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Holocene sea-level change in North Wales : the evolution of the Menai Strait

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Holocene sea-level change in North Wales: the evolution of the Menai Strait

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By

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Abstract

This study adopts a multidisciplinary approach in order to elucidate aspects of relative sea-level change within North Wales during the Holocene, with particular reference to the evolution of the contemporary tidal channel forming the Menai Strait. Micropalaeontological, sedimentological and geophysical evidence has been utilized in conjunction with radiocarbon dating techniques in order to interpret stratigraphical relationships between sedimentary facies deposited within the northeastern region of the Menai Strait.

Micropalaeontological and sedimentological data allied to radiocarbon data obtained from a series of organic-rich horizons demonstrate that relative mean sea level within the northeastern Menai Strait increased from approximately -27m to -6m OD between 11500 and 8000 calendar years BP. Continual, although subsequently reduced rates of relative mean sea-level rise ensured the eventual breaching of a watershed within the central region of the Menai Strait. This rise consequently resulted in the formation of the contemporary tidal strait and the final separation of Anglesey from the mainland at some point between 5600 and 4800 calendar years BP. Relative mean sea level subsequently rose by approximately 1.5m between 6800 and 4000 calendar years BP. The contemporary bathymetrical profile of the main channel probably originated at some point after 6000 calendar years BP.

Excellent correlation between sedimentological and geophysical data demonstrate that sedimentary sequences located beneath the sea-floor within the northeastern Menai Strait comprise a series of alternating layers of terrestrial and marine material which constitute a series of laterally extensive near-horizontal layers extending between -28m and -2m OD. The deposits originated during the early to middle Holocene and reflect a pattern of continual and cyclic environmental change, with conditions fluctuating rapidly between those associated with the existence of low-lying terrestrial marsh and those characterized by the presence of an inter-tidal environment.

Although a reasonable degree of correlation can be made with similarly dated sequences found on more regional and global scales, it remains unclear if the transgressive and regressive phases that these sequences represent, are wholly or partially attributable to either local physical regimes and processes or are a consequence of fluctuations in the pattern of Late Devensian to early Holocene eustatic sea-level rise. Comparison of the sea-level data obtained from North Wales with sea-level reconstructions derived from pre-existing geophysical models indicate that the modelled outputs underestimate the altitude of relative sea level in North Wales during the early Holocene by up to 25m and further demonstrate that marine conditions existed within this area of the Irish Sea as early as around 14000 calendar years BP.

Acknowledgements

I am most grateful to Professor James Scourse, whose role within the scope of this research project went far beyond that normally expected of a supervisor. James played an active role in both guiding and encouraging me over a period of more than four years and was integral in securing the funding that ensured the production of this thesis. I can never repay him for all his valuable time and effort and can only endeavour to live up to his expectations and high standards. I would like to acknowledge that much of the research would not have been possible had it not been for his contribution.

Grateful thanks are additionally extended to Dr Dei Huws for his assistance and guidance with respect to conducting aspects of the work in relation to the production of this thesis. I must also thank Dr Colin Jago for his support, guidance and contribution during the course of the research project. Many thanks are also extended to Dr Jim Bennell for his support and advice in relation to the acquisition of the geophysical data.

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Michael James Roberts
July 2006

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Chapter 1

1 Introduction

Chapter 1 introduces the nature of the research project, defining both the aims and objectives of the study, together with outlining the terminology and conventions utilized within the dissertation. The chapter further provides a series of summarized geographical, geomorphological and geological descriptions of the study area, together with an outline of previous ideas relating to the evolution of the Menai Strait.

1.1 General Introduction

It has long since been established that coastal environments are continually subjected to modification by an extensive range of large and small-scale, natural physical, chemical and biological processes and can therefore be considered to be in a permanent state of flux. The Quaternary geological system, which extended over the last one and a half to two million years, was characterized by numerous glacial or colder stages, interspersed with relatively shorter intervals of warmer conditions termed interglacials. Glacial stages are typified by the large-scale build-up of terrestrial ice sheets between the mid and high latitudes and are associated with a corresponding decrease in global or eustatic sea level; warmer interglacials, however, are characterized by the relatively rapid, large-scale downwasting of these ice sheets, which results in a corresponding rise in global or eustatic sea level. Following the latest, Late Pleistocene, Late Devensian Glacial stage, a rise in global temperature effectively resulted in the large-scale down-wasting of the large terrestrial ice sheets which, as a consequence, increased the volume of water contained within ocean basins. This has given rise to what is commonly referred to within Northwestern Europe as the Flandrian or Holocene marine transgression; where extensive areas of low-lying continental shelf have become submerged by rising sea levels.

On a regional or more localized scale however, relative sea-level change and the subsequent development of a particular coastal environment during the course of such events can be attributed to the complex interplay between numerous physical, chemical and biological processes. It has been established that the development of a particular coastal region can be primarily related to eustatic sea-level change, ice-loading history and the availability of sediment required in order to accommodate the development of any associated coastal geomorphology.

Previous attempts to elucidate the nature of Holocene relative sea-level change within the region of North Wales (Heyworth and Kidson, 1982; Prince, 1988; Bedlington, 1994) have been inhibited by considerable deficiencies with respect to the quality and quantity of sea-level data available. The altitude of Mean Sea Level (MSL) and ultimately the position of the coastline during the early to middle Holocene has, as a consequence, largely been inferred from geophysical models regional glacio-hydro-isostatic models that take into account such factors as the properties and behaviour of the lithosphere and the underlying mantle, changes in ice sheet thickness and variations in global sea level (Lambeck, 1995; Lambeck, 1996; Peltier, 2002).

These models, however, rely heavily upon well dated sea-level index points in order to both constrain and validate the sea-level predictions that they generate. Furthermore, outputs relating to the altitude of MSL and consequently the position of the coastline itself often differ greatly between and within successive generations of the models.

The geophysical models produced by Lambeck (1996) and more recently by Peltier (2002), infer that marine conditions were absent from within the Liverpool Bay region of the Irish Sea prior to approximately 14000 BP. The models indicate that the region subsequently underwent a marine transgression with the Menai Strait experiencing marine conditions by some time after 10500 BP. Data from this region of North Wales may support such a hypothesis and further refine the timing, extent and nature of palaeoenvironmental conditions within this region of North Wales during the early to middle Holocene.

1.2 Aims and objectives

The Menai Strait is located along the coastline of North Wales and separates the Isle of Anglesey from the North Wales mainland (fig. 1.1). The Strait consists of an elongated, narrow, tidal marine channel, containing substantial accumulations of unconsolidated sediment toward its northeastern and southwestern extremes. Previously conducted research has failed to adequately quantify the nature of sea-level change in North Wales, particularly during the early to middle Holocene. Existing data obtained from within the northeastern region of the Menai Strait suggest that this area may contain scientifically important accumulations of marine and terrestrial material, which may provide the

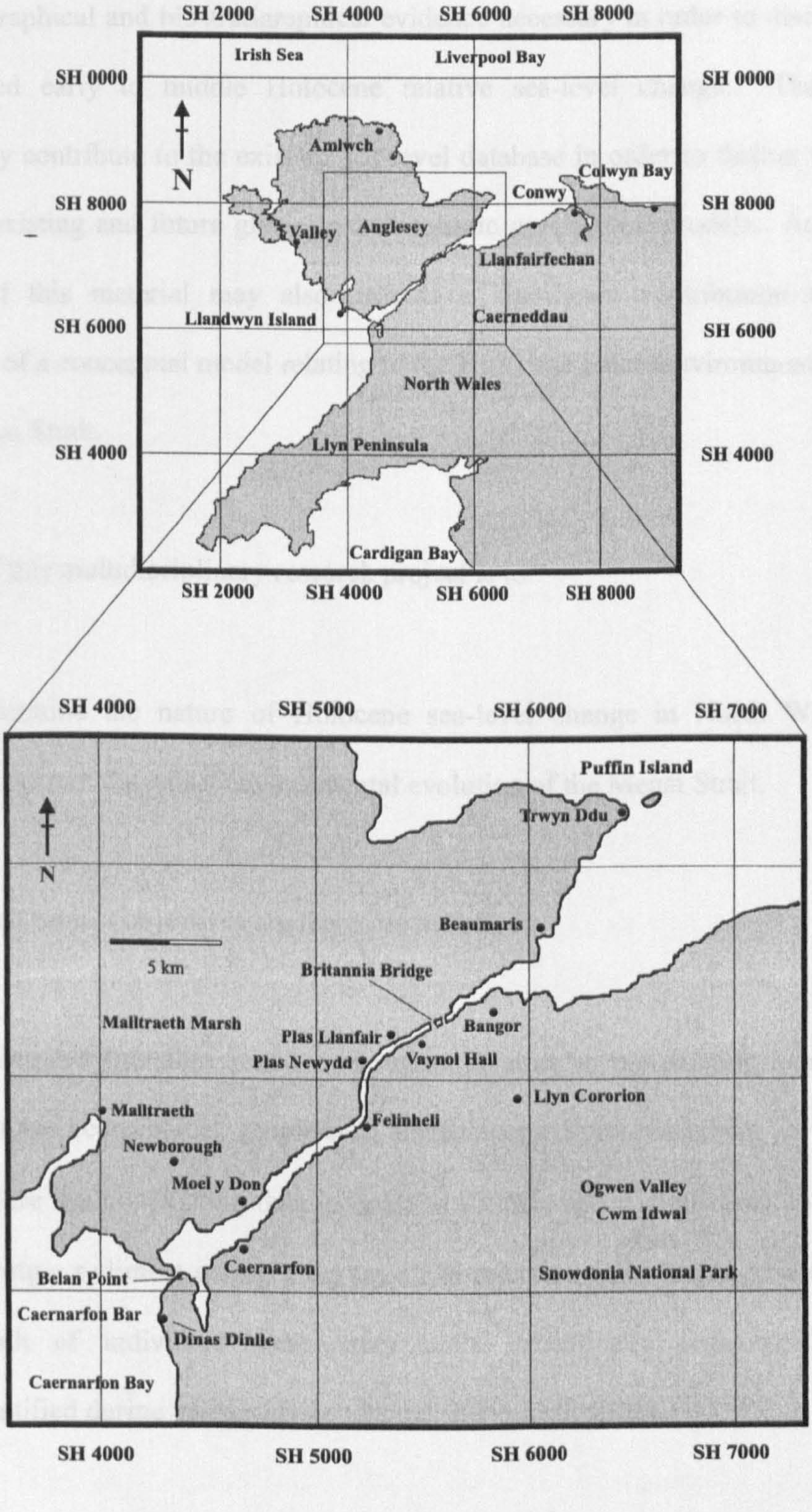

Figure 1.1 Location of the Menai Strait

lithostratigraphical and biostratigraphical evidence necessary in order to discern patterns of localized early to middle Holocene relative sea-level change. The data may additionally contribute to the existing sea-level database in order to further validate and constrain existing and future glacio-hydro-isostatic geophysical models. Acquisition of samples of this material may also provide a significant contribution towards the generation of a conceptual model relating to the Holocene palaeoenvironmental evolution of the Menai Strait.

The aim of this multidisciplinary research project is to:

- Determine the nature of Holocene sea-level change in North Wales and to reconstruct the palaeoenvironmental evolution of the Menai Strait.

The research project objectives are therefore as follows:

- A detailed literature search and review relating to pre-existing local and more regional geotechnical, geophysical and palaeoenvironmental data.
- Utilize the pre-existing data in order to identify specific locations to be sampled during a sediment coring program. Site selection to be based on the nature and depth of individual sedimentary units, specifically organic-rich horizons, identified during previously conducted site investigations.

- A preliminary site investigation in order to obtain, identify and determine the nature and extent of individual sedimentary facies present within the northeastern region of the Menai Strait.
- An integrated lithostratigraphical and biostratigraphical study, allied to the radioisotopic dating of organic-rich horizons, in order to facilitate the generation of a relative sea-level curve for North Wales.
- An integration of the data obtained during the course of the investigation in order to elucidate the nature, extent and timing of coastal palaeoenvironments within and proximate to the Menai Strait.

1.3 Terminology and conventions

1.3.1 Quaternary stage nomenclature

The Quaternary period is conventionally sub-divided into glacial and interglacial stages, together with stadial and interstadial episodes. The simplistic nature of this approach however, lacks precision and may often be difficult to apply to a particular sedimentary sequence (Lowe and Walker, 1997). Problems also arise when attempting to further sub-divide the stratigraphic record and correlate sequences due to regional differences in terms of the development of a particular sedimentary facies.

Early development of Quaternary research within, for example, the British Isles, Europe and America, resulted in the introduction of at least three uniquely separate sets of nomenclature relating to specific climatic episodes, represented stratigraphically within sedimentary deposits. Precise correlation between these episodes has, at times, proved difficult and contentious; however, there appears to be general agreement that the Flandrian episode within the British Isles can be equated with the Holocene identified within European and North American sequences. Contention remains however, when considering the subdivision of the Latest 'Lateglacial', with most investigators in Britain accepting a two-fold sub-division consisting of a Windermere Interstadial and a Loch Lomond Stadial; whilst most northwestern European scientists recognise a more complex sequence of two interstadials interspersed by two stadials. Within the context of this research project however, northwest European nomenclature and stage names have been utilized in conjunction with that favoured by scientists working within the British Isles.

1.3.2 Sea-level datum

Heights have been quoted relative to Ordnance Datum (OD) Newlyn, with respect to all lithological sections and horizons described within this dissertation. Alternative altitudes relating to aspects of sea level in terms of tidal amplitude are indicated where appropriate.

1.3.3 Positioning

Locations are expressed in terms of grid references derived utilizing the Ordnance Survey (OS) grid reference system and are quoted to eight figures, with an associated level of accuracy corresponding to +/- 50m. During the fieldwork conducted in relation to this research project however, a greater degree of accuracy was obtained through the use of a hand-held single frequency Global Positioning System (GPS); consequently the positions quoted relating to the location from which sediment cores were recovered are likely to be accurate to within +/- 5m.

1.3.4 Dates

All dates, unless otherwise stated, are presented in the form of calendar years before present (BP), with the exception of the data derived from radiocarbon analysis, prior to calibration into calendar years BP. The radiocarbon data are presented as ^{14}C years BP, where BP constitutes 1950 Anno Domini (AD). The calibrated dates are presented with error bars representative of two standard deviations.

1.3.5 Units

All units of measurement quoted within the context of this dissertation incorporate the use of S.I. units unless otherwise stated.

1.4 Study area

1.4.1 Rationale for study site location

A decision to confine the study to within the northeastern region of the Menai Strait was made following an initial literature search relating to previously conducted research and an assessment of available data obtained from various projects conducted or funded through both the private and public sector. It became apparent that the volume of pre-existing data relating to the northeastern Menai Strait was far in excess of that which related to the southwestern region. Additionally, the only ground truth data, available in the form of sediment logs, that had been obtained from within the Menai Strait related to the northeaster region. Furthermore, previously conducted work relating to the evolution of the Menai Strait (Ramsay, 1876; Edwards, 1904; Greenly, 1919; Embleton, 1964) suggests that the Menai Strait may have formed following the inundation of two parallel river valleys, separated by a watershed and orientated in opposing directions, during the Holocene transgression. Based on this hypothesis alone an assumption was made at an early stage of the research project that both the southwestern and northeastern region of the Strait would have evolved in similar manner as sea level rose during the early Holocene and inundated the Menai Strait from both ends at a similar rate. Therefore from both a logistical perspective, concentrating on the northeastern region approximately between Menai Bridge and Beaumaris was deemed appropriate given the total area of the Menai Strait and the nature of the pre-existing data that was available.

More specific locations deemed to be appropriate for obtaining sub-surface samples through coring would be determined at a later stage by analyzing all pre-existing geophysical and ground truth data.

1.4.2 Geography and geomorphology

The Menai Strait constitutes a narrow tidal marine channel orientated approximately in a southwest-northeast direction, separating the Isle of Anglesey (Ynys Môn) from mainland North Wales (fig. 1.2). It extends for approximately 28km from Fort Belan through to Puffin Island along the line of the Dinorwic Fault, one of several ancient parallel SW-NE trending fault systems. The width of the Menai Strait at Mean Low Water Spring Tide (MLWST) is remarkably consistent varying between 250m and 700m.

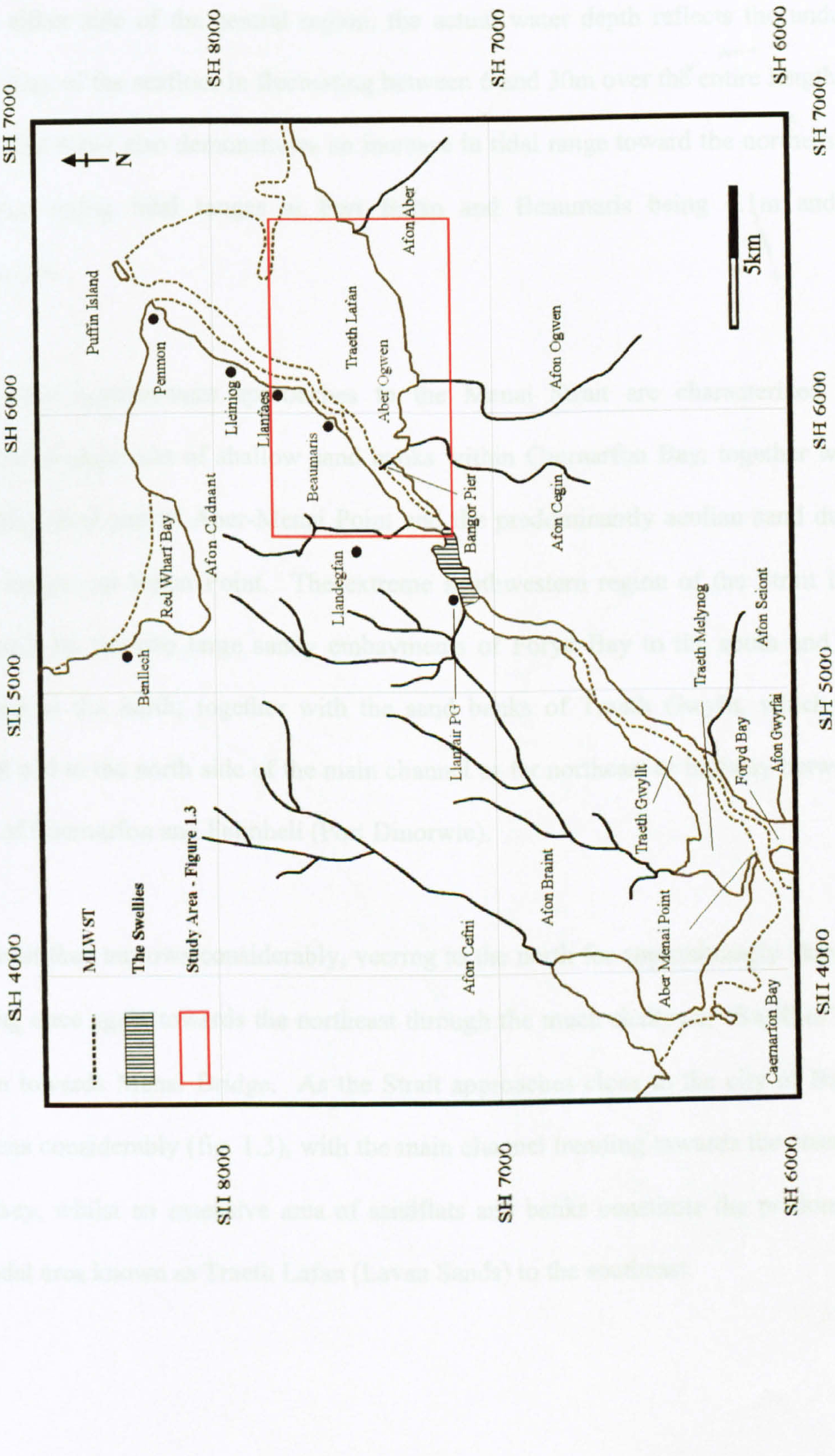

Figure 1.2 Locations proximal to the Menai Strait

At Mean High Water Spring Tide (MHWST), however, the width extends between 300m and 7km. Although the average water depth at MLWST within the Menai Strait is greater either side of the central region, the actual water depth reflects the undulating morphology of the seafloor in fluctuating between 6 and 30m over the entire length of the Strait. The Strait also demonstrates an increase in tidal range toward the northeast, with the mean spring tidal ranges at Fort Belan and Beaumaris being 4.1m and 6.9m respectively.

The central southwestern approaches to the Menai Strait are characterized by an extensive arrangement of shallow sand banks within Caernarfon Bay, together with the protruding sand spit of Aber-Menai Point and the predominantly aeolian sand dunes of Newborough and Belan Point. The extreme southwestern region of the Strait itself is dominated by the two large sandy embayments of Foryd Bay to the south and Traeth Melynog to the north; together with the sand banks of Traeth Gwyllt, which extend parallel and to the north side of the main channel as far northeast as halfway between the towns of Caernarfon and Felinheli (Port Dinorwic).

The Strait then narrows considerably, veering to the north for approximately 2km before trending once again towards the northeast through the much shallower 'Swellies' region and on towards Menai Bridge. As the Strait approaches close to the city of Bangor it broadens considerably (fig. 1.3), with the main channel trending towards the coastline of Anglesey, whilst an extensive area of sandflats and banks constitute the predominantly intertidal area known as Traeth Lafan (Lavan Sands) to the southeast.

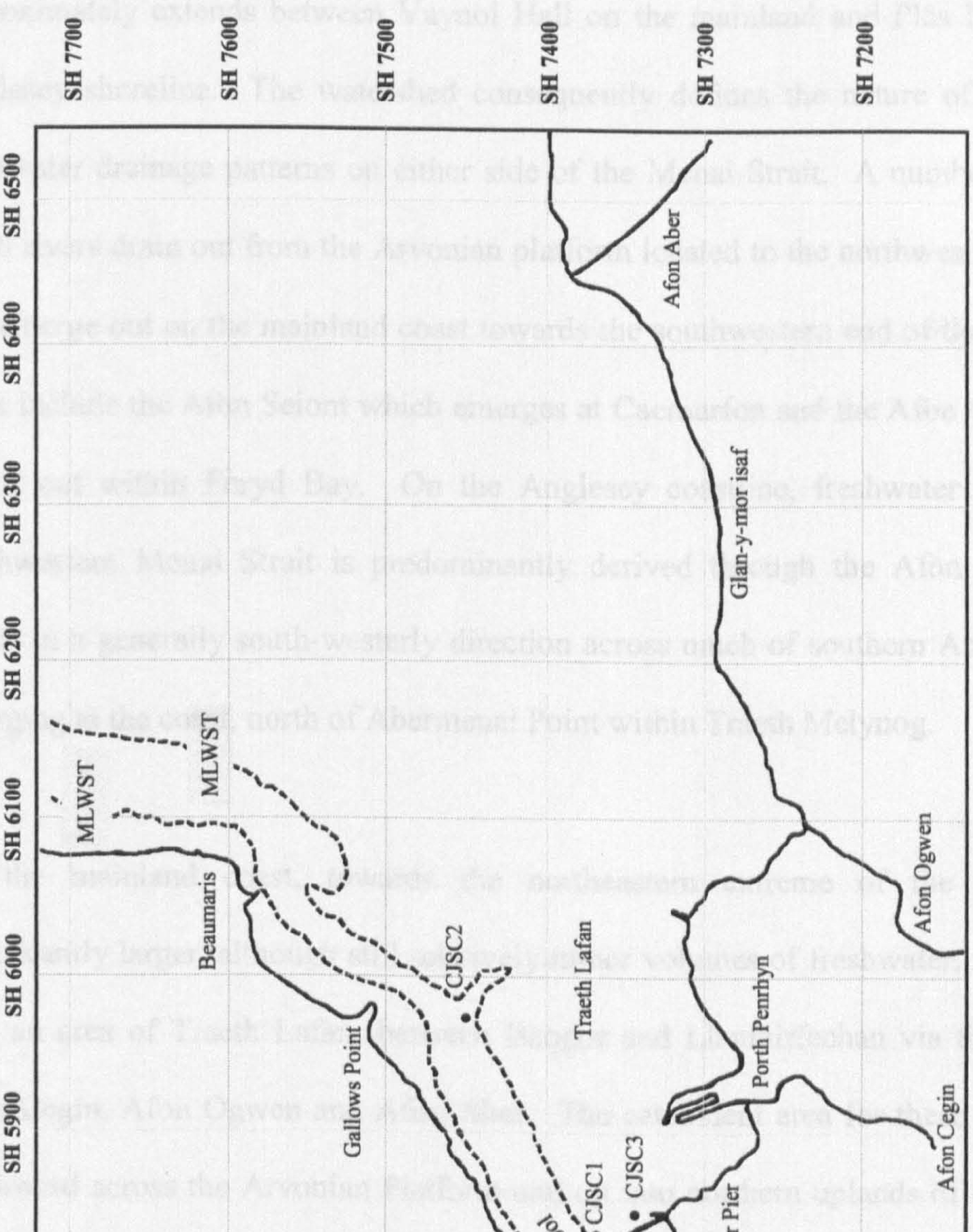

Figure 1.3 The study area within the northeastern region of the Menai Strait

A natural watershed exists within the central region of the Menai Strait and approximately extends between Vaynol Hall on the mainland and Plâs Llanfair on the Anglesey shoreline. The watershed consequently defines the nature of contemporary freshwater drainage patterns on either side of the Menai Strait. A number of relatively small rivers drain out from the Arvonian platform located to the northwest of Snowdonia and emerge out on the mainland coast towards the southwestern end of the Menai Strait; these include the Afon Seiont which emerges at Caernarfon and the Afon Gwyrfai which drains out within Foryd Bay. On the Anglesey coastline, freshwater input into the southwestern Menai Strait is predominantly derived through the Afon Braint, which trends in a generally south-westerly direction across much of southern Anglesey, before emerging at the coast, north of Abermenai Point within Traeth Melynog.

On the mainland coast, towards the northeastern extreme of the Menai Strait, significantly larger, although still relatively minor volumes of freshwater, are discharged over an area of Traeth Lafan, between Bangor and Llanfairfechan via the flow of the Afon Cegin, Afon Ogwen and Afon Aber. The catchment area for these rivers extends southward across the Arvonian Platform and up into northern uplands of the Carneddau mountain range of northern Snowdonia. By comparison and probably reflecting localized variations in annual rainfall, relatively low volumes of freshwater are discharged into the Menai Strait on the Anglesey coastline by the Afon Cadnant which emerges into the Strait approximately 1km northeast of Menai Bridge.

1.4.3 Contemporary dynamical regime

The complex nature of the contemporary dynamical regime that exists within the Strait is primarily governed by the Menai Strait's morphology and the influence of its longitudinal profile upon the tidal cycle (fig. 1.4). As previously stated, tidal ranges are significantly higher within the northeastern region of the Strait and consequently at high water, flow continues within this region toward the southwest; conversely at low water, flow at Caernarfon continues toward the northeast. As a consequence slack water within the Swellies occurs approximately 1.5 hours before local high water. Maximum spring and neap tidal currents experienced around Bangor Pier in the northeastern region approximate to $0.75ms^{-1}$ and $0.5ms^{-1}$ respectively; however, maximum current flow within the Strait can exceed $2.5ms^{-1}$ (Harvey, 1968).

Maximum spring tidal currents in and around Felinheli approximate to $1.2ms^{-1}$; whilst tide gauge data further indicate that mean water levels at Felinheli are significantly higher than at either end of the Menai Strait. According to Harvey (1968) this is probably primarily attributable to frictional effects imparted upon tidal flow by the morphology of the Swellies. Observations conducted by Harvey (1968), relating to the contemporary dynamics of the Menai Strait have indicated that a residual flow of water towards the southwest exists. Estimates relating to the magnitude of this flow indicate that it approximates to 30 million cubic metres of water during one semi-diurnal tidal period, which corresponds to a residual current velocity of approximately $0.15ms^{-1}$ in a southwesterly direction.

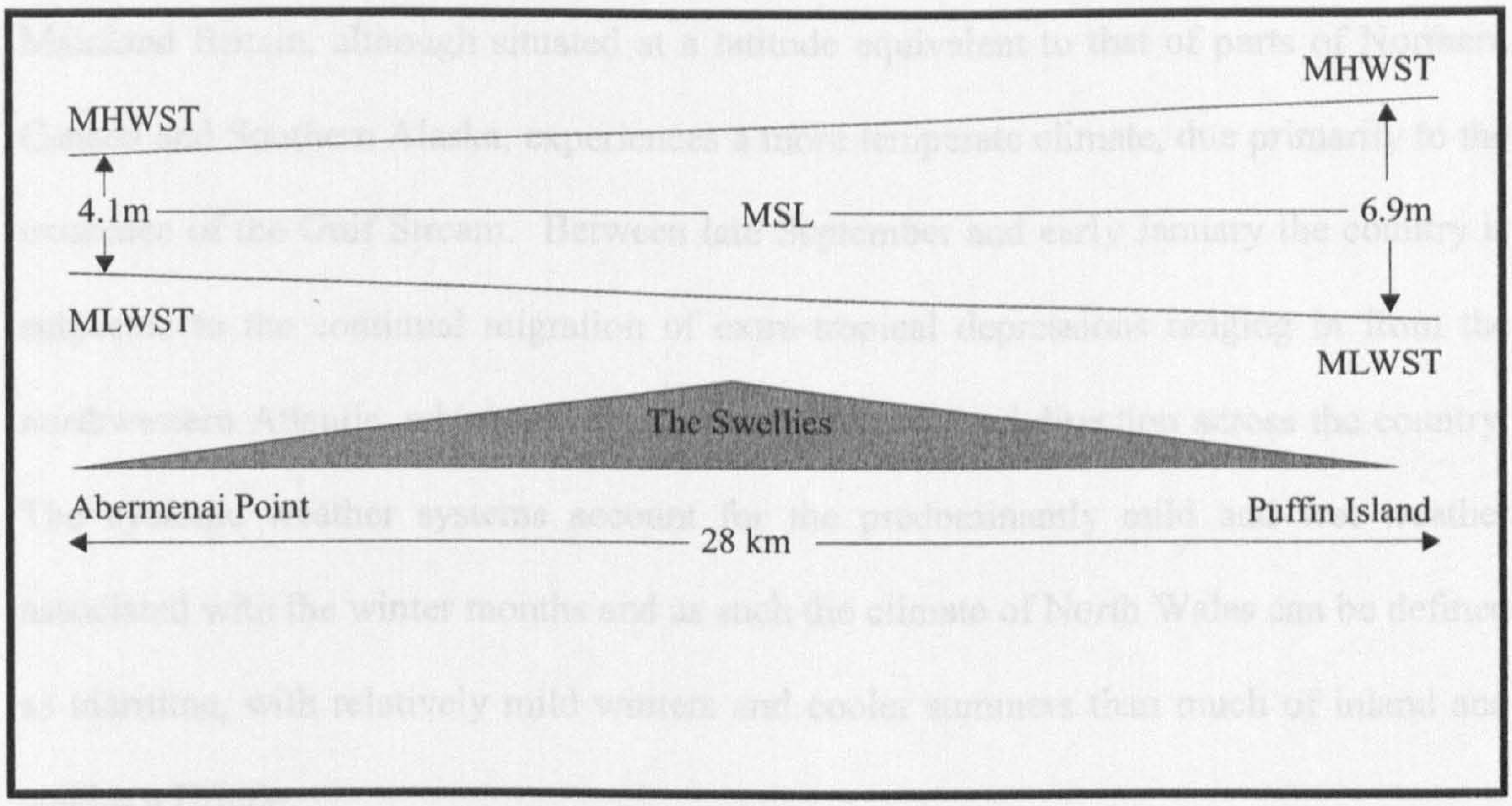

Figure 1.4 (a) Schematic longitudinal cross section of the Menai Strait illustrating differences in tidal range between the southwest and northeast.

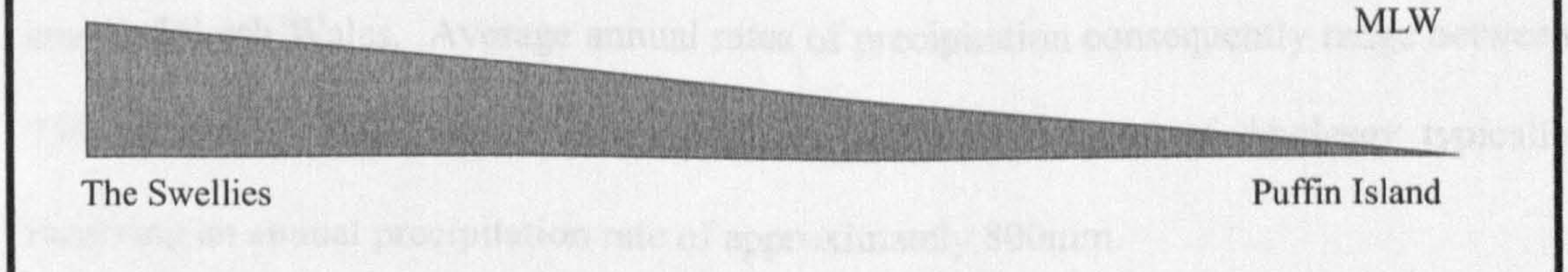

Figure 1.4 (b) Schematic longitudinal cross section of the Northeastern Menai Strait indicating the flow of water during the flood and ebb tide.

1.4.4 Climate

Mainland Britain, although situated at a latitude equivalent to that of parts of Northern Canada and Southern Alaska, experiences a more temperate climate, due primarily to the existence of the Gulf Stream. Between late September and early January the country is subjected to the continual migration of extra-tropical depressions ranging in from the northwestern Atlantic, which travel in a generally eastward direction across the country. The cyclonic weather systems account for the predominantly mild and wet weather associated with the winter months and as such the climate of North Wales can be defined as maritime, with relatively mild winters and cooler summers than much of inland and southern Britain.

During May and early June anti-cyclonic conditions become prevalent and often result in more settled conditions, although cyclonic weather systems also occur and as a result within North Wales, weather conditions, including precipitation and temperature, can be highly variable on both a regional and local scale. Areas within and immediately adjacent to the mountains of Snowdonia can experience as much as nine times the precipitation rate experienced by areas such as Rhyl, situated along the northern facing coast of North Wales. Average annual rates of precipitation consequently range between 750mm and 2500mm, with Valley on the northwestern coast of Anglesey typically receiving an annual precipitation rate of approximately 800mm.

Average January temperatures range between 1 and 7 degrees Celsius, with a marked gradient ranging between Central Snowdonia and Anglesey; average July temperatures range from 10 to 15 degrees Celsius and once again exhibit a similar trend, with Anglesey experiencing higher temperatures. Average January temperatures at Valley range between 3 and 8 degrees Celsius, with average July temperatures ranging between 12 and 19 degrees Celsius. Average monthly hours of sunshine at Valley range between approximately 50 and 200 throughout the year, whilst the prevailing wind direction is from the southwest.

1.4.5 Solid Geology

The geological succession and associated structures of the area surrounding the Menai Strait (fig. 1.5) have been investigated and extensively studied for more than a century. Authors such as Blake (1888) considered the complex Precambrian rock formations found on Anglesey, whilst Ramsay (1876) and Edwards (1904) developed theories relating to the formation of the Menai Strait associated with deglaciation. Greenly (1919) produced a comprehensive report relating to the geology of Anglesey, which included an interpretation regarding the Precambrian rock sequence he termed the 'Mona Complex'.

According to Thorpe *et al.*, (1984) the Precambrian basement that underlies the United Kingdom (UK) consists of series of micro-continental terrains which are bounded by major northeast-southwest striking faults. The southern area of Anglesey and the coastal region of northwest Wales overlie one such fault system. This complex fault system consists of three major fault lines, each orientated parallel to each other and extending from the southwest to the northeast. The Dinorwic Fault which underlies the Menai Strait is bounded to the south by the Aber-Dinlle Fault and to the north by the Berw

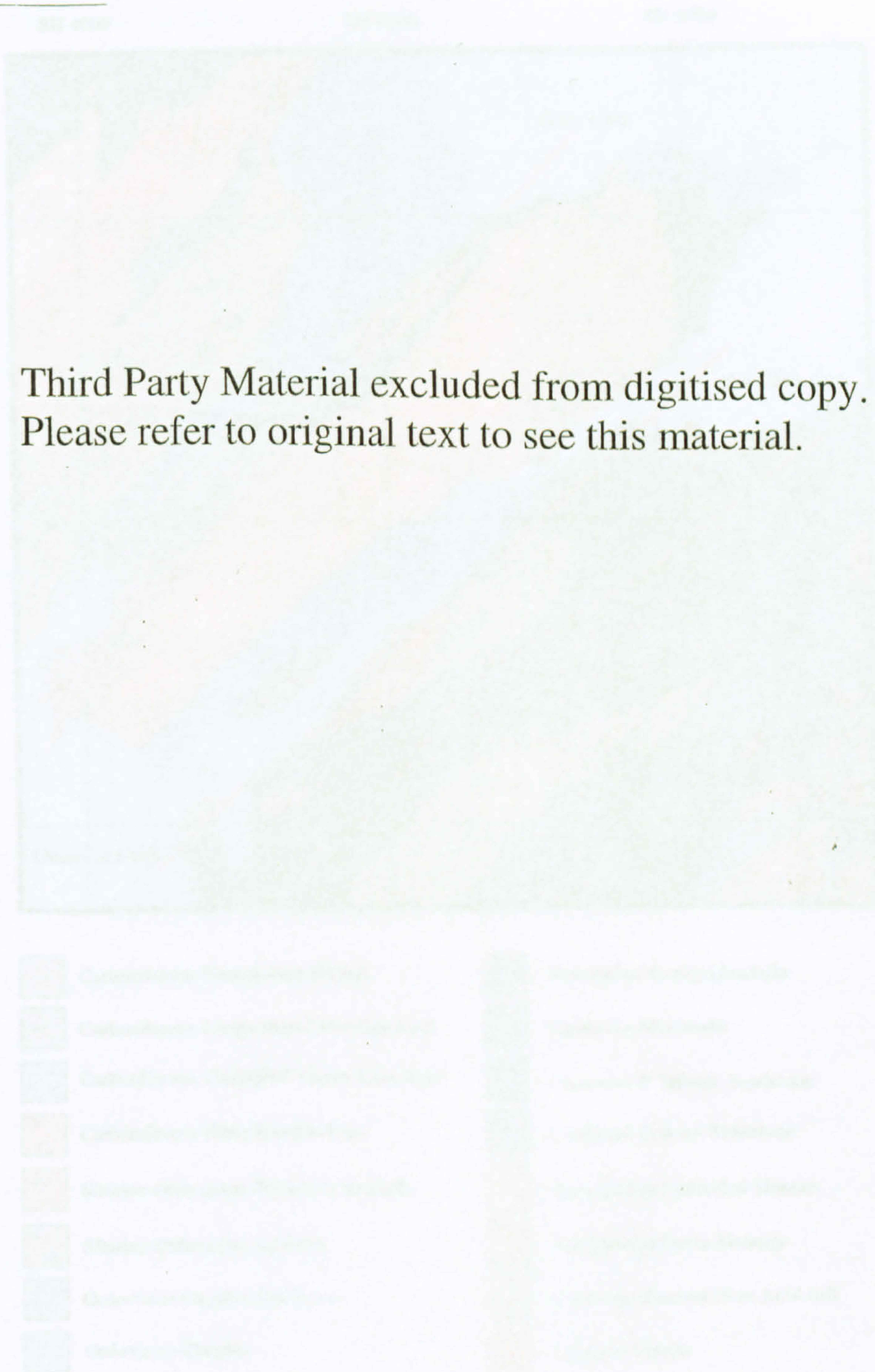

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Figure 1.5 Geological map of Anglesey (Adapted from The British Geological Survey, Geological Map of Wales: 1:250,000 series

Fault, which extends across Anglesey from Malltraeth in the southeast up to Red Wharf Bay in the north. The fault system juxtaposes two areas of significantly differing geological strata, with the Precambrian rocks of Anglesey located to the northwest and the Lower Palaeozoic Welsh Basin formations to the southeast.

The Menai Strait displays a diverse range of geological strata along its shores both in terms of nature and age, with rock formations ranging from the Precambrian 'Mona Complex', through to Carboniferous limestone and sandstones, together with more recent unconsolidated Quaternary and Holocene sediments.

Along the Anglesey shoreline, the southwestern reaches of the Menai Strait are dominated by Lower Carboniferous Viséan limestone formations, overlain in some areas by Upper Carboniferous Westphalian sandstone and red marl deposits; these formations extend as far northeast as Llanfair P.G. The bedrock between Llanfair P.G. and Menai Bridge is composed of the highly metamorphosed, fine grained mica-schist and blue-schist belonging to the Penmynydd series of the Pre Cambrian Mona Complex. To the northeast of Menai Bridge as far as Beaumaris, the Anglesey coast is dominated by rocks belonging to the Gwna group, which also form part of the Mona Complex. These formations consist predominantly of mélanges and appear to have no coherent internal stratigraphy (Gibbons and Ball, 1991); they are considered by Wood (1974) to represent a deformed sedimentary slide deposit. Further north between Beaumaris and Penmon the bedrock consists predominantly of Ordovician conglomerate together with shale and ironstone of Upper Arenig and Llanvirn age. The extreme northeastern reach of the

Menai Strait, north of Penmon towards Puffin Island is underlain by the Viséan Carboniferous limestone.

Along the coast of the mainland, the Menai Strait is almost entirely bounded by either the Carboniferous or Ordovician formations found on Anglesey. The Menai Strait is also characterized by several igneous intrusive formations ranging from Early Palaeozoic through to Tertiary in age.

1.4.6 Quaternary geology

The Quaternary geological period was primarily characterized by the development and expansion of ice sheets over much of the British Isles. During this time, highland areas of the British Isles received significant rates of precipitation, resulting in the development of southward flowing ice sheets which eventually coalesced with ice derived from the Southern Uplands and the Lake District. This ice sheet continued flowing in a generally southerly direction extending out over the low lying area which presently constitutes the Irish Sea, before flowing over Anglesey and parts of the Llŷn Peninsula, subsequent to extending out into Cardigan Bay. A contemporaneously developing ice sheet within the mountains of Snowdonia radiated outwards before coalescing with the southward moving Irish Sea ice sheet within the vicinity of the Menai Strait.

Ice sheet movement during the Late Devensian resulted in the erosion of significant quantities of material from within the Irish Sea Basin. The floor of the northeastern Irish Sea principally consists of relatively soft, Permian-Triassic sandstone deposits, which extend into the Cheshire Basin. To the north of Anglesey, within the Central Irish Sea Basin, the sea floor is predominantly Carboniferous limestone; however, Monian and undivided Lower Palaeozoic formations extend for some 20km to the northwest. The nature and significance of these formations becomes apparent when considering the Quaternary deposits located within the Menai Strait region together with the directions of ice sheet movement. Reworking of these deposits through glacial, glacio-fluvial and more recent post-glacial processes has attributed to the complex pattern of unconsolidated sediments presently overlying the solid geology of the Menai Strait.

Quaternary deposits can, as a result, be found overlying the older rock formations along almost the entire length of the Menai Strait. These deposits represent a complex and continuously oscillating zone of interplay between the major north-south moving Irish Sea ice sheet and the locally derived Welsh ice sheet that radiated outwards from within the central Snowdonia region of North Wales.

The nature of ice movement during this period has predominantly been inferred and delimited utilizing a range of evidence obtained through the examination of till fabric, and lithology, studies of glacial erratics and through the analysis of glacial striae. Attempts at elucidating the Quaternary history of the area surrounding the Menai Strait have been restricted, predominantly due to the profoundly complex nature of interaction between two major ice sheets and a deficiency with respect to the number of inland exposures of Quaternary sediment. Consequently, the extent and number of ice sheet advances within the region during the Late Devensian has proved contentious and has resulted in a number of proposals (Mitchell, 1960; Mitchell, 1972; Synge, 1964; Bowen, 1973; Whittow and Ball, 1970) relating to the timing and extent of ice limits within the region of North Wales.

Exposures of Quaternary sedimentary sequences within North Wales are predominantly confined to areas situated along the coastline, with limited exposures occurring inland. The location of important Quaternary sites, together with areas utilized in relation to sea-level studies within North Wales and Northwest England are illustrated in figure 1.6. Quaternary exposures within North Wales include those found at Aber Ogwen, Glan-y-môr isaf, Lleiniog, Dinas Dinlle and Glanllynnau; whilst Pen-y-bryn, located approximately 2km southeast of Caernarfon provides a rare example of an inland exposure containing deposits relating to at least one cool/cool-temperate interstadial event prior to the onset of the last major glaciation (Addison *et al.*, 1990).

The stratigraphy of the Pen-y-bryn site at Caernarfon provides a multifaceted insight into events that occurred throughout most of the Devensian Stage and commences with sediments attributable to interstadial conditions, deposited during the Early Devensian. These sediments are subsequently overlain by glacigenic sediments possibly attributable to the advance of an Early Devensian Welsh ice sheet, subsequent to the deposition of overlying sediments derived from the Late Devensian.

The Late Devensian Dimlington Stadial was represented by the build-up and subsequent decay of the last major ice sheet to cover the UK and Northern Europe. According to

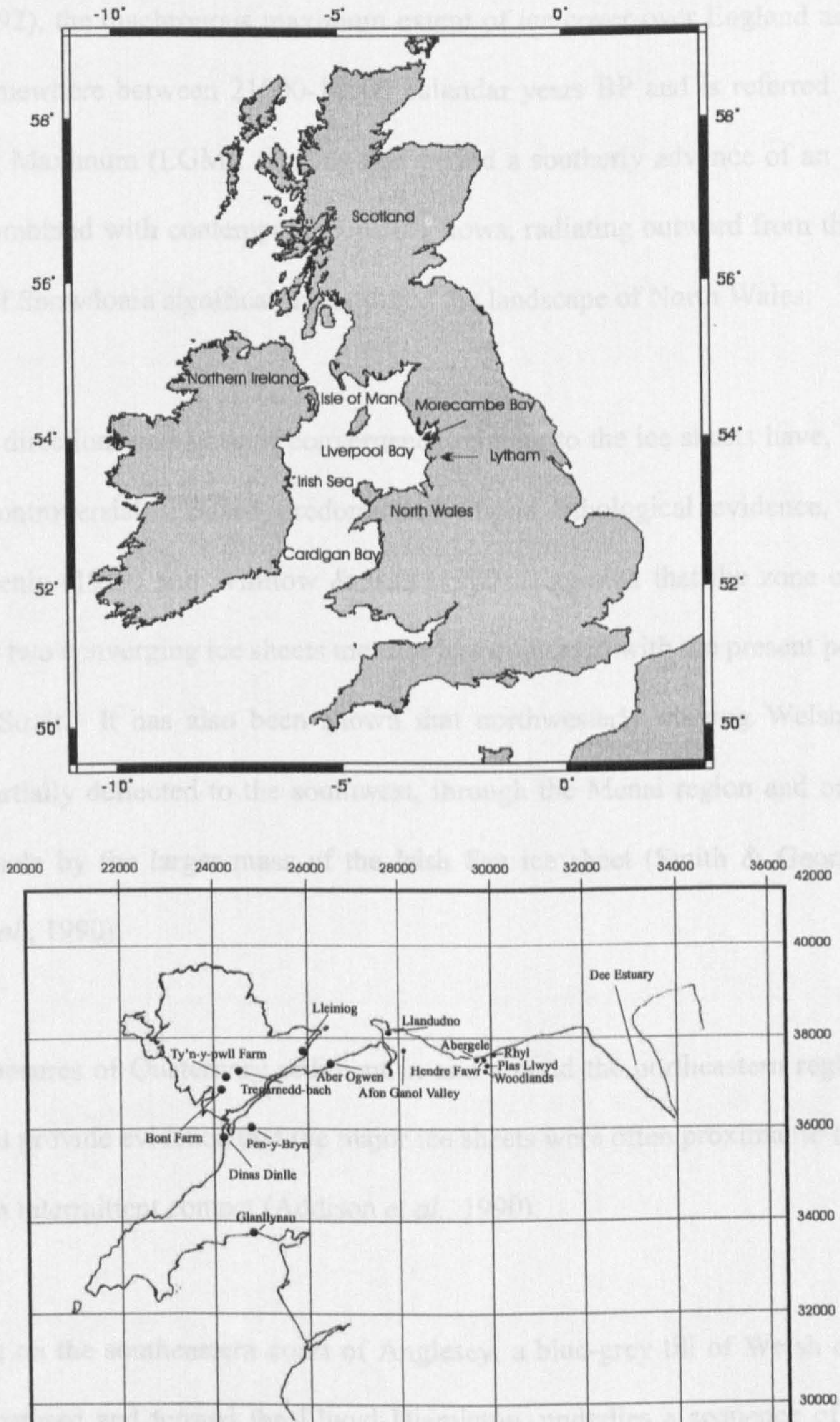


Figure 1.6 Location map for Quaternary exposure sites in North Wales and sea-level study locations mentioned within this thesis

Boulton (1992), the diachronous maximum extent of ice cover over England and Wales occurred somewhere between 21000-18000 calendar years BP and is referred to as the Late Glacial Maximum (LGM). During this period a southerly advance of an Irish Sea ice sheet, combined with contemporaneous ice flows, radiating outward from the nearby mountains of Snowdonia significantly modified the landscape of North Wales.

The precise directions and lines of convergence relating to the ice sheets have, however, remained controversial. Based predominantly upon lithological evidence, Edwards (1904), Greenly (1919) and Whittow & Ball (1970) suggested that the zone of contact between the two converging ice sheets more or less coincided with the present position of the Menai Strait. It has also been shown that northwesterly moving Welsh ice was probably partially deflected to the southwest, through the Menai region and on into the Llŷn Peninsula by the larger mass of the Irish Sea ice sheet (Smith & George, 1961; Addison *et al.*, 1990).

Coastal exposures of Quaternary sediment in and around the northeastern region of the Menai Strait provide evidence that the major ice sheets were often proximal to each other as well as in intermittent contact (Addison *et al.*, 1990).

At Lleiniog on the southeastern coast of Anglesey, a blue-grey till of Welsh origin, not currently exposed and termed the Llwyd Diamicton, underlies a sequence of sand and gravel that in turn is overlain by a series of diamictons comprising five facies, derived from the Irish Sea ice sheet. Whilst on the mainland coast approximately 2km east of

Bangor, to the east of the mouth of the Afon Ogwen and approximately 6km to the south of Lleiniog are sediments derived from the Welsh ice sheet (Llwyd Diamicton), overlain by sediments derived from the Irish Sea ice sheet (Iwerddon Diamicton).

Approximately 1km further to the east at Glan-y-môr isaf, coastal erosion has resulted in the exposure of a more complex sequence of sediments described by Pointon (1982). The sequence (fig 1.6) consists of Welsh till, with an apparently weathered upper surface, overlain by a series of silts sands and gravels, similar to those found to the north at Lleiniog. The sediments are once again predominantly overlain by Irish Sea till along much of the exposure. One shorter section however, does appear to be overlain by Welsh till; Edge *et al.* (1990) attributes this apparent inversion to the weathering of an exhumed surface and the subsequent downslope transport of weathered material which consequently overrode the Irish Sea till.

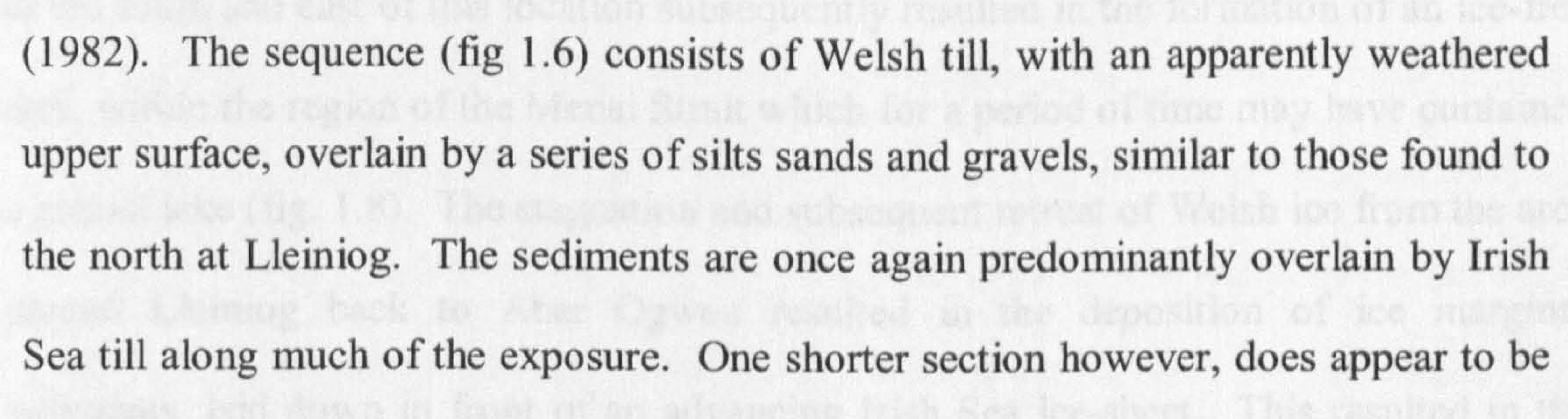


Figure 1.7 Schematic cross section of the Quaternary sediments at Glan-y-môr isaf. From Hart in Addison *et al.* (1990).

According to Edge *et al.* (1990), the stratigraphy of the Quaternary sediments within the northeastern region of the Menai Strait infer that the low lying area was initially inundated by a Welsh ice-sheet which ranged northward through the Ogwen Valley and down onto the coastal plain, depositing till at both Aber Ogwen and Glan-y-môr isaf.

Edge *et al.* (1990) further propose that the coalescence of the Welsh and Irish ice-sheets to the south and east of this location subsequently resulted in the formation of an ice-free area, within the region of the Menai Strait which for a period of time may have contained a glacial lake (fig. 1.8). The stagnation and subsequent retreat of Welsh ice from the area around Lleiniog back to Aber Ogwen resulted in the deposition of ice marginal sediments, laid down in front of an advancing Irish Sea ice-sheet. This resulted in the deposition of Irish Sea till upon what were predominantly glacio-lacustrine deposits.

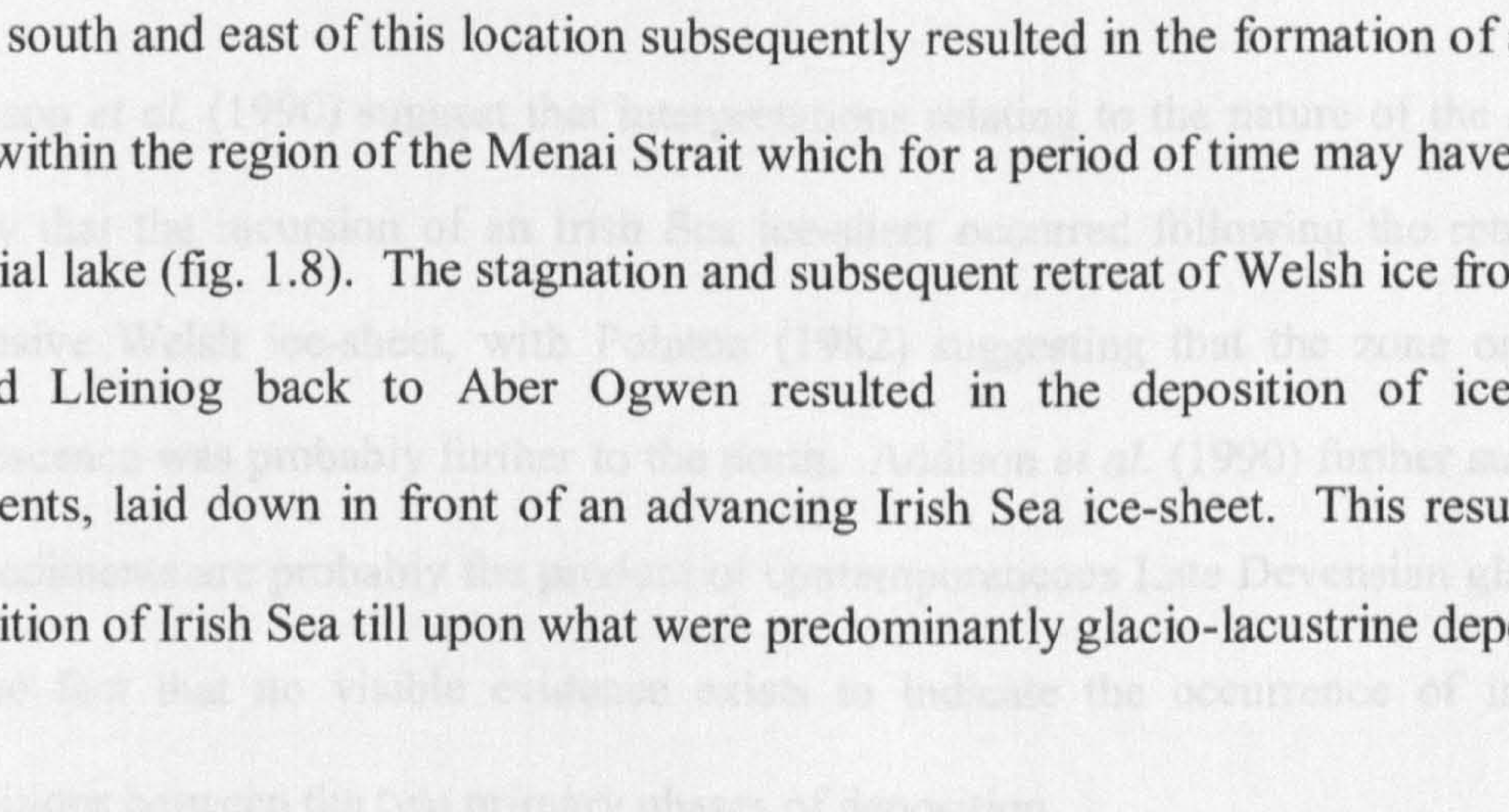
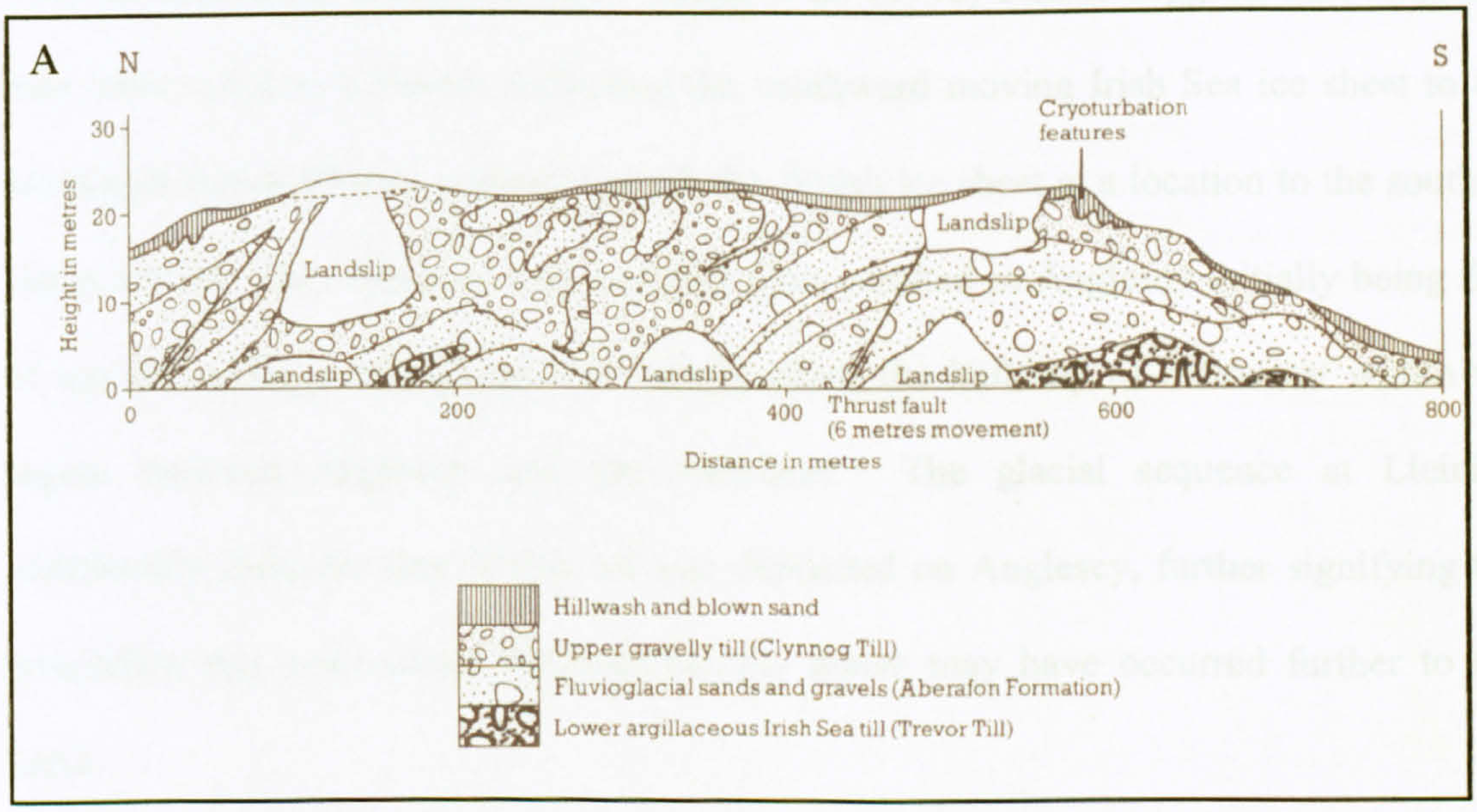


Figure 1.8 Illustration of the interaction of ice-sheets in northwest Wales: a) illustrates the ice-free area between ice-sheets and its effect upon flow direction; b) illustrates ice flow upon coalescence. From Edge *et al.*, in Addison (1990)

Edge *et al.* (1990), also provides an explanation relating to the origin of the sequences found at Glan-y-môr isaf involving the possible formation of a pro-glacial lake and the subsequent progradation of delta facies sediments, together with the effects of sub-aerial weathering and fluvial processes, eventually contributing to the formation of the exposed sequences.

Addison *et al.* (1990) suggest that interpretations relating to the nature of the sediments imply that the incursion of an Irish Sea ice-sheet occurred following the retreat of an extensive Welsh ice-sheet, with Pointon (1982) suggesting that the zone or point of coalescence was probably further to the north. Addison *et al.* (1990) further suggest that the sediments are probably the product of contemporaneous Late Devensian glaciers due to the fact that no visible evidence exists to indicate the occurrence of interstadial conditions between the two primary phases of deposition.

An exposure at Dinas Dinlle located on the mainland coast approximately 4km to the south of Fort Belan and proximal to the southwestern approaches to the Menai Strait, exhibits a complex sequence of distorted sediments that provide important additional evidence relating to aspects of the Late Devensian (fig. 1.9). Early interpretations relating to the multiple till sequences found within the moraine located at Dinas Dinlle (Jehu, 1909; Synge, 1963; Saunders, 1963; Whittow and Ball, 1970; Bowen, 1974) have shown that the exposure possibly provides compelling evidence relating to the readvance of a Late Devensian ice sheet in North and West Wales, indicating that the downwasting of the Late Devensian ice sheet was probably not uniform and may have consisted of at least one re-advance of an ice-margin.



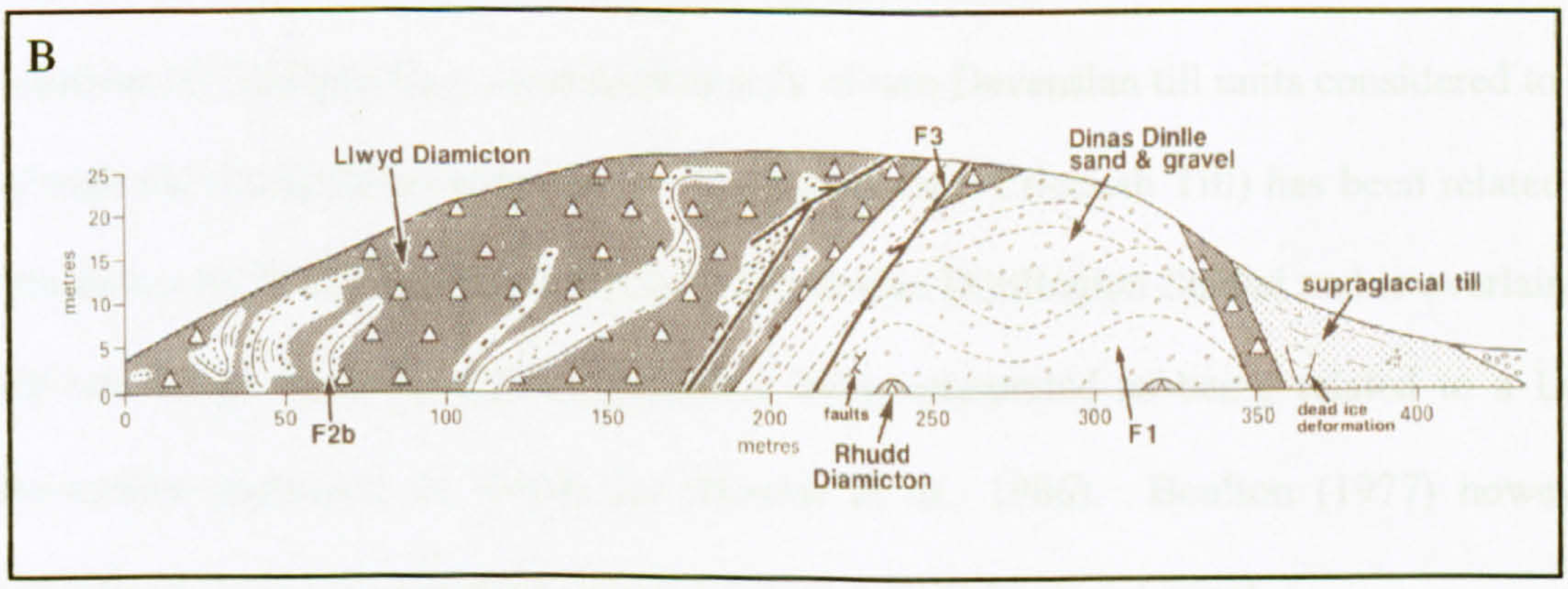


Figure 1.9 Interpretations of Quaternary sedimentary section at Dinas Dinlle taken from Addison *et al.* (1990). A) Interpretation taken from Campbell & Bowen, 1989, after Whittow & Ball, 1970. B) Re-interpretation after Hart, 1990.

The idea of a readvance however remains contentious, with Hart in Addison *et al.* (1990) proposing that the sediments at Dinas Dinlle consist of Irish Sea till being overlain in places by outwash sands and gravels, which in turn are overlain by sediments derived from an advancing Welsh ice sheet. Edge *et al.* (1990) further suggests that Anglesey may have acted as a barrier deflecting the southward moving Irish Sea ice sheet to the southwest and northeast, coalescing with the Welsh ice sheet at a location to the south of Dinas Dinlle. This situation may possibly have resulted in Anglesey initially being free of ice, providing a mechanism that would allow the build-up of meltwater within the region between Anglesey and the mainland. The glacial sequence at Lleiniog additionally indicates that Welsh till was deposited on Anglesey, further signifying the possibility that coalescence between the ice sheets may have occurred further to the north.

The coastal cliff section at Glanllynnau, located further to the south on the northern coastline of Cardigan Bay, consists primarily of two Devensian till units considered to be of regional stratigraphic importance. The lower unit (Criccieth Till) has been related to inundation by Welsh ice during the Late Devensian Dimlington Stadial and is overlain at the site by an upper unit (Llanystumdwy Till), interpreted as being related to a Late Devensian readvance of Welsh ice (Bowen *et al.*, 1986). Boulton (1977) however considered that both units were deposited during a single glacial event.

The Glanllynnau site, however, also contains a sedimentary sequence that is of significant importance in terms of assessing aspects of regional Late Devensian deglaciation (fig.

1.10). The undulating coastal cliff section dissects a sequence of irregular enclosed peat-filled hollows interpreted as a kettle-hole complex. The hollows are infilled with sediment consisting of fine grained lacustrine, inorganic silt interspersed with layers of highly organic mud and peat. The sediments have been analyzed in order to derive detailed biostratigraphic data based upon their pollen and Coleoptera content (Coope and Brophy, 1972; Simpkins, 1974). The site is particularly important, as it indicates that this region was effectively free of ice by approximately 17500 years BP, which coincides with the onset of the Windermere Interstadial.

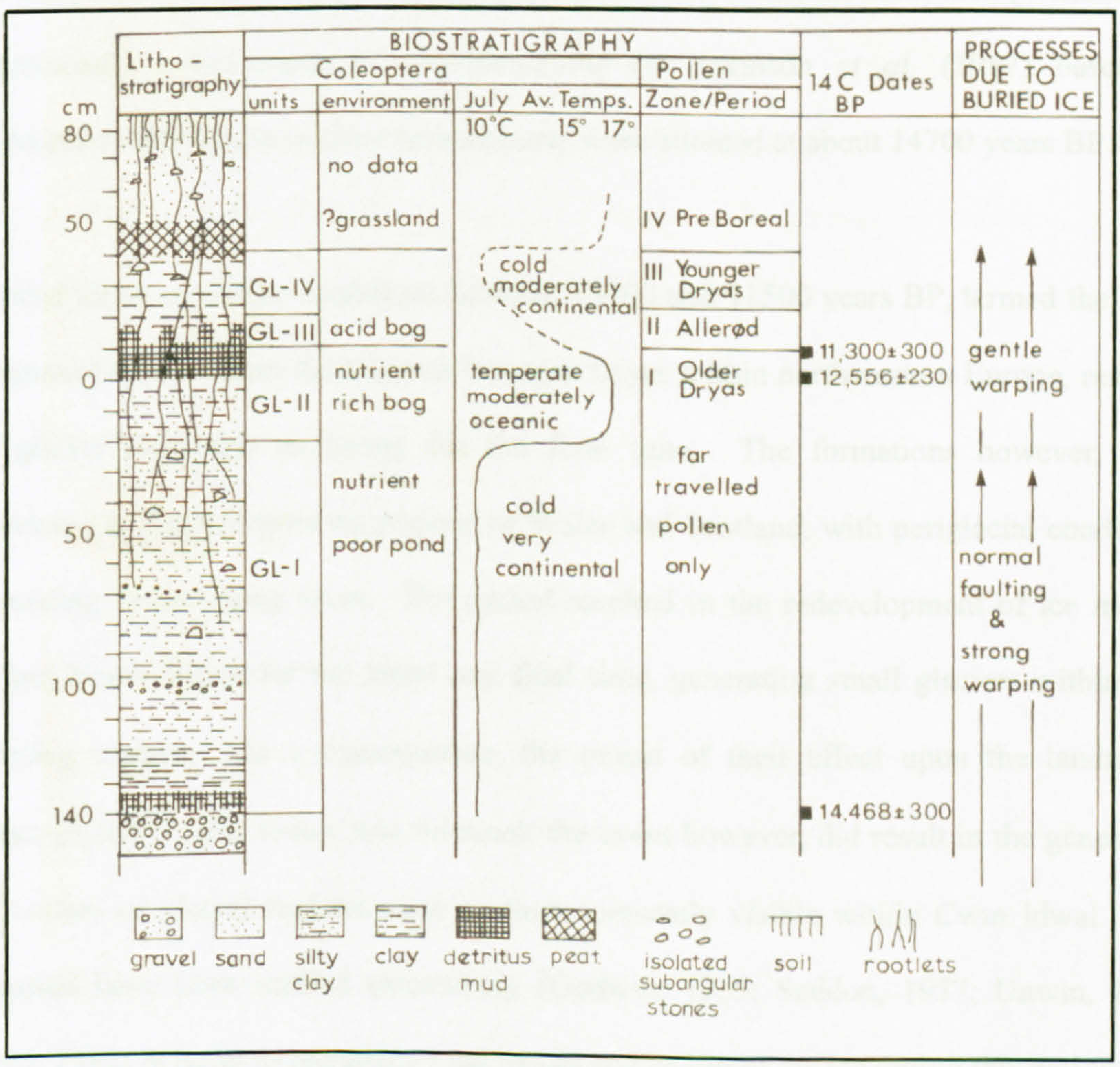


Figure 1.10 Lithostratigraphy, biostratigraphy and chronostratigraphy of Glanllynnau, with inferences relating to changes in local environment and regional climate. (Redrawn from Coope and Brophy, 1972 and Boulton, 1977). From Addison et al (1990).

A distinctive phase of organic sedimentation resulting in the deposition of a detritus mud and clay located within the upper section of the deposit and dated to the Late Devensian, Older and Younger Dryas period, further provides important palaeoclimatic evidence relating to conditions experienced within North Wales prior to the onset of the Holocene.

Climatic warming and a return to interstadial conditions between approximately 15000-13000 years BP resulted in the downwasting of glaciers located within North Wales and the deposition of significant volumes of glacial debris within the local area (Windermere Interstadial). According to reconstructions by Atkinson *et al.* (1987) based on *Coleoptera* remains, maximum temperatures were attained at about 14700 years BP.

A brief return to colder conditions between 13000 and 11500 years BP, termed the Loch Lomond Stadial within the UK and Younger Dryas within northwestern Europe, resulted in glacier formation occurring for the final time. The formations however, were restricted to the mountainous regions of Wales and Scotland, with periglacial conditions persisting in low-lying areas. The period resulted in the redevelopment of ice masses within North Wales for the latest and final time, generating small glaciers within pre-existing cirques. As a consequence, the extent of their effect upon the landscape, although still visible today, was minimal; the event however, did result in the generation of variety of glacial features such as those presently visible within Cwm Idwal. The deposits have been studied extensively (Godwin, 1955; Seddon, 1957; Unwin, 1973; Gray, 1982) in order to reconstruct the extent and nature of the ice during this period.

This period was followed by a return to warmer conditions, similar to those experienced today and consequently defines the onset of the Holocene. Although ice-masses had effectively disappeared from the British Isles by this time, the existence of significantly larger distal ice-masses, such as the North American Laurentide and Scandinavian ice sheets were responsible for the continuous discharge of significant quantities of water into ocean basins. A corresponding rise in eustatic sea level associated with global warming and the downwasting of these terrestrially based ice-masses resulted in what has been termed the Flandrian or Holocene marine transgression and the subsequent inundation of the northwestern European continental shelf. This inundation combined with the regional and local response of the Earth's crust in relation to the effects of loading and unloading by the ice masses were predominantly responsible for the development of the contemporary coastline of the British Isles.

1.4.7 Evolution of the Menai Strait

The exact timing and nature of the processes contributing to the formation of Menai Strait has long been an issue of contention and up to the present day remains largely unresolved. Ramsay (1876) described the Menai Strait as one long, shallow valley, located below sea level, interpreting the valley as a broad glacial groove. Ramsay further implied that ice derived from Snowdonia did not extend as far north as Anglesey and that the Malltraeth and Menai depressions were formed entirely by the action of an Irish Sea ice sheet. The Menai Strait, according to Ramsay, was subsequently formed by the inundation of sea-water following the retreat of Irish Sea glaciers. Ramsay further considered that the islets located within the central region of the Menai Strait to be the weathered remnants of roches moutonnées.

Edwards (1904) rejected the Ramsay hypothesis, recognising the impact glaciers can impose upon a landscape but also suggesting that the southwestern and northeastern depressions within the strait could not be entirely attributable to the erosive powers of ice.

Edwards additionally suggested that contemporary fluvial systems must also have had a significant impact with respect to the erosion of the outer regions of the strait and noted that these systems did not prevail within the central region of the strait.

Greenly (1919) sub-divided the Menai Strait into three regions, comprising of the Eastern, Western and Middle Reaches and subsequently adopted Ramsay's theory of glacial enlargement but applied this to the Western and Eastern Reaches only. Greenly then recognized a natural watershed within the central region, separating what he termed two glacially enlarged river valleys to the southwest and northeast (fig 1.11). Greenly further identified the Afon Seiont at Caernarvon and the Afon Braint at Traeth Melynog as constituting the primary fluvial systems within the southwestern region of the Menai Strait, whilst identifying the Afon Cadnant, 1km to the north of Menai Bridge and the Afon Ogwen at Bangor as their northwestern equivalent. Greenly then proposed that, as the Irish Sea ice sheet retreated from within the Menai Strait, re-advancing Welsh ice ranged out of Snowdonia pushing as far north as Anglesey, restricting the flow of the

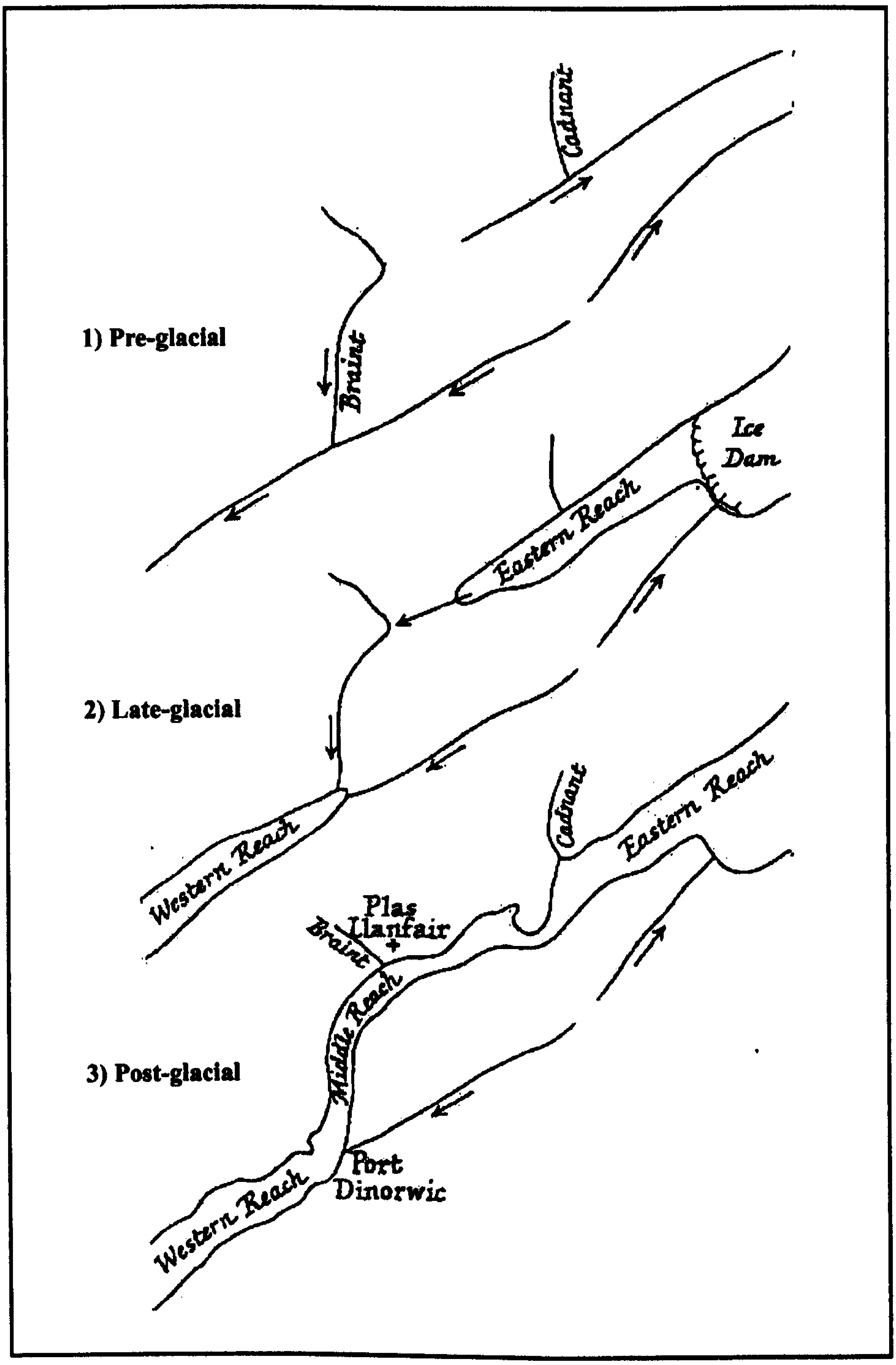


Figure 1.11 Schematic illustrating the hypothesis proposed by Greenly (1919), for the formation of the Menai Strait. From Embleton (1964).

Afon Cadnant out to the northeast. Greenly proposed that the Welsh ice acted as a dam, subsequently resulting in an overflow channel being formed within the central region of the strait as water levels exceeded that of the natural watershed. Greenly further theorised that as sea levels gradually began to rise following the disappearance of the ice, the land also sank, resulting in the inundation and formation of the present day Menai Strait.

Embleton (1964) also rejected Ramsay's theory of glacial excavation, partially as this did not account for the tri-partite nature of the Menai Strait and also because he believed that moving ice did not have significant powers of differential erosion. Embleton further dismissed the ice-dam theory as untenable, refusing to accept that Welsh ice may have advanced as the Irish Sea ice sheet had retreated. Embleton did however accept that both the Eastern and Western Reaches had probably existed as pre-glacial and possibly inter-glacial river valleys and proposed that the watershed that separated them was cut down below present sea level at some time during the last Glacial Period. Embleton additionally postulated that the present day marine channel constituting the Menai Strait was formed approximately 7000-8000 years BP during the latest post-glacial marine transgressive episode (fig. 1.12)

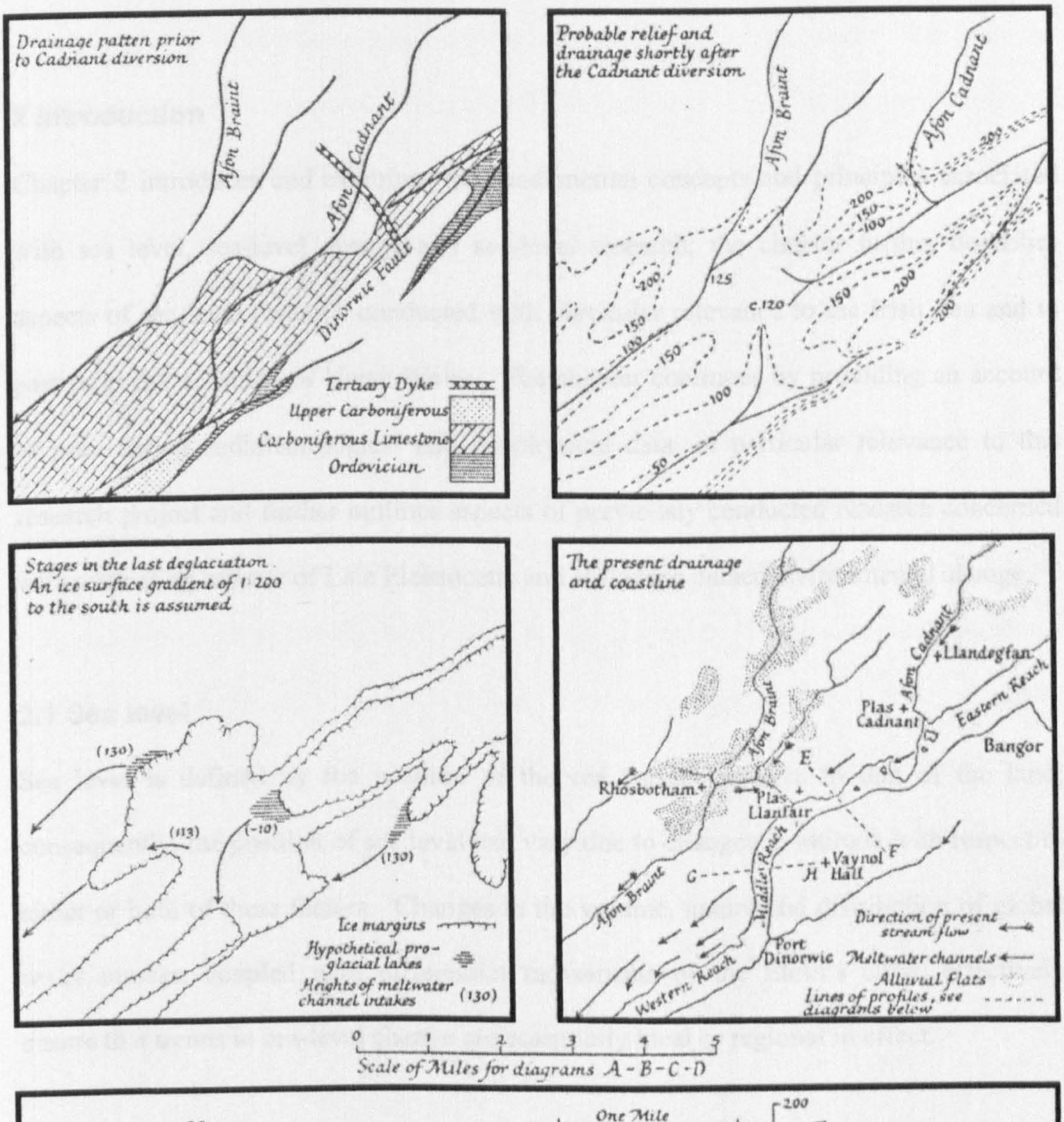


Figure 1.12 Schematic illustrating the hypothesis proposed by Embleton (1964), for the evolution of the Menai Strait. From Embleton (1964).

Chapter 2

2 Introduction

Chapter 2 introduces and examines the fundamental concepts and principles associated with sea level, sea-level change and sea-level research; the chapter further describes aspects of sea-level research conducted with particular relevance to the Irish Sea and in particular the coastline of North Wales. The chapter continues by providing an account of pre-existing sedimentological and geophysical data, of particular relevance to this research project and further outlines aspects of previously conducted research concerned with evaluating aspects of Late Pleistocene and Holocene palaeoenvironmental change.

2.1 Sea level

Sea level is defined by the position of the sea surface relative to that of the land; consequently, the position of sea level can vary due to changes in altitude with respect to either or both of these factors. Changes in the volume, nature and distribution of global water masses, coupled with differential movements of the Earth's crust, effectively ensure that trends in sea-level change are essentially local or regional in effect.

Global fluctuations in sea level are termed eustatic and can principally be related to changes with respect to the volume of water contained within the ocean basins. Eustatic sea level is essentially controlled by changes with respect to the volume of water contained within the ocean basins together with changes in the shape and size of the basins themselves (tectono-eustasy). During the Quaternary such changes have primarily been governed by the large-scale build up and downwasting of terrestrial ice-sheets (glacio-eustasy). Other less significant factors however, can additionally influence the position of eustatic sea level; these include tectonic activity, changes in the geoidal configuration, temperature changes and to a lesser extent the introduction of juvenile water into the hydrosphere through the expulsion of magma.

Changes that occur in sea level on a local or regional scale are, however, frequently very dissimilar to eustatic fluctuations and can either be a consequence of localized change or the result of local changes combined with fluctuations in eustatic sea level. Isostasy refers to a state of gravitational equilibrium between the lithosphere and the underlying asthenosphere and is directly attributable to the response of the underlying mantle to loading or unloading at the Earth's surface. In the context of sea-level change, isostatic movements are primarily attributable to the loading and unloading of the crust in relation to the build-up and subsequent decay of ice sheets (glacio-isostasy); however, secondary factors such as hydro-isostasy and erosional and/or depositional-isostasy can additionally influence the altitude of sea level. It is additionally important to understand that the large-scale build-up and decay of ice masses can exert an isostatic influence on a global scale.

Relative sea-level change can therefore be defined as how the position of sea level varies relative to the land at a particular coastal location and takes into account both eustatic sea-level change and the more localized isostatic movement of the Earth's crust. The nature and scope of each particular sea-level study will, however, determine which particular principal factors need to be taken into account.

2.1.1 Sea-level studies

An abundance of geomorphological and sedimentological evidence within both the terrestrial and marine environment clearly illustrates that sea level has in the past, fluctuated significantly with respect to its contemporary elevation. The implications of sea-level change upon contemporary society are profound and as a result, a great deal of scientific research has been directed towards gaining a comprehensive insight into the mechanisms that contribute to a natural phenomenon that can have extensive consequences upon society as a whole.

Investigations based upon observational evidence with respect to sea-level change have been conducted and well documented within Western Europe from as early as the 17th century; however, according to Devoy (1987), the phenomenon of sea-level change was also investigated by the Chinese over two thousand years ago. Fundamental concepts associated with the exchange of water masses between the land and the ocean through the generation and subsequent decay of ice-sheets were introduced shortly after the publication of Agassiz's glacial theory during the 1840s. During the late 19th century and the first half of the 20th century, the terms glacio-eustasy and glacio-isostasy were introduced through work conducted by Seuss and Daly, as sea-level studies continued to develop (Mörner, 1987). Within the UK, prior to the advent of absolute dating techniques during the 1950s, age determinations were dependent upon relative methods.

In Britain scientists such as Godwin followed on from work by the Swedish geologist Lennart von Post in pioneering the use of pollen analysis in order to determine the relative ages of coastal sediments.

The introduction of the radiocarbon dating technique by Libby during the early 1950s facilitated an enhanced programme of research with respect to aspects of more recent sea-level change. The advent of this and other similar techniques led to the search for a singularly universal eustatic sea-level curve, based on the assumption that a eustatic change would be globally uniform. It is currently acknowledged, however, that gravitational influences result in varying degrees of eustatic sea-level change within different coastal regions (Shennan, 1987) and consequently eustatic changes may not necessarily be comparable at local or even regional level.

During the 1950s and 1960s, however, significant scientific papers were published during a period of intensified research which was conducted in an attempt to produce the definitive global eustatic curve. As a consequence, several contrasting schools of thought emerged, each one proposing very different ideas with respect to the pattern of eustatic sea-level change during the course of the Holocene.

A number of scientists preferred the idea that sea-level rise during the Holocene had taken the form of a curve demonstrating smooth exponential decay (Shepard, 1964; Kidson & Heyworth, 1973); whereas other scientists favoured an oscillatory pattern of eustatic sea-level rise (Fairbridge, 1961; Tooley, 1974). Conflicting interpretations related to the nature of Holocene sea-level change during this period culminated in the International Geological Correlation Programme ((IGCP) Project 61, Sea-level movements during the Last Demiglacial Hemicycle (15000 years)), which took place between 1974 and 1982. As a result of this programme many sea-level researchers became increasingly aware of the need to account for and quantify the many local, regional and global factors that contribute to variations in relative sea level.

Fairbanks (1989) dated the fossilized remains of the reef crest coral *Acropora palmata* located off the coast of Barbados, in an attempt to provide a continuous and detailed record of sea-level change following the last glacial maximum (fig. 2.1). The sea-level record from Barbados is additionally considered to be important because it provides a unique record of sea-level change that extends over 19000 years from close to the LGM up to the present day. The record suggests that the last deglaciation was characterized by two relatively brief periods of accelerated melting superimposed on a smooth and continuous rise of sea level with no reversals. These two 'meltwater puses' have been termed, MWP-1A and MWP-1B respectively and are centered around 14300 cal yr BP and 11300 cal yr BP. Recent research (Liu *et al.*, 2004) possibly identifies the occurrence of other, although smaller, meltwater pulses (MWP-1C and MWP-1D) at around 9500 and 7600 cal yr BP respectively, although these pulses are not apparent in many of the other existing records of sea-level change. The cause and timing of these 'pulse' events are often disputed within the scientific literature however, it is clear that they resulted in sea levels rising globally around some 20m within a period of approximately 500 years (~

40-50mm yr^{-1}). The Barbados record indicates that the rate of sea-level rise substantially decreases after approximately 7000 cal yr BP before attaining its contemporary level.

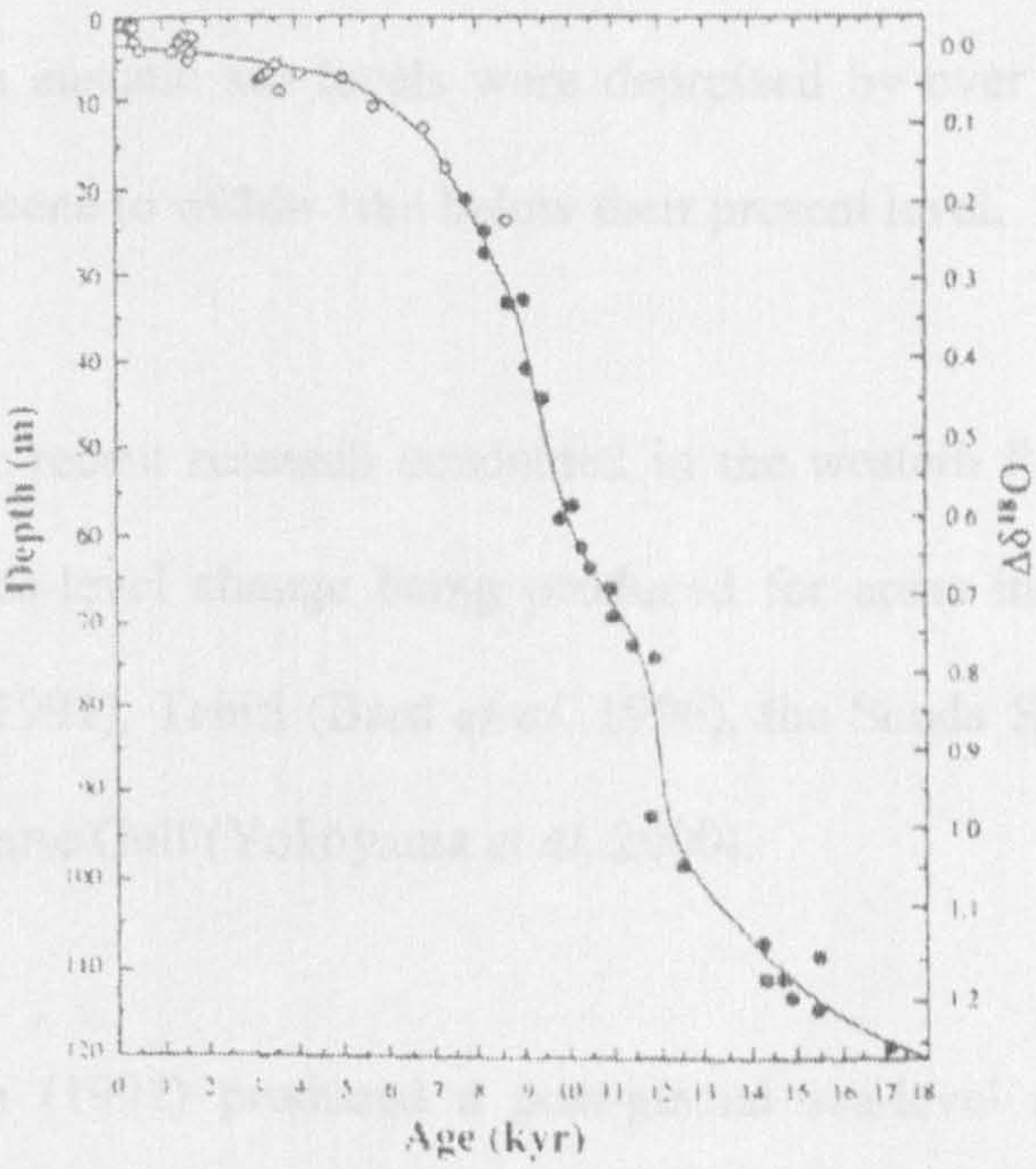


Figure 2.1 'Eustatic Barbados sea-level curve based on radiocarbon dated *Acropora palmata* (filled circles) compared with *A. palmata* age-depth (open circles) for four other Caribbean island locations. From Fairbanks (1989)

Barbados was selected as a study area for a number of reasons, including the fact that its tectonic history was considered to be relatively well understood, experiencing degrees of tectonic uplift of approximately 34cm kyr^{-1}. Schellmann and Radtke (2004) however, suggest that this rate of tectonic uplift may have varied both spatially and temporally and therefore question the validity of the original Barbados curve. Kurt Lambeck for example, suggests that the region may comprise part of a collapsing forebulge zone derived from the loading of the North American continent by the Laurentide ice sheet during the Late Devensian (J. Scourse, pers. comm. 2005).

The location of the islands within the western tropical Atlantic, additionally reduce the degree of gravitational influence imparted by the diminishing ice sheets within the Northern Hemisphere; these factors combined to allow the generation of a curve reflecting eustatic sea-level change. The Barbados sea-level curve reveals that during the last glacial maximum eustatic sea levels were depressed by over 120m, rising rapidly during the Early Holocene to within 10m below their present level.

Subsequent and more recent research conducted in the western Pacific has resulted in records of eustatic sea-level change being produced for areas including New Guinea (Chappell & Polach 1991), Tahiti (Bard *et al.* 1996), the Sunda Shelf (Hanebuth *et al.* 2000), and the Bonaparte Gulf (Yokoyama *et al.* 2000).

Chappell and Polach (1991) produced a post-glacial sea-level record for the Huon Peninsula, Papua New Guinea through dating a core taken from a coral reef terrace (fig. 2.2). The record spans the interval between 11000 and 7000 ^{14}C years BP and demonstrates that during this time coral reef growth kept pace with a relative sea-level rise of 50m. Subsequent to corrections being applied to compensate for localized tectonic uplift, the record compares well with the record obtained for Barbados and further indicates that the greatest rate of sea-level rise corresponded to the time of the Younger Dryas event between 11700 and 10000 cal yr BP.

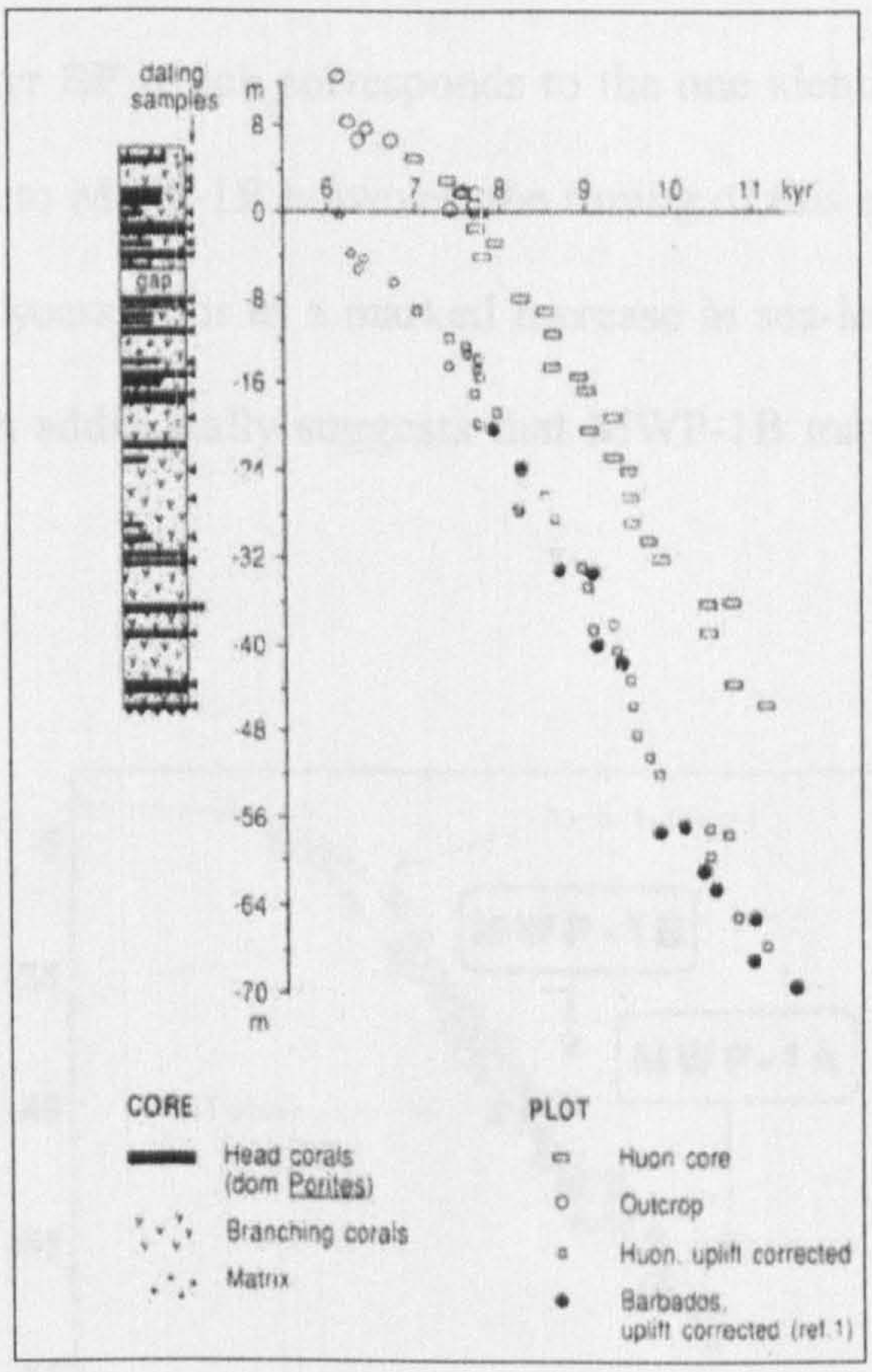


Figure 2.2 Summary core log and age-depth plots with upper series uncorrected for uplift. From Chappell and Polach (1991)

In an attempt to avoid the possible introduction of errors introduced through attempting to quantify complex tectonic movements Bard *et al.* (1996) dated fossil corals from Tahiti, which was deemed to be tectonically relatively stable. The record spans the period between approximately 14000 and 3000 cal yr BP and describes how sea levels rose by around 80m (fig. 2.3).

The data additionally indicate an increased rate of sea-level rise shortly before 13800 cal yr BP, which again corresponds to MWP-1A, initially identified within the Barbados record. The data additionally identifies an increase in the rate of sea-level rise between

11500 and 11000 cal yr BP which corresponds to the one identified within the Barbados record and may relate to MWP-1B however, the timing of this enhanced rate of sea-level rise occurs some 400 years prior to a marked increase in sea-level rise observed in New Guinea. The research additionally suggests that MWP-1B may have been smaller than previously thought.

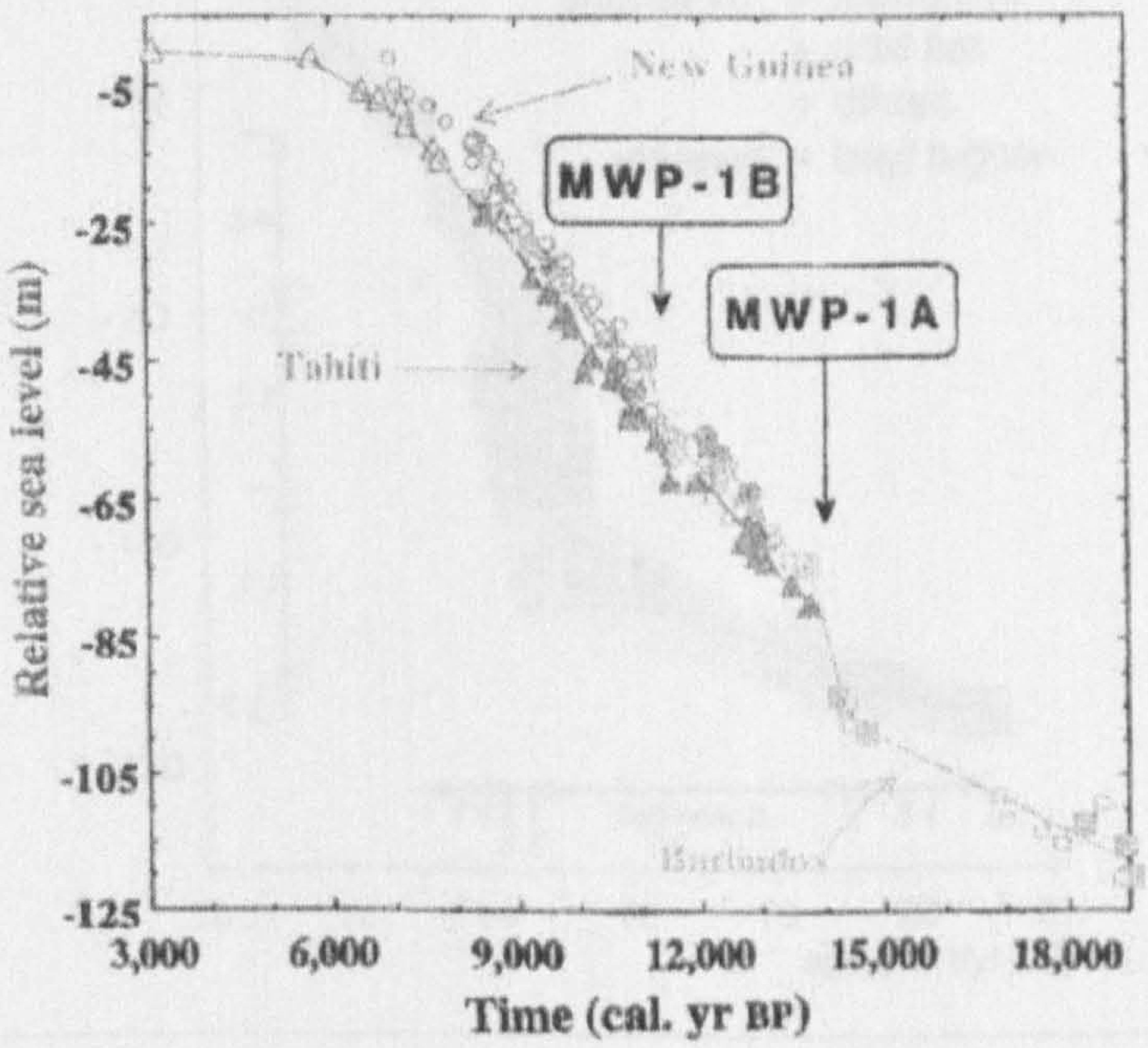


Figure 2.3 Sea-level history reconstructed from drill cores taken from Tahiti (triangles), Barbados (squares) and New-Guinea (circles). From Bard *et al.* (1996)

Hanebuth *et al.* (2000) produced a late-glacial sea-level record for the Sunda Shelf in Southeast Asia through the radiocarbon dating of organic material sub-sampled from a series of shoreline facies identified within a number of sediment cores. The data demonstrate how sea levels rose by over 70m between approximately 22000 and 11000 cal yr BP. The research further sub-divides this record into a series of four time periods which are characterized by sea levels rising at different rates (fig. 2.4). The enhanced rate of sea-level rise which characterizes segment 3 between 14600 and 14300 cal yr BP is attributed to MWP-1A, which may have resulted in sea levels rising by as much as 16m within 300 years.

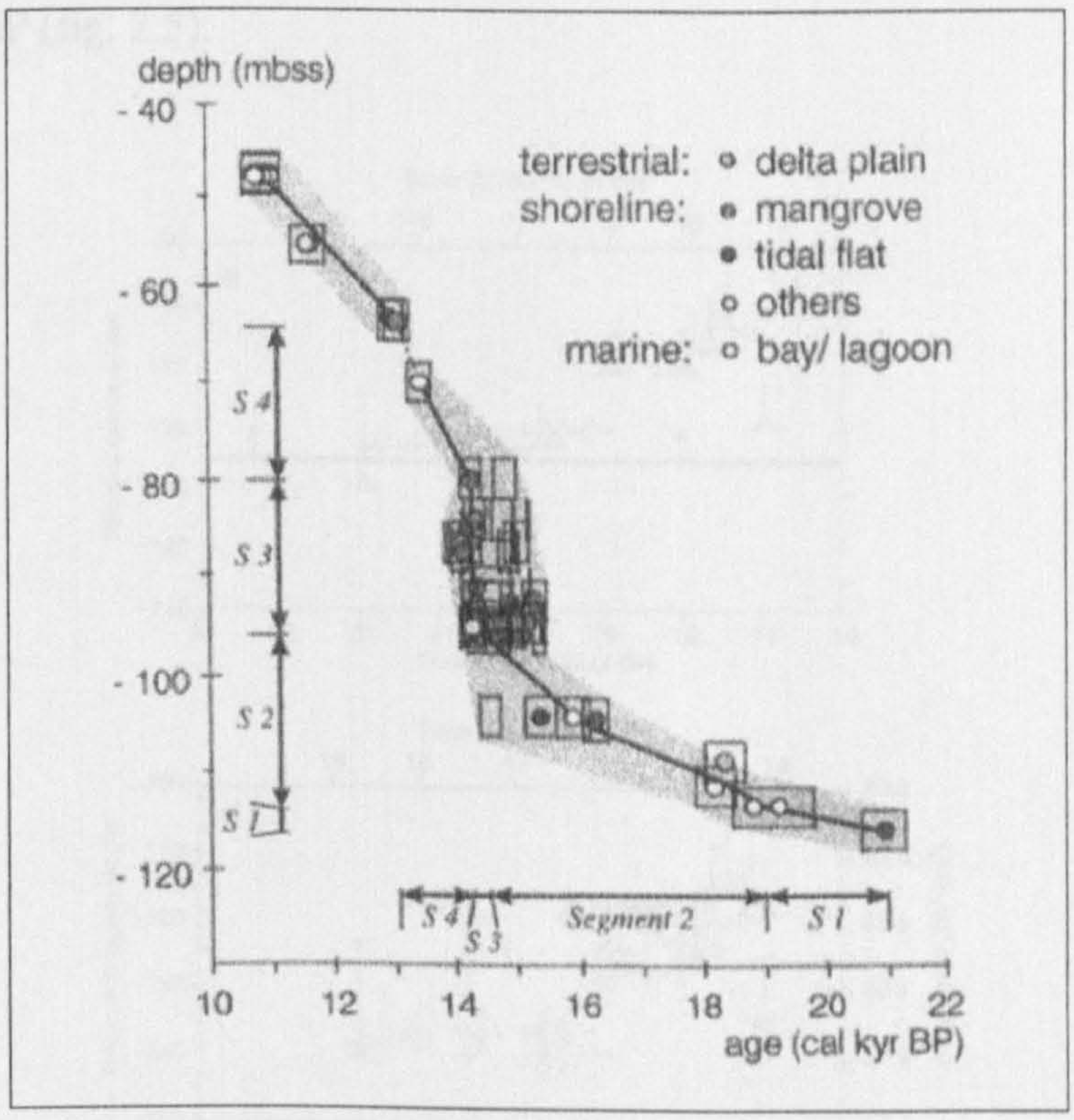


Figure 2.4 Sea-level curve for the Sunda Shelf derived from shoreline facies. From Hanebuth *et al.* (2000)

Yokoyama *et al.* (2000) analyzed a series of sediment facies from the Bonaparte Gulf on the northwestern coast of Australia and identified facies associated with open marine, shallow marine, marginal marine and brackish conditions. The study was undertaken in order to estimate the timing and extent of ice sheets between 22000 to 19000 cal yr BP. The research identified and dated fossilized faunal assemblages associated with specific marine and inter-tidal environments in order to determine that land-based ice volumes were at a maximum between 22000 and 19000 cal yr BP. The research additionally indicated that a rapid decrease in ice volume (10%) occurred within a few hundred years, terminating the LGM at around 19000 cal yr BP, the onset of deglaciation subsequently caused sea levels to rise locally by approximately 15-10m by around 17000 cal yr BP (fig. 2.5).

