionally acceptable.

One may suggest that four critical factors control the success of environmental determination. First and foremost one must recognise that the nature and availability of source material is of far greater significance than any amount of sorting. Secondly, the sample is the key to further analysis. Thirdly, the processing methods must be as sensitive as possible, and, fourthly, that only the most refined statistical and computer analyses should be used on the processed data.

Of these four, processing and analysis have already been discussed in detail, and sampling theory is discussed in the next chapter.

This leaves source material as the possible key to an understanding of environmental sorting.

The Lower Tees Basin provides an excellent study area as source material is sensibly restricted to material available within the watershed and in the immediate offshore environment. Comparative surveys have been completed in areas of diverse source material, to prove the need for a control on source material. Thus, this survey of previous work has provided the present study with the following aims. These in turn provide a key to future chapters.

(1) The restriction of environmental comparisons to a zone of common source material

(2) The need for representative samples

(3) The need for accurate processing techniques

(4) The need for highly sophisticated analytical techniques

CHAPTER 7

A DISCUSSION OF SAMPLING PROCEDURES AND THEIR INTERPRETATION

Introduction

An examination of previous work in environmental sedimentology demonstrates a lack of concern for representative sampling. It goes without saying that, in any subject, analyses and resulting interpretations depend upon the original sample for their validity. Even the most sensitive and sophisticated processing methods, or statistical techniques, will inherit the shortcomings of an inadequate sample. Thus, this present study examines the following aspects of sampling theory in an attempt to obtain more meaningful results in the field of environmental sedimentology.

A. Previous work

B. (i) The number of samples required to obtain meaningful results
   (ii) The positioning of these samples
   (iii) The size of the individual sample
   (iv) The nature or shape of the individual sample; e.g., channel, or sedimentation unit
   (v) When the sample should be collected

C. The choice of sampling plans

D. The particular problems of sampling offshore

E. The interpretation of results

Previous Work

This discussion is limited to works pertaining to sediment sampling and concentrates on beach sampling because of its greater relevance to the present study.

As early as 1937 Thompson demonstrated that the grain size distribution of a sample of beach sand which contained a mixture of several laminae was distinctly different from the grain size distribution when the laminae were sampled individually. Both Otto (1938) and Apfel (1938) supported stratified sampling of layered deposits; Apfel used the term "phase," Otto, the term "sedimentation unit." Emery and Stevenson (1950) similarly provided evidence which supported Thompson's conclusions that individual laminae give results which may be much coarser or finer than the median diameter for the entire sand sample, or a spot sample from the same location. Krumbein (1953, 1956) produced a series of works devoted to the problems of sampling a geological population and the influence of these works may be judged from the following discussion.

Krumbein (1953) argued successfully that the sampling of beach sand involved far more than the merits of a scoop sample versus a sedimentation unit sample. It was demonstrated that the size, depth of penetration, spacing, and time of year, would all critically affect the eventual result. Work completed on the beaches of Lake Michigan suggested that a beach may be divided into zones, which parallel the shoreline, with each zone displaying certain population characteristics. The results of this work are tabulated below:

(1) Choice of sampling plan

Zone boundaries may be located by sample traverses at right angles to the beach. Once delineated, a stratified random design ensures equal coverage of the zones. Alternatively a regimented grid network may be used. An entirely random approach could result in a failure to sample all zones.

(2) Sample spacing

This should be controlled in part by the size of the beach in question, and in part by the purpose of the survey. For example, a study of mean particle size would involve samples from a wide area, whilst a study of inter-zonal differences would demand a more rigid control.

(3) Size of sample

Once the sample location was chosen Krumbein (Ibid.) proved that it was more efficient to collect four small samples from each point rather than one larger sample.

(4) Depth of sample

Sample penetration is also controlled by the purpose of the study. For example, an analysis of seasonal energy variations would demand a series of single lamina samples from each location. A study of present conditions would involve a surface skim sample, and a study of mean particle size would require a sample of as many layers as possible.

In brief, Krumbein's (Ibid.) work brings to light some of the problems of sampling geological data and certainly makes the complexity of the situation more apparent.

Krumbein and Slack (1956) published a detailed study of sampling efficiency on beaches. Their work was organised with one or more of three objectives in mind:

(a) To estimate the mean particle size of the beach

(b) To estimate the variability of deposits with locality and season

(c) To estimate systematic changes from one locality to another

The second objective may be equated with the purpose of this present study and the eight suggested sampling approaches are assessed with this purpose in mind.

(1) Simple random sampling

(2) Stratified random sampling

(3) Cluster sampling

(4) Multi level "nested" sampling

(5) Systematic sampling

(6) Random in cells

(7) Purposive selection

(8) Mixed designs

Before comparing these plans one should remember that in most instances one has to make a practical compromise between costs, time, and the desired degree of reliability.

Of the eight approaches it was observed that stratified random sampling was 80% more efficient than either random or purposive selection with cluster sampling least efficient at 53% below purposive selection. It was further observed that sampling for variability estimates is commonly a function of sample spacing. The results suggest that cluster or multi level samples are most effective on this task, providing at least ten different clusters or sampling units are involved. (See Figs. 44, 42, 43)

One may summarise that this work proved extremely valuable when setting up a sampling design for the present study, although some minor modifications were made after initial testing.

Although Krumbein (1953, op. cit.) was clearly aware of the various sampling problems, he tended to concentrate on the location of samples, rather than the character of the individual sample. It is interesting to note that his individual samples weighed approximately 500 grams, whilst those taken by McIntyre (1959) weighed only 15 grams. This vast difference in sample size has led to much speculation and caused Griffiths (1967) to observe that "no satisfactory definition of the size and shape of the primary sampling unit has yet been offerred." Most recently, Gees (1969) attempted to overcome the practical problems of obtaining a large sample from a single sand lamina. A special frame and pan was designed to facilitate the collection of a 1,000-gram sample. One must conclude that a larger sample will represent a population more effectively than a lesser one (Cochran, Mosteller, Tukey, 1954). The following list incorporates some of the problems which prevent the acquisition of a reliable sample.

(1) A stratified random sampling plan which uses cluster samples at each point should provide the most efficient measure of "within" environment variability.

(2) There is no satisfactory size for an individual sample although a larger sample must naturally be more representative than a lesser one, provided it is from the same population.

(3) The total number of samples is controlled by cost, time, and the size of the study area. Again, no definite ruling has been formulated regarding the minimum number required for the results to be statistically significant.

(4) The nature of the sample varies according to its purpose. The most frequently used types include the channel sample, which incorporates several laminae to obtain an overall picture of the sediment character, and the sedimentation unit which is restricted to single laminae to record "inter-laminar" variability.

(5) In an active environment seasonal differences in current energies can influence the nature of a sample. Samples should be taken, therefore, from laminae or units laid down under similar conditions. If this is not done then comparisons may be invalid.

Although these conclusions do provide some guidelines, it is interesting to note how the various workers, who studied environmental sedimentology, chose their samples.

Sevon (1965, op. cit.) selected beach samples "from somewhere near the mid-tide mark, dune sands from near the crests of dunes, and river sands from convenient localities within the boundaries of the environment." This approach, to perhaps the most important aspect of environmental study, is unlikely to produce significant results, especially in view of the conclusions drawn by Krumbein (1953, op. cit.), Harris (1959, op. cit.), and Middleton (1965, op. cit.) on the environmental zonations which occur under beach, dune, and fluvial conditions respectively.

Chappell (1967, op. cit.), in his study of New Zealand deposits, does not refer to the sample locations, but does acknowledge that each sample was split into four to reduce standard experimental error. Similarly, Moiola and Weiser (1968, op. cit.) refrain from describing their choice of sampling plan or nature of the sample. Klovan and Solohub (1970, op. cit.), who are, at present, best versed in the analysis of particle size data, also fail to recognise the importance of the original sample.

The number of samples chosen also varies. Sevon (1965, op. cit.) took 174 from three environments, beach, dune, and river, whilst Moiola and Weiser (op. cit.) took 120, and Krumbein (op. cit.) took 125. It would appear that the number of samples has been given very little attention. One is faced, therefore, with a situation of almost unparalleled seriousness. The key works on environmental differentiation frequently fail to consider the most important aspect of their study, the original sample. It is no wonder that results to date have proved inconclusive.

Other specific cases include Hails (1967) whose 1,500 samples came largely from borehole samples (a borehole sample cuts across several laminae and is unlikely to produce results which represent the depositional environment as the population may be polygenetic); and Solohub (1967) who completed what is probably the most comprehensive survey of analytical techniques applicable to the study of depositional environments. In the latter example very few sampling controls were used. The samples were collected purposively rather than randomly, and little or no attention was given to the nature or size of the individual sample. Thus, many problems remain unsolved and before the present study was begun a series of tests were run to determine the most suitable sampling approach.

Sampling Approaches Adapted for the Present Study

The purposes of the present study include:

(1) The analysis of present day sedimentary environments to determine their characteristics.

(2) To identify late pleistocene and early holocene environments on the premise that the present is the key to the past.

In the following discussion it is demonstrated that no simple formula could be used to sample all deposits.

Present Day Beach

A test area, 300' x the distance from High Water Mark to Low Water Mark, was randomly chosen in the Tees Bay, and analysed to discover which sampling approach gave the best indication of environmental characteristics. It was unnecessary to repeat Krumbein and Slack's (1956, op. cit.) detailed study of sampling plans and thus a stratified random plan was used, with surface skim samples. The latter were taken to ensure a result in close harmony with present conditions. The major problem, therefore, centred on the number and size of the individual samples (see Fig. 45). Sampling theory demonstrates conclusively that a greater number of large samples is considerably more efficient than fewer, small, samples (Cochran, Mosteller, Tukey, 1954, op. cit.). The following samples were taken primarily to determine what effect different numbers would have on the results and demonstrates that larger number of samples did not necessarily provide the most accurate assessment of the population extremes.

Initially, fifteen samples were taken, each weighing approximately 500 grams. These samples were riffled down to 100 grams before sieving as the excessive amounts of fine sand in a large sample frequently blocked the finer mesh sieves. For comparison, cluster samples were taken from each sampling point, with each sample again riffled down to 100 grams before sieving.

TABLE SHOWING RESULTS OF SAMPLING TESTS ON REDCAR BEACH

	ø mean			ø st. dev.			ø skew			ø kurtosis		
	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.
15 samples	2.38	2.29	2.20	0.63	0.49	0.36	-0.51	-0.38	-0.25	3.04	2.42	1.80
30 cluster samples	2.49	2.36	2.23	0.59	0.45	0.32	-0.47	-0.33	-0.19	3.02	2.29	1.57
60 cluster	2.47	2.35	2.23	0.61	0.47	0.33	-0.49	-0.33	-0.18	3.04	2.37	1.71
120 cluster	2.53	2.37	2.21	0.62	0.47	0.32	-0.57	-0.39	-0.21	3.03	2.29	1.56

Although a larger number of samples will give a closer approximation to the mean (Krumbein, 1953), the above table suggests that when variation from the mean value is required the 30 samples are almost as effective as the 120 sample plan. This result may reflect the restricted sample area but does at least indicate that

30 samples would appear to be representative of the population.

Similarly, Table 151 suggests that 100-gram samples are as effective as 500-gram samples and it would appear to be unnecessary to take a sample larger than 100 grams for the present study.

TABLE TEST OF VARYING SAMPLE SIZE

Sample Size	ø mean		ø st. dev.		ø skew		ø kurtosis	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
12x 50 grams	2.51	2.30	0.72	0.41	-0.49	-0.21	3.04	2.01
12x100 grams	2.48	2.25	0.63	0.34	-0.52	-0.24	3.01	1.5
12x500 grams	2.49	2.26	0.64	0.32	-0.51	-0.20	3.01	1.56

One should note that the original 500-gram sample was riffled to 5x100 grams to prevent the finer sieves from becoming choked. In consequence, each 500-gram sample was composed of five separate sieve analyses.

Present Day Dune Belt

The windward and leeward sides of the dune belt were treated as separate environments, as a result of studies by Udden (1898, op. cit.), Harris (1959, op. cit.), and McKee (1966, op. cit.) Only the windward side of the coastal dune belt could be analysed as the leeward side was either modified by man or obscured as a result of debris deposits. Tables 150 and 152 show that a large number of samples again gives best results and one must conclude that the minimum number of samples chosen should be decided by the variability of the deposit. Once the variability between samples becomes sensibly constant one has reached the optimum number. Table 153 demonstrates that the size of a dune sample between the extremes of 50 and 500 grams does not greatly influence the results. This was only the case when surface skim samples were taken in preference to spot samples, and most probably reflects the more consistent nature of wind energy. It was further noted that the deposit was sufficiently consistent to enable 12 samples to give as adequate results as 120.

TABLE RECORDING THE RESULTS OF SAMPLING TESTS ON DUNE SAND (CRIMDON)

	ø mean			ø st. dev.			ø skew			ø kurtosis		
	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.
12 samples	2.19	2.05	1.89	0.36	0.33	0.315	0.23	+0.09	-0.04	0.98	0.95	0.84
30 cluster samples	2.21	2.09	1.91	0.34	0.33	0.31	0.24	+0.09	+0.01	0.99	0.96	0.85
60 cluster samples	2.18	2.03	1.80	0.34	0.33	0.31	0.28	+0.12	+0.03	0.98	0.95	0.85
120 cluster samples	2.22	2.04	1.82	0.33	0.31	0.27	0.21	+0.08	-0.02	0.99	0.95	0.83

TABLE RECORDING THE INFLUENCE OF VARYING SAMPLE SIZE ON THE ANALYSIS OF DUNE SANDS

	ø mean		ø st. dev.		ø skew		ø kurtosis	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
12x 50 grams	2.18	1.80	0.34	0.31	+0.10	+0.01	0.99	0.87
12x100 grams	2.20	1.87	0.33	0.31	+0.08	-0.02	0.985	0.85
12x500 grams	2.22	1.81	0.34	0.31	+0.09	0.00	0.99	0.85

From Table 153, one may observe that the dune sand proved more consistent in its grain size distribution although the beach sands gave higher kurtosis values.

Samples of wind-blown sand were collected from the surface of the beach to confirm that differential sorting took place. The sampling device consisted of a 10" high by 2" wide frame covered in polythene on all sides, leaving a 2"x10" aperture at the front. This streamlined form minimised wind eddy and was used to collect suspended material. A jar 2" in diameter was sunk into the surface of the beach and used to collect material which was rolled or jumped along the surface. These two fractions were combined, analysed for particle size, and then compared with surface skim samples, which were taken varying distances in front of the sampler.

CRIMDON DUNE AND BEACH

Wind Blown Sample (One Sample)				Beach Skim (Mean of 3 Samples)			
ø mean	ø st.dev.	ø skew	ø kurtosis	ø mean	ø st.dev.	ø skew	ø kurtosis
2.14	0.34	0.02	0.92	1.61	0.39	0.13	1.56

These results prove not only that wind does selectively sort the beach sand, but also that wind-sorted deposits possess a finer mean, less skew and a lower kurtosis value. In summary, it would appear that wind-blown deposits are sufficiently consistent that twelve samples gave representative results.

Present Day River

This third of the major onshore environments created more problems as samples should be taken across the width of the channel, to be fully effective. In shallow water it was fairly easy to obtain surface skim samples from the river bed. In deeper water, particularly where the current was fast flowing, it was necessary to resort to underwater diving, from a boat, and using the anchor rope to maintain position whilst the sample was taken. Some extremely interesting results were obtained and these are recorded in table 155, Perhaps most significant is the observed effect of changing current flow.

In flood conditions, the grain size frequency was coarser but maintained a similar sorting pattern about the mean as did the finer deposit associated with normal flow. In several instances in the Tees and in the tributaries, samples exhibited identical sorting but a very variable mean size depending on current exposure rather than source material (see Chapter 8).

TABLE SHOWING RESULTS OF RIVER SAMPLING[1]

	ø mean			ø st. dev.			ø skew			ø kurtosis		
	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.
40 samples	2.12	1.32	0.85	1.45	1.2	0.73	-0.17	-0.11	-0.33	1.53	1.3	1.15

These results support Krumbein's (1953, op. cit.) contention that it is critical to sample the extreme range of environmental conditions. River samples contained a wider range of grain sizes than either beach or dune environments. This fact is most probably explained by the much greater range of current flow in the river channel. In summary, a stratified random sampling plan proved most successful provided that at each point samples were taken across the full width of the channel (see Fig. 63). (Chapter 8)

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[1] Only one set of samples was taken because of the sampling difficulties.

Lacustrine Shore and Nearshore

The possible presence of a late glacial lake in the Tees Basin makes it imperative that a present-day water body should be examined to determine the environmental characteristics of lake shore and nearshore deposits. A major problem arose in this instance as there is no large fresh water body in the Tees Basin. It was not feasible to analyse samples from outside the Tees as there is no guarantee that source material is similar. Work by Krumbein and Slack (1956, op. cit.) suggested that marine and fresh water beach and nearshore deposits possessed essentially similar sorting characteristics with the exception of the surf zone on the oceanic coast line.

TABLE SHOWING RESULTS OF LACUSTRINE-MARINE COMPARISON

	ø mean			ø st. dev.			ø skew			ø kurtosis		
	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.
12 marine shore samples	1.87	1.63	1.48	0.66	0.53	0.49	-0.14	-0.05	+0.03	1.24	1.11	1.01
12 marine nearshore samples	1.87	1.54	1.23	0.67	0.51	0.43	-0.49	-0.2	+0.06	1.67	1.32	1.11
12 lacustrine shore samples	2.34	2.2	1.91	0.73	0.51	0.29	-0.04	0.02	+0.07	1.24	1.13	1.07
12 lacustrine nearshore samples	2.30	2.25	1.98	1.03	0.62	0.32	-0.09	0.01	+0.1	1.22	1.12	1.06

In an attempt to test this conclusion and to overcome the problem in the Tees the sea coast and a loch shore sand were compared on the north-west coast of Scotland. This region was selected as the present author was familiar with the local source material and hard rock geology. Table 156 shows the results of the analyses and it would appear that Krumlein and Slack (Ibid., op. cit.) are correct. The lake deposits show greater consistency. This one would expect as the sorting is controlled by wave action and would not possess the fetch of the Atlantic winds. Perhaps more significant is the positive skew of the fresh water deposits as compared with the negative skew of the marine deposits. This difference is discussed in the section on interpretation, which follows the discussion of offshore sampling.

Offshore Deposits

The collection of offshore samples with similar precision to those onshore caused some concern. A variety of samplers were tested but none procured an acceptable sample. The various grabs collected spot samples, which were less likely to portray environmental characteristics than a surface skim sample. The dredges bounced along the bottom if insufficiently weighted and could not be lifted if excessively weighted. Core samplers disturb an unconsolidated sand and in the Tees Bay failed to obtain a single sample. The results of these tests are recorded in Table 158. The considerable degree of variation, and obvious sifting of fines from both dredge and grab samples led to the author learning, first, to swim, and secondly, to use an aqualung. The only problem experienced using this technique was the author's genuine fear of water. In all, over thirteen weeks of training ensued before any samples were collected.

TABLE SHOWING THE RESULTS OF ANALYSES ON OFFSHORE SAMPLES

Grab, Dredge, and Core Samples

		o mean			o st. dev.			o skew			o kurtosis		
		Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.
5 samples	GRAB	3.52	2.81	1.0	1.93	1.29	0.91	-0.47	-0.23	-0.09	2.97	1.91	1.32
5 samples	DREDGE	3.41	2.73	1.12	1.84	1.12	0.87	-0.51	-0.26	-0.11	2.89	1.87	1.08
-	CORE	-	-	-	-	-	-	-	-	-	-	-	-
140 samples	SCUBA	3.2	2.08	1.06	1.55	0.65	0.30	-0.48	-0.16	-0.18	2.7	1.33	0.68

This time loss was compensated for by eliminating test samples and using a stratified random plan with 20 to 30 cluster samples from each point.

Table 158 shows the results of the aqualung samples. Despite the greater number of samples involved the mechanical samples gave a much coarser mean size which was only explained when S.C.U.B.A. divers observed the sifting which takes place whilst the sample is being hauled to the surface. The faults of the grabs and dredges were particularly obvious when watched by S.C.U.B.A. divers. One should, in fact, be extremely careful when interpreting samples obtained by such means and the results obtained in this present study must place in question the works of Udden (1914, op. cit.) and Robinson (1968). Both workers used mechanical samples for environmental studies.

Summary and Interpretation of Results

The efficiency of moment measures as a means of separating depositional environments may be assessed from the following table which shows the percentage overlap of values.

TABLE SHOWING PERCENTAGE OVERLAP OF STATISTICAL VALUES

	ø mean	ø st. dev.	ø skew	ø kurtosis
Beach over dune	5	44	0	0
Dune over beach	6	13	0	0
Beach over river	0	0	0	0
River over beach	0	0	0	0
Beach over offshore	15	25	46	56
Offshore over beach	100	100	77	78
River over dune	98	0	100	0
Dune over river	24	0	46	0
River over offshore	50	58	53	19
Offshore over river	84	100	70	100
Dune over offshore	19	5	33	79
Offshore over dune	100	66	68	100

A low value indicates greater success as a means of differentiating between two environments. It would appear that all values may be successful in some instances. This would seem to confirm that a uniform source material is needed before separation becomes successful. However, in Chapter 8 the full survoy of the Tees present day environments does not achieve the high levol of separation obtained in this sample survey. One must assume, therefore, that only in a very restricted area can moment measures successfully differentiate between environments.

At this stage, one is able to consider the significance of these results in terms of the individual particle size curve. Figs. 46 and 47 portray the mean and extreme curves for each environment and one may observe that each has a distinctive shape. In Chapter 6 it was suggested that moment measures are an inefficient means of analysing the characteristics of these shapes and it would appear that very little work has been completed on the explanation of a curve.

Beaumont (1967, op. cit.) did notice a consistent break in the particle size distribution of a boulder clay. This break was equated with the transition from rock fragments to single mineral grains. If one considers Ruhkin's statement (1937) that sorting agents respond to density differences more than size this can have a major effect upon the resultant particle size curve. For example, it is generally considered that beach sands are negatively skewed. The current survey suggests that offshore sands are also negatively skewed. In each case this negative skew is not so much reflection of wave action, it is rather a measure of the availability of shell and organic fragments. In a similar way samples in any environment, which contain a high coal content, possess a negative skew.

This means that a river sand with a high coal content may well display a particle size distribution similar to either a beach or offshore or even a dune sand which has an equally high shell content. This statement agrees with the contention proposed in Chapter 6, that it is the relative influence of source material and sorting which control a particle size curve. Thus, it would appear essential that one should remove heavy minerals, coal, shell fragments, or any mineral of extreme density in order to truly determine whether different depositional agents produce characteristically sorted sands.

If the above hypothesis is correct then the differentiation between environments could be greatly simplified in a region of similar source material. Certainly there is tentative evidence available to suggest that particle size analysis may be a measure of composition.

In brief, the conclusions drawn in this chapter are as follows:

(1) A stratified random sampling plan will provide the best measure of "within environment" variation.

(2) A cluster of 100-gram samples is a more efficient means of eliminating sample errors than a single 500-gram sample.

(3) Samples taken for environmental identification should be restricted to single laminae as they would otherwise be composed of a polygenetic population which may reflect different current energies.

(4) The number of samples needed to obtain a representative sample of a population depends on the area and variability of the deposit.

(5) It would appear that source material may control the particle size characteristics of a deposit.

(6) Environmental comparisons may only be valid when source material is uniform throughout the sample region.

(7) It is inadvisable to compare samples deposited at different times of the year as current energies vary seasonally (see Fig. 4^8).

(8) All minerals and particles of different densities may have to be eliminated from a particle size analysis, if a true reading of sorting energy is required.

(9) The time factor seems more likely to limit the number of samples from present day environments than any other single factor. The results in this chapter involved 27 days of laboratory work.

CHAPTER 8

THE APPLICATION OF SEDIMENTOLOGICAL TECHNIQUES TO DEPOSITIONAL ENVIRONMENTS OF KNOWN ORIGIN

Introduction

The section on sedimentology has involved some apparent deviation from the central theme of sea level change. However, if one hopes to recognise a displaced marine environment by its sedimentary characteristics it is essential to determine, precisely, what these characteristics are. Equally important, one must determine that the sedimentary character of other environments is recognisably different from a marine littoral deposit. This chapter, then, is critical to the thesis aim: if one cannot recognise different present day environments there is little hope of doing so for late pleistocene environments which will have undergone some post depositional alteration.

The chapter is organized into five sections, each dealing with one of the major present day environments:

(1) Littoral
(2) Aeolian
(3) Offshore, Nearshore
(4) Fluvial
(5) Lacustrine

In turn, each environment is examined from seven different aspects:

(1) Particle size

(2) % Heavy minerals

(3) Shell content (grains/1000)

(4) Coal content (grains/1000)

(5) % Rock fragments

(6) Mica content (grains/1000)

(7) Surface texture (light readings)

Littoral Marine Sediments in the Tees Basin

The beaches of the Tees Bay are composed primarily of sand and cover an area from Hartlepool in the north to Saltburn in the south. Random number tables were used to select six sample areas (Fig. 49), and the samples from each area are discussed in turn.

(1) Crimdon Beach (3 miles north of Hartlepool) NZ 495365

Twelve major sampling points were selected on a stratified random basis within a zone bounded by High Water Mark, Low Water Mark, and 300 feet in length. At each of these points twelve cluster samples were taken over an area 10 feet in radius. These cluster samples were used only as a check. All were skim samples to ensure close harmony with present conditions and in total 156 samples were analysed. The results are based on the twelve major sampling points but each of the twelve samples was in fact a composite analysis of thirteen samples. (Fig.50)

Particle Size.

Textural parameters indicate that the dominant zoning of the beach parallels the shore (Fig. 51).[1] This agrees with previous work by Krumbein (1953) and King (1965, op. cit.).

Heavy Minerals.

The heavy mineral content appeared to increase inversely with grain size. This trend may possibly be interpreted as the effect of wave action carrying away all but the denser fines.

Shell Content.

The effect of shell fragments on the distribution of the mean is apparent from Fig. 51, where a belt of coarser material is associated with a zone immediately seaward of High Water Mark.

Rock and Coal Fragments.

Neither showed a trend which could be explained on environmental principles.

Surface Texture.

Quartz particles displayed a fair degree of uniformity using the technique described in Chapter 6. The high degree

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[1] Fig. 51 and similar diagrams for other sites are essentially schematic.

of polish may be equated with the constant swash and backwash of wave action (see Table 173).*

Particle Shape.

Only mica and shell fragments possessed a distinctive "platy" shape. In both cases transportation is easier.

Mica Content.

The mica content was minimal and no significant conclusions could be drawn with reference to its distribution.

(2) Saltburn Beach (Fig. 52)

Particle Size.

The zoning of textural parameters demonstrated the influence of the Skelton beck. This was especially true of skewness, and to a lesser extent, of kurtosis, where the zones turned inland up the left bank of the beck.

Heavy Minerals.

The distribution of heavy minerals contrasts directly with the above values. It varies inversely with size, shell, and rock fragment content.

Rock Fragments and Shell Content.

Rock fragment and shell content were similarly influenced by beach contours. Both were concentrated in the coarser sediment immediately seaward of High Water Mark.

Coal Content.

The source area for coal in the Tees Bay is the coastal

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* Tables are listed by page numbers.

colliery waste tips at Easington and Horden to the North. Although some coal moves south with the longshore current, very little reaches Saltburn.

Surface Texture.

The light sensitive technique, which was described in Chapter 6 produced results consistent with those on Crimdon Beach (Table 173).

Mica Content.

Mica also occurred infrequently and it was not possible to discern any significant trends.

(3) Hartlepool Yacht Club Beach (Fig. 53)

This small bay is sheltered by rocky promontaries to both the north and south and may well prove significantly different from the more exposed beaches in the Tees Bay.

Textural Parameters.

Skewness provides the most interesting pattern of the textural parameters, with maximum negative skew coinciding with a zone just below High Water Mark.

Heavy Minerals.

The concentration of heavy minerals close to low tide compared favourably with results from the previous two sites.

Shell Content.

The shell content, similarly, was highest in the zone immediately below High Water Mark.

Rock Fragments and Coal Content.

No meaningful trend resulted from a plot of rock fragments but coal content showed a concentration in the same region as negative skew.

