Holocene sea-level changes and crustal movements in North Wales and Wirral

Volume One

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Abstract

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Litho-, bio- and chronostratigraphic data have been collected from North Wales and Wirral relating to relative sea-level changes during the Holocene. Over one-hundred and fifty hand cores have been completed, and a seismic refraction survey, pollen and diatom analysis and eighteen new radiocarbon dates established. These data, along with that from previously published material, have been evaluated within a defined methodological framework to establish the sea-level and crustal history of the study area.

Time-altitude and tendency chronologies have been established for the past 8500 ^{14}C-years. These chronologies have been compared with those from Lancashire, Morecambe Bay, Cardigan Bay and Northeast England.

The evidence for differential crustal movements in North Wales and Wirral is examined. Use is made of the results from crustal modelling as well as the available empirical data, and the results are compared with chronologies from adjacent regions.

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Contents of Volume One

Chapter Four: Previous Investigations.

Chapter Five: Field and Laboratory Results.

Chapter Seven: Crustal movements.

Tables in Volume I.

Chapter One.

Introduction.

1.1 Introduction.

In this thesis the results of fundamental research into sea-level changes and crustal movements in North Wales and Wirral during the Holocene are presented. To the north and south of this area are the intensively studied coastlines of Lancashire and Cardigan Bay respectively. In contrast, North Wales has been lacking in sea-level data and is therefore worthy of systematic investigation.

The main aim of this thesis is to establish the sea-level and crustal history of North Wales and Wirral. The approach taken to answer this aim has largely been based upon the collection of field and laboratory data, and the application of some established, and also some new, data analysis techniques. Coastal sediments on this coastline have been the subject of scientific scrutiny since the nineteenth century (Hall, 1866; Strahan 1885,1890; Morris, 1923; Neaverson, 1936; Bibby, 1940; Rowlands, 1955; Hopley, 1963; Tooley, 1978; Manley, 1981; Kenna, 1986; Prince, 1988; Innes *et al.*, 1990) so that conclusions based on field and laboratory data collected as part of this research have been aided by information from these previous investigations. In addition, the recent results of crustal modelling experiments applied to Britain (Lambeck, 1991; Tushingham and Peltier, 1991) provide an invaluable and independent comparison with the field data.

1.2 The Study Area.

Field investigations are orientated towards finding coastal sedimentary sequences that have been deposited within the intertidal zone, or from just above it in a reedswamp and fen environment. On a gently sloping coastline a distinctive zonation of sediment, flora and fauna may become established in the intertidal zone and these zones exist side by side in space

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between Mean Low Water of Spring Tides (MLWS) and just above the Mean High Water of Spring Tides (MHWS).

When a core is sampled, a vertical sequence of sediment is examined for a single point in space. Palaeoenvironmental reconstruction techniques can be applied to this sedimentary column and the characteristics, in terms of sediment type, vegetation and fauna, of the vertical 'zones' or 'strata' identified. These strata can be matched with the corresponding zone in the intertidal area. When the vertical sequence from a core indicates that there has been a change in environment, for example from a sandflat to a reedswamp environment, it is implicit that some factor must have caused a migration of the intertidal zones seawards. This could be due to a number of factors such as a change in relative sea-level, or a change in the sedimentary and tidal regimes.

In very general terms, sediments that are representative of these environments are found along the North Wales and Wirral coastline below +5.00 m OD. A widespread field survey identified four main areas in which investigations were focused: the Malltraeth Marshes on Anglesey, the Afon Ganol Valley, the Clwyd coastal lowlands and north Wirral. These areas, as well as key sites in northwest England and Cardigan Bay, are shown in Fig.1.1. In Fig.1.2 they are identified on a more detailed map of the North Wales and Wirral coastlines.

1.3. <u>The mechanisms of relative sea-level change.</u>

Relative sea-level is controlled by an array of variables which are operative over specific temporal and spatial scales. In this study the timescale under consideration is nominally the Holocene, approximately the last 10,000 ^{14}C-years. The primary source of data used is sediments that have accumulated along the North Wales and Wirral coasts in response to changing relative sea-level.

Some of the processes that control relative sea-level changes over particularly short timescales will not be recorded in such a sedimentary record. Daily tidal changes, for example, will not be recorded, though particularly extreme events which leave behind a distinguishable sedimentary feature may be. Observations of these short time-scale events are best revealed through the analysis of tide gauge data or through geodetic levelling. Using such techniques the precision is higher than in sedimentary analysis, but the time frame is considerably reduced. Earthquakes are extremely short timescale events, but if an epicentre is located offshore a tsunami can result, leaving a sedimentary imprint on affected coastlines (Smith *et al.*, 1991, 1992). Equally, variables that are operative over very long timescales such as the changing distribution of the continents and ocean basins will not produce discernible changes of relative sea-level over a Holocene timescale. Bott (1968) has shown that areas of thick crust adjacent to the Irish Sea basin such as the Lake District, Snowdonia and much of Ireland have tended to resist long-term subsidence. Such a process may produce differential relative sea-level changes around the Irish Sea on a Holocene timescale, but cannot be detected because other variables are so dominant.

When examining Holocene sea-level changes therefore, a limited number of variables are detectable from Holocene coastal sedimentary sequences. In North Wales and adjacent regions two variables have dominated relative sea-level changes through the Holocene. The first is the return of water to the ocean basins since the last glacial maximum, *c.* 18,000 BP. Fairbanks (1989) estimates the water returned to the ocean basins since this date will have produced a 120 m increase in mean sea-level. Other variables tend to modify this rise of sea-level spatially, so that the concept of global or eustatic changes is redundant.

Isostatic readjustment of the Earth's surface following the removal of ice-loads from the northern hemispheric ice-sheets is the other dominant process controlling relative sea-level changes in North Wales during the Holocene. At 18,000 BP, ice sheets covered much of northern Britain, centred over northwest Scotland, the Lake District and Snowdonia in North Wales. When this ice-load was removed because of warming, uplift occurred in these and peripheral areas because of an inflow of magma, accommodated in the Earth's asthenosphere. At the centre of ice-loading in Scotland the process of isostatic uplift has continued through the entire Holocene to the present day because the flowing magma is a particularly viscous fluid. Uplift tends to decay in an exponential form with a half-life between 2000 and 3000 ^{14}C-years (Andrews *et al.*, 1973), though Mörner (1991) has suggested a two stage curvilinear decay. In North Wales, Shennan (1989) suggested that uplift was completed about 5000 BP, though relative sea-level has been rising, perhaps with low wavelength oscillations, since 12,500 BP (Lambeck, 1991).

Second-order factors controlling the registration of relative sea-level changes in coastal areas are consequential on isostasy and eustasy. The first, hydro-isostasy, is caused by a deflection of the sea floor following a sea-level change. The deflection can be up to one third of the actual sea-level change (Fjeldskaar, 1989). Assessment of the influence of hydro-isostatic and other processes which add a load to the ocean floor, such as sediment loading, is made difficult in the Irish Sea because of the lack of independent model results compared with southern hemispheric coastlines (Chappell, 1974). Sea-level will vary over the surface of the Earth as a function of the equipotential surface, and is termed the geoidal surface. The potential at any point on the Earth's surface will vary through time in response, largely, to the changing distribution of mass within the Earth, for example, following deglaciation (Fjeldskaar, 1989). Fjeldskaar (1989) estimated that sea-level in eastern Britain was 10 m away from its equilibrium level at 15,000 BP, but less than 5 m by the start of the Holocene.

Definitions of the terms used in the above description can be found in Appendix 1.

1.4 Structure of this thesis.

Following this introductory chapter the next three chapters provide a context for this investigation with reviews of methodology, techniques and previous investigations.

In Chapter 2 the historical evolution of sea-level studies is described. This research has been carried out with the benefit of the knowledge described in this chapter, and thus represents a baseline for the work presented. Some of the specific questions that will be addressed in this thesis are outlined in this chapter. In Chapter 3 the field and laboratory techniques applied in this research are described with an emphasis on highlighting some of the problems in applying them to the current study. Whilst in Chapter 2 the evolution of the science of sea-level studies is examined, in Chapter 4 the actual results of sea-level investigations in North Wales, Wirral and surrounding regions are described. This chapter therefore provides a geological and geographical context for the study area.

In Chapter 5 the results of the research are presented. The lithostratigraphy, pollen, diatom and seismic refraction data from ten sites are described and an initial evaluation of environmental changes at key sites made. In Chapters 6 and 7 these results are evaluated in terms of sea-level change and crustal movements respectively.

1.5 Summary.

Along the North Wales and Wirral coasts are extensive sedimentary sequences that have formed during periods when coastal ecosystems were migrating landwards in periods of marine inundation and seaward in periods of marine withdrawal. These migrations may be due to changes in relative sea-level or a multitude of other factors, or combination of factors. Information contained in the sedimentary sequences can be extrapolated through the application of palaeoenvironmental reconstruction techniques, thus providing evidence of past environmental change. In this thesis an attempt will be made to separate this evidence into the original process components, while evaluating the methodologies, data and analysis techniques commonly used in sea-level investigations.

Chapter Two

Scientific Framework.

2.1 Historical background.

In this section some of the developments in sea-level studies during the last fifty years are described. The aim of the section is to provide a background to the scientific framework of sea-level studies as it stands today, for it is against this background that this thesis has been completed.

As the science of sea-level studies has progressed explanations and conclusions based largely on field observation and data collection have become aided by geological theory and more recently by the formulation of a methodology within a quite tight scientific framework. Particular data collection methodologies have been developed for differing environments, but here attention is focused on the case of the reconstruction of sea-levels from unconsolidated sediments in Europe, particularly in the UK and the Netherlands.

Data used for the reconstruction of past sea-level changes must have four properties:

(i) **An age.**
(ii) **An altitude in relation to a known datum.**
(iii) **A location.**
(iv) **An indicative meaning (relationship to a former sea-level).**

Until the development of absolute dating techniques in the 1950s age determinations were reliant on relative methods, and in the UK Godwin (1940a, 1940b, 1943, 1945) pioneered the application of pollen analysis to sea-level studies for the relative dating of sediments. Godwin and Clifford (1938) and Godwin (1975) explained how pioneer work into pollen analysis by von Post had demonstrated a uniformity of the pattern and spread of tree species throughout Europe during the Holocene. Correlation of distinctive pollen assemblages, or zones, with varved lake deposits allowed the development of a relative chronology based on pollen assemblages (Godwin, 1975). Godwin (1940a) showed that the tree pollen composition of peats obtained at depths of 100′-170′ in the North Sea was attributable to zone V (*c.* 9000-9500 BP) as they were dominated by birch, pine and hazel, and that peats from 23′ at St.Germans, East Anglia were from zone VII (*c.* 7500 BP+), being dominated by the pollen of deciduous woodland species. From these results Godwin (1940a) was able to postulate that the major Holocene rise in sea-level took place between zones V and VII. Similarly through pollen analytical investigations from Swansea Bay Godwin (1940b) was able to assert that there was a rapid marine transgression during the Boreal period (zone VI). Vermeer-Louman (1934) had shown how the age of basal peats overlying the Pleistocene sands of the western Netherlands decreased with depth, though the relationship of this peat growth to rising sea-levels was not fully established until the work of Bennema (1954a) and van Straaten (1954). Godwin (1940a) and van Straaten (1954) demonstrated awareness of the possible errors in their data by placing error boxes on their sea-level curves, a feature lacking in much subsequent work (Godwin *et al.*, 1958; Fairbridge, 1961; Shepard, 1963; Tooley, 1974).

With the availability of radiocarbon (^{14}C)-dating (Libby, 1952) an absolute age could be assigned to samples of a known altitude and established indicative meaning. Data could now be plotted on a time-altitude graph to form sea-level curves, and in the next twenty-five years or so following the availability of ^{14}C-dating numerous sea-level curves were produced on a regional and global scale. This era of data gathering culminated in the International Geological Correlation Programme (IGCP) Project 61 (1974-82) with the aim of establishing a graph of the trend of mean sea-level in the last 15,000 years and the completion of an *Atlas of Sea-level curves* (Bloom, 1977).

During the 1950s and 1960s numerous sea-level curves were constructed from around the world. Apart from curves constructed from formerly glaciated areas where isostatic uplift has been more dominant than the eustatic rise of sea-level in the Holocene, all showed broadly similar trends, that is a decreasing rate of sea-level rise through the Holocene, especially after *c.* 7000 BP. One of the major conflicts of the time was over the nature of this rise and the possible existence of former periods during the Holocene when sea-level was higher than the present.

Much of the evidence for higher sea-levels than the present came from raised shorelines in the tropics (Daly, 1934; Fairbridge, 1961), particularly in Australia. The controversy that typically such shorelines are not found in other parts of the world has been resolved following the results of crustal modelling experiments (Clark *et al.,* 1978; Peltier, 1980) which showed that at locations remote from the centres of ice loading such features should be expected following the viscoelastic adjustment of the earth to a redistribution of the ice and water load. In tropical areas where there is a wide continental shelf such as the Great Barrier Reef, Chappell (1974) has shown how hydro-isostatic processes can lead to subsidence on outer shelf areas and resulting inner shelf uplift and hence relict raised shorelines.

As to the nature of Holocene sea-level rise, there were two main strands of opinion: those suggesting that sea-level rise took the form of a smooth exponential decay curve (Jelgersma, 1961; Shepard, 1963; Kidson and Heyworth, 1973; 1978) and those who favoured an oscillatory pattern of sea-level rise (Fairbridge, 1961; Mörner, 1969; Tooley, 1974). The differing results and resulting opinions can, in some cases, be explained in terms of the methodology adopted by particular workers. In the Netherlands, for example, only basal peat data were used by Jelgersma (1961, 1966) in the construction of sea-level curves to avoid the problem of compaction within sediments. By definition such a methodology cannot produce apparent falls in sea-level (Shennan, 1983) since the basal peats overlying the Pleistocene sands of the western and northern Netherlands formed under rising groundwater conditions.

Kidson and Heyworth (1979) point out that because of our inability to quantify altitudinal errors fully at present we do not have the technical resources to draw curves to the precision often indicated. Despite the recognition of these errors the two schools of thought remain (Kidson, 1982). Those favouring a smooth rise in sea-level argue that as sea-level rise slowed in the later Holocene it would have variously fallen below or exceeded the rate of sedimentation (Kidson and Heyworth, 1978). Such processes would produce the intercalated sediments typical of coastal sequences which are interpreted as rises and falls of sea-level by others (Tooley, 1974). Nevertheless, the two 'schools' have moved closer together; in the Netherlands Louwe Kooijmans (1974), Roeleveld (1974) and van de Plassche (1982) have produced curves showing variations in the rate of sea-level rise, though the direction of change remains the same and Tooley (1982), for example, modified his chronology for northwest England because of the problems of using altitude in constructing sea-level curves (Shennan *et al.*, 1983).

As van Straaten (1954) had done, Kidson and Heyworth (1979) drew attention to the errors from radiocarbon dating, compaction, relating indicators to a former sea-level, the rare event and the actual meaning of sea "level" when the variations in tidal range are considered. Of particular significance are the variations in tidal range caused by the coastal geometry: for example, in narrow inlets or river estuaries the tidal range will increase landwards. In the Bristol Channel MHWS is +4.40 m OD on a line from the Gower Peninsula to the north Devon coast, but increases to +7.20 m OD near the Wye estuary. Variations in MHWS greater than 1.00 m are found within the Thames estuary, the Humber estuary, Solway Firth and Morecambe Bay. It is this kind of area where sea-level investigations are conducted because the sedimentary evidence is better preserved than in open coast environments (Kidson and Heyworth, 1979).

The greater recognition of errors involved in data collection in the 1970s was accompanied by a growing realisation that there was a complex relationship between sea-level changes and crustal response:

> *"Sea-level variations are modified by many local, regional and global factors; further, (that) spatially uniform changes of sea level, characterised by a single, global curve, represent an unrealistic response of the earth's crust to water mass transfers, and (that) no point on the earth's surface can be regarded as having provided a stable datum for recording an eustatic sea level."*
>
> *Devoy (1987: 7-8).*

These realisations derive largely from work carried out on glacial isostatic readjustment, one of the points of focus of an International Geodynamics Project (1970-79) on movements of the surface and upper part of the earth's interior. The primary objective of this work has been to determine the value of mantle viscosity, which is a variable controlling, for example, mantle circulation and hence plate velocities. The main tool of such investigations has been mathematical modelling, but empirical backup of modelled results has been provided from sea-level data, especially from uplifted and adjacent areas where the results of massive ice-mass transfer can be modelled and tested.

For the last few decades a rather curious relationship has existed between the modelling or geophysical community and the data collection or geomorphological community expressed by Fairbridge (1983,p.3):

> *"Isostasy and eustasy are two intimately related geodynamic processes that can scarcely be understood or measured apart from each other, and yet, strangely enough, they have in the past been studied by specialists of two rather disparate disciplines, geophysics and geomorphology, the practitioners of each rarely possessing any training whatever in the other. This paradoxical situation may explain to some extent the many still unresolved problems that exist in both fields."*

The mathematical language of the models (Peltier, 1974; Clark *et al.*, 1978) is not understood by most geomorphologists and equally the uses and limitations of field data are not well understood by most modellers (Peltier, 1980). The common link between the two groups is isostasy, the history of which is used to determine viscosity at one level of resolution and to subtract from relative sea-level to estimate eustasy at a higher resolution.

Crustal models have two inputs (Peltier, 1980): the ice melt history and rheological variables including viscosity. The models are run and sea-level histories are produced for points on the earth's surface as a check of the ice-sheet histories. Though there are two unknown variables, the two unknown "functionals of the model" can be determined by an iterative process (Peltier, 1976).

Early models assumed that the ice meltwater was spread uniformly over the oceans. This was of course a necessary starting point, but not wholly realistic (Peltier, 1980). The equilibrium surface of the oceans (the geoid) is a surface where the gravitational potential is constant so if there is a local change in this potential, the unbalanced gravitational forces will lead to a redistribution of water masses. In other words a vertical change in ocean level caused by an input not uniformly spread over the oceans will also result in a horizontal change in the ocean surface. If it is assumed that gravitational equilibrium was attained at the maximum of the last glaciation, very rapid ice melt, at a rate greater than the increase in crustal mass from isostasy, would have led to a gravity low and a local reduction in the geoid. When deglaciation is slow the related geoidal deflections tend to be small (Fjeldskaar, 1989). More recent gravitational self-consistent models (Peltier, 1980; Fjeldskaar and Cathles, 1987) have attempted to integrate the geoidal effects of deglaciation. An important consequence of these interactions is that neither the ocean floor nor the land masses achieve equilibrium during periods of sea-level change.

Mörner (1976) drew attention to the possible effects of horizontal geoidal shifts on the interpretation of Holocene sea-level data. However, Bennema (1954b,p.257) was clearly aware of the possibility and consequences of a shifting ocean surface when discussing his Holocene sea-level curve for the western Netherlands;

> *"Assuming that the **shape of sea level** has not changed during the times under review, this absolute rise should apply to the whole globe."*

Mörner's arguments of frequent and apparent random geoidal shifts through the Holocene are unproven. Eronen (1986) asserts that the observed geoidal deformations are so small in postglacial times that they will have had a negligible effect on relative sea-level changes. Instead in the short term they seem very much related to processes of mass transfer, glaciation and deglaciation being the most obvious examples (Peltier, 1980; Fjeldskaar, 1989). Numerous authors (Kidson and Heyworth, 1979; Devoy, 1987; Shennan and Tooley, 1987) consider that Mörner's arguments of a shifting geoid ended the search for a global eustatic curve, and yet, 'global eustatic curves' continue to be published, for example by Fairbanks (1989). These apparent contradictions are a matter of the scale and resolution with which we view the problem. Fairbanks's (1989) curve, for example, derived from coral data in the Atlantic, covers the last 18,000 years and therefore *c.* 130 m of eustatic sea-level rise. At this level of resolution it may well be valid to produce a global eustatic curve, but on a Holocene timescale even with the application of gravitationally consistent crustal models variability is beyond our level of resolution.

In the 1980s the limitations of the methodological framework of sea-level investigations were scrutinised by Shennan (1980, 1982a, 1982b, 1983), Shennan *et al.* (1983), and Tooley (1978, 1982). The outcome and proposals of these works were wide ranging and developed through the decade encompassing the aims of IGCP 200, *Sea-Level Correlations and Applications,* where the emphasis of the project was on high quality local studies producing data that could be analyzed and correlated on larger scales to examine tectonic, climatic, tidal and oceanographic fluctuations (Tooley, 1985a, 1987).

In the UK, therefore, the methods of litho- and bio- stratigraphic analysis used by Godwin and Tooley (1969, 1978) were used as the basis for data collection. The need for full assessment of altitudinal and age errors as well as the true indicative meaning of samples was further emphasised and the need for a consistent nomenclature of terms demonstrated if correlation was to be attempted (Streif, 1979; Shennan 1980, 1982a, 1982b, 1987). Shennan (1983) presents a flow diagram of sea-level research methods in which a data collection strategy based on continuous error assessment leads into three routes of analysis. Route 1: *Local sea-level analysis* is the simplest route involving the identification of local tendencies of sea-level, perhaps leading to the construction of a local sea-level curve. The second and third routes involve larger scales of analysis: *Regional sea-level tendency analysis* and *Analysis of crustal movements*.

Just as Godwin in the 1940s had provided an ecological and methodological starting point for today's investigations in the UK, Bennema (1954a, 1954b), van Straaten (1954) and Jelgersma (1961, 1966) provided such a framework for subsequent investigations in the Netherlands: Roeleveld (1974) in Groningen, Griede (1978) in Friesland and van de Plassche (1982) in Zuid Holland and Zeeland produced very detailed local studies progressing to the development of a regional history (Berendsen, 1984) through the correlation of these local data.

The development of correlative methods was a major focus of the work in Britain and particularly that of Shennan (1982a, 1982b, 1983, 1987), Shennan *et al.* (1983).

> *"It can be argued that even if the sea-level data currently used for correlations*

between different areas were all defined in a suitable form, the techniques of correlation are rarely developed beyond the visual similarities of two or more curves upon a graph. More reliable techniques of correlation are required."

Shennan (1982b: 53).

The need for a data bank of high quality data was realised (Shennan, 1987), to develop and test these methods in the context of hypothesis testing rather than purely inductive data gathering (Shennan and Tooley, 1987). As part of IGCP 200 a databank of ^{14}C dates has been collected for Britain in Durham and analysis carried out upon these data, principally in the examination of tendencies of sea-level (Shennan *et al.*, 1983) and crustal movements (Flemming, 1982; Shennan, 1989) in Britain.

The tendency analysis of sea-level attempts to overcome the inherent problems in using altitude as a variable by plotting the tendency (positive represented by a transgressive overlap, or negative represented by a regressive overlap) against age. Tendency plots are constructed for small areas, for example, the Fenland, northwest England, the Thames estuary, and can then be compared quantitatively. The method was used for analysis of sea-level data in the Netherlands by Roeleveld (1974) and Griede (1978), and for the western European seaboard by Morrison (1976). Shennan *et al.* (1983) argued that the precise registration of sea-level changes may well be site-dependent, but the dominant direction of sea-level change would be registered over a wider area which the tendency approach should be able to pick out. How regressive or transgressive overlaps actually relate to the specific chronology has been questioned by Godwin (1975), Tooley (1978) and Long (1991), who pointed out that the change in direction of movement in sea-level, for example from negative to positive, will take place within the organic sediments and that the actual lithologic switch from freshwater organic sediments to marine or brackish inorganic sediments will be a point within the continuous process of a positive sea-level tendency.

The hypothesis testing methodology has some important consequences for the formulation of research projects. The expansion in the discipline as a whole means that a project such as this, primarily designed to evaluate the evidence for relative sea-level changes and particularly differential crustal movements in North Wales and surrounding regions, will result in a data collection methodology very different to one designed for the examination of high resolution sea-level changes by Long (1991). It has been repeated in the past (Shennan, 1987, 1989; Shennan and Tooley, 1987) that most sea-level research is still inductive, with data collection preceding the formulation of ideas or hypotheses. Such an approach may produce a relatively flexible set of data, but it may not be of the same quality when applied to a specific problem as another set of data which was specifically collected to address the problem in question. Within the discipline the questions being asked cannot be fully answered with contemporary technology, the uncertainty of ^{14}C-dating being a major constraint, so there is a need for the highest quality of data possible. Long (1991) argues that methodological developments have now surpassed data collection strategies, emphasising the need for a more deductive approach.

Therefore data collection need not be the first stage of implementation in a sea-level research project. Instead formulation of primary questions and the design of a data collection strategy addressing these questions should precede the bulk of data collection, or be a parallel feature of a research project.

2.2 Hypothesis testing and regional correlation.

Shennan (1987) and Shennan and Tooley (1987) state that sea-level studies are still very much an inductive science, with data collection leading to an interpretation. More recently there have been examples of explicit data collection, notably by Long (1991) and Shennan (1992). Having identified that the zero isobase (the line of no net contemporary crustal movements due to isostatic forces) crossed the northeast coast close to the Tees estuary and that there was still uplift taking place near Dunbar in southeast Scotland of the order of 0.5 mm/yr (Shennan, 1989), Shennan (1992) targeted an investigation into crustal movements along the Northumberland coast between these two areas. At Alnmouth and at Elwick, close to Holy Island, there was evidence of slightly more uplift during the Holocene relative to the Tees estuary; otherwise the trend was very similar. From this investigation, therefore, it is now possible to say that there is a very sharp edge to the present day zone of uplift along the east coast of the UK.

In a similar way this thesis aims to show a change through time in the crustal histories between Lancashire and Cardigan Bay, but also to determine the type of changes within North Wales itself. It is therefore hypothesised that the observed differences in the crustal histories of south Lancashire and Cardigan Bay in the early and mid-Holocene will be reflected by differential crustal movements along the North Wales and Wirral coasts. Modelled results (Lambeck, 1991) predict greater uplift through the Holocene in Anglesey than Wirral.

2.2.1 The conflict of hypothesis testing and scale in the reconstruction of a sea-level chronology.

One of the recommendations of IGCP 200 (Shennan and Tooley, 1987) was that data collected for the reconstruction of past sea-level changes should come from a small homogeneous area, so that the effects of tidal inequalities, earth movements and variations in the geoidal configuration would be minimised. Examination of the data from adjacent regions to North Wales (Lancashire and Morecambe Bay to the north and Cardigan Bay to the south), and also the crustal rebound models for the UK (Lambeck, 1991), suggests that the North Wales coast has not acted uniformly, in terms of its crustal history through the Holocene. Implicit in the hypothesis to be tested is that there have been differential crustal movements along the North Wales coastline which are a product of a greater residual uplift in the west of the region relative to the east as indicated by the crustal models (Lambeck, 1991), and the data collection strategy has been geared towards the acceptance or rejection of this hypothesis which requires a relatively extensive study area.

Shennan (1980) discussed how each sea-level index point has dimensions of location, age and altitude, and argued that analysis of within-area variance is necessary to establish how representative a single index point is for a defined area. Acceptance of the above hypothesis would mean that sea-level index points collected from the area investigated in this thesis are not representative of relative sea-level changes for the whole of the North Wales coast in terms of their age-altitude position (though the tendency of relative sea-level may still be uniform). A consistent pattern of age and altitude positions of index points along the North Wales coast will lead to a rejection of the hypothesis. Shennan (1980) however, has stated that a limited data set will tend to simplify the real pattern of relative sea-level changes, and here as in most investigations the analysis is limited by the number of sea-level index points.

A sea-level index point provides an age determinant on a transgressive or regressive overlap from which we may infer an increase or decrease in the marine influence over the area which that index point defines. At a single site the pattern of transgressive or regressive overlaps will normally have been established by a programme of coring, and the most representative points will be selected for ^{14}C-dating. In most research projects more hand-cores are completed or more sites sampled than there are resources for ^{14}C-dating. Therefore in areas deficient in ^{14}C-dates the similarity of the lithostratigraphy to a site where ^{14}C-dates are available has been used to infer sea-level chronologies. For example, Tooley (1974) and Bowen (1977) have correlated the altitude of regressive and transgressive overlaps from limited borehole data in North Wales with the altitude of dated overlaps in Lancashire to infer a first approximation North Wales chronology. Just as Shennan (1980) has noted that too few ^{14}C-dates for an area will oversimplify a chronology, lithostratigraphic correlations based on a few boreholes will neglect possible variance.

The variance in the altitude of transgressive and regressive overlaps in North Wales and Wirral is shown in Figs.2.1a and b. These graphs depict the altitude of regressive and transgressive overlaps, sorted by depth below MHWS, recorded in the hand coring programme of this thesis, and show that transgressive and regressive overlaps can be found at any altitude between 0.00 and 7.00 m below MHWS, representing the last *c.*7500 years.

Considering Fig.2.1, one hypothesis for the observed pattern could be that the registration of transgressive or regressive overlaps is not directly controlled by relative sea-level changes. Such a hypothesis would be based on the assumption that most transgressive or regressive overlaps represent increases or decreases in the marine influence, so it would seem possible to devise any sea-level chronology desired for the last *c.*7500 years. Such a hypothesis would, however, be in conflict with evidence from other areas of Britain and Europe, notably the Fenland (Shennan, 1982a, 1986) and the western Netherlands (Hageman, 1969), as well as the implications of the hypothesis that there have been differential crustal movements along the North Wales coast. Additionally Shennan (1982a,p.59) points out that;

> *"A rise, or fall, in sea-level will be recorded by a change in vegetation and/or lithology the nature of which is site-dependent yet the direction of change, or 'tendency of sea-level movement', will be the same over a much wider area."*

A more realistic working hypothesis is therefore that the registration of relative sea-level changes along the North Wales and Wirral coasts, in terms of sedimentary response, has been modified by the individual site characteristics. The implications of this hypothesis and the data of Fig.2.1 are that the lithostratigraphy at some sites will have a low signal to noise ratio, and therefore care needs to be exercised when deciding which sites to use for ^{14}C-dating.

2.3 <u>The development of a data collection methodology.</u>

It has been stated that one of the main aims of this thesis is to evaluate the evidence for crustal movements in North Wales. The evidence necessary for carrying out this aim is preserved in the coastal sequences: however, to make full use of the evidence available a systematic data collection strategy is required. In this section some of the problems in conducting such an analysis, and the methodology adopted to overcome them, are explained. The following structure has been adopted:

2.3.1 **"Differential crustal movements"**, a short explanation of this term and some of the concepts involved.

2.3.1a **The vertical and spatial sampling strategy.** In this section some of the problems of conventional analyses of crustal movements are explained, and a data collection strategy to overcome some of them presented.

2.3.1b **The problems of sediment compaction.** Altitudinal error from sediment compaction is one of the biggest problems in sea-level studies, and particularly in the reconstruction of crustal movements. These errors are elaborated upon using evidence from investigations in the Netherlands.

2.3.1c **The use of basal peat data.** Using basal peat data is a possible solution to the compaction problem. The advantages and problems of using such data are explained, again with reference to investigations carried out in the Netherlands.

2.4 Data collection. Briefly explains how the theoretical considerations previously explained were translated into a field data collection programme.

2.3.1 **"Differential crustal movements".**

Differential crustal movements have been analyzed in the UK from long-term geological data (Churchill, 1965; Flemming, 1982; Shennan, 1983, 1989, 1992), short-term tide-gauge data (Valentin, 1953; Woodworth, 1987), geodetic data (Kelsey, 1972) and mathematical modelling (Lambeck, 1991; Tushingham and Peltier, 1991). Recently attempts have been made to combine the longer-term and shorter-term records (Shennan and Woodworth, 1992). These investigations have revealed broadly similar patterns in the present day distribution of crustal movements: uplift centred in northwest Scotland to subsidence in southeast England. The position of the zero isobase varies, but the most recent analysis of the geological record based on the largest data set (Shennan, 1989) places the zero isobase on a line from the Lleyn peninsula in northwest Wales, through the Wirral to the Tees estuary in northeast England.

This pattern of crustal movements observed today will not have been constant through the Holocene. Not only will the position of the isobases have shifted, but the gradients of these isobases will have changed in response to geological processes such as deglacial isostatic uplift, forebulge migration and hydro-isostasy; the details of which are discussed more fully in Chapter Seven. Data quality and quantity are insufficient to resolve the differential pattern of crustal movements to the extent where it is possible to assign a pattern to a process in anything but the broadest terms, largely because the uneven distribution of data in space and time as highlighted by Shennan (1989). It is not feasible to collect the quantity of data required to reach a level of understanding where we can quantify component processes at a British scale, but very specific data collection and a continuous feedback from modelled results in response to new geological data are a practical way forward. ^{14}C-data in this thesis have been collected with such a framework in mind.

2.3.1a **The vertical and spatial sampling strategy.**

Fjeldskaar (1989) has shown that during the Holocene, spatial shifts in the pattern of the geoid around Britain have been minimal: hence a relative sea-level curve from the British coast is largely a function of **eustasy** and **isostasy**, though variations in the tidal regime and hydro-isostasy are two further unknown variables. The separation of these two primary variables from one curve or set of data has obvious applications, notably in estimating present rates of sea-level change (Woodworth, 1987, 1990; Shennan and Woodworth, 1992).

The separation of these two variables is not simple. The task is made more difficult because methods of analysis have to be devised for the type of data collected, which is rarely orientated to such an operation. One of the most critical problems is uneven data distribution through time and implicitly depth. When examining time and altitude, it is not possible to hold one variable constant and compare how for different geographical areas the other variable changes. To overcome this problem Shennan (1989) subtracted a eustatic constant based on the curve of Mörner (1984) from each sea-level index point used in the analysis. A study of the residuals will reveal the broad patterns of crustal movements.

Quite which curve, or indeed mathematical expression, is used is not particularly important providing the curve is a good estimate of the rates of change of eustasy through time. Shennan (1989) notes that there are particular problems with such analyses in the period 7000-8500 BP, where sea-level was rising rapidly so that any small shift in the age estimate will result in a relatively large change in the residual.

In this thesis attempts have been made to overcome this problem by holding one variable in the time-altitude equation constant for a series of samples taken along the North Wales and Wirral coast. The ideal situation of holding age constant to measure vertical displacement along a coastline is, of course, not possible but it is possible to hold altitude constant and see if it is possible to identify an age gradient. If we hypothesise that there is an age gradient, then the assumption that tidal range will not have changed through time is particularly important. The altitudinal and spatial positions of dated samples are shown in Fig.2.2. The 'constant' altitudes selected (*c.* 9.0, 6.5, 1.8 m below MHWS) were determined by the distribution of data from surrounding regions so that the results from North Wales and Wirral could be placed in a regional context, and the availability of organic sediments at the sites investigated. If there have been detectable differential crustal movements along the north Wales and Wirral coastlines in the last *c.* 7500 years then such a sampling strategy will allow a greater chance of detection than a more evenly distributed altitudinal spread of dated samples. Other techniques for examining crustal movements such as the residual method described above can still be applied.

The difference in the crustal displacement of two areas will be cumulative back in time, so it was necessary to have samples of sufficient age for comparison. The differences in the crustal histories of Cardigan Bay and south Lancashire have been very similar in the last 5000 years (Shennan, 1989) with Cardigan Bay slightly subsiding (-0.11 mm/yr), and south Lancashire apparently stable. Before 5000 BP, south Lancashire was being uplifted so the relative vertical displacement between the two areas is ever increasing back in time. Between 5000 and 7000 BP, *c.* 5.00 m of uplift took place in south Lancashire (Shennan, 1989), resulting in a cumulative vertical displacement relative to Cardigan Bay of *c.* 6.00 m for the last 7000 ^{14}C-years. Some of this displacement may be reflected in the age/altitude distribution of samples along the North Wales and Wirral coasts.

Available dates from the Wirral (Innes, pers. comm.) and south Lancashire (Tooley, 1978) indicate that around Liverpool Bay sediments older than 7000 BP are found below *c.* 6.00 m below MHWS: hence six dates have been collected between 6.00 and 7.00 m below MHWS (Fig.2.2). Two dates have been collected from *c.* 9.00 m below MHWS for comparisons further back in time, together with a series of dates from the upper organic sequences along the north Wales coast (Fig.2.2). Though this dating scheme has been designed primarily for the detection of crustal movements within the region there is also a sufficient spread of data to establish a broad sea-level chronology.

The differential compaction of Holocene sediments does mean that an altitudinal constant is somewhat fallacious. Where precise altitudes are required it is necessary to minimise the compaction error, and this is discussed below.

2.3.1b **The problems of sediment compaction.**

Van de Plassche (1980) has identified five possible causes for obtaining an inaccurate or unreliable value for altitude and in particular for the age of ^{14}C-samples: diachronous boundaries, compaction of sampled peat, root contamination, contamination by older material and the compaction of underlying deposits. The factors affecting the age of a sample are fully examined in Chapter Three (section 3.7): in this section the problem of post-depositional altitudinal displacement is examined.

For the analysis of crustal movements an altitudinal variable is required. Jelgersma (1961) noted that early studies into Holocene sediment compaction (Huizinga, 1940) indicated that the total compaction of peat may reach 98%, but later studies from the Netherlands (Bennema *et al.*, 1954) put the value between 75 and 85%. Bennema *et al.* (1954) note that compaction of inorganic sediments is variable, but low in coarser materials such as marine sands: therefore, total compaction within Holocene sediments can range from 0 to 85%. This variability was confirmed by an investigation into the compaction of marine silts and clays by Skempton (1970). Many factors contribute to the degree of compaction in unconsolidated sediments: time, drainage, overlying load (Tooley, 1978; Greensmith and Tucker, 1986), composition (Jelgersma, 1961), structure and mineralogy (Skempton, 1970).

Visual effects of compaction can be seen from sea-level investigations in the Netherlands. ^{14}C-dates have been taken from the basal peats (referred to as 'Lower peat' by Bennema (1954b), Jelgersma (1961) or 'basispeat' by Roeleveld (1974), Griede (1978)) directly overlying the Pleistocene sands; they are typically older than ^{14}C-dates from the same altitude, or even lower, taken from intercalated sediments. Data collected at Brandwijk to the southeast of Rotterdam by Jelgersma (1961) illustrate this phenomenon. A date of 5665±200 BP at -8.70 m NAP was obtained from an intercalated peat, and two dates from the basal peat of 6050±200 BP at -6.47 m NAP and 5340±60 BP at -5.65 m NAP. The 5665±200 date must have formed between -5.65 m and -6.47 m NAP, but was recorded at -8.70 m NAP, showing that compaction of the order of 2.23-3.05 m had taken place. From Hallum and Bollingawier in western Friesland and Hillegersberg in Zuid Holland compaction values of *c.*3.00 m can be calculated in a similar way from data collected by Griede (1978) and van de Plassche (1980) respectively. Shennan (1989) shows that at 7000 BP the differential displacement between Cardigan Bay and north Lancashire, regions north and south of the study area, was *c.*4.00 m, which is only marginally greater than some of these estimates of possible altitudinal error. If finer resolution changes are to be identified then this potential error needs to be eliminated or reduced.

Because of the variability in the compaction of sediments, correction factors are rarely applied in sea-level studies. An exception was in the work of Kidson and Heyworth (1973) in the Somerset Levels where correction factors based on the work of Skempton (1970) to altitudes up to 1.30 m were applied because a full dataset of engineering test data was available for the boreholes taken. However, Shennan (1980) points out that Kidson and Heyworth (1973) do not deal satisfactorily with the consolidation of peats or the organic content of the clays which Skempton (1970) states leads to significant variability in compaction. In general Heyworth and Kidson (1982) comment that all that can be attempted at present is a recognition of an unquantifiable altitudinal error due to the compaction, and Shennan (1980) goes further to say that until further empirical studies are carried out no correction factors should be applied (*cf.* Devoy 1982). A more detailed study of compaction in the Fenland (Smith, 1985) further emphasises the problems of estimating the compaction of organic sediments. Using the oedometer test, a soil mechanics technique, Smith (1985) estimated that the average height correction required to find the original altitude of peats and clays was 40-50%, but noted that the oedometer test was not error free, because the test will only estimate the compaction of a sediment unit caused by loads from above and not by compressibility under their own weight, which is especially common in peats. We are not yet in a position to apply altitudinal correction factors to unconsolidated sediments.

Clearly if the compaction problem is to be overcome, dates should be obtained from basal peats or secondly from horizons that can be shown to have little altitudinal variability along a profile from their position of intersection with the pre-Holocene surface (where they are basal) to the position of sampling. With deeper sediments it will normally be necessary to take basal samples. This is easier said than done because of the amount of coring required, but has been attempted in this work.

The use of basal peat data is discussed below, largely with respect to work carried out in the Netherlands.

2.3.1c **The use of basal peat data.**

From the construction of the first Dutch sea-level curve (Bennema, 1954a, 1954b) onwards, typically only ^{14}C-dates from the base of the basis peat have been used (van Straaten, 1954; Jelgersma, 1961,1966; Louwe Kooijmans, 1974; Roeleveld, 1974) because of the recognition of the compaction problem, as Jelgersma (1961,p.17) explains:

> *"sea-level changes and tectonic movements cannot be separated and have to be taken together, but the factor of* **compaction** *is eliminated. This has been done by using radiocarbon datings at the base of the Lower Peat, as the underlying Pleistocene sands are practically not affected by compaction."*

Disagreements over the use of basal peat data are largely associated with the indicative meaning and formation of such deposits, and with the Dutch work in particular the criticism that an artificial smoothing of a sea-level curve results (section 2.2). Criticisms based on indicative meaning are not valid for samples taken from the transgressive contacts of basal peats. Effectively there results a dilemma: that samples from the base of basal peats will have undergone relatively limited compaction but do have some question marks as regards their indicative meaning and interpretation, but samples from the top of basal peats will have undergone some compaction but have a well-defined indicative meaning.

The quality of data that can be obtained through such a data collection framework is perhaps best demonstrated by series of ^{14}C-dates obtained from donken river dunes (van de Plassche, 1979; 1982) in Zeeland. Jelgersma (1961) and van de Plassche (1979) have explained that because of the permeability of the sands, steepness of slope and isolated position of the dunes there is little possibility of peat forming independently of the surrounding groundwater.

Twenty-three ^{14}C-dates were collected from the base of the basal peat at Hillegersberg donk (van de Plassche, 1982) yielding a continuous series of dates. These data were combined with other donk data from Rijswegdonk (van de Plassche, 1982), Brandwijk and Barendrecht (Jelgersma, 1961) to produce a time-altitude plot with very high internal consistency, and thus an ideal starting point for examining rates of sea-level changes. Shennan (in prep) has collected data from the transgressive contacts of basal peats in the north Fenland, yielding a similarly consistent series of ^{14}C-dates. As in the Netherlands, over much of the Fenland the pre-Holocene surface slopes gently seaward, suitable conditions for the formation of basal peats and allowing the opportunity for such specific data collection. That others in the UK have not adopted such data collection strategies is largely a function of differing palaeoenvironments.

Bennema (1954a, 1954b) and van Straaten (1954) discuss the basal peat at Velzen in Zuid Holland, attributing its formation to rising groundwater, the level of which was above mean sea level. Jelgersma (1961) considered the process of the basal peat formation more complex: a product of distance to the shoreline, tidal range and the permeability of the sandy subsoil resulting in a variable relationship along the coast. Pollen analysis on the basal peat had shown that it could form independently of a rising sea-level, particularly in areas where the Pleistocene sands were near horizontal. Roeleveld (1974) with reference to De Vries (1974) points out that groundwater levels would have been particularly high throughout the Holocene in some parts of the Netherlands before the introduction of artificial drainage by man, which may have led to the formation of a basal peat several metres above mean sea-level as exemplified by present-day moors and bogs found in parts of the southern and eastern Netherlands. Aware of this problem, van de Plassche (1979) took samples where there was a slope on the Pleistocene surface, determined by the completion of high density coring. Such an approach has been adopted in other investigations with the reconstruction of the palaeogeography of the Pleistocene surface a starting point of investigation. Griede (1978), for example, completed 2079 borings in west and north Friesland, noting that;

> *"De conclusie van van de Plassche (1977), dat geschikte basisveenmonsters voor zeespiegelreconstructie alleen kunnen geselecteerd na een gedetailleerde verkenning van het relief van de pleistocene ondergrond, lijkt dan ook geheel gewettigd." ("The conclusion of van de Plassche (1977) that useable basal peat samples for sea-level reconstructions can only be selected after a detailed study of the relief of the*

Pleistocene underground is certainly true").

Griede (1978,p.52)

In North Wales none of the sites exhibits the shallow gradients in the pre-Holocene surfaces as found in the sites of the western and northern Netherlands. Griede (1978) points out that often oligotrophic moss peats are found directly on the Pleistocene sands in Friesland and in a discussion of the types of basal peats found in the Netherlands Jelgersma (1961) estimates that such oligotrophic swamp peats form higher than *c.* 0.50 m above groundwater level. A *Phragmites* peat will form at or close to MHWS (Godwin, 1940a), and the point where they overlay basal oligotrophic peats is the position that should be dated (Jelgersma, 1961). Again, however, oligotrophic peats have not been recorded as basal in North Wales so this problem does not arise.

2.4 Data collection.

Data collection in the field has focused upon an extensive and detailed lithostratigraphic survey. The survey had to be spatially extensive to cover as much of the coastline as possible and to give the maximum opportunity to identify differential crustal movements within North Wales. For each area the surveys had to be detailed to trace the organic sediments to the depths required and show the spatial significance of the horizons found. These factors were the basis for the entire field investigation.

Such a methodology has been shown to be a valid starting point for the stated aims of the project. However, such a data collection strategy will generate a very large quantity of lithostratigraphic data which have been found to be very challenging in the interpretation of sea-level changes. The very specific data collection strategy adopted in this thesis although geared to answering primary questions has produced data that are suitable for answering the conventional questions as well.

During the first ten months of the research lithostratigraphic work was started in all of the four main areas selected for data collection. Following this initial fieldwork, analysis of the data revealed the depths where peats were found including an organic horizon *c.* 6.00-7.00 m below MHWS. The significance of this and other horizons was tested with further fieldwork and, when their lithostratigraphic persistence was confirmed, sampled for ^{14}C-dating and relevant biostratigraphic analysis.

2.5 Summary.

Drawing upon published information, empirical data and modelled results some hypotheses have been formulated. The theoretical background and data collection strategy adopted to test these hypotheses have been explained. The specific hypotheses to be tested are:

(1) That there are detectable differential crustal movements between Cardigan Bay and Lancashire, reflected in the general south to north increase in uplift in the UK during the Holocene.

(2) That during the Holocene there has been greater cumulative uplift in Anglesey than the Wirral, and accordingly cumulative uplift will increase along the north Wales coastline in a westerly direction.

(3) That the altitudinal variation of transgressive and regressive overlaps is a reflection of greater noise in the sedimentary record of some sites compared with others, rather than an absence of any regional signal in sea-level fluctuations in the area under investigation.

Chapter Three

Data collection techniques.

3.1 Introduction.

In this chapter, the techniques used for raw data collection are described. Greater attention is given to three particularly important techniques used in this work: namely lithostratigraphic analysis, diatom analysis and radiocarbon dating, and also to a new technique with respect to sea-level investigations, shear-wave seismic refraction. For each of the six techniques described, how and why the technique was used and some of the problems associated with it are conveyed. The problems addressed are primarily those which are directly relevant to this research or that have been encountered in it. More general accounts of palaeoenvironmental construction techniques and their associated problems can be found in Tooley (1981), Lowe and Walker (1984) and van de Plassche (1986a).

3.2 Lithostratigraphic analysis.

A browse through the chapter headings in 'Sea-level Research: A manual for the collection and evaluation of data' (van de Plassche, 1986a) gives a list of techniques available to sea-level researchers, but there is no specific reference to lithostratigraphic analysis. As regards data collection in this thesis, lithostratigraphic analysis has been the basis for all subsequent work. It is felt that time spent in the field hand-coring that has produced the greatest understanding of sedimentation and sea-level changes in North Wales and Wirral as well as other areas around the UK coast where the author has worked, particularly the East Kent Fens and Fenland.

> *"Only when a complete stratigraphic survey of the area has been completed can a decision be made about the site with the most representative layers or the most complete sedimentary record, from which a core can be taken for laboratory analysis."*
>
> *Tooley (1981,p.8)*

The data collection methodology geared towards finding organic horizons at specific altitudes meant that a considerable amount of lithostratigraphic data was collected. Additionally these data were an important first stage in the interpretation of relative sea-level change at a site scale. For example, any site where the lithostratigraphy was particularly variable, or seemed to be highly influenced by secondary factors such as coastal dunes or the pre-Holocene surface topography, was abandoned with regard to further palaeobotanical work and ^{14}C dating (Llanfawr, Anglesey, Pentre Mawr and Prestatyn in the Clwyd coastal lowlands).

3.2.1 <u>Lithostratigraphic analysis: Methods employed.</u>

For all hand-cores a Duits' gouge sampler was used (Eijkelkamp, 1990) because of its ease of use. A modified Livingstone piston corer and percussion drill (Merkt and Streif, 1970) were used for the collection of all samples where ^{14}C dating or palaeobotanical work was carried out.

All lithostratigraphy was classified using the Troels-Smith (1955) scheme. The results from all hand cores are presented, in a slightly abbreviated form, in Appendix 5 and the stratigraphic results from piston-coring are presented in full in Appendix 4. Using this scheme, for each stratigraphic unit, or stratum, identified the following were recorded:

1. Upper and lower depths below ground surface.
2. Composition of the unit.
3. Degree of humification of organic horizons.
4. Physical properties of the unit.
5. A short verbal description.

The best way to demonstrate and explain the application of the Troels-Smith scheme is to use a specific example (Tooley, 1978). For Hendre fawr - 29, stratum 2 was recorded as follows:

498-503
Sh3 As1 Th^2(*Phra*)+
nig.3+, strf.0+, elas.0, sicc.2, lim.sup.0
Dark brown/black, slightly stratified and humified peat with some *Phragmites*. Good upper contact.