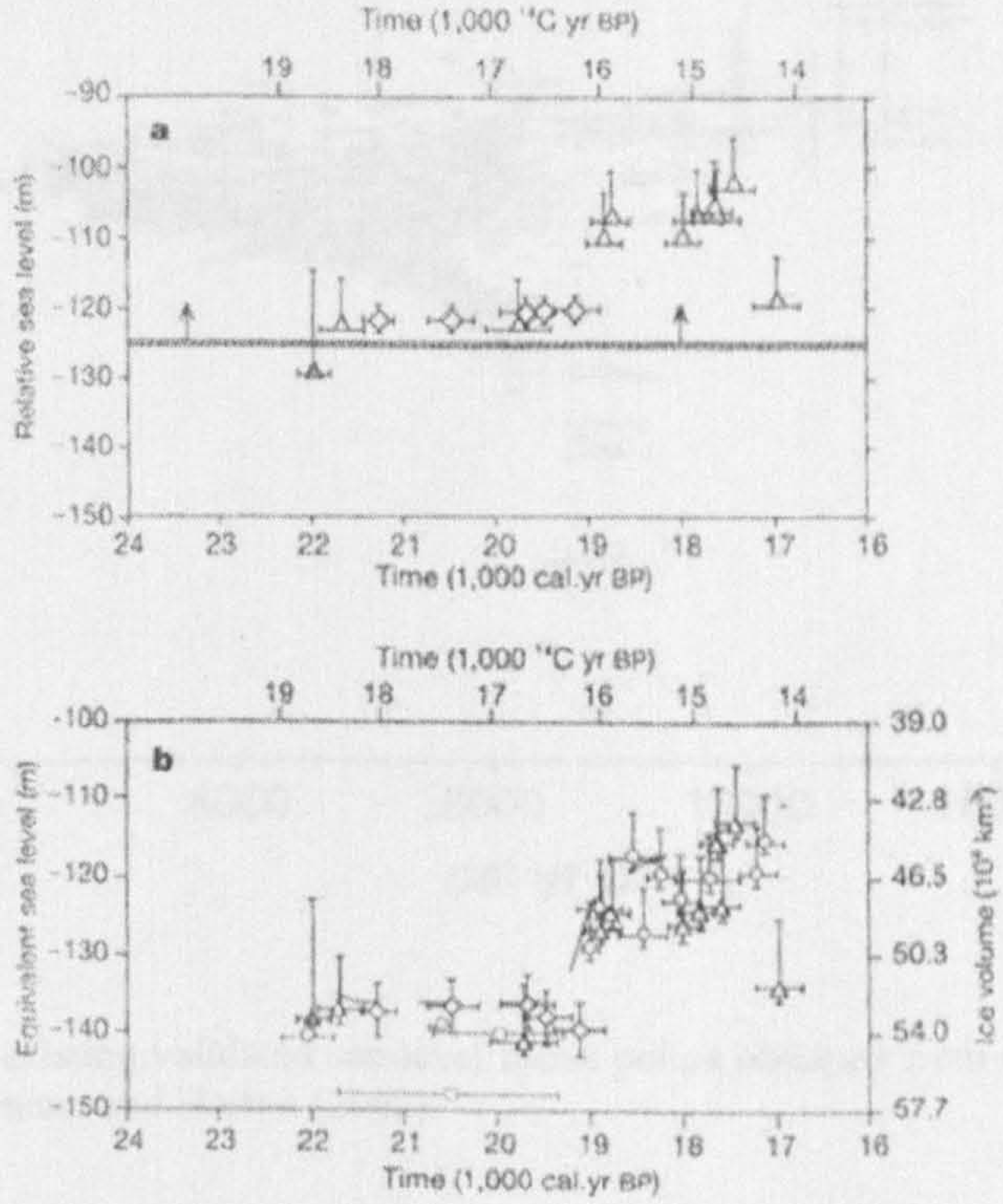


Figure 2.5 Sea level and ice volumes during the LGM. a) Observed sea level for the Bonaparte Gulf. b) Equivalent sea-level and ice-volume estimates. From Yokoyama et al. (2000)

Shennan and Horton (2002) published results from an analysis conducted on the complete data bank of Holocene sea-level index points obtained from Great Britain, the work was undertaken in order to provide an estimate relating to contemporary patterns of crustal movement. The plot (fig. 2.6) illustrates the range of ages and altitudes of all the available data and demonstrates the limited number of index points that have been obtained from depths greater than -20m OD and dated to the early Holocene.

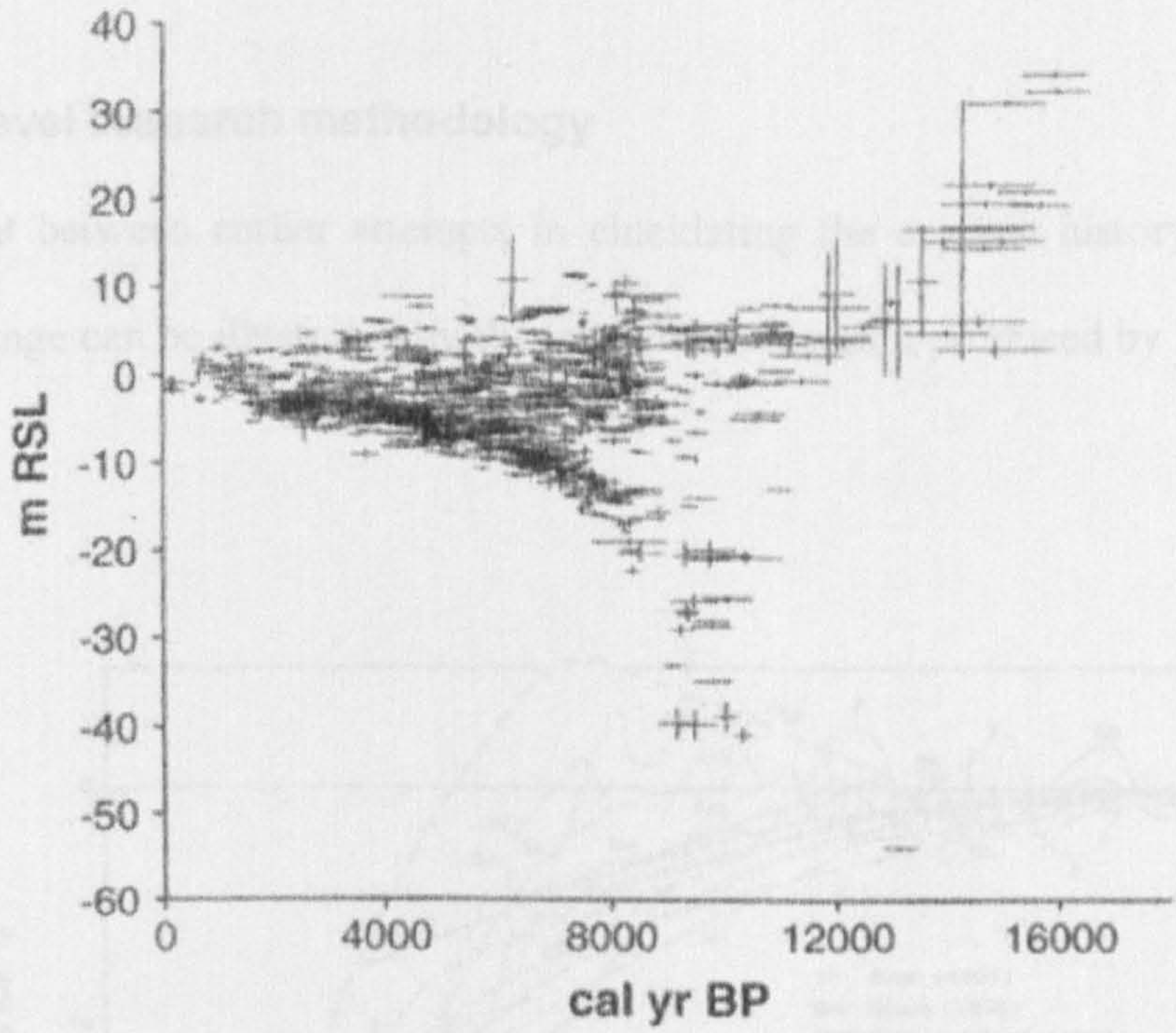


Figure 2.6 Plot of all existing validated sea-level index points obtained from Great Britainfor the past 16000 years. From Shennan and Horton (2002)

Based on the existing and available data, the published research additionally contains a series of fifty two relative sea-level curves for locations throughout Great Britain extending over the last 15000 calendar years. The general trend of each curve varies greatly depending on which region the data relates to, however, the type of curve produced can be placed in one of two general categories. Sea-level curves relating to the regions of Scotland tend to indicate falling relative sea levels during the Late Pleistocene, usually followed by rising relative sea levels during the early Holocene. Areas south of the Solway Firth, including England and Wales tend to indicate rapidly rising relative sea levels occurring during the Late Pleistocene and early to middle Holocene, with the areas experiencing little change in relative sea levels after approximately 5000 calendar years BP.

2.1.2 Sea-level research methodology

Disagreement between earlier attempts in elucidating the eustatic history of Holocene sea-level change can be illustrated by the time-depth diagram produced by Kidson (1986) (fig.2.7).

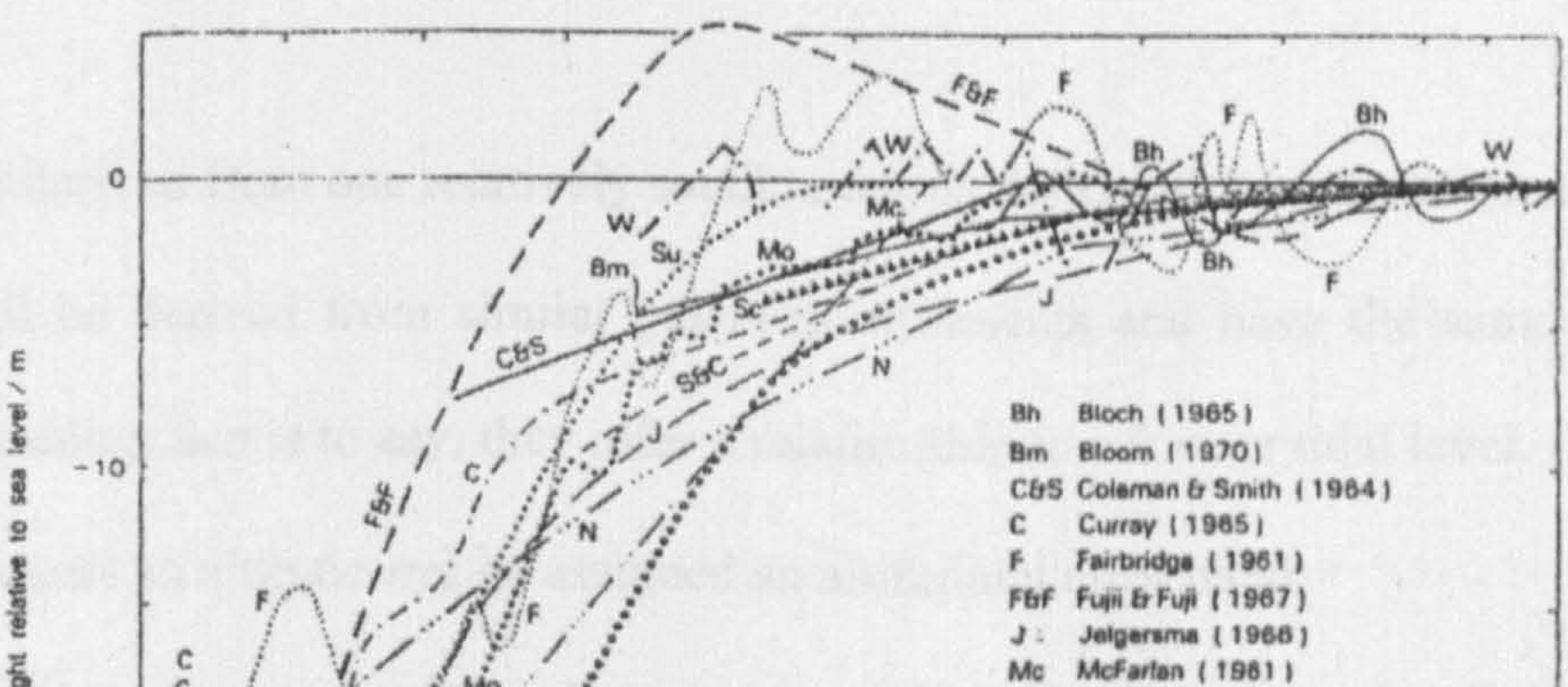


Figure 2.7 Various interpretations relating to sea-level history during the Holocene. From Kidson (1986).

Tooley (1987) suggests that the contrasting interpretations can partially be explained by researcher's failure to adopt a specific methodology and the inadequate quantification of altitudinal errors. As sea-level studies have progressed, so too has the formulation of a rigorously applied methodology, resulting in particular methodologies being applied to different environments. This is especially true in the case of investigations relating to more recent unconsolidated sediments located within parts of Northwest Europe such as the United Kingdom and the Netherlands.

Tooley (1992) suggests a number of criteria be utilized in order to select suitable data points that can ultimately generate age-altitude graphs describing former relative sea levels. These data points, termed sea-level index points, must ideally fulfil the following criteria:

- Be derived from one relatively small and well defined homogenous area.
- All be derived from similar palaeoenvironments and have the same indicative meaning; that is to say, they infer a relationship to a former tidal level.
- Possess an altitude and be assigned an altitudinal error band.
- Possess an age, expressed to two standard deviations, with all dates being corroborated independently through the use of regional pollen diagrams where possible.

The analysis of a sequence of intercalated organic-rich and inorganic sediments may indicate that fluctuations have occurred with respect to the level of the water table at a particular location over a specific period of time, however it is difficult to directly attribute these fluctuations to local or more regional changes in sea level. In an attempt to evaluate locally derived sea-level data in a more objective manner, researchers therefore often examine the available evidence in order to distinguish periods of dominant sea-level tendency. This method of identifying phases of increasing or decreasing marine influence has frequently been utilized during the last 20 years, following its introduction during the mid to late 1970s and has been applied to studies of sea-level change within the UK by researchers such as Tooley and Shennan based at Durham University.

Shennan (1986) highlights the significance of both local and regional positive and negative tendency and additionally demonstrates how regional tendencies of sea-level movement can often be correlated. Although sea-level change within a particular area will in part undoubtedly be attributable to local factors, there remains a need separate these processes or events from more regional effects in order to identify the causal factors that explain synchronous changes found to occur in different geographical regions. Sea-level tendency is usually indicated on a plot of sea-level index points by the use of arrows which specify the inferred direction of marine influence.

The accuracy and precision by which former sea levels can be determined relies heavily upon the ability to adequately quantify errors associated with the indicative meaning of a sea-level index point, its elevation and age; this is particularly important when considering the materials selected for dating and their stratigraphic context.

An example of the former can be illustrated by the fact that material taken from the base of a peat horizon overlying inorganic sediment does not necessarily represent a formation laid down as a consequence of a fall in relative sea level. The formation and migration of tidal spits and sand bars within an estuarine environment can result in the development of saltmarsh conditions within an area previously subjected to inter-tidal conditions throughout a period of relative rise in sea level (Walley, 1996). It has additionally been established that indicative meanings cannot easily be inferred from sequences contained within a saltmarsh, for example pollen derived from species found within the upper marsh are often indistinguishable from those derived by species occupying the middle and lower marsh.

More recently, research has indicated that stratigraphic boundaries denoting the transition between the upper marsh and adjacent reedswamp or fen communities forming close to MHWST can be more accurately established through the application of transfer functions. Research by Scott & Medioli (1978), demonstrated the existence of strong environmental gradients at the marine-terrestrial interface with respect to the distribution of foraminifera. The analysis of specific fossilized microfauna such as foraminifera (e.g. Scott & Medioli, 1978; Gehrels, 1999; Horton *et al.*, 1999; Gehrels and Newman, 2004; Edwards & Horton, 2006), diatoms (e.g. Zong and Horton, 1999) or testate amoebae (Charman *et al.*, 1998) contained within a sedimentary unit has subsequently provided an important and invaluable method with which to more accurately determine the relationship of a deposit to a former position of MHWST.

In simple terms the method utilizes a mathematical approach by statistically examining the distribution of species of organisms within specific contemporary sub-environments within the inter-tidal zone, which in turn can be assigned a range of elevations relative to a tidal framework. The relative abundance of foraminifera within a sediment sample can then be compared with the contemporary data set in order to determine its relationship to a palaeotidal level. The transfer function approach has allowed researchers to expand the range of sediments that can be utilized in order to provide sea-level data as well as reducing the degree of altitudinal error associated with individual index points.

Gehrels *et al.*, 2001 investigated the vertical distribution of foraminifera, diatoms and testate amoebae in order to assess the usefulness of adopting a multiproxy approach in relation to reconstructing former sea levels. The research indicated that although this process can be relatively time consuming, it could improve both the accuracy and precision of Holocene sea-level index points.

The degree of compaction and consolidation experienced by materials within a sedimentary sequence can, according to Heyworth and Kidson (1982), significantly influence the altitude of a sea-level index point. Compaction is the process of increasing the density of a material through the movement of the materials constituent particles, in terms of modifying the nature of their packing arrangement. This usually means that the volume of air contained within sediment is reduced; compaction does not, however, necessarily imply that a significant volume of water is lost from within the sediment body. Consolidation however, refers to a one dimensional change experienced by a body due to the application of a stress or pressure; consolidation can be attributed to the application of a stress which results in a concomitant dissipation of water from within the body.

Woody and *Sphagnum* peat deposits are particularly susceptible to consolidation and, with sufficient overburden, can be compacted by up to 50% and 90% respectively. It has been established that the degree of consolidation experienced by peat deposits is significantly greater than that of clay and sand; however, in a typical estuarine sequence, well developed sequences of estuarine clay are often interbedded with relatively thin peat deposits, resulting in the degree of consolidation often being approximately equal. It is therefore often preferable to utilize basal peat deposits which overly an incompressible substrate and whose degree of compaction can be quantified relatively accurately in order to produce sea-level index points. In some cases however, material formerly constituting the overburden may have been removed, subsequently rendering the degree of compaction difficult to quantify.

Reconstructing aspects of localized relative sea-level change can often require an accuracy of centimetres as opposed to metres and it is therefore essential that all index points be referred to a precise datum to which sea level can be related. Researchers often refer all heights to a national Geodetic Datum without determining a local sea level; as there can often be disparity between the two, a small but sometimes significant degree of error can be introduced at the outset of a sea-level study.

Most sea-level index points indicate the altitude of MHWST, however, the relationship of this altitude to MSL very much depends on the local tidal range; Heyworth and Kidson (1982) acknowledge this problem and highlight the fact that adequate corrections are rarely applied. During periods of significant sea-level change, the actual meaning of sea level within a particular area may also alter as tidal ranges adjust to modifications in coastal geometry (Austin, 1991). The changes in tidal range at a specific location may well be significantly disproportionate to changes that have occurred at a site within the immediate locality, thereby introducing significant errors during correlation between sea-level index points.

Early sea-level curves generally fail to incorporate aspects of change with respect to tidal range that have undoubtedly occurred during the Holocene transgression, as coastal configurations altered and water depths were modified. Heyworth and Kidson (1982) state that this failure may have been justified at the time as no adequate technique for quantifying such changes had been available. Heyworth and Kidson (1982) further state that for many coastal regions, the consequences of such changes upon existing sea-level index points are likely to have been minor, especially over the last 6000 years; however, recent research conducted within the University of Wales, Bangor, School of Ocean Sciences and utilizing a two-dimensional version of the Princeton Ocean model (Uehara *et al.*, in press.), suggests that contemporary tidal ranges in North Wales may differ significantly from those experienced within the region during the early Holocene.

Although the limitations of radiocarbon dating are described within chapter three of this thesis, the degree of precision attributed to radiocarbon dates within some earlier sea-level studies cannot reasonably be justified. As a result, more recent investigations have adopted two standard deviations as the error term used in the generation of age-altitude graphs.

2.1.3 Geophysical modelling

During the 1970s scientists began to realise that a complex relationship existed between sea-level change and the nature of crustal movement. It become apparent that the nature of sea-level change for a particular region may have been significantly influenced by the degree of ice loading/unloading that the localized crust may have experienced. This realisation has led to the development of a relationship between geologists and geophysicists in an attempt to understand processes operating at and beneath the Earth's crust. Mathematical modelling techniques have subsequently been utilized by geophysicists in an attempt to determine values relating to various viscoelastic properties of the Earth's mantle, which ultimately control mantle circulation and hence crustal plate movement. These geophysical models have utilized and relied on empirically derived sea-level data in order to both constrain and test the results that they produce through the input of two variables, which relate to the degree of ice loading and aspects of rheology which include mantle viscosity. The models can conversely be used to predict patterns of relative sea-level change for periods of historical or future time not represented through the presence of empirical data.

Although the geodynamic models often compare well in relation to overall trends on global and regional scales, a significant degree of disparity often arises when comparisons between them are made on a local scale.

2.1.3.1 Lambeck

Lambeck (1991) modelled positions and water depth around the coast of the British Isles from 16000 years BP, under conditions of eustatic sea-level rise combined with glacio-isostatic movement. The model incorporated assumptions relating to crustal and mantle properties and behaviour, combining both the near-field effect of British and Scandinavian Ice-sheets, together with the far-field effects of more distal ice masses such as the Laurentide Ice-sheet over North America; a value for the altitude of eustatic sea level is derived by assessing volumes of meltwater with respect to the surface area of the ocean regions. The ice model assumed that the British and Scandinavian ice masses were confluent and that maximum development of the British Ice-sheet, with a maximum thickness of around 1500m, occurred somewhere over the central regions of Scotland around 23000 years BP.

The degree of agreement between this model and observed data suggested no need to invoke any vertical crustal movements for Great Britain and Ireland other than those associated with glacio-hydro-isostatic processes. The model was additionally used in order to produce constraints on parameters including mantle viscosity and lithospheric thickness, together with the extent and volume of ice constituting the British and Scandinavian ice sheets. The work resulted in the production of a series of sea-level curves for various locations around the British Isles including areas within North Wales. The predicted sea-level curves produced for North and Mid Wales (fig. 2.8) demonstrate a significant degree of spatial variation, suggesting that patterns of sea level have varied between Holyhead and Aberystwyth. The model additionally predicts that sea level may have exceeded its contemporary altitude along the North Wales coastline by up to around 20m approximately 16000 years BP, before falling rapidly over a relatively short period of time to approximately -35m OD by around 12000 years BP.

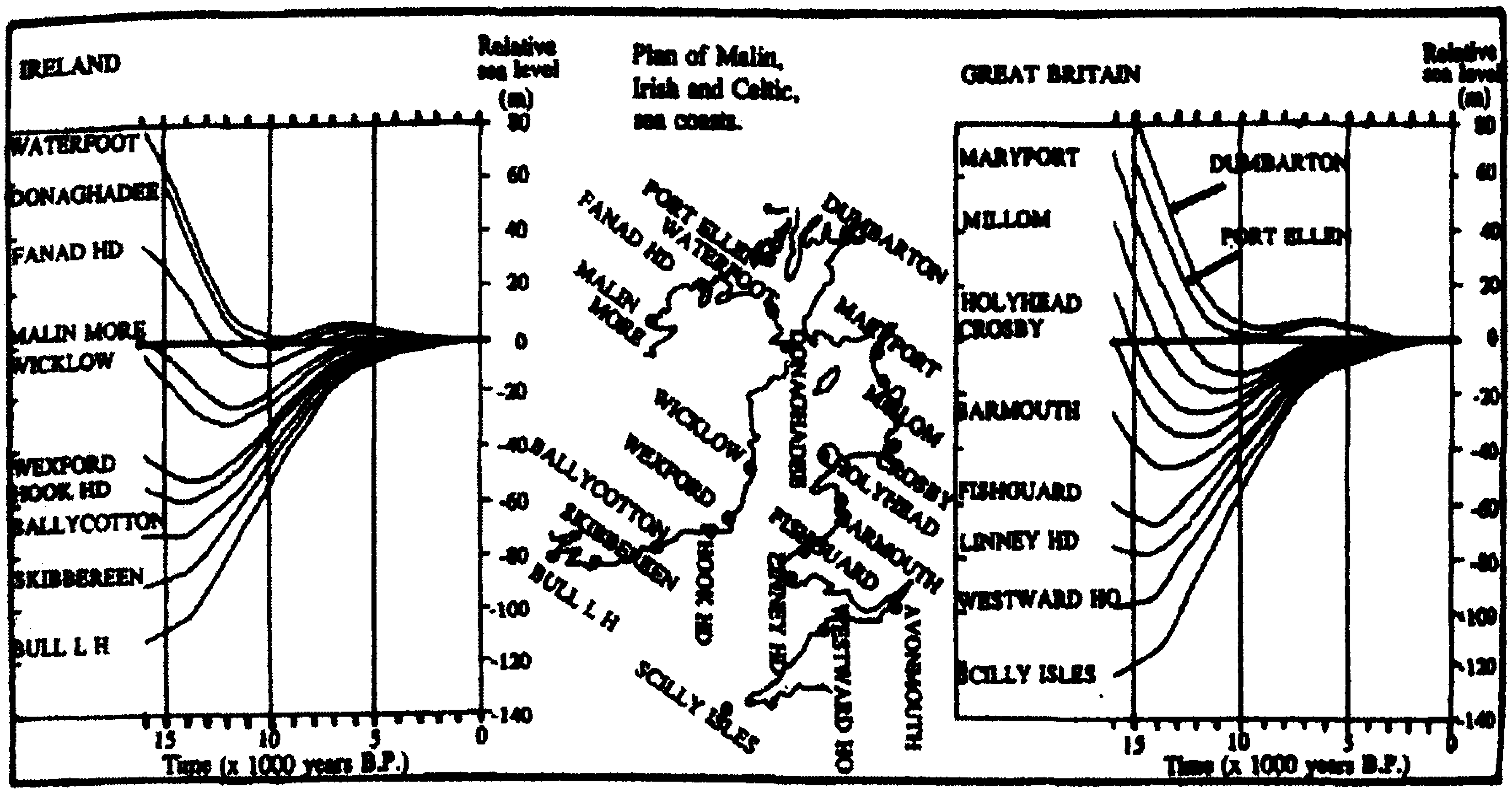


Figure 2.8 Sea-level curves from 16000 BP (after Lambeck, 1991): modelled curves of sea level relative to present day mean sea level for selected points within the Malin, Irish and Celtic seas. From Wingfield (1995)

The model suggests that relative sea levels in North and Mid Wales subsequently rose rapidly over a period of 6000 years, attaining an altitude of around -5m OD by 6000 years BP, before rising at a significantly reduced rate, attaining contemporary levels comparatively recently. Figure 2.9A-B illustrates approximations made with respect to the position of relative sea level from the published work comparing the predicted relative sea levels for North Wales, together with regions located to the north and south using this and later models (Lambeck, 1995; Lambeck, 1996).

Lambeck (1995) produced results derived from the application of a more sophisticated model than the earlier version. The model resulted in the generation of a series of maps depicting the predicted approximate position of shorelines and ice margins for selected epochs between 22000 and 6000 years BP (fig. 2.10 a-g). The data was derived by utilizing a multi-centred ice model developed from pre-existing published data relating to aspects of ice retreat over Britain and Ireland which additionally considers maximum ice extent to have occurred at around 22000 years BP. The ice-sheet over Britain is again considered to have remained separate from that of Fennoscandinavia with a maximum ice thickness of 1500m occurring over central Scotland and 500m over Ireland. Ice retreat is considered to been complete by 12500 years BP followed by a re-accumulation of up to 400m during the Loch Lomond Stadial between 11000 and 10500 years BP. The model additionally attempts to take into account glacio-isostatic effects produced by distal ice masses, together with considering the input from eustatic and hydro-isostatic variables. The model further utilizes seismic data in order to consider the mantle as consisting of a number of radially symmetrical viscous layers with each one possessing differing elastic and viscoelastic properties.

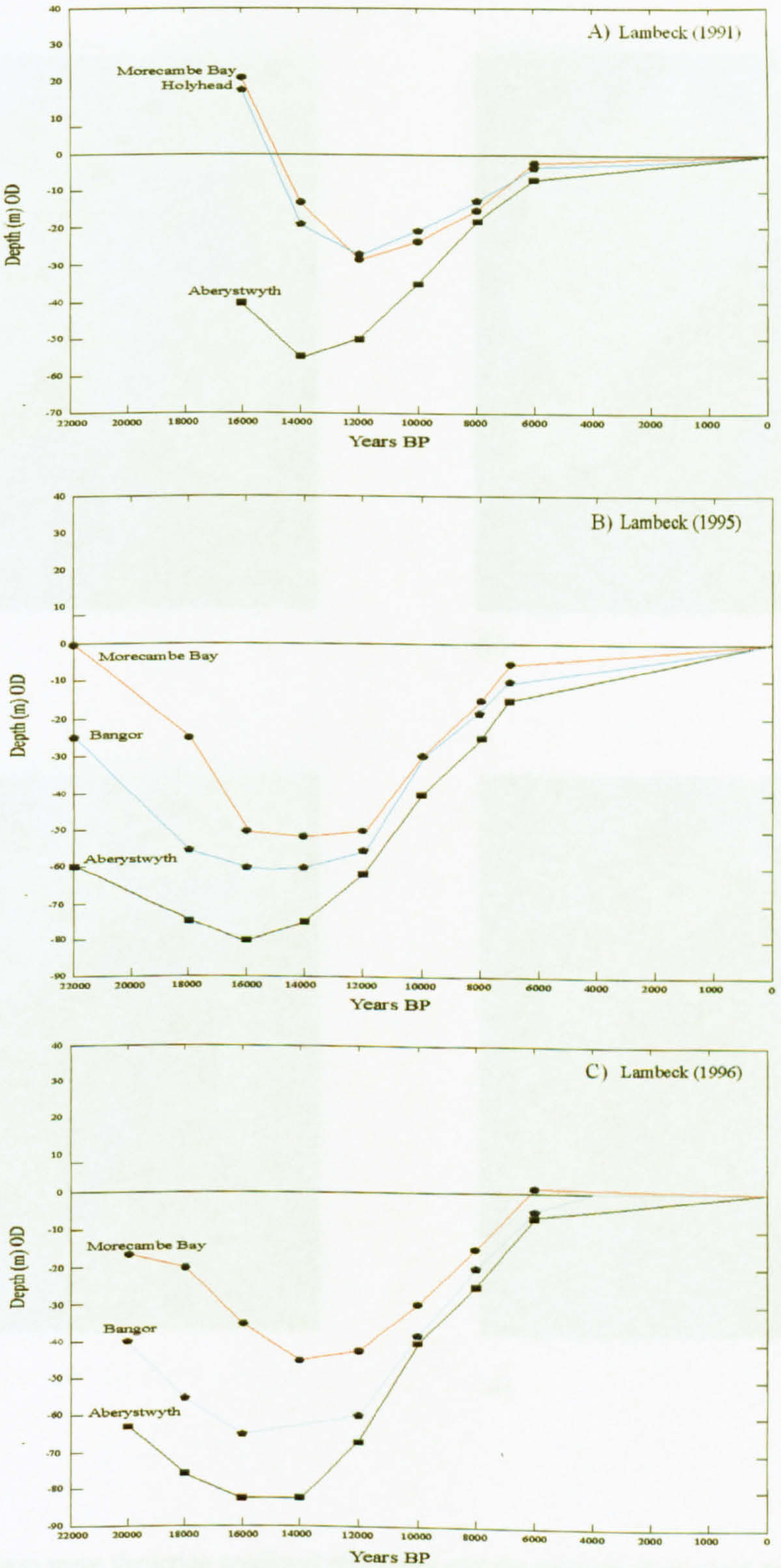


Figure 2.9 Predicted sea-level curves for selected regions of the UK derived from different generations of glacio-hydro-isostatic models. Taken from Lambeck (1991), (1995) and (1996).

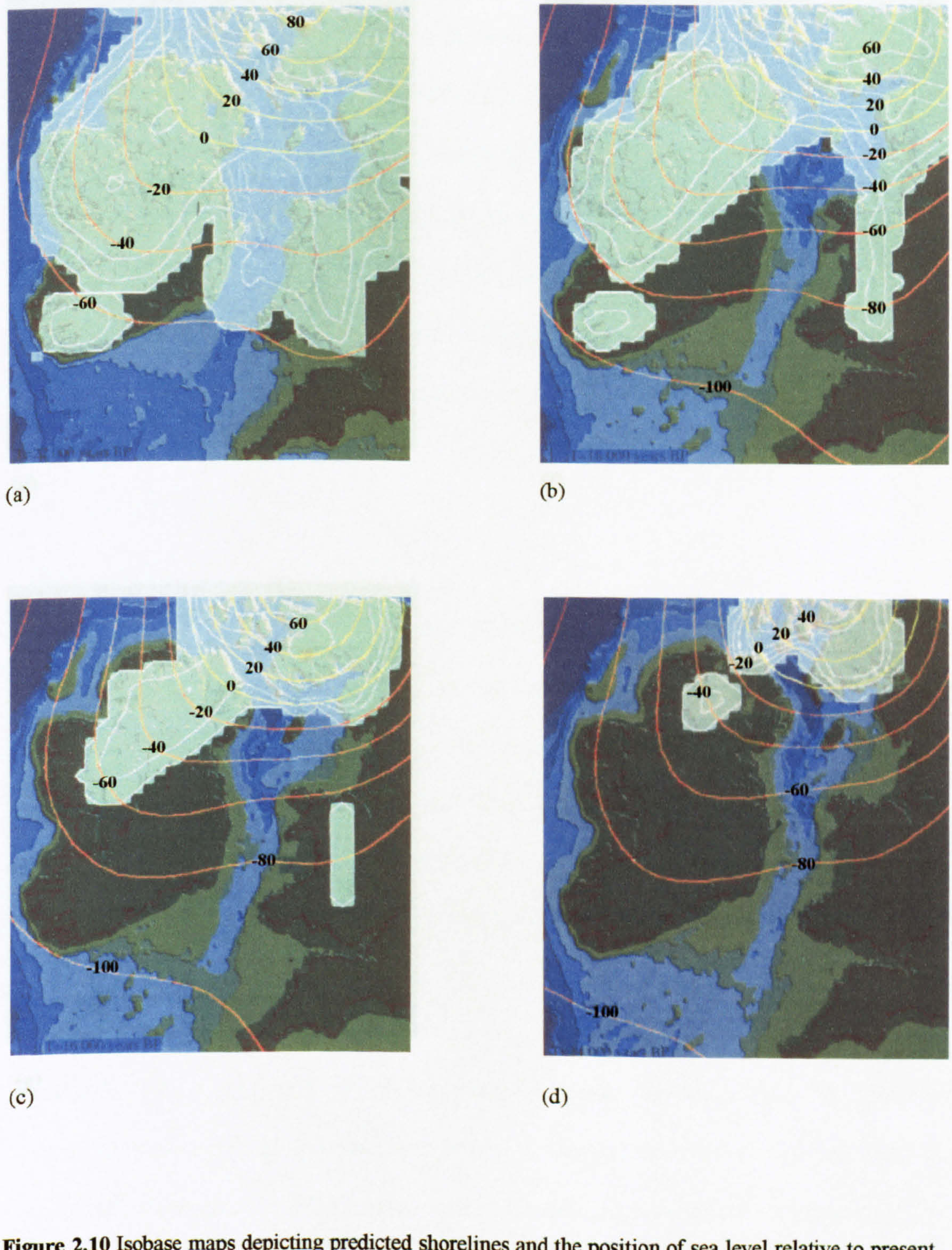
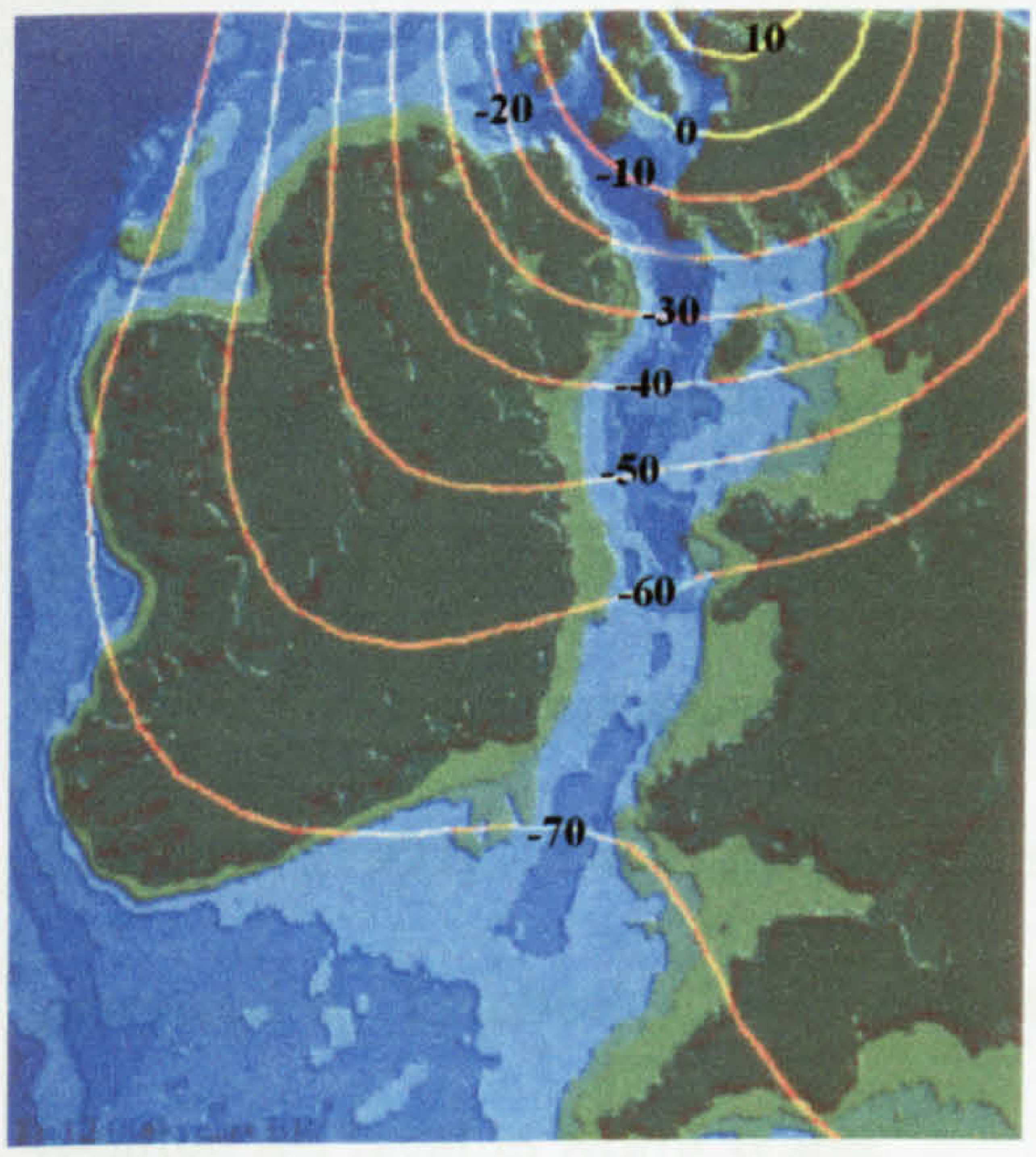
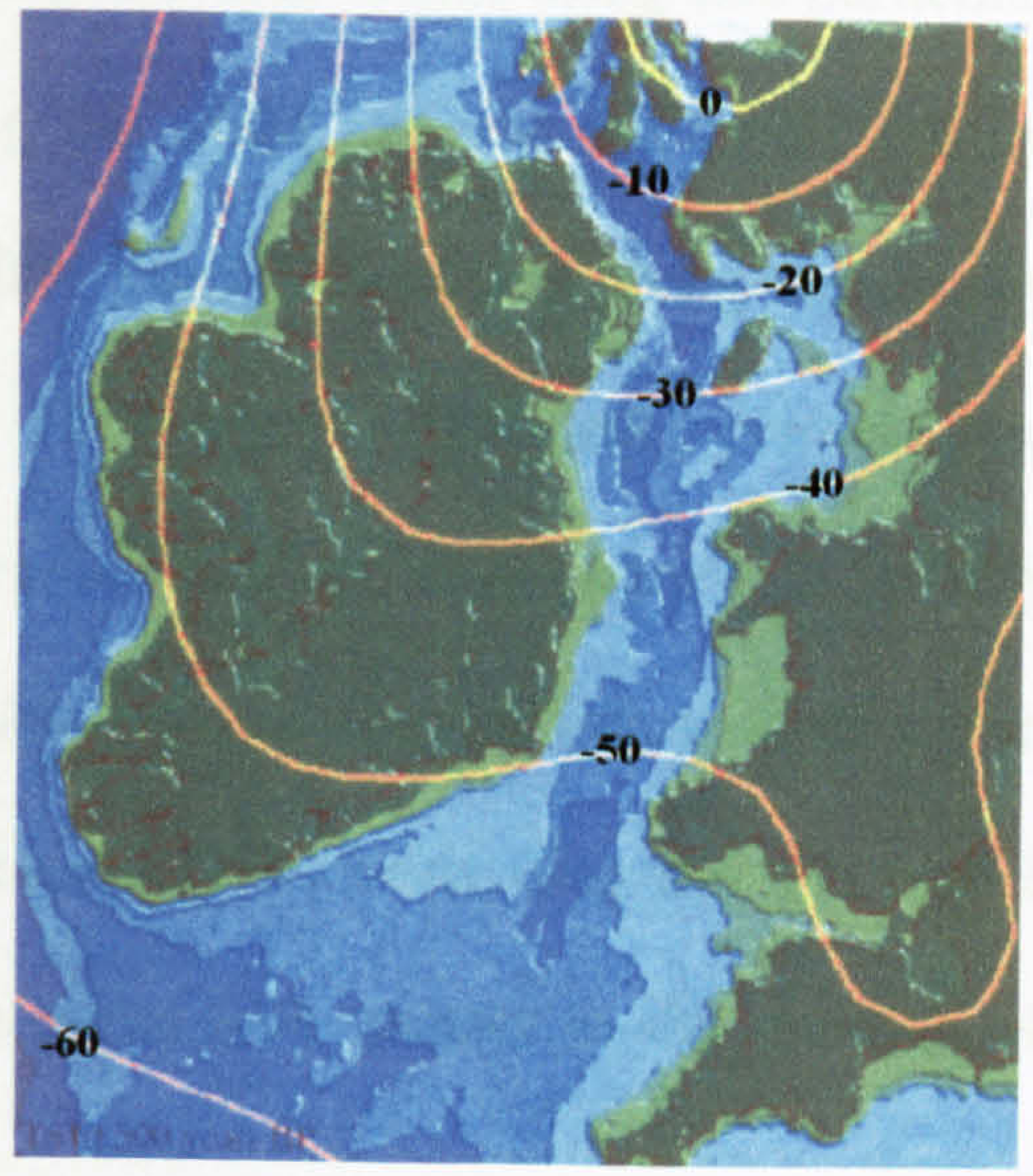


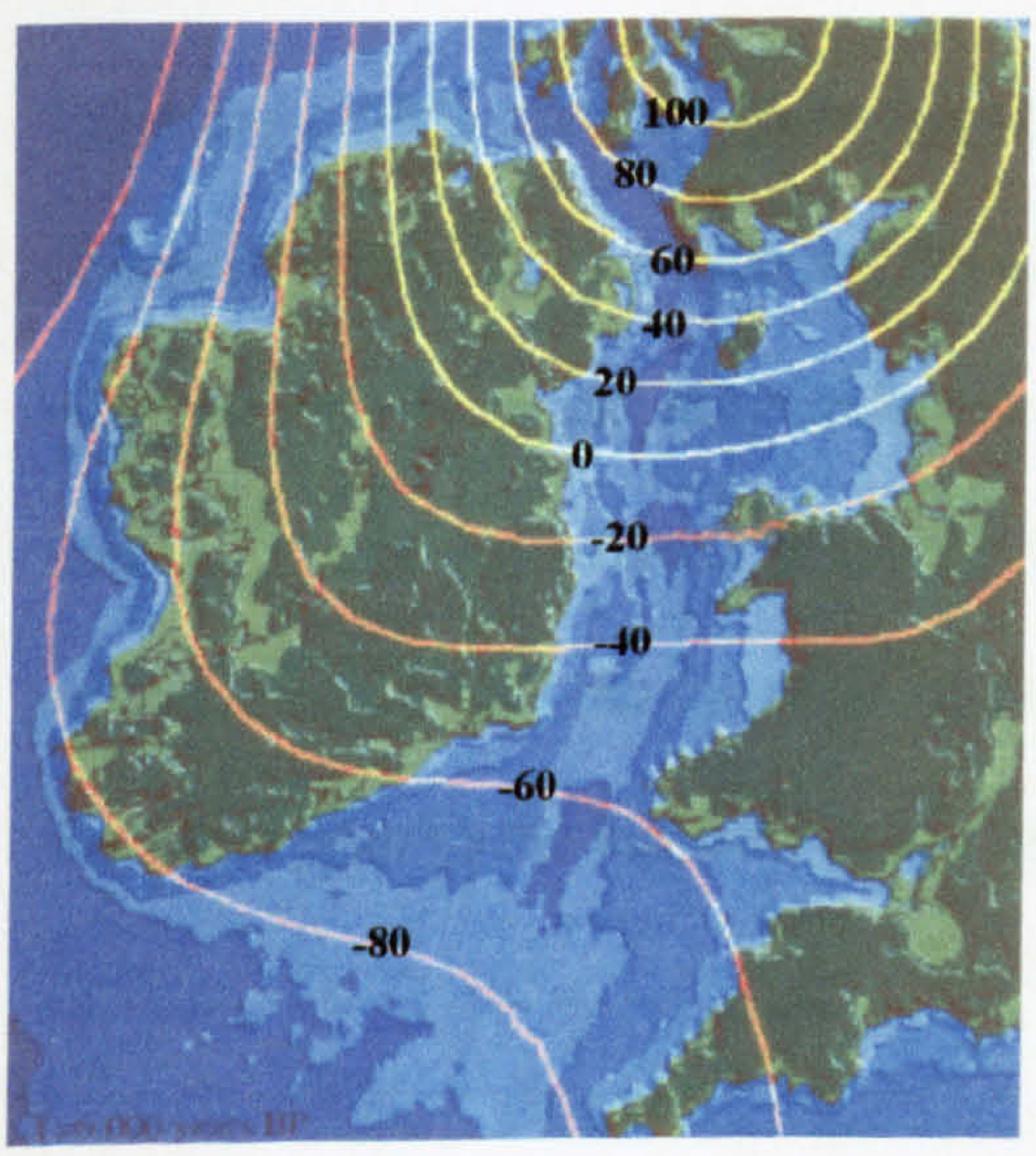
Figure 2.10 Isobase maps depicting predicted shorelines and the position of sea level relative to present levels for selected radiocarbon dates based on Lambeck (1996). (a) 22,000 BP, (b) 18,000 BP, (c) 16,000, BP, (d) 14,000 BP, overleaf (e) 12,000, BP, (f) 10,500 BP, (g) 6,000 BP.


10
-20
0
-10
-30
-40
-50
-60
-70

(e)


0
-10
-20
-30
-40
-50
-60

(f)


100
80
60
40
20
0
-20
-40
-60
-80

(g)

Figure 2.9B, illustrates predicted sea levels relative to North Wales using this particular model with the results suggesting that following the LGM, relative sea levels fell by approximately 35m to around -60m OD by 14000 years BP, before rising rapidly by about 40m between 12000 and 6000 years BP. The model additionally predicts that between the LGM and the onset of the Holocene, relative sea levels were significantly lower for all locations situated between Morecambe Bay and Aberystwyth than shown in Lambeck (1991). During the early to middle Holocene however, this and the model produced by Lambeck (1991) predict similar altitudes with respect to the position of relative sea level in North Wales.

Lambeck (1995) acknowledges that some discrepancies occur between the predicted and observed values for relative sea level over northern areas of Scotland and Ireland and suggests that the model may underestimate Lateglacial ice volumes. The model indicates that Liverpool Bay became gradually inundated between 10000 and 7000 years BP with areas situated along the coastline of North Wales experiencing marine conditions for the first time prior to the last interglacial at sometime between 8000 and 7000 years BP.

Lambeck (1996) produced results specifically related to the degree of glaciation experienced over Ireland, together with sea-level changes within the Irish Sea following the LGM. Comparison of the results with observational data appear to support the idea that maximum ice thickness may have been of the order of 600m over Ireland, with Lateglacial and Holocene sea levels not having significantly exceeding their

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Additional unpublished data derived from later versions of these geophysical models in the form of a personnel communication supplied to the School of Ocean Sciences and as data utilized in Uehara *et al.* (in press) demonstrate how the output relating to the position of relative sea level can vary as these models continue to be modified and evolve as new data becomes available and different modelling techniques are applied. The data utilized in Uehara *et al.* (in press) was obtained using a revised version of the model utilized in Lambeck (1995), using improved ice sheet models for Scandinavia and North America, together with reassessments of global ice volumes and higher resolution rheological formulation. Table 2.1 provides approximated values for the modelled output of relative sea level for North Wales as derived from all available Lambeck data.

More recently, Lambeck *et al.* (2001) utilized sea-level data from a range of locations in order to estimate global changes in ocean and ice volume during and following the Last Glacial Maximum (LGM). The research concluded that ice volumes approached their maximum values 30000 years BP and remained relatively constant until 19000 years BP. The research demonstrates that maximum rises in global sea level of approximately 15mm/year occurred between 16000 and 12500 years BP and between 11500 and 9000 years BP.

Time (years BP)	Lambeck 1991 RSL (m) OD	Lambeck 1995 RSL (m) OD	Lambeck 1996 RSL (m) OD	Lambeck 1999 (pers. com.) RSL (m) OD	Lambeck Uhehara (in press) RSL (m) OD
22000		-25		-36	
20000		-40	-40	-50	
18000		-55	-57	-51	
16000	-10	-60	-62	-53	
14000	-32	-58	-61	-47	
12000	-36	-55	-60	-32	-48
10000	-28	-30	-40	-23	-35
8000	-15	-18	-25	-8	-15
6000	-5	-10	-8	-1.9	-1
4000	-2	-4	-3	-0.9	-0.5
2000	-0.5	-0.5	-0.5	-0.4	0
0	0	0	0	0	0

Table 2.1 Modelled output of relative sea level for North Wales as derived from all available Lambeck data.

2.1.3.2 Peltier

Peltier (1994) utilized relative sea-level data in order to facilitate the development of the ICE-4G (VM2) model which has been designed to determine quantitative estimates for both mantle viscosity and aspects of deglacial history. The model utilizes the Barbados sea-level record of Fairbanks (1989) in order to constrain melting history by providing global control on deglacial processes and to additionally calibrate the ^{14}C dates taken from pre-existing sea-level data. The model provides topographical and ice sheet heights at 1000 year intervals subsequent to the LGM relative to palaeo sea levels at a resolution relating to the inundation of the English Channel, together with the Irish and North Sea. The colour coded bar denotes the time in thousands of years BP that each coded area became inundated by marine conditions.

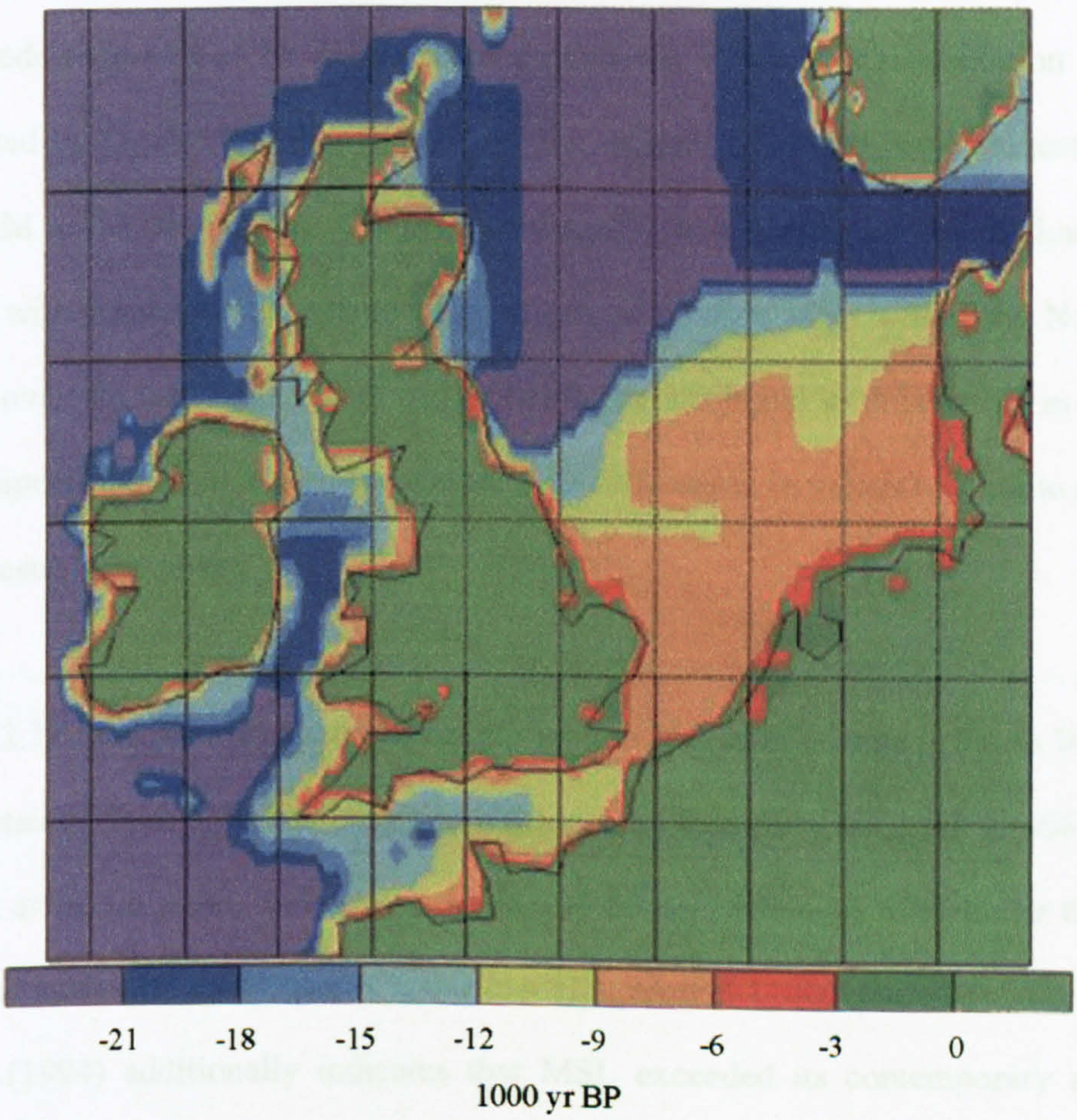


Figure 2.11 Predicted timing and positions of palaeoshorelines using ICE-4G (VM2) model. Taken from Peltier (1994).

Peltier (1994) argues that results presented by the model suggest that previously generated palaeoenvironmental reconstructions may have overestimated degrees of ice cover and therefore significantly overestimated the degree of eustatic sea-level rise that occurred subsequent to the LGM.

An updated version of the ice model, referred to as ICE-5G, together with a new earth model (VM4), has recently been developed and differs from its predecessor as it takes into account new information about the extent of glacial maximum ice sheets in Eurasia.

The models developed by Peltier have a relatively lower spatial resolution than those generated by Lambeck, although both predict degrees of crustal displacement following the LGM to the present day. Degrees of disparity between the models of Lambeck and Peltier with respect to the predicted positions of relative MSL within the North Wales region over the last 12000 years can primarily be attributed to differences in the spatial and temporal extent of ice cover together with differences in values relating to the Earth's viscoelastic parameters.

Figure 2.12 illustrates predicted values for relative sea-level change in North Wales using data obtained from both Lambeck and Peltier. The data from Lambeck is utilized within Uehara *et al.* (in press) and estimates MSL to be approximately 17m lower than that of data obtained from the Peltier ICE-4G model at around 11000 years BP. The data from Peltier (1994) additionally indicates that MSL exceeded its contemporary altitude by approximately 1-2m during the late Holocene.

For an additional comparison, modelled MSL change relating to the northeastern Menai Strait taken from Peltier's ICE-4G and ICE-5G models are presented in table 2.2 (Peltier, pers comm. 2006).

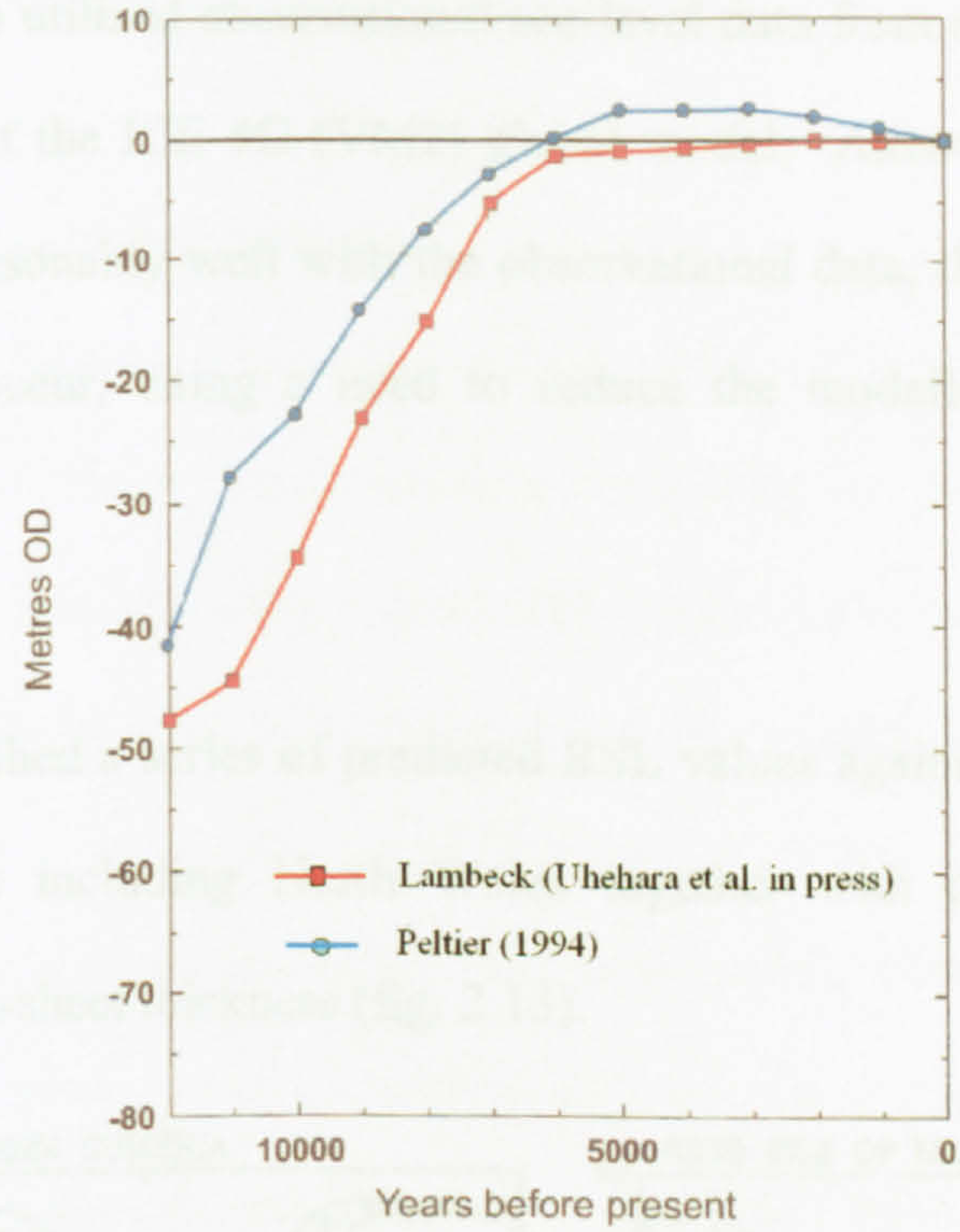


Figure 2.12 Comparison of MSL data obtained from both Lambeck (Uehara *et al.* in press) and Peltier (1994).

Calendar years BP	Peltier Model - 4G VM2 Menai Strait 53.250 355.900 MSL (m) OD	Peltier Model - 5G VM2 Menai Strait 53.250 355.900 MSL (m) OD
16000	-42.97	-61.78
15500	-45.21	-63.12
15000	-48.14	-64.61
14500	-49.82	-64.10
14000	-35.08	-50.07
13500	-33.75	-46.40
13000	-31.57	-42.32
12500	-30.13	-39.35
12000	-29.06	-36.22
11500	-28.27	-34.92
11000	-27.12	-24.26
10500	-24.77	-21.40
10000	-22.35	-18.33
9500	-19.01	-16.37
9000	-15.74	-14.29
8500	-11.48	-10.98
8000	-7.54	-7.80
7500	-5.13	-5.96
7000	-2.86	-4.33
6500	-1.91	-3.08
6000	-1.06	-1.99
5500	-0.33	-1.08
5000	0.31	-0.29
4500	0.85	0.35
4000	1.33	0.93
3500	1.20	0.85
3000	1.05	0.75
2500	0.89	0.63
2000	0.71	0.50
1500	0.53	0.38
1000	0.35	0.25
500	0.17	0.13
100	0.03	0.03
0	0.00	0.00

Table 2.2 Comparison of MSL data obtained from Peltier using ICE-4G and ICE-5G models. (Pers comm. Peltier, 2006).

Peltier *et al.* (2002) utilized observational sea-level data from around the UK in order to test the accuracy of the ICE-4G (VM2) global model. Although the modelled outputs appear to agree reasonably well with the observational data, the authors note that some discrepancies do occur, citing a need to reduce the modelled value for lithospheric thickness.

The research published a series of predicted RSL values against observational data for a range of locations including North Wales together with different permutations of lithospheric and ice-sheet thickness (fig. 2.13).

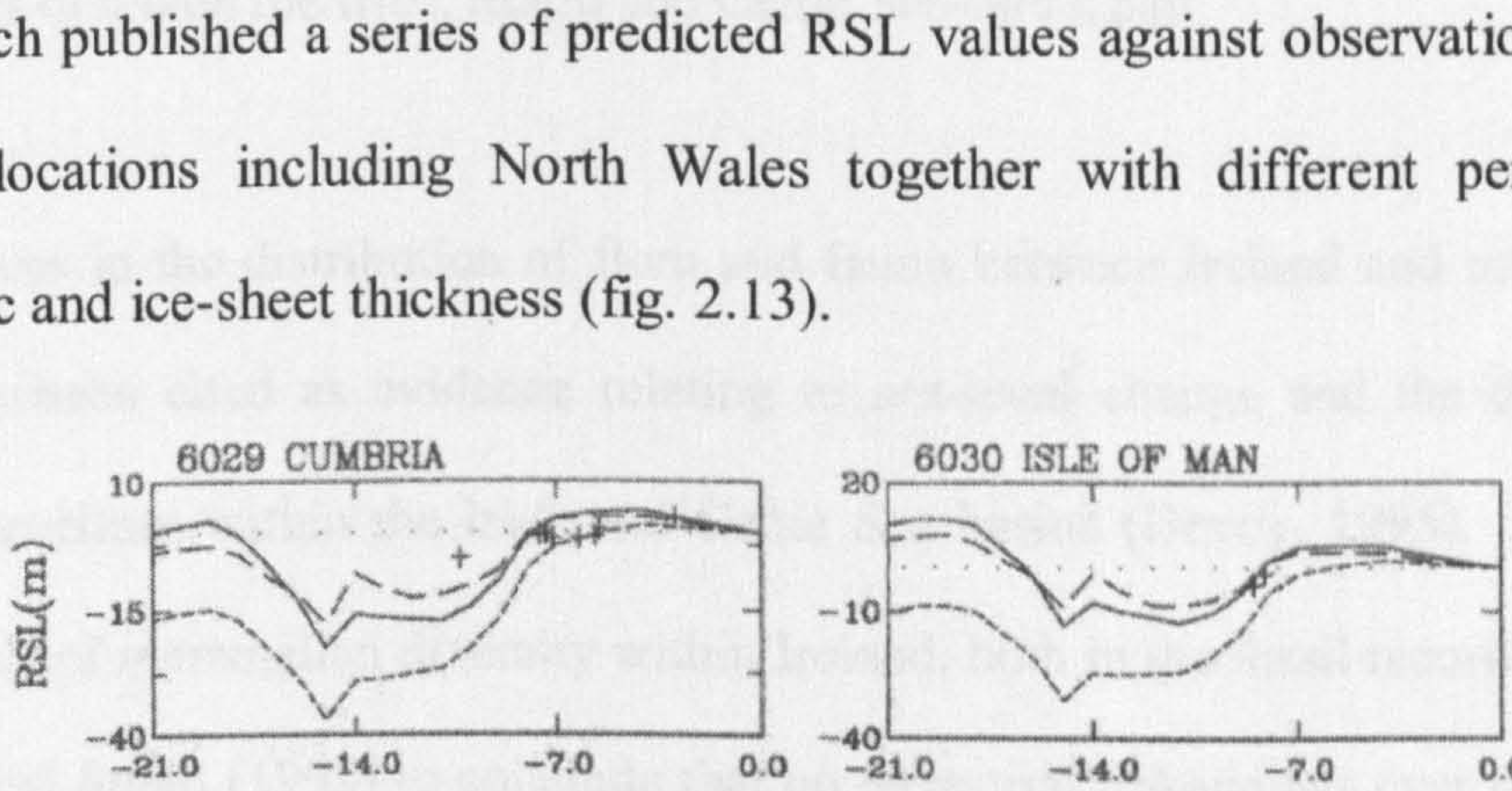


Figure 2.13 Predicted and observed values of RSL using the ICE-4G (VM2) model. Solid lines relate to predicted value with thin ice and thin lithosphere, long dashed lines relate to original ICE-4G model and short dashed lines for thin ice model with original VM2 (120.7km lithosphere). Taken from Peltier *et al.* 2002.

2.1.4 Sea-level research in North Wales

2.1.4.1 Evolution of the Irish Sea

On a more localized scale, the coastal evolution of North Wales can be directly related to aspects of sea-level change on all scales; consequently any investigation on a local scale must additionally consider studies conducted in relation to the evolution of the adjacent shelf seas of which the Irish, Malin and Celtic Seas are a part.

Differences in the distribution of flora and fauna between Ireland and mainland Britain has long been cited as evidence relating to sea-level change and the development of palaeoshorelines within the Irish and Celtic Sea basins (Devoy, 1995). Comparatively low levels of mammalian diversity within Ireland, both in the fossil record and during the present led Stuart (1995) to conclude that no terrestrial linkage has ever existed between Ireland and mainland Britain prior to at least the last major glacial period. Preece *et al.* (1986) suggest that it is difficult to explain the distribution of terrestrial gastropds and some species of rodent without invoking the presence of a Late Pleistocene land-bridge between Ireland and a part of the UK mainland.

Many differing models relating to the evolution of the Irish Sea have been proposed, both by geophysicists (Lambeck, 1991; Lambeck, 1995; Lambeck 1996; Peltier, 1994) and by marine geologists (Eyles and McCabe, 1989; Wingfield, 1995). Whilst some of these models have proved to be highly contentious and have provoked intense debate, much work relating to very specific questions remain unanswered. These models additionally tend to provide only a very general indication relating to the position of the shoreline at specific time intervals. The models additionally differ on a temporal scale but generally indicate that the Irish Sea basin became gradually inundated during a marine transgression between approximately 14000 and 7000 calendar years BP.

A prolonged discussion relating to the different models generated and the approaches utilized within this area of research will not be undertaken within this thesis, however with the exception of Eyles and McCabe (1991) the models generally indicate that the Irish Sea evolved as rising eustatic sea levels and crustal movements combined to allow marine conditions to initially develop within areas of the main channel, running approximately north to south halfway between the contemporary coastlines of Ireland and mainland UK immediately prior to the onset of the Holocene. The models indicate that during the early to middle Holocene continued inundation resulted in the submergence of large areas of Liverpool and Cardigan Bays.

The model produced by Lambeck (1996) indicates that a land-bridge may have existed between southeast Ireland and the southwest of the UK mainland prior to approximately 13000 calendar years BP (fig. 2.10d-e). The model additionally invokes the presence of a large glacial lake occupying much of the main channel region to the north of the land-bridge up to this time. After approximately 12000 calendar years BP and during the early to middle Holocene, the model indicates that continually rising sea levels ensured that sea-water entered the Irish Sea through both the Malin Sea to the north and the Celtic Sea to the south.

Wingfield (1995) additionally invokes the presence of a land-bridge in the southern Irish Sea, although this occurs much later at 10500 calendar years BP. The model additionally suggests the occurrence of another land-bridge further to the north, approximately between the present day position of Isle of Man and Dublin at around 9750 calendar years BP.

Although the models vary greatly on both a temporal and lateral scale with respect to the position of former coastlines, they do provide a good general framework relating to the development of the Irish Sea. It must also be acknowledged however, that these models are poorly constrained due to a deficiency in data obtained from the field especially from the region of North Wales.

2.1.4.2 Early investigations

Earlier studies conducted in relation to evaluating aspects of relative sea level throughout the Late Devensian and Holocene in North Wales were predominantly based on geomorphological, sedimentary and palynological evidence (Ramsay, 1876; Strahan, 1885; Edwards, 1904; Greenly, 1919; Bibby, 1940; Rowlands, 1955; Embleton, 1964; Whittow, 1965; Tooley, 1974; Tooley, 1978; Manley, 1981 Flemming, 1982; Heyworth and Kidson, 1982; Tooley, 1982; Kenna, 1986; Prince, 1988; Shennan, 1989; Bedlington, 1994; Shennan and Horton 2002).

Studies conducted as early as the late eighteenth century and up to the middle of the twentieth century, have consistently identified and referred to boreholes or exposed intercalated sediments containing beds of peat, situated at various locations along the North Wales coast, predominantly within the coastal lowlands between the estuaries of the Conwy and Dee. The research additionally demonstrated that many of these coastal exposures are of Holocene age and consist of deposits of organic material incorporated within layers of finer grained marine sediment. Earlier interpretations relating to relative sea-level change were however, predominantly qualitative rather than quantitative and were limited by an inability to ascribe absolute dates to the sedimentary sequences. Although earlier work established that relative sea levels had probably risen dramatically at some time during the early to middle Holocene, the timing and extent of such a rise remained unclear.

Tooley (1974) utilized data from a range of locations in order to produce an oscillating relative sea-level curve for North West England (fig. 2.14), which described how sea level rose rapidly by over 20m during the early to middle Holocene, before subsequently rising at a more gradual rate in order to attain contemporary elevations during the late Holocene. The curve additionally describes a series of shorter (transgressive) episodes (Lytham I-X) superimposed upon the general trend, which represent a transition from freshwater to marine sedimentary processes or vice-versa. Tooley (1974) utilizing unpublished data, also demonstrated that a degree of correlation existed between transgressive and regressive episodes identified in northwest England and similar episodes identified along the North Wales coast. Tooley (1974) further suggests that sea levels within the northwest England may have exceeded contemporary levels by a few metres on several occasions during the late Holocene.

Tooley (1982) produced a relative sea-level curve for southwest Lancashire, which includes data from part of Liverpool Bay, together with a curve relating to relative sea-level change in Morecambe Bay. The work identifies twelve periods of transgressive and regressive overlap which superseded those identified earlier in Tooley (1974, 1978). Tooley (1982) additionally draws attention to the fact that no single site displays all twelve transgressive/regressive overlaps.

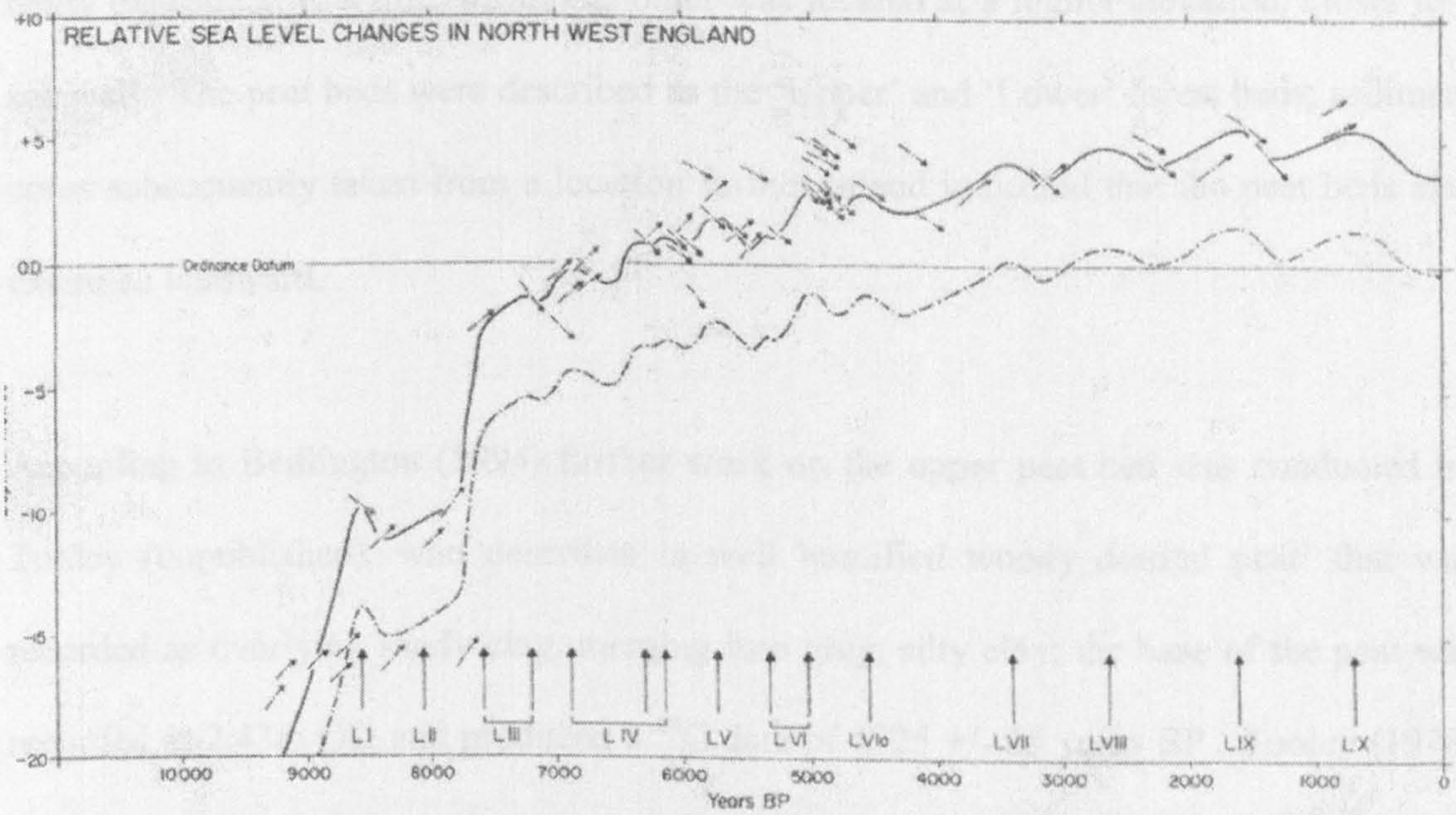


Figure 2.14 Relative sea-level curve for north west England from 9200 ^{14}C years BP. NB. Note timescale. Taken from Tooley (1974).

Manley (1981) indicates the position of up to 50 boreholes taken proximal to the coastline within the Vale of Clwyd from various sources. The nature of coastal evolution within the area is discussed with respect to the work of Tooley (1978) with particular emphasis on the degree of similarity between the altitude of transgressive and regressive contacts identified in both Lancashire and North Wales. The paper postulates that two major marine transgressive phases occurred at the onset of the Mesolithic, resulting in the coastline extending inland up to 4km south of its contemporary position.

One particular sedimentary sequence located at Rhyl has been subjected to a number of detailed investigations over the last century. Two peat beds located towards the eastern end of Rhyl Beach were investigated by Bibby during the 1940's; one was described as being exposed at low tide, whilst the other was located at a higher elevation, closer to a sea wall. The peat beds were described as the 'Upper' and 'Lower' forest beds; sediment cores subsequently taken from a location further inland indicated that the peat beds also extended landward.

According to Bedlington (1994) further work on the upper peat bed was conducted by Tooley (unpublished), who describes 'a well humified woody detrital peat' that was recorded as overlying sandy clay, merging into grey, silty clay; the base of the peat was recorded at 2.43m OD and produced a ^{14}C date of 4725 +/- 65 years BP. Tooley (1978) describes the underlying substrate as 'saltmarsh clay containing sandy and ferruginous partings'. The location of the dated horizon is given as Ordnance Survey grid reference: SJ 0310, 8261. Palynological analysis of sediments immediately adjacent to the lithological horizon indicate a rapid transition from open habitat taxa dominated by Gramineae, *Filipendula* Chenopodiaceae and *Artemisia*, to vegetation dominated by *Alnus*.

A sediment core recovered from an area proximal to Llandudno railway station (Ordnance Survey grid reference: SH 7754, 8191), commenced at an altitude of 3.99m OD and extended to an unknown depth. According to Whittow (1965), the core demonstrates that at this location a sequence of Irish Sea till of unproven depth is overlain by estuarine clay. The clay in turn is overlain by a 1.05m peat deposit, located between -5.21m and -4.16m OD, which in turn is overlain by estuarine clay, beach deposits and brown sand. A sub-sample of peat was subjected to radiocarbon analysis and produced a ^{14}C date of 7635 +/- 52 years BP (Harkness and Wilson, 1974).

Heyworth & Kidson (1982) produced a sea-level curve for North Wales based on two sea-level index points (Table 2.3). The limited data set resulted in the production of a sea-level curve (fig. 2.15) that illustrates the trend of relative sea level rise after approximately 9000 years BP. The curve indicates that the rate of relative sea-level rise decreased throughout the middle Holocene with sea level rising by approximately 8m over a period of 4000 years.

Laboratory Number	Radiocarbon date	Height (m) OD	Site	MHWS (m) OD	N.G.R.	Altitude in Figure 2.2
HV 4348	4725 +/- 65	2.43	Rhyl beach	4.00	SJ 0310 8261	2.43 +/- 0.50
SRR 61	7635 +/- 52	-4.15 to -5.20	Llandudno Station	3.96	SH 7754 8191	-4.60 +/- 1.00

Table 2.3 Sea-level index points for North Wales utilized in Figure 2.8 (Heyworth & Kidson, 1982)

The research further indicates that sea levels have not exceeded their contemporary elevation during the Holocene. According to Heyworth and Kidson (1982), comparison of this curve with sea-level curves derived from regions further to the south may imply that North Wales experienced greater degrees of uplift relative to areas of mid-Wales and southwestern England during the Holocene.

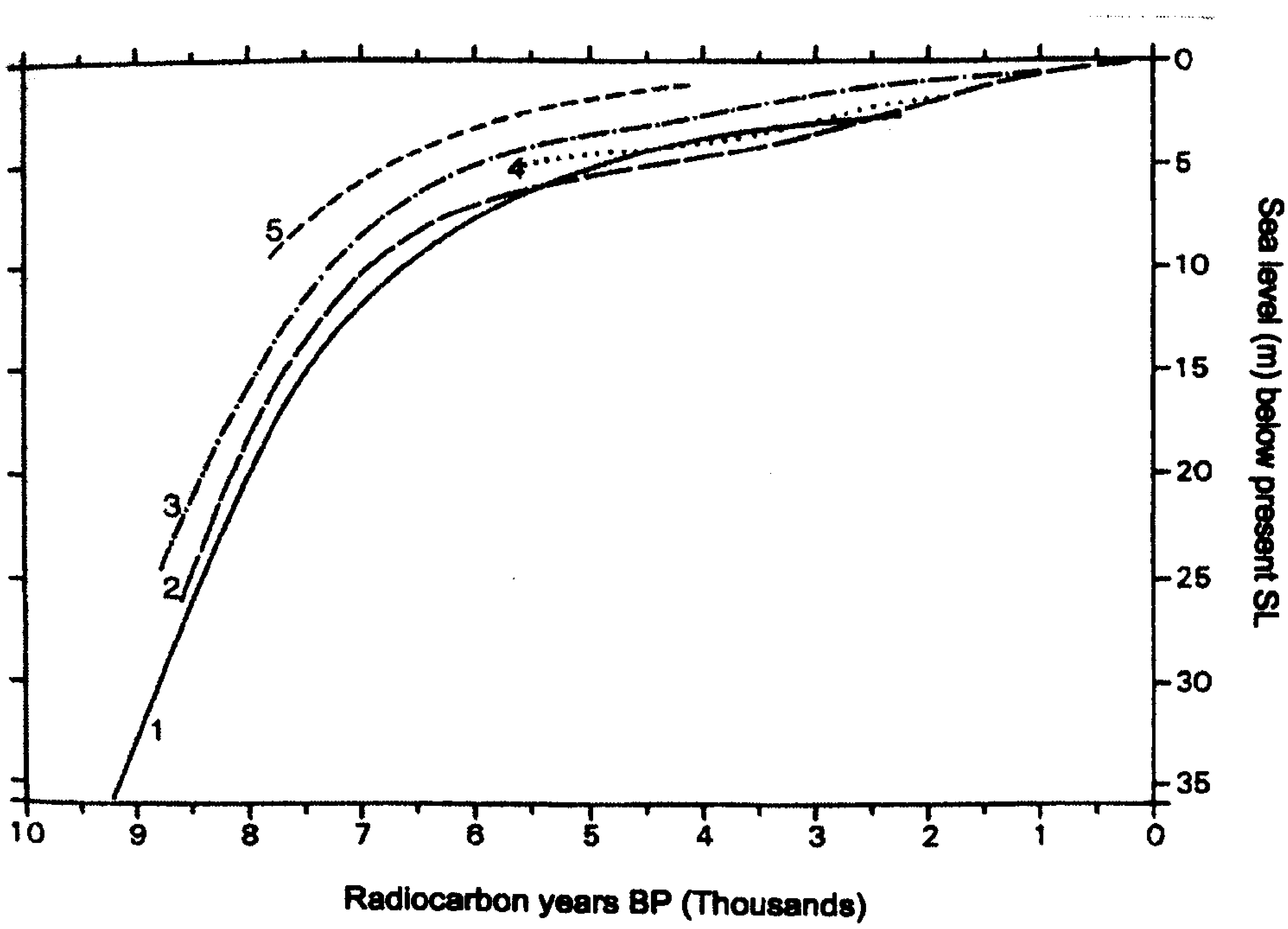


Figure 2.15 Sea levels for 1) Bristol Channel; 2) English Channel; 3) Cardigan Bay; 4) Somerset Levels Trackways; 5) North Wales. MHWST is used as the common datum. From Heyworth and Kidson (1982).

2.1.4.3 Prince (1988)

Analysis of sediments recovered from estuaries in North Wales formed the basis for an investigation relating to Late Devensian and Holocene sea-level movements conducted by Prince (1988). A number of sediment cores were recovered from along the coastline of North Wales, including Anglesey and the lowlands of the Clwyd Plain. Biostratigraphic and lithostratigraphic analyses were combined with the radioisotopic dating in an attempt to assess the effectiveness of indicator techniques in examining aspects of sea-level change. Prince (1988) states that the research utilized microfloral (pollen, freshwater algae, micro-fossils and diatoms) together with microfaunal (foraminifera, ostracoda and mollusca) indicator techniques together with ^{14}C dating.

During the course of Prince's research project, sediment cores were recovered from locations within the Vale of Clwyd. Sub-samples of material taken from a sediment core recovered from Woodlands (Ordnance Survey grid reference: SH 9972, 7895), were subsequently submitted for radiocarbon analysis. The sediment core extended over 16.00m (fig 2.16) and was recovered from a location 3.08m above OD. The sequence contains a series of relatively thin bands of sand, together with isolated layers of peat and *Phragmites*. Two sub-samples of material taken from a woody detrital peat located between -9.15m and -8.93m OD, together with one sub-sample, taken from a layer of clay containing traces of *Phragmites* located at -6.07m, were submitted for radiocarbon analysis. The samples yielded ^{14}C ages of 8540 +/- 70, 8170 +/- 70 and 15070 +/- 130 years BP respectively. Both peat dates were deemed acceptable as sea-level index points, both in terms of their indicative meaning and age. The age of the sub-sample containing *Phragmites*, however, was considered to be anomalous and rejected as a sea-level index point.

Prince (1988) highlights the problems of utilizing single indicator techniques within the field of sea-level research; the research further acknowledges the complex nature of coastal environments together with the suitability and reliability of independent indicator

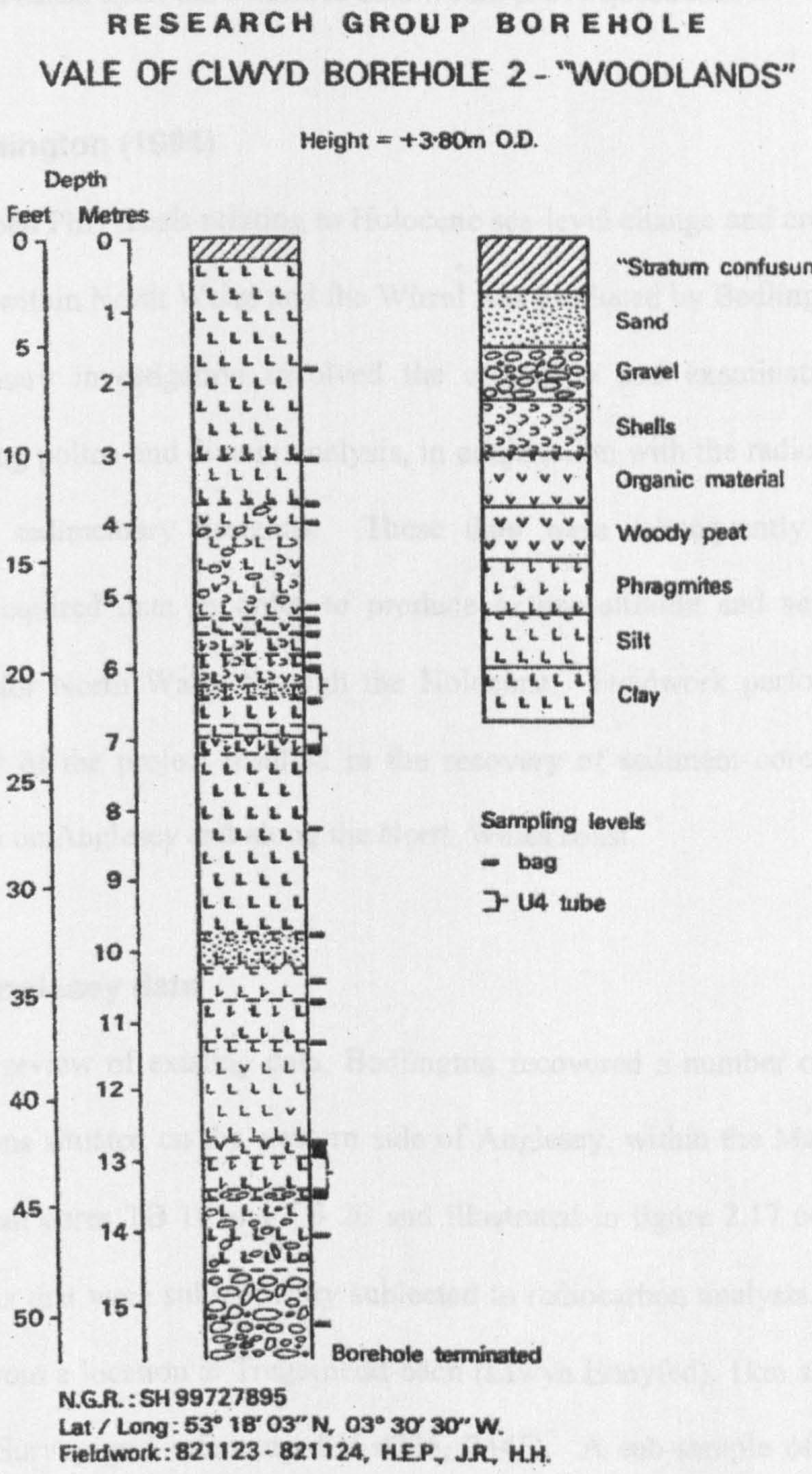


Figure 2.16 Stratigraphy of sediments recovered from Woodlands. From Prince (1989)

techniques. The research concludes that any value attached to the construction of a time-altitude graph based upon the available data would prove questionable.

2.1.4.4 Bedlington (1994)

An unpublished PhD thesis relating to Holocene sea-level change and crustal movements experienced within North Wales and the Wirral was produced by Bedlington (1994). The multidisciplinary investigation involved the collection and examination of sediment cores, utilizing pollen and diatom analysis, in conjunction with the radiocarbon dating of organic-rich sedimentary horizons. These data were subsequently integrated with previously acquired data in order to produce a time-altitude and sea-level tendency chronology for North Wales through the Holocene. Fieldwork performed during the initial stages of the project resulted in the recovery of sediment cores from locations situated both on Anglesey and along the North Wales coast.

2.1.4.4.1 Anglesey data

Based on a review of existing data, Bedlington recovered a number of sediment cores from locations situated on the western side of Anglesey, within the Malltraeth Marshes. Two sediment cores TB 18 and TB 20 and illustrated in figure 2.17 contained organic-rich horizons that were subsequently subjected to radiocarbon analysis. The cores were recovered from a location at Tregarnedd-bâch (Llwyn Ednyfed), 1km south of Llangefni (Ordnance Survey grid reference: SH 4735, 7445). A sub-sample of organic material taken from towards the base of the peat at -4.11m OD in core TB 18 produced a ^{14}C age of 7255 +/- 130 years BP.

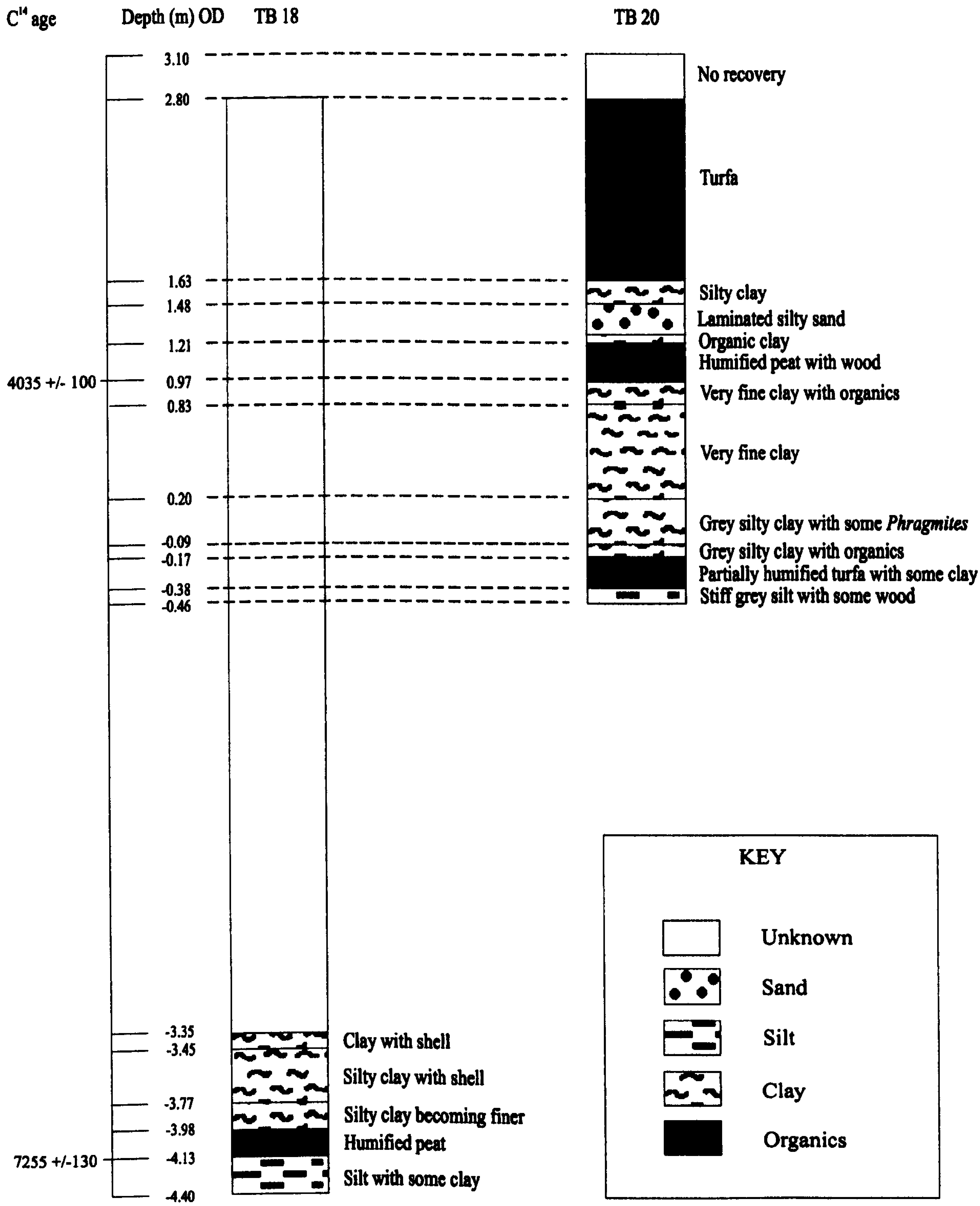


Figure 2.17 Stratigraphy of sediments recovered from Tregarnedd-Bâch by Bedlington (1994)

Sediment core TB 20 was also recovered from the same area and contained a number of organic-rich horizons. A sub-sample of organic material which was recovered from the base of the woody peat at 1.00m OD produced a ^{14}C age of 4035 +/- 100 years.

Subsequent to the additional sedimentological and biostratigraphic analysis of adjacent sediments, the dated sedimentary horizons were accepted as a validated sea-level index points.

2.1.4.4.2 Afon Ganol Valley data

An intensive coring operation located within the Afon Ganol Valley, to the west of Colwyn Bay resulted in the recovery of many sediment cores. Three sub-samples of organic-rich material from sediment core Morfa Penrhyn 20 (figure 2.18) were subsequently submitted for radiocarbon analysis. The core was located within the low-lying region of Morfa Penrhyn, on the southwestern side of the A546 (Ordnance Survey grid reference: SH 8218, 8079). Organic material taken from a depth of 0.28m OD and submitted for radiocarbon analysis produced a ^{14}C age 6335 +/- 115 years BP, subsequent to additional biostratigraphic analysis the horizon was deemed to be an acceptable sea-level index point.

2.1.4.4.3 Abergele data

At least two sediment cores, Hendre Fawr 21 and Hendre Fawr 29 were recovered from a low lying region approximately 2km east of Abergele. Sediment core Hendre Fawr 21

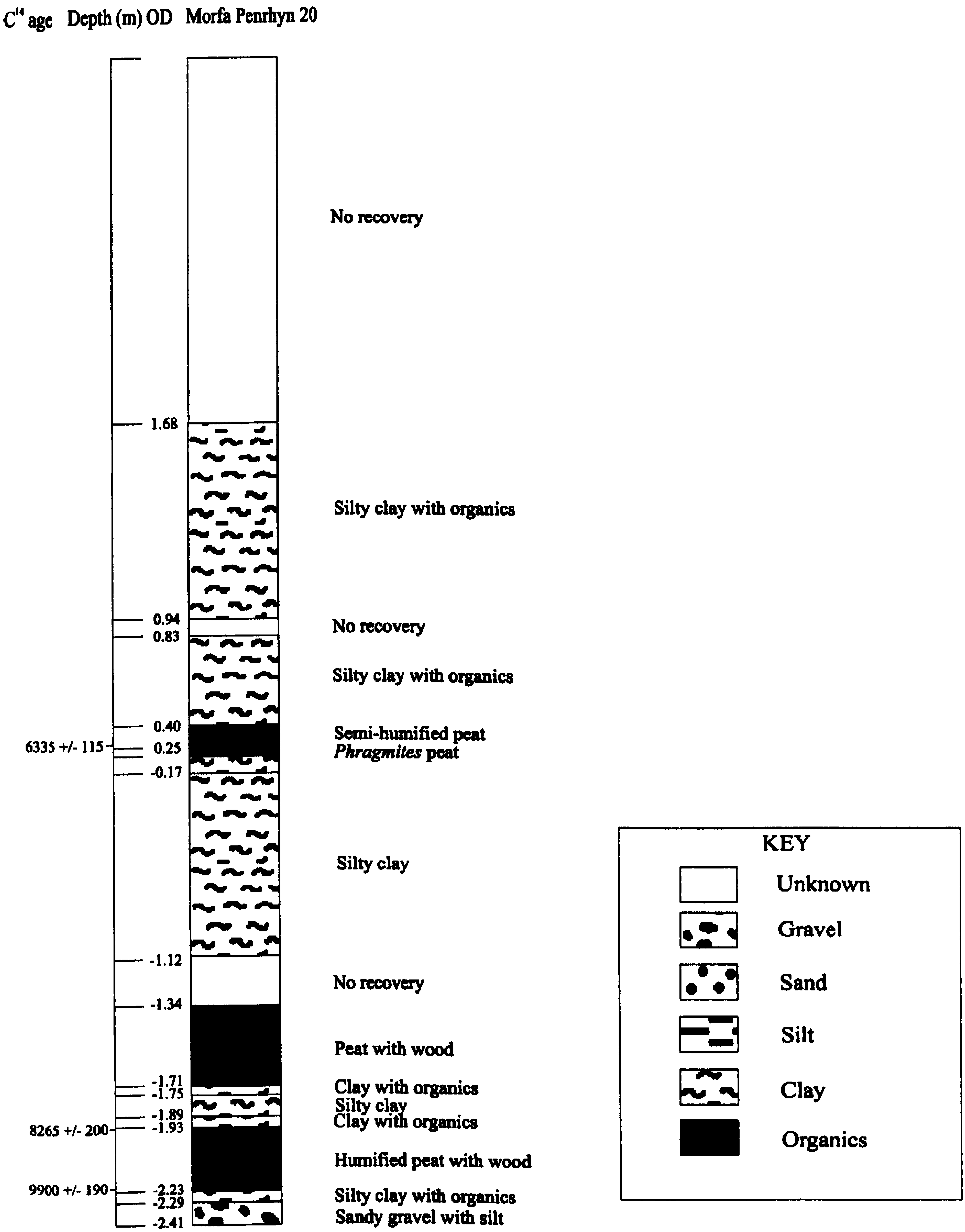


Figure 2.18 Stratigraphy of sediments recovered from Afon Ganol by Bedlington (1994)

(fig. 2.19) commenced at 3.13m OD and extended down over 4.63m to -1.50m OD; the core was located approximately 300m north of the A547 (Ordnance Survey grid reference: SH 9637, 7751). Sub-samples of organic material were taken from depths of -0.93m, 1.27m, 1.70m and 1.87m OD and submitted for radiocarbon analysis. Bedlington (1994) rejects the date produced by the material located at -0.93m OD at 5530 +/-385 as the age of the sediment appears to be anomalously young given its stratigraphical context in relation to the overlying sediments. All other dated horizons were accepted as validated sea-level index points, subsequent to additional analysis.

Sediment core Hendre Fawr 29 (fig. 2.19) commenced at 2.52m OD and extended down over 5.55m to -3.03m OD; the core was located approximately 200m south of the A547 (Ordnance Survey grid reference: SH 9660, 7712). One sub-sample of organic sediment was taken from -2.48m OD and submitted for radiocarbon analysis, producing a ^{14}C age of 7080 +/- 155 years BP; additional sedimentological and biostratigraphic analysis validated the dated horizon as an acceptable sea-level index point.

The research project generated seven new sea-level index points obtained from locations situated along the coastline of North Wales (Table 2.4) and concluded that the North Wales coast has been subjected to a relatively rapid rise in relative sea level throughout much of the early to middle Holocene. The project additionally identified five relatively shorter periods of time when the marine influence along the coast appears to have receded.

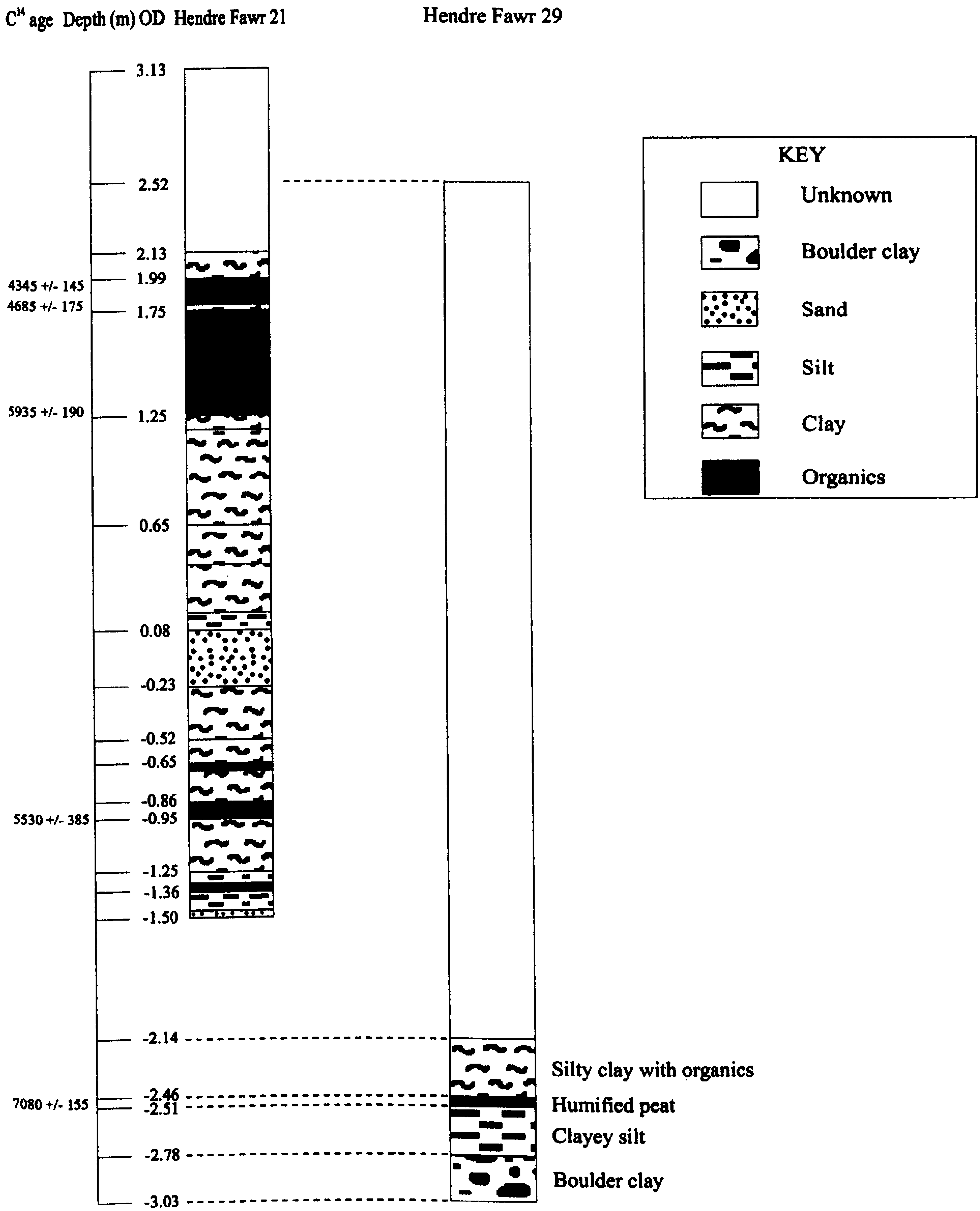


Figure 2.19 Stratigraphy of sediments recovered from Hendre Fawr by Bedlington (1994)

Laboratory Number	Radiocarbon date (BP)	Height (m) OD	Site	MHWS (m) OD	Calibrated Date (BC)
Hv 17820	4035 +/- 100	1.00	Tregarnedd-bach	-1.21	2880-2282
Hv 17810	4345 +/- 145	1.87	Hendre fawr	-2.08	3369-2574
Hv 17811	4685 +/- 175	1.70	Hendre fawr	-2.25	3894-2916
Hv 17812	5935 +/- 190	1.27	Hendre fawr	-2.68	5261-4362
Hv 17815	6335 +/- 115	0.28	Morfa Penrhyn	-3.67	5445-4997
Hv 17814	7080 +/- 130	-2.48	Hendre fawr	-6.43	6185-5610
Hv 17819	7805 +/- 55	-4.11	Tregarnedd-bach	-6.32	6371-5825

Table 2.4 Sea-level index points for North Wales used in Figure 2.19 (Bedlington, 1994)

Bedlington (1994) suggests that relative sea-level rise exceeded 7mm/yr between 8000 and 7000 years BP decreasing to approximately 3.5mm/yr between 7000 and 6000 years BP; he further implies that the sea partially withdrew from many coastal sites on at least two occasions during the middle Holocene. Integrating previously existing sea-level data with data acquired during the course of the research project, Bedlington (1994) was able to generate a relative sea-level curve for North Wales based upon 12 critically assessed sea-level index points (fig. 2.21).

The curve suggests a relatively rapid period of sea-level rise during the early Holocene, prior to a marked reduction in the rate of rise during the middle Holocene; the study further suggests that relative sea levels attained contemporary elevations approximately 2000 calendar years BP.

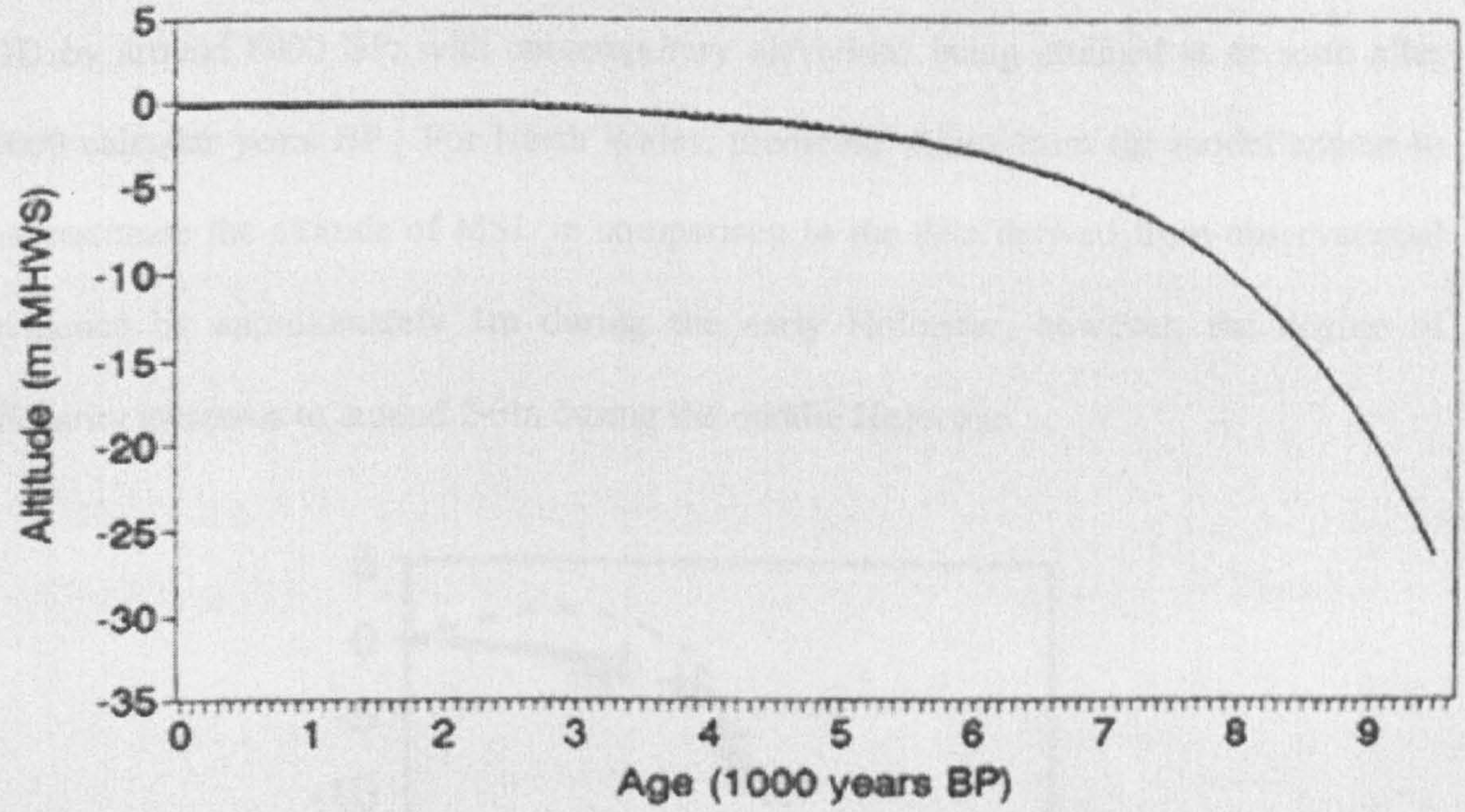


Figure 2.20 Relative sea-level curve for North Wales based on index points from Bedlington (1994)

2.1.4.5 Shennan and Horton (2002)

More than 1200 radiocarbon dated samples that have been utilized in order to constrain existing relative sea-level change within Great Britain were used to provide estimates of contemporary crustal movement. The research plotted sea-level index data together with a predicted trend of RSL for 52 coastal regions of the UK, including North Wales. The graphs illustrate a predicted trend for RSL based on corrections that take into consideration local factors such as sediment compaction and possible changes in tidal range. The study utilized data from the region of North Wales obtained through previous work (Tooley, 1978; Heyworth and Kidson, 1982; Bedlington, 1993). The graph for North Wales (fig. 2.21), indicates that relative sea level within this region of the UK was around -25m OD at approximately 11500 BP, before rising rapidly to approximately -5m OD by around 8000 BP; with contemporary elevations being attained at or soon after 6000 calendar years BP. For North Wales, predicted values from the model appear to overestimate the altitude of MSL in comparison to the data derived from observational evidence by approximately 1m during the early Holocene, however, the degree of disparity increases to around 2-3m during the middle Holocene.