Surface Texture.

A similar light reading to Saltburn and Crimdon seems to support a fairly constant polish on beach sands (Table 173).

(4) Marske Beach (Fig. 54)

Marske lies between Redcar and Saltburn and possesses one of the more exposed beaches south of the estuary. The beach is backed by a low break of slope composed of boulder clay. This deposit has been eroded in places and may, therefore, have contributed to the beach sediment.

Textural Parameters.

The ϕ mean, standard deviation, skewness, and kurtosis all show zoning parallel with the shore. This trend is especially noticeable with skewness which varies from -0.39ϕ near H.W.M. to +0.05ϕ close to L.W.M.

Shell Content and Heavy Minerals.

Values for shell content and skewness again appear to be related with the highest shell content corresponding with negative skew. Heavy minerals demonstrate an opposite trend, and increase seawards.

Rock Fragments, Coal and Mica.

All three proved insignificant as a means of environmental recognition (Tables 181 and 183).

Surface Texture.

The polish exhibited by quartz grains was again comparable with other beach sites (Table 173).

(5) Redcar Beach (Fig. 55)

The northern sector of this beach was created artificially in the late 19th and early 20th centuries, by the construction of the South Gare Breakwater. Prior to that date the Tees estuary extended to Redcar. The present beach is well exposed in all but its southern extremity which is protected by a rocky outcrop which may be a wave cut platform.

Textural Parameters.

All four parameters show parallel zonations more clearly than the other sites. This zonation is particularly noticeable with skewness which varies from -0.45ϕ to -0.2ϕ. This trend may be correlated with an abnormally high shell content (for the Tees)—200 to 400/1000 particles.

Coal Content and Heavy Minerals.

Coal content parallels the distribution of shell fragments whilst heavy minerals again provide the opposite trend, with maximum concentrations in the finer sediments closer to Low Water Mark.

Rock Fragments and Mica.

These particles constitute so small a fraction that, like mica, they produce no significant trend.

Surface Texture.

The polish of quartz grains is so consistent that one can suggest that surface texture may provide a key to environmental character. Tables 173 and 174 demonstrate that all five sites examined so far show little variation.

(6) <u>Seaton Carew Beach</u> (Fig. 56)

The effect of increasing pollution may be observed on the beaches north of the present estuary. Seaton Carew is one such area and the shell content of the beach sediment is only 40% that of the previous site.

Textural Parameters.

Parallel zonation is poorly defined on this beach. Only kurtosis shows a gradation from higher values at H.W.M. to lower values at L.W.M.

Rock Fragments, Heavy Minerals, Coal, and Mica.

Of the above, heavy minerals and rock fragments fail to exhibit any marked trend parallel to high and low water marks. Coal values, although low, do appear to be similar to the distribution of shell fragments.

Shell Fragments.

In contrast to the above properties, shell content clearly emphasises the parallel zonations observed in previous sites. A marked concentration (150/1000) towards H.W.M. is reduced to (90/1000) at L.W.M.

Surface Texture.

Again a high degree of polish gave similar light readings to the other beach sites.

The Significance and Interpretation of Beach Analyses

The value of the previously described analyses may be assessed from the following tables. Their full impetus will not emerge, however, until the results can be compared with those from other environments.

SUMMARY TABLE OF BEACH SEDIMENT ANALYSES

	% Rock Fragments			Coal (Grains/1000)			% Heavy Minerals			Shell (Grains/1000)			Mica (Grains/1000)			(Light Readings) Surface Texture		
	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.
Crimdon	35.0	12.0	1.0	110.0	24.1	2.0	33.2	11.0	0.0	140.0	58.55	19.0	3.0	2.0	0.0	19.0	18.5	16.0
Seaton Carew	32.0	15.0	2.0	41.0	13.25	0.0	37.3	9.08	0.5	193.0	87.2	23.0	1.0	1.0	0.0	20.0	19.0	16.0
Hartlepool Yacht Club	35.0	20.0	6.0	110.0	39.7	7.0	7.8	3.4	0.9	610.0	118.7	2.0	8.0	4.0	0.0	18.0	16.0	14.0
Redcar	20.0	10.0	0.0	19.0	5.3	0.0	28.6	9.0	0.1	712.0	201.9	45.0	10.0	7.0	0.0	20.0	18.0	16.0
Marske	56.0	28.0	3.0	10.0	1.4	0.0	22.10	8.3	1.2	572.0	177.5	54.0	1.0	1.0	0.0	20.0	18.0	16.0
Saltburn	47.0	24.0	0.0	21.0	8.7	0.0	31.2	11.8	1.8	400.0	141.9	68.0	1.0	1.0	0.0	21.0	19.0	16.0
Grand Values	56.0	18.0	0.0	110.0	15.4	0.0	37.3	8.8	0.0	712.0	130.8	2.0	10.0	3.0	0.0	19.0	17.8	14.0

SUMMARY TABLE OF TEXTURAL PARAMETERS FROM BEACH ANALYSES

	ϕ Mean			ϕ st.dev.			ϕ Skew			ϕ Kurtosis		
	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.
Crimdon	1.69	1.63	1.57	0.43	0.40	0.36	-0.23	-0.11	-0.06	2.17	1.71	1.38
Seaton Carew	2.65	2.57	2.48	0.3	0.29	0.26	-0.16	-0.01	-0.09	1.43	1.20	1.09
Hartlepool Yacht Club	2.31	2.23	2.16	0.49	0.44	0.4	-0.24	-0.18	-0.11	1.07	0.98	0.90
Redcar	2.53	2.41	2.21	0.63	0.45	0.32	-0.57	-0.35	-0.14	3.04	2.06	1.57
Marske	2.28	2.04	1.87	0.69	0.52	0.34	-0.39	-0.25	-0.05	1.23	1.01	0.71
Saltburn	2.16	2.06	1.98	0.49	0.44	0.38	-0.49	-0.18	0.0	1.26	0.93	0.76
Grand Values	2.65	2.16	1.57	0.69	0.42	0.26	-0.57	-0.14	-0.23	3.04	1.31	0.71

Textural Parameters.

Textural parameters denote a fair degree of uniformity with the grand mean in excess of 2ϕ, a relatively consistent standard deviation and a dominantly negative skew. Kurtosis was least consistent, and varied from 3.04ϕ to 0.71ϕ. The mean particle size curves were plotted for each environment and show an excellent degree of uniformity in all cases but Seaton Carew. At this latter site the particle size range compared more favourably with the windblown sands described in Chapter 7. The reason for this was not immediately apparent.

Heavy Minerals.

Some success was achieved with areal plots of heavy mineral content. If one considers basic hydrodynamic principles it is probable that heavy minerals will tend to dominate in those size fractions close to the threshold value of a given current energy. This will be true of the fines, where the energy available may be only sufficient to remove the lighter density minerals on all but very rare occasions. Consequently, separations were completed in the finer sand range from 2.3ϕ to 3.8ϕ and Table 342 records the results.[1]

One should note that most beach sands are truncated at 3.4ϕ. In only seven samples was there a residue on the 3.41 to 3.8ϕ sieve.

		% Heavy Minerals	(3.41 to 3.8ϕ)
(i)	Seaton Carew	37 %	21.2%
(ii)	Redcar	23.9%	28.6%
(iii)	Saltburn	27.5%	31.2%
(iv)	Marske	22.1%	

Even so, the 1.66 to 2.3ϕ, 2.31 to 2.75ϕ, and 2.76 to 3.4ϕ fractions provide sufficient evidence to confirm that the percentage of heavy minerals does increase inversely with size.

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[1] Detailed results in the appendices.

SUMMARY TABLE OF PERCENTAGE HEAVY MINERAL CONCENTRATIONS IN BEACH SANDS

	Crimdon				Hartlepool				Seaton			
	1.66 to 2.3ϕ	2.31 to 2.75ϕ	2.76 to 3.4ϕ	3.41 to 3.8ϕ	1.66 to 2.3ϕ	2.31 to 2.75ϕ	2.76 to 3.4ϕ	3.41 to 3.8ϕ	1.66 to 2.3ϕ	2.31 to 2.75ϕ	2.76 to 3.4ϕ	3.41 to 3.8ϕ
	2.1	4.9	28.9	-	2.1	2.4	5.2	-	0.9	1.4	4.8	37.3
	2.1	5.7	22.9	-	2.1	2.6	4.5	-	0.9	1.2	7.3	-
	4.2	3.7	15.7	-	2.4	2.9	6.1	-	0.8	1.1	4.6	-
	2.2	5.1	-	-	2.2	2.7	4.9	-	1.2	1.3	4.5	-
	1.8	9.6	-	-	3.1	4.1	8.7	-	0.7	1.1	4.5	-
	2.5	4.2	0.0	-	1.8	2.1	2.7	-	0.5	1.85	7.8	-
	4.3	4.0	22.3	-	0.9	1.8	4.1	-	1.8	2.1	1.9	21.2
	3.5	4.4	18.1	-	2.8	3.2	4.8	-	0.15	0.7	3.6	-
	3.8	7.7	29.3	-	3.2	3.0	4.8	-	0.9	0.5	3.8	-
	2.2	5.5	27.8	-	1.4	1.9	3.3	-	1.2	1.8	4.7	-
	4.1	9.3	33.2	-	2.9	4.2	7.8	-	1.7	2.3	4.1	-
	3.3	4.5	19.5	-	1.8	3.5	5.2	-	0.8	0.9	3.9	-
Mean	3.0	5.7	24.3	-	2.2	2.9	5.2	-	0.96	1.35	4.8	29.2

	Redcar				Marske				Saltburn			
	1.66 to 2.3ϕ	2.31 to 2.75ϕ	2.76 to 3.4ϕ	3.41 to 3.8ϕ	1.66 to 2.3ϕ	2.31 to 2.75ϕ	2.76 to 3.4ϕ	3.41 to 3.8ϕ	1.66 to 2.3ϕ	2.31 to 2.75ϕ	2.76 to 3.4ϕ	3.41 to 3.8ϕ
	1.5	0.8	2.5	-	1.7	1.3	8.2	-	1.8	2.3	9.6	27.5
	1.2	0.8	3.0	-	2.0	1.5	3.8	-	2.4	2.2	17.4	-
	1.2	0.9	10.8	-	2.3	1.6	8.4	-	2.0	1.9	21.7	-
	1.3	4.9	4.4	-	1.6	7.9	5.7	-	2.0	1.2	8.3	-
	0.9	4.5	12.3	23.9	1.6	1.7	11.4	-	2.6	5.1	18.5	-
	1.4	2.4	0.1	-	1.5	1.8	3.4	-	2.2	1.6	11.5	-
	1.3	0.9	4.8	-	2.1	1.5	9.3	22.1	2.3	1.8	4.9	-
	1.6	2.7	5.3	-	1.8	1.4	3.1	-	2.1	5.2	11.2	-
	1.1	0.8	10.1	-	1.7	8.2	9.6	-	2.5	4.7	16.1	31.2
	0.8	4.3	12.9	28.6	2.2	1.7	5.4	-	2.4	1.9	10.8	-
	1.0	4.1	8.3	-	1.9	1.2	3.5	-	1.9	2.3	9.4	-
	1.2	1.2	0.9	-	2.0	2.3	7.8	-	2.0	4.1	14.2	-
Mean	1.2	2.3	6.3	26.2	1.9	2.7	6.6	22.1	2.2	2.9	12.8	29.3

\- = no size fraction
0.0 = no heavy minerals

Conversely, therefore, one can envisage the availability of heavy minerals effectively modifying the "fine tail" of a frequency distribution.[1]

Shell Content.

Shell fragments behave in a similar fashion to coal when subjected to a current energy. Their lighter density and "platy" shape both lend themselves to easy transportation. It was observed that shell fragments tend to dominate the coarser grades (Table 178) although they cover a wide range of sizes. In the previous chapter on sampling it was noted that negative skewness may be related to shell content. Although this was not universally valid, it did occur in samples from N. W. Scotland (Table 221). Both marine and lacustrine samples were taken and the former were characterised by a negative skew and high shell content. The removal of shell fragments from the analyses resulted in a particle size curve very similar to the lacustrine environment and with a much reduced skewness value.

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[1] This possibility was explored in an area of N.W. Scotland where much of the country rock is metamorphic and granitic. The excess of heavy minerals produced an abnormally well developed fine tail and in fact made up 95% of the 4.1φ fraction.

SUMMARY TABLE RECORDING THE SHELL CONTENT OF BEACH SANDS (GRAINS/1000)

CRIMDON				HARTLEPOOL				SEATON			
1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ
30	20	19	-	20	19	3	-	138	140	120	60
25	21	19	-	68	60	68	-	121	102	96	-
40	41	40	-	610	441	101	-	182	93	51	-
105	51	45	-	103	87	57	-	193	101	62	-
110	101	109	-	180	140	79	-	151	121	94	-
140	138	-	-	71	63	21	-	112	92	48	-
111	40	-	-	85	27	5	-	62	43	23	12
51	32	21	-	21	16	4	-	103	84	37	-
79	53	33	-	108	81	43	-	137	109	81	-
121	111	103	-	19	19	2	-	151	132	103	-
33	20	31	-	556	323	112	-	142	111	80	-
56	36	28	-	382	217	62	-	148	111	77	-
75.1	55.75	44.8	-	185.25	124.4	46.45	-	136.7	103.25	72.7	36.0

SUMMARY TABLE RECORDING THE SHELL CONTENT OF BEACH SANDS (GRAINS/1000)

REDCAR				MARSKE				SALTBURN			
1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ
211	121	133	-	101	240	131	-	103	79	68	-
286	372	236	-	321	209	184	-	182	170	400	-
541	273	235	-	303	130	114	-	158	190	160	79
413	158	123	98	133	114	284	-	210	94	280	-
145	80	165	-	219	210	285	-	91	101	104	-
138	120	190	-	572	245	271	-	192	212	303	-
712	312	162	-	411	301	284	78	241	101	296	-
254	130	154	-	121	54	113	-	78	54	200	-
378	416	228	-	323	195	121	-	116	171	132	84
501	201	213	114	181	121	155	-	132	84	172	-
231	183	127	-	245	147	166	-	95	69	131	-
109	45	63	-	237	138	203	-	184	174	308	-
326.6	205.9	169.1	106.0	263.9	175.3	192.65	78.0	148.5	124.9	212.8	81.5

Coal Content

The coal content of beach laminae varies considerably. One may suggest that this is a function of availability. The majority of coal on the Durham beaches is derived from coastal waste tips at Easington and Horden, some miles north of the Tees Bay. Table (181) indicates the general decrease in coal content in a southerly direction. One should also note that coal has a lower specific gravity than quartz and as a result can be transported by a current which is unable to carry quartz grains of a similar size. In this manner it is possible to envisage coal grains being instrumental in controlling the excentricities of a frequency distribution of particle size.

The summary table (181) indicates that the distribution of coal is not controlled by particle size. The most likely explanation for this difference between coal and heavy mineral distribution is that heavy minerals may be genetically smaller than coal, which can occur throughout the whole size range. In some atypical laminae the coal content exceeded 90% in the -1.1ϕ and $-o.4\phi$ size fractions. One must conclude that coal content can modify the particle size curve considerably, if sufficient is available.

Percentage Rock Fragments

Figs. (50 to 56) demonstrate that little can be learnt from an areal plot of rock fragment content. If, however, one

SUMMARY TABLE SHOWING THE COAL CONTENT OF BEACH SANDS (GRAINS/1000)

NORTH	CRIMDON				HARTLEPOOL				SEATON			SOUTH
	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ	1.66ϕ to 2.3ϕ	2.31ϕ= to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ
	7	10	11	-	40	9	7	-	1	1	2	34
	4	6	25	-	54	24	20	-	0	3	18	-
	10	53	79	-	110	26	39	-	4	2	15	-
	4	9	110	-	71	91	42	-	0	7	9	-
	2	4	-	-	58	21	17	-	6	1	14	-
	29	10	-	-	65	37	36	-	9	4	7	-
	9	5	31	-	21	42	48	-	0	2	7	41
	8	11	22	-	16	12	23	-	0	1	15	-
	3	4	37	-	70	15	9	-	10	11	2	-
	7	61	18	-	109	23	7	-	3	4	1	-
	5	7	82	-	84	18	42	-	5	6	3	-
	21	19	50	-	62	26	37	-	1	0	2	-
MEAN	9.1	16.6	46.5	-	63.3	28.7	27.2	-	3.25	3.5	8.75	37.5

SUMMARY TABLE SHOWING THE COAL CONTENT OF BEACH SANDS (GRAINS/1000)

NORTH	REDCAR				MARSKE				SALTBURN			SOUTH
	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ
	19	11	10	-	1	1	10	-	10	10	10	9
	10	8	2	-	0.0	1	1	-	1	9	20	-
	11	6	2	-	0.0	1	4	-	5	4	2	-
	7	5	1	-	0.0	1	3	-	12	15	17	-
	10	8	2	2	0.0	1	2	-	3	9	21	-
	14	11	3	-	1	2	1	-	19	7	18	-
	19	14	3	-	1	2	0	0	1	11	17	-
	12	3	0	-	2	1	1	-	7	14	7	-
	0	1	0	-	1	1	5	-	8	13	3	2
	16	14	4	1	3	2	8	-	15	19	8	-
	1	0	0	-	0.0	0.0	4	-	4	3	14	-
	2	1	2	-	0.0	0.0	7	-	5	8	1	-
MEAN	10.1	6.8	2.75	1.5	0.75	1.0	3.8	0	7.5	10.2	11.5	5.5

ROCK FRAGMENT CONTENT OF BEACH SEDIMENTS (GRAINS/1000)

Crimdon				Hartlepool				Seaton			
1.66 to 2.3φ	2.31 to 2.75φ	2.76 to 3.4φ	3.41 to 3.8φ	1.66 to 2.3φ	2.31 to 2.75φ	2.76 to 3.4φ	3.41 to 3.8φ	1.66 to 2.3φ	2.31 to 2.75φ	2.76 to 3.4φ	3.41 to 3.8φ
2	1	1	-	15	10	0.0	-	15	2	2	0.0
5	2	2	-	22	12	3	-	11	4	3	0.0
3	1	1	-	6	35	0.0	-	10	15	20	-
7	3	2	-	12	10	3	-	32	21	10	2
5	2	1	-	18	12	4	-	30	25	14	0.0
1	35	2	-	9	7	0.0	-	9	17	21	-
35	24	29	-	7	7	0.0	-	21	14	2	-
19	11	2	-	14	9	2	-	18	9	4	-
21	10	3	-	20	13	1	-	29	27	3	0.0
11	7	2	-	16	14	3	-	32	14	2	1
15	10	3	-	7	6	0.0	-	17	3	7	0.0
7	2	1	-	17	6	0.0	-	20	15	4	0.0

Redcar				Marske				Saltburn			
1.66 to 2.3φ	2.31 to 2.75φ	2.76 to 3.4φ	3.41 to 3.8φ	1.66 to 2.3φ	2.31 to 2.75φ	2.76 to 3.4φ	3.41 to 3.8φ	1.66 to 2.3φ	2.31 to 2.75φ	2.76 to 3.4φ	3.41 to 3.8φ
38	20	4	3	41	5	4	-	28	19	11	0.0
17	8	5	-	47	29	21	-	32	31	20	-
16	7	0.0	-	25	4	3	-	32	31	28	-
10	4	0.0	-	56	5	3	-	18	19	2	-
20	8	0.0	-	32	21	13	-	20	11	0.0	-
31	12	2	-	47	20	4	-	10	9	1	-
25	9	0.0	-	41	17	5	-	11	2	0.0	-
32	8	3	-	29	3	3	-	30	19	9	-
17	16	1	-	33	14	4	-	47	7	1	-
19	12	0.0	-	37	11	6	-	29	13	10	-
21	3	0.0	-	28	4	3	-	32	17	4	-
14	7	2	-	39	12	7	-	14	9	3	-

examines the size fractions separately, the rock fragment content is greatest in the range -1.1ø to + 1.5ø (Table 183). At approximately 1.5ø there is a break in most particle size curves (fig. 57) and this may be equated with the change over from rock fragments to a dominantly mineral grain composition.

A more careful investigation revealed that rock fragments decrease in number, throughout the whole size frequency distribution, from coarse to fine. It is the sudden increase in mineral grains at 1.5ø which creates the characteristic break.

Surface Texture

The surface texture of quartz particles in beach sediments may be subjectively described as "highly polished". A quantitive, objective reading of reflected light gave a reading of 18 on a scale from 1.6 to 25 at A.S.A. 100. It is not yet known whether this characteristic will prove useful as a means of distinguishing between environments. The consistency of values, at least, does not eliminate the technique.

Mica Content (grains /1000)

Very little mica was present in the samples and it could have no effect on the frequency curve. (Table 173) One can only assume that its main value will be a negative one; i.e. its complete absence from wind blown deposits. (Shepard 1964 op.cit.)

Summary

In brief, the main value of this exploratory survey has been to define the variability of beach sand in the Tees Basin, and to discover some of the factors which control its character. The problem which must be solved in this chapter is, the influence of source material composition over sorting agent.

If the latter dominates then it may well be possible to identify all beach sands from the evidence amassed in this present study. If, as is more likely, the former dominates then the present study will have only local significance. In the following sections other sand environments are briefly examined to determine their salient characteristics.

Aeolian Sands: Their significance and interpretation

The dune belt is not continuous along the present coastline and thus only two sites are examined. The distinction between windward and leeward sides was not made, as the leeward side had, in both cases, been artificially modified by man. The first site lies between Hartlepool and Crimdon, to the north of the Tees estuary, whilst the second site is located on an artificially created peninsula. In this latter example the whole dune belt must have developed during the 20th century. The northern dune belt has also formed quite recently, again, as a result of reclamation in the estuary. In fact, a previous dune belt lies inland of the sample site. (fig. 58)

Particle Size (Textural Parameters)

Figs. 60 and 59 demonstrate that parameters are zoned

SUMMARY TABLES OF DUNE SEDIMENT ANALYSES

SITE	% Rock			% Heavy Minerals			Coal			Shell			Mica			Surface Texture		
	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.
Hartlepool-Crimdon	38	19	0	36.29	6.7	0.93	31.0	8.05	0.0	114.0	65.3	3	0	0	0	14	12	10
South Gare	32	17	2	4.78	1.8	0.0	5.0	0.72	0.0	156.0	111.9	51.0	0	0	0	14	11	9
Grand Values	38	18	0	36.29	4.25	0.0	31.0	4.4	0.0	156	88.6	3.0	0	0	0	14	11.5	9

TEXTURAL PARAMETERS

SITE	ϕ Mean			ϕ St. Dev.			ϕ Skew			ϕ Kurtosis		
	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.
Hartlepool-Crimdon	2.2	2.0	1.8	0.35	0.3	0.25	+0.35	+0.15	-0.04	0.99	0.91	0.84
South Gare	2.3	2.25	2.18	0.35	0.32	0.28	-0.14	-0.21	-0.28	1.09	0.99	0.9
Grand Values	2.33	2.06	1.8	0.35	0.31	0.25	+0.35	+0.03	-0.28	1.09	0.96	0.84

parallel to the dune crest. The mean noticeably increases in size towards the dune crest. Possibly this may reflect the increased exposure of the upper portion. The ϕ standard deviation increases towards the foot and crest of the dune from a midway point. The ϕ skewness is greatest at this same midway point, whilst the ϕ kurtosis is most strongly developed at the crest and foot. The summary tables provide a key to their interpretation and allow a comparison with the adjoining beach sediments. (186, 187)

Beach and dune sands appear to have a similar mean size. The standard deviation is greater for beach sands (o.42 ϕ as compared with 0.31 for dune sands). The negative skew of beach sands may differentiate between the two environments. The kurtosis value of dune sand similarly appears to be consistently lower than corresponding beach samples. In general the figures for dune sand indicate a less variable sorting agent with the positive skew, possibly indicative of the reduced shell and coal content.

(fig. 61)

Percentage Heavy Minerals (189)

The heavy mineral content increased in the finer size fractions. Presumably this distribution may have been caused by the removal of similar sized, lighter density material, leaving the "heavy" residual. The percentage values of 15% at Hartlepool and 3.8% at South Gare were much less than the 95% figure in Sutherland. This would suggest that the availability of heavy minerals was a

TABLE RECORDING PERCENTAGE

HEAVY MINERALS IN DUNE SANDS

	Hartlepool-Crimdon				South Gare			
Size Range	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø
	1.5	3.0	13.9	-	0.8	0.7	3.7	-
	1.02	5.6	34.3	-	1.4	1.2	4.6	-
	1.3	4.4	2.8	-	0.8	0.6	3.05	-
	1.1	2.2	9.5	-	1.7	1.13	4.71	-
	1.21	2.3	10.3	-	1.12	1.00	3.12	-
	1.48	2.1	17.12	-	0.0	0.32	1.98	-
	1.43	4.8	2.95	-	0.78	1.2	3.83	-
	1.71	2.71	8.6	-	0.91	0.6	3.09	-
	1.29	6.32	36.29	-	1.52	1.33	4.78	-
	0.93	5.1	27.47	-	1.2	1.41	4.12	-
	1.31	3.2	14.9	-	0.34	0.4	2.1	-
	0.98	4.02	3.4	-	1.18	0.7	2.84	-
Mean	1.27	3.81	15.13	-	0.98	0.88	3.5	-

critical factor and further augments the view that a common source material is essential if one hopes to differentiate between environments.

Shell Content (grains /1000) (191)

The shell content varied between 6% and 12% although there was a progressive change with size.

Coal Content (grains /1000) (192)

Coal occurred infrequently in the South Gare samples but at the Hartlepool-Crimdon site, coal content increased inversely with particle size. The amounts involved would not greatly influence the particle size curve (1.6% in the 3.4 ϕ fraction).

Percentage Rock Fragments (193)

A comparison of rock fragment values indicates little or no significant difference between the environments.

Surface Texture (186)

The surface texture was measurably less polished than beach sands.

TABLE RECORDING THE SHELL CONTENT
(GRAINS/1000) OF DUNE SANDS

	Hartlepool-Crimdon				South Gare			
Size Fraction	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ
	3.0	39.0	42.0	-	84.0	89.0	89.0	-
	32.0	80.0	56.0	-	155.0	121.0	152.0	-
	101.0	70.0	48.0	-	131.0	110.0	92.0	-
	71.0	38.0	82.0	-	78.0	109.0	130.0	-
	110.0	98.0	110.0	-	150.0	123.0	78.0	-
	55.0	77.0	50.0	-	121.0	119.0	93.0	-
	78.0	33.0	49.0	-	138.0	112.0	103.0	-
	114.0	71.0	42.0	-	142.0	103.0	121.0	-
	91.0	101.0	63.0	-	109.0	121.0	87.0	-
	31.0	28.0	38.0	-	156.0	102.0	95.0	-
	27.0	57.0	121.0	-	63.0	138.0	156.0	-
	111.0	63.0	71.0	-	51.0	75.0	122.0	-
Mean	68.6	62.9	64.3	-	115.7	110.1	109.8	-

TABLE RECORDING COAL CONTENT

(GRAINS/1000) OF DUNE SANDS

Size Range	Hartlepool-Crimdon 1.66ø to 2.3ø	Hartlepool-Crimdon 2.31ø to 2.75ø	Hartlepool-Crimdon 2.76ø to 3.4ø	Hartlepool-Crimdon 3.41ø to 3.8ø	South Gare 1.66ø to 2.3ø	South Gare 2.31ø to 2.75ø	South Gare 2.76ø to 3.4ø	South Gare 3.41ø to 3.8ø
	0.0	11.0	20.0	-	0.0	1.0	0.0	-
	0.0	3.0	15.0	-	0.0	0.0	0.0	-
	0.0	2.0	25.0	-	0.0	4.0	0.0	-
	2.0	15.0	2.0	-	0.0	2.0	0.0	-
	0.0	12.0	20.0	-	0.0	0.0	0.0	-
	0.0	10.0	30.0	-	1.0	5.0	1.0	-
	4.0	3.0	11.0	-	0.0	0.0	0.0	-
	1.0	1.0	4.0	-	1.0	2.0	3.0	-
	2.0	4.0	19.0	-	0.0	0.0	0.0	-
	0.0	15.0	31.0	-	Trace	1.0	0.0	-
	0.0	7.0	5.0	-	0.0	3.0	2.0	-
	1.0	6.0	9.0	-	0.0	0.0	0.0	-
Mean	0.83	7.4	15.92	-	0.17	1.5	0.5	-

ROCK FRAGMENT CONTENT OF DUNE SEDIMENTS (GRAINS/1000)

Crimdon-Hartlepool				South Gare			
1.66 to 2.3ø	2.31 to 2.75ø	2.76 to 3.4ø	3.41 to 3.8ø	1.66 to 2.3ø	2.31 to 2.75ø	2.76 to 3.4ø	3.41 to 3.8ø
18	18	24	-	5	8	2	-
3	21	23	-	4	32	2	-
5	0.0	10	-	21	7	6	-
10	20	15	-	8	5	2	-
2	3	0.0	-	22	20	10	-
38	38	37	-	9	6	4	-
12	13	17	-	11	8	7	-
17	15	19	-	14	12	11	-
9	11	20	-	18	13	9	-
18	6	2	-	4	21	7	-
22	17	18	-	5	9	8	-
19	21	13	-	17	12	4	-

Mica Content (grains /1000) (186)

The absence of Mica is typical of windblown deposits (Shepard 1964 op cit) and in keeping with previous works (Bagnold 1954 op cit).