A translation of the above is as follows:

498-503	Depth below ground surface of the stratum in cm.
Sh3	Indicates that 75% (=3) of the stratum is composed of disintegrated or decomposed organic matter.
As1	Indicates that 25% (=1) of the stratum is composed of colloids or grains <0.002 mm (clay).
Th^2(*Phra*)+	Indicates the presence (+) of rhizomes of the common reed *Phragmites communis*, with a medium degree of humification (indicated by the superscript 2).
nig.3+	Indicates the stratum is dark (white=0, black=4).
strf. 0+	Indicates very slight stratification in the sample.
elas. 0	Indicates that the sample has no elasticity i.e. cannot regain its original shape after the application of pressure.
sicc.2	Indicates that the sample is partially saturated with water (water=0, air dry=4).
lim.sup.0	Indicates that the upper boundary of the stratum is diffuse or transitional, with a boundary zone > 1cm.

The composition and physical properties of a stratum are recorded on a five point scale (0-4). For most purposes such a scale provides sufficient resolution and yet is not so precise as to be inflexible or impractical, and is therefore very appropriate for logging data in the field. The best way to become proficient in using the Troels-Smith classification is to do fieldwork with people experienced in using the scheme. Maximum opportunity was taken of this at the start of this Ph.D. with field visits to the Northumberland coast, Morecambe Bay, Dungeness and extended visits to the East Kent Fens and Fenland.

All lithostratigraphic plots have been produced using the program STRAT (Everett and

Shennan, 1987) which was available at Durham until June 1992.

3.2.2 Lithostratigraphic analysis: Problems and sources of error.

Once competence has been gained in using the Troels-Smith scheme, the main source of error in lithostratigraphic analysis is establishing altitude or depth below ground surface of a stratum. The range of estimates of altitudinal error involved in lithostratigraphic analysis is from ±0.10 m to ±0.30 m (Shennan,1980,1982a; Heyworth and Kidson,1982; Ireland,1988), but with hand coring the error is certainly at the lower end of this range. Shennan (1982a) ascribes most of the altitudinal error to the accuracy of benchmarks and sampling density.

More serious altitudinal errors arise in the use of a piston corer because of sediment compression during extrusion, or possible oversampling in the field. A correction based on the ratio of the original length of sample to the extruded length of sample is inappropriate since certain types of sediment compact more than others, for example, fresh organic sediments are prone to much greater compaction on extrusion than inorganic silts or clays. Rather than attempting to apply correction factors, the altitudes of stratum boundaries are taken from adjacent hand-core depths which are subject to minimum error. All piston cores were taken within a few centimetres of a hand core.

3.3 Levelling.

All cores completed have been levelled to a common datum, namely Ordnance Datum, Newlyn, with a Sirrkowski level. Bench mark lists were obtained from the Ordnance Survey or local authorities. Data were logged using the height of collimation method (Bannister and Raymond, 1977).

3.3.1 Sources of error.

Apart from equipment failure there are two main sources of error in determining altitude: incorrect benchmark height, or user error when levelling. All benchmarks used were on the solid rock or boulder-clay surfaces and not in areas of unconsolidated sedimentation where subsidence could have occurred altering the true benchmark height. Additionally, all levelling surveys were closed, and the maximum closure error was 0.08 m at Colwyn Bay Rugby Club.

3.4 Shear-wave seismic refraction.

In April 1990, Dr.Neil Goulty in the Department of Geological Sciences, Durham was approached for advice on the possibility of using seismics to determine the depth of the pre-Holocene surface in a palaeovalley in the East Kent Fens. Following these initial discussions a very successful project was embarked upon with Dr. Goulty and a Geophysics M.Sc. student, Carol Gunn. The project formed an M.Sc. thesis (Gunn, 1990), part of a sea-level Ph.D. thesis (Long, 1991) and a publication (Long *et al.*, 1992), where the use of shear wave seismic refraction on unconsolidated Holocene sediments is reported for the first time.

As part of this thesis a shear wave seismic refraction survey was carried out at Newton Carr in a joint project with Dr. Goulty and another M.Sc. student, Mark Crawley (Crawley, 1991). The different geological setting of Newton Carr meant that the final results were not as conclusive as had been the case in the East Kent Fens. However, this difficult geological setting meant the use of the shear wave technique in such environments was tested further: hence the technique itself was advanced by this second project, and its use within a sea-level context refined.

3.4.1 Aims of the shear-wave seismic refraction survey.

The aims of the seismic refraction survey were twofold, geographical and geophysical. Borehole information indicated that the entrance and exit for the sea at Newton Carr had been from the northwest through West Hoylake, where in bore C7 over 10.00 m of Holocene sediments were sampled (Figs.5.22 and 5.23). However, the coarse sediments at the northwestern end of the site prevented a full hand-coring survey, so the seismic refraction method was employed as a possible means of showing the assumed northwestern dip in the pre-Holocene surface. Second, at Newton Carr, underlying the Holocene unconsolidated sediments was boulder-clay on top of sandstone, providing a very different geological setting to that found in the East Kent Fens (Long, 1991; Long *et al.*, 1992), where the unconsolidated sediments were recorded upon Cretaceous Chalk, and therefore a test of the wider applicability of the seismic refraction method in sea-level research.

3.4.2 **Principles and logistics of the technique.**

The seismic refraction method is a well established technique for determining the thickness of unconsolidated sediments overlying bedrock, or a more consolidated lower surface (Kearey and Brooks, 1984; Sjögren, 1984). At Newton Carr, as with any seismic refraction survey, it was necessary that there was a velocity contrast in the propagation of seismic waves between the unconsolidated Holocene sediments and the underlying boulder-clay. Fig.3.1 illustrates the underlying principles of the method. A source emits an impulsive waveform, with energy being dissipated in all directions. Part of the energy (Direct wave) travels outwards from the source close to the ground surface whilst another part will travel down to the lower layer (boulder-clay) and, obeying Snell's law, is critically refracted along the top of this lower layer (Headwave). Some of this headwave energy is then refracted back to the ground surface at the critical angle.

There are two kinds of seismic wave: compressional (P-waves) and shear (S-waves). In coastal environments P-waves are inappropriate for use since their velocity is strongly affected by the presence of water. The velocity of S-waves defined by eqn.3.1

$$V_s = \sqrt{\left(\frac{\mu}{\tau}\right)}$$ Eqn. 3.1

(*V_s = S-wave velocity, μ = rigidity modulus, τ = bulk density*)

is unaffected by the presence of water because the rigidity modulus of fluids is zero: hence S-waves were used in this study. The rigidity of unconsolidated sediments is much less than that of rocks or more consolidated materials and therefore the velocity of S-waves is relatively slower, and it was expected that such a contrast would exist between the unconsolidated Holocene sediments recorded at Newton Carr and boulder-clay. Long *et al.* (1992) found that typical velocities for S-waves in Holocene sediments in the East Kent Fens were < 100 ms^{-1}, and Goulty *et al.* (1990) report that boulder-clay typically attains velocities > 200 ms^{-1}.

In Fig.3.1, for a receiver close to the source, the first seismic arrival will be the direct wave travelling horizontally from the source to the receiver with a velocity V_0. At a receiver a sufficient distance from the source, the first arrival will be the headwave which has been refracted along the Holocene sediments : boulder-clay interface, propagating with the higher boulder-clay velocity (V_r). The point at which the direct wave first intersects the headwave is called the crossover distance.

A first approximation of the thickness of the upper layer is illustrated in Fig.3.2, where the reciprocal velocity of the two layers is plotted on a distance-time graph. The intercept time and corresponding crossover distance will depend upon the velocity ratio of the upper and lower layers (V_0:V_r), a function of the rigidity modulus and bulk density (Eqn 3.1), and the corresponding depth can be estimated (Eqn.3.2):

$$Depth = \frac{IT \times V_0}{2} \qquad \text{Eqn. 3.2}$$

(*IT = intercept time*)

For the calculation of depths at Newton Carr the Plus-Minus method (Hagedoorn, 1959) was used, a method utilising the principles explained above and fully described in Sjögren (1984).

S-waves were generated in the field by striking a steel stand with a sledge hammer, in a direction perpendicular to the line of receivers (geophones). Geophones were spaced at < 5.00 m intervals in front of and behind the source. A trigger geophone was placed at the source activating the recorder when the steel stand was struck. Initially a 12-Channel Nimbus ES-1210F Seismograph was used to record the seismic traces. Subsequently a 24-Channel EG & G Geometrics ES-2401 Seismograph was used, which as well as printing out seismic traces saved them digitally to a disk. Low signal to noise ratios meant that the application of data filtering techniques was necessary before interpretation, and this was made possible with digitally saved data. This interpretation was carried out by Crawley (1991).

3.4.3 Problems with the seismic refraction technique at Newton Carr.

The initial aim of the seismic refraction survey, to map the pre-Holocene boulder-clay surface at Newton Carr, was hindered by several fundamental problems.

The need for a significant velocity contrast between the Holocene sediments and underlying boulder-clay was explained in section 3.4.2. In areas where seismic profiles were required, at the northern end of the site where hand-coring was particularly difficult, highly cemented marine sands dominated the upper 6.00 m of sedimentation. These sands had higher velocities than the Holocene sediments encountered in the East Kent Fens resulting in only a small velocity contrast with the boulder-clay, and hence serious problems of noise. For receivers far away from a source the signal to noise ratio will naturally decrease, and from Fig.3.1 it is noted that as the thickness of Holocene sediments increases the crossover distance will also increase; therefore when, as at Newton Carr, the initial signal to noise ratio is low there is a finite limit on the distance from the source to the most distant receiver which may be less than the crossover distance. In such cases it is not possible to measure the depth of the pre-Holocene surface. At Newton Carr the signal to noise ratio was so low that where the crossover distance was >60 m, corresponding to a 7-8 m thickness of Holocene sediments, the different signals were impossible to distinguish.

Additional difficulties were caused by the unexpected velocity contrasts within the Holocene sediments, particularly between the cemented marine sands, and peats and clays (Table.3.1). It was not always possible to treat the unconsolidated Holocene sediments as a single layer and modelling was required based on the known lithostratigraphy. Furthermore, over most of the site the boulder-clay was quite thin (*c.* 2 m); hence the first crossover point was not from the boulder-clay, but from the underlying sandstone where velocities were *c.* 800 ms^{-1} (Fig.3.3).

Table 3.1.
Typical sediment velocities at Newton Carr.
Source: Crawley (1991,p.32).

Sediment type	**Shear wave velocity (ms^{-1})**
Soil	40
Blown sand	100
Silt	90
Marine sand	143
Silty-clay	80
Clay	60
Peat	40
Sandstone	800
Boulder-clay	232

Normally, because the sandstone arrivals represented the first crossover point, the boulder-clay signals were swamped, and even with the application of data filtering techniques (Crawley, 1991) picking boulder-clay arrivals, and therefore depths, was extremely difficult. By far the best results at Newton Carr were those measuring the depth to sandstone, or where relatively fine grained unconsolidated sediments overlaid a relatively thick boulder-clay such as Line 1 (section 5.5.3).

3.5 Diatom Analysis.

> *"The margins of the continents are subject to inundation or terrestrialisation as sea levels change with the waxing and waning of the ice caps, or as the crust itself is uplifted, depressed or folded. As these changes occur, the diatom floras will shift accordingly, so that cores taken around the continental margins often reveal a complex history of sea level changes in the diatom record."*
>
> *Round (1991)*

Diatom analysis was completed on the four sites where ^{14}C dates were obtained: Tregarnedd-bâch, Morfa Penrhyn, Hendre fawr and Newton Carr. Standard techniques were used in the laboratory preparation (Appendix 2). Counting and identification were made with reference to the key texts, van der Werff and Huls (1958-74) and Hendey (1964), as well as available reference photographs available in Durham collected by Gabriel Nève. Nomenclature is taken from Hartley (1986), a check-list of diatoms found in British and surrounding coastal waters.

3.5.1 Aims of diatom analysis.

The specific aims of diatom analysis in this study were as follows:

1. To confirm the ecological characteristics of transgressive and regressive overlaps as identified by the lithostratigraphic survey.

2. To confirm that the dominantly inorganic sediments recorded were formed under full or partial marine conditions.

3. To establish the relative degree of marine influence during the formation of inorganic

sequences.

4. To distinguish, if possible, between diatom assemblages associated with organic and inorganic sediments.

5. To confirm the absence of sediment reworking within inorganic sequences.

At the time when diatom analysis was being undertaken, the lack of a single information source on aspects of diatom ecology, particularly life form, led to a quest for this information and the aim of assembling a diatoms database for common species as well as all those identified in North Wales and the East Kent Fens by Long (1991). This is discussed in section 3.5.3.

3.5.2 Diatom counting, the sum and diagram construction.

As with pollen analysis there is no definitive number of individual frustules, or grains, that should be counted per level. Effectively the number should be enough so that the standard error is less than is seen to be significant within the total count. For diatoms, two hundred frustules are recommended by Tooley (1981), and commonly adopted (Shennan,1980; Haggart,1982; Ireland,1988; Long,1991) as well as in this thesis.

There have been three principal ways of expressing diatom counts proposed: the relative abundance method (Andrews,1972), absolute concentration method (Battarbee, 1973) and the most commonly used relative method (Battarbee,1979,1986). The recording of the presence or absence of a taxon has been proposed by du Saar (1969) and Vos and de Wolf (1988).

Ireland (1988) has fully reviewed the first three methods and pointed out that each technique has its advantages and disadvantages. Andrews (1972) argues that there is limited use in obtaining absolute numbers for each species and thus proposes his relative method where a species is grouped as dominant, abundant, frequent, common or rare. Ireland (1988) does say that this method generates data quickly, but this implies that the number of frustules required to classify a species as dominant to rare is small and would therefore seem to combine the problem of low counts with a subjective classification. In this thesis it is felt that the most effective way to examine diatom (and pollen) data is through graphical and statistical analysis: hence the relative method (Battarbee,1979,1986) is used.

The method of recording the presence or absence of a taxon (Vos and de Wolf,1988) has not been widely used but is effective for certain situations, particularly species diversity associated with particular environments. For example, many of the diatom diagrams presented in this thesis show an increasing dominance of one species, usually *Diploneis interrupta*, towards transgressive and regressive overlaps.

All diatom diagrams were constructed using TILIA (Grimm,1990), a PC statistical and diagram package, and were zoned using the technique CONISS (constrained incremental sum of squares cluster analysis).

In the last twenty years there has been much discussion and development in the application of statistical techniques to the zoning, correlation and interpretation of palaeoecological diagrams, usually pollen, though the principles apply equally to diatoms (Birks,1974,1986; Birks and Berglund,1979; Birks and Deacon,1973; Dale and Walker,1970; Gordon and Birks,1972,1974; Pennington and Sackin,1975; Walker and Wilson,1978; West,1970; Yarranton and Ritchie,1972). The definitive version of these discussions appears in Birks and Gordon (1985). These advances have stemmed largely from the difficulties in correlating palaeoenvironmental data from one diagram to the next, and the result is a plethora of available techniques. However, it has been repeatedly noted (Gordon and Birks,1974) that each technique gives very comparable results with all other techniques and indeed zonations carried out by eye, with real differences arising from the sensitivity of different methods (Birks *et al.*,1975). For example PCA (principal components analysis) has been shown to respond well to datasets with rapid gross changes (Shennan and Innes, 1986). Which technique (if any) is used in a particular study will therefore depend on what the aims of that particular study are. Within this thesis it is changes in diatoms (and pollen) at a site scale that are of interest. Since there is no attempt to correlate between sites, zonation is only applied for descriptive purposes, so the particulars of different statistical zoning techniques are not relevant and only one technique has been used for zonation.

3.5.3 **D.I.S. A Diatoms Information System.**

A database system containing information on nearly two hundred diatom species, including all those identified from North Wales and the East Kent Fens, was assembled as part of this investigation. The programming was completed within dBase III+, and information extracted from van der Werff and Huls (1958-74). Additional information on life form was obtained from the Dutch Geological Survey courtesy of Dr. Hein de Wolf and with reference to De Wolf (1982) and Vos and de Wolf (1988). DIS is a menu-driven system allowing searching on species name, ecology (van der Werff and Huls scheme) and life form. For each species a reference and description of its environmental preferences are given.

3.5.4 **The problems associated with the reconstruction of palaeoenvironments from diatom analysis.**

As with any technique of palaeoenvironmental reconstruction there are numerous problems identifiable at all stages of analysis from the collection of samples to final interpretation. This discussion focuses on the problems which are of direct relevance to the stated aims of the diatom analysis (section 3.5.1). A schematic overview and context for these aims is presented below:

3.5.4a **Autochthonous and allochthonous diatoms.**

Autochthonous diatoms are defined as the diatom frustules (or valves) which have lived at the place of deposition (Vos and de Wolf, 1988). In tidal environments the relative abundance of allochthonous diatoms can be significant, and in some cases higher than the autochthonous component (Simonsen, 1969). The processes of diatom mixing are discussed by Beynes and Denys (1982) and Ireland (1988), and in tidal environments are largely due to the dynamic nature of such environments (currents, streaming, breezes, burrowing animals).

Several methods of distinguishing between autochthonous and allochthonous diatoms have been proposed. The relationship of fragmented frustules to long distance transport has been questioned for numerous reasons because fragmentation can be a result of so many other variables: shallow water, presence of a nearby coastline or leaching (Beyens and Denys, 1982). Additionally Vos and de Wolf (1988) point out that elongated and weakly stratified frustules (*Synedra* sp., *Pinnularia* sp.) are more prone to fragmentation than roundish or strongly silicified diatoms. Simonsen (1969), therefore, proposes the use only of benthic diatoms as indicators of autochthonous populations as planktonic forms are more likely to be transported. Beynes and Denys (1982) for the benthic species in each sample calculate the dominant salinity class (van der Werff and Huls scheme) and assert that the diatoms in this class plus the adjoining classes (**MB** and **B** in the case of **BM** being the dominant class) are autochthonous, and other diatoms allochthonous. This method was used and refined by Ireland (1988) to take account of differing salinity distributions in a profile.

Vos and de Wolf (1988) report a method commonly used in palaeoecological studies in the Netherlands, which uses a number of diatom- and non-diatom related criteria and therefore requires some interpretation and intuition. Such a comment is not necessarily a criticism because autochthonous and allochthonous diatoms cannot be expected to fall into simple categories which the purely numerical methods (Beynes and Denys, 1982) assume. The basis of the method is to classify diatoms into ecological groups (based on a salinity tolerance and life-form matrix), and then to examine these groups in a stratigraphic context. If, for example, the occurrence of two similar ecological groups within the same zone would suggest they are autochthonous, especially if the vertical succession of groups reflects a natural sequence (Vos and de Wolf, 1988) such as associated with a regressive or transgressive contact. The co-occurrence of rare species of the same ecological group as the main one identified would strengthen the autochthonous interpretation. Conversely the simultaneous occurrence of two dissimilar ecological groups would suggest one has to be allochthonous. An advantage of this scheme is that planktonic species are not automatically excluded from the interpretation as is the case with the methods of Simonsen (1969) and Beyens and Denys (1982).

3.5.4b **Diatom classification and the influence of salinity on diatom distributions.**

Numerous salinity classification schemes have been established, though the two most common are those of Hustedt (1927-66) and van der Werff and Huls (1958-74), based on field investigations in the Wesser River and Eems-Dollard estuary respectively. No scheme is perfect, but the most important conclusion to note from subsequent laboratory investigations (Admiraal, 1977) is that most species have broader salinity tolerances than these schemes assume. However, Ireland (1988) points out that the van der Werff and Huls (1958-74) classification is able to detect increases and decreases in salinity. In this study, interpretations are based on relative changes in diatom assemblages and therefore the particular accuracies of the schemes in terms of salt concentrations are less relevant.

Here the van der Werff and Huls (1958-74) scheme is used, which has seven divisions based on the chloride content of the water (mg Cl^-/l):

M	Marine	>17000
MB	Marine/brackish	10000-17000
BM	Brackish/marine	5000-10000
B	Brackish	1000-5000
BF	Brackish/fresh	500-1000
FB	Fresh/brackish	100-500
F	Fresh	<100

What is particularly important in sea-level investigations is how this classification mimics true diatom distributions along a salt marsh profile from a supratidal to subtidal location. Round (1971) summarises the results from contemporary investigations into diatom distributions on a salt-marsh, for example, Carter (1932,1933) and Round (1960). Within the intertidal zone, definitive ecological niches were difficult to identify, but based on surveys in the Dee estuary (Round, 1960) there were three distinctive floras identified, which grouped as supratidal, intertidal and subtidal (upper, middle and lower marsh), and which ignoring seasonal fluctuations were primarily controlled by salinity, sediment type and duration of flooding (Round, 1960).

The details of these investigations are too numerous to be reported here. Broad ecological zones, however, have been identified from contemporary studies but do not appear to match the absolute resolution of salinity classification schemes. This is to be expected because of the numerous other, though usually less important, factors controlling diatom distributions such as pH spectrum, nutrient content, temperature, tides and currents (de Wolf, 1982).

3.6 Pollen analysis.

Diatom analysis has been used to confirm the nature of regressive and transgressive contacts identified in the lithostratigraphy, and pollen analysis has been used to confirm this further, specifically to test whether organic/inorganic contacts formed at about MHWS, the level where salt marsh communities form (Tooley, 1978). Pollen analysis on basal peats was to determine their relationship to the former watertable, but pollen preservation was very bad in these peats except at Newton Carr. Pollen analysis was also used as a proxy dating technique, to confirm the results from ^{14}C dating.

All samples upon which pollen analysis was carried out were taken with a piston corer and transported and stored to the standards described by Moore and Webb (1978). Laboratory preparation followed standard methods and is described in Appendix 2. For each sample 150 total land pollen (TLP) have been counted, which is considered sufficient to meet the aims described above. Identification of grains was made with reference to Clapham *et al.* (1962), Faegri and Iversen (1973) and Moore and Webb (1978). Pollen diagrams have been produced using the same techniques described for diatom diagrams using the program TILIA (Grimm, 1990).

3.7 Radiocarbon dating.

^{14}C-dating has been used as an independent means of determining the age of sea-level index points, the specific reasons for which are explained in Chapters 1 and 2. Eighteen ^{14}C dates have been obtained from transgressive and regressive contacts and also the bottom of basal peats at four sites: Tregarnedd-bâch, Morfa Penrhyn, Hendre fawr and Newton Carr.

The lengthy time period required for dating to be completed meant that samples were sent between the middle and end of the second year of this research (April to October, 1991), after all lithostratigraphic, seismic and diatom work had been completed, but before the completion of the pollen work. It was felt that the lithostratigraphic and diatom data gave the most direct indication of the indicative meaning of a sample (as previously shown by Ireland, 1988) and these data were collected first to allow sufficient time for dating.

Two dating laboratories were used: the NERC laboratory at the Scottish Universities Research and Reactor Centre (SRR), East Kilbride and Niedersachsisches Landesamt für Bodenforschung in Hanover (Hv), Germany. All eleven samples from North Wales were dated in Hanover, and those from the Wirral at SRR.

The maximum vertical extent of samples sent for ^{14}C dating was 0.04 m. Pre-treatment and storage of samples followed the recommendations of Mook and van de Plassche (1986). All vertical rhizomes were removed from the sample as well as other rootlets and pieces of wood visible to the naked eye. In one sample (Hv 17815) from Morfa Penrhyn, the *Phragmites* content was very high but the leaves were in a horizontal position and therefore quite likely *in situ*. Samples were sent to the dating laboratories stored in plastic bags (Mook and van de Plassche, 1986).

3.7.1 Problems and sources of error involved with ^{14}C dating.

To assess the potential errors and problems involved with ^{14}C dating, it is necessary to have an insight into, broadly, how ^{14}C-dating works, which is given below in section 3.7.1a. Particular attention is given to the problems caused by the fluctuation in ^{14}C production through time. Other errors, including isotopic fractionation and humic acid infiltration, are largely dealt with by the dating laboratory, and hence are only considered briefly. A full account of these errors can be found in Bowen (1978) and van de Plassche (1986b).

3.7.1a **The principles, processes and meaning of ^{14}C-dating.**

Libby (1952) was the first to report the principles and methods of ^{14}C-dating. He described how ^{14}C, continually being produced in the Earth's upper atmosphere, is taken up directly by green plants during photosynthesis or less directly by other life forms through the food chain. Upon death this exchange ceases and the ^{14}C isotope starts to decay. Hence, given the modern standard of ^{14}C activity and the half-life (5570 ± 30 ^{14}C-years) of the isotope, an age can be calculated by measuring the ^{14}C activity of the sample. The process of measuring ^{14}C activity, or disintegration (beta-particle activity), is described by Bowen (1978). The probability of a ^{14}C atom disintegrating within one minute is $1/4 \times 10^9$, but within one gram of carbon are 6.6×10^{10} atoms, so a steady rate of disintegration is achieved (Bowen, 1978). It is because we are dealing with probabilities that ages are expressed as ± BP. So, for example, a date 5000 ± 50 BP means there is a 68% chance the true date of the sample is within ± 50 ^{14}C years (one standard deviation) of 5000 BP; a 95% probability that it is within two standard deviations (± 100 years) and 99.7% probability it is within three standard deviations *ceteris paribus*.

3.7.1b **Atmospheric fluctuations in ^{14}C production.**

^{14}C is produced in the atmosphere from the bombardment of nitrogen atoms by cosmic rays (Libby,1952; Bowen,1978; van de Plassche,1986b), and for ^{14}C years to match calendar years truly the production of atmospheric ^{14}C should have been constant through time, and indeed space.

Bowen (1978) points out that using tree ring data de Vries (1958) was the first to show that ^{14}C production cannot have been constant through time. Since then, based on dendrochronological crossmatching techniques from the Bristlecone pine (*Pinus aristata*) Suess (1970,1978,1980) has confirmed these fluctuations. Suess (1970) presented a calibration curve showing the relationship of ^{14}C dates and true historical ages of Bristlecone pine wood samples. Since then Suess (1978) comments that the curve has been refined, but without altering its general trend. Between 1965 and 1977, over 700 ^{14}C-dates were made on wood of a known age at the La Jolla laboratory (presented in Suess,1978), extending the calibration back beyond 8000 years ago (Suess,1980).

Superimposed on this general trend are shorter wavelength fluctuations, or Suess wiggles (Suess,1970), rapid changes in apparent ^{14}C production on about a 100 year timescale. Because of such short timescale changes, and given the inherent age estimation error involved in ^{14}C-dating, Pearson *et al.* (1977) have questioned the finer details of the Suess calibration curve. Independent evidence does, however, confirm the existence of these wiggles and to a large extent their form. De Jong *et al.* (1979) carried out ^{14}C-datings on a 500-year section of fossil oak from southern Germany with a calendar age of 3200-3700 BC at the Groningen laboratory in the Netherlands, quantitatively confirming the presence and nature of the Suess wiggles, though they do comment that no fully accepted calibration curve is yet available. Such variations in the rate of ^{14}C production are probably best explained by fluctuations in solar activity leading to moderations in the cosmic-ray flux (de Jong and Mook, 1980).

The effects of non-linear production of atmospheric ^{14}C, and especially medium-term Suess wiggles, on the interpretation of ^{14}C data are considerable. Particular attention has been focused on the effects of plateaus in the ^{14}C/calendar year calibration curve: van de Plassche (1986b) shows how such features can lead to a spurious clustering of ^{14}C-dates.

3.7.1c Isotopic fractionation

During photosynthesis ^{12}C is preferentially taken up by plants relative to ^{14}C (van de Plassche, 1986b): consequently the ^{14}C content of plants is 3-4% lower than that of the atmosphere (Bowen, 1978), a phenomenon referred to as isotopic fractionation. Therefore conventional ^{14}C ages will be older than they really are, and this has been unequivocally shown by Olsson (1986) on samples from lakes, fens and raised bogs.

Corrections to this problem are applied by examining the ^{13}C isotope. The expected fractionation of ^{14}C is about twice that for ^{13}C: hence because we then know two relationships within a three variable case correction factors can be applied. This does still leave the problem of plants taking up carbon through different means, so for example, plants taking up carbon through their roots will be influenced by the sediment composition (Olsson, 1986) compared with plants taking carbon from the atmosphere.

3.7.1d Other errors.

Additional errors are largely related to the contamination of material, both after deposition and after sampling. One of the main problems is organic (humic) infiltration of carbon in solution. Fortunately these soluble acids are removed by chemical treatment providing there is enough resistant material in the sample. So for wood, charcoal and peat there is no serious problem (van de Plassche, 1986b), unlike bone or soil samples. All dated samples in this thesis are on peats, so errors induced by humic acid infiltration should be minimal.

Contamination from older fossilised carbon such as coal is a possible problem in North Wales. For example, Prince (1988) suggests that her anomalous dates from Bont Farm on Anglesey could be the result of the presence of coal fragments. However, Bowen (1978) has shown that even if 1% of the dated sample contains coal, the distortion on the date will only be *c.* 80 years. The dates obtained by Prince (1988) are more than 10,000 years too old, which would require well over 50% of the sample to be composed of coal (Bowen, 1978) and this would presumably have been noticed on submission. A further problem that is unique to areas of carbonate rocks is known as 'hard-water error'. In these areas groundwater is enriched in Dissolved Inorganic Carbons (DICs), thus diluting the ^{14}C:^{12}C ratio. Olsson (1986) has noted the different rates that plants take up carbon dioxide from sediment and suggested that the dating of selective plant macrofossils is a means of overcoming this problem. Such an approach was not possible in the present study.

3.7.1e **Interlaboratory error.**

Interlaboratory error was the focus of a ^{14}C-dating workshop at East Kilbride in 1990 (Baxter, 1990). Scott *et al.* (1990), summarising the results from this and previous interlaboratory studies, conclude that most laboratories are internally consistent, but there is still considerable variability between laboratories. After a survey of twenty labs dating tree ring material Scott *et al.* (1990) report that all of the laboratories involved overlapped in the age range 4800-5200 BP, but for individual samples results differ from 310 to 730 years. Two dating laboratories have been used in this thesis, both of which have been involved in these surveys. Baxter (1990) reports that laboratories, including Hanover, use the results of these surveys to scrutinise their own results, and change their procedures accordingly.

3.8 **Summary.**

In this chapter a description has been given of each data collection technique adopted in this thesis. With the techniques described here, and indeed other palaeoenvironmental reconstruction methods, there are potential problems in their application and inaacuracies in the results obtained. Some problems are beyond the control of the worker, but potential problems which are controllable have been highlighted in this chapter.

Chapter Four
Previous Investigations.

4.1 Introduction.

In this chapter the data from previous investigations that are of relevance to this research are reviewed. The data have been examined region by region, reflecting the approach taken to data analysis in Chapters 6 and 7. As well as Anglesey, the North Wales coast and Wirral, data are also examined from South and North Lancashire, Morecambe Bay and Cardigan Bay.

The main aim of this chapter is to examine each of the ^{14}C-dates from these areas and to test whether they are acceptable as sea-level index points. All of the dates are presented in Tables 4.1 to 4.6 as either 'accepted' or 'rejected'. In addition some background information on Holocene coastal sedimentation, tidal influences and other major features of the coastal geography are presented for each of the areas examined.

4.2 Geological background.

Before a discussion of the data on Holocene sea-level changes later in this chapter, a brief overview of the geology of the Irish Sea area is presented in this section. First, an overview of the geological setting of the Irish Sea will be presented, before an evaluation of deglaciation and the arguments for and against high sea-levels at the end of the last glacial period, and finally a review of some of the influences on sedimentation and tides today.

4.2.1 Geological overview of the Irish Sea area.

The Irish Sea basin can be divided into three main physiographic regions (Eyles and McCabe, 1989). A central trough running from the North Channel and St.George's Channel is the only area where water depths exceed 100 m. Either side of this trough are the shallower waters of the Irish platform in the west and English and Welsh platforms in the east. The lack of relief on the Welsh side of St.George's Channel has been attributed to the effects of Quaternary sedimentation (Garrard, 1977). The origin of St.George's Channel itself is uncertain, though Wingfield (1990) has argued that similar linear deeps in the North Sea originated from the melting of stagnant ice. The lack of high relief topography in the seabed adjoining the depression indicates that it was not formed by glacial erosion or intensified currents (Pantin, 1991).

The structural control of the basin is Caledonian (Thomas, 1985), and Carboniferous rocks outcrop mainly in the western part of the basin, whereas in the east, Permo-Triassic sediments overlie the Carboniferous rocks as a northwestward extension of the fault-bound graben that separates the Welsh Massif from the Pennines in Lancashire and Cheshire. Along the North Wales coast Permo-Triassic sandstones underlie the low-lying areas such as the Clwyd coastal lowlands. Carboniferous Limestone outcrops in areas such as the Great and Little Orme.

The Irish Sea basin is characterised by a high gravity anomaly, with negative anomalies superimposed on this regional pattern indicating a block or basin structure (Bott, 1968). The possibility that the negative anomalies are produced by granite batholiths was discounted by Bott (1968) following the alternating positive and negative magnetic anomalies consistent with a block structure.

Bott (1968) proposes two possible mechanisms controlling the location and formation of basins. Bott (1965) showed that stress distribution associated with a relatively dense or thin crust would normally enhance the stresses causing faulting and the preferential formation of basins. Igneous activity such as that found in the Lake District or the Welsh Massif would be expected to strengthen the crust causing a resistance to subsidence by faulting. Bott (1968) states that such a background adequately explains the present uplift of the Welsh peninsulas and their resistance to subsidence in the past.

The regional gravity high over the Irish Sea basin as a whole indicates a crustal thinning

(Bott, 1968; Bott and Young, 1971). They suggest that the crust is a few kilometres thinner under the Irish Sea than adjacent land areas. Wright *et al.* (1971) do, however, suggest that Bott (1968) has overestimated the value of the gravity high, thereby overestimating the depth of associated basin structures.

4.2.2 Deglaciation and Late-Glacial sea-levels in the Irish Sea basin.

Many views have been expressed relating to the extent of glaciation in Wales during the Late Devensian. Conservative estimates (Synge, 1963) suggest that only a small portion of the North Wales coast was covered by ice in the Devensian. Bowen (1969), however, suggests that most of Wales was covered by ice, with the Welsh and Irish Sea ice-sheets joined. Smith and George (1961) estimate that during the intense periods of glaciation the ice over North Wales was up to 3000′ thick. Its upper layers rode over and striated the eastern scarp face of the Harlech Dome which is 2000′ high. Ice flowed in a radial direction (Smith and George, 1961); east to the Shropshire-Cheshire plain, north towards the Irish Sea, and west along the Lleyn peninsula and into Cardigan Bay. Ice sheets from the Clyde, Southern Scottish uplands and the Lake District converged in the Irish Sea and flowed southwards. Part of this ice-sheet moved towards the Atlantic and part was driven against the North Wales ice-sheet causing movement of ice west across Anglesey and the Lleyn peninsula, and east into the Vale of Clwyd, the Dee estuary and Cheshire plain. Extensions of the Irish Sea ice are found in these areas as Eskdale granite and Ennerdale granophyre (Smith and George, 1961).

In the east of the region Shotton (1977) has summarised the pathways of Late Devensian ice into the Cheshire Plain and south into Shropshire and Staffordshire. Shotton (1977) concludes that ice retreat from the area was complex with halts and minor readvances. Organic deposits in Staffordshire within a fluvio-glacial depression have been dated to 13490±375 BP (Jones and Keen, 1993), who conclude that the area was ice-free by this time.

Recently two hypotheses have been presented regarding the deglaciation of the Irish Sea basin

(Harris, 1991). The 'conventional' view has been reiterated by Harris (1991) following investigations at Wylfa Head, north Anglesey, in challenge to the 'unconventional' view described by Eyles and McCabe (1989).

Eyles and McCabe (1989) have suggested that the prime control on the disintegration of the Irish Sea ice-sheet was relative sea-level, and that the glacial sediments recorded on the margins of the Irish Sea were glaciomarine in origin, for example, high level deltas and flat-topped kames on the Lleyn peninsula (Saunders, 1968; Eyles and McCabe, 1989). They argue that rising sea-levels in the zone of peripheral subsidence adjacent to the ice margin created a calving bay ice margin. Hughes (1987) has explained how calving bays create fast-flowing ice streams reaching deep into an ice sheet, hence accelerating ice sheet collapse through feedback mechanisms. Eyles and McCabe (1989) argue that drumlins, tunnel valleys and morainal banks are indicative of fast centripetal ice flow. However, Harris (1991) found no evidence for glaciomarine sedimentation at Wylfa Head on north Anglesey, and argued that the features observed pointed to a terrestrial glacier challenging the conclusions of Eyles and McCabe (1989).

Harris (1991) points out that both hypotheses of deglaciation are based mainly on sedimentological evidence. This presents difficulties of interpretation particularly in differentiating between glaciomarine sediments deposited by a tidewater glacier and glacially reworked marine sediments deposited by a terrestrial glacier overriding earlier marine deposits (Harris, 1991).

Crustal modelling provides independent data with respect to this problem. Lambeck (1991), from a high resolution model of Britain, predicts that raised beaches, and therefore high sea-levels, should occur around the Irish Sea north of a line from the Lleyn Peninsula to Dublin at 16000 BP, from Morecambe Bay to Drogheda in Northern Ireland at 14000 BP, and from the mid-Cumbria coast to the Isle of Man to Dundalk at 13000 BP. There is, therefore, compatibility between the sedimentological evidence of Eyles and McCabe (1989) and modelled results of Lambeck (1991), though another conclusion from the Lambeck model is that the ice-cap over Britain was considerably thinner than predicted by Boulton *et al.* (1977).

4.2.3 Present Day sediment movements and tides.

A combination of tidal currents and wave action is largely responsible for sediment movement along the North Wales coast. Net sand movement along the coast is from west to east as far as the Dee estuary, and then northwards from the Mersey along the southwest Lancashire coast as far as the Ribble estuary (Pantin, 1991).

An examination of the average grain size of sediments along the North Wales coast and the forces acting upon them gives an indication of the extent of net sediment movement. Miller *et al.* (1977) published a graph of mean velocity 1 m above the sea bed in relation to the diameter of quartz density material ($U_{1\,m}$). Along the whole of the North Wales coast $U_{1\,m}$ > 0.5 m s^{-1} and in the Dee and Mersey estuaries and also through the Menai Strait $U_{1\,m}$ > 1.0 m s^{-1}. Values of $U_{1\,m}$ = 0.25 m s^{-1} are required for the movement of fine sand and 0.7 m s^{-1} for coarse sand. The dominant sediment type between the rivers Clwyd and Wyre in Lancashire is fine-grained sand (0.125 to 0.25 mm diameter) and further west between the Clwyd and Menai Strait medium sands (0.25 to 0.5 mm diameter) are dominant.

Tidal ranges in the northern Irish Sea do vary spatially, ranging from approximately 4 m in the west along the Irish coast to over 8 m in the bays and river estuaries in the east. On the North Wales coast, to the east of the Great Orme, where most of the sites investigated are located, tidal ranges are > 7.0 m. Tidal details are discussed for individual areas and sites later in this chapter and in Chapter 5.

4.3 North Wales and Wirral.

In this section data that have been used for the reconstruction of sea-level changes and crustal movements from the current study area are reviewed. For clarity the section is subdivided into geographical areas: Anglesey, the North Wales coast and Wirral. All the ^{14}C-dates referred to are tabulated in Tables 4.1 to 4.6. Some of these dates have been classified using a system devised in Appendix 3.

4.3.1 Anglesey.

Anglesey was separated from the Welsh mainland some time during the early to mid-Holocene (Embleton, 1964) with the formation of the Menai Strait. At low water, spring tide, a ridge lies approximately 10′ below the surface (Embleton, 1964) which would suggest that separation took place between 8000 and 7000 BP. The Menai Strait, which separates Anglesey from the mainland, is one of several northeast to southwest trending valleys on Anglesey. Another, the Malltraeth depression, is the largest area of unconsolidated sediments on Anglesey.

To the east of Anglesey in Liverpool Bay, the variation in tidal range is minimal, but around Anglesey itself there is over 1 m variation in the height of MHWS. Tidal ranges are highest on the south and east of the island and lowest in the west and southwest. At Menai Bridge MHWS is +3.50 m OD, and at Moelfre on the west coast, MHWS is +3.60 m OD. In contrast, at Llanddwyn Island on the entrance to Malltraeth Bay MHWS is +2.21 m OD. Llanddwyn Island is the nearest tide gauge station to sites that have been investigated and dated in this thesis and in Prince (1988).

Hopley (1963) comments that apart from incidental work, very little has been published with respect to the Anglesey coastline since Greenly (1919). Even less has been published on the Holocene sedimentary history, the exceptions being Hopley (1963) and Prince (1988), and until this study only four ^{14}C dates were available from the coastal sediments of Anglesey (Table 4.1).

Greenly (1928) and Hopley (1963) have recorded ten coastal peat exposures, primarily on the north of the island, Red Wharf Bay and Holy Island. They are typically found at around high water mark and Hopley (1963) states that preliminary pollen analysis on an exposure from Holy Island suggests an age within zones VI and VIIa (*c.* 8000 - 6000 BP). This 'forest bed' sequence overlies post-glacial *Scrobicularia* clays (McMillan, 1949) which are described as purplish-blue tenacious clays up to 3′ thick (*c.* 1.00 m) and were clearly formed in a marine environment (Hopley, 1963).

Hopley (1963) presents a sea-level curve for Anglesey which shows a rising sea-level from the start of the Holocene to *c.* 8000 BP at +25′ above present sea-level. A fall, then rise of sea-level is shown from *c.* 8000-7000 and 7000-6000 BP respectively to a level of +10′ above today's level. A steadily falling sea-level is shown from *c.* 5500 BP to the present. Such a pattern of sea-level change is not feasible for the area, and is incorrect due to the misinterpretation of a 25′ 'raised beach', a common mistake of early workers in North Wales and Lancashire. In Lancashire Gresswell (1953) described such a feature and named it after the type locality at Hillhouse, but this was later disproved by Tooley (1978). Similarly Whittow (1960, 1965) claims that a deposit at Porth Neigwl on the north coast of the Lleyn peninsula was a similar 25′ raised beach, which West (1972) states is more likely to be a storm feature.

Prince (1988) took two deep boreholes in the Malltraeth Marshes at Ty'n-y-pwll Farm which is close to the A5 and at Bont Farm which is at the seaward end of the marsh, close to the village of Malltraeth and the sea embankments. The depth to till (-11.94 m OD at Ty'n-y-pwll Farm and -47.97 m OD at Bont Farm) demonstrates the thickening of unconsolidated sediments towards the sea.

At Bont Farm, the top 23 m were dominated by sands with shell fragments. An *Ostrea* bed was recorded between -7.94 m and -7.99 m OD. Wood fragments were recorded immediately below this bed and again at -11.14 m OD. From 23 m below ground surface to the till at 47 m, silty-clays were dominant and very little organic material was recorded. *Phragmites,* however, was recorded at -23.09 m and -23.81 m OD. Diatom analysis was completed at Ty'n-y-pwll and showed that the inorganic sediments were of marine origin.

The Malltraeth Marshes in the west of Anglesey were recognised by Tooley (1978) and Prince (1988) as an area with a particularly rich sedimentary history. Tooley (unpublished) working in the upper Malltraeth Marshes near Llangefni recorded a peat just below the surface and another thin peat horizon at 2.00 m below ground surface separated by clays which diatom analysis showed to be marine and brackish. More detailed work on the marsh is reported by Prince (1988) following the completion of two deep boreholes in the lower marshes at Ty'y-n-pwll and Bont Farms.

All four ^{14}C-dates collected by Prince (1988) have been rejected. Prince (1988, p.311) concluded that 'many shorter cores, giving greater local lithologic and biostratigraphic control, may have been more valuable'. For each site used by Prince (1988) only one borehole was taken. For obtaining Pleistocene data such an approach is necessary, because of the depth of sediment, but for obtaining Holocene data a broader lithostratigraphic framework is considered more appropriate. On the Malltraeth Marshes in Anglesey, for example, the two cores taken were at the far western edge of the marsh, where Greenly (1919) and Hopley (1963) had reported largely wind and water lain sands.

The lack of suitable material for dating has perhaps led to some erroneous results. At Ty'n-y-pwll Farm above the till surface from -11.14 m OD to -7.99 m OD are sands with wood fragments, overlain by sands with silts and clays. The two dates from this site are SRR-2508, which is a *grey sandy-clay with Typha* and SRR-2507 is dated *shells*. The indicative meaning of these samples is not clear and all are likely to be sub-tidal, and the marine and the marine/brackish dominated diatom assemblage (*Paralia sulcata, Diploneis suborbicularis*) would seem to confirm this. At Bont Farm, a 46 m, almost totally inorganic sequence was sampled. Below 25 m OD slightly laminated clays are found, with silty-clays merging into sands in the upper part of the bore. SRR-2644 is described as a *silty-clay with organic material* and SRR-2502 as *a piece of wood in the sand*. Again there is no identifiable relationship to a former sea-level, since neither date could be regarded as a transgressive or regressive contact,and there is an age inversion on these dates. Clearly a 'piece of wood in the sand' could be of any age, and the explanation of contamination by coal forwarded by Prince (1988) is unlikely to be correct (section 3.7). Given the age inversions, and inconsistent age-altitude distributions and lack of indicative meaning, these dates have to be rejected as sea-level index points, as acknowledged by Prince (1988).

4.3.2 The North Wales coast.

On the North Wales and Wirral coastline Holocene sediments are most common east of the River Conwy where headlands of Carboniferous limestone, such as the Great Orme, are broken by low-lying coastal plains and river estuaries. In these low-lying areas, which consist of the Conwy estuary and Afon Ganol Valley, the Clwyd coastal lowlands, and westwards to the Point of Ayr on the Dee estuary, Holocene sediments are especially prevalent.

The North Wales coast between the Great Orme to the Point of Ayr has, however, been very much developed. The resulting coastal protection in the form of sea walls, reclamation and drainage has led to a loss of natural coastal habitats so that saltmarsh is very rare. This development has enhanced our knowledge of sedimentation in the area, but restricted further investigation. Borehole records from road building have provided a valuable insight into Holocene sedimentation along the routeway of the A55, especially in the Afon Ganol valley and the Clwyd coastal lowlands. However, the coastal strip of land between Abergele and Prestatyn is highly developed, so that the scope for field investigation is limited.

East of Prestatyn the coast is less developed. The marshy pasture that lies north of the A548 is separated from the sea by extensive sand dunes. West of the Conwy towards Bangor the Ordovician rocks form steep headlands near Dwygyfylchi and Llanfairfechan so that there is very little coastal plain.

The potential of the North Wales coast for sea-level investigations has been demonstrated from the writings of numerous early workers, who have observed and examined the peat exposures along the coast. These exposures have been noted at Rhos-on-Sea (Hall,1866), in the Clwyd coastal lowlands at Abergele (Pennant, 1784; Bibby, 1940), Rhyl (Strahan, 1885; Neaverson, 1936; Bibby, 1940) and Prestatyn (Neaverson, 1936).

From these works it has been demonstrated that intercalated Holocene sediments are concentrated in the coastal lowlands between the Conwy and Dee estuaries. In general, Holocene sediments are recorded below +4.00 m OD, the approximate present-day MHWS. At Colwyn Bay MHWS is +3.70 m OD and in the Dee estuary at Hilbre Island, MHWS is +4.07 m OD. There are no values for MLWS at Colwyn Bay, but at Hilbre Island, MLWS is -3.63 m OD, giving a tidal range over 7.5 m.

Of these coastal peats, those at Rhyl have received most attention. At the time of the writings of Neaverson (1936) and Bibby (1940), there were two peats at the eastern end of

Rhyl Beach, one exposed at low tide and the other nearer to the sea wall. These were termed by Bibby (1940) the 'Upper' and 'Lower' forest beds. A boring made by Bibby (1940) on adjacent golf links showed that these peats extend landwards. Pollen analysis showed the lower bed to be dominated by *Alnus, Pinus, Quercus* and also Chenopodiaceae, and the upper by *Alnus* and *Betula*. Bibby (1940), on the basis of this pollen analysis, suggested they are post-Boreal and that the lower bed is probably sub-Boreal or Atlantic in age. Early interpretations of sea-level history recorded in the Clwyd coastal lowlands (Neaverson, 1946) are based primarily on the Upper and Lower forest beds. Rowlands (1955), for example, suggests a simple stratigraphy for the area, with a thin overlying boulder clay, a lower peat equating to the Lower forest bed sequence overlain by blue estuarine clay and an upper peat equating to the Upper forest bed sequence. Subsequent work (Tooley, 1978 unpublished; Manley, 1981; Prince, 1988) has shown the sedimentary history of the area to be much more complex.

A more detailed analysis of the upper peat on Rhyl Beach was completed by Tooley (unpublished). A well humified woody detrital peat was recorded overlying sandy-clay merging into a grey silty-clay, with the regressive overlap recorded at +2.42 m OD. This contact was ^{14}C-dated (Hv 4348) giving a date of 4725±65 BP. The very low *Ulmus* frequencies and persistence of ruderals found in the associated pollen diagram confirms this date is of Flandrian-III age. Morris (1923) compiled a list of mammalian remains found in the Rhyl Beach peat when it was far more extensive. These remains include wolf, fox, great ox, red deer, sheep, horse and pig. Many of these species are domesticated, and Neaverson (1941) has used this fact to suggest that this peat bed must be at least of Neolithic age, an assertion which seems corroborated by this date. The increasing frequencies of Gramineae, Chenopodiaceae and other herb pollen towards the contact indicate salt marsh conditions in the peat immediately above the clays.

Numerous isolated findings and borings have been made elsewhere in the Clwyd coastal lowlands, without a fully systematic lithostratigraphic survey being completed. Pennant (1784) reported that oak trees were visible offshore from Abergele at low tide. Bibby (1940) investigated these deposits and recorded a peat containing *Phragmites*. Pollen analysis showed that the peat was sub-Boreal or Atlantic age, and was formed in an open environment with a high proportion of herbs including saltmarsh indicators present. Strahan (1885,1890) and Neaverson (1936) demonstrated the extent of unconsolidated sediments in the Clwyd coastal lowlands with borings at Rhyl and Prestatyn. Neaverson (1936) reports the results of the Foryd borehole, completed in 1860-61, where two peat layers are recorded at *c.*-9.5 and *c.*-13.00 m OD, intercalated with blue clay. Above *c.*-6.00 m OD sands and gravels were recorded. With a view to dating these horizons, the Foryd borehole was resampled by Prince (1988), but no organic material was found below -5.20 m OD, perhaps suggesting that the spatial extent of the peats found at Foryd was limited. The full succession of sediments in the Foryd borehole are shown below (the ground surface was recorded at +12′)

Sediment	Thickness
Clay	2′0″
Sand	19′0″
Gravel	4′0″
Mud and clay	8′6″
Turf (peat)	0′6″
Blue clay	10′4″
Turf (peat)	1′6″
Blue clay	1′0″
Gravel	3′6″
Red clay	9′8″

Manley (1981) has collated borehole information available for the Clwyd coastal lowlands from early workers and modern commercial borings. The irregular topography of the buried boulder-clay surface is noted, and Manley (1981) has interpreted the altitudinal distribution of peats in terms of the Lytham sequence of transgressions and regressions established for Lancashire by Tooley (1978), but later re-evaluated (Tooley,1982). The altitudes of the peats recorded by Manley (1981) are displayed in Fig.4.1.

