1. Introduction

For decades the perceptions of our past have been dominated by our rather fixed, and as a result flawed, concept of space. As can be seen from the impact of Norman Davies book 'The Isles – A History' (2000) even when we are dealing with a relatively static set of boundary conditions (the 'Isles' of the last 2000 years) we appear to have been incapable of getting to grips with the importance of geographical, social or political boundaries when looking at human history (Davies *ibid*: 1-19). It is consequently unsurprising that archaeologists and other researchers, when looking at the pre-historic period, have frequently failed to appreciate the magnitude of change in both the basic morphology of the globe and the environments it contained over relatively short archaeological timescales.

This lack of application of basic concepts of morphological change contrasts markedly with the acknowledged existence of submerged terrestrial landscapes on the world's continental shelves, which dates back to at least the 19th Century (e.g. Darwin, 1859; Lyell, 1832). Despite this long term knowledge, archaeological studies that address submerged archaeology directly have, over the past century, been somewhat sporadic. Since the mid-part of the 20th Century there has been an exponential increase in research into the location, identification and excavation of shipwreck material, but by contrast and bar one notable set of exceptions (see Masters & Flemming, 1983), the potential for, non-nautical or pre-historic, submerged archaeology has only really been explored over the last decade (e.g. Fischer, 1995a; Coles, 1998; Flemming, 1998). However, as explicitly cited by Coles (1998) the majority of this work is "speculative".

Concomitant, with the realisation of the archaeological potential of the continental shelves there has been a rapid increase in the development (in terms of both extraction and construction) of the worlds' continental shelves. This has inevitably resulted in increased stress on the submerged marine environment and both wreck and submerged prehistoric archaeology. Consequently, if a sensible and pragmatic legislative, and most importantly practical, response to this potential threat is required, our knowledge of such submerged environments, needs to extend beyond the "speculative" without just resorting to the purely site specific.

Recent publications (e.g. Flemming, 1998; 2002; Wenban-Smith, 2002) have started to tackle this question. Such works typically provide excellent syntheses of the current known archaeological record of certain periods and for certain regions. However, these publications fail to identify major problems in reconstructing these archaeological landscapes, for either predictive exploratory purposes or as an intrinsic part of their archaeological interpretation. Furthermore they fail to tackle the potential range of human responses to the attendant, dramatically changing, environmental conditions associated with transgressive and regressive cycles. Finally, such studies tend to simultaneously over-simplify the importance of the modification processes operating on the archaeological record, in terms of multi-episode, syn- and post-transgressive site formation processes.

This last point is key to our understanding of not only the archaeological record but also the Quaternary geological record. Although the impacts of marine transgressions have undergone detailed study with respect to earlier geological periods, the geological community's understanding of regional impacts is severely limited to single-environment case studies which are then extrapolated to global scenarios. This extrapolative style is similarly employed in the small number of archaeological papers that tackle Flemming's (1998) concept of the "taphonomy of submarine occupation" (e.g. Kraft et al., 1983).

Therefore, if we are interested in interrogating the shelf environment for its archaeological resource we have to consider not just the practicalities of exploration, as is the focus of a number of other Aggregates Levy Sustainability Fund (ALSF) proposals (e.g. PD3322, PD3324, PD3362), but the realistic potential of the shelves for yielding useful (certainly in cost-benefit terms) archaeology.

1.1 Rationale

Our requirement to reconstruct submerged archaeological landscapes is multi-fold. Firstly, for the accurate interpretation of the terrestrial record it is essential we have a good understanding of the spatial context of this material. This requires identification of the land-sea boundaries at any point in time and so the extent, and variability, of the terrestrial environment (euphemistically and incorrectly described as the identification of "landbridges"). Secondly, we need to be able to comprehend the archaeological potential of these submerged landscapes, both in terms of primary context material (effectively preserved as a result of submergence) and secondary or even tertiary context material that has been re-worked through one or more cycles of marine inundation and exposure. Finally, recent work (e.g. Coles, 1998; Bailey & Milner, 2002) suggests that the coastal zone may represent a key environment of exploitation in pre-history and thus an essential component of human (as well as a myriad of other fauna and flora) evolution. Therefore, such coastal landscapes, many of which are now submerged, may provide exciting windows on pre-history and therefore need to be located and if possible interrogated.

The nature and scale of palaeo-geographic and palaeo-environmental change of our continental margins is of particular importance to the process of reconstruction, as it can alter radically over not only pre-historic but also historic timescales. For a full appreciation of this topic we need therefore to understand the nature of our continental margins and the short- and long-term processes that affect them. In this respect this approach parallels current thinking in palaeo-environmental research, specifically the use of a nested hierarchy of scales (e.g. Shennan et al, 2000b; Barron et al, 2003). In an ideal world research into the archaeology of submerged landscapes would proceed at a very small, "local", spatial scales (studies of the order of 10's metres through to a few kilometres), thus allowing very fine details to be observed. These smaller scale studies could then be mosaiced into larger "regional" overviews (10's to 100's Km's). In practice, the realities of underwater work render such a bottom-up approach impossible to undertake. Instead, we have to accept that the majority of research on continental shelf archaeology will be undertaken on the regional scale, with only occasional, more detailed analyses of local scale studies being possible. However, the positive adoption of a more top-down approach should be used to maximise the regional data and, through appropriate analysis, utilise it to target effectively the more labour intensive and inevitably cost limited local surveys.

The research presented in this report therefore represents a review of both the extant knowledge of the recent (c. last 2 million years) evolution of the continental shelves and the potential archaeological resource they may contain. Further, it aims to critique the process of submerged landscape reconstruction with particular emphasis on the location of palaeo-shorelines, which as discussed above not only key to delimiting terrestrial regimes but of intrinsic archaeological importance in their own right. Due to the paucity of direct information on many topics of interest, we shall inevitably draw from a wide range of sources as well as presenting information from a variety of different temporal and spatial scales.

1.2 Basic Concepts: Continental Shelves and Sea Level Change

Continental shelves are the submerged portions of the continental margin, which slope gently down from the coastal zone (> 20-30 m depth) to the shelf break (c.100 – 250m depth). The width and area of individual continental shelves varies considerably, ranging from less than a kilometre to hundreds of kilometres (Figure 1), and is controlled by the tectonic history of continental break-up. In general, wide (tens to hundreds of kilometres) shelves tend to be associated with passive (tectonically benign) continental margins, and are relatively shallow; for example, the east coast of North America. Tectonically active continental margins, such as the west coast of South America, are characterised by shelves that are narrow (kilometres or less), steeper and deeper (Pickard & Emery, 1990; Leeder, 1999).

Continental shelves tend to be divided into two main categories. *Pericontinental* shelves are situated along continental margins and are typical of the marine boundaries of major continental landmasses (e.g. America, Asia, Africa, Europe). *Epicontinental* shelves tend be semi enclosed and are situated well inboard of the continental margins (e.g. the North, Adriatic and Baltic Seas (Leeder, 1999).

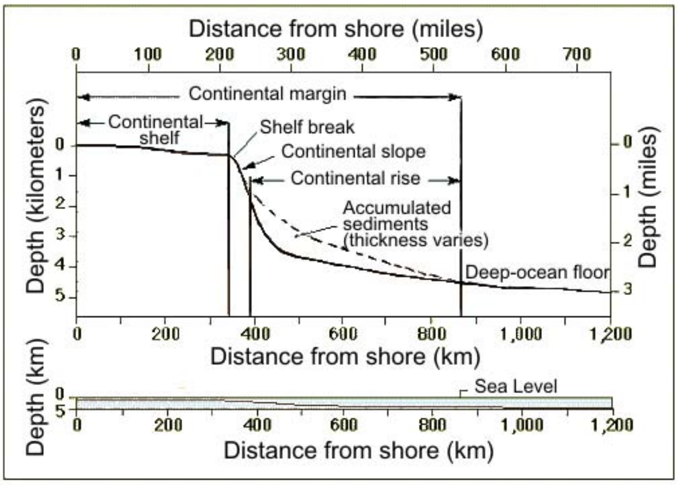


Figure 1. Generalized profile of a continental shelf

Both categories of shelf are susceptible to submergence and emergence induced by sea level change. Over the Quaternary, major (tens to hundreds of metres) changes in sea level have taken place (Rohling et al, 1998; Siddall et al, 2003) resulting in the exposure of and inundation of vast swathes of continental shelf. It has been estimated that the total area of shelf exposed globally during maximum sea level lowstands was potentially equivalent to the size of present day Africa (Figure 2 & Flemming, 1996).

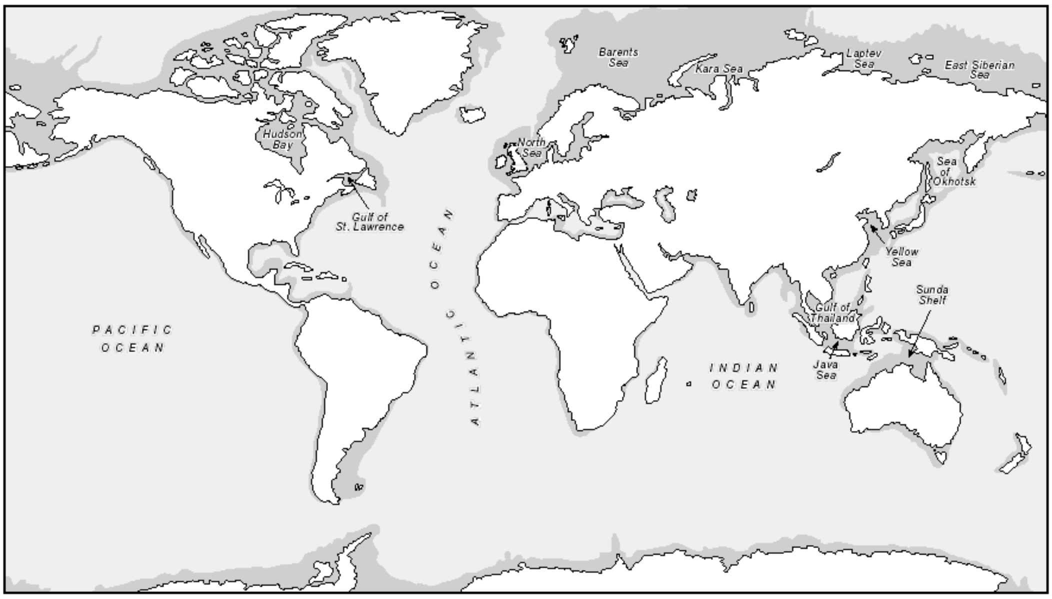


Figure 2. Extent of emergent continental shelves at the Last Glacial Maximum (c. 22 KaBP) (from Bridgland, 2002)

Given that global ocean volume is currently at its highest point since the highstand of Oxygen Isotope Stage (OIS) 5e (c.125 Ka BP: Siddall et al, 2003), it follows that the vast majority of evidence for the occupation of the exposed shelves would currently be submerged under tens of metres of water.

These large scale changes aside, the morphology and sedimentology of individual continental shelves is dictated by the complex interplay of both modern and geo-historical factors, including: global and regional fluctuations in sea-level; variability in sediment input rates and sources; and finally modes and rates of sediment transport. Inevitably, these processes not only affect the geological variability of shelves but also play a major role in determining their archaeological potential.

1.3 Basic Concepts: Continental Shelf Archaeology

Continental shelves are home to two broad categories of archaeology – shipwrecks and inundated terrestrial sites. This project will focus entirely on the latter. The vast majority of continental shelf archaeology is likely to be prehistoric; more specifically, Palaeolithic, Mesolithic and to some extent Early Neolithic. This arises from the fact that on a global scale, eustatic sea levels were at their lowest at various points during the Pleistocene and had broadly stabilized and reached near-present levels in the mid-Holocene (c. 7 ka BP) (Lambeck & Chappell, 2001; Bailey & Milner, 2002). Smaller scale, more localised relative sea level fluctuations resulting from influences such as sedimentation, tectonics or isostasy may have resulted in the submergence of later material in particular areas. Note for instance the underwater remains of a number of Bronze Age and Classical harbour structures in the Mediterranean (Flemming, 1998; Morhange et al, 2001). However, this project will focus primarily on Palaeolithic and Mesolithic material.

Aside from a few notable exceptions (e.g. Masters & Flemming, 1983; Fischer, 1995a; Coles, 1998; Flemming, 1998), the general archaeological attitude towards submerged landscapes has been rather non-committal or speculative. Common assumptions are that sites have been eroded or destroyed by rising sea levels or are almost impossible to find beneath the ocean waters and seabed sediment. Thus, while it is rarely questioned whether these landscapes actually exist, there has been an overall tendency to simply gloss over their role in prehistory. This lack of research can be illustrated by the fact that globally, around 550 submerged archaeological sites are known from the Lower Palaeolithic through to the Bronze Age and beyond (Flemming, 1998). This contrasts somewhat with the quite literally thousands of archaeological sites that are known on land. As a point of comparison, around 1900 sites and findspots are known for the Lower and Middle Palaeolithic period of Britain alone (Wymer, 1999a & b).

An overview of both the archaeological and biogeographical literature also suggests that the actual role of submerged landscapes (rather the actual artefacts it contains) in prehistory is often stereotyped through the terminology that surrounds them. This is explicitly illustrated through the use of the term ‘landbridge’. This seemingly innocuous concept has dominated discourse on continental shelves for at least the past 150 years. Note, for example, Charles Darwin’s statement that:

“The northern parts of the Old and New World’s will have been almost continuously united by land, serving as a bridge” (Darwin, 1859:300)

‘Landbridge’ implies a connection between two otherwise separated areas of land for the purposes of movement, be it of people or animals. With reference to prehistory, 'landbridges' are believed to have facilitated human entry into areas of land that are presently separated by the sea, the classic cases being Beringia; linking Asia and America, and the exposed North Sea Basin, joining Britain and continental Europe:

“The hunters of the Late Glacial arrived in Britain dryshod by walking across the land bridge from the Continent” (Smith, 1992:139).

“The journey of the ancestral Palaeo-Indians across the land bridge between Siberia and Alaska…was the final stage of a process of migration and colonization that had begun 1.5 million years earlier” (Fiedel, 1992:22).

This is even echoed in the recently postulated “out-of-Africa” migrations:

“There is increasing archaeological evidence that Australia was colonized (by boat, because no landbridges existed during the Pleistocene) before 50,000 years ago.” (Stringer, 2000).

However, use of this term has handicapped our perception of submerged landscapes. The problem is that it implies that these areas were merely bridges, thus creating a false perception of submerged landscapes as nothing more than migration corridors or ‘terrestrial avenues’ (Case & Cody, 1987) that allowed access into and out of our present configuration of continents.

In reality, the inhabitants of these areas would probably have perceived them as 'land as place to be' (Coles, 1998:45). Given the long term nature of the colonization process, the size and extent of these areas, and the fact that these colonizers would have little or no conception that they were only “*en route*”, these 'landbridges' would have been perceived as habitable areas of land in much the same way as the rest of the continent, rather than simple conduits for purposeful moves from point A to point B. Coles (1998) has rightly argued for a better understanding of the nature of these areas, and the role they played in habitation as well as migration. This view contrasts somewhat with early work which based its research aims around the idea of these areas as primarily migration corridors. Note for instance, Marcus & Newman's (1983) work, which modelled palaeo-sea levels for the explicit purpose of investigating 'hominid migration routes' while Fladmark (1979) assessed the feasibility of a presently submerged coastal migration route into North America during the Late Pleistocene. Clearly, until quite recently, submerged landscapes have been relegated to a supporting role in the development of human society i.e. that of facilitating movements into the present continental configuration where the majority of the development of human society is assumed to have taken place.

Although, there are significant problems inherent with the concept of landbridges it is necessary to acknowledge that at least such work has some sense of palaeo-geographic space. Disappointingly there is still a significant volume of literature that present archaeological site distributions and palaeo-environmental data in general using modern day topographic maps (e.g. Bell & Walker, 1992; Bocquet-Appel & Demars, 2000: Figures 3 and 4).