Summary

In brief, it would appear that textural parameters, % heavy mineral content, surface texture and mica content may prove useful as aids to environmental recognition.

Fluvial Samples

Five sites were selected for study and once again samples were collected using a stratified random approach. (Figs. 62,63;64.) Two of the sites were tributaries of the Tees, one, the Skelton Beck, was part of a small catchment basin on the Northern Slope of the Cleveland Hills and two were from the Tees itself. (Fig.64.). Again the summary tables may be used to discover any significant characteristics. (195, 196)

Particle Size (Textural Parameters) (Figs. 65 to 69)

The ϕ mean indicated that river sands are usually coarser grained than either beach or dune sands. The standard deviation again proved interesting as there was very little overlap between dune and river sands. Skewness proved positive in all sites but the South Gare estuary. The samples from this latter site suggested that wave action could be the dominant sorting agent. There was little overlap between the kurtosis values of the river and dune samples but only

RIVER SAMPLES

SITE	ø Mean			ø St. Dev.			ø Skew			ø Kurtosis		
	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.
Skelton Beck Saltburn	2.16	2.12	2.09	0.64	0.61	0.59	0.23	0.21	0.19	0.99	0.97	0.95
Thorpe Thewles	1.58	1.31	0.85	1.45	1.11	0.89	0.22	0.12	0.02	1.73	1.48	1.35
Billingham Beck	1.99	1.51	0.92	0.92	0.82	0.73	0.33	+0.16	-0.18	1.24	1.22	1.15
S. Gare Estuary	2.11	2.09	2.06	0.39	0.34	0.31	-0.02	-0.06	-0.09	0.96	0.9	0.82
R. Tees (Neasham)	2.3	1.63	1.1	1.0	0.77	0.34	0.32	0.13	-0.01	1.78	1.64	1.52
Grand Values	2.3	1.73	0.85	1.45	0.73	0.31	+0.33	+0.09	-0.18	1.78	1.24	0.82

SUMMARY OF RIVER SEDIMENT ANALYSES

SITE	% Rock			% Heavy Minerals			Coal			Shell			Mica			Surface Texture		
	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.
Billingham Beck	130	50	10	6.9	2.24	0.9	41	17.4	2	0	0	0	6	3	0	10	8	6
Thorpe Thewles	530	178	8	9.1	2.84	1.2	42	14.2	0	0	0	0	8	3	0	9	7	6
Skelton Beck	140	83	6	31.7	7.2	0.3	30	10.7	0	0	0	0	10	4	0	9	8	7
R. Tees (Neasham)	210	120	9	9.6	3.56	1.5	14	4.2	0	0	0	0	7	3	0	9	7	5
S. Gare (Estuary)	40	23	2	13.0	4.67	0.8	89	40.85	14	10	5	1	4	2	0	14	12	11
Grand Values	530	90.9	2	3.17	4.1		89	17.5	0	19	5	1	10	3	0	14	8.4	5

skewness values appear likely to provide a means of separating river and beach sediments. (Fig.70).

Percentage Heavy Minerals (198)

The heavy mineral content of river sands showed little concentration in the finer size grades. (with the exception of the South Gare site). This characteristic may well assist in the differentiation of river sands from other environments.

Coal content (grains /1000) (200)

The coal content of river sands tended to increase inversely with size but this trend was not consistent. It was not possible to distinguish between environments on coal content; only location, with respect to the source of coal to the north.

Percentage Rock Fragments (202)

The percentage content of rock fragments in river sands averaged 600% more than either beach or dune sands. This major difference may partially be the result of wave action in the surf zone which breaks down the rock particles more effectively than current energy. Alternatively the coarser nature of the fluvial deposits may account for the greater percentage of rock fragments. The South Gare site contained a similar number of rock fragments as beach samples and serves to further emphasize the influence of wave action in this site.

Surface Texture (196)

Quartz grains from river sands possessed a coarse matt

TABLE RECORDING THE PERCENTAGE

HEAVY MINERAL CONTENT OF RIVER SANDS

BILLINGHAM BECK				THORPE THEWLES				SKELTON BECK (SALTBURN)			
1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ
1.4	1.5	1.9	1.1	1.8	1.7	1.9	2.3	7.5	5.5	3.2	0.4
2.0	2.0	6.7	1.9	2.8	1.9	2.3	5.3	8.6	6.1	5.2	4.6
1.7	1.8	2.4	1.2	2.3	2.0	1.7	1.6	8.0	5.6	6.1	31.7
2.1	1.9	6.9	1.7	2.7	7.9	4.0	8.3	7.7	5.5	3.0	0.3
1.5	1.7	3.1	1.6	2.5	2.1	2.3	2.0	8.1	5.6	6.2	28.2
1.3	1.5	1.8	2.3	2.6	2.3	2.5	4.3	8.4	5.8	6.4	10.1
1.7	2.0	5.1	3.1	1.9	1.6	2.1	2.8	7.9	5.4	3.0	0.5
1.4	2.0	5.4	2.9	2.7	3.4	2.6	2.9	8.0	6.0	5.3	9.3
1.9	2.1	3.0	3.6	2.1	6.1	4.1	9.1	7.7	5.6	3.3	0.4
2.2	2.2	3.4	3.2	2.2	1.2	1.9	1.7	8.3	6.1	5.4	7.8
0.9	1.3	1.4	1.1	1.8	1.5	2.3	2.6	8.5	6.3	5.7	15.1
1.2	1.5	1.6	1.0	1.9	1.3	2.1	2.5	7.6	5.1	6.4	12.3
1.6	1.8	3.5	2.06	2.3	2.75	2.5	3.8	8.0	5.7	4.9	10.06

TABLE RECORDING THE PERCENTAGE

HEAVY MINERAL CONTENT OF RIVER SANDS

R. TEES (NEASHAM)				SOUTH GARE ESTUARY			
1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ
2.4	3.7	1.5	3.5	1.1	2.4	5.6	12.8
2.8	4.2	2.7	4.1	0.8	1.7	3.2	5.7
3.1	5.1	9.6	2.8	1.0	2.3	5.1	8.3
2.5	3.9	3.1	4.5	1.4	3.5	8.0	12.5
3.0	4.5	4.2	4.7	1.3	2.7	6.2	13.3
2.7	3.8	1.8	3.1	0.8	1.8	4.0	7.9
2.9	5.1	1.7	3.2	1.0	2.4	8.1	12.6
2.9	5.2	2.1	1.8	1.4	3.1	8.4	13.0
2.4	3.1	1.9	4.1	0.9	1.9	3.9	6.1
3.0	5.6	3.3	7.9	1.1	2.3	4.2	8.2
2.6	3.4	4.9	5.1	0.8	1.6	3.4	7.7
2.8	4.1	2.2	3.1	1.2	2.8	4.7	9.1
2.75	4.3	3.2	4.0	1.06	2.4	5.4	9.8

TABLE RECORDING THE COAL CONTENT

(GRAINS/1000) OF RIVER SANDS

BILLINGHAM BECK				THORPE THEWLES				SKELTON BECK (SALTBURN)			
1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ
40	10	21	18	0	0	38	36	0	0	0	0
10	2	2	11	0	0	5	27	0	28	25	29
12	4	5	14	18	8	11	28	22	5	2	3
15	6	11	17	8	9	10	4	0	0	22	30
25	11	21	23	13	7	14	29	4	21	19	20
36	9	22	41	11	0	2	31	12	14	20	17
39	10	17	24	0	0	5	37	0	3	5	18
22	3	16	27	9	12	40	22	3	24	30	29
17	5	13	40	17	16	17	42	7	21	16	25
24	7	9	32	0	0	24	33	0	0	0	4
13	4	15	37	4	7	19	19	0	3	11	7
33	19	12	10	0	0	23	28	0	7	3	5
23.8	7.5	13.7	24.5	6.7	4.9	17.25	28.0	4.0	10.5	12.75	15.5

TABLE RECORDING THE COAL CONTENT

(GRAINS/1000) OF RIVER SANDS

R. TEES (NEASHAM)				S. GARE (ESTUARY)			
1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ
0	7	9	11	20	45	63	78
0	0	2	5	30	32	51	89
0	3	2	7	27	41	23	45
0	0	0	2	23	21	30	61
Trace	8	7	6	25	28	50	65
0	4	6	9	29	35	54	74
1	6	9	13	21	20	41	59
0	0	4	6	19	27	44	65
0	5	7	8	32	34	56	88
0	0	8	14	27	26	60	77
0	0	3	2	14	19	22	46
1	7	9	12	25	29	31	60
0.2	3.3	5.5	7.9	24.3	28.1	43.75	67.25

ROCK FRAGMENT CONTENT OF RIVER SEDIMENTS (GRAINS/1000)

Skelton Beck				S.Gare				Billingham Beck			
1.66 to 2.3φ	2.31 to 2.75φ	2.76 to 3.4φ	3.41 to 3.8φ	1.66 to 2.3φ	2.31 to 2.75φ	2.76 to 3.4φ	3.41 to 3.8φ	1.66 to 2.3φ	2.31 to 2.75φ	2.76 to 3.4φ	3.41 to 3.8φ
140	130	40	28	4	3	2	-	130	30	34	40
30	11	9	6	11	4	3	-	40	10	65	73
68	52	44	6	14	12	2	-	30	17	14	11
113	109	83	24	9	4	2	-	121	27	31	39
95	64	45	13	40	12	4	-	114	109	71	14
78	41	31	15	7	4	3	-	98	13	17	20
114	88	78	32	9	5	4	-	111	41	38	20
126	111	64	31	14	8	6	-	91	17	21	33
123	103	51	29	31	14	8	-	122	61	35	30
65	27	18	10	17	11	4	-	35	24	18	15
48	14	12	6	19	11	3	-	71	41	40	24
94	29	13	11	12	8	7	-	92	56	58	53

Thorpe Thewles Beck				R.Tees Newsham			
1.66 to 2.3φ	2.31 to 2.75φ	2.76 to 3.4φ	3.41 to 3.8φ	1.66 to 2.3φ	2.31 to 2.75φ	2.76 to 3.4φ	3.41 to 3.8φ
33	14	12	10	198	121	74	62
530	361	239	219	210	96	78	51
90	50	26	8	201	145	71	40
23	42	21	48	176	103	49	22
421	302	153	59	148	65	32	15
338	216	114	46	150	94	30	23
515	403	230	201	191	111	55	19
296	174	93	20	141	87	16	9
49	17	12	9	59	47	31	14
271	139	81	51	132	66	51	21
447	378	202	138	204	159	76	42
329	261	116	72	163	78	47	17

finish which gave light readings in the range 7 to 8 with the South Gare site giving a reading of 12. One may suggest that the higher degree of polish in beach sands does appear to separate it from other environments.

Mica Content (grains /1000) (196)

The mica content was too small to be significant.

Summary

In summary it would seem feasible to differentiate between beach and river sands on the basis of surface texture, shell content, heavy mineral distribution and some textural parameters.

Offshore Samples

Fig. 71[1] depicts the major collection sites for offshore samples. These were selected on a stratified random plan with controls of depth (160 feet) and distance from the shore (2 miles). In all, 130 samples were collected from 40 sites. One can determine the characteristics of this environment from the summary tables and also the characteristics which may prove significant as means of environmental determinism. (204, 205)

Particle Size (Textural Parameters) (Fig. 72)

The offshore samples tend to be finer grained than the environments previously examined. (2.59ϕ as compared with 2.16ϕ,

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[1] Loc. S.L.S. .R. Have no significance other than locational.

OFFSHORE SAMPLES - TEXTURAL PARAMETERS

SITE	ø Mean			ø St. Dev.			ø Skewness			ø Kurtosis		
	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.
LOC.	3.0	2.21	1.0	1.55	0.74	0.5	+0.18	-0.14	-0.48	2.68	1.5	0.92
S.L.S.	3.23	3.04	2.84	0.68	0.52	0.4	+0.18	-0.06	-0.19	2.05	1.28	0.9
R.	2.65	2.53	2.45	0.6	0.41	0.29	+0.11	-0.17	-0.32	2.7	1.86	1.4

SUMMARY TABLE OF OFFSHORE SEDIMENT ANALYSES

	% Rock Fragments			% Heavy Minerals			Coal			Shell		
SITE	Ext.	Mean	Ext.	Ext.	Mean	Ext.	Ext.	Mean	Ext.	Ext.	Mean	Ext.
LOC.	40	15.8	0	23.6	4.95	1.3	740	113.5	4	310	81.6	8
S.L.S.	420	29.1	0	19.8	3.5	1.0	434	88.8	7	359	96.2	0
R.	36	6.9	0	18.6	3.3	0.1	50	8.8	0	362	115.4	0
Grand Values	420	17.4	0	23.6	3.92	0.1	740	70.4	0	362	97.7	0

	Mica			Surface Texture		
	Ext.	Mean	Ext.	Ext.	Mean	Ext.
LOC.	70	6.1	0	15	12	10
S.L.S.	70	7.2	0	14	13	12
R.	15	3.8	0	12	9	7
Grand Values	70	5.7	0	15	11	7

2,06ϕ and 1.73ϕ for beach, dune and river sands respectively). (Table 204).

The standard deviation is greater than that of beach sands but less than that of river sands.

Skewness and kurtosis, unfortunately, are almost identical with values obtained for beach sand. Textural parameters therefore, can only be partially successful as a means of distinguishing between beach and offshore environments. (Fig. 74).

Percentage Heavy Minerals (Fig. 72) (207)

Heavy minerals were concentrated in the finer size grades of both beach and dune sediments. This was not true of offshore samples where the content did not show a specific trend with size. This character compared favourably with the previously discussed fluvial samples.

Shell Content (grains /1000) (208)

There is no significant difference between the two environments, beach or offshore.

Coal Content (grains /1000) (209)

The coal content at Redcar averaged 1% of each sample, whilst at Hartlepool it was occasionally over 10%. Although coal was available from boulder clay in the late pleistocene period, the increase in mining activity in the 20th century has provided much greater quantities, such that the coal content of present day and pleistocene environments is not directly comparable.

TABLE RECORDING THE PERCENTAGE OF HEAVY MINERALS IN OFFSHORE SAMPLES

	LOC.				S.L.S.				R.			
	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ
	3.4	1.9	2.0	-	4.4	2.8	2.4	2.2	1.5	1.2	2.6	4.4
	1.6	3.9	12.9	23.6	1.0	1.1	2.1	1.6	2.0	1.0	2.5	5.8
	1.5	2.9	5.5	-	6.5	2.6	1.8	1.8	1.8	0.1	2.7	18.6
	1.3	3.2	4.3	-	1.4	2.5	3.0	2.0	1.6	4.8	1.8	2.9
	1.3	4.5	10.1	12.0	19.8	4.2	4.8	3.3	3.4	1.5	3.9	5.8
	1.7	4.5	6.2	9.3	1.5	1.6	4.6	11.6	1.7	1.0	2.4	7.1
	2.0	3.4	3.7	3.4	2.8	2.2	3.1	6.2	1.1	0.9	2.8	4.2
	1.1	2.2	2.9	5.5	1.9	1.7	4.1	4.9	1.0	0.6	2.4	8.0
	7.0	3.6	2.3	3.0	3.6	4.2	2.6	2.3	1.5	1.5	2.8	12.2
	1.5	3.2	4.6	8.3	9.6	2.4	2.4	1.6	1.4	1.3	3.1	4.8
	9.9	4.7	2.4	1.5	3.6	1.1	1.5	2.1	2.0	0.8	2.7	9.3
	1.5	2.9	3.8	10.1	5.0	2.2	3.0	3.8	1.9	0.9	2.4	6.2
Mean	2.8	3.4	5.0	8.6	5.1	2.4	2.9	3.6	1.7	1.3	2.7	7.4

TABLE RECORDING THE SHELL CONTENT

(GRAINS/1000) OF OFFSHORE SAMPLES

	LOC.				S.L.S.				E.			
	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ
	12	22	8	10	2	2	1	0	80	43	0	48
	38	39	24	16	80	34	29	12	170	10	3	3
	34	140	17	51	264	111	61	2	300	51	30	11
	180	159	56	23	210	54	10	10	319	163	55	21
	180	73	78	15	252	70	49	36	341	172	119	38
	110	60	58	55	342	203	52	37	362	158	92	78
	165	89	48	23	210	107	99	80	303	212	83	91
	160	90	92	41	168	111	71	18	152	5	2	1
	267	232	65	30	53	70	41	59	340	60	24	9
	60	68	32	28	251	107	84	61	289	71	36	11
	310	150	111	-	359	203	110	44	312	221	92	104
	140	130	70	-	203	101	54	30	240	91	74	52
Mean	138.0	104.3	54.9	29.2	199.5	97.75	55.1	32.4	267.3	104.75	50.8	38.9

TABLE RECORDING THE COAL CONTENT

(GRAINS/1000) OF OFFSHORE SAMPLES

	LOC.				S.L.S.				R.			
Size Fraction	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø
	43	24	30	35	98	72	25	13	10	2	17	50
	18	51	99	500	39	41	23	19	0	0	12	2
	32	18	31	4	37	36	20	49	1	1	3	5
	740	469	160	158	50	45	29	10	2	0	0	7
	21	18	20	60	33	18	40	17	8	0	39	10
	78	49	26	23	370	341	68	32	10	8	4	3
	177	434	111	72	28	24	40	51	12	2	2	23
	7	13	43	80	142	15	11	90	9	2	15	21
	9	11	420	712	329	368	110	78	7	0	0	8
	21	50	41	38	10	8	7	-	10	8	11	31
	31	30	45	-	434	272	181	140	11	1	4	6
	30	50	80	-	62	20	85	173	2	0	0	9
Mean	100.6	101.4	83.8	168.2	136.0	105.0	53.25	61.0	6.8	2.0	8.91	14.6

TABLE RECORDING ROCK FRAGMENT CONTENT

OF OFFSHORE SAMPLES (PERCENTAGE)

	LOC.				S.L.S.				R.			
	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø
	18	18	8	20	420	0	0	0	0	0	19	0
	9	13	9	7	130	30	14	12	10	0	36	7
	8	19	38	12	0	0	2	18	1	0	0	0
	12	14	8	1	43	12	11	8	23	15	8	0
	19	11	10	11	25	15	12	11	21	18	21	22
	28	21	51	38	150	97	34	19	10	7	3	0
	32	23	15	25	10	10	0	0	0	8	0	4
	11	11	8	23	30	31	13	4	9	11	7	14
	3	8	9	0	28	42	0	12	0	0	2	9
	29	19	22	12	20	7	3	0	22	6	4	1
	40	10	3	-	11	3	4	2	8	5	0	1
	12	9	1	-	70	29	7	7	1	0	0	0
Mean	18.4	14.7	15.2	14.9	78.1	22.25	8.3	7.75	8.75	5.8	8.3	4.8

TABLE RECORDING THE MICA CONTENT

OF OFFSHORE SAMPLES (GRAINS/1000)

	LOC.				S.L.S.				R.			
	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.6ø
	23	6	4	1	20	2	1	1	0	0	0	0
	0	0	0	8	1	0	0	0	15	3	1	2
	0	0	0	0	9	1	0	0	0	0	1	1
	30	23	18	11	4	1	1	0.5	10	11	8	11
	0	0	0	0	70	28	21	30	2	2	3	2
	0	0	1	0	1	3	4	20	0	0	0	1
	12	7	70	3	0	0	3	14	5	2	0	3
	2	8	3	5	20	9	12	7	12	9	11	7
	0	0	10	34	22	2	1	2	2	4	5	2
	0	0	0	1	0	0	3	9	0	0	3	2
	0	0	0	-	0	0	3	1	7	12	9	9
	0	0	0	-	0	12	3	5	0	1	0	3
Mean	5.6	3.7	8.8	6.3	12.2	4.8	4.3	7.4	4.4	3.7	3.4	3.6

TABLE RECORDING SILT CONTENT
OF OFFSHORE SEDIMENTS

SITE	% SILT	SITE	% SILT
S.L.S. 1	6.5	LOC. 4	13.48
S.L.S. 1	7.3	LOC. 4	14.28
S.L.S. 1	0.4	LOC. 4	14.58
S.L.S. 2	18.88	LOC. 4	12.82
S.L.S. 2	17.0	LOC. 4	14.77
S.L.S. 2	23.0	LOC. 4	6.65
S.L.S. 3	10.25	LOC. 4	14.12
S.L.S. 3	12.12	LOC. 4	13.11
S.L.S. 3	13.15	LOC. 4	12.28
S.L.S. 6	2.19	LOC. 4	12.7
S.L.S. 6	2.65	LOC. 4	12.2
S.L.S. 6	2.02	LOC. 4	14.25
S.L.S. 7	1.98	LOC. 5	12.43
S.L.S. 7	2.29	LOC. 5	10.43
S.L.S. 7	2.09	LOC. 5	10.76
S.L.S. 8	0.52	LOC. 5	11.1
S.L.S. 8	0.68	LOC. 5	13.21
S.L.S. 8	0.71	LOC. 5	10.0
S.L.S. 9	1.42	LOC. 5	14.28
S.L.S. 9	1.35	LOC. 5	13.41
S.L.S. 9	1.21	LOC. 5	13.36
S.L.S. 4	3.1	LOC. 5	11.8
S.L.S. 4	2.43	LOC. 5	10.52
S.L.S. 4	2.92	LOC. 8	0.9
S.L.S. 10	6.67	LOC. 8	0.61
S.L.S. 10	7.42	LOC. 8	0.6
S.L.S. 10	10.13	LOC. 8	0.68
S.L.S. 11, 12	6.09	LOC. 9	0.93
S.L.S. 11, 12	4.68	LOC. 9	1.0
S.L.S. 11, 12	7.38	LOC. 9	0.78
LOC. 1	16.7	LOC. 9	0.85
LOC. 1	20.5	LOC. 7	0.71
LOC. 1	18.5	LOC. 14	0.41
LOC. 2	5.4	LOC. 15	0.1
LOC. 2	0.91	LOC. 15	1.22
LOC. 2	6.88	LOC. 15	7.98
LOC. 4	12.9	LOC. 15	1.05
LOC. 4	18.13	LOC. 17	1.7
LOC. 4	14.2	LOC. 17	4.4
		LOC. 17	0.14

Percentage Rock Fragments (210)

Beach and offshore environments had a similar rock fragment content.

Mica Content

Mica content was not significantly different from beach sediments. (Table 211).

Summary

None of the above characteristics proved particularly successful in distinguishing between beach and offshore environments. A greater success was achieved by comparing the % silt content (finer than 4 ϕ) (Table 212). This method was not suitable for the zone within the influence of wave base (to a depth of 45 feet) as silt was absent from the size range.

Synthesis

The following discussion considers the relative merits of the various properties of sand-sized sediment to determine the most successful means of environmental identification.

TEXTURAL PARAMETERS

SITE	ϕ Mean			ϕ ST.Dev.			ϕ Skew			ϕ Kurtosis		
	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.
Beach	2.65	2.16	1.57	0.69	0.42	0.26	-0.57	-0.14	+0.23	3.04	1.31	0.71
Dune	2.33	2.06	1.8	0.35	0.31	0.25	-0.28	+0.03	+0.35	1.09	0.96	0.84
River	2.3	1.73	0.85	1.45	0.73	0.31	-0.18	+0.09	+0.33	1.78	1.24	0.82
Off-Shore	3.23	2.59	1.0	1.55	0.55	0.29	-0.48	-0.12	+0.18	2.7	1.54	0.9

Tables (213) and (214) make it quite clear that textural parameters are an inefficient means of distinguishing between environments. This is particularly the case with displaced marine environments, and only wind action is sufficiently inflexible to provide a fairly distinctive sorting range.

TEXTURAL PARAMETERS

% Overlap

	ϕ Mean	ϕ St. Dev.	ϕ Skew	ϕ Kurtosis
Beach over Dune	100%	99%	81%	100%
Dune over Beach	49%	21%	63%	11%
Beach over River	50%	29%	81%	100%
River over Beach	68%	89%	52%	42%
Beach over Offshore	48%	32%	100%	100%
Offshore over Beach	100%	93%	83%	77%
Dune over River	45%	4%	100%	26%
River over Dune	98%	40%	81%	100%
Dune over Offshore	24%	5%	70%	10%
Offshore over Dune	100%	60%	73%	76%
Offshore over River	90%	100%	71%	92%
River over Offshore	59%	90.5%	55%	49%

There may well be some aspects of sorting which moment measures cannot pick out but if one was to attempt an identification of a raised marine sand using the above technique the result would be as follows:

(i) Beach over dune - Skewness successful 19 times out of 100

(ii) Beach over river - Standard deviation successful 79 times out of 100

(iii) Beach over river - kurtosis successful 89 times out of 100

(iv) Beach over offshore - Mean successful 52 times out of 100

(v) Beach over offshore - Standard deviation successful 68 times out of 100

These five most successful separations will average 61% successful; a level which one cannot accept.

Percentage Heavy Minerals (Table 176) (189)(198)(207)

Heavy mineral content is meaningless until individual size fractions are compared. One can observe from the respective tables that wave action and wind are more selective than current flow and the concentration of heavy minerals in the fine fraction of these two environments may prove to be a valuable means of identification.

Shell Content (grains /1000) (Table 178) (191)(208)

Three environments, littoral, nearshore and offshore, and coastal dune contain shell fragments. The most significant trend observed was the influence of shell content on skewness values. A high negative skew could frequently be explained by the percentage of shell fragments in the coarser fraction.

Coal Content (grains /1000) (Table 181) (192)(200)(209)

The absolute coal content cannot be used on a comparative basis because of the very real differences between past and present availability. The relative distribution of coal within a size distribution may, however, prove more valuable.

Percentage Rock Fragments (Tables 183, 193, 202, 210)

The percentage rock fragment content would appear to provide a sure means of identifying a fluvial deposit from the three other basic environments. The fluvial sediments of the Tees Basin contained up to 600% more rock fragments than occurred in other environments. One can hypothesise that the greater efficiency of wave action, breaks down rock fragments into the mineral components more rapidly than current flow. This is probably only true on a relative scale since the gentle gradient of the drainage network in the lower Tees basin is unlikely to encourage rapid erosion. A problem is also envisaged with wind blown sediment in a deltaic complex where the material which composes the deposit, will not have undergone wave action like its coastal relation. Such a wind blown deposit may contain a greater number of rock fragments than is indicated by the present survey.

Surface Texture (Tables 173, 186, 196, 205)

There was little difference between environments with the exception of beach. In this latter, a high polish appears to be imparted by the continual swash and backwash of wave action. This high polish was consistently present in all beach samples. Dune samples showed an intermediate degree of polish, largely because their population is beach derived. The most distinctive environmental characteristics of each environment are listed in the following sub-section.

1.) Beach
    a) A high polish on the surface of quartz grains.
    b) The character of the particle size curve is influenced by coal, shell and heavy minerals.
    c) Heavy mineral content is concentrated in the finer size grades.

2.) Dune
    a) The only environment which can successfully be recognised using moment measures.
    b) Complete absence of mica.
    c) Heavy minerals concentrated in the finer size grades.