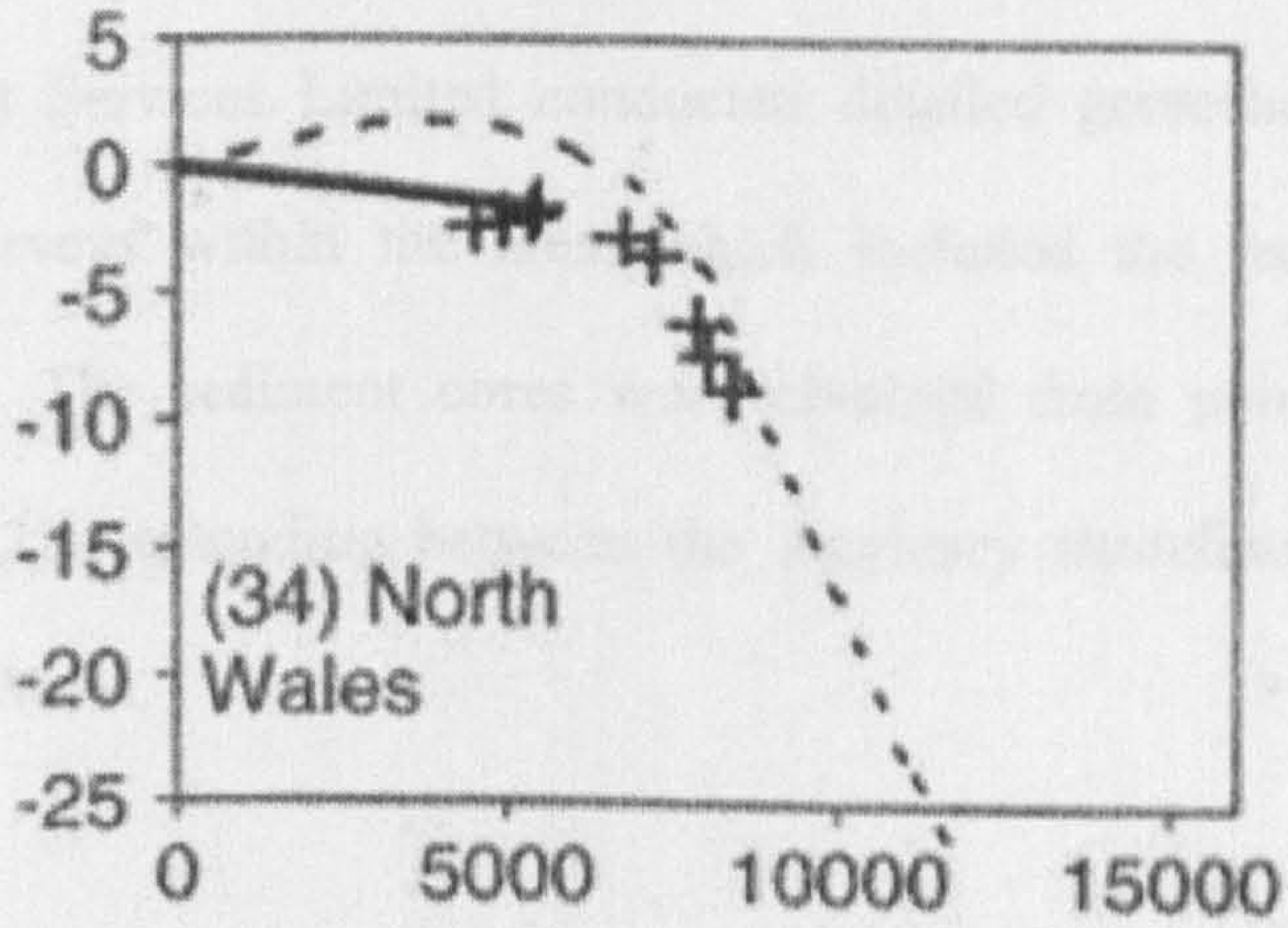


Figure 2.21 Predicted and observed relative sea-level curve for North Wales. Taken from Shennan and Horton (2002)

2.1.5 Sedimentological data

A considerable deficiency exists within the published scientific literature with respect to the volume of available data relating to local and regional near-shore sedimentary sequences. As a consequence, data from additional sources have been utilized and incorporated into this research project; the data has primarily been derived from industrial contractors who have conducted site investigations in conjunction with various civil engineering projects within the northeastern region of the Menai Strait during the course of the last thirty five years.

2.1.5.1 Shell data (1971)

During the latter part of 1970 and early 1971 a marine site investigation was conducted within the southwestern region of Traeth Lafan by Project Engineering and Management Services Limited. The work was undertaken as part of a feasibility study on behalf of Shell (U.K.) Limited in order to determine a possible route across the Menai Strait for an oil pipeline that was to due to extend between Amlwch, on the northern coast of Anglesey, and a petroleum refinery based at Stanlow in Cheshire. Project Engineering and Management Services Limited conducted detailed geotechnical, geophysical and bathymetrical surveys within the area, which included the recovery of thirty three sediment cores. The sediment cores were obtained from points located along four transects (fig. 2.22), extending between the Anglesey shoreline and the foreshore of mainland North Wales.

Sediment logs relating to the cores recovered along transect A (fig. 2.23) indicate that glacial deposits extend to within a few centimetres of the surface towards the mainland shoreline and appear to descend rapidly towards the north before reappearing approximately 10m below the surface (approximately -30m to -35m OD) within the main channel, south of Gallows Point. The logs also indicate the presence of fine clays containing organic material and pockets of peat which extend to at least 9m below the surface (approximately -11m OD), approximately 1km north of the mouth of the Afon Ogwen. The fine grained sediments appear to extend to at least 10m beneath the surface along much of the transect and are overlain by fine and medium grained sands, which appear to become progressively well developed towards the main channel.

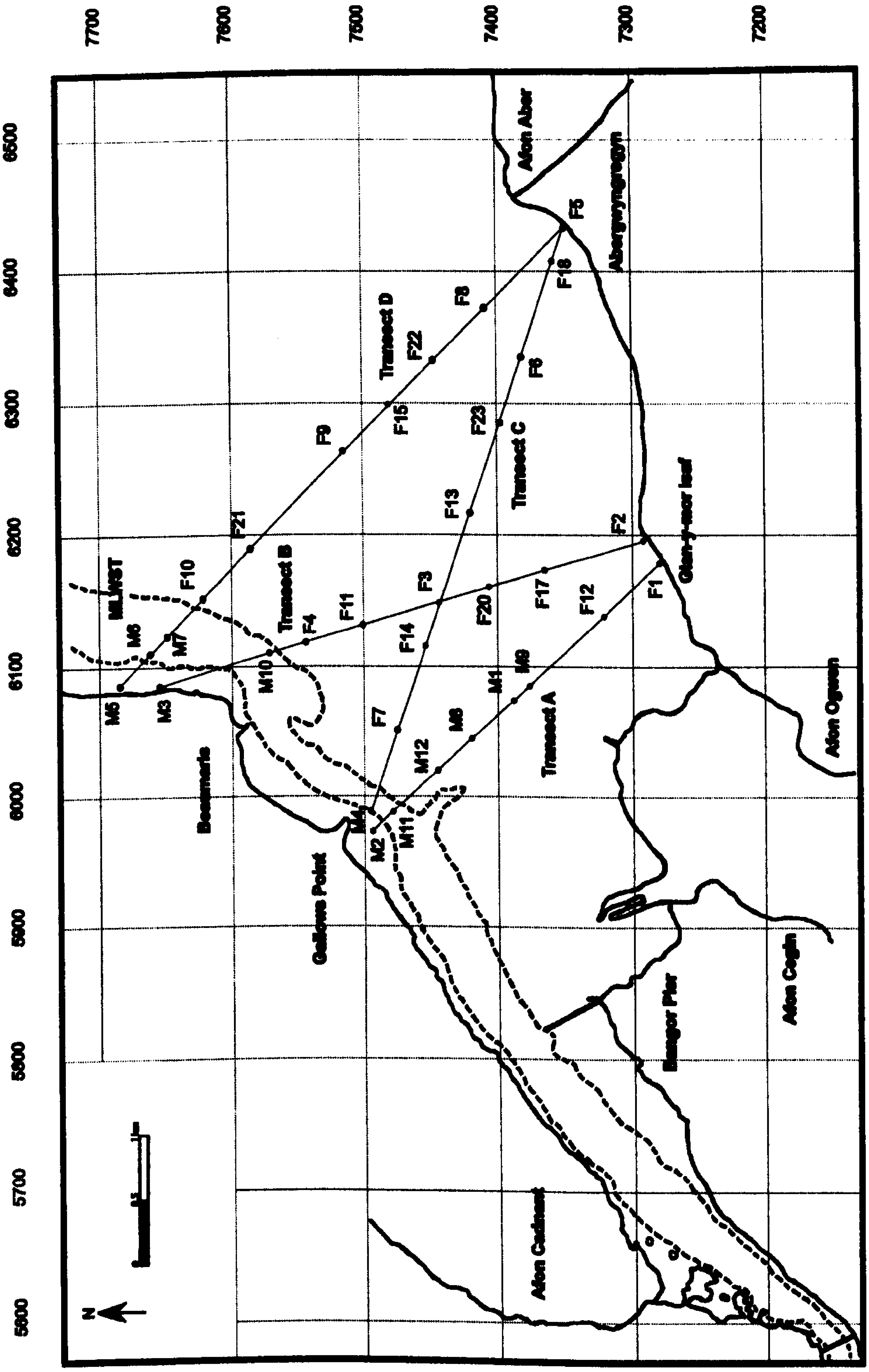


Figure 2.22 Location of transects and sediment cores recovered by Project Engineering Services (Shell UK) Limited 1970-1971

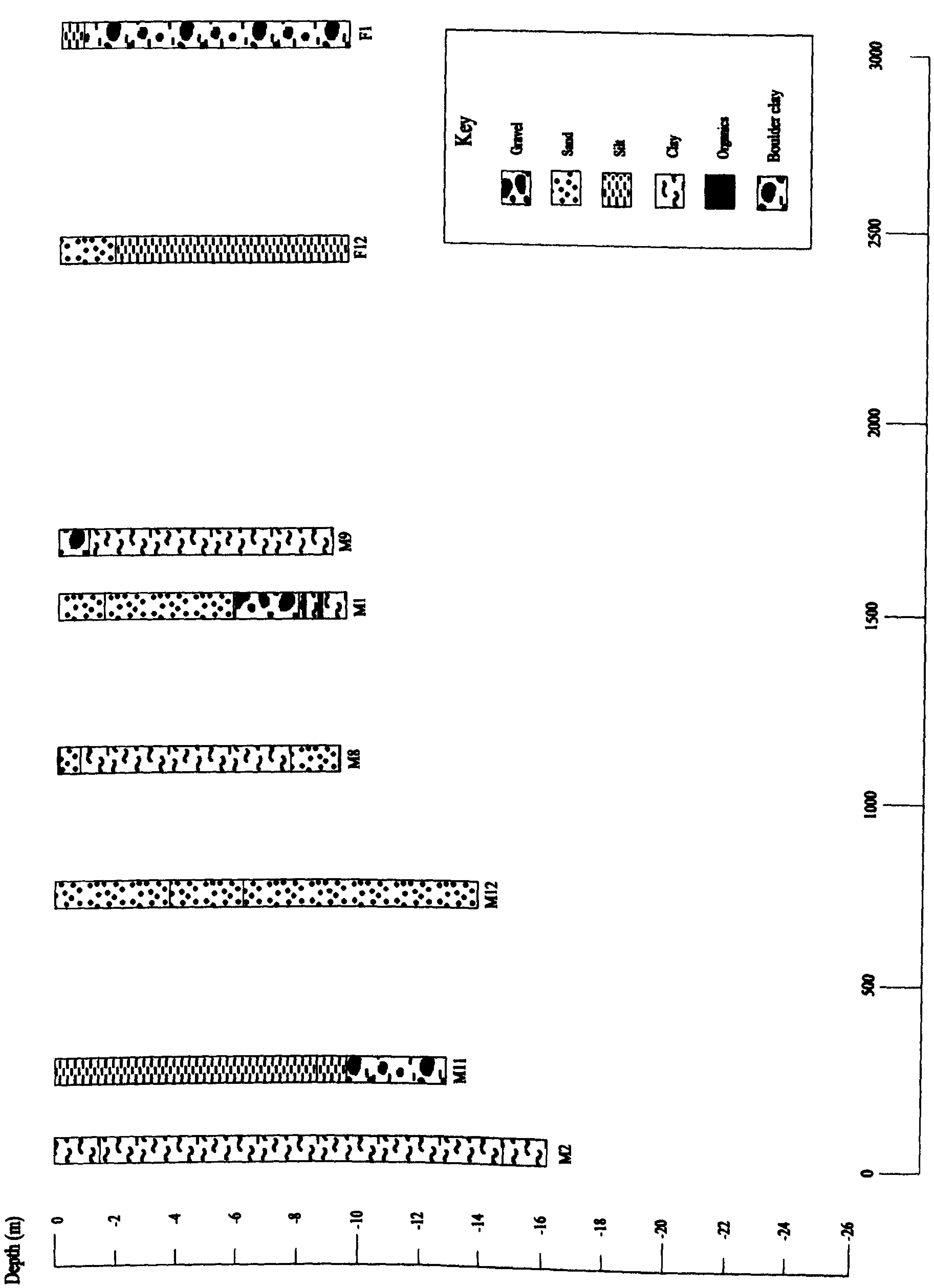


Figure 2.23 Simplified schematic of Shell sediment logs recovered from transect A

Transect B indicates that immediately adjacent to the mainland coast at Glan-y-môr isaf a glacial deposit extends to within a few centimetres of the surface. The sediment logs from transect B (fig. 2.24) further indicate that the surface of this material descends by over 10m approximately 500 metres north of the shoreline and does not appear to be present within 10m of the seabed surface between this point and the shoreline of Anglesey. The sediment logs indicate that the glacial deposit is overlain by a well developed sequence of blue and brown, fine grained silty clay, which appears to increases in thickness towards the central region of the Menai Strait. The surface of the deposit gradually descends towards the north, attaining its lowest elevation where it outcrops within the main channel. Within the clay, a 0.40m peat deposit is noted within sediment log F3, which describes a sediment core recovered from a location within the central region of Traeth Lafan (approximate Ordnance Survey grid reference: SH 6165, 7440), with the peat extending between 5.18m and 4.88m below the surface, approximately -7m OD. To the south of the main channel, a deposit of grey, brown medium and fine sand overlies the clay and attains maximum thickness immediately south of the main channel.

Sediment logs obtained from transect C (fig. 2.25) indicate that the glacial deposits, proximal to the surface of the mainland, appear to descend relatively rapidly with increasing distance towards the northwest. The logs also indicate the presence of well developed sequences of fine grained silty clays overlain by a veneer of medium and fine grained sand. The elevation of the horizon separating the fine and coarse sediment appears to descend towards the region of the main channel.

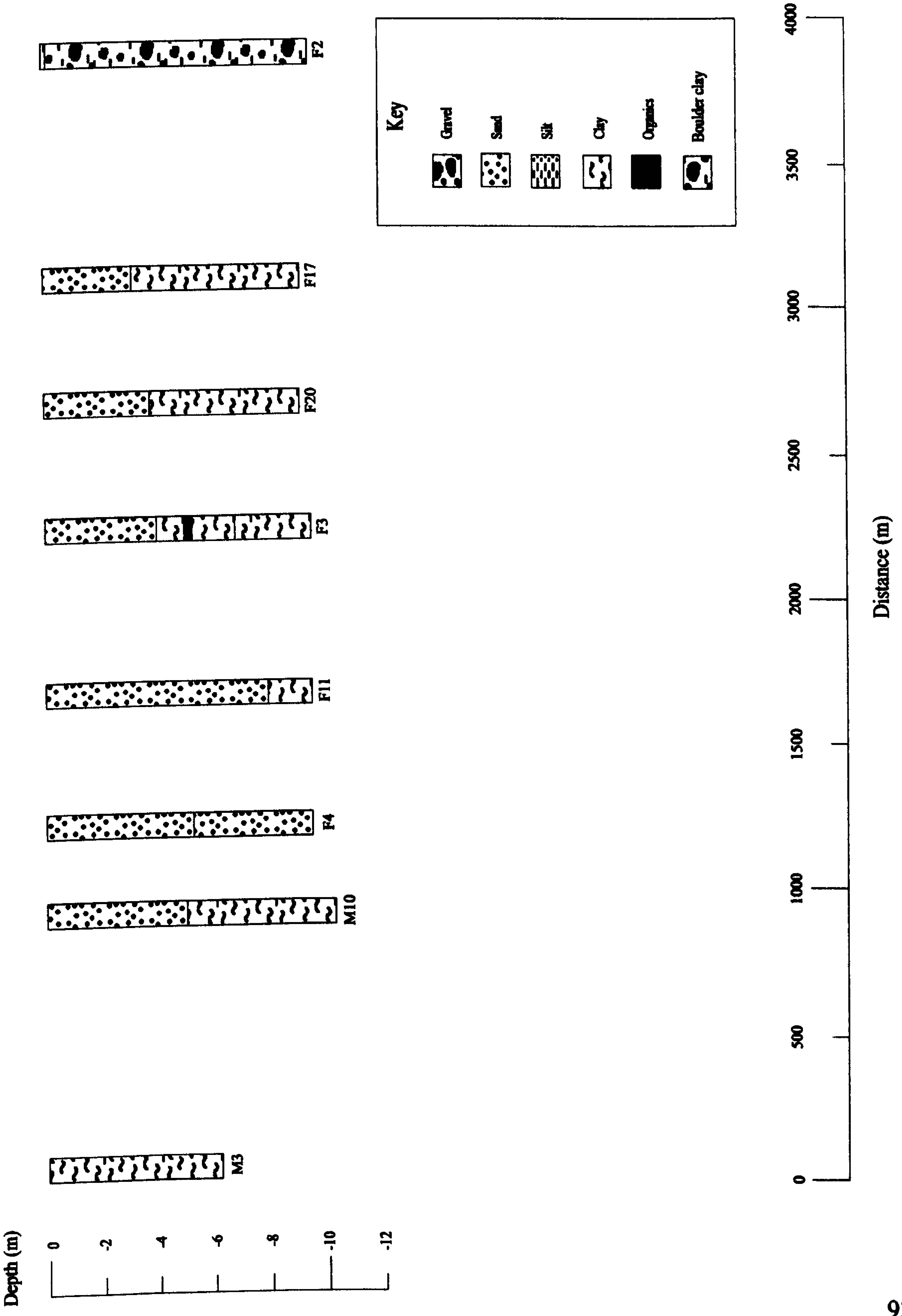


Figure 2.24 Simplified schematic of Shell sediment logs recovered from transect B

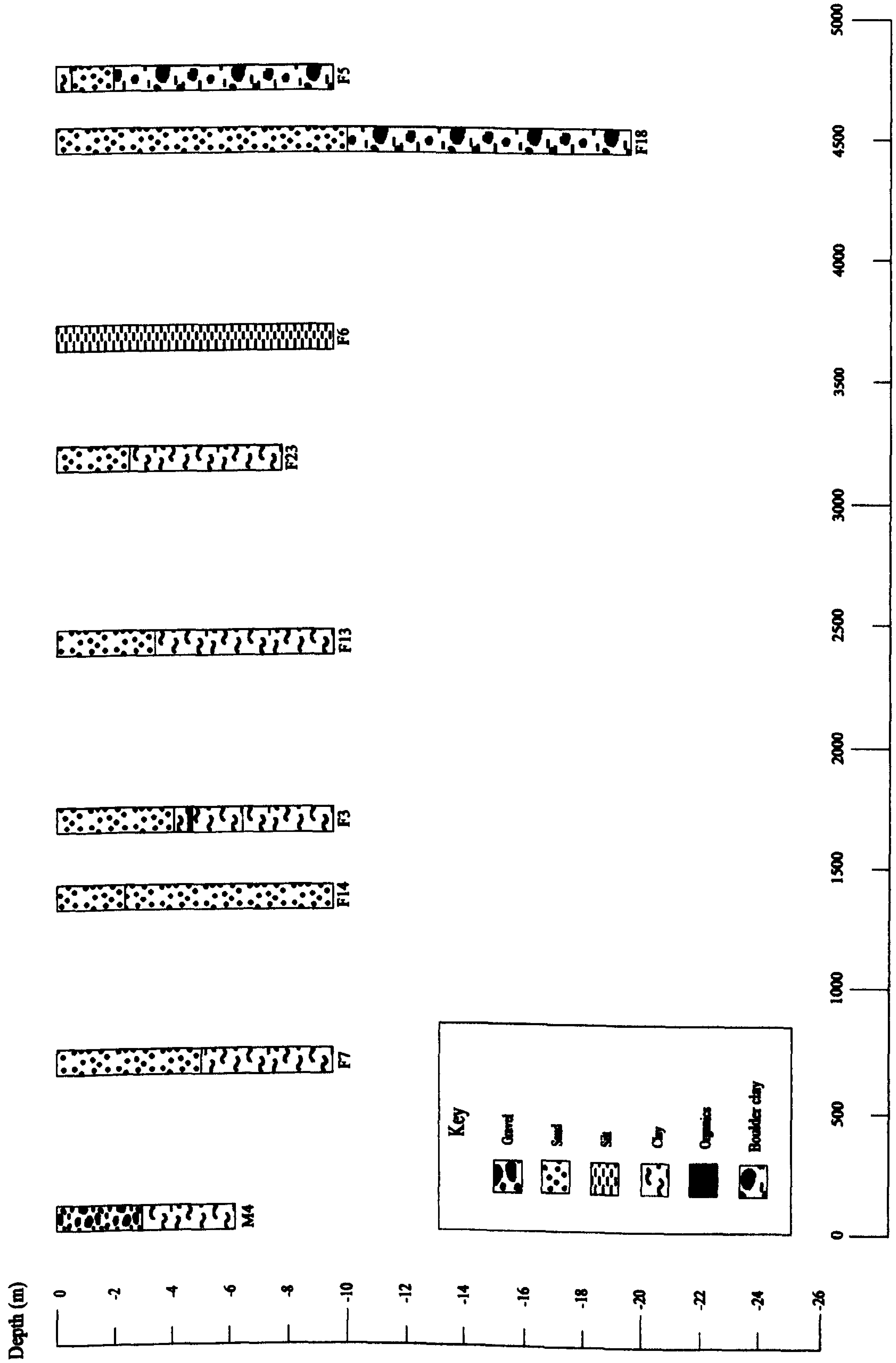


Figure 2.25 Simplified schematic of Shell sediment logs recovered from transect C

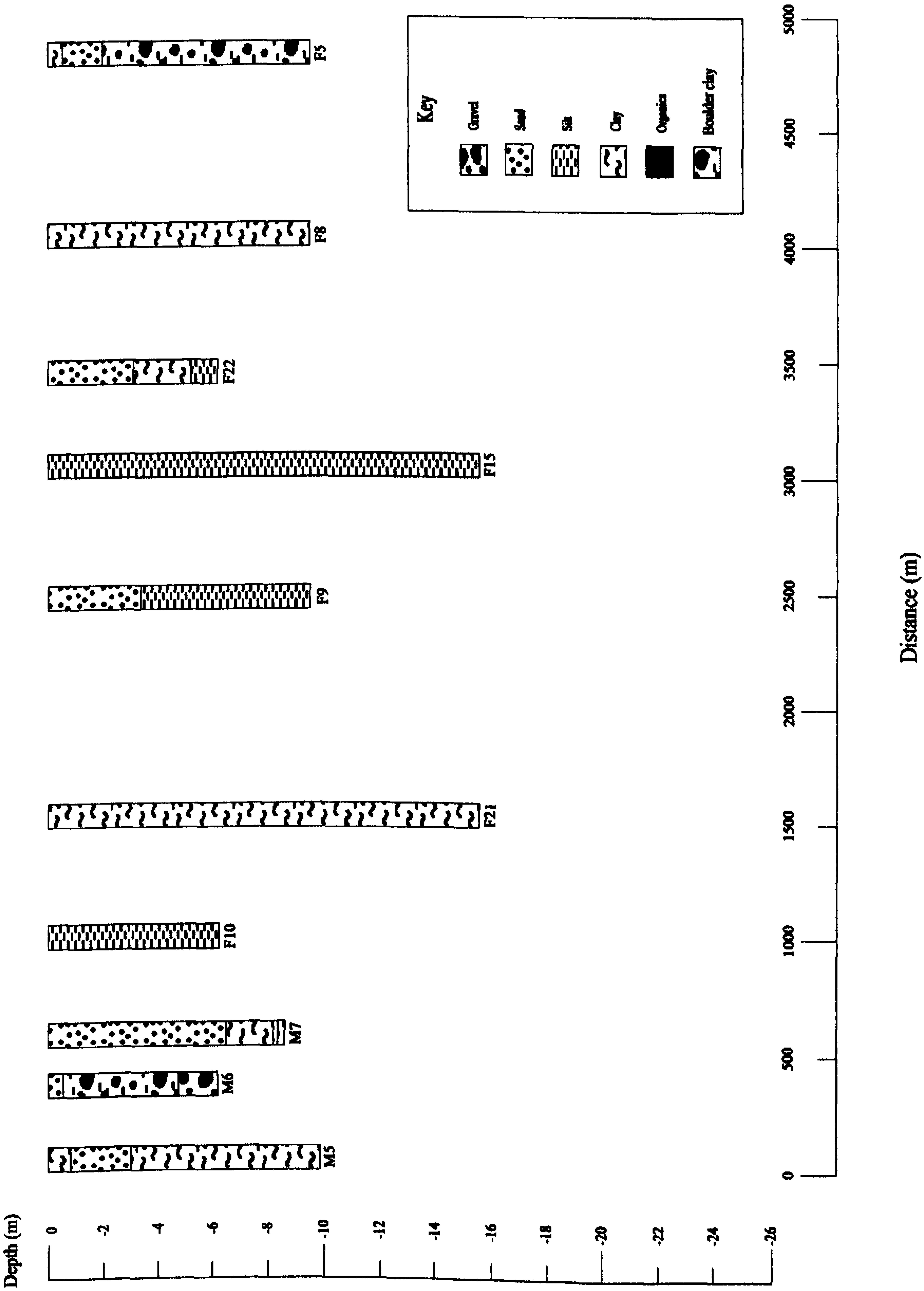


Figure 2.26 Simplified schematic of Shell sediment logs recovered from transect D

Sediment logs obtained from cores recovered along transect D (fig. 2.26) indicate a similar pattern with respect to glacial deposits, clay and sand; however, the transect extends further to the northeast and indicates the presence of glacial deposits proximal to the Anglesey shoreline. The sediment logs additionally indicate the presence of medium and coarse sand further to the north which appear to constitute the floor of the main channel.

2.1.5.2 Osiris data (1986)

During February, March and April 1986, a marine site investigation was conducted on an area of seafloor immediately adjacent to Bangor Pier by Osiris Seaway Limited. The work was undertaken on behalf of Welsh Water (Northern Division), in order to update an existing effluent outfall facility. Osiris, conducted detailed geotechnical, geophysical and bathymetrical surveys which included the excavation of twelve trial pits and the recovery of fourteen sediment cores. Sediments were sampled from points located along two transects orientated approximately northwest to southeast positioned either side of Bangor Pier (fig. 2.27).

The sediment cores were recovered using a Pilcon 2000 cable percussive boring rig using 200mm diameter casing, employing the "Shell and Auger" technique, with the boring mounted on a floating pontoon. The materials recovered during the course of the site investigation are no longer available, however, the borehole records, together with additional geotechnical data were found to be contained in the report entitled: Garth

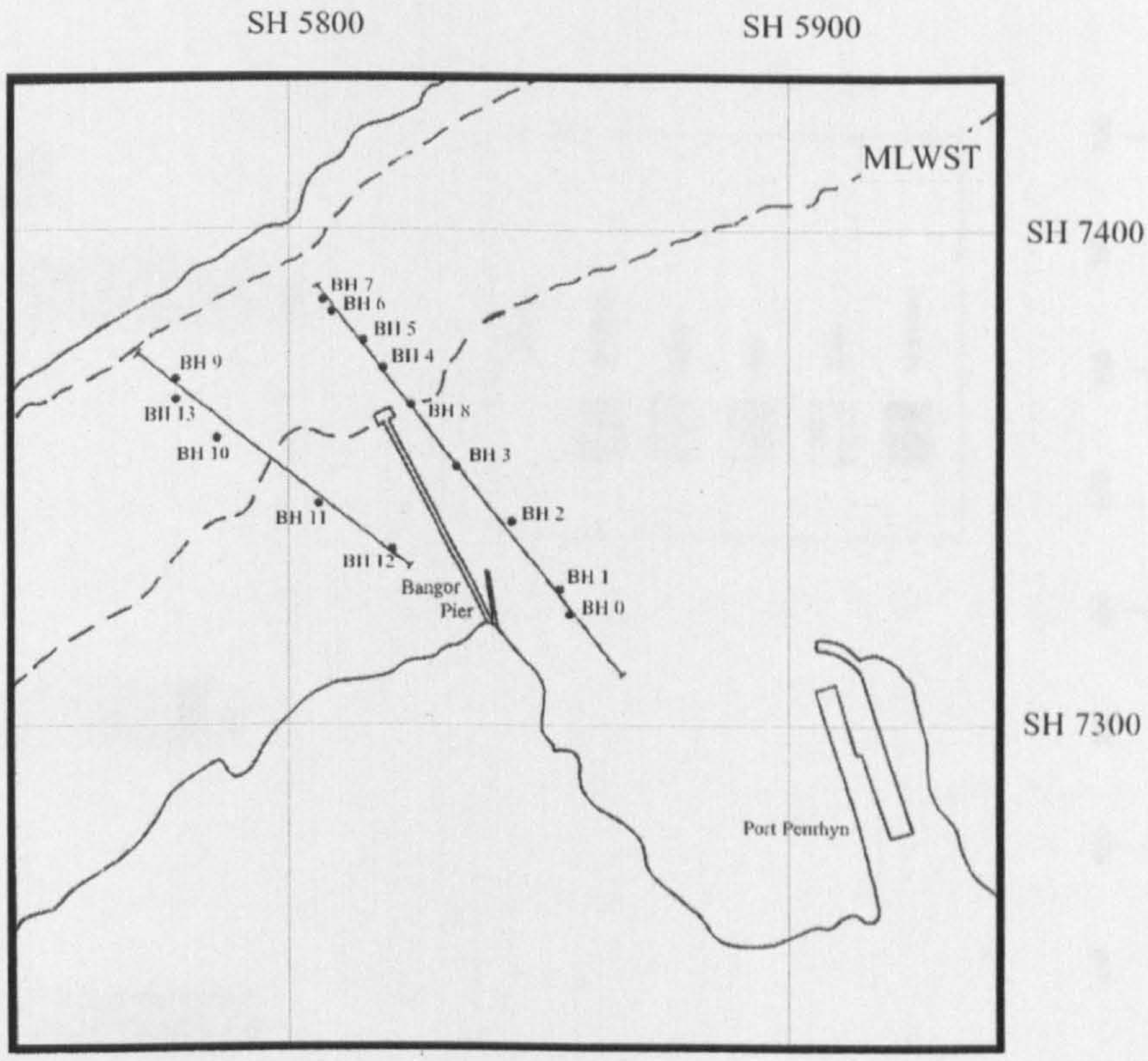


Figure 2.27 Location of transects and boreholes taken by Osiris Seaway Limited. From Osiris (1986)

Outfall, Bangor, Marine Site Investigation, report number D86032 by Osiris Seaway Ltd (1986).

2.1.5.2.1 Northeast transect

Sediment cores 0-8 were recovered from locations situated along a transect orientated southeast to northwest, 150-50m northeast of Bangor Pier (Ordnance Survey grid reference: SH 5865, 7315 to 5805, 7485). The sediment cores were recovered across an area that extended from the inter-tidal mudflats beneath the foreshore, out into the main channel of the Menai Strait. The sediment logs (fig. 2.28) indicate a sequence of coarse

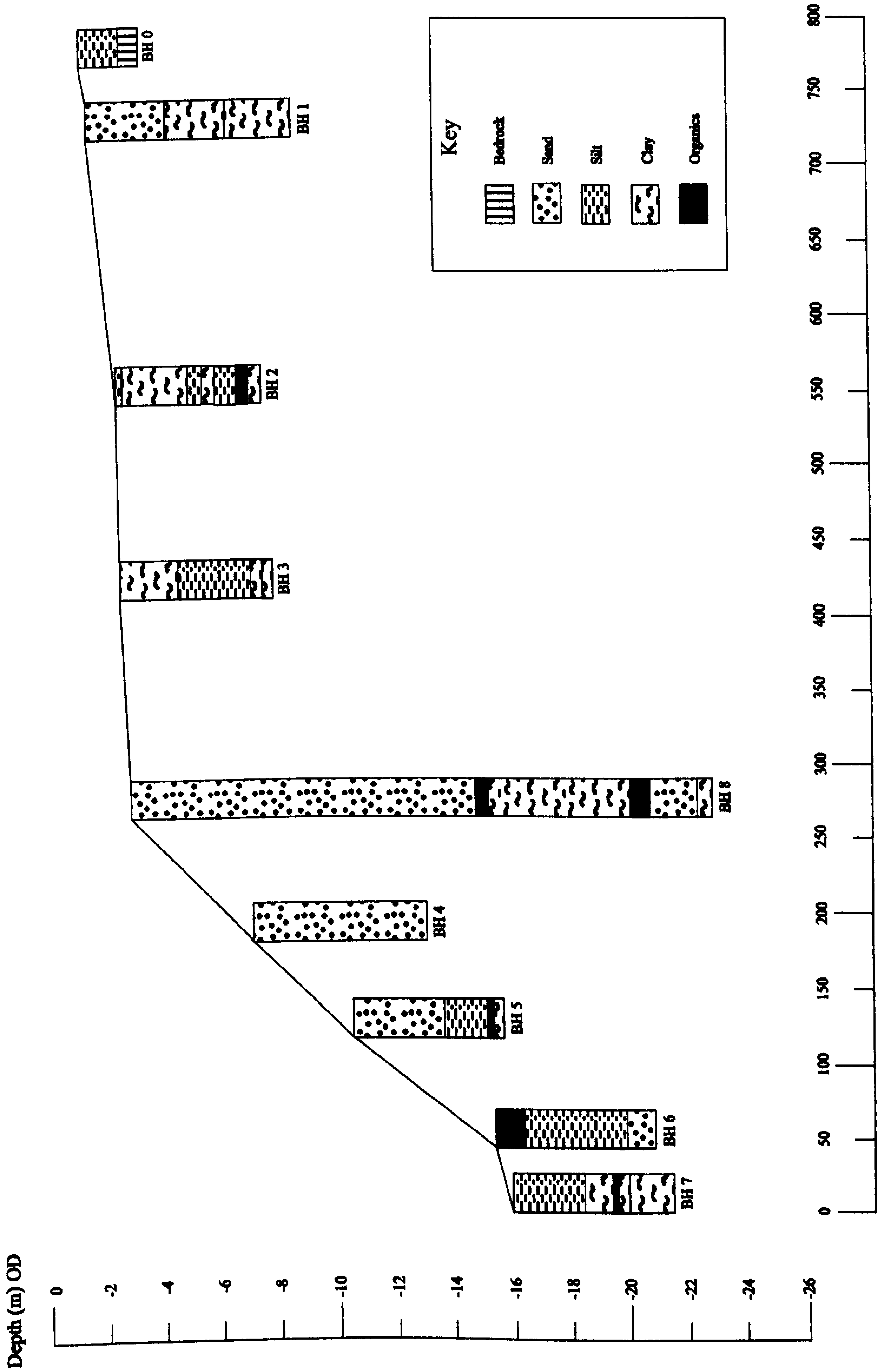


Figure 2.28 Simplified representation of Osiris Seaway sediment logs recovered from the northeast transect adjacent to Bangor Pier

material overlain by discontinuous beds of marine sediment which in turn occasionally interspersed by layers of organic-rich material.

2.1.5.2.2 Southwest transect

Sediment cores 9-13 were recovered from locations positioned along a transect situated between 250-100m southwest of Bangor Pier (Ordnance Survey grid reference: SH 5770, 7370 to 5830, 7335). The transect was orientated approximately west-northwest to east-southeast and extended from within the main channel of the Menai Strait, back onto the inter-tidal mudflats located immediately below the foreshore. Logs from the sediment cores (fig. 2.29) once again indicate the presence marine sediments occasionally interspersed by layers of organic-rich material.

2.1.5.3 Fugro McClelland data (1993)

During the latter part of 1992 and early 1993 a marine site investigation was conducted within the northeastern region of the Menai Strait, to the southwest of the village of Llanfaes, 3km northeast of Beaumaris, by Fugro-McClelland Limited. The work was undertaken on behalf of Welsh Water as a preliminary site investigation with respect to the eventual installation of an outfall pipeline. The company conducted geotechnical and geophysical surveys along a transect orientated from northwest to southeast, extending out over 1,050m from the Anglesey foreshore on the northern side of the main channel across onto the northwestern region of Traeth Lafan. The investigation resulted in the excavation of five shallow trial pits and fourteen sediment cores.

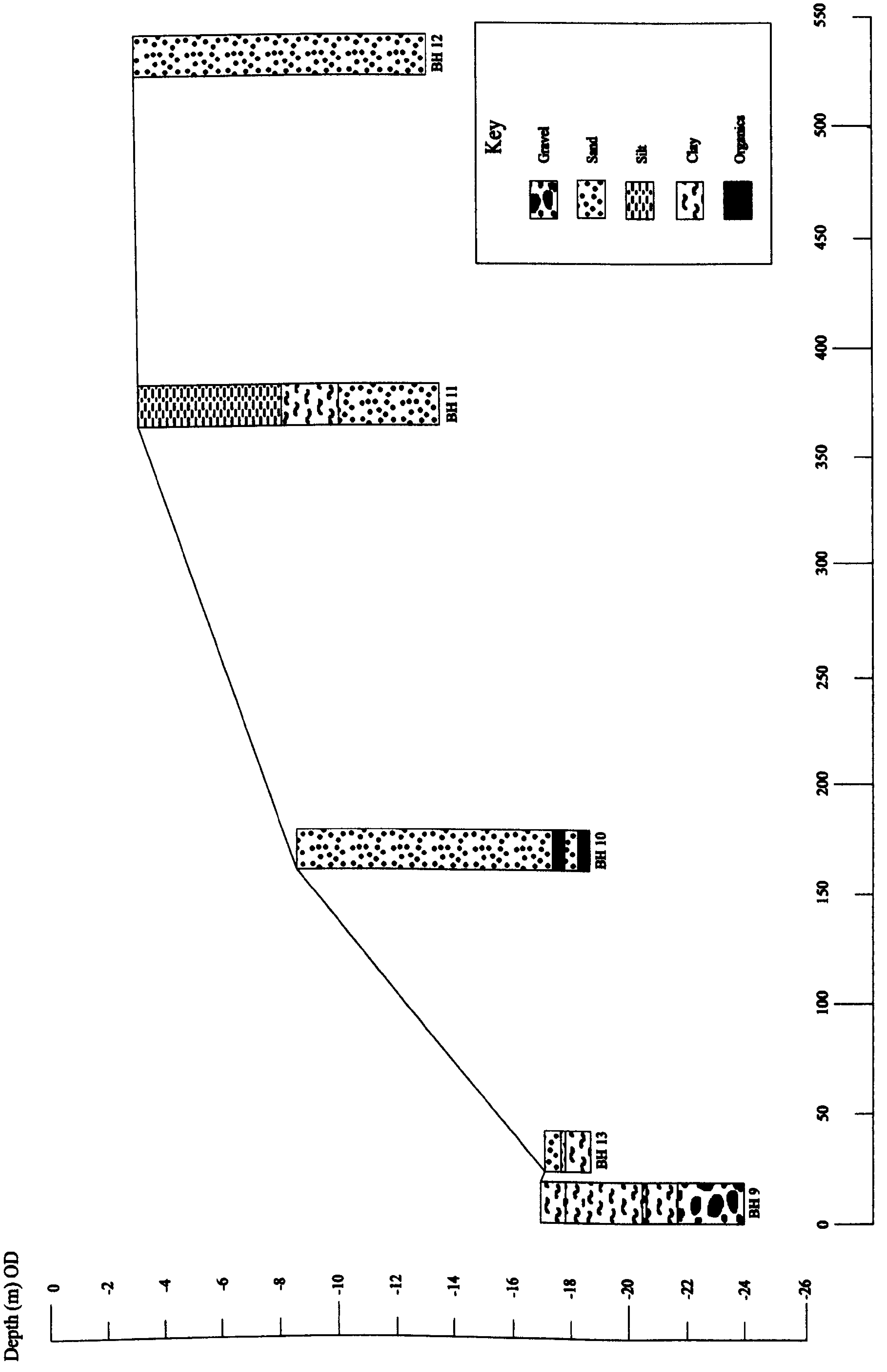


Figure 2.29 Simplified representation of Osiris Seaway sediment logs recovered from the southwestern transect adjacent to Bangor Pier

The available data (Report No. 92/3172-1(02). Welsh Water – Dwr Cymru Llanfaes Outfall. Fugro-McClelland) indicate that the sediments located between the Anglesey foreshore and the edge of the main channel, primarily consist of a diamicton, comprising of cobbles and gravels within a matrix of stiff sandy clay extending to an unproven depth. The altitude of this deposit varies considerably and at times it almost outcrops at the surface, this material is generally overlain by medium and fine grained silty sands. The borehole logs however, do not indicate the presence of any organic-rich deposits at this particular vicinity.

2.1.6 Seismic data

Numerous seismic profiling surveys have been undertaken within the northeastern region of the Menai Strait during the course of the last thirty years and have predominantly been associated with various undergraduate and postgraduate projects carried out under the auspices of the University of Wales Bangor, School of Ocean Sciences. The integration of these data with both the pre-existing and sedimentological data obtained during the course of this research project provides an effective and efficient means of determining the lateral extent of individual sedimentary facies within this region of the Strait. A compilation of such data would additionally identify specific locations within the study area which would ultimately maximize the potential of any future drilling operation. This would ultimately ensure that the recovery of sedimentary sequences deemed most likely to provide potentially important sea-level index data would be obtained in a cost-effective and least time consuming manner.

The northeastern region of the Menai Strait has been subject to a comprehensive degree of seismic investigation over the last thirty five years (fig 2.30). These surveys include the commercial investigations completed by Project Engineering and Management Services Ltd. (1971) and Osiris Seaway Ltd. (1986), together with surveys conducted under the auspices of the School of Ocean Sciences which include: Jones (1978); Cook (1980); Smart (1984); Allan (1985); Ali (1992) and Butcher (1997).

The survey conducted by Project Engineering and Management Services Ltd. (1971) incorporated sparker and boomer surveys in order to ascertain the depth and contours of the underlying bedrock. Pinger profiling techniques were also employed in order to provide shallow, higher resolution surveys that were subsequently correlated with borehole data. Based on interpretations of the collected data, the report states that a reflective horizon exists beneath the sea bed which is consistently greater than 20m below the surface. The seismic velocity of this reflector is of the order expected for a sedimentary sandstone or limestone and is shown to extend beneath the sea bed over much of the northeastern Menai Strait.

Cook (1980), Osiris Seaway Ltd. (1986) and Butcher (1997) conducted various geophysical surveys within the area surrounding Bangor Pier, interpreted cross-sections of which are illustrated in figure 2.31. The surveys consistently demonstrate the presence of a number of strong reflectors extending out from the mainland beneath the sea bed towards the Anglesey shoreline. Osiris Seaway Ltd. (1986) additionally generated a series of seismic profiles around the area of Bangor Pier that correlated well with ground

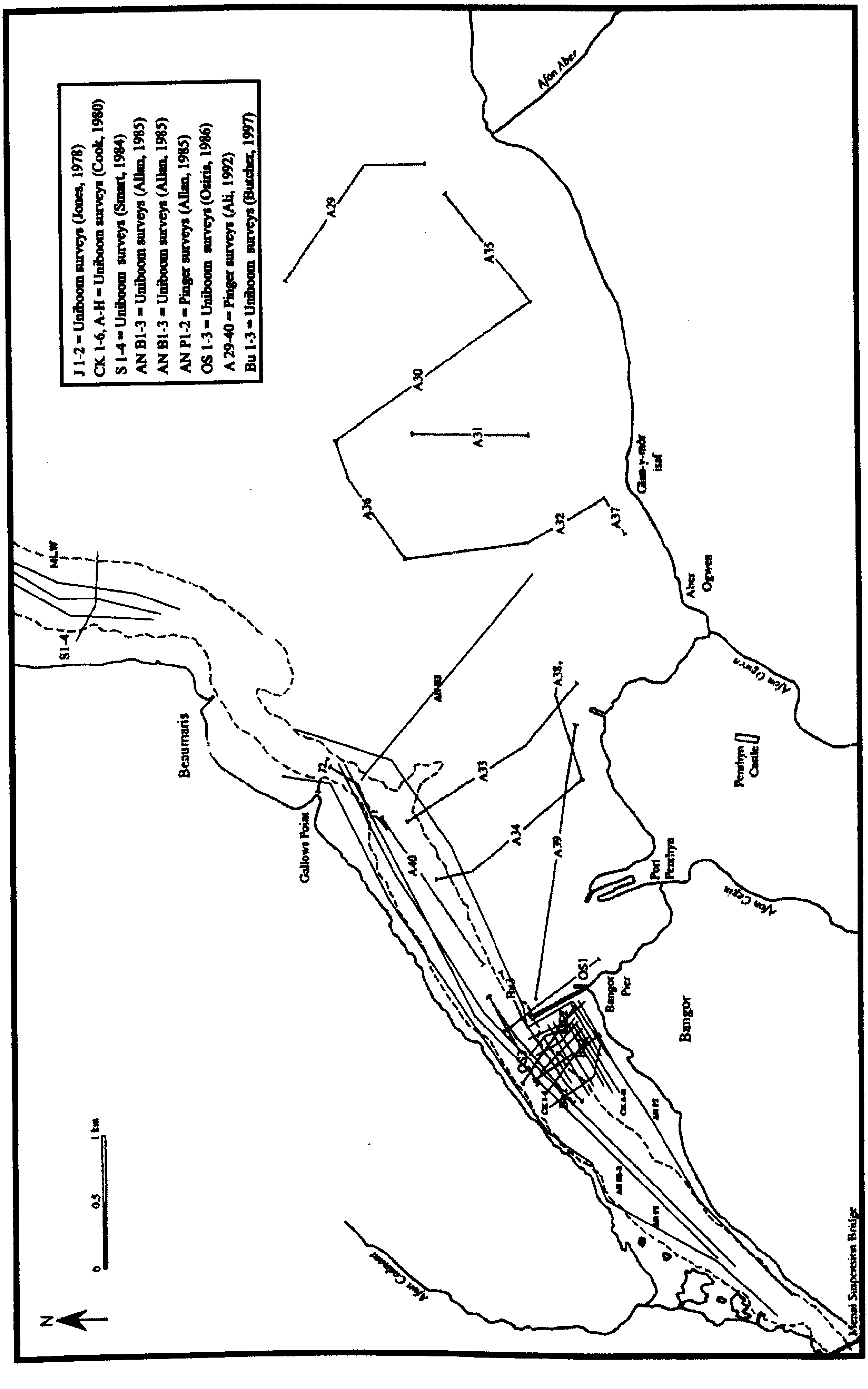
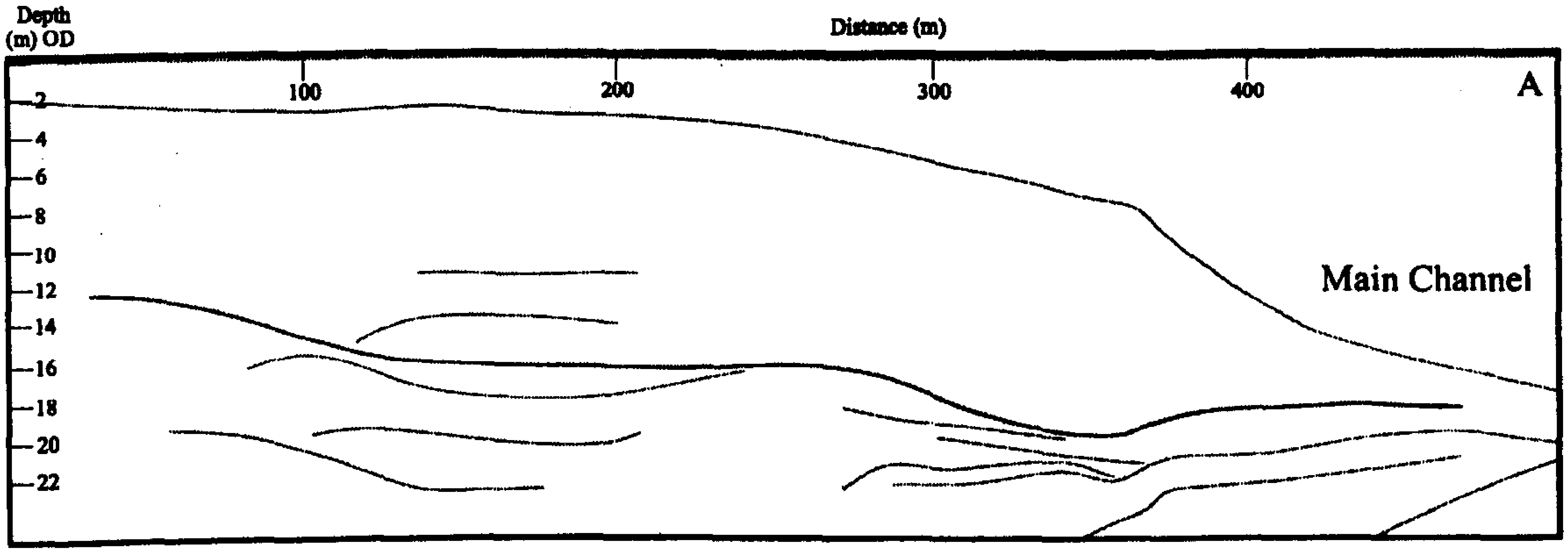
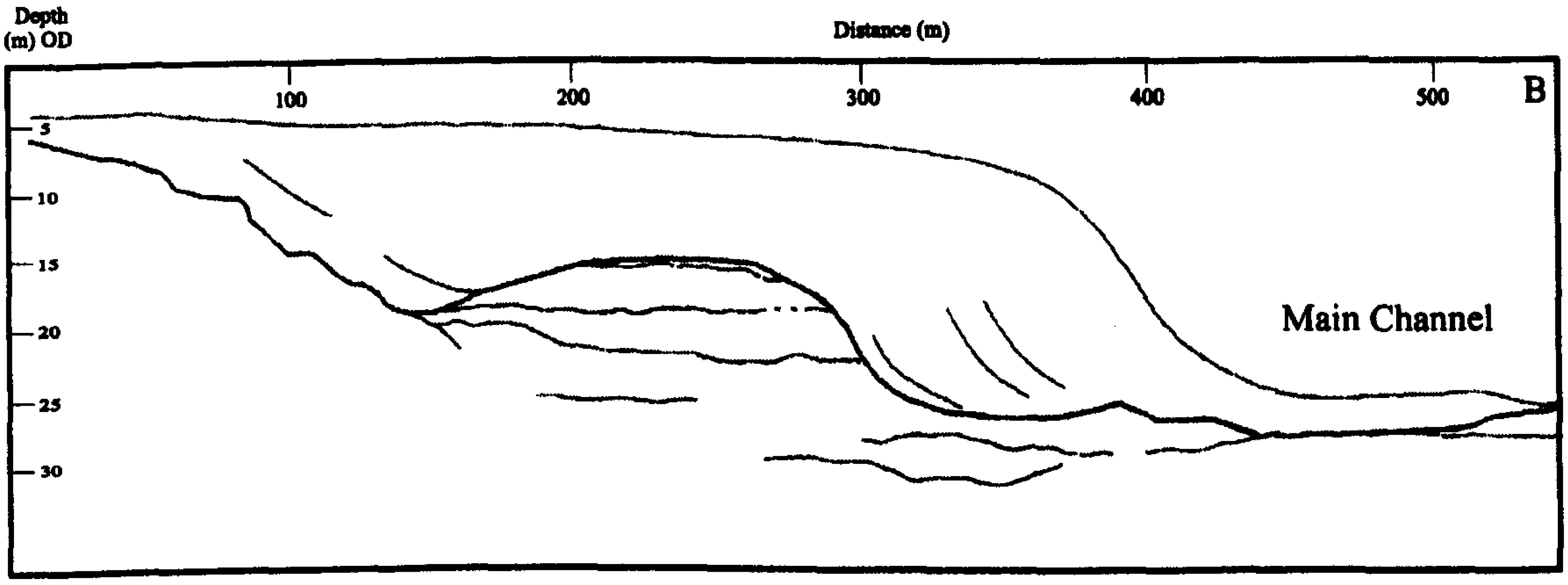


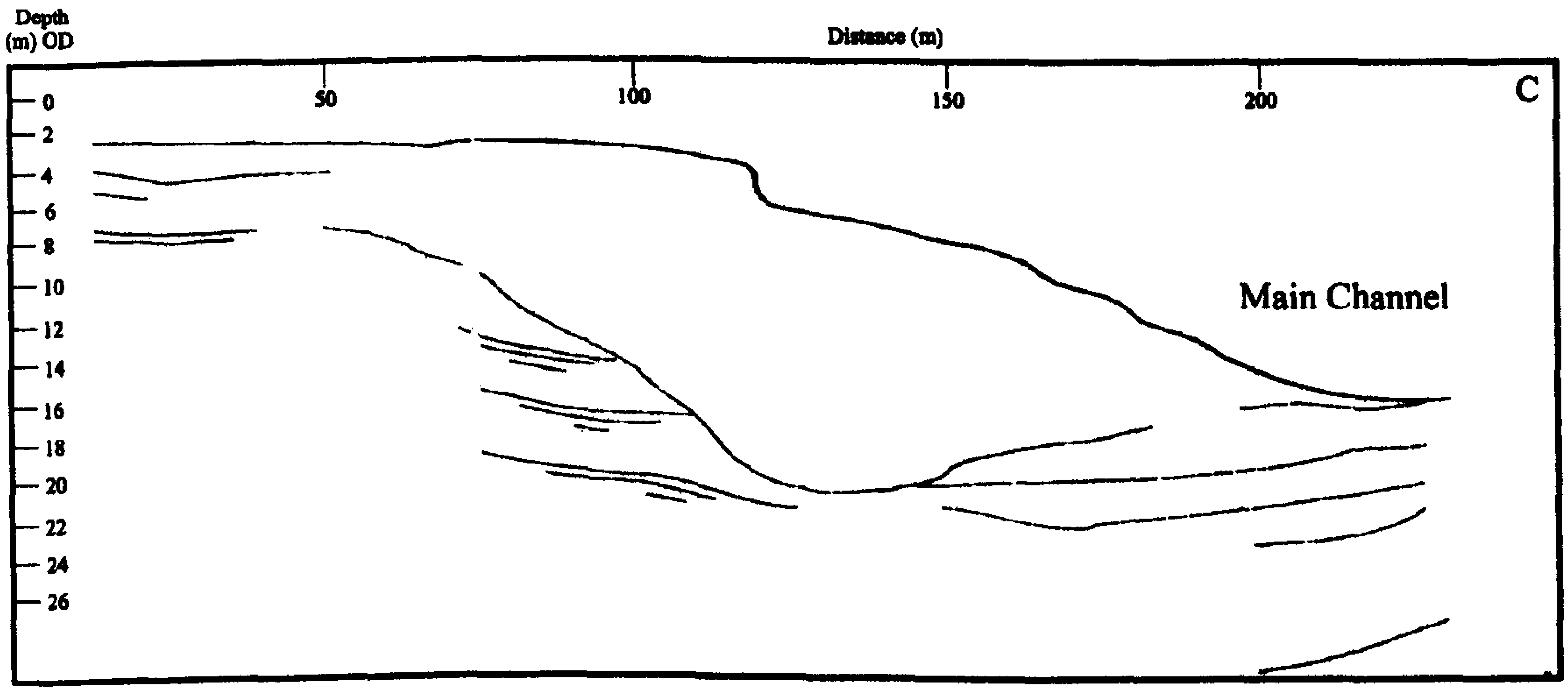
Figure 2.30 Seismic surveys conducted within the northeastern Menai Strait.



Cook (1980)



Butcher (1997)



Osiris Seaway Ltd (1986)

Figure 2.31 Interpreted seismic profiles obtained northeast of Bangor Pier truth data and subsequently resulted in the generation of 3-d cross-sectional profiles relating to the sub-surface strata (fig. 2.32). The data demonstrate that a near-continuous, well-developed sequence of marine sediments interspersed by a number of near-horizontal peat or organic-rich deposits extend out from the mainland shoreline towards Anglesey, beneath the sea bed on either side of Bangor Pier.

A geophysical investigation undertaken by Jones (1978) was conducted using a uniboom source in an area characterized by a relatively deep depression located in the main channel, 500m southwest of Gallows Point (fig. 2.33). Interpretation of the seismic data resulted in the construction of profiles which indicate the presence of intermittent horizontal reflectors at varying depths below the seabed, as shown in figure 2.34.

Additional uniboom and pinger surveys were conducted by Smart (1984), Burton (1984) and Ali (1992), the surveys encompassed the northeastern region of the Strait between Beaumaris and Puffin Island.

Interpretation of seismic data allowed Smart (1984) to distinguish the presence of two main sedimentary facies, namely glacial till and medium grained sand. The glacial till was interpreted as shallowing towards the northeast, approaching the centre of the survey area, outcropping at the surface at Lleiniog, before sloping gently to a depth of -25m OD towards the northeastern end of the survey. The data additionally suggests that this facies dips generally eastwards towards Conwy Bay. Significantly strong seismic reflection

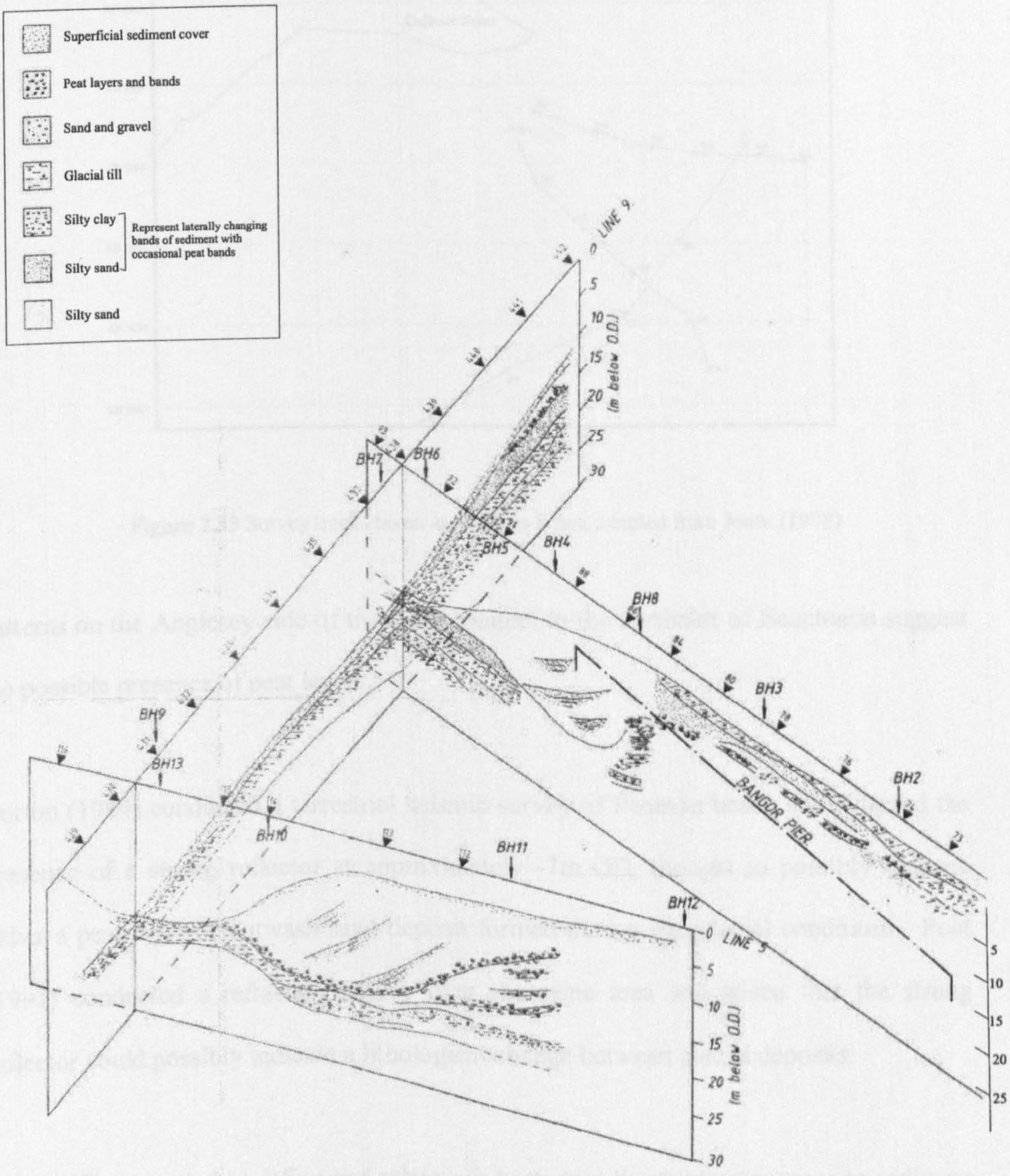


Figure 2.32 Osiris Seaway Ltd interpreted 2-d sections based on seismic and borehole data obtained northeast of Bangor Pier

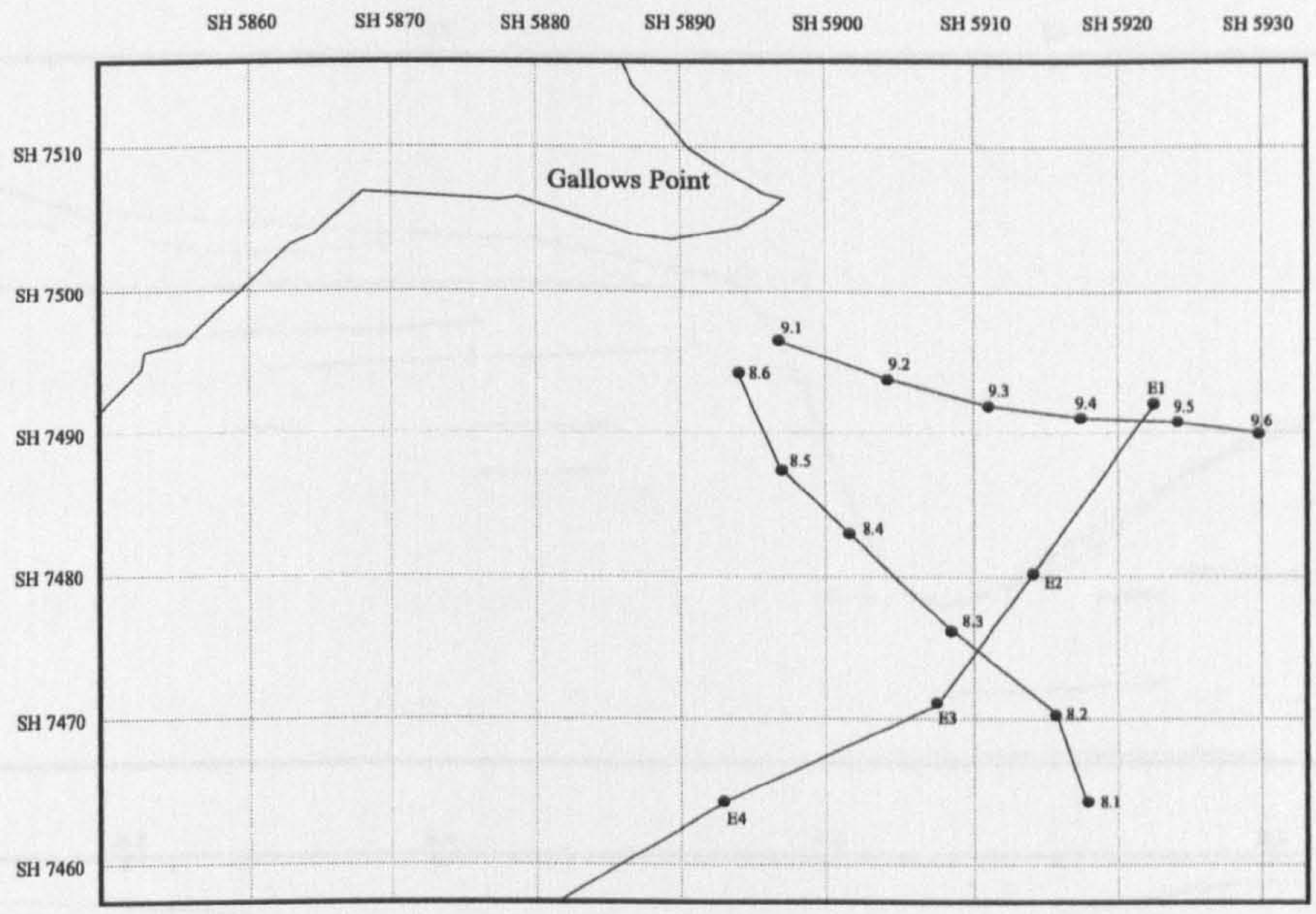


Figure 2.33 Survey tracks taken at Gallows Point, adapted from Jones (1978)

patterns on the Anglesey side of the main channel to the northeast of Beaumaris suggest the possible presence of peat layers.

Burton (1984) conducted a terrestrial seismic survey of Penmon beach and detected the presence of a strong reflector at approximately -7m OD, thought to possibly indicate either a peat layer or outwash sand deposit formed during interglacial conditions. Poat (1991) conducted a refraction survey over the same area and added that the strong reflector could possibly indicate a lithological change between glacial deposits.

Ali (1992) attempted to define and relate sub-bottom sedimentary sequences to sediment transport regimes. The interpreted data set infers the presence of three distinct reflectors, bedrock, glacial/post-glacial sediments and a modern depositional series. Contour plots

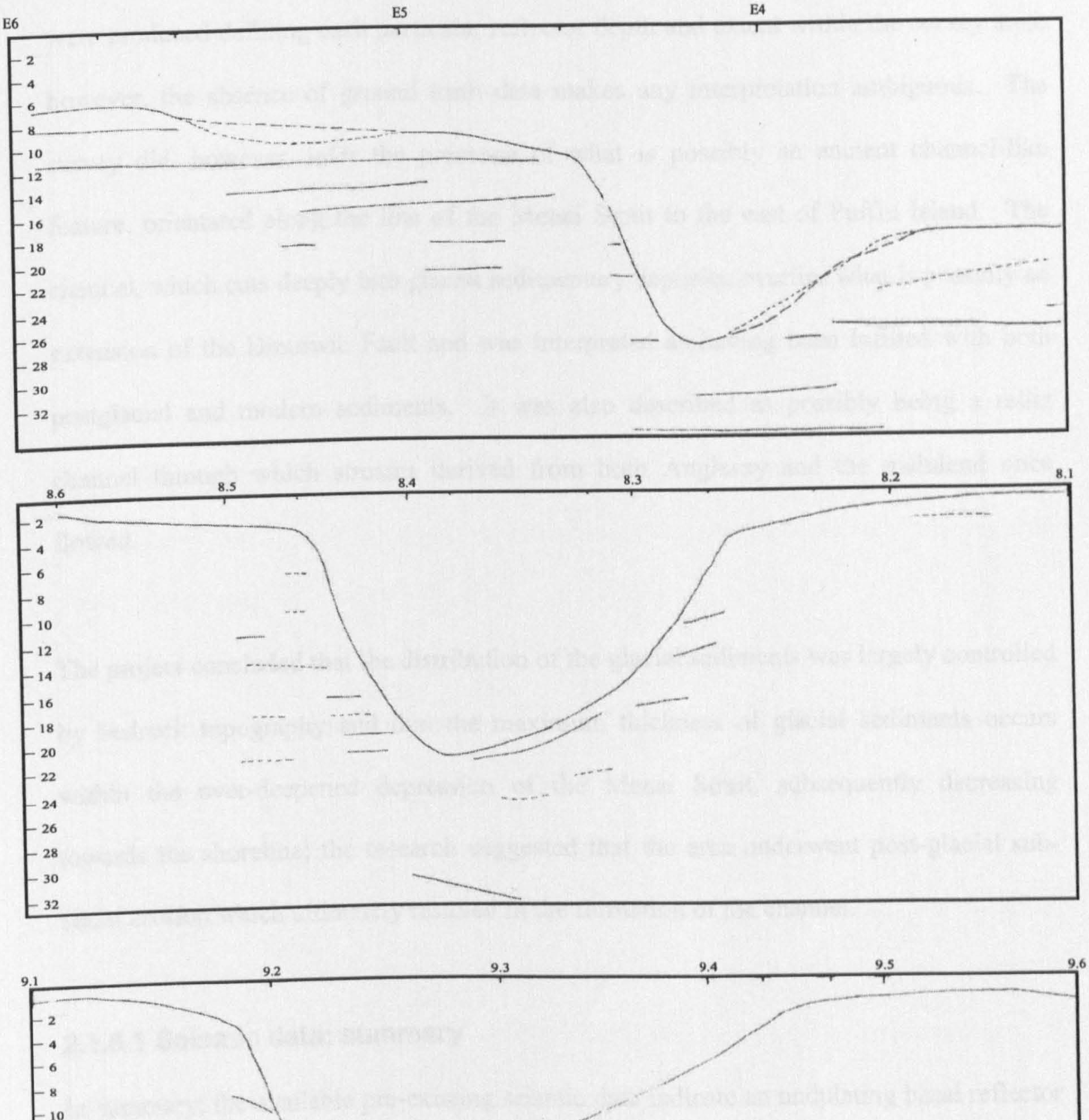


Figure 2.34 Interpreted 2-d seismic sections taken from Gallows Point, adapted from Jones (1978)

were produced defining each particular reflector depth and extent within the survey area; however, the absence of ground truth data makes any interpretation ambiguous. The survey did, however, infer the presence of what is possibly an ancient channel-like feature, orientated along the line of the Menai Strait to the east of Puffin Island. The channel, which cuts deeply into glacial sedimentary deposits, overlies what is possibly an extension of the Dinorwic Fault and was interpreted as having been infilled with both postglacial and modern sediments. It was also described as possibly being a relict channel through which streams derived from both Anglesey and the mainland once flowed.

The project concluded that the distribution of the glacial sediments was largely controlled by bedrock topography and that the maximum thickness of glacial sediments occurs within the over-deepened depression of the Menai Strait, subsequently decreasing towards the shoreline; the research suggested that the area underwent post-glacial sub-aerial erosion which ultimately resulted in the formation of the channel.

2.1.6.1 Seismic data: summary

In summary; the available pre-existing seismic data indicate an undulating basal reflector underlying a series of laterally extensive and characteristically strong near-horizontal reflective horizons that extend out across the Menai Strait beneath the sea bed. These reflectors are numerous and extensive within surveys conducted between the area surrounding Bangor Pier and Gallows Point and appear to become truncated adjacent to the main channel. The available data indicate that these reflective horizons may be less extensive and appear with decreasing frequency to the north and east of Beaumaris.

2.2 Palaeoenvironmental studies

Previous research conducted with respect to aspects of postglacial vegetational development within North Wales have been reviewed in order to provide potential correlation with data obtained from micro and macrofossil analyses conducted on sediments recovered from within the Menai Strait. The data are also useful in providing temporal and spatial data relating to terrestrial conditions within both local and regional environments, subsequent to the LGM.

The Late Devensian and Holocene sediments of Snowdonia have long been the focus for palaeoenvironmental research, based primarily upon palynological studies (Godwin, 1955; Seddon, 1957; Burrows, 1974; Lowe and Lowe, 1989; Tipping, 1993; Ince, 1995; Mighall and Chambers, 1995). As a consequence, aspects of palaeoenvironmental change and vegetational development within the region of Snowdonia are well documented, however, with respect to the low-lying regions of the Arvonian platform and Anglesey little has as yet been published.

2.2.1 Watkins (1991)

Watkins (1991) produced a PhD thesis describing the results of an investigation designed to elucidate the Postglacial vegetational history of lowland lake sites in Gwynedd, utilizing detailed palynological analysis integrated with the radiocarbon dating of organic-rich sediments. A series of ^{14}C dated pollen biostratigraphical diagrams were produced, including one pollen diagram derived from data obtained from Llyn Cororion (fig. 2.35), a small freshwater lake located at approximately 82.5m OD on the Arfon Platform 3km south, southeast of Bangor (Ordnance Survey grid reference: SH 5970, 6875). The diagram identified eight localized pollen assemblage zones within the immediate area surrounding the lake, ranging between approximately 9700 ^{14}C years BP and the present.

The data indicate that an early Post-glacial phase of *Juniperus-Betula* scrub, was succeeded an open *Betula-Corylus* woodland. *Quercus* and *Ulmus* are inferred to have become established by approximately 8800 ^{14}C years BP, prior to a rapid expansion of *Pinus* which occurred soon after. A decline in *Pinus* approximately 7750 ^{14}C years BP coincided with the arrival of *Alnus,* followed by the arrival of *Fraxinus* and *Tilia* at approximately 6500 ^{14}C years BP. The decline in *Ulmus* is dated at Llyn Cororion as occurring at approximately 5000^{14}C years BP and coincides with a reduction in *Tilia* and with a temporary decline in *Quercus*. The research further indicates that anthropogenic activity did not have an appreciable impact upon the landscape until at least 3000 ^{14}C years BP, after which time there appears to be a significant decline with respect to the populations of *Quercus*, *Corylus* and *Betula*.

Records derived from research conducted by Watkins (1991) at other sites within the region also indicate similar successions; however the timing of each event is often significantly different, which illustrates the time-transgressive nature of vegetational

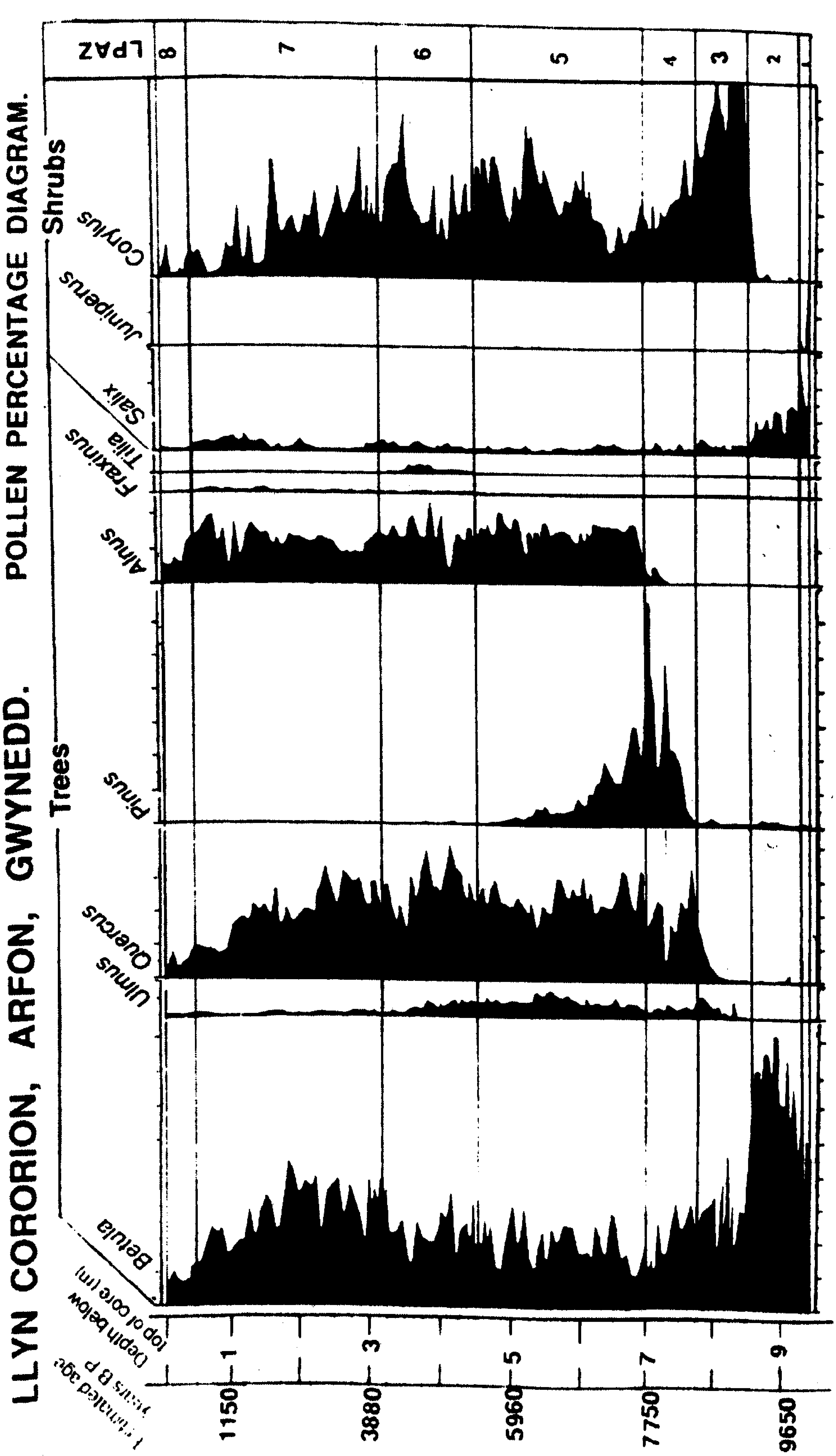


Figure 2.35 Pollen diagram derived from research conducted at Llyn Cororion by Watkins, 1991. From Addison *et al.* (1990).

evolution and highlights the difficulty in attempting to correlate sites accurately without using absolute dating techniques.

2.3 Synopsis

2.3.1 Sea-level change in North Wales

A substantial volume of scientific literature has been produced in relation to sea-level change subsequent to the LGM for much of northwest England, significantly less research however, has been conducted with respect to sea-level change in North Wales. Previously conducted research (Heyworth and Kidson, 1982; Prince, 1988; Bedlington, 1994) has additionally failed to adequately define and quantify the nature of relative sea-level change in North Wales during the Late Pleistocene and early Holocene. Pre-existing studies do however, suggest that relative sea levels were probably rising rapidly throughout the early to middle Holocene from somewhere around -25m OD at the onset of the Holocene before rising less significantly after around 5000 BP, after which time, relative sea level was a likely to have been a few metres lower than its contemporary value.

Pre-existing research has additionally, drawn on evidence taken from a wide geographical area ranging from the western coast of Anglesey to coastal areas within the Clwyd Plain rather than utilizing data obtained from one relatively small and well defined area. Compilation of such data in order to define a sea-level history that relates to one coastal region may introduce a significant degree of error due in part to differential crustal behaviour and more significantly due to the fact that distinctly separate areas within one coastal region will posses unique sedimentological regimes that ultimately result in different coastal evolutionary histories.

Existing glacio-hydro-isostatic models (Lambeck, 1995; Lambeck, 1996; Peltier *et al*, 2002) additionally indicate that much of Liverpool Bay to the north of the present day coastline of North Wales experienced a marine transgression at some point during the early-middle Holocene. The timing of this transgression and the position of the coastline throughout this period however, is inadequately defined on a local and to some extent, even regional scale.

2.3.2 Pre-existing data

Integration of pre-existing seismic (Jones, 1978; Cook, 1980; Smart, 1984; Allan, 1985; Ali, 1992 and Butcher, 1997) and ground truth data obtained from sediment cores recovered from the northeastern region of the Menai Strait (Osiris Seaway Ltd, 1986) indicate that well developed sequences of modern sediment have been deposited above glacial and post-glacial material that in turn overlie the bedrock forming the basement of the Menai Strait. The modern deposits located between Bangor Pier and Gallows Point consist predominantly of marine sediments which are probably intercalated with many relatively thin, near-horizontal beds of peat or organic-rich material located between depths of -6m and -30m OD. These organic deposits appear to be both laterally extensive and continuous, extending out on either side of the Strait towards the main channel. Additionally, the organic formations are predominantly interbedded within very fine clay and silt deposits, which are in turn under and overlain by coarser formations consisting predominantly of sand with some layers of gravel.

Pre-existing borehole, seismic and palaeoenvironmental data indicate that the sediments deposited between Bangor Pier and Gallows Point may provide the necessary evidence required in order to elucidate and quantify the nature of sea-level change experienced within North Wales throughout the early Holocene. The material may additionally provide evidence that could be utilized in order to discern aspects of palaeoenvironmental change that have occurred within the region of the Menai Strait and further constrain and refine existing glacio-hydro-isostatic models. The significant volume of pre-existing data obtained from within the northeastern region of the Menai Strait can moreover, be utilized in order to identify specific 'target' locations within the study area that should be sampled via any future coring programme. The data indicate that coring undertaken at these target locations should result in the acquisition of material that may have been deposited during the early and middle Holocene and therefore provide the evidence necessary to determine the altitude of MSL at specific intervals within this time frame from within a relatively small area.

Chapter 3

3 Introduction

Chapter three describes the laboratory and field techniques utilized during the course of the research project, the chapter describes the acquisition and study of three sediment cores (fig. 3.1) obtained from the northeastern Menai Strait. The chapter additionally describes aspects of a geophysical survey conducted as part of the fieldwork program.

3.1 Fieldwork program

A primary objective of the fieldwork program was to obtain a series of sediment cores from a relatively small area within the Menai Strait. Target areas were identified utilizing previously conducted research in order to capitalize on the possibility of recovering specific stratigraphic units, that could subsequently be subjected to a range of laboratory based analytical techniques. The seismic reflection survey of the area was designed to supplement the coring program by providing data relating to both the lateral and vertical extent of specific deposits contained within the sediment cores.

3.1.1 Levelling

The elevation of the sea-floor at the position of Cemlyn-Jones Sediment Core 1 (CJSC 1), adjacent to the end of Bangor Pier was measured in relation to a temporary bench mark (TBM) located on the deck of the drilling platform 'Coastal Explorer' using a standard cloth measuring tape. The height of the deck was subsequently measured in relation to another temporary bench mark located on Bangor Pier using a Wild T1 laser

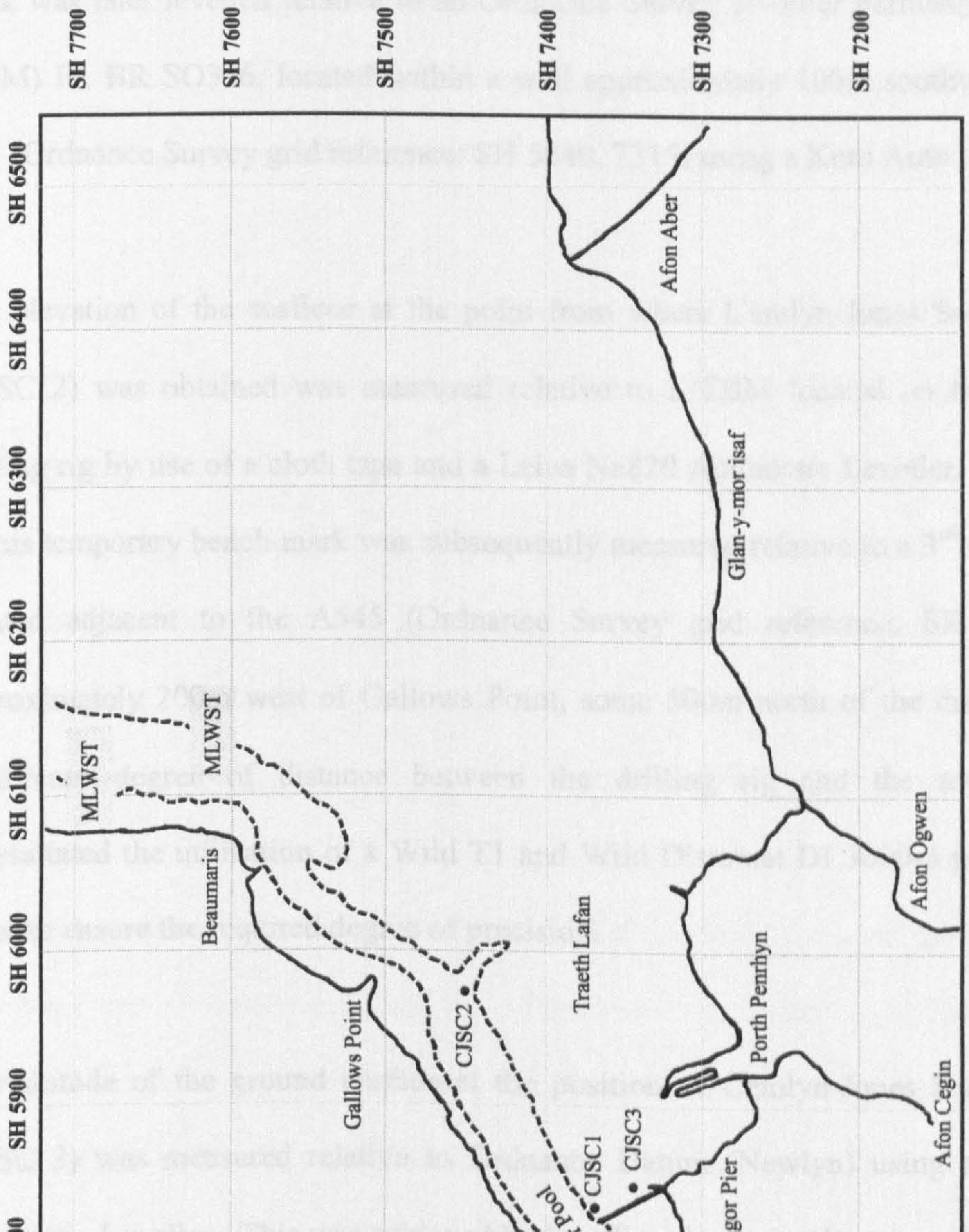


Figure 3.1 Location of sediment cores obtained during the fieldwork program

measuring device and a Wild Distomat DI 3000-1 prism system. The temporary bench mark was later levelled relative to an Ordnance Survey 1st order permanent bench mark (PBM) FL BR SO336, located within a wall approximately 100m southwest of Bangor Pier (Ordnance Survey grid reference: SH 5840, 7315) using a Kern Auto leveller.

The elevation of the seafloor at the point from where Cemlyn-Jones Sediment Core 2 (CJSC 2) was obtained was measured relative to a TBM located on the deck of the drilling rig by use of a cloth tape and a Leica Na820 Automatic Leveller. The elevation of this temporary bench mark was subsequently measured relative to a 3rd order OS PBM located adjacent to the A545 (Ordnance Survey grid reference: SH 5964, 7515), approximately 200m west of Gallows Point, some 500m north of the drilling rig. The significant degree of distance between the drilling rig and the secondary TBM necessitated the utilization of a Wild T1 and Wild Distomat DI 3000-3 prism system in order to ensure the required degree of precision.

The altitude of the ground surface at the position of Cemlyn-Jones Sediment Core 3 (CJSC 3) was measured relative to Ordnance Datum (Newlyn) using a Leica Na820 Automatic Leveller. This was achieved by levelling the coring location relative to the 1st order OS PBM also used in determining the level of CJSC 1.

3.1.2 Position fixing

The location of the point at where drilling commenced, was in all cases determined using a hand-held Garmin 76S Differential Global Positioning System (DGPS) receiver unit, with the co-ordinates being presented as 8 figure OS grid references related to the OSGB36 datum. The position of the two sub-tidal sediment cores was also recorded using an onboard DGPS system, with the co-ordinates being presented in degrees of latitude and longitude initially related to the WGS 84 datum.

3.1.3 Coring

Logistical and technical restraints imposed by conditions found within the marine environment often restrict or deny sea-level researchers any prospect of recovering significantly extensive sequences of sediment from inter-tidal and sub-tidal regions. An opportunity to acquire the services of an industrial 'jack up' drilling rig arose during March 2002 and the rig was subsequently utilized in order to recover sedimentary sequences from normally inaccessible zones located within the study area.

The sediment coring phase of the research project employed two separate coring systems which use similar principal techniques. The systems consisted of an industrial jack-up platform incorporating a free-fall cable tool percussive boring unit, together with a rotary drilling system and a terrestrial Eijkelkamp hand-held percussion coring unit.

3.1.3.1 Marine coring operation

The industrial jack-up drilling platform employed in order to recover sediment cores from sub-tidal areas within the Menai Strait was owned and operated by Seacore Limited, a United Kingdom based marine drilling contractor. The 'Coastal Explorer' mobile drilling rig (fig. 3.2a) employed by Seacore Limited consisted of a hydraulically powered

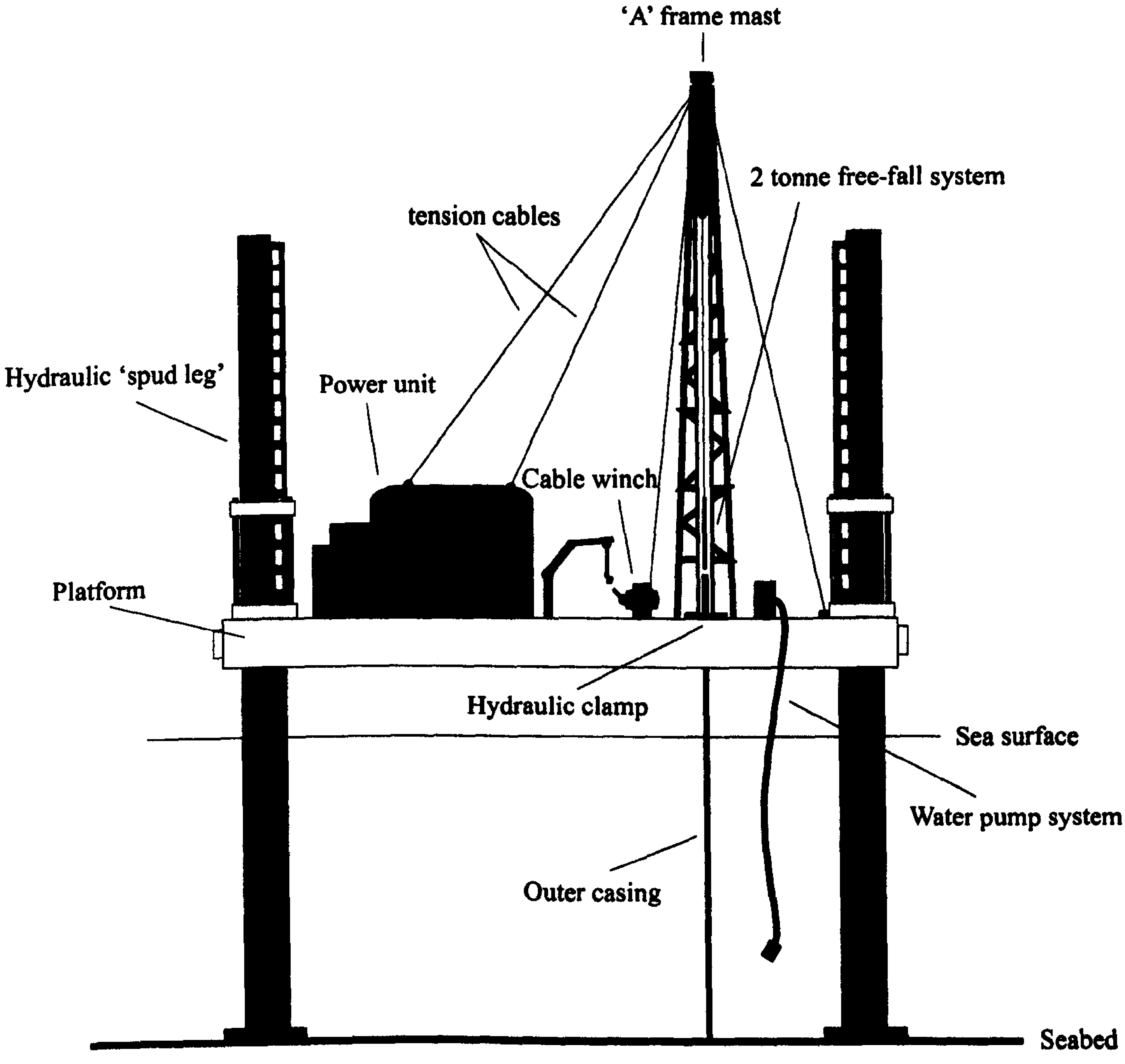


Figure 3.2a) Schematic of the Seacore coastal drilling rig 'Coastal explorer'

working platform, adjustably elevated with respect to the position of sea level by virtue of four hydraulically driven 'spud' legs. The platform incorporated a twin 12m x 2.1m 'A' frame mast which integrated an Edco/Pilcon 2 tonne free-fall winch for cable tool and percussive boring, together with a Dando 250 hydraulic swivel rotary drilling unit. The dual system provided the means to recover continuous sequences of fine grained cohesive sediments, together with an enhanced penetrative ability resulting in the recovery of sands and the capability to continue coring if denser materials were encountered. The system also utilized a hydraulically powered deck clamp used to secure drill casings, together with a mechanical deck tipping unit designed to improve the efficiency of sediment core removal.

The drilling rig was positioned using a GPS navigational system, proximate to or directly above pre-determined target sites, with final positioning accuracy being attained by virtue of the individual and alternate manoeuvrability of each leg. An outer drill casing consisting of a series of 1.5m long, 150mm diameter, threaded steel tubes was subsequently deployed and extended between a hydraulic clamp located on the deck of the platform and the sea-floor. A 0.45m long 100mm diameter PVC sampling tube, located within an open ended steel auger percussive drilling unit, containing a 20mm long cutting head, was then deployed into the outer casing and lowered to the seafloor via a steel cable by means of winch system (fig. 3.2b). A percussive hammer within the sampling unit was continuously raised and allowed to free-fall onto the sediment sampler until the required penetration depth was attained.

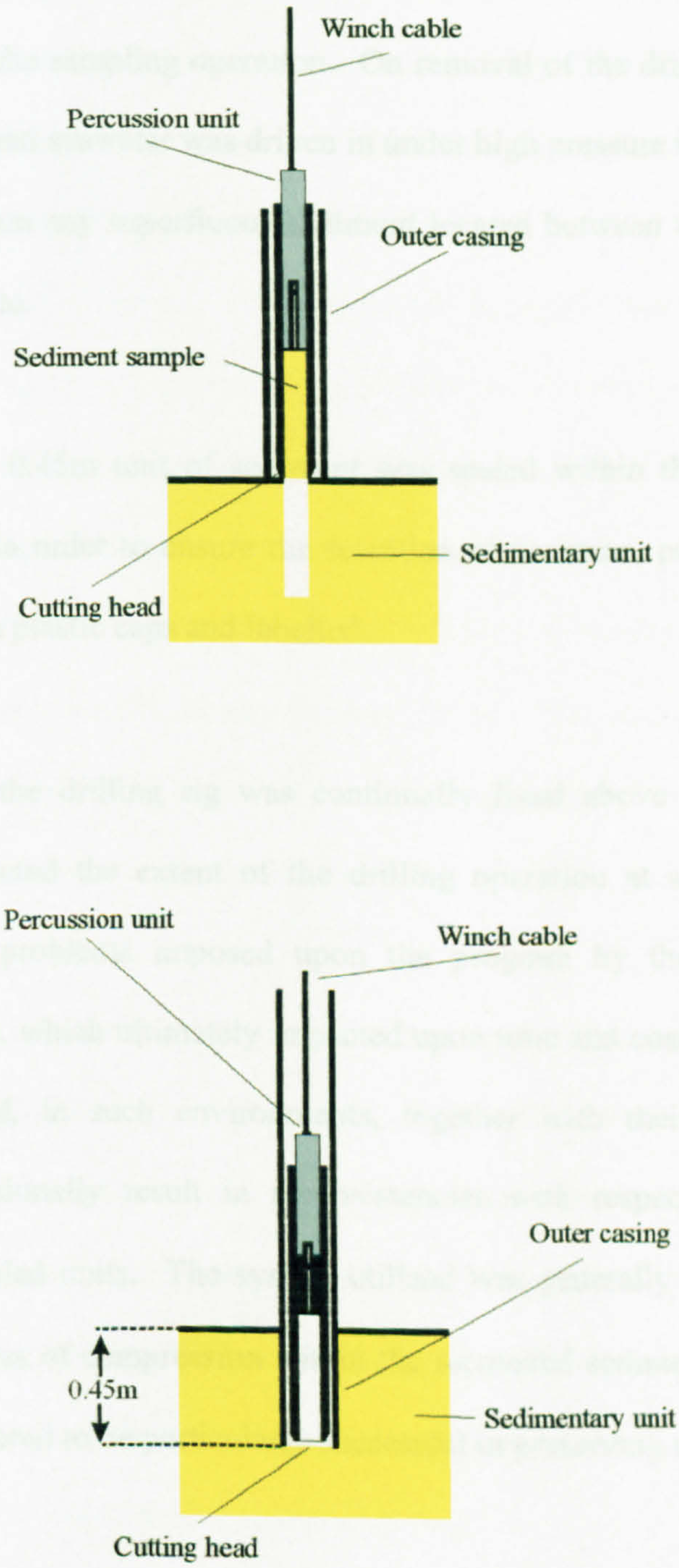


Figure 3.2b) Schematic of the sediment sampling procedure

Subsequent to the removal of the drilling unit and recovery of the sediment sample, the outer casing was driven percussively into the sediment until its maximum depth equated that attained through the sampling operation. On removal of the drilling unit the casing was sealed at the top and seawater was driven in under high pressure in order to pump out or drive into suspension any superfluous sediment located between the outer casing and the base of the borehole.

Upon recovery, each 0.45m unit of sediment was sealed within the sampling tube at either end with wax in order to ensure the retention of moisture, prior to the sampling tube being sealed with plastic caps and labelled.

As the elevation of the drilling rig was continually fixed above MHWST, the only constraints that restricted the extent of the drilling operation at a particular location related to logistical problems imposed upon the program by the properties of the materials encountered, which ultimately impacted upon time and cost. The variability of materials encountered, in such environments, together with their inherent physical properties, can occasionally result in inconsistencies with respect to the degree of recovery within sampled units. The system utilized was generally thought to result in relatively small degrees of compression within the recovered sedimentary sequences (5-15%) and was considered to be particularly successful in preserving depositional features (Walley, 1996).

3.1.3.2 Inter-tidal coring operation

The Eijkelkamp coring system (Model 04.18) (fig. 3.3a), is a particularly cost-effective and appropriate method for recovering reasonably long sequences of fine grained cohesive sediments within terrestrial and inter-tidal environments and was therefore used for this specific purpose. The system was powered by a Benford HP40 MK11 Power Pack hydraulic power unit, linked to a Stanley BR40 hydraulic breaker, which provided the energy required in order to drive the sediment sampler into the ground. The sampling unit consisted of a reinforced 50mm diameter, 1m long steel auger with a hardened steel cutting head, containing a 45mm, 1m long diameter plastic sampling sleeve. The auger was driven percussively into the ground by means of the power-driven hydraulic breaking unit, without employing the use of any drilling fluids. The coring system recovered incremental 1m core samples of sediment by attaching 1m steel extension rods placed between the drilling auger and the hydraulic breaking unit.

Sediment samples were recovered using a manual extraction system consisting of a ball clamp and mechanically driven rod pulling unit, utilizing dual steel rods which provided sufficient leverage in order to extricate the drilling auger from beneath the surface (fig. 3.3b). The plastic sleeve containing the recovered sediment sample was removed, sealed, labelled and replaced following each incremental 1m drilling procedure; prior to the operation being repeated, an additional extension rod was attached in order to ensure that drilling commenced at the succeeding appropriate level.

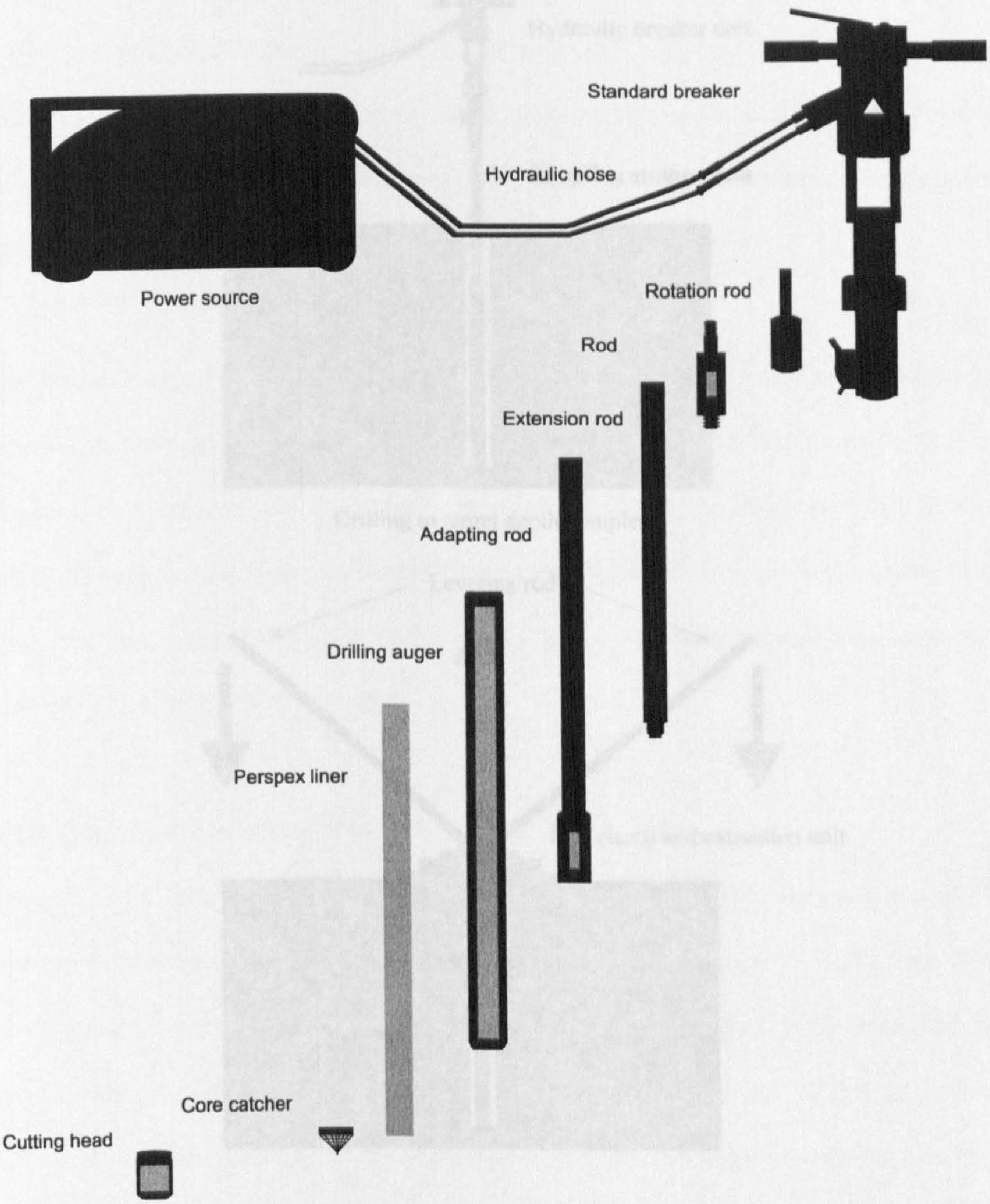


Figure 3.3a) Eijkelkamp terrestrial drilling apparatus

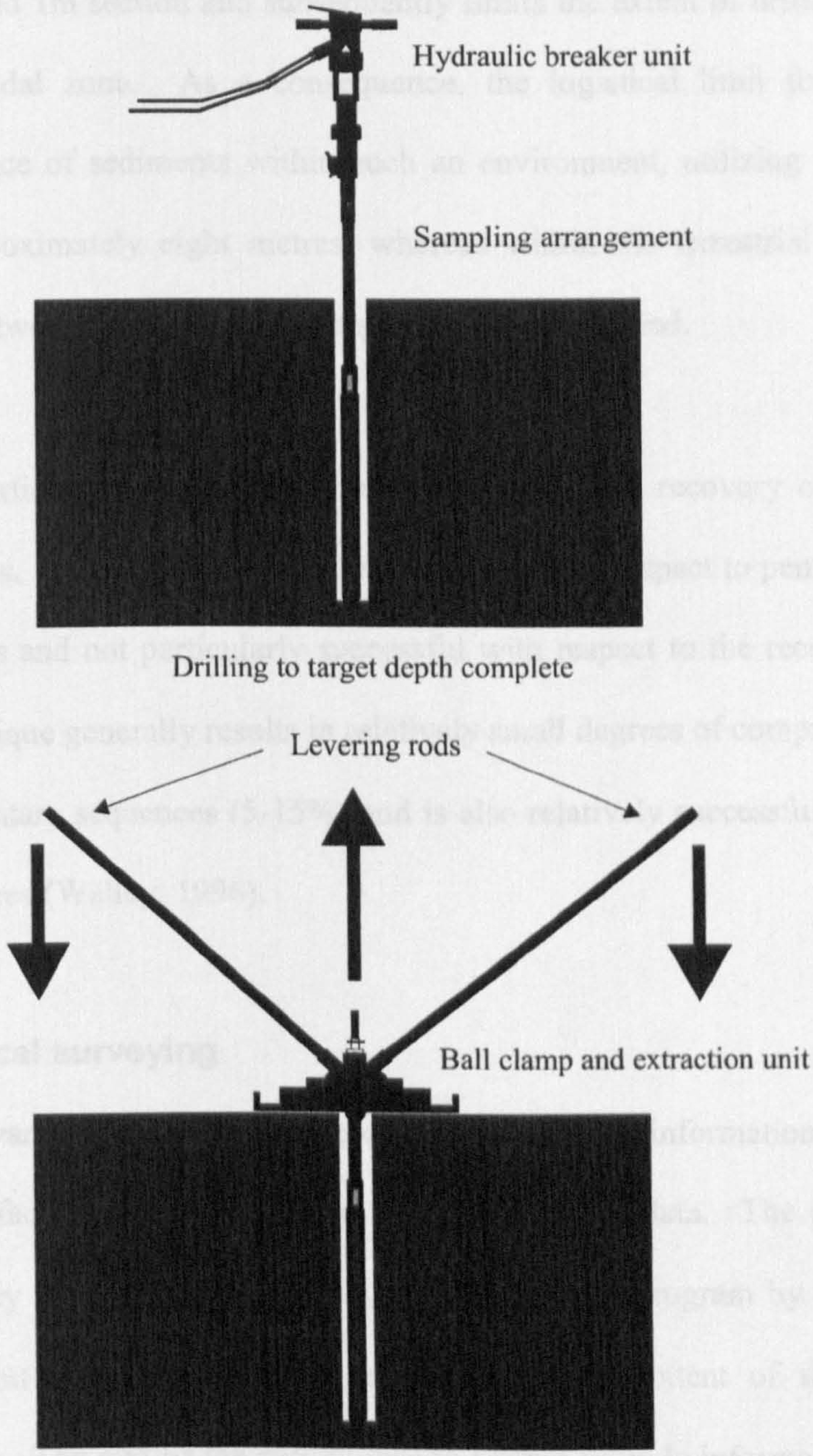


Figure 3.3b) Drilling assembly and extraction system

The time taken in order to recover successive samples of sediment, however, increases with each recovered 1m section and subsequently limits the extent of drilling operations within the inter-tidal zone. As a consequence, the logistical limit for obtaining a continuous sequence of sediments within such an environment, utilizing this particular technique, is approximately eight metres, whereas within the terrestrial environment, cores in excess of twenty metres have been successfully recovered.

The method is particularly successful when employed in the recovery of fine grained cohesive sediments. However, it is much less effective with respect to penetrative ability within clean sands and not particularly successful with respect to the recovery of loose gravel. The technique generally results in relatively small degrees of compression within recovered sedimentary sequences (5-15%) and is also relatively successful in preserving depositional features (Walley, 1996).

3.1.4 Geophysical surveying

It can often be advantageous to integrate geophysical data with information relating to the nature of sub-surface stratigraphy derived through borehole data. The purpose of the geophysical survey was to supplement the sediment drilling program by providing data that would delimit and determine the nature and lateral extent of the sub-surface sedimentary units. The aim of the survey was to further provide information relating to aspects of the antecedent topography which could subsequently be integrated with the sedimentological and biostratigraphical data in order to aid palaeoenvironmental reconstruction.

3.1.4.1 Seismic reflection surveying

Within the field of applied seismology, information is largely obtained from surface recordings relating to the response of sub-surface formations to compressional waves generated by a seismic source at or below the ground surface. Seismic energy radiates outward from a source in the form of a spherical wave-field (for a constant transmission velocity medium) and the diameter of the sphere will subsequently increase with increasing distance from the source, effectively ensuring that wave-fronts tend towards approximating to plane surfaces. The seismic source imparts energy into the ground which creates a cyclic stress within the propagating medium which, in turn, creates very small strain (displacement). At small strain levels, natural materials such as unconsolidated sediment behave as an elastic medium i.e. no plastic deformation occurs as part of the transmission of seismic waves and therefore, the laws of elasticity can be applied (D Huws, pers. comm. 2005).

Two specifically different types of wave can propagate through elastic media (more can occur at the interfaces between media but are not considered here); these waves are referred to as body waves and divide into compressional waves (P-waves) and shear waves (S-waves). Compressional waves propagate through a medium by the alternate compression and dilation of encountered particles contained within the medium, whilst the shear waves displace particles perpendicular to the direction of propagation.

Seismic reflection surveying effectively measures the time taken for compressional wave energy to be reflected back from an interface between two media of contrasting 'acoustic impedance' (fig. 3.4). Acoustic impedance can be related to the inherent physical properties of a medium and is simply the product of a given media's density and compressional wave transmission velocity. Travel times can subsequently be utilized in conjunction with transmission velocity data in order to determine the distance of a given reflective horizon from a compressional wave source-receiver system. General and basic introductions relating to the fundamental principles and techniques associated with seismic reflection surveying can be in found in a number of text books including those of Telford *et al* (1990), Kearey and Brooks (1991) and Reynolds (1997).