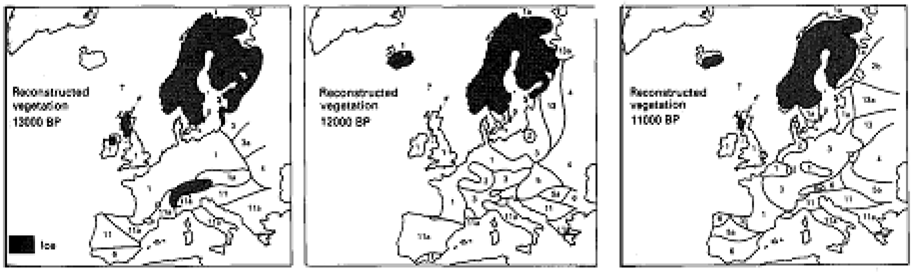


Figure 3. Reconstructed vegetation patterns for the Late Glacial in North West Europe. Note the use of modern shorelines despite the Late Pleistocene dates. (from Bell & Walker, 1992:97).

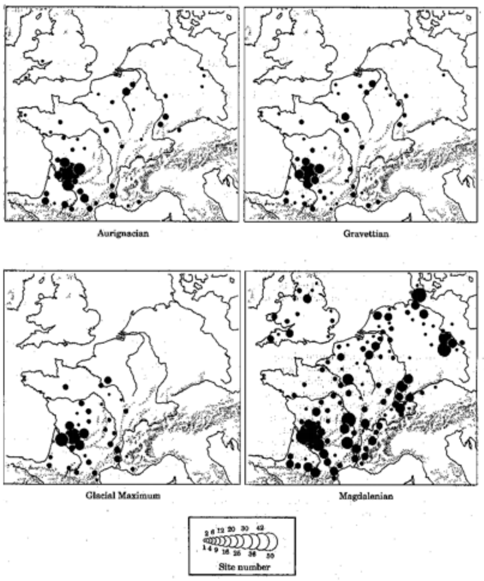


Figure 4. The broad pattern of archaeological site distributions in NW Europe before and after the Last Glacial Maximum. The Aurignacian ranges from 40 to 29 ka BP, the Gravettian from 29 to 22 ka BP, the Last Glacial Maximum from 22 to 16.5 ka BP and the Magdalenian from 16.5 to 11.5 ka BP (from Bocquet-Appel & Demars, 2000:553). Note the use of modern shorelines despite the known major shifts in sea level and hence shoreline positions during this period.

Although, as the authors would undoubtedly argue, such a presentation allows the reader to gain a sense of the patterning of the data in question, in relation to their own geographical knowledge, it suffers from the fact that the information is not placed within its appropriate palaeo-geographic context and serves to marginalize submerged landscapes in favour of the present coastline configuration. Where it does occur, the removal of modern geographical boundaries in reconstructions provides a strong visual reminder of the fact that currently submerged areas were not simply “bridges” connecting two landmasses but that they represented a seamless terrestrial landscape (e.g. Coles, 1998).

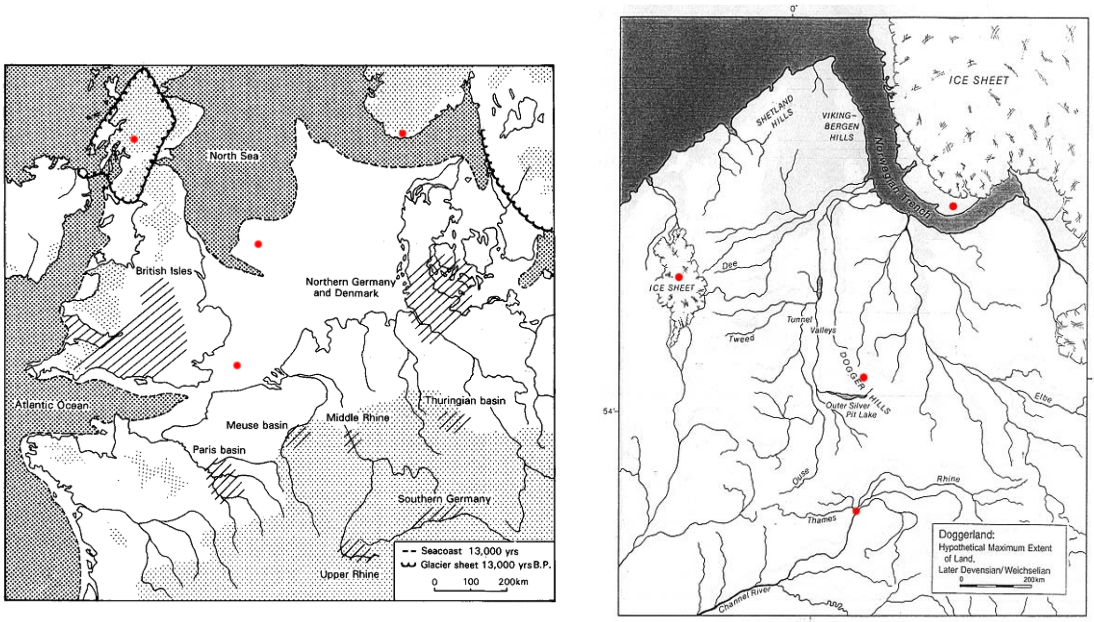
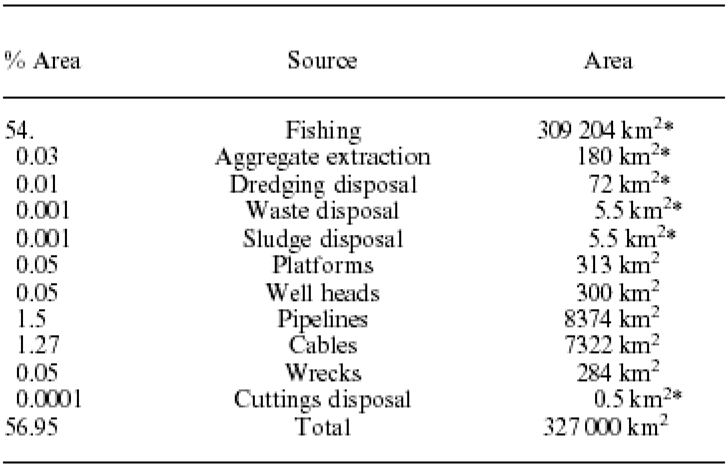


Figure 5. A comparison of two palaeo-geographic reconstructions of North West Europe showing different approaches to displaying palaeo-shorelines. The map on the left is from Housely et al (1997) and depicts the 13 ka (C^{14}) BP shoreline. The map on the right is from Coles (1998) and depicts the coastline between 16 and 13 ka (C^{14}) BP. The important aspect to note is how Coles emphasises the submerged area as an equal part of the landmass and highlights the probable palaeo-river courses. By contrast, Housely et al (1997) still present an overwhelmingly modern image and thus marginalize the submerged area. The red dots have been added to allow orientation.

1.4 Basic Concepts: Industrial Activity on Continental Shelves

Over the course of the twentieth century industrial activity on the continental shelves has increased steadily. Examples of the types of industrial activity taking place underwater include oil, gas and aggregates extraction, cable laying and trawling (Dykes et al, 2001; DTI, 2002). As an example Table 1 provides an indication of the total area in the North Sea affected by these activities.



% Area	Source	Area
54.	Fishing	309 204 km^2*
0.03	Aggregate extraction	180 km^2*
0.01	Dredging disposal	72 km^2*
0.001	Waste disposal	5.5 km^2*
0.001	Sludge disposal	5.5 km^2*
0.05	Platforms	313 km^2
0.05	Well heads	300 km^2
1.5	Pipelines	8374 km^2
1.27	Cables	7322 km^2
0.05	Wrecks	284 km^2
0.0001	Cuttings disposal	0.5 km^2*
56.95	Total	327 000 km^2

Table 1. Physical disturbance of the North Sea seabed by human activities in terms of both percentage area, and absolute values (modified from de Groot, 1996).

These activities are likely to affect archaeological assemblages on, or buried in the seabed through physical disturbance of the seabed, and/or sub-seabed sediment. For example, aggregate extraction can intensively disturb bottom sediment by substratum removal and alteration of bottom topography (de Groot, 1996). Studies have indicated that dredging may remove up to 5 metres of the sub-surface section (Desprez, 2000). Any archaeological material caught by a dredge will inevitably be removed from their depositional context and in the worst case scenarios destroyed. In either case the spatial, and hence temporal, relationships of an assemblage, and the information they contain, could be lost. Although the percentage area affected by aggregates is extraction is relatively small (see Table 1), the actual quantity of material removed from the seabed, which could include archaeological material, could be significant. This is because the key resource for the aggregate industry frequently coincides with zones of high archaeological potential, at least in terms of Palaeolithic material. Consequently, the greater integration of archaeological research with the industrial extraction (as supported by the ALSF scheme) could provide a significant increase in our knowledge of the shelf archaeology.

Similarly, the offshore oil and gas industries affect the seabed through construction of pipelines and platforms, and also by drilling for exploration and extraction purposes (Pickering, 1999; Flemming, 2002). This latter activity in particular could affect archaeological material buried at great depths within the seabed as well as on the seabed surface. Destruction of archaeological material or its removal from its context can also result from the burial of submarine telecommunications cables, and bottom trawling.

1.5 Report Structure

In order to re-assess the archaeological potential of the continental shelves we consider that there are 4 key themes that need to be considered:

- *Theme 1 – The regional reconstruction of submerged landscapes*

  A review of this topic should enable us to determine if current techniques of reconstruction are adequate enough to enable the wider investigation and management of the archaeological resource.

- *Theme 2 – The nature of the pre-submergence archaeological deposits*

  A review of current terrestrial archaeology and known submerged sites should provide an indication of the research potential that the submerged record has, both in terms of highlighting what material is likely to be present, as well as the research questions it is geared to addressing. Such a review should also provide some indication of the patterns that exist in terrestrial environments, and whether these are applicable to the continental shelf situation. Within the time constraints of this study it was necessary to narrow our spatial scope and so we have chosen the North-west European continental shelf as an illustrative case study.

- *Theme 3 – The modification of archaeological deposits by marine transgressions and regressions*

  A review of the impacts of marine transgressions and regression should provide an understanding of the nature and scale of landscape and coastal change in response to sea level fluctuations and how individual deposits of archaeological material may be affected by these forces.

- *Theme 4 - Predictive modelling of submerged archaeological sites*

  A review of current techniques of predictive modelling should provide an assessment of whether current modelling techniques are adequate or applicable to submerged continental shelf archaeology in the light of existing knowledge, and any insights drawn out of the previous three Themes.

1.6 Methodology

In order to tackle these 4 key issues for submerged archaeological studies this project has undertaken a wide-ranging literature review, in terms of both space and time. Literature from research disciplines spanning archaeology, anthropology, ethnography, oceanography, geology, biogeography and geophysics have been used. Although definitively resolving these issues was impossible for an 18 month study we aimed, at the very least, to identify the principle research questions to be set to the community over the next decade. Similarly, within the time constraints it was not possible to acquire new data to answer such broad questions. Therefore an essential component of the project include interaction with the large number of field based “terrestrial” and “marine” projects supported by the Aggregates Levy Sustainability Fund.

2. Theme 1: The Regional Reconstruction of Submerged Landscapes

The regional reconstruction of submerged landscapes, has been a desire of archaeological, geological and geomorphological researchers for at least the last 150 years. However, although during this period a multitude of reconstructions have been presented in both academic and popular literature we rarely consider the accuracy of such representations. Even more disappointingly, if inherent problems of reconstruction are identified they are very rarely propagated through the modelling process and so the reader is left with what appears to be a definitive statement of palaeo-shoreline location.

Theme 1 aims to analyse the process of submerged landscape reconstruction in order to assess and if possible quantify the potential errors. Having provided a representative review of current approaches (Section 2.1) the Theme will explore the key drivers behind the process, namely:

- The processes of sea level change (Section 2.2)
- The documentation of sea level change (Section 2.3), and
- The modelling of sea level change (Section 2.4)

This critical review will then be used to illustrate the potential errors involved with the application of a variety of sea-level sources with an equivalent variety of base levels (a term used within this report to describe various proxies for ancient land surfaces: Section 2.5). This latter section will be quantitatively and qualitatively illustrated by a number of reconstructions for the NW European continental shelf.

2.1. A Review of Existing Palaeo-geographic Reconstructions

Critical to a re-assessment of continental shelf archaeology is a review of the way in which submerged landscape reconstructions have so far been approached by archaeologists, and other Quaternary scientists. Such an examination of extant palaeo-geographic maps, and critically the approaches and modes of thinking underpinning them, is deemed necessary to assess how we currently produce and most importantly use such reconstructions to inform our archaeological interpretations and even our strategy for archaeological exploration of the shelf. Considering the ubiquitous use of such maps in a wide range of Quaternary studies we felt it essential to extend this review to include a wide range of sources looking at both archaeological and environmental reconstructions. A review was undertaken as follows:

- 85 maps have been randomly selected from a wide-ranging set of articles from across the disciplines. They have been compared qualitatively and quantitatively in order to assess the variability between different authors' interpretations of palaeo-shorelines
- A sourcing exercise has also been undertaken to determine what information has gone into the creation of these palaeo-geographic maps. This process aims to highlight the way that information regarding past sea level change is being used, or misused.

Even this limited review highlights significant variability in shoreline position between reconstructions. For example, as can be seen from Figure 6, a comparison of four reconstructions for the North-West European continental shelf at c. 12 – 10 ka

BP (uncalibrated C^{14} dates) gives reconstructed coastline positions that vary by a maximum of 250 kilometres and more typically between 20 and 30 kilometres.

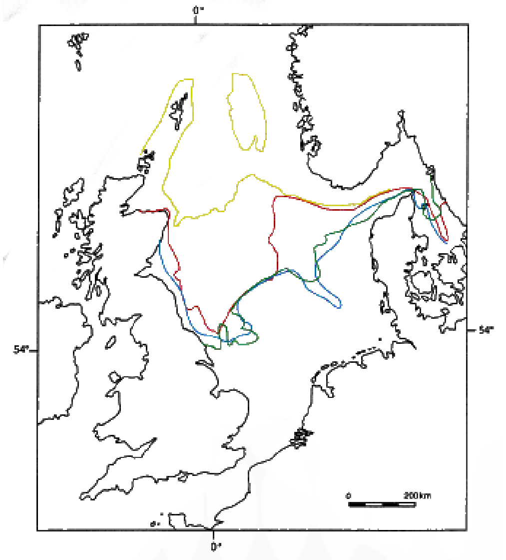


Figure 6. Comparisons of North Sea shorelines obtained from palaeo-geographic reconstructions found in archaeological publications. Yellow, = Bjerck, 1995 (c.12-11 ka BP); Red = Jonsson, 1995 (c.10-9 ka BP), Blue = Schild, 1996 (c.11-10 ka BP), Green = Newell & Constandse-Westermann, 1996 (12.8-10.3 ka BP). All of these dates are in uncalibrated C^{14} years. Modern shorelines are from Coles (1998).

Similar scales of shoreline position variability could be seen to occur between suites of papers from a global range of geographical areas. Analysis of the accompanying literature suggests a number of potential sources of these large discrepancies in coastline reconstructions. The two key sources of error appear to be the choice of sea-level data and the stratigraphic time horizon used to represent the ancient landscape. Figure 7 demonstrates the range and popularity of sea-level sources used in these reconstructions.