3.) River
    a) A very high concentration of rock fragments.
    b) A more variable and yet better balanced particle size curve i.e. it is the only environment where the coarse and fine tails are symmetrical when plotted on arithmetic probability paper.
    c) Absence of shell fragments.

4.) Offshore

a) No single parameter can be considered as unique to the offshore environment.

b) The above conclusion resulted in further study and it was discovered that the % silt content (finer than 4 ø) was much greater in offshore sediments than in comparable river, dune or beach sediments.

Mica Content

The complete absence of mica from a wind blown sediment provides useful negative evidence, if mica is fairly common in other environments within the immediate vicinity. The tables (186,173,196,205, 211) demonstrate that very little mica is present in the sandy deposits of the lower Tees basin. This survey agrees with recognised studies (Shepard 1964) that mica usually settles in standing water and is usually fairly common as a coarse fraction in lake muds.

Lacustrine Environment

At this stage one must consider the problem of the lacustrine environment. In the previous chapter a comparative study of marine and lacustrine shorelines was used to make up for the lack of a suitable fresh water body in the lower Tees. The Sutherland survey can have some value providing one makes allowances for the source material differences (Figs. 76, 75). The most significant result related to the similarities between marine and lacustrine particle size curves once the shell content was removed from the former. The results may be assessed from the following tables and graphs. (Tables 220, 221, 222, 223)

1.) The surface texture of marine sand grains is more highly polished.

2.) The shell content of marine sands allows immediate recognition of the sample.

3.) The gradual increase of % heavy minerals with decreasing size is more easily recognised in the marine samples.

Other Samples

So far, samples have been heavily concentrated in the Tees basin and the question can be raised as to the representative qualities of such a localised environment. In part, this problem was acknowledged in Chapter 3 when beach samples from Ireland, the Firth of Forth, and Durness (Sutherland) were graphically compared to demonstrate the regional differences which arise from exposure and source material. (Fig. 77). A similar extension of sampling to contrasting areas produced the following results. (Figs. 78 to 82).

The particle size curves suggest that sorting agents will create uniformity within each environment unless there is an abnormally different source material. More specifically the Ireland beach sample showed an unusual degree of truncation, whilst the Sutherland offshore sample possessed a wider range of grain sizes, than those from the Tees. Mineral comparisons did not provide any evidence which contradicted the conclusions already drawn from the Tees Samples. (Appendix 5).

SUMMARY TABLE OF SEDIMENTARY PROPERTIES
OF SAMPLES FROM MARINE AND LACUSTRINE
ENVIRONMENTS, NEAR DROHAN (SUTHERLAND, SCOTLAND)

	SHELL CONTENT			SURFACE TEXTURE			% HEAVY MINERALS			% ROCK FRAGMENTS		
	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.
MARINE	908	527.7	284	19	18	15	11.6	3.0	0.3	8	3	3
LACUSTRINE	0.0	0.0	0.0	14	12	10	37.1	5.6	1.4	2	1	2

TABLE RECORDING TEXTURAL PARAMETERS OF MARINE AND LACUSTRINAL DEPOSITS FROM DROMAN, SUTHERLAND, SCOTLAND

	ϕ Mean			ϕ St. Dev			ϕ Skew			ϕ Kurtosis		
	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.
MARINE	1.87	1.48	1.19	0.66	0.58	0.49	-0.49	-0.21	+0.03	1.24	1.12	1.01
LACUSTRINAL	2.56	2.39	1.96	0.83	0.69	0.58	-0.11	+0.12	+0.31	1.95	1.5	1.02
MARINE LESS SHELL	2.12	1.91	1.78	0.64	0.58	0.5	-0.14	+0.01	+0.16	1.2	1.1	1.0

TABLE RECORDING HEAVY MINERAL CONTENT (PERCENTAGE) OF MARINE AND LACUSTRINAL DEPOSITS (DROMAN, SUTHERLAND, SCOTLAND)

	MARINE				LACUSTRINAL			
	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ
	0.9	2.5	7.3	-	2.5	1.4	3.0	4.1
	0.3	0.5	3.0	-	2.9	2.3	2.5	37.1
	0.6	1.3	3.0	5.0	4.7	4.2	5.1	6.8
	0.9	1.9	4.1	6.4	3.6	2.4	4.2	7.4
	0.5	0.8	3.1	5.6	4.1	3.8	5.9	14.4
	0.8	1.8	8.0	11.6	2.7	2.2	2.6	5.9
MEAN	0.66	1.46	4.75	7.15	3.4	2.7	3.7	12.6

TABLE RECORDING THE HEAVY MINERAL CONTENT OF DUNE AND BEACH SANDS FROM DURNESS (SUTHERLAND, SCOTLAND)

	1.66 to 2.3φ	2.31 to 2.75φ	2.76 to 3.4φ	3.41 to 3.8φ
BEACH	0.9	2.5	7.3	30.79
BEACH	0.3	0.5	3.0	41.84
DUNE	1.2	4.7	49.36	94.94
DUNE	0.99	3.19	50.52	95.45

Other Salient Characteristics

The singular lack of success in discovering a characteristic unique to offshore sands led to the examination of other factors.

1) Shape of the particle size curve

Figures 83 and 84 show that each environment possesses a characteristic curve when plotted on arithmetic probability paper. This curve is more sensitive to slight differences in particle size than moment measures and it may well be that this could provide a means of identification. For example, the lacustrine and marine offshore environments each have a distinctive "reverse L." shaped curve, a dune curve is closest to the vertical, whilst a a fluvial curve is generally much flatter and a beach curve usually exhibits a sudden levelling of the curve gradient in the fine size grades. The main problem is to find a technique capable of quantifying this data to determine the statistical significance of such characteristics.

2) Percentage silt content (212)

Samples taken below 45 feet in the Tees Bay contained a high degree of silt which was absent from beach sands. The silt content varied from 0% at 45' depth to 42% at 120 feet depth. Beach and surf zone sediments were usually truncated at the 3.8ϕ or 4.1ϕ fraction.

Conclusion

The problem which emerges from this survey relates to the complex interrelationships of the many variables both "within" and "between" the five major present day environments. The need is clearly for some integrated approach where all variables from each environment can be incorporated into a single analysis with the result proving or disproving the concept of sorting agents and regimes. To this end, the author turned to trend surface analysis, factor analysis and discriminant function analysis.

Results

Trend surface analysis produced several distinctive trends. Coal content notably decreased in a southerly and westerly direction, whilst the silt content in offshore samples increased to seaward. On the other hand, heavy mineral content, rock fragments, and shell content did not appear to possess any trend.

It was concluded that trend surface analysis could not be used in the Tees basin as an aid to environmental recognition.

Factor analysis has already been discussed in chapter seven and was used to good effect by Klovan (1966 op.cit.) and Solohub (1967 op.cit.) to define the major energies controlling the different despositional environments. One can see its immediate application to the current situation as it can include all the variables which have been previously discussed and produce a factor loading ratio to explain the variation between individual samples.

Two separate analyses were performed; The first used only particle size as Klovan (ibid) and Solohub (ibid) and the second incorporated the additional variables analysed in the present study. The results obtained were most encouraging and were more successful than either of the two previously mentioned works. As the factorial technique was identical this improvement must be attributed to improved sampling, improved processing, or both. Klovan used Krumbein's data from Barataria Bay (op.cit.Chapter 7), whilst Solohub's data from Lake Winnipeg may have been sampled inadequately. Also, Solohub's samples were processed using only ½ø sieve units. The author wrote to Solohub to enquire about his sampling methods but received no reply and was later advised that he was in Nigeria. Certainly, his thesis makes no reference to sampling theory and as far as can be gathered his samples were purposefully selected spot samples.

Klovan (1966 op.cit.) noted three dominant factors which were designated:
(1) Wind-wave energy
(2) Current energy
(3) Gravity settling

The present study similarly recognises three dominant factors but on the basis of the results would separate wind from wave action and accord gravity settling to a fourth factor. This latter is common to all environments and may dominate any of the five major environments.

In the majority of cases (Table 228) three factors give a 90% level of explanation of the variation but in some instances a further factor was significant. The triangular graph proved to be an adequate means of presenting the results of three factor plots providing the three factors explained 90% of the variation. (Fig.86)

Interpretation of Results

Factor Analysis (1) Particle Size Data

The first factor analysis used only particle size data (see table).

Figs. (87) and (86) show the initial plot and zoning of the present day environments in the Tees. Immediately, one can observe the separation of samples into environmental groups. In addition, each environment may be further subdivided. For example, Fig. (86) shows one offshore group, one dune group, but three beach and two river. The three beach zones appear to be those parallel to the H.W.M., whilst the two separate river groups appear to represent the respective influence of current flow and gravity settling. The factor loadings also prove that the influence of wave action extends to 45 feet below low water mark. All offshore samples in this shallower water fall within the beach plot. Those offshore samples which fall between the two fluvial groups are the deep water samples taken below 100 feet. The silt content was omitted from the input data and consequently they gave a factor ratio similar to the river samples which involved gravity settling as the major factor. Fig.(86) clearly demonstrates the close affinities between marine and freshwater littoral

TABLE RECORDING SAMPLE LOCATION, COMPUTER NUMBER AND FACTOR LOADINGS, BASED ON PARTICLE SIZE DATA.

			%	
SAMPLE LOCATION	COMPUTER NUMBER	F1	F2	F3
Crimdon Dune 5' to 10'OD ^{1}	D01	0.76	35.5	64.0
Crimdon Dune 5' to 10'OD ^{2}	D02	5.4	27.6	66.8
Crimdon Dune 5' to 10'OD ^{3}	D03	3.0	31.5	65.39
Crimdon Dune 33'OD ^{1}	D04	0.7	38.8	60.4
Crimdon Dune 33'OD ^{2}	D05	0.7	35.9	63.26
Crimdon Dune 18'OD ^{1}	D06	6.7	57.16	36.08
Crimdon Dune 18'OD ^{2}	D07	6.8	57.7	35.6
Crimdon Dune base ^{1}	D08	6.0	50.9	43.4
Crimdon Dune base ^{2}	D09	6.0	50.5	44.0
South Gare Dune 1	D10	1.5	35.25	63.2
South Gare Dune 2	D11	1.5	35.1	63.5
South Gare Dune 3	D12	1.0	37.8	61.5
South Gare Dune 4	D13	0.7	38.2	61.1
Crimdon Beach 1	B01	3.3	83.6	13.1
Crimdon Beach 2	B02	3.3	82.3	14.4
Crimdon Beach 3	B03	2.7	78.1	19.5
Crimdon Beach 4	B04	2.6	77.0	20.4
Crimdon Beach 2A	B05	3.7	71.1	25.1
Crimdon Beach 2A	B06	3.9	70.3	25.8
Crimdon Beach 4A	B07	3.9	68.7	27.4
Crimdon Beach 4B	B08	3.8	65.4	30.8
Crimdon Beach 1A	B09	3.6	69.9	26.5
Crimdon Beach 1B	B10	3.9	71.8	24.4
Crimdon Beach 3	B11	3.1	72.0	24.9
Crimdon Beach 3	B12	3.5	69.3	27.2
Marske Beach 6 ^{1}	B13	10.0	36.9	53.5
Marske Beach 6 ^{2}	B14	10.7	32.9	56.4
Marske Beach 5 ^{1}	B15	9.6	33.7	56.7
Marske Beach 5 ^{2}	B16	7.5	43.0	49.5
Marske Beach 4 ^{1}	B17	6.7	41.6	51.6
Marske Beach 4 ^{2}	B18	9.8	32.2	58.0

TABLE RECORDING SAMPLE LOCATION, COMPUTER NUMBER AND FACTOR LOADINGS, BASED ON PARTICLE SIZE DATA. (Continued)

			%	
SAMPLE LOCATION	COMPUTER NUMBER	F1	F2	F3
Marske Beach 3 ^{1}	B19	8.7	38.4	61.6
Marske Beach 3 ^{2}	B20	13.8	23.0	63.2
Marske Beach 2 ^{1}	B21	2.6	43.8	53.6
Marske Beach 2 ^{2}	B22	1.6	48.6	49.7
Marske Beach 1 ^{1}	B23	14.4	15.3	70.3
Marske Beach 1 ^{2}	B24	12.5	18.3	69.2
Redcar Beach 1 ^{1}	B25	26.4	6.2	67.4
Redcar Beach 1 ^{2}	B26	27.1	5.1	67.8
Redcar Beach 2 ^{1}	B27	27.4	5.6	67.1
Redcar Beach 2 ^{2}	B28	26.4	6.3	67.4
Redcar Beach 3 ^{1}	B29	29.5	2.4	68.1
Redcar Beach 3 ^{2}	B30	31.5	0.07	67.8
Redcar Beach 4 ^{1}	B31	34.0	0.9	65.1
Redcar Beach 4 ^{2}	B32	33.8	0.2	66.0
Redcar Beach 5 ^{1}	B33	30.6	2.6	66.8
Redcar Beach 5 ^{2}	B34	30.5	4.9	64.6
Redcar Beach 6 ^{1}	B35	27.3	7.4	65.3
Redcar Beach 6 ^{2}	B36	29.1	4.4	66.6
Hartlepool Yacht Club 1A	B37	17.5	24.7	57.8
Hartlepool Yacht Club 1B	B38	17.5	24.3	58.2
Hartlepool Yacht Club 2A	B39	10.5	29.9	59.6
Hartlepool Yacht Club 2B	B40	12.4	27.1	60.5
Hartlepool Yacht Club 3A	B41	20.2	18.9	60.7
Hartlepool Yacht Club 3B	B42	16.4	22.8	60.8
Billingham Beck 2 ^{1}	R01	8.6	87.6	3.8
Billingham Beck 2 ^{2}	R02	9.1	83.8	7.1
Billingham Beck 1 ^{1}	R03	19.3	48.3	32.4
Billingham Beck 2 ^{2}	R04	17.6	51.4	31.0
R Tees 1	R05	18.6	80.9	0.6
R Tees 2	R06	15.4	78.6	6.0
R Tees 3	R07	18.7	74.7	6.6
R Tees 4	R08	17.2	72.5	10.3

TABLE RECORDING SAMPLE LOCATION, COMPUTER NUMBER AND FACTOR LOADINGS, BASED ON PARTICLE SIZE DATA. (CONT'D)

			%	
SAMPLE LOCATION	COMPUTER NUMBER	F1	F2	F3
Thorpe Thewles 1	R09	12.6	80.3	7.1
Thorpe Thewles 2	R10	14.8	73.7	11.5
Thorpe Thewles 3	R11	12.5	76.2	11.3
Thorpe Thewles 3	R12	10.3	85.4	5.0
Hartlepool Yacht Club 1	W01	87.6	10.2	2.1
Hartlepool Yacht Club 1 [1]	W02	87.4	11.8	0.8
Hartlepool Yacht Club 2	W03	88.4	6.4	5.2
Hartlepool Yacht Club 2 [2]	W04	88.4	6.5	5.1
Hartlepool Yacht Club 2 [2]	W05	76.7	2.9	20.4
Loc 2	W06	63.9	1.2	34.9
Loc 2	W07	51.2	9.3	39.5
Loc 1	W08	73.1	13.1	13.8
Loc 14	W09	0.6	52.4	47.0
Loc 16	W10	6.8	40.0	53.2
Loc 1	W11	82.2	12.6	5.2
Loc 1	W12	75.9	15.3	8.8
Loc 12	W13	6.3	36.5	57.3
SLS 4	W14	53.3	17.7	29.0
SLS 4	W15	54.1	17.8	28.2
SLS 4	W16	51.9	19.1	29.1
SLS 1	W17	88.0	7.56	4.4
SLS 1	W18	88.9	8.3	2.8
SLS 1	W19	63.2	6.9	29.9
SLS 2	W20	81.4	7.3	11.3
SLS 2	W21	77.0	6.2	16.8
SLS 2	W22	83.6	7.0	9.4
SLS 9	W23	80.6	4.1	15.3
SLS 9	W24	81.5	4.5	14.0
SLS 9	W25	76.3	3.6	20.2
SLS 8	W26	76.7	3.3	20.0
SLS 8	W27	75.0	3.2	21.8
SLS 8	W28	73.6	2.5	23.9

TABLE RECORDING SAMPLE LOCATION, COMPUTER NUMBER AND FACTOR LOADINGS, BASED ON PARTICLE SIZE DATA.

			%	
SAMPLE LOCATION	COMPUTER NUMBER	F1	F2	F3
R6	W29	22.6	11.4	66.0
R6	W30	26.8	8.4	64.8
R6	W31	24.1	11.7	64.3
R6	W32	24.9	10.9	64.2
SLS 10	W33	85.2	4.7	10.1
SLS 10	W34	83.1	4.5	12.7
SLS 10	W35	79.6	7.3	13.1
Loc 15	W36	0.5	71.2	28.3
LOC 15	W37	4.8	40.6	54.5
LOC 15	W38	24.7	66.1	9.2
LOC 15	W39	9.8	45.0	45.2
R 5	W40	35.9	2.4	61.7
R 5	W41	34.1	2.2	63.7
R 5	W42	35.9	2.7	61.4
R 5	W43	32.1	2.8	65.1
R 4	W44	26.7	60.8	12.6
R 4	W45	24.1	62.9	13.1
R 4	W46	16.2	71.0	12.8
R 4	W47	25.8	1.7	72.5
LOC 7	W48	31.0	24.3	44.8
LOC 7	W49	34.4	20.9	44.8
LOC 7	W50	33.8	17.4	48.7
LOC 7	W51	40.7	11.4	47.9
R ??	W52	38.3	2.8	58.8
R ??	W53	36.4	1.5	62.0
R ??	W54	40.6	2.8	56.6
R ??	W55	42.3	3.3	54.3
LOC 5	W56	63.6	6.0	30.5
LOC 5	W57	59.4	8.8	31.8
SLS 11, 12,	W58	84.4	5.9	9.7

TABLE RECORDING SAMPLE LOCATION, COMPUTER AND FACTOR LOADINGS, BASED ON PARTICLE SIZE DATA. (CONT'D)

			%	
SAMPLE LOCATION	COMPUTER NUMBER	F1	F2	F3
SLS 11, 12,	W59	87.4	6.5	6.1
SLS 11, 12,	W60	85.7	6.3	8.0
SLS 7	W61	93.3	5.2	1.5
SLS 7	W62	92.8	5.3	1.9
SLS 7	W63	91.8	5.8	2.4
SLS 3	W64	49.1	15.4	35.5
SLS 3	W65	50.4	17.2	32.4
SLS 3	W66	50.9	14.9	34.2
SLS 6	W67	67.7	11.3	21.0
SLS 6	W68	71.5	10.3	18.2
SLS 6	W69	69.4	10.7	19.9
LOC 5	W70	59.9	9.0	31.1
LOC 5	W71	56.8	8.6	34.6
LOC 5	W72	59.3	8.8	31.9
LOC 5	W73	61.4	8.5	30.2
LOC 5	W74	59.3	9.0	31.7
LOC 5	W75	57.6	9.5	32.9
LOC 5	W76	57.7	11.2	31.1
LOC 5	W77	61.7	8.7	29.6
LOC 5	W78	55.5	10.8	33.7
LOC 5	W79	56.8	8.8	34.5
LOC 5	W80	60.6	8.1	31.3
LOC 8	W81	46.2	15.1	38.7
LOC 8	W82	42.6	15.6	41.8
LOC 8	W83	37.6	20.3	42.2
LOC 8	W84	44.8	15.3	40.0
LOC 10	W85	6.0	42.5	51.4
LOC 10	W86	5.8	42.6	51.6
LOC 10	W87	5.3	43.2	51.6
LOC 10	W88	7.9	38.8	53.3

TABLE RECORDING SAMPLE LOCATION, COMPUTER AND FACTOR LOADINGS, BASED ON PARTICLE SIZE DATA. (CONT'D)

			%	
SAMPLE LOCATION	COMPUTER NUMBER	F1	F2	F3
LOC 4	W89	76.6	15.1	8.4
LOC 4	W90	65.8	21.3	12.9
LOC 4	W91	79.0	11.3	9.7
LOC 4	W92	78.5	9.2	12.3
LOC 4	W93	81.6	8.0	10.4
LOC 4	W94	80.7	7.3	11.9
LOC 4	W95	80.8	8.4	10.8
LOC 4	W96	80.7	7.7	11.7
LOC 4	W97	67.4	5.5	27.1
LOC 4	W98	81.3	7.1	11.5
LOC 4	W99	81.5	6.2	12.4
LOC 4	W100	79.1	7.3	13.6
LOC 4	W101	80.0	5.9	14.1
LOC 4	W102	80.4	5.0	14.6
LOC 4	W103	77.3	6.6	16.04
LOC 15	W104	3.2	41.5	55.4
LOC 15	W105	4.8	40.4	54.9
LOC 15	W106	7.7	36.6	55.7
LOC 9	W107	54.5	8.3	37.2
LOC 9	W108	55.7	8.2	36.1
LOC 9	W109	52.3	8.8	40.0
LOC 9	W110	51.7	8.9	39.4
R 1	W111	35.2	2.9	61.9
R 1	W112	36.0	0.9	63.2
R 1	W113	39.7	2.3	58.0
R 1	W114	37.6	3.6	58.8
R 2	W115	36.9	1.7	61.4
R 2	W116	37.3	0.6	62.1
R 2	W117	38.6	1.1	60.3
R 2	W118	38.8	0.6	60.6
LOC 6	W119	4.1	52.1	43.5

TABLE RECORDING SAMPLE LOCATION, COMPUTER AND FACTOR LOADINGS,
BASED ON PARTICLE SIZE DATA. (CONT'D)

SAMPLE LOCATION	COMPUTER NUMBER	F1	F2	F3
LOC 6	W120	3.8	59.4	36.8
LOC 6	W121	1.2	59.7	39.2
LOC 6	W122	1.4	64.0	34.6
LOC 17	W123	15.4	62.7	22.0
LOC 17	W124	28.5	57.9	13.7
LOC 17	W125	10.6	80.6	8.9
LOC 17	W126	10.5	67.3	22.2
R 13	W127	1.7	43.4	54.9
R 15	W128	0.0	53.4	46.6
R 9	W129	31.2	1.0	67.8
R 9	W130	31.1	2.1	66.9
R 9	W131	32.7	0.3	67.0
R 9	W132	29.5	2.3	68.2
R 7	W133	38.5	3.9	57.6
R 7	W134	41.1	2.2	56.7
R 7	W135	40.8	1.9	57.3
R 7	W136	43.9	1.5	54.6
R 8	W137	74.2	0.4	25.4
R 8	W138	71.9	0.1	28.0
R 8	W139	72.7	0.2	27.1
R 8	W140	71.6	0.2	28.3

deposits. This similarity creates a major problem which must be solved if one is to draw positive conclusions concerning the late-glacial history of the Tees Basin. The recognition of marine deposits from lacustrinal deposits laid down under similar conditions may have to rely on the discovery of indicator fossils.

<u>Discriminant Function Analysis</u> (<u>Particle Size Data only</u>)

This technique is useful for a variety of problems involving classification and is applied in this instance to the results of the previously discussed factor analysis. The aim was to determine the number of groups or facies into which one could classify the samples.

The following table show the results which were obtained. (Table 236). In all, 14 groups can be recognised but these may be grouped into six "super-facies".

To explain the significance of the above results one must first clarify exact nature of discriminant function analysis.

Discriminant functions may be described as lines which best separate samples into groups. The maximum number of discriminant functions for a particular problem is the lesser of two numbers, G-1, and N, (where G is the number of groups and N is the number of variables measured for each sample.) The similarity of a sample to a group depends on:-

1) The dispersion of the group in discriminant space.
2) The distance in discriminant space between the sample and the position of the mean of all samples forming the group.

RESULTS OF DISCRIMINANT FUNCTION ANALYSIS PERFORMED ON SAMPLES OF KNOWN ORIGIN FROM THE TEES BASIN

Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9	Group 10	Group 11	Group 12
D01	D06	B01	B25	B20	R01	R06	W40	W01	W06	W14	W44
D02	D07	B02	B26	B23	R02	R07	W41	W02	W07	W15	W45
D03	D08	B03	B27	B24	R05	R08	W42	W03	W19	W16	W46
D04	D09	B04	B28	B41	R09	R11	W43	W04	W28	W48	
D05	W09	B05	B29	W29	R10	R12	W52	W05	W56	W49	
D10	W119	B06	B30	W30	W38	W123	W53	W08	W57	W50	
D11	W127	B07	B31	W31		W125	W54	W11	W70	W51	
D12	W128	B08	B32	W32		W126	W55	W12	W71	W64	
D13		B09	B33				W111	W17	W72	W65	
B13		B10	B34				W112	W18	W73	W66	
B14		B11	B35				W113	W20	W74	W81	
B15		B12	B36				W114	W21	W75	W82	
B16		R03	W47				W115	W22	W76	W83	
B17		R04	W129				W116	W23	W77	W84	
B18		W36	W130				W117	W24	W78		
B19		W120	W131				W118	W25	W79		
B21		W121	W132				W133	W26	W80		
B22		W122						W27	W97		
B37								W33	W107		
B38								W34	W108		
B39								W35	W109		
B40								W58	W110		
B42								W59			
W10								W60			
W13								W61			
W37								W62			

"SUPER FACIES"

(1) Groups 1, 2,
(2) Groups 3, 4, 5
(3) Group 8
(4) Groups 6,7
(5) Groups 9, 10, 11,
(6) Group 12.

The technique may be applied to several classificatory problems and in the present study is used for:-

(a) Distinguishing between established sample categories.

(b) Placing "unknown" samples within the above categories.

A careful examination of (Table 236) suggests that the technique is only partially successful. Possibly it is too sensitive for the data, as it recognises several groups within each environmental zone which do not emerge from the three factor plot (Fig. 86).

However, the main test of the technique will be in the following chapter when the samples of unknown origin are fitted into the previously categorised "known" samples.

Factor Analysis (2)   All Sedimentary Characteristics

If one examines Table 238 and Fig. 87 one can see that the results of this analysis have not proved successful. The only exception is the river samples which have a consistently high loading on factor 2. Whilst the other three environments are dominated by factor 1.

Possibly one can explain this failure by the inclusion of shell fragments in the analysis. The fluvial samples were the only group which did not contain shell fragments. Alternatively, the inclusion of the extra variables may have resulted in one variable cancelling out a second one such that neither gave a high loading. One possible solution could be to run each set of variables, eg. heavy minerals, or rock fragments, separately. Most probably the sedimentary date was inadequate and should have included the whole size range rather than only the central values.

FACTOR ANALYSIS 2 (All Sedimentary Data)

		% Factor Loading		
	Sample	Factor 1	Factor 2	Factor 3
BEACH	Seaton Carew Beach 2	96	0	4
	Saltburn Beach	82	9	10
	Beach North of Saltburn	85	1	14
	Marske Beach 1	85	2	13
	South Gare Seawardside 10	85	4	11
	Redcar Beach 3	87	2	11
(FIRTH OF FORTH)	Musselborough Beach 1	63	19	18
	Hartlepool Yacht Club Beach 3	33	33	34
	Hartlepool Yacht Club Beach 1	98	1	1
	Crimdon Beach 1	85	5	10
	Crimdon Beach 3	55	5	45
SUTHERLAND, SCOTLAND	Droman Beach A	85	5	10
" "	Droman Beach B	85	5	10
DUNE	South Gare dune D.	82	5	13
	South Gare dune A	87	2	11
	Cliff Slip hunt cliff	54	32	14
(FIRTH OF FORTH)	Musselborough sand dune	66	18	16
	Crimdon dune 2	65	31	4
	Crimdon dune 18'OD	72	13	15
	Crimdon dune 33'OD	92	1	7
	Crimdon dune 5'OD	77	12	11
(SUTHERLAND, SCOTLAND)	Droman dune	85	5	10
	Droman dune	85	5	10
RIVER	Saltburn River sand	9	72	19
	Thorpe Thewles River sand 4	14	54	32
	Saltburn flood sand 1967	6	68	26
	Thorpe Thewles 1	6	71	23
	Thorpe Thewles 2	18	81	1
	Billingham Beck 1	12	68	20
	Billingham Beck 2	9	74	17

FACTOR ANALYSIS 2 (All Sedimentary Data)

		% Factor Loading		
	Sample	Factor 1	Factor 2	Factor 3
OFFSHORE	S.L.S. 10	32	17	51
	S.L.S. 4	65	17	18
	LOC 2	35	17	48
	S.L.S. 3	84	5	11
	LOC 12	74	13	13
	R 5	89	3	8
	R 1	90	3	7
	LOC 16	94	4	2
	S.L.S. 9	64	19	17
	R 2	80	12	8
	R 8	90	4	6
	LOC 7	49	28	23
	LOC 1	27	22	51
	S.L.S. 6	64	19	17
	LOC 10	88	4	8
	R 9	86	2	12
DROMAN	A Site 1	84	2	14
	B Site 1	75	10	15
	A Site 2	85	4	11
	B Site 2	87	2	11
	C Site 2			

Cumulative % of variability accounted for by siz factors

F1	F2	F3	F4	F5	F6
42%	82%	92%	95%	97%	99%

In summary, when the author first became interested in factor analysis the only programme available,was for 60 samples and the present study involved several hundred samples and the author is indebted to Dr. J. E. Klovan, who rewrote his existing programme to encompass 200 samples and who also performed the discriminant function analysis. One should point out that it is not possible to compare two different factor analyses as the factor loading ratios are the result of the interactions of all samples included in the analysis. Theoretically, the removal of one sample could alter the factor loadings of all other samples. Although the author is studying to master both factor and discriminant function analysis, at the time of writing only 289 samples including unknowns were able to be analysed and this restriction effectively curtailed the efforts made to obtain representative samples. Even so, the results have proved fairly encouraging and are summarised along with the remainder of this chapter in the following discussion.