Fig.4.1 shows the number of times organic sediments are recorded for 0.50 m altitudinal blocks, as indicated by the second y-axis. The first y-axis indicates the probability of organic sediments being recorded for each altitudinal block, calculated from the following simple equation:

$$Pr = \frac{\textit{frequency of organic sediments}}{\textit{number of cores reaching altitude}} \qquad \text{Eqn. 4.1}$$

A graph showing just frequency against altitude will always exaggerate the importance of the upper organic sediments, so the probability factor is introduced to normalise the distribution. The greatest effects of a probability function are clearly on the deeper sediments at depths where few cores will reach, so there is the danger here of exaggerating the relevance of these lower organic sediments. Additionally, within the Clwyd coastal lowlands, there seems to be a greater concentration of organic sediments in the west so a plot of all cores will tend to minimise any geographical variations, and this is reflected in the maximum probability attained being only 0.33.

It is noted that the data displayed in Fig.4.1 are coarse resolution data obtained largely from commercial borings. Four, fairly distinctive phases of organic sedimentation do seem apparent, however, in the altitudinal ranges *c.*-13.00 m OD, *c.*-9.00 m OD, *c.*-3.00 to -2.00 m OD and *c.*-1.00 to +3.00 m OD.

Some of the boreholes used in the analysis by Manley (1981) were from commercial bores made prior to the construction of the Abergele-Llanddulas bypass in 1963-1966. These records were first analysed by Tooley (unpublished) and preliminary pollen analysis was carried out on samples obtained from the Clwyd county surveyor. These preliminary investigations led Tooley (unpublished) to comment that the data:

> *"serve to indicate an area, together with the Malltraeth Marsh in Anglesey, which is the most important in north Wales for studying land- and sea-level relationships during the Flandrian."*

The subsequent field survey proved abortive because of the tough sediments seaward of the bypass. Upon this assertion, for this thesis, a field investigation was carried out at Pentre Mawr adjacent to the bypass, but again the tough sediments in the seaward direction proved difficult to penetrate. A site further east at Hendre-fawr did, however, prove to be more satisfactory than even the preliminary results at Abergele suggested and so a full investigation was possible in the Clwyd coastal lowlands.

Prince (1988) completed three relatively deep boreholes in the Clwyd coastal lowlands at Woodlands, Plâs Llwyd and Old Foryd Road, with dates obtained from Woodlands and Plâs Llwyd (Table 4.1).

The four dates from Woodlands are:

SRR 2642	**8480±60 BP**	**-2.67 m OD**
SRR 2643	**15070±320 BP**	**-6.87 m OD**
SRR 2511	**8540±70 BP**	**-9.00 m OD**
SRR 2510	**8170±70 BP**	**-9.12 m OD**

The lower two dates are from two layers of woody detrital peat on a blue-grey silt, the biogenic layers containing almost no minerogenic fraction. The pollen assemblage, dominated by Cyperaceae, Gramineae, Chenopodiaceae and *Polygala,* leads Prince (1988) to suggest that the peats were formed in saltmarsh conditions close to MHWS and therefore acceptable as sea-level index points.

The upper two dates are clearly in error, being far too old for their altitude, and show an age-inversion. The material used for the dates is described as 'pinkish clay with *Phragmites*' which has no obvious indicative meaning, and which Prince (1988) suggests is probably reworked. These dates are not acceptable as sea-level index points.

The Plâs Llwyd dates (see Table 4.1 for details) are from material described as blue-grey silts with *Phragmites*, which lithologically has a very broad relationship to a former water-level:

SRR 2508	**11420±80 BP**	**-6.19 m OD**

SRR 2509 9610±50 BP -9.54 m OD

SRR 2508 is rejected by Prince (1988) because of the inconsistent age-altitude position. SRR 2509, dated to 9610 BP at -9.54 m, does seem a little high for this age if the Lancashire model is applied; at Heysham Head in southern Morecambe Bay a date of 8925±200 BP was obtained at an altitude of -16.04 m OD (Tooley, 1978). Prince (1988) has accepted this date pointing to the pollen evidence with an assemblage dominated by Cyperaceae, other herbs and *Corylus*. Examining the pollen diagram, small quantities of *Alnus* and *Quercus* are also present. Acceptance of this date would lead to the conclusion that at around *c.*9500 BP, more cumulative uplift had taken place in north Wales than Lancashire and Morecambe Bay. Recent estimates of crustal uplift in Britain point to the opposite (Shennan, 1989), although Lambeck (1991) makes no real distinction between the early-Holocene relative sea-level histories of north Lancashire and north Wales.

Apart from dates collected by Prince (1988) and the single date obtained by Tooley (1978) for Rhyl Beach, the only other available ^{14}C-date from the coastal sediments of the North Wales coast is from Llandudno station (SRR-61, 7635±52), on the western side of the Llandudno peninsula (*Radiocarbon, v16/2*), and also reported in Heyworth and Kidson (1982).

There has been a focus on the coastal sediments found in Anglesey and in the Clwyd coastal lowlands; this is where early investigations and indeed subsequent ^{14}C-dating have concentrated. There are, however, other parts of the North Wales coastline where unconsolidated sediments have accumulated, many of which are described in Chapter 5 and thus only mentioned here. Of particular importance is the Afon Ganol valley linking the Conwy estuary with Penrhyn Bay off Rhos-on-Sea. Tooley (pers.comm.) has explored the potential of Rhos-on-Sea golf course and Arber (1984) has reported the gross lithostratigraphy of the Afon Ganol following commercial borings prior to the construction of the A55 coast road where up to 20 m of unconsolidated sediments were recorded. Eastward, towards the Point of Ayr, where the Dee enters Liverpool Bay, are sediments which await sampling, though provisional investigations at Prestatyn did suggest that there were problems with wind-blown sands on this part of the coast (Neaverson, 1946).

4.3.3 Wirral and north Cheshire coast

The Wirral peninsula, bounded in the west by the River Dee and the east by the River Mersey, is composed of a Triassic plateau with higher sandstone ridges, particularly in the west. The tidal range on the Mersey at Liverpool is 8.4 m, with MHWS recorded at +4.37 m OD. The nearest tide gauge station to the site on the north Wirral coast from which ^{14}C-dates have been obtained is Hilbre Island. Here MHWS is recorded at +4.07 m OD. Tidal ranges decrease inland along the Dee and Mersey. So on the Mersey, for example, the tidal range at Widnes is 4.5 m, compared with 8.4 m at Liverpool.

The boulder-clay deposits of the north Wirral dip gently in a south to north trend; however superimposed upon this pattern are undulations and incisions into the boulder-clay forming narrow buried channels where Holocene sediments have accumulated (Kenna, 1986). These channels are probably associated with the previous meanderings of the Birket and Fender rivers. In north-west Wirral is what has been termed by Kenna (1986) the western depression between Hoylake and West Kirby. Unlike other areas of Holocene sedimentation on the Wirral this area is a large open coast system, and therefore less likely to be affected by complex local sedimentation factors (Innes *et al.*,1990), and it was therefore a site chosen for thorough investigation in this thesis (section 5.5).

Coastal peats have been noted on the Wirral since the nineteenth century at Leasowe and Dove Point (Morton, 1863; Reid, 1913; Erdtman, 1928; Travis, 1929) and along the Dee and Mersey estuaries (Maidwell, 1920). *Scrobicularia* clays have also been noted throughout the whole region (De Rance, 1871). The findings of these early workers are summarised by Innes (1983) and Kenna (1985). Innes (1983) points out that the formation of the peat beds of the north Wirral coast was by no means synchronous, since pollen evidence places the exposed peat bed at Dove point pre-elm decline and that at Leasowe post-elm decline. More recently the construction of sea defences on the north Wirral coast has exposed buried unconsolidated sediments and the information derived from these investigations including ^{14}C-dates has been assembled by Kenna (1986). The information is derived from a number of investigations with varying objectives, though principally archaeological (Kenna, 1979; Innes and Tomlinson, 1983), and thus has to be carefully scrutinised in terms of its full value for sea-level investigations. Additionally a database of ^{14}C-dates has been collected for the north Wirral by Innes (unpublished), some of which are from the coastal sediments where there is evidence of marine conditions. In this section these data, particularly the lithostratigraphy and ^{14}C-dates (Table 4.2), are reviewed.

Kenna (1986) has presented a 'lithostratigraphic model' for the Wirral based on the data presented by early workers and modern commercial borings identifying nine stratigraphic units which have been placed into a chronostratigraphic framework by a mixture of ^{14}C-dating, pollen analysis and archaeology. The general features of the Kenna (1986) model are: a basal peat, followed by inorganic sedimentation up to *c.*5500 BP where organic sedimentation dominates for *c.*2 ka and finally water-lain and wind-blown sands. Considering the data that were available to Kenna (1986), such a model is a good summary, but in the light of further data collected by Innes (unpublished) and for this thesis, it can only be regarded as a first approximation of the generalised lithostratigraphy on the north Wirral.

The main deficiency of this lithostratigraphic model is that it does not distinguish between the sedimentary histories of protected inland sites and exposed coastal sites. At Bidston Moss and Reeds Lane where quiet water sedimentation has prevailed the upper peat beds are thicker than in coastal sites.

The oldest dates from the coastal sediments of the north Wirral have been collected by Innes (unpublished) at Bidston Moss (SRR 2926) and Dove Point (SRR 2927 and 2928):

SRR 2926 7360±60 BP -1.00 m OD

SRR 2927 7010±50 BP -0.90 m OD

SRR 2928 6510±50 BP -0.80 m OD

An additional date from Bidston Moss (Innes, unpublished) is:

SRR 2924 4740±70 BP +1.99 m OD

At Bidston Moss in the upper end of the Fender Valley 3.0 m of organic sediments have accumulated between -1.0 m and +2.0 m OD. This is the period when, according to Kenna's (1986) model, there should be inorganic sedimentation in the form of *Scrobicularia* clays (De Rance, 1871). The location of this site, at the upper end of a valley, can explain this difference, though it is curious that organic sedimentation ceases at an altitude and time when on other parts of the north Wirral organic sedimentation begins (*c.* 4700 BP). The organic sediments at Bidston Moss are overlain and underlain by blue/grey clays, but their origin has not been proven because of an absence of diatoms in these clays (Innes, pers.comm.). It is possible, therefore, that the beginning and cessation of organic sedimentation at Bidston Moss are not due to the decreasing and increasing influence of marine conditions despite the comparable altitudes of the two ^{14}C-dates. The dates themselves are real since they sandwich the Flandrian I/II and II/III boundaries which approximate to *c.* 7000 BP and *c.* 5000 BP respectively. It would seem that further evidence is required before the Bidston Moss dates can be definitely accepted or rejected as sea-level index points.

Dove Point is a coastal site lying slightly to the Hoylake end of north Wirral. The two dates from this site have been collected from an open section where a peat was recorded lying upon a thin wedge of clay, which in turn overlies boulder-clay (Innes, unpublished). A ^{14}C-date on the regressive contact of this peat (SRR 2927) gave an age of 7010±50 ^{14}C-years. The pollen evidence shows unequivocally salt-marsh conditions in the bottom few centimetres of the peat with particularly high frequencies of Chenopodiaceae pollen. Diatom frustules were limited in the clay beneath the peat, but *Coscinodiscus* sp. were found (Innes, pers.comm.) to demonstrate the marine origin of the clay and confirm the validity of this date as a sea-level index point. The second date recorded at Dove Point was from a tree stump found in the basal peat at -0.80 m OD. This sample yielded an age of 6510±50 BP, very similar to a sample dated at Mockbeggar Wharf, where the remains of *in situ* oak and birch yielded an age of 6460±40 BP at -0.18 m OD. Both of these dates have been classified as group 6 dates.

The transgressive overlap of the basal peat at +0.41 m OD found at Wallasey has been dated to 6420±60 BP. At this contact were high frequencies of Chenopodiaceae pollen along with other saltmarsh indicators such as *Artemisia* and *Armeria*: it is overlain by blue/grey clays

(Kenna 1986) and hence it is a perfectly acceptable sea-level index point.

The blue/grey clays and silts in the altitudinal range *c.*-1.00 m OD to *c.* +2.00 m OD were first described by Reade (1871) as *Scrobicularia* clays. The marine origin has been confirmed by diatom analysis completed at Park Road, Meols (Innes, unpublished) in the upper part of the stratum below the upper peat regressive contact.

Work based on the exposed coastal peats had led to the conclusion that this upper peat consisted of just one unit. At Park Road this upper peat is split in two by a thin clay band (Kenna, 1986; Innes, unpublished). Four dates have been obtained from Park Road and are listed below:

GU 1312	**4315±70 BP**	**+2.86 m OD**
SRR 2693	**4620±50 BP**	**+2.78 m OD**
SRR 2929	**5120±50 BP**	**+2.70 m OD**
SRR 2694	**5250±50 BP**	**+2.31 m OD**

The context for all of these dates has been established from detailed pollen and diatom analysis (Innes, unpublished). In the silty-clay below the regressive overlap the diatom assemblage is dominated by *Diploneis interrupta* with marine indicators including *Paralia sulcata, Podosira stelliger, Coscinodiscus apiculatus* and *Diploneis didyma*. At the contact the proximity of salt marsh conditions is demonstrated by the presence of Chenopodiaceae and *Plantago maritima*. The regressive overlap was dated to 5250±50 BP at an altitude of +2.31 m OD.

Pollen analysis has shown that the peat at Park Road was probably forming under reedswamp conditions with alder-carr and mixed deciduous woodland nearby. However, before the regressive overlap with the thin clay wedge is a rise in the values of obligate aquatic taxa such as Nymphaea, and also *Hydrocotyle*. This level at +2.70 m OD is interpreted as a rise in the groundwater table and is coincidental with the elm decline, 0.10 m below the regressive overlap has been dated to 5120±50 BP.

Long (1991) has discussed how a rise in aquatic pollen within peats is a proxy for the first signs of a positive movement in sea-level. He argues that a change in the direction of sea-level, from negative or stable to positive, will cause a change in vegetation communities but may not be of sufficient speed or magnitude to cause a change in lithology so that the dating of these features within peats gives a more precise date for tendencies of sea-level change at a particular site. At Park Road, however, after this rise in the water table the radiocarbon dates clearly establish a decrease in the rate of sedimentation which is not necessarily consistent with a positive tendency of sea-level. The elm decline date (SRR 2929) is therefore only used as a indicator of organic sedimentation taking place and not a proxy for wider sea-level changes.

The upper peat at Park Road is split by a thin clay 0.01 m thick. On either side of this clay the respective increase and decrease in the marine influence was demonstrated through the high Chenopodiaceae values and the dominance of brackish water diatoms in the clay compared with fresh and fresh/brackish within the peat (Innes, unpublished). The date for the end of this marine event was 4620±50 BP.

Reeds Lane is an inland site lying within the Fender Valley between Park Road and Bidston Moss, and here the upper organic sequence is over 1.5 m thick. Two radiocarbon dates have been collected from the transgressive and regressive contact on this peat:

SRR 1574 2620±40 BP +3.02 m OD

SRR 1575 4700±70 BP +1.50 m OD

Pollen evidence, and indeed the altitude, suggest that the date for the regressive contact is too young. The sample is taken from a black *Phragmites* peat so contamination by younger carbon is a possibility. This date, therefore, has to be rejected as a sea-level index point. Of the date for the transgressive contact Kenna (1979) states that it is taken from the top of the **eroded** brown peat for which the pollen assemblage is typical of an alder fen community. An eroded contact is not always suitable as a sea-level index point, though it does give a date for organic sedimentation at the site. Diatom analysis does confirm that this peat is overlain by marine and marine/brackish inorganic sediments.

Additionally, Kenna (1986) reports three dates from tree trunks and bone from within a peat sequence from Wallasey and Mockbeggar Wharf (Table 4.2). Though not sea-level index points they provide further dates on periods of organic sedimentation and all fall in the age range 3800 to 3980 BP. At Wallasey, where the dates on the oak and pine trunks are taken the transgressive contact of the peat has been dated to 3490±60 BP, and therefore all the dates from the Wallasey sequence are in stratigraphic order. The other date from this 'upper organic sequence' of 3695±110 BP at +3.05 m OD in Morton was originally reported by Godwin and Willis (1964) from a tree trunk on the coast. Unfortunately no other information, including stratigraphic context, is provided and it is therefore not even suitable as a date indicating organic sedimentation.

Summary

The Holocene sediments of the North Wirral have been shown to hold a rich history of environmental change. This history has recently been exploited as a means of providing a context for numerous archaeological investigations in the area which have been summarised by Cowell and Innes (in prep). The North Wirral has a complex palaeogeography with a series of narrow channels incising on the boulder-clay surface. In these narrow channels Holocene sediments have been deposited, but their deposition is likely to have been influenced by local factors such as perturbations in local stream and river drainage, perhaps as a result of deforestation. However, Kenna (1986) and Innes *et al.* (1990) have identified Newton Carr as a potential site where these local influences will be less severe.

4.4 North-west England.

Data for three areas of northwest England are discussed in the following sections. First of all southwest Lancashire, defined as the area between the rivers Mersey and Ribble. Second the Fylde and northwest Lancashire between the rivers Ribble and Wyre, and finally the coastal areas of Morecambe Bay. The ^{14}C-dates available from these areas are tabulated in Tables 4.3 to 4.5.

4.4.1 <u>South-west Lancashire.</u>

Unconsolidated sediments of Holocene age have been recorded along the length of the coast of southwest Lancashire and Merseyside between the rivers Mersey and Ribble, a distance of approximately 60 km. The coastal plain, bounded in the east by Triassic sandstones, has been heavily developed, but low-lying agricultural land to the east of Formby and Southport has yielded a number of important sites for palaeoenvironmental investigations, with up to 18.0 m of unconsolidated sediments recorded at Downholland Moss. Sand dunes line the coast between Formby and Southport, but behind these dunes was a moss environment (Tooley, 1978). Drainage and peat cutting mean that little of these environments remains, but at Downholland Moss and Martin Mere peat still forms the surface sediment. The sand dunes, with their northern extreme at Southport, typically form a coastal belt three miles wide. In the vicinity of Southport the dunes are up to 80′ high, but further south they are typically 20′ to 30′ high (Steers, 1964).

Throughout the coast of Liverpool Bay between the River Ribble and Great Orme at Llandudno, tidal range is quite consistent. At Formby, the closest tide gauge station to Downholland Moss, the tidal range is 8.90 m and MHWS is recorded at +4.07 m OD, and at Southport +4.10 m OD. This compares with +4.07 m OD at Hilbre Island in the Dee estuary and +3.70 m at Colwyn Bay on the North Wales coast. Preston lies at the landward extent of tidal activity on the Ribble. Here the tidal range is much reduced (4.20 m) with MHWS recorded at +3.40 m OD.

Between the River Alt, which enters the sea just to the south of Formby, and the southern shores of the Ribble are a number of sites that have yielded nineteen ^{14}C-dates which are presented in Table 4.3. These sites include Downholland Moss, New Cut, Martin Mere, Altmouth and Formby Foreshore.

Detailed lithostratigraphic, biostratigraphic and ^{14}C data are presented for Downholland Moss in Tooley (1974, 1978, 1985b). Fifteen cores were taken in an east to west transect revealing a series of intercalated clays, silts and peats. The deepest core (DM-16) awaits dating, but the lithostratigraphy was recorded as follows (Tooley, 1985b,p.213):

Bed	Altitude (m OD)	Description
11	+3.20 to +1.33	Peat.
10	+1.33 to +1.23	Clayey silt.
9	+1.23 to +1.02	Peat.
8	+1.02 to +0.27	Clayey silt.
7	+0.27 to +0.05	Peat.
6	+0.05 to -2.97	Fine sandy silt.
5	-2.97 to -3.25	Peat.
4	-3.25 to -5.13	Fine sandy silt.
3	-5.13 to -5.62	Peat.
2	-5.62 to -8.92	Sand.
1	-8.92 to -9.80	Clay.

Using macrofossil evidence and data derived from nearby cores Tooley (1985b) ascribes the intercalations to changes in the marine regime rather than changes in the fluvial regime.

The oldest sample from Downholland Moss (Hv 3936) was dated to 6980±55 BP and taken from an altitude of -0.38 m OD. The sample comes from a black organic sand overlain by a blue clay. The age of this sample is corroborated with pollen evidence from Red Moss, and the presence of saltmarsh pollen taxa confirms the environment in which the sediment accumulated.

The most complete core that has been dated is DM-15. At the base of this core silty-clays with iron staining were recorded overlain by a gyttja. This regressive overlap, at +0.15 m OD, was dated to 6750±175 BP. The pollen evidence, at the regressive overlap, shows a mixed woodland environment close by, with saltmarsh conditions locally. This organic horizon is overlain by clay which then passes into a laminated gyttja at +1.05 m OD. This second regressive overlap was dated to 6050±65 BP. Diatoms were present in the top of this 20 cm thick gyttja and were investigated by du Saar (1969). He concluded that the peat was formed under brackish conditions, possibly in a reedswamp environment. The transgressive overlap at +1.25 m OD was dated to 5565±205 BP. The diatom analysis in the clays above these organic sediments shows a gradual increase in the marine influence and du Saar (1969) concluded that sedimentation took place in a well-exposed tidal area. There was a return to organic sedimentation at +1.86 m OD, but the date for this episode (4045±395 BP) is considered too young by Tooley (1978).

The east to west transect at Downholland Moss is over 2 km in length. Tooley (1974) ascribes cores from the western margin of the moss to the former tidal flat and lagoonal zone, and those from the eastern margin to the perimarine zone. This interpretation aids our understanding of the lithostratigraphy since the cores from the eastern margin of the transect contain thicker organic horizons than those further west (Tooley, 1978, Fig.33). DM-15 is located slightly nearer to the seaward (western) end of the transect, but central enough to exhibit lithologic features derived from sedimentation in the tidal flat and lagoonal zones. DM-15 shows evidence for three separate phases of marine and terrestrial sedimentation, but from Downholland Moss as a whole five are recognised (Tooley, 1978,p.102):

Phase	**Time Limits (Years BP)**	**Boundary**	**Mean Height (m OD ±1σ)**
V	~2335	Sand dune	+5.08
IV	(4800)-4545	Regress.	+3.37±0.29
		Trans.	+2.90
DM-III	(5900)-5615	Regress.	+1.80±0.38
		Trans.	+0.86±0.31
DM-II	(6500)-6050	Regress.	+1.07±0.50
		Trans.	+0.33±0.18
DM-I	6980-6755	Regress.	-0.19±0.28
		Trans.	-0.72±0.47

The ^{14}C-dates in Table 4.3 have been classified as explained above. Though all the dates fall into one of the categories, three have to be rejected altogether because they are inexplicably young and not in stratigraphic sequence relative to other dates from the same core (DM-11) (Tooley, 1978). Another date has been rejected (Hv 2684: 4045±395 BP) because of the very large standard error. If a 95% confidence limit was placed on the date, it has a 1580 year age span.

4.4.2 **North Lancashire.**

The Holocene coastal sediments of North Lancashire have been intensively studied, principally by Tooley (1978). North Lancashire is defined here as the peninsula of land between the River Ribble to the south and Morecambe Bay to the north. This area is referred to as Fylde in Amounderness by Tooley (1978). Keuper Marls and Sandstones underlie the whole area, but this solid surface is covered by till and towards the coast are Holocene sediments up to 18 m thick. Tooley (1978) has investigated sites in the southwest of the area in the vicinity of Lytham and Nancy's Bay and concluded that:

> *"In the south Fylde there is direct evidence of nine marine transgressions between 8570 and 1370 radiocarbon years ago, and indirect evidence of a tenth transgression from the sand-dune area of the coast. The evidence for these transgressions does not derive from a single site, but from four sites - Nancy's Bay, the Starr Hills, Lytham Common and Lytham Hall Park - all of which lie within the former township of Lytham." (Tooley 1978,p.105).*

In this section some of the data used to construct this sequence of 'transgressions' and 'regressions' referred to by Tooley (1978) are examined. In Chapter 6, the chronology itself and the methodology used in its construction are reviewed. The ^{14}C-dates that have been collected from North Lancashire are tabulated in Table 4.4.

The earliest ^{14}C-date to be collected from North Lancashire comes from Heyhouses Lane, Lytham. A *limus* underlain by fine grey clay was recorded at -9.75 m to -9.62 m OD, and the regressive overlap was dated to 8575±105 BP. The transgressive overlap was dated to 7820±60 BP. A pollen diagram was prepared from this *limus* showing a tree assemblage dominated by *Betula, Pinus, Quercus* and later *Ulmus*. *Alnus* and *Tilia* were very rare, confirming that the *limus* is from the chronozone Flandrian I. This assemblage and date are comparable with the results from the local type site, Red Moss. Low frequencies of saltmarsh indicators are recorded at the regressive overlap, but the frequencies of aquatic pollen are high, notably *Typha latifolia, Myriophyllum alterniflorum, Lemna* and *Hydrocotyle*, confirming that marine sedimentation did end at *c*.8575±105 BP. On the transgressive overlap, high frequencies of Chenopodiaceae are recorded showing the proximity of saltmarsh conditions when organic sedimentation was replaced by clastic sedimentation at 7820±60 BP.

The deepest sediments that have been dated in North Lancashire come from the Starr Hills, Lytham where a woody, detrital peat was recorded from -11.21 m to -11.13 m OD. The tree pollen is very similar to that found at Heyhouses Lane with *Pinus, Betula* and *Quercus* dominant. The transgressive overlap of this peat, which was overlain by a fine grey clay, was dated to 8390±105 BP. Chenopodiaceae and aquatic pollen attained high frequencies at this transgressive overlap.

All three of these dates from the early Holocene are excellent sea-level index points. The pollen data corroborate the ^{14}C-dates obtained and also their indicative meaning. It is very gratifying that all of these dates from the early Holocene are acceptable, bearing in mind the problems of sampling that were apparent for similar sediments from North Wales and Cardigan Bay examined later in this chapter.

The regressive overlap (8575±105 BP) has been used by Tooley (1978) to define the end of the marine phase Lytham I, and the other two dates (8390±105 BP and 7820±60 BP) the start of and continuation of Lytham II.

After 7820±60 BP the sedimentary evidence from North Lancashire indicates a period of rapid sea-level rise. The end of this period is marked by an organic horizon from Nancy's Bay. Two ^{14}C-dates were obtained from this organic horizon (7605±85 BP from the transgressive overlap and 6950±175 from the regressive overlap). This age inversion necessitated the rejection of one of these dates and on the basis of the pollen analysis the later date of 6950±175 BP was rejected. However, the date which has been accepted by Tooley (1978) does require some scrutiny.

First of all, it is not a regressive overlap which we would expect to mark the culmination of a marine phase, but a transgressive. The regressive contact of the peat at -2.46 m OD was dated to 6950±175 BP giving an age-inversion on these dates. The younger date, on the regressive overlap, has been rejected on the basis of the pollen evidence (Tooley, 1978) with a large proportion of open habitat taxa and low alder frequencies not compatible with the Regional Pollen Assemblage Zone established at Red Moss (Hibbert *et al.*, 1971). The pollen evidence Tooley (1978,pp.65-67) describes comprises just one level for the whole peat horizon. In a coastal peat, the pollen assemblage will vary largely in response to fluctuations in the water table rather than just the regional pollen rain. Therefore, immediately after or on the approach to a marine contact, the proportion of open habitat taxa will be high as the salt marsh front recedes landwards (Godwin 1978, Long 1991). Godwin (1978) and Shennan (1980) have discussed how alder and oak frequencies vary through an intercalated peat, with alder values dropping towards contacts as the watertable rises. To decouple regional and local influences on a coastal peat pollen assemblage, and therefore to reject a date on the basis of pollen evidence, a succession of levels is required and this is not the case for the lower peat at Nancy's Bay-10. Further, the accepted date for the transgressive overlap in this peat is from a sharp contact (Tooley, 1978). Data from this period in North Wales may help resolve some of these problems.

In North Lancashire therefore, the early Holocene was characterised by periods of rapid sea-level rise and short periods of sea-level stagnation, or perhaps fall (Tooley, 1978). Rates of sea-level rise approaching 44 mm yr^{-1} have been calculated by Tooley (1989), but here some questions about one of the data points central to this calculation have been made. This important issue is considered more fully in Chapter 6.

At Nancy's Bay the organic horizons sampled during the lithostratigraphic survey were shown to be widespread over the site (Tooley, 1978). An organic horizon was sampled at *c.*-2.5 m OD in eight cores and the ^{14}C-data from this horizon have just been discussed. This lowest organic horizon is overlain by a fine grey clay approximately 1 m thick. A second organic horizon was recorded at *c.*-1.0 m OD, and in Nancy's Bay - 10 was described as a well humified, monocot. peat with some *Phragmites*. Two ^{14}C-dates were obtained from this horizon: the regressive overlap was dated to 5880±180 BP and transgressive overlap to 6885±80 BP. Because of this age inversion the younger date was rejected by Tooley (1978).

Certainly the altitude of the sample is inconsistent with the age as indicated in Table 4.4. The peat is only 0.13 m thick and herb pollen, including saltmarsh indicators such as Chenopodiaceae and *Artemisia*, attain very high frequencies throughout. The date of 6885±80 BP on the transgressive overlap is therefore acceptable as a sea-level index point.

Sediments below OD at Nancy's Bay are largely clastic, separated by two thin organic horizons. In contrast, as is the case with so many sites within the region, sediments above OD have thicker and more extensive organic sequences. Between 6290 and 5775 BP, seven ^{14}C-dates were obtained from Nancy's Bay. Four of these dates are from regressive overlaps and three from transgressive overlaps.

In Chapter 6, the stratigraphy of Nancy's Bay will be compared with Hendre fawr in North Wales. At this stage, however, it is useful to make some observations about the data from the sediments above OD at Nancy's Bay. In Fig.4.2 the lithostratigraphy from Nancy's Bay - 6 for the period in question is shown.

This very complex stratigraphy shows short-lived marine transgressions, separated by periods of brackish- and freshwater sedimentation (Tooley 1978). Tooley (1978) has not tried to distinguish the 'transgressions' and 'regressions' identified in strata 2 to 5, and this would seem sensible. The whole period seems to be characterised by very subtle changes in sedimentation with respect to the organic content of the sediments. Clays are recorded in stratum 5 and 8, for example, but the organic content is always at least 25%, indicating that open marine conditions never persisted at Nancy's Bay between 6290 and 5775 BP.

All of the seven ^{14}C-dates from the period 6290 to 5775 BP have been shown by Tooley (1978) to have formed at, or close to MHWS. All are accepted as sea-level index points as indicated in Table 4.4.

A withdrawal of marine conditions is indicated throughout sites across the Fylde around 5000 BP. There are four ^{14}C-dates marking this withdrawal; three from the Lytham area and one from Peel on the north of the Fylde.

Lab code	Age (BP)	Alt. (m OD)	Site
Hv 3845	5005±45	+3.09	Lytham
Hv 2919	4960±210	+3.39	Lytham
Hv 4344	4895±95	+2.87	Lytham Moss
Hv 3933	4800±75	+2.24	Peel

The effects of this withdrawal were widespread:

> *"The Lytham-Skippool valley was evacuated of water, and the western Fylde ceased being an island after a period of 1700 years: marine sedimentation ended throughout Lytham Moss and most of Lytham Common, and subsequent transgressions were recorded directly in Lytham Hall Park, a limited area to the southwest of the Park, and northern end of the Lytham-Skippool valley". (Tooley, 1978,p.111).*

At Lytham Moss, a *Phragmites* peat was recorded upon a blue clay. At this regressive overlap, which was dated to 4895±95 BP, Gramineae, saltmarsh indicators including Chenopodiaceae, and aquatic pollen were recorded. Shortly afterwards, this assemblage was replaced by one dominated by Sphagnum. A succession from middle marsh, through to upper marsh and finally to raised bog is therefore indicated at Lytham.

Summary

The 12 m thick Holocene sediments from the coast of North Lancashire have produced a long and full record of sea-level changes. These sediments have been analysed by Tooley (1974, 1978) where the Lytham chronology of sea-level changes was presented. In this section the Lytham scheme has only been mentioned briefly because it was later re-evaluated by Tooley (1982) when a chronology of sea-level tendencies was presented. This chronology is discussed more fully in Chapter 6.

4.4.3 Morecambe Bay.

Morecambe Bay is bounded to the south by the Fylde and Pilling Marshes. To the north is the Lake District from which several rivers drain into the Bay, forming three main estuaries. In the north are the Leven and Kent estuaries and in the east of the Bay, just to the south of Lancaster, is the Lune estuary. The Bay itself is approximately 20 km across and at low tide extensive sand flats are exposed stretching across the Bay, pierced by channels originating at the main river mouths.

Lithostratigraphic information and ^{14}C-dates have been collected from within the Bay, as well as from the mosses adjacent to the Bay and within the northern river valleys. Those dates that have been collected from within the Bay have been termed 'offshore' dates and come largely from the Leven estuary.

^{14}C-dates from Morecambe Bay are characterised by large differences in altitude between onshore and offshore dates. In general, for comparable periods, offshore dates are comparatively deeper than those onshore. Palaeotidal changes through the Holocene have been put forward as a possible, or partial, explanation for this phenomenon. Terrestrial organic sediments found in the centre of the Bay demonstrate the extent that its morphology will have changed through time, and this will have had some effect on tidal patterns (Devoy, 1987). Today there is variation in tidal ranges at tide stations around the Bay, but these are relatively small and certainly not sufficient to explain anomalies in the distribution of ^{14}C-dates. MHWS, for example, attains higher values at tidal stations in the northwest of Morecambe Bay: +4.75 m OD at Barrow, compared with +3.90 m OD at Arnside on the east of the Bay.

The materials from which the offshore dates were established in the Leven estuary came from the Morecambe Bay Barrage feasibility survey, and those from Heysham Harbour were obtained from the site of the nuclear power station. The stratigraphic relationships of these samples are shown in Tooley (1974) who notes that the peats were encountered in these boreholes at heights ranging from -11.13 m to -17.60 m OD. These peats were typically hard, consolidated and laminated, and were overlain by inorganic sediments of marine origin (Tooley, 1974; Zong, 1993), and underlain by varved clay deposits. The inorganic sediments were in many cases sands containing shell fragments of *Cerastoderma edule*, the common cockle, or valves of *Mytilus edulis*, the common mussel (Tooley, 1974).

The eight offshore dates are reported in Shotton and Williams (1971), Tooley (1974), Huddart *et al.* (1977) and Zong (1993), and classified in Table 4.5. Pollen analysis completed on five of the samples (Huddart *et al.*, 1977) confirmed that the ^{14}C-dates were from the Flandrian-I chronozone. Additionally, on three of the samples rising watertables are indicated by the replacement of aquatic taxa by saltmarsh communities of Gramineae, *Plantago maritima, Aster*-type, *Armeria* and Chenopodiaceae (Tooley, 1974). For the other two samples only one spectrum pollen diagrams were produced so the possibility of rising watertables cannot be rejected. Diatom analysis was completed on the cores from the Leven estuary (Zong, 1993). In the clastic sediments above the peat, marine and marine-brackish planktonic diatoms were dominant. Taken together Tooley (1974) states that between 8925±200 and 7995±80 BP these data confirm Morecambe Bay was being transgressed consequent upon a rise of sea-level from *c.* -20.0 to -15.0 m OD. Zong (1993) has classified these three offshore dates as transgressive overlaps, though four of the dated samples were collected from the middle of peat beds as indicated in Table 4.5.

Twenty-two further dates have been collected from the Morecambe Bay area (Table 4.5). The details with respect to these dates have been recently presented in full by Zong (1993), and therefore do not need repeating here. Four dates are rejected altogether: a date at Lousanna because of its very large standard error (±450 ^{14}C-years), and those at Silverdale Moss because of age-inversions. Based on the analysis of all ^{14}C-dates from Morecambe Bay, Zong (1993) has identified seven periods of both positive and negative tendencies using the method of Shennan *et al.* (1983). It was noted that seven periods of negative tendency in Morecambe Bay were not consistent with the lithostratigraphic record and the inconsistencies were explained by the interpretation of eight of the sixteen regressive overlaps as representing periods of a reduced rate of sea-level rise, for example, when a saltmarsh peat forms in association with a rising groundwater table. A further category of tendency, 'probably positive tendency', representing periods when the rate of sea-level rise slowed enough for organic sedimentation to begin, was therefore introduced (Zong, 1993) and led to the development of the chronology presented below. This modification recognises the arguments of Streif (1978) and Kidson and Heyworth (1976) that the conditions most favourable for the formation of regressive overlaps are with a slowly rising sea-level. It should be noted that Shennan *et al.* (1983) only interpret positive and negative tendencies as a relative increase or decrease in the marine influence respectively, which does not necessarily imply rises or falls in sea-level.

Sea-level tendency model 2 for Morecambe Bay
Source: (Zong, 1993).

Period One (RR): Rapid Rising.

RR1: 10000 - 8750 BP. Very rapid rise to -17.0 m MHWS.
RR2: 8750 - 8100 BP. Slower rate of sea-level rise. *c.*2.5 mm/yr.
RR3: 8100 - 7800 BP. Rapid rise.

Period Two (FR): Fluctuating Rising.

FR1: 7800 - 6800 BP. Continuously rising sea-level with fluctuations. Rates between 3.5 and 1.5 mm/yr.
FR2: 6800 - 5800 BP. Slight rise, then fall of sea-level (*c.*-0.5 mm/yr)
FR3: 5800 - 5150 BP. Continuously rising sea-level with fluctuations. Rates between 4.0 and 2.5 mm/yr.
FR4: 5150 - 4150 BP. A rapid rise (*c.*7.0 mm/yr) until 5000 BP, followed by a fall after 4800 BP.
FR5: 4150 - 3500 BP. A rise, then fall of sea-level.

Period Three (SF). Small scale fluctuations.

Details unknown.

This chronology is compatible with the sea-level curve presented by Zong (1993), but there are some anomalies with the results from the tendency analysis. Between 5200 and 5000 BP a negative tendency has been established, yet in the corresponding periods (the end of FR3 and start of FR4) a rapid rise in sea-level has been described. Again, on the tendency plot a probable positive tendency is established between 4900 and 4500 BP, yet in FR4 after 4800 BP a fall in sea-level has been described.

Shennan (1989) makes a clear distinction between onshore and offshore ^{14}C-dates collected from Morecambe Bay. The former show an exponential decline in uplift during the Holocene, which has been approximately linear for the last 6000 years at 0.35±0.12 mm/yr (Shennan, 1989). However the offshore dates on a graph of residual crustal movements plot well below the onshore dates (*c.* 10 m) and indeed if the offshore dates were considered in isolation relative stability would have to be inferred for Morecambe Bay during the Holocene.

In an analysis of sea-level data from the North Sea region and northwest England Shennan (1987) noted that curves from uplifted areas reveal consistently low uplift values between 8500 and 8000 ^{14}C-years BP. The offshore dates from Morecambe Bay and those from the Starr Hills, Lancashire, exemplify this statement. Shennan (1987) adds that this is a difficult period from which to obtain precise time and altitude fixed points because of very rapid changes in the modelled eustatic curve (Shennan, 1982b, 1987) so that slight shifts in the time factor could lead to very low residuals. Despite these problems, the consistent differences observed between the onshore and offshore data within Morecambe Bay do point to distinctive and separate crustal histories. Accordingly Zong (1993) has not drawn a single sea-level curve for the region, making separation between the offshore and onshore data. The apparent 10 m offset in the offshore dates relative to the onshore dates, primarily from the north of the Bay, is explained by Zong (1993) as a combination of three localised factors:

(1) Localised glacio-isostatic uplift in the north of the Bay from the Lake District Ice-cap.

(2) Palaeotidal changes.

(3) Sediment loading and hydro-isostasy in the early Holocene.

Zong (1993) argued that shallow waters upon a relatively flat topographic surface in the 8th - 9th millennium would result in a lower tidal range than at present. Consequently MHWS would be lower and hence sea-level index points from this period artificially low in altitude.

Arguments of residual uplift in northern Morecambe Bay because of the Lake District Ice-cap are less plausible. The distance from the onshore to offshore sites is less than 10 km and ice in the Lake District had disappeared by 14500 BP. Uplift following deglaciation will follow an exponential decay pattern (Andrews, 1970), and with a small ice-cap such as that in the Lake District the recovery period is short.

The main distinction between the two sets of dates for Morecambe Bay is that they are from onshore and offshore localities, rather than their relative positions in terms of latitude and longitude. Hence the explanation for the differences lies in factors such as palaeotidal changes, hydro-isostasy, sediment loading and compaction with perhaps a very real rapid rise in sea-level after c.8000 BP which is not satisfactorily modelled in the eustatic curve used in the analysis of Shennan (1989) and Zong (1993).

<u>**Summary**</u>

The data from Morecambe Bay show that the registration of relative sea-level changes in the area has been complex. This may be due to the imposition that the geography of the Bay has made on available sampling locations. Sites that have yielded litho-, bio- and chronostratigraphic data vary from open water sites in the Bay itself to protected locations in river valleys of the Leven and Kent, such as Roundsea Wood and Helsington Moss.

The comparison of onshore and offshore dates is difficult because there is no overlap in their respective time spans. The offshore dates come from much deeper and older material, and until sediments of comparable age are sampled, the full extent of the variability cannot be quantified. Investigations of this sort are underway in the Heysham area (Tooley, pers. com.).

One of the most prominent features of the Holocene stratigraphy around Morecambe Bay is the withdrawal of marine conditions, when extensive areas of tidal flat were colonised by *Phragmites*, *Scirpus* and *Juncus*, and finally by alder/oak fen. Tooley (1987) has noted the coincidence of this event with the elm decline in Britain and speculated that the contraction of the Bay in the mid-Holocene may be due to a fall in sea-level, or perhaps a massive input of sediment. In Morecambe Bay the elm decline has been placed within the range 5435-4810

BP (Tooley, 1987). The effects of forest clearances during this period could increase soil erosion and hence lead to an increased sediment supply into the Bay.

4.5 Cardigan Bay.

Sea-level curves have been produced for Cardigan Bay by Wilks (1977), Kidson and Heyworth (1978), and Heyworth and Kidson (1982). All three curves show a smoothly rising sea-level, with decreasing rates of rise towards the present producing a curve exponential in form (Kidson and Heyworth, 1978), akin to the curves produced by Dutch workers for the Netherlands. The very different form of curve produced for Cardigan Bay compared with Lancashire, where oscillations are included, is due to the different interpretation of intercalated organic and inorganic sediments by respective workers.

Most of the ^{14}C-dates used to produce these curves come from sites in or adjacent to the Dovey estuary: Clarach, Ynyslas and Borth Bog. Prince (1988) has collected very early Holocene samples from Harlech, and Heyworth and Kidson report an early Holocene date from offshore on the southern side of Cardigan Bay. These dates have been classified and tabulated in Table.4.6.

Cardigan Bay indents the west Wales coastline between the Lleyn peninsula and St David's Head. Holocene sediments that have been recorded from around Cardigan Bay have largely been confined to the river estuaries that drain into the Bay near Portmadoc, Barmouth and Aberdovey. The tidal range within Cardigan Bay is lower than along the north and south Wales coasts. The mean spring tide range at Aberystwyth is 4.3 m, compared with 5.0 m at Holyhead and 8.4 m at Liverpool to the north and 6.3 m to Milford Haven to the south.

The four ^{14}C-dates collected by Prince (1988) from Harlech constitute some of the oldest and deepest material dated for sea-level investigations in the UK.

SRR 2502 10080±50 BP -47.55 to -47.43 m OD Group 4b

SRR 2641	**9900±60 BP**	**-47.12 to -46.71 m OD**	**Group 4b**
SRR 2640	**9750±70 BP**	**-46.71 to -46.31 m OD**	**Group 4b**
SRR 2501	**11200±110 BP**	**-45.81 to -45.29 m OD**	**Group 4b**

Apart from the upper date (SRR 2501) they are in stratigraphic sequence. All four samples are from blue-black organic clays, overlain by silts and sands containing shell fragments. Though some arboreal pollen types were present, the pollen assemblage associated with these samples was dominated by Cyperaceae, and Prince (1988) points out that no recognisable glacial deposits were found and that the foraminiferal and ostracodal assemblages were unlikely to be pre-Holocene.

The indicative meaning of these samples is less certain. From the pollen evidence Prince (1988) deduces that the samples formed just below MHWS and that the lithostratigraphy points to a deep channel deposit formed in response to a rapidly rising sea-level. If, for example, one of the samples had formed at MHWS, under a rapidly rising sea-level the position of MHWS would have shifted horizontally making it unlikely that the other three samples could have formed under the same conditions. Additionally, under such circumstances distinctive changes in sedimentation must occur and yet all the samples come from blue-black clays with no major changes in pollen or diatom composition throughout. These inconsistencies mean that these dates must be classified in group 4b, and are reinterpreted here as representing sub-tidal deposits, and therefore representing the minimum sea-level for the very early Holocene in central Cardigan Bay.

The largest and most intensively studied estuary in Cardigan Bay is the Dovey, located 10 km north of Aberystwyth. Steers (1964) has described that in this coastal area the peneplain formed during the Tertiary Period and that later uplift and down-cutting ensued. The area has subsequently been glaciated and the form of east-west valleys will have been modified by glacial erosion and deposition.

Wilks (1979) has described the typical lithostratigraphy on the south side of the Dovey estuary. Intertidal clays underlie the whole area beneath *c.*-0.50 m OD. Inland at *c.*5150 BP, these clays were overlain by a *Phragmites* peat, passing up into a woody peat and in some areas into raised bog. On the coast the estuarine clays outcrop along with *in situ* tree stumps of pine and oak. Heyworth and Kidson (1982) note a gentle gradient of about 2.00 m in 5 km in the altitude of the tree stumps from the lower northern end to the higher southern end and a corresponding decrease in their age from *c.*5400 BP to *c.*3900 BP. Wilks (1979) has interpreted this lithostratigraphy in terms of a barrier migrating northwards reducing the marine influence in the estuary and hence the formation of a regressive overlap. As the rate of sea-level rise was reduced in the later Holocene, the rate of sedimentation was periodically greater than the rate of rise of sea-level; hence when the barrier disintegrated terrestrial sedimentation continued (Wilks, 1977). Claims of a regressive overlap 6 km north at Clarach similar to that at Borth in terms of age and altitude (Taylor, 1973) would throw doubt on Wilks's (1979) hypothesis of a barrier causing the regressive overlap in the Dovey estuary because of apparent regional significance. However, Wilks (1977) has shown through diatom and micro-faunal analysis that the clays at Clarach are freshwater in origin, and not marine as claimed by Taylor (1973).

At Clarach Bay, Heyworth *et al.* (1985) have shown that after *c.*6000 BP sea-level changes were the dominant influence on sedimentation at the site. At the site, sedimentation took place under essentially freshwater conditions, but the diatom and pollen evidence points to variations through the sediment column in the marine influence (Heyworth *et al.,* 1985). These sediments recorded at Clarach Bay are akin to those of the perimarine zone described by Hageman (1969). Hence the ^{14}C-dates from Clarach represent the maximum level of the sea without being so far removed from the marine influence so that a raised bog develops.

Though Heyworth *et al.* (1985) state that there are salinity variations through the sedimentary column, these variations are in general small. In all levels fresh and fresh-brackish diatom frustules account for at least 60% of the total diatom sum, and fresh species always account for *c.*30% of the sum with very little variability. However, there were variations in the quantity and type of marine and brackish species which have been used to corroborate the ^{14}C-dates. An example is given below.

At -1.22 m OD, a ^{14}C-date of 5170±90 BP was obtained (Har 300) on a marsh peat. Below this sample marine species were absent and the paucity of identifiable species suggested the diatoms present were largely allochthonous (Heyworth *et al.*, 1985). The ^{14}C-dated sample was taken at the lithostratigraphic switch to marsh peat, where also the number of diatom species increases including the presence of low quantities of marine species (Heyworth *et al.*, 1985). In Table 4.6, therefore, this date has been assigned Group 2 status.

Kidson and Heyworth (1978) present a synthesis of the data from Cardigan Bay with respect to relative sea-level changes. Before *c.*5000 BP, sea-level rise they state was rapid so that peat formation was limited to widely separated and brief periods. After *c.*4000 BP sedimentation was in equilibrium with the slower rate of sea-level rise at ever decreasing rates but approximating a smooth exponential decay curve. Given such a model, then the variability in the marine influence described at Clarach Bay and in the Dovey estuary would be attributable to variations in sediment accumulation. Wilks (1979) does state that variations in sea-level rise are possible but their confirmation awaits techniques of analysis producing higher resolution.

Summary

Cardigan Bay is distinct in many ways from the areas further north which have received attention in this chapter. There is no evidence, for example, of uplift during the Holocene, and estimates even suggest minor subsidence (Shennan, 1989).

In terms of this research, examining the work completed in Cardigan Bay has been particularly instructive, because of the alternative explanations offered to explain the formation of intercalated sediments in coastal areas, compared with those who have carried out recent investigations further north. The most systematic work to be carried out in Morecambe Bay during the last two decades has been completed by Zong (1993), and earlier by Tooley (1974). In Lancashire the work of Tooley (1969, 1974, 1978, 1982) represents the most complete analysis.