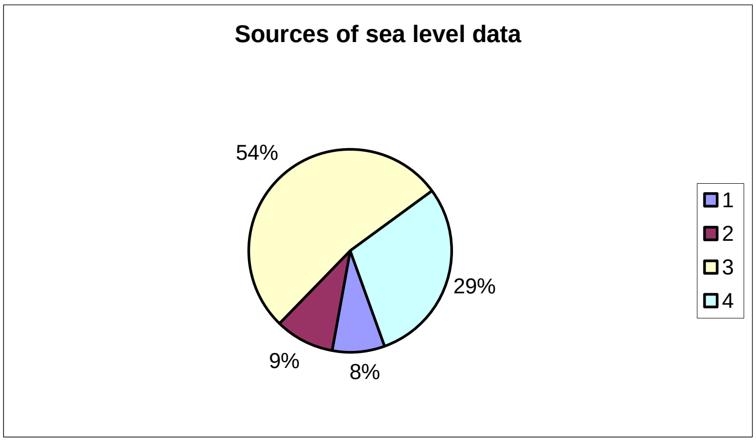


Figure 7. A pie chart to illustrate the range of information sources used in 85 palaeo-geographic reconstructions. 1) Global-eustatic data. 2) Sea Level models 3) Non mainstream sea level data source and 4) No data (n = 85).

This simple analysis suggests that only 17% of authors actually gave any indication of what sea-level data had been used for their palaeo-shoreline reconstructions. Within this group there was an effectively even split between those using a global eustatic curve (Section 2.2.3) and those using sea level models (Section 2.4). By far the majority of the papers (54%) although alluding to the use of sea-level data in their reconstructions (as well as frequently discussing its complexities) used non mainstream sea level data. For example, Bocquet-Appel & Demars (2000: Figure 3) reference Adams & Faure (1997) a paper which deals primarily with palaeo-vegetation. Palaeo-shorelines in the source reference are dealt with only very briefly and from only a background to the main issue. Finally, and even more disappointingly, twenty-nine percent of the articles provided no indication as to where the sea level data and resulting palaeo-shoreline position had come from (e.g. Dolukhanov, 1993; Housley et al, 1997).

The second major issue identified from this analysis is the idea that the continental shelf is purely a relict landscape. This manifests itself in the selection of the modern seabed as being the most accurate representation of the past sub-aerial landscape (i.e. that the modern bathymetric contours equate to past shorelines). Several authors do mention (but do not factor into their reconstructions) that sedimentary and erosive processes are likely to have altered this surface (e.g. Coles, 1998; Shennan et al, 2000b), but rather than taking the next step and attempting to incorporate stratigraphic complexities into palaeo-geographic reconstructions they are ignored in favour of an approach which simply ‘drains the landscape’.

However, it is worth pointing out that when these issues are seen in context, the use or mis-use of reconstructions is often not as dire as it seems. Frequently, an exhaustive review of the sea level change process or an exact position of the shoreline is not essential. Van Andel (1989) has for instance highlighted this very point and made use of OIS based reconstructions to draw out broad general conclusions with respect to the settlement- subsistence systems and migration of hunter gatherers since the Last Glacial Maximum. Similarly, the recent Stage 3 project used the –100m contour as a proxy for the OIS 3 shoreline (which was on average located at –80m) in its Global Circulation Models for palaeo-climate modelling (Van Andel & Davies, 2003). For higher resolution work though, more accurate shorelines are required. Hence in the case of the Stage 3 project, modelled shorelines (e.g. Lambeck, 1995) were used ‘meso-scale’ palaeo-climate models (Barron et al, 2003).

Therefore, while the above criticisms of existing work may seem unduly harsh, it is probably worth noting Van Andel and Tzedakis's comments in relation to the reconstructions and the nature of archaeological research:

"Ours is a historical science where…incomplete information produces tentative syntheses, which generate the inspiration for new observations that modify the existing syntheses as comprehension deepens in a circular fashion" (Van Andel & Tzedakis, 1996:481)

The reconstructions and papers examined in this study therefore constitute the 'tentative syntheses' (with respect to the study of submerged landscapes) in question. However, while this situation may have been adequate in the past, it is no longer so in the light of initiatives to take the study of submerged landscapes to the next level, that of actively studying them, managing them and integrating the archaeological resource they contain with the mainstream body of terrestrial archaeological work.

Consequently, if we are to move to the next level of submerged landscape reconstruction, it is necessary to provide both an overview of: the sea level change phenomena (Section 2.2); and how we can assess the applicability of such data to a variety of stratigraphic horizons (Section 2.3). Particular emphasis, in this project, has been placed on quantifying variability between different models in an attempt to assess the errors in both extant and future reconstructions.

2.2 Sea Level Change: an Overview

2.2.1. Introduction

To express the sea level change phenomena in the most general terms possible, it is the superimposition of two independent movements - that of the sea surface and that of the land surface (Pirazzoli, 1996; Douglas, 2001a).

Factors influencing these movements are a diverse complex of processes that interact on a number of spatial and temporal scales. They range from astronomical factors operating from outside the Earth; such as variations in the planet's angular velocity, to factors operating on the Earth's surface; like the global distributions of glaciers and meltwater and finally, factors working within the Earth's interior; such as displacements of mantle material (Pirazzoli, 1993 and 1996; Douglas, 2001a). Many of these factors are interconnected and operate in conjunction with each other. The identification of the dominant influence on sea level change at a particular place and time depends on the temporal and spatial scale on which it is observed.

Before launching into a more detailed explanation of the processes involved, it is worth pointing out that there does exist a certain amount of confusion and ambiguity in the ideas and terminology surrounding sea level change (Mörner, 1976; Clark, 1980). Factors affecting sea level change can be classified in terms of the spatial extent of their outcomes (i.e – global versus local processes), the temporal extent of their outcomes (i.e. short term versus long term processes), or the medium in which they operate (i.e vertical movements of the sea surface versus vertical movements of the land surface).

Problems do arise over the use of these classifications. With respect to the first two categories, definitions of short and long term or global and regional may vary according to the scale and scope of each researcher's approach. For instance, although the term 'global' might be assumed to imply a uniform change affecting the entire planet, Long and Roberts (1997) define global factors as those influencing "one or more ocean basins" (1997:25). Therefore, throughout this document, for the purposes of consistency 'long term' will refer to timescales of thousands to millions of years and 'short term' to scales of days to hundreds of years. Spatially, 'global' will refer to scales of tens of thousands of kilometres or more, 'regional' to hundreds to thousands of kilometres, and 'local' to tens of kilometres or less.

Over a time scale of millions of years the dominant factors involved in global sea level fluctuations consist of plate tectonic induced changes in ocean basin geometry. As the oceanic crust spreads out from submarine ridges, it tends to thicken, increase in density and subside, thus taking the level of the water surface down with it (Pirazzoli, 1996; Lambeck & Chappell, 2001). The long term movement of continental and oceanic crustal plates can result in changes of up to several hundred metres as ocean basins are created or destroyed and expand or shrink (see Figure 8A; and section 2.2.2).

On timescales of tens of thousands of years, the periodic exchange of mass between the Earth's ice sheets and oceans as a result of glacial-interglacial cycles provides the dominant contribution. This includes both eustatic (changes in ocean volume and its distribution) and isostatic (movement of continental and oceanic crust due to shifting loads) components (see Figure 8B; and Sections 2.2.2 and 2.2.3 respectively).

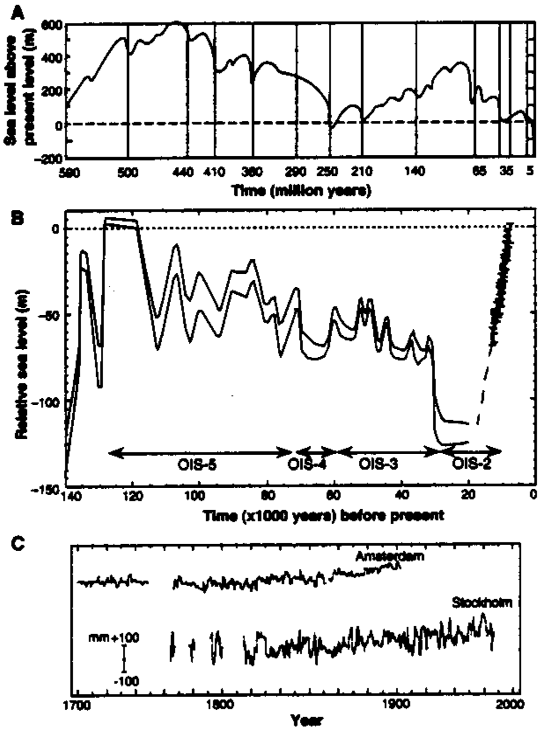


Figure 8. Sea level records illustrating change over multiple time scales: A) Tectonically induced changes affecting global ocean volume over millions of years as inferred from seismic sequence stratigraphy data. B) Glacially induced changes spanning tens of thousands of years as inferred from coral reef data from the Huon Peninsula, Papua New Guinea and northwestern Australia. C) Climatically and tidally induced changes operating on a decadal scale as inferred from historical tide gauge data from Amsterdam and Stockholm. (from Lambeck & Chappell, 2001:680)

Finally over periods of tens of years or less, oceanographic, meteorological and tidally induced changes such as air pressure, storms and water temperature become important (see Figure 8C; and Sections 2.2.3.2) (Long & Roberts, 1997; Lambeck & Chappell, 2001). These can lead to sea level changes of up to several metres in regional and local contexts.

In spatial terms, some factors are more dominant in particular areas than others. This can result in major discrepancies observable in the sea level records of different parts of the world, as Figure 9 clearly shows.

In all cases, short timescale and regional to local variations are superimposed on top of a longer term, global signature of sea level. The outcome of this variation is that an absolute global measurement of sea level change may not be applicable when studying specific regions or areas, and thus, where possible sea level change is discussed in terms of the relative sea level change affecting a particular area. In some instances though, a lack of relative sea level data means there is no recourse but to use global sea level to provide an approximation.

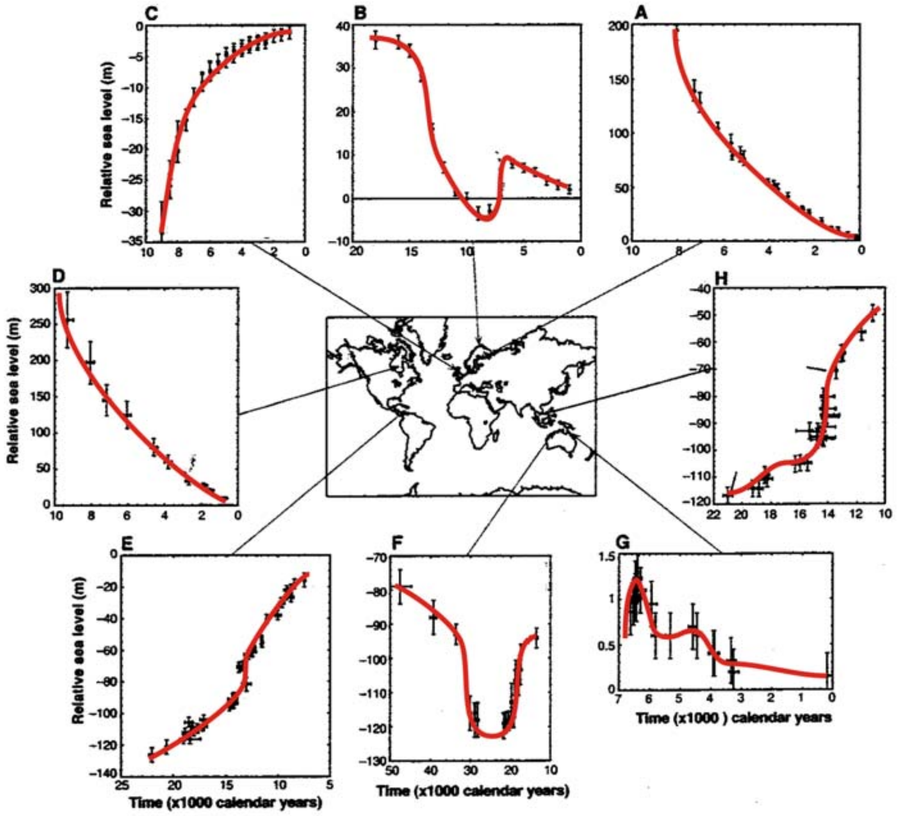


Figure 9 Relative sea level curves for a number of different areas: A) Ångerman, Gulf of Bothnia, Sweden; B) Andøya, Nordland, Norway; C) Bristol Channel, England; D) Hudson Bay, Canada; E) Barbados; F) Bonaparte Gulf, Northwest Australia; G) Orpheus Island, Queensland, Australia; H) Sunda Shelf, southeast Asia. These curves are not all drawn to the same scale. Note the range of variation in the vertical and horizontal axes (modified from Lambeck & Chappell, 2001:681)

Sea level change in relation to archaeology deals with the Pleistocene, and to some extent the end of the preceding Pliocene epoch, as it is during this period when the first artefacts and hominids appear (c. 2.5 million years ago: Klein, 1999). Throughout this time period, the interplay between variations in the Earth’s orbit and axial tilt; ice sheet dynamics; and ocean circulation have resulted in a long-term (c. 41,000 years in the early Pleistocene and Pliocene and c. 100,000 years from c. 800 Kyr BP onwards) cycle of climate change consisting of alternating glacial and interglacial phases (Zachos et al, 2001; Lambeck et al, 2002a). This is observable in the records of oxygen isotope ratios of marine cores reaching far back into the Quaternary (e.g. Imbrie et al, 1984; Bassinot et al, 1994; and Figure 10). As the growth of major continental ice sheets requires significant quantities of water, evaporation from the oceans increases in glacial phases, resulting in the preferential removal of the light ^{16}O isotope, thus enriching the oceans with the heavier ^{18}O isotope. Conversely, this situation is reversed during the warming phases of interglacial phases resulting in the relative depletion of ^{18}O. This ratio can be measured by examining the remains of planktonic formanifera and calcareous nanofossils from deep-sea sediment cores as these record the chemical composition of the oceans at the time they were alive (Lambeck et al, 2002a).

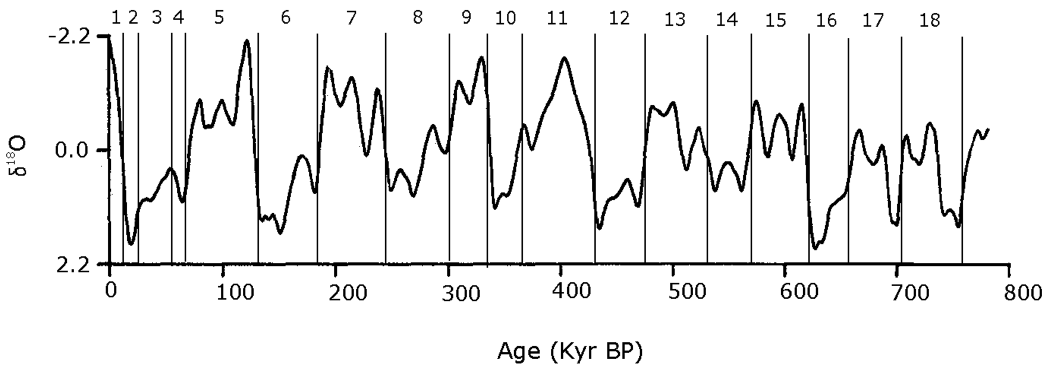


Figure 10. The oxygen isotope record from 800 Kyr BP till present. The greater the value of the $\delta^{18}O$ measurement, the greater the extent of the global ice sheets. The approximate timing of the oxygen isotope stages have been superimposed on the record. Even numbered stages represent relatively cold periods, while odd numbers represent warm stages (modified from Imbrie et al, 1984).

Factors operating as a result of these cycles lead to: variations in the volume of water in the oceans; the deformation of both ocean basins and continents; the density of ocean water; dynamic changes affecting water masses and modifications to the Earth's equipotential geoid. These variations have the potential to affect the movement of both the sea and land surfaces thus producing sea level fluctuations. Each of these factors will now be discussed individually, and the ways in which they interact to form shifting patterns of sea level change over space and time will be demonstrated in the synthesis at the end of this section (Section 2.2.6).