Conclusions

This chapter set out to test the feasibility of identifying a known depositional environment from its sedimentary character. If successful it will provide the key to an understanding of the late and post-glacial history of the Tees Basin. Each variable is considered in turn and its value carefully assessed.

1) Particle Size

Detailed analyses of several hundred samples from different known environments demonstrated that each environment has a typical "curve" when plotted on arithmetic probability paper. The "curve" may succeed in identifying two samples when moment measures fail. The mineralogy of deposits indicated that particle size measurements may, in part, reflect sample composition. This was particularly noticeable in samples which contained abnormally high percentages of light density shell and coal fragments.

2) Particle shape

A pilot survey indicated that the shape of sand size quartz grains has no environmental significance in the lower Tees Basin. This conclusion disagreed with the work of MacCarthy (1935) and Beal and Shepard (1956). The shape of shell fragments and mica, did however, result in differences in the distribution of each. Both may occur as coarse fractions in a deposit composed predominantly of much finer material.

Surface Texture

The reflected light from quartz grains was measured using a Western Mark IV light meter. The degree of polish in the marine littoral deposits exceeded all other environments, including lacustrine, and would appear to be a valuable means of recognising a beach sand.

Percentage Heavy Minerals

It was not so much the total content, but the distribution of heavy minerals within the sample size range which provides the key to environmental identification. In both dune and beach sands selective sorting results in a concentration of heavy minerals in the finer size fractions. This selective sorting did not appear to occur in fluvial and offshore deposits. In Sutherland (N.W.Scotland) the sands are composed very largely of weathered granitic and metamorphic "shield" rocks which contain a high percentage of heavy minerals. The effect of this source material on both beach and dune sands, is most distinctive.

SUTHERLAND (N.W. SCOTLAND)

Percentage Heavy Minerals

Dune Sand				Beach Sand			
1.66φ to 2.3 φ	2.31φ to 2.75φ	2.76φ to 3.4 φ	3.41φ to 3.8 φ	1.66φ to 2.3 φ	2.31φ to 2.75φ	2.76φ to 3.4 φ	3.41φ to 3.8 φ
1.1	4.7	49.4	95.0	0.9	2.5	7.3	-
0.99	3.19	50.52	95.45	0.2	0.5	3.0	-

Coal Content

Coal content showed a marked decrease in a southerly and inland directions. This reflected the location of source area (Coastal waste to the north). Thus, coal content cannot be used for the present study as the availability of coal was less in the late Pleistocene and early Holocene. The distribution of coal fragments within a sample may be of value independently of the total content. For this latter reason coal content was calculated for the samples of unknown origin which occur in the Tees.

Shell Content

Three environments, dune, offshore, and beach contain shell fragments. The most noticeable concentration occurs along the H.W.M.

of beaches and may be equated with an increased negative skew and more extensive "coarse tail" in a sample. One should note, however, that it is unlikely that shells will occur as extensively in late Pleistocene and early Holocene time. The coastal tract will only recently have been flooded by the eustatic rise of sea level and the water would be less saline and probably very muddy as a result of the rapid influx of glacial meltwater.

Mica Content

Mica tends to concentrate in standing water bodies. It does not occur frequently in sandy deposits but is present in the Tees in small quantities in all but windblown deposits.

Rock Fragments

The rock fragment content appears to be related to two factors:

1) The erosional efficiency of the environment.

2) The proximity of the sample to the rock source.

1.) The beach samples contained very few rock fragments probably because wave action is the most efficient erosional agent in the Tees. An exception to this occurred close to the Long Scar Rock (Seaton Carew) where both beach and offshore samples contained a greater percentage of rock fragments.

2.) The fluvial deposits in the Tees basin contained 600% the number of rock fragments that occurred in other environments. This high content would appear to reflect the low rate of erosion in the lower Tees drainage basin, which is in turn a function of the very gentle gradient of the lower reaches. (Chapter 4.)

Concluding Statement

One should reiterate that despite the many, varied results obtained from the analyses, two factors stand out in significance.

1) The strong evidence in favour of particle size analysis being partly a measure of individual sample composition. This fact would explain, along with the three factors of sampling, processing and analysis, why previous works have proved inconclusive.

   It would appear that current energy responds to density and shape as well as size. This fact has been known for some time, Ruhkin (1937 op.cit.) but does not appear to have been given the attention it deserves in studies of environmental sedimentology.

2) The second important point refers to the success of factor analysis as a means of distinguishing between environments. This success was achieved using only particle size and later improved upon by the inclusion of other mineralogical variables.

It remains to observe whether these conclusions may be applied, with similar success, to the late and post-glacial environment of the lower Tees Basin.

CHAPTER 9

THE APPLICATION OF SEDIMENTOLOGICAL TECHNIQUES TO THE DEPOSITS OF THE LOWER TEES BASIN

Introductory Statement

The primary aim of this chapter is to determine whether displaced marine deposits occur in the Tees Basin; both above and below present Ordnance Datum, by using the sedimentary techniques outlined in Chapters 6 and 8. In the ideal situation positive identification should be supported by both morphological and fossil, faunal or floral evidence.

The study can be divided into six basic sections:

(1) General commentary on the "fossil" sedimentary environments in the Tees Bay.

(2) Specific sites which have been identified as marine deposits by previous workers.

(3) Sites which could possess marine terrace deposits.

(4) Other sand and gravel deposits in the Tees Basin.

(5) Buried sands below the present sea level.

(6) Synthesis: Factor analysis, discriminant function analysis; and conclusion.

Before proceeding one should note the following changes in approach which have been instigated as a result of the findings in Chapter 8.

(1) Detailed discussions of individual sedimentary characteristics have been avoided; unless they are of particular significance.

(2) Moment measure values have been omitted as they proved to be an inefficient measure of the particle size curve.

1) "Fossil" Sedimentary environments in the Tees Bay

The conclusions drawn in Chapter 4 suggest that two related processes were responsible for the surface deposits in the lower Tees; the deglaciation pattern, and its effect on meltwater drainage. It was suggested that some of the higher terraces 90' OD and above) were related to individual marginal lakes ponded back by the easterly retreating ice tongue, whilst the lower terraces could be related to a single water body which could have been either marine or fresh water. It seemed more probably that the latter was correct as the retreating ice tongue would certainly have formed a drainage plug in the mouth of the Tees basin. Some preliminary investigations were carried out to see if it was possible to positively identify the depositional environment of the laminated clay which occupies part of the lower Tees basin (fig. 10, Chapter 3).

The Laminated Clay

Previous workers have suggested three origins for this deposit:

1) A lacustrine clay of late glacial age (Radge 1939 op. cit.)
2) A shear clay formed under pressure beneath an active ice sheet and later melted out under conditions of stagnant ice. (Carruthers 1953 op. cit.)
3) An estuarine or marine clay (Agar 1954 op. cit.)

Any of these may be correct, but certain characteristics may negate. 2 and 3.

A shear clay is usually deposited in saturated conditions beneath a stagnant ice mass. When this occurs it is usual for the laminae to be contorted and discontinuous with no size or density gradient. (Jorgenson 1965) In contrast to the above statement the lower Tees laminated clay has reasonably continuous laminae which possess ripple marked surfaces. Each laminae is separated from its neighbour by a thin sandy layer which in some cases contains up to 20% mica. Although the laminae are not necessarily varves this density sorting between them would seem to favour a water lain origin.

Agar 1954 (op. cit.) noted that the laminated clay was interbedded with silty sand towards its outer limits. It is likely that coarser particles would increase towards the shoreline of a water body and the following experiment was conducted to confirm this trend. Spot samples were purposefully taken from the laminated clay every two feet from vertical sections in various clay pits and temporary sections (see fig. 88 A.) Each sample was analysed for its silt content and (Fig. 88 B) indicates that the silt content does increase towards the periphery of the deposit.

This evidence, combined with the earlier observations confirms that the deposit is almost certainly water lain. Isolated boulders also occur in the clay and one particular specimen of Shap Granite (Agar 1954 op. cit.) suggests very strongly that floating icebergs occupied the surface of the water body. The boulders most probably fell from bergs as they gradually melted, and the laminae around the boulders are contorted.

One is still faced with the problem of a lacustrine versus marine origin and samples were tested on an "X" ray diffractometer to discover if nodular glauconite was present. This mineral has been recognised as a marine indicator by several workers, Dietz 1942, Powers 1957, Pratt 1962, and Jorgenson 1965. Fig. 89 shows the characteristics of glauconite and Fig. 90 the similarities between glauconite and biotite, the mineral to which it rapidly alters under none-marine conditions. Fig. 91. shows the results of analyses on the Tees laminated clay and it would appear that biotite is present but not glauconite. Although this is negative evidence, it does not contradict the most likely hypothesis to explain the origin of the Tees laminated clay; that of an ice-dammed lake. Certainly, salinity, temperature, and turbidity requirements do not eliminate the Tees as an area of glauconite formation. Similarly it is unlikely that oxidation will have destroyed any glauconite which may have previously existed, as samples were taken from a freshly excavated site.

TABLE RECORDING CONDITIONS REQUIRED FOR GLAUCONITE FORMATION (After Pratt 1962.)

1) Stratigraphic Renge - Pre-Cambrian to Present.

2) Present areal distribution 65° S to 80° N off most oceanic coasts and mainly on the continental shelves away from large streams.

3) Salinity. Known to originate only in marine waters of normal salinity (33.8 to 34.4 parts per thousand)

4) Oxygenation. Formation requires slightly reducing conditions.

5) Formation is facilitated by the presence of decaying organic matter.

6) Depth - mainly neritic - moderate to shallow (10 to 400 fathoms is most common occurrence)

7) Temperature - Wide tolerance but formation not favoured by markedly warm waters (11°C. to 2°C. most favoured)

8) Turbulence. Evidence of turbulence is commonly found in associated sediments

9) Sedimentary influx - probably slight, preferably just enough to supply needed elements

One very interesting fact, which came to light during the perusal of borehole records, was the occurrence of what appeared to be a fairly continuous layer of laminated clay extending beyond the present coastline to a maximum depth of 116' O.D. (Fig. 92). If this is genuinely the same deposit, or a deposit of similar age it would appear that sufficient isostatic uplift had taken place by the time the Tees was deglaciated such that the late glacial sea level was at least 116' below that of present. If this was the case then the 82' O.D. late glacial raised shoreline would require some rapid sea level movements. Hopefully the following chapter on the chronology of events will clarify this situation.

Marginal Sands

Agar (1954 op. cit.), Smith (personal communication) and Land (personal communication) all noted the occurrence of two sand layers marginal to the laminated clay. One was interbedded with the clay, and the other overlay it unconformably. Agar (ibid.) described this upper sand as a shoreline deposit because it occupied a notch cut into the surface of the underlying boulder clay, and suggested that it marked the level of an +82' O.D. late glacial raised shoreline. The deposit was noted to be discontinuous and was not necessarily related to the laminated clay. In addition, the notch was only observed on the south side of the present Tees, although sand deposits were recognised at a similar height on the northern side. This sand crops out near Park End Farm (NZ 520175) and Agar (personal communication) described the deposit as a distinct notch cut in boulder clay at 75' O.D. and 10' above the limit of the laminated clay. This deposit warranted particular attention as its character and mineral content could give some indication of the depositional environment.

Agar (1954) further noted the occurrence of sand at the following locations:

1) West Hartlepool 80' O.D.
2) Wolviston Grange 70' O.D.
3) Roseberry Road Norton 50' O.D.
4) Stainsby School. Middlesbrough 55' O.D.
5) Bowesfield Land 60' O.D.
6) Acklam, Middlesborough 55' O.D.
7) Berwick Hills, 30' O.D.
8) Thorntree (Middlesbrough 60' O.D.
9) Park End (Middlesbrough) 70' O.D.
10) Eston Cemetary 70' to 85' O.D.
11) Marske 70' O.D.

All were regarded as marginal sands, possibly related to the body of water in which the laminated clay was laid down.

These wide occurrences of sand deposits adjoining and overlying the laminated clay led Smith (personal communication) to conclude that a sand bed probably overlay the laminated clay. If one was to recreate the conditions during deglaciation one could envisage an ice dammed lake being fed by numerous meltwater streams gradually receding as the ice melted and the meltwater streams and runoff flowing over the laminated clay bed of the lake leaving braided delta deposits on its surface. Whilst this layer need not necessarily be continuous it would certainly provide a very likely explanation for the current bedded sand deposits which occur intermittently over the lower reaches of the Tees basin.

Summary

These two depositional groups, the laminated clay and the marginal sands largely dominate the lower reaches of the Tees basin. Several isolated laminated clay beds occur elsewhere in the Tees (Hurworth, Coatham Stob., Low Hail) but the remainder of the surface deposits are largely glacial or fluvio-glacial. Some warrant specific comments in section four of this study (chronology) but it would appear that the laminated clay and its marginal sand deposits may hold the key to the late and post glacial history of the Tees basin.

2) SPECIFIC SITES RECOGNISED AS MARINE BY PREVIOUS WORKERS

In all, there are seven records of marine deposits above the influence of the present tidal range in the Tees basin.

1) Veitch 1883. A sandy deposit containing shells at Saltburn. Later confirmed by Barrow 1888.

2) Tute 1883. A marine or estuarine shelly deposit northwest of Redcar at Warrenby.

3) Marine or estuarine fill in the tributaries of the Tees. (Agar, 1954)

4) A 75' to 82' sand notch on the south side of the Tees. (No marine faunal remains.) (Agar, 1954)

5) A 41' notch containing a yellow sand with occasional shells. (Agar, 1954)

6) A raised storm beach grading into an offshore bar on the north side of the present basin. (Gaunt, 1967)

7) A terrace of marine warp at Hartlepool. (Gaunt, 1967)

Each of the above sites is examined in turn to assess its validity. Sediment analyses are discussed and compared where possible.

1) The Saltburn deposit containing a distinct shell assemblage

The deposit was recognised near the mouth of the Skelton Beck in the side of a conical mound of glacial deposits, named Cat Nab (NZ667216). There are, in fact, two deposits; one a fine clayey sand, and the other a medium sized gravel. Both deposits contained some shells and shell fragments and certainly appeared to suggest marine conditions.

However, a careful investigation of the precise stratigraphy and the surrounding area suggested that an alternative explanation was possible. Fig. 92. demonstrates that the gravel bed is not on a wave cut notch but is an integral part of Cat Nab. The same figure also shows the position of the sandy clay deposit which also contained shell fragments.

Cat Nab was originally exposed to the influence of high spring tides before the construction of the present coast road and breakwater. Even at the present time its surface is covered with a thin veneer of sand and shell fragments; which are probably wind-blown. The surface sheet flow which is shown in Fig. 92. (Section A-B) (photo in Appendices) has carried with it shells and shell fragments and given the impression of an "in situ" occurrence. Sedimentary analyses on the sand lens suggest that it could be a washing limit of the Skelton beck. (Table 255) Not only is there evidence of current bedding (Fig. 93); the particle size curve does not resemble that of a normal beach. (Fig. 94) An examination of sand deposits throughout the Durham region has led the author to believe that shell fragments will respond as sand grains when subject to water sorting. In this way, fluvial or fluvio-glacial sands and gravels may serve to concentrate shell fragments which occurred in the source material. The glacial clays of County Durham frequently contain shell fragments which were probably absorbed by the ice as it passed over deposits laid down on the sea bed during the preceding inter-glacial period. Thus, it is possible for shell fragments to occur in a non-marine-deposit.

Barrow (1888) noted that the Saltburn deposit contained a wide range of shells, all of which occurred on the present beach. Some of the present day shells were absent from the raised deposit, and this led Barrow (ibid.) to suggest that environmental conditions were different when the raised deposit was formed. However, a collection of the shell fragments enabled one to demonstrate that all could have been blown in a 30-mile-an-hour wind.

Thus, in summary, one must suggest that the close proximity of this site to present sea level is an equally likely explanation of the shell content as a raised shoreline. Rose (pers. comm. 1967) also examined this site and similarly concluded that the supposed raised shoreline deposit was of questionable origin. One should acknowledge, however, that road alterations and landscaping have taken place since both Veitch and Barrow examined the site and it may also be possible that the marine deposit was destroyed.

TABLE SHOWING SEDIMENTARY CHARACTER OF SUPPOSED MARINE DEPOSIT AT SALTBURN

SITE	2.3φ to 4.1φ % Heavy Minerals	2.3φ to 4.1φ % Rock Fragments	2.3φ to 4.1φ % Coal	2.3φ to 4.1φ % Shell	2.3φ to 4.1φ % Mica	Surface Texture
Sample 1	4.1	21	-	2	0.2	9
Sample 2	3.2	33	-	4	0.8	11
Sample 3	3.5	18	-	2.5	0.2	12
Sample 4	3.4	25	-	3.8	0.6	10
MEAN	3.5	24	-	3.75	0.45	10.5

2) Marine or Estuarine mud with shells at Warrenby, near Redcar.

Warrenby, (NZ 581249) is situated west of Redcar on land which was reclaimed from the estuary. The area was examined and it is certain that Tute (1883) was describing a deposit which occurred within the reclamation dyke. It is possible that the deposit was estuarine mud used as fill or alternatively that it was an "in situ" deposit overlain by fill. In either case it was not felt necessary to analyse the deposit.

3) Marine or Estuarine fill in the lower Tees and Tributary Valleys

This deposit was described by Agar 1954 as a grey alluvium and was observed to occur to a maximum depth of -84 O.D. in the present estuary, rising to the base of a peat bed just below Ordnance Datum. This same grey alluvium is recorded in the tributary valleys as far inland as Wynyard Park (NZ 420250), 5 feet below ground level, at 55' O.D. At this site and several others organic debris was observed (tree debris and roots), but there is no evidence of marine remains above present O.D. The deposit would appear to be associated with the gradual rise of sea level from -84' O.D. to present O.D., where it grades into a fresh water peat bed.

Some confusion has occurred with this deposit as it appears to be continuous from estuarine to alluvial environments. All the organic remains are terrestial (leaves, nuts, branches, antlers, (Agar 1954) and the name estuarine alluvium relates to its location at depth, not its mode of origin. Almost certainly this deposit was laid down when the streams gradually silted up as sea level rose from -84' O.D. to its present level.

4) A sand deposit notched in boulder clay at 75' to 80' O.D. on the south side of the Tees

Agar (1954 op. cit.) is again responsible for the interpretation of this deposit as a marine notch. It was suggested that the sand could have been deposited in either a lacustrine or marine environment. However, the notch is incorporated in a graph of sea level change, despite the absence of any supporting evidence. One can only surmise that this decision reflected Agar's knowledge of the original sequence of 25', 50', and 100' levels which were recorded in Highland Britain. Agar (pers. comm. 1967) did, in fact, suggest that the 82' level was related to the supposed "100'" level in Scotland. This nomenclature and height classification (25', 50', 100') is no longer popular.

The following analyses were performed on those sites listed on page which Agar considers as marginal sands, and which are still accessible. (The majority of sites were exposed in temporary excavations during urban and industrial expansion whilst Agar was employed by Middlesbrough Corporation and are now inaccessible.)

(a) West Hartlepool 100' O.D. (NZ 477299) (Brierton)

This site consists of a large mound of sand containing current bedding and some tilted gravel beds. In addition there were distinct zones in the sequence where the laminae were noticeably finer and more horizontal.

As a result of these variations a detailed stratified random sampling plan was used to obtain 42 sedimentation unit samples. (Fig. 95.) Tables 259 and 260 demonstrate that these samples may be divided into groups, each of which may be related to a different depositional environment.

The inadequacy of textural parameters is emphasized when the results are compared with that of factor analysis. Factor analyses of thirty of the samples recognises three distinct groups:-

1) Samples A and C
2) Sample B
3) Samples 1, 2, 3,

The three groups coincide with the site stratigraphy (Fig. 95 .) and it would appear that "A" and "C" were deposited under similar energy conditions. A comparison with (Fig. 86.) (Chapter 8) would suggest that the three distinct zones, which are recognised at Brierton, may be equated with present day offshore, beach, and river conditions, on the basis of factor loading ratios.

TABLE RECORDING TEXTURAL PARAMETERS OF SAMPLES

FROM BRIERTON (WEST HARTLEPOOL 477299)

Sample Number	ø Mean	ø Standard Dev.	ø Skewness	ø Kurtosis
3	2.35	1.46	-0.14	1.01
1B	2.6	1.17	-0.21	1.0
2C	2.53	1.2	-0.18	1.04
1a	2.56	1.22	-0.26	0.93
1b	2.25	1.4	-0.29	0.99
1A	2.59	1.16	-0.12	1.53
4C above 3C	2.37	0.68	-0.04	1.07
2	2.55	1.37	-0.25	0.97
$4A^{(2)}$	2.65	1.17	-0.18	1.03
2	2.57	1.33	-0.2	0.97
$2A^1$	0.87	0.85	-0.27	0.94
2C	1.37	1.05	-0.08	1.1
2B fg	1.2	1.13	-0.08	1.11
$2A^2$	1.11	0.89	-0.24	1.23
$A3^1$	1.78	0.99	0.16	1.54
$A3^2$	1.72	0.95	0.14	1.41
$2B_1$	1.52	1.1	0.09	1.11
C3	1.97	0.54	0.23	1.03
$C2^2$	1.97	0.6	0.19	1.17
$A2^1$	1.95	0.96	0.29	1.49
$A2^2$	1.88	0.96	0.21	1.56
$A1^1$	1.72	1.0	0.15	1.68
$A1^2$	1.63	1.0	0.0	1.64
Top $3A_2$	2.32	0.74	0.22	1.01
Top $3A_1$	2.2	0.72	0.08	1.12
4C above $3C_1$	2.32	0.68	0.11	1.07
$C5^1$	2.03	0.51	0.17	0.93
$C5^2$	2.08	0.52	0.19	0.92
$C4^1$	2.02	0.57	0.22	1.03
$C4^2$	2.13	0.54	0.2	1.04
$C6^1$	2.08	0.55	0.11	1.04
$C6^2$	2.09	0.52	0.14	0.95
$C2^1$	2.04	0.63	0.23	1.22
$C1^1$	2.34	0.7	0.19	1.28
$C1^2$	2.38	0.7	0.24	1.37
$B3^2$	2.88	0.65	0.16	1.0
$B2^1$	2.85	0.65	0.1	0.99
$B2^2$	2.57	0.68	0.09	1.02
$B1^1$	2.67	0.62	0.12	1.11
$B1^2$	2.54	0.7	0.12	1.02

TABLE RECORDING SEDIMENTARY CHARACTERISTICS OF BRIERTON (WEST HARTLEPOOL NZ477299)

	Mica (grains/1000)				Coal (grains/1000)			
Sample Number	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø
C6	0	0	0	0	0	0	0	0
C4	1	Trace	Trace	1	5	0	0	19
2B	1	8	1	1	1	12	Trace	1
4C above 3C	1	2	1	Trace	28	10	8	8
A2	Trace	10	9	11	0	Trace	1	2
C5	0	0	1	5	Trace	Trace	Trace	Trace
C2	10	0	3	5	10	11	8	3
2C	0	1	7	5	11	12	10	10
2A	0	0	3	3	12	12	39	5
C3	0	0	5	0	2	Trace	4	12
3C Bottom	0	4	9	8	27	30	20	10
4A	0	0	6	17	132	61	70	110
Top 3A	0	0	2	5	3	15	9	12
Mi 53B	1	20	8	11	40	21	11	6

		% Rock Fragments				% Heavy Minerals			
Sample Number	Surface Texture	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø
C6	8	119	42	38	17	2.6	2.6	2.4	2.1
C4	6	20	13	9	39	2.2	4.3	2.8	9.7
2B	7	110	47	21	28	5.7	3.1	10.4	13.4
4C above 3C	9	71	22	11	2	2.7	2.1	1.3	1.3
A2	8	28	28	7	0	3.8	3.0	2.6	2.1
C5	7	62	54	41	13	3.0	3.5	4.0	2.2
C2	8	28	31	30	5	4.4	3.9	4.5	5.4
2C	6	130	42	20	0	7.2	4.0	13.0	3.2
2A	9	37	18	15	17	23.0	16.6	6.4	9.0
C3	6	64	47	38	17	2.5	3.3	3.8	32.7
3C Bottom	8	61	40	12	2	1.7	2.2	1.6	1.1
4A	8	160	50	41	50	1.9	1.4	1.8	11.0
Top 3A	7	165	45	3	2	2.5	2.3	2.6	2.0
Mid 3B	10	52	30	19	3	2.5	2.2	2.6	1.5

No Shell Content.

The absence of shell fragments, and the presence of a veneer of red stony clay overlying the deposits would seem to favour an origin marginal to an ice sheet. In this way one can explain the wide variety of environmental conditions in such a limited area. Raistrick (1931 op. cit. Chapter 3) described the deglaciation stages in the Tees (Fig. 12.) and Beaumont 1970 (in press) suggested that the ice margin may have followed the contours quite closely on the northern side of the Tees. The ice would, of course, be thicker away from the snout and the ice margin would probably rise in a N.N.E. direction.

Certainly, a comparison of one group of Brierton samples with the sand content of boulder clays from the Tees and Northumberland suggests that an ice marginal origin is possible. There would appear to be very little difference indeed. The particle size graphs of the two other environmental groups appear to confirm an origin in standing water (Fig. 96.) and running water (Fig. 95). This threefold environmental complex could possibly be explained as an ice contact Kame delta where the energy was sufficient to separate the three size fractions of boulder clay, gravel, sand and clay. The height of the mound, which stands 20 feet above the surrounding area is difficult to explain if one discounts an ice contact origin. Only wind action could create such a feature, and the stratigraphy, mica content, and sorting characteristics would seem to preclude the influence of wind action.

(b) Park End Farm (Middlesbrough. N.Z. 520175) Eston Cemetary (NZ. 548188) (Table 263)

Both of the above sites are described by Agar (op.cit.) as examples of marginal sand. In each case some difficulty was experienced in procuring undisturbed samples. This was particularly so at Eston Cemetary. Two samples were analysed from each site and the results of particle size analyses alone were sufficient to confirm that the sands most probably represented a washing limit of a low energy environment, overlain by a coarser sand which was possibly of deltaic origin. (Fig. 97.). The sorting pattern of either of these samples could not possibly be confused with a marine beach similar to the present day environment and it would seem more logical to equate the lower sand with the washing limit of an ice dammed lake and the upper sand with a meltwater current entering the lake when it had receded to a lower level:

(See Table) Sedimentary analyses suggest that the two coarse and two fine deposits are similar and may extend along an axis parallel with the contours. This distribution pattern agrees with findings by the Middlesbrough Corporation (Agar Personal Comm. 1967) and augments Agar's conclusion that the

TABLE RECORDING SEDIMENTARY CHARACTERISTICS OF SAMPLES FROM PARK END FARM (NZ 520175) AND ESTON CEMETARY (NZ 548188)

		Mica (grains/1000)				% Rock Fragments				Coal (grains/1000)				% Heavy Minerals			
Sample	Surface Texture	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø
Park End Coarse	8	8	Trace	1	0	121	48	36	7	0	0	0	0	6.4	6.0	3.2	3.3
Park End Fine	9	21	12	19	11	20	11	12	1	0	0	0	0	2.7	7.9	4.0	7.6
Eston Coarse	7	5	2	Trace	1	119	54	31	2	0	0	0	Trace	8.1	4.2	5.1	5.4
Eston Fine	8	17	18	3	12	0	0	1	0	0	0	0	0	1.2	1.8	1.0	1.4

deposits concerned were marginal to a water body which occupied the lower reaches of the present drainage basin.