The methodology adopted by these workers has been developed from the work of Sir Harry Godwin, notably Godwin (1940a, 1943, 1945), and later developed at Durham (Tooley, 1974, 1978, 1982; Shennan, 1980; Shennan *et al.*, 1983). Godwin accepted the strong possibility of a fall or 'regression' of sea-level in the Fenland during the Holocene, "...When the Fen Clay marine incursion had reached its greatest extent and the lagoonal clays extended to within a very short distance of the surrounding uplands, a phase of constancy, or more likely of regression of sea-level led to widespread formation of fresh-water peat above the Fen Clay surface" (Godwin 1978,p.68). Those working in Cardigan Bay have taken an alternative approach to explain such lithostratigraphic features: "...There seems little reason to invoke oscillations in sea-level (of magnitude less than that of storm surge events) to account for any other transgressive or regressive features observed" (Kidson and Heyworth, 1978,p.749).

4.6 Conclusions.

In order to assess relative sea-level changes and crustal movements in North Wales it is necessary to make comparisons with changes in adjacent areas. In this chapter therefore, data from the west coast of Britain between St.David's Head in west Wales and Morecambe Bay in Cumbria have been examined. The ^{14}C-dates from these coastal areas have been scrutinised and a list of acceptable dates has been presented in Tables 4.1 to 4.6. Those ^{14}C-dates that have been accepted as sea-level index points will be used in the analysis completed in subsequent chapters.

Chapter Five.

Field and Laboratory Results.

5.1 Introduction.

In this chapter results from the lithostratigraphic and biostratigraphic surveys in North Wales and the Wirral are presented, along with the results from seismic refraction surveys at Newton Carr.

The lithostratigraphy from ten sites has been examined and these are grouped into four areas; the Malltraeth Marshes on Anglesey, the Afon Ganol valley between Rhos-on-Sea and Llandudno Junction, the Clwyd coastal lowlands and north Wirral (Fig.1.1). The methodology and overall scheme of data collection has been fully explained in Chapter 2, while in this chapter the reasons for individual site selection are discussed.

For each of the major sites (where palaeobotanical work or ^{14}C-dating has been carried out) there is a description of the lithostratigraphic, diatom and pollen data followed by a short synthesis of environmental changes that have occurred at the site during the Holocene. The associated diagrams are referred to in the text, with a key to the lithostratigraphic plots to be found in Appendix 8 at the back of Volume II. Two types of map are presented; a simple plot showing the locations of the boreholes at each of the sites, and also colour maps from the Ordnance Survey 1:25,000 series to provide a suitable geographical context for the sites.

5.2 ANGLESEY.

The Malltraeth Marshes are the largest area of marine alluvium in Anglesey, forming an area of wet marshy pasture. The marsh is partly artificial, following reclamation which began in 1788 (Steers, 1964) when a dam was built across the mouth of the marsh and the Afon Cefni was straightened and embanked. The marsh has a southwest to northeast trend, parallel to the Menai Strait between Caernarfon and Bangor, and is approximately two kilometres wide. The sites that have been investigated lie at the northeastern end of the marsh, about ten kilometres from the sea. This southwest corner of Anglesey is dominated by sand dunes; to the north of Malltraeth Bay are dunes at Aberffraw and to the south the dunes of Newborough Warren. At the mouth of the Afon Cefni is an extensive area of sands, the Malltraeth Sands, which are flooded at high tide.

The results from the boreholes carried out by Prince (1988) indicated that west of the A5 on the Malltraeth Marshes organic sediments were rare. This conclusion was confirmed by discussions with workers clearing out the marsh ditches on a field visit. One of the main objectives of lithostratigraphic work on the Malltraeth Marshes was to sample organic material suitable for radiocarbon dating. Hence it was decided to concentrate the stratigraphic investigations in the upper part of the marsh, east of the A5.

Three sites were examined, Llanfawr, Llangefni and Tregarnedd-bâch, in May and June, 1990 and June, 1991 (Fig.5.1 and 5.2a). Of these, Tregarnedd-bâch proved the most suitable for further investigation bearing in mind the objective of sampling deep organic material.

Lithostratigraphic and biostratigraphic data from the three sites investigated are presented below.

5.2.1 **Llanfawr**

After the completion of four hand-cores at Llanfawr (Fig.5.2a) it became apparent that organic sediments were scarce at the site: hence the stratigraphic investigation was abandoned. The data are, however, presented in Appendix 5, describing a series of silt and silty-clays resting on top of a coarse orange sand base.

5.2.2a **Llangefni**

Six hand cores were completed at Llangefni in a northeast to southwest transect, complementing the transect across the Malltraeth Marshes at Tregarnedd-bâch. The location of cores is shown in Fig.5.2b and the resulting lithostratigraphy in Fig.5.3 (The key to this and further lithostratigraphic plots can be found in Appendix 8). Core L1 is taken 20 m in from the edge of the marsh, and L6 200 m further on in the centre of the valley. The steep gradient of an impenetrable surface between L2 and L4, dropping nearly 6 m in only 60 horizontal metres, is clear in Fig.5.3. The deepest core (L4) reaches 7.20 m below ground surface, the same as the deepest recorded sediments at Tregarnedd-bâch.

The unconsolidated sediments at Llangefni were recorded upon an impenetrable grey silty sand-base. The deepest unconsolidated sediments recorded were from -4.81 m to -4.71 m OD, in L4, as a dark brown compact humified peat with small amounts of *turfa*. Only 0.10 m of this stratum was sampled, so it was unclear what lay beneath this horizon. From this bottom peat there was a gradual transition into a grey clay with *turfa* and some *Phragmites*. This stratum had an organic content of >25%. This deep organic deposit, presumably a basal peat, was only fully recorded in L4, though in L5 a silty-clay with some humified *turfa* was recorded between -4.32 and -4.19 m OD.

Overlying this deep organic deposit was a suite of inorganic sediments. The deepest of these were silty-clay horizons found below approximately -2.00 m OD in L4 and L5. In L5, this was recorded as a dark grey silty-clay with shells including *Scrobicularia* from -4.19 to -1.81 m OD, and in L4 as a dark grey silty-clay immediately above the basal organic deposit with a gradual transition into a grey silt with shells from -2.81 m to -1.73 m OD. In L4, the shells which include *Scrobicularia* were well preserved, but concentrated at -1.91 m and -2.14 m OD. The other four cores at Llangefni reached no deeper than -2.0 m OD; hence these deep, fine-grained, inorganic sediments were not recorded in other cores.

With the exception of L3, within an altitudinal window of -2.00 m to +1.50 m OD, coarse grey sands and silts were sampled. This unit was recorded to a maximum depth of -2.40 m OD in L6 as a coarse grey sand, where it also proved impenetrable. In L5 and L4, this stratum overlay silty-clays and was recorded as a coarse grey sand and grey laminated sand with a small fraction of silt (<25%) respectively. In L4, 5 and 6, this grey sand was overlain by grey sandy-silts which were slightly laminated and became finer towards the top of the stratum with some iron-staining. In these three cores the altitudinal window for this stratum was +1.17 m to +2.14 m OD. In L1 and L2 from +0.95+/-0.10 m OD to +2.1+/-0.05 m OD minerogenic sedimentation had also taken place. In both cores there was a pronounced fining upwards from laminated grey sandy-silts near the base to grey, iron-stained silty clays at the top of the stratum. Here, therefore, near to the edge of the area of Holocene deposition, inorganic sediments were much finer than in L4, 5 and 6.

In L3, from -1.12 m to -0.10 m OD, sand with silt was deposited as was the case with other cores at the site. Above this altitude, however, the nature of sedimentation differs somewhat. From -0.10 m to +0.63 m OD was a gravel deposit with some silt and sand overlain by a partially humified *turfa* with some clay (+0.63 m to +1.85 m OD).

This partially humified peat merged into a very fresh *turfa* with *Phragmites* which extended to the surface. Towards the centre of the valley in L4 - L6, this surface peat became slightly crumbly with a very small clay fraction. There was a consistent thinning of this surface peat from L1 to L6 from 0.61 m in L1 to 0.12 m in L6.

The surface altitude of cores at the site ranged from +2.74 m OD in L1, to +2.28 m in L3. The altitude of the cessation of inorganic sedimentation varied by only a few centimetres over the whole site: therefore, the variation in surface altitude reflected the thickness of the surface peat.

No biostratigraphic analysis was carried out at Llangefni. Instead, pollen and diatom analysis were attempted at Tregarnedd-bâch, where a more extensive lithostratigraphic survey was possible.

5.2.2b **Llangefni: Summary of the lithostratigraphy.**

1. The unconsolidated sediments at Llangefni were deposited upon an impenetrable grey

sandy base.

2. A dark compacted peat was recorded between -4.81 m and -4.91 m OD.

3. Between -4.70 m and -2.00 m OD grey silty-clays with *Scrobicularia* shells were recorded.

4. Coarse grey sands were recorded between -2.00 m and +1.50 m OD.

5. Fresh *turfa* of variable thickness was recorded at the surface at Llangefni.

5.2.3a **Tregarnedd-bâch, transect**

The lithostratigraphy of a transect taken across the width of the Malltraeth Marshes from SE to NW at Tregarnedd-bâch, east of the A5, is illustrated in Fig.5.4 and the location of these cores in Fig.5.1 and 5.2b. Sixteen hand cores were completed at this site with the objective of establishing the nature of the gross lithostratigraphy of the upper Malltraeth Marshes, and also looking for deep organic material suitable for radiocarbon dating. Two piston cores were taken for palaeobotanical work and ^{14}C-dating at TB18 and TB29.

At the base of most cores was a grey or orange/brown sandy-gravel which was impenetrable with a hand-corer. This surface dipped quickly in a south easterly direction between TB1 and TB5, then rose gently between TB5 and TB12.

The deepest sediments definitely of Holocene age were organic and were manifest as very compact brown, slightly red humified peat in TB4, 5, 6 and 18, and an organic clay in TB8. This basal peat had an altitudinal range of -4.42 m to -3.15 m OD with a maximum thickness of 0.17 m in TB5. In the deepest cores (TB5, 6 and 17), the peat was thickest. In TB4, beneath the humified brown peat was a 0.04 m piece of wood, then 0.14 m of organically enriched silty-clay before the sandy gravel was reached at -3.51 m OD. In TB7, between -3.68 and -3.73 m OD was a piece of detrital wood which was probably oak.

These deep organic sediments were overlain by dark and battleship-grey silty-clays. For the purposes of describing the lithostratigraphy of these and some of the above inorganic layers it is convenient to split the transect into two sections at the natural break in sampling between TB9 and TB10.

Starting with the northwestern cores TB1 - TB9, the silty-clays had an altitudinal range of -3.89 m OD in TB6, to -0.57 m OD in TB7. Shells, including *Scrobicularia,* and *Phragmites* with humification values of 2 or 3 were consistently found in this stratum. In TB4, there was at least 25% *Phragmites* from -3.25 m to -2.75 m OD within the grey silty-clays overlying the basal peat.

In TB1 to TB9, the relatively fine grained silty-clays were overlain by grey laminated sands with a small silt component and some shells. In TB5, it was noted that shell frequencies increased towards the base of the stratum. The altitudinal range of this stratum was from -2.23 m to +0.36 m OD. These laminated sands were deepest and thickest in TB4, but at the base of this stratum in TB4 was a unique coarse gravel deposit with abundant *Scrobicularia* and other shells from -2.23 m to -2.31 m OD. With the exception of TB9, there was a very slight fining upwards of this stratum (in the form of an increased silt:sand ratio), especially noticeable towards the northwestern edge of the valley.

In TB10 to TB15, below approximately 0.00 m OD, as with the northwestern end of the transect inorganic sedimentation dominated, but here the sediments were considerably finer (clay and silty-clays). Also at the base of TB11 and TB12 between -1.78 m and -1.33 m OD was substantial organic enrichment of the clays in the form of partially humified *turfa* and *Phragmites*. At this altitude in other cores there was a negligible organic component.

Between approximately 0.00 m OD and +1.80 m OD the sediments were dominated, though not completely, by silt-clay sediments with *Phragmites* roots. Variations to this pattern were in the form of silty-sand accumulations and organic horizons. A thin organic horizon was recorded in six cores across the transect at an altitude consistently in the range of +0.95 m to +1.52 m OD and a maximum thickness of 0.24 m. It was typically recorded as a brown humified peat with some *turfa* and clay (TB1). In TB5, the clay content was recorded as

50%, but in the other five cores was < 25%. In the cores where this organic horizon was recorded it was flanked above and below by silt-clays whereas in those where it was not recorded there was typically a 25% sand component in the sediments, for example TB3, 4 and 7. At the southeastern extreme of the transect (TB12 to TB13), in the altitudinal range +0.55 m to +1.78 m OD a buttery silty clay with >25% *turfa* or *Phragmites* along with alder and birch fragments was recorded.

In TB1 from +1.19 m to +1.55 m OD, and TB2 from +1.03 m to +1.32 m OD, was a very coarse, grey, laminated sand. In TB2, this stratum had a very sharp upper contact with a light brown organic silty-clay above. The organic silty-clay was also present in TB1 and TB3.

The surface sediment across the whole site at Tregarnedd-bâch was a thick, fibrous, very fresh *turfa*. This stratum attained a maximum thickness of 1.23 m in TB2, and was never less than 0.50 m (TB5) thick. In TB9, there was clay enrichment of the peat, but this was very localised.

The surface altitude ranged from +2.78 m to +3.51 m OD. As at Llangefni, the altitudes were lower in the centre of the valley.

5.2.3b **Tregarnedd-bâch, grid**

A brown humified peat with some *turfa* was noted between +0.95 m and +1.52 m OD in six cores along the Tregarnedd-bâch transect. A grid of nine cores (3 x 3, with a 30 m spacing) was completed to assess the spatial extent of this organic horizon to see whether it was a suitable horizon for radiocarbon dating (Fig.5.5). Additionally further information on the nature of sedimentation at the edge of the valley was obtained from this investigation.

Table 5.1.
Stratigraphic details. Tregarnedd-bâch grid.

Stratum	Components	Alt. range (m OD)	Cores	Characteristics and Anomalies
1	As2,Ag2 Th(*Phrag*)+	*c.*-1.0 to +1.0	6/7	Coarser in TB26. Finner at top of stratum.
2	Sh2,Dl1,Th1	*c.* +0.80 to +1.20	5/7	A *limus* component in TB24, 27.
3	Ga2,Ag2	*c.* +1.1 to +1.4	5/7	Slightly laminated
4	As3,Ag1	*c.* +1.2 to +1.6	5/7	Coarser in TB26. High *Phragmites* component. Wood in TB21.
5	Sh2,As1,Th1	*c.* +1.45 to +2.0	9/9	Organic clay, sometimes with a *limus* component.
6	Th3,Sh1	*c.* +1.75 to +2.7	9/9	Fresh *turfa*.

The overall characteristics of the lithostratigraphy at Tregarnedd-bâch, in terms of pattern, altitude and composition, have already been described in 5.2.3a. Hence results from the grid of cores have been simply tabulated above in Table 5.1.

5.2.3c <u>Tregarnedd-bâch: Summary of the lithostratigraphy.</u>

1. Basal peats have formed at Tregarnedd-bâch between -4.42 m and -3.15 m OD.

2. Between -3.15 m and +1.00 m OD inorganic sedimentation dominated in the form of silty-clays. In the centre of the valley, between -2.00 m and 0.00 m OD, sands with silts have accumulated.

3. A thin, humified organic horizon was recorded across most of the site between +1.00 and +1.50 m OD, though this horizon was more prevalent towards the margins where it merged into the surface peats.

4. A very fresh surface *turfa* was recorded across the whole site up to 1.20 m thick.

5.2.3d **Tregarnedd-bâch - 18: Diatom Analysis.**

Fifteen samples from stratum 3-6 were prepared for diatom analysis. No diatoms were found in any of these samples.

5.2.3e **Tregarnedd-bâch - 18: Pollen Analysis.**

Eight samples were prepared for pollen analysis from stratum 2 and 3. Pollen was extremely rare in these samples: hence it is not possible to construct a pollen diagram. A count of 20 TLP was completed at 675 cm to confirm that saltmarsh conditions were prevalent at this level. The following taxa were identified.

Pinus	2
Ulmus	2
Quercus	4
Alnus	1
Gramineae	7
Cyperaceae	1
Chenopodiaceae	1
Aster-type	1

5.2.3f **Tregarnedd-bâch - 29: Diatom Analysis.**

Ten samples were prepared for diatom analysis from stratum 1, but no diatoms were found.

5.2.3g **Tregarnedd-bâch: Synthesis.**

At Tregarnedd-bâch, and also at Llangefni, inorganic sediments dominate lithostratigraphic profiles. The deepest sediments sampled, along with sediments nearest to the surface, were organic, indicating at least two terrestrial phases of sedimentation at the sites. Evidence of a third terrestrial phase is apparent at Tregarnedd-bâch, where organic sediments are recorded at cores near to the margins of the marsh at an altitude of *c.* +1.00 m OD. The lithostratigraphic evidence from sites on the Malltraeth Marsh suggests that during the Holocene, marine conditions have been persistent, with three periods of terrestrial conditions of varying strength.

The deepest organic sediments were recorded as a dark brown humified peat with some wood and humified *Phragmites* remains. These sediments have accumulated upon a basal gravel surface, sometimes separated by a thin silty-clay. Transect 1 at Tregarnedd-bâch was made all the way across the marsh, and from this transect it is apparent that these deepest organic sediments are found where the valley is deepest, presumably where the Afon Cefni and the numerous local springs draining into the marsh would have passed through.

It should be noted that the lithostratigraphy at Llangefni and Tregarnedd-bâch is not typical of the lower Malltraeth Marsh. Evidence from Bont Farm and Ty'n-y-pwll Farm (Prince, 1988), where the Holocene sediments are dominated by silts and sands, suggests that the Malltraeth Marsh was dominated by an extensive area of tidal flat through the Holocene. For the most part, sediments at Llangefni and Tregarnedd-bâch are indicative of such an environment, but the basal and surface peats do confirm that their marginal location has led to a greater sensitivity to changes in sedimentation or fluctuations in relative sea-level than at sites on the marsh that are closer to the sea.

The basal peat recorded at Llangefni and Tregarnedd-bâch suggests that, during the period of its formation, the water table was rising gradually, ponding back the waters of the Afon Cefni and Afon Ceint. There is no evidence that the inorganic sediments recorded above the basal peat are derived from a fresh water environment. The shells of *Scrobicularia* are found throughout the sites, and the marsh has been shown to deepen westwards towards the sea.

5.2.4 North Anglesey.

Greenly (1919) and Hopley (1963) have noted ten exposed peat beds on the beaches of

Anglesey, including some on the north of the island. Hopley (1963) asserts that these peats, often found near the point of high tide, are of Flandrian II age, which is unusually old for such peats. A search was therefore made of the north island for these sediments. On the exposed coasts of the north and west at Porth Tywyn-mawr, Porth Trwyn, Cemlyn Bay and Cemaes Bay no peats were found. On the north-west coast in the protected bay at Traeth Dulas semi-organic sediments were found in the upper salt-marsh, but these had formed on an eroded silty-clay surface and therefore were not suitable for radiocarbon dating, so no further work was carried out.

5.3 THE AFON GANOL VALLEY

The location and extent of the Afon Ganol valley are illustrated in Figs.5.6 and 5.7. This narrow valley (approximately 5 km long) connects the mouth of the River Conwy near Llandudno Junction in the west with Penrhyn Bay at Rhos-on-Sea in the east. The broad characteristics of the lithostratigraphy in the western half of the valley have been briefly described by Arber (1984) from available engineering borehole records used in the construction of the A55 North Wales coast road. From this study it was shown that unconsolidated sediments persisted through the western portion of the valley from Mochdre to Llandudno Junction.

Such an extensive area of unconsolidated sediments, which had received limited investigation in the past, was worthy of close examination in this study. The palaeogeography of this site was, however, quite complex. A thorough analysis of the palaeogeography of the valley was necessary to provide a context for the litho- and biostratigraphic analysis attempted. Based on present day estimates, the effects of varying tidal ranges at either end of the Afon Ganol Valley would appear to be minimal. At Colwyn Bay, the nearest tide gauge station to the east, MHWS is +3.70 m OD, and at Conwy in the west, MHWS is +3.60 m OD. In the early- to mid Holocene the Great Orme to the north would have been an island, before sands were deposited in the depression where Llandudno now stands. This change in the geometry of the coastline will have had an effect on tides, as would the changing distribution of sand flats in Conwy Bay. Sands have formed within a dynamic system of west to east sediment drift and in the Conwy estuary do add an unknown quantity to the analysis of the unconsolidated sediments within the Afon Ganol valley.

Lithostratigraphic analysis was carried out at three sites in the Afon Ganol valley between May 1990 and August 1991. In May 1990, an exploratory transect of twelve cores was completed at Morfa Penrhyn in the northeastern end of the valley. A series of intercalated peats and clays was found including a basal peat at -2.00 m OD. A second transect was completed at the site in September 1990, which confirmed the spatial continuity of the basal peat and its suitability for ^{14}C dating. Fig.5.7 shows that Morfa Penrhyn is less than 750 m from the sea at Penrhyn Bay, the assumed entrance and exit for the sea at the site during the Holocene. Arber (1984) however, in his summary of the A55 borehole records, showed that the unconsolidated sediments in the southwestern part of the valley deepened in a westward direction from *c.*10 m below ground surface near Dolwyd to *c.*15 m below ground surface adjacent to the Conwy estuary. If, therefore, the whole Afon Ganol valley was one sedimentary system in the mid- to late Holocene, the results described by Arber (1984) imply that the entrance and exit for the sea was in the southwest and not in the northeast at Penrhyn Bay. If such a scenario were true, the interpretation of the lithostratigraphy at Morfa Penrhyn would be quite difficult because of the increased distance from the open sea and the implications this could have in estimating tidal range. Additionally the question of how representative the lithostratigraphy at Morfa Penrhyn was of the whole system was a concern. To understand the lithostratigraphic, subsequent palaeobotanical and ultimately ^{14}C data, these questions had to be addressed.

An obvious solution was to core on the Morfa Rhyd golf links to find the depth of Holocene sediments eastwards but this was not possible because of the coarse nature of these sediments. Experience from Newton Carr had also shown that seismic refraction results over such sediments are unreliable in gauging the depth to the pre-Holocene surface.

The following investigations were undertaken to try and resolve these questions:

1. A lithostratigraphic survey at Colwyn Bay Rugby Club, 1 km further west of Morfa Penrhyn. These investigations would help determine whether the palaeovalley was deepening

westwards.

2. An examination of the original borehole records completed to aid the design and building of the A55 trunk road through the Afon Ganol Valley. These records are held by the construction engineers: Travers Morgan and Partners in East Grinstead.

The lithostratigraphic investigations at Colwyn Bay Rugby Club showed that it was part of the same sedimentary system as Morfa Penrhyn. The borehole records indicated that there may be a bottleneck in the Afon Ganol Valley between Glan Aber Farm in the west and Mochdre in the east. If this was the case, it would suggest that there were two separate sedimentary systems in the Afon Ganol Valley: one open to the sea in the east at Penrhyn Bay and the other open to the sea in the west near Llandudno Junction. To confirm or refute this possibility, lithostratigraphic investigations were undertaken at Glan Aber Farm.

The results from these investigations are presented below and the overall question of determining the entrance and exit for the sea in the Afon Ganol valley is addressed in section 5.3.5.

5.3.1a Morfa Penrhyn, Rhos-on-Sea

The characteristics of the lithostratigraphy at Morfa Penrhyn have been established from the completion of twenty hand cores and one piston core, in two transects taken normal to each other (Figs. 5.8, 5.9 and 5.10).

The convex dip of an impenetrable surface on the northern edge of the site is apparent in Transect 1 (Fig.5.9). In MP 5-8, coring stopped at just above -2.00 m OD, in a very compact woody peat. In MP 9-11, the shallow depths recorded were because of a grey silty-sand preventing deep hand-coring.

Transect 2 (Fig.5.10) crosses transect 1 near MP8. It was completed running normal to the slope where sediments were known to be deepest in an attempt to investigate further the deep peats found in Transect 1, as well as to build up a 3-dimensional picture of the lithostratigraphy at the site. In six of the eight cores on this transect deep peats were found at variable depths up to 5.77 m below ground surface (just below -2.0 m OD) resting upon the coarse sandy-gravel base.

Where sampled, the base of the unconsolidated sediments proved to be a coarse grey sand, often with gravel or small angular pebbles. Especially clear in Transect 2 was the basal peat resting on this surface which was recorded in every core deeper than -1.50 m OD, except MP12. In the very deepest five cores (MP5,13,18,19,20), however, this basal peat was split by a light grey, fairly stiff silty-clay with organic enrichment including eroded peat balls (<25%), a feature also found at Colwyn Bay Rugby Club (section 5.3.2). This inorganic stratum was up to 0.20 m in thickness within an altitudinal range of -1.96 m to 1.45 m OD. These basal peats have typically been described as amorphous red/brown partially humified peats, sometimes with a 25% wood content, which included birch twigs and alder. They were extremely compact, so that on more than one occasion the corer became stuck and took a considerable effort to retrieve. Their thickness varied more or less in proportion with the depth of sampling, since where a core reached deeper than *c.* -1.50 m OD, sediments below were typically organic.

These basal peats were overlain consistently by a fine blue/grey silty clay with some partially humified *turfa* near the base and top of the stratum. The 'altitudinal window' for the deposition of this inorganic stratum was 2.00 m (*c.* +0.50 m to -1.5 m OD). Where the basal impenetrable surface intersected this window, however, basal peats continued to form (5 out of 6 cores) and this feature was particularly clear in Transect 1 (MP 2-4). Where the basal peats were forming within the altitudinal window of clay deposition, there was a negligible wood component compared with the deeper peats. In MP 2-4, for example, they were described as very dark humified peats with some *Phragmites* and a small minerogenic component.

In twelve out of the sixteen cores reaching to a depth of at least 0.00 m OD, an organic deposit was recorded with an altitudinal range of +0.10 m to +0.95 m OD, resting upon the blue/grey silty-clay. In MP21, this organic deposit rested upon an impenetrable surface.

The thickness of this organic deposit exceeded 0.20 m in only two cores. Along the north western edge of the site this deposit was recorded as a fresh *turfa/Phragmites* peat, which in MP2 was 0.38 m thick. Elsewhere in Transect 1, and throughout Transect 2, this organic deposit was recorded as a dark brown partially humified peat with up to 25% *turfa* and/or *Phragmites*. In seven out of the eleven cores where the deposit was recorded, there was an erosive upper contact with a *Lim.sup.* of at least 1 being recorded. There was no apparent spatial pattern of such erosive contacts.

Overlying this organic deposit was a silty clay with a variable but small amount of organic enrichment in the form of *turfa* rootlets. This deposit extended up to the base of the top soil (0.30 m - 0.40 m below ground surface), but from 1.00 m to 1.50 m below ground surface became slightly coarser (a silt-clay), drier and iron-stained. Inorganic sedimentation in the form of silts and clays was therefore found throughout the site from *c.* +2.00 m OD to ground surface. In these upper strata although the composition of sediments was quite consistent over the site their appearance, in terms of colour, changes appreciably. In cores PM 1-8 on Transect 1, and in Cores PM 12,18,19 and 20 in Transect 2, this upper inorganic deposit was typically battleship-grey, or especially near the northern margins of the site blue/grey. Elsewhere these upper sediments were grey-brown or khaki brown.

Again the exception to this pattern was found in the north western extreme of the site, adjacent to the break in slope marking the edge of the unconsolidated sediments. In PM2, a *Phragmites*-rich peat was recorded between +0.72 m and +1.09 m OD, and above this between +2.06 and +2.47 m OD was a dark *turfa* with *Phragmites* and some clay. In PM1, above the basal sandy silt was a humified peat with some woody remains (probably oak) was recorded.

Over the sampled area the surface altitude varied from +3.89 m OD (PM1) to +3.24 m OD (PM12). Excluding these two cores the altitudinal surface range was only 0.22 m (+3.32 to +3.54 m OD).

5.3.1b **Morfa Penrhyn: Summary of the lithostratigraphy.**

1. The unconsolidated sediments at Morfa Penrhyn have been deposited upon a coarse sandy gravel base.

2. Below -1.50 m OD, a partially humified red/brown peat with a variable wood content has formed. In the very deepest cores this peat was split in two by a thin silty-clay horizon.

3. In the north and east of the site basal peats continued to form on a rising impenetrable surface, becoming fresher and more abundant towards the margins of the site.

4. Away from the impenetrable surface between *c.*-1.50 m and +0.50 m OD were fine grained blue/grey silty-clays. This stratum was overlain by a thin peat bed (0.10 - 0.20 m thick) containing *Phragmites* and some *turfa*, which is in turn overlain by a battleship-grey silty-clay up to an altitude of *c.* +2.00 m.

5. Below the top soil was a silt-clay with iron-staining merging into the silty-clay below.

6. Along the north-western margins of the site surface peats have formed.

7. In the south-eastern corner of the site the unconsolidated sediments coarsen and were impenetrable with a hand-corer.

5.3.1c **Morfa Penrhyn - 20: Diatom Analysis.**

The lithostratigraphy at Morfa Penrhyn was shown to be consistent over the site, with two primary organic horizons at *c.*-1.5 m and 0.0 m OD. Investigations at Colwyn Bay Rugby Club, over one kilometre further to the south-west within the Afon Ganol Valley, revealed a similar distribution. MP-20 was selected for diatom and pollen analysis because it revealed a full, and deep stratigraphic sequence.

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Forty-two samples from MP-20 were prepared for diatom analysis, of which twenty-five levels were possible to count, and in three others it was possible to identify some frustules. A diatom diagram for MP-20 is displayed in Fig.5.11.

Below 448 cm, no diatoms were recorded. At 448 cm two *Diploneis didyma* frustules were recorded. The characteristics of each of the defined zones are described below.

MP-20a (434-342 cm, -0.96 to -0.04 m OD)

Dominated by marine and brackish forms, with *Podosira stelliger, Paralia sulcata* and *Nitzschia navicularis* typically attaining values of 20% throughout this zone. The lower boundary is defined by the base of the diagram.

MP-20b (342-320 cm, -0.04 to +0.16 m OD)

The lower boundary of this zone is defined by the increase in the proportions of *Nitzschia navicularis* and *Diploneis didyma* and a fall in the proportion of *Podosira stelliger*. Brackish forms dominate *cf.* marine in MP-20a.

MP-20c (320-313 cm, +0.16 to +0.23 m OD)

The lower boundary of this zone is defined by a very sharp fall in *Nitzschia navicularis* and rise in *Diploneis didyma*. In this zone, immediately before the regressive overlap the MB *Diploneis didyma* accounts for >80% of total diatoms.

MP-20d (300-296 cm, +0.38 to +0.42 m OD)

The lower boundary of this zone is defined by a transgressive overlap, below which no diatoms were counted. The zone is dominated by the brackish diatom *Navicula peregrina*, with *Diploneis ovalis, Nitzschia navicularis, Caloneis formosa, Diploneis didyma* and *Nitzschia socialis* attaining values >5% of total diatoms.

MP-20e (296-292 cm, +0.42 to +0.46 m OD)

The lower boundary of this zone is defined by a sharp fall in the quantities of *Navicula peregrina*, and increases in the quantities of *Diploneis didyma* and *Nitzschia navicularis*. In this zone *Diploneis didyma* accounts for *c.*50% of total diatoms with *Nitzschia navicularis, Podosira stelliger* and *Paralia sulcata* the other species of note.

MP-20f (292-251 cm, +0.46 to +0.87 m OD)

The lower boundary of this zone is defined by a sharp fall in *Diploneis didyma* and rises in *Nitzschia navicularis, Podosira stelliger* and *Paralia sulcata*. The characteristics of this zone are very similar to MP-20a, with the aforementioned species dominating. *Diploneis smithii* and *Scoliopleura tumida* are also found in quantities >5% total diatoms.

MP-20g (251-235 cm, +0.87 to +1.03 m OD)

The lower boundary of this zone is defined by a rise in the quantities of *Diploneis smithii* to >40% total diatoms. *Scoliopleura tumida, Diploneis didyma, Podosira stelliger* and *Paralia sulcata* also attain values >5% total diatoms.

MP-20h (235-217 cm, +1.03 to +1.21 m OD)

The lower boundary of this zone is defined by a rise in the quantities of *Nitzschia navicularis* and *Scoliopleura tumida* and a sharp fall in quantities of *Diploneis smithii*. The zone is characterised by *Nitzschia navicularis, Scoliopleura tumida* and a wide variety of marine forms including *Coscinodiscus* sp. and *Triceratium* sp.

The diatom analysis has shown that the silts and clays at Morfa Penrhyn between *c.*-1.00 m and +1.00 m OD were deposited in a marine brackish environment. Throughout the diagram the marine species *Paralia sulcata* and *Podosira stelliger* along with the brackish species *Nitzschia navicularis* are dominant. The main changes in this simple pattern are adjacent to the regressive overlap at +0.23 m OD and transgressive overlap at +0.38 m OD when the environment was passing from upper saltmarsh to fen and back.

5.3.1d Morfa Penrhyn - 20: Pollen Analysis.

Three samples from the dated organic horizon in core MP-20 were prepared for pollen analysis. The results are described below and displayed in Fig.5.12.

MP-20a (313-309 cm, +0.25 to +0.29 m OD)
The pollen composition through this diagram is consistent with a slight rise in *Quercus* frequencies to the top of the diagram. Saltmarsh indicator species include Chenopodiaceae and *Aster*-type.

5.3.2a Colwyn Bay Rugby Club

In May, 1991 six cores were completed at Colwyn Bay Rugby Club (Colwyn Bay RC) as part of the investigation into the overall pattern of sedimentation in the Afon Ganol valley (Fig.5.13). The main objective of the investigation was to compare the pattern of sedimentation at Morfa Penrhyn and at a site further down the Afon Ganol valley. Such information was required to assess the direction of water movement through the valley during the Holocene. Two further cores were taken in July, 1991 as part of a search for sediments containing diatoms within the eastern sector of the Afon Ganol valley.

The deepest recorded Holocene sediments recorded at Colwyn Bay RC were khaki-brown, solid silts from -2.94 m to -3.04 m OD in CB1. This silt was overlain by a grey silty clay with black streaks in CB1, and recorded as the deepest sediment in CB2 and CB7.

The deepest organic sediments recorded had an altitudinal range from -2.63 m to -1.58 m OD and a maximum thickness of 0.36 m in CB7. In CB1, 2 and 7 this organic horizon overlay grey silty-clays, but in CB5 was only 0.08 m thick, overlying a basal gravel. It was described as a humified brown/red amorphous peat. In CB1, the base of this horizon contained unidentifiable shells and some very fine inorganic material, and in CB2 there was a small silt component throughout the deposit.

Overlying this organic horizon was a thin stiff grey silt with some clay, which in CB2 was slightly laminated and in CB5 contained a 0.17 m chunk of wood which was identified as alder. This horizon was in turn overlain by another organic horizon with an altitudinal range of -1.90 m to -0.60 m OD. This peat was typically described as an amorphous red/brown peat with some *Phragmites* and wood including birch twigs, with the *Phragmites* content increasing towards the top of the stratum. In CB4, near the edge of the valley, there was only one lower, thick organic horizon from -0.60 m to -1.08 m OD overlying the basal gravel containing a *c.*25% wood content within the *Substantia humosa* peat matrix. In CB6, these lower organic horizons were absent and battleship-grey silty-clays with some shells were recorded.

In CB2 a 0.42 m piece of hard wood overlay the previously described organic horizon: otherwise battleship-grey silty-clays with some *turfa* and *Phragmites* dominated sedimentation between *c.*-1.40 m and *c.*0.00 m OD.

In four cores within an altitudinal range of -0.06 m to +0.39 m OD was an organic horizon, which in CB1 had a sharp upper contact. Within the humified red/brown peat matrix of this horizon were abundant and quite fresh *Phragmites* and detrital wood including birch and alder. Where this organic horizon was absent (CB5 and 6), blue/grey silty-clays were recorded.

Above this organic horizon inorganic sedimentation in the form of blue/grey and battleship-grey silty-clays with small amounts of *turfa* and *Phragmites* were recorded. Above *c.* +2.00 m OD, the silt content increases (to *c.*50%) and there was some iron-staining.

In CB2, from +1.96 m to +1.81 m OD a dark brown peat was recorded with abundant detrital wood, possibly oak. This organic horizon was also recorded in CB7 and there was evidence for it in CB1 and CB4, where organically enriched clays were recorded from

+1.46 m to +1.23 m OD and +1.93 m to +1.83 m OD respectively.

In cores where unconsolidated material was sampled the surface altitude ranged from +3.15 m to +3.34 m OD.

5.3.2b **Colwyn Bay RC: Summary of the lithostratigraphy.**

1. A basal red/brown amorphous peat was recorded between -2.63 m and -1.58 m OD. In the centre of the valley, this peat was underlain by a stiff silt possibly of Holocene age.

2. A thin stiff silty-clay was recorded overlying this basal peat, which was in turn overlain by another red/brown peat with woody remains with an altitudinal range of -1.90 m to -0.60 m OD.

3. Between -1.40 m and 0.00 m OD silty-clays with some *turfa* and *Phragmites* were recorded.

4. A thin *Phragmites*-rich peat was recorded between -0.06 m and +0.39 m OD.

5. Grey clays and silty-clays were recorded above this peat, though in four cores a thin organic clay was recorded at approximately +1.90 m OD.

5.3.2c **Colwyn Bay Rugby Club: Diatom Analysis.**

At Morfa Penrhyn, no diatoms were found below 432 cm below ground surface (-0.94 m OD) where two peat horizons had been identified and two ^{14}C-dates had been obtained. The lithostratigraphy recorded at Colwyn Bay RC, only 1 km inland of Morfa Penrhyn, was very similar to that recorded at Morfa Penryhn. To corroborate these dates, and in view of the absence of diatoms at Morfa Penrhyn, diatom analysis was attempted at Colwyn Bay RC.

A number of hand-cores were completed at Colwyn Bay RC, with the diatom preparation carried out on-site courtesy of a very helpful B&B in Rhyl. Twenty-nine samples were prepared from the crucial lower levels, but as at Morfa Penrhyn no diatoms were found.

5.3.3 Glan Aber farm.

For reasons explained in section 5.3, in late August, 1991 two transects of cores were completed at Glan Aber farm. Transect 1 (Fig.5.14) shows the cross valley lithostratigraphy from the northern edge of the valley to the railway line. The location of these cores is shown in Figs. 5.6 and 5.7.

Unconsolidated sediments were recorded upon a coarse mixed gravel base, composed of coarse sands and angular pebbles. This solid gravel surface was reached in all cores except GA5, 6 and 7. In GA7, sampling stopped at -4.90 m OD in a dark brown humified peat with some woody remains. This peat had a transitional contact into a blue-grey silty-clay with *Phragmites* at -4.47 m OD. This peat was therefore at least 0.43 m thick in GA7.

The silty-clay horizon was recorded in cores GA6, 7 and 8 with an altitudinal range of -4.47 m to +0.03 m OD. In GA7, the *Phragmites* content increased towards the base of the horizon.

Overlaying the silty-clays in GA6, 7 and 8, and overlaying the basal gravels in the other cores were a series of very thick organic sediments with an altitudinal range of -0.85 m to +3.75 m OD. In GA7 a *limus* with *Phragmites* and some wood was recorded between the transition from silty-clays to peat from -0.85 m to -0.56 m OD. Below c.+1.5 m OD the organic sediments were recorded as a brown, slighfly red peat with abundant wood, including alder, and some *Phragmites*. Above c.+1.50 m OD, the wood content of these organic sediments decreased while the *Phragmites* content increased along with the presence of semi-humified *turfa* within the peat matrix.

Within an altitudinal range of +0.82 m to +3.00 m at variable altitudes was a clay or organic-clay horizon. In general, the organic content of this horizon increased towards the edge of the valley at GA9. However, in every core abundant and relatively fresh *Phragmites* was recorded. This organic-clay horizon is visible in Fig.5.15 (Transect 2). Additionally, a rising impenetrable surface towards the eastern end of the Afon Ganol Valley is well illustrated in Fig.5.15.

5.3.4 Afon Ganol Valley. Overview of the A55 borehole records.

The lithostratigraphic descriptions in these borehole records made very little distinction between the different types of unconsolidated sediments. Typically, the Holocene sediments were recorded as "Soft grey clay with decaying plant remains and pockets of brown peat", though mottled clays, sands and mixed gravels are recognised. Typically where Holocene sediments were recorded, soft clays with peat were recorded overlying a gravel base. In Fig.5.16, therefore, only the thickness of clay with peat overlying gravels or boulder-clay is plotted in a series of cores from central valley positions.

Fig.5.16 clearly shows an increasing depth of Holocene sediments towards the southwestern end of the valley as noted by Arber (1984), with the pre-Holocene surface rising to *c.*+1.00 m OD in cores 19 and 20 at the eastern end of the transect. A synthesis of these two cores and the lithostratigraphy recorded throughout the Afon Ganol Valley is described below.

5.3.5 Synthesis of the middle Afon Ganol lithostratigraphy and pre-Holocene surface depths.

Following the lithostratigraphic survey at Morfa Penrhyn, as explained in section 5.3, subsequent investigations were focused upon attempting to establish from which direction the sea entered and exited the Afon Ganol valley. In such an elongated valley (5 km long and typically less than 0.5 km wide) the potential for variations in tidal range is vast, so it was necessary to establish the relationship of sediments from which ^{14}C-dates were taken to the to an open coast it would have been difficult to interpret lithostratigraphic features of the sampled sites within the context of coastal lithostratigraphic models (e.g. Godwin, 1978). The data described above strongly indicate that, for most of the Holocene, the valley must have been open to the sea at its southwestern and northeastern ends near Llandudno Junction and also at Penrhyn Bay.

Godwin (1978) has summarised the typical spatial pattern of sedimentation in coastal areas such as the Fenland, contrasting largely organic sediments in landward locations with largely inorganic sediments seawards. Though the Afon Ganol valley is a narrow valley, a similar contrast would be expected between landward and seaward locations, or in this case up valley and down valley locations. Indeed Long (1991) has described such a pattern of sedimentation in a palaeovalley of similar dimensions to the Afon Ganol valley in the Hacklinge/Deal area of the East Kent Fens. At Glan Aber farm in the central Afon Ganol valley a surface peat up to 4.00 m thick stretches across the entire valley (Fig 5.14). If the source of the upper marine sediments at Morfa Penrhyn and Colwyn Bay RC was from the west, then it would not be possible for thick peats to form at Glan Aber from a depth of -0.85 m OD to the present day surface. Therefore, while these peats have been forming (c.6000 ^{14}C-years) the source of marine sediments for the eastern sector must have been through Penrhyn Bay. A bottleneck in the valley, where the underlying sands, gravels and boulder clay rise close to the surface, is the most likely cause of the thick peats at Glan Aber Farm. In Fig. 5.17 are shown the depths of the pre-Holocene surface from hand coring and commercial records in the central Afon Ganol valley between Glan Aber farm and Station Road, Mochdre (the borehole records obtained from Travers Morgan identify boulder clay underlying the unconsolidated sediments, therefore pre-Holocene). Where it is known, the +4.00 m contour is plotted (unconsolidated sediments do not occur above +4.00 m in the Afon Ganol valley).

The lithostratigraphy of selected cores along the length of the Afon Ganol valley from Morfa Penrhyn in the east to Glan Aber farm in the western sector, including core B30 from Station Road, Mochdre at the bottleneck in the valley, is presented in Fig.5.18. The figure demonstrates the similarity of the lithostratigraphy of sites in the eastern sector (Morfa Penrhyn and Colwyn Bay RC), and the very great dissimilarity between the aforementioned sites and Glan Aber farm in the west.

5.3.6 The Afon Ganol Valley: Synthesis.

The litho- and biostratigraphic investigations from the Afon Ganol Valley at Morfa Penrhyn, Colwyn Bay RC and Glan Aber Farm have shown that the environmental history is complex. Two distinct sedimentary systems have been identified. In both systems there is evidence of marine inundation and withdrawal in the Holocene, but also that these events were not always synchronous.

Caution has to be expressed at this stage, since there is no palaeobotanical evidence available from Colwyn Bay RC and Glan Aber Farm. No diatoms were found at Colwyn Bay RC, and the lithostratigraphic survey was completed late on in the research at Glan Aber Farm, so palaeobotanical investigations were not possible. This does not alter the facts of the lithostratigraphic survey, but does mean that interpretations made about sea-level changes are based largely on one type of data and therefore need qualification.

The unique geography of the area provides satisfactory explanation for the variability found. During the later Holocene, for example, during periods of marine inundation, the whole of the Afon Ganol Valley would have been flooded, so that the area to the north, Llandudno and Rhos-on-Sea, would have been an island, separate from the Welsh mainland. Such dramatic changes in coastal geometry would have had dramatic effects on local tidal and sedimentary patterns. Additionally, both the southwestern and northeastern entrances to the Afon Ganol Valley are narrow, so there will always have been the possibility of barriers forming and blocking the natural entrance and exit of the sea.

More detailed comments are reserved to the following chapter because of the difficulties that the ^{14}C-dates from Morfa Penrhyn have presented.

5.4 Clwyd coastal lowlands

The Clwyd coastal lowlands (Figs. 5.19 and 5.20) are a large coastal area which has been infilled with sediments during the Holocene. The area where unconsolidated sediments are found is bounded by Abergele in the west, Prestatyn in the east, and Rhuddlan in the south which lies some 5 km inland of the present coastline. Recent investigations in the Clwyd coastal lowlands (Manley, 1981; Prince, 1988) indicated that in the central part of this area and towards the present coastline, coarser marine sedimentation dominates; hence the three sites investigated for this thesis are towards the margins of the lowlands.

There are no tide gauge stations along the coast of the Clwyd coastal lowlands. To the west at Colwyn Bay MHWS is recorded at +3.70 m OD, and to the east in the Dee estuary MHWS has been recorded at +4.00 m and +4.07 m OD at Mostyn Quay and Hilbre Island respectively. Tidal values at Colwyn Bay have been used to correct ^{14}C-dates from the Clwyd coastal lowlands, though it is worth noting that MHWS is recorded at +4.00 ± 0.30 m OD throughout the whole of Liverpool Bay between Colwyn Bay and the Ribble in Lancashire. We can reasonably expect therefore, that tidal values from Colwyn Bay are a good approximation for coastal sites along the Clwyd lowlands.

West of the River Clwyd, between Rhyl and Abergele, the coastal plain is wide (up to 5 km) and the sedimentary record is both rich and accessible. East of Rhyl however, towards Prestatyn and beyond, the coastal plain is narrow (1-2 km wide) and developed, so there is virtually no agricultural land. Blown sands have covered the intercalated peats, silts and clays between Rhyl and Prestatyn (Neaverson, 1936) so that lithostratigraphic investigations are difficult.

Most of the land within the Clwyd coastal lowlands between Abergele and Rhyl have been reclaimed since the early nineteenth century (Englefield *et al.*, 1990). In 1807 sea embankments were constructed, and further reclamation was necessary for the construction of the Chester to Holyhead railway in 1847 (Englefield *et al.*, 1990). The reclamation and over-development of the area was of course highlighted in February 1990 by the severe flooding at Towyn.

5.4.1a Pentre Mawr, Abergele

The investigation into the borehole records from the Abergele-Llandulas bypass (Tooley, unpublished) has been described in section 4.3.2. These records clearly suggested a rich sequence of unconsolidated sediments in north Abergele warranting a comprehensive stratigraphic survey.

Residential development and the completion of the bypass restricted coring to the Pentre Mawr park (Figs. 5.20 and 5.21) where seventeen hand-cores and one piston core were completed. A transect of eight cores is described below.

5.4.1b Pentre Mawr, Abergele. Transect 1

The lithostratigraphy recorded in a line of cores running from the southern landward edge of the site to the northern seaward edge of the site is illustrated in Fig.5.22. Unconsolidated sediments were recorded upon a gently sloping impenetrable sandy surface.

The deepest unconsolidated sediments sampled were in PM18 to a depth of -1.39 m OD where a grey/brown peaty-silt was recorded merging into a full organic horizon from -1.19 m to -0.62 m OD. At the base of this full organic horizon unidentified wood was recorded; otherwise a very dark brown/black fully humified peat was recorded. Only in the top 0.05 m of this horizon are *turfa* remains recorded. Below this organic horizon, and above the basal gravels in cores PM5 - PM7, was a grey silty-clay with some sand.

In cores PM 5, 6, 7, 8 and 18, this organic horizon was overlain by a thin inorganic blue/grey silty-clay with some organic enrichment and a maximum thickness of 0.19 m in PM18. The altitudinal range of this horizon was from -0.51 to -0.16 m OD. As can be seen in Fig.5.17 this clay thinned and the organic content increased landwards. Landward of PM5, this inorganic horizon was not recorded.

Again referring to cores PM18 - PM5, this inorganic horizon was overlain by an organic deposit with an altitudinal range of -0.32 m to +0.43 m OD, and maximum thickness of 0.75 m. This deposit was typically recorded as a partially humified medium brown peat with some *turfa*. In PM6, detrital wood was recorded at the base of this horizon. In all cores where this deposit was recorded were partings of fine inorganic clays at variable altitudes.

In cores PM4 - PM2 the thin inorganic horizon present between -0.51 m and -0.16 m OD was absent and so organic sediments dominated between +0.02 m and +1.49 m OD. Once again, there were blue/grey inorganic silty-clays between the basal gravels and this organic horizon which in PM2 have a sharp upper contact. This organic horizon was typically a well-humified dark brown peat, but in PM4, *turfa* and detrital wood were recorded throughout the sequence.

The organic deposit described for cores PM18 - PM2 was overlain by a predominantly inorganic deposit with an altitudinal range of +0.35 to +1.60 m OD. This deposit thinned landwards, with an increasing organic content and a rising altitude. In PM18, the most seaward core, this deposit was 0.34 m thick and described as sticky grey clay with some *Phragmites*. In PM5 - PM8, the organic content of this horizon remained under 25%, but landward (cores PM4 -PM2) was at least 25%, and the horizon was typically described as a grey/brown organic clay.