2.2.2 Tectonic Displacement of Oceanic and Continental Crust

Long-term tectonic movements of the portions of the crust that form the ocean basins will inevitably modify the distribution of oceanic water on the basis of the 'bathtub principle' (Leeder, 1999). Assuming that the total volume of ocean water is conserved, if the containing ocean basins grow larger or smaller due to tectonic processes, the distribution of ocean volume, and hence the height of the ocean surface, will be modified (Figure 11).

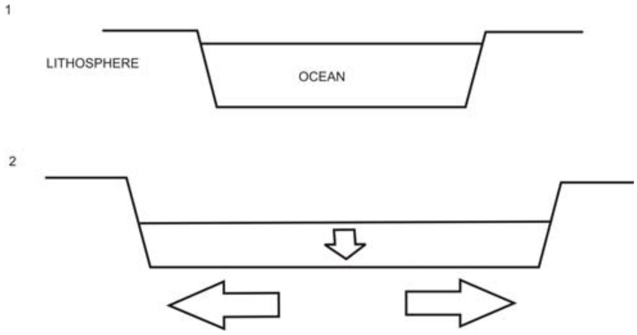


Figure 11 Schematic representation of tectono-eustasy. If water volume is conserved, the expansion of the ocean basin by tectonic movement will lead to a reduction in the height of the ocean surface as the volume of water is spread over a greater area.

Over a timescale of hundreds of millions of years, these '*tectono-eustatic*' processes create and shape the earth's ocean basins and thus represent the primary control on sea level (see Figure 8A).

Tectonic movements also have the potential to alter the height of the land surface. Localized tectonic activity can be caused by factors such as crustal plates faulting, folding or tilting thereby resulting in vertical movements of the land surface. While these vertical movements are usually gradual and continuous (a consequence of the viscous flow of mantle material over tens of thousands of years), they do sometimes take the form of rapid spasmodic events such as earthquakes, which can result in the uplift or downwarping of the land surface to a significant degree in a very short space of time (Pirazzoli, 1996). These '*coseismic*' (rapid crustal displacement occurring at the time of an earthquake) events are caused by earth movements, usually associated with crustal plate boundaries, as built up stress is rapidly released (Goudie, 2001).

In coastal areas these movements will create localized relative sea level fluctuations. For example, evidence from the John's River in Washington State (Northwest USA) points to periods of relative sea level fall punctuated by sudden relative sea level rises ranging from 0.15 to 1.5m. These have been interpreted as coseismic subsidence events. That these displacements are highly regionally variable is illustrated by evidence from Netart's Bay in the neighbouring state of Oregon which displays contemporaneous coseismic displacement of a maximum of 0.5m (Long & Shennan, 1998). More dramatic examples of coseismic uplift are observable in a number of areas, notably Crete, where an earthquake occurring at c. 450 AD resulted in uplift of 9 metres in the western part of the island (Goudie, 2001).

Long term tectonic movements are observable in a number of areas, such as the Huon Peninsula of New Guinea where flights of coral terraces dating back to some 300,000 years have been raised up to 1000 metres above present sea level (Chappell & Shackleton, 1986; Lambeck & Chappell, 2001). The speed of long term tectonic uplift varies considerably with the causes of the movement. In ancient mountain belts associated with early phases of plate collision it can be up to 5mm/yr, while in zones of current mountain building it can be up to 20mm/yr (Goudie, 2001). In fact, these movements are far more common than often realized. For example, Southern England might be assumed to be tectonically stable area. Nevertheless it has still experienced uplift of between ~0.1 and ~0.9mm/year for the past 3 million years (Maddy et al, 2001; Westaway et al, 2003). Over the course of 100,000 years this results in uplift of between 10 to 90m, clearly not an insignificant amount. In fact areas regarded as tectonically stable tend to exhibit displacements ranging from 1.1mm/year to –4.2mm/year. As a point of comparison, areas affected by isostatic factors (Section 2.2.4) move at a rate of between 15 and –7.5mm/year (Pirazzoli, 1993).

2.2.3 Eustatic Controls on Sea Level

Before going straight into a discussion of the factors that result in the addition or subtraction of water to the oceans, it is worth clarifying some of the terminology and concepts that surround this aspect of sea level change.

Addition or subtraction of water is simply one way in which ocean volume can be modified. Other factors are the distribution of water about the planet's ocean basins and the thermal expansion of water. These factors all serve to create sea level changes by raising or lowering the vertical height of the ocean surface.

Traditionally, changes in the level of the ocean surface were thought to be uniform across the globe. This was based on the ancient Greek geographer Strabo's idea that no slope could exist on the ocean surface and thus the ocean surface had to remain at the same level above the centre of the earth. Subsequently, in 1885 this hypothesis was formalised in the concept of *'eustatic'* - vertical displacements of the ocean surface occurring uniformly across the globe - sea level changes by the Austrian geologist Suess (Mörner, 1987; Pirazzoli, 1991; 1996; Douglas, 2001a).

However, in recent years the validity of this concept has been questioned. For a start, given the variation inherent in regional sea levels highlighted in Section 2.2.1, the concept of a uniform global sea level change may not be applicable to geographically restricted situations. Indeed, some researchers have argued that the very concept of a uniform global change in sea level is of rather limited value because of this variation (e.g. Lambeck, 1996) and, with respect to archaeology, because human societies live by reference to a perceivable local sea level rather than an abstract global one (e.g. Van Andel, 1989). In addition, methodological difficulties tend to prevent the elucidation of a truly global sea level record. As Stanley points out,

"[The] quest for a single stable position on the world's surface to serve as a standard from which to derive a reliable sea level curve for the late Quaternary till present remains frustrating as such a point may not exist." (Stanley, 1995:3)

In addition, satellite altimetry has revealed that the ocean surface is not in fact a level surface and does not change uniformly over time (Mörner, 1980, 1987). Some researchers therefore now see eustatic variations simply as changes in ocean level (e.g. Mörner, 1976; 1980; 1987), or effectively a change in ocean volume by addition or removal of water (e.g. Lambeck, 1995; 1996; Long & Roberts, 1997). Note the differences in the quotations below:

"The best definition of eustasy is simply 'ocean level changes' regardless of its causation and implying vertical movements of the ocean surface (Mörner, 1976:125)

"The oceanic (or eustatic) variables control the global volume of water in the ocean basins" (Long & Roberts, 1997:25)

"'Eustatic sea-level change' … is the spatially uniform signal produced by direct mass exchange between the ice sheets and the oceans" (Milne et al, 2002:364)

"The concept of eustasy…a uniform change of sea level occurring everywhere from addition or thermal expansion of water" (Douglas, 2001a:8)

Indeed, short term dynamic sea level changes though, such as those induced by meteorological or oceanographic causes, tend to be excluded from definitions of eustatic change, despite the fact they do alter the height of the ocean surface in regional and local contexts (see section 2.2.3.2) and can be thought of as oceanic variables. This division is more the result of tradition, in that eustasy was once seen as globally uniform, rather than logic (Mörner, 1987).

As there is no strict consensus on the meanings and usage of the various terms, this paper will therefore adopt the position that eustatic changes represent variations in global ocean volume and its distribution across the earth's surface. Therefore Section 2.2.2.1 will deal with eustatic shifts induced by volume changes caused by the addition or removal of water, whilst Section 2.2.2.2 will address those caused by redistribution of ocean volume, including oceanic variables.

2.2.3.1 Controls on Volume Change in the Oceans

Minor potential inputs to ocean volume come from atmospheric water, rivers, lakes e.t.c. as part of the hydrological cycle. Table 1 gives an impression of the volumes of water stored during various stages of the present day hydrological cycle.

Water Source	Present volume (km^3)	Equivalent water depth
Biological water	700	2 mm
Rivers and channels	1700	5 mm
Swamps	3600	10 mm
Atmospheric water	13,000	36 mm
Moisture in soils and the unsaturated zone	65,000	18 cm
Lakes and reservoirs	125,000	35 cm
Ground water	$4x10^6$ to $60x10^6$	11 to 166 m
Frozen water	$32.5x10^6$	90 m
Oceans and seas	$1370x10^6$	3.8 km

Table 2. Estimates of the present day volumes of water stored in different parts of the hydrological cycle. Equivalent water depth, represents the total potential contribution to ocean volume of such sources, and is calculated using the present day ocean surface area (361.3 x 10^6 km^2) and the assumption that the water is evenly distributed across the globe (modified from Pirazzoli, 1996)

It is clear from this that atmospheric water, lakes, rivers, marshes, peat bogs and so on could potentially contribute relatively little to present ocean volume – a layer of water some 58.3 cm thick evenly distributed worldwide. In contrast, the potential impacts of groundwater and frozen water are in the order of tens of metres (Pirazzoli, 1996).

In warm epochs, which lack evidence for large-scale continental glaciation, such as the late Triassic, changes in lake and ground water storage in response to monsoonal fluctuations are believed to have resulted in fluctuations in global sea level of the order of several meters and thus dominate the observed eustatic sea level signal. However, in geological epochs subject to the cyclical growth and decay of massive ice sheets, such as the Pleistocene, lacustrine and groundwater fluctuations represent only a small component of the volumetric changes (Jacobs & Sahagian, 1993).

Therefore, with respect to these later periods, the single most important volumetric input is related to the cyclical growth and decay of the Earth's ice sheets (Pirazzoli, 1996; Lambeck et al, 2002a). Essentially, the growth of the ice sheets remove water from the oceans and locks it up in glaciers, thus decreasing global ocean volume. However, as the glaciers retreat, glacial meltwater enters the oceans, thus increasing their volume. For instance, the most commonly used estimation for the volume of water removed from the oceans at the Last Glacial Maximum (LGM: c. 22 Kyr BP), is a layer around 121 +/- 5 metres thick evenly distributed across the world's oceans, a volume of 437.2 x 10^8 km^3 (Fairbanks, 1989; Bard et al, 1990). Although as with most sea-level data this figure is currently under debate with current estimates ranging from 116 m to 140 m (Grosswald & Hughes, 2002; Huhyrechts, 2002; Lambeck et al., 2002; Peltier, 2002; Yokoyama et al, 2000), whilst Siddall et al. (in prep) provide compelling evidence for a LGM lowstand of 125 m with uncertainty bounds between 120 and 126 m. In terms of total global ocean volume this represents a potential volume difference of 5% but as will be demonstrated in Section 2.5 this can represent a variation in palaeo-coastline position of several 10's if not 100's of kilometres. If other factors contributing to sea level change are left aside for the moment, and if meltwater volume is assumed to be evenly distributed, these '*glacio-eustatic*' or '*ice volume equivalent*' changes are not spatially variable, but are solely a function of time (Lambeck, 1995; 1996; Lambeck & Chappell, 2001). As a result, glacio-eustasy is frequently regarded as having a 'global' influence.

At this point, it should be noted that in some instances the terms glacio-eustasy and eustasy are conflated and taken to mean the same thing. Examples of this include many of the numerical models of sea level change (see section 2.4 for more detail). Note for instance the statement by Milne and co-authors at the start of Section 2.2.2 , and the quote below:

"We adhere to the conventional meaning and use the term 'eustatic' synonymously with 'meltwater' (Milne et al, 2002:364).

In addition, to those contributions from the hydrological cycle, and its variability with time, we also have to consider a number of factors which may modify the volume of water in the ocean basins and hence the overall water level. Changes in atmospheric pressure, temperature and salinity of seawater can have an impact on sea level – from millimetres up to several metres. This results from the fact that these changes alter the density of water, and thus its volume. Denser water is principally the product of lower temperatures and increased salinity and as such occupies a smaller volume of space, thus resulting in a sea level fall. The reverse is true of warmer, less saline water, which occupies a larger space. It has been calculated that a temperature variation of 1°C over a 4000m thick layer of water, or alternatively a salinity change of 4%, will produce a change in volume equivalent to 0.6m of vertical height. At present the contribution of thermal expansion to 20th century global eustatic sea level is estimated to be of the order of 2 to 7 cm (Douglas, 2001b).

Until 1960 the Mediterranean, for example, exhibited a trend of rising relative sea level of around 1 to 2 mm yr^{-1}. This trend reversed sign until 1994 when relative sea level began rising again, this time at a rate of c. 20 mm yr^{-1}. Increases in atmospheric pressure have been interpreted as causing the reversal of the trend from the 1960s to the 1990s, while the mid 1990s increase has been correlated with temperature changes in the upper waters (surface to 200m depth) of the Mediterranean (Tsimplis & Rixen, 2002). These changes though represent averages over the whole of the Mediterranean Basin, even within this relatively restricted area, local variations in sea level are apparent. Over a period of 6 years (1993-1998) satellite altimetry has revealed that relative sea levels in the Ionian Basin (east of Sicily) have been falling at a rate of 15–20mm yr^{-1}, while the Levantine Basin (south of Crete) has exhibited a rise of 25-30mm yr^{-1}. Spatial variability in sea surface temperatures is not sufficient to suggest that it is the sole driving force behind these variations, additional influences are believed to include decadal scale fluctuations of the general circulation patterns of the Mediterranean, as well as local changes in salinity (Cazanave et al, 2001; Tsimplis & Rixen, 2002).

Over the Quaternary timescale, the storage of large amounts of freshwater during glacial stages in the form of ice sheets would have increased the salinity of the oceans. During the last glaciation for instance ocean salinity increased by around 3.5%. This, in conjunction with lower temperatures, would have resulted in a minor sea level fall, probably of the order of centimetres to a few meters (Pirazzoli, 1996).

2.2.3.2 Mechanisms for the Re-distribution of Ocean Volume

On a global scale the principal mechanism by which the volume of ocean water is re-distributed is via modifications to the Earth's gravitational field. The ocean surface approximately correlates to the geoid, an equipotential surface of the Earth's gravitational field. The correlation is only approximate because influences such as waves and tides cause ocean level to deviate from the geoid on orders of up to several meters. However, if these influences were removed, the two surfaces would correspond.

The term equipotential surface can be taken to mean one in which all energy is evenly distributed. This can be thought of as a level surface, or alternatively one in which no work is required to move about it. The broad structure of the geoid follows the rough shape of the Earth; an ellipsoid of radius 6378.137 km at the equator and 6356.753 km at the poles. This is a product of the Earth's rotation, which gives the planet a slight equatorial bulge and minor flattening at the poles (PSMSL, 2003).

The geoid itself however is not a completely level ellipsoidal surface; its surface does in fact undulate, roughly correlating with the earth's topography. Therefore it follows that if the ocean surface corresponds roughly to this equipotential surface, then it too exhibits topographical variations in the form of bumps and depressions. For example, bulges in the ocean surface develop around seamounts as these large masses produce a gravitational attraction towards themselves (Mörner, 1976; Douglas, 2001a; PSMSL, 2003).

Assuming for the moment that the planet was rigid, resulting in the geoid remaining stable over time, then the concept of eustasy as a uniform global phenomenon would be valid (Figure 12A). The geoid though is a function of the Earth's gravity, which is itself a function of the planet's structure, rheology, density, rotation and astronomical gravity. Consequently, any temporal changes to these will modify the geoid and thus the distribution of ocean water rendering any concept of a globally uniform sea level invalid (Figure 12B).

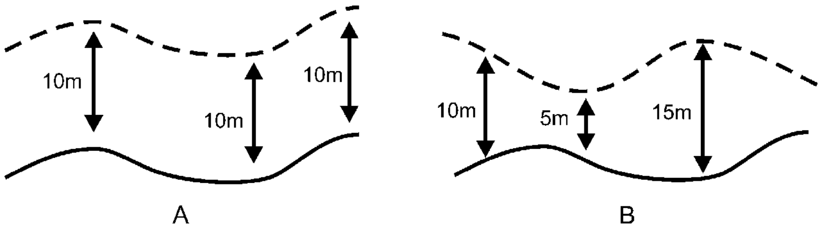


Figure 12. The solid line is the position of the geoid at time *t*, the dotted line is the position of the geoid at time t_1. A) The geoid is uneven, but stable over time, so the concept of a global uniform sea level change is valid. B) The geoid fluctuates over time, rendering the concept of a global uniform sea level change invalid. (After Mörner, 1980)

Factors that modify the geoid, and hence sea level, can be divided into two broad categories – those that affect the Earth's gravity field by modifying the planet's rotational pattern, and those that do so by modifying the gravitational attraction of materials on and within the Earth.