5) <u>A 41' notch in the laminated clay, composed of yellow, clean sand and which contains occasional shells</u>

Agar (1954) recognised this deposit which occurred in the Ormesby (NZ498188) and Middle Beck Valleys (NZ508186). There was no evidence of the sand notch on the land between the two valleys, and Agar (ibid.) based his marine hypothesis on the presence of isolated shells, identified as Cardium edule. The deposit was discovered during a sewer excavation and consequently the present author was only able to locate the layer in hand dug holes. Samples were taken from three such holes in the Ormesby Beck Valley but the deposit could not be found in the Middle Beck. The analyses of the three samples suggest that the dominant energy was running water (Table 265). Both the particle size curves (Fig. 98), and rock fragment content seem to confirm this and again one could hypothesise that the sand was laid down in a deltaic complex associated with the ice-dammed lake which probably occupied the lower Tees. The presence of shell fragments in sandy deposits is not unusual in the Tees as some of the stony clays originated offshore. Fluvial and fluvio-glacial sand and gravel deposits, which are formed from these stony clays, frequently contain several shell fragments. It would seem that the shell fragments are concentrated in the sand and gravel

TABLE RECORDING SEDIMENTARY CHARACTERISTICS
OF SAMPLES FROM THE ORMESBY BECK VALLEY

		Mica (grains/1000)				% Rock Fragments				Coal (grains/1000)			
Sample	Surface Texture	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ
1	8	0	1	0	0	411	210	140	12	12	1	0	0
2	11	3	1	1	2	310	96	72	60	10	3	1	0
3	7	0	Trace	Trace	1	120	84	61	20	2	0	0	0

		% Heavy Minerals				Shell (grains/1000)			
Sample	Surface Texture	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ
1	8	7.0	4.7	3.4	3.0	Trace	Trace	0	0
2	11	6.4	4.5	22.75	2.3	Trace	0	0	0
3	7	4.1	4.7	3.6	1.4	0	0	0	0

fractions when the clay is broken down by current flow. This would explain the occurrence of shell fragments in many sands and gravels to heights of 200' O.D. in North East England (Anderson, 1939).

Sissons (personal communication, 1967) considered that the sand at 41 O.D. was most likely to be of fluvial origin and that the shell fragments may be derived from an archaeological site.

In summary, it would appear that there is some reason to doubt that the 41' O.D. deposit is marine. There is no other evidence to support a post-glacial sea level at this height. If Agar's identification is valid then the notch must be of late glacial age. Smith and Francis (1967, op. cit.) note that the 41' O.D. sea level is absent from the north side of the Tees and it would seem that a similar conclusion should be drawn for the south side.

6) The Raised Storm Beach which grades into an offshore bar on the North side of the River Tees, between Throston (NZ490335) and Greatham (NZ492284)

Gaunt, (in Smith and Francis, 1967, op. cit.) described the occurrence of a sand ridge, with some gravel, which was 300 to 400 yards wide, and trended north to south for over 3¼ miles between Throston and Greatham. It was widest (650 yards) near Rift House (NZ 495310) where it possessed an asymmetrical profile, with the steeper slope facing west. Elsewhere, Gaunt (ibid) described the ridge as rounded and roughly symmetrical.

The constituent sediments were described as clean sand and pan gravel, both horizontal and current bedded. The gravel was well rounded and occasional shell fragments (possibly a Cardium species) were recognised. (Trechmann had previously recorded shells in a currented bedded gravel at Throston (1915)). The deposits became noticeably finer in a southerly direction and the ridge dipped south from 140' OD to 80' OD. (a gradient of 17.2 feet per mile). This relatively steep dip, for a shoreline deposit led Gaunt (ibid) to suggest that the storm beach gradually became an offshore bar towards its southern limit.

In the present study it was noted that the ridge did not end at Greatham as Gaunt (ibid) suggests, but continues inland almost parallel with the A689. Wolviston to Hartlepool road and consists of pea gravel, coarser gravel, sand, silt, and clay lenses, all frequently overlain by a thin layer of reddish stony clay. The ridge also continues to drop from 80' OD north of Greatham to 70' OD at Newton Bewley (NZ465267) and to 65' OD immediately east of Wolviston (NZ460260). An excellent exposure of the ridge occurs in a gravel and sand pit east of Newton Bewley at the junction of the A689 and the road to Dalton Piercy (NZ482278). This excavation produced the following stratigraphy. (See Photographs Plate 3).

5'7" medium gravel
5'6" red stony clay
2'0" coarse gravel
5'0" pea gravel
2'6" current bedded sand
2'0"+medium gravel

This stratigraphy is not what one would expect to find in a raised storm beach, or even an offshore bar. In both cases these high energy environments are very well sorted.

In order to discover the origin of these deposits it is almost unnecessary to complete detailed sedimentary analyses. Both the morphology and location of the feature would suggest an ice marginal or ice-contact feature, paralleling the north west facing slope of the ice tongue as it retreated in a north easterly direction. This explanation fits in with the assumed pattern of ice retreat in the Tees Basin (Raistrick 1931, Beaumont 1970 in press).

In further support of this alternative explanation are two similar sand and gravel ridges. These are especially distinct at Sadberge (NZ342169) above 200' OD), and at Long Newton (NZ382164) (120' OD). The three ridges most probably represent successive still stands in the ice retreat with the lowermost being the supposed raised storm beach near Hartlepool.

If one examines closely Gaunt's reasons for describing the deposit as a raised storm beach one is forced to conclude that they are both very tenuous indeed. The first was the presence of shell fragments, and the second was the close proximity of the ridge to a terrace of marine warp upon which Hartlepool was situated. Gaunt (ibid.) felt that the terrace and the sand and gravel ridge were genetically and chronologically related. On sedimentological grounds alone, it is highly unlikely that a current energy capable of creating a raised storm beach up to 650 yards wide would deposit an estuarine mud in the nearshore environment.

The accompanying table 442 of sedimentary analyses, particle size curves (Fig. 99) and factor analyses (Fig.199) all suggest that running water was the dominant sorting energy. The author was also able to discuss the origin of the ridge with both Smith and Francis of the geological survey and Francis accompanied the author to the Newton Bewley site. Both agreed with the author that the feature was of fluvial or fluvio-glacial origin and discounted any marine influence.

7) <u>The Terrace of Marine Warp</u>

This deposit forms a continuous planation from the Crimdon Beck (NZ485367) in the north and follows the contours of the present Tees valley, in the south. Smith (in Smith and Francis,

TABLE RECORDING THE SEDIMENTARY CHARACTERISTICS OF SAND DEPOSITS FROM THE SUPPOSED RAISED STORM BEACH OR OFFSHORE BAR AT NEWTON BEWLEY (NZ 465266)

		Mica (grains/1000)				% Rock Fragments				Coal (grains/1000)			
Sample	Surface Texture	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ
Lower Red Sand	8	Trace	Trace	1	1	140	37	18	5	0	Trace	Trace	Trace
Lower Red Sand	6	Trace	Trace	2	2	250	58	20	8	0	Trace	0	0
Lower Red Sand	8	0	Trace	Trace	2	325	200	98	51	18	4	3	Trace
Yellow Sand	11	1	4	2	7	27	12	2	0	7	1	3	0

		% Heavy Minerals				Shell (grains/1000)			
Sample	Surface Texture	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ
Lower Red Sand	8	3.3	1.8	0.7	1.1	Trace	0	0	0
Lower Red Sand	6	4.8	1.9	1.2	1.9	0	0	0	0
Lower Red Sand	8	3.1	1.4	0.5	1.7	0	0	0	0
Yellow Sand	11	7.1	1.5	3.2	0.8	Trace	Trace	0	0

1967 op. cit.) describes the feature as a distinct break of the slope at about 80' OD (the base of the break of slope, in fact, occurs at 60' OD) and which was composed of a series of ill-defined subterraces. It varied in width from 500 yards at Hart Station (NZ480361) to 2 miles south of West Hartlepool. The feature is considered to be largely erosional and the "marine" deposits consist of isolated patches of brown to grey clay. This clay rarely exceeds 3 feet in depth, is stoneless or contains a few small, well rounded stones and grades imperceptibly into the underlying boulder clay. No marine shells have been found but some small encrustations of calcium carbonate, thought to have been produced by marine worms, are present in cracks and on the upper surface of the underlying limestone. Some patches of sand and gravel were noted in temporary excavations at the northern end of the terrace and interpreted by Anderson (1947) as a raised beach deposit.

One can suggest several possible origins for this terrace, and associated deposits, and the merits of each are critically assessed in the following section.

(1) A terrace of marine warp.

(2) An embayment created by meltwater drainage flowing from NNE to SSW alongside an ice plug in the lower Tees.

(3) A fluvial terrace related to the present river Tees.

(4) The ponding beds of meltwater by an ice plug to form an ice dammed lake.

1) A terrace of marine warp

One must discover a marine deposit to support this hypothesis. The author feels that this has not been done. The so-called marine warp is described as reworked boulder clay without any occurrence of marine fauna or flora: The limestone encrustations are unlikely to be related to this planation as they occur beneath the "upper" boulder clay (S. E. Durham Geological Survey Memoir 1967). Anderson (1947 op.cit.) was first to describe a raised beach deposit on the terrace and a recent housing development on the north west outskirts of Hartlepool provided a series of temporary exposures of the stratigraphy: -

18" soil, subsoil, and shells, shell fragments
victorian pottery, clay pipe stems

7'9" red boulder clay

Limestone solid

The shell content which occurs only in the soil layers most probably stems from the common habit of using seaweed as fertilizer. Further, if one looks more closely at the sedimentology of the supposed 'erosional' terrace it seems strange that a predominantly erosional environment should produce a marine warp and not a sand or gravel deposit.

In consequence, one must conclude that the geological survey were largely influenced in their interpretation of this deposit by the previous "marine" hypothesis proposed by Anderson (1947, op. cit.), by the close proximity of the terrace to the present coastline, and by the similarity in height between this terrace and the supposed late-glacial level on the south side of the Tees, which was described by Agar (1954, op. cit.).

In both instances there was no positive evidence to favour a marine origin and the author has already made known his opinion that the 82' O.D. level on the south side of the Tees is more likely to be lacustrinal than marine. One must, in fairness to the geological survey, acknowledge that the terrace is remarkably uniform.

2) An embayment created by meltwater drainage flowing alongside an ice plug in the lower Tees or an ice dammed lake

This hypothesis can be used to good effect to explain many of the more undulating planations at higher levels in eastern county Durham. The most likely sequence of events was one of an almost stagnant ice mass preventing the seawards drainage and enforcing meltwater to move along the ice margin.

There is no doubt that there was an excessive amount of meltwater in the south Durham area, as the many spillways and meltwater channels testify (Ferryhill Gap NZ302320, Aycliffe NZ285225, Hope House NZ333251). The presence of an eastward retreating ice sheet in the lower Tees must have prevented much of this meltwater from reaching the sea. Thus it is possible for the supposed terrace of marine warp to be formed partly by marginal meltwater drainage and partly by meltwater ponded back to create a proglacial lake. The terrace could possibly have formed contemporaneously with other levels in the Tees either by a single large water body or by a smaller marginal lake. The fourth hypothesis is preferred to the second because of the very gentle gradient exhibited by the terrace.

3) A fluvial terrace related to the present drainage basin

It is possible that the terrace was formed by run off during the early stages of the evolution of the present drainage basin.

In summary, the Hartlepool terrace of marine warp typifies the problem which was discussed in Chapter 2; that any terrace in a coastal location is too frequently presumed to have originated under marine conditions.

The previous discussion has shown that none of the seven deposits can be regarded as definitely of marine origin. In fact, those deposits which occur on the north side of the Tees can be identified as fluvio-glacial or lacustrinal, with a fair degree of certainty. On the south side of the Tees, Agar's 41' O.D. and 82' O.D. sand filled notches can both be more logically explained as lacustrinal and deltaic features related to a late-glacial ice dammed lake, which gradually receded as the ice melted. The occurrence of shell frag ments in the lower of these notches is not unusual for this region. It seems that the Cheviot ice which occupied this region had been diverted down the coast by the Scandinavian ice which was standing offshore, and in the process had assimilated marine deposits.

The Saltburn deposit which contained a wide range of shells was no longer visible, and was probably destroyed early in the 20th century when the coast road was widened and re-routed. Two deposits in the same locality were examined and neither was considered to be marine.

Two factors were taken into consideration when discussing this raised beach deposit.

(1) The site was sufficiently close to the present range of sea level to have been well within the range of a high spring tide assisted by an onshore wind. Even today,

the spring tides break against the promenade and cause sand and shells to be deposited on the surface of Cat Nab.

(2) The deposit contained shells which occur on the present beach and Veitch in his article expresses concern that the Saltburn Improvement company had exposed the alluvial sand which contained the shell fragments and at the same time destroyed the evidences of ancient kitchen middens which once existed. The present author examined this alluvial sand, which still exists on Cat Nab, and is convinced that it represents a washing limit of the Skelton Beds. Only a few shell fragments were observed and the author is equally convinced that the supposed raised beach deposit at Saltburn is of archaeological origin.

SPECIFIC SITES RECOGNISED AS POSSIBLY MARINE AFTER THE MORPHOLOGICAL SURVEY

Sand deposits, which could possibly be compared with the present day shoreline, did not occur on all terraces and the following section concentrates on these sites which:

(1) possessed a gradient which did not preclude a marine origin

(2) contained a sand or gravel deposit which could have been laid down under marine conditions

The following Table 451 divides the levelled terraces into three sediment groups: sand, washed stony clay or laminated clay, and red stony clay. One can observe that the majority of terraces were composed of washed boulder clay and laminated clay which is far more likely to result from a low energy environment such as would exist in an ice dammed water body, or as a result of meltwater run-off.

TABLE RECORDING THE SEDIMENTS ON TERRACES IN THE TEES BASIN

* The number is similar to that used in Chapter 4.

A. SAND

6 Cat flat 84'
10 I.C.I. Wilton 78', 80',
13 Spencer Beck Farm 100'
15 Sandy Flat 99.63
16 Stainsby Hall 77', 93'
17 High Leven 122', 116'
19 Spittal Flat 118'
32 Coatham Stob 94'
33 Coatham Stob 79'
34 Stockton-Norton 59'
41 Claxton 45'

B. WASHED CLAY

4) up and down profile
5) Ox close to Pontac Farm
7 Blacks' Bridge 47'
10 I.C.I. Wilton 93', 58'
11 Lackenby Hall 75'
12 Normanby 50'
14 Coulby Manor 106', 108',
15 Sandy Flat 46'
18 Ingleby Barwick 76'
20 Howe Hill 77'
20b Howe Hill 108'
23 Girsby 145'
24 Old School Girsby 130'
25 Low Entercommon 174', 166',
26 Low Hail 134'
29 Middleton St. George 134'
30 Long Newton 113'
31 Elton 106'
35 Howden Hall (33' per mile)
38 Wolviston 109'
39 Marsh House 59'
40 Middle Burn Toft 53',73',68',
42 Cowpen Bewley(17.64' per mile)
43 Throston 60'

C. RED STONY CLAY

2 Windy Hill
3 Marske Cliff
27 Garden House
28 Hurworth Moor
36 Warren House Farm
37 Woodside

These water bodies need not necessarily have existed for a great length of time as the author has observed quite distinct shoreline terracettes and washed deposits, to a depth of 6", result from temporary flood water on the Canadian Prairies.

One should note that sedimentological studies cannot provide a positive means of distinguishing a marine beach from a lacustrine beach and one must, therefore, rely on the morphological survey and fossil, faunal or floral evidence. (The validity of negative evidence, the absence of shell fragments, and absence of the surface polish which a marine beach sand possesses are discussed later.)

The third group, which occur on unaltered stony clay, all possess gradients which preclude a littoral origin, and it is the first group which possess sand deposits that could possibly be formed under marine conditions.

Sandy Flat (Fig. 102)

Three samples were taken at approximately 99' O.D., from a drainage trench. The sand deposit was structureless and no shell fragments occurred. Table 280 records the sedimentary characteristics of the sand and together with the particle size curves (Fig. 102) these characteristics suggest that running water was responsible for its deposition:

(1) The symmetry of the coarse and fine

(2) The apparent absence of a distinguishable trend in the heavy mineral content.

TABLE RECORDING SEDIMENTARY CHARACTERISTICS OF THREE SAMPLES FROM SANDY FLAT (NZ 493158)

		Mica (Grains/1000)				% Rock Fragments			
Sample Number	Surface Texture	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ
1	9	1	2	Trace	0	75	57	34	6
2	11	Trace	Trace	0	0	20	13	9	3
3	10	1	Trace	1	0	64	24	7	1

		Coal (Grains/1000)				% Heavy Minerals			
Sample Number	Surface Texture	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.40ϕ	3.41ϕ to 3.8ϕ	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ
1	9	5	0	0	0	7.2	4.0	12.0	4.2
2	11	1	Trace	1	0	2.5	2.3	2.6	1.8
3	10	1	Trace	1	0	5.0	3.5	3.3	6.0

Spittal Flat (Fig.100)

This terrace occurred at 118' O.D. Two sand samples were taken from separate hand dug holes. There was some evidence of fine bedding but no distinct stratification. Table 281 records the sedimentary characteristics and it is interesting to note that the particle size curves (Fig. 102) appear similar to some offshore samples. The most dominant characteristics of a marine beach sand (a high polish on the grains, and shell content) are both absent and the particle size curve indicates a finer grained deposit formed under lower energy conditions than occur along the present coast.

TABLE RECORDING SEDIMENTARY CHARACTERISTICS OF SAND SAMPLES FROM LEVELLED TERRACES WITH SUPERFICIAL SAND DEPOSITS

		Mica (grains/1000)				% Rock Fragments				Coal (grains/1000)				% Heavy Minerals			
Sample	Surface Texture	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø	1.66ø to 2.3ø	2.31ø to 2.75ø	2.76ø to 3.4ø	3.41ø to 3.8ø
Spittal Flat 1	9	Trace	Trace	Trace	1	109	57	15	0	0	0	6	2	3.3	2.9	4.1	5.8
Spittal Flat 2	14	Trace	Trace	1	1	118	52	12	2	10	7	12	1	3.1	2.6	2.7	2.8
Cat Flat 1	11	12	2	3	Trace	18	15	2	2	2	0	Trace	1	2.7	3.2	2.8	2.5
Cat Flat 2	12	23	6	4	1	18	18	8	20	4	2	3	6	3.4	2.1	3.3	6.1
ICI Wilton	8	1	17	6	10	51	27	13	3	4	2	1	0	2.7	2.1	2.6	1.8
Spencer Bede (1)	9	0	4	9	8	62	27	3	0	7	4	2	0	1.7	2.1	1.5	1.2
Spencer Bede (2)	7	0	Trace	1	4	71	38	12	4	5	1	0	0	1.8	1.9	1.3	1.2
Stainsby Hall (1)	6	Trace	7	8	6	51	17	11	2	0	Trace	1	2	3.8	3.1	2.4	1.9
Stainsby Hall (2)	11	0	0	Trace	14	30	10	4	0	0	0	Trace	0	4.1	2.8	2.1	0.9
High Leven	7	0	9	2	7	24	6	1	0	0	0	4	2	2.7	2.1	1.2	1.1
Stockton-Norton (1)	12	0	2	3	22	18	3	0	0	8	1	1	0	3.1	4.0	4.6	0.3
Stockton-Norton (2)		0	0	1	1	43	12	2	0	7	3	0	0	6.3	5.5	4.6	4.5
Stockton-Norton (3)		0	0	4	6	18	3	9	0	28	10	5	4	5.3	10.0	4.6	5.4

Cat Flat, Spencer Beck and Stainsby Hall (Fig. 109 and Fig. 103)

Exactly the same problem occurs with the above three sites as did with Spittal Flat deposits. All four sites possess the characteristics of a low energy wave deposited environment but do not possess the high polish and shell content which characterises the present day beach. The deposits therefore could be classified as lacustrinal on this negative evidence. However, it would be preferable to have this classification supported by fossil faunal or floral evidence as well as morphology.

High Leven, and Stockton-Norton (Fig. 103)

Both of the above sites produced results which suggested running water as the depositional agent. This was especially true of the Stockton site where the samples were taken from two trenches excavated in current bedded sand and gravel. These trenches lay to the north of a very short, but nevertheless very distinct break of slope which occurred at 59' OD. It seems probably that the sample site represents deltaic sediment entering the water body responsible for etching the terrace.

The High Leven deposit was less easily recognised, but the particle size curve is perhaps the most positive means of identification.

The symmetrical coarse and fine tails are typical of deposits laid down in running water and the terrace was probably formed by meltwater or runoff.

Coatham Stob

This site was examined separately because it was the only levelled site, which could be a shoreline, where there was no problem of sample collection. Primarily, two deposits were recognised; a superficial sand deposit with increasing coarse material to the north, and an underlying laminated clay which contained occasional boulders, some of which were striated. The sand was observed to change its texture from coarse sandy gravel in the north to a fine sand in the south, and this transgression could possibly be explained as the influence of a current energy which gradually reduced in strength as it met with the influence of the standing water in which the laminated clay was deposited. The laminated clay was most probably a deep water deposit and the sand a shallow water deposit which was laid down after the water body started to recede. It seems probable that this laminated clay was of similar age and origin to the large deposit on the south side of the present Tees and if so then the drift geology shown in Fig. 11 (Chapter 3) should be modified to show this continuation of the laminated clay. A total of ten samples confirmed that the silt content of the deposit increased towards the periphery of the clay pit and this was taken to indicate a water lain origin.

Table showing the % silt content of the laminated clay at Coatham Stob.

Distance from the Periphery	% Silt
150'	0.8%
120'	0.7%
90'	1.2%
60'	2.8%
50'	2.6%
40'	4.8%
30'	6.9%
20'	18.1%
10'	21.5%
1'	20.8%

Fig. (104) shows the precise location of samples, Fig. 105, the particle size curves, and table 288 the results of sediment analyses.

Site Description

The samples were collected on a stratified random plan and each sample site is described in the following section.

Sites 1, 2, 3, and 5

These four sites were disregarded as evidence of recent tipping and reworking suggested that results would be meaningless.

Site 4

Stratigraphy

1" laminated clay
1½" sand
1'6" red fill + mg lmst erratics
2" angular gravel
1" sand
2" gravel

The stratigraphy is complex and would seem to indicate a very variable influence of water sorting such as one would expect in a braided delta where channels are constantly changing. Running water is indicated, rather than wave action, by the presence of turbulent flow structures in the deposits.

<u>Site 6</u>

A thin bed of coarse sand and fine gravel was recorded with several coal bands incorporated into the sand. These segregated coal bands could possibly indicate the influence of density upon gravity settling rates. The presence of these density layers could possibly be interpreted as evidence of deltaic or equilibrium conditions in the transporting agent.

<u>Site 7</u>

The upper 4 feet consisted of a stratified gravel containing well rounded stones. Several striated pebbles were noticed and even more interesting, several flints occurred. These most probably came from the offshore environment north of the Tees and were carried to their present location by the Cheviot ice sheet. Also in this gravel were several "armoured mud balls" which consist of a nodule of boulder clay rolled along by running water or wave action and which collects small pebbles on its surface. Below the gravel was a 6' to 8' thick bedded sand which gradually became finer towards its base. An increase in sediment size towards the top of a stratigraphic column is usually taken as evidence of a regressive sequence which indicates the gradual drying out of a water body. This would certainly appear to agree with the supposed pattern of events envisaged for the Tees Basin, of an ice dammed lake, gradually receding as the climate ameliorated and the ice melted.

Size 8

A six foot layer of orange sand occurred at this site, interbedded with several fine coal bands.

Site 9

The sand bed in Site 8 was appreciably thicker (6' to 10') and was underlaid by a fine sandy clay, gradually merging into the underlying laminated clay. A similar regressive sequence as occurred at Site 7 further supports the hypothesis of a receding water body, although the gravel layer is absent in this site.

Site 10, 11, 12, 13, 14

All the above sites possessed a similar stratigraphy of 6' to 10' of finely bedded sand overlying a transition layer of laminated sandy silt, which in turn overlies true laminated clay. The sand visibly becomes finer as one moves south and it is interesting to note the mineralogical changes which accompany this trend. (Table 288) The most significant one is the increasing content of light density coal fragments in a southerly direction which could possibly be interpreted as evidence of a weaker transporting energy.

Table showing the location of samples at

Coatham Stob

Site 4	Sample 1	
Site 6	" 2	
Site 7	" 3	
Site 8	" same as 3^1	
Site 9	" same as 3^2	
Site 10	" Yellow Sand	1
Site 11	" Yellow Sand	2
Site 12	" Yellow Sand	3
Site 13	" 4, 4_1, 4_2	
Site 14	" 5_1, 5_2, 5_3 5_4	

One may observe that the high polish and shell content of marine beach sands are again absent but should note that shell fragments do occur occasionally. The individual characteristics are again of little significance on their own, although the variable range of coal content is most easily explained by differential settling in standing water or possibly deltaic conditions.

The particle size curves possess the reverse L shape of lacustrinal and some offshore sands and the former is considered a more likely origin because of the close affiliation with the adjoining laminated clay.

Factor analyses were performed on some of the Coatham Stob samples, and with the exception of two samples which possessed almost equal 30-30-30 factor loadings, suggested a lacustrine or marine nearshore origin. The two samples with almost equal factor loadings may possibly have been resorted after their original

TABLE SHOWING SEDIMENTARY CHARACTERISTICS
OF SAND SAMPLES FROM COATHAM STOB

		Mica (grains/1000)				% Rock Fragments				Coal (grains/1000)			
Sample	Surface Texture	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ
Yellow Sand 1	11	0	0	5	12	41	10	50	15	8	3	0	0
Yellow Sand 3	7	Trace	0	Trace	Trace	23	30	20	13	2	31	4	10
2	12	0	2	2	5	160	90	48	31	18	5	9	5
4	14	10	10	11	10	83	41	18	0	23	17	Trace	4
1	11	0	0	0	5	39	21	17	0	2	38	57	78
Same as 3	8	3	0	0	31	43	5	3	0	30	2	0	5
Same as 3	9	0	Trace	Trace	10	14	5	40	45	11	25	60	21
4 No 2	10	0	0	0	0	54	23	15	11	22	8	2	1
4 No 1	9	1	3	10	11	37	32	33	3	22	20	20	21
5 No 2	12	0	Trace	1	-	70	42	41	-	32	25	10	-
5 No 3	11	1	Trace	Trace	Trace	90	33	14	9	121	28	10	9
5 No 1	12	Trace	Trace	Trace	30	32	31	3	7	20	32	9	40
5 No 4	13	0	Trace	Trace	Trace	100	20	18	10	21	10	5	1
Yellow Sand 2	15	Trace	Trace	Trace	Trace	109	57	15	0	0	0	6	2
3	11	Trace	Trace	Trace	Trace	18	15	2	2	10	7	27	1

TABLE SHOWING SEDIMENTARY CHARACTERISTICS
OF SAND SAMPLES FROM COATHAM STOB

Sample	Surface Texture	% Heavy Minerals				Shell (grains/1000)			
		1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ
Yellow Sand 1	11	2.4	2.4	2.9	6.1	0	0	0	Trace
Yellow Sand 3	7	2.3	2.4	2.5	2.7	0	0	0	0
2	12	2.3	1.6	4.5	7.9	0	0	0	0
4	14	2.5	0.2	4.0	1.9	0	0	0	0
1	11	2.9	3.4	7.1	2.9	0	0	0	0
Same as 3	8	3.3	2.9	4.0	5.8	2	0	0	0
Same as 3	9	2.7	2.7	2.9	2.7	0	0	0	0
4 No 2	10	3.2	2.6	2.8	2.8	Trace	0	0	Trace
4 No 1	9	2.5	2.0	2.0	2.2	Trace	Trace	Trace	Trace
5 No 2	12	6.3	5.0	5.4	-	Trace	Trace	Trace	-
5 No 3	11	2.4	2.2	2.2	1.5	0	0	0	0
5 No 1	12	4.8	4.2	5.1	6.8	0	0	0	0
5 No 4	13	2.9	2.3	2.5	37.1	0	0	0	Trace
Yellow Sand 2	15	2.9	2.2	2.0	2.8	0	0	0	0
3	11	2.5	1.4	3.0	4.1	0	0	0	0

deposition and the absence of a dominant factor could be indicative of a polygenetic deposit. (Fig. 99)

Three other levelled terraces were factor analysed and the results conformed with morphological evidence in supporting a lacustrinal or offshore origin for Cat Flat and Spittal Flat, [redacted], and a fluvial origin for Sandy Flat [redacted].