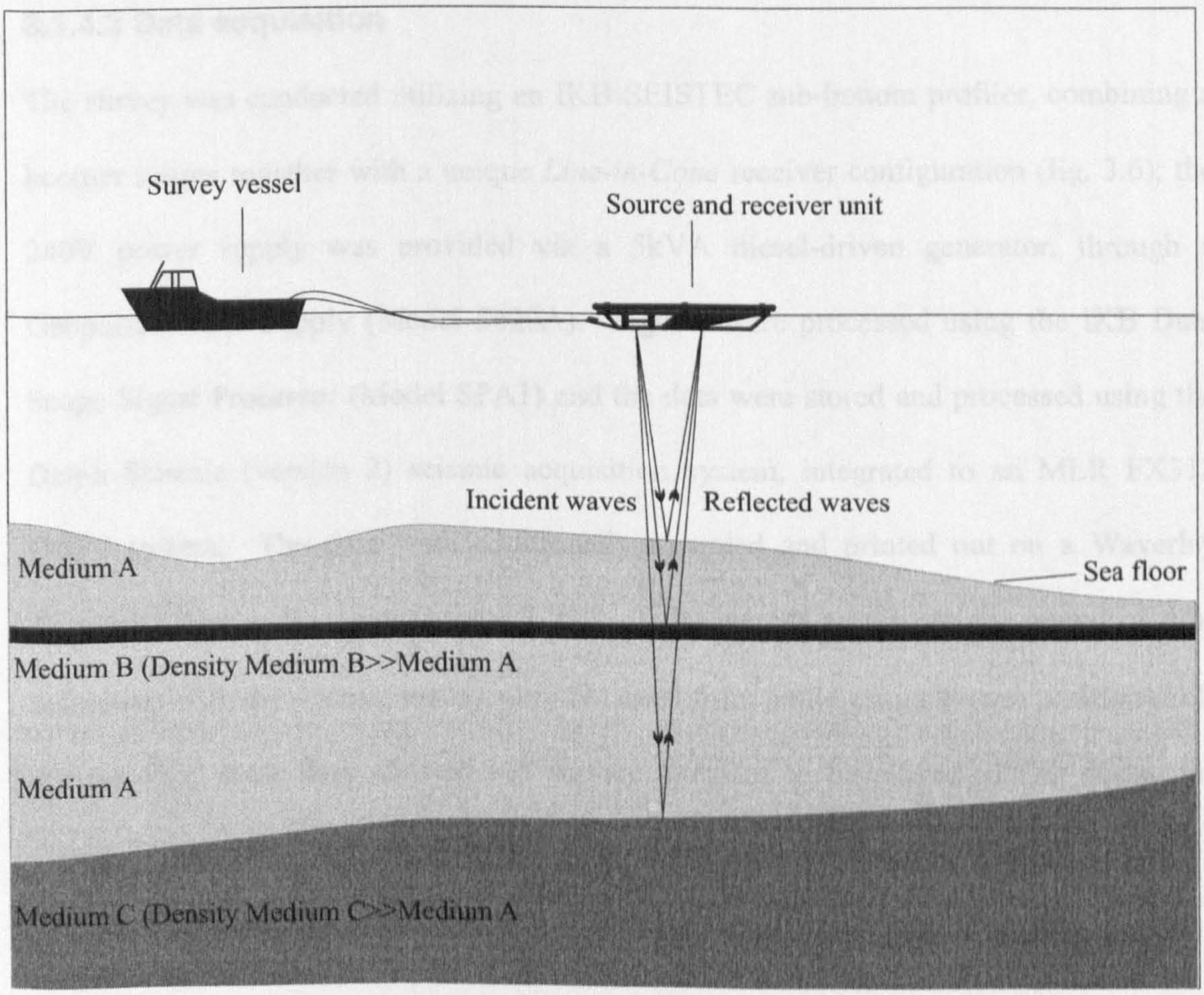


Figure 3.4 Schematic of a seismic reflection survey

3.1.4.2 The seismic survey

A seismic reflection survey (fig. 3.5) was conducted within the northeastern region of the Menai Strait between the 14th and 15th of July 2003, specifically between Bangor Pier and the northeastern side of Gallows Point. The survey area encompassed the inter-tidal region of the Lavan Sands and the sub-tidal zone within the main channel and, for the purposes of seismic profiling, can be considered as a shallow water environment; details relating to the orientation and position of the survey lines are presented within chapter four.

3.1.4.3 Data acquisition

The survey was conducted utilizing an IKB-SEISTEC sub-bottom profiler, combining a boomer source together with a unique *Line-in-Cone* receiver configuration (fig. 3.6); the 240V power supply was provided via a 5kVA diesel-driven generator, through a Geopulse Power Supply (Model 5420A). Signals were processed using the IKB Dual Scope Signal Processor (Model SPA1) and the data were stored and processed using the Delph Seismic (version 2) seismic acquisition system, integrated to an MLR FX312 DGPS system. The data were additionally recorded and printed out on a Waverley Thermal Linescan Recorder (Model 3700). Tidal heights relating to the period of time coincident with the seismic survey were obtained from a tide gauge system positioned off Bangor Pier, these data allowed sea surface altitudes to be related to OD during the survey period.

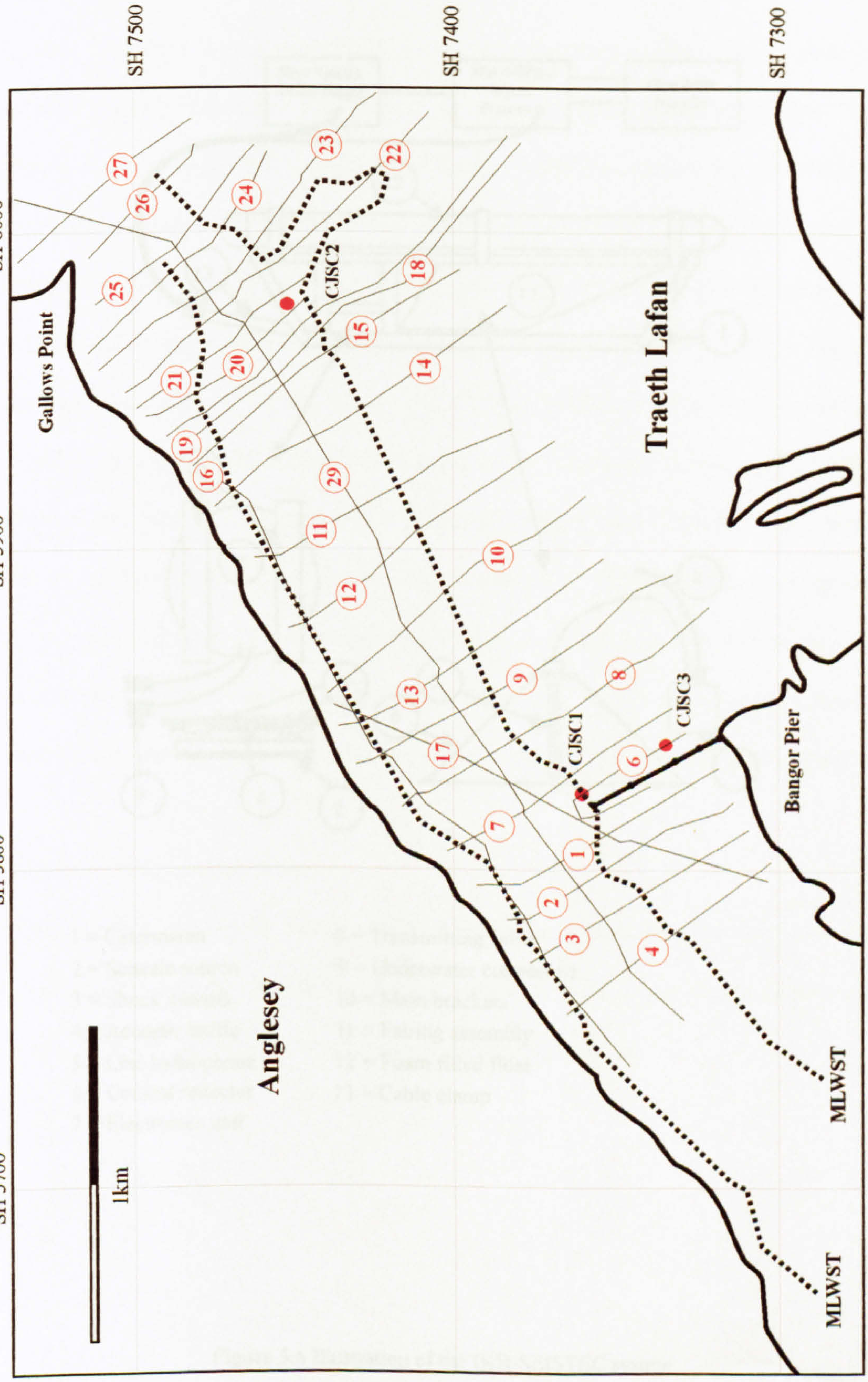
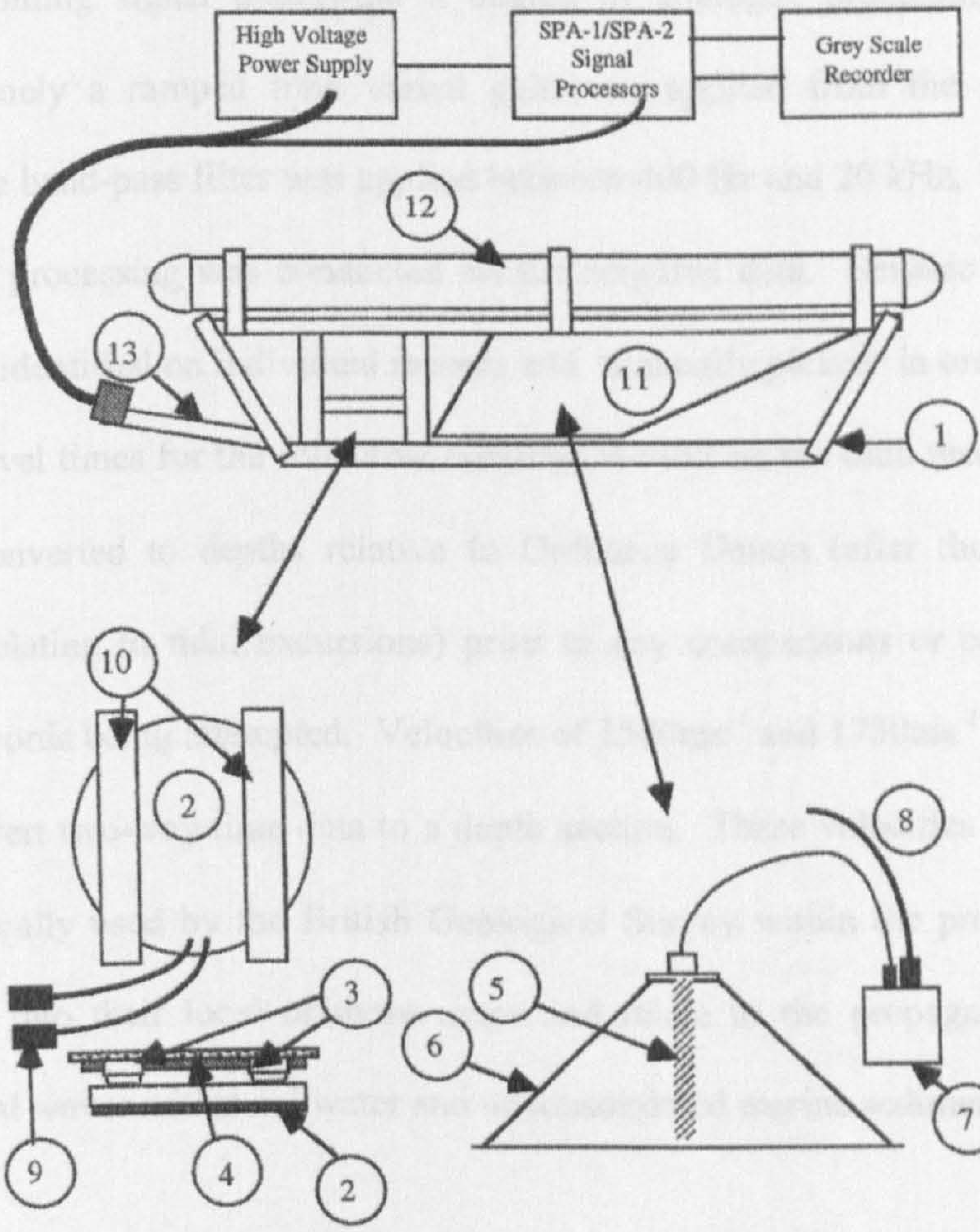


Figure 3.5 Seismic survey transects



1 = Catermaran
2 = Seismic source
3 = Shock mounts
4 = Acoustic baffle
5 = Line hydrophone
6 = Conical reflector
7 = Electronics unit
8 = Transmitting cable
9 = Underwater connectors
10 = Main brackets
11 = Fairing assembly
12 = Foam filled float
13 = Cable clamp

Figure 3.6 Illustration of the IKB-SEISTEC system

3.1.4.4 Interpretation

The raw incoming signal underwent a degree of analogue processing before being recorded; namely a ramped time varied gain was applied from the seafloor arrival onwards and a band-pass filter was applied between 400 Hz and 20 kHz. Other than this, no additional processing was conducted on the acquired data. Seismic reflectors were subsequently identified on individual records and 'manually picked' in order to determine individual travel times for the reflective horizons viewed on the each record. These data were then converted to depths relative to Ordnance Datum (after the application of corrections relating to tidal excursions) prior to any comparisons or correlations with additional records being attempted. Velocities of $1500ms^{-1}$ and $1750ms^{-1}$ were utilized in order to convert two-way time data to a depth section. These velocities were applied as they are typically used by the British Geological Survey within the production of data incorporated into their local offshore maps and relate to the propagation velocity of compressional waves within saltwater and unconsolidated marine sediments respectively.

3.2 Laboratory procedures

The multi-proxy, laboratory based, analytical program was designed to obtain data from the sedimentary sequences obtained during fieldwork which would further provide the means to elucidate aspects of local palaeoenvironmental change.

3.2.1 Sediment description

Stratigraphic descriptions and core logs relating to the sediments recovered during fieldwork are based primarily on visual description. The sediment cores have been divided into sequential units principally based on variations in lithology. Estimates and descriptions relating to grain size are based on Troels-Smith (1955) whereby sedimentary components possess a unique abbreviation relating to their principal constituents where:

As = Argilla steatodes (clay)
Ag = Argilla granosa (silt)
Ga = Grana arenosa (medium and fine grained sand)
Gs = Grana saurralia (coarse sand)
Gg = Grana glareosa (gravel)

The relative proportion of sediment grain sizes within a particular unit of a sediment core is indicated on a four point scale such that, at all times the sum constitutes four. At points where minor contributions of other elements contribute to the overall sedimentary assemblage, the minor constituents are indicated by the + symbol. Sediment colour is indicated by the use of alphanumeric Munsell Soil Colour Charts. Verbal descriptions are additionally provided and relate to the general appearance of the sediment together with a description of any visible internal structure or characteristic. Elevations are provided alongside the sediment core logs with respect to depth (m) in relation to OD and depth (m) below the seabed surface.

3.2.2 Sediment sampling

Following recovery, and an initial period of storage, the sediment core samples were split laterally, with one half being re-sealed and labelled prior to being placed in a permanent storage facility in order to provide an archived record of the sedimentary sequences obtained.

The remaining sections of sediment core were then sub-sampled at strategically defined levels considered to be of relevance to the research project. Incremental 0.5cm sub-samples were obtained from regions of the sediment cores containing organic-rich deposits, with additional sub-samples being taken from the underlying and overlying inorganic sediment. The possibility of contamination through 'smearing' during the coring process was reduced by the removal of the outer portion of sediment from the 'semicircular', 0.5cm sub-samples of sediment. The sub-samples were further sub-divided in order to produce three smaller sub-samples of sediment, sufficient in volume so as to provide adequate material for future micropalaeontological and radiocarbon analysis.

3.2.3 Micropalaeontological analysis

3.2.3.1 Foraminifera

A study of foraminifera contained within the recovered sediments was primarily designed to examine changes in foraminiferal assemblage composition both within and between adjacent sedimentary facies, proximal to the organic-rich deposits within the sediment cores. The resulting micropalaeontological data was designed to be compared to a modern analogue, representing contemporary sub-environments within a macrotidal estuary in South Wales. The strategy was designed in order to allow preliminary inferences to be made in relation to the nature of the dominating palaeoenvironmental conditions that possibly prevailed during the *in-situ* development of the inorganic sedimentary facies.

3.2.3.1.1 Introduction

Foraminifera are unicellular, cytoplasmic organisms enclosed within a self-generated protective test. They can be found in abundance within a variety of marine environments, ranging from the inter-tidal zone through to the deep ocean. A large volume of literature and research has been produced relating to the taxonomy, nature and distribution of foraminifera within the marine environment (Loeblich and Tappan, 1988; Murray, 1979, 1991; Austin, 1991) together with their usefulness as indicators of sea-level change (Scott and Medioli, 1978; Gehrels, 1999; Gehrels *et al.*, 2001).

Temperate coastal environments can range from exposed beaches to sheltered estuaries and from salt marshes to tidal channels. Similarly, conditions experienced within those environments may vary significantly on a range of time scales. It is the nature and inherent physico-chemical conditions prevailing at a particular location which ultimately controls the ecology contained therein. The distribution of benthic foraminiferal species within a given marine environment is therefore ultimately governed by responses to the constraints imposed by the prevailing conditions associated with a particular environment.

Temperate tidal mashes that have developed within the upper reaches of the inter-tidal zone often possess very strong environmental gradients across their surface and as a result, a correspondingly strong ecological zonation also exists which reflects the tolerances of individual species to the unique and intrinsic characteristics of separate sub-environments located across the marsh. The environmental gradients within the marsh are in turn primarily controlled by surface elevation relative to mean sea level and associated variations with respect to salinity (Scott and Leckie, 1990; Jennings and Nelson, 1992; Gehrels, 1994). Modern ecological studies clearly indicate that particular species of foraminifera dominate specific sub-environments across temperate tidal marshes and as such assemblages demonstrate a strong vertical zonation with respect to mean sea level. As the vertical range in height between these sub-environments is regarded as relatively small, any small variation with respect to mean sea level may instigate significant changes in terms of the distribution of foraminiferal populations across a tidal marsh.

The analysis of fossil foraminiferal assemblages may therefore be utilized in order to support palaeoenvironmental reconstruction and assist in the reconstruction of former Holocene sea levels. Adoption of the uniformatarian approach and the use of modern analogues in order to develop palaeoenvironmental models can often however, be complicated by the fact that fossil assemblages have invariably been subjected to some degree of post-depositional modification.

3.2.3.1.2 Sample preparation

With respect to the fossil assemblage study conducted on the sediment cores recovered from the Menai Strait, sub-samples were taken from levels immediately above and below the peat layers. The samples were subsequently weighed and the volume of sediment noted. The samples were then dried at 96°C and weighed before being washed through a clean 63μm sieve in order to remove any fine grained sediment. The samples were subsequently dried at 96°C before being processed through 125μm and 63μm sieves, with each proportion being weighed and retained separately.

Sample collection and identification with respect to the modern foraminiferal study was conducted during June 2002 and was carried out by the author together with final year Geological Oceanography and Ocean Science students based at the University of Wales, Bangor, School of Ocean Sciences, under the strict supervision of Professor James Scourse. The samples collected for this study were recovered from a transect across an area of tidal marsh, situated approximately 2km northeast of Wharley Point, within the Taf Estuary in Carmarthenshire, South Wales. The samples consisted of approximately 40g of material scraped from the surface of the substrate using a clean trowel. Each sample was washed through a 63μm sieve and stained in Rose Bengal before being dried for several hours at approximately 90°C.

3.2.3.1.3 Foraminifera counts and identification

Following preparation, a proportion of the >125μm fraction of the sample was transferred carefully onto a gridded picking tray. With the aid of an Olympus (Model C011) low power stereoscopic microscope, foraminifera were then picked from evenly spaced transects using a fine brush. These were subsequently placed onto an adhesive slide consisting of individually numbered gridded sections for identification at a later stage. The adopted strategy required that a minimum number of 300 individuals be selected from each analyzed sub-sample examined from the contemporary environment. At least 300 individual specimens were additionally collected from within each analyzed sub-sample wherever possible.

Individual foraminifera were identified to the lowest taxonomic level possible using a reference collection belonging to the University of Wales, Bangor and by using foraminifera keys produced by Haynes (1973), Murray (1979) and Loeblich and Tappan (1988). Micrographs contained within Austin (1991) were also utilized and classification was based upon Loeblich and Tappan (1988).

3.2.3.1.4 Presentation of results

Assemblage distribution diagrams based on species percentages calculated from the total number of individuals counted at each level, were constructed for each of the sediment core. The assemblage diagrams were constructed using GpalWin (version 99.0606) developed at the Historical Botany and Palynology Laboratory in the University of Marseille (Gouery, 1997). Whilst no attempt has been made in order to define specific foraminiferal assemblage zones within the diagrams, sediment logs have been reproduced and placed alongside the diagrams in order to provide a stratigraphical context for each analyzed sample. Comparisons between the fossil data and modern analogues were undertaken using the Primer v.5.2.4. multivariate cluster analysis package (Clarke and Warwick, 2001). The program utilized a 3-dimensional scaling approach in order to project the degree of similarity between individual assemblages. The data can be orientated and viewed from any specific perspective, in order to enhance or display the degree of similarity or dissimilarity between assemblages.

3.2.3.2 Pollen analysis

The sampling strategy was designed produce a series of pollen diagrams that would provide a preliminary insight into both the local and more regional vegetational assemblages that prevailed during the time of sediment accumulation at horizons subjected to ^{14}C analysis. Correlation of the palynological data with a pre-existing data set (Watkins, 1991; Watkins *et al.* in press) was designed to provide an initial estimation relating to the age of each horizon and to therefore additionally provide corroboration in relation to the additionally derived ^{14}C data set.

3.2.3.2.1 Introduction

Pollen analysis has become the most significant and arguably the most successful technique within the field of palaeoenvironmental reconstruction (Lowe and Walker, 1997). Aspects relating to the study and application of pollen analysis within the fields of biostratigraphy and palaeoenvironmental reconstruction, together with general techniques and problems, have been described in many textbooks (Faegri and Iverson, 1975, Birks and Birks, 1980, Faegri and Iverson 1989). The preservation of pollen grains and spores incorporated within sediment bodies ultimately provides a basis for the reconstruction of former vegetation. This evidence can be allied to other methods of palaeoenvironmental reconstruction and can subsequently allow inferences to be drawn relating to both temporal and spatial changes concerning climatic and environmental conditions throughout the geological past.

The use of pollen within the field of palaeoenvironmental reconstruction can be attributed to the fact that pollen grains are not only extremely resistant to degradation but are also produced in vast quantities. As a consequence, sufficient pollen can very often be obtained from relatively small samples of sediment, providing data integral to the reconstruction of former vegetation assemblages and consequently allowing inferences to be drawn in relation to prevailing palaeoenvironmental conditions. Palaeoenvironmental reconstruction however, relies heavily upon the ability to identify pollen grains and spores to the lowest taxonomic level. The relationship between the preserved assemblage and that of the original living assemblage is also critical, due to the diverse and inconsistent nature of pollen production and dispersal. It has also been established that pollen grains are susceptible to differential rates of degradation and this may often lead to bias within the preserved assemblage. These problems are, however, generally overcome by the analysis of modern pollen dispersion, deposition and preservation patterns. A variety of mechanisms lead to the eventual dissemination of pollen grains and spores throughout the environment, these primarily include transportation by wind, water and other living organisms such as insects, birds and animals. Significantly large quantities of pollen grains and spores however, remain unused and can subsequently become incorporated and preserved within sediments.

A statistical analysis of a given fossil assemblage at a point within a sedimentary sequence provides an index related to the possible former distribution of vegetation. The index can also be monitored for changes throughout the sediment core, indicating possibly both temporal and spatial variations related to past vegetation assemblage, from which inferences can be drawn with respect to regional and/or local environmental change.

3.2.3.2.2 Sample preparation

Within the laboratory, sub-samples of organic-rich sediment were selected for palynological analysis from levels within the organic deposits proximal to their respective points of contact with underlying and overlying inorganic sediment.

Several techniques have been developed in order to extract pollen from a sediment matrix, all of which may be modified slightly in order to compensate for sediment composition. The samples are subjected to various chemical and mechanical treatments in order to ensure maximum sediment matrix removal without impinging on the natural concentration and quality of the pollen initially contained within the sample. The method employed within this study closely follows the standard technique developed for the preparation of organic sediments used by Fægri and Iversen (1989).

3.2.3.2.3 Pollen counts and identification

Counting of identifiable individual pollen grains is generally conducted until a predetermined number, termed the pollen sum, is attained. This number can vary depending on the nature of the investigation and with respect to this particular study, a count of 300 was deemed to be sufficient. Counting was conducted using a standard HM ZEISS (16) microscope under a magnification of x400. Critical magnification was conducted utilizing x1000 magnification, together with immersion in anisol. Pollen grains were counted along regularly spaced traverses, whose spacing were dependant on pollen concentration; in each case complete coverage of at least half of each prepared slide was completed. Identification of individual pollen grains to the lowest taxonomic level was conducted using the pollen keys of Fægri and Iversen (1975, 1989), a reference collection held at the School of Ocean Sciences, University of Wales, Bangor and the photographs/micrographs of Moore and Webb (1978) and Moore *et al.* (1991).

In order to ensure that as many organic horizons as possible could be examined and sufficient pollen counts obtained, a pre-determined pollen sum of 300 was adopted.

- Pollen Sum (P) = $\sum$(trees + shrubs + herbs)
- Indeterminable (ID) % calculated from $\sum$(P+ID)

Invariably a component of the pollen assemblage will be unidentifiable due to both the effect of natural processes wrought upon the structure of the pollen grain and damage induced by the preparation method. Deterioration of individual pollen grains may therefore be attributed to factors such as corrosion, degradation or mechanically induced damage. The concealment of individual grains by minerals and detritus present within the prepared sample may additionally modify pollen counts. Classification of indeterminable grains was conducted by adopting the methodology of Berglund and Ralsa-Jasiewiczowa (1986).

Pollen grains derived from aquatic plants, together with plant spores were excluded from the pollen sum, although they were counted as they can often be useful in aspects of palaeoenvironmental reconstruction.

No attempt was made in discerning between *Corylus* and *Myrica*, although according to Moore and Webb (1978), identification is possible, the process was considered to be too time consuming given the degree of abundance of these grains.

3.2.3.2.4 Presentation of results

The percentage pollen diagrams produced were designed to reflect the concentration of each individual species relative to the pollen sum. Absolute pollen analysis is based upon changes within the total number of grains per unit volume of sediment sample or pollen concentration. The method was conducted by the introduction of a known quantity of exotic pollen into a measured quantity of sediment sample. The observed ratio of exotic pollen to that of fossil pollen allows the actual pollen numbers of the various taxa present within the sample to be estimated.

As very few individual horizons were examined with respect to this research project, it was considered that percentage pollen data should be plotted individually with respect to each organic-rich horizon and compared to data obtained from Llyn Cororion by Watkins (1991) in order to provide an estimation relating to the age of the sediment.

3.2.4 Radiocarbon dating

The sub-sampling strategy and subsequent ^{14}C analysis of organic-rich material recovered proximal to the organic-inorganic contacts was designed to provide data that could be used in conjunction with palaeoenvironmental data in order to provide age control for the relative sea level and palaeoenvironmental development of the Menai Strait.

3.2.4.1 Introduction

Carbon exists in three principle isotopic states within the biosphere; ^{12}C constitutes approximately 98.89% of the total carbon, whereas the ^{13}C isotope accounts for close to 1.11%. The remaining unstable isotope ^{14}C has been approximated to constitute 1 in every 10^{12} parts of carbon that exists within the system. ^{14}C is constantly produced in the upper atmosphere as a result of collisions between free neutrons generated by the cosmic ray flux and atoms of atmospheric nitrogen. As ^{14}C is unstable it steadily decays back to its original form over time, resulting in the emission of negatively charged electrons also known as beta particles (fig. 3.7). All isotopic forms of carbon are subjected to processes operating within the atmospheric system, including oxidisation and the subsequent formation of carbon dioxide. Rapid mixing ensures that carbon isotopes are absorbed by all biological organisms, such that atmospheric ratios are essentially maintained within the biosphere.

$$^{14}_{7}\mathrm{N} + \text{neutron} \longrightarrow {}^{14}_{6}\mathrm{C} + \text{proton}$$

$$^{14}_{6}\mathrm{C} + \text{decay} \longrightarrow {}^{14}_{7}\mathrm{N} + \text{particle}$$

Figure 3.7 Formation of ^{14}C

As organic tissue is constantly replenished during the lifespan of an organism, any decay of ^{14}C is offset by continued absorption. Following death, however, replenishment ceases and the amount of ^{14}C present within a particular organism decreases at a fixed rate (fig. 3.8).

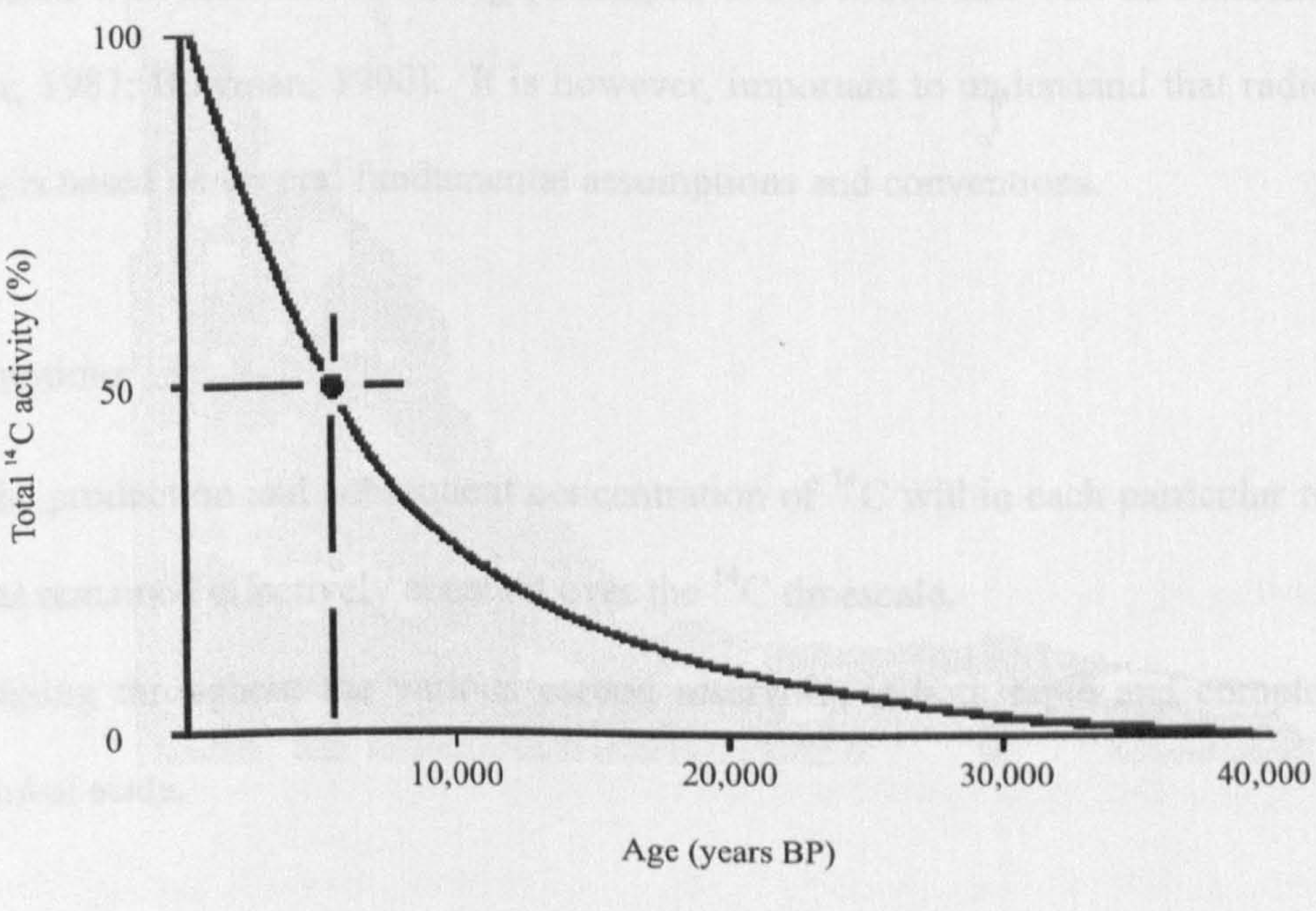


Figure 3.8 Decay curve for ^{14}C. From Roberts (1998)

Pioneering work by Libby during the 1940s (Libby, 1955) demonstrated that the amount of ^{14}C activity within a sample of material could be related to a time whereupon ^{14}C replenishment ceased, effectively indicating the age of death. Libby determined that the time taken for half a sample's ^{14}C to decay could be shown as 5,568 (5570) ±40 ^{14}C years (subsequent work has shown this to slightly underestimate the true figure). However, the limits of radiocarbon dating are strongly dependant upon the ability of the apparatus employed, as difficulties in the detection of ^{14}C emissions escalate with increasing age. In general, the useful limit of radiocarbon dating is defined as approximately eight to ten times the half-life of ^{14}C, or about 40,000 years; beyond this time the effectiveness of the apparatus utilized in detecting increasingly smaller degrees of radioactivity becomes limited.

An abundance of literature exists relating to the application, methods and problems associated with radiocarbon dating (Gillespie, 1984; Mook and Van de Plassche, 1986; Taylor, 1987; Bowman, 1990). It is however, important to understand that radiocarbon dating is based on several fundamental assumptions and conventions.

Assumptions

1) The production and subsequent concentration of ^{14}C within each particular reservoir has remained effectively constant over the ^{14}C timescale.
2) Mixing throughout the various carbon reservoirs is both rapid and complete on a global scale.

3) Isotopic ratios within individual samples have remained unaltered apart from the radioactive decay of ^{14}C since replenishment ceased.
4) The half-life of ^{14}C is accurately known.
5) Levels of ^{14}C activity can be measured with appropriate accuracy and precision.

Conventions

1) During geological times, activity of ^{14}C within the carbon-containing material has remained constant during the formation of that material.
2) The degree of ^{14}C activity is defined by a standard oxalic acid which is distributed by the United States Bureau of Standards (NBS).
3) All radiocarbon dated samples are subsequently corrected for isotopic fractionation and are dependant upon a determined ^{13}C / ^{12}C ratio.
4) All radiocarbon age determinations are based upon the "Libby half-life" of 5568 years.
5) All radiocarbon ages are quoted with respect to years BP (Before Present), taken to be years before 1950 AD.

3.2.4.2 Sources of error

The random nature of radioactive decay causes a statistical uncertainty to arise in the counting of ^{14}C beta emissions over a finite period of time. Precision is improved with increased counting periods and larger samples; although errors still arise in the decay rate measurement of reference standards, samples and background measurements. It is assumed that this effect causes rates of ^{14}C decay to vary by a given amount about a true value expressed in terms of a standard error (deviation). The distribution of this random decay about a true value is expressed via a probability curve, which demonstrates normal, or Gaussian distribution. Values of age can therefore only be determined to within particular statistical limits as an error term is introduced which relates only to the precision of measurements.

Error can also be introduced due to the nature of the surrounding environment in which the sample was formed, for example, areas containing carbonate rock formations or newly deglaciated areas can induce what is termed as hard-water error within a sample (Lowe and Walker, 1997). The effect occurs as water passing through the formations can often contain relatively high concentrations of dissolved carbon based compounds. Aquatic plants eventually preserved within a sample can incorporate carbonate-enriched water during their lifespan leading to a dilution of the ^{14}C:^{12}C ratio which can result in an anomalously old radiocarbon date.

Other significant sources of error result from the contamination of particular samples, either as a result of the incorporation of older, in-washed, allochthonous material, or by the introduction of younger carbon via penetrative root systems. Possible contamination via the downward movement (leaching) of humic acids through soil horizons, together with the effects of bioturbation through faunal activity, can also introduce significant error, due to the introduction of younger carbon.

3.2.4.3 Calibration

The assumption that ^{14}C production has remained constant over time has since been shown to be incorrect; temporal variation has been demonstrated by the comparison of tree ring data with results obtained through radiocarbon analysis. It has been shown that radiocarbon dates older than approximately 2,500 years BP are significantly lower than dates obtained using dendrochronology. Secular variation relating to the production of ^{14}C can be attributed to several factors including variation within the Earth's magnetic field, modulation of the cosmic ray flux and the influence of the oceanic reservoir upon the carbon availability.

Anthropogenic activity over the latter part of the twentieth century has also influenced ^{14}C levels as the combustion of fossil fuels has led to an increase in the production of inert ^{12}C, thereby effectively diluting the ^{12}C / ^{14}C ratio. This dampening effect has subsequently been overcompensated for by the detonation of thermonuclear devices which have increased the levels of ^{14}C within the global system. Spatial variation of ^{14}C production is also known to occur due to the variable nature of Earth's magnetic flux. Production generally increases with increasing latitude and also varies with altitude, maximum production occurring at an altitude of approximately 15 km (Aitkin, 1990). As a consequence of these observations radiocarbon dates are conventionally subjected to calibration procedures in order that they may be expressed in terms of a calendar age.

During the late 1950s and early 1960s discrepancies between radiocarbon dates and the calendar ages of modern wood samples were used as evidence to suggest that ^{14}C levels may have varied significantly over time. This effect has subsequently been confirmed utilizing dendrochronology and indicates that atmospheric activity of ^{14}C has fluctuated considerably throughout the Holocene. Records of ^{14}C variation have subsequently been obtained from lake sediments in Switzerland (Lowe and Walker, 1997) and extend back into the Lateglacial. Discrepancies appear to increase with increasing age and result in radiocarbon ages underestimating calendar ages by between 1000-1700 years within samples dated as originating to the onset of the Holocene.

The principles of radiocarbon calibration are based upon the incremental growth rates of trees, where natural seasonal perturbations within annual growth rates produce characteristic signatures which can be systematically cross-referenced with older sources. A significant feature of dendrochronology is that samples of known age can also be radiocarbon dated. Subsequently a method of cross-correlation is available, whereby a comparison of both the radiocarbon and dendrochronological ages of a timber sample can be made. Any temporal variation in the atmospheric production of ^{14}C would subsequently cause radiocarbon dates to deviate from those obtained via dendrochronology. The first curves to provide information on how these trends varied in the recent geological past were produced by Hans Suess in the 1960s; the curve was based upon the tree ring record of the long lived, North American, bristlecone pine (*Pinus aristata*). The original curve subsequently confirmed that major discrepancies between radiocarbon and calendar age did actually occur and that this was invariably caused by temporal variations in production of ^{14}C. The general trend of the curve indicates a clear similarity up to about 2,500 years ago, followed by systematic divergence, whereby radiocarbon dates appear to be younger.

Dendrochronology has enabled a record of seasonal growth rates to be constructed; however, the practical limit of this technique extends to approximately 11500 calendar years BP. Several attempts have been conducted in providing an independent and accurate chronological record spanning the last 20000 calendar years, including the use of lake varves, ice core records and uranium-thorium methods. The techniques have often been questioned in terms of their precision but further indicate that radiocarbon dates appear to consistently underestimate ages derived utilizing alternate methods. The dendrochronological record of the bristlecone pine has now been established to cover a period extending over 8000 years and similarly over 7000 years, for that of the oak in Ireland (Bowman, 1990). Although dendrochronology provides a method of radiocarbon calibration that is limited to this period, other methods of extending calibration have been established. Bard *et al.* (1990) investigated uranium-thorium ages via mass spectrometry within Barbados corals and were thereby able to provide a means of extending the calibration of radiocarbon dates beyond those of dendrochronology.

The recent introduction of computer based high precision calibration packages based upon a range of data sets provides a means of calibration for radiocarbon dates derived from a range of sources. The CALIB (version 5.0) ^{14}C age calibration program based on (Stuiver and Reimer, 1998) provides a method of calibration extending over almost 24000 calendar years. The program utilizes a number of data sets in order to calibrate radiocarbon dates produced by samples of varying age and origin; calibrated ages and probability distributions relating to a samples true age are derived following the input of reported ^{14}C ages and $\delta^{13}C$ estimates.

3.2.4.4 Sample selection and submission

Sub-samples of organic-rich sediment selected for dating were taken from points immediately adjacent to points of lithological change within the sediment cores, proximal to the point of contact between the organic-rich material and the underlying or overlying inorganic sediment. Seventeen organic-rich sub-samples of sediment were submitted to the NERC Radiocarbon Laboratory at East Kilbride for radiocarbon dating under allocation number 1027-0403 and were accepted on the 24/09/2003. The dates were received on the 26/05/2004; however, supplementary tests were conducted on two sub-samples with the additional results being received on the 22/07/2004. An examination of the sub-samples was initially conducted in an attempt to pick out a sufficient quantity of plant macrofossil material for dating, however, this proved unsuccessful. As a consequence sixteen of the sub-samples submitted for dating were composed of organic detritus containing variable quantities of lithic material, whilst one sub-sample, SUERC-2511 taken from 3/2 top consisted of wood fragments recovered from within a matrix of organic detritus.

3.2.4.5 Methodology

Seventeen sub-samples were digested in 1M HCL at 80°C for 8 hours, washed free of mineral acid with distilled water and then digested in 0.5M KOH at 80°C for a further 2 hours. The digestion was repeated until no further humic material could be extracted. The residue was then rinsed free of alkali, prior to being digested in 1M HCL, again at 80°C for 2 hours; the remaining material was rinsed free of acid, dried and homogenised. CO_2 was subsequently recovered through the heating of a sub-sample of homogenised material of known weight with CuO within a sealed quartz tube; graphite targets were then derived from the gas through Fe/Zn reduction.

Two additional graphite targets were prepared through the combustion of the remaining homogenised material from two sub-samples within high purity O_2 in a high pressure bomb, utilized for radiometric analysis. Sub-samples of the isotopically homogenised gas from the combusted samples were subsequently prepared for ^{14}C analysis utilizing the reduction process described previously.

The prepared graphite targets were subsequently tested at the SUERC AMS facility located at East Kilbride.

3.2.4.6 Reporting and calibration of dates

The results were reported as conventional radiocarbon years BP (relative to AD 1950) and percentage modern ^{14}C and were expressed at the $\pm 1\sigma$ level for overall analytical confidence; carbon content by weight and $\delta^{13}C_{PDB}$ ‰ values were additionally presented.

The reported dates were subjected to calibration through the CALIB (version 5.0) ^{14}C age calibration program devised by Stuiver *et al.* (2004) and are expressed at both the 1σ and 2σ level for overall analytical confidence.

Chapter 4

4 Introduction

Chapter four presents an account of sedimentological, stratigraphical and micropalaeontological data obtained during the study, together with an account relating to the results obtained from a geophysical survey conducted within the northeastern region of the Menai Strait. The chapter additionally reports results derived from radiocarbon analyses performed on seventeen organic sub-samples submitted to the NERC radiocarbon laboratory at East Kilbride.

4.1 Sedimentological and stratigraphical data

A detailed examination with respect to the sedimentology and stratigraphy of three sediment cores recovered during the early stages of the research project has been conducted, with descriptions relating to the sediments and their stratigraphic context being produced.

4.1.1 Cemlyn-Jones sediment core 1 (CJSC 1)

The sediment coring operation commenced at an elevation on the sea-floor of -4.12m OD. The drilling unit was positioned toward the seaward end of Bangor Pier (fig. 4.1) approximately 50m off its starboard side, on the southern flank of Bangor Pool within the main channel of the Menai Strait (Ordnance Survey grid reference: SH 5830, 7365). The drilling operation recovered a sequence of unconsolidated sediments extending down to 31.30m beneath the sea-bed to -35.42m OD (fig. 4.2).

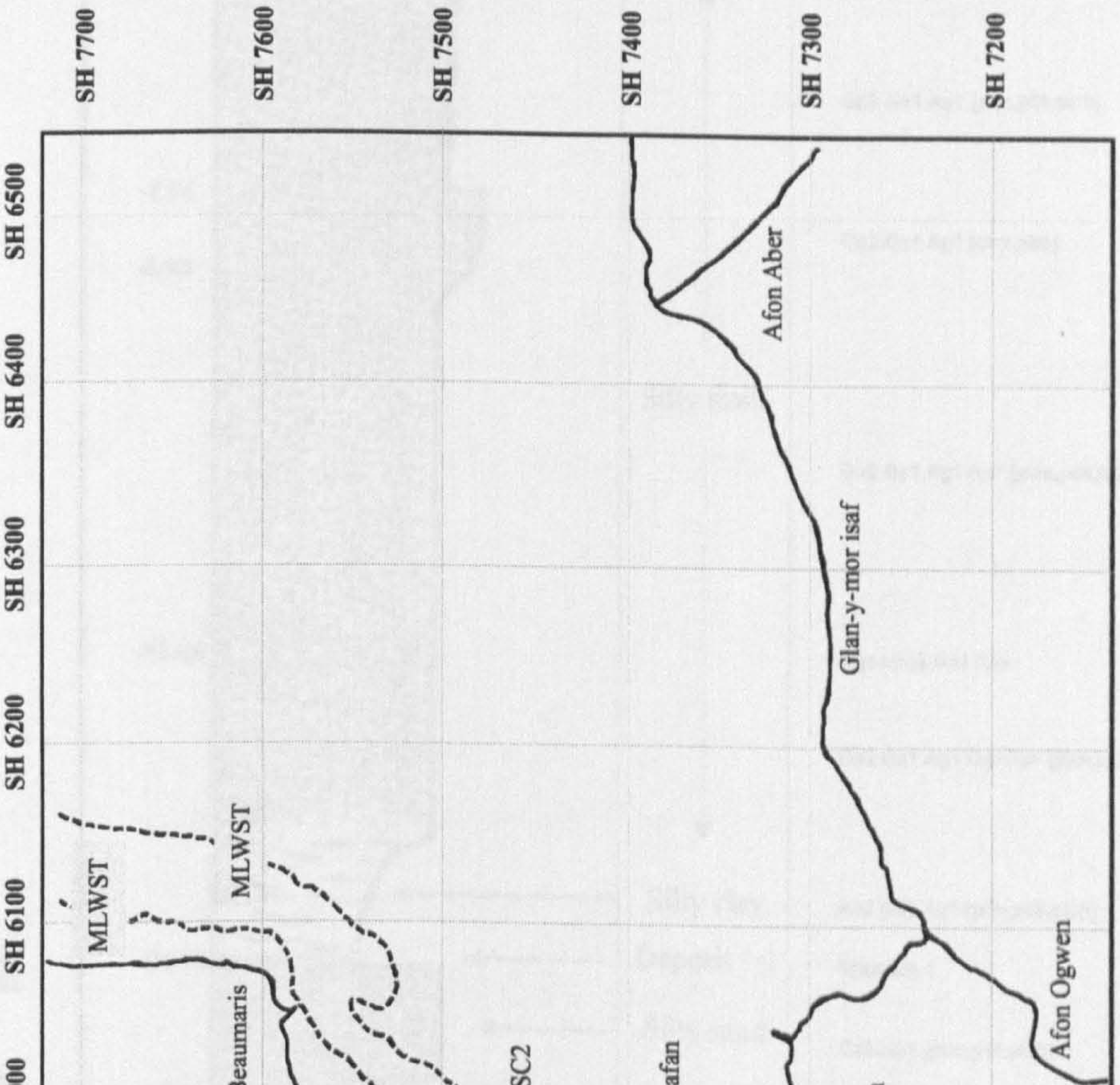


Figure 4.1 Location of sediment cores obtained during the course of the study

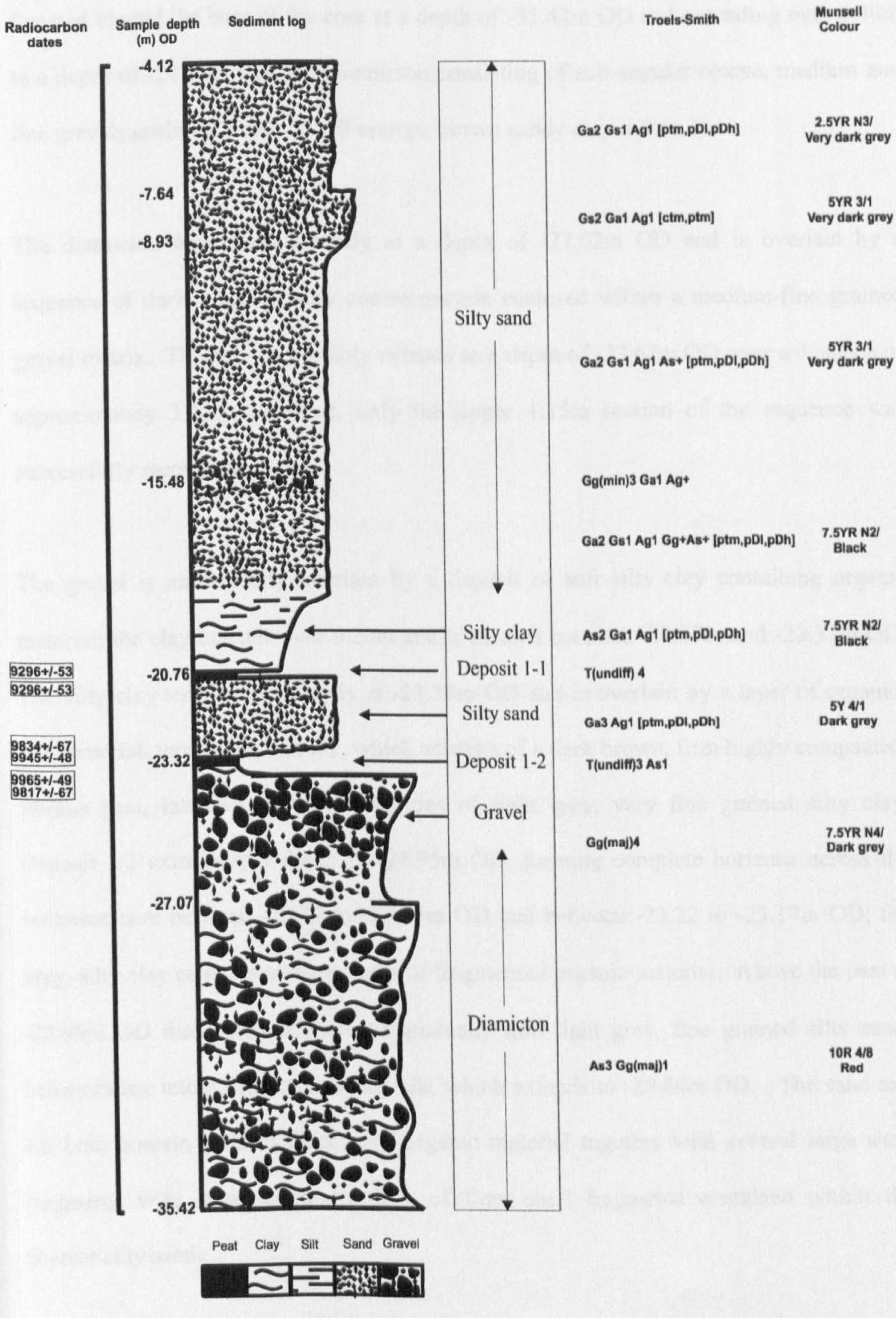


Figure 4.2 Sediment log for CJSC 1, obtained proximal to Bangor Pier

Located toward the base of the core at a depth of -35.42m OD and extending over 8.40m to a depth of -27.02m OD, is a diamicton consisting of sub-angular coarse, medium and fine gravels enclosed within a stiff orange, brown sandy clay matrix.

The diamicton terminates abruptly at a depth of -27.02m OD and is overlain by a sequence of dark, angular, very coarse gravels enclosed within a medium-fine grained gravel matrix. The deposit possibly extends to a depth of -23.62m OD over a distance of approximately 3.40m; however, only the upper 1.15m section of the sequence was successfully recovered.

The gravel is immediately overlain by a deposit of soft silty clay containing organic material; the clay extends over 0.20m and is located between -23.57m and -23.37m OD. The silty clay terminates abruptly at -23.37m OD and is overlain by a layer of organic-rich material, termed deposit 1/2, which consists of a dark brown, firm highly compacted, fibrous peat, interspersed with quantities of light grey, very fine grained silty clay. Deposit 1/2 extends to a depth of -22.95m OD, forming complete horizons across the sediment core between -23.37 to -23.36m OD and between -23.22 to -23.17m OD; the grey, silty clay contains an abundance of fragmented organic material. Above the peat at -22.95m OD the sediment coarsens gradually into light grey, fine grained silty sand, before fining into a light grey, sandy silt, which extends to -20.84m OD. The sand and silt both contain isolated patches of organic material together with several large shell fragments with increased proportions of finer shell fragments contained within the coarser silty sand.

At -20.84m OD the sandy silt is terminated abruptly by the onset of a very dark brown, highly compacted, firm, fibrous organic-rich layer, termed deposit 1/1, which extends over 0.18m. The deposit terminates abruptly at -20.66m OD and is overlain by light grey, very fine grained, laminated silty clay.

The silty clay coarsens rapidly over 0.05m grading into light grey, fine grained silty sand containing fragments of shell; the silty sand extends to -19.92m OD where it fines into silty clay containing isolated patches of organic material. The silty clay extends between -19.87m OD and -18.57m OD and contains an abundance of organic material and very fine dark lithic particles, together with fine shell fragments. Located centrally within the silty clay, between -19.38m OD and -19.10m OD is a structure that may possibly represent the remains of an infilled burrow, approximately 0.27m in length and 0.04m in diameter. The structure contains fine gravel and broken shell enclosed within a light grey, fine grained sandy matrix. Immediately above this feature a yellow/brown fibrous organic formation is located between -19.10m OD and -19.02m OD. The upper section of the organic deposit almost extends across the entire width of the sediment core, however, with increasing depth the formation's lateral extent decreases. Towards the base of the infilled structure, a yellow, brown fibrous organic formation, similar to the material located above, is once again found on either side of sediment core. A similar organic deposit is also located between -19.67 to -19.75m OD and once again does not extend across the entire width of the sediment core. These sporadically occurring organic deposits extend between -19.42 OD and -19.31m OD, varying between 0.01and 0.03m in thickness.

At -18.57m OD the sediment begins to coarsen upward, grading rapidly from silty clay into light grey, fine grained silty sand which extends to -17.52m OD. Between -17.52m and -17.44m OD, the sediment appears to be much finer and lighter in colour and contains a higher proportion of silt and clay sized particles. Between -17.44m and -16.22m OD the sediment consists of grey, medium-fine grained silty sand containing medium sized shell fragments. A very thin band of organic material is incorporated within this sediment at approximately -16.74m OD and is located immediately below a lens of lighter, finer silt extending to -16.61m OD. Above -16.22m OD the sediment begins to contain an increasing proportion of fine gravel, which eventually gives rise to a complete band of darker medium-coarse, sub-angular gravel which is incorporated within a fine grained sandy matrix, located between -15.88m and -15.83m OD. Gravel continues to be incorporated within the fine grained silty sand and forms another significant band between -15.57m and -15.38m OD. The gravel disappears above -15.38m OD, where slightly lighter, medium-fine silty sand containing shell fragments and organic material, together with occasional evidence of lamination, extends to -13.17m OD.

Between -13.14m and -12.97m OD the sediment begins to contain a greater proportion of silt and clay. Fine silty sand subsequently extends to -11.99m OD, where the sediment incorporates a significant proportion of complete and broken shell belonging to various species of marine mollusca, including those of *Mytilus, Cerastoderma, Tapes* and *Littorina*. Above -11.67m OD, the sediment once more consists of light grey, fine grained silty sand that subsequently extends up to -10.60m OD, where, over a distance of 0.03m it once again begins to incorporate whole and fragmented shell.

Between -10.37m and -10.12m OD the sediment consists of light grey, very fine grained silty sand, incorporating an increasing proportion of shell debris similar in composition to that located below. The sediments appear disturbed, as the silty sand and shell seem to have been separated vertically in order to form entirely separate units. Between -10.12m and -10.00m OD, the sediment consists entirely of whole and broken shell enclosed within a matrix of fine silty sand. At -9.72m OD the sediment once again consists of light grey fine grained silty sand and extends up to -9.39m OD, where it is overlain by another layer of whole and fragmentary shell.

This layer subsequently extends in an almost unbroken sequence up to -8.10m below OD, where it is overlain by a very dark grey, fine grained silty sand containing finer shell fragments, together with a few isolated examples of complete shell. Above -7.69m OD the sediment consists of grey, fine, very occasionally, medium grained silty sand. This sediment contains abundant medium-fine shell fragments together with a few isolated examples of shells belonging to various marine mollusca. Scattered within the fine sediment matrix are slightly larger light and dark lithic fragments, together with isolated fragments of organic material. This deposit extends to the top of the sediment core located at -4.12m OD, although there is a marked colour change at -4.57m OD, where the sediment abruptly becomes yellow, brown in colour.

4.1.2 Cemlyn-Jones sediment core 2 (CJSC 2)

The operation that resulted in the retrieval of CJSC 2 was conducted from a location approximately 1km to the southwest of Gallows Point (fig. 4.1), with the drilling rig being positioned on the southern edge of the Menai Strait's main channel (Ordnance Survey grid reference: SH 5975, 7465). The sediment coring operation commenced at a point on the sea-floor 7.51m below OD with the drilling operation recovering a sequence of unconsolidated sediments that extended 24.50m below the surface at -32.01m OD (fig. 4.3).

The base of the core is characterized by layers of light grey, fine grained silty sand interspersed with layers of orange, brown, medium grained sand containing abundant quantities of broken shell. Between the base of the core and -31.86m OD is a 0.15m layer of grey laminated very fine grained silty sand containing an abundant quantity of organic and calcareous material. This layer of fine silty sand terminates abruptly at -31.86m OD and is replaced by orange, brown medium-coarse grained sand containing medium and fine grained sub-angular lithic fragments, together with a large quantity of broken shell. This deposit extends to at least -31.56m OD where it is replaced between -31.36m and -30.97m OD by a very fine grained, grey silty sand interspersed with horizontal darker bands of silt, containing several isolated coarse-medium gravel and shell fragments. The sediment contains an abundance of coal fragments together with a large quantity of organic material, including some plant remains.

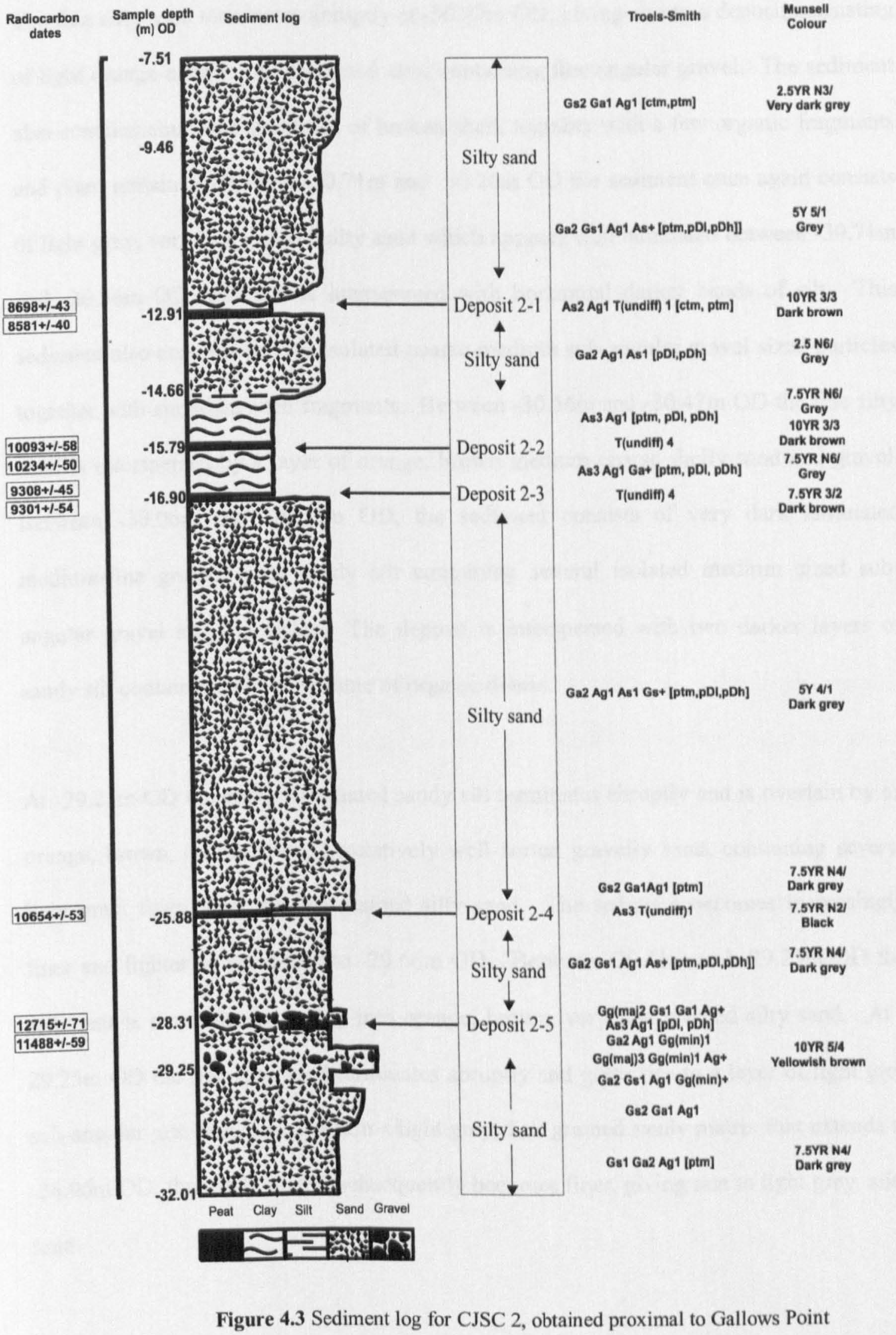


Figure 4.3 Sediment log for CJSC 2, obtained proximal to Gallows Point

The fine silty sand terminates abruptly at -30.97m OD, giving rise to a deposit consisting of light orange-brown coarse grained sand containing fine angular gravel. The sediment also contains abundant quantities of broken shell, together with a few organic fragments and plant remains. Between -30.71m and -30.26m OD the sediment once again consists of light grey, very fine grained silty sand which appears well laminated between -30.71m and -30.56m OD, where it is interspersed with horizontal darker bands of silt. This sediment also contains several isolated coarse-medium sub-angular gravel sized particles together with abundant shell fragments. Between -30.56m and -30.47m OD the fine silty sand is interspersed by a layer of orange, brown medium-coarse shelly sand and gravel. Between -30.06m and -29.25m OD, the sediment consists of very dark laminated medium-fine grained grey sandy silt containing several isolated medium sized sub-angular gravel sized particles. The deposit is interspersed with two darker layers of sandy silt containing a large volume of organic debris.

At -29.25m OD the darker laminated sandy silt terminates abruptly and is overlain by an orange, brown, coarse grained, relatively well sorted gravelly sand, containing several light gray, finer bands of fine grained silty sand. The sediment becomes increasingly finer and lighter as it extends to -29.66m OD. Between -29.41m and -29.25m OD the sediment is much finer, grading into orange, brown, very fine grained silty sand. At -29.25m OD the fine silty sand terminates abruptly and gives rise to a layer of light grey sub-angular gravel enclosed within a light grey, fine grained sandy matrix that extends to -28.96m OD; the sandy matrix subsequently becomes finer, giving rise to light grey, silty sand.

Between -28.76m and -28.21m OD the sediment consists of orange, dark grey, medium grained silty sand containing a few sub-angular gravel sized particles, together with a small quantity of organic material and fragments of shell. The silty sand terminates abruptly at -28.31m OD giving rise to a 0.07m thick layer of dark and light grey, laminated silty clay termed deposit 2/5, which contains a relatively high proportion of organic material and a few lithic fragments together with crystals of calcium sulphate. Above the laminated silty clay at -28.24m OD the sediment coarsens rapidly, grading into dark grey, fine grained gravel containing larger angular rock fragments and some organic material. The gravel continues to coarsen upward until it terminates abruptly at -27.98m OD.

At this point the coarse gravel is replaced by light gray, fine grained sandy silt, containing some organic material which extends to -27.85m below OD, where it grades rapidly into a darker, medium-fine grained silty sand containing traces of gravel interspersed with several darker lenses of silt. The medium-fine grained silty sand merges into a darker olive green, grey medium-fine sand at -27.16m OD; the slightly coarser sediment contains abundant quantities of broken shell and organic material. Between -27.11m and -26.16m OD, a hiatus within the sedimentary sequence occurs, as no material was recovered from within the sampling unit. The sequence resumes at -26.16m OD with grey, very fine grained silty sand, containing organic material, which grades gradually into grey, finer sandy silt containing a higher proportion of organic material.

At -25.89m OD the sandy silt terminates abruptly and is overlain by a 0.02m layer of dark brown, firm, fibrous and organic-rich material termed deposit 2/4. The deposit is in turn, immediately overlain by light grey silty clay containing abundant quantities of organic material, together with crystals of calcium sulphate. The sediment subsequently coarsens into darker medium-fine grained sand above -25.83m OD and contains an abundant quantity of calcareous material, together with a significant proportion of coal fragments. The sediment subsequently appears to become lighter in colour, as well as containing an increased proportion of broken shell, however this section of the core contains two very dark grey bands of fine grained silty sand between -25.38m and -25.33m OD, before grading into the darker olive green, grey silty sand containing an increased proportion of shell debris.

This fine silty sand extends to -20.54m OD, at which point the sediment begins to grade into a series of light grey, fine sandy silts and silty clays. The dark grey, silty sand located between -25.51m and -20.54m OD appears to contain a series of light grey, fine grained silty laminae, together with isolated larger shell fragments; the laminae are particularly distinct between -20.96m and -20.54m OD; the sediment additionally becomes much lighter in colour above -21.61m OD.

The sediments fine upward above -20.31m OD, grading into light grey, laminated sandy silt containing darker mottled patches. The darker mottling terminates at around -19.41m OD and the sediment becomes significantly finer, grading into a very finely laminated silt and eventually laminated clay at -17.06m OD; at this point the laminated clay contains abundant quantities of organic material. The clay extends up to -16.94m OD, where it terminates at the base of a layer consisting of dark brown, firm, highly compacted fibrous material termed deposit 2/3. The layer extends to -16.87m OD and is in turn immediately overlain by light gray, laminated, fine grained silty clay.

The clay grades gradually into light grey, laminated, fine grained silty sand which extends up to -16.78m OD; the sediments located above the peat contain organic material, fragments of shell and crystals, possibly of calcium sulphate. At -16.78m OD the sediment grades into light grey, laminated, silty clay which extends up to -16.38m OD, where it is overlain by dark grey, laminated, silty sand, containing abundant quantities of coal fragments and organic material. The deposit extends to -16.02m OD where it gradually grades into grey, fine grained silty clay, extending up to -15.86m OD.

At -15.86m OD the organic content within the fine sediment increases dramatically giving rise to a laminated and highly organic clay, termed deposit 2/2, consisting of alternating light and dark grey laminae. The deposit extends to -15.73m OD, where the degree of organic content becomes abruptly reduced. Above the organic clay, a very light gray, fine grained silty clay containing an abundance of organic detritus coarsens upward, gradually giving rise to a light grey, sandy silt, containing organic material and fragments of shell. The sandy silt extends from approximately -14.91m OD and coarsens gradually upward, merging into light grey, fine grained silty sand at approximately -14.31m OD. Above this point, finer silty material increases in proportion within the sand, giving rise to a mottled and sometimes laminated silty sand, which also contains a higher proportion of organic material, together with significant quantities of fine grained coal fragments. The sediment continues to fine upward, grading into light grey, silty clay and terminates abruptly at -13.07m OD.

At this point the clay is interspersed by a series of three separate organic-rich layers, collectively termed deposit 2/1, located between -13.07m and -12.97m OD. The layers consist of dark brown, highly compressed, fibrous organic-rich material, with the lower deposit extending upward over approximately 0.03m and forming a complete horizon across the entire width of the core. A narrow band of clay separates the lower organic formation from a central formation that is of similar vertical extent. The central organic deposit is also separated from an upper organic formation, of variable vertical extent, by a band of clay; however, the two upper organic deposits fail to extend laterally across the entire width of the core. The organic-rich deposits are overlain by light grey, silty clay, containing large isolated fragments of *Mytilus* shell, together with smaller shell fragments and nodules of iron pyrite.

Above -12.51m OD the sediment consists of light and dark grey, strongly laminated silty sand which extends to -12.02m OD before becoming increasingly finer, grading into grey, strongly laminated silty clay containing isolated fragments of shell by -11.46m OD. As the sediment extends upward, the laminations become less distinct, giving rise to the sediment taking on a dark mottled appearance between -11.21m and -10.76m OD. Above this depth, between -10.56m and -10.16m OD the sediment is strongly laminated, before appearing mottled once again, gradually coarsening upward into grey, fine grained sand above -9.91m OD.

The sediment continues to coarsen upward, grading into medium-fine silty sand, as well as becoming lighter in appearance above -9.06m OD. The sand additionally contains increasingly higher proportions of broken shell and calcareous material, together with occasional bands of finer silty material as it approaches the surface which is located at an altitude of -7.51m OD.

4.1.3 Cemlyn-Jones sediment core 3 (CJSC 3)

CJSC 3 was recovered from a position located toward the landward end of Bangor Pier, on inter-tidal mudflats (fig.4.1), approximately 300m southeast of CJSC 1 (Ordnance Survey grid reference: SH 5845, 7335). Sediment coring commenced at a point on the surface 3.05m below OD, with the drilling operation recovering a sequence of unconsolidated sediments that extended to 6.00m below the surface, at -9.05m OD (fig. 4.4).

At the base of the core, between -9.05m and -8.67m OD, the sediments consist of light grey, occasionally laminated silt containing a small amount of clay. The sediment becomes gradually finer, incorporating a greater proportion of clay, between -8.67m and -8.55m OD. The light grey, silty clay subsequently extends to -7.89m OD; however, above -8.05m OD, it appears to contain a greater proportion of organic material.

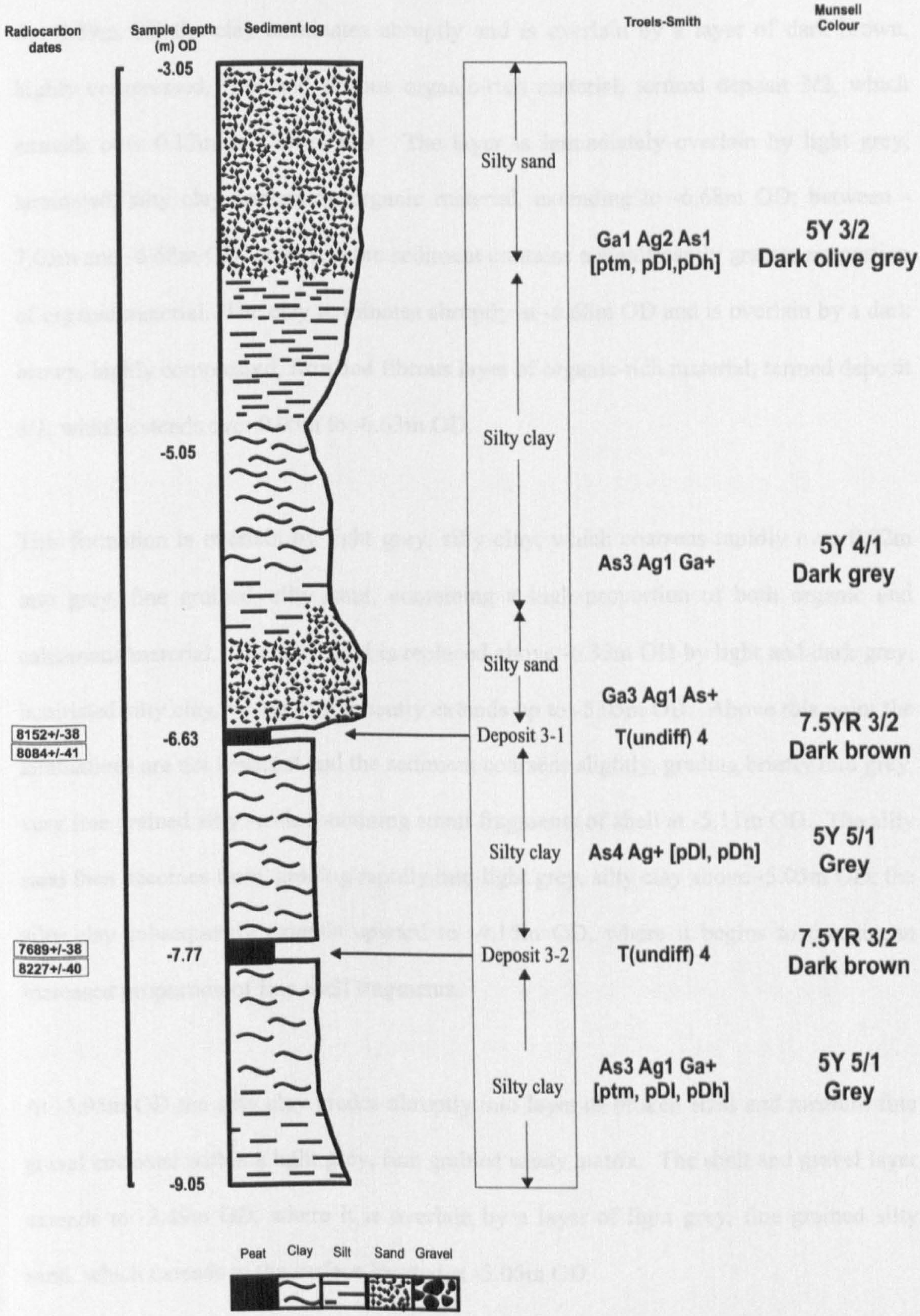


Figure 4.4 Sediment log for CJSC 3, obtained adjacent to Bangor Pier

At -7.89m OD the clay terminates abruptly and is overlain by a layer of dark brown, highly compressed, firm and fibrous organic-rich material, termed deposit 3/2, which extends over 0.12m to -7.77m OD. The layer is immediately overlain by light grey, laminated, silty clay containing organic material, extending to -6.68m OD; between -7.05m and -6.68m OD, however, the sediment contains a significantly greater proportion of organic material. The clay terminates abruptly at -6.68m OD and is overlain by a dark brown, highly compressed, firm and fibrous layer of organic-rich material, termed deposit 3/1, which extends over 0.05m to -6.63m OD.

This formation is overlain by light grey, silty clay, which coarsens rapidly over 0.02m into grey, fine grained, silty sand, containing a high proportion of both organic and calcareous material. The silty sand is replaced above -6.33m OD by light and dark grey, laminated silty clay, which subsequently extends up to -5.05m OD. Above this point the laminations are not apparent and the sediment coarsens slightly, grading briefly into grey, very fine grained silty sand, containing small fragments of shell at -5.11m OD. The silty sand then becomes finer, grading rapidly into light grey, silty clay above -5.05m OD; the silty clay subsequently extends upward to -4.15m OD, where it begins to contain an increased proportion of fine shell fragments.

At -3.95m OD the silty clay grades abruptly into layer of broken shell and medium-fine gravel enclosed within a light grey, fine grained sandy matrix. The shell and gravel layer extends to -3.49m OD, where it is overlain by a layer of light grey, fine grained silty sand, which extends to the surface located at -3.05m OD.

4.2 Geophysical data

The geophysical survey was primarily conducted in an attempt discern the lateral extent and surface morphology of specific deposits identified within the sediment cores. The strategy utilized the technique of marine seismic reflection surveying in an attempt to correlate reflective horizons identified beneath the sea-bed with data obtained from the sedimentological and stratigraphical study of the three sediment cores.

4.2.1 The geophysical survey

The seismic reflection survey (fig. 4.5) conducted within the northeastern region of the Menai Strait consisted of 24 relatively short (1-2km), parallel transects orientated in an approximately northwest to southeasterly direction, perpendicular to the longitudinal profile of the Strait. The relatively evenly-spaced individual transects extended between the region of Bangor Pier and Gallows Point approximately 3km to the northeast. The survey additionally included two transects (16 and 29) extending over a distance greater than 1.5km which were orientated in a southwest to northeasterly direction; these survey lines were located proximal to the shoreline of Anglesey along the northwesterly flank and central region of the main channel. Transect 6 was orientated parallel to Bangor Pier in order to examine the nature of the subsurface beneath the inter-tidal zone immediately adjacent to the structure, whilst transect 17 was orientated in order to bisect the main channel at an oblique angle from southwest of Bangor Pier to the Anglesey shoreline immediately to the north of Port Penrhyn.

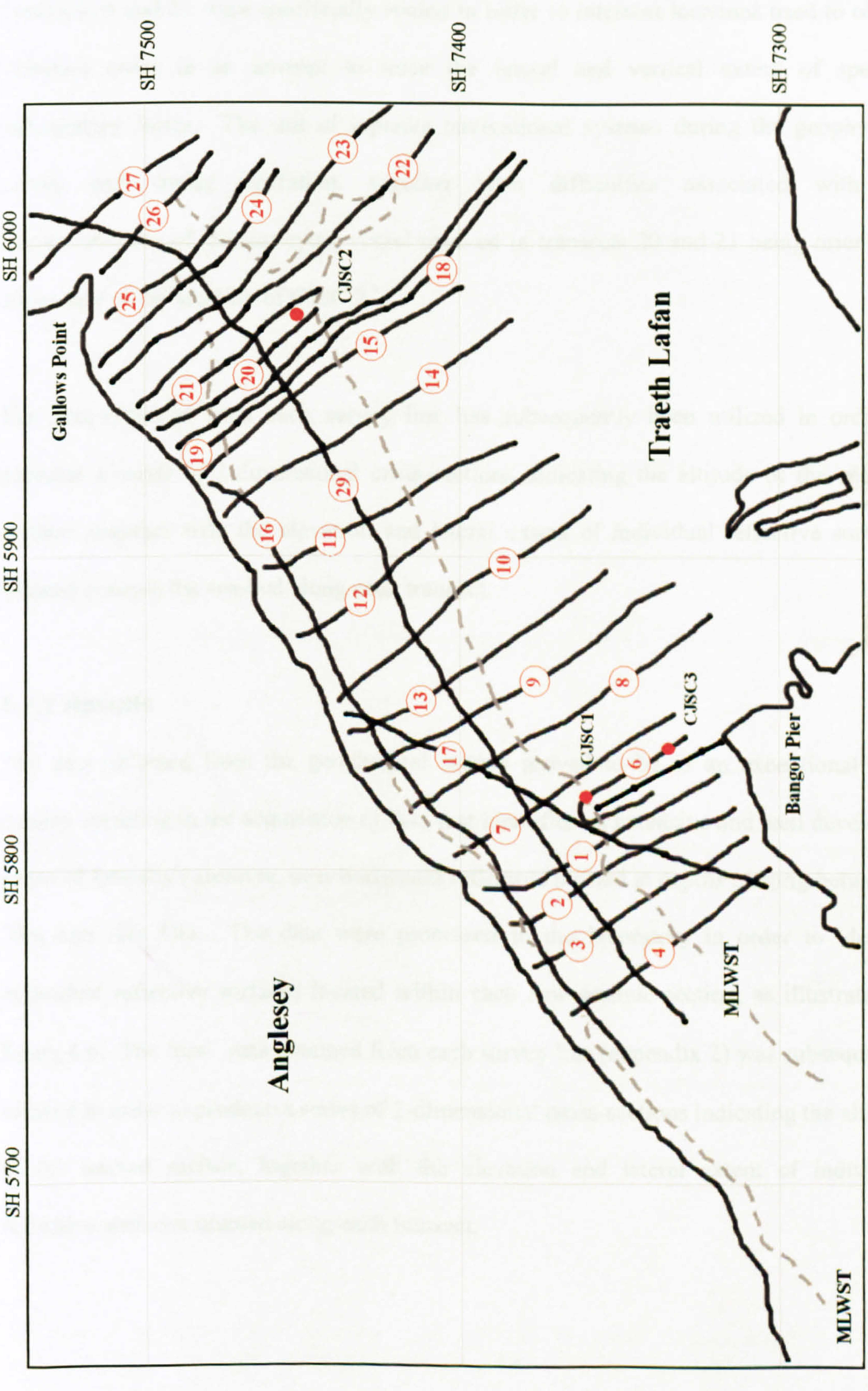


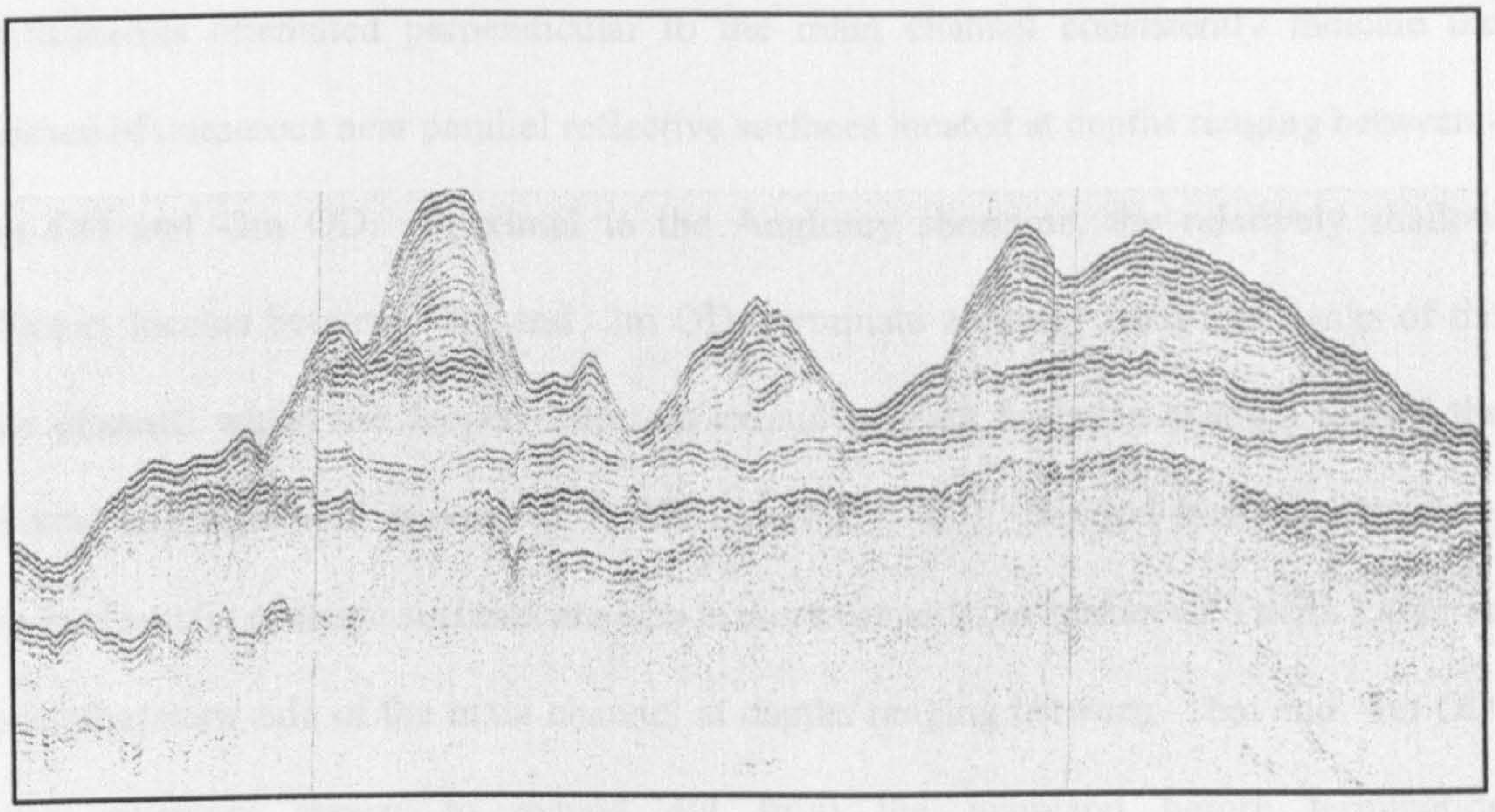
Figure 4.5 Plot of survey transects undertaken during the geophysical survey

Transects 6 and 21 were specifically routed in order to intersect locations used to obtain sediment cores in an attempt to trace the lateral and vertical extent of specific sedimentary facies. The use of separate navigational systems during the geophysical survey and coring operation, together with difficulties associated with the maneuverability of the surveying vessel resulted in transects 20 and 21 being orientated either side of the location of CJSC 2.

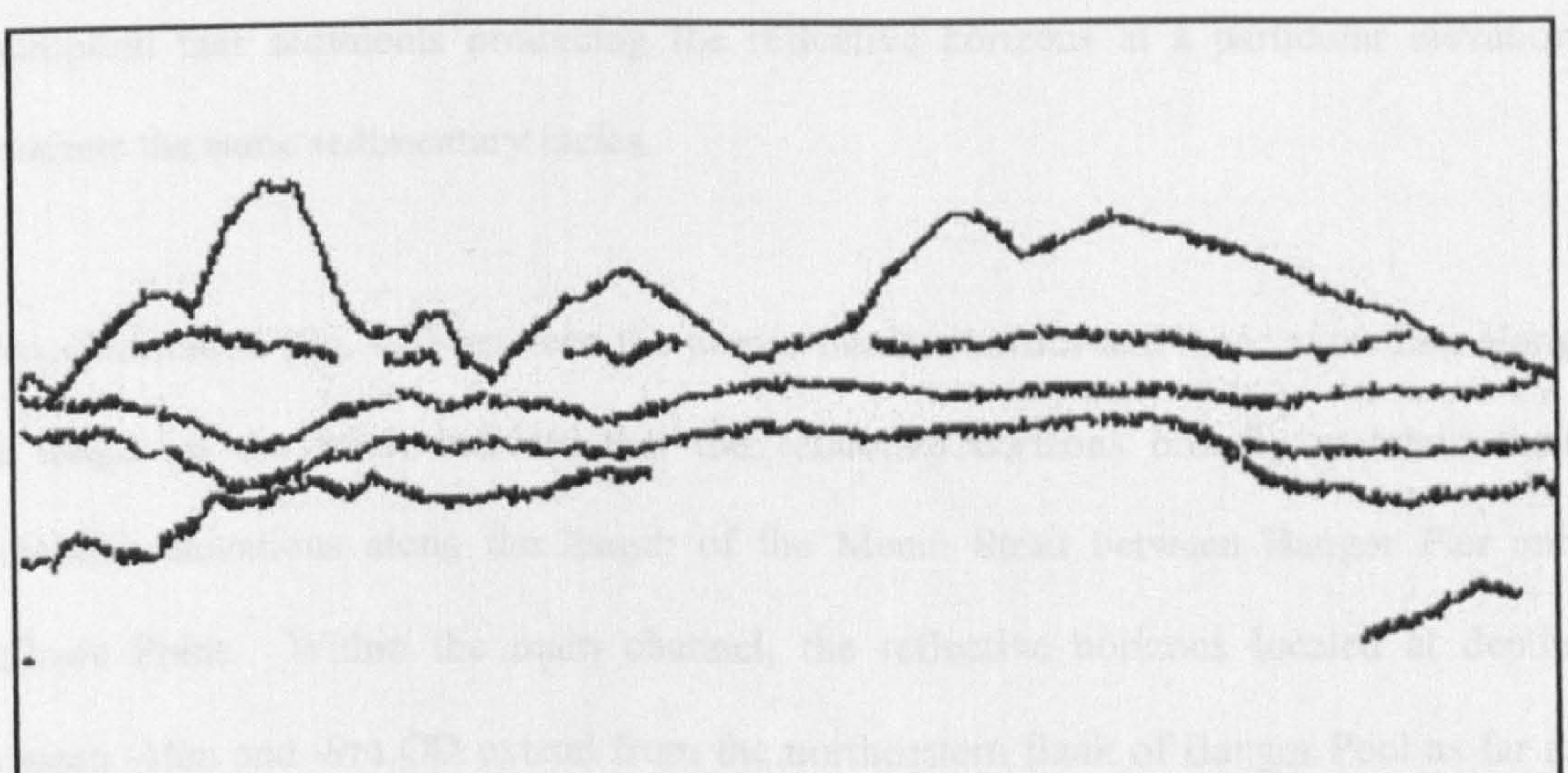
The data obtained from each survey line has subsequently been utilized in order to generate a series of 2-dimensional cross-sections indicating the altitude of the sea-bed surface, together with the elevation and lateral extent of individual reflective surfaces situated beneath the sea-bed along each transect.

4.2.2 Results

The data obtained from the geophysical survey proved to be of an exceptional high quality, resulting in the acquisition of data that identifies an extensive and well developed series of laterally extensive, near horizontal reflectors located at depths ranging between -30m and -2m OD. The data were processed in the laboratory in order to identify individual reflective surfaces located within each *raw* seismic section, as illustrated in figure 4.6. The 'raw' data obtained from each survey line (appendix 2) was subsequently utilized in order to produce a series of 2-dimensional cross-sections indicating the altitude of the seabed surface, together with the elevation and lateral extent of individual reflective surfaces situated along each transect.



'Raw' data from a section of transect 16, proximal to Bangor Pool



'Picked' reflective horizons taken from a section of transect 16

Figure 4.6 Comparison of 'raw' data obtained along a section of transect 16 during the survey and the picked' reflective horizons utilized in the production of the seismic sections

The transects orientated perpendicular to the main channel consistently indicate the presence of numerous near parallel reflective surfaces located at depths ranging between -30m OD and -2m OD. Proximal to the Anglesey shoreline, the relatively shallow reflectors located between -8m and -2m OD, terminate abruptly along the flanks of the main channel, whilst the deeper reflectors extend beneath the main channel toward the sub-tidal and inter-tidal regions of Traeth Lafan (fig. 4.7). Several laterally extensive, near-horizontal reflective surfaces are also present beneath the surface of Traeth Lafan on the southeastern side of the main channel at depths ranging between -16m and -4m OD. These reflectors appear to extend out from the mainland before terminating approximately 200m from the flanks of the main channel. An attempt at correlating reflectors located on either side and within the main channel has been based on the assumption that sediments producing the reflective horizons at a particular elevation constitute the same sedimentary facies.

Cross-correlation (fig. 4.8) between the perpendicular profiles and those extending along the length of the Strait indicate that the reflective horizons broadly maintain their respective elevations along the length of the Menai Strait between Bangor Pier and Gallows Point. Within the main channel, the reflective horizons located at depths between -16m and -9m OD extend from the northeastern flank of Bangor Pool as far as Beaumaris and appear to terminate abruptly on the southwestern flank of the depression located within the main channel at Gallows Point.

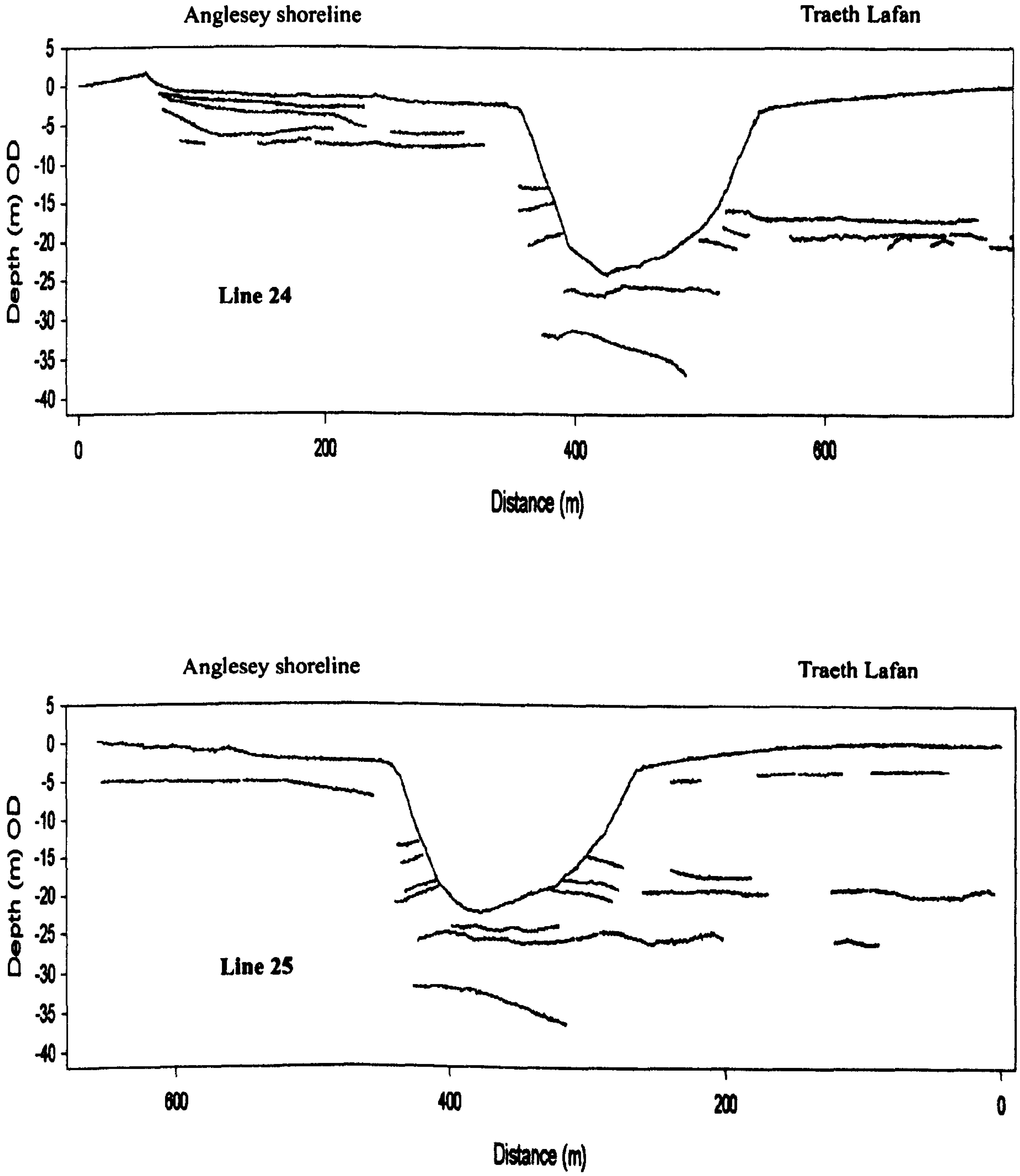


Figure 4.7 Seismic sections obtained from transect lines 24 and 25, proximal to Gallows Point

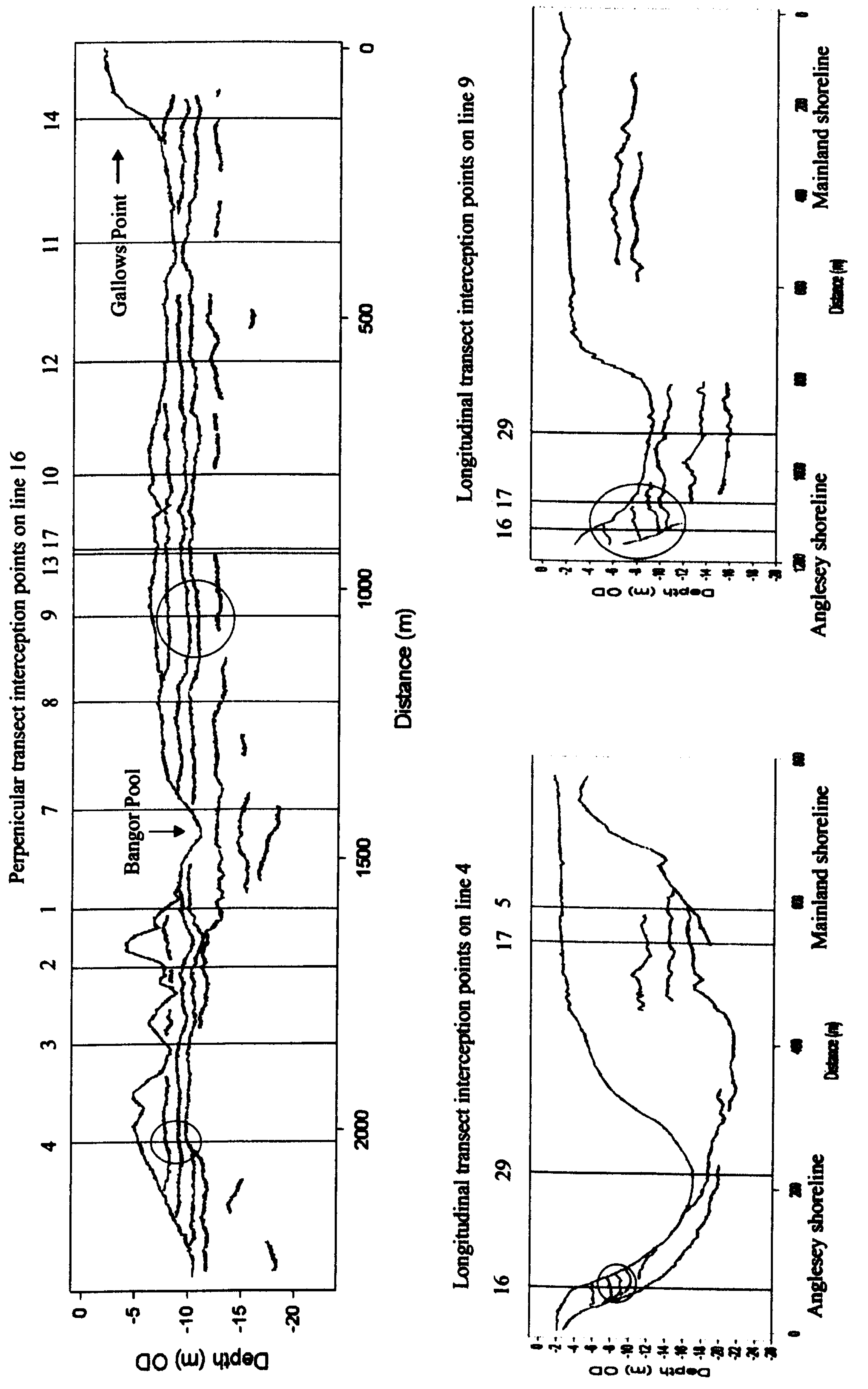


Figure 4.8 Correlation of reflectors between longitudinal transect 16 and perpendicular transects 4 and 9

The altitude of deeper reflective horizons identified within the central region of the main channel at Bangor Pool, additionally correlate extremely well with sedimentary horizons identified within the sediment cores. The appearance of these deeper reflective horizons within the seismic records produced during the survey can primarily be attributed to the undulating morphology of the sea-floor; as the depressions at Bangor Pool and Gallows Point result in a reduction with respect to the thickness of overlying sediment, producing what can effectively be termed as a 'seismic window'. The attenuation of seismic energy as it propagates through a material continues with increasing depth thereby making it progressively difficult to discern reflected energy from horizons located at progressively deeper elevations; this probably accounts for the non-appearance of the deeper reflective horizons within seismic sections retrieved from other regions within the survey area. The deeper horizons occur at depths ranging between -35m and -23m OD and appear to either undulate gradually or be gently inclined to the horizontal.

The 2-d sections orientated perpendicular to the main channel and obtained southwest of Bangor Pier indicate that the shallow reflectors extending between the main channel and the Anglesey shoreline terminate abruptly against a reflective horizon appearing to descend steeply from the Anglesey coastline toward the main channel. The inclination of the reflective horizon decreases sharply from a depth of approximately -16m OD, before becoming indiscernible beneath the main channel (fig. 4.9). Horizontal reflectors situated beneath the inter-tidal region, adjacent to the mainland shoreline, additionally appear to terminate proximal to a reflective horizon descending similarly steeply towards the main channel.

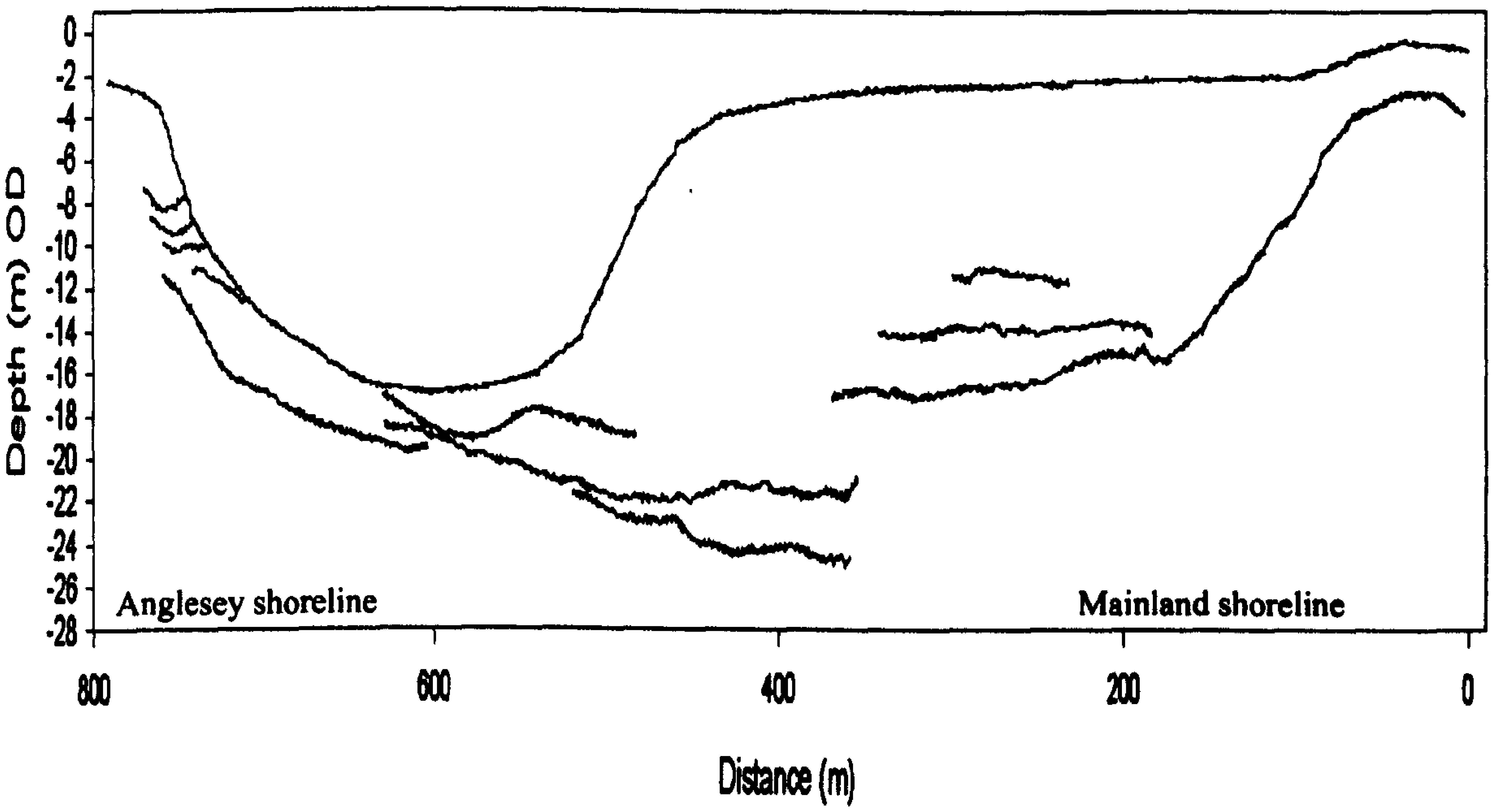
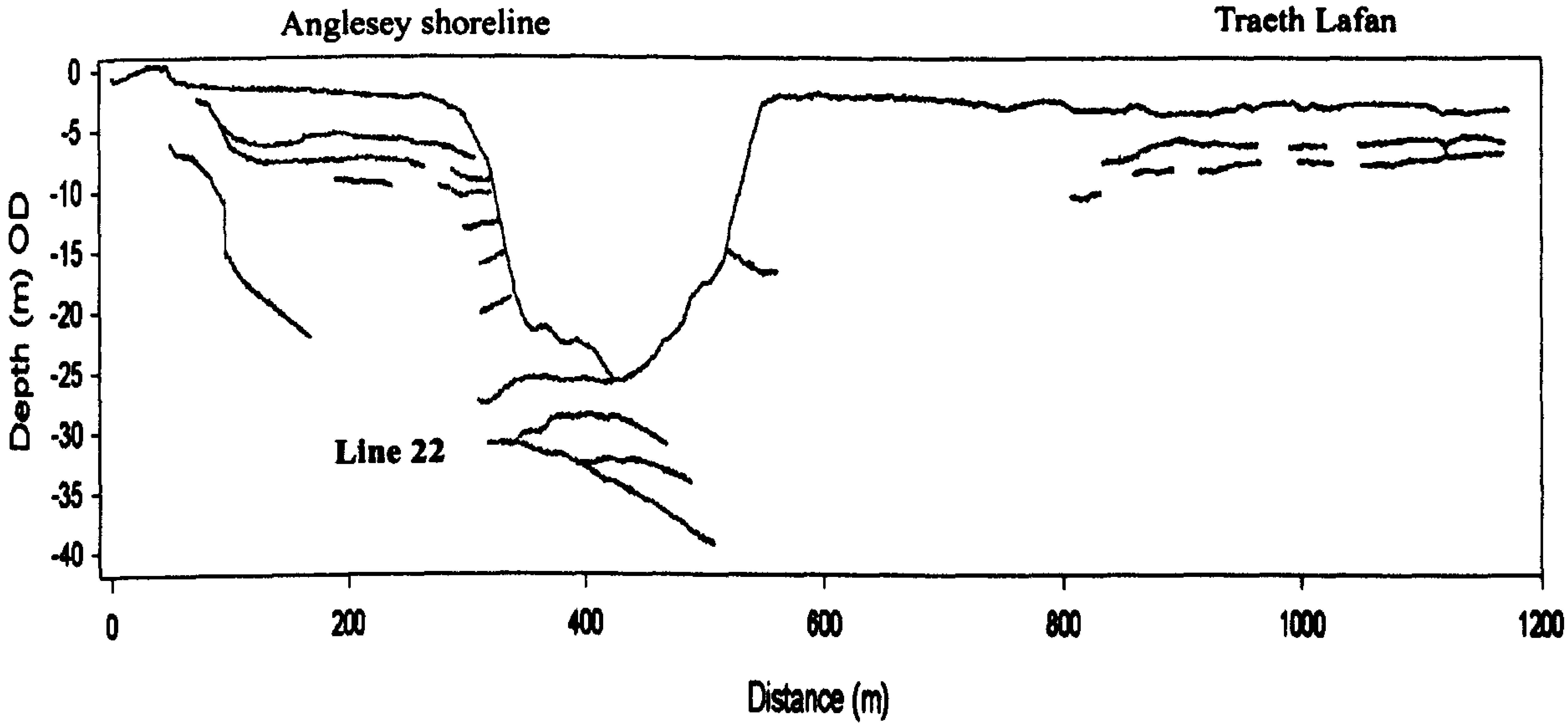


Figure 4.9 Seismic section derived from transect line 3

The 2-d sections obtained from within the region of Gallows Point indicate that the horizontal reflectors terminate against a reflective horizon descending steeply from the Anglesey shoreline towards the centre of the main channel. Two horizons visibly terminate against the flanks of this reflector at depths of -32m and -30m respectively, approximately 3m beneath the sea-floor within the deepest section of the depression (fig. 4.10).



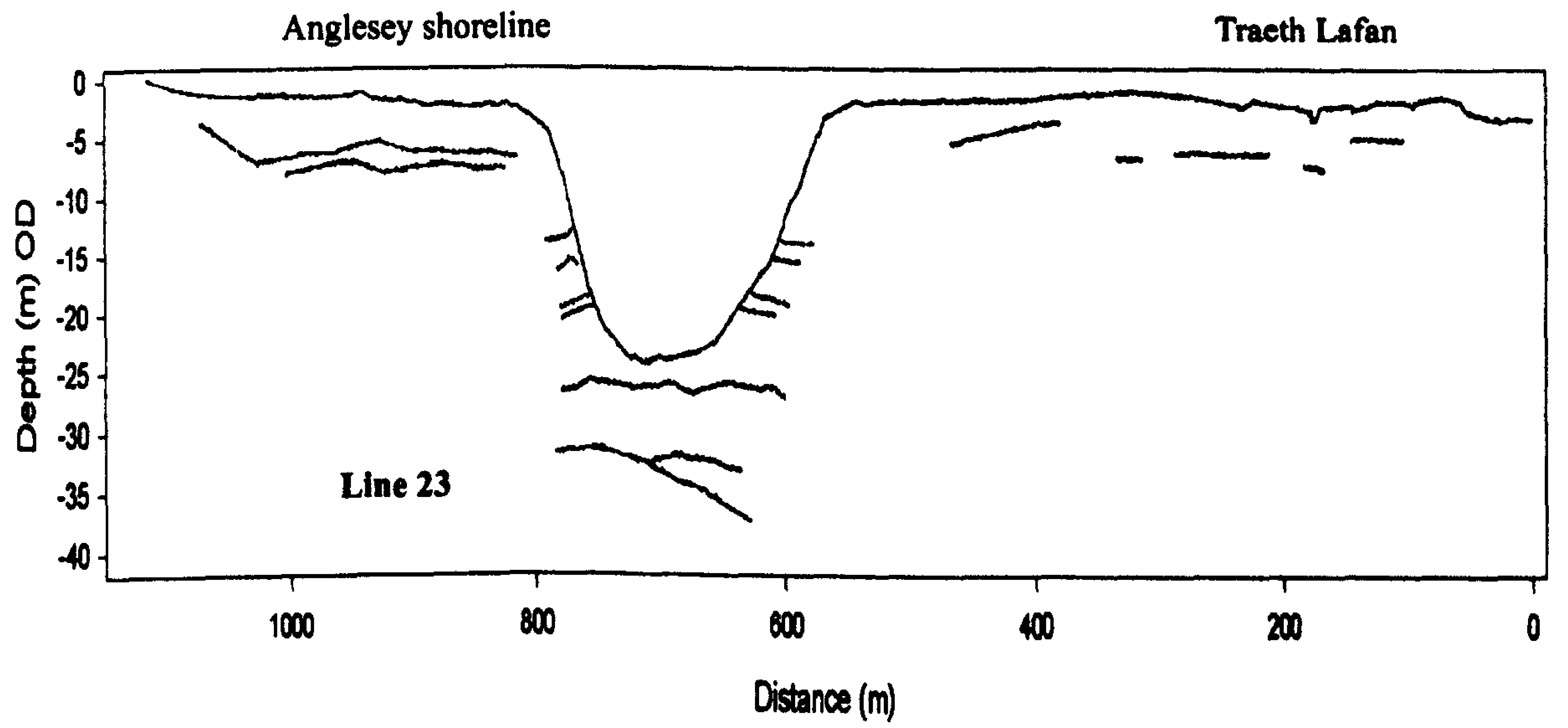


Figure 4.10 Seismic sections derived from transect lines 22 and 23

4.4.3 Comparison of reflection and borehole data

Transect 6 orientated in order to intersect the locations of cores recovered adjacent to Bangor Pier, indicates the presence of 2 near horizontal, parallel reflectors at elevations of -8.0m and -6.5m OD respectively, proximal to the location of CJSC 3. These reflective surfaces correlate well with deposits 3/1 and 3/2 located at -7.77 and -6.61m OD and extend over 200-300m towards the northwest (fig 4.11).