Modifications to the planet's rotational pattern tend to result in the movement of the entire geoidal ellipsoid. These changes are caused by large scale mass redistributions on and within the planet, such as the movement of mantle material by convection currents over the long term.

Similarly, the transfer of water between oceans and ice sheets over the glacial-interglacial cycles of the Quaternary can also have an effect on geoidal variation. The magnitude of the masses involved in these redistributions is such that they can alter the planet's rate of rotation and axial tilt (the angle of its axis of rotation). Changes to the planet's rate of rotation, will lead to geoid height varying in opposite sign about the equator and the poles. For instance, an increase in rotational rate will result in the geoid (and hence sea level) rising around the equator, and falling at the poles, while a decrease will result in the reverse. Movement of the planet's rotational axis in a lateral direction (commonly known as polar drift), modifies the geoid such that sea level at the equator remains stable, while highstands or lowstands are experienced in the northern and southern hemispheres, depending on the direction of drift (Mörner, 1980; 1986; 1987; Pirazzoli, 1996; Milne et al, 2002).

Since variations in the gravitational attractions of different materials on, and in the planet also serve to give the geoid its irregular relief, changes in their distribution of these materials will result in corresponding movements of the geoid. This can be illustrated by looking at the modification of the geoid by the changing ice masses of the Quaternary. This is observable in that during glacial phases, the gravitational attraction of the accreting ice sheets increases, thus pulling water towards them. This is observable as a relative sea level increase close to the ice sheets and a fall further away (Clark, 1980; Fjeldskaar & Kannestrom, 1980; Mörner, 1980; Lambeck, 1996; Milne et al, 2002).

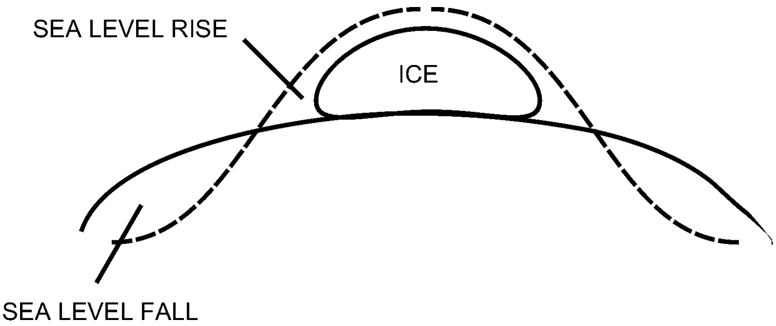


Figure 13. A schematic representation of the modification of the geoid by the gravitational attraction of an ice sheet. The solid line is the undeformed (pre-ice sheet) geoid and the dotted line represents the geoid after modification by the gravitational attraction of the ice (After Fjeldskaar & Kannestrom, 1980)

As the ice sheets melt, the reverse process occurs as their gravitational attraction decreases. Although the effects of this tend to be most significant close to the ice sheets, they should not be underestimated as it has been demonstrated that during the last glacial phase the Scandinavian ice sheet had such an effect on the waters of the

Aegean Sea, some 2000-2500km from the centre of the ice mass. The vertical displacement of the ocean surface in this instance was of the order of several metres (Lambeck, 1996).

In addition, the redistribution of materials of different densities within the planet's interior as a result of mantle flow and crustal displacement serves to modify the geoid further. This is a feedback process in that the changing distributions of ocean volume will in turn lead to differential loading of the crust and thus additional geoid deformation until equilibrium is reached (Clark, 1980). Deformations of geoid relief resulting from processes operating within the Earth can be rapid; up to 10-30mm/year (Mörner, 1986). Therefore, with respect to sea level change in relation to the glacial cycles of the Quaternary, this is a major factor that needs to be considered.

The advent of satellite altimetry measurements have provided a quantitative global perspective on geoidal variations in sea-level, with fluctuations in relief of nearly 200m and wavelength undulations of the order of several thousand kilometres having been identified (Donovan, 1979; Pirazzoli, 1996). For example, a geoid hump of c. 76m (measured with reference to the best fitting geoidal ellipsoid) exists over New Guinea, while a depression of c. -104m exists over the Maldive Islands, representing a total difference of 180 metres (Mörner, 1976).

The effect of geoidal changes on sea level, or '*geoidal-eustasy*' (Morner, 1976; 1987; Long & Roberts, 1997) is another of the ambiguous terms encountered in sea level research. Morner (1976) and Long & Roberts (1997) firmly classify it as a eustatic factor, due its influence on the ocean, while Lambeck (e.g. 1993a, b; 1995; 1996) distinguishes it from the eustatic change (which in his context of use relates solely to glacio-eustasy) and uses it in conjunction with isostatic processes on the basis that their effects vary regionally, and that it is in some measure caused by the shifting distributions of ice, water and mantle material. In this document the former position will be adopted, given the influence of the geoid on the distribution of global ocean volume.

Tides also influence the distribution of the ocean water volume and hence relative sea level on a local to regional scale (Shennan et al, 2000a, b). This is highlighted by the fact that on very small temporal and spatial scales (e.g. one beach over a period of one day) the position of the sea surface is not stable, but varies over a vertical range of several tens of centimetres to several metres. Globally, tidal ranges vary from a maximum of 18 metres in the Bay of Fundy (Canada) to less than 0.5 metres in the near tideless Mediterranean. Even within localized regions a significant degree of variation is possible, for instance Arklow, in southeast Ireland has a tidal range of 2m, while Avonmouth (west of England), on the other side of the Irish Sea has a tidal range of 14 metres (Plag et al, 1996).

Globally, tides are governed by gravitational forces in that the gravitational attraction of the Moon and the Sun pull ocean water towards them resulting in the creation of a tidal bulge. This is manifested as high tide in some areas, while the redistribution of ocean water results in a low tide in other areas. Variations in tide level may therefore take place if these gravitational forces are modified. For instance, when the position of the Sun and Moon are such that their attractive forces operate in conjunction with each other higher, spring, tidal levels will result. Conversely, when their forces operate against each other, they create lower, neap, tides. These combinations of orbital geometry occur regularly to the point where neap and spring tides occur approximately every 14 days (Davis Jr., & Fitzgerald, 2004).

On regional scales basin dimensions represent a major influence on the oceanic tidal wave as it crosses the shelf. The oceanic tidal wave in fact rotates around amphidromic points (nodes where tidal range is zero) as a result of forces generated by the Earth's rotation (the Coriolis effect). Rotation is anticlockwise in the northern hemisphere and clockwise in the southern hemisphere. On shallow shelves and in enclosed basins, such, as the North Sea, tidal waves reflect off the coastline and encounter subsequent incoming tidal waves. The waves interact and are then deflected by the Coriolis force to one side of the basin. This deflection results in water piling up on one side of the basin, thus amplifying the tidal range in that area, while on the other side of the basin, tidal ranges decreases. This can be seen in the North Sea where tidal ranges on the east coast of Britain are of the order of 3-4m, while on the Norwegian and Danish coasts have ranges of less than 1m (Open University, 1989; Davis Jr. & Fitzgerald, 2004)

Finally, on a local scale, the configuration of basin morphology will also influence tide levels to a great extent. For instance, the water level in a lagoon depends to some extent on the ratio between its surface area and the cross sectional area of its inlets. In certain situations, this ratio may lead to a lagoon experiencing a different water level to that of the open coast (Open University, 1989; Pirazzoli, 1996). This has been highlighted by investigations of tidal distortion in a salt marsh on the east coast of North America. In this instance it was found that local Mean High Water (MHW) varied within the salt marsh by up to 55cm and also potentially differed from oceanic Mean Sea Level by a similar magnitude. In addition spatial variations were also noted with respect to the flood frequency and inundation duration of the local tides. These modifications to the oceanic tidal regime have been interpreted as a consequence of local morphology, for example; the greatest tidal distortions were noted at furthest away from the inlet (Van der Molen, 1997).

Tides vary over time as well as space. In relation to sea level fluctuations, major tidal parameters such as elevation amplitude may be altered as a result of the modification of the local coastal configuration and bathymetry by transgressive or regressive events (Scourse & Austin, 1995; Shennan et al, 2000a; Shennan & Horton, 2002). For example, tidal modelling suggests that the most rapid increases in Holocene tidal range that took place in the western North Sea region were coincident with the most rapid palaeogeographical shifts resulting from sea level rise. High tide at Flamborough Head is estimated at 1.6m above mean tide level at 8 Kyr BP, 1.9m at 7 Kyr BP and 2.1m at 6 Kyr BP (Shennan et al, 2000b). In comparison, present day Mean High Water Spring Tide (MHWST) at Bridlington (Flamborough Head) is 2.55m above mean sea level. More dramatic changes have been modelled further south with the Holocene breaching of the Straits of Dover by relative sea level rise transforming the tidal regimes of both the southern North Sea and eastern English Channel from ones of low tidal amplitude (<0.5m) to states approaching the current level of tidal action; around 2m (Scourse & Austin, 1995).

Finally, dynamic factors, such as winds or currents have the potential to alter local sea levels by up to several metres by holding back or pushing forward tides. In exceptional circumstances, such as a combination of high tide, high winds and low atmospheric pressure, anomalously high sea levels or storm surges may result. For example, the North Sea storm surge of 1953 resulted in a local sea level rise of up to 3m above normal and flooded low lying areas of Britain and the Netherlands. Storm surges of up to 5m have been observed in the North Sea and the Bay of Bengal, while satellite altimetry has shown that current forces of the Gulf Stream can create sea surface bulges of similar magnitude above the geoid. Conversely, combinations of high pressure and offshore winds may create negative storm surges, or unusually low sea levels (Mörner, 1987; Pirazzoli, 1991; 1996; Open University, 1989). Collectively, sea level changes induced by dynamic factors and changes in water density (see section 2.2.3.1) are known as ‘steric’ variations (Pirazzoli, 1996).

The above examples are all from very recent periods, and may not be exact representations of the situation happening in the past given the climatic variations taking place over the Quaternary. As with tidal variations, changes in overall bathymetry with changing sea level will result in a changing wave climate. Van der Molen & de Swart (2001) have modelled changes in wave climate for the Holocene, their results suggesting mean wave height has steadily increased since 7.5 ka BP (although this did assume a modern wind climate).

2.2.4 Isostatic Controls on Sea Level

Changes in both basin volume and ocean volume represent only first order approximations of the changing sea level situation. Additional, and more localized, changes are caused by the Earth’s response to shifting loads – such as ice sheets and oceans – which is governed by the principle of isostasy. According to this theory, all parts of the Earth’s crust float on a denser underlying layer, and are in balance, or gravitational equilibrium, with each other. Consequently, any changes in the thickness or density of the crust will alter the system such that it will try to return to equilibrium through flowage of the underlying layer, and movement of the crustal elements.

Geophysical and geological evidence suggests that this is indeed the case with the lithosphere (the outermost shell of the Earth’s structure, some 100 km thick and encompassing the crust and the uppermost portion of the mantle), floating on top of a denser underlying layer – the mantle – which itself is divided into upper and lower sections on the basis of density, the lower mantle being more dense. The placement of loads on the Earth’s surface therefore results in the elastic deformation of the lithosphere and flowage of the viscous mantle material beneath (Figure 14).

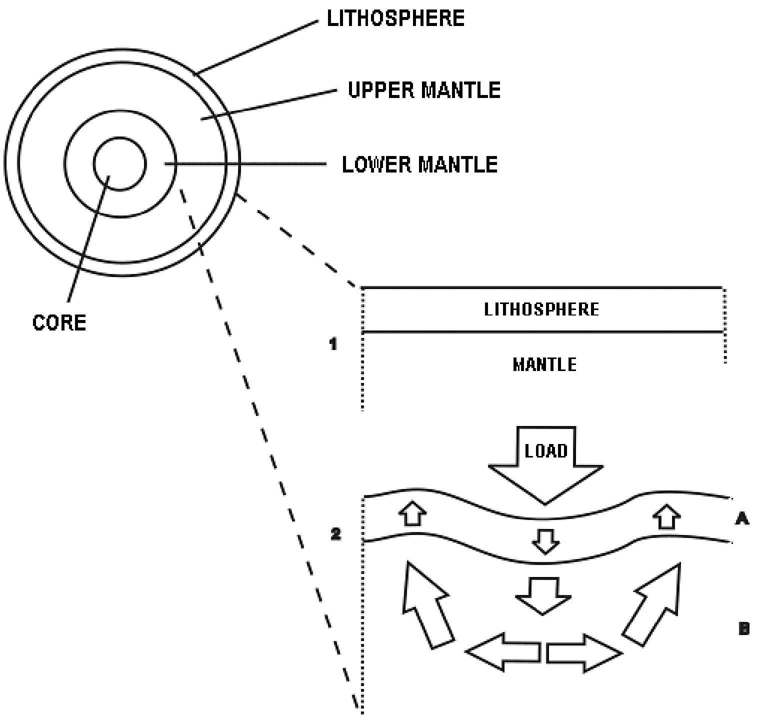


Figure 14. A schematic representation of the control of earth rheology on isostatic adjustment (not to scale). Stage 1 – Lithosphere and mantle are in a state of isostatic equilibrium. Stage 2 – Lithosphere and mantle respond to loading through A) elastic deformation of lithosphere and B) viscous flow of mantle

The lithosphere responds elastically to changing loads, such as ice sheets and oceans, on timescales of hundreds to thousands of years. This deformation is occurring almost instantaneously by comparison with the changes taking place in the denser material below it. The movement of the lithosphere displaces the mantle material below, but since this is denser than the layer above, its response takes the form of a viscous flow over a long period of time. The upshot is that deformation of the Earth’s surface occurs not just at the point in time at which the loads vary, but also for thousands of years afterwards. For example, the isostatic uplift of North America and Scandinavia is only around half complete despite the fact that the ice sheets that constituted the loading factor had all but disappeared by 8 ka BP (Van Andel, 1989; Pirazzoli, 1996; Johnston, 1995; Lambeck, 1995, 1996; Lambeck & Chappell, 2001; Milne et al, 2002).

2.2.4.1 Glacio-isostasy

In relation to the glacial cycles of the Quaternary, the placement of a large ice mass on the Earth’s surface leads to the subsidence of the crust directly beneath it. In tandem around the margins of the ice sheet a raised marginal rim or forebulge develops (Figure 15).