Summary

This survey of the sediments associated with levelled terraces has proved interesting. There still remains the problem of lacustrine versus marine, although the absence of marine flora and fauna and the predominance of poorly sorted, fine silty deposits does seem to favour a much lower energy environment than one would expect from late glacial marine conditions.

OTHER SANDY DEPOSITS IN THE TEES

These samples include sediments which were discovered during field work, and which were not associated with a terrace. It is possible that these sands could provide further evidence of environmental conditions in the late and post-glacial periods.

(1) Hurworth NZ315114

(2) Wynyard NZ415246

Initially, each site is described and later its sedimentary characteristics discussed and compared with earlier analyses.

Hurworth

This site was located at 120' OD just north of the present river Tees floodplain. The site was very similar to Coatham Stob as a sand deposit was associated with a laminated clay. As at Coatham Stob the extraction of clay for brick making allowed easy access to the deposits, and the following stratigraphy was recorded:-

13"	Soil
2'9"	contorted laminated clay
5'0"	fine sand, current bedded in part
10'0" +	laminated clay

The sand deposit was sampled in two groups, one from the current bedded sand laminae, and one from the unbedded sand (prefixed "H.") The sand lay unconformably on the clay deposit and therefore need not be chronologically related to the underlying deposit.

Analyses

Table 292 records the sedimentary characteristics and one can observe that the unbedded samples possess a greater surface polish, an exceptionally high mica concentration, and an equally high content of rock fragments and coal when compared with other sample locations.

Shepard (1964 op. cit.) suggested that a high mica content occurs in low energy deltaic environments and in standing water. The

TABLE RECORDING SEDIMENTARY CHARACTERISTICS OF SAND SAMPLES FROM HURWORTH BRICK PIT (NZ315114)

		Mica (grains/1000)				% Rock Fragments				Coal (grains/1000)				% Heavy Minerals			
Sample	Surface Texture	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ	1.66ϕ to 2.3ϕ	2.31ϕ to 2.75ϕ	2.76ϕ to 3.4ϕ	3.41ϕ to 3.8ϕ
H1	12	80	10	2	Trace	100	30	5	2	20	15	7	3	4.1	2.6	2.0	6.5
H2	14	50	54	Trace	Trace	78	18	2	0	248	22	7	22	2.6	6.5	4.2	2.1
H3	11	111	84	2	2	233	70	25	0	183	53	32	10	5.9	2.5	1.7	1.5
H4	13	112	3	8	0	224	83	13	0	45	0	0	0	2.9	1.4	3.4	5.9
H6	14	106	29	9	2	100	30	0	0	75	45	15	15	4.4	1.6	2.4	2.3
1	10	0	0	0	0	90	60	170	41	20	30	11	17	3.5	7.7	6.9	6.1
2	9	0	1	1	5	89	29	28	2	50	33	41	35	3.1	6.2	11.2	7.1
3	10	Trace	Trace	Trace	1	98	10	10	9	100	20	15	11	2.5	3.6	5.0	6.8
4	11	0.5	7	3	1	1	18	1	0	72	13	11	0	2.9	4.6	8.7	5.6
5	12	0	0	0	0	39	31	29	42	11	10	19	23	2.8	4.2	2.3	4.5
6		Trace	0	Trace	2	41	111	22	20	24	Trace	25	38	2.9	5.5	6.5	6.2

high coal content could similarly be explained as the influence of a weaker current energy giving way to gravity settling.

However, the particle size curves (Fig. 106) show quite clearly a consistent difference between the bedded and unbedded deposits. Both are extremely fine grained and also cover a restricted range of grain sizes. This almost certainly reflects a consistent current energy rather than restricted source material. The unbedded deposits show the reverse L shape of lacustrine or marine nearshore and offshore deposits whilst the bedded deposits show this coarse tail to a much lesser extent. One can tentatively suggest that the environment of depositions could be a deltaic complex with near equilibrium conditions between erosion and deposition such that only a very restricted range of grain sizes would be transported.

In this way, one could envisage the mica rich deposit being laid down in standing water and the associated current bedded sands being deposited in a braided delta. Certainly the dip of the current bedding varied considerably from E.N.E. to W.N.W. (as one would expect in a braided delta).

Fig.100, which shows the factor loadings of the two deposits clearly separates the mica rich offshore or near shore deposit from the current bedded deposit. This latter is difficult to interpret as it falls within the range of marine beach, lacustrine beach, and some offshore samples. (See Fig. 86 chapter eight). The absence of any present day alluvial fan or deltaic deposits in the Tees makes it difficult to predict where its deposits should fall on the triangular graph, but a logical position would be between littoral and fluvial deposits.

One must conclude that this fine, current bedded deposit from Hurworth does not resemble any of the known environments, previously encountered in the Tees and thus cannot be identified on the premise that the present is the key to the past.

Wynyard Sand Pit (NZ415246)

This sand pit is exposed on the south facing bluff making the northern limit of the Billingham beck flood plain approximately one mile north east of Thorpe Thewles (NZ402234). The pit has been filled in during the past few years but the following stratigraphy was observed

16' to 20'	red stony clay (striated stones)
4'0"	current bedded sand and gravel
1'2"	hard almost consolidated sand with occasional clay nodules towards the base
3"	clayey sand
8'0"	coal and sand interbedded (2" sand 1" coal at regular intervals
1'6" +	basal layer of large boulders, some striated

Samples were taken from the two main sand beds with a third sample unit from the thin layer of fine sand which marked the basal layer of the stratigraphy in most parts of the pit. Table 469 records the sedimentary characteristics and the most destructive characteristic is the very high rock fragment content which was found to occur in present day fluvial environments in the Tees. In this case, it is possible that the rock fragment reflects the close proximity of the sand to the boulder clay from which it probably originated. Beaumont (pers. comm. 1967) suggested that the sediments were probably deposited in an ice contact zone as this would explain the large boulder layer.

The particle size curves show the two main sand beds with very similar size distributions, whilst the clayey sand stands apart (Fig. 107). Factor analysis, (Fig.109) similarly shows this difference and it is noteworthy that the two main layers possess the same factor loading ratio as present day fluvial sands, but seems also to overlap with littoral sands. One must return to the particle size curves for further explanation, and the symmetrical fine and coarse tails are a noted characteristic of fluvial sands.

Summary

These two sites, Hurworth and Wynyard, were easily accessible and enabled one to complete a full sampling program. In this way it was possible to test the validity of identifying fossil environments by comparing their factor loading ratio with those of known environments. One must conclude that the technique is not fully satisfactory as the current bedded sand at Hurworth defied

TABLE RECORDING SEDIMENTARY CHARACTERISTICS OF SAND SAMPLES
FROM WYNYARD SAND PIT (NZ 415246)

		Mica (grains/1000)				% Rock Fragments				Coal (grains/1000)				% Heavy Minerals			
Sample	Surface Texture	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ	1.66φ to 2.3φ	2.31φ to 2.75φ	2.76φ to 3.4φ	3.41φ to 3.8φ
Basal Sand	13	2	1	1	2	332	96	72	60	10	3	1	20	2.7	1.4	1.8	17.3
2	7	0	0	Trace	Trace	180	130	103	71	0	5	0	0	6.4	4.5	22.7	2.3
3	8	0	0	0	0	200	309	260	260	0	0	Trace	Trace	5.4	3.8	2.6	2.3
4	6	Trace	Trace	Trace	Trace	510	600	125	110	Trace	Trace	5	6	7.0	4.7	3.4	3.0
A	7	0	0	0	1	168	99	71	41	Trace	Trace	Trace	Trace	4.8	4.8	3.2	2.5
B	10	0	1	0	0	411	210	140	12	13	17	0	0	6.4	6.0	3.2	3.3
C	6	Trace	Trace	Trace	Trace	240	180	150	160	Trace	0	Trace	Trace	6.4	4.3	3.0	4.8

positive identification. One explanation for this failure could be the absence of alluvial fans and deltaic sediments from the present day environments in the Tees.

Data Processing

Factor analysis 1. (Particle Size Data)

Fig. 86 (Chapter eight) shows the three factor ratio's of known and unknown environments and Table 299 records the loading ratios for unknown environments.

In this chapter the factor loadings of each sample site have been plotted individually to aid interpretation, (Fig. 100) and it was only partly successful. The main problem was to distinguish between sands of marine and of lacustrinal origin. This problem had arisen because there was no large freshwater body in the Lower Tees, and partly because there was no positive means of distinguishing between the two environments. The absence of a high polish on the grains, and the absence of shell in the terrace samples can only be regarded as negative evidence.

A second similar problem was the recognition of deltaic sediments which occur frequently in the fossil sands and which are absent from the present daysands in the Tees basin.

Discriminant Function Analysis

A discriminant function analysis was performed on the results of factor analysis to determine which groups of known samples the unknown samples resembled. Table 303 records the results of the analysis and it is immediately apparent that the unknowns fall into four major facies (Group 3, Group 7, Group 13, and Group 14). The majority of unknowns are concentrated in groups 13 and 14, which are

Table Recording Sample Location, Computer Number and Factor Loadings of "Unknown" Samples From the Tees

(Based on Particle Size Data)

			%	
Sample Location	Computer Number	F1	F2	F3
Wynyard Sand C (1)	U01	3.1	85.2	11.7
Wynyard Sand C 2	U02	4.3	80.4	15.3
Wynyard Sand A (1)	U03	2.0	82.8	15.2
Wynyard Sand A (2)	U04	1.2	84.2	14.6
Wynyard Sand B (1)	U05	1.1	79.0	19.9
Wynyard Sand B (2)	U06	0.8	78.7	20.5
Wynyard Basal Sand (1)	U07	77.5	3.4	19.2
Wynyard Basal Sand (2)	U08	76.0	3.1	20.9
Coatham Stob (2) (1)	U09	62.3	0.9	36.8
Coatham Stob (2) (2)	U10	71.7	0.1	28.2
Coatham Stob (1) (1)	U11	54.9	7.4	37.7
Coatham Stob (1) (2)	U12	52.9	9.0	38.2
Coatham Stob 4 (1)	U13	42.1	12.0	46.9
Coatham Stob 4 (2)	U14	40.7	13.2	46.1
Coatham Stob 3 (1)	U15	34.0	30.4	35.6
Coatham Stob 3 (2)	U16	34.8	29.6	35.6
Wynyard (1)	U17	6.4	87.7	5.4
Wynyard 1A	U18	6.6	86.0	7.4
Wynyard 2	U19	4.4	82.6	13.0
Wynyard 2A	U20	3.7	86.1	10.2
Wynyard 3	U21	4.5	80.9	14.6
Wynyard 3A	U22	2.9	87.4	9.7
Wynyard 4	U23	1.8	89.7	8.5
Wynyard 4A	U24	1.4	92.4	6.2
Brierton A1 (1)	U25	11.0	63.5	25.4
Brierton A1 (2)	U26	12.7	59.6	27.6

(Based on Particle Size Data)

Sample Location	Computer Number		%	
		F1	F2	F3
Brierton A2 (1)	U27	14.3	55.8	29.9
Brierton A2 (2)	U28	15.2	54.6	30.23
Brierton A3 (1)	U29	14.8	58.4	26.8
Brierton A3 (2)	U30	15.2	57.4	27.4
Brierton B1 (1)	U31	43.5	11.7	44.8
Brierton B1 (2)	U32	35.0	20.1	44.9
Brierton B2 (1)	U33	43.1	13.2	43.7
Brierton B2 (2)	U34	36.3	19.3	44.5
Brierton B3 (1)	U35	53.1	8.7	38.2
Brierton B3 (2)	U36	52.5	10.2	37.3
Brierton C1 (1)	U37	20.9	27.3	51.8
Brierton C1 (2)	U38	20.2	28.7	51.1
Brierton C2 (1)	U39	6.9	47.1	46.0
Brierton C2 (2)	U40	6.8	46.8	46.4
Brierton C6 (1)	U41	9.2	40.3	50.44
Brierton C6 (2)	U42	7.5	43.6	48.9
Brierton C3 (1)	U43	6.9	47.4	45.7
Brierton C3 (2)	U44	6.1	49.0	44.8
Brierton C4 (1)	U45	7.4	43.2	49.1
Brierton C4 (2)	U46	7.6	48.4	51.4
Brierton C5 (1)	U47	7.9	41.3	50.8
Brierton C5 (2)	U48	7.2	42.7	50.1
Hurworth 1	U49	4.7	38.1	57.2
Hurworth 1A	U50	6.2	37.1	56.7
Hurworth 2	U51	6.9	35.1	58.0
Hurworth 2A	U52	4.3	38.3	57.5
Hurworth 3	U53	8.7	30.9	60.5
Hurworth 3A	U54	5.9	34.0	60.1
Hurworth 4	U55	13.1	25.4	61.5

(Based on Particle Size Data)

			%	
Sample Location	Computer Number	F1	F2	F3
Hurworth 4A	U56	12.2	26.1	61.7
Hurworth 5	U57	9.9	29.2	60.9
Hurworth 5A	U58	7.1	32.7	60.3
Hurworth 6	U59	5.6	37.2	57.2
Hurworth 6A	U60	5.7	36.0	58.3
Hurworth H1A	U61	89.9	3.7	6.4
Hurworth H1A (1)	U62	89.9	3.8	6.3
Hurworth H2A	U63	84.4	2.5	13.2
Hurworth H2A (1)	U64	87.1	3.8	9.1
Hurworth H3A	U65	90.5	4.0	5.6
Hurworth H3A (1)	U66	91.9	4.5	3.7
Hurworth H4A	U67	89.6	3.5	6.9
Hurworth H4A (1)	U68	91.0	4.0	5.1
Hurworth H5A	U69	94.7	5.0	0.3
Hurworth H5A (1)	U70	94.0	4.3	1.7
Hurworth H6A	U71	92.4	4.2	3.4
Hurworth H6A (1)	U72	90.9	3.7	5.4
Brierton 2A 1	U73	6.3	91.0	2.7
Brierton 2A (2)	U74	7.7	88.3	4.0
Brierton 2B (1)	U75	14.6	74.3	11.1
Brierton 2B (2)	U76	17.8	61.3	20.9
Brierton 2C (1)	U77	11.7	85.5	2.8
Brierton 2C (2)	U78	15.9	68.5	15.6
Newton Bewley Gravel Pit Red Sand	U79	32.8	54.0	13.3
Newton Bewley Gravel Pit Red Sand	U80	29.6	55.8	14.6
Newton Bewley Gravel Pit Red Sand	U81	30.5	53.0	16.4
Newton Bewley Gravel Pit Yellow Sand	U82	6.6	55.2	38.2

Sample Location	Computer Number	% F1	% F2	% F3
(Based on Particle Size Data)				
Sandy Flat	U83	31.2	55.8	13.0
Sandy Flat	U84	34.5	51.3	14.2
Sandy Flat	U85	28.9	54.0	13.1
Spittal Flat	U86	64.1	8.1	27.8
Spittal Flat	U87	61.2	9.2	29.6
Cat Flat	U88	53.7	11.1	33.2
Cat Flat	U89	52.5	7.8	39.7

TABLE RECORDING RESULTS OF DISCRIMINANT FUNCTION ANALYSES ON UNKNOWN SAMPLES

Group 13	Group 14	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9	Group 10	Group 11	Group 12
W39	W63	D01	D06	B01	B25	B20	R01	R06	W40	W01	W06	W14	W44
W85	W67	D02	D07	B02	B26	B23	R02	R07	W41	W02	W07	W15	W45
W86	W68	D03	D08	B03	B27	B24	R05	R08	W42	W03	W19	W16	W46
W87	W69	D04	D09	B04	B28	B41	R09	R11	W43	W04	W28	W48	
W88	W89	D05	W09	B05	B29	W29	R10	R12	W52	W05	W56	W49	
W104	W90	D10	W119	B06	B30	W30	W38	W123	W53	W08	W57	W50	
W105	W91	D11	W127	B07	B31	W31		W125	W54	W11	W70	W51	
W106	W92	D12	W128	B08	B32	W32	Brierton 2A^1	W126	W55	W12	W71	W64	
	W93	D13		B09	B33			Brierton 2A^2	W111	W17	W72	W65	
Brierton C2^1	W94	B13		B10	B34			Brierton 2B^1	W112	W18	W73	W66	
Brierton C2^2	W95	B14		B11	B35			Brierton 2B^2	W113	W20	W74	W81	
Brierton C6^1	W96	B15		B12	B36			Brierton 2C2	W114	W21	W75	W82	
Brierton C6^2	W98	B16		R03	W47				W115	W22	W76	W83	
Brierton C3^1	W99	B17		R04	W129				W116	W23	W77	W84	
Brierton C3^2	W100	B18		W36	W130				W117	W24	W78		
Brierton C4^1	W101	B19		W120	W131				W118	W25	W79		
Brierton C4^2	W102	B21		W121	W132				W133	W26	W80		
Brierton C5^1	W103	B22		W122						W27	W97		
Brierton C5^2		B37								W33	W107		
1 Hurworth	Coatham Stob 1^1	B38		Wynyard A2						W34	W108		
Hurworth 1A	Coatham Stob 1^2	B39		Wynyard B^1						W35	W109		

TABLE RECORDING RESULTS OF DISCRIMANT FUNCTION ANALYSES ON UNKNOWN SAMPLES (Continued)

Group 13	Group 14	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9	Group 10	Group 11	Group 12
Hurworth 2	Hurworth H1A	B40		Wynyard B^2						W58	W110		
Hurworth 2A	Hurworth H1A	B42		Brierton $A1^1$						W59			
Hurworth 3	Hurworth H2A	W10		Brierton $A1^2$						W60	Brierton $B3^1$		
Hurworth 3A	Hurworth $H2A^1$	W13		Brierton $A2^1$						W61			
Hurworth 4	Hurworth H3A	W37		Brierton $A2^2$						W62			
Hurworth 4A	Hurworth $H3A^1$			Brierton $A3^1$									
Hurworth 5	Hurworth 4A			Newton Bewley Yellow Sand									
Hurworth 5A	Hurworth $H4A^1$												
Hurworth 6	Hurworth 5A												
Hurworth 6A	Hurworth $5A^1$												
	Hurworth 6A												
	Hurworth $6A^1$												

composed entirely of offshore samples. This result emphasises the problem which has been reiterated on several occasions that there is no positive sedimentological means of identifying a freshwater from a marine deposit laid down under similar conditions.

Group 3 consists primarily of present day beach sands and it is interesting to note that the following unknowns occur in this group:-

1) three Wynyard samples
2) four Brierton samples
3) one Newton Bewley sample

This relationship cannot be readily explained as the respective particle size curves of the beach samples and the unknowns do not appear similar.

Group 7 is predominantly composed of river samples and the four Brierton samples which correlate with this group do possess the characteristic particle size curve of a fluvial sand.

In summary, discriminant function analysis has not succeeded in simplifying the classification of 'unknowns", despite the main concentrations of samples into groups 13 and 14 which are composed of offshore samples. It is hoped that multiple factor analysis incorporating all sedimentary values may prove successful.

Factor analysis 2. (All Sedimentary Data) (See Table 306).

The results of this analysis show all samples except for ice interglacial raised beach from Ireland, with a high loading on factor 2. This was what one could expect after the results of a similar analyses on known samples. (Fig. 187.) Almost certainly, the cause of this failure was the shell fragment content which was high in all the known samples but fluvial and low or absent in all the unknown samples but for the Ireland interglacial raised beach.

In consequence one must conclude that it would be better to complete a separate factor analysis for each variable and then assess its value independently. In the ideal case one should extend the study over the whole size sand range so that there would be ten variables for each mineral group rather than four as was the case in the present study.

TABLE RECORDING THE RESULTS OF FACTOR ANALYSIS ON SAMPLES OF UNKNOWN ORIGIN (All sedimentary Data).

Sample	% Loading Factor 1	% Loading Factor 2	% Loading Factor 3
Coatham Stob Yellow Sand 1	2	92	6
" " " " 3	2	96	2
Coatham Stob 1	1	96	3
Coatham Stob 4	4	66	30
Coatham Stob 4_2	4	86	10
Coatham Stob 4_1	2	96	2
Coatham Stob 5_2	2	94	4
Coatham Stob Same as 3	3	96	1
Coatham Stob 3	6	73	21

TABLE RECORDING THE RESULTS OF FACTOR ANALYSIS ON SAMPLES OF UNKNOWN ORIGIN (All sedimentary Data). (CONTD.)

Sample	Factor 1	% Loading Factor 2	Factor 3
Brierton Top 3A	1	96	3
Brierton 2C	2	95	3
Brierton Mid 3B	2	93	5
Brierton 3C Bottom	2	94	4
Brierton C4	5	90	5
Brierton 4C above 3C	1	98	1
Brierton A2	8	78	14
Brierton C2	3	95	2
Brierton C5	3	90	7
Wynyard Basal Sand	1	92	7
Wynyard C	3	89	8
Wynyard A	2	90	8
Wynyard 3	1	90	9
Wynyard 2	1	90	9
Hurworth 3	4	86	10
Hurworth H3	4	84	12
Hurworth 1	1	97	2
Hurworth 5	2	97	1
Hurworth H6	6	67	27
Newton Bewley	4	89	7
Girsby Flat	4	92	4
Egglescliffe 3	7	90	3
Egglescliffe 4	2	97	1
Radcliffe 1	3	79	18
Stockton-Norton 1	48	43	9
Ireland - supposed interglacial beach	82	16	2
Edin Raised marine sand	2	30	68
Fluvo Glacial Sand Carron Valley Edinburgh	1	93	6
Edin raised marine sand	2	96	2
Edin raised marine sand	5	81	14

GENERAL CONCLUSION TO CHAPTER NINE AND TO THE SECTION ON SEDIMENTOLOGY

Chapter Nine

The results of this chapter have proved fairly satisfactory. It would appear that the particle size curve, and the factor analyses based upon it provide the most successful means of identifying fossil environments. One must conclude that the ideal sampling conditions which were experienced with present day environments could not be applied to fossil environments for the following reasons.

1) Access
2) Time factor
3) Limitations to the number which could be factor analysed.

Access

Several of the fossil sand deposits in the Tees had been destroyed by urban and industrial development. Also, farming practices frequently prevented the necessary excavation to gather representative samples from accessible sites.

The Time Factor

The time factor not only limited the number of samples, but also the number of analyses which could be performed on each sample. Frequently, all samples were analysed for particle size and then grouped by factor analysis. Samples were then purposefully selected from the different groups for further sedimentary analyses. In this way the emphasis on sampling moved away from the number of samples to the nature of the individual sample (e.g., channel, spot, skims, sedimentation unit, size).

Factor Analysis

As was previously mentioned there were severe restrictions on the number of samples which could be analysed. These restrictions were partly a reflection of the size of the computer and partly the availability of programmes. At the time of writing the author was able to run over 200 samples on one programme at Edmonton (Alberta, Canada) with ten variables. It is hoped that a programme to handle 500 samples with 15 variables will be available in the very near future.

Despite these limitations it would appear that sedimentary analyses of terrace deposits tend to confirm the results of the morphological survey. The majority of terraces in the lower Tees would appear to have been formed partly by ice marginal drainage and partly by the washing limit of ice dammed or moraine dammed lakes. There would appear to be little evidence for raised shorelines, despite the seven sites which previous workers had classified as marine.

The absence of marine shells and the poorer sorting of deposits does suggest that a less powerful energy was responsible for the sandy deposits which occur on some of the terraces. Hopefully the following chapter on fossil faunal or floral evidence will provide more conclusive information on the origin of the terraces.

Sedimentology Section

This section on sedimentology was largely experimental and in retrospect the author recognises many limitations in the completed work. It was difficult to foresee these limitations until after the samples had been analysed and it is at least gratifying that more recent work completed in Canada has benefited from this present study.

The limitations referred to relate primarily to the mineralogical identifications which were restricted to the medium to fine sand fractions. This restriction was imposed partly by the time factor, but mainly to ensure that all samples could be compared with one another. During the course of the study it was realised that particle size analyses of environmental deposits have proved inconclusive partly because of sampling inadequacies but mainly because workers failed to realise that particle size analysis was in part a measure of sample composition. The current study went part way to solving that problem by examining the distribution of minerals of different shapes and densities e.g. mica, coal, heavy minerals and shell fragments.

The success of factor analyses on the particle size data was most encouraging for the study of present day environment, and was partly successful in a study of "fossil" environments. This success has led the author to suggest the following approach to future work in the field of environmental sedimentology.

1) Particle size analysis should be applied to minerals of different densities and shapes, within each sample.

For example:-

¼ø Particle size analysis of quartz grains
¼ø Particle size analysis of coal grains
¼ø Particle size analysis of shell fragments
¼ø Particle size analysis of heavy minerals
¼ø Particle size analysis of rock fragments
¼ø Particle size analysis of mica

Once sufficient samples have been analysed from both known and unknown environments a 10 variable factor analysis should be completed on all samples. (10 variables for each mineral group 1 variable = 1 size fraction)

In this way one is more likely to achieve perfect environmental separation, than has been achieved to date. In conclusion one may list the important results which have emerged from this sedimentological study:

A. <u>Systematic</u>

1) Moment measures have recently been used to describe particle size distributions. The present study would suggest that they are an inefficient means of

describing these curves. The author must support Doeglas (1962 op. cit.) in his belief that the particle size curve is a more discerning means of sample description, when plotted on arithmetic probability paper.

What is required is some means of computerising the curve to produce a descriptive mathematical equation. This would eliminate the present situation where one has to rely on subjective comparison.

2) Particle size analysis should take into account compositional differences. Current energies respond to density and shape as well as size (Ruhkin 1937 op. cit.) It is the distribution of each mineral within a sample which provides the environmental character, not the total amount.

The failure of previous workers to recognise the importance of this factor is considered to be a major weakness and although it has not been fully exploited in this thesis, a frequency curve of each density group should provide a far more sensitive measure of environmental sorting.

3) Multivariate factor analysis of all data proved to be a far more valuable and efficient means of comparing samples than attempting to compare individual sample properties.

4) Discriminant function analysis proved to be a sensitive

classificatory technique which subdivided known environments into sub groups. It was employed as a means of collecting the unknown samples with the known samples and the results were only partly successful.

B. Regional

1) A study and analysis of previously described marine deposits in the Tees led to the author questioning their authenticity.

2) Sedimentary characteristics succeeded in differentiating fluvially formed terraces from lacustrine or marine terraces, with a similar degree of success as was experienced with precise levelling. The major problem was how to distinguish between the essentially similar deposits which can occur under identical conditions in both marine and freshwater conditions. It was concluded that only fossil faunal or floral evidence could positively distinguish between the two environments, although theoretical considerations, circumstantial and negative evidence appeared to favour a lacustrinal origin.

3) Offshore

The author was unable to obtain equipment to collect core samples from depth beneath the sea bed and must therefore rely solely on the descriptive analyses of commercial boreholes. These are discussed in the following section which deals with fossil faunal or floral evidence and chronology.

SECTION 4

FOSSIL FAUNAL AND FLORAL EVIDENCE
AND
CHRONOLOGICAL CONSIDERATIONS

CHAPTER 10

FOSSIL FAUNAL AND FLORAL EVIDENCE, AND THE CHRONOLOGY OF EVENTS IN THE LOWER TEES BASIN

Introductory Statement

In this chapter fossil evidence and chronology have been combined as the latter is based very largely on the former in the Lower Tees. The aim of the study was to find further evidence which might prove or disprove the existence of raised and submerged shorelines in the research area.