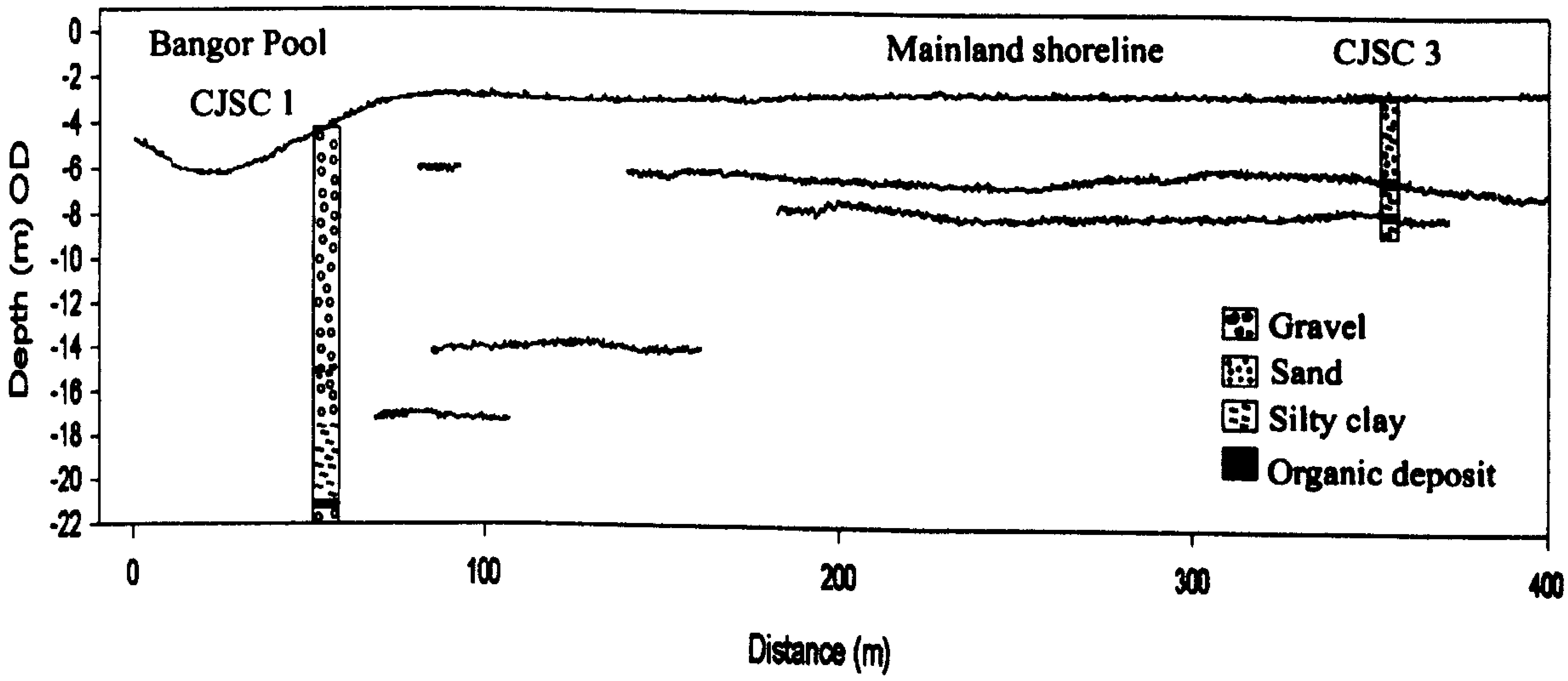


Figure 4.11 Transect 6 taken northeast of Bangor Pier and location of CJSC 1 and CJSC 3

The reflectors do not appear proximal to the southeastern flanks of the main channel, however, the seismic data indicates the presence of what may possibly be an erosional contact within this area. Surveys conducted by Cook (1980), Osiris (1986) and Butcher (1997) distinguish similar seismic sequences at this position, with Butcher (1997) describing the terminating horizon as "an unconformable sequence boundary, separating a lower series containing a number of near parallel reflectors, from an upper sequence of sediments demonstrating a very discernable form of internal structure".

Transect 7 located on the northeastern side of Bangor Pier indicates the presence of relatively shallow reflective horizons that correlate well with those identified within transect six. The seismic section additionally identifies deeper reflectors extending beneath the floor of the main channel that correlate extremely well with deposits 1/2 and 1/1 identified within CJSC 1 (fig. 4.12).

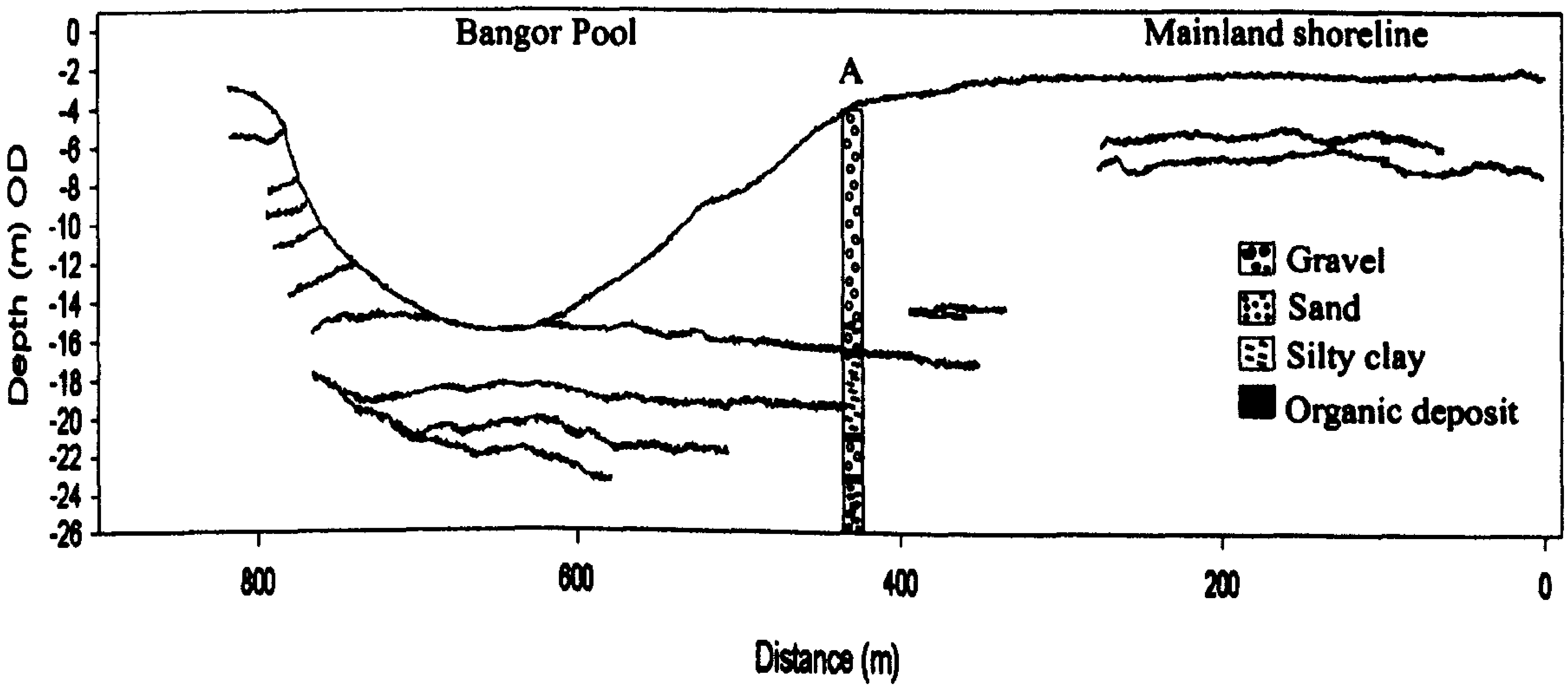
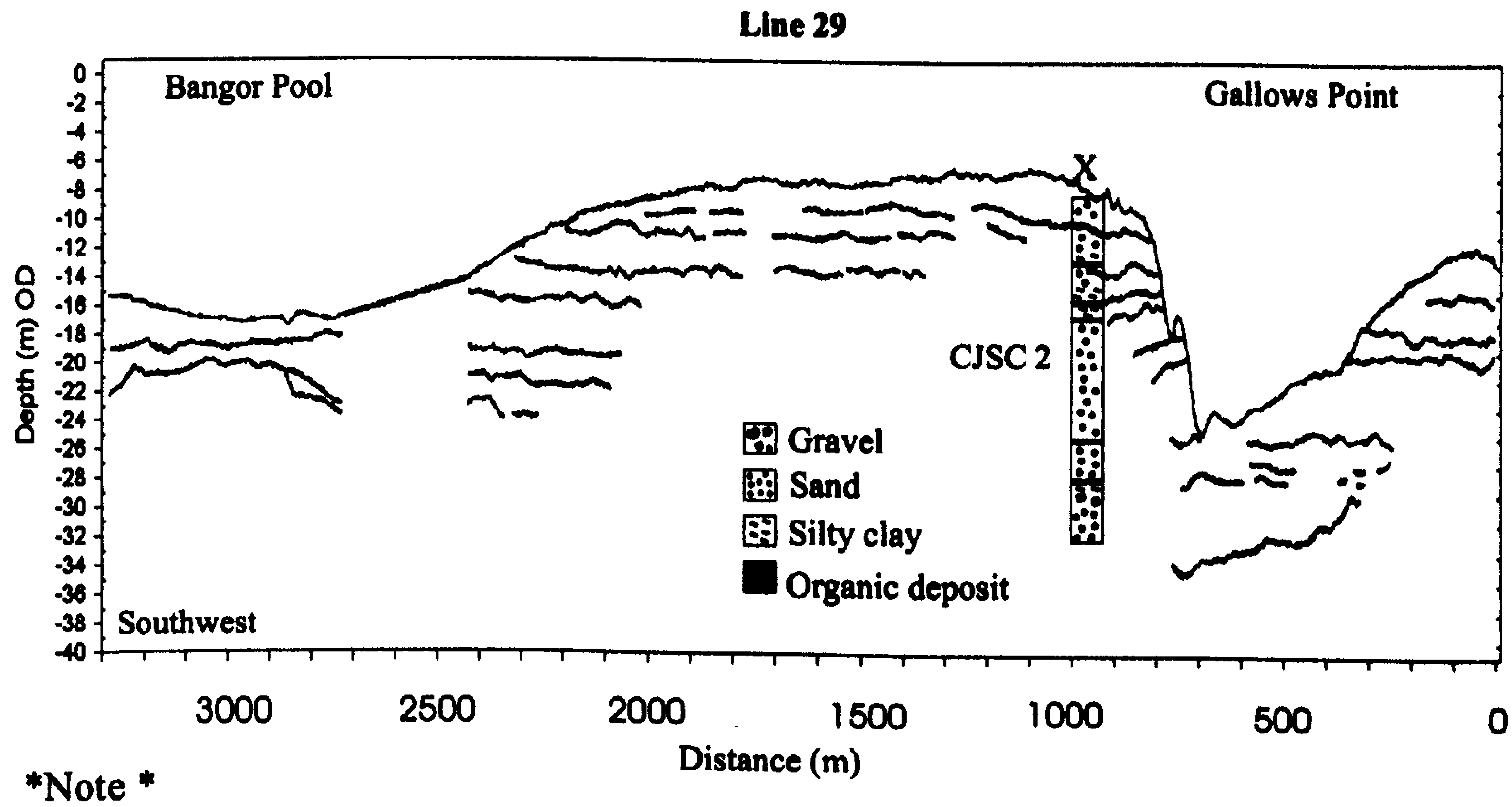


Figure 4.12 A comparison between the reflectors obtained from transect 7 taken northeast of Bangor Pier and the lithoilogy of CJSC 1

* Note *

CJSC 1 was recovered approximately 50m to the southwest of location A marked on the seismic section.

The seismic section obtained from transect 19 demonstrates the presence several near-horizontal reflective horizons beneath the main channel that correlate well with organic-rich horizons 2/2 and 2/1 identified within CJSC 2. Transect 29 additionally identifies these reflective horizons and demonstrates that they terminate abruptly against the southwestern flanks of the depression at Gallows Point (fig. 4.13).



*Note *
CJSC 2 obtained from a location approximately 100m south of position X and approximately 100m east of position Y.

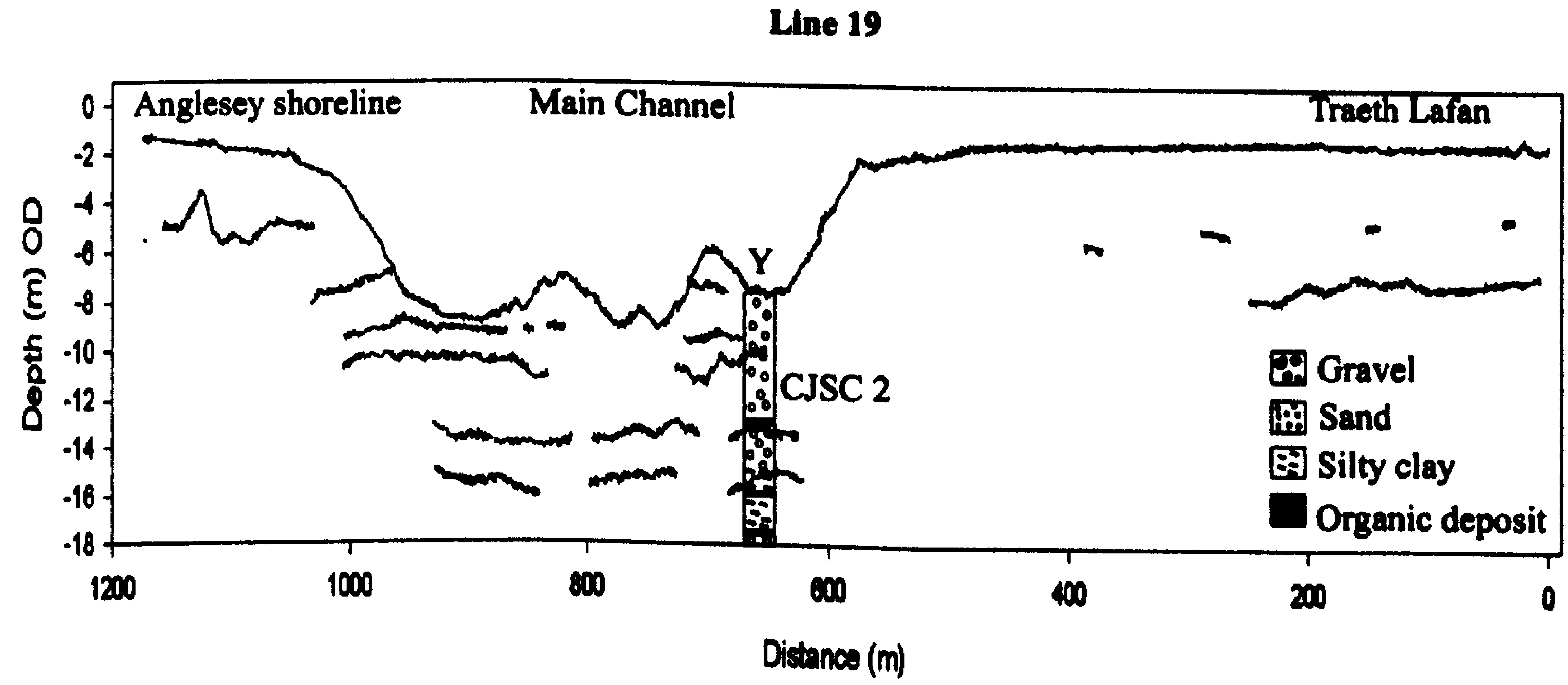


Figure 4.13 Seismic sections from transects 29 and 19 in comparison with the lithology of CJSC 2

4.3 Micropalaeontological data

Micropalaeontological analytical techniques were conducted with respect to sediments sub-sampled from within the sediment cores in an attempt to obtain evidence relating to palaeoenvironmental conditions and aspects of palaeoenvironmental change that may have occurred within the Menai Strait during the course of the Holocene.

4.3.1 Foraminifera analysis

A preliminary analysis of the foraminiferal assemblages contained within sub-samples of sediment removed from within the cores has been designed to generate a relatively low resolution model relating to the distribution of foraminiferal species within the sediment core sections. The analysis primarily concentrates upon points proximal to stratigraphical horizons, where a distinctive facies change occurs and attempts to identify changes with respect to the foraminiferal assemblages contained therein.

The implemented sub-sampling strategy dictated the number and distribution of analyzed sub-samples, as a consequence of this strategy, a greater number of sub-samples were examined immediately proximal to the organic-rich deposits. As a result, no attempt has been made in order to define specific fossil foraminiferal zones within the sediment cores and within the distribution diagrams produced with respect to this analysis.

4.3.1.1 CJSC 1

Sub-samples were examined from inorganic sediment adjacent to the sides of the organic-rich deposits 1/2 and 1/1 respectively, located towards the base of the sediment core.

Eight sub-samples were analyzed from depths between -20.02m and -20.65m OD located above peat deposit 1/1; with an additional fifteen being examined from depths located between -20.85m and -23.11m OD from within the sedimentary facies separating deposits 1/1 and 1/2. Two additional sub-samples were analyzed from the sediment underlying deposit 1/2 at depths between -23.37m and -23.82m OD; five of the twenty five sub-samples were found to contain very few or no foraminifera. Figure 4.14 illustrates the fossil assemblages contained within the analyzed sub-samples, displaying the assemblages with respect to their stratigraphical context.

Sub-samples extending between -23.47m OD and -21.00m OD are characterized by the domination of hyaline foraminifera, predominantly *Haynesina germanica* (16-49%) together with significant quantities of *Elphidium williamsoni* (9-19%). The relative proportion of *Ammonia batavus* increases proximal to the organic-rich deposits, coinciding with presence of finer sediment. Epifaunal foraminifera such as *Cibicides lobatulus*, *Asterigerinata mamilla,* and *Gavelinopsis praegeri* are also present and increase in proportion within the coarser sediment located between the organic-rich formations. Smaller proportions of porcellaneous foraminifera such as *Quinqueloculina seminulum* and *Quinqueloculina pygmaea* additionally contribute to the total assemblage.

Immediately below deposit 1/1 and extending between -21.00m and -20.85m OD, the sediments are characterized by the dominance of hyaline foraminifera such as *Haynesina germanica, Ammonia batavus* and *Elphidium williamsoni*. Epifaunal dwelling species such as *Cibicides lobatulus* and *Asterigerinata mamilla* together with small numbers of

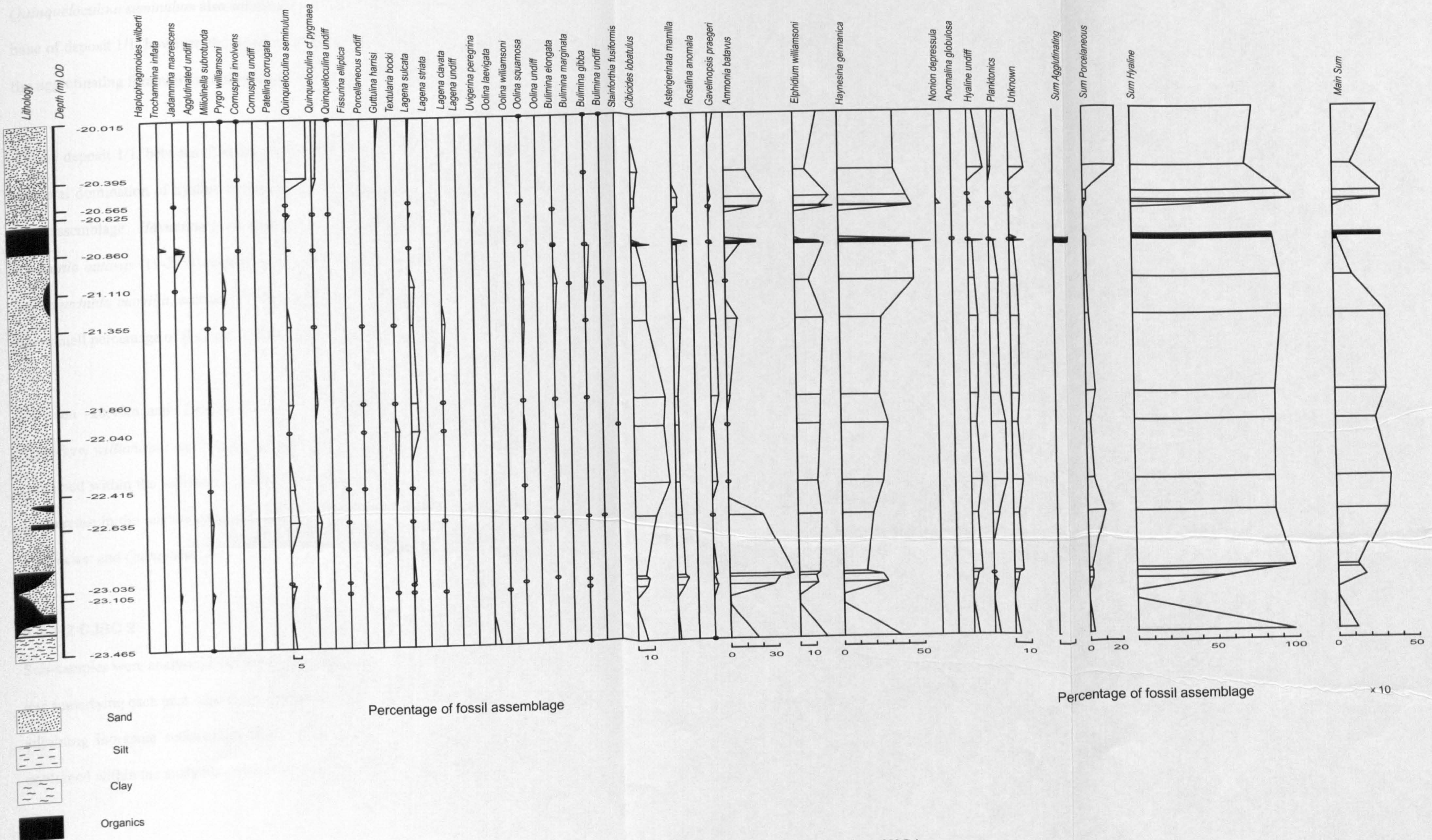


Figure 4.14 Foraminifera diagram for sub-samples taken from CJSC 1

Quinqueloculina seminulum also contribute toward the total assemblage. Proximal to the base of deposit 1/1, however, the inorganic sediment contains an increasing proportion of the agglutinating foraminifera *Jadammina macrescens* and *Trochammina inflata.*

Above deposit 1/1, between -20.64m and -20.48m OD, the sediment is characterized by the total domination of hyaline foraminifera which accounts for between 94-98% of the total assemblage. *Haynesina germanica* (43-47%), *Elphidium williamsoni* (16-25%) and *Ammonia batavus* (19-24%) together with smaller proportions of *Cibicides lobatulus* and *Asterigerinata mamilla*, account for the bulk of the assemblage; however, there is also a very small percentage of *Quinqueloculina seminulum* present.

Between -20.48m and -20.02m OD hyaline species including *Haynesina germanica, Elphidium williamsoni* and *Ammonia batavus* once again dominate the fossil assemblage contained within the sediment. At this point, however, the sediment is characterized by an increase in the relative proportion of the porcellaneous foraminifera *Quinqueloculina seminulum* and *Quinqueloculina pygmaea*, which constitute 18% of the total assemblage.

4.3.1.2 CJSC 2

Sub-samples were analyzed from within the sedimentary sequence immediately overlying and underlying each peat deposit or organic-rich formation at discrete intervals within the adjoining inorganic sedimentary facies. Figure 4.15 illustrates the fossil assemblages contained within the analyzed sub-samples, with respect to their stratigraphical context.

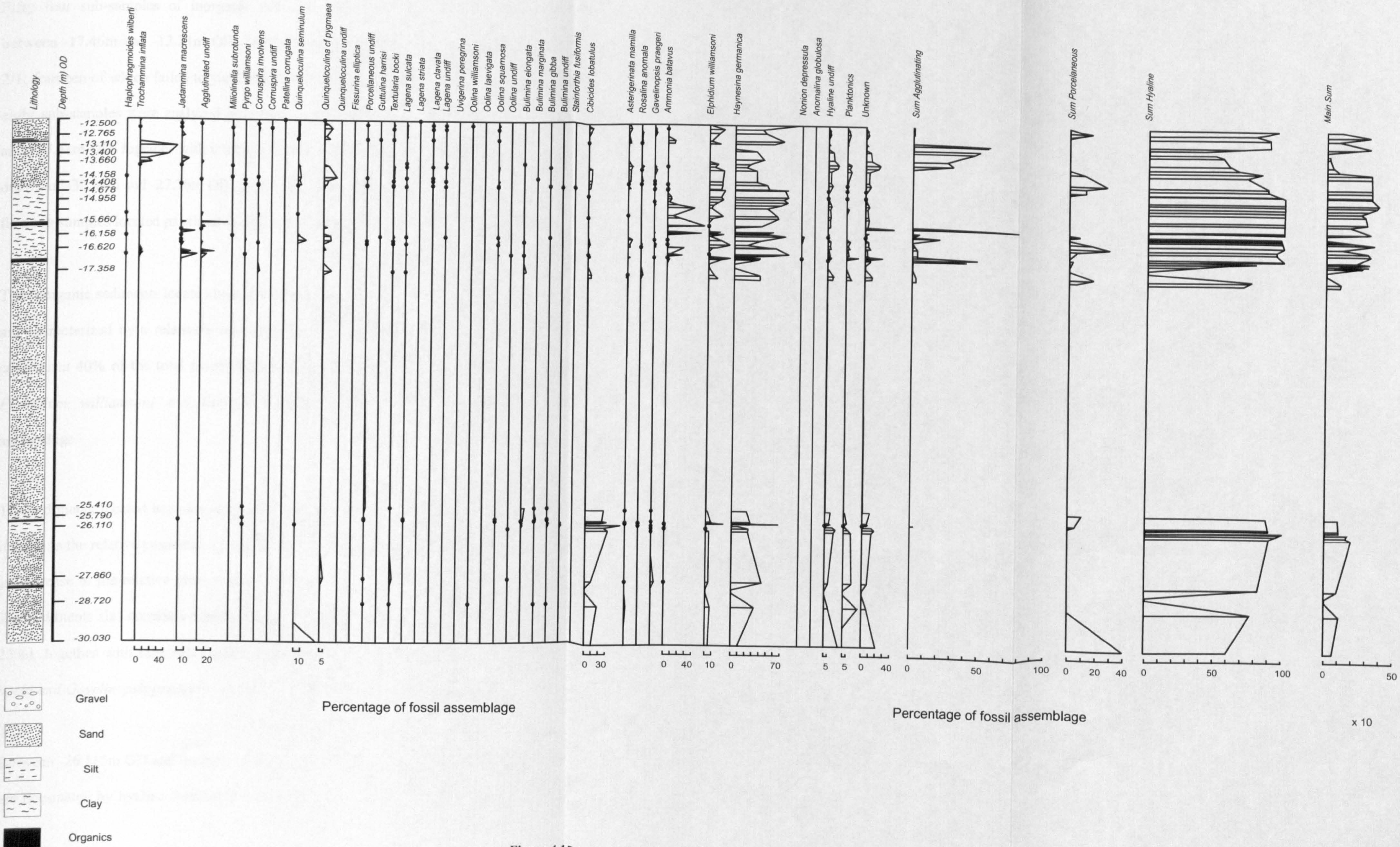


Figure 4.15 Foraminifera diagram for sub-samples taken from CJSC 2

Fifty four sub-samples of inorganic sediment were examined from depths ranging between -17.46m and -12.21m OD, located from beneath deposit 2/3 to above deposit 2/1; fourteen of which failed to yield sufficient quantities of foraminifera. An additional eight sub-samples were analyzed proximate to deposit 2/4 between depths of -26.12m and -25.41m OD, together with a further thirteen inorganic sub-samples located between depths of -30.04m and -27.76m OD, proximal to the organic-rich clay termed deposit 2/5; five sub-samples located proximal to deposit 2/5 contained few or any foraminifera.

The inorganic sediments located beneath deposit 2/5, at a depth greater than -30.03m OD are characterized by a relatively high proportion of *Quinqueloculina seminulum* which constitutes 40% of the total assemblage. Lower proportions of *Haynesina germanica, Elphidium williamsoni* and *Cibicides lobatulus* constitute the remainder of the assemblage.

The sediments located between -28.73m OD and -27.86m OD indicate a decrease with respect to the relative proportion of porcellaneous foraminifera present, coincidental with an increase in the relative proportion of *Haynesina germanica* and *Cibicides lobatulus.* The sediments also contain a notable proportion of planktonic foraminifera (between 14-23%), together with relatively small proportions of *Elphidium williamsoni, Textularia bocki and Gavelinopsis praegeri.*

Between -26.115m OD and the base of deposit 2/4 located at -25.89m OD, the sediments are dominated by hyaline foraminifera, with the data indicating a distinctive rise in the relative proportion of *Cibicides lobatulus* present (33-59%). Decreasing relative proportions of *Haynesina germanica* (30-11%) and increasing relative proportions of planktonic foraminifera (4-12%), additionally characterize the sediments within this section of the core.

Above deposit 2/4 at a depth of -25.86m OD and extending up to -25.41m OD, the sediment is characterized by increasingly larger relative proportions of *Cibicides lobatulus* (2-34%). The sediments are, however, dominated by large proportions of *Haynesina germanica, Elphidium williamsoni,* and *Ammonia batavus*. The sediment additionally contains a relatively small proportion of *Quinqueloculina seminulum* and planktonic foraminifera, and is additionally characterized by a slight decrease with respect to the relative proportion of both *Haynesina germanica* and *Elphidium williamsoni* present.

Immediately beneath deposit 2/3, between -17.46m and -16.94m OD, the sediment is dominated by *Haynesina germanica* (between 22-42%) and *Elphidium williamsoni* (between 10-14%). The sediments additionally contain relatively low proportions of both *Ammonia batavus* and *Cibicides lobatulus,* together with increasing quantities of *Quinqueloculina pygmaea* and smaller quantities of *Quinqueloculina seminulum.* Relatively small proportions of agglutinating foraminifera are present within the very fine grained sediments immediately beneath the organic-rich deposit and constitute 2-3% of the total assemblage at this point within the sedimentary sequence.

Examination of sub-samples recovered from immediately above deposit 2/3, between -16.80m and -16.40m OD, demonstrate that the sediments are characterized by the presence of the agglutinating foraminifera, which at times constitutes up to 47% of the total assemblage. The proportion of *Jadammina macrescens* present within the fine grained sediment located immediately above deposit 2/3 constitutes 25% of the total assemblage, whilst with increasing elevation, increasing proportions of *Haynesina germanica* (11%-80%) and *Elphidium williamsoni* (1%-33%) further characterise this section of the sedimentary sequence.

Between -16.40m and -16.08m OD the fine silty clay is dominated by *Haynesina germanica* and *Elphidium williamsoni*, however, the sediments are characterized by a marked increase in the relative proportion of the porcellaneous foraminifera *Quinqueloculina seminulum* and *Quinqueloculina pygmaea*. One sub-sample located between deposits 2/3 and 2/2 at a depth of -16.01m OD, contains relatively high proportions of agglutinating foraminifera. Immediately below organic clay deposit 2/2 the sediments are characterized by the hyaline species, *Haynesina germanica, Elphidium williamsoni* and *Ammonia batavus*, however, small proportions of agglutinating foraminifera are also present.

Above deposit 2/2, the examination of one sub-sample recovered from a depth of -15.72m OD indicates that the sediments in this region of the core are dominated by agglutinating foraminifera, which constitute up to 77% of the fossilized assemblage. The bulk of this component (65%), however, consists of undifferentiated agglutinating foraminifera, with *Jadammina macrescens* constituting the additional 12%. *Haynesina germanica* (9%) and *Ammonia batavus* (7%), together with a few undifferentiated hyaline foraminifera constitute the remainder of the assemblage.

The sediment located between -15.69m and -14.56m OD is dominated by hyaline foraminifera, with relatively high proportions of *Haynesina germanica* varying between 40% and 78%. The proportion of *Elphidium williamsoni* present within this section of the sequence is highly variable and fluctuates between 0% and 22%; the proportion of *Ammonia batavus* contained within the sediments similarly varies between 3% and 56%.

Between -14.56m and -13.72m OD the sediment is characterized by an increase with respect to the relative proportion of porcellaneous foraminifera present. Although *Haynesina germanica* and *Elphidium williamsoni* continue to dominate, *Quinqueloculina seminulum* and *Quinqueloculina pygmaea* contribute between 3% and 24% of the total assemblage. Examination of the sediments extending between -13.72m and -13.11m OD located immediately below deposit 2/1 demonstrates that the sediment is characterised by the increasing dominance of the agglutinating foraminifera, including *Trochammina inflata* and *Jadammina macrescens*. Relatively high proportions of *Haynesina germanica* and *Elphidium williamsoni* constitute the remainder of the fossilized assemblage.

The sediment overlying deposit 2/1 at -12.86m OD and extending to -12.21m OD contains proportions of hyaline, porcellaneous and agglutinating foraminifera, with

Haynesina germanica, Elphidium williamsoni and *Ammonia batavus* dominant. The proportion of porcellaneous foraminifera such as *Quinqueloculina seminulum* and *Quinqueloculina pygmaea* is greater toward the central region of this section, whereas a smaller proportion of agglutinating foraminifera appear throughout.

4.3.1.3 CJSC 3

Sub-samples were examined from inorganic sediment adjacent to the sides of two organic-rich deposits termed 3/2 and 3/1 respectively, located towards the base of the sediment core. The distribution of foraminifera assemblages with respect to their stratigraphical context are illustrated in figure 4.16.

Four sub-samples were analyzed from depths between -6.32m and -6.63m OD located above deposit 3/1; with an additional six sub-samples being examined from depths located between -6.70m and -7.76m OD from within the sedimentary facies separating deposits 3/1 and 3/2. Six additional sub-samples were analyzed from the sediment underlying deposit 3/2 at depths ranging between -7.89m and -9.02m OD; five of the sixteen sub-samples were found to contain very few or no foraminifera.

The assemblages within the sediments underlying deposit 3/2 are dominated by hyaline foraminifera principally comprising *Haynesina germanica, Ammonia batavus* and *Elphidium williamsoni.* Relative proportions of *Ammonia batavus* decrease, whilst small quantities of agglutinating foraminifera occur within the sub-samples of sediment examined proximal to the base of the organic-rich deposit.

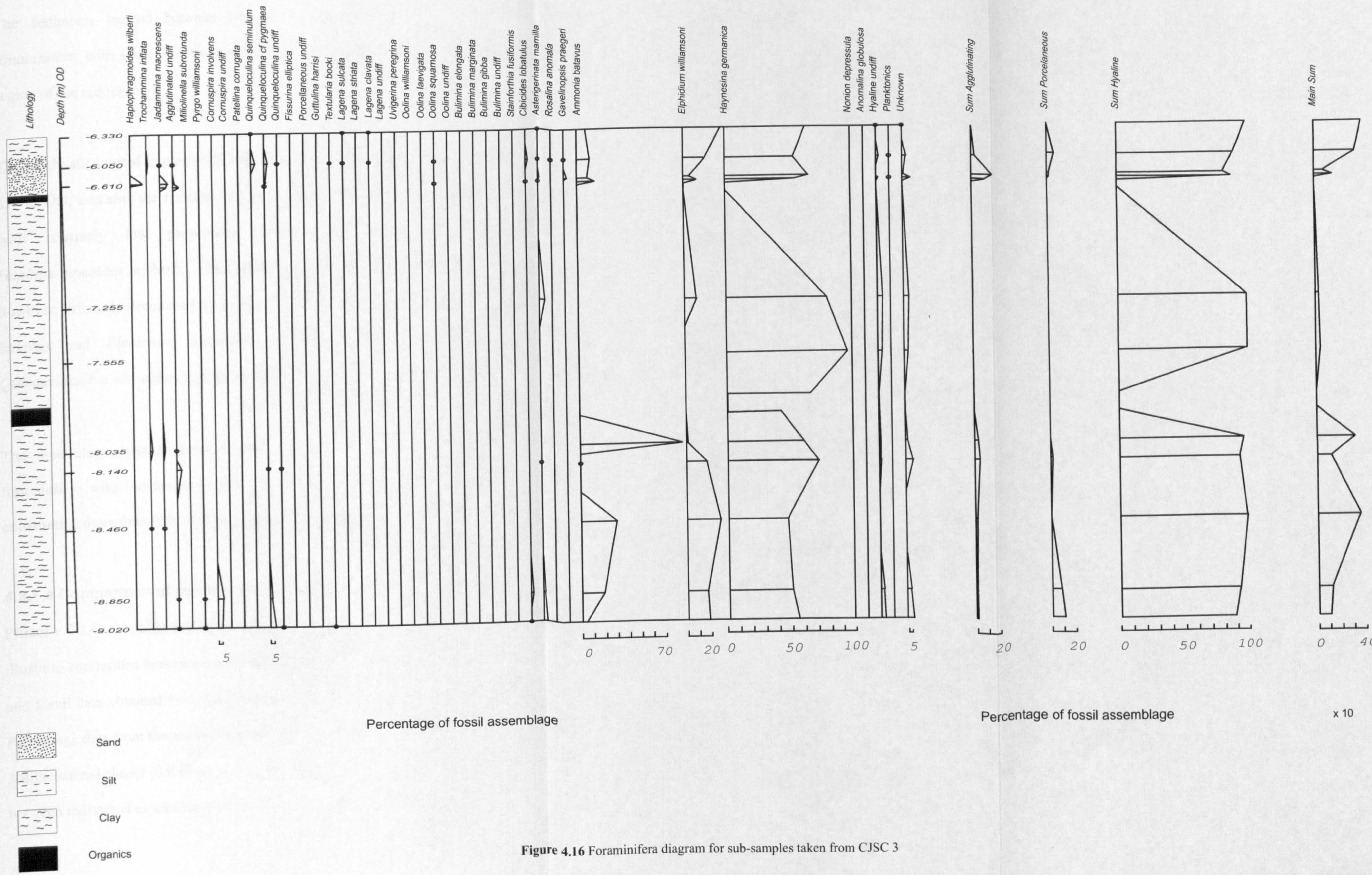


Figure 4.16 Foraminifera diagram for sub-samples taken from CJSC 3

The sediments located between deposit 3/2 and deposit 3/1 contain very few foraminifera; with small quantities of hyaline foraminifera occurring within the central region of the sequence.

The sandy silt located immediately above deposit 3/1 at -6.63m OD and extending to -6.49m OD, contains the remains of unidentifiable agglutinating foraminifera, together with relatively low proportions (<10%) of *Jadammina macrescens* and *Haplophragmoides wilberti*. The assemblages within the analyzed sediments are, however, primarily dominated by hyaline foraminifera *Haynesina germanica, Ammonia batavus* and *Elphidium williamsoni*; whilst relatively small proportions of *Quinqueloculina seminulum* and *Quinqueloculina pygmaea* are also present.

The fine clay situated above -6.49m OD, is dominated completely by hyaline foraminifera with *Haynesina germanica, Ammonia batavus* and *Elphidium williamsoni* constituting more than 95% of the total fossil assemblage.

4.3.1.4 Comparison of modern and of fossil assemblages

Primer v.5.2.4 was utilized in order to conduct a multivariate cluster analysis designed to illustrate similarities between a modern analogue obtained from within the Taf Estuary and fossil data obtained from the inorganic sediments adjacent to organic-rich deposits. Percentage data from the modern assemblages are presented in Table 4.1 and result in the 3-dimensional cluster plot illustrated in figure 4.17, which illustrates degrees of similarity between individual assemblages obtained from specific sub-environments

Taf Estuary Foraminifera	High marsh				High marsh grass				Middle marsh				Middle marsh Halimione				Low marsh				Mud				Sandy mud				Sand			
foram species	HM1	HM2	HM3	HM4	Hmg1	Hmg2	Hmg3	Hmg4	MM1	MM2	MM3	MM4	MMh1	MMh2	MMh3	MMh4	LM1	LM2	LM3	LM4	M1	M2	M3	M4	Sm1	Sm2	Sm3	Sm4	S1	S2	S3	S4
Textularia bocki	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0
Haplophragmoides wilberti	0.0	0.0	0.0	1.0	0.0	8.1	1.1	22.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	4.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Trochammina inflata	36.7	3.7	3.0	1.0	75.3	65.6	40.4	27.0	2.9	1.0	2.1	0.0	15.0	3.3	0.0	0.0	1.2	0.0	5.5	2.0	0.0	1.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jadammina macrescens	19.0	16.7	0.0	0.0	22.7	22.2	9.0	15.0	1.9	7.0	3.1	3.4	2.0	47.8	5.0	2.0	7.2	1.0	26.3	1.0	0.0	4.1	4.9	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0
Miliammina fusca	0.0	5.6	0.0	2.0	0.0	0.0	16.9	2.0	0.0	0.0	0.0	0.0	0.0	1.1	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Agglutinated undiff	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Miliolinella subrotunda	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	2.1	1.9	4.0	5.1	8.1	5.8	2.0	4.0	4.0	8.0	4.0
Pyrgo williamsoni	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Spiroloculina excavata	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cornuspira sp	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cornuspira involvens	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Patellina sp	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Quinqueloculina cf pygmaea	1.3	56.5	10.0	0.0	0.0	0.0	10.1	0.0	0.0	0.0	0.0	0.0	48.0	12.0	62.0	4.0	8.4	23.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Quinqueloculina bicornis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	3.0	0.0	0.0
Quinqueloculina seminulum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.6	1.0	0.0	0.0	0.0	1.0	10.1	1.2	6.8	17.0	9.0	26.0	18.0
Qinqueloculina clarensis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0
Porcellaneous undiff	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Textularia bocki	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lagena sulcata	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	1.0	0.0	2.0	1.0	1.0	1.2	1.0	0.0	0.0	1.0	0.0
Lagena sebgera	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lagena clavata	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	1.0	0.0	0.0
Lagena striata	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lagena sp	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oolina laevigata	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oolina williamsoni	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.0	1.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	1.1	0.0	0.0	1.0	0.9	0.0	2.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0
Oolina squamosa	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	2.0	0.0	0.0
Oolina sp	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bolivina variabilis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bolivina spathula	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bulimina elongata	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	3.9	0.0	1.0	7.1	2.3	0.0	8.0	6.0	3.0	0.0
Bulimina marginata	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	4.0	4.0	0.0	2.0
Bulimina gibba	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	2.0	0.0	0.0	0.9	5.0	3.0	5.1	1.2	10.7	0.0	0.0	0.0	0.0
Bulimina sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0
Stainforthia fusiformis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cibicides lobatulus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.4	1.0	2.2	7.8	7.9	7.2	12.2	22.0	21.2	20.2	39.3	24.3	23.0	17.0	11.0	16.0
Asterigerinata mamilla	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.1	0.0	0.0	4.8	0.0	1.1	3.0	4.0	5.2	0.0	2.0	13.1	10.1	9.2	17.5	11.0	24.0	4.0	17.0
Rosalina anomala	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	5.0	0.0	4.0
Planorbulina distoma	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	1.0	1.0
Ammonia batavus	0.0	3.7	3.0	18.4	2.1	0.0	0.0	0.0	2.9	11.0	5.2	4.5	0.0	0.0	0.0	0.0	7.2	2.0	0.0	3.0	20.8	23.7	13.2	5.0	5.1	10.1	2.3	5.8	23.0	14.0	35.0	33.0
Elphidium crispum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0	1.0	0.0	0.0	5.0	0.0
Elphidium williamsoni	43.0	12.0	74.0	71.8	0.0	4.1	20.1	34.0	33.0	27.0	45.8	28.1	15.0	29.4	30.0	83.0	31.2	62.0	50.5	48.5	15.8	21.7	5.6	18.0	10.1	4.0	10.4	3.9	2.0	0.0	2.0	0.0
Haynesina germanica	0.0	0.9	10.0	5.8	0.0	0.0	1.1	0.0	55.0	3.0	42.7	64.0	8.0	5.4	2.0	11.0	27.8	11.0	11.0	5.8	42.6	32.0	43.2	29.0	33.3	19.2	22.0	12.6	4.0	12.0	0.0	6.0
Nonion depressula	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	0.0	47.0	0.0	0.0	6.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	1.0	0.0
Cancris auricula	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0
Guttulina harrissi	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Uvigerina peregrina	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Anomalina globulosa	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Trifarina angulosa	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0
Gyroidina sp	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0
Fissurina sp	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Patellina corrugata	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gavelinopsis praegri	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	8.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0
Globoquadrina hexagona	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hyaline undiff	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Planktonics	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0
INDETERMINABLE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	2.0	0.0	0.9	3.0	0.0	0.0	0.0	0.0
UNKNOWN	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0

Table 4.1 Modern foram data obtained from sub-environments within the Taf Estuary

within the Taf Estuary. Samples representing high, mid and low marsh regions, together with those obtained from mud and sandflats were included in an attempt to identify biofacies within the sediment cores. The analysis was specifically conducted on regions within the sediment cores where a sufficient number of sub-samples had been deemed to have been examined.

Variance between the foraminiferal assemblages obtained from specific sub-environments within the contemporary estuary are displayed in figure 4.17, which clearly illustrates a linear trend between the sub-environments in relation to their location and altitude within the estuarine environment. The results of comparisons between these data and the assemblages obtained from within the sediment cores are displayed within figures 4.18 a-i.

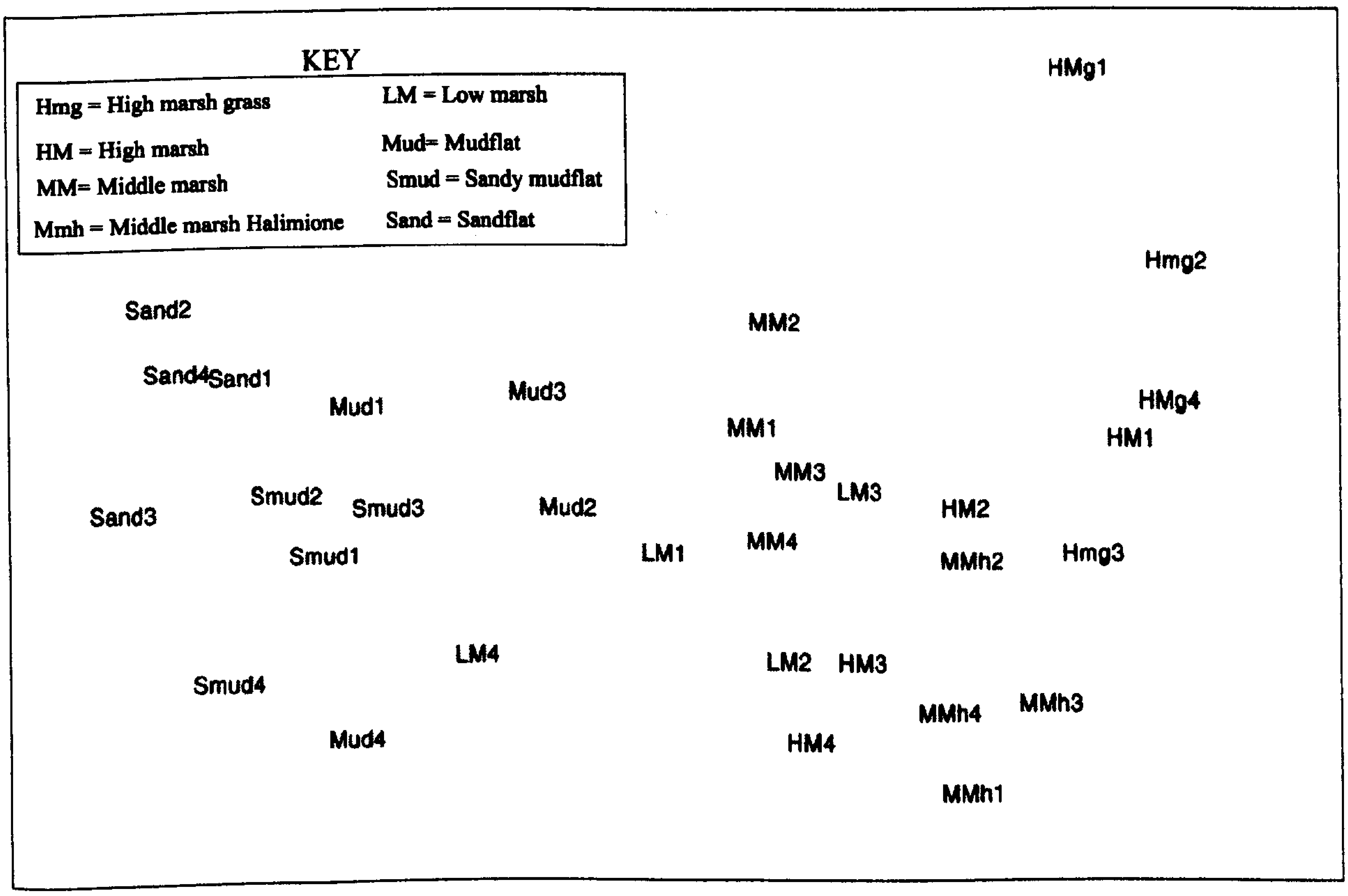


Figure 4.17 Statistically derived 3-dimensional similarity plot of foraminiferal assemblages from from sub-environments located within the Taf Estuary

4.3.1.4.1 CJSC 1

Data from the inorganic sediments located above deposit 1/2 demonstrate a clear trend with decreasing proximity from the upper surface of the organic-rich deposit (fig. 4.18a). The assemblages adjacent to the deposit possibly represent a low marsh or sandy mudflat biofacies, whilst with increasing distance away from the deposit, the assemblages appear to represent a biofacies associated with a higher energy environment.

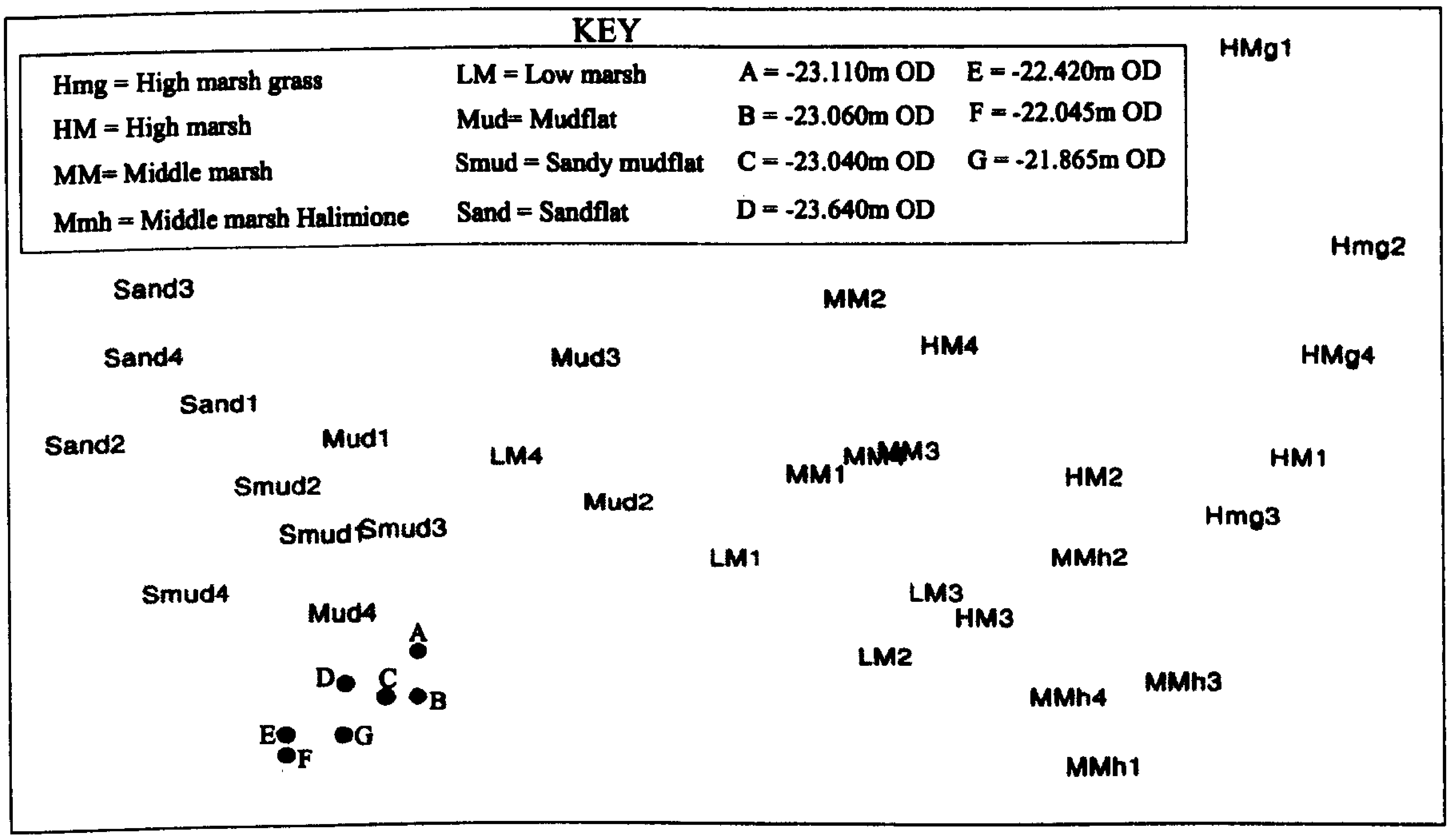


Figure 4.18a Comparison of modern analogue with assemblages located above 1/2 top

The multivariate analysis conducted on assemblages contained within sediments located beneath deposit 1/1 (fig.4.18b) demonstrates that the biofacies exhibits a considerable degree of similarity to that of the modern analogue. The assemblages contained within sediment sub-sampled approximately 0.30m below the deposit possibly represent a biofacies associated with a high energy environment, whereas with increasing proximity towards the organic-rich deposit, the assemblages appear similar to those found within a contemporary lower marsh area.

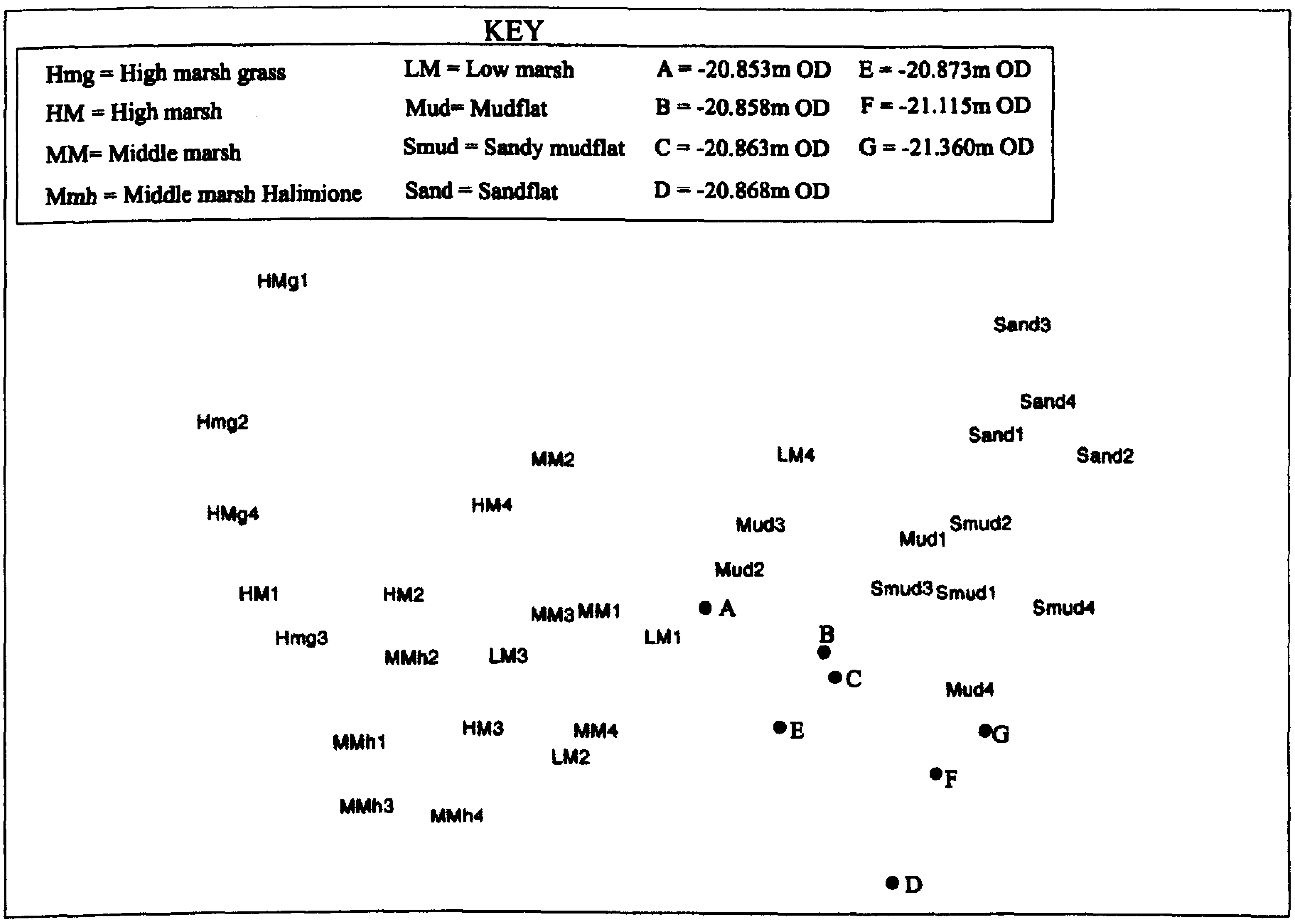


Figure 4.18b Comparison of modern analogue with assemblages located below 1/1 bottom

The data obtained from the sediments located immediately above deposit 1/1 (fig 4.18c), display similar attributes to those located above 1/2 and may again represent a biofacies associated with an inter-tidal region adjacent to a region of low marsh or mudflat. The assemblages obtained from above this region, although dissimilar from those immediately adjacent to deposit 1/1, do not correlate adequately with the modern data and consequently do not define a specific biofacies.

4.3.1.4.2 CJSC 2

Data from the inorganic sediments located above deposit 2/4 demonstrate a clear trend with increasing proximity from the upper surface of the organic-rich deposit (fig. 4.18d). The assemblages adjacent to the deposit possibly represent a middle or low marsh

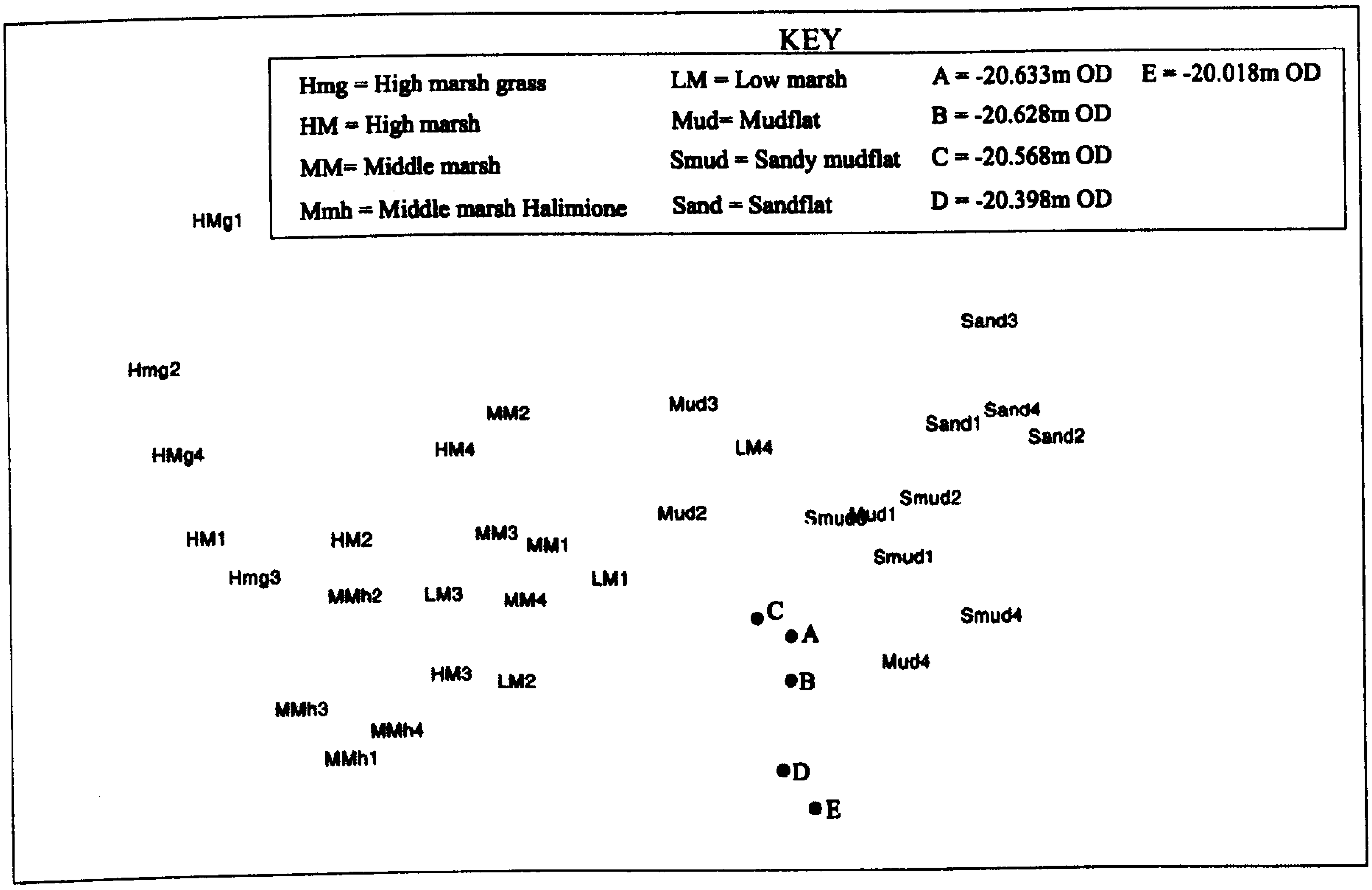


Figure 4.18c Comparison of modern analogue with assemblages located above 1/1 top

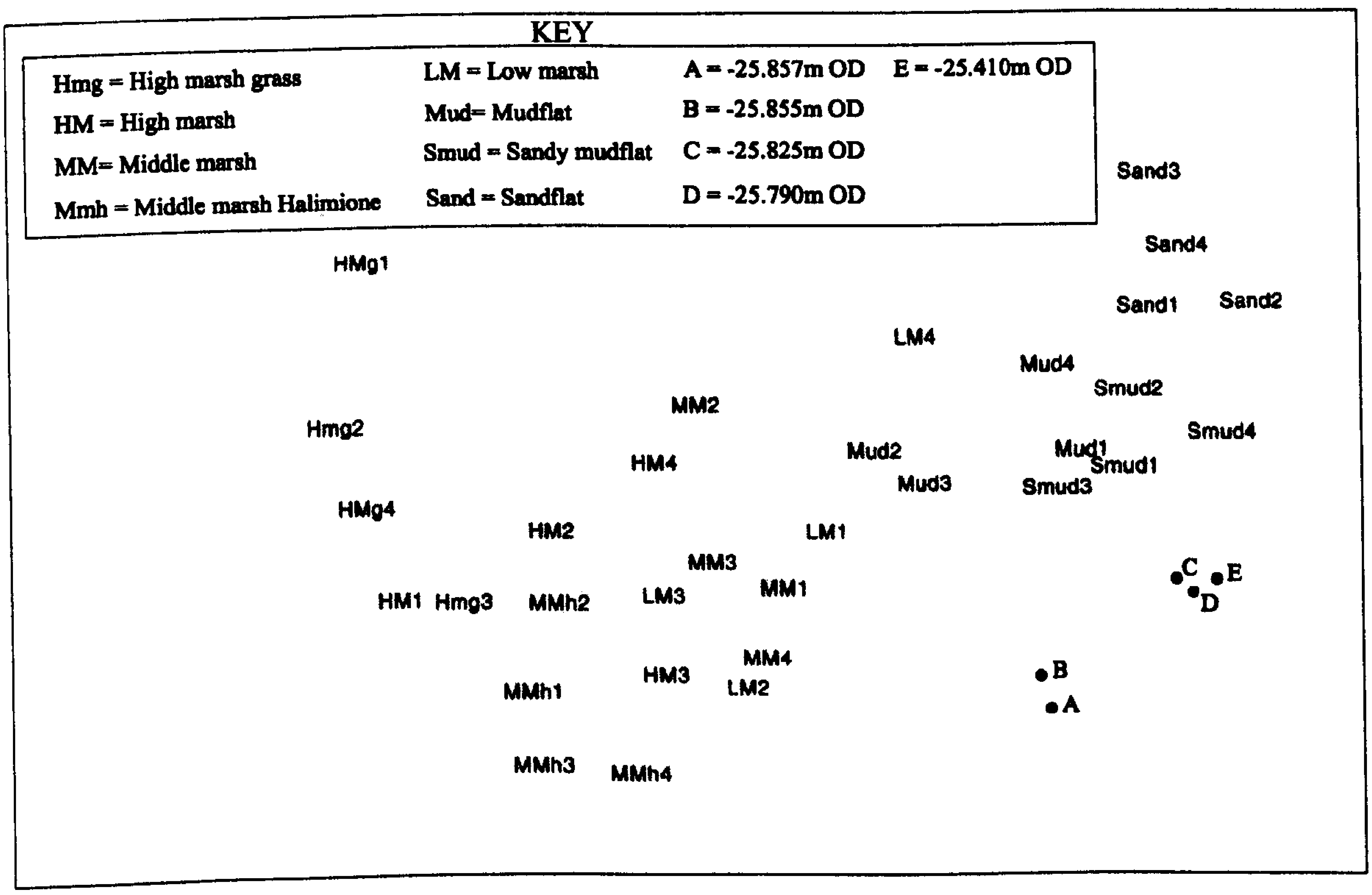


Figure 4.18d Comparison of modern analogue with assemblages located above 2/4 top

biofacies, whilst above the deposit the assemblages indicate a transition to an environment characterized by a biofacies associated with higher energy conditions.

The data obtained from the sediments located immediately above deposit 2/3 (fig. 4.18e), indicate that the assemblages represent a biofacies associated with a middle marsh environment. The assemblages obtained from above this region, although dissimilar from those immediately adjacent to deposit 2/3, do not correlate adequately with the modern data and therefore do not define a specific biofacies.

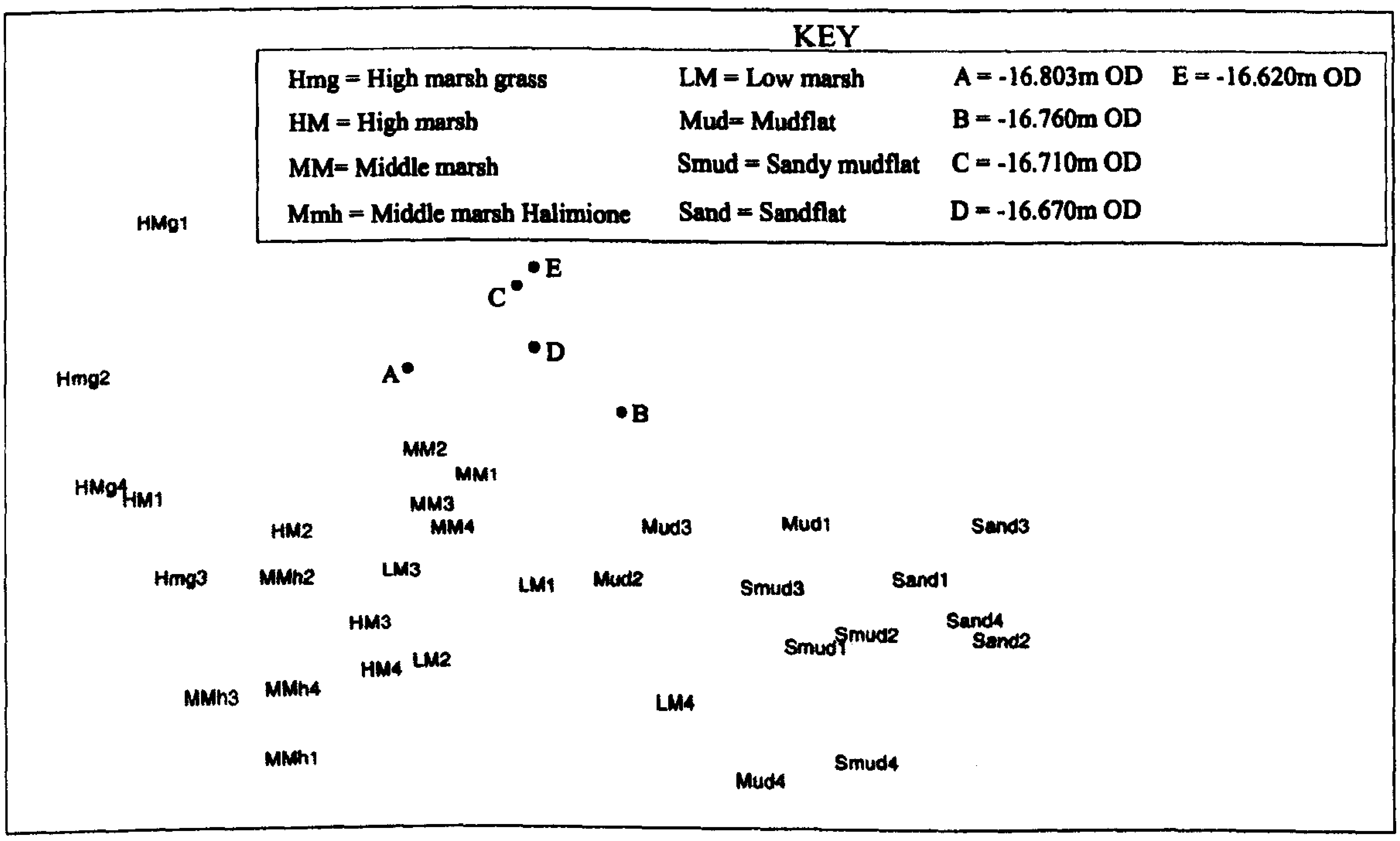


Figure 4.18e Comparison of modern analogue with assemblages located below 2/3 top

The multivariate analysis indicates that assemblages located below deposit 2/2 (fig. 4.18f) represent a biofacies associated with a relatively high energy environment such as an inter-tidal sand or mudflat. The analysis indicates that, with increasing proximity toward the base of the organic-rich deposit, the assemblages become similar to those typically found within a middle or low marsh.

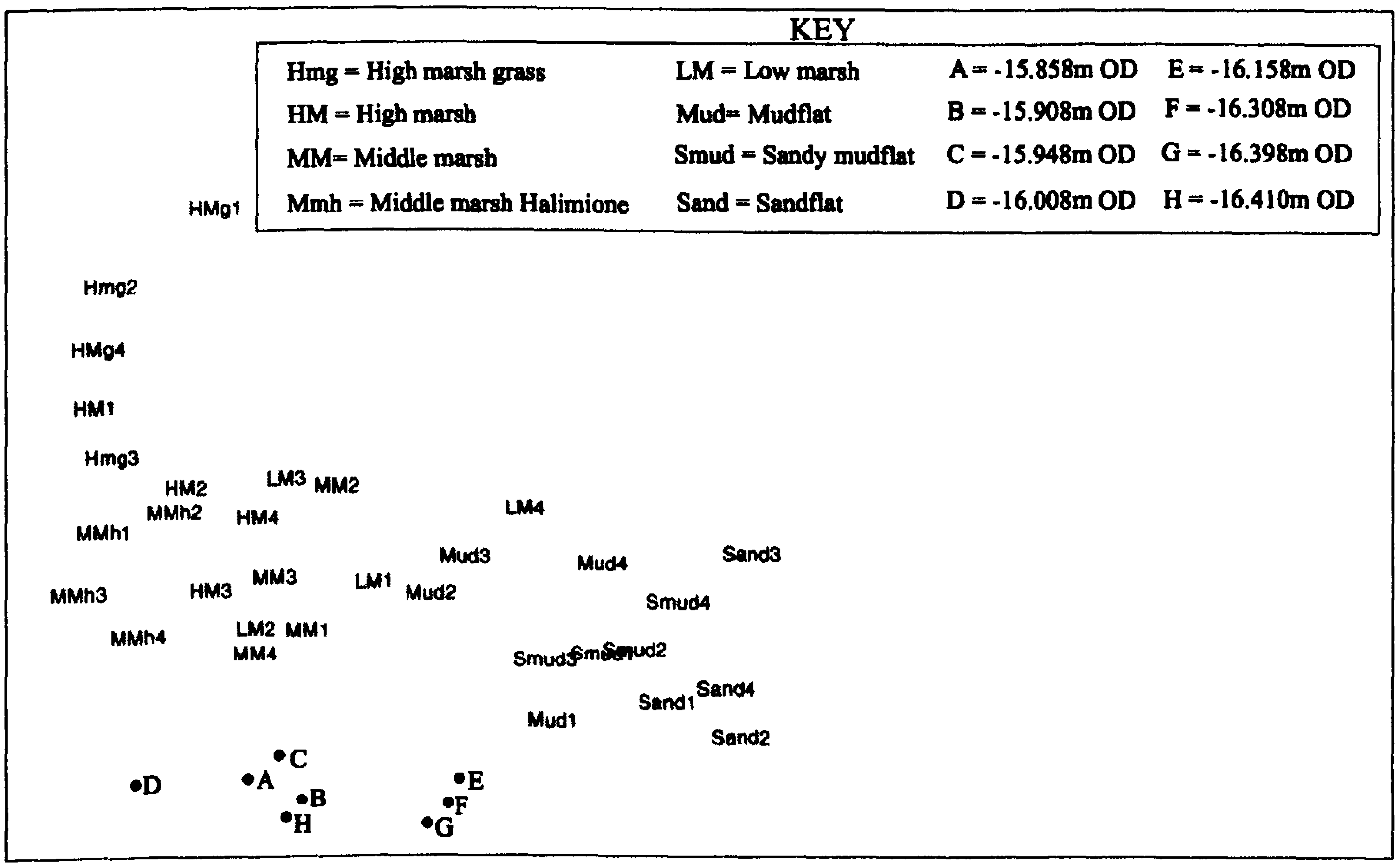


Figure 4.18f Comparison of modern analogue with assemblages located below 2/2 bottom

The analysis conducted on assemblages within sub-samples recovered from above deposit 2/2 (4.18g) did not display a trend similar to that exhibited by the modern analogue, although the sediments may represent a biofacies similar to that found within a contemporary middle or low marsh environment.

The multivariate analysis indicates that assemblages located furthest below deposit 2/1 (fig. 4.18h) represent a biofacies similar to that of a contemporary sandy mudflat, associated with a relatively high energy environment. The assemblages contained within sub-samples extending up to the base of the deposit exhibit a trend similar to that taken by the modern analogue. The assemblages immediately adjacent to the base of deposit 2/1 may represent a biofacies similar to one found within a contemporary middle or high marsh environment.

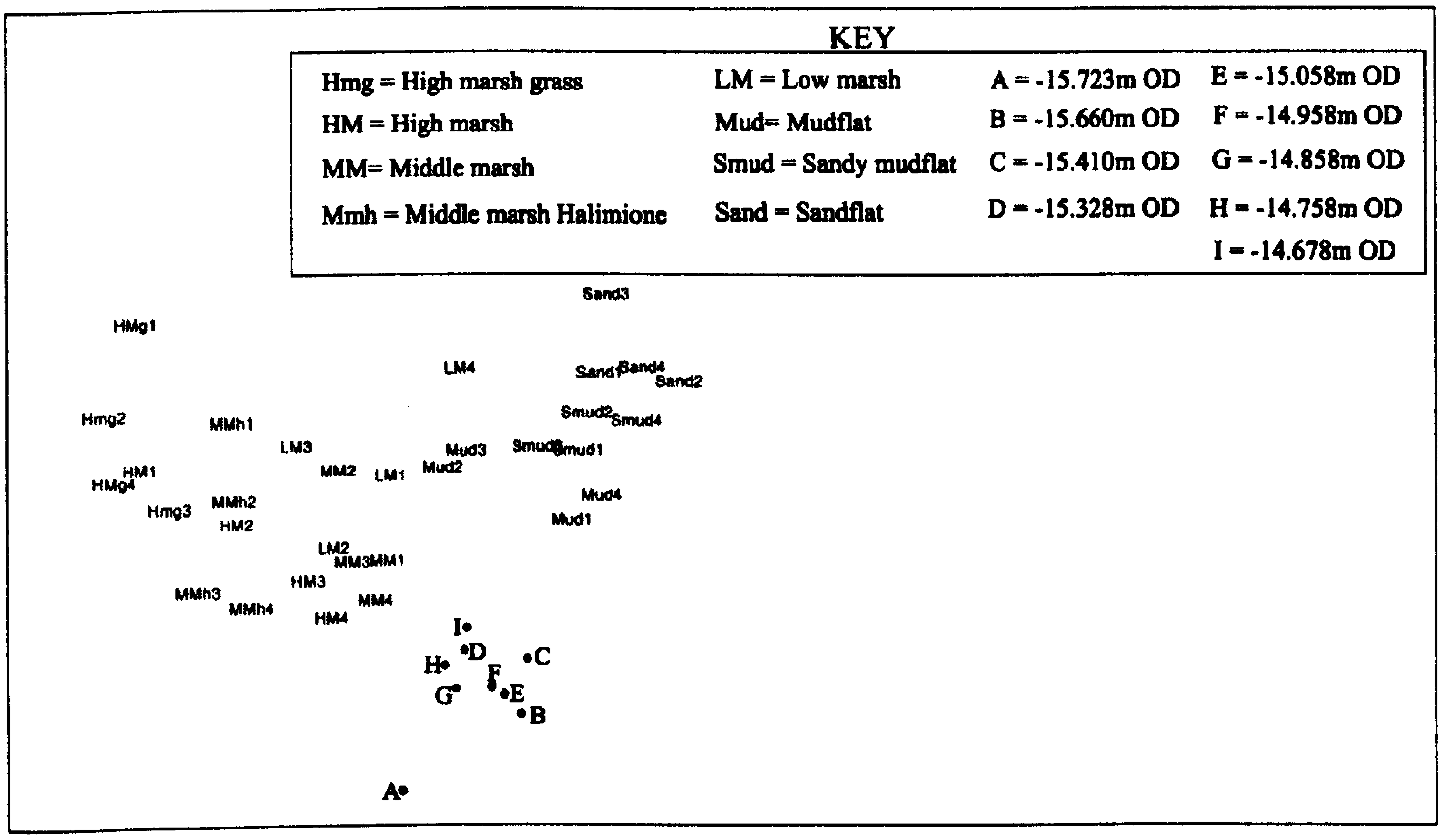


Figure 4.18g Comparison of modern analogue with assemblages located above 2/2 top

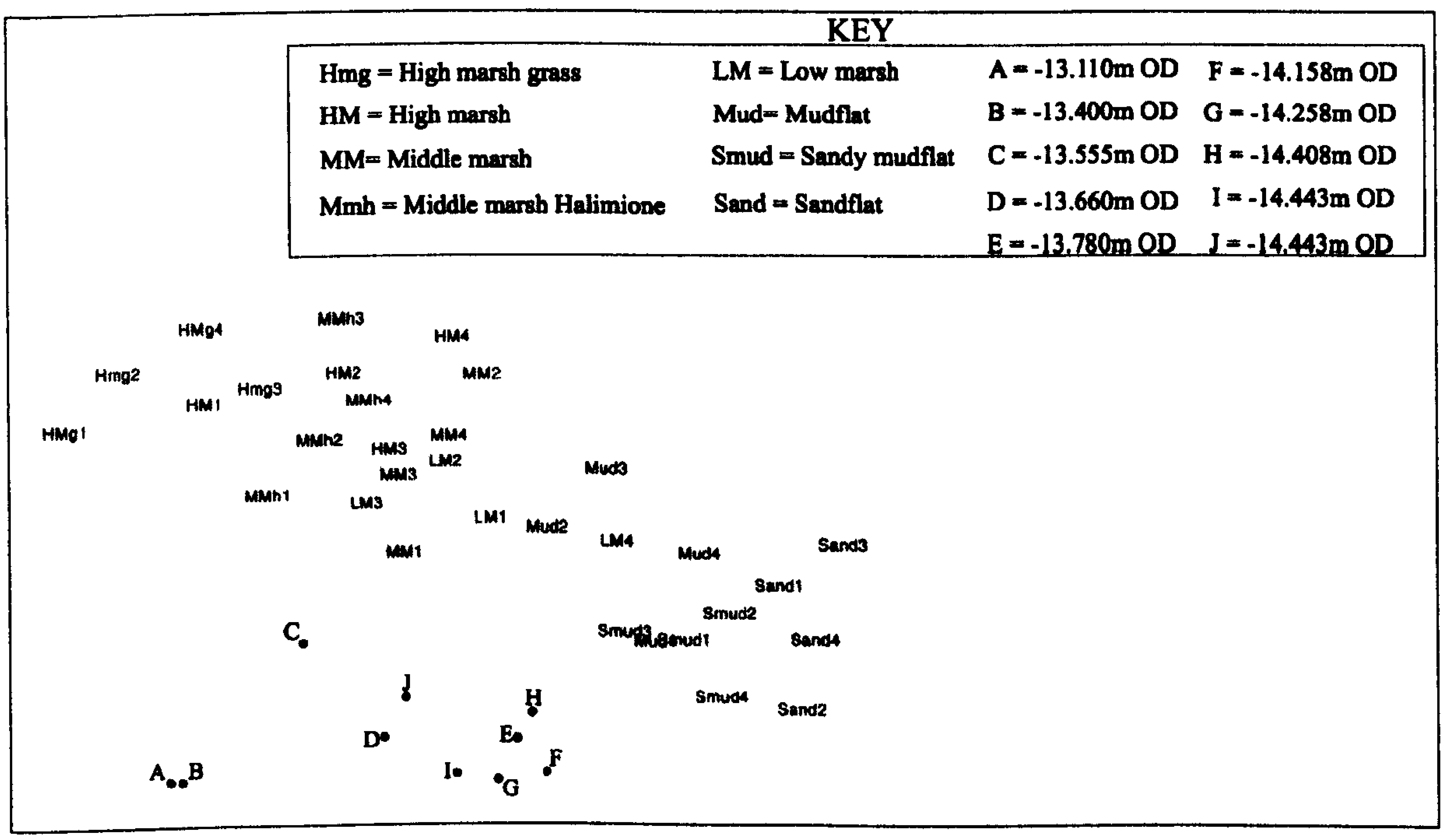


Figure 4.18h Comparison of modern analogue with assemblages located below 2/1 bottom

The analysis conducted on assemblages within sub-samples recovered from above deposit 2/1 (4.18i) did not display any trend similar to that exhibited by the modern analogue, although the sediments immediately adjacent to the organic-rich deposit may represent a biofacies similar to that found within a contemporary mudflat or low marsh environment.

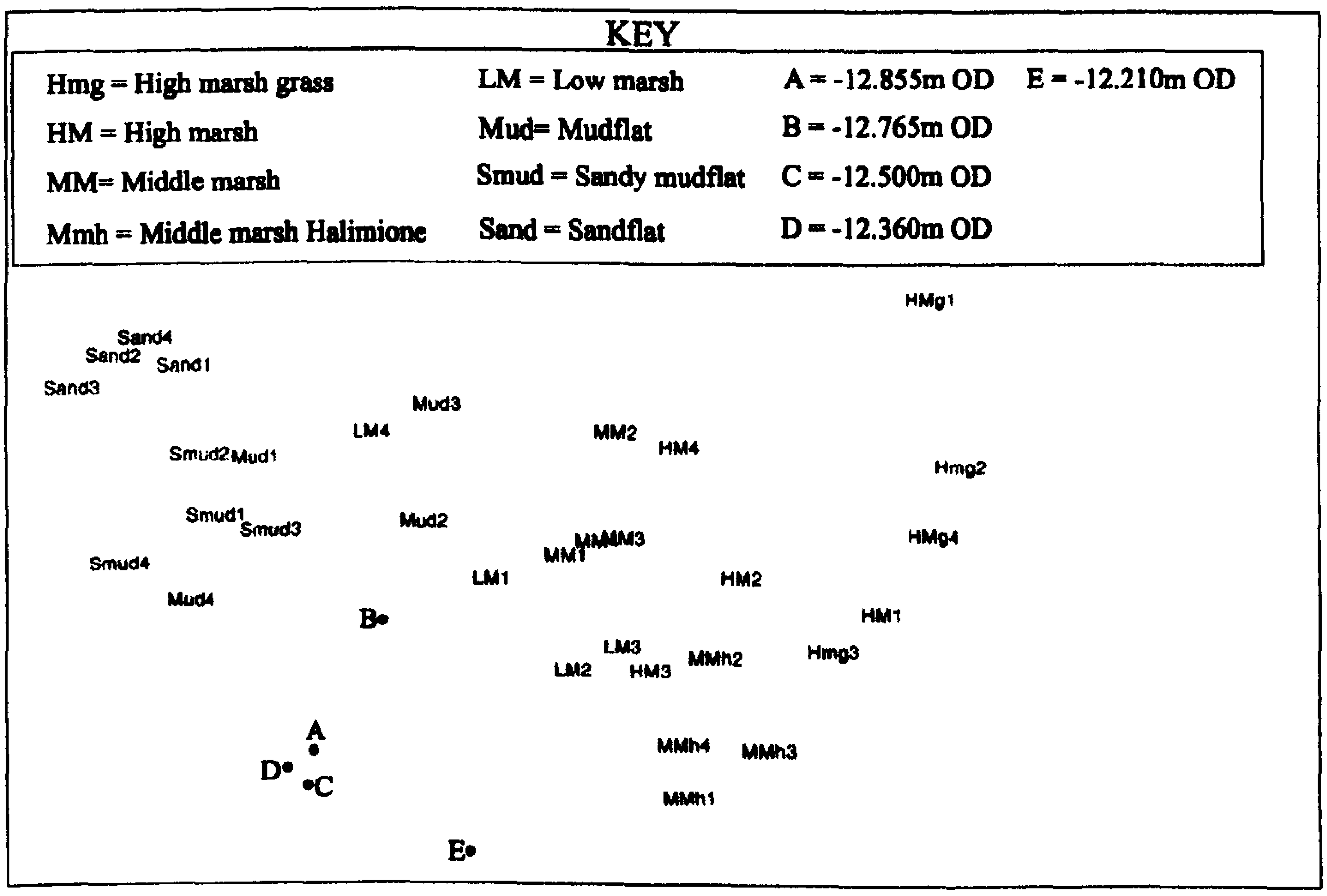


Figure 4.18i Comparison of modern analogue with assemblages located above 2/1 top

4.3.2 Pollen analysis

Pollen analysis was initially conducted in order to generate an elementary biostratigraphic diagram relating to the vegetational assemblages present within the immediate area at the time of formation. The biostratigraphic data was to be principally used in order to determine approximate ages for the organic sediments prior to radiocarbon analysis, through correlation with an existing well dated and recently calibrated Holocene biostratigraphical record (fig. 4.19) obtained from Llyn Cororion,

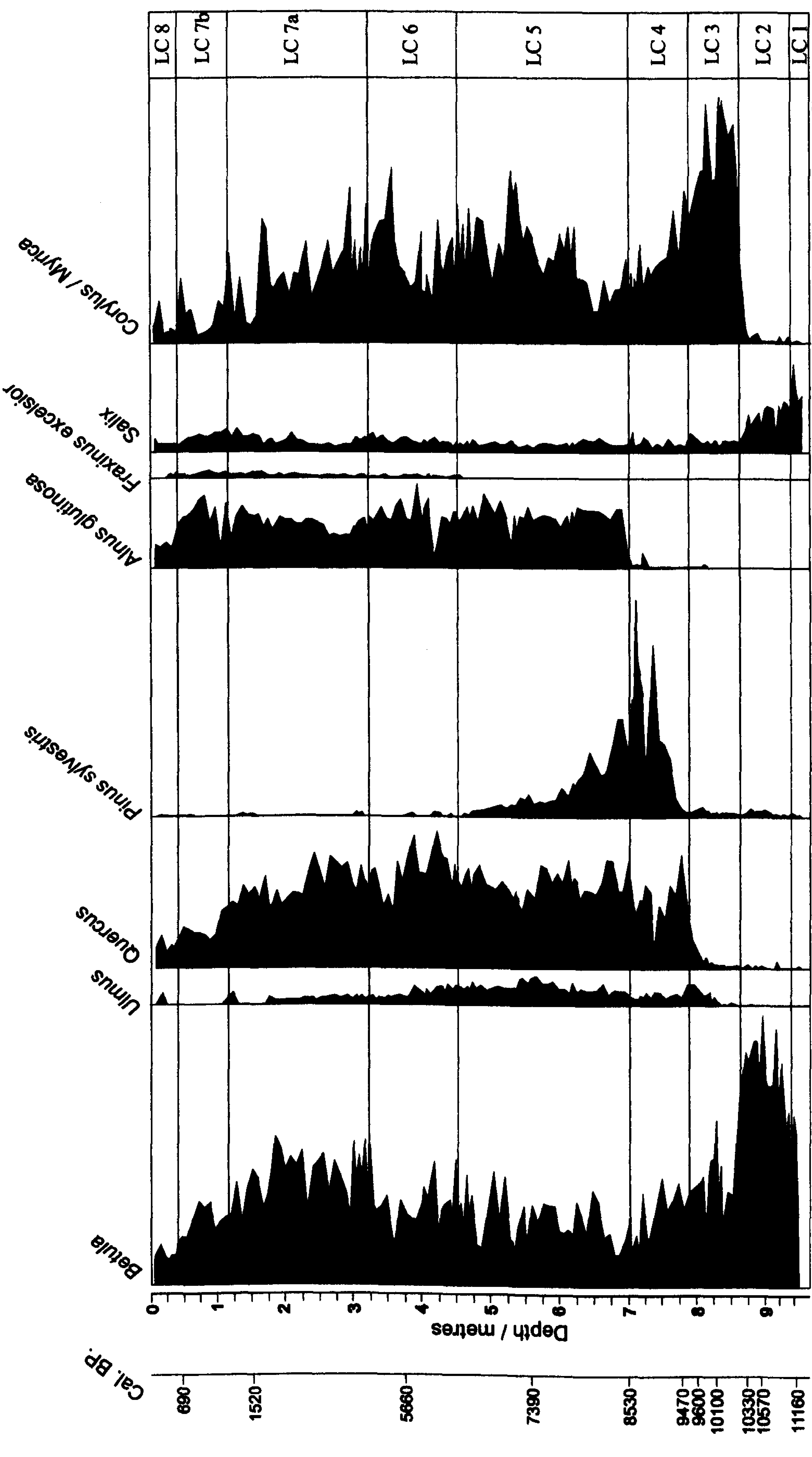


Figure 4.19 Pollen stratigraphy, Llyn Cororion, Gwynedd including calibrated age scale (Stuiver et al., 1998), adapted from Watkins 1991

located 5km to the south of the Menai Strait (Watkins, 1991). The chrono-biostratigraphical diagram (fig. 4.19) was produced through the analysis of pollen in conjunction with the radiocarbon dating of 11 organic-rich horizons identified within a single sediment core. As discussed in chapter 2 the pollen diagram identifies a number of local pollen assemblage zones and biostratigraphic events which are described in table 4.2 below. Pollen data was additionally obtained from the Menai Strait sediment cores in order to gain an insight with respect to local vegetational development, together with providing information relating to the nature of palaeoenvironmental evolution within the Menai Strait during the Lateglacial and early Holocene.

Lab ref.	Depth cm	Biostratigraphic event	^{14}C age BP	Cal. years BP
SRR 3467	047 - 049	Rise in Cannabaceae	780 ± 60	690
SRR 3468	151 - 153	End of *Ulmus* decline	1585 ± 65	1520
SRR 3469	375 - 377	*Ulmus* decline	4985 ± 65	5660
SRR 3470	559 – 561	Empirical limit *Fraxinus*	6450 ± 65	7390
SRR 3471	701 – 703	Empirical limit *Alnus*	7745 ± 65	8530
SRR 3472	779 – 781	Rational limit *Pinus*	8425 ± 70	9470
SRR 3473	803 – 805	Rational limit *Quercus*	8660 ± 65	9600
SRR 3474	833 – 835	Empirical limit *Ulmus*	8845 ± 70	10100
SRR 3475	875 – 877	Rational limit *Corylus*	9215 ± 65	10330
SRR 3476	891 – 893	Empirical limit *Corylus*	9365 ± 70	10570
SRR 3477	947 – 949	Onset organic sedimentation	9680 ± 65	11160

Table 4.2 Existing radiocarbon dates from Llyn Cororion (Watkins 1990, 1991) and their calibration using CALIB 4.3 (Stuiver *et al.*, 1998). Calibrated ages are shown without error bars and rounded to the nearest decade; for ^{14}C plateaux where a number of alternative calibrated ages are possible the mid-point age has been chosen.

The sampling strategy was primarily designed to examine the pollen biostratigraphy within the lower and upper sections of the organic deposits, proximate to and within material subsequently to be submitted for radiocarbon analysis. The data utilised in the construction of the pollen diagrams included arboreal, shrub and herbaceous taxa that constituted more than 1% of the total pollen sum, omitting aquatic taxa and spores.

The pollen data obtained from the analyzed sub-samples were compared to the biostratigraphical data obtained from Llyn Cororion in order to estimate an approximate age for each individual sub-sample. The estimation was based on a manual 'best fit' approximation that related pollen percentage values from each analyzed sub-sample with percentage values present within the Llyn Cororion data. The results of this approximate estimation are shown in figure 4.20.

4.3.2.1 CJSC 1

Five sub-samples of organic-rich material taken from deposit 1/2, together with nine sub-samples selected from deposit 1/1 were subjected to pollen analysis.

4.3.2.1.1 Deposit 1/2

Two sub-samples taken from between -23.37m and -23.35m OD at the base of deposit 1/2 were subjected to analysis and contain relatively high concentrations of pollen (60,000-70,000 grains cm^{-3}). The lower section of the deposit (fig. 4.21) is characterized by significant quantities of both herbaceous and arboreal pollen, with relatively high frequencies (40-50%) of both Gramineae and *Betula* dominating the assemblage. The

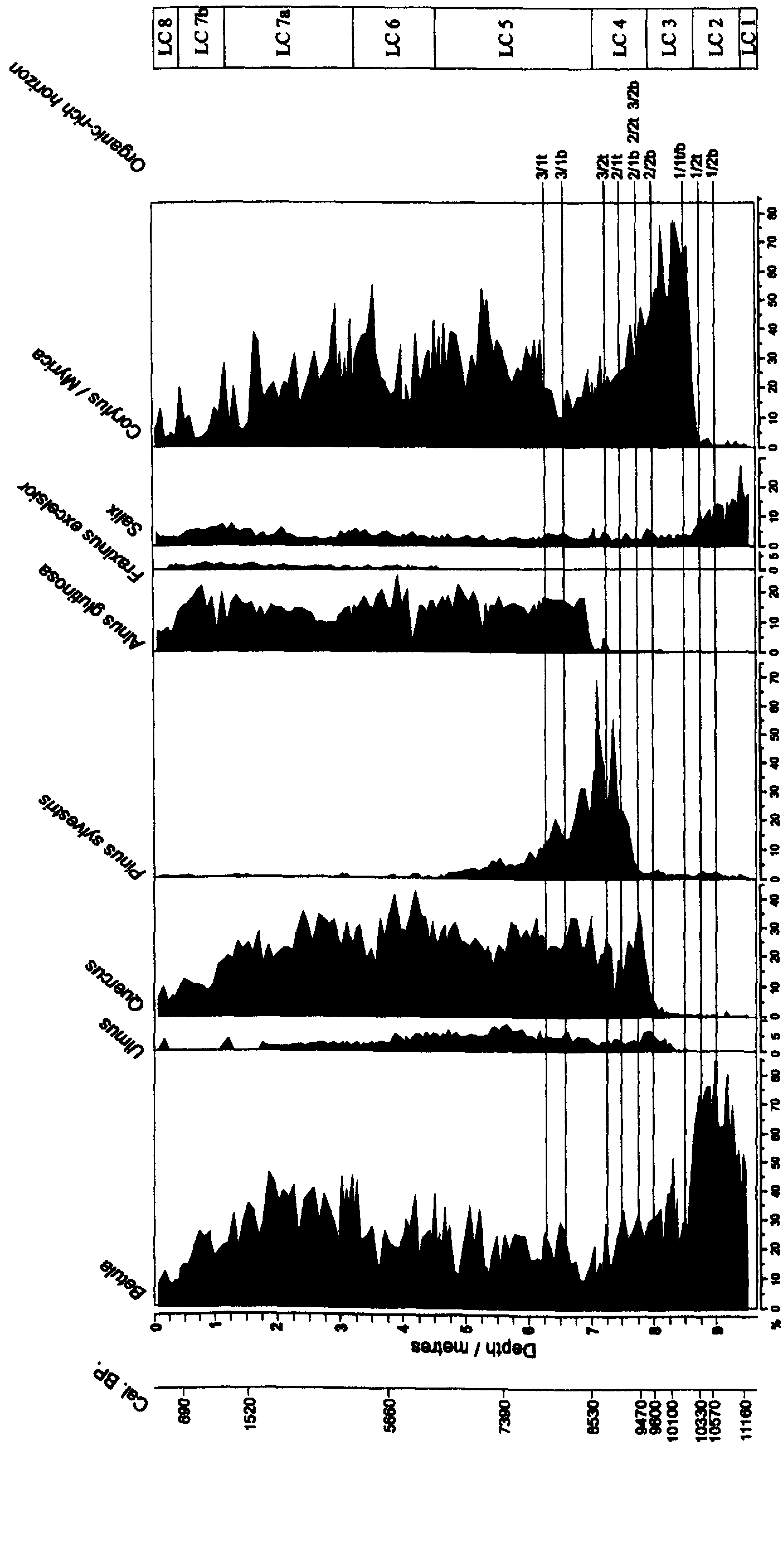


Figure 4.20 Pollen stratigraphy, Llyn Cororion, Gwynedd including calibrated age scale (Stuiver et al., 1998) and illustrating pollen stratigraphical correlation with analyzed organic-rich sub-samples, adapted from Watkins 1991

assemblage is also characterized by low frequencies of *Salix* (5-10%), together with a relatively high proportion of indeterminable, crumpled or concealed pollen.

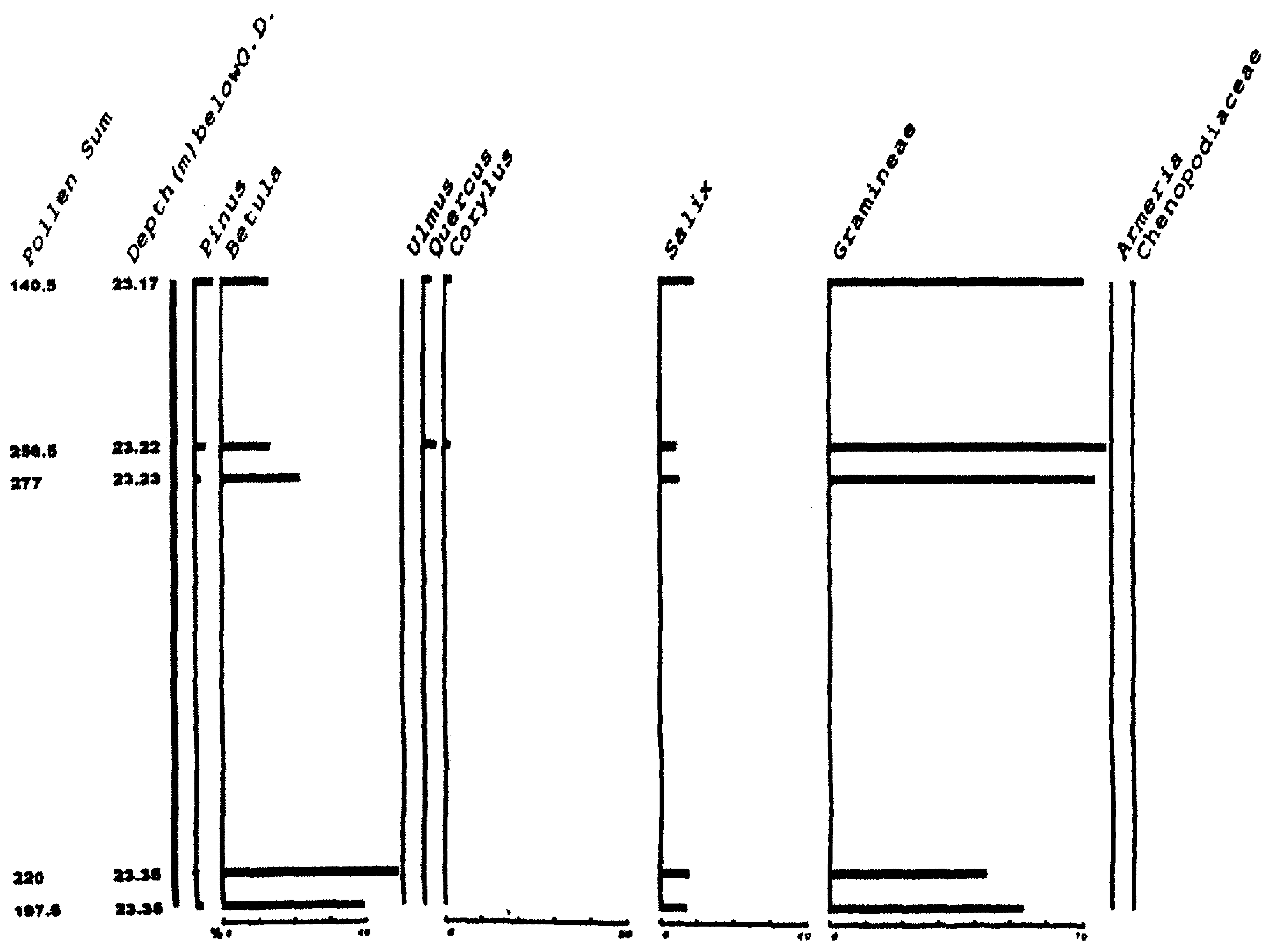


Figure 4.21 Pollen diagram representing sub-samples taken from deposit 1/2

Three sub-samples were also analyzed from the upper section of deposit 1/2 and were taken from depths ranging between -23.23m and -23.17m OD; the sub-samples were recovered from the section of the deposit that constituted the uppermost, complete horizon of organic material contained within Unit U43. The relative concentration of pollen within the sample located at the base of the horizon is higher (>42,000 grains cm^{-3}) in comparison with the concentrations of pollen found within the overlying samples (11-

14,000 grains cm^{-3}). The pollen spectrum within this section of the organic-rich deposit is consistently dominated by herbaceous pollen with Gramineae constituting approximately 70% of the total assemblage. The relative proportion of *Betula* has, however, decreased significantly and constitutes between 10-20%, whilst the proportion of *Salix* remains relatively constant. Very small proportions of *Corylus* are also present within the upper two samples. This horizon also contains a relatively high proportion of indeterminable pollen which is either crumpled or concealed.

4.3.2.1.2 Deposit 1/1

Six sub-samples were taken from the lower and central sections of deposit 1/1, located entirely within Unit D39 between -20.83m and -20.77m OD (fig.4.22). Three additional sub-samples were taken from slightly higher elevations within the upper regions of the deposit located towards the base of Unit U38, at depths ranging between -20.75m and -20.69m OD. Concentrations of pollen initially increase upward from the base of deposit rising from 25,000 to 160,000 grains cm^{-3} over 0.02m. The concentration subsequently decreases toward the upper regions of the deposit, where it is as low as 9,000 grains cm^{-3}. Relatively high frequencies of pollen, primarily comprising Gramineae (40-50%), *Corylus* (20-30%), *Betula* (10-20%) and *Salix* (5-10%) dominate the assemblage throughout the section, with the relative proportions remaining approximately constant between -20.83m to -20.77m OD within the central and lower region of the deposit. The relative proportions of Gramineae and *Betula* decrease by approximately 50% within the upper section of the deposit and this decrease coincides with a relative increase with respect to the proportion of both *Corylus* and *Salix* which together, constitute between

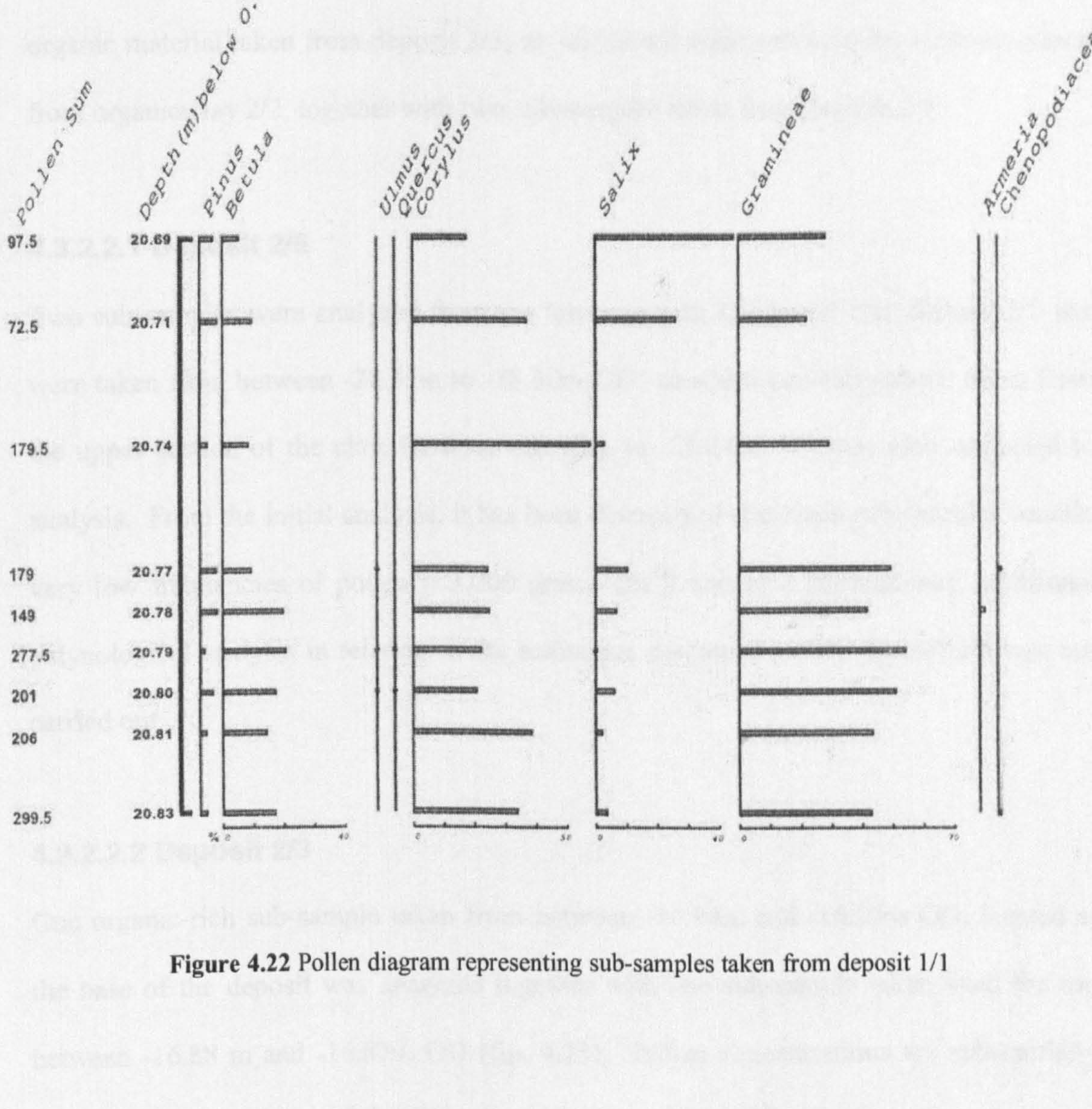


Figure 4.22 Pollen diagram representing sub-samples taken from deposit 1/1

60-70% of the total assemblage throughout the upper section. Very low frequencies of Chenopodiaceae and *Armeria* appear sporadically throughout the deposit and at any level, constitute no more than 2% of the total assemblage. The sub-sample once again also contains a significant proportion of crumpled and concealed, indeterminable pollen.

4.3.2.2 CJSC 2

Three sub-samples were analyzed from deposit 2/5, together with two sub-samples of organic material taken from deposit 2/3; an additional eight sub-samples were examined from organic clay 2/2, together with two sub-samples taken from deposit 2/1.

4.3.2.2.1 Deposit 2/5

Two sub-samples were analyzed from the lower section of organic clay deposit 2/5 and were taken from between -28.31m to -28.30m OD; an additional sub-sample taken from the upper section of the clay, between -28.25m to -28.24m OD, was also subjected to analysis. From the initial analysis, it has been determined that these sub-samples contain very low frequencies of pollen (<3,000 grains cm^{-3}) and as a consequence, additional palynological analysis in relation to the sediments contained within deposit 2/5 was not carried out.

4.3.2.2.2 Deposit 2/3

One organic-rich sub-sample taken from between -16.94m and -16.93m OD, located at the base of the deposit was analyzed together with one sub-sample taken from the top between -16.88 m and -16.87m OD (fig. 4.23). Pollen concentrations are substantially higher toward the base of the deposit (>90,000 grains cm^{-3}), as opposed to the upper regions of the peat (<30,000 grains cm^{-3}). The pollen assemblage within the deposit is dominated by the herbaceous component however arboreal and shrub pollen also constitute a significant proportion. The assemblage throughout the deposit is dominated by Gramineae (60-70%), together with significant contributions from *Corylus*, *Betula*, *Salix* and *Pinus*. The relative proportion of *Corylus* present is much higher than that of *Betula*, whilst proportions of *Salix* are much higher towards the upper region of the deposit. Relatively small proportions of *Pinus* and Chenopodiaceae also appear to be present throughout the deposit, together with a relatively high proportion of crumpled or concealed, indeterminable pollen.