Overlying this inorganic deposit was an organic horizon present in all cores except PM5 and PM1 with an altitudinal range of +0.88 m to +1.99 m OD. This horizon thickened seaward and reached a maximum thickness of 0.60 m in PM18 where it was described as a very dark brown/black humified peat. In PM18 and the other seaward cores (PM6 - PM8) the transition into the underlying and overlying inorganic deposit was gradual with up to 0.10 m of organic clays marking the transition from pure organic to pure inorganic sedimentation. In PM7 and PM4 some detrital wood was recorded in this horizon. In PM1, a partially humified organic clay was recorded between +2.50 and +2.66 m OD resting upon an impenetrable gravel surface. This organic deposit was higher than in other cores, but did follow the trend of each sedimentary horizon rising along with the pre-Holocene surface landwards. In PM5, this pure organic unit was absent but a thin organic clay was recorded between +1.95 m and +2.04 m OD overlain by a sandy-silt deposit.

Seaward of PM4, above *c.* +1.50 m OD and rising to *c.* +2.50 m in PM1, inorganic sedimentation persisted to the surface. A coarse sandy gravel was recorded within an altitudinal range +1.31 to +3.00 m OD and a maximum thickness of 0.22 m in PM6. In PM1, a 0.76 m sandy gravel was recorded resting upon the basal organic deposit. Otherwise this upper inorganic deposit was consistently recorded as a silt-clay. Immediately above the underlying organic deposit it was a grey/brown silt-clay, and above this for the top metre or so of the profile there was a degree of iron staining.

The surface altitude along the profile varied between +4.45 m OD in PM1 and +3.40 m OD in PM18 with a fairly consistent downward slope seawards.

5.4.1c Pentre Mawr - 8, Pollen Analysis.

Fourteen samples were prepared for pollen analysis. A diagram is presented in Fig.5.23 and described below.

PM-8a (433-397 cm, -0.81 to -0.45 m OD)
This zone has very consistent frequencies of tree and herb species, with *Quercus, Alnus* and Gramineae dominant. A few Chenopodiaceae and *Aster*-type pollen present.

PM-8b (242-238 cm, +1.10 to +1.14 m OD)
Very similar to PM-8a, with slightly lower frequencies of Gramineae and higher frequencies of Cyperaceae.

PM-8c (238-215 cm, +1.14 to +1.37 m OD)
Through this zone, very high frequencies of *Alnus* are replaced with high frequencies of Cyperaceae. During this transition, high frequencies of *Filicales* are recorded.

PM-8d (215-200 cm, +1.37 to +1.52 m OD)
In this zone, frequencies of Gramineae and *Alnus* recover, while those of Cyperaceae fall. *Quercus* and *Polypodium* are also recorded in moderate abundance.

5.4.2a Hendre fawr

Sampling at Pentre Mawr was restricted because of residential development and new road building. Efforts were therefore focused upon finding a site in open land east of Abergele, but sufficient distance away from the River Clwyd. Hendre-fawr proved a very suitable site, located 2 km east of Abergele, where an 800 m transect from the limit of marine sedimentation seawards was possible.

5.4.2b **Hendre fawr, Transect 1**

Twenty hand cores were completed at Hendre-fawr in a south to north transect (Figs. 5.24 and 5.25). A piston core (HF21) was taken for radiocarbon dating and biostratigraphic analysis. The sampling interval varied between 25 m and 50 m.

The base sediments recorded at Hendre-fawr were either very coarse gravels or a coarse orange sand layer which was never penetrated with a hand corer. Northwards along the transect, beyond HF15, these basal sediments were not sampled because of the increased depth of unconsolidated material (> 7.50 m).

The deepest Holocene sediments recorded were very fine blue/grey clays, which in HF17 were sampled to a depth of -3.87 m OD. *Turfa* and *Phragmites* rhizomes were found throughout this stratum, but especially near the upper contacts of the stratum. Attributing an altitudinal range to this clay stratum is not simple, because of the complexity of the lower lithostratigraphy at Hendre-fawr, which is clear in Fig.5.25. Considering cores north of HF14 inclusive, this blue/grey clay stopped between -2.00 and -2.50 m OD to be replaced by either sand or an organic horizon.

This organic horizon was found as an intercalated stratum in HF19 and HF15, and has been described as a brown/grey organic clay with *Phragmites* found within the altitudinal range -2.34 to -2.52 m OD, but less than 0.05 m in thickness. Southwards (landward) of HF14, this organic deposit continued as a basal peat resting upon the rising pre-Holocene surface from an altitude of -2.58 m OD in HF14 to -0.29 m OD in HF10. From HF11 another intercalated organic 'finger' emerged with an altitudinal range of -0.63 m OD to -1.16 m OD and thickness of 0.10 m +/-0.05 m. This second intercalated organic horizon was typically described as a semi-humified *turfa* with never more than 25% wood and/or *Phragmites* content and excellent transitional upper and lower contacts. In HF14, for example the stratum was assigned the Troels-Smith description: *Sh2,Th²2 Dl+*. In HF10, the most landward core where this basal peat was recorded (also the highest altitude at which it is recorded), it was far less humified and was recorded as a *turfa* with some *Phragmites*. In three cores (HF21, 17 and 20) there was evidence of a third, very thin organic horizon below OD. They were recorded as follows:

HF21	-0.69 to -0.66 m OD	Laminated *turfa/Phragmites* peat.
HF17	-0.23 to -0.16 m OD	Humified peat with sand.
HF20	-0.06 to -0.03 m OD	Peaty clay.

Whether or not these three horizons are part of the same sedimentary unit is not possible to say. This organic unit recorded in HF21 was separate from the other two organic horizons described above since they were both present lower down in HF21.

Between these two primary organic fingers described (HF21-14 and HF19) were fine-grained inorganic sediments, except in HF14 where slightly laminated sands were found. These were typically very fine and plastic blue/grey clays with some eroded *turfa* and *Phragmites*. This stratum thickened seaward as a result of a deepening impenetrable surface reaching a maximum thickness of 1.64 m in HF19.

In cores HF15 to HF18, these two lower organic horizons and blue/grey clays were absent, and from an altitude of *c.*-2.50 m OD to *c.*0.00 m OD in these cores grey, fairly coarse, wet sands dominated. In three of the four cores (HF15-HF18) the sands were recorded as slightly laminated. In HF18, these inorganic sediments were finer. Above the deep fine clays already described was a silty sand horizon from -1.93 m to -1.32 m OD, and a fine clay horizon from -1.32 m to -0.53 m OD, which was then replaced by coarser, slightly laminated sands. Laminated grey sands were also found landward of HF14 in cores HF11-HF12 with an altitudinal range of -0.68 m to +0.72 m OD, which was *c.*0.50 m higher than in the more seaward cores. In HF19, a profile similar to HF13 was found with two lower organic horizons intercalated with blue/grey clays with *Phragmites*. From -0.45 to -0.15 m OD, however, the grey sand was recorded.

The lithostratigraphy of cores HF10-HF20 shows clearly that the only locations where the lower organic intercalations are absent were where laminated sands have been deposited.

Above the grey sands (*c.* 0.00 m OD) in the seaward cores, and above the higher of the two organic fingers already described, clays and silty-clays were recorded (with the exception of sand horizons, already described). This inorganic horizon had an altitudinal range of -1.06 to +1.58 m OD (HF12) and was typically described as a blue/grey buttery clay or silty-clay with *Phragmites* and occasionally small quantities of eroded *turfa*. Landward, this inorganic horizon thinned because of a rising impenetrable surface intersecting the above organic horizon which pinches out this clay horizon at HF8.

Within an altitudinal range from +1.00 m to +2.20 m OD, organic sedimentation dominated at Hendre-fawr. In four cores (HF7, 13, 18 and 20) there were inorganic sediments recorded between these altitudes. In HF8 and HF20, blue/grey and battleship grey clays were recorded. In HF13, silty-sands, coarsening with depth, and in HF18 a slightly laminated grey sand were recorded.

On the landward edge of the transect this organic unit was recorded as one horizon thickening in a seaward direction as the impenetrable basal surface dipped southwards from 0.25 m in HF3 to 0.70 m in HF6. In cores HF3 - HF6, this organic horizon was typically described as a dark brown/black partially humified *turfa* peat with some *Phragmites* and detrital wood. The wood content increased towards the base of this stratum where alder was identified. Beneath this organic horizon a thin humified organic clay was recorded *c.* 0.05 m in thickness. In cores HF4, 5, 6 and 8 this organic horizon rested directly on the impenetrable surface.

Seaward of HF8, this organic horizon was split in two by a thin organic silty-clay which varied in thickness from 0.03 to 0.20 m. In HF11, for example, it was 0.08 m thick and described as a dark grey organic-clay with transitional upper and lower contacts into the surrounding peats, with Troels-Smith components $As3, Th^{3}1\ Sh+$. The altitudinal range of this predominantly inorganic horizon was +1.70 m to +2.23 m OD.

Below the thin organic clay, the organic horizon had a thickness of up to 0.69 m (HF9). The composition of the horizon was fairly consistent, both through the stratum and along the transect, typically two parts *turfa* and two parts *Substantia humosa*, usually with some *Phragmites* and detrital wood which reached 25% in HF11. Towards the base of this horizon the *Phragmites* content increased and the peat became a lighter brown. In three cores this has led to a separate horizon being recorded as a semi-humified *turfa* with *Phragmites* (HF21) in the bottom 0.10 m of this main organic horizon.

Overlying the organic clay described above, the organic horizon had a maximum thickness of 0.39 m. This horizon was very compact, blacker, and generally more humified than the organic horizon below the organic clay though light *turfa* rootlets were usually recorded. In four cores the upper contact of this peat was eroded.

Overlying the organic horizons over the whole site was a grey, dry sandy-silt with iron-staining, which became more pronounced towards the top of the stratum. The exception is in HF16, where an orange-brown waste gravel was sampled. Overlying this horizon was the topsoil.

In cores where unconsolidated material was sampled (i.e. all except HF1), the surface altitude ranged from +3.24 m to 3.93 m OD, but was typically less than +3.75 m OD.

5.4.2c **Hendre-fawr, Transect 2.**

In terms of one of the overall research objectives, the finding of a dateable basal organic horizon at *c.*-2.5 m OD in Transect 1 was very significant. In June 1990, therefore, a second transect normal to the first was completed (Fig.5.26). This transect was completed to confirm that this deep organic horizon was present in more than a restricted location, and thus a significant feature of the lithostratigraphy at Hendre-fawr, and also to gain an insight into the three-dimensional pattern of the lithostratigraphy in the south-western part of the Clwyd coastal lowlands.

The surface altitudes of the cores in transect 2 were lower than in transect 1 because they were taken from the side of a ditch to avoid coring through the very tough and dry upper silty-clay sequences.

Excluding the two most eastern cores (HF27 and 28) the lithostratigraphy of transect 2 was very similar to that of transect 1, so the description here is brief. The lithostratigraphy of HF27 and 28 is described separately at the end of this section.

The deepest unconsolidated sediments found in HF23, 24 and 29 were directly on top of boulder-clay. In HF24, a thin silty-sand directly overlay the boulder-clay which was in turn overlain by a thin organic silt. Organic silt overlay the boulder-clay in HF23 and 29 within an altitudinal range -2.31 m to -2.53 m OD. In HF29 from -2.48 m to -2.53 m OD was a fully organic deposit described as a brown/black slightly stratified peat with some *Phragmites* and a transitional upper contact.

These organic sediments were overlain by battleship-grey silty-clays, which dominated sedimentation up as far as the upper organic sequences beginning at *c.* +1.50 m OD. The coarse sands noted between *c.*-2.5 m and 0.00 m OD were recorded in this transect in HF23 and HF25. Within an altitudinal range -0.75 m to -0.27 m OD in three cores was a thin organic horizon, typically a partially humified *turfa/Phragmites* peat.

The upper organic sequence in this transect was similar to that in Transect 1, in terms of altitude and the thin slightly organic clay splitting the organic horizon in two. However, in this transect the organic sequences were generally less humified with abundant *turfa* and *Phragmites*; for example in HF23 their composition was recorded as $Th^2 3, Th^2 (Phrag) 1\ Dl+$. Towards the western end of the transect the wood content increased with abundant oak and alder found in HF26. These organic sediments were overlain by silty-clays from *c.* +2.20 m OD.

5.4.2d **Hendre-fawr: Summary of the lithostratigraphy.**

1. The depth of unconsolidated sediments at Hendre fawr increased in a seaward direction.

2. Thin basal peats have formed between -2.50 m and -0.50 m OD.

3. The two lower peat intercalations (-2.50 m and -1.00 m OD) have been eroded by coarse sandy channel fill deposits.

4. Between -1.00 m and +2.00 m OD, relatively fine silty-clays dominated sedimentation.

5. Between +2.00 m and +3.00 m OD organic sedimentation dominated, though in all but the most landward cores, a thin organic-clay splits this organic sequence into two separate horizons.

6. Above this thick organic sequence an iron-stained silty-clay, often with some sand, was recorded.

5.4.2e **Hendre fawr -21: Diatom Analysis.**

Thirty-nine samples were prepared for diatom analysis from HF-21, of which twenty-six samples contained sufficient diatoms to count. Diatoms were absent from the middle inorganic horizons (stratum 10-14).

In Figs. 5.27 and 5.28, diatom diagrams from the lower and upper parts of HF-21 are presented respectively. The zones identified from these two diagrams are described below.

Fig.5.27: Lower Diatoms.

HF-21a (444-436 cm, -1.31 to -1.23 m OD)

The lower boundary of this zone is defined by the base of the diagram at the transgressive overlap between stratum

3 and 4. The zone is characterised by high values of *Diploneis interrupta* (c.80% total diatoms), with low values of other brackish and also marine and marine/brackish species.

HF-21b (436-429 cm, -1.23 to -1.16 m OD)
The lower boundary of this zone is defined by a sharp fall in *Diploneis interrupta* values. In this zone *Nitzschia navicularis, Navicula peregrina,* and *Diploneis didyma* attain values >10% total diatoms.

HF-21c (429-410 cm, -1.16 to -0.97 m OD)
The lower boundary of this zone is defined by a rise in the quantities of *Nitzschia navicularis, Diploneis interrupta* and *Diploneis smithii*. These three species dominate the zone, which is also characterised by a decrease in the diversity of marine species *cf.* HF-21b.

HF-21d (410-408 cm, -0.97 to -0.95 m OD)
The lower boundary of this zone is defined by a fall in the values of *Nitzschia navicularis* and *Diploneis smithii*, and a rise in the value of *Diploneis interrupta* which dominates the zone (>80% total diatoms).

HF-21e (397-394 cm, -0.84 to -0.81 m OD)
The lower boundary of this zone is defined by a transgressive overlap between stratum 6 and 7. The zone is characterised by high values of *Navicula peregrina*.

HF-21f (394-370 cm, -0.81 to -0.57 m OD)
The lower boundary of this zone is characterised by a fall in the proportion of *Navicula peregrina*, and a rise in the values of *Nitzschia navicularis* and *Nitzschia punctata*. The zone is characterised by *Nitzschia navicularis* and marine/brackish species, in particular, *Nitzschia punctata, Diploneis didyma* and *Diploneis smithii*. The marine species *Podosira stelliger* and *Paralia sulcata* are also present.

HF-21g (370-359 cm, -0.57 to -0.46 m OD)
The lower boundary of this zone is defined by a fall in the proportions of *Nitzschia punctata, Diploneis didyma* and *Diploneis smithii*, and a rise in the proportion of marine species: *Podosira stelliger* and *Paralia sulcata*. The zone is therefore characterised by marine species and *Nitzschia navicularis*.

<u>Fig.5.28: Upper Diatoms.</u>

HF-21h (214-202 cm, +0.99 to +1.11 m OD)
The lower boundary of this zone is defined by the base of the diagram in Fig.6.5. This zone is characterised by the brackish species *Diploneis interrupta* and *Nitzschia navicularis*.

HF-21i (202-190 cm, +1.11 to +1.23 m OD)
The lower boundary of this zone is characterised by a fall in the proportion of *Diploneis interrupta*, and rise in *Nitzschia navicularis*. *Nitzschia navicularis* dominates this zone along with a variety of marine and marine/brackish species, in particular *Actinophylus undulatus, Podosira stelliger* and *Paralia sulcata*.

HF-21j (190-186 cm, +1.23 to +1.27 m OD)
The lower boundary of this zone is dominated by a fall in the proportion of *Nitzschia navicularis* and a rise in the proportion of *Navicula peregrina, Diploneis interrupta* and *Diploneis smithii*, which dominate the zone.

HF-21k (140-138 cm, +1.75 to +1.77 m OD)
The lower boundary of this zone is defined by the transgressive overlap between stratum 18 and 19. The zone is dominated by *Diploneis interrupta* (>80% total diatoms).

HF-21l (138-132 cm, +1.77 to +1.83 m OD)
The lower boundary of this zone is defined by a fall in the proportion of *Diploneis interrupta* and a rise in *Navicula peregrina* and *Nitzschia navicularis*. This zone is characterised by these three species and *Diploneis incurvata*.

HF-21 m (132-129 cm, +1.83 to +1.86 m OD)
The characteristics of this zone are the same as HF-21k.

5.4.2f <u>Hendre fawr - 21: Pollen Analysis.</u>

Two pollen diagrams are presented from Hendre fawr - 21 (Figs 5.29 and 5.30). These diagrams are described below.

<u>Fig.5.29 Lower Pollen.</u>

HF-21a (408-402 cm, -0.95 to -0.89 m OD)
Frequencies of tree pollen remain consistent through this zone with *Pinus* and *Quercus* dominant. This PAZ is co-incident with a thin humified-peat which has a peak in *Lemna* (aquatic) and Chenopodiaceae at 404 cm.

<u>Fig.5.30 Upper Pollen.</u>

HF-21b (184-183 cm, +1.39 to +1.38 m OD)
This zone is immediately above the regressive overlap in HF-21 and is characterised by high frequencies of Gramineae and Chenopodiaceae, as well as *Alnus* and *Corylus*.

HF-21c (183-174 cm, +1.38 to +1.47 m OD)
This zone is characterised by high frequencies of Gramineae, with *Alnus* and *Quercus* the dominant trees.

HF-21d (145-143 cm, +1.68 to +1.70 m OD)
Two centimetres below a transgressive overlap, this zone is dominated by *Alnus* and Gramineae.

HF-21e (143-141 cm, +1.70 to +1.72 m OD)
Relative to HF-21d, this zone has higher frequencies of Chenopodiaceae and Gramineae, but lower frequencies of *Alnus*.

5.4.2g <u>Hendre fawr - 29: Diatom Analysis.</u>

Nine samples from HF-29 were prepared for diatom analysis from stratum 4. The diatom diagram from HF-29 is presented in Fig.5.31, from which two zones have been identified and are described below.

HF-29a (498-488 cm, -2.44 to -2.34 m OD)
The lower boundary of this zone is defined by the base of the diagram between stratum 4 and 3. This zone is characterised by high values of *Nitzschia navicularis* (*c*. 50% total diatoms), *Diploneis smithii, Paralia sulcata*, falling frequencies of *Diploneis interrupta* and rising frequencies of *Nitzschia punctata*.

HF-29b (488-480 cm, -2.34 to -2.26 m OD)
The lower boundary of this zone is defined by a rise in the values of *Nitzschia punctata*. This zone is dominated by *Nitzschia punctata* and *Nitzschia navicularis* with *Paralia sulcata*.

5.4.2h **Hendre fawr: Synthesis.**

At Hendre fawr twenty-one cores were taken in a south to north transect (Fig.5.25) from the edge of the Clwyd coastal lowlands seaward. The first core was taken at the landward extreme of Holocene sedimentation. Northwards, this transect shows that the depth of unconsolidated sediments increases and in HF-17 exceeds 7.00 m. The present coastline lies 2 km beyond the most seaward core, and lithostratigraphic work nearer to the coast (Manley, 1981 and Prince, 1988) indicates that the thickness of unconsolidated sediments continues to increase seawards.

At Hendre fawr therefore, the sea would have approached the site in periods of marine inundation from the north, and perhaps from the west where the River Clwyd flows today. The lithostratigraphy at the site has revealed four distinct phases of organic, terrestrial sedimentation, separated by inorganic sediments which diatom analysis have shown to be largely of marine origin. This very straightforward story is the most simple interpretation of the stratigraphic evidence from the site, but the lithostratigraphic evidence in particular reveals an additional and rich history of local environmental changes.

The biostratigraphic evidence for Hendre fawr comes from HF-21, a core taken *c*. 400 m north of the landward edge of Holocene sedimentation and also HF-29, further seaward. At such a large site it is a little simplistic to reconstruct local environments from one core, especially as the lithostratigraphy at the site does show considerable local variation before the final two terrestrial phases. The diatom evidence unequivocally demonstrates, however, that the inorganic sediments at the site are marine or brackish in origin.

Diatom diagrams from the second phase of marine sedimentation (Figs. 5.27 and 5.31) are available from HF-21 and also HF-29, further seaward. In HF-29, frequencies of the brackish species *Diploneis interrupta* are lower, as could be expected in a more seaward location. However, as described in section 5.2.4b, channel deposits are common below 0.00 m OD in the form of laminated sands. Spatial variation in diatom assemblages in an 800 m transect within a 3 km stretch of sedimentation could adequately be explained by a proximity to tidal channels and/or distance to the open sea. During periods of marine sedimentation, a lower saltmarsh and mud flat environment where fine-grained clays and silts would have been deposited was dominant. Superimposed on these features was a complex marsh drainage network with wide channels in which laminated coarser material has accumulated. This channelling led to the erosion of peats formed in the first two terrestrial phases identified at the site.

In contrast, peats formed in the later two terrestrial phases are thicker, more extensive and less eroded. This could be due to a number of factors, notably a longer duration of peat formation, and also less post-depositional sediment compaction. The higher frequency of tree pollen and lower frequencies of aquatic pollen suggests that during the later terrestrial phases the site would have been at least partially wooded. These two later periods of terrestrial sedimentation are separated by a brief period when clays were deposited. The fine-grained, organically-enriched clays and their associated diatom assemblage show an upper saltmarsh environment. Brackish species completely dominate the diatom assemblage and saltmarsh pollen taxa are prevalent at the peat - clay contacts.

At this stage it is not possible to say with any certainty whether the periods of marine withdrawal, when the tidal flat and lower saltmarsh were colonised by *Phragmites* and oak/alder fen, were caused by a change in relative sea-level or sedimentation.

5.4.3 Prestatyn

As part of the general lithostratigraphic survey in and around the Clwyd coastal lowlands a series of handcores were completed in the coastal lowlands east of Prestatyn. Seaward of the site was an extensive coastal dune system. It was expected that this dune system would influence recent sedimentation, but the hope was that deeper sediments would have accumulated independent of such influences.

Such hopes were not fulfilled: therefore only one transect of eight cores was completed at the site, with each core terminating in laminated grey sands between c. +0.75 and +2.00 m OD. Fig 5.32 illustrates the lithostratigraphy at the site, from the edge of the basin (P1) to the coastal railway (P8), showing the sands rising towards the surface seawards (the location of these cores can be found in Fig.5.20). Overlying these sands, which were impossible to core through beyond a metre or so, were grey and blue/grey silty-clays, with abundant *Phragmites* found in P2. This silty-clay horizon had an altitudinal range of +0.75 m to +2.60 m OD: in cores P1 to P4 it was overlain by an organic horizon, and in cores P5 to P8 by a stiff iron-stained silt-clay horizon.

In cores P1, 2 and 7 was a separate peat distinct from the top organic horizon, and thus intercalating the silty-clay. This peat, with an altitudinal range of +1.94 m to +2.56 m OD, was thickest in P1, where it was recorded as a light brown *Phragmites* peat with some humified *turfa*. The top organic horizon, with an altitudinal range of +2.41 m to +3.30 m OD, was variable in composition in terms of the *turfa* content, but was otherwise a very dry crumbly dark brown peat with some birch remains and blown sand.

A thick and very peaty top soil with blown sand extended across the site. Like the pure organic horizon below, this peaty top soil was extremely dry and crumbly.

The lithostratigraphy at Prestatyn indicates that there have been two distinct periods of marine sedimentation at Prestatyn in the late Holocene. The inability to penetrate the laminated sands, however, prevented analysis of the sediments from the early to mid-Holocene: thus the site was not selected for further investigation.

5.5 North Wirral: Newton Carr, Hoylake.

Newton Carr is located in north-west Wirral in a low-lying depression between the coastal towns of Hoylake and West Kirby, approximately one kilometre from the present day coastline. The coast of the north Wirral is dominated by sand dunes and at Newton Carr blown sands were prevalent in the surface sediments of cores taken nearest to the coast. Deeper sediments at the site revealed no evidence of blown sands.

Hilbre Island tide gauge station lies 3 km to the north-west of Newton Carr. Here the height of MHWS is +4.07 m OD, and for MLWS -3.63 m OD, giving a tidal range of 7.70 m OD. Newton Carr does lie close to the mouth of the River Dee, but the heights of MHWS at Mostyn Quay and Connah's Quay within the estuary are +4.00 m and +3.95 m OD, so it would seem that Hilbre Island is a good estimate for the tidal range at Newton Carr.

The possibility of examining sites on the Wirral had been considered from very early on in the research. This possibility became a reality following discussions with Dr.J.Innes about Newton Carr, a site in north-west Wirral. Dr.Innes had obtained borehole records from Merseyside County Council indicating a very rich sequence of Holocene sediments and completed pollen analysis on peat samples showing unambiguously that the inorganic/organic intercalations were formed through changes in sea-level, and in need of further investigation.

Until the recent past (Innes *et al.*, 1990), investigations into coastal sedimentation on the Wirral were restricted to coastal peat exposures, or to narrow buried channels running normal to the north Wirral coast where the influence of local factors on sedimentation was high. The County Council borehole records indicated that Newton Carr had been open to the coast in a north-westerly direction, and that sedimentation had taken place in a sizeable depression where the signal-to-noise ratio of regional and local influences was likely to be favourable. Additionally, the borehole records showed that deep organic sediments were present at the site at *c.*-2.00 m and -5.00 m OD. The results from these borehole records are summarised below and fully examined in Innes *et al.* (1990).

A comprehensive lithostratigraphic survey was completed at Newton Carr in August 1990, which more than confirmed the optimism induced by the borehole records. A seismic refraction survey and further lithostratigraphic work were completed in the spring of 1991; the results and reasons for these surveys are described in section 5.5.3.

Newton Carr has proven to be an exceptional site for examining Holocene sea-level changes, and in turn crustal movements, in its own right and in providing a link between north Wales and the intensively studied Lancashire coastline (Tooley,1969;1974;1978). Additionally the work completed at the site has provided a lithostratigraphic and environmental context for coastal archaeological investigations by Merseyside County Council.

5.5.1 Newton Carr, Hoylake. County Council borehole records.

The location and lithostratigraphy of Water Authority boreholes are illustrated in Figs 5.34 and 5.35 respectively. The boreholes were sampled as a grid, but the overall lithostratigraphy is most effectively shown in a transect. These figures along with descriptive prose appear in Innes *et al.* (1990), so only the broadest characteristics are pointed out in this section.

Fig.5.35 shows three distinct organic horizons, the nature of which is explained below. The terminology of lower, middle and upper peat as used by Innes *et al.* (1990) is adopted for this description:

Lower peat: -5.10 m to -5.30 m OD.

Thin compact peat with wood fragments overlying pebbly sand and boulder clay. Only found in Bore 7, the deepest core and nearest to the sea. Overlain by cohesive blue-grey silt.

Middle peat: -2.90 m to -2.00 m OD.

Present in five cores: in 7, 8 and 9 overlying the blue-grey silts, in 10 and 14 overlying pebbly sands which represents the surface of the pre-Holocene drift (Innes *et al.*,1990). Towards the south and east of the site, where the pre-Holocene surface rises, the peat was basal. At this southern, landward end of the site, this peat was overlain by silty-clays. Seaward silty-clays were recorded immediately on top of the peat, but soon pass into a thick sand horizon.

Upper peat: +1.50 m to +3.20 m OD.

In the northerly seaward cores this upper peat was absent, with the sand extending up to the surface alluvium. In all cores south of the River Birket where Holocene sedimentation has taken place this upper peat was present. This peat contained very little wood, macrofossils being restricted mainly to *Phragmites*. Additional information that these borehole records provided was on the overall shape and dimensions of the basin where Holocene sedimentation has occurred. In general, the pre-Holocene (boulder clay) surface slopes in two directions: steeply from south-east to north-west normal to the River Birket, and with a shallower gradient from north-east to the west, parallel to the Birket and towards the entrance and exit for the sea beyond C7 (at Newton Carr unconsolidated sediments have accumulated on boulder-clay and can thus be identified as pre-Holocene). Transects 1 and 3 were taken along the steep slope, and Transect 2 normal to these.

5.5.2a Newton Carr, Hoylake. Transect 1.

The locations of all hand-cores completed at Newton Carr are shown in Figs. 5.33 and 5.36, with the lithostratigraphy of transect 1 illustrated in Fig.5.37.

The lithostratigraphy of Core C7 is taken from the County Council borehole records, and is included in the transect to show the relationship of a deep seaward core to those sampled landwards. The description of C7, in the context of the three-dimensional pattern of sedimentation, is given as part of transect 2 (section 5.5.2b). The pre-Holocene surface sloped gently in a north-westerly direction, with the Holocene sediments accumulating on a pink sandy-gravel base.

Referring to the hand-cores only, the deepest Holocene sediments recorded were pinky-grey silty-clays, down to a minimum altitude of -0.47 m OD in NC5. Above *c.* +1.00 m OD, the silty-clays were grey or blue/grey in colour, with increasing quantities of *Phragmites* towards the top of the stratum where these inorganic sediments were overlain by organic sediments. Overall the altitudinal range of this horizon was from -0.47 m to +1.98 m OD in NC5. In

NC5 and NC7, grey silty-sands separated these silty-clays from the overlying organic sediments.

The organic horizon shown in Fig.5.25, which correlates with the 'upper peat' described in section 5.5.1, had an altitudinal range of +1.70 m to +3.27 m OD. It was thicker in landward cores (1.44 m in NC3) and seaward of NC6 and the River Birket was absent. In NC4 and NC7, this organic horizon was split into two by a thin *Phragmites*-rich clay. In these two cores, the lower part of the organic horizon was a medium to light brown *limus* with *Phragmites*. In NC3, though only one organic horizon was present, the lower part is also a *limus* with *Phragmites*. The altitudinal range of this *limus* deposit was, therefore, from +1.70 m to +2.28 m OD.

Above the *limus*, the composition of this organic horizon was variable within a dark brown, humified peat matrix. The variability was in the quantity of wood, including birch and alder, *turfa*, and other macrofossils including seeds. There was no obvious spatial consistency to this variability; the proportion of these other elements in the peat matrix did not exceed 25%.

Immediately above this upper organic horizon was a battleship-grey silty clay with small quantities of *turfa*, which merged gradually into a grey/brown, iron-stained sandy-silt horizon. This upper inorganic horizon was recorded directly below the top soil, and had an altitudinal range of +2.86 m OD in NC5 to +4.19 m OD in NC3. The surface altitude in Transect 1 ranged from +4.26 m to +4.56 m OD.

5.5.2b <u>Newton Carr, Hoylake. Transect 2.</u>

Fig.5.35, illustrating the County Council boreholes, shows a 'middle peat' between -2.00 and -2.50 m OD, present in the line of cores between Core 7 and Core 14. Hand coring was completed along this line, principally to relocate this peat and find where on the site it became basal, and also to gain an insight and understanding of the three-dimensional lithostratigraphy at Newton Carr.

The lithostratigraphy from this ten core transect, including a piston core (NC17), is presented in Fig.5.38. The transect approximately followed the line of the River Birket, normal to the main south-east to north-west slope. There was a general increase in the depth to boulder-clay in a north-westerly direction (towards C7 and NC30, where sampling was impossible beyond 7.00 m below ground surface), but other variations in the depth to boulder-clay in this transect were undulations within the main dip slope already identified.

The compact 0.20 m thick peat resting upon the boulder-clay surface in C7 was overlain by a cohesive blue grey silt with an altitudinal range of -5.10 m to -2.45 m OD.

In all cores in transect 2, reaching as far as -2.00 m OD, an organic horizon was found in the altitudinal range -2.90 m to -1.67 m OD. This organic horizon, typically < 0.25 m thick, was a well-humified, dark brown and compacted peat. Wood and *Phragmites* were found in most cores where this horizon was sampled, with the wood content increasing lower down the horizon. In NC17 and NC12, where this peat was basal resting on weathered boulder clay, large pieces of alder were found. In NC12, the upper contact of this horizon was slightly eroded, with a *lim.supp.* of 1, but elsewhere there was a gradual transition into the overlying inorganic sediments.

Apart from in the two most seaward cores (C7 and NC30), these overlying inorganic sediments, comprising varying combinations of silt through to clay, had an altitudinal range of -2.10 m to +2.14 m OD. The upper altitude was defined by the transition into organic sediments, or what has so far been referred to as the 'upper peat'. Below c.+1.00 m OD, this horizon was typically described as a silty-clay, though in NC17, the silt fraction was higher than elsewhere. The colour of the lower part of this silty-clay stratum did vary from pinky-grey in the more seaward cores (NC10, 11 and 12), to a battleship- or blue-grey in the more landward locations (NC14, 17 and 15).

In Transect 1, an upper organic horizon was identified as having an altitudinal range of +1.70 m to +3.27 m OD. Over the whole of transect 2, the altitudinal range for this horizon was +1.26 m to +3.35 m OD. If only cores seaward of NC13, inclusive, are considered the range is +2.57 m to +3.27 m OD. Seawards of NC13, silt and silty-clay sedimentation continued to a higher altitude in the sedimentary column. In NC10, 11 and 12, silts with some sand were recorded between c.0.00 m and +2.00 m OD. Between 0.20 m and 0.50 m before this thick inorganic horizon is replaced by full organic sedimentation, a fine-grained partially organic clay replaced the coarser silts and silty clays. The organic material in these clays was typically humified *turfa* and *Phragmites* rhizomes. Seaward of NC13, where the upper organic sediments were absent, the upper organic sequence was very much as described for Transect 1 with a light brown *limus* merging with a darker *substantia humosa* in the upper part of the stratum. In NC14, 17 and 15, this upper organic sequence was thicker and also divided into two by a thin organic clay, though thick enough to be clearly visible on the lithostratigraphic plot in Fig.5.27.

The lower of these two organic horizons, with an altitudinal range of +1.26 m to +2.35 m, was described as a fresh *limus* with *Phragmites* and detrital wood. In the upper few centimetres of this horizon, the peat darkened and was more humified. It is here in NC14 that 25% charcoal was recorded. The clay separating the two upper organic horizons was typically 0.20 m to 0.30 m thick, and in NC14 was described as a fine blue/grey clay with *Phragmites* and some *detritus*. The upper and lower contacts of this clay with the overlying and underlying peats were very transitional. The highest organic horizon in this sequence (cores NC14 to NC17) had an altitudinal range of +2.09 m to +2.66 m OD, and had the same characteristics as the upper organic sequence described in Transect 1, and cores NC10 to NC12 in this transect, namely a thin light brown *limus* merging with a darker humified *substantia humosa*.

In C7 and NC30, these organic sequences were absent: instead there were relatively coarse organic sediments above c.-2.00 m OD. From this altitude to +3.41 m in NC30 very wet, slightly laminated grey sands were recorded. The sands were quite fine, with a very small fraction of silt present. Also in this core, detrital wood with a vertical orientation was sampled between -0.30 m and +1.30 m OD.

The top inorganic horizon displayed a slight coarsening seawards from iron-stained silt with some clay and sand in NC15 to a laminated sand with some silt and iron staining in NC30.

5.5.2c <u>Newton Carr, Hoylake. Transect 3.</u>

A third transect of cores, parallel to the first and normal to the second, was completed at Newton Carr to confirm the pattern of lithostratigraphy at the eastern end of the site (Fig.5.39). The depths to boulder-clay on this transect were also used as an initial test of the accuracy of the first seismic refraction line.

The features of the lithostratigraphy found in transect 3 replicate those found in transects 1 and 2 and the commercial boreholes. Between *c.*-1.50 m and *c.* +1.50 m OD silty-clay sediments were recorded, overlain by a thick organic sequence between *c.* +1.50 m and *c.* +3.00 m OD. As in Transect 1, north of the River Birket (NC24) the upper organic sequences were absent and replaced by slightly laminated sands with some silt.

5.5.2d <u>Newton Carr, Hoylake. Summary of the lithostratigraphy.</u>

1. A woody basal peat was recorded at -5.30 m OD, overlain by silty clays.

2. A humified peat was recorded extensively across the site between -2.50 m and -1.50 m OD, as both an intercalated and a basal peat.

3. Above this peat, north of the River Birket coarse sands dominated sedimentation, while south of the Birket a sequence of finer-grained intercalated sediments was recorded, including:

4. Silty clays from -1.50 m to +1.50 m OD.

5. An organic sequence between +1.50 m and +3.00 m OD, split in two by a thin organic clay. Below this thin clay, the organic sediments were predominantly *limus*, and above humified peats.

6. Above +3.00 m OD, iron-stained silty clays were recorded.

5.5.3 Newton Carr, Hoylake. Results of the seismic refraction survey.

Five seismic refraction lines were completed at Newton Carr, but because of the numerous problems encountered (section 3.4.3) pre-Holocene depths could only be established on two. On all of the lines the depth to sandstone was established. The locations of the two lines where pre-Holocene depths were established are shown in Fig.5.34, and the resulting modelled depth profiles in Fig.5.40.

On Line 1 (Fig.5.40a) there was a very close correlation between seismic depths and hand-core depths, because of the absence of high velocity sand layers overlying the boulder-clay. The slope of the pre-Holocene surface in a northerly direction is clear in Fig.5.40a replicating the hand-core results of Transect 3 (Fig.5.39) along which the line was shot.

On Line 5 (Fig.5.40b), boulder-clay depths were only established for a 25 m section of the line where there was no hand-core control. The depths established show no dip in either the boulder-clay or the sandstone surfaces.

5.5.4a Newton Carr - 17: Diatom analysis.

Sixty-nine samples were prepared for diatom analysis from NC-17. In general levels from the coarser inorganic and humified organic sediments were not possible to count. A diagram from the lower section of the core is presented in Fig.5.41 and one from the upper section in Fig.5.42. The characteristics of each of the zones identified are described below.

Fig.5.41. Lower Diatoms.

NC-17a (633-626 cm, -1.91 to -1.84 m OD)
The lower boundary of this zone is defined by the base of the diagram, between stratum 3 and 4. This zone is dominated by *Nitzschia navicularis, Podosira stelliger* and *Paralia sulcata*. *Scoliopleura tumida, Rhaphoneis amphiceros, Diploneis didyma,* and *Coscinodiscus apiculatus* are also prominent species.

NC-17b (626-619 cm, -1.84 to -1.77 m OD)
The lower boundary of this zone is defined by a fall in the value of *Navicula peregrina*, and rise in the values of *Navicula distans* and *Cocconeis distans*. This zone is characterised by falling frequencies of *Nitzschia navicularis*

and rising frequencies of *Paralia sulcata*. Other prominent species include *Podosira stelliger* and *Coscinodiscus apiculatus*.

NC-17c (578-568 cm, -1.36 to -1.26 m OD)

Between 619 and 578 cm, no diatoms were counted. In this zone *Podosira stelliger* and *Paralia sulcata* are the most common species in this zone, but also notable are *Nitzschia navicularis, Triceratium favus, Gyrosigma litorale, Coscinodiscus apiculatus* and *Actinophylus undulatus* producing a mixed marine and marine/brackish assemblage.

Fig.5.42. Upper diatoms.

NC-17d (318-312 cm, +1.24 to +1.30 m OD)

The lower boundary of this zone is defined by the base of the diagram. The zone is characterised by low species diversity with *Diploneis interrupta* the dominant species with *Navicula peregrina, Navicula pusilla, Synedra acus,* and *Diploneis didyma* also present.

NC-17e (312-304 cm, +1.30 to +1.38 m OD)

The lower boundary of this zone is defined by a fall in the frequencies of *Synedra acus* and *Diploneis interrupta* and a rise in the frequencies of *Navicula peregrina* and *Diploneis smithii* which are the dominant species in this zone.

NC-17f (304-283 cm, +1.38 to +1.59 m OD)

The lower boundary of this zone is defined by a fall in the frequency of *Diploneis smithii* and a rise in the frequencies of *Diploneis interrupta* and *Podosira stelliger*. This zone is characterised by a much higher species diversity than the zones below with *Diploneis interrupta* the dominant species.

NC-17g (257-246 cm, +1.85 to +1.96 m OD)

No diatoms were present in the levels below the lower boundary of this zone. This zone is characterised by a fresh and brackish assemblage with *Navicula peregrina, Stauroneis anceps* and *Synedra capita* the most dominant species.

NC-17h (246-231 cm, +1.96 to +2.11 m OD)

The lower boundary of this zone is defined by a sharp rise in the frequency of *Pinnularia gentilis*, which is the dominant species in the zone. Also present are *Cymbella aspera, Navicula peregrina* and *Diploneis interrupta* producing a fresh and brackish assemblage.

NC-17i (231-203 cm, +2.11 to +2.39 m OD)

The lower boundary of this zone is defined by the disappearance of *Pinnularia gentilis* and increase in the frequency of *Diploneis interrupta* and *Scoliopleura tumida*. The zone is characterised by fluctuating frequencies of the brackish species: *Navicula peregrina, Diploneis interrupta* and *Scoliopleura tumida* along with *Diploneis ovalis, Podosira stelliger* and *Paralia sulcata*.

NC-17j (203-195 cm, +2.39 to +2.47 m OD)

The lower boundary of this zone is defined by the disappearance of *Diploneis interrupta* and *Scoliopleura tumida*, increases in the frequency of *Navicula peregrina*, and appearance of *Nitzschia subtilis*. This zone is dominated by *Navicula peregrina* though *Synedra ulna, Nitzschia subtilis* and *Nitzschia scalaris* attain values >10% total diatoms.

NC-17k (195-188 cm, +2.47 to +2.54 m OD)

The lower boundary of this zone is defined by a sharp increase in the frequency of *Pinnularia gentilis* and a fall in the frequency of *Navicula peregrina*. The zone is dominated by *Pinnularia gentilis* with *Nitzschia subtilis*.

NC-17l (188-166 cm, +2.54 to +2.76 m OD)

The lower boundary of this zone is defined an increase of *Pinnularia gentilis* which accounts for >90% total diatoms throughout the zone. *Cymbella aspera* and *Eunotia parallela* are the only other species recorded in every level through this zone producing almost an entirely fresh assemblage.

NC-17 m (166-155 cm, +2.76 to +2.87 m OD)

The lower boundary of this zone is defined by a fall in the frequency of *Pinnularia gentilis*, which still dominates the zone along with *Stauroneis anceps* and *Navicula peregrina*.

NC-17n (155-150 cm, +2.87 to +2.92 m OD)

The lower boundary of this zone is defined by the disappearance of *Pinnularia gentilis* and increase in the frequency of *Diploneis interrupta* to c.75% total diatoms. *Navicula peregrina* and *Caloneis formosa* are also present producing a brackish assemblage.

5.5.4b Newton Carr - 17: Pollen Analysis.

A pollen diagram from the basal peat of NC17 is presented in Fig.5.43 and from the upper peats in Fig.5.44.

Fig.5.43: Lower Pollen.

NC17-a (652-640 cm, -2.10 to -1.98 m OD)

This zone is characterised by the tree pollen of *Betula, Pinus, Quercus* and *Alnus* and the pollen of *Corylus* and Gramineae.

NC17-b (640-632 cm, -1.98 to -1.90 m OD)

In this zone there is a slight fall in the proportion of tree pollen and rise in herb pollen relative to NC-17a. This is because of a rise in the frequency of Gramineae and Cyperaceae.

Fig.5.44: Upper Pollen.

NC-17c (286-152 cm, +1.56 to 2.90 m OD)

Levels have been counted at each of the four organic/inorganic lithologic contacts recorded in the sediments above +1.00 m OD at NC-17. Tree pollen types are dominated by *Quercus* and *Alnus*, though at 154 cm, *Betula* is recorded in higher frequencies. *Corylus* and Gramineae are recorded at frequencies between 10 and 20% throughout the zone. Chenopodiaceae, *Artemisia* and *Aster*-type are also recorded throughout this zone.

5.5.5 Newton Carr, Commercial Bore - 7.

NC-C7 and NC-C8 were collected by Merseyside County Council, and have proven to be very accurate in their sediment description. The peat samples from these cores were obtained by J.Innes and pollen analysis completed (Innes *et al.* 1990), and as part of this thesis ^{14}C-dating and diatom analysis were carried out.

NC-C7 is located in the northwestern corner of Newton Carr, nearer to the sea than any other core. The pre-Holocene surface has been shown to dip towards the northwest, so the deepest sediments are recorded here. An organic layer was recorded *c.* 10 m below ground surface (*c.* -5.0 m OD), overlain by silts and clays. Diatom and pollen analysis showed that the silts and clays were marine in origin, so a ^{14}C-date was obtained from the transgressive overlap of this peat.

The sediments either side of the dated peat (labelled stratum 2 below) were described as follows.

3	980-715 cm	-2.45 to -5.10 m OD	Saturated, cohesive blue silt.
2	980-1000 cm	-5.10 to -5.30 m OD	Dark brown silty peat with wood fragments.
1	1000-1200 cm	-5.30 to -7.30 m OD	Unsorted, impure grey to brown silty-sand with pebbles, cobbles and angular rock fragments including granite, volcanics and coarse grained sediments.

Three samples were prepared for diatom analysis from stratum 3. A full count was only possible for one level (979 cm). The results from this level are tabulated below.

Paralia sulcata	6
Podosira stelliger	10
Coscinodiscus sp.	3
Actinophyllus undulatus	4
Surrirella fastuosa	6
Nitzschia scalaris 70	
Diploneis didyma	4
Nitzschia punctata	1
Nitzschia navicularis	2
Diploneis interrupta	1
Navicula peregrina	33
Cymbella aspera	8
Pinnularia sp.	5

A pollen diagram from the basal peat is presented in Appendix 7, and described below.

NC-C7a (1000-992 cm, -5.30 to -5.22 m OD)
This zone is dominated by *Betula, Pinus, Ulmus, Quercus, Corylus*, Gramineae and low frequencies of *Alnus*.

NC-C7b (992-970 cm, -5.22 to -5.10 m OD)
The lower boundary of this zone is defined by a rise in the frequency of *Alnus* and fall in the frequency of Gramineae: otherwise this zone has the same characteristics as NC-C7a, though the frequency of herbs rises.

The diatoms form a marine/brackish assemblage in the silts and clays immediately above the peat. In the peat itself the frequency of herbs rises towards the transgressive overlap and the saltmarsh indicators Chenopodiaceae and *Artemisia* are recorded. The dated transgressive overlap therefore represents a period when there was a transition from a fen environment to an upper saltmarsh environment.

5.5.6 Newton Carr, Commercial Bore - 8.

NC-C8 is located in the northwestern corner of Newton Carr. An organic horizon was recorded *c.* 8 m below ground surface (*c.* -3.0 m OD). The sediments either side of this dated peat (labelled stratum 2) were described as follows.

3	750-820 cm	-2.40 to -3.10 m OD	Moderately soft dark grey to brownish grey silty clay with remains of peat in the lower part.
2	820-860 cm	-3.10 to -3.50 m OD	Brown, well compressed and decomposed peat. Not saturated. Clayey in lower part.
1	860-950 cm	-3.50 to -4.40 m OD	Saturated blue grey sandy silt.

A pollen diagram from stratum 2 is presented in Appendix 7, and described below.

NC-C8-a (820-860 cm, -3.10 to -3.50 m OD)
Trees and shrub pollen remain consistent throughout this zone with ***Betula, Pinus, Ulmus, Quercus, Alnus*** and *Corylus* present. Herb pollen is dominated by Gramineae, though towards the top and bottom of the zone the diversity of herb pollen increases to include *Taraxacum*-type, Chenopodiaceae and *Artemisia*. Some aquatic pollen, particularly *Lemna*, are found in the lower part of the zone.

5.5.7 Newton Carr: Synthesis.

From the lithostratigraphic survey, the Newton Carr basin has been shown to deepen from south to north-west. The thickest sequence of Holocene sediments (*c.* 10 m) was recorded in Bore C7 at the far north-west of the site. It was not possible to core seawards of this core because of the thick sand deposits. Attempts to overcome this problem by employing seismic refraction techniques were only partially successful. However, the increasing coarseness of sediments to the north-west of the site indicates that this was where marine phases influencing the site originated.

The terrestrial phase of sedimentation recorded in C7 at -5.30 m to -5.10 m OD contains evidence of local and regional environmental changes. The dramatic increase in alder at -5.22 m OD reflects the spread of alder throughout the UK between *c.* 8000 and 7000 BP. Before the onset of saltmarsh conditions at -5.10 m OD a wooded fen environment is indicated with oak, alder, pine and birch the dominant trees. Where there is a lithologic change from organic to inorganic sedimentation an upper-saltmarsh environment is inferred because of a marine/brackish diatom assemblage dominated by *Nitzschia scalaris* and *Navicula peregrina*.

Nearly 3.00 m of inorganic sediments, described as a cohesive blue silt, were deposited at Newton Carr before the next terrestrial phase was recorded. This second phase was extensive, being recorded in all cores of sufficient depth at the site. Like the organic sediments from the first terrestrial phase, the peats were very humified with only limited *Phragmites* and other plant remains. There are two separate pollen diagrams for this peat at the site; from NC-17 and at a more seaward location, C8. At NC-17 alder and oak are particularly dominant, whilst at the more seaward location, a more mixed tree assemblage with birch and pine is recorded. These differences enable a distinction between local and more regional vegetation to be made, so that the higher proportion of alder towards the edge of the Newton Carr basin is attributable to its local dominance within a wooded fen environment.

In NC-17, the second marine phase is recorded between -1.90 m and +1.57 m OD. A close examination of the lithostratigraphy from NC-17 indicates variation in the strength of the marine influence with laminated sands and organic clays being recorded within this altitudinal range. Between cores however, the sequence and altitudes of these lithostratigraphic features are not at all consistent, implying that the variation in lithology is largely due to the changeable microtopography of the saltmarsh landscape. In such environments sands can be deposited in a channel, whilst organic clays are forming on an adjacent hummock. The dendritic drainage pattern of the saltmarsh would certainly account for the altitudinal and spatial irregularity of lithologic changes within this marine phase. The diatom analysis supports the notion of a saltmarsh and mud flat environment.