Fossil Faunal and Floral Evidence

The fossil evidence is considered under five headings:-

1) Marine fossil evidence onshore
2) Freshwater fossil evidence onshore
3) Freshwater fossil evidence below present O.D.
4) Shallow water marine fossils offshore at depth
5) Conclusion

The most important aim of this study was to determine whether marine or lacustrinal conditions dominated the late and post-glacial evolution of the lower Tees basin.

Hopefully, one may be able to assess the validity of the theoretical considerations in chapter one, the morphological analyses in chapter four, and the sedimentological studies in chapter nine.

1) Marine fossil evidence onshore

A search for marine macro-fossils was carried out during both the morphological and sedimentological surveys. The results of this search have already been described, and took the form of isolated occurences of shell fragments in both coastal wind blown deposits and in some superficial sand and gravel deposits.

Shell fragments in coastal wind blown locations

(a) Hartlepool

An example of this sediment occured at Hartlepool where the boulder clay cliffs were frequently coated with a thin veneer of sand, which contained numerous small shell fragments.

(b) Saltburn and Huntcliff

The ground surface was strewn with sand, shells, and shell fragments at both these sites, which occur in the southernmost portion of the research area. Polyethylene bags were used to capture samples of sediment in suspension during a wind gusting to 45 mph. The samples contained between 2% and 7.5% shell fragments.

The main value of the above sites is to demonstrate the carrying capacity of wind energy and this confirms that the shell fragments on Cat Nab could easily have been wind blown and not necessarily washed out of a raised beach deposit.

Shell fragments in sands and gravels

Several of the sand and gravel deposits in the lower Tees basin contained isolated shell fragments.

1) Throston (Trechmann 1915 op.cit.)
2) Coatham Stob (present study)
3) Newton Bewley (present study)
4) Middle Beck, Ormesby Beck (Agar 1954 op.cit.)
5) Saltburn (Veitch 1883 op.cit., Barrow 1888 op.cit.)

All were discussed during the relevent sedimentological studies, and it was felt that one could postulate two origins.

1) Glacial origin
2) Archeological origin

The likelihood of their being "in situ" marine deposits was considered and rejected for several reasons (chapter nine). The most difficult site to examine was the supposed raised beach at Saltburn, which was described by Veitch 1883 op.ct., and Barrow 1888. The "beach" contained a wide variety of identifiable shell fragments, all of which were common on the present day beach, and was adjacent to two ancient kitchen middens. Both this site, and the middens have since been destroyed by road improvements. The sedimentology of a continuation of this "beach" which was described by Veitch (op.cit.) suggested running water rather than wave action was responsible for its deposition.

The Laminated Clay deposit

This deposit occupies much of the lower Tees and it has already been suggested that it was formed in an ice dammed lake (Radge 1939 op. cit.). Many isolated terrace fragments surround this deposit, are superimposed on, or cut into, its surface. Very few indeed contain any marine shell fragments and this led the author to consider whether shells would be present in a late glacial raised beach. Certainly the occurrence of shells in interglacial sands and gravels suggests that they would easily have survived the ravages of weathering. One should also note that the Firth of Forth contains a low lying clay of post glacial origin (the Carse clay) and although it does contain shells, the supposed late glacial shorelines which surround it are non-fossiliferous (Sissons pers comm 1967). If one considers the probable sequence of events in the late-glacial history of the two regions, the Firth of Forth and the lower Tees, it is possible that shells would not occur in late-glacial deposits. The immediate coastal environment would have only recently been inundated by the eustatic rise of sea level and the less mobile marine species would take some time to colonise the newly acquired territory. This time may be greater than the time for isostatic crustal rebound to commence and thus the higher shorelines would not possess any shell content. This situation almost certainly occured in the Champlain Sea, (St. Lawrence Valley, Quebec, Canada) where the clay deposits were the subject of much conjecture until foraminiforal micro fossils were found. These fossils confirmed that the Champlain Sea was in fact an arm of the sea and not a freshwater lake. (Gadd 1964).

On similar grounds one would expect the Tees laminated clay to contain evidence of these highly mobile microfossils if it was laid down during a marine incursion. Twenty fresh samples of the clay were analysed using the flotation techniques described in chapter seven (alcohol, or carbon tetrachloride). Coal was the main constituent of the light density flotation, whilst a microscopic examination of the mixture revealed only pollen spores, which were identified as of carboniferous origin (Beaumont 1967). The absence of foraminifera from this deposit and from sands associated with it does lend weight to the lacustrinal hypothesis which the present author favours, especially in view of their presence in the Champlain Sea deposits.

Summary

No further marine fossil remains were discovered in the Tees and one may conclude that it is more likely that the late and post glacial history of the lower Tees was dominated by lacustrinal conditions than by successive late and post-glacial marine incursions as suggested by Agar (1954 op. cit.).

2) Freshwater fossil evidence onshore

The purpose of this section is to determine whether meltwater lakes left any record in the form of peat deposits.

Throughout this thesis the emphasis has always been on finding displaced marine deposits. The inability to find any "in situ" marine fossils has resulted in the suggestion of an alternative hypothesis to explain the surface features and deposits. This hypothesis calls for the gradual retreat of an ice tongue in a coastward direction, which would prevent the natural drainage of the meltwater. This meltwater would drain around the margin of this ice tongue and collect in hollows to form small, proglacial lakes. In the latter stages of deglaciation it was possible that a large water body occupied the lower reaches of the present drainage basin and the laminated clay was most probably laid down in this lake.

One would expect some of the smaller marginal lakes, which occured in hollows on the higher land (above 90'OD), to have taken longer to dry out than a solely ice dammed lake, and it is possible that some of these may contain organic mud or peat deposits. It is similarly possible that some of the lower basins may also contain organic deposits.

It is possible that the discovery of such deposits could provide positive evidence of former lacustrinal conditions in the Tees, and may also provide some indications of late and post glacial environmental conditions.

Previous literature

Previous workers record the occurrence of two buried peat deposits, both on the north side of the Tees, in the valley of the Billingham Beck (NZ430236) (Agar, op. cit.) and North Burn (NZ460272) (Smith, personal communication, 1967). In addition to the above sites Blackburn (1952, op. cit.) recognised zone II deposits near Neasham (NZ332112), whilst there is evidence of larger lakes at Bradbury Carrs (NZ313256) and Morden Carrs (NZ321260), where peat is close to 40' thick. Agar, (1954, op. cit.) also recorded buried peat beds at a similar height above sea level as the North Burn and Billingham Beck valleys (54' O.D.) in the valleys of the Middle and Ormesby Becks on the south side of the Tees.

The Present Study

Two further peat deposits were discovered during field work. One was an extension of the bed which is exposed in the North Burn, and the other a kettle hole at Dinsdale (NZ327105), not far from where Blackburn (op. cit.) discovered the elk skeleton in zone II peat. Each of the above-mentioned sites is examined in the following section. The stratigraphy is described and the pollen zone determined.

Billingham Beck Valley

Agar (1954, op. cit.) describes the stratigraphy of this site as:

1'0"	Brown alluvium
4'0"	Black peat

3'0" Grey silty clay - some sand lenses

The peat contained tree debris and fresh water shells, whilst the grey silty clay contained in situ tree roots. Both deposits occured over the whole of the flood plain of the becks, between Wolviston Mill (NZ 429239) and the tributary which flows through Wynyard Park (NZ 414213).

A pollen sample from the base of the peat recorded a reed dominated vegetation with few trees. The presence of some domesticated grass pollen suggested that the site post dated the development of agriculture in the local area. Dr. J. Turner of the Durham Botany Dept. placed the basal layer in zone VI and the upper most layer in zone VIIb. This would suggest that the lake was on a reed swamp which existed from 7000 BP to 3000 BP and silted up during subboreal conditions. This silting was possibly hastened by deforestation which accompanied the expansion of agriculture.

In conclusion, this site serves only to indicate that lacustrinal or swampy conditions occupied this beck valley, until 3000 BP, with a shoreline at 54' ± 2.53'.

North Burn

A silty peat bed, rich in fresh water shells occurs in this beck valley near Stob House farm (NZ 458272). The bed was 12 feet thick and was overlain by 7 feet of brown alluvium interbedded with sand and gravel. The site was particularly interesting as it occured quite close to a major break of slope near Middle Burn

Toft (NZ 457279). The associated terrace had been modified by the deposition of 14 feet of alluvium and thus could not be levelled. However, the occurrence of a nearby peat bed could mean that the break of slope had been marginal to a freshwater lake.

This possibility was further strengthened when the peat bed was found to extend over the whole of the terrace flat, beneath the brown alluvium. However, the pollen assemblage shows that the deposit was laid down in zone VIIb and not in the late glacial period when meltwater was at its peak. However, it is possible that conditions were too muddy for peat to form until the lake was beginning to silt up (the peat is up to 25% silt).

The following hypothesis may explain both the existence of a lake in this locality and the formation of the several terrace remnants which surround it.

The ridge which Gaunt (1967 op. cit.) described as a raised storm beach runs from S.W. to N.E. between Wolviston (NZ 454258) and Greatham (NZ 491278). This ridge provides an effective barrier which could easily have held back meltwater. The sequence of terraces which were recorded near Middle Burn Toft (chapter four) could all be related to a water body in this enclave. The higher terrace occurs at 74' and is very short and ill defined. Possibly it reached the highest limit of the water before it broke through the ridge at the present location of the North Burn. The successively lower levels down to the main one at 52' could all reflect the different stages in the gradual silting of the lake.

Middle and Ormesby Becks

Agar (1954 op. cit.) recorded the occurrence of organic remains and a peat bed in these two beck valley's, where he also described a raised beach sand containing shells. The presence of several artifacts, the peat bed, and a prehistoric hearth all point to the likelihood of the supposed marine notch being a lacustrinal feature and the prehistoric hearth may well support Sisson's (pers comm 1967) view that the shells are of archaeological origin. The present author was unable to locate the bed, despite assistance from Agar regarding its location, as urban development had obliterated the natural features.

Dinsdale

The discovery of this site could mark the most significant find of organic material in the lower Tees. The site was located quite by chance when the author stepped onto the surface of the still actively growing basin peat and noticed the nearby birch trees swaying with the impact of his shovel. An initial boring attained a depth of 33 feet below ground level and the following detailed stratigraphy was later recorded when it was realised that the basin possessed a continuous pollen sequence from zone I to the present day (including the possibility of zone I oscillations). The site is at present being studied in detail by a member of the Cambridge Botany Dept. who has taken samples for

Stratigraphy of the Peat in the Dinsdale Kettle Hole

Centimetres	
0 - 10	grey gleyed organic clay, downwashed from field and rootlets
10 - 20	mainly peat - a little clay
20 - 25	more clayey
26 - 46	peat (36 - 38 - wood fragments and some clay)
46 - 48½	clay layer
48½ - 51½	peat
51½ - 56	some clay bands in peat
56 - 60	peat
60 - 80	Fen peat with leaf fragments and seeds
80 - 90	transition - highly humose peat. Nig. 3, Humo. 3.
90 - 119	Detritus mud - Limus Detrituosus - leaf fragments 100 - 119 - more plant fragments
119 - 168	peat with abundant leaves
168 - 226	as 90 - 119, with less fragments towards the bottom
226 - 317	Detritus mud (Limus Detrituosus)
317 - 337	more compact - greenish-brown - Limus humuosus
337 - 338½	mid-khaki organic mud
338½ - 342	light khaki organic mud
342 - 343	transition
343 - 370	pink clay (grey after exposure to air)
398 -	darker pink with buff coloured bands at 414 - 417 430 - 432 450 471 - 473 491 - 494 530 - 532 545 - 547
574 - 578	transition
* 578 -- 586	organic layer (black)
586 - 594	transition
594 - 611	pink clay with some organic bands (Argilla steatodes)
* 611 - 618½	organic layer
618½ - 700	pink clay with a lot of organic bands
700 - 765	pink clay with several minor organic bands
765 - 815	pink-grey clay - possible evidence of organic bands
815 - 850	pink clay, amorphous

C14 dating, (at the time of writing no results are available). The present author did complete some basic studies on the lower pollen zones and Dr. Turner of the Durham Botany Department was able to confirm a late glacial assemblage.

The ground level of the kettle hole is 125' O.D. and the pollen sequence provides evidence of the site being permanently deglaciated before 12000 B.P. It is also possible that the many organic layers in the pink clay could provide valuable information regarding the late glacial micro environment. (There is fully 230 centimetres of sediment below the organic band which was thought to represent the Bølling interstadial.

Summary

The full significance of this site will not be known until it has been fully analysed. Nevertheless, it would appear that the Tees may have been free of ice at a relatively early stage in the retreat of the Weichselian ice.

Summary of fossil, faunal and floral evidence above present Ordnance Datum

It would appear that there is more fossil evidence for lacustrinal conditions in the Tees than marine. Therefore, one can suggest that the alternate hypothesis of a late-glacial lake complex is more feasible than a marine incursion to 82' OD. This lake complex would probably have consisted initially of a series of smaller individual marginal lakes in the early stages of deglaciation (in the levelled zone 170' to 90') with a gradual amalgamation of the meltwater into one water body as the ice retreated east into the vicinity of the present estuary (levelled terraces 85' to 35').

3) Freshwater fossil evidence below present Ordnance Datum

Previous work

Cameron (1878) first discussed the scientific implications of the occurrence of a submerged peat bed at West Hartlepool. He noted 8' of peat and observed tree remains up to 12 feet in circumference and 18' - 20' inlength.

Ingram (1909) further described this peat bed which had been recognised in 1833 during dock excavations. The area which had been excavated was known as the "Slake" and was described as a shallow stretch of water which became an arm of the sea at high tide. The peat bed appeared to be interbedded with estuarine muds in its upper layers and would appear to have lain very close to sea level during its formation. Ingram described sizeable tree debris and noted that the peat occurred to a depth 20' below Low Water Mark.

Meanwhile, Simpson (1904) described a similar deposit at Redcar on the southern side of the Tees mouth. Simpson (ibid) notes that the Redcar deposits are more extensive than the Hartlepool deposits and are covered by a variable thickness of beach sand.

Simpson (ibid) did not record the depth of peat but noted that on very rare occasions it was exposed at low tide.

Trechmann 1947 examined the flora, fauna and archaelogical remains in the Hartlepool peat and placed its age between 8000 and 9000 BP. Smith (in Smith and Francis 1967 op.cit.) obtained a C.14 date on an antler from the deposit and the results ranged from 8100 ± 180 BP to 8700 ± 180 BP. This date agrees well with Trechmann's figure.

Smith and Gaunt (in Smith and Francis op.cit. 1967) note that the deposit occurs at a maximum depth of -35' OD and thus sea level must have been at least 40' below ordnance datum 9000 years ago. If one examines the graphs of the eustatic rise of sea level (figs. 14 and 15(it would appear that sea level was between 90' and 120' below present O.D. at 9000 BP.

Jelgersma (1961) suggested 65' below O.D. for the Dutch coast but even this figure is deeper than the Hartlepool peat. It would seem, therefore that the peat deposit did not occur precisely at sea level but at least 25' if not 80' above mean sea level.

The present author was unable to locate the deposit at Redcar but was able to study the many borehole and excavation records at the offices of the Tees and Hartlepool Port Authorities. One such record provided the following stratigraphy.

Ground Level 11.99 feet (O.D. 11.99' below G.L.)

	Depth below G.L.
Made Ground	15'
Grey sandy silt	33'
Dark blue silt	42'
Soft light brown peat	50'
Soft dark brown peat	55'6"
Soft light grey silty (organic content)	58'6"
Brown sandy stony clay	64'0"
Boulder clay	69'6"

The organic layers occur to a depth of -48.60 O.D. and thus would suggest that sea level must have been below that level 9000 years ago. Also, the deposit rests on Boulder clay, not marine deposits, and is not interbedded with marine deposits. This would suggest that the seashore was some distance away. It seems probable that the eustatic rise of sea level exceeded the rate of peat growth as isostatic rebound lessened. This would explain the estuarine mud and shells which are interbedded with the upper layers of the peat, in nearly borehole records.

Summary

All one can conclude from this evidence is that sea level was at least 55' to 60' below present Ordnance Datum Circa 9000 B.P.

4) Shallow Water Marine Deposits at Depth

The author was unable to obtain samples of this or any other sub bottom sediments below ordnance datum. Agar (1954) does record the existence of a sandy shell bed buried beneath the present estuary at -24' O.D. which may have been a beach or which may simply have been a shell bed covered by fluvial deposition.

Chronology of events in the Tees

The evidence presented in this thesis does suggest that no raised shorelines occur in the Tees. If one refers back to Figs. 4, 5, one can see that at 9000 B.P. only 85' of eustatic sea level rise remained and sea level was probably close to -90' at that time (average figure based on radio carbon graphs by workers listed on Figs. 4;, 5;). Thus, there is no likelihood at all of a post-glacial high sea level in the Tees Basin. The pollen sequence at Dinsdale suggests that the deglaciation of the research area was probably complete before 12000 B.P. The only raised shorelines which could exist in the Tees would, therefore, be late glacial and would occur close to present sea level. This being the case, one can eliminate the supposed Saltburn raised beach as its fauna is not late glacial. It is known that the Holderness region was still glaciated after 18500 ± 400 B.P. (Penny and Coope, Catt., 1969) and this would imply a fairly rapid rate of ice melt. Possibly the present near shore zone was still occupied by Cheviot ice for some time after the area between the 250' contour and the coast was ice free. The inland ice tongue would certainly have been much thinner and thus melt more rapidly.

Despite the above hypotheses, the deglacial chronology of the Tees basin is still far from complete. The author searched every site for late-glacial floral and faunal evidence which could have provided a radio carbon date.

At Coatham Stob a tree root layer was discovered in the upper layers of the laminated clay. However a close examination of the overlying sand showed evidence of heavily oxidised "in situ" roots extending down to the laminated clay where they spread out laterally. A sample was sent to Kew Garden and it turned out to be Alder. Probably the reducing conditions in the laminated clay led to better preservation than in the overlying sand. In addition, the various sites where shell fragments were discovered did not yield sufficient amounts to enable one to attempt a radio carbon date.

Summary

In this brief but valuable chapter, further evidence was gained in support of lacustrinal conditions in the lower Tees Basin during late and post-glacial time. This is certainly what one would expect in a basin which saw the confluence of the Lake District and Cheviot ice and would consequently be subjected to meltwater inundation when the Cheviot ice retreated down slope and effectively blocked the natural drainage. It is probable that many of the terraces in the Tees, the laminated clay, and associated sands and gravels all resulted from these conditions.

The evidence for raised shorelines in the Tees is very tenuous indeed and on theoretical grounds alone, could only occur close to present O.D. and be of late-glacial age.

In conclusion, the need is for radio-carbon dates to clarify the chronology of events.

CHAPTER 11

CONCLUSION

Introductory Statement

Each chapter and section of the thesis was provided with an individual conclusion. The aim of this last chapter, therefore, is to draw overall conclusions regarding the respective successes and failures of the various techniques. One must remember that the aims of the thesis were twofold:

1) To further the development of a methodology for the study of displaced shorelines.
2) To test the methodology on a selected region, the lower Tees basin.

Consequently, this conclusion is subdivided into two sections; systematic and regional.

A. Systematic
   (I) Introduction
   (II) Morphology
   (III) Sedimentology
   (IV) Fossil Faunal, Floral, Chronology
   (V) Future Work

B. Regional
   (I) Introduction
   (II) Morphology
   (III) Sedimentology
   (IV) Fossil evidence, Chronology
   (V) Future Work

Systematic

It was realised at an early stage of the thesis that an integrated approach, which involved morphological, sedimentological, and fossil evidence, was essential if one wished to obtain reliable results.

Morphology

(a) Onshore

Sissons (1963) demonstrated that one could distinguish fluvio-glacial terraces and raised marine shorelines in the Firth of Forth, on their deviation from the horizontal. It was suggested that a raised shoreline would be warped by isostatic crustal rebound and would dip coastward with a maximum tilt of 6.28 feet per mile. In contrast a fluvio-glacial terrace possessed a much steeper dip (e.g., 30 feet per mile). Obviously the technique was limited to areas which had been subjected to isostatic rebound sufficient to exceed the late and post-glacial eustatic rise of sea level.

In the present study, the results of a test survey suggested that certain factors had to be determined before one could obtain meaningful results.

(1) It was most important that one should determine the precise nature of the isostatic uplift. The technique could not be used for inter-regional comparisons

unless the two regions had the following factors in common:

(a) Identical time of deglaciation.

(b) Uniform amount of uplift.

(c) All shorelines compared fell between the same isobases and were identically orientated with reference to the centre of uplift.

The technique has validity once the above conditions are fulfilled. It will not, however, allow one to determine the chemical content of the water. Thus, whilst one may be able to distinguish between a fluvio-glacial terrace and a raised shoreline, it is not possible to determine whether the raised shoreline was formed by a marine or fresh water body.

(b) Offshore

Very little work had been completed on the offshore environment and in the present study an attempt was made to locate bottom and sub-bottom terraces.

One could not emulate the accuracy of the land survey, but nevertheless it was possible to recognise submerged terraces to depths of 180'. The seismic survey proved costly but the limited number of sounding runs did reveal the presence of terraces cut in the surface of the boulder clay.

Sedimentology

This aspect of the thesis involved by far the most work and yet produced the least conclusive results.

(a) Known Environments

A variety of mineralogical tests were completed following a study of methods and approaches. The emphasis was placed on the recognition of the depositional environments of sand deposits. It was suggested that a depositional agent responded to the size, density, and shape of particles. One could therefore fault previous studies of particle size analysis for failing to place sufficient emphasis upon the composition of each sample. Emphasis was also placed on the nature of the individual sample. In a finely bedded sediment it was essential that each lamina should be regarded as a sampling unit. It was easier to obtain a surface skim from present environments than to obtain a mono-genetic sample from a fossil sand.

The results of particle size analysis were processed using factor analysis. This multivariate technique classifies sediments according to the dominant factors responsible for their deposition. It was first applied to particle size analysis by Klovan (1966) with encouraging but only partial success. One must attribute the greater success of the present study to the nature of the individual sample and the restriction of samples to a locality with uniform source material.

An attempt was made to achieve even better separation by including other mineralogical data met with failure, largely because shell fragments dominated all but one environment (fluvial). The following table records the most valuable indicator characteristics of known sands from the Tees basin.

TABLE RECORDING INDICATOR CHARACTERISTICS OF KNOWN SANDS FROM THE TEES BASIN

Beach

1) High polish on the surface of quartz grains.
2) Concentration of heavy minerals in the fine sand fraction.
3) Concentration of shell fragments in the coarse sand fraction.
4) Distinctive cut off of particles in the range 2.75ϕ to 3.4ϕ

Dune

1) Complete absence of mica.
2) Very restricted grain size distribution (Leptokurtic).
3) Distinctive particle size curve on Arithmetic Probability paper (almost vertical).
4) Marked concentration of heavy minerals in the fine sand fraction.

River

1) Very high rock fragment content.
2) Symetrical coarse and fine tails on the particle size curve.
3) Wider range of grain sizes than either beach or dune.

Offshore

1) Much higher silt content than beach which it otherwise resembles in all facets but the high polish on the surface of quartz grains.

Lacustrine

1) Identical sorting pattern to a marine beach without shells.
2) Finer grain size than beach.
3) Resembles offshore samples in particle size distribution.

Fossil Environments

The many fossil sands which occur in the Tees were subjected to similar analyses as the known environments. Factor analysis of particle size data again proved valuable, but failed when other data was included. One must conclude that factor analysis is a more efficient means of describing a particle size distribution than moment measures which were found to be inadequate. The shape of the particle size curve was also sensitive to environmental differences and one could frequently identify a deposit on this characteristic alone.

The survey ran into some difficulty with samples which fell between the fluvial and littoral environments when factor loadings were plotted on a triangular graph. It was felt that these were most probably deltaic sands. One would certainly expect deltaic conditions to occur frequently around the shorelines of a lacustrinal basin.

Future Work

It was concluded that factor analysis probably held the key to environmental studies and the following approach was suggested as a result of the present study.

1) Analysis of the mineral content of the full sand size fraction.
2) Factor analysis of the distribution of each mineral group within the sample.

Again one should stress that sedimentological evidence alone would be inadequate. However, when combined with morphological and fossil evidence it provided a very valuable additional source of information in the study of displaced shorelines.

Offshore studies

The present study was unable to extend its sedimentological techniques to anything but the surface sediments on the sea bed. It was demonstrated that mechanical samplers were less efficient than a S.C.U.B.A. diver who was able to observe the nature of the deposit before taking a sample.

Fossil Evidence and Chronology

Fossil Evidence

The main factor to emerge from the study was the very great care which was necessary to determine whether a displaced marine fauna was truly indicative of a change in sea level. It was also considered important to examine possible marine deposits for microfossil content as well as for the more obvious macro-fossils. Microfossils are more mobile and would inundate a newly submerged area more rapidly. Similarly one must also examine sites for evidence of fresh water peat or organic beds which would provide positive evidence of freshwater conditions. This positive approach is far sounder than using the absence of marine fauna or flora to prove a displaced marine environment did not exist.

There is no doubt that fossil evidence is still the most conclusive means of determining the existence of a displaced marine environment, above sea level, and a displaced terrestrial deposit below sea level.

Chronology

It was proved that one could only correlate displaced shorelines in different areas by the use of absolute dates. Similar height above present sea level or a similar degree of isostatic warping were not necessarily indications of a similar age. One cannot overemphasise the need for absolute dates in any study of the Quaternary, not only sea level change.

REGIONAL

Morphology

The topography of the lower Tees contains little relief. A field survey located several short terrace remnants which all approximated to the horizontal. It was felt that they represented the shoreline terraces of a series of ice dammed proglacial lakes (90' to 170' O.D.) probably combining in the later stages of deglaciation to form a single water body (80' to 35' O.D.).

Sedimentology

It was felt that the key to the late and post-glacial history of the lower Tees lay with the origin of the laminated clay which occupied much of the lower reaches of the present drainage basin. The sedimentological evidence tended to confirm that this deposit was laid down in an ice-dammed lake which was formed by meltwater trapped in front of an eastward retreating ice tongue. The majority of terraces which occur around this deposit were most probably formed during its maximum extent whilst the lower terraces and deltaic deposits were laid down during the latter stages of deglaciation. Above 85' O.D. the height of some terraces suggested that they were not related to this single water body, but to lesser individual lakes which had dried out independently of the larger body.

Fossil evidence and Chronology

The study of the Lower Tees led to a refutal of previous workers hypotheses concerning the existence of a late-glacial and a later post-glacial marine incursion. None of the seven supposed marine sites contained satisfactory marine evidence, in fact, several contained virtually irrefutable evidence of a non-marine origin.

Several freshwater peat deposits suggested that much of the area which was occupied by meltwater drainage had remained as low lying marshy ground, suitable for peat formation until the end of Zone VIIb in the pollen zone sequence. Peat deposits also confirmed the existence of a low sea level, at least -60' OD 9000 years ago.

Summary of Sea-Level Change in the Lower Tees Basin

It would appear from this study that no sea levels, above that of present, have occurred in the Lower Tees Basin since the retreat of the last ice sheet. There is evidence to suggest that the buried post glacial valley of Tees is graded to a sealevel of -160' OD and it could be interpreted that this level marked the freeing of the natural drainage from the restrictions imposed upon it by the ice retreat. This is however unlikely as there would have been a considerable time lag between the onset of normal drainage and the erosion of the buried valley. At the present time it is impossible to determine history of the late glacial sea level but after the year 9000 BP to present one could obtain the dates to graph the post glacial rise. One could possibly determine the rate of isostatic uplift and hence the total amount of uplift and therefore the ice thickness in the Tees if one compared this rise with the known rate of the eustatic rise of sea level.

One is forced to conclude that the major disappointment turned out to be the absence of raised shorelines in the Tees. The area had been chosen specifically because there was evidence of high sea levels. This discovery meant that it was not possible to test the methodology which was devised for the recognition of a raised marine deposit. However, it was equally as valuable to disprove the existence of raised shorelines in the Tees as it would have been to confirm them. An area which must now be examined is the strip of coastland between Tyne mouth and St.Abbs Head where several persons (Sissons, pers. comm. C.A.M. King pers. comm.) have noted marked coastal terraces.