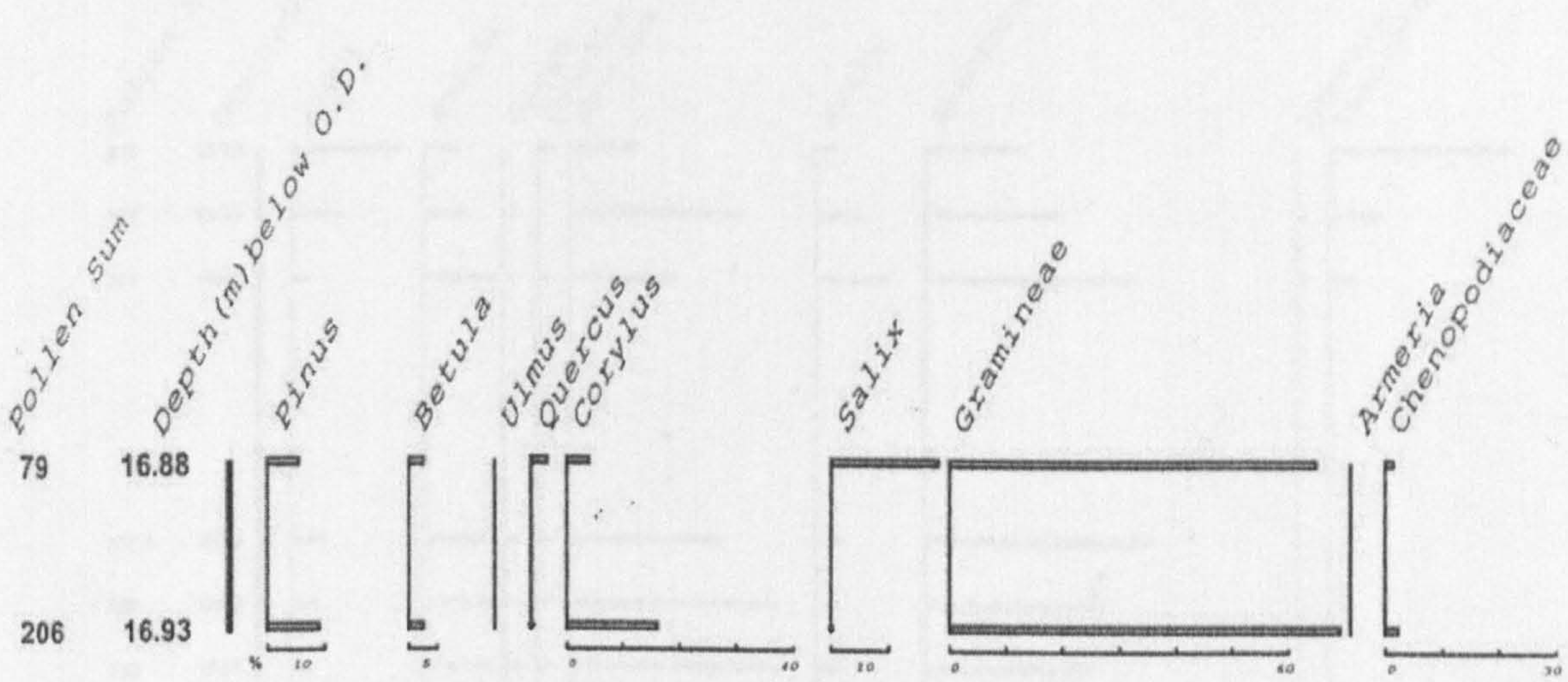


Figure 4.23 Pollen diagram representing sub-samples taken from deposit 2/3

4.3.2.2.3 Deposit 2/2

Five sub-samples were taken from the lower and central sections of the laminated organic clay deposit 2/2, located entirely within Unit D21 between -15.84m and -15.79m OD (fig.4.24). Three additional sub-samples were taken from slightly higher elevations within the upper regions of the clay located towards the base of Unit U20, at depths ranging between -15.76m and -15.73m OD. High concentrations of pollen (>150,000 grains cm^{-3}) are present within the central and lower regions of the organic clay, whilst concentrations vary between 20-400,000 grains cm^{-3} within the upper section of the deposit. The pollen assemblage throughout the deposit is dominated by pollen derived from trees and shrubs (50-70%) with the remainder of the assemblage being composed of pollen derived various from herbaceous taxa.

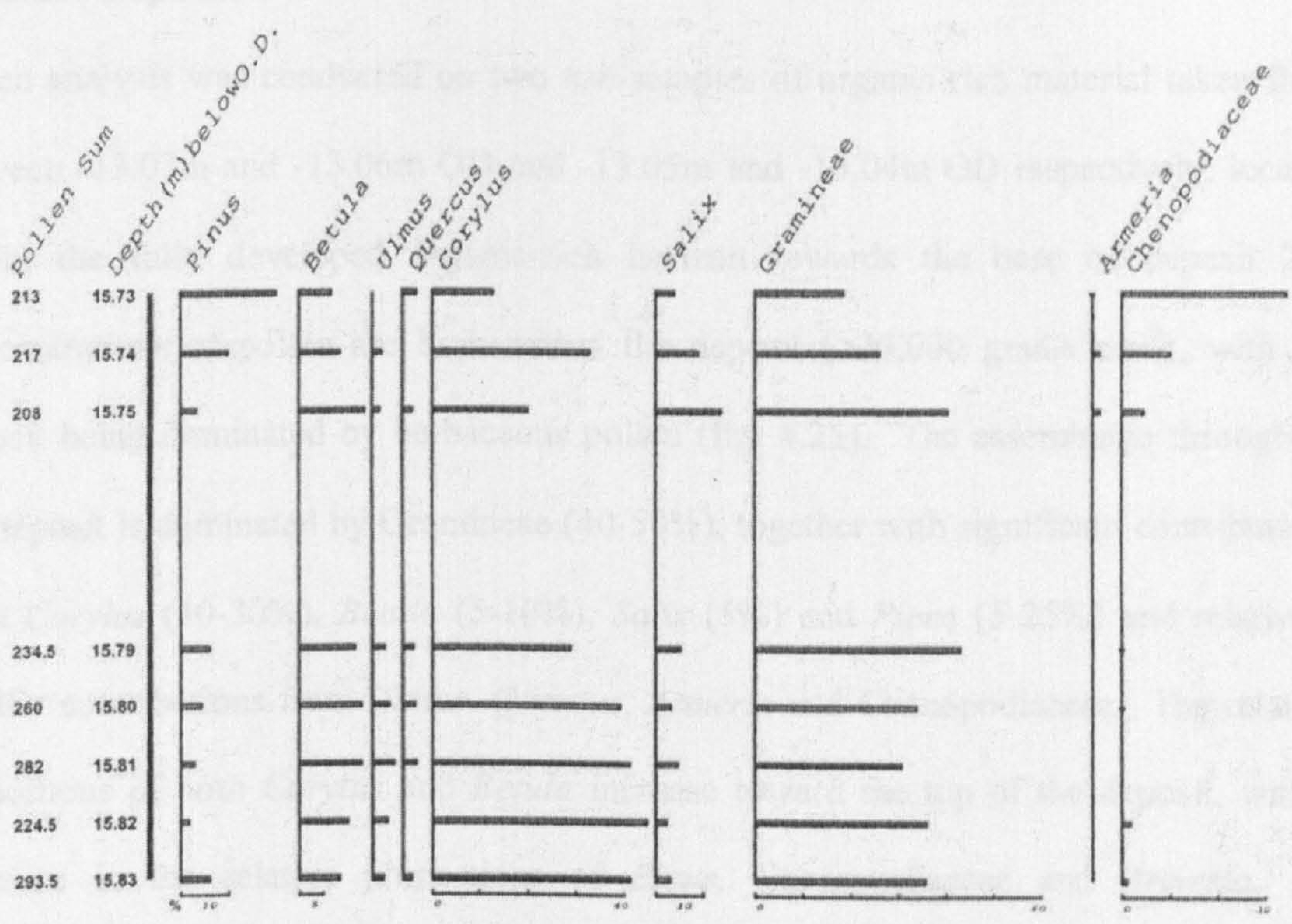


Figure 4.24 Pollen diagram representing sub-samples taken from deposit 2/2

Frequencies of *Corylus* (30-40%), Gramineae (30-40%) and *Betula* (5-10%), together with lower frequencies of *Salix* (3-5%), Pinus (3-8%), *Quercus* (2-3%) and *Ulmus* (2-5%) remain relatively constant throughout much of the deposit. The deposit also includes relatively minor proportions of Chenopodiaceae and *Armeria*, together with a significant quantity of crumpled, corroded and concealed, indeterminable pollen. The three sub-samples taken from within the upper region of the deposit demonstrate a significant increase with respect to the relative proportions of both *Pinus* and Chenopodiaceae, together with a decrease in the relative proportions of Gramineae, *Betula*, *Salix* and *Corylus*.

4.3.2.2.4 Deposit 2/1

Pollen analysis was conducted on two sub-samples of organic-rich material taken from between -13.07m and -13.06m OD and -13.05m and -13.04m OD respectively, located within the fully developed organic-rich horizon towards the base of deposit 2/1. Concentrations of pollen are high within the deposit (>20,000 grains cm^{-3}), with the deposit being dominated by herbaceous pollen (fig. 4.25). The assemblage throughout the deposit is dominated by Gramineae (40-50%), together with significant contributions from *Corylus* (10-30%), *Betula* (5-10%), *Salix* (5%) and *Pinus* (5-25%) and relatively smaller contributions from *Ulmus*, *Quercus*, *Armeria* and Chenopodiaceae. The relative proportions of both *Corylus* and *Betula* increase toward the top of the deposit, with a decrease in the relative proportions of *Pinus,* Chenopodiaceae and *Armeria*. A considerable proportion of the pollen located within the samples was defined as indeterminable, being predominantly either crumpled or concealed.

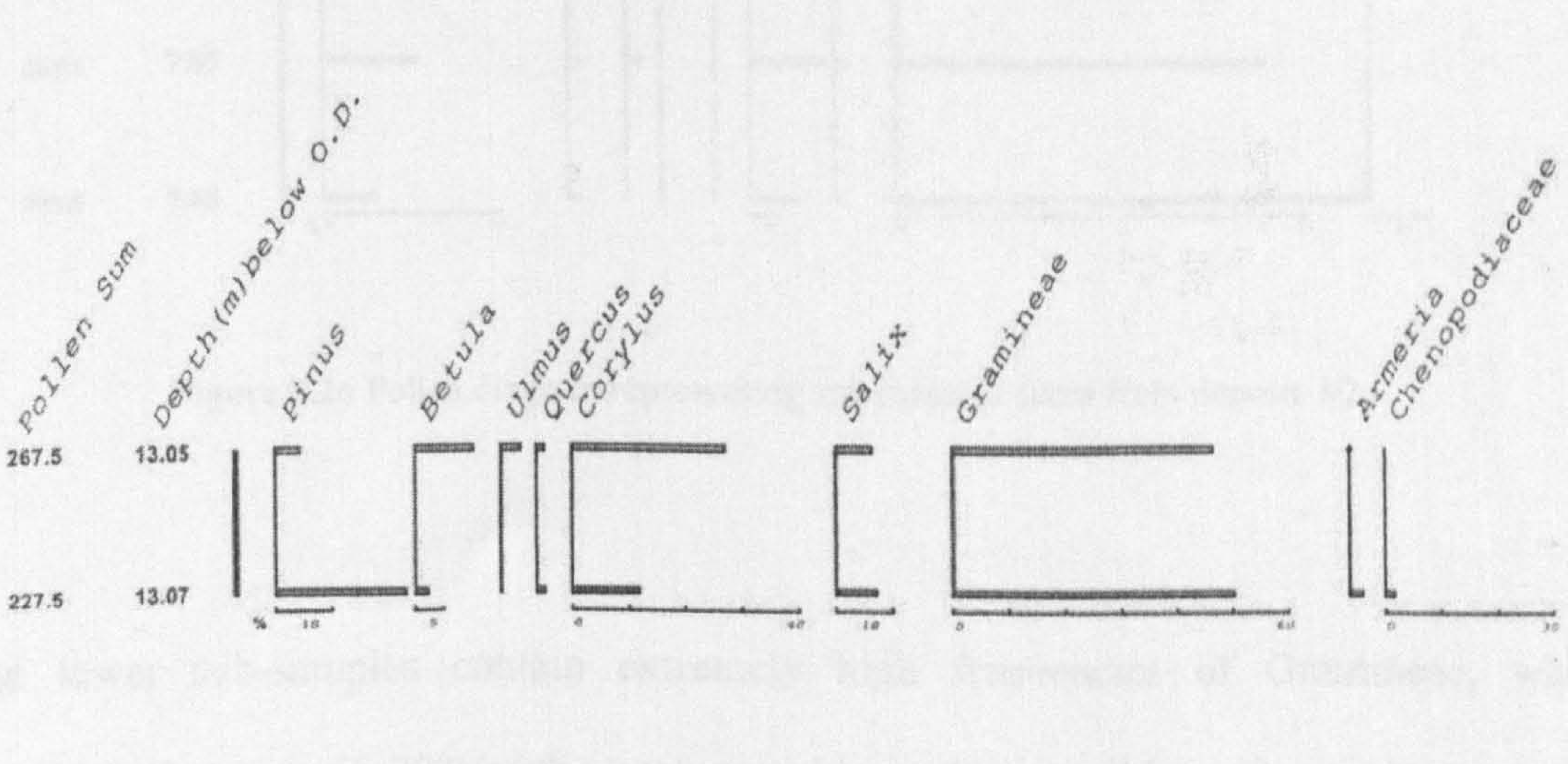


Figure 4.25 Pollen diagram representing sub-samples taken from deposit 2/1

4.3.2.3 CJSC 3

Three sub-samples were analyzed from organic-rich deposit 3/2, together with two sub-samples of organic material taken from deposit 3/1.

4.3.2.3.1 Deposit 3/2

Pollen analysis was conducted on three sub-samples taken from -7.88m, -7.85m and -7.77m OD (fig. 4.26). Pollen concentrations are relatively high throughout the deposit, ranging between 100,000-150,000 grains cm^{-3}.

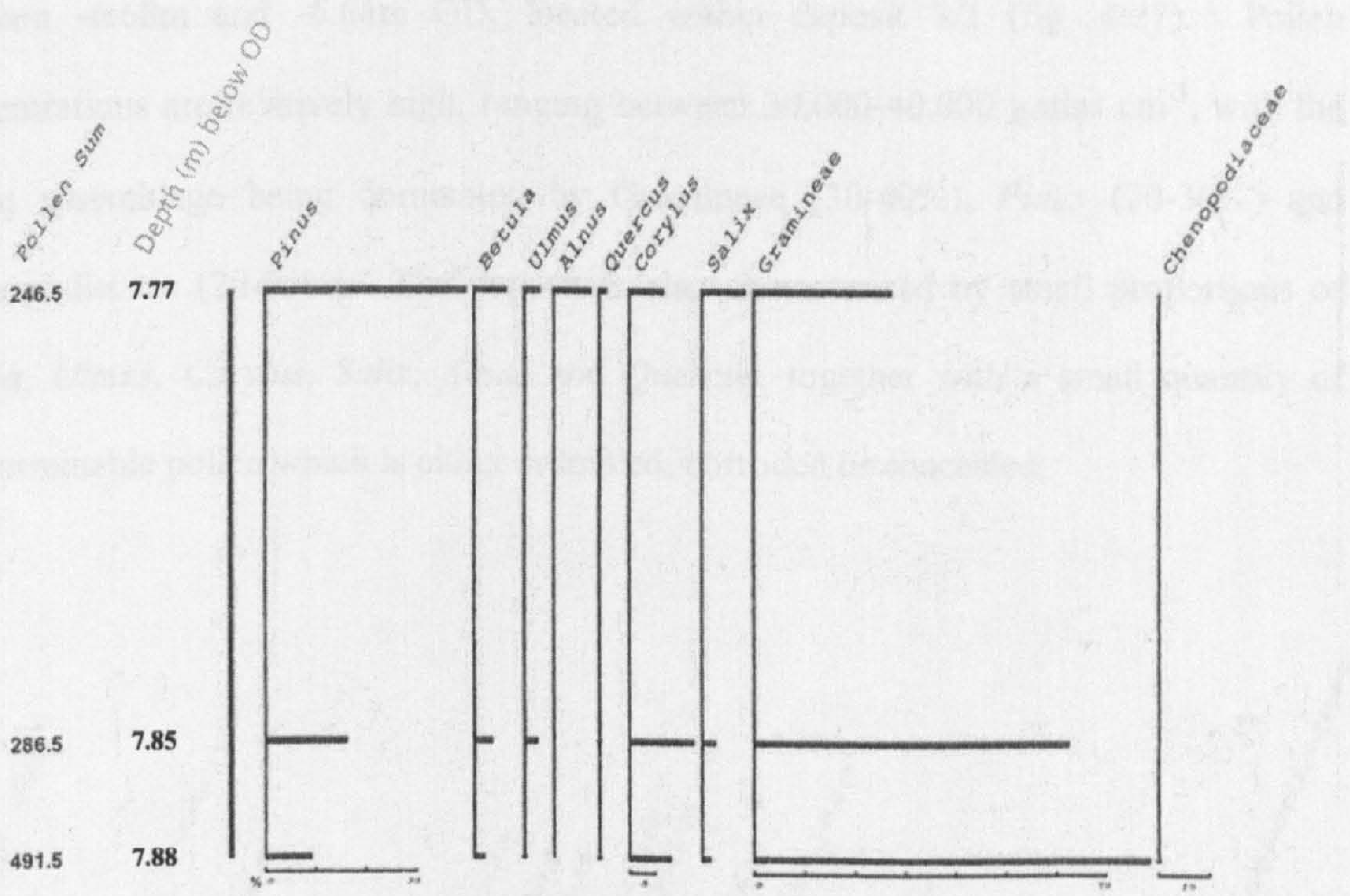


Figure 4.26 Pollen diagram representing sub-samples taken from deposit 3/2

The lower sub-samples contain extremely high frequencies of Gramineae, which constitutes between 60-70% of the total assemblage; the assemblage also contains smaller quantities of *Pinus* (10-15%) and *Corylus* (5-10%), together with minor contributions from *Betula*, *Ulmus* and *Salix*. The upper sub-sample demonstrates a rise of over 30% in the relative proportion of *Pinus* present within the deposit, coincident with the appearance of *Alnus*, which constitutes 5% of the total assemblage. The assemblage additionally contains a relatively low proportion of pollen defined as indeterminable.

4.3.2.3.2 Deposit 3/1

Pollen analysis was conducted on sub-samples of organic-rich material taken from between -6.68m and -6.64m OD, located within deposit 3/1 (fig. 4.27). Pollen concentrations are relatively high, ranging between 30,000-40,000 grains cm^{-3}, with the pollen assemblage being dominated by Gramineae (30-40%), *Pinus* (20-30%) and Chenopodiaceae (20-25%). The deposit is also characterised by small proportions of *Betula*, *Ulmus*, *Corylus*, *Salix*, *Alnus* and *Quercus*, together with a small quantity of indeterminable pollen which is either crumpled, corroded or concealed.

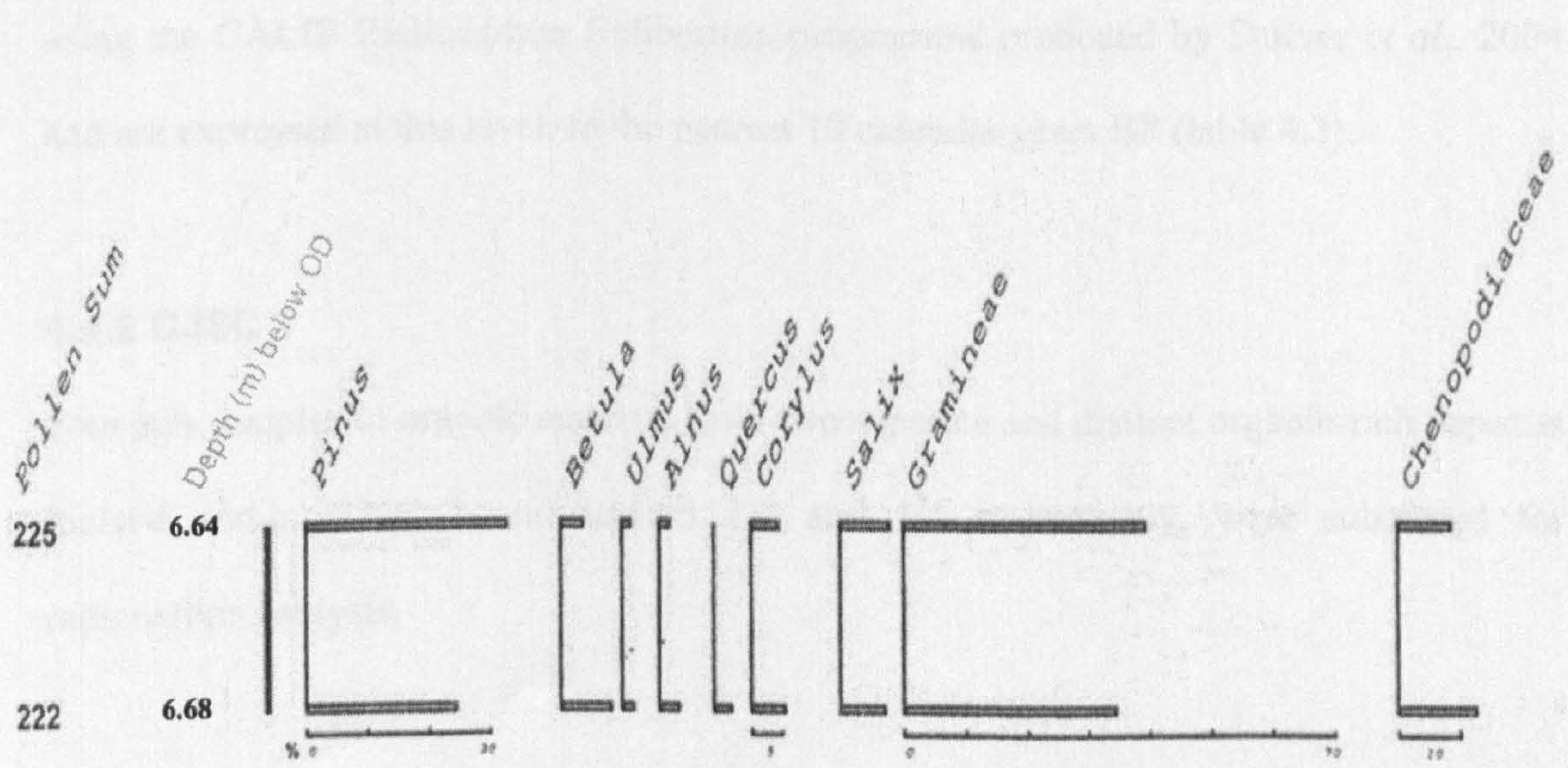


Figure 4.27 Pollen diagram representing sub-samples taken from deposit 3/1

4.4 Radiocarbon data

Seventeen sub-samples of organic-rich sediment taken from deposits located within CJSC 1-3 were submitted to the NERC Radiocarbon Laboratory, located in East Kilbride, Scotland for radiocarbon analysis. All sub-samples submitted for radiocarbon analysis consist of material taken from stratigraphic horizons that constitute the point of contact between organic-rich deposits and underlying or overlying inorganic sediment. The results of these analyses have been reported as conventional radiocarbon years Before Present (BP) relative to ANNO DOMINI (AD) 1950 and have been expressed at the +/-1 sigma (σ) level for overall analytical confidence. The report also provides data relating to the % modern ^{14}C enrichment of each submitted sub-sample, together with the % carbon content by weight of each sub-sample.

4.4.1 Calibration

All conventional radiocarbon dates have subsequently been calibrated to sigma 2 values using the CALIB Radiocarbon Calibration programme produced by Stuiver *et al.*, 2004 and are expressed at this level, to the nearest 10 calendar years BP (table 4.3).

4.4.2 CJSC 1

Four sub-samples of organic material from two separate and distinct organic-rich deposits located within CJSC 1 and termed 1/2 and 1/1 respectively, were submitted for radiocarbon analysis.

Core	Location OS NGR (SH)	Publication Code	Laboratory Reference	14C Enrichment % Modern (+/- 1 sigma)	Radiocarbon date (+/-1 sigma) years BP	Carbon content (% by wt)	13C (PDB) 0/00 (+/- 0.1)	Depth (m) OD	Calibrated date (1 sigma) cal BP	Calibrated date (2 sigma) cal BP
CJSC 1	5830, 7365	SUERC-2496	1/2 bottom	28.92 +/-0.18	9965 +/- 49	10.0	-31.9	-23.37 to -23.36	11242-11549	11222-11896
		SUERC-2493	1/2 top	29.00 +/-0.17	9945 +/- 48	1.5	29.2	-23.08 to -23.07	11232-11546	11202-11626
		SUERC-2579	1/2 bottom (rpt)	29.46 +/-0.24	9817 +/- 67	11.0	-31.7	-23.37 to -23.38	11171-11255	10892-11547
		SUERC-2578	1/2 top (rpt)	29.40 +/-0.24	9834 +/- 67	1.0	-29.7	-23.08 to -23.07	11172-11295	11117-11549
		SUERC-2492	1//1 bottom	29.84 +/-0.18	9714 +/- 49	5.2	-27.8	-20.85 to -20.84	11092-11197	10793-11226
		SUERC-2491	1/1 top	31.44 +/-0.21	9296 +/- 53	8.0	-27.4	-20.66 to -20.65	10293-10575	10268-10669
CJSC 2	5975, 7465	SUERC-2508	2/5 bottom	23.93 +/-0.18	11488 +/- 59	1.0	-28.1	-28.29 to -28.28	13192-13784	13159-13816
		SUERC-2507	2/5 top	20.54 +/-0.18	12715 +/- 71	1.5	-27.5	-28.23 to -28.22	14382-15584	14341-15700
		SUERC-2506	2/4 top	26.55 +/-0.18	10654 +/- 53	2.0	-28.0	-25.89 to -25.88	12432-12884	12357-12946
		SUERC-2503	2/3 bottom	31.42 +/-0.21	9301 +/- 54	4.4	-27.3	-16.94 to -16.93	10402-10576	10270-10670
		SUERC-2502	2/3 top	31.39 +/-0.17	9308 +/- 45	6.0	-27.2	-16.86 to -16.85	10424-10577	10287-10670
		SUERC-2501	2/2 bottom	27.97 +/-0.17	10234 +/- 50	2.0	-26.8	-15.84 to -15.83	11703-12289	11659-12348
		SUERC-2500	2/2 top	28.47 +/-0.21	10093 +/- 58	1.0	-26.5	-15.73 to -15.72	11356-11891	11262-12106
		SUERC-2498	2/1 bottom	34.36 +/-0.17	8581 +/- 40	7.5	-27.7	-13.08 to -13.07	9498-9596	9487-9678
		SUERC-2497	2/1 top	33.87 +/-0.18	8698 +/- 43	3.0	-28.4	-13.02 to -13.01	9554-9698	9546-9887
CJSC 3	5845, 7335	SUERC-2512	3/2 bottom	35.91 +/-0.18	8227 +/- 40	10.0	-27.8	-7.88 to -7.87	9089-9395	9030-9398
		SUERC-2511	3/2 top	38.40 +/-0.18	7689 +/- 38	56.0	-27.9	-7.78 to -7.77	8409-8536	8392-8584
		SUERC-2510	3/1 bottom	36.55 +/-0.18	8084 +/- 41	6.0	-27.4	-6.69 to -6.68	8823-9225	8780-9248
		SUERC-2509	3/1 top	36.25 +/-0.17	8152 +/- 38	3.3	-26.9	-6.65 to -6.64	9025-9233	9010-9258

Table 4.3 Radiocarbon data obtained from analyzed sub-samples taken from sediment cores recovered from the northeastern Menai Strait

4.4.2.1 Deposit 1/2

Sub-samples were submitted from the lower and upper boundary of deposit 1/2 adjacent to the point of contact with the underlying and overlying inorganic sediment. The two sub-samples, termed 1/2 bottom and 1/2 top respectively, were recovered from between -23.37m to -23.36m OD and from between -23.08m to -23.07m OD. Sub-sample 1/2 bottom was taken from within an isolated 0.01m organic-rich deposit located at the base of Unit U43, which is immediately overlain by a small quantity of grey clay. Unit D44, recovered from between -23.57m and -23.37m OD, indicates the presence of 0.20m of organically enriched grey silty clay underlying the sub-sampled deposit. The organic content by weight of sub-sample 1/2 bottom has been reported as being 10.0%, producing a conventional radiocarbon age of 9965 +/- 49 years BP.

Sub-sample 1/2 top was taken from an upper section of Unit 43 consisting of both organic material and grey, sandy silt, immediately overlain by a highly disturbed section of the core extending over 0.13m, containing both organic material and grey, silty sand. The organic content of the sediment core increases greatly from 0.08m beneath the sub-sampling point, giving rise to a horizon consisting completely of brown, fibrous organic-rich material. The organic content by weight of sub-sample 1/2 top has been reported as being 1.5% and has produced a conventional radiocarbon age of 9945 +/- 48 years BP.

Following the initial analyses conducted on sub-samples 1/2 bottom and 1/2 top, supplementary tests were conducted on residual material remaining from the initial testing procedure, in order to address homogeneity concerns with respect to the radiocarbon analysis procedure. This effectively resulted in repeat tests being carried out on samples 1/2 bottom and 1/2 top. The organic content by weight of the residual material associated with sub-sample 1/2 bottom has subsequently been reported as being 11.0% and has produced a conventional radiocarbon date of 9817 +/- 67 years BP. Similarly, the supplementary test conducted upon the residual material derived from sub-sample 1/2 top has resulted in the organic content by weight of the sub-sample being reported as being 1.0%, with the material producing a conventional radiocarbon age of 9834 +/- 67 years BP.

4.4.2.2 Deposit 1/1

Sub-samples were submitted from the lower and upper boundary of deposit 1/1 and were termed 1/1 bottom and 1/1 top respectively. The sub-samples were recovered from between -20.85m to -20.84m OD and from between -20.66m to -20.65m OD. Sub-sample 1/1 bottom was taken from the base of deposit 1/1, located within the central section of Unit D39; the organic-rich material at this point is immediately underlain by grey silty, clayey sand. The organic content by weight of sub-sample 1/1 bottom has been reported as being 5.2% and has produced a conventional radiocarbon age of 9714 +/- 49 years BP. Sub-sample 1/1 top, taken 0.09m from the base of Unit U38, at the top of the organic-rich deposit, is immediately overlain by grey clay, containing organic material. The organic content by weight of sub-sample 1/1 top has been reported as being 8.0% and has produced a conventional radiocarbon date of 9296 +/- 53 years BP.

4.4.3 CJSC 2

Nine sub-samples of organic-rich material from five separate deposits located within CJSC 2 were also submitted for radiocarbon analysis. The organic-rich samples originate from three deposits termed 2/4, 2/3 and 2/1 respectively, together with two organic-rich layers of laminated clay, termed 2/5 and 2/2.

4.4.3.1 Deposit 2/5

An organic-rich layer of laminated clay termed 2/5, extending between -28.31m to -28.22m OD and contained entirely within the lower section of Unit D48, was sub-sampled towards its lower and upper boundary, proximal to the points of contact between the underlying and overlying inorganic sediment. Two sub-samples, termed 2/5 bottom and 2/5 top respectively, were submitted for radiocarbon analysis and were taken from between -28.29m to -28.28m OD and from between -28.23m to -28.22m OD. Sub-sample 2/5 bottom was taken 0.02m from the base of Unit D48, which in turn appears to be underlain by dark grey, very fine grained silty sand with traces of fine gravel. The organic content by weight of sub-sample 2/5 bottom has been reported as 1.0% and has produced a conventional radiocarbon age of 11488 +/- 59 years BP.

Sub-sample 2/5 top was taken from the upper boundary of the organic clay which appears to be immediately overlain by laminated bands of coarse sand and silt. The organic content by weight of sub-sample 2/5 top has been reported as being 1.5%, producing a conventional radiocarbon age of 12715 +/- 71 years BP.

4.4.3.2 Deposit 2/4

One sub-sample was submitted for radiocarbon analysis from the upper boundary of deposit 2/4, which extends between -25.91m and -25.88m OD. The deposit is contained entirely within Unit U44 and the sub-sample was taken adjacent to the point of contact with the overlying inorganic sediment, located between -25.89m and -25.88m OD. The sediment beneath the 0.03m thick deposit is underlain by dark grey, silty sand, which fines upward into light grey, silty clay immediately adjacent to the base of the organic-rich deposit. The deposit is immediately overlain by 0.04m of light grey, clay, which subsequently rapidly coarsens into dark grey, medium-coarse silty sand. The organic content by weight of sub-sample 2/4 top has been reported as being 2.0% and has produced a conventional radiocarbon age of 10654 +/- 53 years BP.

4.4.3.3 Deposit 2/3

Two sub-samples were submitted for radiocarbon analysis from the lower and upper boundary of deposit 2/3. The deposit is located entirely within the lower, central section of Unit U24 and extends over 0.09m between -16.94m and -16.85m OD. The two sub-samples termed 2/3 bottom and 2/3 top respectively, were taken from between -16.94m to -16.93m OD and from between -16.86m to -16.85m OD. The sediments immediately underlying 2/3 bottom and overlying 2/3 top are composed of light grey, silty clays containing a large proportion of organic detritus. The organic content by weight of sub-sample 2/3 bottom has been reported as being 4.4% and has produced a conventional radiocarbon age of 9301 +/- 54 years BP. The organic content by weight of sub-sample

2/3 top has been reported as being 6.0% and has produced a conventional radiocarbon date of 9308 +/- 45 years BP.

4.4.3.4 Deposit 2/2

An organic-rich layer of laminated clay termed 2/2, extending between -15.84m and -15.72m OD is located within the upper section of Unit D21 and the lower section of Unit U20. Two sub-samples, termed 2/2 bottom and 2/2 top respectively, were submitted for radiocarbon analysis and were taken from between -15.84m and -15.83m OD and from between -15.73m and -15.72m OD. Sub-sample 2/2 bottom was recovered from the base of the organically enriched laminated clay situated within the central region of Unit D21 where it is immediately underlain by grey clay, interspersed with organic material. The organic content by weight of sub-sample 2/2 bottom has been reported as being 2.0% and has produced a conventional radiocarbon age of 10234 +/- 50 years BP. Sub-sample 2/2 top was taken from the upper boundary of the laminated organic clay 0.03m from the base of Unit U20, immediately overlain by laminated bands of light grey, clay containing isolated fragments of organic material. The organic content by weight of sub-sample 2/2 top has been reported as being 1.0%, producing a conventional radiocarbon age of 10093 +/- 58 years BP.

4.4.3.5 Deposit 2/1

Two sub-samples were submitted for radiocarbon analysis from within the organic sediments termed deposit 2/1. The organics are located entirely within the lower section of Unit U13 and extend over 0.09m between -13.08m and -12.97m OD. Two sub-samples, termed 2/1 bottom and 2/1 top respectively, were taken from between -13.08m to -13.07m OD and from between -13.02m to -13.01m OD. Sub-sample 2/1 bottom was taken from the base of a 0.03m organic-rich deposit forming a complete horizon across the sediment core, which immediately overlies light grey, silty clay containing a large proportion of organic detritus. The organic content by weight of sub-sample 2/1 bottom has been reported as being 7.5% and has produced a conventional radiocarbon age of 8581 +/- 40 years BP. Sub-sample 2/1 top was taken from the base of an organic deposit located 0.01m above an underlying organic-rich deposit. The horizon is underlain by 0.01m of light grey, silty clay and is overlain by 0.01m of light grey clay, subsequently overlain by 0.02m of organic-rich material. The organic content by weight of sub-sample 2/1 top has been reported as being 3.0% and has produced a conventional radiocarbon date of 8698 +/- 43 years BP.

4.4.4 CJSC 3

Radiocarbon analyses were performed on three sub-samples of organic-rich material and one sub-sample consisting of individual wood fragments obtained from two organic horizons, termed 3/2 and 3/1 respectively.

4.4.4.1 Deposit 3/2

Two sub-samples were submitted for radiocarbon analysis from the lower and upper boundary of deposit 3/2. The deposit is located towards the lower section of Unit U5 and extends over 0.11m between -7.88m and -7.77m OD. The two sub-samples termed 3/2 bottom and 3/2 top respectively, were taken from between -7.88m to -7.87m OD and from between -7.78m to -7.77m OD. The sediments immediately underlying 3/2 bottom and immediately overlying 3/2 top are composed of light grey, silty clays containing significant quantities of organic detritus. The organic content by weight of sub-sample 3/2 bottom has been reported as being 10.0% and has produced a conventional radiocarbon age of 8227 +/- 40 years BP. Prior to submission for radiocarbon analysis, the organic sub-sample termed 3/2 top was pre-treated with 5% potassium hydroxide and 10% hydrochloric acid, in order to retrieve fragments of wood from within the organic matrix that constituted the bulk of the sub-sample. These individual fragments of wood were subsequently submitted for radiocarbon analysis and have been reported as having an organic content by weight of 56.0% and have produced a conventional radiocarbon date of 7689 +/- 38 years BP.

4.4.4.2 Deposit 3/1

Two sub-samples were submitted for radiocarbon analysis from the organic material termed deposit 3/1. The organic-rich deposit is located within the central section of Unit U4 and extends over 0.05m between -6.69m and -6.64m OD. Two sub-samples, termed 3/1 bottom and 3/1 top respectively, were taken from between -6.69m to -6.68m OD and from between -6.65m to -6.64m OD. The sediments immediately underlying 3/1 bottom and immediately overlying 3/1 top are composed of light grey, silty clays containing significant quantities of organic detritus. The organic content by weight of sub-sample 3/1 bottom has been reported as being 6.0% and has produced a conventional radiocarbon age of 8084 +/- 41 years BP. The organic content by weight of sub-sample 3/1 top has been reported as being 3.3% and has produced a conventional radiocarbon date of 8152 +/- 38 years BP.

Chapter 5

5 Introduction

Chapter five provides a discussion relating specifically to each individually dated contact within the context of the sedimentological, micropalaeontological and radiocarbon data. The discussion additionally relates to these data as evidence for the identification and validation of a series of sea-level index points which are subsequently integrated with pre-existing sea-level data in order to facilitate the generation of a relative sea-level curve for North Wales. The sea-level data for North Wales is subsequently discussed and compared with existing sea-level data on both a regional and global scale. The chapter finally discusses the available evidence in order to generate a hypothesis which describes the Holocene evolution of the Menai Strait with particular reference to Holocene relative sea-level change in North Wales.

5.1 Sea-level data

This section discusses the data obtained during the course of the research project in an attempt to identify, assess and subsequently validate individual sea-level index points obtained from within the study area. The section additionally examines a relative sea-level curve produced by incorporating the aforementioned data with pre-existing sea-level data and further compares the resultant curve with existing models of relative sea level relating to coastal evolution within North Wales during the Holocene.

5.1.1 Sea-level index points

5.1.1.1 Altitudinal data

As discussed in chapter two, local or regional relative sea-level curves are primarily derived through the acquisition and integration of a series of sea-level index points, which identify the changing position of sea level through time in relation to a known datum. Ideally each individually utilized index point should provide reasonably accurate and precise information specific to its location, altitude, age and indicative meaning, together with an indication relating to sea-level tendency.

Each sea-level index point utilized within the context of the research project has been evaluated and assessed in terms of its constituent criteria. The assessment has provided a means of validating individual points, together with identifying and defining the limits of precision and accuracy intrinsically associated with each sea-level index point. The following section relates to individual sedimentary contacts identified during the course of the project, considered to possibly represent a former position of sea level. The section deals with the dated contacts within a chronostratigraphical order, based upon both the derived age of the deposit and its stratigraphical context and possible origin. The section additionally provides an assessment of each dated contact's suitability as a sea-level index point and further defines each index point's limits of precision and accuracy.

The positional co-ordinates of all potential sea-level index points assessed within the scope of this research project have been established to a reasonable degree of precision and can be confidently quoted to within +/- 5m.

The altitude of the index points upon recovery and their relationship to Ordnance Datum (Newlyn) can be quoted to an acceptable degree of precision, as in all instances this aspect of fieldwork should have introduced errors of no more than +/- 0.10m. Additional and more significant altitudinal corrections, however, need to be considered when evaluating each sea-level index point in terms of both its post depositional history and indicative meaning.

The altitude and relationship of each dated horizon to the elevation of sea level during and subsequent to formation has been assessed with consideration given to the degree of post-depositional compaction and consolidation possibly experienced by each deposit, together with an assessment relating to any possible post-depositional modification, displacement or re-working. The discussion additionally provides an assessment of the deposit's relationship to MSL, and considers the effect of possible variations in tidal range experienced at specific locations along the North Wales coast during the Holocene. The indicative meaning of each dated horizon in terms of its relationship to a former sea level has been addressed utilizing macro and micropalaeontological analyses, including an examination relating to the nature of foraminiferal assemblages within the inorganic sediments immediately adjacent to each dated contact.

As previously discussed, the degree of post-depositional consolidation and compression experienced by fine grained sediments and organic deposits within extensive sedimentary sequences can introduce appreciable degrees of error with respect to establishing the true position of former sea levels. An estimation relating to the degree of compaction and consolidation experienced by the organic formations assumes that the deposits have not been subjected to any appreciable degree of erosion and that they represent the remnants of a relatively undisturbed deposit. It must be noted however, that post-depositional modifications are often difficult to quantify, primarily due to uncertainties relating to the possible removal of sediment which may have constituted pre-existing overburden and also when assessing deposits recovered from sedimentary cores containing sequences of unconsolidated sediment of unproven depth.

As a consequence, no attempt has been made within the scope of this study to quantify the degree of compaction and consolidation experienced by any deposit although their potential effect on the altitude of each organic-rich horizon has been considered. Research conducted by O'Loughlin (2001) indicates that peat deposits can undergo significantly enhanced degrees of compaction and may reduce in volume by up to 90%. It must additionally be noted that underlying fine grained sediments may also have experienced an indeterminable degree of compaction and consolidation.

Unpublished research (Uehara *et al.*, in press), conducted within the School of Ocean Sciences, using 2D Princeton Ocean Model bathymetry and data obtained from existing glacio-hydro-isostatic models (Lambeck, unpublished and Peltier, 1994), appears to indicate that within North Wales, mean tidal range has increased by over 1.50m between the early to middle Holocene (fig. 5.1). As this information was derived utilizing existing geophysical models and not the acquired data, its integration into the contemporary data set could be regarded as questionable. As a consequence allowances for change in tidal range have not been directly integrated into the utilized data set; an attempt has however been made in order to incorporate possible variations in tidal range into the altitudinal error term that relates to each index point. This has been done as such changes need to be considered and quantified wherever possible if the true nature of relative sea-level change is to be both accurately and precisely determined.

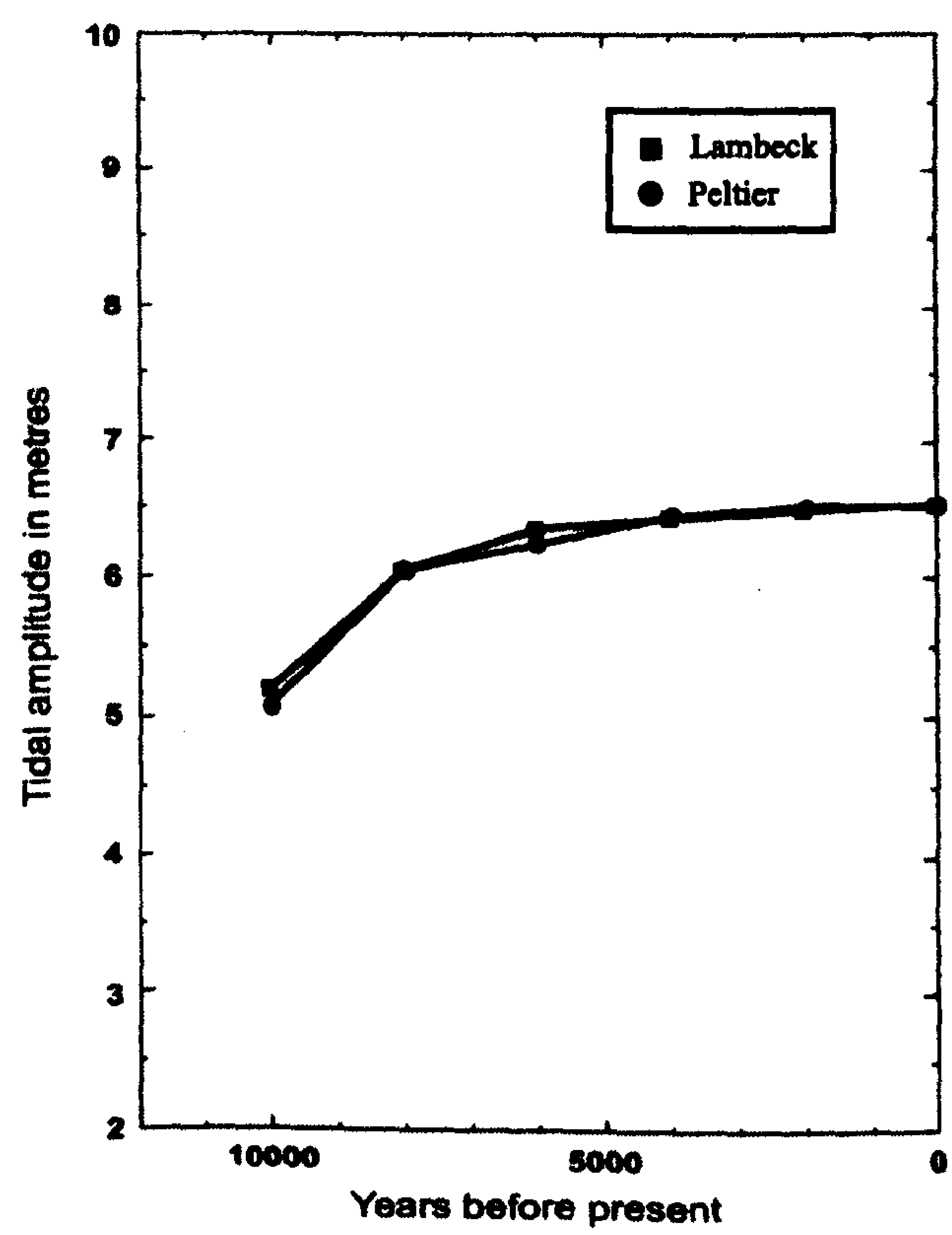


Figure 5.1 Modelled tidal amplitude change for Bangor, taken from Uehara *et al.* (in press) using 2D Princeton Ocean Model bathymetry based on Peltier (1994) and Lambeck (unpublished)

The indicative meaning of each dated horizon has been assessed utilizing lithological, micropalaeontological and plant macrofossil data. These data attempt to establish the relationship of the dated contact to the former position of MHWST by examining the nature of fossilized foraminiferal assemblages within the sediments located above or below each organic-inorganic horizon. The fossil assemblages are subsequently compared with modern analogues taken from a range of inter-tidal marine environments, in order to infer the nature of their *in-situ* environment. It is however, acknowledged that this preliminary investigation is limited in terms of identifying the specific relationship of the horizon to the position of former MHWST and that this limits the degree of accuracy associated with the dated contacts. Plant macrofossils obtained from within each organic-rich deposit have also been examined by Dr Charles Turner from the Open University as a means of supplementing the micropalaeontological data. This information has been utilized in order to support any palaeoenvironmental interpretation that has been made.

Difficulty in accurately determining the uncertainties relating to the degree of post depositional compaction/consolidation and possible variation in tidal range over time, together with possible errors in determining the indicative relationship of each deposit to a former mean sea level have been incorporated with errors relating to the measurement of the contemporary elevation of each dated contact in order to produce an overall altitudinal error (appendix 1.1). This 'altitudinal' error has subsequently been combined with errors relating to the determination of the age of each sample in order to generate an overall degree of error which encompasses both the possible altitude and age component of each index point (table 5.1).

5.1.1.2 Radiocarbon data

All sub-sampled material submitted for dating was taken immediately adjacent to the point of contact between the organic-rich material and the underlying or overlying inorganic sediments and as a consequence, invariably incorporate a proportion of lithic material. The inorganic material contained within the sub-samples, however, is probably a consequence both of contamination from the adjacent inorganic sedimentary facies, associated with the sub-sampling strategy, together with the introduction of allochthonous sediment during the natural *in situ* accumulation of the organic material by freshwater runoff or tidal in-washing.

The sampling and sub-sampling strategy employed in order to transfer the sediments that constitute the sub-samples from their *in situ* environment to the radiocarbon laboratory prior to analysis, was designed to limit the degree of possible contamination imposed upon the dateable material. Other than the unavoidable sources of contamination that invariably occur during the formation of organic deposits (Mook and Van de Plassche, 1986), natural contamination derived through root penetration is considered to be minimal, as no recognizable evidence relating to the presence of any root-like material is visible proximal to and within the organic deposits. The degree of humification and contamination of adjacent organic deposits through the natural downward migration of organic material contained within younger humic acids together with the effects of

	Source	ID	Original altitude (MHWST) (m) OD	Contemporary tidal range (m)	Altitude (MSL) (m) OD	Nature of contact	Palaeotidal range (Estimated) (m)	Error +ve (m)	Error -ve (m)	Thickness of deposit (m)	Thickness of underlying organics (m)	Compression error +ve (m)	Compression error -ve (m)	Levelling error +ve and -ve (m)	Indicative meaning error range +ve and -ve (m)	Datum error +ve and -ve (m)	Total altitudinal error +ve (m)	Total altitudinal error -ve (m)	Minimum altitude (m) OD	Maximum altitude (m) OD
1	Cemlyn Jones Core 1	1/1 top	-20.68	6.70	-24.03	Transgressive	5.10	0.80	0.00	0.18	0.18	1.80	0.00	0.03	0.50	0.10	3.23	0.63	-24.66	-20.8
2	Cemlyn Jones Core 1	1/1 bottom	-20.84	6.70	-24.19	Regressive	4.60	1.05	0.00	0.18	0.01	0.10	0.00	0.03	0.50	0.10	1.78	0.63	-24.82	-22.41
3	Cemlyn Jones Core 1	1/2 top	-23.08	6.70	-26.43	Transgressive	4.20	1.25	0.00	0.42	0.05	0.50	0.00	0.03	0.50	0.10	2.38	0.63	-27.06	-24.05
4	Cemlyn Jones Core 1	1/2 top repeat	-23.08	6.70	-26.43	Transgressive	4.20	1.25	0.00	0.42	0.05	0.50	0.00	0.03	0.50	0.10	2.38	0.63	-27.06	-24.05
5	Cemlyn Jones Core 1	1/2 bottom	-23.37	6.70	-26.72	Regressive	4.20	1.25	0.00	0.42	0.01	0.10	0.00	0.03	0.50	0.10	1.98	0.63	-27.35	-24.74
6	Cemlyn Jones Core 1	1/2 bottom repeat	-23.37	6.70	-26.72	Regressive	4.20	1.25	0.00	0.42	0.01	0.10	0.00	0.03	0.50	0.10	1.98	0.63	-27.35	-24.74
7	Cemlyn Jones Core 2	2/1 top	-12.97	6.80	-16.37	Transgressive	5.60	0.60	0.00	0.10	0.03	0.30	0.00	0.03	0.50	0.10	1.53	0.63	-17	-14.84
8	Cemlyn Jones Core 2	2/1 bottom	-13.07	6.80	-16.47	Regressive	5.60	0.60	0.00	0.10	0.01	0.10	0.00	0.03	0.50	0.10	1.33	0.63	-17.1	-15.14
9	Cemlyn Jones Core 2	2/2 top	-15.72	6.80	-19.12	Transgressive	4.00	1.40	0.00	0.13	0.13	1.30	0.00	0.03	0.50	0.10	3.33	0.63	-19.75	-15.79
10	Cemlyn Jones Core 2	2/2 bottom	-15.86	6.80	-19.26	Regressive	3.80	1.50	0.00	0.13	0.01	0.10	0.00	0.03	0.50	0.10	2.23	0.63	-19.89	-17.03
11	Cemlyn Jones Core 2	2/3 top	-16.86	6.80	-20.26	Transgressive	5.00	0.90	0.00	0.07	0.07	0.70	0.00	0.03	0.50	0.10	2.23	0.63	-20.89	-18.03
12	Cemlyn Jones Core 2	2/3 bottom	-16.94	6.80	-20.34	Regressive	5.00	0.90	0.00	0.07	0.01	0.10	0.00	0.03	0.50	0.10	1.63	0.63	-20.97	-18.71
13	Cemlyn Jones Core 2	2/4 top	-25.83	6.80	-29.23	Transgressive	2.40	2.20	0.00	0.02	0.02	0.20	0.00	0.03	0.50	0.10	3.03	0.63	-29.86	-26.2
14	Cemlyn Jones Core 2	2/5 top	-28.24	6.80	-28.24	Transgressive	Unknown	Unknown	Unknown	0.07	0.07	0.00	0.00	0.03	0.50	0.10	Unclear	Unclear	Void	Void
15	Cemlyn Jones Core 2	2/5 bottom	-28.31	6.80	-28.31	Regressive	Unknown	Unknown	Unknown	0.07	0.01	0.00	0.00	0.03	0.50	0.10	Unclear	Unclear	Void	Void
16	Cemlyn Jones Core 3	3/1 top	-5.58	6.70	-8.93	Transgressive	5.80	0.45	0.00	0.05	0.05	0.50	0.00	0.10	0.50	0.10	1.65	0.7	-9.63	-7.28
17	Cemlyn Jones Core 3	3/1 bottom	-5.63	6.70	-8.98	Regressive	5.80	0.45	0.00	0.05	0.01	0.10	0.00	0.10	0.50	0.10	1.25	0.7	-9.68	-7.73
18	Cemlyn Jones Core 3	3/2 top	-6.72	6.70	-10.07	Transgressive	6.10	0.30	0.00	0.12	0.12	1.20	0.00	0.10	0.50	0.10	2.2	0.7	-10.77	-7.87
19	Cemlyn Jones Core 3	3/2 bottom	-6.84	6.70	-10.19	Regressive	5.80	0.45	0.00	0.12	0.01	0.10	0.00	0.10	0.50	0.10	1.25	0.7	-10.89	-8.94
20	Heyworth & Kidson (1982)	Rhyl Beach	2.43	7.30	-1.22	Regressive	7.20	0.05	0.00	Unknown	0.02	0.20	0.00	0.03	0.50	0.10	0.88	0.63	-1.85	-0.34
21	Heyworth & Kidson (1982)	Llandudno Station	-4.15 to -5.20	6.70	-8.04	Unclear	6.10	0.30	0.00	1.05	1.05	10.50	0.00	0.56	0.50	0.10	11.96	1.16	-9.2	3.92
22	Prince (1990)	Woodlands (1)	-9.00	7.30	-12.65	Transgressive	6.40	0.45	0.00	0.22	0.15	1.50	0.00	0.03	0.50	0.10	2.58	0.63	-13.28	-10.07
23	Prince (1990)	Woodlands (2)	-9.12	7.30	-12.77	Regressive	6.20	0.55	0.00	0.22	0.03	0.30	0.00	0.03	0.50	0.10	1.48	0.63	-13.4	-11.29
24	Bedlington HF 21 (1994)	Hendre Fawr (1)	1.87	7.30	-1.78	Regressive	7.20	0.05	0.00	0.12	0.05	0.50	0.00	0.03	0.50	0.10	1.18	0.63	-2.41	-0.6
25	Bedlington HF 21 (1994)	Hendre Fawr (2)	1.70	7.30	-1.95	Transgressive	7.20	0.05	0.00	0.50	0.33	3.30	0.00	0.03	0.50	0.10	3.98	0.63	-2.58	2.03
26	Bedlington HF 21 (1994)	Hendre Fawr (3)	1.27	7.30	-2.38	Regressive	7.10	0.10	0.00	0.50	0.02	0.20	0.00	0.03	0.50	0.10	0.93	0.63	-3.01	-1.45
27	Bedlington HF 29 (1994)	Hendre Fawr (4)	-2.48	7.30	-6.13	Unclear	7.10	0.10	0.00	0.05	0.03	0.30	0.00	0.03	0.50	0.10	1.03	0.63	-6.76	-5.1
28	Bedlington TB 20 (1994)	Tregarnedd Bach (1)	1.00	4.20	-1.1	Regressive	4.10	0.05	0.00	0.24	0.03	0.30	0.00	0.03	0.50	0.10	0.98	0.63	-1.73	-0.12
29	Bedlington TB 18 (1994)	Tregarnedd Bach (2)	-4.11	4.20	-6.21	Regressive	3.80	0.20	0.00	0.17	0.04	0.40	0.00	0.03	0.50	0.10	1.23	0.63	-6.84	-4.98
30	Bedlington MP 20 (1994)	Morfa Penrhyn	0.28	7.30	-3.37	Regressive	7.00	0.15	0.00	0.14	0.03	0.30	0.00	0.03	0.50	0.10	1.08	0.63	-4	-2.29
31	Bedlington TB 18 (1994)	Tregarnedd Bach (3)	-3.96	4.20	-6.06	Transgressive	3.60	0.30	0.00	0.15	0.19	1.90	0.00	0.03	0.50	0.10	2.83	0.63	-6.69	-3.23
32	Bedlington HF 21 (1995)	Hendre Fawr (5)	-0.93	7.30	-4.58	Regressive	7.10	0.10	0.00	0.09	0.02	0.20	0.00	0.03	0.50	0.10	0.93	0.63	-5.21	-3.65

Table 5.1 Tabulated sea-level index point altitudinal data incorporating error estimates

contamination through bioturbation has also been considered. With the exception of material above deposit 1/1 top, the sediments contain no evidence of direct contamination through bioturbation; the downward leaching of younger, mobile humic acids derived from overlying material, however may have possibly partially influenced some of the radiocarbon dates obtained from material taken from the lower sections of the organic-rich deposits.

All contacts have been radiocarbon dated and subsequently calibrated into calendar years using the CALIB Radiocarbon Calibration programme produced by Stuiver *et al.* (2004). Pollen analysis has been utilized in order to provide additional palaeoenvironmental data and also in order to provide an independent form of dating in relation to determining the approximate age of each contact. This method utilized the previously generated well-dated pollen record obtained from Llyn Cororion by Ruth Watkins (Watkins, 1991). A first-order approximation relating to the possible age of each individual contact was made by making a comparison between the arboreal pollen assemblage within each sample and that of the pre-existing well-dated pollen record from Llyn Cororion.

The underlying solid geology adjacent to and extending beneath some areas of the Menai Strait consists of Westphalian coal bearing sandstone and Carboniferous Viséan limestone. The sandstones predominantly outcrop toward the southwestern region of the strait however, Carboniferous limestone outcrops along much of the central region of the strait on the mainland side, extending northeast from Port Dinorwic as far as 1.5km southwest of Bangor Pier. A significant proportion of the solid geology within the region is additionally overlain by material associated with glacial processes and were predominantly deposited during the latter stages of the most recent Dimlington, Late Devensian Glacial that occurred during the Late Pleistocene.

The contemporary pattern of predominant freshwater drainage into the northeastern region of the Menai Strait is likely to be very similar to the pattern prevalent throughout the region during the course of the Holocene and as such, does not and has probably never, discharged directly over these carbonate-rich potential sources of contamination. For this reason it is highly probable that levels of dissolved carbonate and inert carbon introduced into the organic sediments during the period of their formation were relatively low and consequently, unlikely to have significantly influenced the radiocarbon dates through the recognized phenomenon known as hard-water error. Small fragments of coal were however, found within sediments proximal to some of the organic deposits and may have been derived through tidal-washing from regional marine deposits and eroded terrestrial sites. The effect that this potential source of contamination may have had upon the radiocarbon dates has at present not been adequately quantified however; the effects may be significant in some cases may need to be considered further in relation to some of the more anomalous radiocarbon dates.

As consideration has been given to levels of inert carbon introduced into the organic deposits at the time of their formation from terrestrial sources, consideration must also be given to the possible effects derived from levels of inert carbon introduced through processes operating within the marine environment. Considerable quantities of coal-bearing rocks such as the Upper Carboniferous, Westphalian Red Beds, are located within the region, although they appear to be predominantly confined to the southwestern vicinity of the Menai Strait. The erosion of these deposits, through the action of water, ice and wind has unquestionably resulted in the introduction of older inert carbon into the regional sedimentary system.

Ancient carbon by its nature will invariably contain a negligible quantity of ^{14}C; consequently contamination will result directly from the dilution of ^{14}C levels as a result of introducing significant quantities of inert carbon. Research has shown that within sediments containing low proportions of organic material, the addition of 5% inert carbon may possibly add up to 400 years on to the true age of a sedimentary deposit. The available evidence however, does suggest that this form of contamination is probably limited in terms of its effect and extent and as such can probably in the context of this investigation, be deemed as relatively insignificant.

As a small number of inorganic deposits within the three sediment cores appear to contain minor traces of coal, possibly derived from within the Carboniferous formations, each sub-sample has been subjected to a cursory examination using a Nikon (Kyowa) low power stereoscopic microscope with x 40 magnification prior to submission for radiocarbon analysis. Although no allochthonous carbon-based material appears to be discernable within the sub-samples, the difficulty in differentiating or distinguishing fragments of inert carbon from within an organic deposit utilizing this technique alone must be noted. Given the stratigraphical context of the radiocarbon dates and the excellent correlation between the radiocarbon dates and the estimated dates, derived through correlation with the existing biostratigraphical data of Llyn Cororion (Fig. 4.20), the degree of contamination this effect may have imparted upon the radiocarbon dates can be regarded as relatively minimal.

Sub-aquatic photosynthesis and groundwater uptake conducted by certain species of flora within carbonate-rich environments may impart a significant degree of dilution with respect to the levels of ^{14}C present within a sample of dated material. Sub-samples of organic material taken from within the sediments submitted for radiocarbon analysis have been subjected to an investigation conducted in order to ascertain the nature of any plant macrofossils contained within them, by Dr Charles Turner of The Open University based at Milton Keynes. Results from this investigation demonstrate that at least two sub-samples of organic material are overlain by inorganic sediments containing abundant quantities of plant material probably derived through the presence of aquatic flora; as a consequence, in these particular cases the possibility of contamination through sub-aquatic photosynthesis may be considered to be potentially significant. The possibility of hard-water error, needs to be considered as a potential source of contamination when considering the radiocarbon dates and plant remains identified within the predominantly fine grained clay located above organic deposits 2/3 and 3/2. In either case, an abundant quantity of plant material belonging to fresh or brackish aquatic dwelling flora, specifically *Ruppia maritima* and *Zannichellia palustris* has been identified. As a consequence, ^{14}C deficient carbon may possibly have been introduced into the organic material, imparting a slight but significant degree of error with respect to the results of the radiocarbon analysis.

The organic deposits adjacent to these inorganic sediments have been subjected to palynological analysis and appear to contain relatively low levels of pollen derived from the presence aquatic flora. The evidence may possibly reflect the colonization of an intertidal zone proximal to MHWS by aquatic flora, following a transition from a terrestrial environment to an environment experiencing brackish conditions, following an increase in relative sea level. This palaeoenvironmental change may have resulted in the occurrence of sub-aquatic photosynthesis which may have significantly affected the ^{14}C levels present within the organic deposits.

Taking into consideration the underlying geology and the fact that Carboniferous deposits occur throughout the Menai Strait, it is possible that proportions of dissolved carbon within the freshwater system at the time of formation may have been significant. On the basis of this evidence, it is also possible that levels of dissolved carbonate introduced into organic sediments during the period of their formation may be significant and as a consequence may have slightly influenced the radiocarbon dates through the recognized phenomenon known as hard-water error.

Standard deviations associated with each of the radiocarbon dates appear to be relatively consistent, with variations predominantly attributable to the derived ages of individual sub-samples; with standard deviations as expected, appearing to increase with increasing radiocarbon age.

5.1.1.2.1 CJSC 1

The six radiocarbon dates derived from the sub-samples taken from deposits within CJSC 1, have all produced dates representative of the very early Holocene and agree well in terms of their stratigraphic context, with the organic deposits becoming successively younger with increasing elevation. Replicate analyses of organic-rich material submitted from within deposit 1/2, designed to address homogeneity issues, have resulted in the production of dates relatively consistent with the initially derived values and can almost be completely accounted for within the expressed analytical confidence values.

The conventional radiocarbon ages produced by the submitted material within deposit 1/2 coincide with a period of time closely associated with a major ^{14}C 'plateau', which as a consequence may possibly account for some or all of the variation associated with the derived conventional radiocarbon ages of the analyzed material. Although there appears to be some evidence relating to bioturbation immediately above deposit 1/1 the ages produced through radiocarbon analysis from the upper contact does not appear to have been adversely affected through the introduction of any allocthonous carbon.

This conclusion is based upon the age and stratigraphical context of the deposit with respect to dates derived from the underlying organic-rich deposit and that the dates correspond approximately with what would be expected when comparing the arboreal pollen assemblage with data derived from Llyn Cororion.

5.1.1.2.2 CJSC 2

With the exception of deposits 2/5 and 2/2, the radiocarbon dates derived from the submitted material located within the core agree well in terms of their stratigraphic context, with organic-rich deposits 2/4, 2/3 and 2/1 appearing to become successively younger with increasing elevation.

Subsequent to the dating of deposit 2/5 a re-examination of the material indicates that the top and bottom of the sediment unit may have been incorrectly labelled immediately following recovery. A discussion relating to this anomalous deposit is provided in section 5.1.1.3.1. Palynological evidence from sub-samples taken from within deposit 2/2 call the validity of the dates produced by deposit 2/2 to be questioned and an account of this is provided in sections 5.1.1.3.9 and 5.1.1.3.10.

5.1.1.2.3 CJSC 3

With the exception of deposit 3/2 top, all sub-samples contained within CJSC 3, submitted for radiocarbon analysis have produced conventional radiocarbon ages consistent with respect to their stratigraphical context. The degree of disparity with respect to deposit 2/3 top cannot fully be accounted for, following calibration into calendar years BP at the 2 sigma level and a discussion relating to this apparently anomalous date is provided within section 5.1.1.3.14.

5.1.1.3 Sediment core data

5.1.1.3.1 Deposit 2/5

The radiocarbon dates produced by the sub-samples taken from the lower organic clay situated between -28.31m and -28.24m OD within CJSC 2, result in an apparent age inversion with respect to the stratigraphic context of the submitted material. The lower sample, termed 2/5 bottom, produced a radiocarbon date of 11488 +/-59 years BP, whilst the overlying sample, termed 2/5 top, at an elevation 0.07m greater, produced a date of 12715 +/-71 years BP. The conventional radiocarbon age produced by sub-sample 2/5 top coincides with a period of time directly associated with a major ^{14}C 'plateau' and is reflected by the range of possible calendar ages produced as a result of the calibration procedure. The calibrated age range derived from both submitted sub-samples however, does not adequately account for the degree of disparity between the dated sediments within deposit 2/5.

In light of the anomalous radiocarbon dating results, a more detailed lithological examination has been subsequently conducted. The materials comprising the organic clay were recovered from immediately beneath a 0.45m sampled unit of sediment and were contained within a 0.20m section of the sampler constituting the cutting head and were labeled up as Unit D48. Upon closer examination it is apparent that the deformation of laminae within this unit, attributable to the coring process, is not consistent with the more conventional pattern observed elsewhere; where in the case of laminated sediments the outer edges of the laminae appear at a lower elevation than their more central counterparts (fig 5.2). The pattern of deformation within Unit D48 appears to be the inverse of what would normally be expected and consequently calls into question the stratigraphic context of the dated material. Preliminary observation also indicates that the lithology of the adjoining sedimentary facies appear to possess a far greater degree of similarity to those within Unit D48 subsequent to any inadvertent inversion of the sample following recovery.

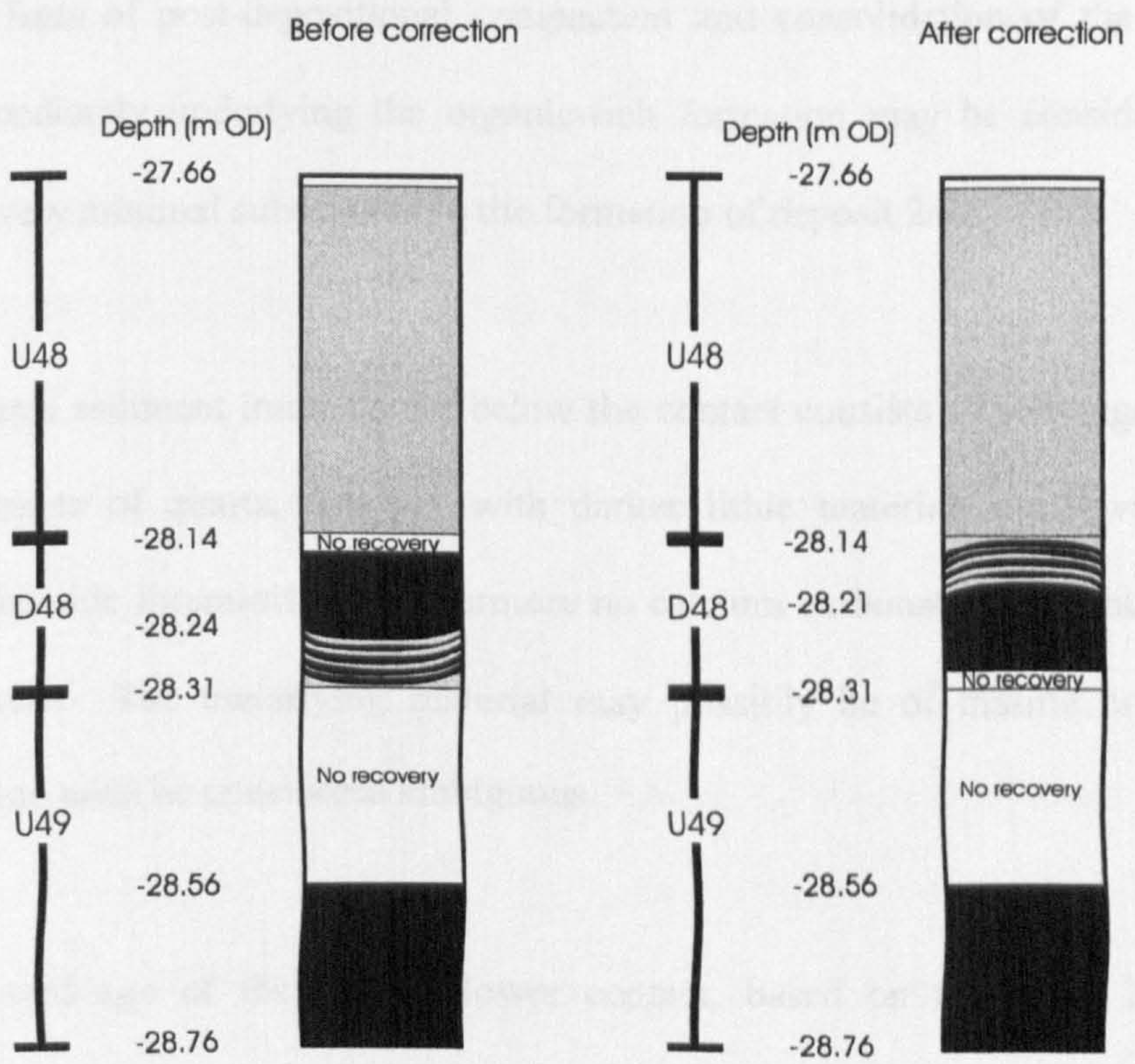


Figure 5.2 Schematic diagram illustrating the effect on altitudinal data caused by incorrect labelling of unit D48

This evidence, together with the results of the radiocarbon dating process, suggests the strong possibility that the top and bottom of Unit D48 was incorrectly labeled during the recovery procedure. Consequently all data relating to the elevation of the dated horizons constituting deposit 2/5 have been subjected to correction in order to account for this error. The altitude of the lower contact which is in fact probably the upper contact has subsequently been revised to -28.14m OD, whilst the altitude of the upper contact, subsequently defined as the lower contact, has been re-recorded as being at -28.21m OD. The organic clay overlies at least 4m of fine grained silty sand interbedded with intermittently occurring beds of coarser sand and gravel extending to an unproven depth. Lithology of the underlying material, together with well-correlated seismic data suggests that the effects of post-depositional compaction and consolidation of the sedimentary facies immediately underlying the organic-rich formation may be considered to have been relatively minimal subsequent to the formation of deposit 2/5.

The inorganic sediment immediately below the contact consists of sub-angular and sub-rounded grains of quartz, together with darker lithic material, mica with very few fossilized benthic foraminifera, furthermore no calcium carbonate fragments were found to be present. The underlying material may possibly be of marine origin but this interpretation must be considered ambiguous.

The calibrated age of the revised lower contact, based on the result derived from radiocarbon analysis suggests that the deposit may have begun to form between 15700 and 14340 calendar years BP. Calibration of the radiocarbon date on the revised upper contact indicates the age of the material constituting the upper contact to be between 13160 and 13820 calendar years BP. Analysis of the organic-rich material constituting both contacts and the central region of the deposit, yielded insufficient quantities of pollen in order to allow any form of biostratigraphical correlation or palaeoenvironmental interpretation. However, a number of coal fragments appear to be present within the deposit, highlighting the possibility of contamination with respect to the modification of carbon content.

Another possible source of contamination that may need to be considered with respect to this sample relates to the introduction of inert carbon into the deposit at some point in time that cannot be determined. Analysis of a sub-sample of material reveals the presence of an unidentifiable fossilized Carboniferous spore identified within the laminated organic clay located toward the top of organic deposit 2/5. Although a single spore may have limited impact on the overall date itself the possibility that a number of spores may have been incorporated within the dated sub-sample, subsequently leading to the production of an over-estimated age needs to be considered.

Additional plant macrofossil analyses conducted on the organic-rich materials indicate that the deposit may represent wet or boggy conditions adjacent to dwarf willow shrub tundra (C. Turner, pers. comm. 2004). These data indicate that the deposit formed under terrestrial conditions possibly at a time prior to or coincident with the initial development of arboreal vegetation.

The nature of the deposit together with the dates obtained from them suggest that a degree of contamination may have occurred, however, radiocarbon dates obtained from overlying organic-rich material indicate that the material was almost certainly deposited prior to the onset of the Holocene.

Foraminifera are sparse or entirely absent within both the organic-rich formation and the adjacent inorganic sedimentary facies, with eleven out of thirteen examined horizons yielding very few specimens. Analysis of a sub-sample taken from approximately 0.5m beneath the revised lower contact consists of an assemblage that is dominated by hyaline foraminifera and primarily comprises of *Haynesina germanica, Elphidium williamsoni* and *Cibicides lobatulus,* together with a proportion of planktonic foraminifera. The quantity and quality of the data however, does not permit an adequately justifiable interpretation with respect to the origin of the inorganic sediments and consequently their environment of deposition remains unclear.

One possible tentative interpretation may be that the inorganic deposits represent washover marine deposits that contain an integrated organic-rich deposit formed within a back-barrier freshwater pool. Lithological and micropalaeontological analyses further suggest that the sediments adjacent to the dated contacts may have been subjected to a significant degree of erosion and/or reworking. Lithological and stratigraphical data fail to provide evidence intimating the relationship of the dated contacts to a former sea level and consequently the deposits cannot justifiably be considered as accurate or valid sea-level index points.

5.1.1.3.2 Deposit 2/4

The organic-rich material constituting deposit 2/4 top within CJSC 2 has been recorded at an elevation of -25.87m OD, and is underlain by approximately 2.3m of medium and fine grained silty sand, which extends above deposit 2/5. Any post-depositional compaction and consolidation experienced by the underlying substrate subsequent to the deposition of deposit 2/4 would be difficult to quantify and as such no attempt has been made with respect to correcting the altitude of the deposit in relation to this effect. The possible degree of post-depositional compaction and consolidation experienced by the organic horizon itself has additionally been deemed as slight, given the overall thickness of the deposit which constitutes some 0.02m. Any changes in tidal range since the time of deposition may possibly result in the introduction of a considerable degree of error in relation to determining the relationship of the deposit to the former position of MSL, however this is additionally difficult to quantify.

Results derived from radiocarbon analysis suggest that the organic-rich material may possibly have been deposited between 12950-12360 calendar years BP during the Younger Dryas or Loch Lomond stadial. Pollen analysis was not conducted on material constituting the dated horizon and consequently biostratigraphical correlation cannot be applied in order to substantiate the validity of the calibrated dates. The stratigraphical context of the deposit in relation to other dated horizons within the immediate vicinity additionally provides support in relation to the derived age of the material.

The possibility of *in-situ* and post-depositional contamination of the sample with respect to the modification of its carbon content has been assessed and deemed negligible; however, as no independent means of correlation exists with respect to validating the age of the material, the calibrated age must be treated with some degree of caution.

Micropalaeontological analysis of the overlying silty clay and silty sand demonstrates that the sediment contains a large quantity of fossilized benthic foraminifera. Above the contact, the sediments are dominated by large proportions of *Haynesina germanica, Elphidium williamsoni,* and *Ammonia batavus*, together with an increasingly larger relative proportion of *Cibicides lobatulus*. The sediments contain a relatively small proportion of *Quinqueloculina seminulum* and planktonic foraminifera, whilst a slight decrease with respect to the relative proportions of *Haynesina germanica* and *Elphidium williamsoni* is apparent with increasing altitude. Comparisons with the modern analogues obtained from within the Taf Estuary indicate that the sediments immediately above deposit 2/4 may represent an environment similar to that of a low marsh or inter-tidal mudflat, with the overlying assemblages inferring a transition to a more energetic environment, such as a sandy mudflat.

The relatively abrupt change from organic to inorganic sedimentation may probably represent a rapid transition from terrestrial to marine conditions. Consideration must however be given to the possibility that the sediments located adjacent to the dated contact may also have been subjected to a degree of erosion or reworking, effectively removing any evidence pointing to a more gradual transition.

The organic material additionally provided little or no evidence in terms of plant macrofossil data in order to substantiate its environment of deposition. It is possible however that the dated contact could represent terrestrial conditions immediately prior to the onset of marine conditions, however, the relationship of the dated contact to the position of MSL at the time remains unclear. Seismic data indicate that the deposit constitutes part of a near-horizontal reflective horizon that may extend over a distance of several metres some 18.5m beneath the sea floor within the proximity of Gallows Point.

It is apparent that an element of uncertainty exists in relation to both the age of the dated material and its indicative meaning. Consequently the degree of accuracy associated with the contact, in terms of considering it as a validated sea-level index point is acknowledged.

5.1.1.3.3 Deposit 1/2 bottom

The altitude of the contact has been recorded at -23.37m OD. Given the stratigraphical context of the organic deposit, located almost immediately above a largely incompressible substrate of sub-angular gravel and glacial till, the degree of compaction and consolidation experienced by material located toward the base of the organic formation has probably been minimal.

Results derived from radiocarbon analysis suggest that the deposit probably formed between 11220-11550 calendar years BP. These dates derive from the amalgamation of two results obtained through the dating of two organic samples originating from the same sub-sample, initially dated in order to address homogeneity concerns. Although appearing to underestimate the calibrated radiocarbon age of the material by approximately 1200 years, the pollen data further indicate that the formation of the organic deposit almost certainly took place during the initial onset of the Holocene. For the purposes of the research project, the two dates derived from the analysis of the sample have been considered separately, together with the respective degree of precision associated with their derivation. Differences relating to the age of the sub-sample resulting from both dating procedures are considered to be minimal and amount to approximately 3% of the derived mean age; the degree of disparity can probably be attributed to the non-homogeneous nature of the organic deposit. The possibility of *in-situ* and post-depositional contamination of the sample with respect to the modification of its carbon content has also been assessed. Differences between the radiocarbon date and the age estimated through correlation with the biostratigraphical data from Llyn Cororion may be partially attributable to the possibility of contamination through the presence of aquatic flora, as plant macrofossils identified as fragments of *Zannichellia palustris*, together with *Chara* oospores have been observed within organic material constituting the bulk of the deposit (C. Turner, pers. comm. 2004).

Micropalaeontological analysis of the underlying fine grained silty clay demonstrates that the sediment contains relatively few foraminifera. The assemblage is dominated by *Haynesina germanica*, *Elphidium williamsoni* and *Ammonia batavus* suggesting the presence of inter-tidal conditions. A more tentative interpretation would be that the deposit represents a low energy mudflat or tidal creek, however, this interpretation is questionable given the low numbers of foraminifera obtained during the analysis. The abrupt change from inorganic to organic sedimentation, however, may imply the occurrence of a localized fall in relative sea level, with terrestrial conditions rapidly succeeding those associated with an inter-tidal environment.

Consideration however, must additionally be given to the possibility that the sediments located adjacent to the contact may also have been subjected to a significant degree of erosion or reworking, effectively removing any evidence pointing to a more gradual transition. Pollen and plant macrofossil analyses conducted on the organic sediments, located at the contact indicate that following the transition from marine to terrestrial conditions, the site was characterized by the development of a freshwater pond.

Analyses indicate that the organic material probably represents material deposited within a terrestrial environment at a point above the influence of MHWST; however, the altitude of MSL in relation to the deposit remains unclear. The inorganic-organic horizon may therefore not accurately represent a former position of MSL and these uncertainties need to be considered when assessing the accuracy of the index point.

5.1.1.3.4 Deposit 1/2 top

The altitude of the contact has been recorded at -23.08m OD. Given the stratigraphical context of the deposit, located almost immediately above a largely incompressible substrate of sub-angular gravel and glacial till, the degree of compaction and consolidation experienced by the deposit can be considered to have been minimal. The dated horizon does, however, form the upper contact of what was at one time very probably a highly compressible organic sequence and as a consequence some consideration needs to be given to the possible degree of post-depositional compaction and or consolidation that the contact may have experienced.

The calibrated age of this particular deposit, based on radiocarbon analysis suggests that the deposit probably formed between 11550 and 11200 calendar years BP. Although appearing to underestimate the true age of the material by approximately 1000 years, the palynological data additionally supports the radiocarbon data by indicating that the formation of the organic deposit probably took place during the onset of the Holocene. The possibility of *in-situ* or post-depositional contamination of the sample with respect to the modification of its carbon content must be considered likely due to the presence of a number of *Chara* oospores within the analyzed material (C. Turner, pers. comm. 2004). Quantifying the degree of possible contamination is however problematic, however, considering the stratigraphical context of the dated contact in comparison to the overlying radiocarbon dated sediments, the degree of contamination is probably low. As a consequence the derived age of the dated material together with the associated degree of precision and accuracy can be regarded as acceptable.

The foraminiferal assemblages contained within the inorganic sediment located immediately above the organic deposit are dominated by hyaline foraminifera, predominantly consisting of *Haynesina germanica*, *Elphidium williamsoni* and *Ammonia batavus*, together with relatively small quantities of *Quinqueloculina seminulum* and *Jadammina macrescens*. The assemblages indicate the presence of inter-tidal conditions and suggest a transition between a low marsh and a low energy sandy mudflat. The apparently abrupt change from organic to inorganic sedimentation probably represents a localized rapid transition from terrestrial to marine conditions. Micropalaeontological analysis of the sediments located above the contact suggests a relatively rapid but smooth transition from low energy mudflat into a more dynamic marine environment. The stratigraphy of the sediments, together with the micropalaeontological data further suggest the possibility that a degree of erosion or contemporaneous macro-faunal disturbance may also have occurred at or immediately above the dated contact. As a consequence, difficulties arise when attempting to precisely establish the horizon's true indicative meaning and its relationship to MSL.

Lithological and micropalaeontological analyses suggest that the sediments within and adjacent to the dated horizon probably represent a relatively rapid transition from open terrestrial conditions into an environment that became increasingly dominated by marine processes. The sediments representing this change may also have been subjected to a degree of erosion and as a consequence do not accurately reflect the position of MHWST. The organic-inorganic contact probably represents the former position of sea level within the Menai Strait and as such fulfils the criteria required in order to be considered a sea-level index point, however the precise relationship of the contact to MSL remains unclear. Attempts in relating the dated horizon to MSL therefore, acknowledge the degree of confidence associated with the assessment of the dated contact as a sea-level index point.

5.1.1.3.5 Deposit 1/1 bottom

The altitude of the contact is recorded as -20.84m OD, with the organic material immediately overlying 2.73m of silty sand. The stratigraphical context and age of the deposit suggest that sea level may have risen relatively rapidly within this area of the Menai Strait during the early Holocene. Sedimentation rates during this period additionally appear to have been relatively high and as a consequence primary compaction and consolidation of the underlying organic sediments may have occurred prior to the formation of this organic-rich deposit. Accordingly, as the contact forms the base of a compressible deposit the degree of compaction and consolidation experienced within the lower section of this particular deposit may be considered as minimal.

The calibrated age of this particular deposit, based on results derived from radiocarbon analysis suggests that formation probably took place between 11230 and 10790 calendar years BP. Pollen data obtained from the material sub-sampled from within the dated horizon suggests that the deposit may have formed around 10200 calendar years BP, underestimating the calibrated radiocarbon age by approximately 800 years. The pollen data additionally indicate that the organic deposit probably formed during the early Holocene. The possibility of *in-situ* or post-depositional contamination of the sample with respect to the modification of its carbon content has been assessed based on lithological and plant macrofossil evidence. These data suggest that the effects of contamination can be considered negligible, consequently the calibrated radiocarbon age of the dated material together with the associated degree of precision and accuracy have been regarded as acceptable.

Foraminiferal assemblages within the sediment located beneath the organic deposit are dominated by hyaline foraminifera together with increasingly higher proportions of agglutinating foraminifera appearing to occur immediately proximal to the dated horizon. The assemblages consist predominantly of *Haynesina germanica, Elphidium williamsoni* and *Ammonia batavus.* Foraminiferal assemblages within the sediment contain decreasing proportions of *Cibicides lobatulus,* together with increasingly larger proportions of *Jadammina macrescens* and *Trochammina inflata,* occurring toward the inorganic-organic contact. The foraminiferal data indicate that the location probably consisted of an inter-tidal mudflat which was succeeded by the development of a lower saltmarsh characterized by brackish-saline conditions prior to the onset of organic sedimentation. Lithological and micropalaeontological data suggest the possibility that a small but not inconsequential degree of erosion may also have occurred at or immediately below the dated contact. As a result, difficulties arise when attempting to accurately establish the horizon's relationship to MSL, therefore, acknowledgement relating to these uncertainties have been taken into account.

Lithological and micropalaeontological data suggest that the sediments within and adjacent to the dated horizon may represent a relatively rapid transition from inter-tidal conditions into an environment characterized by terrestrial sedimentation. However, it is also highly probable that this apparently rapid transition has either resulted in a degree of erosion or non-deposition occurring proximal to the dated contact. Consequently the degree of accuracy associated with the dated horizon has been considered and accounted for.

5.1.1.3.6 Deposit 1/1 top

The altitude of the contact has been recorded as -20.66m OD, with the dated horizon's constituent organic formation overlying 2.73m of silty sand. The effects of primary consolidation and compaction within the underlying sediments are considered to have taken place prior to the onset of organic sedimentation, although this inference must be considered tentative. The dated horizon does, however, form the upper surface of what was at one time, very probably a highly compressible organic deposit, therefore consideration must be given to any post-depositional change that may have occurred in relation to the original altitude of the deposit.

The calibrated age of this particular deposit suggests that the deposit probably formed between 10670 and 10270 calendar years BP. An estimation relating to the age of the horizon based on biostratigraphical correlation with pre-existing palynological data, correlates well with the calibrated radiocarbon age of the sample, with the degree of disparity amounting to between 100 and 500 years. These data indicate that formation of the organic deposit almost certainly took place during the early Holocene. Lithological and macrofossil evidence indicate that *in-situ* and post-depositional contamination of the sample with respect to the modification of its carbon content can be regarded as negligible; consequently the calibrated radiocarbon age of the dated material together with the defined limits of precision and accuracy can be regarded as acceptable.

Micropalaeontological data indicate that foraminiferal assemblages located within the sediment immediately above the organic deposit are dominated by hyaline foraminifera, predominantly *Haynesina germanica*, *Elphidium williamsoni* and *Ammonia batavus*, with relatively small proportions of *Quinqueloculina seminulum* and *Jadammina macrescens*. The assemblages suggest the presence of inter-tidal conditions, similar to those found between a low marsh and a low energy sandy mudflat. The apparently abrupt change from organic to inorganic sedimentation may represent a localized rapid transition from terrestrial to marine conditions. The data obtained from the analyses of sediments located above the contact, suggest a relatively rapid but smooth transition, possibly from low energy mudflat into a more dynamic marine environment. Increasing proportions of porcellaneous foraminifera, principally *Quinqueloculina seminulum,* approximately 0.20m above the contact, possibly infer that the initially rapid transition into a more dynamic regime may have been followed by a temporary transition into more quiescent environmental conditions for a relatively short period of time.

Lithological and micropalaeontological data do not suggest that any significant degree of erosion may have occurred at or immediately above the dated contact; however, the analyses do not provide the data necessary in order to accurately relate the horizon to MSL. Plant macrofossil and pollen analysis conducted on the organic sediment, located at the dated horizon indicates that the contact may possibly represent flooded turf (C. Turner, pers. comm. 2004), which suggests the rapid inundation of a terrestrial environment.

The data suggest that the sediments within and adjacent to the dated horizon probably represent a relatively rapid transition from open terrestrial conditions into an environment that became increasingly dominated by marine processes.

The organic-inorganic contact may well therefore represent the former position of sea level within the Menai Strait and as such fulfils the criteria required in order to be considered a sea-level index point. The available micropalaeontological evidence, however, does not accurately deduce the dated horizon's relationship to MSL and consequently attempts in utilizing the dated horizon with respect to evaluating the position of a former sea level, acknowledge the limited degree of accuracy identified with respect to the assessment of this sea-level index point.

5.1.1.3.7 Deposit 2/3 bottom

The altitude of the contact is recorded as -16.94m OD, with the organic-rich deposit overlying approximately 9m of medium and fine grained silty sand of marine origin, which in turn, overlies deposit 2/4. If the calibrated age of deposit 2/4 dated to between 12950-12360 calendar years BP can be considered to be relatively accurate, the calibrated age of deposit 2/3 implies that the underlying 9m of sediment will been deposited within a timeframe of approximately 2000 years. A more detailed chronostratigraphical interpretation relating to the origin of the underlying deposit has not been possible given the first-order approach adopted during this investigation however, more detailed sedimentological and geotechnical analyses may support a more detailed interpretation as to the timing and origin of this inorganic deposit. As a consequence it is difficult to quantify any effects that may have been experienced by the underlying sediments subsequent to the accumulation of organic-rich material that constitutes deposit 2/3. As the contact forms the base of what was once probably a highly compressible layer, it can be argued that any post-depositional compaction and consolidation may have had a minimal effect upon the altitude of the dated contact.

The calibrated age of deposit 2/3 bottom, indicates that the deposit probably formed between 10670 and 10270 calendar years BP. The dates derived from the upper and lower contacts within deposit 2/3 are similar given the limits of precision and accuracy associated with the radiocarbon dating process. Although the palynological analysis of the deposit failed to yield many fossilized arboreal pollen grains it was found that the relatively small assemblage obtained predominantly consisted of grains of *Betula*, *Corylus*, *Salix* and *Pinus* with a small proportion of *Quercus*. The relative proportions of both *Betula* and *Corylus* appear to be similar, which when compared to data obtained from Llyn Cororion and from deposit 1/1 indicate an early Holocene age for the material which appears to be consistent with the radiocarbon data. The possibility of *in-situ* or post-depositional contamination of the sample with respect to the modification of its carbon content has been assessed based on lithological and plant macrofossil evidence. These data suggest that in this particular case any effect relating to the possible contamination of the deposit may be considered negligible. The stratigraphical context and age of the deposit with respect to the underlying sediment additionally implies that the calibrated age may be deemed as acceptable.

The foraminiferal assemblages located immediately beneath peat deposit 2/3 are dominated by hyaline foraminifera, including *Haynesina germanica* and *Elphidium williamsoni*. The sediments additionally contain low proportions of both *Ammonia batavus* and *Cibicides lobatulus,* together with increasing quantities of *Quinqueloculina pygmaea* and small quantities of *Quinqueloculina seminulum* toward the base of the organic-rich deposit. Relatively small proportions of agglutinating foraminifera are present within the sediments immediately proximal to the contact which suggests the possibility that relatively low energy saline-brackish conditions may have prevailed at this location, prior to the accumulation of the organic-rich material constituting deposit 2/3. It must be acknowledged, however, that this interpretation is based on a limited volume of micropalaeontological data and should therefore be regarded as tentative. The relatively rapid transition from the deposition of fine grained silty sand to organic-rich sedimentation may additionally imply a rapid fall in sea level. The presence of a relatively thin layer of fine grained silt and clay located immediately beneath the contact may also imply a relatively smooth transition to terrestrial conditions with minimal erosion occurring at this location, prior to the deposition of materials constituting deposit 2/3.

As a result of this relatively tentative interpretation based on a limited volume of data, difficulties arise when attempting to accurately establish the horizon's relationship to MSL. It is apparent however that the deposit represents a transition between marine and terrestrial sedimentation and that the contact can be deemed as an acceptable sea-level index point.

5.1.1.3.8 Deposit 2/3 top

The altitude of the contact is recorded within CJSC 2 as -16.87m OD, with the dated horizon's constituent organic formation overlying approximately 9m of silty sand. It has been assumed that the effects of primary consolidation and compaction within the underlying sediments may have taken place prior to the onset of organic sedimentation. The dated contact however may possibly form the upper surface of what was at one time a highly compressible organic-rich deposit.

The calibrated age of the contact suggests that the deposit probably formed between 10670 and 10290 calendar years BP. An estimation relating to the age of the horizon based on biostratigraphical correlation with pre-existing palynological data was not possible due to low proportions of arboreal pollen within the analyzed sub-sample. The calibrated age of the sample is approximately identical to the age derived from the underlying inorganic-organic contact, which indicates that the organic-rich deposit probably formed over a relatively short period of time during the early Holocene.

Lithological and macrofossil data do not provide evidence to suggest that any *in-situ* and post-depositional contamination may have occurred with respect to the modification of the carbon content within the sub-samples recovered from the contact.

Examination of sub-samples located immediately above the contact demonstrates that the foraminiferal assemblages within the sediments are dominated by agglutinating foraminifera. The proportion of *Jadammina macrescens* present within the fine grained sediment located immediately above peat unit 2/3 constitute 25% of the total assemblage, whilst with increasing elevation, increasing proportions of *Haynesina germanica* and *Elphidium williamsoni* further characterize the sediments.

The micropalaeontological data indicate that the sediments located immediately adjacent to the dated contact almost certainly represent conditions associated with an environment proximal to MHWST. The data additionally indicate that the sediments may demonstrate the occurrence of a relatively rapid but smooth transition from conditions similar to those found within the central region of a saltmarsh to conditions associated with an inter-tidal mudflat.

Lithological and micropalaeontological data do not suggest that any significant degree of erosion may have occurred at, or immediately above the dated contact; however, the analysis is limited with respect to accurately assessing the relationship of the contact to MHWST.

The organic-inorganic contact may well therefore possibly represent the former position of sea level within the Menai Strait and as such fulfils the criteria required in order to be considered a sea-level index point. The available micropalaeontological evidence, however, does not accurately deduce the dated horizon's relationship to MHWST and consequently any attempt in utilizing the dated horizon with respect to evaluating the position of a former sea level must acknowledge the limited degree of accuracy identified with respect to the assessment of the contact as a sea-level index point.

The inherent uncertainties relating to both the indicative meaning and the relationship of the contact to MSL necessitate the incorporation of a relatively enhanced altitudinal error term which reflects the relatively poor quality of the available data associated with this particular index point.

5.1.1.3.9 Deposit 2/2 bottom

The altitude of the contact is recorded within CJSC 2 as being -15.86m OD, with the organic-rich laminated clay deposit termed 2/2 overlying approximately 1m of fine grained silt and clay, which in turn, overlies deposit 2/3. The stratigraphical position of the deposit, located above sediments considered to be particularly susceptible to substantial degrees of compaction and consolidation, suggests that the altitude of the contact may have been significantly higher during the time of deposition. It is however, difficult to quantify any effects that may have been experienced by the underlying sediments subsequent to the accumulation of organic-rich material that constitutes deposit 2/2.

Sub-samples 2/2 bottom and 2/2 top, consisting of highly organic, laminated clay and situated approximately 0.90m above deposit 2/3, both produced significantly older radiocarbon dates than expected, with respect to both the radiocarbon dates produced by deposit 2/3 and the altitude of this deposit. Although the radiocarbon dates produced by the submitted material once again coincide with a period of time directly associated with a major ^{14}C 'plateau', the degree of disparity between the conventional radiocarbon age of this deposit and that of the underlying organic-rich deposit 2/3 cannot be accounted for following calibration at the 2 sigma level.

Biostratigraphical correlation utilizing palynological data obtained from the material sub-sampled from within the dated horizon in conjunction with data obtained by Watkins (1991) indicates that the material constituting the dated contact may have been deposited much later than the radiocarbon data suggests. Pollen analysis conducted upon material located at an equivalent depth to those submitted for radiocarbon analysis within deposit 2/2 suggests a possible explanation for the anomalously older radiocarbon dates.

A visual comparison made between the percentage pollen assemblage in deposit 2/2 and the pollen percentage diagram obtained from Llyn Cororion (Fig. 4.20), suggests that the deposit formed much later than the radiocarbon dates indicate. Pollen concentration levels within the deposit further indicate that the deposit formed in a terrestrial environment as opposed to one dominated by marine processes. Throughout deposit 2/2, the relative proportion of fossilized *Corylus* pollen present within any given sub-sample consistently exceeds that of *Betula*, often by a factor greater than 8:1. Visual comparisons with the chronostratigraphical pollen data from Llyn Cororion indicate that this type of situation only occurred during a short period during the very early Holocene, between approximately 10000 and 9600 BP.

The results from the radiocarbon dating of the lower and upper contacts suggest the deposit formed between 12350 and 11660 calendar years BP. Furthermore this age conflicts with data obtained from Llyn Cororion, as the pollen diagram (Fig. 4.10) indicates that *Corylus* did not become established in North Wales until around 10300 BP. Consequently the anomalous results may therefore be attributable to the fact that the organic clay may represent older reworked organic material, deposited within a terrestrial environment, incorporating pollen specific to the time of deposition. It must, however, be noted that the radiocarbon dates derived from the deposit represent a combination of both the older reworked material and the younger pollen incorporated *in situ*.

The foraminiferal assemblages located beneath peat deposit 2/2 are dominated by hyaline and agglutinating foraminifera indicating the presence of relatively low energy inter-tidal conditions prevailed at this location subsequent to the formation of deposit 2/2. The micropalaeontological data indicate that a transition from sandy mudflat to conditions associated with the development of a saltmarsh occurred prior to the onset of terrestrial sedimentation that led to the development of deposit 2/2. The inaccurate calibrated age of the organic-rich material constituting the contact subsequently invalidates any further attempt relating to a more detailed interpretation of the sediments underlying the dated contact.

Disparity between the palynological and radiocarbon data provides strong evidence that there has been a degree of modification with respect to the carbon content contained within deposit 2/2. The pollen data and stratigraphical context of the deposit suggest that the calibrated radiocarbon age can therefore be regarded as inaccurate, thereby causing the dated contact to be considered an invalid and inaccurate sea-level index point.

As a result of the interpretation it is apparent that although the deposit represents a transition between marine and terrestrial sedimentation, there is sufficient evidence to suggest that the calibrated date inaccurately reflects the time of deposition. The contact has therefore been deemed an invalid and inaccurate sea-level index point.

5.1.1.3.10 Deposit 2/2 top

The altitude of the contact has been recorded within CJSC 2 as being -15.72m OD, with the dated horizon's constituent organic formation overlying approximately 1m of fine grained silt and clay, which in turn overlies deposit 2/3. It has been noted that given the scope of this research project, it may be difficult to quantify the effects relating to consolidation and compaction within the underlying sediments, subsequent to the formation of deposit 2/2. For the purposes of this study, the compressibility of deposit 2/2 has been considered to be similar to that of the other organic-rich deposits recovered from within the Menai Strait and as such forms the upper surface of what was probably a highly compressible organic-rich deposit.

The calibrated age of the contact suggests that the deposit probably formed between 12110 and 11260 calendar years BP. As in the case of the underlying contact, these dates are out of context with respect to dates obtained from both underlying and overlying deposits. As in the case of 2/2 bottom, palynological data additionally indicate the contact to be significantly younger than the radiocarbon date suggests; biostratigraphical correlation with the Llyn Cororion data indicate the age of the deposit to be approximately 9400 calendar years BP.

Examination of foraminiferal assemblages within the sediments located above the contact demonstrate that relatively low energy inter-tidal conditions probably prevailed shortly after the deposition of the organic-rich clay and that the contact probably represents a transition between terrestrial and marine sedimentation.

The micropalaeontological data indicate that the sediments located immediately adjacent to the dated contact almost certainly represent conditions associated with an environment proximal to MHWST. The data additionally indicate that the sediments may demonstrate the occurrence of a relatively rapid but smooth transition from conditions similar to those found within the central region of a saltmarsh to conditions associated with an inter-tidal mudflat; however, the analysis is limited with respect to accurately assessing the relationship of the contact to MHWST.

As in the case of 2/2 bottom, inaccuracies associated with the age of the dated material result in the dated contact being rejected as an accurate sea-level index point. Given the radiocarbon data and stratigraphical context of deposit 2/2, the palynological data and subsequent interpretation relating to this particular deposit highlights the advantages of adopting a multidisciplinary approach with respect to assessing the validity of individual sea-level index points.

5.1.1.3.11 Deposit 2/1 bottom

The altitude of the contact is recorded within CJSC 2 as -13.07m OD, with the organic-rich material overlying approximately 2.6m of fine grained silty sand and silty clay of marine origin, which in turn, overlies deposit 2/2. The age and stratigraphical context of deposit 2/1 with respect to the assessments conducted on the underlying deposits termed 2/3 and 2/2 implies that the underlying marine sediment may have been deposited over a relatively brief period of time after 10500 but prior to approximately 9700 calendar years BP. Although difficult to quantify, some effects relating to primary compaction and consolidation may therefore not have occurred prior to the accumulation of the organic material constituting deposit 2/1. As a consequence, a degree of post depositional compaction and consolidation may have occurred subsequent to the formation of deposit 2/1, however, any such altitudinal correction would be extremely difficult to quantify.

The calibrated age of deposit 2/1 bottom, indicates that the deposit probably formed between 9680 and 9490 calendar years BP. Biostratigraphical correlation of palynological data obtained from the material sub-sampled from within the dated horizon with the Llyn Cororion data indicates that the organic-rich material may have been deposited approximately 9410 calendar years BP. The possibility of *in-situ* or post-depositional contamination of the sample with respect to the modification of its carbon content has been assessed based on lithological and plant macrofossil evidence. These data suggest that the effects of contamination can be considered negligible, as no evidence relating to the presence of aquatic flora or allochthonous, older carbon-rich material was observed. The stratigraphical context and age of the deposit with respect to the underlying sediment additionally implies that the calibrated age may be deemed as acceptable.

The foraminiferal assemblages located immediately beneath peat deposit 2/1 are characterized by the increasing dominance of the agglutinating foraminifera, including *Trochammina inflata* and *Jadammina macrescens*, together with relatively high proportions of *Haynesina germanica* and *Elphidium williamsoni*. The data indicate that the sediments underlying the dated contact probably represent a transition from low energy inter-tidal conditions, possibly similar to those found within a mudflat, to conditions associated with those found within the central region of a contemporary saltmarsh.

The data therefore indicate that the contact fulfils the criteria required in order to be considered a validated sea-level index point; although accurately relating the dated contact to the altitude of MHWST appears to be limited by the quality of the available data.

5.1.1.3.12 Deposit 2/1 top

The altitude of the contact is recorded within the sediment core as -12.97m OD, with the dated horizon's constituent organic formation overlying approximately 2.6m of silty sand and silty clay. As in the case of the underlying contact, uncertainties exist relating to the degree of primary consolidation and compaction that may have occurred subsequent to the development of deposit 2/1. The dated material however, forms the upper surface of what was probably at one time a highly compressible organic-rich deposit.

The calibrated age of the contact suggests that the deposit probably formed between 9880 and 9546 calendar years BP. Biostratigraphical correlation utilizing palynological data obtained from the dated contact with data obtained from Llyn Cororion indicates the organic-rich material to have been deposited at approximately 9110 calendar years BP. The calibrated age of the sample in relation to the dates obtained from the underlying contact indicates that the material comprising deposit 2/1 was probably deposited over a relatively short period of time.

Lithological and macrofossil data do not provide evidence to suggest that any *in-situ* and post-depositional contamination may have occurred with respect to the modification of the carbon content within the sub-samples recovered from the contact.

Examination of sub-samples located immediately above the contact demonstrates that the foraminiferal assemblages within the sediments are dominated by hyaline, porcellaneous and agglutinating foraminifera with *Haynesina germanica, Elphidium williamsoni* and *Ammonia batavus* dominant. The sediments additionally contain proportions of *Quinqueloculina seminulum* and *Quinqueloculina pygmaea*, together with a smaller proportion of agglutinating foraminifera. The assemblages infer that the sediments may be derived from conditions similar to those associated with a low energy inter-tidal environment, with some freshwater influence, possibly the lower region of a saltmarsh or inter-tidal mudflat.

The micropalaeontological data indicate that the sediments located immediately adjacent to the dated contact almost certainly represent conditions associated with environments located within the upper regions of the inter-tidal zone.

The lithological and stratigraphical data may indicate the possibility that some erosion may have occurred at, or immediately above the dated contact, however, this is difficult to quantify. The relationship of the index point to MHWST is additionally difficult to quantify, however, the age of the material appears to be valid. The dated contact has therefore been accepted as a valid sea-level index point, although the limited degree of accuracy associated with the horizon's indicative meaning has to be acknowledged.

5.1.1.3.13 Deposit 3/2 bottom

The altitude of the contact has been recorded within CJSC 3 as -7.89m OD; with the organic-rich material overlying approximately 1.1m of fine grained sandy silt silty clay of marine origin, which in turn, overlies at least 0.4m of fine grained silty sand. The age and stratigraphical context of deposit 3/2 with respect to the assessments conducted on the deposits located within CJSC 1 and 2, together with available seismic data implies that the underlying marine sediment may have accumulated over a relatively brief period of time. Although difficult to quantify, some effects relating to primary compaction and consolidation may not have occurred prior to the accumulation of the organic material constituting deposit 3/2.

The calibrated age of deposit 3/2 bottom, indicates that the deposit probably formed between 9400 and 9030 calendar years BP. Biostratigraphical correlation of the palynological data obtained from the material sub-sampled from within the dated horizon with respect to the Llyn Cororion data predicts that the organic-rich material may have been deposited approximately 9410 calendar years BP. The predicted age based on the palynological data correlates extremely well with the calibrated age of the material. The possibility of *in-situ* or post-depositional contamination of the sample with respect to the modification of the contact's carbon content has been assessed based on lithological and plant macrofossil evidence. These data suggest that the effects of contamination can be considered negligible, as no evidence relating to the presence of aquatic flora or allochthonous, older carbon-rich material was noted. The stratigraphical context and age of the deposit with respect to dated contacts within the other sediment cores additionally implies that the calibrated age may be deemed to be acceptable.

The foraminiferal assemblages within the sediments underlying peat deposit 3/2 are primarily dominated by hyaline foraminifera, comprising *Haynesina germanica, Ammonia batavus* and *Elphidium williamsoni.* Relative proportions of *Ammonia batavus* decrease, whilst small quantities of agglutinating foraminifera occur within the sub-samples of sediment examined proximal to the base of the peat deposit. Comparisons to the modern assemblages obtained from the Taf Estuary infer that the sediments located beneath the contact could possibly represent a transition from inter-tidal mudflat to salt marsh.

The data indicate that the contact fulfils the criteria required in order to be considered a validated sea-level index point; although accurately relating the dated contact to the altitude of MHWST appears limited, due primarily to the quality of the available data.

5.1.1.3.14 Deposit 3/2 top

The altitude of the contact is recorded within the sediment core as -7.77m OD, with the dated horizon's constituent organic formation overlying approximately 1.1m of sandy silt and clay. As in the case of the underlying contact, uncertainties exist relating to the degree of primary consolidation and compaction that may have occurred subsequent to the development of the dated contact. The dated material however, forms the upper surface of what was probably at one time a highly compressible organic-rich deposit.

The calibrated age of the contact suggests that the deposit probably formed between 8580 and 8390 calendar years BP. Biostratigraphical correlation utilizing palynological data obtained from the dated contact with data obtained from Llyn Cororion indicates the organic-rich material to have been deposited at approximately 8810 calendar years BP. This evidence together with comparisons made with respect to the dates obtained from the underlying and overlying contacts, indicates that the material comprising 3/2 top may have produced an anomalously young date. The data indicate that the degree of accuracy associated with the calibrated date must be considered limited, although lithological and macrofossil data do not provide any evidence to suggest that any form of contamination may have occurred.

When considering deposit 3/2 alone, the dates derived from the lower and upper contacts initially appear to agree reasonably well in terms of their respective ages and their stratigraphic context. However sub-samples contained within the overlying deposit have produced conventional radiocarbon dates significantly older than the radiocarbon date derived from the apex of the underlying organic-rich deposit. The degree of disparity with respect to the age of sub-sample 3/2 top and the overlying sub-samples approximates to 200 years on calibration at the 2 sigma level and cannot be accounted for with respect to uncertainties associated with the radiocarbon dating process.

The radiocarbon date derived from sub-sample 3/2 top, which initially appears to be anomalously young, was obtained from analysis performed on wood fragments recovered from within the sub-sample of organic material taken from the apex of the deposit. Given the stratigraphical context and age of the overlying deposit located approximately 1.00m above this deposit, contamination through bioturbation or migration of humic material appears highly unlikely; however the possibility of contamination through root penetration may need to be considered further. Palynological and lithological analyses further indicate that the deposit was, in all probability, formed within a terrestrial environment.