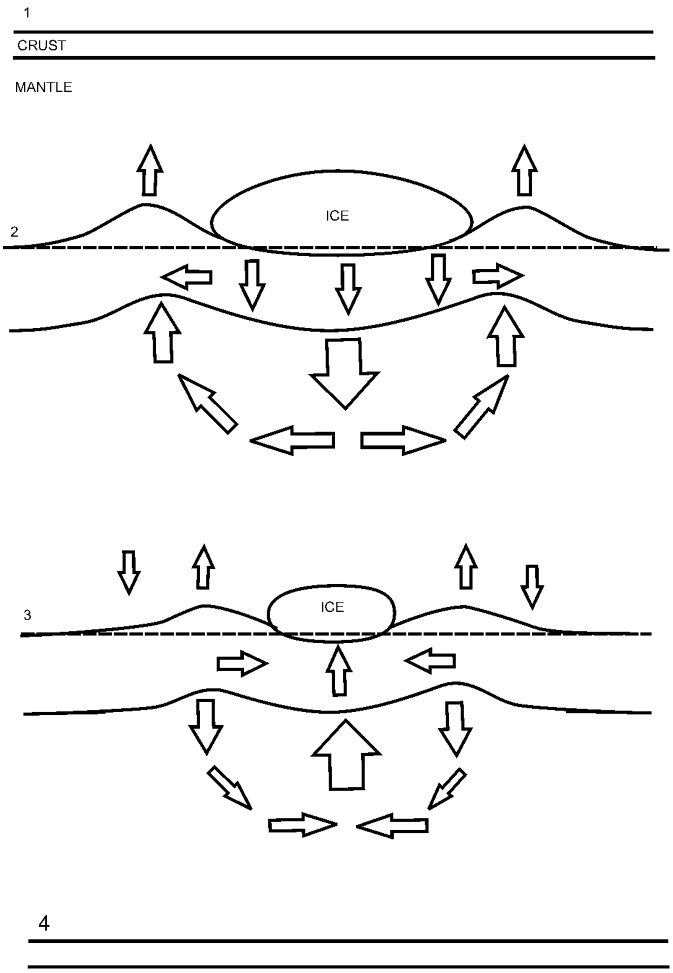


Figure 15. Schematic representation of the Earth's isostatic response to changing ice loads: 1) No ice sheet. The crust is in a state of isostatic equilibrium. 2) Growth of ice sheet. Weight of ice sheet depresses crust beneath it and leads to uplift around the ice margins through elastic deformation of the lithosphere and viscous flow of the mantle. 3) Decay of ice sheet. Reduction of load leads to crust uplifting beneath it and forebulge migrating back to centre of glaciation. 4) No ice sheet. Crust returns to a state of isostatic equilibrium. (After Pirazzoli, 1996).

The removal or retreat of an ice sheet in turn removes the load from the crust, thus resulting in the land below it uplifting and the forebulge dissipating (Figure 14). Simple models of this process predict that the forebulge should only comprise around 10 percent of the maximum rebound since mass must be conserved during and after deglaciation and the lateral extent of the forebulge is greater than that of the central rebound area (Johnston, 1995).

Isostatic movements stemming from ice sheet growth and retreat are known as '*glacio-isostatic*'. Glacio-isostatic changes vary in both time and space as a consequence of the spatial, as well as temporal distribution of the ice sheets. This, in conjunction with the other factors outlined in this document, can lead to significant differences in relative sea level change between different regions in the same time period (see Figure 9). Should land uplift exceed the glacio-eustatic rise, sea level will appear to fall and vice versa.

2.2.4.2 Hydro-isostasy

Variation in volume and distribution of water masses, for instance during cycles of glaciation or deglaciation, can also lead to uplift or subsidence of the oceanic crust, thus adding a further isostatic contribution to sea level change. As meltwater is added to the oceans, the increased weight of water will lead to the subsidence of the ocean floor in relation to the land surface. If the rate of subsidence exceeds the glacio-eustatic increase, then a regional sea level fall will take place (Johnston, 1995). Like glacio-isostasy, these '*hydro-isostatic*' processes continue to operate even when the meltwater input into the oceans has ceased due the long term viscous flow of mantle material. This is observable in Figure 9G, which illustrates that the continental shelf off Queensland, Australia has been slowly subsiding since the glacio-eustatically induced highstand of 6000 BP (Lambeck & Chappell, 2001).

Like glacio-isostasy, hydro-isostasy is spatially and temporally variable, since it depends on the fluctuating distribution of large masses, in this case, ocean water. Consequently, the hydro-isostatic effect tends to increase as one moves seaward, as the size of the meltwater load varies with topography in that shallow continental shelves will be loaded with less water than deep ocean basins and will therefore be subject to a lesser degree of subsidence (Pirazzoli, 1996) (Figure 16).

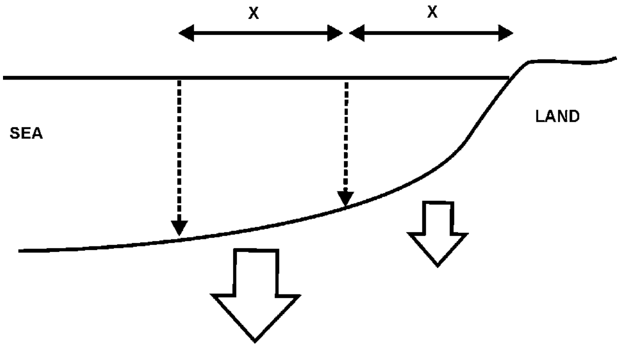


Figure 16. A schematic representation of the topographical variations in water loading effects. Close to the shoreline, water volume (and hence mass) is reduced due to the shallow topography. Further away, depth increases and therefore so does the mass of water in the water column. The increased load leads to a higher rate of subsidence in the deeper parts of the shelf (after Johnston, 1995; Pirazolli, 1996).

2.2.4.3 Other isostatic influences

Ice sheets and oceans are not the only loads that result in the isostatic adjustment of the planet. The accumulation of significant quantities of sediment over short timescales (i.e. up to hundreds of years) such as near major river deltas may lead to isostatic subsidence of the order of a few millimetres a year (*sediment-isostasy*). For example, the Netherlands is estimated to be subsiding at a rate of 2.5mm/yr as a result of the weight of sediment deposited in its delta basin (Goudie, 2001). Similar loading effects take place over longer timescales (i.e up to tens of thousands of years) as well, notably as a consequence of the deposition of sediment on exposed continental shelves during sea level lowstands (Reynolds et al, 1991; Pirazzoli, 1996)

Similarly, the extrusion of large quantities of lava by volcanoes also has the potential to load the crust to the extent that isostatic equilibrium is disrupted (*volcano-isostasy*). Hawaii, for instance, is estimated to be subsiding at a rate of 4.8mm/year.

Finally, the activation of isostatic processes does not necessarily have to involve the addition of a load onto the surface of the lithosphere; changes in the density of the crust itself will have the same effect. As the oceanic crust emerges and spreads away from submarine ridges, it cools and thickens, thus increasing in density, and begins to subside (*thermo-isostasy*). This process can also be reversed if the moving crust encounters a hot spot such as a lava source (Pirazzoli, 1991; 1996).

2.2.5 Sedimentary Controls on Sea-Level

In addition to being a driver of sediment-isostasy, sedimentary processes also have the potential to alter sea level on a local to regional scale. Assuming that the volume of water within a given basin remains constant, the deposition of significant quantities of sediment on the seabed will result in a sea level rise as the added sediment alters the geometry of the basin holding the seawater by reducing its volume (decreasing accommodation space), while erosion leads to the reverse process (increasing accommodation space: see Section 4). It has been calculated, that the amount of sediment annually removed from the United States has the potential to raise sea level by 1.5 cm every thousand years (assuming that no other influences on sea level were operating). This process is sometimes termed "*sedimento-eustasy*" (Donovan & Jones, 1979; Mörner, 1986). In reality, the effects of sedimentation on sea level tend to be mitigated by sediment-isostasy and compaction induced subsidence created by fluid escape. The former has been described in section 2.2.3.3, while the latter involves a reduction in volume of the sediment as its water content reduces due to increasing weight of the sedimentary overburden. The magnitude of compaction is significant, with a thickness reduction of an individual sedimentary unit of up to 70% being possible (Donovan & Jones, 1979; Reynolds et al, 1991; Swift & Thorn, 1991). Both these processes serve to increase the available accommodation space; or available volume within which sediment may be subaqueously deposited, which would otherwise have been decreased by sediment deposition (Leeder, 1999). In doing so, they also cause the vertical displacement of the ocean surface (assuming that water volume has remained constant).

In addition, sedimentary processes have the potential to instigate local transgressions and regressions without the need for a change in sea level. At this point it is worth stating that regressions can be defined as the seaward movement of the shoreline, and transgressions as its landward movement. These processes may be brought about by relative sea level fluctuations initiated by the factors described in the previous sections. However, the deposition of significant quantities of sediment on the continental shelf, such as at the mouth of a river delta, may result in the expansion of the coastal plain, and thus the shoreline, seawards without sea level change actually taking place. Alternatively, the erosion of shoreline sediment may result in the shoreline moving landwards. These processes are known respectively as '*progradational regression*' and '*erosional transgression*' and are distinguished from shoreline movement induced by purely sea level change (be it eustatically driven, isostatically driven, or a combination of the two) which are termed '*forced regression*' and '*forced transgression*' (Leeder, 1999). It is worth keeping in mind therefore that marine transgression and regression may involve combinations of all the aforementioned processes (See Discussion in Chapter 4).

During the Holocene in North Germany, for instance, regressive layers of peat developed where bog growth resulting from a water table rise (itself induced by the slowly rising sea level) was sufficient to compensate, or even exceed, the local rise in sea level and hence result in a temporary reversal of the movement of the shoreline (Streif, 2004 and Figure 17).

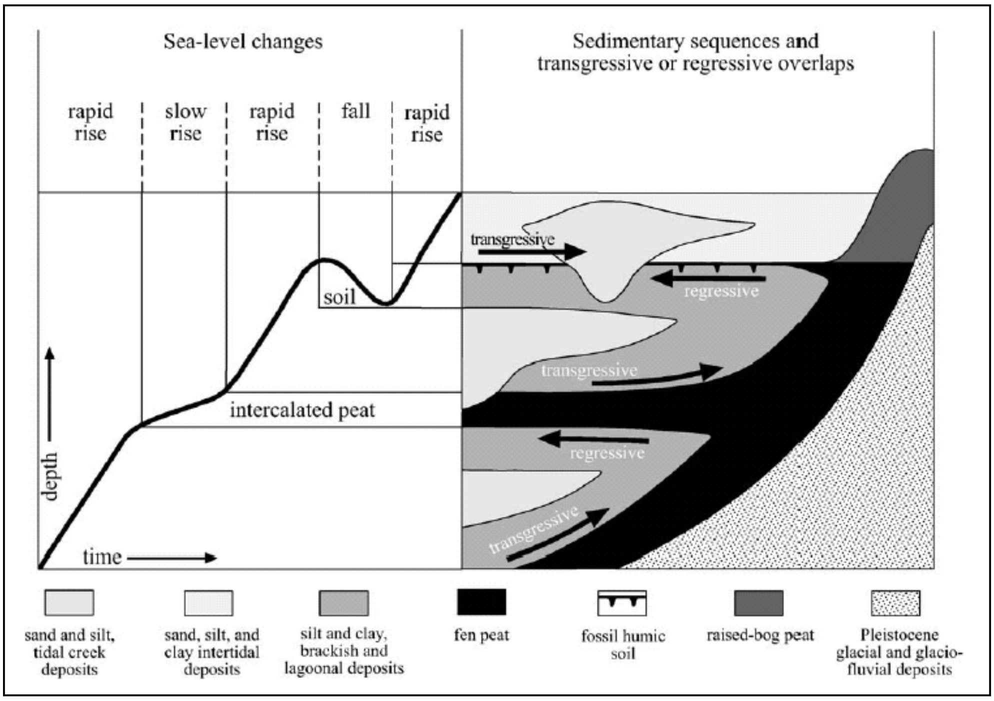


Figure 17. Diagram illustrating how progradational regression may come about under sea level rise. Note the regressive intercalated peat layer that forms during a slow rise in sea level (From Streif, 2004).

Coastal progradation takes place when the quantity of sediment supplied exceeds that removed by marine transport. This is particular common in areas receiving large quantities of fluvial sediment, such as deltas. Rates and magnitudes of delta progradation therefore vary spatially and temporally depending on the rates of the above two variables. For example, it has been calculated on the basis of present day measurements that it would take between 11,600 and 12,700 years for the Amazon River to prograde across the adjacent continental shelf (a distance of 320 km and a depth of 90m at the shelf break, creating a shelf volume of 4.75 X 10^{12} m^3). In contrast, similar calculations for the Nile reveal that it would take between 28,000 and 140,000 years to prograde across 50 km of shelf (depth of shelf break here is 250m, creating a volume of 1.25 X 10^{12} m^3: Burgess and Hovius, 1998). These are estimates, and in reality would be mitigated by sediment compaction, sediment isostasy and changes in both the marine and fluvial processes by a number of processes including sea level change.

2.2.6 A Synthesis of Sea Level Change

Most considerations of Quaternary sea level tend to ignore the smaller scale components such as steric changes, tidal changes and sedimentary processes. As a result, in areas not suffering from rapid coseismic events, the relative sea level changes for a particular place and time should at least take into account glacio-eustatic change, geoidal fluctuations, local glacio-hydro-isostatic change and local tectonics.

An example of the amalgamation of these processes can be seen in the Holocene sea level curves from the North Sea region. This region has been chosen because it has provided a great deal of sea level data and it illustrates well the range of variation possible in sea levels within a relatively restricted region (see Figure 18).

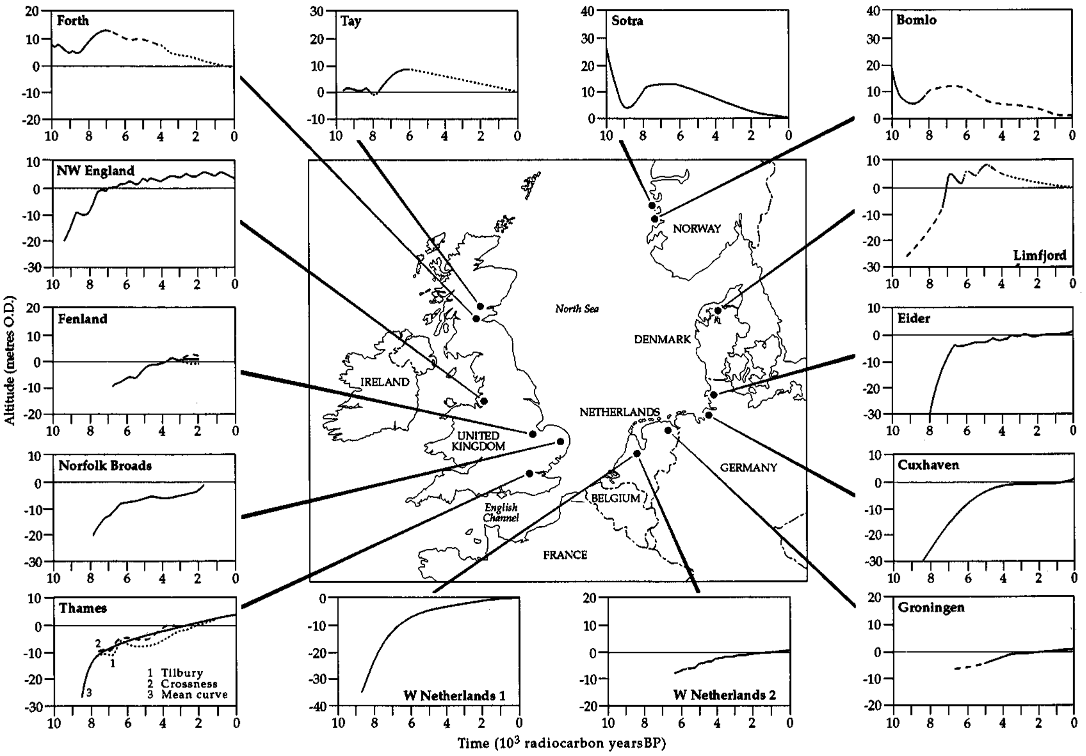


Figure 18. Holocene relative sea level curves from around the North Sea. Note the range of variation between even relatively close locations (Shennan, 1987).

The complexity in these sea level curves is principally a result of the proximity of the region to the British and Scandinavian ice sheets during glacial phases, which resulted in complex isostatic, eustatic and geoidal fluctuations (Figure 19). Although it should be noted that there is still significant debate on the dimensions and glacial/deglacial history of these ice sheets (Sejrup et al, 1998 vs Bowen et al, 2002).