In NC-17, the third phase of terrestrial sedimentation identified by Innes *et al.* (1990) is recorded between +1.57 m OD and +2.90 m OD. The more detailed lithostratigraphic and biostratigraphic work completed as part of this study has however shown that this terrestrial phase of sedimentation is separated by a further marine episode between +2.12 m OD and +2.37 m OD. The most landward two cores in Transects 1 and 2 do not show evidence of this fourth marine phase, but all other cores taken at Newton Carr do. The prevalence of organic remains within the sits and clays, and the more limited spatial extent of this fourth marine phase, indicate that saltmarsh conditions were prominent at the site but fully open marine conditions did not occur. A diatom assemblage dominated by brackish forms -*Diploneis interrupta, Navicula peregrina* and *Scoliopleura tumida*- with low frequencies of both marine and fresh/brackish species confirms this view.

Chapter Six.
Sea-level Changes.

6.1 Indicative Meaning of transgressive and regressive overlaps.

A sea-level index point must have an indicative meaning and a relationship to a former tide level so that an altitudinal correlation can be made with other sea-level index points, which will also have established indicative meanings.

Contemporary studies have been discussed by Tooley (1978) which reveal a wide range of estimates for the formation of organic deposits with respect to sea-level. Shennan (1980) states that in intercalated coastal sequences, deposits found one above the other without an hiatus must have formed in environments that existed side by side in space. So, the transition from a saltmarsh to freshwater community has an indicative range equal to the range of the transition from one community to the other and not that of the individual community. Preuss (1979) quotes the indicative range of *Phragmites* to be 0.70 m, while Shennan (1982a) quotes a *Phragmites* peat directly above or below a saltmarsh deposit as having an indicative range of 0.20 m.

> *"Therefore the level where pollen, diatom, macrofossil and stratigraphic analysis reveal a change in sedimentary environment provides the best sample for ^{14}C dating."*
>
> *Shennan (1980, p.209).*

Kidson and Heyworth (1979) note that sequences within a saltmarsh are not good transitional features to place indicative meanings upon, but the boundary between upper marsh and a reedswamp or fen community forming close to MHWS can be more accurately placed. For instance although saltmarsh pollen families Gramineae and Chenopodiaceae are easy to recognise, their separation into species is impossible. Therefore upper marsh species such as *Agropyron pungens,* middle marsh species such as *Halimione portulacoides* and lower marsh species such as *Spartina patens* are indistinguishable. Conversely a vegetation community forming at *c.* MHWS is usually quite distinguishable from one forming above it, perhaps as a fen community. The following examples collected as part of this thesis help demonstrate these ideas.

Figs. 5.28 and 5.30 show pollen and diatom data from Hendre fawr-21, strata 15 to 17 where a regressive overlap is recorded between strata 16 and 17. Between +1.11 m and +1.23 m OD a middle marsh environment is indicated by the dominance of *Nitzschia navicularis* (Round, 1960) with a strong marine influence shown particularly by the presence of *Paralia sulcata, Podosira stelliger* and planktonic *Coscinodiscus* species (de Wolf, 1982). Immediately below the regressive overlap there is a switch in the diatom assemblage to one dominated by the brackish species *Navicula peregrina* and *Diploneis interrupta* and the marine/brackish *Diploneis smithii*. Carter (1933), following investigations at Ynyslas, noted that *Navicula peregrina* and *Diploneis interrupta* have a strong preference for the upper levels of a saltmarsh, and although *Diploneis smithii* is a marine/brackish species he noted that it was rare in the lower levels of a marsh and very much associated with the higher levels of the marsh. At +1.26 m OD, 0.01 m into the peat, the proximity of saltmarsh conditions is indicated by the very high Chenopodiaceae and Gramineae count along with the presence of *Artemisia* and Aster-type and the remains of *Phragmites* macrofossils. Above this level the saltmarsh indicators decline to be replaced by a semi-forested environment.

Between +1.11 m and +1.32 m OD there is clearly a transition from a marine/brackish middle saltmarsh environment through to an upper marsh or reedswamp environment and then into a terrestrial environment. The sample has a definable indicative meaning and is therefore appropriate for dating.

In the above example the succession of environments inferred from the stratigraphic evidence is consistent with a contemporary spatial model of environments to be found between lower sandflat and fen. These particular environments have a relationship to sea-level, or MHWS: therefore we can state that the stratigraphic changes recorded at Hendre fawr-21 are the result of changes in the level of the ground surface in relationship to sea-level. Commenting upon work completed by Cheesbrough *et al.* (1969), Tooley (1978) observes that saltmarsh environments can, however, have wide altitudinal ranges. In the Ribble estuary *Puccinellia* marsh was recorded between +3.90 m and + 4.90 m OD, and *Spartina* between +2.89 m and +4.45 m OD. But as Shennan (1980) states, where these environments are recorded adjacently within the stratigraphic profile, interpretation of change can be more accurate. This change need not necessarily be the result of a change in sea-level, but could be due, for example, to increases or decreases in the rate of sedimentation, changes in tidal range, or a tectonic event.

6.1.1 Biostratigraphic Indicators.

The characteristics of the changes in pollen profiles in response to watertable and sea-level movements have been investigated in a number of contexts (Godwin, 1978; Tooley, 1978; Long, 1991). In this study there has been a more pronounced reliance upon diatom analysis, providing an opportunity to qualitatively assess the changes in diatom composition through stratigraphic profiles.

Inspection of the diatom diagrams constructed from Morfa Penrhyn, Newton Carr and Hendre fawr appeared to show a subtle interchange in the frequencies of particular species which did not always appear directly related to the salinity classification used. At Hendre fawr, for example, *Diploneis interrupta* and *Navicula peregrina* universally increase in frequency towards regressive and transgressive overlaps and often co-exist together within inorganic horizons. *Nitzschia navicularis* is rarely found in abundance with *Navicula peregrina*, though sometimes with *Diploneis interrupta*. Round (1960) notes that *Diploneis interrupta* and *Navicula peregrina* seem to prefer upper marsh environments, though Vos and de Wolf (1988) place *Navicula peregrina* in an ecological group favouring intertidal and subtidal areas. In contrast Carter (1933) and Round (1960) state that *Nitzschia navicularis* is more typical of lower or middle marsh. At Morfa Penrhyn the co-existence of *Nitzschia navicularis* and marine species, particularly *Paralia sulcata* and *Podosira stelliger,* was noted and at Hendre fawr this pattern is repeated (zones HF-21g, i and l). Certain species, notably *Diploneis didyma*, appeared to have a less predictable pattern of occurrence.

In order to resolve some of these questions, correlation and Principal Components Analyses (PCA) were carried out on five diatom datasets: Hendre fawr -21 (Upper and lower), Hendre fawr -29, Morfa Penrhyn -20, Newton Carr -17. The PCA, in particular, was useful in assessing whether salinity tolerance of species was the main factor controlling frequencies at transgressive and regressive overlaps.

6.1.1a <u>The Diatom Data.</u>

The raw, stratigraphically constrained data from each of the five sites were examined. In general species which attained 5% of the total diatoms were included in the analysis, the exception being where a species is common only to one of the datasets and therefore of less value to a wider synthesis such as *Synedra capita* at Newton Carr. Except for the Hendre fawr -29 data, a square root transformation was applied to reduce skewness. A transformation was not applied to Hendre fawr - 29, because skewness was typically between ±1.

6.1.1b <u>Correlation.</u>

Correlation, using Pearson's measure, was carried out on the five transformed datasets. The results for the species discussed above are for three sites in Tables 6.1 to 6.3 below.

Table 6.1. <u>Morfa Penrhyn: correlation results.</u>

Paralia s.	1.000						
Podosira s.	0.544	1.000					
Diploneis d.	-0.727	-0.593	1.000				
Nitzschia p.	-0.022	-0.222	0.177	1.000			
Nitzschia n.	0.452	0.411	-0.488	0.266	1.000		
Diploneis i.	-0.094	-0.355	-0.104	0.290	0.022	1.000	
Navicula p.	-0.267	-0.467	0.001	-0.152	-0.326	0.687	1.000
	Par s.	Pod s.	Dip d.	Nit p.	Nit n.	Dip i.	Nav p.

The most striking feature of this matrix is the lack of strong correlations, particularly negative. The strongest correlations are with species within the same or adjacent salinity class (*Navicula peregrina* with *Diploneis interrupta* and *Paralia sulcata* with *Podosira stelliger*). Though *Diploneis didyma* is classified as a **MB** species its strong negative correlation with *Paralia sulcata* is plausible; Round (1960) has noted the preference of *Diploneis didyma* for upper marsh environments.

Table 6.2. Hendre fawr - 29: correlation results.

Paralia s.	1.000					
Podosira s.	0.638	1.000				
Nitzschia p.	0.442	0.591	1.000			
Nitzschia n.	-0.627	-0.618	-0.702	1.000		
Diploneis i.	-0.061	-0.420	-0.782	0.156	1.000	
Navicula p.	-0.098	-0.384	-0.664	0.304	0.597	1.000
	Par s.	Pod s.	Nit p.	Nit n.	Dip i.	Nav p.

From this much smaller dataset, which had little skewness within the raw data, there are more stronger correlations including those already identified from Morfa Penrhyn. Additionally there is a strong negative correlation between the **BM** species *Nitzschia punctata* and the **B** species *Diploneis interrupta, Navicula peregrina* and *Nitzschia navicularis*.

Table 6.3. Newton Carr: correlation results.

Paralia s.	1.000					
Podosira s.	0.832	1.000				
Diploneis d.	0.591	0.615	1.000			
Nitzschia n.	0.769			1.000		
Diploneis i.	-0.109	0.028	0.199		1.000	
Navicula p.	-0.480	-0.422	-0.271		0.131	1.000
	Par s.	Pod s.	Dip d.	Nit n.	Dip i.	Nav p.

This matrix demonstrates some of the problems in comparing correlations between datasets. The correlations between marine species remain strongly positive, but that between the brackish species *Diploneis interrupta* and *Navicula peregrina* is weak (0.131). The main difference in the diatom counts at Newton Carr compared with other sites is that counts were possible within the organic as well as the inorganic sediments. On the whole the organic sediments were dominated by fresh species but some brackish species, particularly *Navicula peregrina*, were present whilst other brackish species such as *Diploneis interrupta* were conspicuously absent. These patterns will lead to a low correlation amongst the brackish species. The very strong correlation between *Nitzschia navicularis* and the full marine species is also exaggerated because of counting in organic sediments where both are absent. Caution should also be added to this relationship because of the very low frequencies of *Nitzschia navicularis* and little fluctuation within the upper inorganic sediments.

6.1.1c **Principal Components Analysis.**

PCA is a scaling or transformation procedure which takes no account of the serial order of data. Using PCA a large dataset can be simplified so that the variance within the data is expressed as series of new variables (Principal Components). There are two methods that can be used in PCA: the correlation or covariance methods. The correlation method is useful when comparing datasets because each variable has equal weighting and is thus less influenced by the effects of dominant variables. Dominant variables are a problem with the covariance method, but Daultrey (1976) does point out that the covariance method can have greater interpretative power because of a more direct relationship between the Principal Components and original variables.

PCA has been widely applied in ecological studies to data that is being examined for spatial variations (Williamson, 1978) and also stratigraphic or temporal variations (Shennan and Innes 1986). Single levels are used as the base unit for comparison and:

> *"principal components analysis seeks to represent in low-dimensional space the similarities, defined in a mathematical sense, between samples, it follows that samples*

of similar composition, irrespective of which sequence they are derived from, will, if the ordination is an accurate representation of the original data, be positioned together in the ordination." (Birks and Berglund, 1979, p.269).

Despite the widespread application of PCA and other ordination techniques to ecological datasets a number of problems have been identified and assumptions questioned. In the analysis conducted here an attempt is being made to find environmental correlates with vegetation. Beals (1973) has discussed the complex relationship between an individual species and its environment, noting that the frequency of a particular species is not due to a single factor. Thus, although the frequency of a particular diatom species may seem to be largely related to salinity, this factor cannot be seen as isolated from other environmental variables.

Both the correlation and covariance methods have been applied to the five datasets. Table 6.4 (overleaf) shows that the percentage contribution of PC1 to total variance tends to be greater when using the covariance method. For the Newton Carr dataset, which has dimensions of 15 variables by 51 cases, PC1 accounts for 50.69% of variance using the covariance method, compared with 24.55% using the correlation method.

Table 6.4. Variable loadings for PC1.

	Correlation					Covariance				
	Morfa Penrhyn	Hendre fawr (Lower)	Hendre fawr (Upper)	Hendre fawr - 29	Newton Carr	Morfa Penrhyn	Hendre fawr (Lower)	Hendre fawr (Upper)	Hendre fawr - 29	Newton Carr
% Contribution	25.38	29.99	54.14	58.67	24.55	40.06	59.87	70.82	82.12	50.69
Paralia sulcata (M)	0.592	-0.498	-0.880	0.533	0.663	-1.731	-0.365	-0.979	4.364	-1.670
Podosira stelliger (M)	0.752	-0.119	-0.904	0.763	0.720	-1.261	0.235	-1.487	2.150	-1.469
Nitzschia socialis (M)	-0.407				0.451	0.017				-0.592
Actinophyllus und. (MB)			-0.948					-1.039		
Diploneis didyma (MB)	-0.419	-0.375			0.598	3.017	-0.284			-0.768
Diploneis smithii (BM)	0.082	-0.182	0.394	-0.867	0.295	-0.110	-0.768	0.859	-6.018	-0.799
Scoliopleura tumida (B)	0.007	-0.470			0.426	-0.162	-0.363			-1.289
Caloneis formosa (B)	-0.374				-0.064	0.082				-0.111
Nitzschia navicularis (B)	0.467	-0.882	-0.911	-0.705		-1.568	-2.461	-3.801	-11.558	
Nitzschia punctata (B)	-0.129	-0.607	0.145	0.952		0.071	-2.073	-0.024	29.971	
Diploneis interrupta (B)	-0.635	0.946	0.891	-0.733	0.270	0.102	4.599	3.912	-7.868	-2.666
Navicula peregrina (BF)	-0.779	-0.042	0.234	-0.739	-0.284	0.903	-0.786	0.097	-2.429	0.138
Nitzschia subtilis (F)					-0.564					1.168
Pinnularia gentilis (F)					-0.766					4.906

These results using the correlation method are particularly consistent with salinity appearing to be the main factor behind the loadings calculated at four of the sites. At Morfa Penrhyn, Newton Carr and Hendre fawr - 29 marine species have a strong positive loading and fresh or brackish species neutral or negative loading, and at Hendre fawr (Upper) marine species have negative loadings and brackish positive but this does not alter the interpretation.

All of the marine or brackish species in the above list are classified by de Wolf (1982) as benthonic except for *Podosira stelliger* and *Actinophyllus undulatus* which are classified as planktonic. Both of these species are marine, *Podosira stelliger* 'most commonly found in the saltiest parts of estuaries' (van der Werff, 1958-74). Correlations and the PCA have shown the association of these two species with the benthonic marine *Paralia sulcata* indicating that life position of species is not a significant influence over these results. However, van der Werff (1958-74) and Vos and de Wolf (1988) classify *Paralia sulcata* as planktonic. A wider review of the literature reveals just as ambiguous a picture. du Saar (1969) classifies the species as both benthonic and planktonic with Cleve-Euler (1951-55) suggesting that *Paralia sulcata* becomes planktonic in the autumn, though it is largely a benthonic species.

Vos and de Wolf (1988) have discussed the importance of separating the allochthonous from the autochthonous components, and indeed this point has been elaborated upon in Chapter 3. In the case of *Paralia sulcata* there are times when it can fall into either of these categories but here there is a strong case to suggest it is mainly autochthonous.

(i) *Paralia sulcata* is the most abundant of the marine diatoms recorded at all sites. The frequency of planktonic forms (e.g. *Auliscus sculptus* and *Actinophyllus undulatus*) tends to be less. Where *Paralia sulcata* is a dominant species, Kjemperund (1981) suggests it is usually in its autochthonous form.

(ii) Long (1991), who classified *Paralia sulcata* as benthonic, noted that in the East Kent Fens the species was largely recorded in fine-grained, low energy sediments. In North Wales this pattern is repeated.

From the covariance method, the results from Table 6.4 are not always so straightforward to interpret, particularly in the case of the large Newton Carr dataset. The component loadings at this site for *Paralia sulcata* (M), *Diploneis interrupta* (B) and *Pinnularia gentilis* (F) using the covariance method are -1.670, -2.666 and +4.906 respectively. Though *Diploneis interrupta* is a species which does co-exist with *Pinnularia gentilis* at Newton Carr, *Paralia sulcata* is not and yet has a loading closer to that of *Pinnularia gentilis*. The problem is caused because *Diploneis interrupta* and *Pinnularia gentilis* are often very dominant species, attaining values up to 90% total diatoms, and by definition cannot be dominant together. The covariance method will assign quite different loadings to variables with such distributions. *Paralia sulcata* is never a dominating species at Newton Carr: hence it does not have such a strong component loading. When *Pinnularia gentilis* is taken out of the analysis, the loading of *Paralia sulcata* is similar (-0.517), but *Diploneis interrupta* has a completely different loading (+4.156).

Despite the differences in component loadings identified between the correlation and covariance methods, both illustrate the contrast between organic and inorganic sedimentation at Newton Carr (Figs. 6.1 and 6.2) when the component scores are plotted. Using the correlation method, no obvious environmental label could be assigned to PC2. At Newton Carr, however, with the covariance method PC2, accounting for 21.94% of variance, does appear to be distinguishing between periods of brackish and marine dominated assemblages within inorganic sediments compared with PC1. For PC2 all species, except four, have neutral loadings. The exceptions are:

Paralia sulcata	-2.015
Podosira stelliger	-1.340
Diploneis interrupta	+2.866
Navicula peregrina	+1.982

In Fig.6.2, levels 1-2, PC2 has a positive loading reflecting the dominance of *Diploneis interrupta* (Fig.5.42) compared with levels 40-48 where marine species are more prominent (Fig.5.41).

6.1.1d **PCA: Overview and conclusions.**

The following observations are noted following PCA on diatom data.

■ Using the correlation method, the broad trend in component loadings for PC1 appears largely related to salinity class. Salinity is a good proxy for the degree of marine conditions at a site: therefore the diatom patterns found can reasonably be said to be primarily a function of the interplay between marine and terrestrial conditions. In more complex datasets, such as at Newton Carr, the pattern is not always so clear when using the covariance method. Beals (1973) argues that PCA is most successfully applied to data where the correlations of species are likely to be linear, or near linear with their environment, and that only a narrow range of heterogeneity is tolerated in the analysis. The more complex datasets used in this analysis come from sites where the levels are derived from a wider range of sediment types. In turn this increases the number of species included in the analysis and decreases their independence from each other.

■ At Newton Carr and other sites, particularly Morfa Penrhyn and Hendre fawr (Upper and Lower), the most rapid changes in the trend of the graph of PC1 are associated with sediments adjacent to transgressive or regressive overlaps.

■ Using the definition put forward by Vos and de Wolf (1988) such rapid changes could be interpreted as an indirect indication that the diatom assemblages are autochthonous. Vos and de Wolf (1988) defined seven diatom salinity classes and argued that the species two salinity classes removed from the dominant class are likely to be allochthonous. Non-neutral Component loadings for the datasets examined here tend to fall into 'marine' or 'brackish' groups and PC1 tends to reflect the balance between these two groups, displaying quite rapid switches between the two at or adjacent to lithological changes.

It must be stressed however, that PC1 rarely accounts for more than 50% of variance within any dataset and the factors identified here are by no means the only controlling variables. Our limited knowledge of diatom taxonomy is a problem; for example, the classification of *Paralia sulcata* as either benthonic or planktonic. In all of the diatom diagrams produced here and also those from similar coastal environments (Lancashire (Tooley, 1978), the East Kent Fens (Long, 1991)) it is rare that species from one salinity class completely dominate. This widespread pattern is perhaps a reflection of the wide salinity tolerances (e.g. *Cyclotella striata* 1000-17000 mg Cl/L, *Navicula peregrina, Caloneis formosa, Diploneis didyma, Diploneis ovalis* 5000-17000 mg Cl/L) of many species as well as the inwashing of planktonic and epiphytic types.

■ One of the initial reasons for carrying out PCA was to examine the changes in the frequencies of particular species and the association of species in different salinity classes. Based on this small sample of five sites the following observations are possible:

(i) The brackish species *Diploneis interrupta* and *Navicula peregrina* are not correlated or have an inverse correlation with marine species.

(ii) Correlation and PCA showed that the brackish species *Nitzschia navicularis* and *Nitzschia punctata* were associated with marine species at some sites, and at four sites one or other of these species were strongly correlated with *Paralia sulcata* and *Podosira stelliger.*

At Sandfield Farm in the East Kent Fens *Paralia sulcata* and *Nitzschia navicularis* were found to be abundant (Long, 1991). Inspection of the diagrams from this site shows that when the frequencies of one of these species rise, those of the other fall, but when one is dominant the frequencies of the other are still high. At Creich, NE Scotland (Smith *et al.*, 1991) in a detailed diatom diagram *Nitzschia punctata* and *Diploneis didyma* are restricted to the zones where *Paralia sulcata* is dominant, though Smith *et al.* (1991, 1992) and Shi *et al.* (1991) have suggested that these zones are the product of a tsunami event.

■ It is not possible to interpret all of the results. In all five datasets it is difficult to attach an 'environmental label' to PC2 and PC3 using the correlation method.

■ Though patterns and trends have been identified using PCA, there is doubt as to whether the analysis has enhanced understanding beyond what can be obtained from the summary graphs on the diagrams themselves. At present we can differentiate assemblages on the basis of salinity class, but within-class variations are not well understood within the context of sea-level changes.

In contrast, studies of the vegetation history of the British Isles have revealed a broadly consistent pattern in the changes of tree pollen through the Holocene. This pattern can be identified largely as the result of a few controlling factors such as climatic change, competition, stabilising soils and migration. It is not possible to establish such a general model of changes in the frequency of diatom species at a transgressive or regressive overlap, except perhaps that we would expect a relationship between the dominant salinity class and sediment type. Within these broad salinity classes numerous different species can dominate: thus it must be concluded that PCA is quite limited in this respect. This conclusion reflects Beals' (1973) observation that PCA is best applied to environments where correlations of species are likely to be near linear with the environment.

6.2 New ^{14}C-dates from North Wales and Wirral.

New ^{14}C-dates have been tabulated in Table 6.5. A calibration program (Stuiver and Reimer, 1993) became available upon completion of this thesis: therefore calibrated dates are included in Table 6.1. In this section each of these dates is assessed as a sea-level index point.

6.2.1 Tregarnedd-bâch, Malltraeth Marshes.

Hv 17820 4035±100 BP +1.00 m OD

The lithostratigraphy associated with this sample has been described in 5.2.3. This sample has been taken from the base of a woody peat overlying a light grey buttery clay and is therefore interpreted as a regressive overlap. Pollen was absent from this sample and diatoms absent from the clay below so it is difficult to assign a precise indicative meaning to the dated sample. However Tooley (unpublished) completed spot diatom and pollen analysis from a core less than a kilometre from Tregarnedd-bâch and within the same sedimentary system. An upper peat was recorded with a regressive overlap 1.70 m below the surface (at TB-29, the regressive overlap is 2.14 m below surface) with brackish and marine diatoms recorded in the clays and pollen associated with saltmarsh environments recorded in the peat. This sample is a good sea-level index point, forming at MHWS: however, because of the absence of biostratigraphic information at the precise location of the sample, it should be regarded as having formed somewhere between MHWS and the upper limit of fen peat formation, but can be classified as a Group 3 date.

Hv 17819 7255±130 BP -4.11 m OD

Hv 17818 7435±185 BP -3.96 m OD

The lithostratigraphy associated with these samples has been described in 5.2.3. These two older dates from Tregarnedd-bâch are inverted and biostratigraphic data were sparse so a full interpretation is made quite difficult. The tree pollen that was found throughout the peat included *Ulmus, Quercus* and *Alnus* implying a Flandrian II age. The age inversion does mean that at least one of these dates must be rejected. The pollen assemblages indicating a mixed woodland environment do suggest that the younger date (7255±130 BP) is correct.

6.2.2 Morfa Penrhyn, Rhos-on-Sea.

Hv 17815	**6335±115 BP**	**+0.28 m OD**
Hv 17816	**8265±200 BP**	**-1.94 m OD**
Hv 17817	**9900±195 BP**	**-2.21 m OD**

In section 5.3 it was described how extensive coring in the Afon Ganol Valley proved that Morfa Penrhyn was a site open to the sea since at least the mid-Holocene. Hand-coring at Morfa Penrhyn and Colwyn Bay RC revealed an intercalated sequence with three main organic horizons, the bottom horizon being basal.

A limited pollen count from the top of the basal organic horizon (-1.89 to -2.23 m OD) revealed an assemblage dominated by Gramineae with the trees and shrubs *Betula, Pinus, Ulmus, Alnus* and *Corylus* also recorded. Though the count was limited, an early Flandrian II assemblage was indicated. The two ^{14}C-dates obtained from the top and bottom of this lower organic horizon (Hv 17816 and Hv 17817) are of Flandrian I age. The two ^{14}C-dates for this horizon are in sequence and imply a slow rate of accumulation and are likely to be correct. However, it is not possible that sea-level was at *c.* -2.00 m between 9900 and 8250 BP so the pollen evidence must be assessed.

Hibbert and Switsur (1976) completed detailed ^{14}C-dating of pollen zones from Tregaron near the Dovey estuary and Nant Ffrancon in Snowdonia, providing a chronostratigraphic control for the North Wales pollen data. At Tregaron *Ulmus* was found to be established by 9550±200 BP, but *Alnus* was not recorded until 7130±180 BP in conflict with the evidence from Morfa Penrhyn. At Nant Ffrancon the *Alnus* curve begins at 8450±150 BP, and *Alnus* was first recorded at 9100±180 BP. This apparent irregularity in the timing of the first appearance of *Alnus* has been discussed by Bennett and Birks (1990) and it is therefore possible that *Alnus* pollen was present at 8265 BP, and hence that the two ^{14}C-dates from this lower organic horizon are not sea-level index points.

Below -0.94 m OD diatoms were not present at Morfa Penrhyn so the origin of the lower sediments could not be established. Between -0.94 m and +0.28 m OD the diatoms show marine/brackish conditions were present at the site (Fig.5.9). The sediments are fine, three parts clay and one part silt, suggesting that they have been deposited in middle or upper marsh. The high frequencies of marine species are not necessarily in conflict with this. Carter (1933), for example, following investigations on Canvey Island commented that *Paralia sulcata*, the dominant marine species at Morfa Penrhyn, is such a common and widely distributed marine diatom that it is frequently deposited on all parts of a saltmarsh even though it is not a real marsh inhabitant. The most dominant brackish species is *Nitzschia navicularis* which Carter (1933) found in lower marsh environments at Ynyslas. Round (1960), working in the Dee estuary, noted, however, that *Nitzschia navicularis* tended to be absent from areas of coarse sand and more common in middle and upper marsh. Those species which Round (1960) found to be exclusive to sandy lower marsh sites such as *Caloneis formosa* and *Scoliopleura tumida* are rare in the inorganic sediments between -0.94 and +0.28 m OD.

Towards the regressive overlap at +0.28 m OD (zone MP-20c), the proportion of marine diatoms falls, but the marine/brackish species *Diploneis didyma* becomes abundant. Round (1960) recorded *Diploneis didyma* throughout marshes in the Dee estuary and noted that it was more abundant on the upper marsh, and van der Werff (1957-74) notes the preference of the species for clayey environments. A rise in *Diploneis didyma* towards regressive overlaps is also a common feature at Marsh Lane and Hacklinge in the East Kent Fens (Long, 1991).

The ^{14}C-dated sample was taken from the lower section of a 0.14 m thick peat, rich in *Phragmites*. This peat was shown in 5.3.1 to be widespread at the site, and was also recorded further inland at Colwyn Bay RC. As the peat horizon was quite thin and the contact with the overlying clays was very sharp only the lower contact has been dated. The pollen analysis (Fig.5.10) indicates a transition from upper saltmarsh to an open, perhaps semi-forested environment. At the contact between the peat and the underlying clay Chenopodiaceae and *Aster*-type are found along with high frequencies of Gramineae and low frequencies of tree species. Above this, the saltmarsh taxa disappear and *Quercus* frequencies in particular rise. The tree species recorded indicate a Flandrian II assemblage, corroborating the ^{14}C-date.

The diatom and pollen analysis shows that the regressive overlap dated at 6335±115 BP (Hv 17815) is transitional and can be classified as a group 3 date.

Despite the eroded contact at +0.39 m OD between the peat and the overlying silty-clays the diatom succession recorded in zones MP-20d to MP-20f indicates a smooth transition from upper saltmarsh conditions with *Navicula peregrina* and then *Diploeneis didyma* dominant through to a marine/brackish environment similar to that of zone MP-20a.

6.2.3 Hendre-fawr.

Hv 17810	**4345±145 BP**	**+1.87 m OD**
Hv 17811	**4685±175 BP**	**+1.70 m OD**
Hv 17812	**5935±190 BP**	**+1.27 m OD**
Hv 17813	**5530±385 BP**	**-0.93 m OD**
Hv 17814	**7080±155 BP**	**-2.48 m OD**

At Hendre fawr four main organic horizons were recorded and shown to be widespread over the whole site (Fig.5.25). At HF-29 a basal peat was recorded with a transgressive overlap at -2.46 m OD which was dated to 7080±155 BP (Hv 17814). In the clays above this transgressive overlap a transition from a middle-upper marsh environment to middle-lower marsh environment is inferred from the diatom analysis (Fig.5.31), so the date is classified as a group 2 date. In zone HF-29a, immediately above the transgressive overlap brackish species dominate, including *Diploneis interrupta*, preferring intermediate and higher levels of the marsh (Round, 1960) and occurring in the supratidal area close to the position of mean high water (Vos and de Wolf, 1988). In zone HF-29b marine species increase along with the brackish/marine species *Nitzschia punctata*, a species which prefers the moister and lower zones (Carter, 1933).

The lithostratigraphic, biostratigraphic and ^{14}C evidence from this sample reveals a change from terrestrial to an upper marsh then mid- to lower marsh environment, and thus an increase in the marine influence. The start of this marine episode was at 7080±155 BP.

The PCA (section 6.1.1c) indicated that 58% of variance within the HF-29 diatom diagram was because of the encroachment of marine conditions.

A basal peat is found in HF-21, 0.15 m higher than in HF-29, with a regressive overlap recorded at -1.31 m OD. Between this transgressive overlap and the regressive overlap at -0.95 m OD, an increasing, then decreasing marine influence is apparent from the *Diploneis interrupta* and *Nitzschia navicularis* curves (Fig.5.27). *Diploneis interrupta*, most common in upper saltmarsh environments, is prevalent in levels adjacent to the transgressive and regressive overlaps.

The pollen diagram in Fig.5.29 indicates the existence of a wet upper saltmarsh or reedswamp environment dominated by Chenopodiaceae and Gramineae with Caryophyllaceae present and the aquatic species *Lemna* and *Typha latifolia* immediately above the regressive overlap at -0.95 m OD. The abundant remains of *Phragmites* in the peat confirm the pollen evidence. Together the pollen and diatom evidence indicates a transitional switch from marine/brackish to freshwater conditions.

The ^{14}C-date of 5530±385 BP cannot be accepted as a sea-level index point because it is too young and out of stratigraphic sequence with other dates from HF-21. This error may have arisen because of the very low carbon content of this sample which has also resulted in a very large standard error of 385 ^{14}C-years. At a 95% confidence level the possible age range of this sample is 1540 ^{14}C-years making it unacceptable as a sea-level index point. This ^{14}C-date would be expected to lie between 5935 and 7080 BP, the dates determined for peat horizons above and below that between -0.95 and -0.86 m OD.

Above the transgressive overlap at -0.86 m the diatoms indicate a return to a brackish/marine, intertidal environment. The next fully organic sediments in HF-21 are recorded at +1.25 m OD, a full 2.00 m of inorganic sedimentation between *c.* 6500 and 5935 BP. Ten separate strata were recognised within these 2.00 m, reflecting large fluctuations in the diatom flora (Figs. 5.27 and 5.28) within this inorganic horizon. Vos and de Wolf (1988) draw attention to the problems of allochthonous diatoms (section 3.5.4a) leading to misinterpretation of a diagram. However, most contemporary studies (Carter (1932, 1933), Round (1960)) do point to wide ecological tolerances for most species, so that in a dynamic saltmarsh environment changes in composition through a sedimentary sequence are inevitable. The lithostratigraphy for Hendre fawr was described in section 5.4.3 and displayed in Fig.5.25. Laminated sands were recorded between -2.50 m and 0.00 m OD in seaward cores which are the result of meandering tidal channels. These channels would have created a varied saltmarsh topography with moist channels, sheltered escarpments, hummocks and pans subjected to wetting and drying. Such an array of microenvironments will lead to a varied diatom flora. Carter (1932) noted particular algal formations associated with particular saltmarsh microenvironments at Ynyslas and Canvey Island, and how subtle changes in conditions led to marked changes in diatom and algal populations. For example, on Canvey Island he noted that in pans where silting was prevalent, the diatom flora tended to be sparse with *Scoliopleura tumida* the most common species, but where silting was less advanced a more diverse and abundant flora was observed.

The environments associated with the regressive overlap at +1.25 m OD were discussed in section 6.1 as an example, and the date was assessed as a group 3 date. The pollen assemblage (Fig.5.38) associated with this regressive overlap is Flandrian II confirming the ^{14}C-date of 5935±190 BP. This regressive overlap marks the beginning of a period dominated by organic sedimentation at Hendre fawr which is recorded slightly later at Newton Carr.

Hv 17811 (4685±175 BP, +1.70 m OD) represents the end of this organic phase at Hendre fawr and the beginning of a short period (approx. 300 ^{14}C years) ending with a dated regressive overlap at 4345±145 BP at an altitude of +1.87 m OD (Hv 17810). Before the transgressive overlap frequencies of the saltmarsh pollen type Chenopodiaceae increase to frequencies of 20% TLP. The inorganic sediments above this overlap are fine-grained with some organic enrichment in the form of *Phragmites* rhizomes or semi-humified *turfa*. The diatom assemblage during this phase of inorganic sedimentation is brackish, dominated by *Diploneis interrupta*. At the beginning and end of this period *Diploneis interrupta* attains *c.*90% of total diatoms (zones HF-21k and HF-21 m). In the middle of this inorganic layer the marine, benthonic species *Diploneis incurvata, Paralia sulcata* and *Triceratium* sp. are recorded in small quantities confirming that there were marine conditions at the site during this period. An upper marsh environment is proposed for this period.

A limited pollen count was possible at the regressive overlap (Hv 17810). Gramineae and the saltmarsh indicators Chenopodiaceae and *Aster*-type were recorded at +1.88 m OD, 1.00 cm above the lithologic contact.

Between +1.25 m and +1.99 m OD two distinct periods of terrestrial sedimentation have been recorded, and of the four switches between organic and inorganic sedimentation, three have been dated. Between +1.11 m OD and +1.25 m OD the marine influence decreases, and at Hendre fawr a change from an upper marsh environment to a fen environment took place at 5935±190 BP. Detrital wood is recorded during both terrestrial phases in many of the cores taken, and the pollen evidence shows that a mixed woodland environment was present on the site, or close by. On the whole however, the peat is quite humified, so it is not possible to say unequivocally whether or not the site was forested. Peat formation continued for more than 1000 ^{14}C-years during the first terrestrial phase, so there was certainly sufficient time for woodland to become established.

Lithostratigraphic, pollen and diatom analysis have shown that all of the contacts dated at Hendre fawr represent a switch from marine to terrestrial conditions or vice versa. One date (Hv 17813) must be rejected because of the very large standard error as well as not being in stratigraphic sequence, though the indicative meaning of this contact is unequivocal.

6.2.4 Newton Carr.

SRR 4514	**6680±75 BP**	**-1.92 m OD**
SRR 4640	**7810±55 BP**	**-3.50 m OD**
SRR 4641	**7805±55 BP**	**-5.10 m OD**

The oldest date at Newton Carr (SRR 4641), taken from the transgressive overlap of a deep basal peat, was obtained from commercial borings by Merseyside County Council (section 5.5.1). The pollen diagram from this peat (Appendix 7) shows that there was a major rise in *Alnus* just below the transgressive overlap, which Innes *et al.* (1990) used as a proxy for a date of 7200 BP (Hibbert *et al.*, 1971), 600 ^{14}C years after the actual date obtained.

The rise in *Alnus* marks the Boreal-Atlantic boundary in the definition of Flandrian pollen zones but the timing in the rise in *Alnus* at individual sites has been shown to vary (Bennett, 1990; Tallantyre, 1992). Chambers and Elliot (1985) dated the major rise in *Alnus* at 8500 BP in North Wales, and Bush and Hall (1989) identified alder macrofossils from sediments dated to 9500 BP in Yorkshire.

At the transgressive overlap there is a rise in Gramineae and Chenopodiaceae indicating the presence of saltmarsh conditions. The diatom assemblage in the clays above this overlap is a marine/brackish assemblage confirming the marine origin of the overlying sediments. The transgressive overlap, dated at 7805±55 BP, does not necessarily represent the beginning of an increase in marine conditions, but a time when the marine influence was increasing. As discussed in section 5.5, this peat shows a mixed wooded fen environment existed before the rise in saltmarsh species. The change from woodland to saltmarsh was most likely caused by an increase in the marine influence. Therefore, the date of 7805±55 BP represents a time during this period of change.

SRR 4514 is taken from the transgressive overlap of a peat which is recorded throughout the site. Core NC-17 was selected for dating because here this peat is basal (Chapter 2) and all of the organic/inorganic lithologic boundaries recorded at Newton Carr were present in this core. The date of 6680±75 BP agrees with the pollen assemblage (Fig.5.44) dominated by *Ulmus, Quercus* and *Alnus*. Throughout this peat (approx. 20 cm thick) the pollen composition is very consistent, the main change being a fall in the frequencies of *Alnus* and a rise in the frequencies of Gramineae at -2.00 m OD (8 cm below the transgressive overlap). This switch follows a small peak in the frequencies of aquatic pollen (*Lemna*). This small change is evidence of a rising watertable at Newton Carr before the dated transgressive overlap, a feature more fully discussed in section 6.3. The high frequencies of Gramineae and the presence of Chenopodiaceae at the dated contact are, however, an indication of the proximity of saltmarsh conditions. In core C7, *c.* 500 m seaward of NC-17, pollen from a peat also at *c.* -2.00 m OD shows a similar record, though frequencies of *Quercus* and Chenopodiaceae are higher. These features can be explained by the different locations of these cores. In a more seaward location the regional pollen rain will be more abundant and saltmarsh taxa more prevalent.

NC-17 is located at the southeast corner of the site. Today this is the furthest point from the sea, and in view of the palaeogeography of the site, it is likely that the sea had inundated the whole of Newton Carr by 6680±75 BP.

Above this transgressive overlap the diatoms show an increasing marine influence with increasing frequencies of *Paralia sulcata* recorded between -1.90 and -1.78 m OD. Seven levels were counted at 2 cm intervals above the transgressive overlap with two zones identified. The main distinction between the two zones is the replacement of *Navicula peregrina* with the marine species *Navicula distans*. The more dominant marine species such as *Paralia sulcata* and *Podosira stelliger* are present in both zones. Above -1.70 m OD diatoms were less prevalent and broken, but the coarser-grained sediments are indicative of an intensification of marine conditions as saltmarsh gave way to sand flat.

Throughout the southern and central part of Newton Carr two phases of organic, terrestrial sediments are recorded between *c.* +1.50 and +3.00 m OD. At Newton Carr these sediments accumulated between 5465±90 and 2825±40 BP. Similar sediments at comparable altitudes and age have been recorded extensively throughout the Wirral and these have been termed the 'Upper Forest Bed' by Kenna (1985). The new data from Newton Carr demonstrate that there were periods of marine inundation within this largely terrestrial phase. The ^{14}C-dates from these organic sediments are tabulated below.

SRR 4510	**2825±40 BP**	**+2.87 m OD**
SRR 4511	**4525±65 BP**	**+2.39 m OD**
SRR 4512	**4965±40 BP**	**+2.10 m OD**
SRR 4513	**5465±90 BP**	**+1.59 m OD**

At NC-17 a regressive overlap is recorded at +1.57 m OD where a *limus* with *Phragmites* and *turfa* lie upon a clay. In the grey-blue silty-clays immediately below this lithologic contact, the diatom assemblage indicates marine/brackish conditions, probably upper saltmarsh. *Podosira stelliger* and *Paralia sulcata* are recorded, though brackish species dominate, notably *Diploneis interrupta* and *Navicula peregrina* with increasing frequencies of *Diploneis ovalis* near to the organic-inorganic contact. Immediately above the regressive overlap diatoms were absent, but the proximity of saltmarsh conditions is demonstrated by the presence of *Artemisia* and Chenopodiaceae. The tree pollen dominated by *Quercus, Ulmus, Alnus* and some *Tilia* corroborate the ^{14}C-date at this regressive overlap of 5465±90 BP.

Before the start of organic sedimentation within a fresh water environment at 5465±90 BP, the biostratigraphic evidence suggests that an upper marsh environment had existed for some time at Newton Carr, and at NC-17 there is evidence of a short period of terrestrial sedimentation approximately 30 cm before the dated contact. Here an organic clay was recorded between +1.19 m and +1.26 m OD, and is separated from the dated horizon by fine grained silty-clays. NC-17 is relatively far from the present coastline and this may partially explain the magnitude of the terrestrial influence, but together the evidence does suggest that the decreasing marine influence at 5465±90 BP was part of a gradual and perhaps slow process.

Between +1.85 m and +2.02 m OD, diatoms were present in the *limus.* The assemblage was fresh/brackish, with *Navicula peregrina* and the fresh species *Stauraneus anceps* and *Synedra capita* dominant. This assemblage contrasts with the humified peats between +2.10 and +2.02 m OD where the fresh species *Pinnularia gentilis* dominates. At +2.10 m OD a transgressive overlap was dated to 4965±40 BP when a woodland fen environment gave way to an upper marsh environment where silty clays have been deposited.

The diatoms present in these clays suggest that the salinity range is similar to the clays below the regressive overlap at +1.57 m OD, though the assemblages are somewhat different. In this thin clay *Scoliopleura tumida* is consistently recorded, while frequencies of *Paralia sulcata* and *Podosira stelliger* are lower. Vos and de Wolf (1988) note that *Scoliopleura* *tumida* flourishes in intertidal or sub-tidal zones where irradiance is sufficient for photosynthesis, suggesting shallower water depths. The very fine clays and *Phragmites* recorded in the clays suggest an upper saltmarsh environment (Evans, 1965). At +2.37 m OD, this thin clay is overlain by a *limus*, with the regressive overlap dated at 4525±65 BP. Either side of this clay the pollen evidence shows the proximity of saltmarsh conditions and the lower frequencies of *Ulmus* corroborate the ^{14}C-dates from after 5000 BP. Peat formation continued at Newton Carr until 2825±40 BP. Within the context of the 'Upper Forest Bed' sequence described by Kenna (1985) this cessation of peat formation is considerably later than at Park Road, but comparable with the sheltered site at Reeds Lane.

6.3 The interpretation of sea-level change data: North Wales and Wirral.

In this section some of the problems in determining a sea-level chronology in general, and using the tendency method in North Wales in particular, are noted. The problems discussed can be classified under five broad topics:

(i) Implications of the lithostratigraphic data collected: the altitude of transgressive and regressive overlaps recorded.

(ii) Sediment supply and marsh growth under different rates of sea-level rise and fall.

(iii) Water table movements and the position of transgressive and regressive overlaps within the context of water table movements.

(iv) Statistical significance of data.

(v) Data from other regions, notably south-east England.

The policy of IGCP200 was to collect data suitable for the analysis of sea-level changes from small, homogeneous, areas which can then be correlated with data from adjacent areas (Tooley and Shennan, 1987). The tendency method of analyzing sea-level changes reflects this approach, based on the assumption that the registration of increases and decreases of the marine influence through time will be consistently apparent at sites within a region, and hence a suitable tool of correlation (Shennan, 1983).

In section 2.2.1, the variability in the altitude of transgressive and regressive overlaps in North Wales and Wirral was explored. It was noted that a transgressive or regressive overlap had been recorded at any altitude along these coasts above *c.*-7.00 m MHWS and that this was probably because of the variability in the registration of larger 'eustatic' changes in sea-level at a site scale. A tendency analysis, building up a picture of changes from the site scale upwards, may pick out variability allowing an assessment of sites where the local influence is particularly strong, but in practical terms this is difficult to achieve, for example, resources are rarely available to collect the number of ^{14}C-dates necessary for such an undertaking.

Figs 6.3a and b show the probability of organic sedimentation occurring at each of the eight sites investigated. The probability of organic sediments occurring within 0.50 m altitudinal windows (also a proxy for age) is expressed on the right hand y-axis, and shown by cross-hatched bars. The results from all cores completed in North Wales and Wirral have been summed to form a cumulative probability curve against which the results from individual sites can be compared. The division of organic and non-organic sedimentation is a coarser division than positive and negative tendencies, and indeed the interpretation of this processed data is different. For example, a peak in the curve for the probability of organic sedimentation will not necessarily coincide with a distinct period of negative tendencies because:

(i) An inherent error in comparing the two sets of results arises because a specific altitude will not always correspond with a specific age between sites.

(ii) The tendency method distinguishes between periods when the marine influence is increasing or decreasing (Shennan *et al.*, 1983), while the method of recording the probability of organic sedimentation is more a proxy for when the marine influence was strong or weak.

The method is, however, an attempt to overcome the problems of data deficiency which limit the tendency analysis. The lower organic sediments at Morfa Penrhyn and Colwyn Bay RC have been excluded from the analysis following doubts on their origin.

The cumulative probability curve reflects the pattern at Hendre fawr in the Vale of Clwyd and Newton Carr on the Wirral (Fig.6.4). This is because the sites have very similar lithostratigraphy and chronology (Chapter 5) and are the sites where most cores have been completed. However, the similarity of the two sites does suggest that they do show a clearer regional signal. Both sites occupy large open coast basins where the areal extension of sedimentary horizons is large. Commenting upon Newton Carr basin within the context of the Wirral, Innes *et al.* (1990,p.7) note:

> *"deep sediments accumulated within it could well provide an accurate record of transgressive and regressive events, avoiding the complex local sedimentary environments of the incised buried river channels elsewhere on this coast".*

The obvious difference in the pattern of organic sedimentation between Hendre fawr, which it seems may have a strong regional to local signal, and Pentre Mawr less than 5 km away is obvious from Fig.6.3b. In 5.4.1 the lithostratigraphy at Pentre Mawr was described, where three main and distinctive peat horizons were recorded between *c.* +1.50 and -1.00 m OD (Fig.5.22). At Hendre fawr (Fig.5.25), organic sediments are rare between these altitudes. The prevalence of intercalated, though typically organic, sedimentation between *c.* +1.50 and -1.00 m OD suggests a series of positive and negative tendencies at Pentre Mawr, and pollen analysis (Fig.5.23) indeed demonstrates that these sediments are formed from the interplay of terrestrial and marine conditions at the site. The diatom record from the inorganic sediments between these altitudes at Hendre fawr shows no obvious major change in salinity from a wider change in actual sea-level: indeed the location of Hendre fawr at the margins of the Vale of Clwyd would be expected to be conducive to peat growth. Clearly a quite different pattern of tendencies would result from Pentre Mawr compared with Hendre fawr which may be a poor reflection of any regional signal. It is important to note, however, that tendencies are recording increasing and decreasing marine influence, which can be the result of a number of processes.

Quantification has been provided in theory by Allen (1990). A differential equation shows the relationships between saltmarsh growth, sea-level and sediment supply:

$$\frac{dE}{dt} = \frac{dS_{min}}{dt} + \frac{dS_{org}}{dt} - \frac{dM}{dt} - \frac{dP}{dt} \qquad \text{Eqn. 6.1}$$

E is the elevation of an upward growing marsh surface at time *t*. S_{min} and S_{org} are the thickness of added minerogenic and organic sediment, *M* the relative sea-level and *P* a compaction variable. Allen (1990) assumes that the term dS_{min}/dt will be negative to the landward side of a saltmarsh because of the decreasing incidence of tidal flooding relative to the lower marsh. Conversely the term dS_{org}/dt will be higher at the landward edge of a saltmarsh, with elevation being a key variable since halophyte species do not grow below a certain tide level. Using loading factors observed in the Severn estuary Allen (1990) suggests that what type of marsh (mainly minerogenic or mainly organic) will depend very much on the relative strength of the organogenic supply and the rate of upward sea-level movement, with minerogenic sediment supply exerting a minor influence. This balance is used to explain the phenomenon that in areas of rising sea-level in some marshes minerogenic sediments are accumulating while in others organic sediments are forming.

The subtlety of these balances is important. Peats can and do form on marsh surfaces under conditions of rising sea-level as well as under falling sea-level (Orson *et al.,* 1985; Allen, 1990; Zong, 1993). It should be noted, however, that negative tendencies do not imply a causal process, but a decrease in the marine influence. When the rate of organogenic supply is high an apparent regressive tendency will be produced because the increase of elevation of the marsh survey can increase at a faster rate than sea-level. Through time towards the present the *dM/dt* part of the relationship has decreased. *dM/dt* is the only variable in the relationship that can be consistent over a large area, so as the contribution from this variable diminishes variability in gross lithostratigraphy and sometimes tendencies of sea-level will increase.

Orson *et al.* (1985) have investigated the growth of saltmarshes under conditions of rising sea-level on the U.S. Atlantic and Gulf coasts. They outline three possible saltmarsh responses to a rising sea-level:

(i) Drowning of the marsh system if vertical accretion is less than coastal submergence.

(ii) Stability when the input of sediment is equal to submergence.

(iii) Expansion.