As in the case of deposit 2/2 comparisons between the pollen assemblages observed within each deposit and the data obtained from Llyn Cororion provide additional evidence in relation to identifying if aspects of contamination or modification of the samples carbon content need to be considered. Pollen data recorded from within the upper contact of deposit 3/2 indicate that the arboreal assemblage is largely dominated by Pinus with smaller proportions of *Betula*, *Alnus*, *Ulmus*, *Corylus* and *Salix*. Pollen data from deposit 3/1 demonstrate that the same species also dominate the assemblage within the sample, although in slightly different proportions. A comparison between each of these samples with the assemblages found at Llyn Cororion suggest deposit 3/2 top to be approximately 750 years older than deposit 3/1 bottom. The estimated age of deposit 3/2 top is based on an apparent 5% decrease in the relative proportion of *Quercus* present coincident with the presence of a relatively high proportion of *Pinus* (40%). This estimation may be considered to be ambiguous, given that the relative proportions of both species fluctuate markedly throughout the early Holocene and very few sub-samples were examined from each section of the organic-rich deposits. The differences could also be attributable to a localized fluctuation in both the number and type of tree present within the study area, rather than representing more regional fluctuations. The same could also be said with respect to abrupt although short scale fluctuations within the Llyn Cororion data set.

With respect to the replicate dating of the sub-samples constituting deposit 1/2, there appears to be a degree of disparity between the dates derived from the smaller quantities of material and those derived from the dating of the entire homogenized sub-sample. The degree of difference however, does not account for the degree of discrepancy encountered within sediment core 3. The disparity may possibly therefore be attributable to the accuracy of the radiocarbon date, in terms of the dated material and its relationship to the *in situ* deposit, as opposed to issues relating to precision; as the anomalously young date associated with sub-sample 3/2 top may be a consequence of having dated younger root material contained within the deposit. Alternatively, the possibility that the degree of accuracy related to the dates obtained from deposit 3/2 is greater than those associated with deposit 3/1 may also need to be considered.

Micropalaeontological analyses conducted on sub-samples located above the dated contact have proved inconclusive due to the presence of relatively few fossilized benthic foraminifera; it is therefore difficult to establish the relationship of the contact to MHWST without additional data. The presence of small quantities of fossilized benthic hyaline foraminifera such as *Haynesina germanica* and *Elphidium williamsoni* may indicate that the inorganic sediments located immediately above to the dated contact represent conditions associated with environments located within the upper regions of the inter-tidal zone.

The relationship of the contact to MHWST is difficult to quantify, however, the age of the material appears to be valid. The dated contact has therefore been accepted as a valid sea-level index point, however, as in the case of many of the other index points identified within the sediment cores, the limited degree of accuracy associated with the dated horizon's indicative meaning has to be acknowledged.

5.1.1.3.15 Deposit 3/1 bottom

The altitude of the dated contact has been recorded within CJSC 3 as -6.68m OD, with the organic-rich material overlying over 1.1m of silty clay, which in turn, overlies deposit

3/2. The derived age and stratigraphical context of deposit 3/1 with respect to the assessments conducted on the underlying organic-rich deposit implies that the age of the deposit is questionable; consequently, uncertainties exist relating to how rapidly the underlying marine sediment may have accumulated. Although difficult to quantify, it is possible that some effects relating to primary compaction and consolidation may not have occurred prior or subsequent to the accumulation of the organic material constituting deposit 3/1.

The calibrated age of deposit 3/1 bottom, indicates that the deposit probably formed between 9250 and 8780 calendar years BP. Biostratigraphical correlation of the palynological data obtained from the material sub-sampled from within the dated horizon with respect to the Llyn Cororion data predicts that the organic-rich material may have been deposited approximately 8190 calendar years BP. The predicted age based on the palynological data underestimates the mean calibrated age by over 800 years, which may indicate that the calibrated age of the deposit may inaccurately reflect the age of the deposit. Watkins (1991) indicates that local vegetational assemblages were characterized by a rapid expansion of Alnus at 8514±120 calendar years BP; the palynological data indicate the presence of Alnus within sediment obtained from both this and the underlying contact. If the calibrated age of this deposit is accepted as correct, then it would imply that Alnus had become established prior to 9010 calendar years BP. The evidence therefore suggests the possibility that the calibrated age of this contact may be questionable.

The possibility of *in-situ* or post-depositional contamination of the sample with respect to the modification of the contact's carbon content has been assessed based on lithological and plant macrofossil evidence. These data suggest that the effects of contamination through the presence of aquatic flora can be considered negligible, however small fragments of charcoal were observed within the deposit and these may possibly have contributed to an anomalously old radiocarbon date being derived from the submitted material. The stratigraphical context and age of the deposit with respect to the underlying dated contacts within the sediment core additionally imply that the calibrated age may be deemed as inaccurate.

Micropalaeontological data relating to the examination of foraminiferal assemblages within the inorganic silty clay located immediately beneath the dated contact proved inconclusive. The presence of small quantities of fossilized benthic hyaline foraminifera such as *Haynesina germanica* and *Elphidium williamsoni* may, as in the case of the underlying material, indicate that the inorganic sediments represent conditions associated with environments located within the upper regions of the inter-tidal zone.

The data indicate that the contact is questionable in terms of fulfilling the criteria required to be considered a valid sea-level index point. The possibility that the calibrated age of the contact may be inaccurate, together with difficulties in accurately relating the dated contact to the altitude of MHWST, indicates that the contact is limited in terms of its use as an accurate sea-level index point.

5.1.1.3.16 Deposit 3/1 top

The altitude of the contact is recorded within CJSC 3 as -6.63m OD, with the dated horizon's constituent organic formation overlying approximately 1.1m of silty clay. As in the case of the underlying contact, uncertainties exist relating to the degree of primary consolidation and compaction that may have occurred subsequent to the development of the dated contact; however, the dated material forms the upper surface of what was probably at one time a highly compressible organic-rich deposit.

The calibrated age of the contact suggests that the deposit probably formed between 9258 and 9010 calendar years BP. Biostratigraphical correlation utilizing palynological data obtained from the dated contact with data obtained from Llyn Cororion indicates the organic-rich material to have been deposited at approximately 7950 calendar years BP. This evidence together with comparisons made with respect to the dates obtained from the underlying contacts, once again indicate that the organic material analyzed from the contact may have produced an anomalously old date. The data indicate that the degree of accuracy associated with the calibrated date may be questioned, although lithological and macrofossil data do not provide any evidence to suggest that any form of contamination may have occurred.

Micropalaeontological data indicate that the sediments above the dated contact contain the remains of unidentifiable agglutinating foraminifera, together with relatively low proportions of *Jadammina macrescens* and *Haplophragmoides wilberti*. The assemblages within the analyzed sediments are, however, primarily dominated by hyaline foraminifera *Haynesina germanica, Ammonia batavus* and *Elphidium williamsoni*; whilst relatively small proportions of *Quinqueloculina seminulum* and *Quinqueloculina pygmaea* are also present. The assemblages infer that the material adjacent to the contact may represent an environment associated with the upper region of an inter-tidal zone, with the assemblages contained within sediments above this point indicating that the location became increasingly influenced by marine conditions as water depth gradually increased.

As in the case of most of the dated contacts, the relationship of the contact to MHWST is difficult to quantify, the age of the material additionally appears to be questionable. Consequently the limited degree of confidence associated with the dated contact effectively limits its use as an accurate sea-level index point; any utilization of the contact must therefore acknowledge the limited degree of accuracy associated with the dated horizon's indicative meaning and calibrated age.

5.1.2 Pre-existing regional sea-level data

Sea-level index points identified through research conducted by Heyworth & Kidson (1982), Prince (1988) and Bedlington (1994) have been assessed and integrated into this research project in order to supplement the data obtained from the sediment cores recovered from the Menai Strait (Table 5.2). A brief review relating to the pre-existing sea-level data obtained from North Wales has been conducted within chapter 2. This was undertaken in order to justify the inclusion of any such point within a sea-level index dataset, subsequently utilized within this study in order to produce a relative sea-level curve for North Wales.

Source	Location	Altitude (m) OD	14C date	Description
Heyworth & Kidson	Rhyl Beach	2.43	4725	Regressive overlap, thickness of peat unclear
Heyworth & Kidson	Llandudno Station	-4.69	7635	Unclear, possibly regressive contact
Prince 1990	Woodlands (1)	-9.00	8170	Regressive contact
Prince 1990	Woodlands (2)	-9.12	8540	Regressive contact
Bedlington 1994	Hendre Fawr (1)	1.87	4345	Regressive contact
Bedlington 1994	Hendre Fawr (2)	1.70	4685	End of organic sedimentation
Bedlington 1994	Hendre Fawr (3)	1.27	5935	Regressive contact
Bedlington 1994	Hendre Fawr (4)	-2.48	7080	Transgressive contact
Bedlington 1994	Tregarnedd Bach (1)	1.00	4035	Regressive contact
Bedlington 1994	Tregarnedd Bach (2)	-4.11	7255	Regressive contact
Bedlington 1994	Morfa Penrhyn	0.28	6335	Regressive contact
Bedlington 1994	Tregarnedd Bach (3)	-3.96	7435	Transgressive contact

Tale 5.2 Pre-existing sea-level index point data

All raw radiocarbon dates associated with the sea-level index points have been calibrated to calendar years BP using the calibration package (Stuiver *et al.*, 1998b) applied to the Menai Strait radiocarbon data.

The original altitude of the index points relative to OD have also been corrected in order to relate them to MSL and additionally incorporate error terms calculated from contemporary tidal data and the available lithological and micropalaeontological evidence.

An organic-rich sub-sample obtained from a sequence at Llandudno Station produced a ^{14}C date of 7635 +/- 52 years BP (Harkness and Wilson, 1974). The research however, does not adequately define the altitude of the dated sub-sample to OD and merely states that it was obtained from between -5.21m and -4.16m OD. This consequently introduces a significant altitudinal error term with respect to the index point; as a consequence the index point has been rejected from the data incorporated within the final sea-level curve. The data is discussed and included within the study itself as it demonstrates the existence of a deposit that could be re-sampled and dated at some point in the future.

Another deposit initially rejected by Bedlington (1994) and termed Hendre Fawr 5 has been included in this data set. The index point was initially rejected as it was considered to be anomalously young in relation to its stratigraphic context. Calibration at the sigma 2 level indicates that this may not be the case and as a consequence the data point has been utilized within this study.

5.1.3 Relative sea-level change in North Wales

The integration of pre-existing sea-level data (Heyworth and Kidson, 1982; Prince, 1988; Bedlington, 1994) with the data obtained during the course of this research project facilitates the generation of a relative mean sea-level curve for North Wales (fig.5.3) based on a total of twenty seven validated sea-level index points (Table 5.3). The data suggest that mean sea levels were rising at a relatively reduced rate immediately prior to the onset of the Holocene, rising from approximately –29m to –28m OD between 13000 and 12000 calendar years BP. The data subsequently indicate that at the onset of the Holocene, approximately 11500 calendar years BP, relative sea level within the region was at -27m OD and beginning to rise rapidly. This rapid rise, equivalent to approximately 0.6cm/yr, continued over a period of approximately 3000 years. After 8500 calendar years BP, the rate of rise decreased markedly, as the altitude of relative sea level rose to approximately -2m OD by around 5000 calendar years BP. Following this period, although the overall trend indicates that the rate of sea-level rise was probably minimal a lack of data results in a failure to adequately quantify the actual rate of sea-level change and furthermore provides no evidence that sea levels may have exceeded those of the present day.

Tendency analysis applied to the data from North Wales infers that whilst relative sea levels in the region have risen throughout much of the Holocene, the rise may have been punctuated by a series of brief periods where relative sea levels may have fallen. The question as to whether the tendency data represent actual falls in relative sea level or simply represent localized changes in sedimentological regimes due to the influence of locally occurring geomorphological features, such as coastal barriers, is discussed in more detail within section 5.5.

5.1.4 Comparison with far-field sea-level data

A comparison between the data derived from North Wales and sea-level data obtained from studies conducted in other regions of the world has also been made. The data from North Wales indicate that relative sea levels may have been rising at a reduced rate prior to around 12000 calendar years, whilst data from Barbados (Fairbanks, 1989) indicate that eustatic sea levels rose at reduced rates between 13500 and 11500 calendar years BP. Studies conducted in Barbados (Fairbanks, 1989), New Guinea (Chappell & Polach

	Source	Location	ID	Material	SUERC code	C14 age 1950 BP	+/-	Age Cal yr BP	+/-	Original altitude (MHWST) (m) OD	Altitude (MSL) (m) OD	Nature of contact	Total altitudinal error +ve (m)	Total altitudinal error -ve (m)	Minimum altitude (m) OD	Maximum altitude (m) OD
1	Cemlyn Jones Core 1	Menai Strait	1/1 top	Peat	SUERC-2491	9296	53	10470	201	-20.68	-24.03	Transgressive	3.23	0.63	-24.66	-20.8
2	Cemlyn Jones Core 1	Menai Strait	1/1 bottom	Peat	SUERC-2492	9714	49	11010	217	-20.84	-24.19	Regressive	1.78	0.63	-24.82	-22.41
3	Cemlyn Jones Core 1	Menai Strait	1/2 top	Peat	SUERC-2493	9945	48	11410	212	-23.08	-26.43	Transgressive	2.38	0.63	-27.06	-24.05
4	Cemlyn Jones Core 1	Menai Strait	1/2 top repeat	Peat	SUERC-2578	9834	67	11330	216	-23.08	-26.43	Transgressive	2.38	0.63	-27.06	-24.05
5	Cemlyn Jones Core 1	Menai Strait	1/2 bottom	Peat	SUERC-2496	9965	49	11560	337	-23.37	-26.72	Regressive	1.98	0.63	-27.35	-24.74
6	Cemlyn Jones Core 1	Menai Strait	1/2 bottom repeat	Peat	SUERC-2579	9817	67	11220	328	-23.37	-26.72	Regressive	1.98	0.63	-27.35	-24.74
7	Cemlyn Jones Core 2	Menai Strait	2/1 top	Peat	SUERC-2497	8698	43	9720	171	-12.97	-16.37	Transgressive	1.53	0.63	-17	-14.84
8	Cemlyn Jones Core 2	Menai Strait	2/1 bottom	Peat	SUERC-2498	8581	40	9580	96	-13.07	-16.47	Regressive	1.33	0.63	-17.1	-15.14
9	Cemlyn Jones Core 2	Menai Strait	2/2 top	Organic Clay	SUERC-2500	10093	58	11680	422	-15.72	-19.12	Transgressive	3.33	0.63	-19.75	-15.79
10	Cemlyn Jones Core 2	Menai Strait	2/2 bottom	Organic Clay	SUERC-2501	10234	50	12000	345	-15.86	-19.26	Regressive	2.23	0.63	-19.89	-17.03
11	Cemlyn Jones Core 2	Menai Strait	2/3 top	Peat	SUERC-2502	9308	45	10480	192	-16.86	-20.26	Transgressive	2.23	0.63	-20.89	-18.03
12	Cemlyn Jones Core 2	Menai Strait	2/3 bottom	Peat	SUERC-2503	9301	54	10470	200	-16.94	-20.34	Regressive	1.63	0.63	-20.97	-18.71
13	Cemlyn Jones Core 2	Menai Strait	2/4 top	Peat	SUERC-2506	10654	53	12650	295	-25.83	-29.23	Transgressive	3.03	0.63	-29.86	-26.2
14	Cemlyn Jones Core 2	Menai Strait	2/5 top	Organic clay	SUERC-2508	11488	59	13490	329	-28.24	-28.24	Transgressive	Unclear	Unclear	Void	Void
15	Cemlyn Jones Core 2	Menai Strait	2/5 bottom	Organic clay	SUERC-2507	12715	71	15020	680	-28.31	-28.31	Regressive	Unclear	Unclear	Void	Void
16	Cemlyn Jones Core 3	Menai Strait	3/1 top	Peat	SUERC-2509	8152	38	9130	124	-5.58	-8.93	Transgressive	1.65	0.7	-9.63	-7.28
17	Cemlyn Jones Core 3	Menai Strait	3/1 bottom	Peat	SUERC-2510	8084	41	9010	234	-5.63	-8.98	Regressive	1.25	0.7	-9.68	-7.73
18	Cemlyn Jones Core 3	Menai Strait	3/2 top	Wood fragments	SUERC-2511	7689	38	8490	96	-6.72	-10.07	Transgressive	2.2	0.7	-10.77	-7.87
19	Cemlyn Jones Core 3	Menai Strait	3/2 bottom	Peat	SUERC-2512	8227	40	9210	184	-6.84	-10.19	Regressive	1.25	0.7	-10.89	-8.94
20	Heyworth & Kidson (1982)	Rhyl	Rhyl Beach	Peat	Hv 4348	4725	65	5450	136	2.43	-1.22	Regressive	0.88	0.63	-1.85	-0.34
21	Heyworth & Kidson (1982)	Llandudno	Llandudno Station	Peat	SRR 61	7635	52	8440	95	-4.15 to -5.20	-8.04	Unclear	11.96	1.16	-9.2	3.92
22	Prince (1990)	Clwyd Plain	Woodlands (1)	Peat	SRR 2510	8170	70	9200	201	-9.00	-12.65	Transgressive	2.58	0.63	-13.28	-10.07
23	Prince (1990)	Clwyd Plain	Woodlands (2)	Peat	SRR 2511	8540	70	9510	182	-9.12	-12.77	Regressive	1.48	0.63	-13.4	-11.29
24	Bedlington HF 21 (1994)	Clwyd Plain	Hendre Fawr (1)	Peat	Hv 17810	4345	145	4980	455	1.87	-1.78	Regressive	1.18	0.63	-2.41	-0.6
25	Bedlington HF 21 (1994)	Clwyd Plain	Hendre Fawr (2)	Peat	Hv 17811	4685	175	5300	433	1.70	-1.95	Transgressive	3.98	0.63	-2.58	2.03
26	Bedlington HF 21 (1994)	Clwyd Plain	Hendre Fawr (3)	Peat	Hv 17812	5935	190	6780	463	1.27	-2.38	Regressive	0.93	0.63	-3.01	-1.45
27	Bedlington HF 29 (1994)	Clwyd Plain	Hendre Fawr (4)	Peat	Hv 17814	7080	155	7900	283	-2.48	-6.13	Unclear	1.03	0.63	-6.76	-5.1
28	Bedlington TB 20 (1994)	Malltraeth	Tregarnedd Bach (1)	Peat	Hv 17820	4035	100	4540	285	1.00	-1.1	Regressive	0.98	0.63	-1.73	-0.12
29	Bedlington TB 18 (1994)	Malltraeth	Tregarnedd Bach (2)	Peat	Hv 17819	7255	130	8070	276	-4.11	-6.21	Regressive	1.23	0.63	-6.84	-4.98
30	Bedlington MP 20 (1994)	Conwy valley	Morfa Penrhyn	Organic material	Hv 17815	6335	115	7190	275	0.28	-3.37	Regressive	1.08	0.63	-4	-2.29
31	Bedlington TB 18 (1994)	Malltraeth	Tregarnedd Bach (3)	Peat	Hv 17818	7435	185	8220	376	-3.96	-6.06	Transgressive	2.83	0.63	-6.69	-3.23
32	Bedlington HF 21 (1995)	Clwyd Plain	Hendre Fawr (5)	Peat	Hv 17813	5530	385	6370	883	-0.93	-4.58	Regressive	0.93	0.63	-5.21	-3.65

Table 5.3 Tabulated sea-level index point dataset utilized in the generation of the North Wales sea-level curve

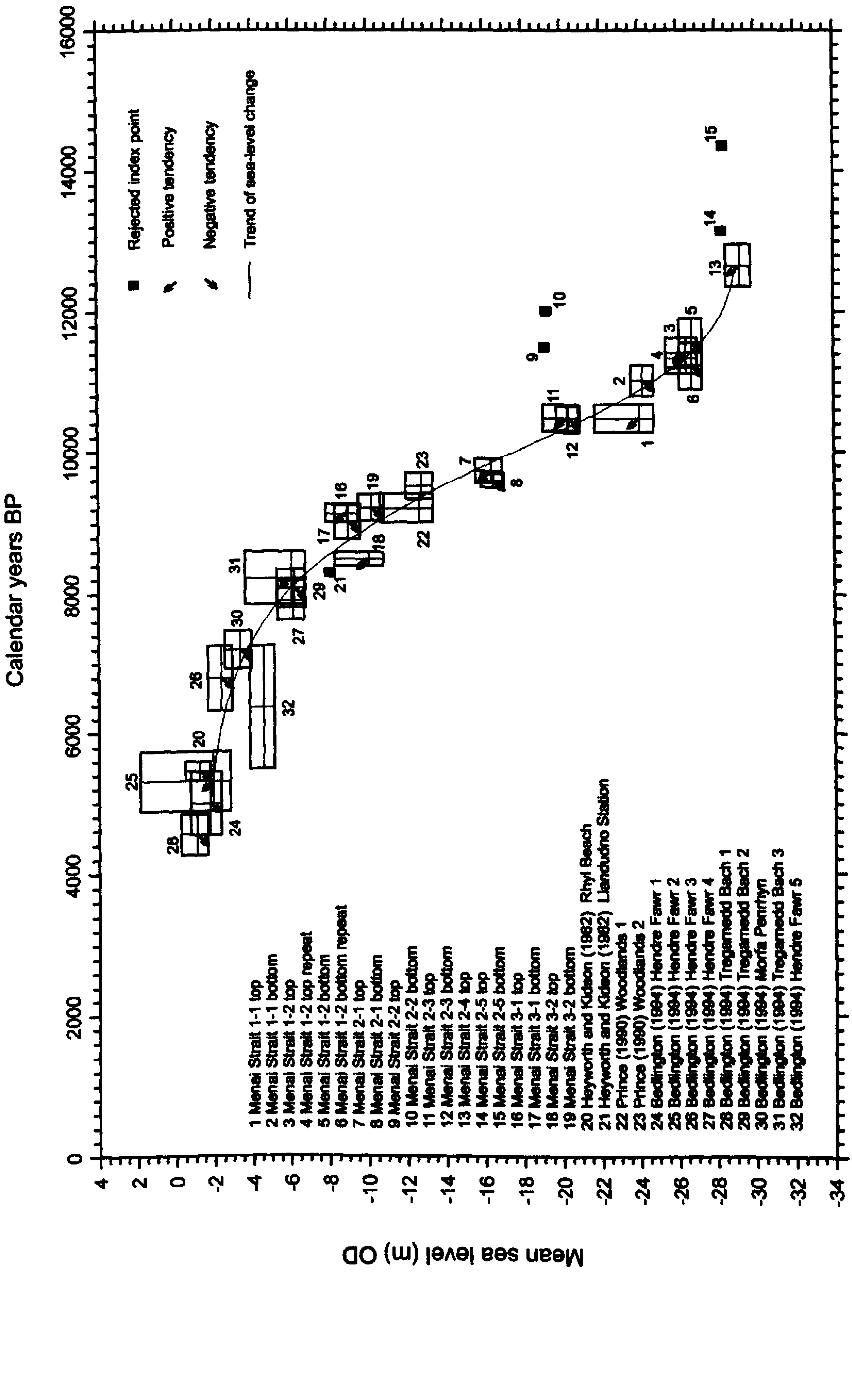


Figure 5.3 Relative mean sea-level curve for North Wales

1991), Tahiti (Bard *et al.* 1996), on the Sunda Shelf (Hanebuth *et al.* 2000) together with the data from North Wales indicate that sea levels subsequently rose rapidly over the next 5000 years before this rapid rate of rise reduced significantly after around 6000 calendar years BP.

Data obtained from Tahiti (Bard *et al.* 1996), additionally indicate that sea levels were rising at reduced rates prior to around 14200 calendar years BP. The data from Tahiti indicate that sea levels subsequently rose rapidly between 14200 and 13900 calendar years BP (MWP-1A) before rising at a more reduced rate throughout most of the early and middle Holocene.

Work conducted by Hanebuth *et al.* (2000) on the Sunda Shelf demonstrates that sea levels rose at relatively rapid rates subsequent to the accelerated rise that characterizes MWP-1A; this period of accelerated sea-level rise being identified as occurring some 400 years earlier than that indicated by the data from Tahiti.

The period covered by the data obtained from North Wales extends approximately between 12000 and 4000 calendar years BP, therefore no comparison can be made with regard to the timing and extent of MWP-1A between data obtained during the course of this study and previously acquired data. Data collected from the region of the Bonaparte Gulf (Yokoyama *et al.* 2000) primarily relates to the Late Pleistocene, relating to sea-level change immediately subsequent to the LGM and up to approximately 17000 calendar years BP.

Integrating data from previous sea-level studies with data obtained from the Yellow Sea, Liu *et al.* (2004), suggests that postglacial sea-level change in the Western Pacific may have been episodic, with periods of rapid sea-level rise punctuated by intermittent periods of little or no change. The research utilizes data from an extensive collection of sea-level indicators obtained from both near-shore environments and the submerged continental shelf (fig. 5.4).

Material dated to the early Holocene was obtained from a sequence of sediments underlying a more recently formed deltaic feature. Liu *et al.* (2004) attribute the formation of the earlier sequence to a temporary pause during a period of rapid postglacial sea-level rise subsequent to MWP-1B.

The study identifies four relatively brief periods of time between 14500 and 7000 calendar years BP that were characterized by rapid sea-level rise, these being between approximately 14400-14000, 11900-11300, 9400-9100 and 7500-7100 calendar years BP. The work correlates the earlier of these two phases with MWP-1A and MWP-1B and identifies the two subsequent phases of increased sea-level rise as mwp-1c and mwp-1d respectively.

Intervening periods between these 'pulses' are characterized by relatively slow or negligible rises in the altitude of relative sea level, these being 14000-11900, 11300-9400, 9100-7500 and for a prolonged period after approximately 7100 calendar years BP.

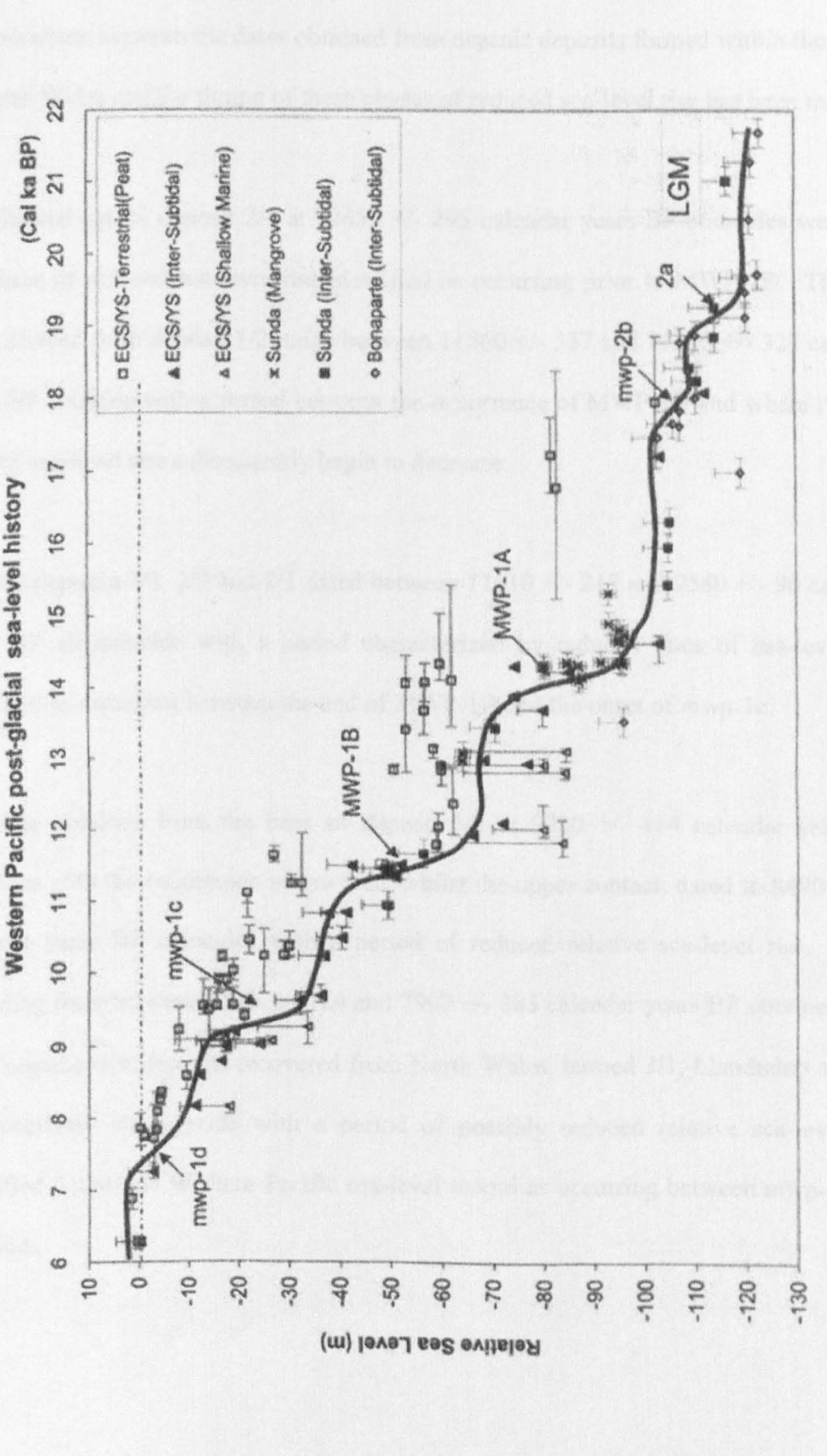


Figure 5.4 Postglacial relative sea-level curve for the Western Pacific. Taken from Liu *et al.*, (2004)

A comparison between the dates obtained from organic deposits formed within the region of North Wales and the timing of these phases of reduced sea-level rise has been made.

The derived age of deposit 2/4 at 12650 +/- 295 calendar years BP coincides well with the phase of reduced sea-level rise identified as occurring prior to MWP-1B. The four dates derived from deposit 1/2 range between 11560 +/- 337 and 11220 +/- 328 calendar years BP coincide with a period between the occurrence of MWP-1B and where rates of relative sea-level rise subsequently begin to decrease.

Organic deposits 1/1, 2/3 and 2/1 dated between 11010 +/- 217 and 9580 +/- 96 calendar years BP all coincide with a period characterized by reduced rates of sea-level rise identified as occurring between the end of MWP-1B and the onset of mwp-1c.

The date obtained from the base of deposit 3/2 at 9210 +/- 184 calendar years BP coincides with the occurrence of mwp-1c, whilst the upper contact, dated to 8490 +/- 96 calendar years BP coincides with a period of reduced relative sea-level rise. Dates extending from between 9130 +/- 124 and 7900 +/- 283 calendar years BP obtained from other organic-rich deposits recovered from North Wales, termed 3/1, Llandudno and HF 4 respectively all coincide with a period of possibly reduced relative sea-level rise identified within the Western Pacific sea-level record as occurring between mwp-1c and mwp-1d.

Dates obtained from Morfa Penrhyn in North Wales however, coincide with the occurrence of mwp-1d. All other organic deposits analyzed during the course of the study conducted in North Wales date to the middle or late Holocene where rates of sea-level rise both regionally and globally became reduced as the volume of meltwater discharge into the ocean basins decreased significantly.

5.1.5 Comparison with regional sea-level data

The relative sea-level curves produced by Shennan and Horton (2002) from regions located to the north and south of North Wales, including Cumbria, Morecambe and Lancashire, together with Mid and South Wales (fig. 5.5) display trends of rapidly rising relative sea levels during the Late Pleistocene and early to middle Holocene, with little change in relative sea level after approximately 5000 calendar years BP.

The sea-level curve derived for North Wales during this study indicates that relative sea levels were at approximately -30m OD at the onset of the Holocene. The limited volume of data utilized in Shennan and Horton (2002) leads them to suggest that relative sea levels in North Wales were less than -25m OD at this time. The work further indicates that relative sea levels were at approximately -22m OD at this time in Lancashire, -25m OD in Mid Wales and at -30m OD in South Wales.

The data from North Wales suggests that relative sea levels rose rapidly between 11500 and 9000 calendar years BP, at a rate of approximately 8mm/yr. This rate is almost identical to the estimated rate of early Holocene relative sea-level rise derived for North Wales in Shennan and Horton (2002).

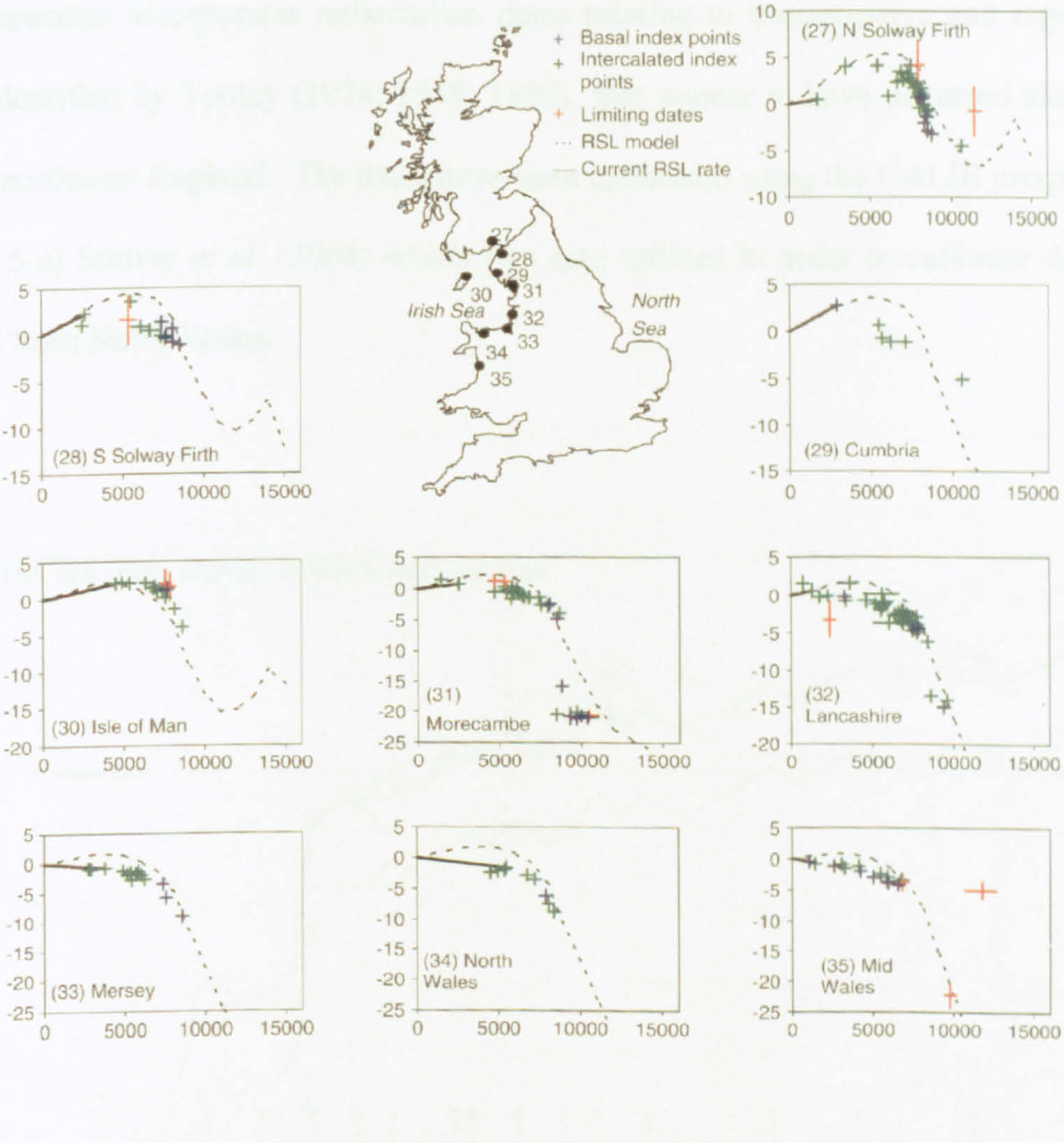


Figure 5.5 Diagrams illustrating relative sea-level change from various locations within western regions of Great Britain. Taken from Shennan and Horton (2002)

A more detailed comparison between the derived relative sea-level history of North Wales and that of northwest England (Tooley, 1974; Tooley 1978; Tooley 1982; Tooley and Zong, 1996) (fig. 5.6) has been made. The studies indicate that the nature of relative sea-level change was similar for both regions throughout much of the Holocene; although both regions experienced different ice-loading histories, in terms of the timing and extent of crustal loading and associated isostatic recovery.

The comparison incorporates radiocarbon dates relating to transgressive and regressive phases identified by Tooley (1974; 1978; 1982), that appear to have occurred along the coast of northwest England. The dates have been calibrated using the CALIB programme (version 5.0) Stuiver *et al.* (2004) which was also utilized in order to calibrate the data obtained from North Wales.

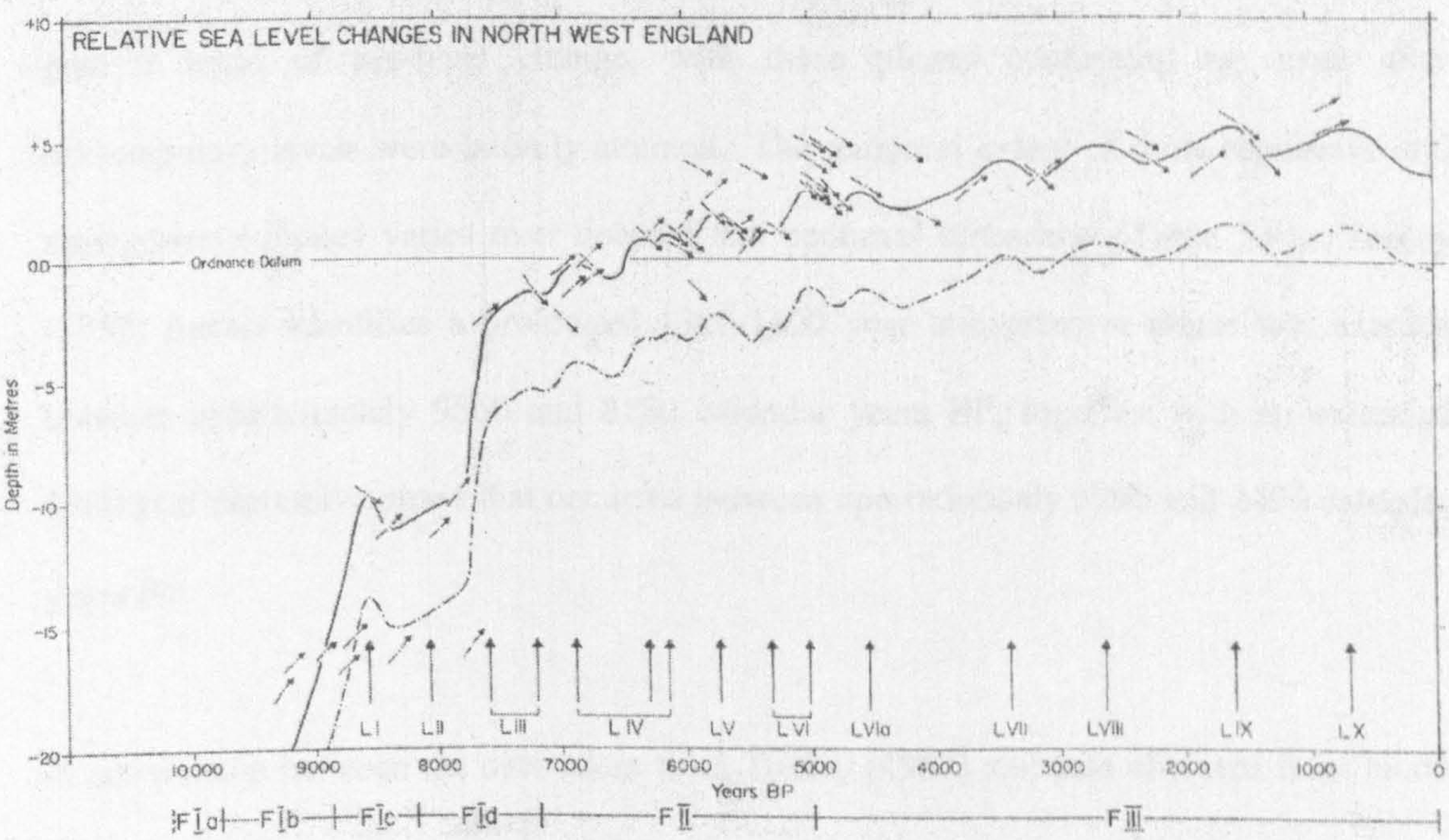


Figure 5.6 Relative sea-level changes in north-west England from 9200 to 0 years BP (Tooley, 1974). Note that the graph uses radiocarbon dates as opposed to calibrated dates and that the continuous line represents MHWST, whilst the dotted line represents the altitude of MSL.

The data presented in Tooley (1978) and Tooley (1982) indicate that in northwest England sea levels rose relatively rapidly during the early to middle Holocene with the rate of rise decreasing after around 7000 calendar years BP; the data additionally indicate that contemporary sea levels were attained by approximately 4500 calendar years BP. Tooley and Zong (1996) state that relative sea levels rose at relatively reduced rates of between 3.5-5.0mm yr^{-1} between 10300 and 8870 calendar years BP. Sea level subsequently rose rapidly at a maximum rate of 36.7mm yr^{-1} between 8870 and 8510 calendar years BP, followed by fluctuating rates between 8510 and 3500 calendar years BP. Tooley (1982) additionally describes a series of twelve transgressive and regressive phases that appear to have occurred throughout the Holocene, superimposed on the more general trend of sea-level change, with these phases continuing to occur after contemporary levels were initially attained. The temporal extent of these regressive and transgressive phases varies over decadal and centurial timescales (Table 5.4). Tooley (1982) further identifies a prolonged 1300-1400 year transgressive phase that extends between approximately 9560 and 8180 calendar years BP, together with an extended 1300 year regressive phase that occurred between approximately 5790 and 4490 calendar years BP.

A comparison between the data taken from Tooley (1982) and data obtained from North Wales is illustrated in Table 5.5. The table illustrates possible regressive and transgressive phases identified in northwest England and North Wales together with the calibrated ages derived from Tooley (1982). Calibrated dates utilized in order to generate

Transgressive overlaps					
No	14C years BP	+/-	Cal age BP	+/-	ID
T1	9270	200	10530	610	Birm. 141
	9195	195			Birm. 139
	8925	200			Birm. 140
	8740	65	9830	290	Hv. 3361
T2	8480	205	9560	580	Hv. 5224
	8390	105			Hv. 4343
	7995	80			Hv. 3362
	7825	120			Hv. 5228
	7820	60			Hv. 4345
	7750	100			Har. 3709
	7605	85	8390	190	Hv. 4125
T3	6980	55	7810	120	Hv. 3936
	6885	80			Hv. 4126
	6870	95			Hv. 5228
	6850	60			Hv. 6208
	6810	130	7690	240	Hv. 6209
T4	6535	110	7430	180	Hv. 3934
	6460	40			SRR. 1496
	6420	60	7310	130	SRR. 1494
T5	5985	195	6840	440	Hv. 5651
	5950	85	6780	220	Hv. 4129
T6	5734	129	6570	360	Q. 256
T7	5470	155	6270	350	Hv. 2686
T8	3695	110	4070	340	Q. 620
	3490	60	3750	160	GU. 1271
T9	3090	135	3260	360	Hv. 2917
	2820	55			Hv. 3842
	2620	40			SRR. 1574
	2335	120			Hv. 4709
	2330	65	2420	270	Hv. 9260
T10	1545	35	1440	80	Hv. 3481
T11	925	50	830	100	GU. 1311
	805	70	780	130	Hv. 4417
T12	540	40	580	70	SRR. 1403
	550	40	580	70	SRR. 1402

Regressive overlaps					
No	14C years BP	+/-	Cal age BP	+/-	ID
R1	8575	105	9610	290	Hv. 4346
R2	7370	75	8180	160	Hv 5225
R3	6780	95	7620	180	Hv. 3935
	6750	175	7630	310	Hv. 2680A
R4	6495	95	7410	160	Hv. 6210
	6290	85			Hv. 4131
	6250	55			Hv. 5294
	6230	85			Hv. 5227
	6060	65			Hv. 3368
	6050	80	6960	220	Hv. 8649
R5	5875	200	6760	470	Hv. 6207
	5865	115			Q. 261
	5775	85	6590	190	Hv. 4128
R6	5435	105	6190	240	Hv. 3844
	5395	280			Hv. 4713
	5277	120			Q. 85
	5260	385	5970	920	Hv. 2685
R7	5015	100	5790	200	Hv. 3460
	5005	65			Hv. 3845
	4960	50			Hv. 3841
	4900	450			Hv. 3052
	4845	100			Hv. 4418
	4800	75			Hv. 3933
	4830	140			Hv. 4347
	4725	65			Hv. 4348
	4760	45			Hv. 3840
	4700	70	5450	140	Hv. 1575
R8	4616	112	5280	310	Q. 86
	4545	90			Hv. 2679
	4190	150			Hv. 2920
	4090	170			Hv. 4705
	3980	70	4490	310	Birm. 1013
R9	3150	160	3330	380	Hv. 2918
R10	2270	65	2290	170	Hv 2916
	1795	240	1800	520	Hv 5215
R11	1370	85	1270	210	Hv. 4706
R12	390	55	410	100	Hv. 5219
	170	65	150	...	Hv. ----

Table 5.4 Transgressive and regressive phases identified within Northwest England. Taken from Tooley (1982)

Tooley (1982)			Roberts (2006)			
No	Phase	Date (Cal yr BP)	Date (Cal yr BP)	Horizon location/ID		
	Transgressive					
	Regressive		12350	2-4		
	Transgressive					
	Regressive		11900 11110	1-2		D
	Transgressive					
	Regressive		11230 10270	1-1		E
	Transgressive					
	Regressive		10670 10290	2-3		F
T1	Transgressive	10530 9830				
R1	Regressive	9610	9680 9550	2-1	Woodlands	H, I or J
T2	Transgressive	9560				
	Regressive		9390 8390	3-2		K
	Transgressive					
	Regressive		9240 9010	3-1		L
	Transgressive	8390				
R2	Regressive	8180	8440 7900	Llandudno HF 4	TB 2-3	M
T3	Transgressive	7810 7690				
R3	Regressive	7620 7630				M or N
T4	Transgressive	7430 7310				
R4	Regressive	7410 6950	7190	Morfa Penrhyn		N
T5	Transgressive	6840 6780				
R5	Regressive	6760 6590	6780	HF 3		
T6	Transgressive	6570				
	Regressive		6370	HF 5		
T7	Transgressive	6270				
R6	Regressive	6190 5970				
R7	Regressive	5790 5450				
R8		5280 4490	4540	TB 1	HF 1-2	
T8	Transgressive	4070 3750				
R9	Regressive	3330				
T9	Transgressive	3250 2420				
R10	Regressive	2290 1800				
10	Transgressive	1440				
R11	Regressive	1270				
T11	Transgressive	830 780				
T12	Transgressive	580				
R12	Regressive	410 150				

Table 5.5 Comparison between transgressive and regressive phases identified within Northwest England. Taken from Tooley (1982) and sea-level index points identified in North Wales.

the relative sea-level curve for North Wales have been placed alongside these data, together with their respective sources.

The table demonstrates that no correlation can be made between regressive and transgressive phases identified to have occurred within North Wales prior to around 10000 calendar years BP and phases identified in Tooley (1982). This is probably primarily attributable to the age and depth of the sediments obtained from the Menai Strait and highlights the benefits of utilizing a drilling rig with a specific research aim in mind rather than perhaps utilizing data acquired through a commercial project or obtained utilizing a drilling technique in an inter-tidal environment that limits the depth of a given sediment core. The volume of information available additionally makes it unclear if deeper and possibly older sediments are present at the locations sampled in northwest England.

The data from North Wales indicate that at least four regressive/transgressive phases may have occurred within the region of the Menai Strait prior to around 10000 calendar years BP; these are represented by organic deposits 2/4, 1/2, 1/1 and 2/3, which in many cases appear to correlate well with seismic reflective horizons D, E and F.

Several phases of organic sedimentation identified as R1-R5 (table 5.4) and dated to the early and middle Holocene, between 9610 and 6590 calendar years BP have been interpreted by Tooley (1982) as representing local regressive phases. Data acquired from within the Menai Strait, together with data obtained from other regions of North Wales appear to indicate that phases of organic sedimentation additionally occurred during this period. There appears to be good correlation between the timing of these phases at locations throughout North Wales and in northwest England.

Tooley (1982) identifies a period of organic sedimentation representing a regressive phase (R1) which is centred at around 9610 +/- 290 calendar years BP, this coincides well with both the lower and upper contacts of organic-rich deposit 2/1 obtained from the Menai Strait, dated to 9580 +/- 100 and 9720 +/- 170 calendar years BP respectively. The onset of this phase of organic sedimentation additionally coincides well with a date of 9510 +/- 180 obtained from the lower contact of an organic deposit recovered from the Clwyd Plain at Woodlands by Prince (1988).

Tooley (1982) subsequently identifies a transgressive phase (T2) that extends from approximately 9560 +/- 580 calendar years BP, until at least 8390 +/- 190 calendar years BP. Data from the Menai Strait however, indicate that two regressive phases of sedimentation occurred during this extended transgressive period; these periods are represented by deposits 3/2 and 3/1 respectively. At Woodlands on the Clwyd Plain however, a date obtained from the upper contact of the organic deposit recovered by Prince (1988) indicates that organic sedimentation continued until 9200 +/- 201 calendar years BP.

Tooley (1982) subsequently identifies the occurrence of another regressive phase (R2) centred at 8180 +/- 160 calendar years BP prior to the occurrence of another transgressive phase (T3) that extended from 7810 +/- 120 calendar years BP, until at least 7690 +/- 240 calendar years BP. The timing of this phase correlates reasonably well with dates obtained from the organic deposits recovered from Llandudno, as discussed in Heyworth and Kidson (1982) and dated to 8440 +/- 100 calendar years BP, together with a date obtained from Hendre Fawr 4 recovered from the Clwyd Plain (Bedlington, 1994), dated to 7900 +/-283 calendar years BP.

Tooley (1982) subsequently identifies three regressive phases (R3, R4 and R5) during the middle Holocene that centre around 7620, 7180 and 6680 calendar years BP. No correlation can be made with any currently available data obtained from North Wales with the earliest of these three phases to be identified in northwest England.

Regressive phase R4 dated to between 7410 and 6950 calendar years BP, correlates well with the organic deposit obtained from Morfa Penrhyn and dated to 7190 +/- 275 calendar years BP by Bedlington (1994).

The age of regressive phase R5 dated to around 6760 and 6590 calendar years BP, additionally correlates well with the dated horizon identified as HF 3 which has been dated to 6780 +/- 463 calendar years BP (Bedlington, 1994).

Seismic data obtained from the Menai Strait identify the presence of a series of strong, near-horizontal reflective horizons that probably constitute organic-rich material (reflectors M and N). These sediments were not sampled during the sediment coring programme, however they are deposited above organic-rich horizons dated to the early Holocene; their stratigraphic context therefore implies that these organic-rich sediments could potentially correlate with phases R2, R3 or R4.

Regressive phase R6 identified by Tooley (1982) occurs around 6190 and 5970 calendar years BP. An organic deposit termed HF5 obtained from the Clwyd Plain (Bedlington, 1994) and dated to 6370 +/- 883 correlates well with this regressive phase.

Tooley (1982) indicates that regressive conditions continued to occur throughout the middle Holocene as represented by phases R6, R7 and R8. The occurrence of phases R7 and R8 between 5790 and 4490 calendar years BP correlate well with dated sequences identified on both the Clwyd Plain (HF1 and HF2) and on Anglesey (TB1) in Bedlington (1994).

No correlation can be made with any phases dated to the late Holocene in Tooley (1982) as no data for this period is currently available from the region of North Wales.

5.1.6 Comparison with pre-existing sea-level data and geophysical models

The sea-level curve produced by Heyworth and Kidson (1982) indicates that within the region of North Wales MSL may have risen from approximately -28.5m to -8.5m OD between 10000 and 8000 calendar years BP; this rate correlates well with the rates derived from the data produced by Peltier (2002). Heyworth and Kidson (1982) additionally suggest that between 8000 and approximately 4500 calendar years BP, relative MSL rose at a much reduced rate, rising from -8.5m to -5m OD. This interpretation correlates well with the curve produced utilizing data obtained from Lambeck (unpublished). Heyworth and Kidson (1982) acknowledge that differences with respect to the altitude of MSL in North Wales with areas further to the south may indicate that North Wales experienced an enhanced degree of isostatic uplift during the Holocene; the data obtained during the course of this research project appears to support this idea.

Comparison of the relative MSL curve generated through this study with the geophysical models produced by Lambeck (unpublished) and Peltier (2002) indicates that both models may significantly underestimate the altitude of relative MSL during the Late Devensian and early Holocene (fig. 5.7). The models both suggest that the altitude of relative MSL rose at similarly rapid rates during the early Holocene and generally agree that relative MSL was at approximately –4m OD at around 6500 calendar years BP. During the early Holocene, the Peltier data appears to underestimate the position of relative MSL by approximately 5m, whilst the Lambeck curve underestimates MSL by approximately 15m.

A comparison between the modelled data and the data obtained from the Menai Strait incorporating corrections relating to possible variations in tidal range appears to introduce little discernable difference with respect to the degree of correlation between the derived relative MSL curve and the modelled outputs.

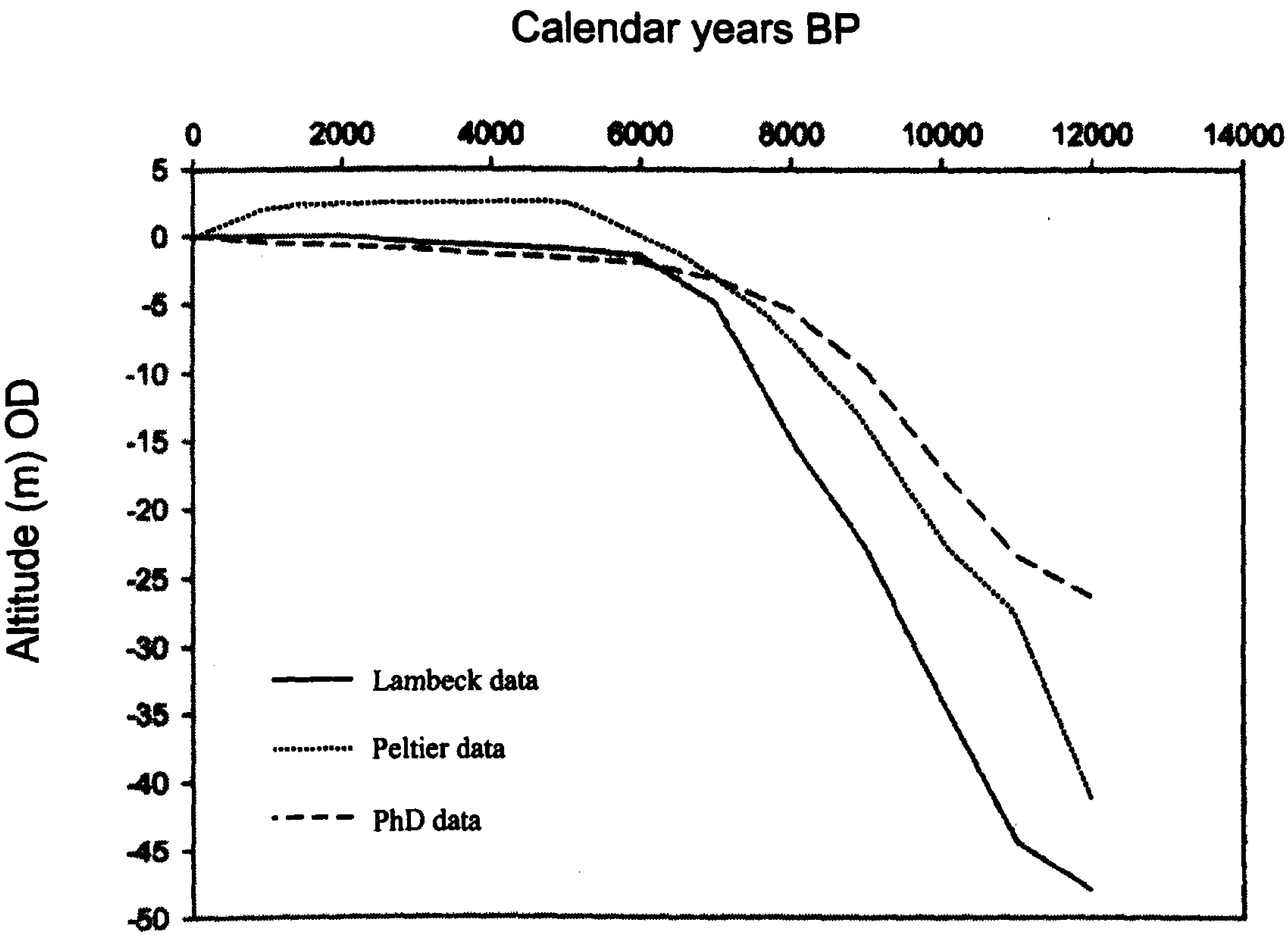


Figure 5.7 Comparison of relative MSL curve and geophysically modelled data

Data from studies such as Fairbanks (1989) indicate that eustatic sea levels rose at an enhanced rate of approximately 50mm yr^{-1} during MWP-1A, between approximately 11500 and 11000 calendar years BP; this was subsequently followed by a rise of approximately 11mm yr^{-1} during the following 2000 calendar years. Therefore it can be stated that between 11500 and 9000 calendar years BP, eustatic sea levels rose by some 50m at an average rate of approximately 20mm yr^{-1}. The relative sea-level curve derived for North Wales indicates that sea levels rose by approximately 18m during this period which equates to an average of approximately 7.2mm yr^{-1}. These data imply that North Wales may have experienced rates of isostatic uplift approximating to around 12-13mm yr^{-1} during this period. This rate of uplift compares well with the estimate generated through data supplied to the University of North Wales, Bangor by Lambeck (pers comm., 1999) (table 2.1) as shown in Figure 5.8.

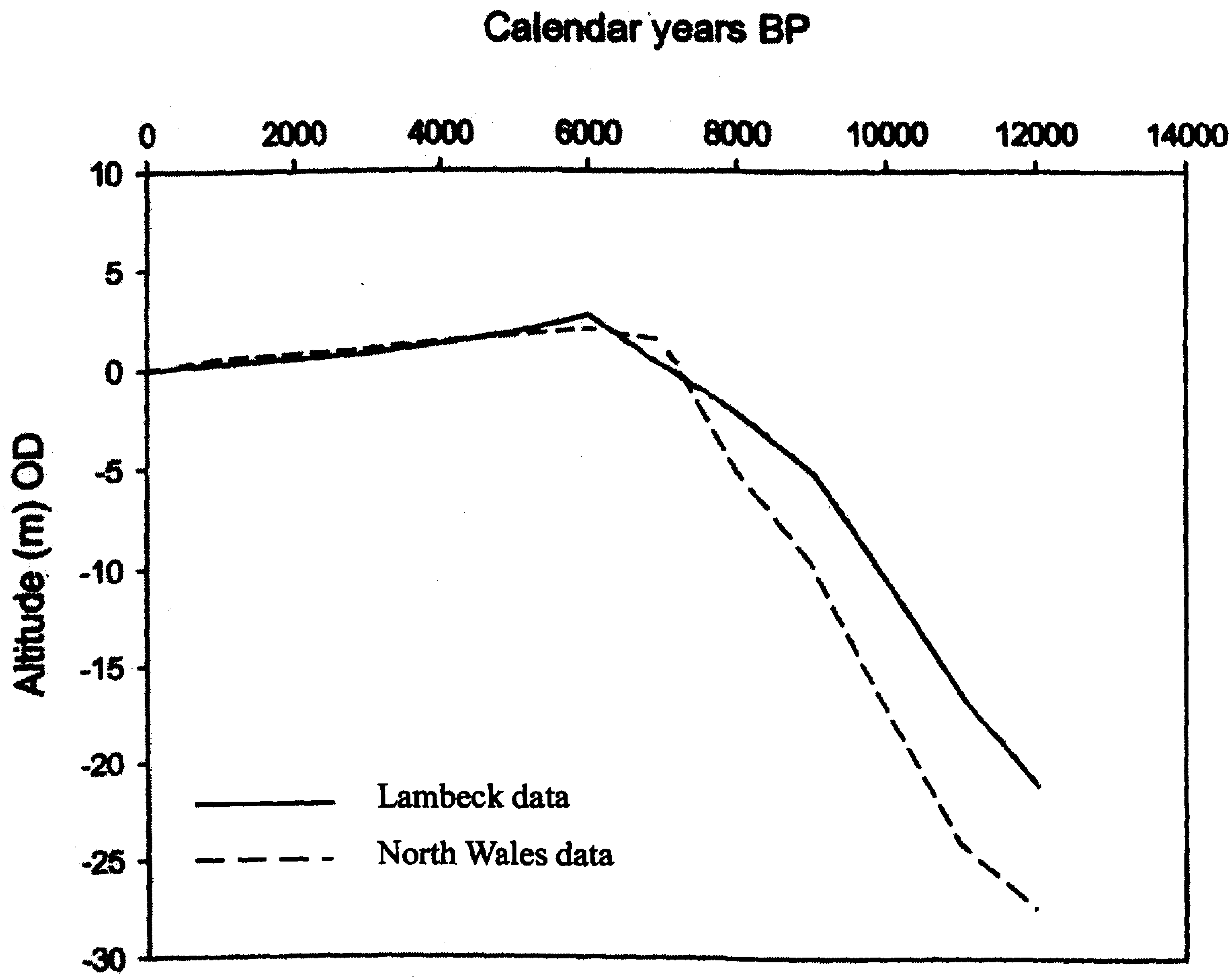


Figure 5.8 Comparison of inferred isostatic change between observed and modelled data

Bedlington (1994) indicates that within the region of North Wales relative MSL rose rapidly during the early Holocene, rising from approximately -31m to -12.5m OD between 10000 and 8000 calendar years BP; this interpretation correlates well with the relative MSL histories produced by both Heyworth and Kidson (1982) and Peltier (1992).

The data obtained during the course of this research project indicates that prior to and during the early Holocene the altitude of MSL was considerably higher than that suggested by previous research.

5.1.7 Sea-level change in North Wales and the existing sea-level record

The sea-level records from areas such as Barbados, Tahiti and the Sunda Shelf all correlate well with the data obtained from North Wales in terms of demonstrating that maximum rates of sea-level rise were attained on a local, regional and global scale during the early to middle Holocene, and that these rates decreased significantly after approximately 6000 calendar years BP.

Although a reasonable degree of correlation can be made with respect to the occurrence and timing of peat deposits found both in North Wales and some areas of the Western Pacific, with the exception of Liu *et al.* (2004) and Hanebuth *et al.* 2000, much of the data relating to relative sea-level change from other regions has been derived from the dating of coral reef formations rather than organic-rich sediments such as peat deposits. Furthermore, these regions have and continue to be characterized by fundamentally different environmental regimes and processes which ultimately determine how each region responds to processes operating on a global to local scale. Differences in these physical, chemical and biological processes operating on varying temporal and lateral scales ultimately result in a unique geological record being produced for any given location. This ultimately results in specifically different methodologies and techniques being applied to the various sea-level studies conducted within different geographical regions.

The response of each location to rapid variations in the altitude of MSL over varying timescales would differ depending on the nature of the local environment; this would consequently affect how any such change would be preserved within the geological record. For example, the response of a coral reef to fluctuations in sea level occurring over centurial or decadal time scales may be significantly more difficult to determine than changes that occur within a temperate estuarine environment characterized by saltmarsh development. The ability to discern and correlate palaeoenvironmental changes to changes occurring in sea level over relatively short periods of time is additionally limited by the degree of accuracy and precision inherently associated with the dating technique applied to a particular sample.

Local sedimentological processes may additionally be important and make it difficult to correlate similar sequences identified at locations separated by significant distances. Differences with respect to the physical environment and processes operating within the North Yellow Sea and in the coastal region of North Wales are probably significant in terms of correlating the data utilized in Liu *et al.* (2004) with the data obtained from North Wales.

As a consequence the degree of correlation between the formation of the organic deposits found in North Wales and the stepwise nature of relative sea-level change inferred for the

Western Pacific, although relatively good, is limited with respect to this study in terms of being cited as possible evidence indicating or reflecting fluctuations in the Lateglacial and Holocene eustatic sea-level record.

On a more regional and local scale, slight differences occur in terms of the timing, extent and number of regressive and transgressive phases identified in northwest England and North Wales. Relatively good correlation can be made between a number of transgressive and regressive phases identified as occurring during the early and middle Holocene. Subtle differences could possibly be attributable to localized hydro-dynamical and sedimentological regimes and processes. However, within the context of this study the available evidence is insufficient in terms attributing the simultaneous occurrence of these phases at locations extending over more than 150 km of coastline to processes operating on a larger than regional scale.

As discussed in chapter two, differences with respect to the altitude of relative sea level on a regional and local scale can predominantly be related to localized patterns of crustal uplift and subsidence or patterns of sedimentation and erosion. In the case of assessing relative sea-level change in locations situated within semi-enclosed shelf-sea systems such as the Irish Sea, consideration may additionally need to be given to the evolution of the shelf sea region as a whole.

Throughout the Late Devensian and much of the Holocene the degree of ice-loading and unloading experienced throughout northern regions of the UK would have varied significantly. Shennan and Horton (2002) illustrate differences with respect to the relative sea-level history of locations situated between South West Scotland and Mid Wales as shown in figure 5.5. The differences can largely be attributed to differences in the response of the crust to the volume of ice loading and unloading on both a temporal and lateral scale. In the case of examining particular aspects of the evolution of the Irish Sea, consideration may therefore need to be given to these differential crustal movements; as they may have influenced the influx of seawater into what is effectively an enclosed shallow basin extending over several hundreds of kilometeres at some point during the Late Devensian and early Holocene.

Although a significant volume of literature has been produced relating to the evolution of the Irish Sea subsequent to the LGM, many aspects of relative sea-level change within the region remain poorly understood. Shennan and Horton (2002) point to the fact that many of these unanswered questions can primarily be related to deficiencies within the existing UK sea-level index database (fig. 2.6). The authors highlight the fact that very few index points older than approximately 8000 calendar years BP exist within the current UK dataset.

Seismic data obtained from the Malin Sea off the coast of Portrush, Northern Ireland by Cooper *et al.* (2002) indicate the occurrence of intercalated peat deposits located at a depth of approximately -30m OD. The interpretation of seismic data suggests that a peat deposit is located within a well-developed sequence of marine material. Based on pre-existing data Cooper *et al.* (2002) infer the occurrence of an early Holocene sea-level lowstand within the region and estimate the age of the peat to be between 11000 and 10000 ^{14}C years BP; subsequent fieldwork undertaken using a vibro-coring system during 2005 resulted in the acquisition of a sample of organic material which has been dated to 11500 ^{14}C years BP (A. Cooper, pers comm. 2006).

Relative sea-level change for this region of the UK during the Late Devensian and early Holocene may be important in understanding how Irish Sea relative sea levels may have changed within what was at that time, an isolated low-lying basin situated to the southwest of Northern Ireland.

The limited volume of available data indicates that around 13500 calendar years BP, areas in and around the Malin Shelf off the coast of Northern Ireland experienced a marine transgression. Evidence from the Menai Strait through CJSC 2 indicates that the deposition of significant volumes of marine material, together with at least two phases of organic sedimentation occurred prior to 12650 calendar years BP.

The transgressive sequence observed within this region can be related to the fact hat eustatic sea-level rise exceeded rates of localized isostatic uplift immediately prior to the onset of the Holocene. The transgression ultimately resulted in areas of the northern Irish Sea and Liverpool Bay experiencing an initial marine incursion through rising relative sea levels.

The age of this initial marine transgression fits well with the derived age of the material obtained from organic-rich deposit 2/4 observed within CJSC 2 and may additionally account for the sequence of marine material located towards the base of the sediment core. One possible explanation relating to the formation of intercalated organic-rich deposits 2/5 and 2/4 observed within the Menai Strait could relate to comparatively similar rates of rising eustatic sea level and crustal uplift being experienced within the region of Northern Ireland during the Late Devensian. This may have resulted in little or no change in relative sea level for brief periods of time within this region. Local hydro-dynamic and sedimentological processes could therefore have had an effect on controlling the influx of sea-water through the North Channel of the Irish Sea. The timing of the transgression and interplay between eustatic sea level and rates of isostatic uplift off Northern Ireland could account for the marine deposits identified towards the base of CJSC 2 and could also have contributed to the formation of some of the earliest terrestrial sequences observed within the Menai Strait.

The origins of the alternating sequences of marine and organic-rich deposits dated to the early Holocene however, are more difficult to explain. Deposits 1/2, 1/1, 2/3, 2/2, 2/1, 3/2 and 3/1 all formed between approximately 11500 and 9000 calendar years BP which relates to a period characterized by the occurrence of MWP-1B (eustatic sea-level rise ~ 40-50mm yr^{-1}), followed by relatively high, although reduced rates of eustatic sea-level rise (~ 12mm yr^{-1}) occurring over the next 2000 years. The sea-level record for North Wales does not extend beyond 12000 calendar years BP and as a consequence does not represent the period of time coincident with MWP-1A. The relative sea-level record for

North Wales additionally does not reflect a relatively enhanced rate of relative sea-level rise coincident with MWP-1B occurring around the onset of the Holocene. The field data moreover, indicate that a generally consistent rate of relative sea-level rise (~ 7mm yr^{-1}) occurred in North Wales between 11500 and 9000 calendar years BP.

During this period however, tendency analysis performed on organic-rich deposits dated to this time indicate that the general trend of relative sea-level rise was punctuated by several periods where sea levels appear to have fallen or remained static. A reasonable degree of correlation can be made between deposits that occur within the Menai Strait and with others identified elsewhere in North Wales and northwest England. Similarly a degree of correlation can be made between these more regional deposits and the more distal sequences identified as occurring within the Yellow Sea.

A number of possible explanations may therefore be invoked in order to account for occurrence of the sedimentary sequences observed within the Menai Strait:

- The intercalated organic-rich deposits and marine material may represent independently developed sequences which formed in response to rapidly rising relative sea levels and localized sedimentological regimes.
- The sequences may have developed purely in relation to fluctuations with respect to rates of eustatic sea-level rise and ultimately relate to fluctuating rates of meltwater input into the ocean basins during this period.

- Some or all of the sequences may be attributable to a combination of both local and more regional regimes and processes operating in conjunction with periodic fluctuations within the eustatic sea-level record.

Between 11500 and 9000 calendar years BP the deposition of significant quantities of sand or alternatively the formation of barrier islands towards the northeastern end of the Menai Strait may have had an impact on the hydro-dynamical regime and consequently the palaeo-environmental conditions prevalent within this area of the Menai Strait at this time. Relatively low-energy hydro-dynamical conditions within the area located immediately behind any barrier may have periodically ensured that any such area gradually infilled with silt and clay, eventually allowing the development of saltmarsh conditions. Subsequent breakdown of the barrier through rising relative sea levels, storm action and/or changing current regimes would subsequently ensure the drowning of any terrestrial deposits formed towards the rear of the barrier.

One problem associated with this hypothesis is that it invokes the formation of a considerably large barrier complex at a time when relative sea-levels were rising at enhanced rates. Work conducted by Walley (1996) demonstrates that a considerably large-scale barrier formation developed proximal to the Taf Estuary in South Wales during the middle to late Holocene; the barrier formed in response to the prevailing hydro-dynamical regime and prevailing wind direction. At the time of formation rates of relative sea-level rise were not at a maximum and sediment accumulated as it was continually transported to the area from the offshore region.

Although barrier formation and degradation is one possible explanation that would account for the sequences of intercalated organics within the Menai Strait, no direct evidence is currently available with which to support this hypothesis.

Intercalated organic-rich sequences dated to the middle and late Holocene formed as the rates of eustatic sea-level rise decreased markedly. Therefore organic-rich deposits dated to have formed earlier than approximately 6000 calendar years BP may be more easily attributable to a process such as barrier formation and subsequent degradation.

The idea that eustatic sea-level rise was in some way 'episodic' or 'pulsed' during the Late Devensian and early Holocene is not generally accepted by the academic community (J. Scourse, pers comm. 2006). However data from the Menai Strait, which correlates reasonably well with data from other areas of North Wales and more regional data from Morecambe Bay additionally appears to correlate reasonably well with data obtained from the Yellow Sea (Liu *et al.* 2004). Although this is not sufficient evidence to suggest the occurrence of fluctuations within the eustatic sea-level record, it does demonstrate that on a local scale, similar sequences are observed at many different locations during this period.

Alternatively, the sequences may have formed in response to a combination of processes which combined in order to generate the observed sequences. One hypothesis may therefore be that initial marine conditions and early organic-rich deposits were formed in response to the interplay between eustatic and isostatic effects further to the north which ultimately controlled the influx of water into the Irish Sea basin for a brief period of time prior to the onset of the Holocene.

On a local scale, subsequent and relatively rapid rates of sea-level rise, combined with evolving hydro-dynamical and sedimentological regimes, may have resulted in the development of the early to middle Holocene sedimentary sequences observed throughout the region. Alternatively, small or significantly large-scale fluctuations in the rate of eustatic sea-level rise may have contributed to all or some of the organic/inorganic sequences observed at different locations. More recent alternating sequences of terrestrial and marine material could be attributed to localized sedimentological patterns that predominated during the middle to late Holocene.

5.2 The evolution of the Menai Strait

Integration of the relative sea-level data with sedimentological, micropalaeontological, geophysical evidence, together with ^{14}C data has facilitated the development of a hypothetical, chronostratigraphical model relating to the palaeoenvironmental evolution of the northeastern Menai Strait during the Holocene. This section presents the model and discusses aspects of palaeoenvironmental development with respect to the evidence obtained during the course of this research project.

5.2.1 Solid geology

The solid and structural geology of the study area have been described in chapter one and although a considerable volume of research has previously been conducted, it has become apparent that very little is known with respect to the nature and morphology of the unexposed solid geology beneath the position of MHWST.

The geology of the coastline between Bangor Pier and Gallows Point is predominantly characterized by a mélange associated with the Pre-Cambrian Mona Complex on the Anglesey shoreline, whilst Cambrian phyllite, Ordovician shale and Carboniferous limestone are located on the shore of the mainland (Greenly, 1919). The integration of pre-existing lithological data (Project Engineering and Management Services Ltd., 1971; Osiris Seaway Ltd., 1986) with seismic data obtained during the course of this research project indicate that the surface of the Pre-Cambrian rock descends rapidly towards the south between the Anglesey shoreline and the main channel. This contrasts with the surface of the bedrock located on the mainland coast, which appears to descend gradually northward, probably attaining its lowest elevation somewhere between -40m and -50m OD within the central reaches of the main channel, where it unconformably overlies the Pre-Cambrian strata.

Borehole and geophysical data derived from the report produced by Osiris Seaway Ltd. (1986), together with seismic data obtained from transects 22-26 appear to confirm that the slope of the bedrock surface is significantly greater on the Anglesey side of the Menai Strait. The reflective characteristics and nature of horizon A, identified on transects 22-24 (fig. 5.9), indicate that the reflector probably represents the surface of bedrock, which descends southward toward the main channel with a gradient of approximately 1:10 beneath the floor of the depression located at Gallows Point. The interpretation is based on the fact that bedrock was not encountered in either of the sediment cores obtained from within the central region of the Strait and that the characteristics of reflector A, observed within transects 21-27 are noticeably dissimilar from those of other reflectors identified within the region. The strongly inclined reflector is represented through a very intense seismic signal characterized by an almost linear and smooth appearance. The interpretation indicates that the longitudinal, southwest–northeastern profile of the bedrock descends from an altitude of approximately -5m OD, where it outcrops at the surface within the Swellies, to at least -40m OD at Gallows Point.

Sediment core data obtained from the report produced by Project Engineering and Management Services Ltd. (1971) indicate that the surface of the underlying bedrock does not occur within at least 10m of the surface between the main channel and the mainland. A deficiency in available data results in uncertainty when considering the depth, morphology and nature of bedrock beneath the surface of the Traeth Lafan.

5.2.2 Glacial and post-glacial sedimentary deposits

CJSC 1 exhibits a characteristic and distinctive sedimentary sequence of unproven depth towards the base of the core; data obtained during the seismic survey additionally fail to indicate the vertical extent of this sequence. The physical properties of the material suggest that the visible part of the sequence probably comprises of a glacial till which was deposited at some point during the Late Devensian. The surface altitude of the material identified as glacial till at -27.02m OD correlates reasonably well with the altitude of reflector B observed within transect 3 and 29 (fig.5.10). The physical

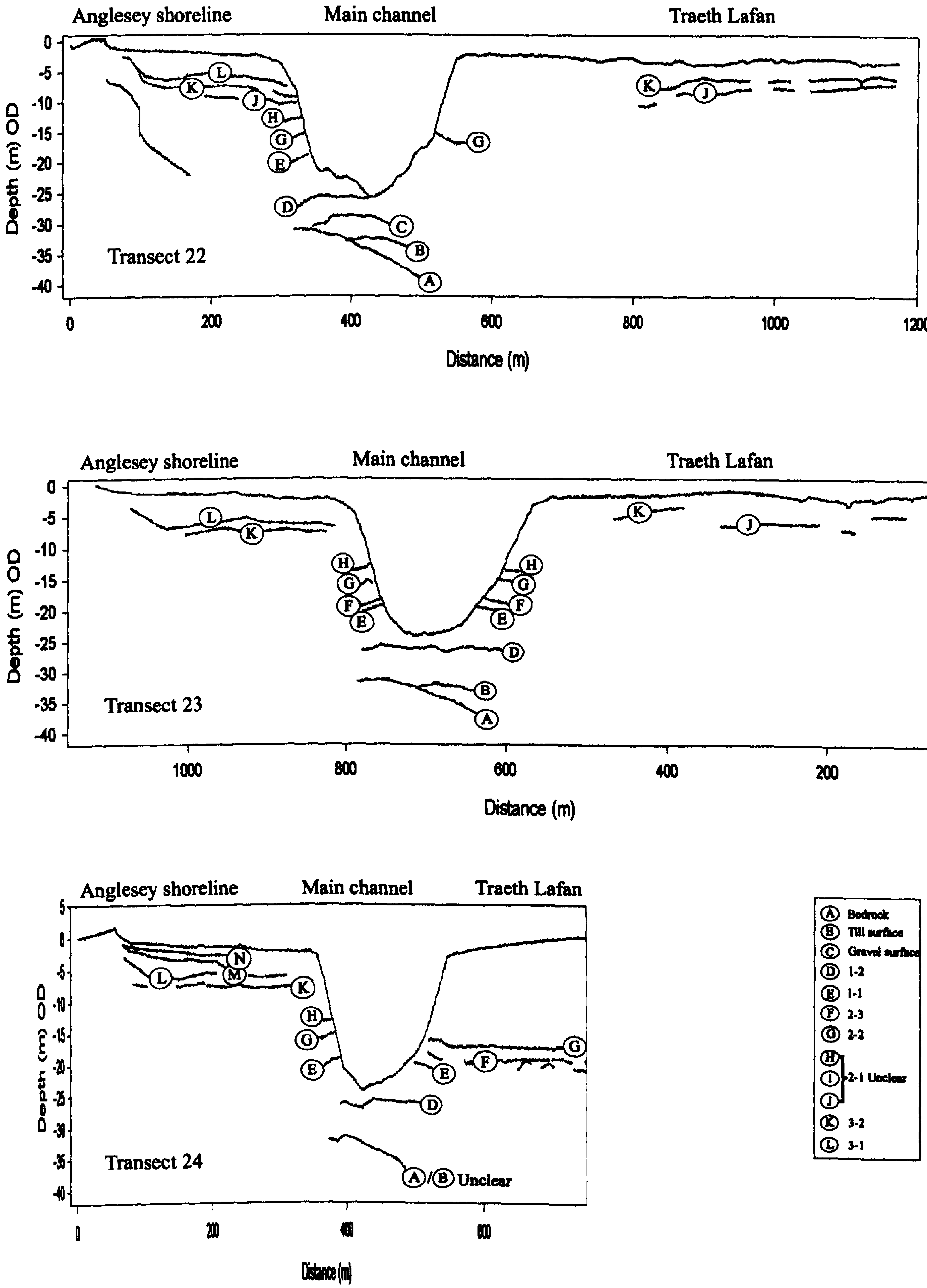


Figure 5.9 Correlation of reflectors within seismic sections obtained through transects 22, 23 and 24 within the region of Gallows Point

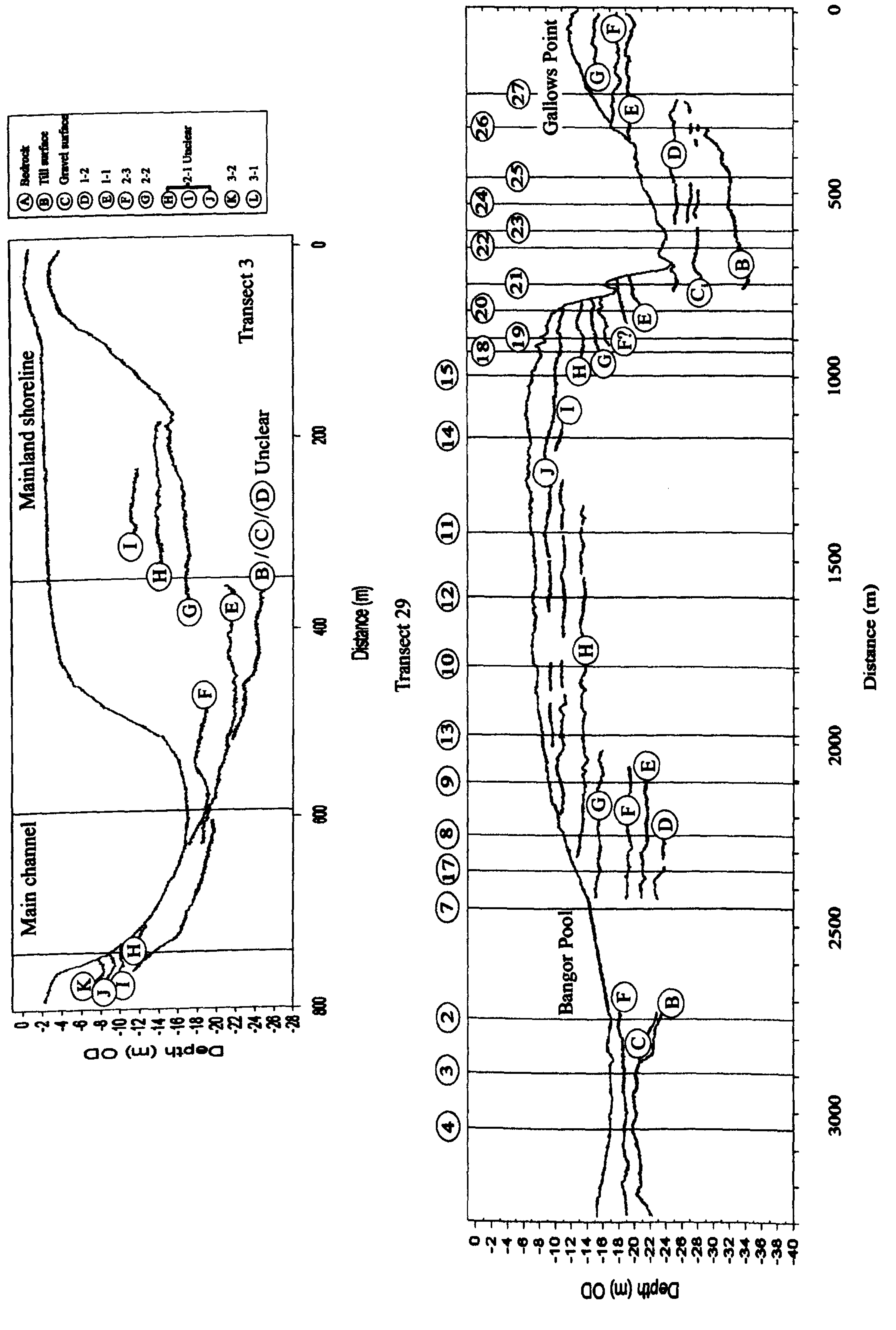


Figure 5.10 Seismic sections representing longitudinal transect 29 and perpendicular transect 3

properties and altitude of the deposit additionally correlate well with sediments described within core logs produced by Osiris (1986).

Transect 29 indicates that the deposit represented by reflective horizon B attains maximum altitude beneath the central region of Bangor Pool effectively forming a ridge of material at this location; the deposit may possibly represent the remnants of a glacial landform. The seismic data additionally indicate that the surface altitude of reflector B decreases with increasing distance towards the northeast. The relatively strong reflector appears hummocky and discontinuous in comparison to overlying reflectors and again appears to be present towards the northeast within transects 22-27.

An interpretation of previously acquired seismic data from within this region by Kirby (2003) additionally identifies the presence of a similar reflector at Gallows Point, which was interpreted to represent the surface of glacial till. Transect 29 further demonstrates that the surface altitude of the horizon increases from -34m OD to -26m OD with increasing distance towards the northeast, beyond the depression at Gallows Point. The surface correlates well with data obtained approximately 2km to the northeast by Fugro McClelland (1993), which indicate that within the main channel, the surface of glacial till occurs at -22m OD.

The integration of pre-existing with recently acquired data indicates that the surface altitude of glacial material deposited within the area of the main channel undulates significantly from southwest to northeast.

CJSC 1 demonstrates that the glacial till is overlain by a sequence of coarse, medium and fine, angular and sub-angular gravels beneath Bangor Pool. One possible interpretation relating to the origin of the gravels is that they may relate to the action of glacio-fluvial meltwater, during the retreat or melting of local ice within or proximal to this region of the Menai Strait. This tentative interpretation is largely based on the lithology and shape of the material, as the gravels appear to comprise predominantly of local 'Gwna green schist fragments; their shape and lithology possibly indicate that they may have experienced a minimal degree of transport subsequent to being eroded from a localized source. Additionally their relatively large size indicates that a considerable flow regime may have been required in order to transport them over any significant distance, these conditions may well have prevailed during the Late Devensian. The organic-rich deposits deposited immediately above the gravels additionally constrain the development of the gravel deposit to the Late Devensian.

The surface of the lithological horizon identified at -23.62m OD correlates well with reflector C, identified within transects 3, 4, 17 and 29. Within the vicinity of Bangor Pool, the surface of the deposit appears to undulate gently between -25m and -24m OD beneath and perpendicular to the main channel; transect 29 additionally demonstrates that reflective horizon C merges with underlying reflector B which represents the surface of glacial till. Seismic data suggest that the gravel may be confined to within the region of the main channel, forming a lens of material located on the northeastern side of a ridge formed by glacial material. Data from CJSC 2 indicate that the reflectors located at a similar elevation at Gallows Point comprise an entirely separate sedimentary facies, as the sediment core extended beyond -32m OD and failed to encounter any glacial material.

5.2.3 Deposits 2/5 and 2/4

A preliminary examination of the material located towards the base of CJSC2 between -32.01m and -28.21m OD indicates that the sediments were predominantly deposited under marine conditions. This tentative interpretation is based primarily on microfaunal evidence, given the abundant quantities of foraminifera present almost throughout the sequence. The deposits additionally contain abundant quantities calcium carbonate in the form of broken shell fragments, these fragments have not however been positively identified as originating from species of marine mollusca. The interpretation does not however, adequately describe the probable origin of all the material present below -28.21m OD and as a consequence more detailed analyses are required in order to substantiate this interpretation.

Radiocarbon dating of the organic-rich contacts termed 2/5 bottom, 2/5 top and 2/4 top indicate that the sediments are probably Late Devensian in origin. The relationship of the two lower contacts to a former position of sea level has not been accurately discerned and their value in terms constructing a chronostratigraphical framework for the sediments deposited within this region of the Menai Strait appear to be very limited. The indicative meaning or relationship of the contacts to MSL may be addressed using additional analytical techniques; however, there exists a need to demonstrate that the organic-rich sediment contained within deposit 2/5 does not represent significantly older allochthonous material. The surface altitude of deposit 2/5 at -28.14m OD correlates extremely well with horizon C_1 identified within transect 29 at approximately -28m OD, which may indicate that the deposit represented by this reflective horizon is considerably extensive, maintaining a near constant elevation over at least 150m within the region of Gallows Point.

Palynological analyses demonstrate that the strongly laminated organic clay contains extremely low concentrations of pollen; consequently inhibiting an interpretation relating to the nature of local palaeoenvironmental conditions at the time of deposition. Evidence from plant macrofossil analysis suggests that the deposit may represent a boggy area adjacent to dwarf willow shrub tundra, with the deposit containing a considerable quantity of plant material derived from the localized presence of both *Salix* and Musci (C. Turner, pers. comm. 2004). Micropalaeontological analysis of the adjacent inorganic sedimentary facies indicates that marine conditions prevailed locally prior and subsequent to the conditions that led to the deposition of the material constituting the organic-rich clay, with the inorganic sediments containing small but significant quantities of fossilized benthic foraminifera and broken shell. The data indicate that deposit 2/5 almost certainly formed under terrestrial conditions although its altitude with respect to the position of MSL remains unclear.

Micropalaeontological data obtained from the inorganic sediments underlying and overlying organic-rich deposit 2/4, indicate that brackish inter-tidal conditions prevailed prior and subsequent to the formation of the deposit which has been dated to 12,650 calendar years BP. Data from the sediments overlying the contact indicate a relatively abrupt but smooth transition from a saltmarsh environment to conditions similar to those of a sandy mudflat, possibly under the influence of brackish-saline conditions. The analogous texture and physical appearance of the material in relation to other organic-rich horizons identified as having formed under terrestrial conditions additionally suggests a terrestrial origin for deposit 2/4.

Palynological analysis was not conducted on the organic-rich material due to time constraints and as such, an independent form of temporal correlation is unavailable for the deposit; consequently a degree of uncertainty exists when considering the date of deposition. Stratigraphically, however, the age of the deposit appears to correlate well with other well-dated organic-rich horizons and on that basis has been deemed as acceptable. The organic-rich material provided insufficient plant macrofossil data, consequently limiting any interpretation in relation to discerning local palaeoenvironmental conditions at the time of deposition.

The seismic data indicate that the early sequence of sediments containing organic-rich deposits 2/5 and 2/4 are concentrated within what is effectively a depositional basin located immediately beneath the depression at Gallows Point. The lateral extent of the sequence is primarily controlled by the undulating morphology of the underlying glacial material and the steeply sloping bedrock descending to the southeast from the Anglesey shoreline. During the Late Devensian and its associated period of lower relative sea level, the promontory at Gallows Point would have been considerably more extensive, extending further out over the region occupied by the present day Menai Strait; as relative sea level began to rise, marine sediments would have subsequently been deposited within an embayment which faced a relatively sheltered and shallow marine environment to the southeast.

Some material deposited beneath horizon 2/5 may possibly be of fluvial origin, although this interpretation is based purely on the absence of carbonate fragments and foraminifera. This interpretation may lead to a suggestion that the contemporary route taken by the main channel within this region of the Menai Strait could correlate with a freshwater drainage pattern of the Late Devensian, at least as far northeast as Gallows Point. The deposits possibly represent sediments laid down by a laterally migrating fluvial system, perhaps an earlier version of the contemporary Afon Cadnant, originating to the southwest then flowing northeast, trending along a route similar to the one taken by the contemporary main channel.

The lithology, micropalaeontology, stratigraphy and age of the sediments located towards the base of CJSC 2, combined with the seismic data indicate that marine conditions existed within the extreme northeastern region of the Menai Strait during the Late Devensian, immediately prior to the onset of the Holocene. The data further suggest that during this time, marine conditions may have been interspersed on at least two occasions by periods of lower relative sea level, resulting in the accumulation of the terrestrial deposits termed 2/5 and 2/4. The block diagram (figure 5.11a) illustrates how the northeastern Menai Strait would probably have appeared during the Lateglacial at around

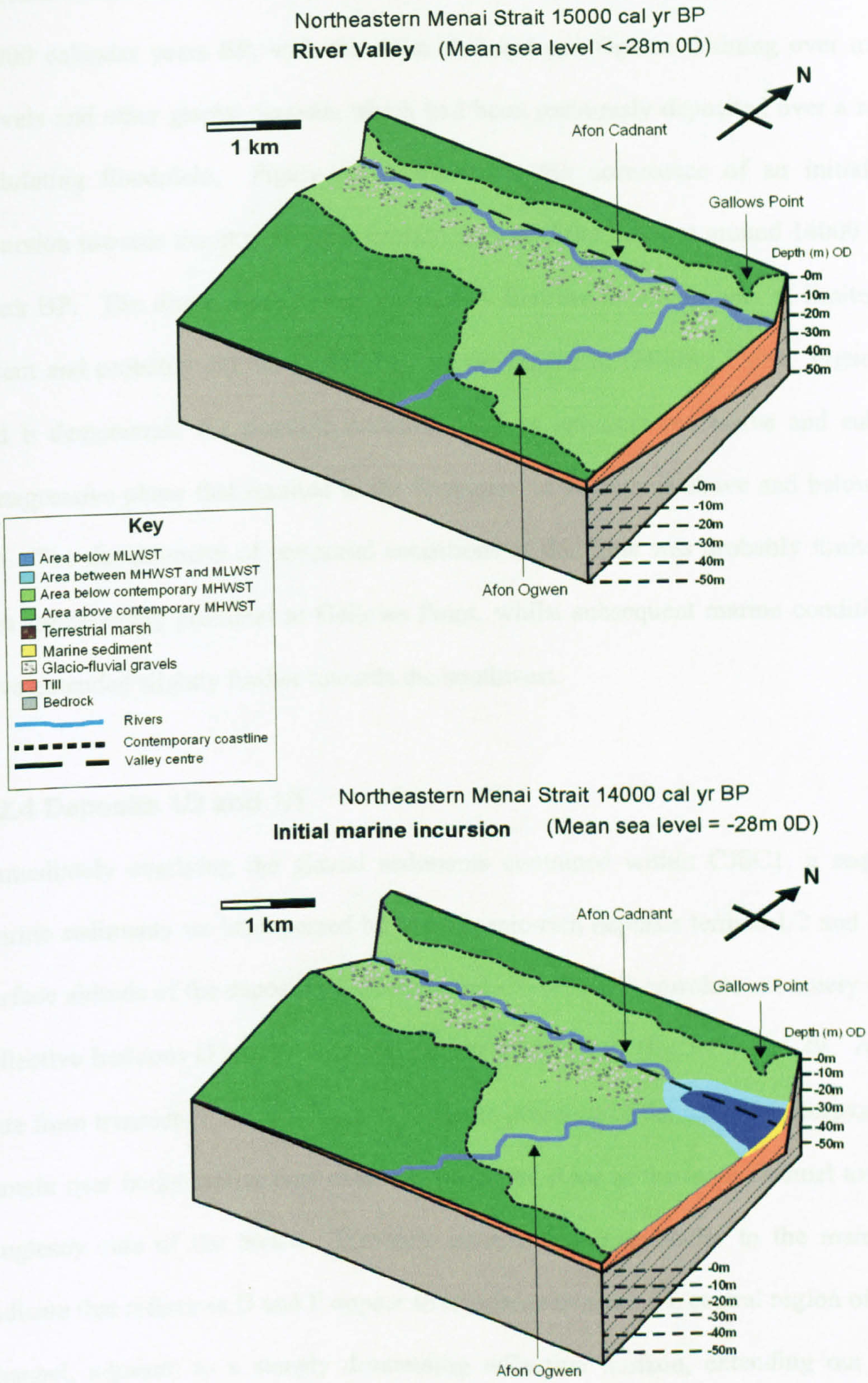


Figure 5.11 Block diagrams illustrating the development of the Menai Strait between 15000 and 14000 calendar years BP and an initial marine incursion

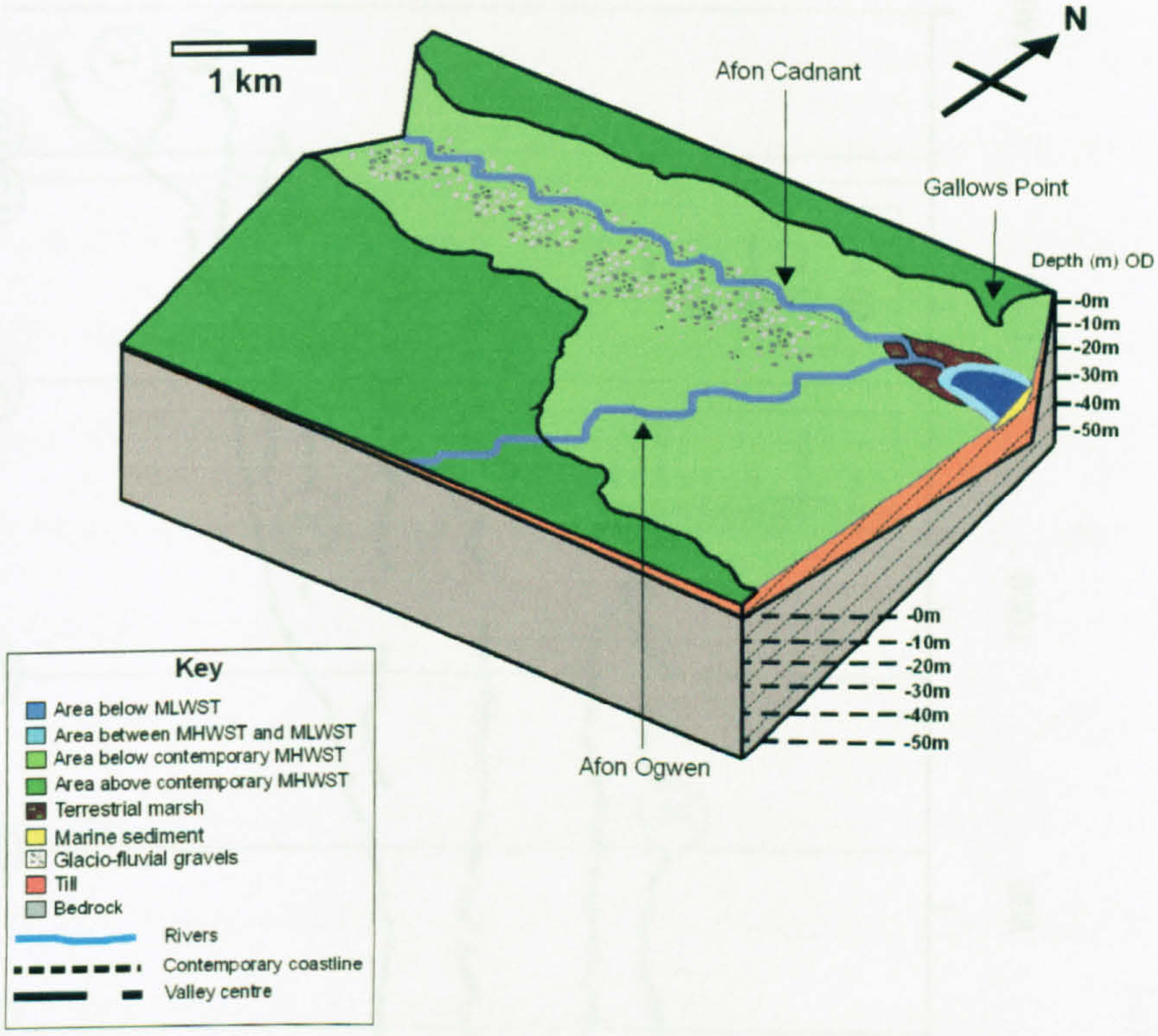
15000 calendar years BP, with the Afon Cadnant and Ogwen draining over meltwater gravels and other glacial deposits which had been previously deposited over a relatively undulating floodplain. Figure 5.11b illustrates the occurrence of an initial marine incursion towards the extreme northeastern region of the Strait at around 14000 calendar years BP. The diagram additionally indicates that the incursion was of limited lateral extent and probably did not extend beyond the region of Gallows Point. Figures 5.12a and b demonstrate the possible occurrence of an apparent regressive and subsequent transgressive phase that resulted in the formation of sediments above and below deposit 2/5. The development of terrestrial conditions at this time was probably limited to the area immediately proximal to Gallows Point, whilst subsequent marine conditions may have extended slightly further towards the southwest.

5.2.4 Deposits 1/2 and 1/1

Immediately overlying the glacial sediments contained within CJSC1, a sequence of marine sediments are interspersed by two organic-rich deposits termed 1/2 and 1/1. The surface altitude of the deposits at -22.95m and -20.66m OD correlate extremely well with reflective horizons D and E identified within transects 17 (fig.5.13) and 29. Additional data from transects 1 and 7 further indicate the presence of the reflective horizons, which remain near horizontal as they extend beneath the floor of the main channel towards the Anglesey side of the Strait. Transects orientated perpendicular to the main channel indicate that reflectors D and E appear to terminate beneath the central region of the main channel, adjacent to a steeply descending reflective horizon, extending out from the Anglesey shoreline.

Northeastern Menai Strait 14000-13500 cal yr BP

Initial marine incursion (Mean sea level = -28m OD)



Northeastern Menai Strait 13500-13000 cal yr BP

Second marine incursion (Mean sea level = -28m OD)

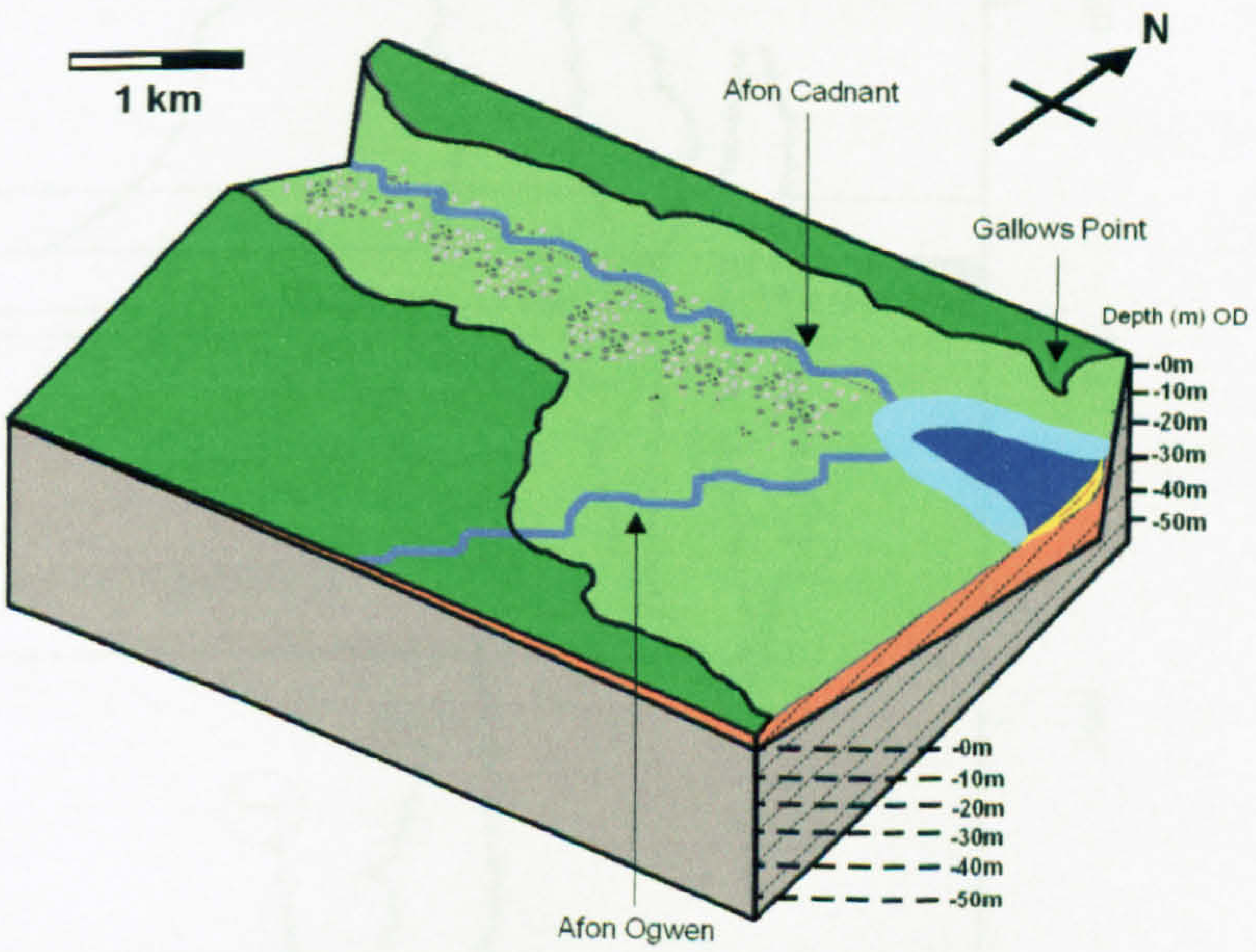


Figure 5.12 Block diagrams illustrating the development of the Menai Strait between 14000 and 13000 calendar years BP and the development of deposit 2/5

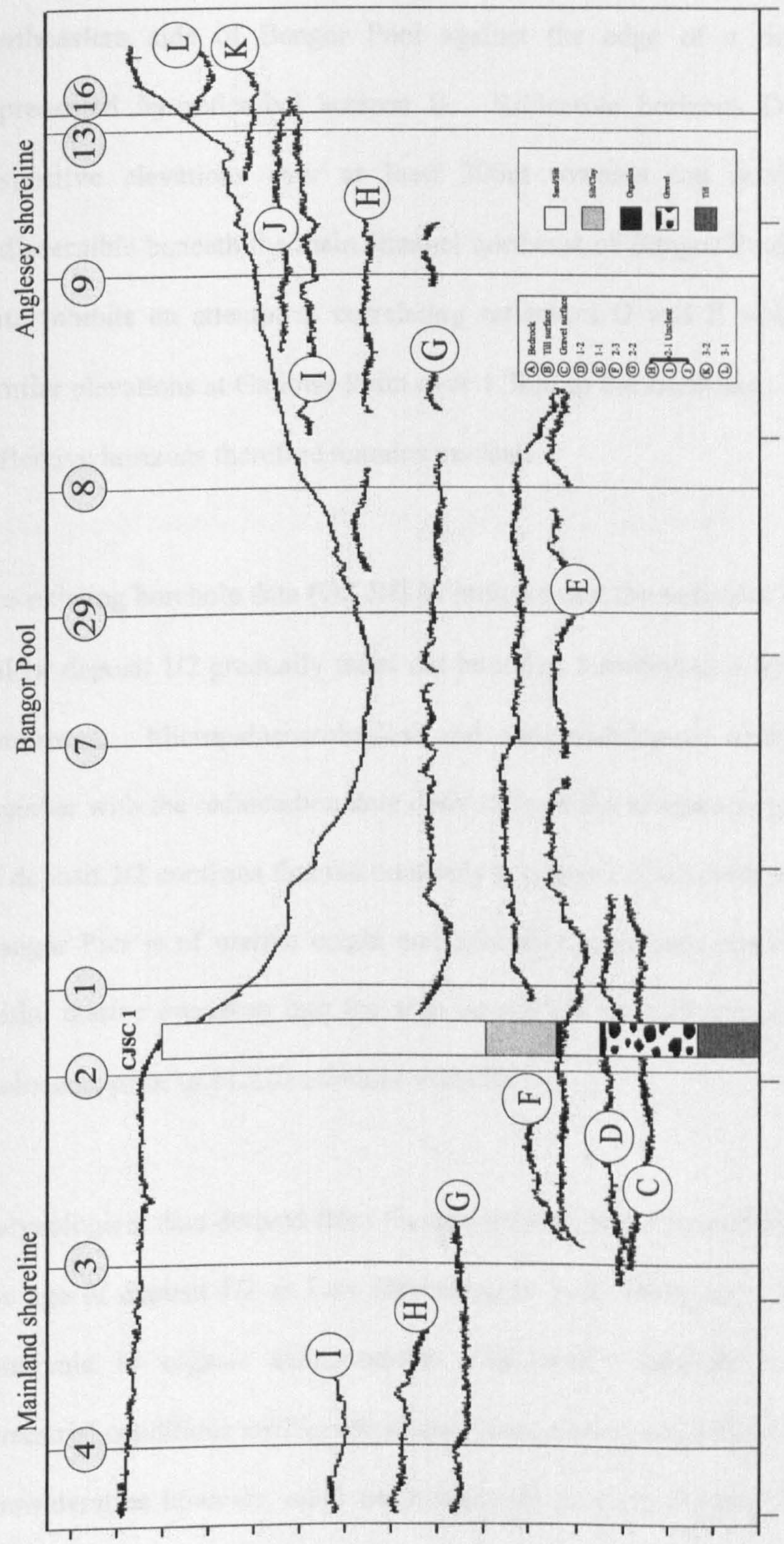


Figure 5.13 Seismic section representing transect 17 and points of intersection

Transect 29 additionally indicates that the reflectors similarly terminate on the northeastern side of Bangor Pool against the edge of a ridge of glacial material represented by reflective horizon B. Reflective horizons D and E maintain their respective elevations over at least 300m towards the northeast before becoming indiscernible beneath the main channel northeast of Bangor Pool. The available seismic data inhibits an attempt at correlating reflectors D and E with horizons identified at similar elevations at Gallows Point over 1.3km to the northeast. The lateral extent of the reflective horizons therefore remains unclear.

Pre-existing borehole data (OS-BH 9) indicate that the sediment constituting the material below deposit 1/2 gradually fades out laterally, terminating a few hundred metres to the southwest. Micropalaeontological and sedimentalogical analysis of the silty sand, together with the radiocarbon date derived from the inorganic-organic contact at the base of deposit 1/2 confirms that the relatively thin layer of sediment underlying deposit 1/2 at Bangor Pier is of marine origin and probably represents material deposited during an initial marine incursion into the area during the Late Devensian or at the onset of the Holocene, prior to 11,220 calendar years BP.

Palynological data derived from the organic-rich horizon additionally appears to confirm the age of deposit 1/2 as Late Devensian or early Holocene. The abrupt change from inorganic to organic sedimentation additionally indicates a rapid transition, with terrestrial conditions swiftly succeeding those associated with an inter-tidal environment. Consideration however, must additionally be given to the possibility that the sediments located adjacent to the inorganic-organic contact may also have been subjected to a significant degree of erosion or reworking, effectively removing evidence pointing to a more gradual transition. Pollen and plant macrofossil analyses conducted on the organic sediments, located above the contact indicate that following the transition from marine to terrestrial conditions, the site was characterized by the development of a freshwater pond, probably surrounded by fairly open grassy conditions, bounded to the south and southwest by a well-developed *Salix* and *Betula* scrub (C. Turner, pers. comm. 2004).