Figure 19. One representation of the extent of the British and Scandinavian ice sheets at the beginning and end of the Last Glacial Maximum. Ice limits are based on multiple sources. See Lambeck (1993b) for summary. The map on the left depicts the situation at 22000 (C^{14}) yr BP, when the British ice sheet was at its maximum extent, and the map on the right depicts the onset of deglaciation at c. 18000 (C^{14}) yr BP (modified from Lambeck, 1995)

In areas under the greatest weight of ice, i.e. the central part of the glacier, the dissipation of the ice sheets tends to result in the domination of the glacio-isostatic contribution such that the land uplifts at a higher rate than the glacio-eustatically induced increase in ocean volume, resulting in a local sea level fall (Lambeck & Chappell, 2001) as exemplified by the curves in Figure 20.

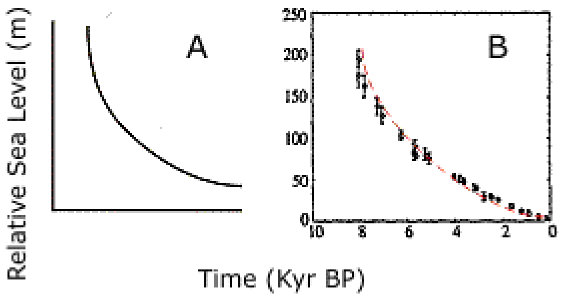


Figure 20. Sea level change near the centre of glaciation. A) Generalized curve B) Ångermanälven, Gulf of Bothnia, Sweden (modified from Lambeck et al, 1998).

Towards the margins of the ice sheets, given that the weight of ice is somewhat less than at the glacial centre, land rebound initially dominates before being overtaken by glacio-eustatic increases. Once glacial melting ceases however, the continuing process of isostatic uplift once again becomes the dominant process. The sea level curve therefore shows an initial relative sea level fall, then a sharp rise and finally a gradual fall (Figure 21).

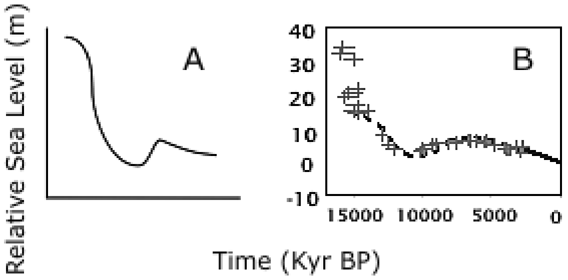


Figure 21. Sea level changes at the ice margins. A) Generalized curve. B) Arisaig, NW Scotland. Crosses represent observed sea level indicators (see section 3), line represents predicted sea level (see Section 2.4. Modified from Shennan & Horton, 2002)

Just beyond the margins of the ice sheets, bulges in the land surface develop as a result of the weight of the ice mass displacing mantle material outwards, away from the centre of glaciation (see Figure 15). Sea level change in these areas therefore takes the form of a very rapid rise, resulting from the combination of the subsidence of the forebulge due to the reduction in the weight of ice, and the glacio-eustatic increase. Once melting ceases, sea level rise continues due to the continuation of forebulge subsidence, albeit at a reduced rate (Figure 22).

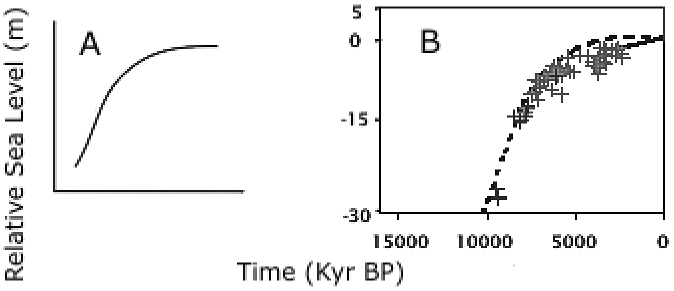


Figure 22. Sea level changes beyond the ice sheets A) Generalized curve B) Bristol Channel, SW England. Crosses represent observed sea level indicators (see section 3), line represents predicted sea level (see Section 2.4. Modified from Shennan & Horton, 2002)

Further away from the ice sheets, beyond the area of the forebulge, glacio-eustatic and hydro-isostatic changes dominate, hence the initial sea level rise tends to be rapid, but once meltwater influxes into the ocean cease, the load of water on the ocean floor pushes it down, thus leading to a very slow sea level fall (see Figure 23: Lambeck, 1996; Lambeck & Chappell, 2001).

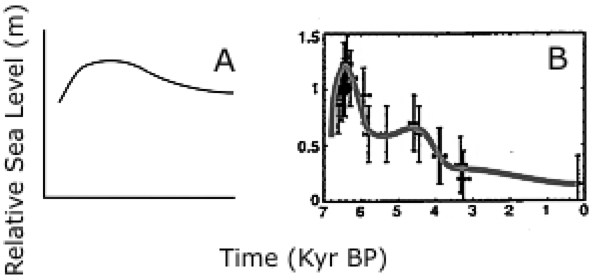


Figure 23. Sea level change far from the ice sheets. Given the distance of the North Sea region from the European ice sheets, no curves of this sort are found in this area. A) Generalized curve B) Sea level change at Orpheus Island, Queensland, Australia (modified from Lambeck & Chappell, 2001)

2.3 Documenting Past Sea Level Change

2.3.1 Introduction

A number of lines of evidence exist which make possible the documentation of past sea level changes. The most complete and highest resolution, records tend to provide estimates of local relative sea level trends since the start of the Holocene, and to some extent the post-LGM Pleistocene. This is a consequence of the fact that a large proportion of the earlier record has either been destroyed by advancing ice sheets or obscured by postglacial sea level rises (Lambeck & Chappell, 2001). To quote Pirazolli (1996:83):

> *"There is no way of accurately measuring sea level changes and vertical isostatic movements prior to deglaciation; in these areas estimates can only be based on assumptions and modeling or on proxy data, rather than on direct observation."*

However, even the post-deglaciation sea level record suffers from a number of gaps. For instance, it is often assumed that sea level indicators are rapidly submerged or exposed by transgressive and regressive events, respectively. In reality, even when the rate of relative sea level rise was much greater than at present, such as during the Late Pleistocene, features stayed in the intertidal zone for periods ranging from decades to thousands of years. To illustrate this point, it has been calculated that assuming a rate of relative sea level rise of 160mm/yr (compared to the estimated present day rate of 1.5mm/yr) and a tidal range of 2m, a feature will remain in the intertidal zone for 13 years. At the other end of the scale, assuming a rate of 1mm/yr and a tidal range of 14m, the time spent in the intertidal zone increases to 14,000 years (Plag et al, 1996). Given that wave effects may operate between -15m below mean low water and 10m above high water during fair weather, and can extend as deep as 200m during storms, this means that the potential for erosion and destruction of the sea level record is very high indeed (Open University, 1989; Plag et al, 1996).

There are a number of exceptions to this rule, notably the coral reefs of the Huon Peninsula in Papua New Guinea, which have been tectonically uplifted beyond the reach of destructive processes associated with the onset of the last glacial cycle and consequently provide a semi continuous record of sea level change over the past 300,000 years. These and some other types of sea level indicators permit the reconstruction of broad trends in sea level far back into the Quaternary. Conversely, detailed (centimetric) analysis of a range of organic and inorganic indicators can be used to give high resolution records of sea level change on a local scale. These curves although do not necessarily provide information on process do provide a very accurate indication of the magnitude and sense of change particularly during the mid- to late-Holocene in many parts of the world.

Even when sea level indicators are available, care must be taken over their interpretation as they rarely give an exact position of sea level. Instead they tend to provide an estimated vertical range, which can vary from anywhere between several centimetres to several metres, depending on the indicator in question. Although these figures may not seem to be of particularly large magnitude, they can have significant implications for the reconstruction of past landscapes (see Section 2.5). What follows now is a synopsis of the most commonly used indicators of past sea level change, and the errors margins inherent in their use (Section 2.3.2), the critical issue of dating indicators (Section 2.3.3) and finally the most common methods of displaying sea level data (Section 2.3.4).

2.3.2. Indicators of Past Sea Level Change

2.3.2.1 Erosional geomorphological indicators

A number of geomorphic and geological features can be related to past sea level. These can take the form of erosional features created by wave, tidal and surf action. If they can be identified and dated, they will indicate the position of the palaeo-shoreline. Erosional indicators are only preserved in competent rocks and include features such as notches, benches, platforms, pools, potholes and sea caves (Plag et al, 1996; Pirazzoli, 1996). A distinction should also be made between features that have been created due to the differential erosion of weaker rock layers rather than sea level position (*structural notches*), and those that are a direct result of wave and surf action (*abrasion notches*). The accuracy of the various indicators depends on the exposure of the site, and also the type of the indicator. Tidal notches for example, are relatively precise indicators; their bottoms are situated near the lowest tide level, their vertexes near MSL and their tops where waves regularly splash at high tide. Wave abrasion of an erosional bench or platform however, may occur anywhere between the highest level reached by storm waves and the maximum depth at which wave action shifts sediment (Pirazzoli, 1996).

2.3.2.2 Coral Reefs

Coral reefs also provide a measure of past sea level fluctuations. Because of light requirements, most corals are restricted to the sub-littoral zone, with their upper limit close to mean low water spring tide. If a particular species of coral can be identified and dated, and its habitat preferences are known, then raised or submerged coral reefs can provide an estimate of past sea level that is accurate usually to within a few metres (Pirazzoli, 1996). The Caribbean species *Acropora palmata* for example, tends to be restricted to the upper 5 metres of water. Dated examples of this species, and the species *Porites asteroides*, off Barbados have provided a sea level curve going back to the Last Glacial Maximum (LGM). When corrected for local tectonic uplift, the data provided an estimate of a glacio-eustatic rise of 121 +/- 5 metres since the LGM (Fairbanks, 1989 and Figure 24). The correction for tectonic uplift is obtained by identifying a past shoreline for which mean sea level was believed to be similar to that of the present day, usually the Oxygen Isotope Stage 5e or mid-Holocene highstand, and measuring how high above the present shoreline it is. Assuming that uplift has been consistent over the intervening time period, this method provides an estimate of the rate of crustal movement. The need to include a tectonic uplift correction was necessitated in this case, because the researchers were attempting to isolate and ascertain the glacio-eustatic component of the post glacial sea level rise. Had this correction not been made, the Barbadian coral record would have only provided a measure of relative sea level change in this localized area.

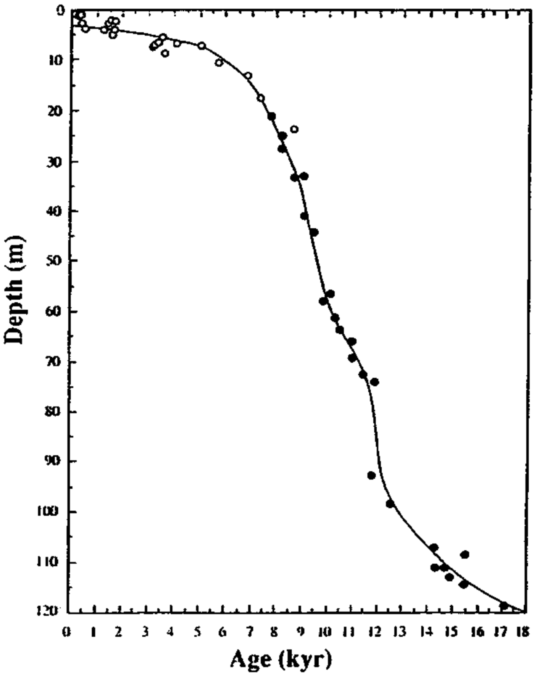


Figure 24. Sea level curve obtained from Caribbean coral reefs. Timescale is in uncalibrated ^{14}C years. The filled circles represent dated *A. palmata* samples from Barbados, and the open circles *A. palmata* from four other Caribbean islands. The data has been corrected for an estimated mean tectonic uplift of 34 cm kyr^{-1} (modified from Fairbanks, 1989).

Tectonically uplifted coral reefs on the Huon peninsula of New Guinea provide a record of sea level highstands going back some 300,000 years. The estimate of the glacio-eustatic sea level change since the LGM, based on information for this area is 130m below present sea level (Chappell & Shackleton, 1986). The 9 m discrepancy between these two, coral reef based, estimates for the LGM lowstand may represent the problems of the eustatic concept (Section 2.2.3) or the inherent errors of the method (e.g. environmental range of habitat and dating).

2.3.2.3 Biological indicators - Macrofossils

One means of obtaining a record of sea level change involves looking at the remains of fossilised marine organisms. Marine organisms and biotic communities tend to be arranged in horizontal bands along the slope of the continental shelf that correspond to certain water depths (*biological zonation*). Therefore, if the habitat preferences of a group of fossils are known, and they can be dated; their distribution provides an indication of sea level at that point in time.

For instance, on rocky shores the littoral fringe, or supra-littoral zone (an area that is never submerged but is wetted by surf) tends to be dominated by lichen and Cyanobacteria; the mid-littoral zone (submerged by tides and waves) is home to algae and fauna such as barnacles, limpets and mussels, while the infra-littoral, or sub-littoral, zone (mean sea level to 25–50m) is densely populated by brown algae, and various species of coral, sponges and molluscs (Laborel & Laborel-Deguen, 1995; Pirazzoli, 1996). In addition to the fossils themselves, certain species may leave behind distinctive traces of their activity. The grazing habits of limpets, for example, create distinct erosional patterns. If these patterns can be identified and dated, they too can indicate past sea level (Laborel & Laborel-Deguen, 1995; Pirazzoli, 1996).

Recent studies in the ancient harbour of Marseilles have utilized the presence of dated fossils of the barnacle *Balanus amphitrite* to produce a sea level record for the past 4000 years with a precision of +/- 10cm. In terms of biological zonation, the distribution of this particular species stops abruptly at mean sea level, thus making it a particularly accurate sea level indicator. A similar sea level record had already been obtained from La Ciotat (35 km to the east), this time using a species of calcareous algae - *Lithophyllum lichenoides* (Laborel & Laborel-Deguen, 1995; Morhange et al, 2000).

It must be pointed out that not all biological indicators, have habitat ranges as narrow as *B. amphitrite*. The mussel species *Mytilus edulis* for example has been recorded at depths ranges of less than 5 m down to 20m in the North Sea (Kearney, 2001). Furthermore, significant regional differences may occur in the distribution of individuals of the same species. The polar species *Portlandia arctica*, for example, is found off east Greenland at depths of between 10 and 60 metres. However, it is restricted to a depth of 6m off northeast Greenland. The differences result from the environmental contexts of the two regions. In the latter, the dominance of the polar current in shallow water permits the survival of the species at a lesser depth (Plag et al, 1996). This highlights the need to consider the local environmental conditions when using fauna as sea level indicators.

Plant macrofossils such as tree stumps or vegetation, can provide evidence of sea level fluctuations when found in submerged contexts (Kearney, 2001). These however, tend only to provide broad qualitative indications, i.e – that sea level has risen, or limiting values of sea level change rather than quantitative estimates accurate to within less than several metres. For example, in the case of submerged forests, sea level must have been lower than the tree roots at their time of growth; however, the determination of numerical extent of this change requires analysis of other sea level indicators. This is necessitated by the fact that many coastal or riparian species are not exclusively restricted to the shoreline, but may also occur inland and in upland zones. An example of this is *Pinus taeda*, which, though common in shoreline areas along the US Atlantic coast also occurs inland in the piedmont zone. Exceptions to this consist of species which survive almost exclusively in the intertidal zone, such as mangrove trees, or salt marsh environments such as the *Spartina* species of grass (Long et al, 1999; Pirazzoli, 1996; Kearney, 2001).This is especially true of the latter environment, in that vegetation zonation is such that divisions within a salt marsh can be recognised. For example, in most New England salt marshes the low marsh (up to Mean High Water (MHW)) is dominated by *Spartina alterniflora* (tall) while the high marsh (up to highest spring tide level) is characterised by *Spartina patens*, *Distichlis spicata* and *S. alterniflora* (stunted). Should sufficient freshwater enter the marsh, the high marsh plants will be replaced down to the level of the MHW spring level, by species such as *Phragmites australis* and *Scirpus robustus*. This final zone is termed the upper marsh (Van de Plassche et al, 1998).