Expansion has been found to be common at the mouth of river estuaries in the recent past because of increased sedimentation rates. Froomer (1980) reported a rapid expansion of the saltmarshes in Chesapeake Bay since the 1800s and Harrison and Bloom (1977) recorded vertical accretion rates of 2.0 to 6.7 mm/year in Connecticut. Tooley (1982) has recognised the potential for huge changes in sediment supply in the past caused by the activities of man. Tooley (1982) has speculated that the post-5000 BP sedimentary regime must have been spectacularly altered by forest clearance which could well produce intercalated sediments in coastal areas independently of movements in sea-level. The scale of forest clearance in prehistoric times is explored in Simmons and Tooley (1981).

Further light can be shed upon this problem by examining the pollen from organic sediments. A wider study of vegetation changes through basal peats was not possible in this study because of the absence in pollen at Tregarnedd-bâch and Morfa Penrhyn. From Newton Carr, however, there are two pollen diagrams from basal peats which when examined within the context of work from elsewhere allow some conclusions to be drawn.

The interplay of different vegetation types and its implication in terms of water table movements has been examined by Long (1991). At sites throughout the East Kent Fens, but particularly at Marsh Lane, it was noted that the pollen record in organic sediments indicated that the water table was rising well before there was a change to inorganic sedimentation. Tooley (1978) also drew attention to this phenomenon:

> *"The interpretation of lithologic boundaries in stratigraphic successions within the coastal zone may contribute a significant source of error, particularly when the effective height of a marine transgression is under consideration. The error arises from the fact that the boundary zone may occupy a whole stratum in the stratigraphy as the approaching marine conditions gain ascendancy at the site, but before inorganic sedimentation begins."* *Tooley (1978: 18).*

At Marsh Lane, Long (1991) identified the beginning of the rise in the local water table, and thus an indication of the onset of marine conditions, to be coincident with a fall in the frequency of *Alnus* and a rise in the frequencies of Gramineae, other saltmarsh indicators and a short-lived rise in the frequency of aquatic pollen. This feature was recorded *c.*0.15 m below the switch from organic to inorganic sedimentation and was dated along with the transgressive overlap, the difference in the two dates being 400 ^{14}C years. The implication of this result was that the water table had been rising for 400 ^{14}C years while organic sedimentation was taking place.

At Newton Carr before the dated transgressive overlap at 6680±75 BP (SRR 4514) the vegetation record is similar to that identified by Long (1991) at Marsh Lane (section 6.2.4), though the small peak in *Lemna* takes place immediately before the fall in *Alnus* and rise in Gramineae. Godwin and Clifford (1938) and later Shennan (1980) have used the interplay of *Alnus* and *Quercus* as a proxy for approaching marine conditions. They suggested that in drier periods fens with alder developed, but in periods of increased wetness (e.g. under a rising water table) the alder would be destroyed, with associated increases in the regional pollen rain which in the Fenland was *Quercus*. At Newton Carr, however, the regional pollen does not increase as *Alnus* frequencies fall but frequencies of saltmarsh taxa do and this is suggested as evidence of approaching marine conditions at Newton Carr before the dated transgressive overlap.

Geyh (1980) and Shennan (1980) estimate that 40 index points per thousand years per region are required to show a wholly real pattern of sea-level tendencies. Where such data are not available, or it is not possible to collect such a quantity, a tendency analysis may not simplify the pattern, but where a knowledge of the lithostratigraphy of an area is limited a totally unrepresentative pattern of tendencies may result. The contrast between Pentre Mawr and Hendre fawr emphasises this point. Pentre Mawr was the first site to be investigated, and in other circumstances, perhaps a shorter time available for fieldwork, may have been used as the site for further investigation and ^{14}C-dating.

Shennan *et al.* (1983) comment that comparing one area with another using sea-level curves is limited, *"Detailed interpretation of regional phenomena cannot be made from an evaluation of only sea-level index points on a time-altitude diagram, because the errors involved in the estimation of past altitudes permit only the identification of a broad sea-level band. Therefore it is difficult to evaluate the accuracy of chronological correlation schemes based on the comparison of sea-level curves."*

Shennan et al. (1983,p.402).

The question to ask is therefore: does the tendency approach based on a limited data set always produce a correct chronology? The possibility for incorrect chronologies has been demonstrated.

Using the tendency approach (Shennan, 1982a and Shennan *et al.,* 1983) on a set of sea-level index points from the Fenland, and in this case, distinctive periods of positive and negative tendencies were clear. The sites from which data have been collected in North Wales are more disparate, and also quite different in their physical characteristics, from open basin sites in the Clwyd coastal lowlands, to restricted valley sites in the Afon Ganol valley. Shennan (1982a) does point out differences in the timing of marine events within the Fenland, but the influence of secondary factors on the sedimentary regime would be expected to be more variable across the suite of sites in North Wales and Wirral. Problems with intra-regional correlation of sea-level data using the tendency analysis have been reported by Long (1992). Analyzing data from the East Kent Fens Long (1992) comments:

"A comparison with similar chronologies from elsewhere in southeast England has shown that southeast England experienced a similar sea-level tendency during less than 1000 years of the last 7500 cal. years BP. Thus, the nature of coastal sedimentation (freshwater or saltmarsh peat, and marine/estuarine sands, silts and clays) does not reflect the operation of a regional driving mechanism, and is not necessarily affected by changes in the altitude of the sea."

Long (1992: 198).

These data from southeast England and also from northeast England (Plater and Shennan, 1992) lead Shennan *et al.* (1992) to comment that

> *"During the later part of the Holocene, the coastal systems of northeast and southeast England are characterised by a range of responses to relatively slow rates of sea-level change coupled with local variations in sediment supply and groundwater table movements. While the 'tendency' approach to sea-level investigations provides a considerable amount of detail regarding the sensitivity of coastal types to past changes in sea-level and more site-specific factors, the 'altitude/time' approach has proved to be a robust framework for quantifying rates of change during the last 10,000 years."*
>
> *Shennan et al. (1992: 164).*

The data collected from North Wales would seem to support these views.

6.3.1 Tendency analysis: North Wales and Wirral.

The probability analysis has shown that the altitudinal distributions of organic sediments at Newton Carr and Hendre fawr are similar, and that the origin of the dated lithologic contacts may reflect regional rather than local processes. Below tendencies of sea-level from these data are constructed. The lithostratigraphy at Park Road (Wirral) is also similar to Newton Carr and Hendre fawr: hence the dates from this site are used to reconstruct tendencies of sea-level. Other sites from the study area do not always fit this pattern.

6.3.1a Sea-level tendencies: Newton Carr and Hendre fawr.

7800 BP

A positive tendency of sea-level is recorded at 7805±70 BP (SRR 4641) on a transgressive overlap from Newton Carr.

7080-6680 BP

A period of positive tendencies is recorded in this period from two dates on transgressive overlaps of basal peats from Newton Carr and Hendre fawr (SRR 4514, Hv 17814).

5930-5460 BP

At Newton Carr and Hendre fawr a thick upper peat split in two by a thin clay was extensively recorded between *c.* +3.00 and +1.00 m OD. The lower regressive overlaps on these peats indicate a period of negative tendencies after *c.*5930 BP when peat formation began at Hendre fawr. At Newton Carr peat formation began 400 ^{14}C-years later. Similar lithostratigraphy was recorded at Park Road (Innes and Bedlington, in prep) and there peat formation began even later at 5250±50 BP, 700 ^{14}C-years after Hendre fawr.

5000-4620 BP

Transgressive overlaps from both sites and also Park Road define this period of positive tendencies (SRR 4512, Hv 17811).

4600-4300 BP

A period of negative tendencies, with one regressive overlap recorded at either site (SRR 4511, Hv 17810). At Rhyl Beach a regressive overlap was dated at 4725±65 BP.

***c*.2800 BP**

From a transgressive overlap at Newton Carr. No date for the corresponding overlap was obtained from Hendre fawr because of a slightly eroded contact and the absence of diatoms in the above clays.

Four periods of positive and two periods of negative tendencies have been identified from the ^{14}C-dates available for the two sites. The dates cluster to form distinct periods of positive and negative tendencies. However when data from adjacent sites such as Rhyl Beach are included in the analysis then overlapping tendencies are apparent. This chronology (Fig.6.5) is now evaluated with respect to other index points, as well as the litho- and biostratigraphic information from the North Wales and Wirral coasts, and where possible an interpretation is attempted.

6.3.1b **Evaluation of tendencies from Hendre fawr and Newton Carr with index points from North Wales and Wirral.**

The earliest ^{14}C-date obtained from Hendre fawr or Newton Carr was *c.*7800 BP, but two earlier dates are available from Woodlands in the Vale of Clwyd (Prince, 1988). Prince (1988) ^{14}C-dated two thin detrital peats obtaining dates of 8540±70 BP (SRR 2511) and 8170±70 BP (SRR 2510). Effectively therefore, both of these dates represent negative and then positive tendencies. It can be said, however, that before the earliest date sea-level tendencies were negative since the sample was taken from the peat lying directly upon blue-grey silt at an altitude of -9.12 m OD (Prince, 1988).

Similar sediments to those sampled at Woodlands have been recorded elsewhere in Liverpool Bay. Neaverson (1936) reported a peat bed at *c.*-13.00 m OD from Foryd, only a few kilometres from Woodlands, but there is no dating control on this lower peat. In Lancashire, Tooley (1978) recorded a regressive overlap at Heyhouses Lane dated at 8575±105 BP and a transgressive overlap dated to 8390±105 BP close by at Starr Hills. Comparable data from around Liverpool Bay do suggest that a regional process was operative, and that the positive and negative tendencies identified were the result of actual changes in relative sea-level. During this period uplift in North Wales and Lancashire would have exceeded 1.00 mm/yr, so that, providing sea-level was not rising by more than this figure, there would have been a fall in relative sea-level. Organic sediments from this period have been sampled and dated at a variety of locations along the British coastline, suggesting that there was certainly a halt in the rapid rates of sea-level rise during the early Holocene allowing these sediments to form.

A positive tendency has been identified at 7805±55 BP from a transgressive overlap at Newton Carr. In section 6.2 it was shown that this date represented a point of time during an increase in the marine influence, rather than the start or end of it. The sample itself was taken from the transgressive overlap of a basal peat, so it is possible that conditions of increasing marine influence had existed at the site for some time before 7800 BP and actually led to the formation of the basal peat as the water table rose.

Between the positive tendency identified at 7800 BP and that from 7080 to 6600 BP, two ^{14}C dates are available. The first from Llandudno (Heyworth and Kidson, 1982) is a within-peat date so the tendency of sea-level implied from this date is unclear, though Long (1991) has used within-peat dates as indicators of a negative tendency. The altitude of the dated sample was -5.19 m OD, which, when corrected to local tidal level, is within 0.02 m of the dated sample from Newton Carr (SRR 4641) but the date from Newton Carr is older (7805±70 BP *cf.* 7635±52 BP). There are a number of possibilities to explain the relationship between these two dated samples:

(i) The two dates overlap when a two-sigma error is applied. It is therefore possible that the samples were formed as part of the same process. Under such circumstances slight variation in the precise timing of the registration of a wider process can be expected between sites modified by local sediment supply.

The age difference in the dates may be real and;

(ii) Greater uplift has taken place on the Wirral since *c.*7800 BP with respect to the Llandudno area.

(iii) The date from Newton Carr was taken from the transgressive overlap of a basal peat so its original altitudinal position can have only been altered by compaction of the peat itself.

(iv) Other unquantifiable factors have been operating; for example, a change in the tidal range.

Modelled results (Lambeck, 1991) and other dates collected in this thesis suggest that explanation (ii) is unlikely and that the explanation lies either in (i), (iii) and (iv) or some combination of these factors. In Fig.6.10 the date from Llandudno is represented as a negative tendency.

The second date from Tregarnedd-bâch, Anglesey (Hv 17819), is from a regressive overlap, dated at 7255±130 BP. At the altitude that this peat had formed (-6.32 m below MHWS), organic sediments have been recorded at other locations along the North Wales coast. Two dates from the transgressive overlaps of these peats help distinguish the periods of positive tendencies between 7080 and 6600 BP. The date of 7255±130 from Anglesey would seem a good indicator of the start of peat formation during this period.

Before 7255±130 BP a fall in sea-level is not required to explain the patterns observed. Between 8170±70 BP and 7805±70 BP sea-level rose rapidly; the later date from Newton Carr is 3.70 m above the earlier one from Woodlands. Though the date of 7635±52 from Llandudno is a within-peat date, it is likely that sea-level was rising at the time, but not as rapidly as before 7800 BP.

The withdrawal of marine conditions at around 7000 BP has been recorded at a number of sites along the North Wales and Wirral coasts. On this coast, sediments of this age are typically recorded *c.* 6 to 7 m below MHWS and organic sediments have been recorded at this altitude at Tregarnedd-bâch and Llangefni on Anglesey, at Hendre fawr in the Clwyd coastal lowlands and at Newton Carr on the Wirral. The two ^{14}C-dates available from the regressive overlap are 7255±130 BP from Tregarnedd-bâch and 7010±50 BP from Dove Point. Greater uplift taking place in Anglesey relative to the Wirral would explain this difference, but to conclude this on the basis of two data points is fraught. An equally viable explanation could be the relative location of the two dates within the particular sites from which they were obtained. Dove Point is a coastal site where a withdrawal of marine conditions would have taken place later than at an inland site. Tregarnedd-bâch, on the other hand, is located several kilometres away from the present coastline and would therefore be a site more sensitive to small changes in marine conditions.

The transgressive overlaps associated with the peats along the North Wales and Wirral coasts that formed around 7000 BP have been dated at Hendre fawr and Newton Carr. The earliest date of 7080±130 BP comes from Hendre fawr and represents the start of a period of positive tendencies.

Three published dates from the Wirral (Kenna, 1986) indicate a period of positive tendencies between 6510±50 and 6420±40 BP. Two of these dates (from Mockbeggar Wharf and from

Dove Point) are from oak tree stumps surrounded by peat on the boulder-clay surface. The other is from a basal peat at Wallasey. All are recorded between 1.70 and 2.31 m above the dated transgressive overlap at Newton Carr (6680±75 BP) and therefore form a distinctive group. However, all three dates are indicative of a rising groundwater table which may be a continuation of the positive tendencies of sea-level recorded between 7080 and 6680 BP. The date from Newton Carr represents the end of this phase of positive tendencies, but the diatom assemblages and lithostratigraphy above the dated transgressive overlap do indicate a gradual and increasing marine influence. Marine diatoms, notably *Paralia sulcata*, indicate increasing water depths, and sediments coarsen from a fine-grained silty-clay adjacent to the transgressive overlap to a dark-grey silty sand 0.12 m above. This type of sediment is indicative of a lower saltmarsh or sandflat environment (Evans, 1965). On the Wirral, using today's tidal parameters this would be 2.50 m below MHWS so it is plausible that while lower saltmarsh sediments were being deposited at Newton Carr, 2.00 m higher at Dove Point, Wallasey and Mockbeggar Wharf organic sediments were being formed by and then overtaken by a rapidly rising groundwater table. The period of positive tendencies from 7080 to 6680 BP is therefore extended to 6420 BP.

Such a consistent pattern of transgressive and regressive overlaps, positive and negative tendencies in North Wales and Wirral in the period *c.*7500 - 6500 BP do indicate that a regional factor is largely responsible for the observed patterns. Examination of data from other regions along the British coast confirms this view. Shennan (1989) has shown that the recent crustal history of northeast England is similar to North Wales. This fact in itself does not necessarily mean that the pattern of transgressive and regressive overlaps is comparable, because when reconstructing crustal history only the altitudes of sea-level index points are considered. However, recent data presented by Shennan (1992) show that the pattern of transgressive and regressive overlaps is similar. At Cowpen Marsh on Teesside a basal peat is recorded at -2.67 m to -2.71 m OD, dated at 7065±45 BP. At Elwick in Northumberland, regressive overlaps are dated at 7180±45 and 7230±45 BP, and the associated transgressive overlaps are dated to 6935±45 BP and 6875±45 BP. However, Shennan (1992) concludes that the dates from the regressive overlaps at Elwick can be interpreted as representing a period of positive tendencies. The similarity of these dates to those in North Wales is quite striking, though there is some question whether their indicative meanings are precisely the same.

From the Hendre fawr and Newton Carr data only, a period of negative tendencies was identified from 5930 to 5460 BP. However between 6420 and 5930 BP, the lithostratigraphy recorded from a number of sites indicate a period of negative, and then positive, tendencies though the exact pattern is variable between sites. At Hendre fawr, a thin peat is recorded between -0.95 and -0.86 m OD. The date from the regressive overlap (Hv 17813) was erroneous: however, the regressive overlap 2.20 m higher was dated to 5935±190 BP: so this thin peat must have formed before this date. Organic sediments are recorded at Glan Aber Farm above -1.00 m OD; however they are 3.00 m in thickness so there is no indication of positive tendencies of sea-level immediately after a negative tendency some time between 6420 and 5930 BP.

At Morfa Penrhyn a thin peat is recorded at *c.* 0.00 m OD. The spatial extent of this horizon has been demonstrated to be extensive since it is recorded at the nearby Colwyn Bay RC. A date of 6335±115 BP at +0.28 m OD from Morfa Penrhyn provides a date for a negative tendency in sea-level between the dated periods of positive and then negative tendencies of sea-level from Hendre fawr and Newton Carr. The altitude of the dated regressive overlap is *c.* 1.00 m higher than recorded at Hendre fawr and Glan Aber Farm, so it is not necessarily indicative of the same process in time. Until more dates are available from this period, however, the possibility remains that they may be.

In Fig.6.10 therefore, a negative tendency is shown at 6335 BP. The diatom data from Morfa Penrhyn clearly show an increasing marine influence above the transgressive overlap from this dated peat (+0.39 m OD), so a positive tendency is implied after the negative tendency at 6335 BP. The confined location of this site does suggest that it is a localised feature.

A particularly interesting similarity of the lithostratigraphy between Newton Carr and Hendre fawr is the upper organic sediments. Figs 5.25 and 5.38 from Hendre fawr and Newton Carr respectively show a thick upper organic sequence between *c.* +1.50 and +3.00 m OD, split by a very thin clay (*c.* 0.20 to 0.30 m thick). The dates (^{14}C-years BP) associated with this feature are given below:

	Regress/o	Trans/o	Regress/o	Trans/o
Hendre fawr	5935±190	4685±175	4345±145	
Newton Carr	5465±90	4965±40	4525±65	2825±40
Park Road	5250±50	4620±50		4315±70

From these dates a period of negative tendencies was identified from 5930 to 5460 BP and from 4600 to 4300 BP and positive tendencies between 5000 and 4620 BP and at *c.* 2820 BP. At Rhyl Beach a regressive overlap dated at 4725±65 BP extends the second phase of negative tendencies back in time. At Tregarnedd-bâch a regressive overlap was dated to 4035±100 BP, and within-peat dates at Wallasey (3910±100 and 3800±40 BP) are recorded. During this period organic sediments were forming at Newton Carr and the diatom record during this period indicates no withdrawal of terrestrial conditions with an entirely fresh or fresh/brackish assemblage dominated by *Pinnularia gentilis, Nitzschia subtilis* and *Cymbella aspera*. This phase of negative tendencies is therefore extended forwards to 3800 BP.

There is a large range in the timing of the start of peat formation at the three sites shown in the table above. Variation in the rates of sedimentation at a site scale (Allen, 1990) could be a satisfactory explanation of the range of dates for the switch from inorganic to organic sedimentation, especially as the rate of sea-level rise slows. The earliest switch to organic sedimentation is at Hendre fawr, though at Newton Carr a phase of reduced and then increased marine influence is apparent before the dated regressive overlap. In diatom zones NC-17d and e, 0.21 m below the regressive overlap, *Diploneis interrupta* dominates along with the fresh/brackish species *Navicula pusilla* and *Synedra acus*. In the corresponding lithostratigraphy a 0.07 m thick organic clay with *Phragmites* and *turfa* was recorded. Co-incidentally the start of this freshening episode is at the same altitude as the regressive overlap at Hendre fawr, but there is a temporary return to marine conditions before fully organic sediments and a return to full terrestrial conditions are recorded.

The phases of negative, positive and then negative tendencies identified from sites on the Wirral and in the Clwyd coastal lowlands are not repeated at all other sites investigated. At Pentre Mawr, in the west of the Clwyd coastal lowlands, organic sedimentation ceases at *c.* +1.50 m and the start of marine conditions is recorded at +1.52 m OD in core PM-18. At this altitude is a transgressive overlap dominated by Gramineae and other saltmarsh indicators such as *Aster*-type. Though there is no chronostratigraphic control at Pentre Mawr, this transgressive overlap, at +1.52 m OD, represents the end of organic sedimentation at the site (Fig.6.3), whereas at Hendre fawr a major phase of organic sedimentation is just beginning.

There are some anomalies in the lithostratigraphic data for sites investigated during the mid- to late Holocene period. However, for the sites where ^{14}C-dating has been applied, it has been shown that they were open coast sites and their palaeogeography has been established. Based upon the data that are available it is felt therefore that the pattern of tendencies established from Newton Carr, Hendre fawr and Park Road for the mid- to late Holocene is an accurate reflection of regional trends.

A provisional chronology of tendencies is presented below. At this juncture the following points should be made:

(i) There is a degree of subjectivity in preparing this chronology. When all the lithostratigraphic and biostratigraphic data available from North Wales and Wirral are considered, exceptions to the tendencies identified can be found.

(ii) The above point is made because of the large amount of lithostratigraphic data collected. A lithostratigraphic survey was carried out at ten sites. If, for example, ^{14}C dates had been obtained from the first three or four sites examined (Pentre Mawr, Hendre fawr and Llangefni), it is suggested that the tendency record (with such a small sample size) would be quite different.

(iii) In Fig.6.10, sea-level index points indicating a negative tendency in sea-level are evenly distributed. The exceptions to this observation are between 7000 and 6350 BP, and between

3600 and 2800 BP. If ^{14}C-dates were obtained from organic sediments between -1.50 m and 0.00 m OD at Glan Aber Farm, Pentre Mawr and Hendre fawr, and from the upper organic sediments at Llangefni, Tregarnedd-bâch, Glan Aber Farm and Morfa Penrhyn, these 'gaps' would be filled. In Lancashire, which has a similar crustal history to North Wales (Tooley, 1978), dates from regressive overlaps during these periods are recorded at Downholland Moss (6760±95 and 6750±175 BP) and Lytham (3150±150 BP).

(iv) In essence, this analysis has been restricted and requires the above qualifications because of the limited size of the dataset and the uneven distribution of dates through time.

Table 6.6. Tendencies of sea-level based on available ^{14}C-dates.

Positive	Negative	Number of data points
	8540	1
8170		1
7800		1
	7630	1
	7255-7010	2
7080-6420		5
	6335	1
6300*		
	5935-5120	3
4965-4315		3
	4725-3800	6
3490		1
2820-2620		2

* Implied from the lithostratigraphy.

6.3.2 Time-altitude analysis.

A time-altitude plot of sea-level index points from North Wales and Wirral is presented in Fig.6.7. Altitudes are expressed as metres below MHWS.

A curve representing the trend of these data has also been plotted. This curve is considered a good fit because all the data points fit within a ±2.00 m band, the supposed standard error on a sea-level index point (Shennan, 1982a, 1989). The average residual of all the sea-level index points from this modelled curve is 0.59 m (mean modulus), and the maximum residual is 1.44 m.

A smooth, exponential curve has been drawn because:

1. The equation of the curve, being exponential, is easy to differentiate and thus calculate rates of change of sea-level.

2. With curve-fitting programs where more than second order polynomial expressions are generated, artificial changes in gradient are apparent. In Chapter 7 where crustal movements are examined an estimation of the rate of sea-level rise during the Holocene is required. Because of the errors involved in the collection of data, the simplest curve possible that can also be differentiated should be used. However, a curve-fitting program will produce more replaceable results than those obtained by a technique involving trial and error.

3. Curves are easy to generate for different regions and datasets. In section 6.4 the need for fitted sea-level curves in comparing the time-altitude chronology of different regions is discussed.

There are limitations to this type of analysis, notably that a smooth curve is unlikely to reflect reality and as one moves back in time one is dependent upon fewer and fewer data points and cannot pass through the origin.

The equation of this summary curve is:

$$y = \frac{1}{15} e^{0.63x}$$ Eqn. 6.2

y = depth below MHWS, x = age (BP).

The residuals for transgressive and regressive overlaps were also investigated, and revealed an interesting and consistent pattern that was reproduced in other areas. The average residual for transgressive overlaps was -0.67 m, and for regressive overlaps -0.13 m, in other words, the altitude of regressive overlaps are consistently lower in altitude relative to regressive overlaps than predicted.

6.4 Regional Correlation.

Correlation of sea-level involves identifying characteristics associated with available data, and comparing this characteristic with data from different regions. It has been noted that the properties of a sea-level index point are (1) A location, (2) An age, (3) An altitude and (4) An indicative meaning.

Traditional approaches based upon comparing time/altitude plots for different locations are restrictive because of the inherent altitudinal error. Shennan (1982a) criticised the comparison of actual sea-level movement, be it rises and falls of sea-level, or tendencies of sea-level movement from age/altitude plots, noting that the combined age and altitude "cannot be expected to reveal mutually exclusive 'rises and falls' in past sea-levels" (Shennan, 1982a, p.59). The tendency approach (Shennan, 1982a; Tooley, 1982; Shennan *et al.*, 1983) is a logical attempt to overcome this limitation when correlating between regions by using age in combination with indicative meaning, though some of the problems in applying the technique have been discussed. Time/altitude analysis is, however, a robust method for determining the overall pattern of sea-level change on a 10,000 year timescale (Long, 1992; Shennan *et al.*, 1992). Time/altitude plots from surrounding regions are therefore described in section 6.4.1.

Using data from North Wales and elsewhere, difficulties in applying the tendency technique have been explained. It must be stressed, however, that these criticisms are within the context of a small dataset. Where a positive or negative tendency has been identified in North Wales and Wirral there is evidence available from other sites contradicting the tendency identified. In dynamic coastal environments this is to be expected, but when the dataset is small and there is such variability, actually deciding upon a chronology becomes somewhat subjective and there is a high probability of error. With a lot more data, if a pattern is there it should be more discernible and statistically valid. Conceptually and intuitively it is difficult to have full faith in chronology when one piece of evidence is contradicted by another, but easier when several pieces of supporting data are only contradicted by one or two other pieces of data through the whole time series.

Hendre fawr and Newton Carr have been used, correctly or incorrectly, as a starting point for the development of a chronology of tendencies. The similarity and location of the sites were forwarded as a justification for the approach. It also represented an attempt to filter the signal from the noise, since it provided a lithostratigraphic model in which it was assumed that gross lithostratigraphic differences between the two control sites and others were a product of local processes, the location of cores taken and post-depositional changes. Additionally, with so much inter-regional variability. if a correlation based on the tendency technique is to be attempted then initial assumptions must be made.

In section 6.4.1, therefore, the chronology determined will be used as a model to compare against sea-level index points from a number of sites. If there is good agreement in the data, it is expected that the lithostratigraphy recorded at the test sites will have similar characteristics to that at Hendre fawr and Newton Carr. Subjectivity must come into the analysis at some stage. Here subjectivity will arise when deciding whether sites that fit the North Wales/Wirral model, based upon Hendre fawr and Newton Carr, are sites which are 'good' sites within the region concerned.

6.4.1 Correlation of sea-level data using time/altitude techniques.

In Figs.6.8 to 6.10, time/altitude plots for Lancashire, Morecambe Bay and Cardigan Bay are presented. A smooth curve has been drawn through the sea-level index points, using the methods described in section 6.3.2 for North Wales.

6.4.1a **Lancashire.**

A noticeable feature of the Lancashire curve is that the difference between index points and fitted curve increases as one moves back in time. Again, as one moves back in time, the curve is a far better description of the North Lancashire dataset. Also, an exponential curve is by definition smooth. For this dataset, there is therefore a resulting loss in detail between *c.* 9000 and 7500 BP.

The importance of the two dates (Hv 4706 and Hv 4125) that have been examined from Nancy's Bay in Chapter Four is highlighted in Fig.6.8. Curve-1 bisects the two points, but this is not necessarily the best curve to use. Curve-2 has been forced towards the earlier date, and reflects the apparent rapid rise in sea-level more satisfactorily. However, the shape of Curve-2 has been determined more heavily by the earlier end points and is therefore less accurate in the mid- and late Holocene. The ambiguities of some of the datapoints from Lancashire and the rapid changes during the early Holocene mean that the fitted curves need to be treated with caution, and in this case a smooth curve is not an entirely good description of the data.

The average residual of transgressive overlaps is -0.75 m, and for regressive overlaps +0.53 m. For the Lancashire dataset therefore, transgressive overlaps are an average of 1.28 m lower than regressive overlaps, relative to the predicted curve.

The ^{14}C-data for Lancashire have been collected and reported in Tooley (1974, 1978, 1982, 1985c). The Lytham chronology of sea-level changes (Tooley, 1974, 1978) was developed from these data and later modified by Tooley (1982).The Lytham chronology still forms the framework for interpretations of sea-level from around Liverpool Bay, for the Wirral (Kenna, 1986) and North Wales (Bowen, 1977), for example. The chronology was established by examining the variation in age-altitude position of sea-level index points, principally from Fylde in Amoulderness. From this examination, Tooley (1978) identified ten transgressions that had affected the Lancashire coast. Some observations are given below.

The wide altitudinal spread of transgressive and regressive overlaps found in North Wales and Wirral has been noted throughout this thesis. Variability is to be expected because few of the variables which determine a coastal sedimentary response to changing sea-level will be constant even over short distances. In the Afon Ganol valley for example, Glan Aber Farm, which has a very protected inland location, has a quite different lithostratigraphy to nearby Morfa Penrhyn, which has a more exposed location. The indicative meaning of a sea-level index point, that it is formed somewhere near to MHWS, is not in question, but in view of the gross lithostratigraphic evidence available, how well each individual sea-level index point represents the regional pattern must be questioned. Most correlations are based upon the identification of regional patterns, so how well these patterns reflect the original data is important.

Tooley (1978,p.107) states "Lytham III is recorded exclusively from Nancy's Bay". Lytham III is representative of a silty-clay sandwiched between two peat horizons with transgressive and regressive contacts at -2.51 m and -1.30 m respectively. Inorganic marine sediments are also recorded between these altitudes at other sites throughout southwest Fylde at Lytham Common and Lytham Moss (Tooley, 1978). This raises an interesting point of emphasis. If, for example, the chronology was documenting phases of terrestrial domination rather than marine, it may have been stated that "marine conditions are found throughout the Fylde, but Terrestrial phase X is recorded exclusively at Nancy's Bay". The Lytham phases imply that there are definitive periods when marine conditions are not recorded. In fact, the opposite is true, with marine sediments dominating and phases when organic, terrestrial sediments happen to occur which are when the marine influence in the coastal areas was not so strong. This alternative way of looking at the Lancashire data avoids the implied step from site stratigraphy to regional pattern. Stating that "Terrestrial Phase X, **exclusively** found at Nancy's Bay" implies a singularity about the peats found in Nancy's Bay which therefore need not be formed by a regional change in relative sea-level.

These observations, as well as the observations made by Shennan (1980), as to the definition of 'transgression' and 'regression' mean that it is not possible to correlate the North Wales sequences with the Lytham chronology, but this does not prevent correlation of individual events and altitudinal data.

The earliest ^{14}C-dates from Lancashire and North Wales show many similarities. At Woodlands in the Clwyd coastal lowlands a regressive overlap at 13.07 m below present day MHWS was dated at 8540±70 BP (Prince, 1988) and at Heyhouses Lane on the Fylde, a regressive overlap at 13.75 m below present day MHWS was dated to 8575±105 BP. A positive tendency in sea-level was recorded at 8390±105 from Starr Hills on the Fylde, whilst in North Wales this was recorded slightly later at 8170±70 BP. These dates are tentatively interpreted as reflecting a period of a reduced rate of sea-level rise. Peats at this altitude, though not dated, have also been recorded at Foryd (Strahan, 1890) in the Clwyd coastal lowlands.

At Heyhouses Lane, this period of peat formation ended at 7820±60 BP (Tooley, 1978) and was followed by a period of rapid sea-level rise (Tooley 1978, 1989). In North Wales a period of rapid sea-level rise is also indicated, though the smaller altitudinal range and earlier cessation of peat formation at Woodlands (8170±70 BP) mean that the calculated rates are less than in Lancashire.

The date of 7820±60 BP was recorded at -9.65 m OD, and the next date recorded in the Lancashire sequence is 7605±85 BP (Hv 4125), recorded at -2.33 m OD. Taken together, these two dates indicate that there was *c.* 7 m of sedimentation in *c.* 200 ^{14}C-years, a rise of *c.* 34 mm per ^{14}C-year for the period 7800 to 7600 BP (Tooley, 1989). In Chapter 4, the later date (7605±85 BP) was questioned on the basis of the palaeobotanical evidence, but it was also noted that evidence from North Wales may help to accept or refute the arguments for such periods of rapid sea-level rise.

The questioned date was recorded at -2.33 m OD. Three ^{14}C-dates from North Wales have been obtained from an altitude ±0.50 m of -2.33 m OD (corrected for present day MHWS). They are 7255±130 BP, 7080±155 BP and 6680±75 BP from Tregarnedd-bâch, Hendre fawr and Newton Carr respectively. The ^{14}C-date accepted by Tooley (1978) is older than any of these, whilst the date which has been rejected (6950±175 BP from -2.46 m OD) is within the cluster of dates obtained for North Wales. Shennan (1989) has shown that there has been marginally greater uplift in north Lancashire than south Lancashire during the Holocene, but the differences are not sufficient to explain the age differences identified.

Further conflicting evidence for such rapid sea-level rise comes from lithostratigraphic evidence around Liverpool Bay. With such rapid rates of sea-level rise between *c.*7800 and 7600 BP, and within the altitudinal window of *c.*-10.00 to -2.50 m OD, organic sediments would not be expected to occur in coastal sequences within the vicinity of the Fylde. However, at *c.*-5 m OD peats are recorded throughout the region at Downholland Moss (Tooley, 1985b), Wirral (Innes *et al.*, 1990; this thesis), the Afon Ganol valley (this thesis) and Llandudno (Heyworth and Kidson, 1982) where a ^{14}C-date of 7635±52 BP was obtained from -5.21 m OD. Variable sediment compaction rates and/or palaeotidal changes are possible explanations of these variations, but as already noted, the differences in MHWS around Liverpool Bay between the Great Orme and the River Ribble are today only ±0.30 cm.

During the period *c.*8100 BP to *c.*7100 BP, approximately 7 m of sedimentation took place on the North Wales coastline, so there is evidence for relatively rapid sea-level rise. However, there is no evidence for rates of the order of 34 mm per ^{14}C-year. In both North Wales and Lancashire however, these conclusions are based on a handful of ^{14}C-dates and no doubt a more definite chronology will emerge in the future.

In the mid- to late Holocene the correlation is less clear (Fig.6.12). Fig.6.12 is a plot of all the ^{14}C-dates listed in Tables 3.4 and 3.5 for north and south Lancashire. In the period *c.*7000 to *c.* 6000 BP positive tendencies are recorded in Lancashire, matching the pattern identified for North Wales, but throughout this period and beyond, dates from regressive overlaps occur frequently. When the Lancashire data are examined at a site scale however, a clearer picture emerges, particularly when data from the Nancy's Bay area are considered. The lithostratigraphy at Nancy's Bay - 10 was recorded by Tooley (1978, pp.64-65) as follows (Annotated form):

Height (m OD)	*Description.*
+1.52 to +1.22	Str. conf. Brown clay, with peaty partings and rounded stones above, passing down into black, oxidised peat.
+1.22 to +1.02	Sh⁴4. Oxidised peat.
+1.02 to +0.87	Th²4. Partly humified monocot. peat, with occasional blue, beetle elytra.
+0.87 to +0.76	As3, Th²(*Phra.*)1. Blue clay, rich in *Phragmites*.
+0.76 to +0.45	Th²(*Phra.*)4. Partly humified *Phragmites* peat.
+0.45 to -0.48	As3, Sh⁴1, Th²(*Phra.*)+. Ag+. Grey-blue clay, becoming buff towards base, with black organic partings and silty partings.
-0.48 to -1.14	Ag4. Sh⁴+. Grey silt, with very occasional organic partings.
-1.14 to -1.27	Th³4. Th²(*Phra.*)+. Well humified monocot. peat with some *Phragmites.*
-1.27 to -2.40	Ag4. Sh⁴+. Th²(*Phra.*)+. Blue-grey silt.
-2.40 to -2.48	Th⁴4. Completely humified monocot. peat.
-2.48 to -2.98	Ag4 Running wet, coarse blue silt.

In summary, at Nancy's Bay - 10, thin peats are recorded at *c.*-2.50 and -1.00 m OD, and then after a period of clastic sedimentation peat formation begins again at +0.45 m OD continuing upwards, but penetrated by a thin clay between +0.76 and 0.87 m OD. At Hendre fawr - 21 and 29, where ^{14}C-dates have been obtained, thin peats are recorded at *c.*-2.50 and -0.95 m OD; then peat forms between +1.37 m OD and continues until +1.99 m OD though it is penetrated by a thin clay between +1.82 and +1.75 m OD. At Newton Carr the lithostratigraphic record is very comparable. The upper organic sediments at Hendre fawr begin 0.92 m higher than at Nancy's Bay, but the respective ^{14}C-dates on these regressive overlaps are very close: 6025±85 BP at Nancy's Bay and 5935±190 BP at Hendre fawr. The transgressive overlap at -1.14 m OD was dated at Nancy's Bay to

6885±80 BP. An erroneous date was obtained from Hendre fawr on the corresponding overlap: however, stratigraphically, the Nancy's Bay date fits, and the pollen assemblage at Hendre fawr is Flandrian II, dominated by *Quercus*. Interestingly at Nancy's Bay and Hendre fawr there are abnormally high frequencies of *Pinus* (>20% TLP). Resampling of this peat at Hendre fawr should be a priority.

At Nancy's Bay terrestrial sediments are recorded to the surface, whilst at Hendre fawr and Newton Carr there is a return to marine conditions. As the rate of sea-level rise has slowed through the Holocene the influence of secondary factors, or even the location of where boreholes were taken within a site, needs to be considered if meaningful correlations are to be made. Nancy's Bay is a relatively protected site within the Ribble estuary compared with Hendre fawr and Newton Carr. In North Wales surface organic sediments are also recorded, but these are also at relatively protected sites such as Glan Aber Farm and Llangefni.

An important conclusion arises from these observations. A regional chronology will incorporate data from a number of sites within that region. Each of the sites will have slightly different characteristics, and by definition cannot display all the characteristics of a regional chronology because the location of sampling points is a variable. For northwest England, Tooley (1982) has identified 12 periods of positive and 12 periods of negative tendencies in *c.* 9200 ^{14}C-years, representing a distinct period, on average every 383 ^{14}C-years. The chronology for Lancashire has been devised by considering each ^{14}C-date sequentially so that if there are a number of dates from different sites showing a series of transgressive and regressive overlaps in a time sequence, a corresponding series of positive and negative tendencies have been assigned. This produces a large number of 'events', and a quite different chronology from that in North Wales, where there has been an attempt to look for patterns in the dates resulting in fewer 'events'. Correlations of the tendency chronologies between the two areas are therefore invalid.

In the later Holocene however, there are indications of events that took place on a regional scale. In western Britain there is strong evidence for a withdrawal of marine conditions between *c.* 4500 and *c.* 5000 BP. In North Wales and Wirral, regressive overlaps within or close to this period have been recorded at Rhyl Beach (4725±65 BP), Hendre fawr

(4345±145 BP), Park Road (5250±50 BP) and Newton Carr (4525±65 BP). In Lancashire regressive overlaps have been recorded at Altmouth (4545±90 BP), Lytham (5005±45 BP and 4960±210 BP), Heyhouses Lane (4895±95 BP) and Peel (4800±75 BP). Evidence from elsewhere will be considered in the following sections.

6.4.1b Morecambe Bay

The fitted curve for Morecambe Bay is a good match (Fig.6.9), but is not intended to be an extrapolation beyond the oldest datapoint. The curve does not pass through the cluster of offshore dates; indeed the different crustal histories of the onshore and offshore sites are a satisfactory reason for not forcing the curve (Shennan, 1989). However, it is clear that there were comparatively rapid rates of sea-level rise in the early Holocene (Tooley, 1974; Zong, 1993).

Between *c.* 6000 and *c.* 3500 BP the sea-level index points lie either immediately on top of the fitted curve, or immediately below. Upon investigation a geographical distinction was found between the two sets of points. Those lying below the curve are all from sites in the Leven estuary: Skelwith Pool (Zong, 1993), Ellerside Moss (Oldfield and Statham, 1963) and Roundsea Wood (Birks, 1982; Zong, 1993) and those points above the curve come from the Kent estuary further east and the southern shores of Morecambe Bay. Commenting upon periods of organic sedimentation in the Leven and Kent estuaries, Zong (1993) does make the observation that corresponding organic sediments tend to be *c.* 1.00 m in the Kent. There appears to be no obvious explanation for the differences.

Concentrating on the ^{14}C-dates from onshore sites, the rates of change of sea-level after 7700 BP (the earliest onshore date) have been much less in Morecambe Bay than in North Wales. This difference is mainly due to the greater residual glacio-isostatic uplift in the Morecambe Bay area. In Morecambe Bay for example, organic sediments that had formed at *c.* 7000 BP are found 2 to 3 m below MHWS, whereas in North Wales they are typically recorded at 6 to 7 m below MHWS. In North Lancashire sediments of this age were recorded *c.* 6 m below MHWS, showing a closer match with the North Wales data than the Morecambe Bay data.

6.4.1c **Cardigan Bay**

Kidson and Heyworth (1978) and Heyworth and Kidson (1982) have developed a sea-level curve for Cardigan Bay based upon radiocarbon dates presented in Chapter 4, as well as dates from submerged tree stumps, which they note is 'almost perfectly exponential in form' (Kidson and Heyworth, 1978, p.750). Kidson and Heyworth go on to suggest that this is a reflection of a return to equilibrium conditions following changes in the glacio-eustatic balance before 10,000 BP. Before *c.*5000 BP, sea-level rise, they state, was rapid so that peat formation was limited to widely separated and brief periods. After *c.*4000 BP sedimentation was in equilibrium with the slower rate of sea-level rise at ever decreasing rates but approximating a smooth exponential decay curve. Given such a model, the variability in the marine influence described between the main sites in Clarach Bay and the Dovey estuary would be attributable to variations in sediment accumulation. This assertion is challenged by evidence from elsewhere. Tooley's (1978, 1989) identification of rapid rates of sea-level change in northwest England can be correlated with particular catastrophic events such as the breakup of the Scandinavian and Laurentide ice-sheets.

Apart from one offshore date, all others from Cardigan Bay are after 6370 BP so there is no evidence either to corroborate or to refute rapid sea-level changes in the area. The derivation of the exponential curve (Kidson and Heyworth, 1978) is therefore the most simple interpolation of the available data. In Fig.6.11 it can be seen that the curve for Cardigan Bay is always underneath the North Wales/Wirral curve.

Correlations with data from the Cardigan Bay area can only be made after 6370 BP, when the rate of sea-level rise was slowing, and the signal becoming less clear. The major feature of the lithostratigraphy at Borth Bog and Ynyslas (Wilks, 1977, 1979) is, however, an intertidal peat overlain by *Phragmites* peat at *c.*0 m OD, passing into a woody peat above (Wilks, 1979). ^{14}C-dates taken at this regressive overlap range from 6026±135 BP (Godwin and Willis, 1961) to 5150±90 BP (Wilks, 1977).

Detailed palaeobotanical analysis has been completed upon these sediments at Ynyslas (Wilks, 1979). At the regressive overlap dated to 5150±90 BP, the transition from intertidal to terrestrial conditions is demonstrated. Wilks (1979) also comments that the whole 'regression' spanned the period *c.*6000 to *c.*4700 BP ('regression' was defined by Wilks (1979,p.17) as "responses to a combination of relative sea-level change and the local rate of sedimentation"). Noting that no well-established sea-level curve indicates such a sustained fall of sea-level over such a long period, and that Glacial rebound was very limited in Cardigan Bay, Wilks (1979) states that this 'regression' cannot be due to a fall in relative sea-level. This is not entirely logical, since sea-level does not need to fall for the whole of the period 6000 to 4700 BP. A fall in sea-level at the start of the 'regression' could be enough to initiate a period of peat formation, and even if sea-level rose subsequently, providing it did not rise too rapidly, peat formation could continue. In such a case the regression would have been caused by a fall in sea-level, though not sustained by it.

Wilks (1979) acknowledges a fall in the rate of sea-level rise and the possibility of barrier building in the Dovey estuary as possible causes of this widespread regressive overlap. That this regressive overlap, so widespread in the estuaries of central Cardigan Bay, would seem to be correlated with similar features of comparable age in North Wales, Lancashire and Morecambe Bay implies that the concentration on local factors as explanation (Wilks, 1979) may only be one part of the story. However, it must be acknowledged that the variability in the timing of this regressive overlap in central-west Britain could well be explained by the rate of sea-level rise slowing, and different marshes producing varying responses in the timing of a lithological change.

6.4.1d Synthesis.

The fitted curves from the four regions considered are displayed in Fig.6.11, The curves from North Wales/Wirral and Lancashire are very similar after 7000 BP as predicted by Tooley (1978), but before this date there is a departure in the curves. The sparsity of data before *c.*7500 BP, and problems of fitting a curve through dates of this period mean that the curves shown in Fig.6.11 should not be used for estimating rates of change before this date. The Morecambe Bay curve is consistently above the North Wales curve, and for Cardigan Bay consistently below.

The departures of transgressive and regressive overlaps for the three areas calculated are:

Table 6.7: Residuals of transgressive and regressive overlaps.

Region	Transgressive overlaps (m)	Regressive overlaps (m)
North Wales/Wirral	-0.67	-0.13
Lancashire	-0.74	+0.53
Morecambe Bay	+0.07	+0.11

In all cases, though for Morecambe Bay the difference is negligible, transgressive overlaps are lower than regressive overlaps relative to the predicted values. There are two logical explanations for this observed pattern.

(1) The curves produced are the simplest fit of the entire dataset, and therefore smooth. However, in periods of peat formation sea-level will normally rise more slowly than when inorganic sediments are being deposited.

(2) In Chapter Two, it was described how the compaction of peats may be as high as 90%, and certainly the compaction for peats will be higher than for clays, silts and sands (Bennema *et al.,* 1954). Since transgressive overlaps are taken from the top of peats, overlain by inorganic sediments, there is a far greater potential for compaction. Most organic sediments that were sampled below the surface showed a large degree of compaction.

Though both explanations are no doubt valid in some cases, the consequences of the second explanation have been recorded in the field, and it is the simpler of the two (Birks and Birks, 1980). If explanation (2) is generally valid, it implies a greater smoothness in the time/altitude data than shown (though it is not proposed to apply a correction factor). The use of a smooth exponential curve would, however, seem a positive way forward in assessing the problem of sediment compaction and the differences between dated transgressive and regressive overlaps and may suggest oscillations in sea-level to be of a lesser magnitude in the Liverpool Bay area than previously thought.

6.5 Conclusions.

In this chapter the ^{14}C-dates collected from North Wales and Wirral have been examined for their quality as sea-level index points. Their depositional environments have been discussed in this and the previous chapter. This information has been drawn together so that a chronology of tendencies and time-altitude movements of sea-level could be established.

Difficulties have been found in correlating this chronology with those from other regions. The shortage of data does mean that tendency chronologies cannot be a totally reliable tool of correlation. Time-altitude data have been shown to be more robust, since they identify where sea-level was rather than what it was doing at any one time. Ultimately however, reliance has been placed on comparing raw data. By adopting this approach the interpretations of others are, to an extent, by-passed. This is not a rejection of these interpretations, but an attempt to apply one means of thinking to a whole dataset. When there is so much disagreement over whether a regressive overlap is caused by an actual fall in relative sea-level or not, this approach would seem valid.

Tendency analysis has been applied to the data from North Wales which has enabled a chronology of marine withdrawals and inundations to be established for individual sites and groups of particular sites. To be able to go further and state to what extent these inundations and withdrawals are caused by changes in relative sea-level is a big step. To be able to make this step, one would expect to be able to correlate tendency chronologies between sites and areas. The problems in comparing a tendency chronology from North Wales and Lancashire demonstrated that this was very difficult.

Trying to correlate a marine withdrawal, for example, is an attempt to correlate a process. Regional processes that occur in coastal sedimentary systems are subject to modification at a site scale, so the correlation becomes unreliable. A time-altitude plot shows where sea-level was at a particular point in time. Inferring falls in sea-level has been recognised as unreliable because of the problems of differential sediment compaction. For the areas that have been investigated in this thesis however, comparing time-altitude data in itself is reliable because the trend of sea-level through the Holocene has been of a fairly continuous rise: thus if one is not too concerned with identifying periods of sea-level fall, the main error is one of altitudinal displacement. Tendency analysis tries to identify individual events which have more chance of having a random distribution, as explained above. In essence, tendency analysis can potentially tell us more about actual sea-level **changes**, but with the data available is more prone to error.

Five periods of positive and negative sea-level have been identified for North Wales and Wirral. Also the broad altitudinal trend of sea-level has been established. It is anticipated that if more data become available for the area, then the chronology of tendencies may require considerable update, whereas the modifications required to the time-altitude results would be less severe.

Chapter Seven

Crustal Movements.

During the maximum of the last glaciation (20-18,000 BP) up to 10^{23} g of water were concentrated in the northern hemispheric ice-sheets (Peltier, 1980). Following deglaciation this concentrated mass has been redistributed evenly throughout the ocean basins, with spatial variations as a function of gravitational potential. This change in the distribution of mass is largely responsible for the pattern of uplift and subsidence throughout the Holocene and that which we can observe today.