Radiocarbon data indicate that the organic material constituting horizon 1/2 top is of approximately the same age as 1/2 bottom, consequently it is highly probable that terrestrial conditions existed briefly and were maintained for no more than perhaps 200 years at this location. Pollen and plant macrofossil analyses conducted on the organic sediment, located at the contact additionally indicate that the dated horizon probably represents organic sedimentation within a freshwater pool surrounded by fairly open grassy conditions. The area would have been bounded to the south and southwest by a *Salix* and *Betula* scrub. Palynological data additionally appear to reflect the initial establishment of *Corylus* within the local area.

Correlation between deposit 1/2 and reflective horizons identified at similar altitudes within transects located towards Gallows Point appear ambiguous, due primarily to limitations associated with the seismic technique employed during the survey. Data from CJSC 2 does, however, indicate that the sediments located at similar altitudes further towards the northeast similarly represent a transition from marine to terrestrial conditions during the Late Devensian or early Holocene.

Lithological and micropalaeontological analyses of the sediments overlying deposit 1/2 suggest that the contact represents a relatively rapid but smooth transition from open terrestrial conditions into an environment that became increasingly dominated by marine processes, under brackish-saline conditions. Micropalaeontological data obtained from the sediments located above horizon 1/2 and from below horizon 1/1 indicate that the dominance of marine conditions and an associated increase in water depth, gradually slowed as conditions were reversed; this probably lead to the development of a saltmarsh environment with brackish-saline conditions for a brief period of time, subsequent to the re-establishment of terrestrial conditions and the deposition of organic-rich deposit 1/1.

Radiocarbon data from the base of deposit 1/1 indicate that terrestrial conditions were re-established at this location by approximately 11,000 calendar years BP. Pollen and plant macrofossil analyses conducted on the organic sediment, located at the dated contact indicate that the horizon probably represents organic sedimentation within a marsh or reedswamp, bounded locally to the south and west by fairly open grassland (C. Turner, pers. comm. 2004). The data additionally reflect the development of arboreal taxa during the early Holocene through the domination of *Corylus* and *Betula* within the local area.

Radiocarbon data taken from the upper contact of deposit 1/1 in conjunction with sedimentological data from the overlying inorganic material indicate a rapid transition from terrestrial to saline-brackish conditions at approximately 10,470 calendar years BP; this suggests that terrestrial conditions prevailed at this location for up to 500 years. Pollen and plant macrofossil data suggest that the contact may possibly represent flooded turf (C. Turner, pers. comm. 2004), indicating the rapid inundation of a terrestrial environment. The data additionally indicate that the organic contact prior to inundation represents a terrestrial environment characterized by fairly open grassy conditions, once again bounded to the south and west by a scrub consisting predominantly of *Corylus, Betula* and *Salix.*

Near-horizontal reflective horizon E identified within the seismic data between -22.0 and -21.0m OD correlates reasonably well with the surface altitude of deposit 1/1 at -20.66m OD. Within transect 29 the reflector can be seen extending beneath the floor of the main channel over approximately 400m before becoming indiscernible to the northeast of Bangor Pool. As in the case of the underlying reflectors, horizon E appears to terminate against reflector B, beneath the deepest section of Bangor Pool.

Seismic data from transects taken proximal to Bangor Pier indicate that the marine and terrestrial deposits located between -24m and -20m OD, all terminate against the flanks of a steeply descending reflector extending out from the coastline of Anglesey, beneath the central region of the main channel.

The data indicate that the marine deposits interspersed by organic-rich horizons 2/5, 2/4, 1/2 and 1/1 are confined to the east of Bangor Pool and to the west of Gallows Point by two ridges of glacial material; the deposits are additionally constrained to the north by the configuration of the Anglesey shoreline. If laterally extensive organic formations occur within a depositional basin located between Bangor Pool and Gallows Point as seems to be the case, then it appears that marine conditions have been replaced by a terrestrial environment within this area on at least two occasions during the Late Devensian and early Holocene. This sequence of sedimentation may be directly attributable to changes in relative sea level; however, consideration must also be given to the possibility that changes in coastal configuration may possibly be responsible. As shown in chapter two, research by Walley (1996) demonstrated that during a period of sea-level rise, the development of saltmarsh conditions can often occur, due primarily to the formation, orientation and progradation of a coastal barrier complex within the marine environment.

The data imply that during the time inorganic sedimentation was taking place, conditions within the area were probably similar to those found within a low energy estuarine environment, with a relatively low volume of freshwater draining over reasonably extensive inter-tidal deposits; with saltmarsh conditions probably predominantly confined to the southeastern peripheries of the existing Strait adjacent to the mainland. Successive falls in relative sea level or the development of a barrier complex further to the northeast probably resulted in these sediments being succeeded and overlain by deposits associated with the development of saltmarsh and a terrestrial environment. Freshwater drainage patterns would maintain their approximate trend, draining across areas of low-lying marsh prior to draining into the sea, probably somewhere immediately to the southeast of Gallows Point.

The relative sea-level curve generated through the analysis of the organic-inorganic contacts and incorporating data from previous research suggests that relative sea level within North Wales rose relatively rapidly during the Late Devensian and early Holocene, increasing from -23m OD to -18m OD between 11,000 and 10,000 calendar years BP. The stratigraphy of the sediments deposited within the study area indicate that as the altitude of MSL increased, the accumulation of sediments, derived predominantly through marine processes, kept pace with this rate of rise. The rapid accumulation of marine sediments within the depositional basin encompassing the northeastern Menai Strait effectively ensured that water depths remained relatively shallow.

The block diagrams in figure 5.14 illustrate the development and lateral extent of saltmarsh and marine conditions that resulted in the formation of organic-rich deposit 1/2 and the overlying marine sediment at the onset of the Holocene. An additional regressive and transgressive phase subsequently gave rise to the formation of deposits at and immediately above organic-rich deposit 1/1. The regressive phases resulted in the development of saltmarsh conditions which extended throughout much of the northeastern region of the Strait between Gallows Point and the present day position of Bangor Pool, whilst the transgressive phases additionally resulted in marine conditions extending much further towards the southwest.

5.2.5 Deposits 2/3, 2/2 and 2/1

Sedimentological and micropalaeontological data indicate that the sediments overlying deposit 1/1 consist of approximately 2m of very fine grained silt and clay. The data

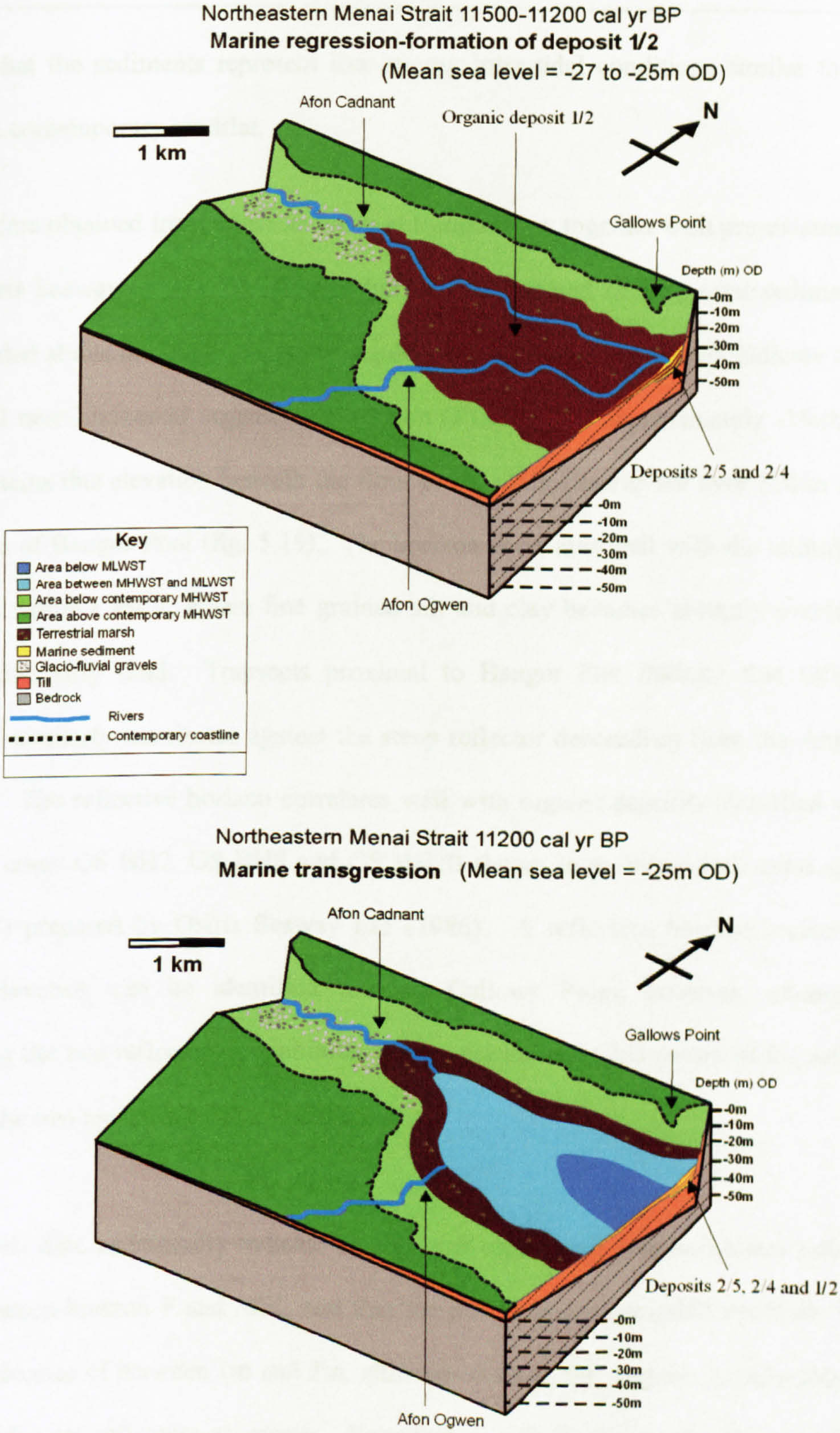


Figure 5.14 Block diagrams illustrating the development and drowning of deposit 1/2 within the Menai Strait between 11500 and 11200 calendar years BP through an initial regressive and subsequent transgressive phase

suggest that the sediments represent low energy inter-tidal conditions similar to those seen on a contemporary mudflat.

Seismic data obtained from transects taken at Bangor Pier, together with pre-existing data from Osiris Seaway Ltd (1986), indicate that between 1m and 2m of marine sediment has accumulated above horizon E, representing deposit 1/1 . The data further indicate that an additional near-horizontal organic-rich horizon (F) occurs at approximately -19.0m OD and maintains this elevation beneath the floor of the main channel for over 1.3km within the region of Bangor Pool (fig. 5.15). The horizon correlates well with the altitude of a transition within CJSC1, where fine grained silt and clay becomes abruptly overlain by medium-fine silty sand. Transects proximal to Bangor Pier indicate that reflective horizon F similarly terminates against the steep reflector descending from the Anglesey coastline. The reflective horizon correlates well with organic deposits identified within sediment cores OS BH7, OS BH8 and OS BH10 shown in an interpreted cross section (fig. 2.32) prepared by Osiris Seaway Ltd (1986). A reflective horizon located at a similar elevation can be identified towards Gallows Point; however, attempts in correlating the two reflectors are inhibited due to the indiscernible nature of the reflector between the two locations.

The seismic data additionally indicate that at least eight other near-horizontal reflectors occur between horizon F and MSL and that the reflectors are separated vertically by an average distance of between 1m and 2m, although at times this may be considerably less, causing adjacent reflectors to merge. Excellent correlation between all perpendicular transects and the longitudinal seismic profiles, demonstrate that the reflectors (G-N)

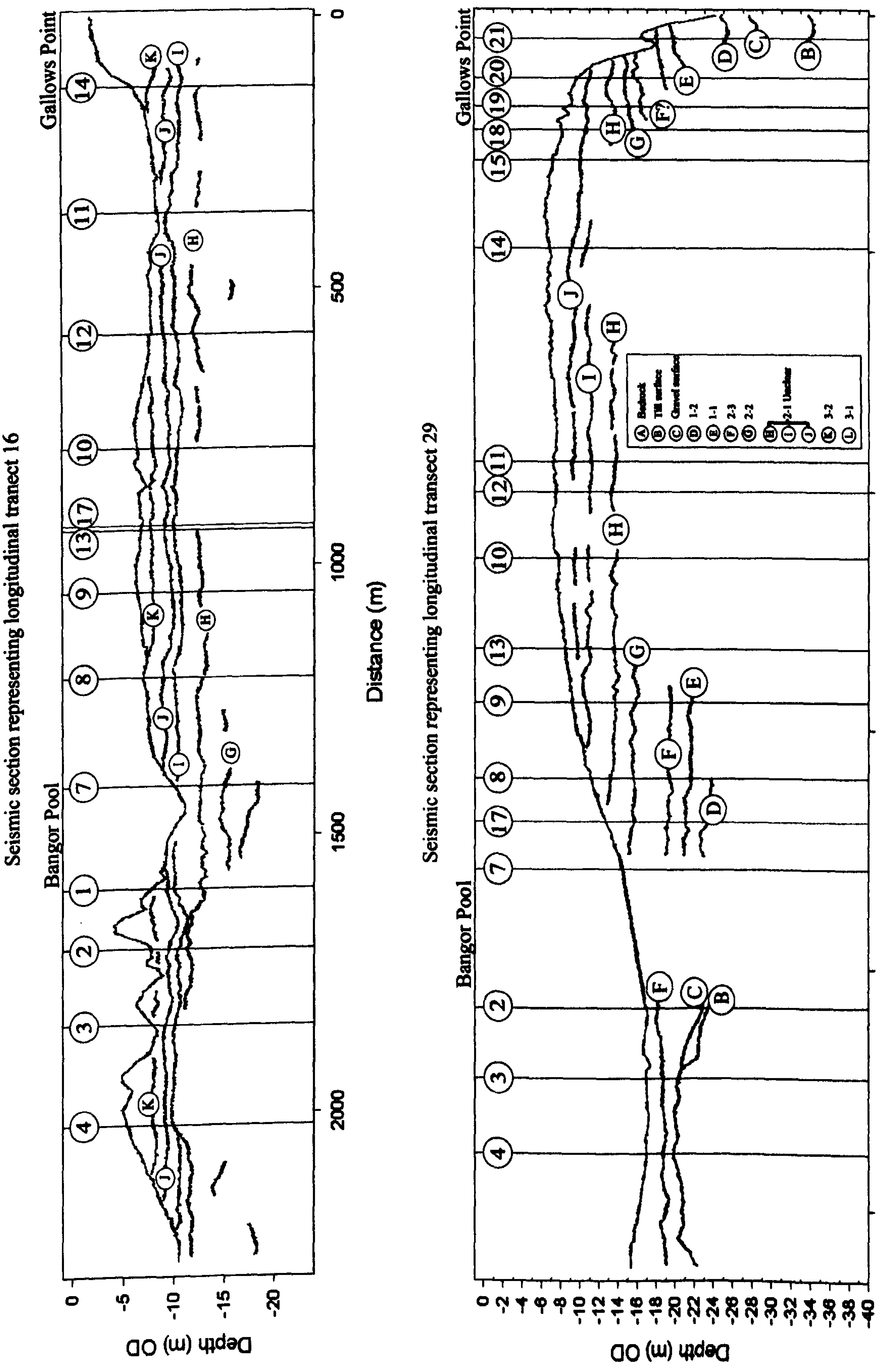


Figure 5.15 Seismic sections representing longitudinal transects 16 and 29, indicating points of intersection with perpendicular

maintain near-horizontal elevations and extend almost parallel to each other between Bangor Pier and Gallows Point (figs. 5.15 and 5.16). The reflectors appear to be almost continuous within the seismic profiles and terminate abruptly at the seabed surface adjacent to the depressions located at Bangor Pool and Gallows Point. Their lateral extent appears to be controlled by the configuration of the Anglesey coastline and the undulating morphology of the seafloor. There is also an excellent degree of correlation between the altitude of reflective horizons identified on either side of undulations on the seabed, as illustrated within transects 16 and 29.

Excellent correlation between the surface altitude of the reflective horizons and organic-rich, deposits located within CJSC 2 and CJSC 3 confirm that the reflectors represent a change in facies within the sedimentary sequences located beneath the seabed. Micropalaeontological and radiocarbon data from those deposits subsequently provide evidence relating to aspects of palaeoenvironmental change during the early Holocene.

Transect 6 (fig. 5.17) demonstrates that reflector G maintains a near-horizontal elevation at an altitude of between -17.0m and -16.0m OD on either side of Bangor Pier, with transect 7 additionally indicating that the horizon outcrops within the centre of the main channel approximately 100m to the northeast of Bangor Pier at -15.5m OD. The horizon correlates reasonably well with OS BH6 which identifies an organic deposit at the surface within the main channel located at -15.3m OD.

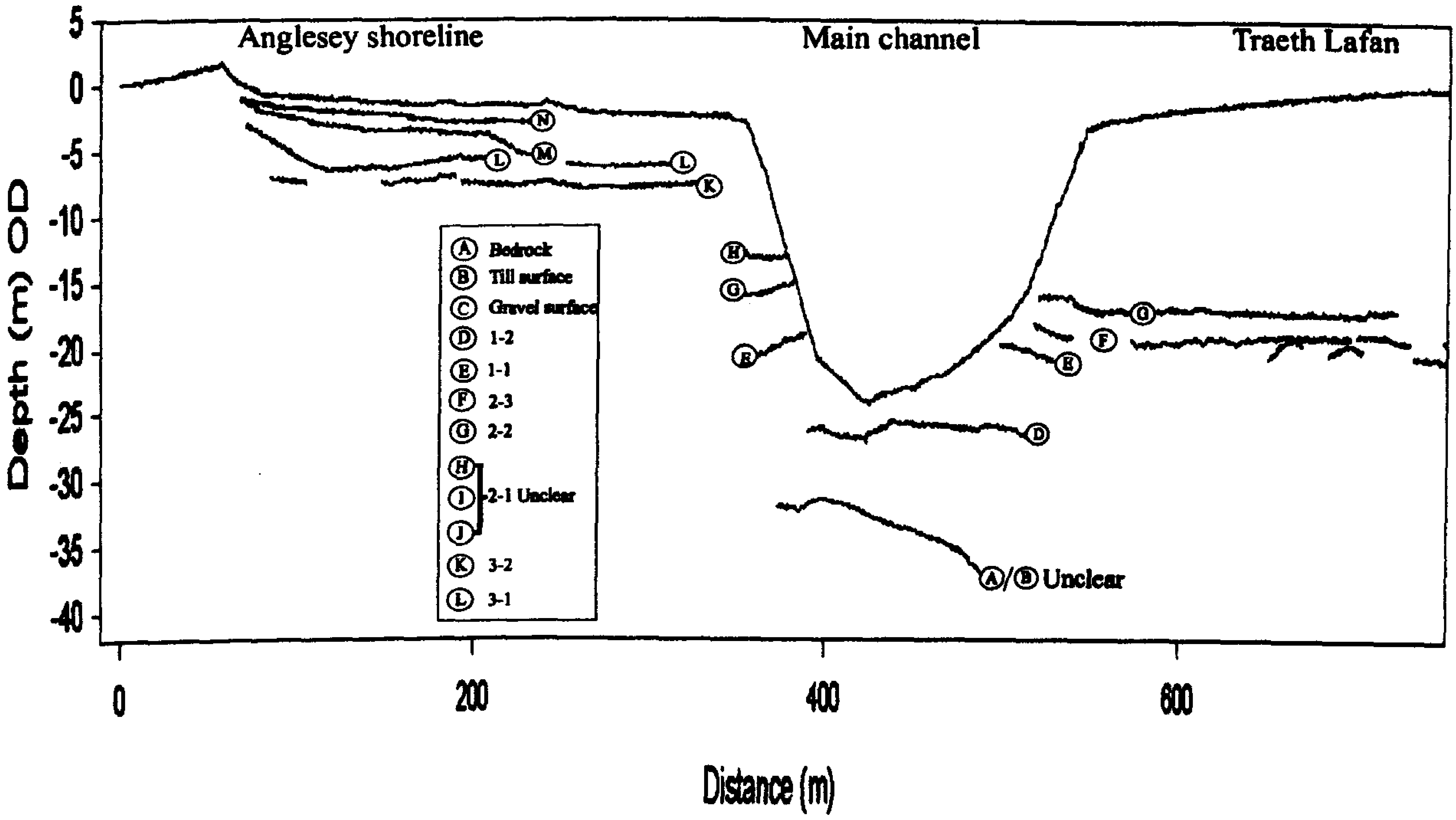


Figure 5.16 Seismic section obtained from transect 24, demonstrating probable correlations between adjacent reflective horizons

Data from transect 17 indicate the possibility that reflector G may merge with overlying reflector H within this region of Bangor Pool at approximately -16.0m OD. Data from transect 17 indicate the possibility that reflector G may merge with overlying reflector H within this region of Bangor Pool at approximately -16.0m OD. Data from the core logs of OS BH8 and OS BH10 additionally indicate that peat deposits G and H appear to merge to the northeast of Bangor Pier.

Correlation between the upper sequence of reflective horizons present at Bangor Pool and those identified at Gallows Point has proved difficult, due primarily to the abundance of reflective horizons identified to the southwest of the depression and the fact that the

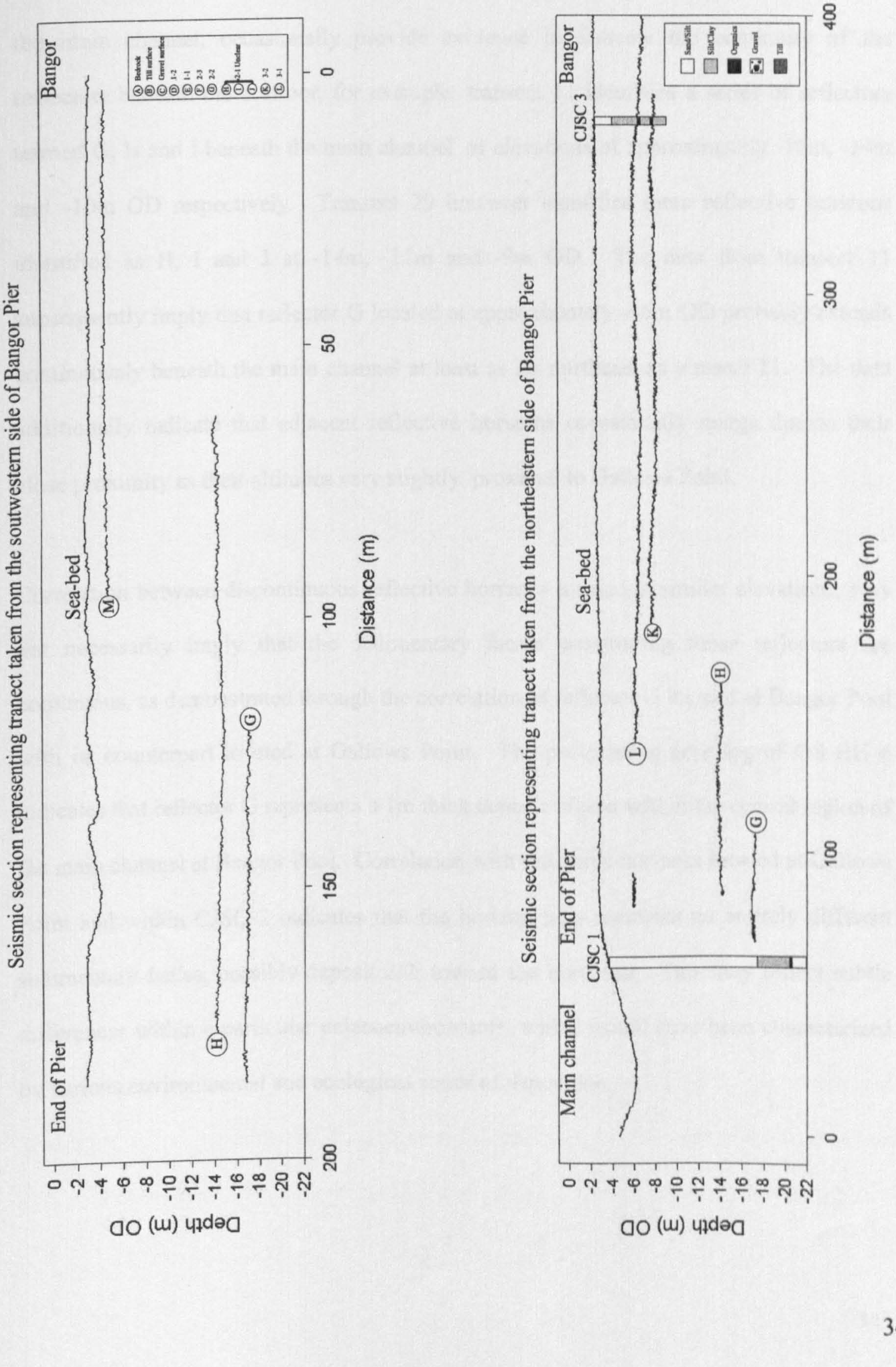


Figure 5.17 Seismic sections representing transect 6 taken from either side of Bangor Pier

reflectors are at times difficult to discern. Transects orientated parallel to the direction of the main channel, occasionally provide evidence to indicate the continuity of the reflectors beneath the seafloor, for example, transect 11 identifies a series of reflectors termed G, H and I beneath the main channel at elevations of approximately -16m, -14m and -10m OD respectively. Transect 29 however identifies three reflective horizons identified as H, I and J at -14m, -11m and -9m OD. The data from transect 11 subsequently imply that reflector G located at approximately -16m OD probably extends continuously beneath the main channel at least as far northeast as transect 11. The data additionally indicate that adjacent reflective horizons occasionally merge due to their close proximity as their altitudes vary slightly, proximal to Gallows Point.

Correlation between discontinuous reflective horizons located at similar elevations, may not necessarily imply that the sedimentary facies constituting those reflectors are continuous, as demonstrated through the correlation of reflector G located at Bangor Pool with its counterpart located at Gallows Point. The pre-existing core log of OS BH 6 indicates that reflector G represents a 1m thick deposit of peat within the central region of the main channel at Bangor Pool. Correlation with reflective horizons located at Gallows Point and within CJSC 2 indicates that the horizon may represent an entirely different sedimentary facies, possibly deposit 2/2, toward the northeast. This may reflect subtle differences within a particular palaeoenvironment, which would have been characterized by various environmental and ecological zones of deposition.

Sedimentological and micropalaeontological analyses conducted on the inorganic and organic-rich deposits contained within CJSC 2 indicate that marine conditions continued to be interspersed with periods of terrestrial sedimentation on at least three occasions between 10,470 and 9,580 calendar years BP.

The data from the inorganic-organic contact at the base of deposit 2/3 indicate that a transition between marine conditions and those associated with a terrestrial environment occurred approximately 10,470 calendar years BP. This date at an elevation of -16.94m OD closely resembles that obtained from the upper contact of deposit 1/1 located at an elevation of -20.66m OD. Seismic and borehole data indicate that the two deposits are separated by at least 4m of marine sediment, interspersed by two laterally extensive organic-rich deposits; however the sea-level curve generated by this research project indicates that relative sea level was rising at a rate of approximately 5mm/yr during this period.

If sedimentation rates are equated to the rate of relative sea level during this time, a difference of approximately 700 years would be expected in terms of the respective ages of deposits 1/1 top and 2/3 bottom. The relatively similar age of the samples questions the degree of confidence that can be associated with the derived radiocarbon dates for either or both of the contacts. As can be observed within the relative sea-level curve, the index point generated by 1/1 top appears to be anomalously young when compared to the general trend of the cure and implies a prolonged period of terrestrial sedimentation, when compared to the date derived from the underlying contact. Evidence of bioturbation is, however, apparent within the inorganic sediment overlying deposit 1/1 and this disturbance is one possible explanation that may account for an anomalous radiocarbon date produced by 1/1 top, possibly produced through the introduction of younger carbon.

The micropalaeontological data and radiocarbon dates produced by the organic-rich contacts forming part of deposit 2/3 demonstrate that marine conditions were briefly interspersed by a period of terrestrial sedimentation at approximately 10,475 calendar years BP. Palynological and plant macrofossil analyses conducted on sub-samples taken from within the deposit proved inconclusive and as such, a limited and tentative attempt at interpreting the local palaeoenvironment has been undertaken. The data suggest that the surrounding area may have been dominated by open grassland, with local arboreal taxa being dominated by both *Corylus* and *Salix*.

The absence of reflective horizons E and F could be attributed to the lateral extent of marine conditions within the Menai Strait during the early Holocene. The 10m sequence of marine sediments within CJSC 2 that extend between organic-rich horizons 2/4 and 2/3 may demonstrate that any development of terrestrial conditions between 12,650 and 10,475 calendar years BP simply did not extend to this location.

Consideration, however, must also be given to the possibility that organic deposits previously located between deposits 2/4 and 2/3 may have been subjected to erosion, effectively ensuring the removal of evidence relating to the existence of terrestrial conditions at this location.

Analysis of the fine grained silt and clay overlying deposit 2/3 indicate that relatively low energy brackish and saline saltmarsh conditions replaced a terrestrial environment shortly after 10,475 calendar years BP and that these conditions were maintained prior to the development of deposit 2/2. Deposit 2/2, located between -15.86m and -15.73m OD, almost certainly represents a period of terrestrial sedimentation, with the deposit consisting of organic-rich clay. This interpretation is based primarily on the fact that relatively high concentrations of pollen and plant macrofossils occur within the analyzed sub-samples.

The radiocarbon dates produced by the organic-rich material located at the point of contact with the underlying and overlying inorganic material appear to be anomalously old at between 12,350 and 11,260 calendar years BP. The palynological data however indicate that the deposit formed approximately between 9,580 and 9,410 calendar years BP. The relative sea-level curve generated during this research project additionally suggests an age of approximately 9,500 calendar years BP for a deposit representing MSL located at an elevation of -16.0m OD. The data demonstrate clearly that the laboratory derived age of the material does not accurately reflect the probable age of the deposit and consideration must therefore be given to the possibility that the analyzed material may have been contaminated by the presence of older in-washed carbon. As the deposit incorporated significantly older reworked allochthonous material, deposited at this location, it almost certainly simultaneously incorporated locally derived quantities of pollen, which more accurately reflects the time of deposition. Seismic data through reflectors G and H indicate the extensive development of organic-rich deposits within the area during this period of time.

Assuming that these reflectors represent the existence of a low-lying terrestrial environment, it is highly probable that this environment contained isolated pools that received freshwater through drainage from tributaries of the Cadnant or Ogwen. This interpretation may account for the presence of older allochthonous carbon and the anomalous dates derived from sub-samples analyzed from within deposit 2/2.

Plant macrofossil data from organic-rich material sub-sampled from the lower and upper contacts indicate that the deposit additionally contains material derived from a nearby saltmarsh (C. Turner, pers. comm. 2004).

Seismic data indicate the presence of a complex sequence of reflective horizons within the region of Gallows Point, all of which appear to terminate abruptly against the southwestern, northwestern and southeastern sides of the depression (fig. 5.18). Specific correlation between the organic-rich deposits and any of the near-horizontal reflectors extending from Bangor Pool proves difficult, due to the quality of the available data and the fact that the altitude of each reflector appears to increase with increasing proximity toward the depression. It is however, probable that horizons 2/3 and 2/2 could be correlated with horizon F or G, this does not seem unlikely given their stratigraphical context and probable age.

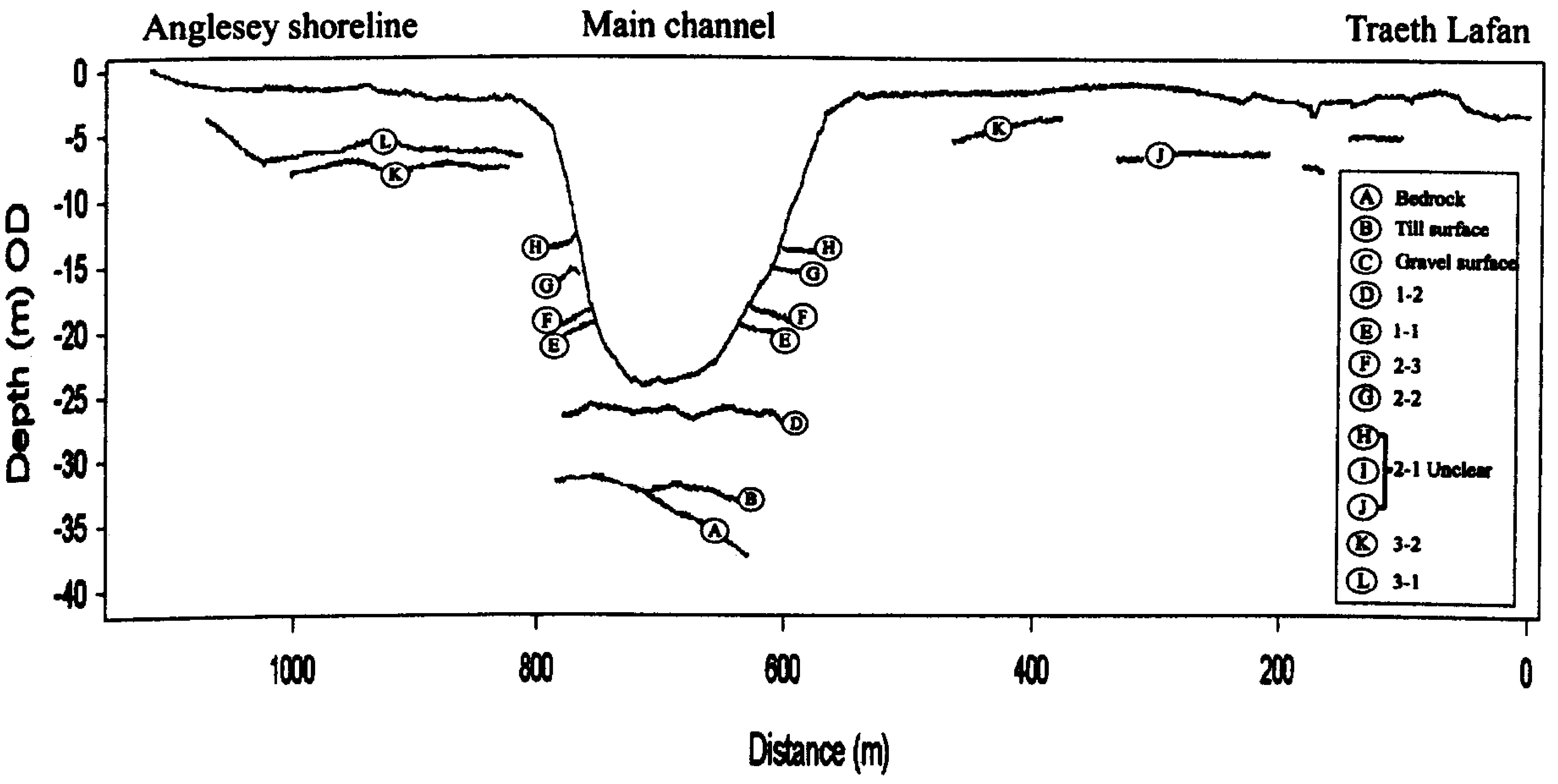


Figure 5.18 Seismic section obtained from transect 23, demonstrating probable correlations between adjacent reflective horizons

Deposit 2/2 is overlain by approximately 1.0m of fine grained silt and clay and contains an abundant quantity of fossilized benthic foraminifera, indicating a return to marine conditions. The timing of this environmental transition is unknown; however, it is constrained by data from the underlying and overlying organic-inorganic contacts which indicate the transition occurred between 10,475 and 9,720 calendar years BP. Micropalaeontological data indicate that the overlying fine grained sediments represent inter-tidal-brackish conditions; the sediments contain abundant quantities of foraminifera and ostracoda, dominated by *Cyprideis torosa* (J. Whittaker, pers. comm. 2004). The ostracoda within the sediment consist both of juveniles and mature individuals, with complete specimens being commonplace; these data indicate that minimal reworking of the sediment probably occurred during this period and that the sediments represent in-situ conditions.

The fine grained sediments are succeeded by approximately 1.6m of fine grained silty sand, which may indicate a change in environmental conditions. Micropalaeontological data indicate that the sediments probably represent inter-tidal conditions similar to the development of a saltmarsh, due primarily to the abundant quantities of agglutinating foraminifera present. The data provide clear evidence that the sediments between deposits 2/2 and 2/1 represent material deposited under very shallow marine-brackish conditions. The dates obtained from the overlying organic-rich horizon additionally suggest that the deposits were laid down over a relatively brief period of time, as sea level continued to rise rapidly, with sedimentation rates ensuring that water depths remained relatively shallow.

The sediments abruptly give rise to a series of organic-rich deposits located at -13.07m OD, which again indicate a transition from marine conditions to the establishment of terrestrial sedimentation. The upper and lower contacts of the deposit indicate that the organic-rich sediments were deposited between 9,720 and 9,580 calendar years BP. The quality of seismic data obtained through transects 19 and 29 ensure a degree of uncertainty when attempting to correlate the deposit with horizons identified within the region; subsequently horizons H, I or J, may relate to deposit 2/1. Improvement on this interpretation is additionally limited due to the complex interplay between the orientations of reflective horizons located at this point.

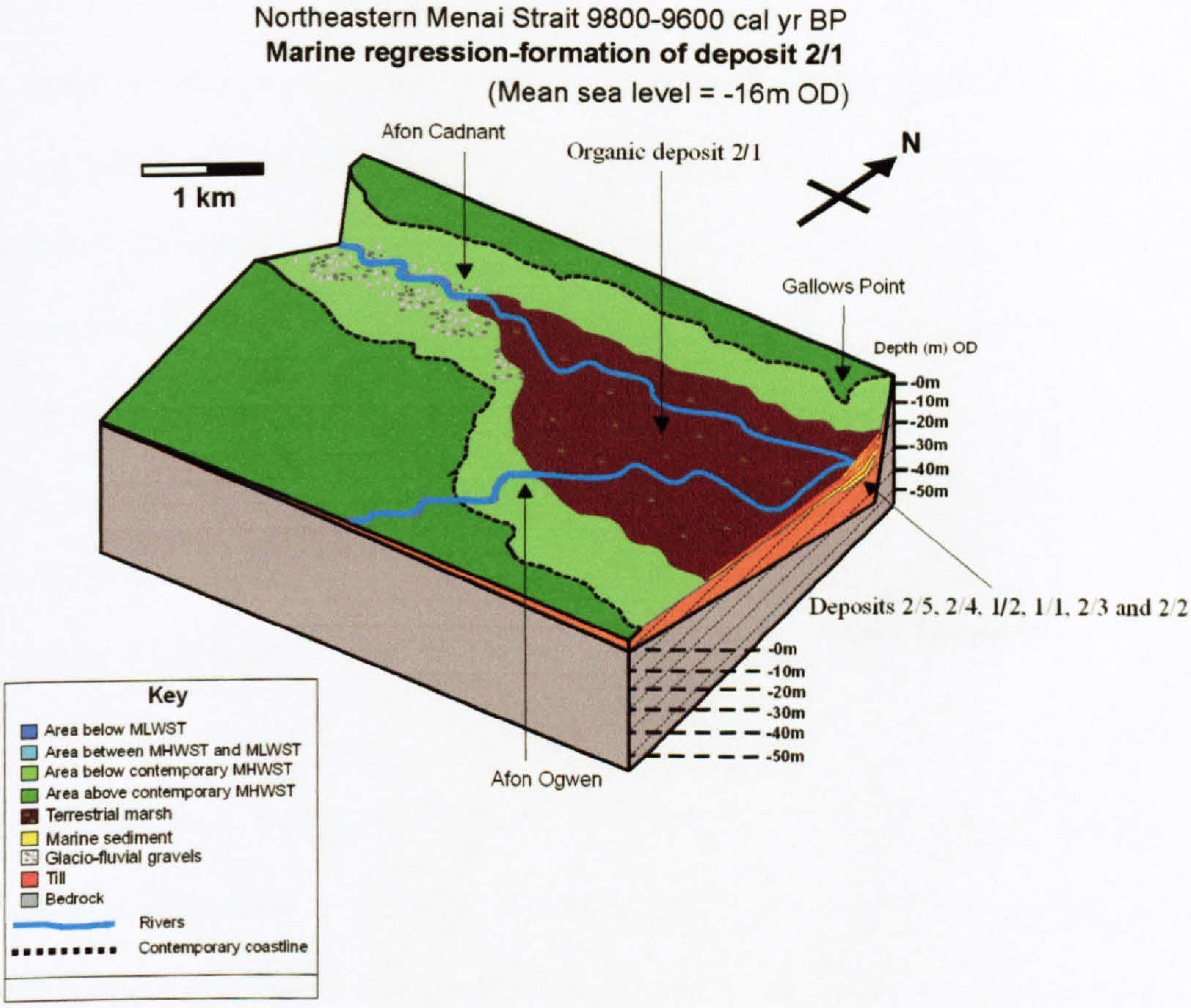
The data demonstrate that within the northeastern Menai Strait during the early Holocene, subsequent to the deposition of deposit 1/1, marine conditions were interspersed with at least five periods of terrestrial sedimentation over a period of approximately 2000 years. Terrestrial conditions were characterized by the continual and brief redevelopment of saltmarsh and low-lying freshwater marsh, as relative sea levels fluctuated during a period of time associated with a rapid rise in eustatic sea level.

Marine conditions within the area were represented by the development of shallow sandflat and mudflat which rapidly encroached over areas of newly developed saltmarsh and areas of low-lying freshwater marsh. Water depth probably remained relatively shallow, with inter-tidal conditions persisting within periods of marine influence. The inter-tidal region was undoubtedly characterized by zones of variable salinity, with regions of low salinity related to the freshwater drainage pattern of the time.

Block diagrams shown in figures 19 and 20 illustrate the lateral extent and continual alternating development of saltmarsh and marine environments throughout the early Holocene within the area between Gallows Point and Bangor Pool.

5.2.6 Deposits 3/2 and 3/1

The data indicate a continued alternation between shallow inter-tidal and terrestrial deposits, subsequent to the deposition of deposit 2/1. At least five additional near-horizontal reflective horizons are identified at elevations greater than -8.0m OD within transects obtained during the seismic survey. The nature and characteristics of the



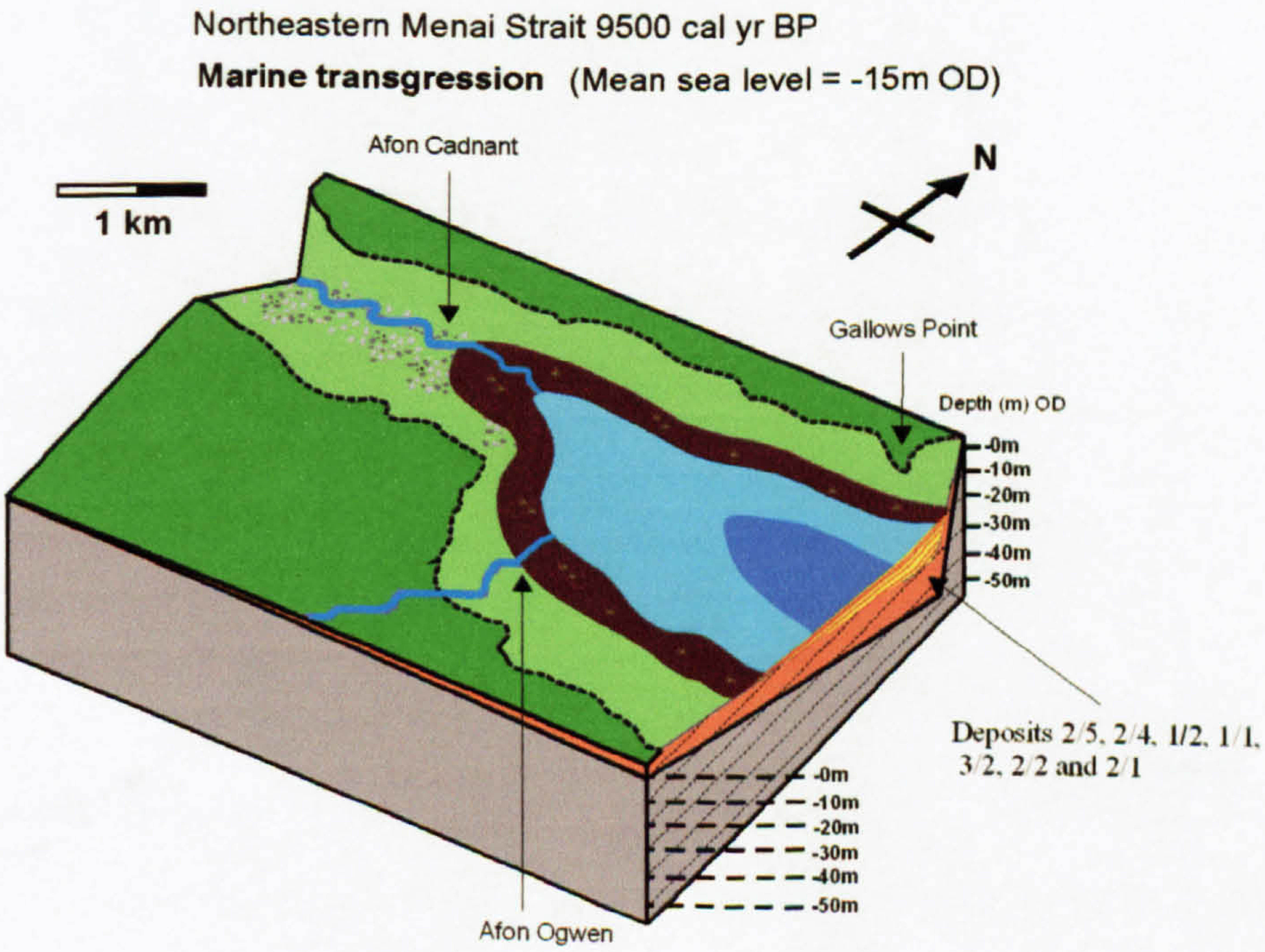


Figure 5.19 Block diagrams illustrating the development and drowning of deposit 2/1 within the Menai Strait between 9600 and 9500 calendar years BP through successive regressive and transgressive phases

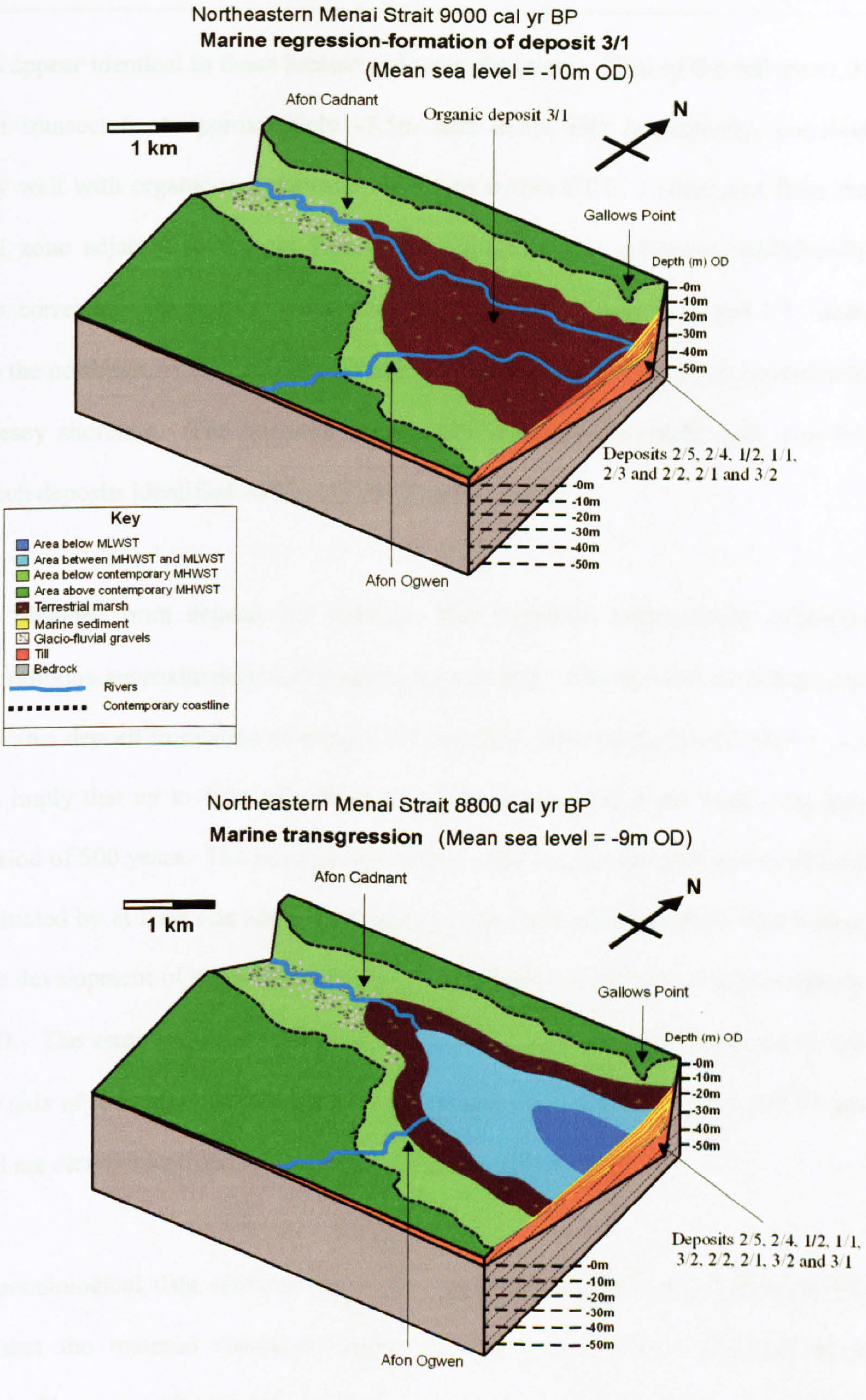


Figure 5.20 Block diagrams illustrating the development and drowning of deposit 3/1 within the Menai Strait between 9000 and 8800 calendar years BP through successive regressive and transgressive phases

reflectors appear identical to those located at lower elevations. Two of the reflectors, K and L in transect 6 at approximately -7.5m and -6.5m OD respectively, correlate extremely well with organic-rich deposits identified within CJSC 3 recovered from the inter-tidal zone adjacent to Bangor Pier. The altitude of the reflectors, additionally appear to correlate well with horizons identified within transects 7, 9 and 27, taken further to the northeast, as far as Gallows Point, as well as within transect 16, proximal to the Anglesey shoreline. The horizons additionally correlate extremely well with the organic-rich deposits identified within OS BH 2 and 3.

The date obtained from deposit 3/2 indicates that terrestrial sedimentation replaced marine conditions approximately 9,210 calendar years BP. The age and stratigraphical context of this deposit in relation to deposit 2/1, together with the degree of relative sea level rise imply that up to 4.6m of sediment may have been deposited within the area over a period of 500 years. The seismic data additionally suggest that this period of time was punctuated by at least one additional phase of terrestrial sedimentation, which gave rise to the development of materials represented by reflective horizon J at approximately -9.0m OD. The remnants of this deposit appear to be predominantly confined to the Anglesey side of the main channel and further towards the southeast beneath the Traeth Lafan and are clearly identified within transects 10, 12, 16 and 29.

Micropalaeontological data obtained from the sediments located beneath deposit 3/2 indicate that the material represent inter-tidal conditions, possibly proximal to a saltmarsh. Plant macrofossil data indicate that the terrestrial sediments constituting deposit 3/2 possibly represent material deposited within a reedswamp (C. Turner, pers. comm. 2004). Radiocarbon data from the upper contact of deposit 3/2 suggest that terrestrial conditions were maintained for approximately 700 years within the northeastern Menai Strait; this appears excessive given that the data indicate a period of rapid relative sea-level rise at this time; the accuracy of the date obtained from the upper contact is therefore questionable.

Inorganic sediments located immediately above the contact indicate the relatively rapid return of marine conditions, with approximately 1.0m of inter-tidal sedimentation, probably representing a low energy environment, being deposited above the dated contact. Terrestrial conditions represented by the formation of deposit 3/1 at -6.68m OD appear to have returned for a brief period of time by 9,010 calendar years BP.

The age of the dated horizons within CJSC 3 appear questionable given their respective stratigraphical context in comparison with the available palynological and sea-level data; consequently a degree of caution must be associated with the timing of any environmental change interpreted to have occurred within the area between 9,210 and 8,490 calendar years BP. It is clear, however, that deposits 3/2 and 3/1 represent phases of terrestrial sedimentation during this period, with plant macrofossil data indicating that the sediments within deposit 3/2 probably represent material deposited within a brackish pool or ditch, probably adjacent to an alder swamp; with deposit 3/1 containing material derived from an adjacent saltmarsh (C. Turner, pers. comm. 2004). Given the altitude of the deposits in CJSC, and their derived age in the context of the evolution of the Menai

Strait; it is possible that sediments originating from the southwestern region, containing a higher level of inert carbon may have been deposited at this location at any time after approximately 8000 calendar years BP.

Seismic data additionally indicate that the presence of at least two additional terrestrial deposits at altitudes of -3.0m and -2.0m OD. The reflectors do not appear to be as laterally extensive as other lower horizons and appear to be confined to areas towards Gallows Point. Based on the estimated trend of relative sea level within this area, the predicted age of these deposits would be between 7800 and 6300 calendar years BP.

These upper deposits represent areas of terrestrial sedimentation that interspersed periods characterized by the presence of shallow inter-tidal conditions within the northeastern Menai Strait, that were maintained until approximately 6300 calendar years BP.

5.2.7 Evolution of the contemporary tidal channel

Throughout the study area, the lateral extent of the near-horizontal, alternating marine-terrestrial sequences are confined by the underlying morphology of the bedrock and the glacial deposits. The morphology of the seabed additionally defines the distribution of the sedimentary sequences, with the shallower sequences appearing to terminate abruptly on both sides of the main channel. Lower sequences additionally terminate immediately adjacent to the two depressions located at Bangor Pool and Gallows Point. The stratigraphy, age and distribution of the sedimentary sequences within the study area demonstrate clearly that during the early Holocene, shallow inter-tidal marine conditions were frequently and briefly succeeded by terrestrial sedimentation, associated with environments characterized by the development of low-lying terrestrial marsh.

The topography, nature and distribution of the sedimentary sequences imply that at one time they extended continuously across the Menai Strait, between the Traeth Lafan and the Anglesey shoreline. The termination patterns of the terrestrial sedimentary sequences proximal to the main channel and depressions at Bangor Pool and Gallows Point indicate that the contemporary bathymetrical profile of the main channel was formed subsequent to the deposition of the upper organic-rich sediments.

Data resulting from the generation of the relative sea-level curve produced during this research project indicate that sea levels within the region of the Menai Strait continued to rise throughout the early and middle Holocene, with relative sea level rising by approximately 23m between 11000 and 6000 calendar years BP.

The sea-level curve generated by these data applies to the region of North Wales encompassing both the southwestern and northeastern Menai Strait. The data therefore imply that sea levels rose at similar rates throughout the local area, with the southwestern region of the Menai Strait probably experiencing similar palaeoenvironmental change and rates of sea-level change. It is therefore highly probable that both extremes of the Menai Strait experienced similar rates of marine inundation, with both the southwest and northeastern regions being characterized by the alternating development of marsh and inter-tidal environments as sea level rose rapidly during the early Holocene. As the

Menai Strait became progressively inundated from both the southwest and northeast, the elevated central section, would have formed a final terrestrial corridor linking Anglesey to the mainland (fig. 5.21).

According to Harvey (1968), the mean spring and neap tidal ranges at Menai Bridge are 6.6m and 3.4m respectively. Unpublished research (Uehara *et al.*, in press) however, suggests that North Wales may have experienced an increase in tidal range of approximately one metre during the early to middle Holocene. Bathymetrical data recorded on Admiralty Chart 1464 produced for the area indicates that the shallowest region of the Swellies occurs around Cribbin Rock and Ynys Gorad Goch, approximately 200m northeast of the Brittania Bridge. The seabed surface at this location is at an average altitude of approximately -5.3m OD, which indicates that the average water depth at Mean Low Water Spring Tide (MLWST) within this region is of the order of 2.0m. Due to the strong currents present within the central region of the Menai Strait, the sea-bed surface over a distance of approximately 1.5km within the area of the Swellies consists predominantly of exposed bedrock with minimal unconsolidated marine sediment present.

An attempt to ascertain the timing of the breaching of the central region has assumed that unconsolidated sediment has always been absent from this region and ignores any effect that changes in bathymetry may have had on tidal range within this region of North Wales. Extrapolation of the bathymetrical and tidal data with respect to the relative sea-level curve derived for the area, together with ignoring the possible effects of changes in

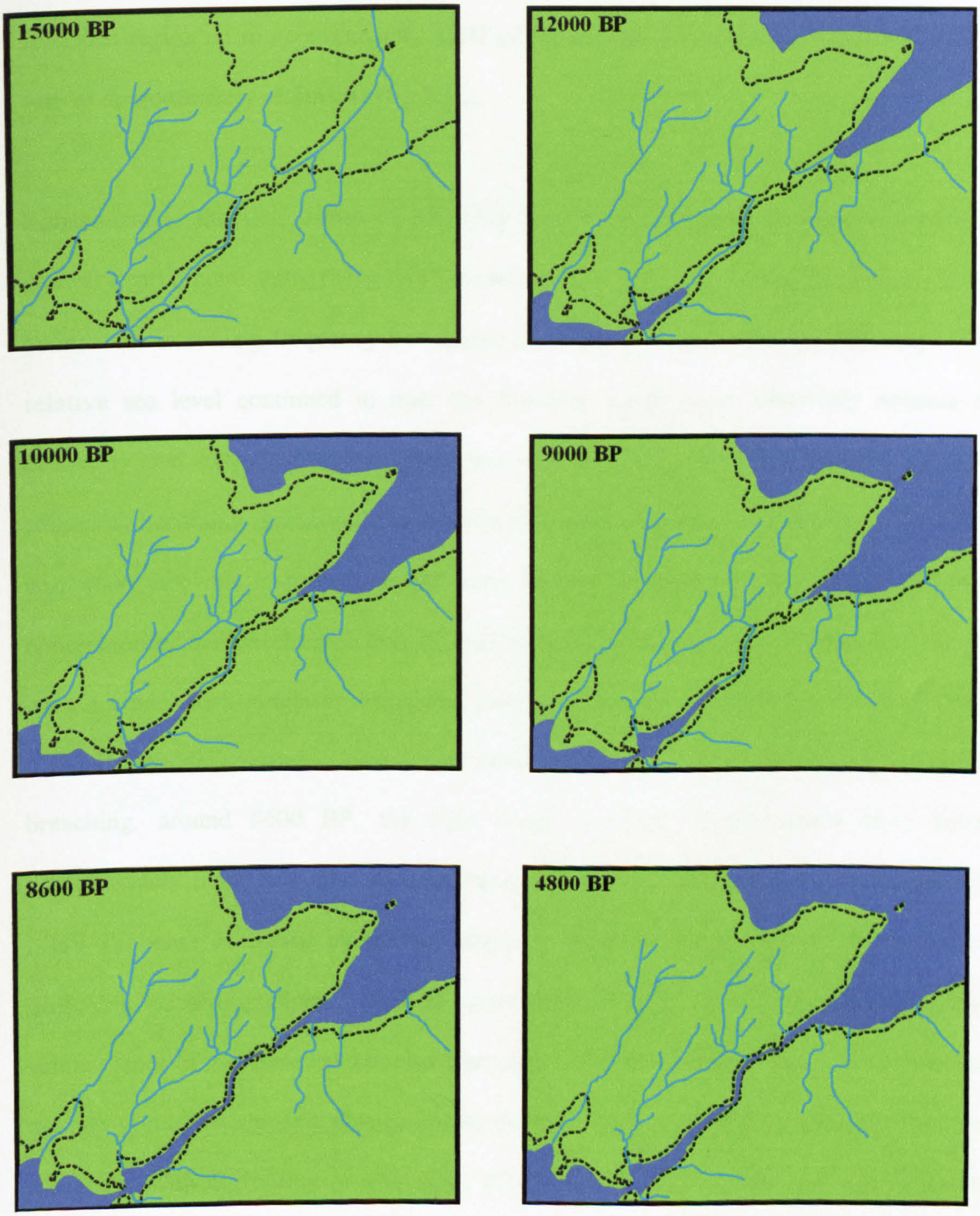


Figure 5.21 Schematic illustrating the gradual inundation of the Menai Strait through rising relative sea-levels during the Lateglacial and early Holocene

tidal range, infers that marine conditions were probably entirely absent within the Swellies region up to approximately 8600 calendar years BP when the altitude of MSL was at approximately -8.5m OD (fig 5.22).

Subsequent to this date, times of MHWST would have ensured the breaching of the central region; continually rising relative sea levels would have caused this breaching to occur with increasing frequency throughout the early part of the middle Holocene. As relative sea level continued to rise, the Swellies would have effectively become a causeway that extended between Anglesey and the mainland; with exposure of this causeway becoming increasingly infrequent (fig 5.23). Between approximately 5600BP and 4800 BP, this causeway would have become permanently submerged and the contemporary marine channel that extends between Beaumaris and Caernarfon would have formed, with Anglesey becoming permanently isolated from the mainland (fig. 5.24). Palaeotidal research (Uehara *et al.*, in press) indicates that at the time of the initial breaching, around 8600 BP, the tidal range in North Wales would have been approximately 0.5m less than its contemporary value. This relates to the altitude of MHWST being decreased by 0.25m, which would result in the timing of the initial breaching occurring slightly later at approximately 8400 BP. The date for final submergence of the causeway remains inaccurately defined due primarily to a decrease in the rate of relative sea-level change during the latter part of the middle Holocene. Errors associated with attempting to accurately determine both the altitude and age of index points, combined with uncertainties relating to the palaeobathymetry of the central region

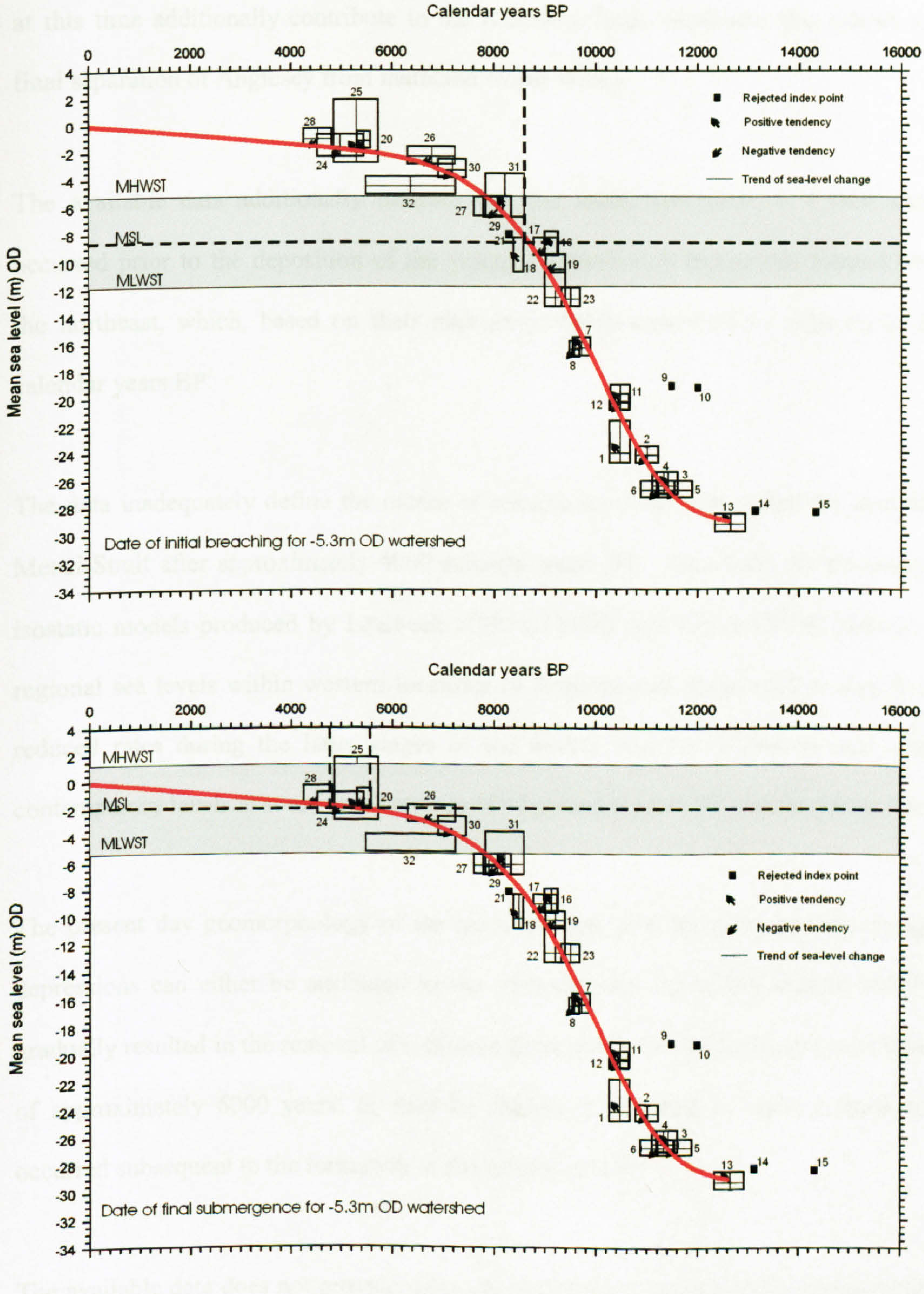


Figure 5.22 Sea level curves demonstrating timing of the initial breaching and final submergence of the causeway within the central region of the Menai Strait

at this time additionally contribute to the relatively large timeframe that relates to the final separation of Anglesey from mainland North Wales.

The available data additionally indicate that the initial formation of a tidal channel occurred prior to the deposition of the younger organic-rich formations located toward the northeast, which, based on their altitude probably continued to form up to 6300 calendar years BP.

The data inadequately define the nature of relative sea-level rise within the area of the Menai Strait after approximately 4000 calendar years BP. Data from the glacio-hydro-isostatic models produced by Lambeck (1995), (1996) and Peltier (1994) indicate that regional sea levels within western localities of England and Wales rose at significantly reduced rates during the latter stages of the middle and late Holocene and attained contemporary levels at some time between 6000 calendar years BP and the present day.

The present day geomorphology of the main channel with the characteristic elongated depressions can either be attributed to the contemporary dynamical regime which has gradually resulted in the removal of sediment from within the main channel over a period of approximately 6000 years; or may be related to a period of rapid erosion which occurred subsequent to the formation of the marine channel.

The available data does not provide adequate information relating to the lateral extent of the uppermost reflective horizons termed M and N, which are assumed to represent

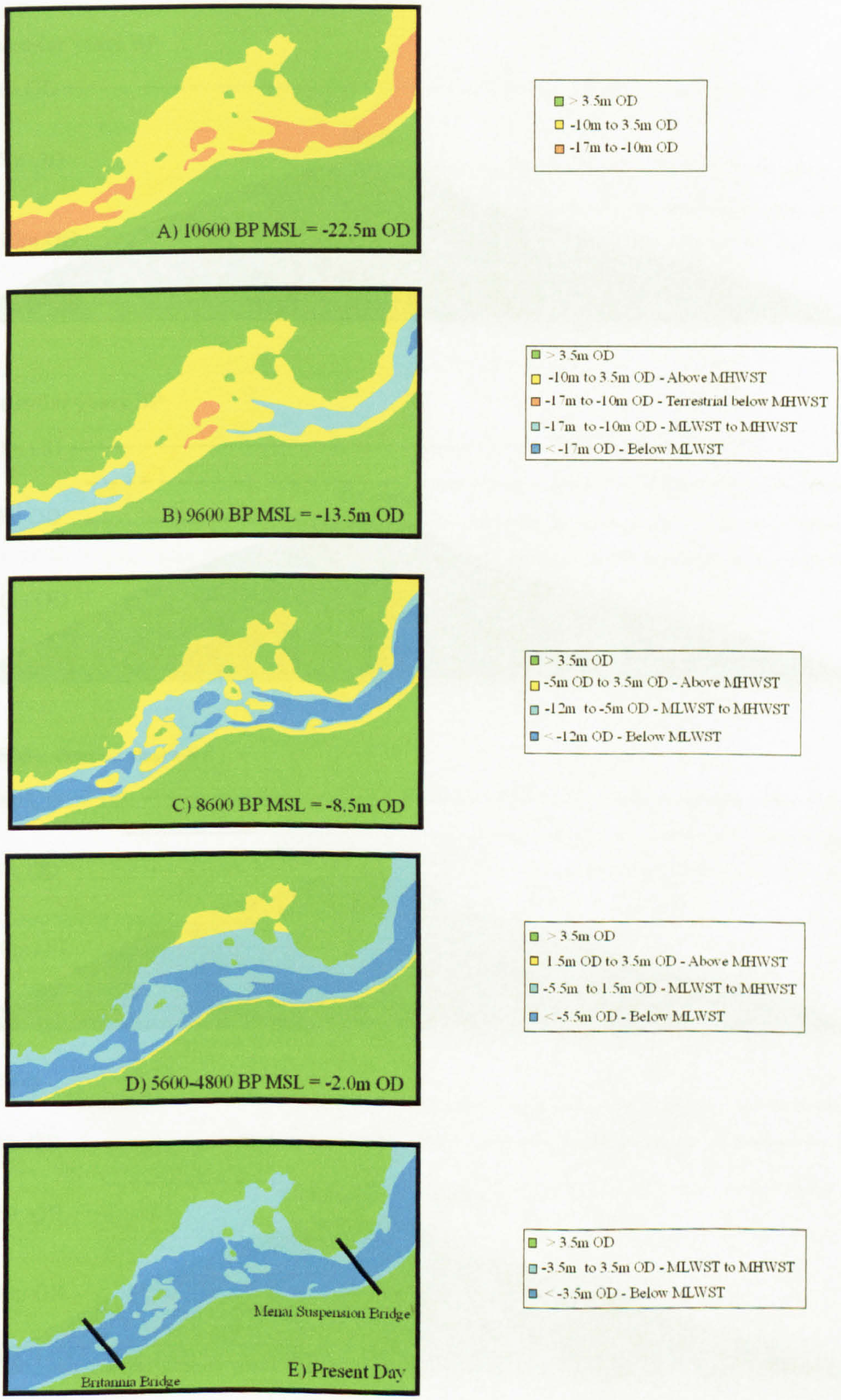


Figure 5.23 Schematic illustrating the flooding of the 'Swellies' central region of the Menai Strait during the early to middle Holocene

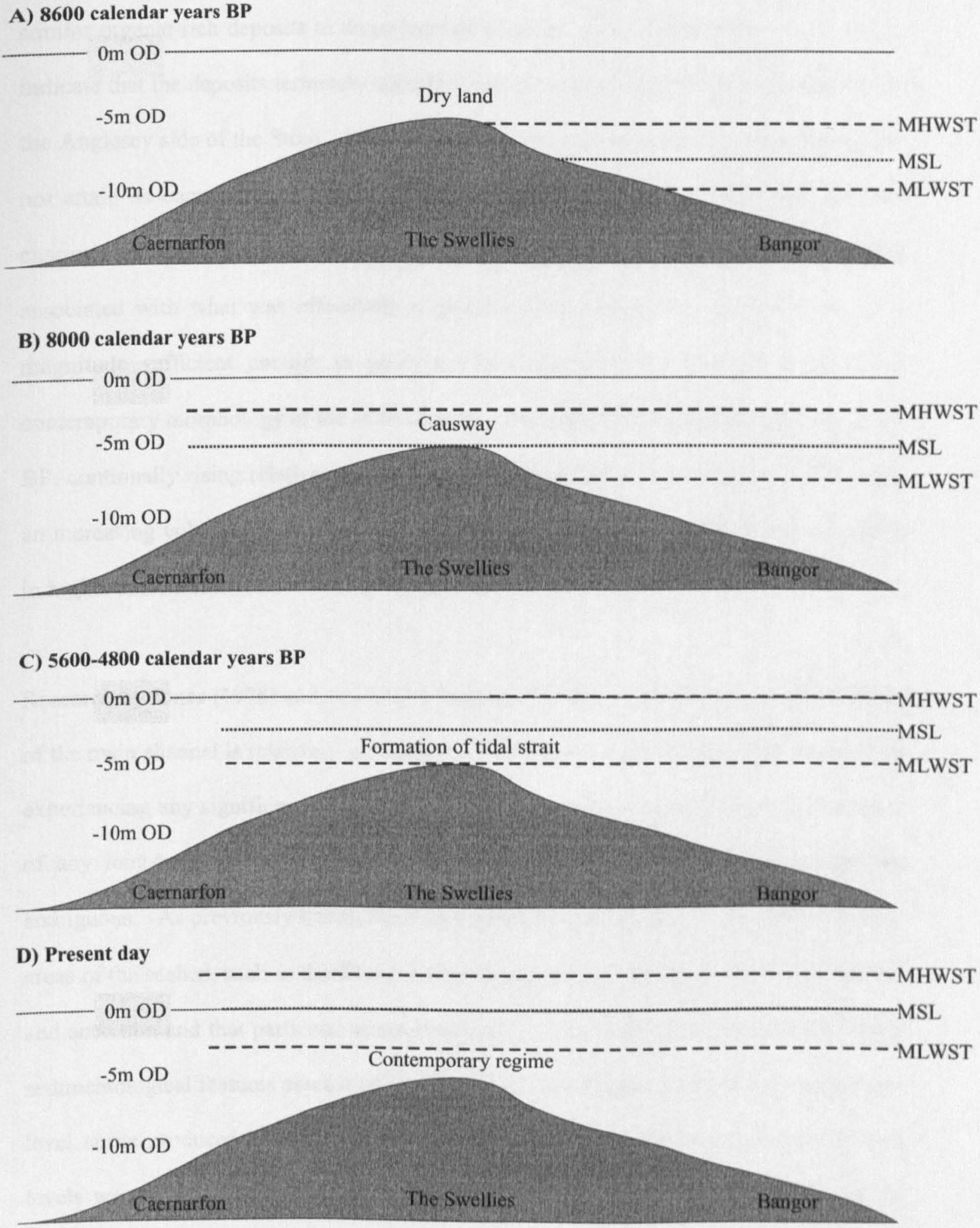


Figure 5.24 Schematic cross-section illustrating the height and timing of MSL in relation to the flooding of the 'Swellies' central region of the Menai Strait during the early to middle Holocene

similar organic-rich deposits to those located beneath. The seismic data does, however, indicate that the deposits terminate abruptly immediately adjacent to the main channel on the Anglesey side of the Strait. This may possibly be evidence that the main channel did not attain its contemporary form, immediately subsequent to the evolution of the tidal channel between 5600 and 4800 calendar years BP. The flow of water initially associated with what was effectively a juvenile tidal channel, was probably not of a magnitude sufficient enough to generate the scouring action required to form the contemporary morphology of the main channel. After approximately 4800 calendar years BP, continually rising relative sea levels ensured that during each successive tidal cycle an increasing volume of seawater was forced through the narrow tidal channel, resulting in higher current flow.

Research by Jones (1978) and Ali (1992) suggests that the contemporary geomorphology of the main channel is relatively stable and that the main features of the Strait may not be experiencing any significantly appreciable degrees of erosion or accretion. The absence of any long-term or accurate data, however, ensures that this interpretation remains ambiguous. As previously stated, the dynamics of the Menai Strait ensure that particular areas of the seabed, such as the Traeth Lafan do experience significant degrees of erosion and accretion and that particular areas experience the formation and movement of many sedimentological features associated with contemporary marine processes. If, as the sea-level curve produced by Bedlington (1994) and this thesis suggest, contemporary sea levels were attained within North Wales relatively recently, then the formation of the contemporary bathymetrical profile of the Menai Strait probably took place over a period several thousand years subsequent to 4800 calendar years BP, as relative sea level rose by approximately 2.0m in order to attain its contemporary level.

The data indicate that initial breaching of the Menai Strait took place approximately 8600 calendar years BP and that final exposure of a causeway linking the Anglesey to mainland North Wales occurred between approximately 5600 and 4800 calendar years BP. The intervening period would have been characterized by the causeway becoming exposed with decreasing frequency. Subsequent to 4800 calendar years BP, relatively shallow water inter-tidal conditions within the region of the Swellies would have ensured continual although reduced development of marsh areas over much of the northeastern Menai Strait. These areas were bisected within the region of the main channel by what was a juvenile version of the contemporary Menai Strait which would have been characterized by relatively minor tidal current flow. As relative sea level continued to rise over the next several thousand years, the channel would have been characterized by the development of strong tidal currents, resulting in the scouring of sediments from within the region of the main channel. The removal of sediments from within this region would have probably coincided with the deposition of marine sediments over large areas of the Traeth Lafan, as relative sea levels continued to rise until the present day.

The contemporary morphology of the Menai Strait, together with the formation of the main channel can in all probability be attributed to processes that occurred subsequent to 4800 calendar years BP. Contemporary dynamical studies by Harvey (1968) and Ali (1992) conducted within the northeastern region of the Menai Strait demonstrate the presence of a residual current together with a net sediment transport flowing toward the southwest. Relatively strong contemporary current flow effectively ensures the removal of fine grained sediments from within the vicinity of the main channel, resulting in the dominance of coarser grained sediments and shell debris at the seabed.

Seismic data obtained by Cook (1980), Osiris Seaway Ltd. (1986) and Butcher (1997), together with lithological data obtained from CJSC 1 demonstrate that the sediments located immediately adjacent to the main channel on the mainland side of the Menai Strait at Bangor Pool, are separated from the near-horizontal deposits by what Butcher (1997) terms a sequence boundary. The data indicate that the material located above the boundary display significantly dissimilar patterns of deposition, with the sediments appearing to have been deposited within what appears to be a pre-existing channel, parallel and adjacent to the position of the contemporary main channel. The lithological data obtained from CJSC 1 indicates that the sediments possibly represent reworked material, possibly deposited as the main channel has migrated slightly towards the north, at some time subsequent to its formation.

The absence of organic-rich deposits within the sediment cores recovered by Project Engineering and Management Services Ltd. (1971) from beneath the Traeth Lafan may provide evidence that terrestrial conditions were laterally restricted to the area, southwest of Beaumaris. The absence of fine grained sediments and organic-rich material beneath the Traeth Lafan may also be attributable to the more exposed position of this location with respect to Liverpool Bay and frequently occurring northerly winds, that would have contributed to the erosion and reworking of any fine grained sedimentary deposits.

The intercalated organic-rich deposits identified within the northeastern region of the Menai Strait appear characteristically similar to other sequences identified throughout the northwest of Britain. Shennan and Horton (2002) demonstrate that intercalated deposits provide the majority of dated index points that are utilized in the generation of local sea-level curves and although problems have been identified with respect to the utilization of these index points, they are effective in providing reasonable indications relating to the nature of relative sea-level change.

With respect to the northwest of England and North Wales, much of the sea-level index data previously utilized within this field of research has been derived from deposits located between -10.0m and 5.0m OD. The sea-level curves produced by Shennan and Horton (2002) indicate that a total of twelve index points located beneath -10.0m OD are available for the entire northwest of England and Wales and that these were largely derived from areas of Morecambe Bay and the coast of Lancashire. This research project identifies eleven intercalated index points, together with two additional basal index points, between -26.0m and -10.0m OD from the region of the Menai Strait. Insufficient evidence is available at the present time to suggest that some of the intercalated organic-rich sequences actually represent more regional-scale periods of palaeoenvironmental change or indeed fluctuations within the global sea-level record. Further research would be required in order to determine whether the sequences originated due to large-scale processes rather than more localized physical regimes.

Chapter 6

6 Introduction

The overall aim of this study was to generate a qualitative and quantitative palaeoenvironmental framework relating to the evolution of the Menai Strait subsequent to the Late Devensian Dimlington Stadial, primarily through identifying aspects of sea-level change within North Wales during the course of the Holocene. Chapter 6 presents a series of conclusions relating to the project's initial aims and objectives and further outlines a programme of possible future research deemed to be of relevance.

6.1 Conclusions

This research project has utilized a multidisciplinary approach in order to investigate the stratigraphy of sediments located within the northeastern region of the Menai Strait in North Wales. Lithostratigraphic, biostratigraphic and geophysical evidence has been integrated with radiocarbon data in order to generate a series of hypotheses which describe:

- The altitude of relative mean sea level within the region of North Wales throughout the early and middle Holocene and its relationship with respect to the formation of the Menai Strait.

- The palaeoenvironmental evolution of the northeastern Menai Strait during this period and the mechanisms which contributed to the process.

The findings of the research project were as follows:

Micropalaeontological and radiocarbon evidence obtained from material located at the inorganic-organic contacts integrated with pre-existing data demonstrate that within North Wales at the onset of the Holocene, relative mean sea level was at approximately -26m OD. The evidence demonstrates that marine conditions existed towards the extreme northeastern end of the Menai Strait as early as around 14000 calendar years BP and that the altitude of relative sea level increased rapidly between the early and middle Holocene. Between 11000 and 7500 calendar years BP, the northeastern Menai Strait was characterized by marine conditions, which were frequently interspersed by periods of terrestrial sedimentation, as relative sea level rose by approximately 22m. Comparisons between the data obtained during the course of this research project and data obtained from other areas of the UK and within the Western Pacific lead to a tentative suggestion that some periods of terrestrial sedimentation may possibly relate to the occurrence of regional or even global fluctuations in rates of sea-level rise rather than simply representing more localized processes. This is indicated by the fact that a reasonable degree of correlation can be made between the independent development of organic-rich sequences at locations within North Wales and other areas in northwest England (Tooley, 1978, 1982) and in the Yellow Sea (Liu *et al.* 2004).

Between 8600 and 6300 calendar years BP, relative sea levels rose at a much reduced rate; during which time the central region of the Menai Strait was probably breached for the first time by rising sea levels encroaching from both the southwest and the northeast.

The initial breaching probably resulted in the formation of an inter-tidal causeway which existed for approximately 3000 years, prior to the formation of the contemporary tidal channel and the separation of Anglesey from mainland North Wales between 5600 and 4800 calendar years BP. The evidence indicates that relative sea level continued to rise, albeit at a reduced rate, up to at least 5000 calendar years BP, where it attained an altitude of approximately -2m OD. The available data does not adequately define the position of relative sea level subsequent to this time.

Geophysical and sedimentological evidence shows that within the northeastern region of the Menai Strait, unconsolidated sediments located between Bangor Pier and Beaumaris predominantly consist of a series of inter-tidal sediments, intercalated by at least eleven near-horizontal, laterally extensive organic-rich horizons which accumulated through terrestrial sedimentation. Geophysical evidence delimits that the lateral extent of the marine and terrestrial sediments within this area and demonstrates that their distribution is primarily governed by the morphology of the underlying bedrock and glacial geology. Lithological and micropalaeontological evidence demonstrates that the inorganic sedimentary deposits that separate the organic-rich horizons were predominantly derived through marine processes.

Foraminifera, pollen and plant macrofossils contained within the sediment located proximal to the inorganic-organic contacts has been used in an attempt to identify individual sedimentary facies and to discern aspects of local ecological change. The evidence demonstrates that between 11000 and 6300 calendar years BP, the northeastern region of the Menai Strait was characterized by the existence of low-energy inter-tidal environments, which were frequently but briefly replaced by the development of low-lying terrestrial marsh. After approximately 8000 calendar years BP the rate of sea level rise decreased dramatically, however this continued rise eventually resulted in the formation of the contemporary tidal channel.

The evidence indicates that at some point after approximately 6300 calendar years BP, changes with respect to the hydro-dynamical regime resulted in a significant degree of erosion. Increased current flow, which can be associated with a continued rise in sea level, probably accounts for the Menai Strait's contemporary bathymetrical profile, which is characterized by elongated hollow depressions such as those located at Bangor Pool and Gallows Point. The incising of the main channel, within sediments that had previously accumulated as inter-tidal and low-lying terrestrial marsh deposits within the northeastern region of the Menai Strait, accounts for the termination patterns of reflective horizons evident within geophysical records obtained from within the study area. Foraminifera assemblages contained within the inorganic sediments adjacent to the inorganic-organic contacts provide evidence to suggest that during the latter stages of terrestrial sedimentation, marine inter-tidal conditions gradually encroached landward, inundating low-lying land and resulting in the formation of saltmarsh and inter-tidal mudflat. The evidence demonstrates that this situation reversed, with sediments reflecting the seaward encroachment of terrestrial sedimentation as relative sea level apparently began to fall. The research demonstrates that this pattern of environmental change repeated itself on at least eleven occasions during the early and middle Holocene.

The utilization of seismic reflection surveying techniques proved invaluable in terms of determining the lateral extent of different sediment facies identified within a series of sediment cores. This resulted from an excellent degree of correlation between seismic reflective horizons identified within the seismic records and the occurrence of individual organic-rich deposits identified within each sediment core.

The evidence demonstrates that the intercalated organic-rich horizons within the sequences of marine sediment represent successive transgressive and regressive phases of relative sea level change. The evidence additionally demonstrates the occurrence of an enhanced rate of relative mean sea level rise during the early Holocene. Based on the available evidence the reasons for the development of alternating terrestrial and marine sedimentation remain unclear. They may be attributable to localized sedimentological processes or may more significantly, represent more regional or global fluctuations in rates of sea-level rise. Although reasonable correlations can be made with respect to the timing and occurrence of similar sequences at other locations on a range of lateral scales, it would be extremely tenuous and/or difficult at best to invoke such a mechanism given the limited volume and quality of the evidence currently available.

The research additionally demonstrates the need, wherever possible, for researchers to adopt a unified methodology in order to effectively correlate studies on a larger than local scale. The study also demonstrates that local, regional and global factors all need to be taken into consideration when attempting to understand the development and palaeoenvironmental evolution of an area which is ultimately a small component within a much larger system.

The study will further contribute invaluable information to the existing UK sea-level dataset, as sea-level index points relating to the Late Devensian and early-middle Holocene are currently under-represented and relate to a period of rapid sea-level rise and crustal movement. The data will therefore be useful to geophysicists in terms of constraining or modifying parameters such as ice volume, mantle viscosity and crustal thickness.

6.2 Further research

The extent of sea-level change within the northeastern Menai Strait has been successfully defined during the period of the early Holocene, however, the nature of sea-level change subsequent to approximately 8000 calendar years BP remains ambiguous. Additional data is therefore required from organic-rich horizons within the region of the northeastern Menai Strait at altitudes greater than approximately -6m OD, in order to elucidate the nature of middle to late Holocene sea-level change.

Similarly the nature of Holocene palaeoenvironmental change within the southwestern region of the Strait remains unclear and therefore this area warrants additional study, in order to validate the hypothesis generated by this investigation.

Supplementary data from sediment cores recovered from within the study area would perhaps provide additional correlation with the findings of this study, together with refining the conceptual palaeoenvironmental model relating to the evolution of the Menai Strait.

An additional and more detailed micropalaeontological examination of the inorganic sediments immediately adjacent to the organic-rich sedimentary contacts would probably provide greater control and further insight into aspects of palaeoenvironmental change.

Future more detailed investigations related to the nature and availability of pre-existing sea-level data, sediment core material and sea-level studies conducted on both a regional and local scale may provide additional evidence relating to the occurrence of small but possibly significant fluctuations in rates of eustatic sea-level rise subsequent to the LGM.

References

Addison, K., Edge, M.J. and Watkins, R. (*eds.*) (1990). The Quaternary of North Wales: Field Guide. Quaternary Research Association, Coventry, England.

Aitkin, M.J. (1990). *Science-based Dating in Archaeology*. Longmans, London.

Ali, A. (1992). Sedimentological, geophysical and oceanographic studies of postglacial and contemporary sedimentary processes of the NE Menai Strait and Conwy Bay (Wales, U.K.). Unpublished Ph.D thesis, University of Wales, Bangor.

Allan, D. (1985). Seismic stratigraphic analysis of the northeast Menai Strait. Unpublished M.Sc thesis, University of Wales, Bangor.

Atkinson, T.C., Briffa, K.R. and Coope, G.R. (1987). Seasonal temperatures in Britain during the past 22,000 years, reconstructed using beetle remains. *Nature,* **325**, 587-592.

Austin, R.M. (1991). Modelling Holocene tides on the NW European continental shelf. *Terra Nova*, **3**, 276-288.

Austin, W.E.N. (1991). Late Quaternary foraminiferal stratigraphy of the Western UK continental shelf. Unpublished Ph.D thesis, University of Wales, Bangor.

Bard, E., Hamelin, B., Fairbanks, R.G. and Zindler, A. (1990). Calibration of the ^{14}C timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados corals. *Nature*. **345**, 405-410.

Bard, E., Hamelin, B., Arnold, M., Montaggioni, L., Cabioch, G., Faure, G. and Rougerie, F. (1996). Deglacial sea-level record from Tahiti corals and the timing of global meltwater discharge. *Nature*. **382**, 241-244.

Bedlington, D.J. (1994). Holocene sea-level changes and crustal movements in North Wales and Wirral. Unpublished Ph.D thesis, University of Durham.

Berglund, B.E and Ralska-Jasiewiczowa, M. (1986). *Pollen analysis and pollen diagrams*. In Berglund, B.E. (Ed) Handbook of Palaeoecology and Palaeohydrology. John Wiley & Sons, New York.

Bibby, H.C. (1940). The submerged forests at Rhyl and Abergele, North Wales: data for the study of postglacial history IV. *New Phytologist*. **39**, 220-225.

Birks, H.J.B. and Birks, H.H. (1980). *Quaternary Palaeoecology*. Edward Arnold, London.

Blake, J.F. (1888). Introduction to the Monian System of Rocks. *Quarterly Journal of the Geological Society of London.* **44**, 463-547.

Boitier, D.J. (1982). A sub-bottom and seabed investigation of the Menai Strait south of the Britannia Bridge. Unpublished M.Sc thesis, University of Wales, Bangor.

Boulton, G.S. (1977). A multiple till sequence formed by a Late Devensian Welsh ice-cap: Glanllynnau, Gwynedd. *Cambria*, 4, 410-431.

Boulton, G.S. (1992). Quaternary. In Duff, P.McI.D. & Smith, A.J. (*eds.*) Geology of England and Wales. *The Geological Society of London*, 413-444.

Bowen, D.Q. (1973). The Pleistocene succession in the Irish Sea. *Proceedings of the Geologists Association.* **84**, 249-272.

Bowen, D.Q. (1974). The Quaternary of Wales. In Owen, T.R. (*ed.*) *The Upper Palaeozoic and Post-Palaeozoic Rocks of Wales*, University of Wales Press, Cardiff, 373-426.

Bowen, D.Q., Rose, J., McCabe, A.M. and Sutherland, D.G. (1986). Correlation of Quaternary glaciations in England, Ireland, Scotland and Wales. *Quaternary Science Reviews.* **5**, 299-340.

Bowman, S. (1990). *Interpreting The Past, Radiocarbon Dating.* University of California Press.

Burrows, C.J. (1974). Plant macrofossils from Late-Devensian deposits at Nant Ffrancon, Caernarvonshire. *New Phytologist.* **73**, 1003-1033.

Burton, C.F. (1984). Geotechnical / Geophysical survey of Penmon Beach, N. Wales. Unpublished M.Sc thesis, University of Wales, Bangor.

Butcher, J.A. (1997). Seismic stratigraphy of shallow water Quaternary sediments around the U.K. Unpublished Ph.D thesis, University of Wales, Bangor.

Chappell, J. and Polach, H. (1991). Post-glacial sea-level rise from a coral record at Huon Peninsula, Papua New Guinea. *Nature.* **349**, 147-149.

Charman, D.J., Roe, H.M. and Gehrels, W.R. (1998). The use of testate amoebae in studies of sea-level change: a case study from the Taf Estuary, South Wales, UK. *The Holocene.* **8**, 209-218.

Clarke, K.R. and Warwick, R.M. (2001). Change in marine communities: An approach to statistical Analysis and interpretation. 2nd edition. PRIMER-E: Plymouth.

Cook, M.R. (1980). Geophysical-Hydrographic investigation of part of the Menai Strait southwest of Bangor Pier, with regard to it's feasibility for use as a pleasure craft marina. Unpublished M.Sc thesis, University of Wales, Bangor.

Coope, G.R. and Brophy, J.A. (1972). Late glacial environmental change indicated by coleopteran succession from North Wales. *Boreas.* **1**, 97-142.

Cooper, J.A.G., Kelley, J.T., Belknap, D.F., Quinn, R. and McKenna, J. (2002). Inner shelf seismic stratigraphy off the north coast of Northern Ireland: new data on the depth of the Holocene lowstand. *Marine Geology.* **186**, 369-387.

Devoy, R.J.N. (1987). Introduction: First principles and the scope of sea-surface studies. In R.J.N. Devoy (*ed.*) Sea Surface Studies: A Global View, London, Croon Helm, 1-33.

Devoy, R.J.N. (1995). Deglaciation, Earth crustal behaviour and sea-level changes in the determination of insularity: a perspective from Ireland. From: Preece, R.C. (ed.) Island Britain: a Quaternary perspective. Geological Society Special publication. **96**, 181-208.

Edge, M., Hart, J. AND Pointon, K. (1990). The sequences at Aber Ogwen and Glan-y-môr Isaf in Addison, K., Edge, M.J. and Watkins, R. (*eds.*). The Quaternary of North Wales: Field Guide. Quaternary Research Association, Coventry, England. 119-130.

Edwards, W. (1904). The Glacial Geology of Anglesey. *Proceedings of the Liverpool Geological Society.* **1904-1909**, 26-37.

Edwards, R. and Horton, B.P. (2006). Developing detailed records of relative sea-level change using a foraminiferal transfer function: an example from North Norfolk, UK. *Philosophical Transactions of the Royal Society.* **364**, 973-991.

Embleton, C. (1964). The deglaciation of Arfon and southern Anglesey and the origin of the Menai Strait. *Proceedings of the Geological Association.* **75**, 407-430.

Eyles, N. and McCabe, A.M. (1989). The Late Devensian (<22,000 BP) Irish Sea Basin: the sedimentary record of a collapsed ice sheet margin. *Quaternary Science Reviews.* **8**, 307-351.

Fægri, K. and Iversen, J. (1975). *Textbook of pollen analysis.* Munksgaard.

Fægri, K. and Iversen, J. (1989). *Textbook of pollen analysis.* John Wiley & Sons, New York.

Fairbanks, R.G. (1989). A 17,000-year glacio-eustatic sea-level record: influence of glacial melting rates on the Younger Dryas event and deep ocean circulation. *Nature.* London **342**, 637-642.

Fairbridge, R.W. (1961). Eustatic changes in sea-level. *Physics and Chemistry of the Earth.* **5**, 99-185.

Flemming, N.C. (1982). Multiple regression analysis of earth movements and eustatic sea-level change in the United Kingdom in the past 9000 years. *Proceedings of the Geological Association.* **93** (1), 113-125.

Fugro-McClelland. (1992). FML Report No. 92/3172-1(02). Welsh Water – Dwr Cymru Llanfaes Outfall. Fugro-McClelland.

Gehrels, W.R. (1994). Determining relative sea-level change from salt-marsh foraminifera and plant zones on the coast of Maine, USA. *Journal of Coastal Research.* **10**, 990-1009.

Gehrels, W.R. (1999). Middle and Late Holocene Sea-Level Changes in Eastern Maine Reconstructed from Foraminiferal Saltmarsh Stratigraphy and AMS ^{14}C Dates on Basal Peat. *Quaternary Research.* **52**, 350-359.

Gehrels, W.R., Roe, H..M. and Charman, D.J. (2001). Foraminifera, testate amoebae and diatoms as sea-level indicators in UK saltmarshes: a quantitative multiproxy approach. *Journal of Quaternary Science.* **16**, (3) 201-220.

Gehrels, W.R. and Newman, S.W.G. (2004). Salt-marsh foraminifera in Ho Bugt, western Denmark, and their use as sea-level indicators. *Danish Journal of Geography.* **104** (1), 97-106.

Gibbons, W. and Ball, M.J. (1991). A discussion of Monian Supergroup stratigraphy in Northwest Wales. *Journal of the Geological Society of London*, **148**, 5-8.

Gillespie, R. (1984). *Radiocarbon User's Handbook.* Oxford University Committee for Archaeology.

Godwin, H. (1955). Vegetational history at Cwm Idwal: A Welsh plant refuge. *Svensk Botanisk Tidskrift.* **49**, 35-43.

Goeury, C. (1997). Gestion, traitement et représentation de données de la paléoécologie. XVéine Symposium de l'A.P.L.F. Lyon. 31.

Gray, J.M. (1982). The last glaciers (Loch Lomond Advance) in Snowdonia, North Wales. *Geological Journal.* **17**, 111-133.

Greenly, E. (1919). The Geology of Anglesey. *Memoirs of the Geological Survey*, 2 volumes, London.

Hanebuth, T., Stattegger, K. and Grootes, P.M. (2000). Rapid flooding of the Sunda Shelf: A Late-Glacial Sea-Level Record. *Science.* **288**, 1033-1035.

Harkness, D.D. and Wilson, H.W. (1974). Scottish Universities Research and Reactor Centre Radiocarbon Measurements II. *Radiocarbon. 16*, 2, 238-251.

Hart, J. (1990). A re-interpretation of the sequence at Dinas Dinlle. in Addison, K., Edge, M.J. and Watkins, R. (*eds*.). The Quaternary of North Wales: Field Guide. Quaternary Research Association, Coventry, England. 63-70.

Harvey, J.G. (1968). The flow of water through the Menai Straits. *Geophysical Journal of the Royal Astronomy Society*. **15**, 517-528.

Haynes, J.R. (1973). Cardigan Bay recent foraminifera (cruises of the R.V. Antur, 1962-1964). *Bulletin of the British Museum* (Natural History) Zoology Supplement. **4**, 8-245.

Heyworth, A. and Kidson, C. (1982). Sea-level changes in southwest England and Wales. *Proceedings of the Geological Association*. **93**(1), 91-111.

Horton, B.P., Edwards, R.J. and Lloyd, J.M. (1999). A foraminiferal-based transfer function: implications for sea-level studies. *Journal of foraminiferal Research*. **29**, 117-129.

Ince, J. (1995). Late-glacial and early Holocene vegetation of Snowdonia. *New Phytologist*. **132**, 343-353.

Jehu, T.J. (1909). The glacial deposits of western Caernarvonshire. *Transactions of the Royal Society of Edinburgh*. **47**, 17-56.

Jennings, A.E. and Nelson, A.R. (1992). Foraminiferal assemblage zones in Oregon tidal marshes – relation to marsh flora zones and sea-level. *Journal of Foraminiferal Research*. **22**, 13-29.

Jones, S.J. (1978). The sedimentary history of Gallows Point. Unpublished M.Sc thesis, University of Wales, Bangor.

Kearey, P. and Brooks, M. (1991). An Introduction to Geophysical Exploration (2nd Edition). Blackwell Science.

Kenna, R.J.B. (1986). The Flandrian sequence of north Wirral (N.W. England). *Geological Journal*. **21**, 1-27.

Kidson, C. and Heyworth, A. (1973). The Flandrian sea-level rise in the Bristol Channel. *Proceedings of the Usher Society*. **2**, 565-584.

Kidson, C. (1986). Sea-level changes in the Holocene. In O. Van de Plassche (*ed*.) Sea-level Research: A manual for the collection and evaluation of data, Norwich, Geo Books. 27-64.

Kirby, E. (2003). The seismic stratigraphy of the Menai Strait. Unpublished B.Sc thesis, University of Wales, Bangor.

Lambeck, K. (1991). Glacial rebound and sea-level change in the British Isles. *Terra Nova.* **3**, 379-389.

Lambeck, K. (1995). Late Devensian and Holocene shorelines of the British Isles and North Sea from models of glacio-hydro-isostatic rebound. *Journal of the Geological Society of London.* **152**, 437-448.

Lambeck, K. (1996). Glaciation and sea-level change for Ireland and the Irish Sea since Late Devensian/Midlandian time. *Journal of the Geological Society of London.* **153**, 853-872.

Lambeck, K., Yokoyama, Y. and Purcell, T. (2001). Into and out of the Last Glacial Maximum: sea-level change during Oxygen Isotope Stages 3 and 2. *Quaternary Science Reviews.* **21**, 343-360.

Libby, W.F. (1955). Radiocarbon dating, 2nd Edition, University of Chicago Press, Chicago.

Liu, J.P., Milliman, J.D., Shu Gao and Peng Cheng. (2004). Holocene development of the Yellow River's subaqueous delta, North Yellow Sea. *Marine Geology.* **209**, 45-67.

Loeblich, A.R. and Tappan, H.T. (1988). Foraminiferal genera and their classification. Von Nostrand Rheinhold Company, New York.

Lowe, J.J. and Lowe, S. (1989). Interpretation of the pollen stratigraphy of Late Devensian Lateglacial and early Flandrian sediments at Llyn Gwernan, near Cader Idris, North Wales. *New Phytologist.* **113**, 391-408.

Lowe, J.J. and Walker, M.J.C. (1997) 2nd ed. *Reconstructing Quaternary environments.* Longmans, London.

Manley J. (1981). Rhuddlan and coastal evolution. Landscape History **3**, 1-15.

Mighall, T.M. and Chambers, F.M. (1995). Holocene vegetation history and human impact at Bryn y Castell, Snowdonia, North Wales. *New Phytologist.* **130**, 299-321.

Mitchell, G.F. (1960). The Pleistocene history of the Irish Sea. *British Association for the Advancement of Science.* **17**, 313-325.

Mitchell, G.F. (1972). The Pleistocene history of the Irish Sea: second approximation. *Scientific Proceedings of the Royal Society of Dublin.* A4 **13**.

Mook, W.G. and van de Plasshe, O. (1986). Radiocarbon dating. In van de Plassche, O. (ed) *Sea-level Research: A manual for the collection and evaluation of data.* Geo Books, Norwich.

Moore, PD. and Webb, J.A. (1978). An illustrated guide to pollen analysis. Hodder and Stoughton, London.

Moore, P.D., Webb, J.A. and Collinson, M.E. (1991). *Pollen Analysis*. Blackwell Scientific Publications, London.

Mörner, N-A. (1987). Models of global sea-level changes. In M.J. Tooley and I. Shennan *(eds.)* Sea-level Changes, Oxford, Blackwell Ltd. 332-354.

Munsell Colour (1975) *Munsell Soil Colour Charts*. Kollmorgen Inc., Baltimore Maryland

Murray, J.W. (1979). British nearshore foraminiferids. Synopses of the British Fauna No. 16. Academic Press.

Murray, J.W. (1991). Ecology and palaeoecology of benthic foraminifera. Longman, London.

O'Loughlin, C. (2001). The one-dimensional compression of fibrous peat and other organic soils. Unpublished P.hD thesis, University of Dublin, Trinity College.

Osiris Seaway Ltd. (1986). Marine Site Investigation, Garth Outfall, Bangor. Report No. D86032. Osiris Seaway Ltd., Clwyd.

Peltier, W.R. (1994). Ice-Age palaeotopography. *Science.* **265**, 195-201.

Peltier, W.R. (2002). Global glacial isostatic adjustment: palaeogeodetic and space-geodetic tests of the ICE-4G (VM2) model. *Journal of Quaternary Science.* **17**, 491-510.

Peltier, W.R., Shennan, I., Drummond, R. and Horton, B. (2002). On the postglacial isostatic adjustment of the British Isles and the shallow viscoelastic structure of the Earth. *International Journal of Geophysics.* **148**, 443-475.

Poat, C.M. (1991). Geotechnical and Geophysical properties of typical beach overburden materials, Anglesey. A comparison of modelled and field data. Unpublished M.Sc thesis, University of Wales, Bangor.

Pointon, W.K. (1982). Glacigenic deposits along the Eastern Menai Straits. Unpublished M.Sc. thesis, City of London Polytechnic.

Preece, R.C. (ed.) Island Britain: a Quaternary perspective. Geological Society Special publication. **96.**

Prince, H.E. (1988). Late-glacial and Post-glacial sea-level movements in North Wales with particular reference to the techniques for the analysis and interpretation of unconsolidated estuarine sediments. Unpublished Ph.D thesis, University of Wales, Aberystwyth.

Project Engineering and Management Services Ltd. (1971). Report on the Menai Straits and Lavan Sands feasibility study. Contract 171. Project Engineering and Management Services Ltd., London.

Ramsay, A.C. (1876). How Anglesey became an Island. *Quarterly Journal of the Geological Society of London.* **22**, 116-122.

Reynolds, J.M. (1997). An introduction to applied and environmental geophysics. John Wiley and Sons.

Roberts, N. (1998) 2nd ed. The Holocene-An Environmental History. Blackwell, Oxford.

Rowlands, B.M. (1955). The glacial and post-glacial geomorphological evolution of the landforms of the vale of Clwyd. Unpublished M.A thesis, University of Liverpool.

Saunders, G.E. (1963). The glacial deposits and associated features of the Lleyn Peninsula of south-west Caernarvonshire. Unpublished M.Sc. thesis, University of Bristol.

Schellmann, G. and Radtke, U. (2004). A revised morpho- and chronostratigraphy of the Late and Middle Pleistocene coral reef terraces on Southern Barbados (West Indies). *Earth Science Reviews.* **64**, 157-187.

Scott, D.B. and Medioli, F.S. (1978). Vertical zonations of marsh foraminifera as accurate indicators of former sea-level. *Nature.* **272**, 528-531.

Scott, D.K. and Leckie, R.M. (1990). Foraminiferal zonations of Great Sippewissett saltmarsh (Falmouth, Massachusetts). *Journal of Foraminiferal Research.* **20**, 248-266.

Seddon, B. (1957). Late-glacial cwm glaciers in Wales. *Journal of Glaciology.* **3**, 94-99.

Shennan, I. (1986). Flandrian sea-level changes in the Fenland. 1: The geographical setting and evidence of relative sea-level changes. *Journal of Quaternary Science.* **1**, (5-6) 511-526.

Shennan, I. (1987). Holocene sea-level changes in the North Sea. In M.J. Tooley and I. Shennan (*eds.*) Sea-level Changes, Oxford, Blackwell Ltd. 109-151.

Shennan, I. (1989). Holocene crustal movements and sea-level changes in Great Britain. *Journal of Quaternary Science.* **4**, (77-89).

Shennan, I. and Horton, B. (2002). Holocene land- and sea-level changes in Great Britain. *Journal of Quaternary Science.* **17**, (119-154).

Shepard, F.P. (1964). Thirty five thousand years of sea-level. In: *Essays in Honour of K.O. Emery*, Los Angeles, University of Southern California Press. 1-10.

Simpkins, K. (1974). The late-glacial deposits at Glanllynnau, Caernarvonshire. *New Phytologist.* **73**, 605-618.

Smart, P.D.N. (1984). A seabed and sub-bottom survey of the northeast Menai Strait. Unpublished M.Sc thesis, University of Wales, Bangor.

Smith, B. and George, T.N. (1961). *British Regional Geology, North Wales.* Geological Survey and Museum, London.

Strahan, A. (1885). The Geology of the Coasts adjoining Rhyl, Abergele and Colwyn. Explanation of the Quaternary, sheet 79 (N.W). London.

Stuart, A.J. (1995). Insularity and Quaternary vertebrate faunas in Britain and Ireland. From: Preece, R.C. (ed.) Island Britain: a Quaternary perspective. Geological Society Special publication. **96**, 111-125.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCornac, F.G., van der Plicht, J. and Spurk, M. (1998). INTCAL98 radiocarbon age calibration, 24,000-0 cal BP. *Radiocarbon.* **40**, 1041-1084.

Stuiver, M., Reimer, P. J., and Reimer, R. W. (2004). CALIB 5.0. [WWW program and documentation].

Synge, F.M. (1963). A correlation between the drifts of south-east Ireland and those of West Wales. *Irish Geography.* **4**, 360-366.

Synge, F.M. (1964). The glacial succession of west Caernarvonshire. *Proceedings of the Geologists Association.* **75**, 431-444.

Taylor, R.E. (1987). *Radiocarbon Dating – An Archaeological Perspective.* Academic Press, London.

Telford, W.M., Geldart, L.P., Sheriff, R.E. and Keys, D.A. (1976). Applied Geophysics, Cambridge University Press, Cambridge.

Thorpe, R.S., Beckinsale, R.D., Patchett, P.J., Piper, J.D.A., Davies, G.R. and Evans, J.A. (1984). Crustal growth and late Precambrian-early Paleozoic plate tectonic evolution of England and Wales. *Journal of the Geological Society of London.* **141**, 521-536.

Tipping, R. (1993). A detailed early postglacial (Flandrian) pollen diagram from Cwm Idwal, North Wales. *New Phytologist.* **125**, 175-191.

Tooley, M.J. (1974). Sea-level changes during the last 9000 years in north-west England. *Geographical Journal.* **140**, 18-42.

Tooley, M.J. (1978). Sea-level changes: North-West England during the Flandrian Stage. Oxford. Clarendon Press.

Tooley, M.J. (1982). Sea-level changes in northern England. *Proceedings of the Geologists Association.* **93**, 43-51.

Tooley, M.J. (1987). Sea-level Studies. In M.J. Tooley and I. Shennan (*eds.*) Sea-level Changes, Oxford, Blackwell Ltd. 1-24.

Tooley, M.J. (1992). Recent sea-level changes. In J.R.L. Allen and K. Pye (*eds.*) Saltmarshes: Morphodynamics, Conservation and Engineering Significance. 19-40.

Troels-Smith, J. (1955). Karakteriering af løsejordarter. Danmarks Geologiske Undersøgelse. Ser IV, 3.

Uehara, K., Scourse, J.D., Horsburgh, K.J., Lambeck, K. and Purcell, A. (in press). The tidal evolution of the northwest European shelf seas from the Last Glacial Maximum to the present day. *Journal of Geophysical Research.*

Unwin, D.J. (1973). The distribution and orientation of corries in northern Snowdonia, Wales. *Transactions of the Institute of British Geographers.* **58**, 85-97.

Walley, S.S. (1996). Holocene evolution of a coastal barrier complex. Unpublished Ph.D thesis, University of Wales, Bangor.

Watkins, R. (1991). Post glacial vegetational dynamics in lowland North Wales. Unpublished Ph.D thesis, University of Wales, Bangor.

Watkins, R., Allen, R. M. and Scourse, J.D. (in press). The influence of topography and anthropogenic activity on the vegetation history of the Arfon Platform, North Wales, UK.

Whittow, J.B. (1965). The interglacial and post-glacial strandlines in N Wales. In: Whittow, J.B. and Wood, P.D. (*eds.*) Essays in Geography for Austin Miller, Reading. 94-117.

Whittow, J.B. and Ball, D.F. (1970). North-west Wales. In: Lewis, C.A. (*ed.*) *The glaciations of Wales and adjoining regions*. Longman, London. 21-58.