In this chapter the evidence for crustal movements in North Wales, Wirral and surrounding regions is examined. Isostatic uplift and associated peripheral subsidence occur because the Earth has a particular interior structure. In section 7.1, some of the features of this structure are described along with the main forces that are operative upon this structure and lead to a change in mass distribution. Crustal movements are examined using two main techniques: the residual method (Shennan, 1989) and a new technique comparing the rates of change of relative sea-level between regions. In section 7.4 the results using these two techniques are compared with the results from crustal modelling by Lambeck (1991).

7.1 Basic Physical Concepts.

If a force is applied to a body, the two extreme possible outcomes are (1) that the body regains its former shape completely, in which case it can be said to be perfectly elastic, or (2) that it maintains completely its new and altered shape, in which case it is perfectly plastic. Bodies that behave elastically will deform to an extent proportional to the force applied. In other words below their elastic limit they obey Hooke's law. The elastic limit is defined as the maximum force that can be applied to a body so that it can still maintain its original dimensions. Hooke's law can be expressed as:

$$\frac{Stress}{strain} = constant \qquad \text{Eqn. 7.1}$$

Strain expresses the change in dimensions of a body, and is written in the form:

$$strain = \frac{e}{l} \qquad \text{Eqn. 7.2}$$

(e = extension, l = original length)

Stress is defined as force per unit area, so with respect to equation 7.1 as the force per unit area (stress) on an elastic body increases there is a greater change in the dimensions of that body for Hooke's law to be obeyed. Following the removal of that force, the body will start to regain its former dimensions. The Earth is not a perfectly elastic body, but the concepts of stress and strain are very important when considering crustal deformation in response to the application and then removal of loads. The simplest models of the response of regions of the Earth to applied stress derive from these concepts, that is linear elastic deformation (Bott, 1982).

When there is a change in the distribution of mass at the surface of the Earth, the resultant change in radius at a particular point in space is dependent on the structure and properties of the lithosphere and asthenosphere. The lithosphere comprises the crust and upper mantle and can be divided into three rheological layers (Bott, 1982). The surface crust is a strong, brittle layer 20-40 km thick. A plastic layer separates the crust from the lower zone, a transitional layer between the lithosphere and asthenosphere. The asthenosphere is the weak zone of the mantle where isostatic adjustments are accommodated (Bott, 1982).

The recovery of the Earth's surface towards equilibrium following deglaciation is primarily determined by the viscosity of the lower part of the lithosphere and asthenosphere, and also the flexural rigidity of the lithosphere. The viscosity of a fluid is a measure of that fluid's resistance to motion and flexural rigidity is defined as the resistance of an elastic sheet or beam to bending. For narrow loads (usually with a diameter less than the thickness of the lithosphere) both factors are significant, but for wider loads (greater than the thickness of the lithosphere), viscosity is the dominant factor.

These basic concepts are sufficient for a general understanding of the current pattern of crustal movements over the Earth. In regions where the ice-load was greatest such as the Gulf of Bothnia and eastern Canada, the amount of recovery has also been greatest (Fairbridge, 1983). When it comes to the registration of these processes as a physical entity on the Earth's surface the issue is far more complex. Explanations of their occurrence can be made only with reference to empirical data and theory.

7.2 The pattern of crustal movements in Britain from empirical data.

Before the availability of ^{14}C-dating techniques the estimation of relative crustal movements in Britain was largely reliant on the altitudinal correlation of geological features. At this stage Wright (1914) and Daly (1934) had demonstrated the broad pattern of crustal movements in Britain with uplift in the north and subsidence in the south. By correlating stratigraphic sequences from coastal areas Godwin (1945) showed that there was relative subsidence along the south coast and Fenlands relative to the Somerset Levels and south Wales.

The location of North Wales and northwest England, Tooley (1978) notes, in a position marginal to the area of maximum ice-loading means that it is a critical area in which to examine Holocene crustal movements. However, in the area as a whole the analyses of crustal movements, and indeed relative sea-level changes in general, were held back by the preconceived idea of a 25′ raised shoreline (Wright, 1914; Gresswell, 1953; Whittow, 1960; Hopley, 1963) until Tooley (1969, 1974 and 1978) proved the hypothesis incorrect. Despite this work, correlations continued to be made with the 25′ beach, for example Andrews *et al.* (1973) working on the Cumbrian coast.

Andrews *et al.* (1973) concluded that during the last 13,000 years 18.00 m of isostatic recovery had taken place along the Cumberland coast and that this represented a small fraction (5%) of the total recovery for the area. This conclusion was flawed by a number of factors. First, the data used by Andrews *et al.* (1973) to construct a sea-level curve came from a variety of types of sample, but particularly shells. The indicative range of these samples was not stated. Second, Andrews *et al.* (1973) integrated these data with offshore ^{14}C-dates from Morecambe Bay (discussed in Chapter Four) on the assumption that the small distance between Duddon Estuary and Morecambe Bay meant that isostatic recovery was uniform in the two areas through the Holocene. Examination of these data (Tooley, 1974; Shennan, 1989; Zong, 1993 and this thesis) has shown this assertion to be incorrect. Third, the estimation of a 400-500 m depression in the Cumbria area during the Devensian period from ice-loading has been shown to be far too large (Mörner, 1991; Lambeck, 1991; Tushingham and Peltier, 1991). Andrews *et al.* (1973) thus overestimated the total uplift since 18000 BP in Cumbria, and underestimated the amount of Holocene uplift.

By assimilating data from Morecambe Bay, the Lancashire coast, the North Cheshire Plain and North Wales, Tooley (1978) was able to make some statements regarding Holocene crustal movements, which subsequent analyses (Shennan, 1989; this thesis) have shown to be correct. Tooley (1978) showed that there was little altitudinal displacement of stratigraphic features between north Lancashire and North Wales, but that further north in Morecambe Bay there was a sudden increase in gradient. Similarly, differences between these data and that for south Wales during the early Holocene led Tooley (1978) to conclude that the Lancashire and North Wales coasts were being uplifted until *c.* 6000 BP.

Tooley (1978) correctly asserted that the explanation for these observed patterns required a more detailed chronology of deglaciation in the eastern Irish Sea. Though the debate regarding the chronology of deglaciation continues, it has in many ways been superseded by the results from crustal modelling. Lambeck (1991) in particular has shown that both ice extent and ice thickness over Britain were much less than previously thought (Mitchell, 1972; Boulton *et al.*, 1977). Tushingham and Peltier (1991), in a recent model, also suggest a restricted ice-cap over Scotland with no connection to the Fennoscandinavian ice sheet and predict 'submergence' in the Tees, Cumberland coast and Merseyside during the Holocene. Neither Lambeck (1991) nor Tushingham and Peltier (1991) discuss the possible effects of the Welsh ice sheets on crustal rebound.

Investigations into crustal movements in Britain have focused largely upon the effects of glacio-isostatic readjustment. The broad pattern of crustal movements established for Britain, an exponential decay in uplift in the north and linear subsidence in the south, is satisfactorily explained by the glacio-isostatic theory. However, there are numerous examples of local variations which cannot be explained by glacio-isostasy. Devoy (1977), for example, working in the Thames estuary established that subsidence was greater in the outer Thames estuary than the inner estuary. Later Shennan (1989) showed that in the estuary as a whole there was enhanced subsidence before 6000 BP, followed by a period of stability and then uplift. Devoy (1977) suggested that enhanced sediment loading in the outer estuary could be a possible explanation and Shennan (1989) added the possibility that changes in tidal range following the connection of the English Channel with the North Sea, or a collapsing forebulge, needed further investigation. In Morecambe Bay the relative subsidence of offshore sediments relative to onshore sediments does suggest that increased loading of the crust from sediment or water has been significant along parts of the British coastline.

7.3 Analysis of crustal movements from Empirical data.

The Holocene relative sea-level record is a function of the differential rate of eustatic and isostatic changes, as well as the operation of local processes such as differential rates of sedimentation (Kidson and Heyworth, 1978), the effects of coastal barriers (Jennings and Smyth, 1985), or changes in tidal and coastal configurations (Hinton, 1992). Concentrating on the two main factors, it can be said that:

$$\frac{dR}{dt} = \frac{dE}{dt} - \frac{dI}{dt} \qquad \text{Eqn. 7.3}$$

where R is relative sea-level, E is eustasy, I is isostasy and t is time.

$$\therefore \frac{dI}{dt} = \frac{dE}{dt} - \frac{dR}{dt} \qquad \text{Eqn. 7.4}$$

When crustal movements are being examined from Holocene sea-level data there are steps that need to be taken.

(i) If absolute values of movement are required eustasy and isostasy need to be separated, implying we have a prior knowledge of eustasy.

(ii) If we are concerned only with the relative difference in crustal movements between areas, on the assumption that eustasy will have been constant over a large area we can compare the rates of change of relative sea-level.

7.3.1 <u>The subtraction of a eustatic constant from a relative sea-level curve.</u>

For the British and the North Sea coastlines the technique of subtracting a eustatic constant from relative sea-level curves and sea-level index points has been developed by Shennan (1987, 1989). A smoothed regional 'eustatic' curve (Mörner, 1984 and shown in Fig.7.1) is subtracted from relative sea-level points, corrected to MHWS, using time as a reference producing residual points from which a residual curve can be derived. The residuals will give an estimate of uplift or subsidence. Two models of eustasy were presented by Shennan (1989), one including oscillations and the other without. In this analysis the model without oscillations has been applied, replicating the method adopted by Shennan (1989).

Shennan (1989) applied this methodology to 429 sea-level index points throughout Britain, collected through IGCP Projects 61 and 200, producing a series of residual curves for fifteen regions. 633 sea-level index points are now available in the Durham database (Long and Shennan, 1993). At the time of their analysis only two sea-level index points were available from North Wales so there was no analysis carried out on North Wales, but results were obtained for South and North Lancashire, Morecambe Bay (Fig.7.2) and Cardigan Bay (Fig.7.3) as described below.

South Lancashire.

An exponential decrease in uplift until *c.*5000 BP, followed by relative stability. Dates are only available from *c.*7100 BP onwards.

North Lancashire.

As in South Lancashire an exponential decline in uplift is apparent before 5000 BP, followed by very slight linear uplift of 0.10±0.10 mm/yr to the present day. Shennan (1989) also noted three outliers (the oldest dates) warranting further investigation. These residuals are discussed in the next section.

Morecambe Bay.

Shennan (1989) notes the distinction between onshore and offshore dates and the results obtained apply to the onshore series. An exponential decline in uplift is apparent before 6000

BP, followed by linear uplift at a rate of 0.35±0.12 mm/yr, based on the offshore dates only.

Cardigan Bay.

The analysis revealed a slight subsidence through the later Holocene at a rate of -0.11±0.08 mm/yr.

7.3.1a <u>Application of the residual method to new data from North Wales and Wirral.</u>

A plot of residuals from North Wales and Wirral is shown in Fig.7.4. After *c.*7800 BP the trend of the data points for the two sets of data is quite similar and is consistent with the expected trend of a decrease the amount of uplift up to *c.*5000 BP, followed by relative stability. Such a trend was identified for the adjacent South Lancahire (Shennan, 1989) and Tooley (1978) commented that the whole Liverpool Bay region should act uniformly in response to deglaciation.

The term 'relative stability' after *c.*5000 BP needs to be examined with respect to the North Wales/Wirral datasets since all points after 5000 BP lie below the y=0 line, the residuals becoming increasingly negative towards the present day. The interpretation of this pattern is that uplift continued in the area beyond 5000 BP, albeit at a slower rate, to *c.*3000 BP. There is evidence of similar residuals in adjacent South Lancashire (Shennan, 1989), but not in the Fylde or further north in Morecambe Bay. To the south, in Cardigan Bay, residuals are consistently negative. The consistency of these results supports the model of Shennan (1989).

Similarities were noted in the sea-level record between northeast England and North Wales/Wirral. Shennan (1992) has analysed the crustal residuals from sites in northeast England and shown that there is an increase in uplift between sites in the Tees estuary (Sproxton, 1989) and Elwick in northern Northumberland. A linear fit for the last 5000 years indicates zero uplift in the Tees estuary, as would be the case for North Wales between the Conwy and Mersey. Interestingly, however, the negative residuals during the last 5000 years derived from the North Wales data are repeated for the Tees and Hartlepool with a similar magnitude (0.00 to -1.00 m). The negative residuals over the last 3000 ^{14}C-years need not necessarily be due to recent subsidence around Liverpool Bay. The effects of recent drainage in coastal lowlands dominated by organic surface sediments, for example, were demonstrated by Godwin (1978). Silt islands and roddens are visual evidence of the loss of peat over the whole Fenland, and at Holme Post in the western Fenland over 11 feet of peat were lost between 1848 and 1932 (Godwin, 1978). At most sites in North Wales and Wirral the surface sediments are inorganic. However, iron-staining and the 'blocky' structure of many of these sediments (cracked and flaky compared with the very consistent and plastic deeper silts and clays) are evidence of drying and oxidation. The prediction by Shennan (1989) that the Tees and Wirral areas have a similar crustal history during the recent past seems vindicated by the new data.

Before 7800 BP, as in North Lancashire, the residual points deviate from the expected trend. The two points in question are from the Vale of Clwyd (Prince, 1988) with very similar time and altitude characteristics to two outliers from Heyhouses Lane, Lancashire.

Table 7.1: Deep dates from North Wales and Lancashire.

Site	Lab Code	Date (BP)	Alt[1]	Al[2]
Woodlands	SRR 2510	8170±70	-9.00	-12.95
Woodlands	SRR 2511	8540±70	-9.12	-13.07
Heyhouses Lane	Hv 4345	7820±60	-9.65	-13.65
Heyhouses Lane	Hv 4346	8575±105	-9.75	-13.75
Starr Hills	Hv 4343	8390±105	-11.14	-15.14

Alt[1] - Altitude (m OD.)
Al[2] - Altitude (m below MHWS.)

These 'outliers' indicate that there was a period of relative subsidence around Liverpool Bay and in Morecambe Bay in the early Holocene, approximately 8000 BP. The following points help explain this apparent anomaly.

(i) The general form of the relative sea-level curves between Cardigan Bay and North

Lancashire, including that for the North Wales coast, has been shown to be a negative exponential. One of the characteristics of such a curve is that the rate of change will decrease through time, but the eustatic curve in the period 8800 to 6000 BP (the period in which these anomalies are apparent) does not have this characteristic. Fig.7.1 shows that the gradient of the eustatic curve is greater in the period 7000 to 6000 BP than the period 8500 to 7000 BP. Such a feature is contrary to accepted patterns of a decreasing rate of sea-level rise during the Holocene (Jelgersma, 1961; Kidson and Heyworth, 1978; Tooley 1978; Fairbanks, 1989; Lambeck, 1991).

In Fig.7.5 a residual curve, derived from the eustatic curve (Shennan, 1989) and the fitted curve for North Wales, is plotted. Between *c.* 8500 and 6000 BP the direction of the rate of change of the eustatic and fitted curves is opposite; hence the residual curve first moves away from the y=0 line, then turns towards it. The possibility exists that the 'outliers' in the North Lancashire and North Wales datasets result from the eustatic curve not reflecting reality during the early to mid- Holocene.

(ii) Shennan (1989) noted that in periods of relatively rapid sea-level rise, the possible error when analysing crustal residuals was greater. In such periods, a small age difference between actual and predicted values (from Mörner's eustatic curve) will produce disproportionately large altitudinal differences.

(iii) There is the overall question of trying to separate the eustatic and isostatic components (Lambeck, 1991) and how far residuals are a true expression of crustal movements.

(iv) In point (i) it was asserted that the 'eustatic' curve adopted by Shennan (1989) may be inaccurate for the early Holocene. If this was the case, the anomalies from other regions would be expected. In general however, this is not the case (Shennan 1989, Fig.8). An exception nevertheless, is from the outer Thames estuary (Devoy, 1977; Shennan, 1989) where there is evidence of enhanced subsidence *c.* 8000 BP.

Devoy (1989) has speculated that this enhanced subsidence was caused by sediment loading and/or hydro-isostasy, though changes in the tidal regime following the opening of the Strait of Dover have also been proposed. What is particularly interesting about the similar phenomenon identified around Liverpool Bay and Morecambe Bay is that it occurs in a geographically contained area, indicating that there could be a discernible causal process. If the spatial distribution of locations where this subsidence had been identified was more random then identifying a cause would be more difficult.

The problem does remain that there are relatively few ^{14}C-dates from this period around the British coast. Until there is more evidence available, the possibility that the phenomenon is more widespread, and thus indicative of a more rapid sea-level rise in the early Holocene than previously thought, remains open. However, if these apparent anomalies are confined to particular geographical areas, the possibility is that they are caused by sediment loading and/or hydro-isostasy.

7.3.2 Analysis of crustal movements from calculated rates of change of relative sea-level.

Quinlan and Beaumont (1981) outline some of the problems in determining the value of either eustasy (*E*) or isostasy (*I*) in the sea-level equation. The concept of a stable area in which to measure *E* (Shepard, 1963) has been shown by Clark *et al.* (1978) to be invalid because of, for example, elastic deformation of the ocean basins from meltwater. Determining *I* from, for example, tilted shorelines demands particular local conditions. Geoidal shifts (Fjeldskaar, 1989) then mean that values of *E* or *I* defined locally cannot necessarily be applied regionally.

These problems aside, there is good reason for attempting to separate these two variables. Estimates of present day rises in sea-level are dependent upon separating land movements from tide gauge records (Emery and Aubrey, 1985; Woodworth, 1987; Alcock *et al.*, 1989) and recently Shennan and Woodworth (1992) have attempted to integrate the techniques of separating *E* and *I* for short timescale tide gauge records and the longer-term Holocene geological record. Ultimately, the strategic result of sea-level research is reliant on this area of fundamental research, and the separation of these variables over different timescales by

Shennan and Woodworth (1992) is an important step in this direction.

At any period through the Holocene net uplift will have taken place at a location when the rate of vertical, positive land movement exceeds the rate of change of eustatic sea-level rise (Eqn 7.4) and net subsidence will occur when the rate of change of sea-level is greater than the rate of vertical land movement. To establish the chronology of uplift and subsidence at a particular location this calculation is required. On the supposition that we cannot measure E accurately, analysing rates of change of relative sea-level data (dR/dt in Eqn 7.4) is a method of comparing differential crustal movements between areas. Between Cardigan Bay and Morecambe Bay on the west coast of Britain we can assume that E has been more or less constant through the Holocene, so the observed differences in the rates of change of relative sea-level will reflect differences in crustal movements between areas.

Every sea-level index point has an altitudinal and age error: hence it is not possible to compare rates of relative sea-level change by calculating the gradient between a series of index points. The data need to be smoothed and this smooth dataset analysed. In Chapter Six it was described how smooth curves had been fitted to the areas in question. Though several methods were available, notably the option of fitting a spline curve, an exponential curve was used not least because the curves produced can be examined mathematically as well as graphically. Some of the problems and possible inaccuracies of generating a curve through a set of sea-level index points have been examined: nevertheless it is necessary to attempt such an analysis. Generating such curves allows the comparison of dR/dt, rather than R and R i.e. one relative sea-level curve with another (Devoy, 1977; Haggart, 1989), $E - R$ (Shennan, 1987, 1989) or $R - I$ (Flemming, 1982).

7.3.2a <u>Calculating rates of change of sea-level.</u>

Each of the smoothed curves generated in Chapter Six is an exponential expression; therefore we can calculate the gradient, or rate of change, function. The sea-level index points from North Wales can be described by the expression:

$$R = \frac{1}{15} e^{0.63t} \qquad \text{Eqn. 7.5}$$

The rate of change is therefore expressed as:

$$\frac{dR}{dt} = \frac{0.63}{15} e^{0.63t} \qquad \text{Eqn. 7.6}$$

where R is relative sea-level, and t is time.

The gradient function was established for each area, and the resulting curves are displayed in Fig.7.7.

7.3.2b <u>Possible error in the calculation of rates of change.</u>

The rate of change function is the first differential of the fitted sea-level curve, so difficulties in fitting curves will lead to errors in calculating rates of change. When differentiated any original errors will be enhanced, so caution is required when analysing rates of change. In Fig.7.6 the rates of change from North Wales/Wirral, Lancashire, Cardigan Bay and Morecambe Bay are displayed, including two curves from Lancashire. The first curve L1 is the average best fit curve, whereas the second L2 was forced more strongly through the index points from the early Holocene to reflect the rapid rates of sea-level rise identified from the area (Tooley, 1989). The large departure of the two curves L1 and L2 in the later Holocene enforces the view that before 7500 BP the models become inaccurate because of a lack of data, enhanced errors from rapid changes and the simple characteristics of the models.

The exponential expressions generated have two parameters; a constant and an exponent. In order to model the relative steepness of the L2 curve in the later Holocene, the exponent value has to be increased, and then to obtain realistic altitudinal values, the constant decreased. When the exponent is increased, however, the curve becomes more curvilinear in form. In L2, the repercussions of this are that for the early Holocene rates of change of sea-level are greater than fitted for Morecambe Bay. This result is not supported by available data (Shennan, 1989). The conclusion that the technique is only useful where the smoothed data are exponential in form is tempting, and appears generally valid if a ±2.00 m error is acceptable, but is a route into a circular argument.

7.3.2c Interpretation of rates of change of sea-level.

Comparing rates of change of sea-level is a method of comparing relative crustal movements between areas and does not give a direct indication of whether an area is being uplifted or is subsiding since E and I are not being separated. The results from crustal modelling (Lambeck, 1991) are in the form of relative sea-level curves for different locations where there is no attempt to separate E and I. It is not possible to use any area along the west and northwest coasts as a control as discussed by Tooley (1978) and later proved by Lambeck (1991): *cf.* Kidson and Heyworth (1978).

In Fig.7.7, the rates of change for the last 7500 ^{14}C years are displayed and the corresponding values at 500 year intervals in the table below.

Table 7.2: Rates of relative sea-level change (mm/yr).

^{14}C-years	N.Wales	Lancs (L1)	Lancs (L2)	Morecambe Bay	Cardigan Bay
500	-0.006	-0.005	-0.001	-0.011	-0.011
1000	-0.008	-0.008	-0.002	-0.013	-0.015
1500	-0.011	-0.010	-0.004	-0.016	-0.020
2000	-0.015	-0.015	-0.006	-0.020	-0.027
2500	-0.020	-0.020	-0.009	-0.025	-0.038
3000	-0.028	-0.028	-0.014	-0.031	-0.050
3500	-0.038	-0.039	-0.021	-0.039	-0.066
4000	-0.052	-0.054	-0.032	-0.048	-0.089
4500	-0.072	-0.076	-0.049	-0.060	-0.119

5000	-0.098	-0.105	-0.074	-0.074	-0.161
5500	-0.134	-0.146	-0.114	-0.092	-0.217
6000	-0.184	-0.203	-0.174	-0.114	-0.295
6500	-0.0252	-0.283	-0.267	-0.141	-0.390
7000	-0.346	-0.394	-0.408	-0.175	-0.524
7500	-0.474	-0.548	-0.624	-0.216	-0.703
8000	-0.649	-0.762	-0.954	-0.268	-0.945

Before *c.*3500 BP, the rate of change of relative sea-level is less for the Morecambe Bay region than N.Wales/Wirral. Moving back in time the difference between the two areas increases and the curves for the two regions are quite distinct. After 3500 BP, the rates of change are so small that no significance can be attached to the apparent differences between the curves. There is no real distinction between the Lancashire L1 curve and that for N.Wales/Wirral. Using this technique with the currently available data, Lancashire and North Wales have a very similar relative sea-level record.

The Cardigan Bay curve is distinct from the N.Wales/Wirral and Lancashire curves: this would seem to vindicate the conclusions of Shennan (1989). The existence of only one data point after 6000 BP is a bigger constraint when comparing rates of change rather than crustal residuals because of the effect singular end data points can have on the overall shape of the curve. If a linear trend is assumed for the last 6000 ^{14}C-years the distinction is still apparent.

As has been stated, the results from the recent past should be treated with caution. Drainage in coastal areas has caused a disappearance of recent organic sediments and thus a record of sea-level changes in the last *c.*2000 years. Tide gauge data do, however, provide a potential means of obtaining a very recent record of sea-level changes and their spatial variation.

In the UK, there are currently 34 'A Class' tide gauge stations (Woodworth, 1987). The data from these stations have been analysed at a UK scale by Woodworth (1987) and within the context of data from other European stations by Woodworth (1990) and Woodworth *et al.* (1990). Woodworth (1987) reports that only 11 UK tide gauge stations have 20 or more years' data since 1916, precluding meaningful comparisons with the other 23. Furthermore, only 4 stations have sufficient data to provide a time series of sea-level changes in the twentieth century: Newlyn, Sheerness, North Shields and Aberdeen. Despite the limited number of stations that can be used in an analysis of crustal movements, Woodworth (1987) has shown that sea-level is rising fastest in Sheerness and slowest in Aberdeen (the difference being just under 2 mm per year).

In conclusion, from comparing rates of change of sea-level it is possible to state that there has been relative submergence of Cardigan Bay and relative uplift of Morecambe Bay, relative to North Wales and the Wirral through the Holocene. Our knowledge of the recent past is limited by the lack of sea-level index points younger than 2000 BP.

7.3.3 Assessment of techniques.

Using a region by region approach, the results from these analyses are consistent. Using the model of Shennan (1989) as a baseline, the results for North Wales and Wirral using both techniques fit well. Some points that can be made with respect to the techniques are:

(i) The residual method appears a more robust technique when using relatively small datasets. For example, using the residual method it was possible to pick out 'negative residuals' during the recent Holocene in North Wales which have also been found in Teesside (Shennan, 1992). Whether or not the analysis is sufficiently accurate over the last 3000 ^{14}C-years to say with any confidence that this is evidence for subsidence in the recent past is open to question, but the similarity of response of two distinct regions to relative sea-level changes could be established.

An alternative approach to analysing rates of change, using a spline function compared with an exponential curve (Long 1991), was more successful at distinguishing changes in the early Holocene period over small distances. Within southeast England, reduced rates of change of sea-level were established in East Kent and West Sussex relative to east Kent and the Thames estuary at *c.*3000 BP. These differences were also detected using the residual technique which was carried out at a greater spatial resolution than by Shennan (1989).

(ii) With more data, so that more reliable curves can be developed, the analysis of rates of change of sea-level has much potential in the interpretation of observed patterns. Shennan (1989) comments that areas needing further investigation include forebulge collapse and crustal movements over relatively short distances. For such analyses, an estimation of the rate of change of spatial gradients of isobases is required. If sufficient data were available, this does correspond to the second differential of the original fitted sea-level curve. This function is so far removed from the original function, that attempting it without far better models will produce very unreliable results.

(iii) Using both techniques together is an effective way of analysing crustal movements on a regional scale and both techniques require more data from the early Holocene in particular.

7.4 Comparison with existing models and theories.

In the previous sections the evidence for crustal movements from the new ^{14}C-dates collected from North Wales and Wirral was explored within a regional context. The data were shown, by using two different techniques of analysis, that North Wales and Wirral conform well to the most recent model of crustal movements in Britain based upon empirical data. The anomalies in the data that previous analysis had revealed were further confirmed by the analyses here. Differences that exist between this analysis and that carried out by Shennan (1989) are that there is some evidence of slight subsidence in the recent past around Liverpool Bay and that the crustal histories of Lancashire and North Wales cannot really be differentiated.

In the following section the new data from North Wales and Wirral are examined with respect to theoretically based models at inter- and intra-regional spatial scales.

7.4.1 Crustal modelling.

Crustal models, or models of glacial isostasy and postglacial relative sea-level change, calculate the relative sea-level as a function of time and geographic co-ordinates. The inputs to the models are deglaciation histories of the major ice-sheets and rheological parameters including lithospheric thickness. For the sea-level researcher, the most interesting results are the sea-level histories, but the models are also used to assess variables such as deglaciation models (Lambeck, 1991), lithospheric thickness (Peltier, 1986) and viscosity (Cathles, 1975).

The rheology of the Earth is assumed to be either 'Maxwellian' or 'Burgers' viscoelastic (Peltier, 1987). In the model developed by Lambeck (1991) for the British Isles the response of the Earth's surface was approximated by a linear viscoelastic Maxwell body. In more general terms this means that the initial response of the interior of the Earth to an applied stress is Hookean elastic (Section 7.1), and in the final response is 'Newtonian viscous'; in other words the response is modified by a viscosity factor. The viscosity factor will vary as a function of the radius of the Earth (Peltier, 1987).

Clark *et al.* (1978) explain some of the limitations and advances in early simulation models. Early models (e.g. Peltier and Andrews, 1976) modelled the distortion of a solid surface of the Earth thus ignoring the relative rise of continental land masses to the ocean basins (Walcott, 1972; Clark *et al.,* 1978; Chappell, 1974; Hopley, 1983). To overcome this problem Clark *et al.* (1978) calculated relative sea-level from changes in the separation of the ocean floor and ocean surface. In times of rapid ocean volume changes, these two surfaces are dynamic (Fjeldskaar, 1989). These types of model are described as gravitationally self-consistent viscoelastic.

Using this model Clark *et al.* (1978) identified six 'sea-level zones', within which sea-level signatures should be similar. Of relevance to the British sea-level record were three zones.

Zone I: Glaciated areas.

In these zones a gradual unloading of ice from *c.* 18000 BP caused relative uplift e.g. NW Scotland.

Transition Zone between I and II: The Ice Margin.

The typical relative sea-level curve for the last 18000 ^{14}C-years is described by Clark *et al.* (1978) as displaying relative emergence followed by relative submergence as the rate of change of eustatic sea-level exceeds any residual isostatic component. Such a curve approximates to those described by Lambeck (1991) for North Wales.

Zone II: Collapsing Forebulge Submergence.

From these areas, the relative sea-level record shows continual submergence e.g. southeast England.

To estimate relative sea-level changes around the UK Lambeck (1991) adopted a much finer resolution model. The ice-sheet model based upon that of Boulton *et al.* (1977) was at a 0.25° latitude and 0.50° longitude definition, and the coastline at a 0.15° definition. When the Scottish ice-sheet was separate from the Fennoscandinavian ice-sheet, and had a maximum ice thickness of 1500 m, the predicted results fitted observations well (When the two ice-sheets were modelled as one, the centre of uplift was predicted to be in eastern Scotland compared with western Scotland). These observations led Lambeck (1991) to conclude that there was no need to invoke significant tectonic movements when explaining the pattern of relative sea-level changes.

7.4.2 Comparison of results from empirical data and modelled output.

One of the problems in making this comparison is precisely what to compare. Lambeck (1991) presents a series of relative sea-level curves from regular points around the UK coastline and a map showing the spatial pattern of the altitude of relative sea-level, relative to today's value. These data allow a statement as to which areas were emerging or submerging relative to others, but not necessarily which are uplifting or subsiding. From the empirical data it has been possible to calculate rates of change of relative sea-level and residual values from a eustatic model. These are not the same type of output as Lambeck (1991) produced. It is possible, however, to compare spatial patterns.

7.4.2a <u>Northwest England, North and Central Wales, Northeast England.</u>

Placing sites on these coastlines between Aberystwyth and Maryport (southern Solway Firth) on the west coast, and between Hartlepool and Berwick on the northeast coast, based on Lambeck (1991, Fig.4), into an order of increasing total submergence since the beginning of the Holocene produces the following list:

Maryport	S.Solway Firth
Berwick	Northumberland/Scotland border
Millom	Duddon estuary, Cumbria
Morecambe Bay	S.Cumbria/N.Lancashire
Blythe and Holyhead	S.Northumberland and Anglesey
Southport	S.Lancashire
Rhyl	N.Wales
Crosby	Merseyside
Hartlepool	Tees estuary, Cleveland
Aberdaron	S.Lleyn peninsula, Co Conwy
Aberystwyth	Cardigan Bay

In this thesis, and by Shennan (1989), it has been shown that crustally Wirral and Teesside are similar. Lambeck (1991) suggests slightly greater emergence in Teesside (Hartlepool) than Merseyside (Crosby), but the differences are small. At Crosby the minimum sea-level relative to present mean sea-level is estimated at -35.00 m at 12,000 BP and -42.00 m at 12,500 BP in Hartlepool. At 7000 BP, sea-level at Crosby is predicted at between -6.00 and -7.00 m below current levels and at Hartlepool *c.*-10.00 m. The predicted results agree well with the empirical data from Merseyside for *c.*7000 BP, but from the single date from the Tees estuary at this time (7065±45 BP, -2.69 m OD) Lambeck (1991) does appear to have overestimated submergence for Teesside since the early to mid Holocene.

Within the sites from the west coast for the last 7000 ^{14}C-years there is greater consistency with the empirical data. At 7000 BP, some of the predicted values from the northwest coast and Wales are as follows.

Table 7.3. Predicted and actual sea-level values at 7000 BP.

Location	Prediction (m MHWS)	Nearest ^{14}C-date (m MHWS)	
Morecambe Bay	-2.5	7150±80, -2.81 m	Skelwith Pool
Holyhead	-5.0	7255±110, -6.32 m	Tregarnedd-bâch
Rhyl	-6.0	7080±155, -6.43 m	Hendre fawr
Southport	-6.0 to -7.0	7015±90, -4.27 m	New Cut
Crosby	-6.0 to -7.0	6680±75, -5.99 m	Newton Carr
		7010±50, -4.97 m	Dove Point
Aberystwyth	-10.0	No dates	
		7000 BP, -11.0 m*	

* From the sea-level curve for Cardigan Bay, Heyworth and Kidson (1982, Fig.5).

The fit between the predicted and actual results is quite consistent. The difference in the ^{14}C-dates for Newton Carr and the nearby Dove Point illustrates the possible variability and possible error when examining single dates. However one of the major features identified along the northwest coast has been the large decrease in submergence in Morecambe Bay relative to Lancashire (Tooley, 1978; Zong, 1993; this thesis) and this has been replicated by Lambeck (1991).

The most noticeable feature predicted by Lambeck (1991) about the North Wales coast is the east to west decrease in submergence. This subject is discussed below.

7.4.2b <u>The evidence for differential crustal movements in North Wales and Wirral.</u>

In Chapter Two a proposal for possible differential crustal movements in North Wales was outlined. It was hypothesised that if samples could be collected from a consistent, deep enough altitude, with a minimisation of errors it may be possible to discern consistent differences in their age. At an altitude *c.* 6.00 to 7.00 m below current MHWS, it was estimated that an age of *c.* 7000 BP should be obtained. Additionally, a ^{14}C-date was obtained from 9.27 m below MHWS at Newton Carr, to compare with a published date from Llandudno at 9.15 m below current MHWS (Heyworth and Kidson, 1982). These dates are tabulated below.

Table 7.4. Sea-level Index Points from 6.0 to 7.0 m below MHWS.

Area	6.0-7.0 m below MHWS	9.15-9.27 m below MHWS
Wirral	6680±75 BP	7805±75 BP
N.Wales	7080±155 BP	7635±52 BP
Anglesey	7255±130 BP	

Since the mid-Holocene, and for a consistent altitude, if one area has experienced greater submergence than another, it will have a younger ^{14}C-date for that altitude. For the 6.0 to 7.0 m below MHWS altitudinal range there is evidence of increased submergence from west to east, with the three dates forming a geographically consistent series. Qualification is, however, required.

(i) The standard errors on the dates from Hendre fawr (N.Wales) and Tregarnedd-bâch (Anglesey) do have large standard errors.

(ii) When more data are included, the trend is less clear. For example, the ^{14}C-date from Dove Point (Innes, unpublished) is older and at a higher altitude than the date from Newton Carr tabulated above.

(iii) The analysis only takes one cross-section in time.

(iv) There are only three dates on this cross-section.

However, further points can be made to support the hypothesis of consistent differential crustal movements.

(i) All of the samples were collected as part of one project, using a consistent methodology, rather than from a number of different projects by different workers with disparate aims. The samples are from basal, or near basal peats: hence the altitudinal error on these dates is likely to be less than from those collected elsewhere.

(ii) Although the older two dates from Llandudno and Newton Carr show an opposite trend, these are only two samples, and the Llandudno sample is not from a basal peat (*cf.* Newton Carr) and was collected from a commercial core.

Clearly any firm conclusions are restricted by the lack of data, and in particularly the lack of data from the early Holocene. There is, however, tentative support for the results from Lambeck (1991) that there has been greater submergence in Wirral than in Anglesey.

7.4.2c **Possible Explanations of differential crustal movements in N.Wales and Wirral.**

The northwest of Wales, including Anglesey, is closer to the centre of ice-loading in Britain when projected onto a line orthogonal to this centre. For this reason alone it is reasonable to expect slightly greater isostatic uplift on Anglesey, and this is a satisfactory explanation of the observed differences in the fitted and empirical data. Another possible reason for differential crustal movements is residual uplift from the Welsh ice-sheet centred over Snowdonia.

The effects of the Welsh ice-sheet on uplift have not been incorporated into crustal models for Britain, so any estimate will be crude. It is, however, useful to attempt to establish the order of magnitude of the effects that can be expected through the Holocene and this can be done by using some simple relationships between ice thickness and total uplift, and estimates of uplift decay. In the central region of an ice-cap McGinnis (1968) estimates that total uplift can be estimated as follows:

$$U = T_i \frac{\rho_i}{\rho_r} \qquad \text{Eqn. 7.7}$$

(U=Uplift, T_i=Ice thickness, ρ_i=Density of Ice (0.9 g/cm^3), ρ_r=Density of Rock (3.2 g/cm^3).)

In the table below are estimates of the residual uplift to be expected at 7000 BP in the

Snowdonia region based on a range of ice thickness estimates. The values are based upon the above relationship and a range of uplift decay half-life between 2000 and 3000 years (Andrews, 1970).

Table 7.5. Estimated Residual Uplift from the North Wales Ice-sheet.

Half-life	50 m Ice thickness	100 m Ice thickness	200 m Ice thickness
Total Uplift	14 m	28 m	56 m
2000 year half-life	0.35 m	0.68 m	1.00 m
2500 year half-life	0.87 m	1.75 m	3.50 m
3000 year half-life	1.05 m	2.20 m	4.00 m

With a small ice-sheet recovery is likely to be more rapid (Walcott, 1970), so the true figure of residual uplift is likely to be in the lower range of the best estimates. Any effect from the Welsh ice-sheet on the observed Holocene sea-level record is likely to be small. In the late Pleistocene and very early Holocene, the effects could become significant. In conclusion, the solution of this problem would appear to be at the limits of our current methods of analysis and data collection techniques.

7.5 Conclusions.

The analysis in this chapter has shown that there may have been greater Holocene uplift in the west of the study area than in the east, and that the crustal history of North Wales and Wirral fits well into the geographical pattern of uplift and subsidence proposed by Shennan (1989). Techniques that are available to analyse crustal movements do not however, give a precise indication whether uplift or subsidence is taking place at a location, but whether there is relative movement compared with another area.

High precision geodetic levelling surveys, linked in with the analysis of tide gauge and GPS

(Global Positioning System) data, are being planned for the near future by a number of organisations concerned with coastal flooding. If these surveys prove successful then it will be possible to isolate the crustal component of contemporary sea-level movement.

Chapter Eight

Conclusions

8.1 Introduction.

In this concluding chapter an attempt is made to draw together some of the main issues that have arisen whilst carrying out this research. The sub-sections of this chapter broadly reflect the structure of the thesis: framework and data analysis, exploration of the results and the future. This chapter starts with some observations relating to the framework of sea-level research, questioning whether the existing structures for research are the most efficient for the most progress to be made in the future.

8.2 The framework of sea-level research.

Tooley and Shennan (1987) have noted that the exponential increase in the quantity of literature related to sea-level during the last thirty years. They noted that these works can be grouped under two main headings: fundamental and strategic research. In this thesis the results of fundamental research only have been presented.

The approach required and the techniques adopted to address fundamental sea-level research projects at a Holocene timescale vary according to location. In Britain, sedimentological and geomorphological techniques are widely used, and in North Wales, where the coast has largely been submerging, sedimentological techniques have predominantly been used.

The results from this thesis are a direct contribution to the knowledge base of sea-level change at an area scale. As with most research projects that have been conducted at this scale, there has also been a regional synthesis and interpretation of the new data. Through time, these interpretations may be modified, questioned, or even rejected, but the raw data upon which they are based will remain. In Chapter 6 it was shown that comparing the interpretations of different sea-level work was often more difficult than comparing the original results.

During the last twenty-five years most low-lying coastal areas in Britain have been the focus of sea-level investigation. There are considerably more ^{14}C-dates available from the Fenland than any other part of the British coast, but from Cardigan Bay and the south Wales coast, the Somerset Levels, the south coast of England, East Kent, the Thames estuary, the Essex Marshes and Norfolk coast, the northeast coast of England, the Firth of Forth and Tay estuary, the Moray Firth, western Scotland, Morecambe Bay, the Lancashire coast and North Wales and Wirral between 10 and 50 ^{14}C-dates have been collected. A qualification that is often attached to interpretations of data in this and other work is that data are unevenly distributed in space and time. This above is not an exhaustive list of low-lying coastal areas in Britain, but quite thorough. The fact that there are uneven distributions of data must imply that there is some duplication of work and resources.

We have a satisfactory knowledge of the pattern of sea-level changes and crustal movements on a Holocene timescale. Is the cost/benefit of sea-level investigations at an area scale therefore, the best use of resources ? That detailed chronologies can be established using the tendency technique has been both accepted and criticised in this thesis. With sufficient data the technique should produce very valuable interpretations, but the resources available for each study in each area are rarely sufficient for this type of analysis. For comparisons between areas therefore, time-altitude techniques have been, and continue to be used. The essence of time-altitude data is, that they are sufficient for the analysis of general patterns and making comparisons, but limited in the analysis of detail. With a very detailed analysis, quantification of the uncertainties that exist in trying to correlate between regions may be established.

To this end it may be worth considering the organisation of sea-level research in Britain. Though there have been schemes, such as the IGCP, which aim to provide a central focus for research in different institutions, there is no central control or body of information. In the Netherlands, for example, most sea-level work is organised through the Dutch Geological

Survey. In Britain the Institute of Hydrolog~~ical Research~~y performs a similar role in the field of hydrology. There may be some merit in considering whether such a body, concerned with sea-level or coastal issues, may provide the most efficient framework for future strategic and fundamental research. The ~~LOESS~~ LOIS project is being run under the auspices of the ~~Institute of Hydrological Research~~ Plymouth Marine Laboratory, but using the expertise available in universities, and this would seem a positive framework.

8.3 <u>The analysis of sea-level data.</u>

The terms 'sea-level chronology' and 'sea-level history' have often been used in this thesis: "...the main aim of this thesis is to establish the sea-level and crustal history of North Wales and Wirral." (Chapter 1). In Chapter 6 this aim was developed, but it was shown that 'sea-level chronology' could have a number of meanings.

Two of these are particularly important: the time-altitude chronology and tendency chronology. Because there has only been a limited attempt to speculate about periods of falling relative sea-level, constructing the first type of chronology was relatively straightforward. Providing that the location, age, altitude and indicative meaning of index points had been established, then they could be plotted on a time-altitude graph. Such a graph is quite satisfactory for comparing the differences or similarities in the broad trend of sea-level between regions, perhaps as a result of glacio-isostatic readjustment, but not for comparing higher resolution events such as the withdrawal or inundation of marine conditions. The first of these processes can be considered smooth (i.e. glacio-isostatic uplift is generally thought of as smooth), whilst the second set of processes are more random in their effect, timing and location.

A tendency chronology attempts to provide a means of correlating these higher resolution events and processes. The registration of some of these events at particular sites will vary depending on local conditions: thus, some sites may be more appropriate for tendency analysis than others. In this thesis an attempt was made to determine whether each site displayed a regional signal, though there is subjectivity involved in such an exercise. To overcome this type of problem, there is no escaping the need for larger datasets if the full value of the technique is to be obtained.

8.4 Coastal Changes in North Wales and Wirral.

Data collected for this thesis have shown that the North Wales coast has been subjected to relative sea-level rise throughout the Holocene. This has resulted in long periods of increasing marine influence along the coastline, though five short periods when the marine influence receded have also been identified.

The earliest Holocene sediments from the North Wales coast were collected from the Clwyd coastal lowlands by Prince (1988). Before 8540 BP, the Clwyd coastal lowlands would have been inundated by the sea from a northerly direction, reaching Woodlands, 1 km inland of the present coastline, by this date. Borehole evidence (Manley, 1981) suggests that the boulder-clay surface does gradually slope seawards, hence Hendre fawr, which was investigated in this thesis, would have been unaffected by sea-level rise in this very early Holocene period. The sea would have also been present in the lower Malltraeth Marshes and in the western extreme of the Afon Ganol valley, but once again not at the sampling sites: Glan Aber Farm and Tregarnedd-bâch.

Between 8000 and 7000 BP it seems likely that there would have been major changes in the coastal configuration as sea-level rise averaged and probably exceeded 7 mm/yr during this millennium. Towards the end of this period peats began to form in the upper Malltraeth Marshes as the marine influence pushed further up the valley. In the Clwyd coastal lowlands the sea penetrated inland, 2 km beyond the present coastline.

One of the conclusions arising from the field investigations was that these massive environmental changes were manifest in quite different ways at different sites along the coast. In the Afon Ganol Valley, for example, the sea should have flooded the valley from two different directions, leaving the higher ground near Mochdre between the two halves. Yet, though the palaeogeography of the western half of the valley was suitable for marine inundation, terrestrial conditions persisted for long periods.

Towards the end of this period (7255-7010 BP) and also later between 6000 and 5000 BP the sea partially withdrew from all of these coastal sites. In the Clwyd coastal lowlands this would have resulted in a 3 km seaward shift of the coastline. Throughout this thesis it has been stated that falls in sea-level are not absolutely required to explain the phenomena identified, but a 3 km shift in a coastline does require a significant environmental change: thus falls in sea-level may be recorded in North Wales and Wirral during the periods of negative tendencies identified in Chapter 6. Finding a cause for any possible fall in sea-level is more difficult since by this time uplift in North Wales and Wirral was negligible.

The correlation between sites in the very recent past is poor. As the rate of sea-level rise slowed down, stopped, or even fell, modifications to the regional signal at a site scale became greater. In some of the more protected sites such as Tregarnedd-bâch and Glan Aber Farm peat formation continued through the late Holocene and continues today.

8.5 Selected events.

In this section two particularly interesting features of the sea-level history of North Wales and Wirral are emphasised. The question of rapid sea-level change during the Holocene has been highlighted by a number of workers and is thus considered, along with the evidence for differential crustal movements in North Wales.

8.5.1 Rates of sea-level rise.

In chapters 3 and 6 it was explained how rates of sea-level rise approaching 34 mm/yr during the early- to mid Holocene had been obtained by Tooley (1989). Data from North Wales also suggested that there were periods of rapid sea-level rise, but not to the magnitude found in Lancashire. Using data from the Clwyd coastal lowlands, between the altitudes -9.00 m OD and -2.48 m OD, rates of only 7.2 mm/yr are obtained. If data from Newton Carr are combined with these data, then rates of 10.00 mm/yr can be obtained.

Considering the potential altitudinal and temporal errors for individual sea-level index points, the method of obtaining rates of change from two points only may be misleading. Taking the series of ^{14}C-dates from North Wales and Wirral as a whole, rates of sea-level rise in North Wales approximate to the following values:

8000 - 7000 BP	*c.*7 mm/yr
7000 - 6000 BP	*c.*3-4 mm/yr

These values may be low because they are based on an average of a series of dates, and also because the time frame is quite long. Between 8000 and 7000 BP it is quite likely that there were times when sea-level rise did exceed 7 mm/yr, but this cannot yet be established from the available data.

8.5.2 Differential crustal movements in North Wales.

There are many difficulties in trying to analyse crustal movements from sea-level data. The two main methods used in this thesis both have deficiencies, but nevertheless have produced results that are comparable and consistent with each other. The analysis has shown that cumulative uplift during the Holocene has probably been greater in the west of the study area than the east.

The analysis of the new ^{14}C-data has shown that there is no real distinction in the Holocene crustal histories of North Wales and south Lancashire. There was however, greater uplift in north Lancashire and greater submergence in Cardigan Bay.

The Holocene pattern of uplift and subsidence in Britain can be explained by the proximity of a site to the former centre of ice-loading. In Chapter 7, a very simple analysis attempted to discern whether the North Wales ice-sheet would have had an effect on uplift through the Holocene. Though the analysis was simple, based on a series of assumptions and carried out largely as an experiment, it seemed that the impact of the Welsh ice-sheet on Holocene uplift was small. If we are to fully explain the pattern of uplift and subsidence in Britain, then consideration and quantification of other factors, which should have an explainable geographical pattern, needs to be carried out.

At present the contributions that help explain patterns of crustal movements from the sea-level community and modelling community complement each other. The next step could be to apply geophysical modelling to areas where there are anomalies, or difficulties in explaining sea-level data. For example, what is the potential for subsidence due to water, or sediment loading in the early- to mid Holocene around Liverpool Bay ? This would seem a logical test, since such a phenomenon would help explain the particularly rapid sea-level rise that has been identified in the area. A very rich set of data exists to help any such experiment.

8.6 The Future.

There are, of course, many unanswered questions arising from this research. Within the context of the British coastline, the data relating to sea-level change in North Wales and Wirral are now quite adequate. As emphasised in this chapter, the expectation is that the collection of more data will not radically change the time-altitude analysis completed in this thesis, though in time the interpretation of tendencies of sea-level may change considerably.

Some sites are worthy of much closer scrutiny simply to understand the wider environmental changes that were taking place through the Holocene. Detailed palaeobotanical work at Glan Aber Farm, or a new site in the western Afon Ganol Valley, would be very valuable in this respect. It would also be valuable to have more ^{14}C-dates from the very early and very late Holocene. As indicated in the first section of this chapter on the framework of sea-level research however, a detailed analysis of selected areas may be preferable to piecemeal work in a number of areas.

Geodetic levelling linked in with GPS and tide gauge surveys do need to be completed. North Wales may not necessarily be the best area in which to carry out such a survey, because the relative earth movements today are small. An area of known subsidence, such as the Thames estuary, or known uplift, such as western Scotland, may be more logical choices because of better signal-to-noise ratios. Successful results from such a survey would enhance our knowledge of present-day processes in North Wales and throughout Britain. This kind of work may help answer some of the imponderables that every regional survey faces, and would thus be a contribution to strategic and fundamental research. Additionally, it would enhance our understanding of the historical data that already exists, including those presented in this thesis.

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