The remains of both faunal and floral sea level indicators can also be moved about after they die, and thus the elevation at which they are found may not be an accurate representation of their position in the past. Sea level reconstructions that use biological indicators must therefore ensure that they come from in situ and not derived contexts.

2.3.2.4 Biological indicators – Microfossils

Investigations of sea level using foraminiferal data can be conducted on two temporal scales: one utilises microfossils to look at long term geological scale changes, the other to provide unparalleled high resolution data over the Holocene.

The classic method of using micro-fossils is the extraction of oxygen-isotope records from benthic foraminifera (Shackleton, 1987). As described in Section 2.2.1 the ratio of ^{18}O to ^{16}O in the oceans acts as a proxy indicator of past glacio-eustatic sea level change (Chappell & Shackleton, 1986). This ratio is recorded in the calcareous skeletons of benthic foraminifera and hence can be extracted from the fossil record. However, temperature variations in the abyssal ocean also affect the oxygen isotope ratio of benthic foraminifera. Sea level curves derived from this data are therefore a combination of global (continental ice volume) and local (ocean temperature) components (Figure 25). Therefore a measurement of the oxygen isotope ratio from deep sea foraminifera therefore provides only a first approximation of continental ice volume and hence glacio-eustatic sea level (Shackleton, 1987).

A more accurate second approximation can be obtained by combining planktonic foraminiferal records with their benthic counterparts, as the temperature effect in the former is judged to be minimal (Shackleton, 1987; Chappell et al, 1996). Even so, they are still regarded to have realistic uncertainties of up to ± 20 m (Rohling et al., 1998). Oxygen isotope records go back as far as 5 million years ago (Lambeck et al, 2002a), however, though they only provide a continuous sea level record for the past 140,000 years (Rohling et al, 1998) and in the absence of detailed relative sea level records, have often represented the only recourse when looking at past sea level change over long timescales.

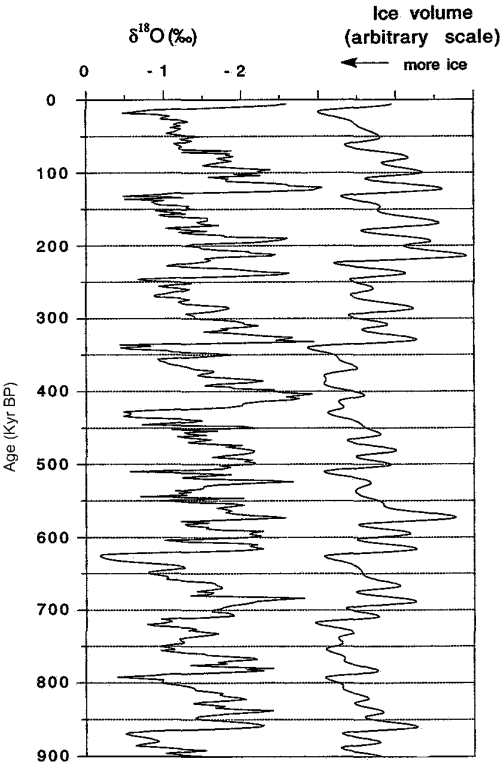


Figure 25. Oxygen isotope record from ocean core MD900063 compared to modelled global ice volumes over the Pleistocene (modified from Bassinot et al, 1994).

A method has recently been developed that allows estimations of past glacio-eustatic sea level lowstands up till 500,000 years ago to be made (Figure 26: Rohling et al, 1998). It involves examining evidence of salinity conditions in the Red Sea during glacial phases in conjunction with a model of water flow between the Red Sea and the open ocean. The basic premise is that at times of lower ocean volumes resulting from the growth of ice sheets, water flow between the Red Sea and the ocean will be reduced, thus leading to increasingly saline conditions which in turn affect the composition of the local benthic and planktonic foraminiferal communities (Sirocko, 2003).

When corrected for local tectonic uplift this technique has yielded depths for the major lowstand events of the last 500,000 years: OIS 6: 131 +/- 6m bpsl; OIS 8: 120 +/-8m bpsl; OIS 10: 122-134 +/-9m bpsl; OIS 12: 139 +/-11m bpsl (all measurements are in metres below present sea level - bpsl).

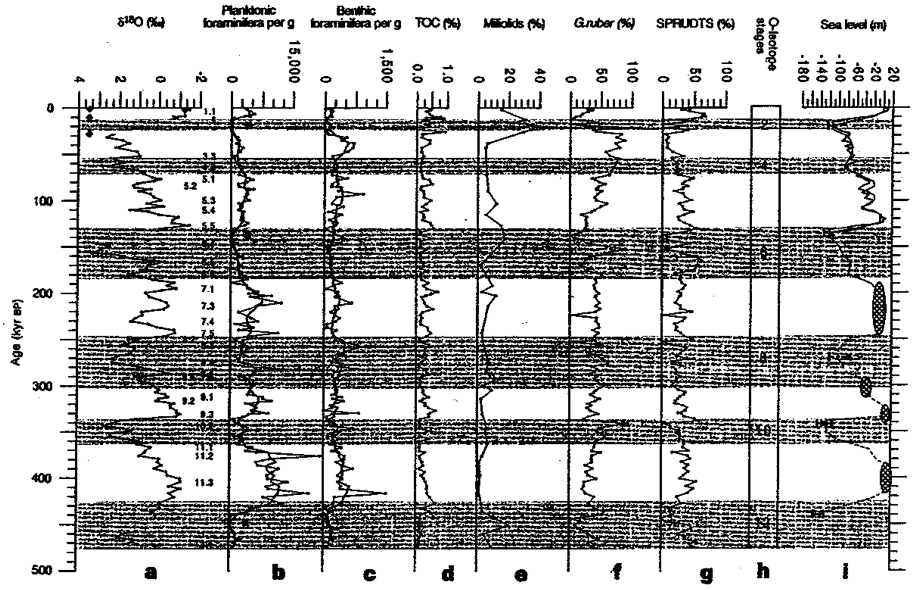


Figure 26. The results of Rohling et al's (1998) inference of sea level lowstands for the past half million years. Column A represents OIS data, columns B to G represent foraminiferal information, column H denotes the OIS stage and column I represents the inferred sea level. The shaded areas in column I represent the error margins involved in the estimation of past highstands. Highstands have been deduced from coral terrace and OIS data, while lowstands have been inferred from Red Sea salinity data.

More recently, this method has been extended to allow a continuous approximation of global eustatic sea level from 470 Ka to present to be made (Figure 27: Siddall et al, 2003). This reconstruction is claimed to be accurate to within +/- 12m and to provide centennial scale resolution for the period between 70 and 25Ka, the highest so far for this period (Figure 28) (Siddall et al, 2003).

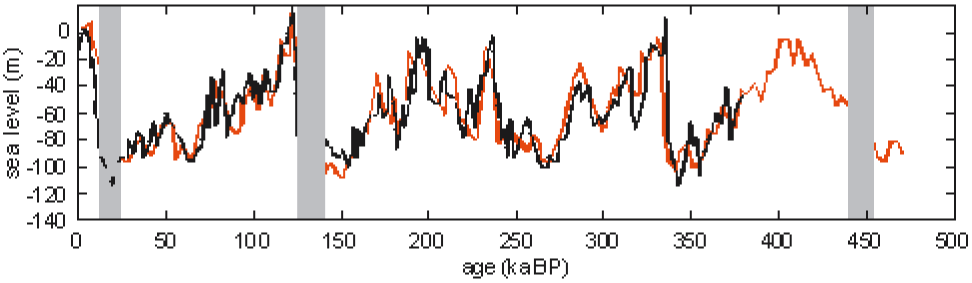


Figure 27 Sea level change over the past 470 Ka obtained from salinity conditions in the Red Sea. The grey bands represent gaps in the record resulting from aplanktonic conditions. The red and black lines represent data from two different Red Sea cores (from Siddall et al, 2003).

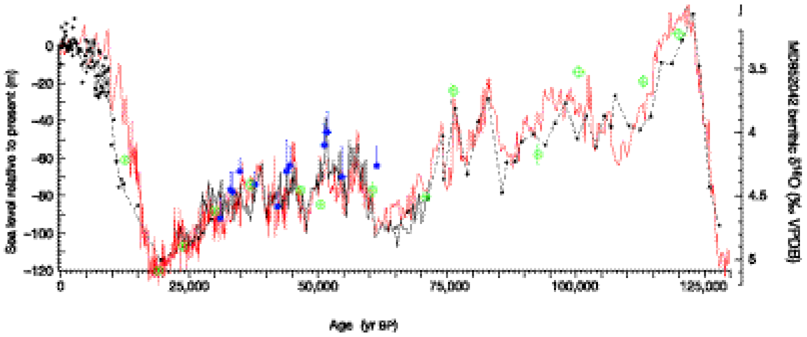


Figure 28 High-resolution sea level record from 125 Kyr BP till the present as obtained from Red Sea data. Red line = benthic oxygen isotope record, black line = sea level record obtained from core KL11, broken black line = centennial scale resolution record from core KL11, blue and green circles = dated coral records (modified from Siddall et al, 2003).

High resolution temporal studies can also be undertaken and again this method utilises the habitat preferences of certain species of diatoms and foraminifera. The vertical distributions of foraminifera in particular, are closely related to tide levels and thus have the potential to provide high resolution and detailed records of relative sea level change (Van de Plassche et al, 1998). This can be done using foraminiferal transfer functions, or statistical methods that extract the ecological data from modern distributions of salt marsh foraminifera, and which can then be applied to fossil foraminiferal distributions to obtain palaeo-ecological data. (Edwards & Horton, 2000). For example, low marsh and mudflat environments in the UK tend to be dominated by *Ammonia beccarii*, *Haynesina germanica* or the *Elphidium* species. Subtidal environments though contain a high proportion of the *Reophax* species (Edwards & Horton, 2000).

Analysis of AMS dated foraminiferal assemblages from sediment cores taken from Poole Harbour have identified four phases of sea level change in this area; rising relative sea level from 4700 till 2400 cal BP, stable to falling from 2400 till 1200 cal BP, a brief rise between 1200 and 900 cal BP and then stable to falling until a renewed rise between 400 and 200 cal BP. This contrasts somewhat with the earlier record of sea level change in this area, which could only indicate a constant rise over the past 5500 years (Edwards & Horton, 2000; Edwards, 2001).

Microfloral evidence, in the form of pollen, can also be used as a sea level indicator, in that it can be used to reconstruct past coastal environments on the same principle as plant macrofossils (see section 2.3.2.3). If the elevations and dates of these pollen remains are known, then their relationship to past sea level can be inferred. Pollen distributions however are influenced by a number of taphonomic factors such as the nature of local air and water transport pathways, the size and strength of the pollen grain and the preservational conditions of the deposition site. In addition, pollen deposited in the intertidal zone can also suffer extensive reworking as a result of tidal forces (Long et al, 1999).

2.3.2.5 Sedimentary and stratigraphic indicators

Analysis of sedimentary sequences can also provide clues as to sea level change in the past. This arises from the fact that the types of sediment deposited under marine conditions are different to those laid down under terrestrial conditions. For example, muds and clays are usually deposited in calm water or low energy environments such as sheltered coastal basins. Changes between layers can be determined by biostratigraphical, granulometric and physiochemical analysis. In all cases the occurrence of marine sequences above terrestrial ones implies a transgressive event, while a terrestrial layer overlying a marine one implies a regressive event (Pirazzoli, 1996). Examples of commonly used sedimentary indicators include beachrock – beach sediments deposited in the intertidal zone and cemented by calcium carbonate. These deposits are generally regarded as providing good estimates of past mean sea level. Their accuracy varies within a vertical limit depending on the local tidal range. Near tideless areas, such as the Mediterranean, are characterised by thin layers of beachrock, while in macrotidal areas they can be greater than 3 metres in thickness (Pirazzoli, 1996).

Dated transitions between peats formed under freshwater and brackish conditions also allow sea level inferences to be made. Freshwater peats only provide an upper limit for past sea levels as they can form at any altitude given the presence of stagnant water. Brackish peats however, can provide a better estimation of the past shoreline, as they are generally located near mean sea level, though their altitude can vary as a result of local topography and tidal range (Pirazzoli, 1996). Stratigraphic analysis of sediment from the Pacific North West coast of North America has revealed sequences of marsh peats, with well preserved vegetation, overlain by intertidal mud. This has been interpreted as rapid coseismic subsidence and transgression of the land (Long & Shennan, 1998). In all cases, the appearance of freshwater peats above brackish ones deposits indicates regression, while brackish deposits above freshwater ones are a sign of transgression (Lambeck & Chappell, 2001). The accuracy of peat deposits however is relative and in many instances the changes cannot be quantified (Van der Molen, 1997). More accurate sea level estimates though can be made on the basis of combining sedimentological information with the biological they contain (see Sections 2.3.2.3 and 2.3.2.4). Notable examples of these sorts of studies include biostratigraphical investigations of foraminifera and vegetation from salt marsh sediments on the east coast of the USA and the south coast of Britain (e.g. Edwards, 2001; Van de Plassche et al, 1998) that have provided a number of high resolution Holocene sea level curves.

However, sediment compaction may result in errors when sequence stratigraphy is used as a means of providing a measure of sea level change. As described in section 2.3.4 the weight of overburden may lead to fluid loss induced compaction. In sediments with a high water content this can lead to a significant decrease in the thickness of the layer, up to 90% in the case of some peat layers. As a result the apparent elevations of the sea level indicators may be rather less than they really were at the time of deposition (Pirazzoli, 1996).

Over very long timescales (i.e. hundreds of thousands to millions of years), stratigraphy on continental shelves can provide an image of the pattern of sea level change over time. The basic premise is that each large-scale sea level fluctuation removes sediment from the continental margins and re-deposits it in recognisable patterns that can then be used to interpret palaeo-sea level trends.

For example, during lowstands large portions of the continental shelf are exposed to the atmosphere and channel cutting by rivers draining the land right down to the lowstand shoreline occurs. As marine transgression takes place, these terrestrial deposits will be overlain by a marine sequence. If the cycle continues, these in turn will be overlain by a successive layer of terrestrial lowstand deposits and so on. This technique has provided relatively coarse sea level curves going back hundreds of millions of years (see Figure 8A). On a shorter timescale though, such as the period since the LGM, sequence stratigraphy data can provide preliminary information as to the location of past shorelines, and thus a qualitative rather that quantitative estimate of past sea level that can then be narrowed down through use of other sea level indicators (Leeder, 1999; Pirazolli, 1996). The types of environments typically encountered on the continental shelf are described in more detail in Theme 3 (Section 4).

Caution must always be taken with stratigraphic interpretations and in particular care should be taken over the dating and general temporal interpretation of sequences. This can be best illustrated through an example of extreme event, storm surges or tsunamis, sedimentation rather than that associated with stable sea levels. This is the case in western and northern Scotland, where a layer of marine sand deposited around 7100 to 7200 yr (C^{14}) BP has been interpreted as the result of a tsunami initiated by the Storegga slide, an underwater landslide that took place off western Norway. This layer is currently located between –1.1 and 8.9m above current Mean High Water Spring tide depending on the extent of local uplift (Dawson & Smith, 2000; Smith et al, 2000). In western Norway, the effects of this tsunami and the main Holocene transgression can be distinguished on the basis that the former deposited beds of marine sand, rip up clasts of peat, marine silt and gyttja, and coarse plant material, while the latter laid down sequences of homogenous gyttja with some silt and fine sand (Bondevik et al, 1998).

2.3.2.6 Archaeological Indicators

Archaeological evidence can also be used to provide indications of sea level change. Submerged terrestrial artefacts or structures represent convincing evidence of sea level rise. Examples of these are diverse and range from Roman harbour constructions to Neolithic monuments to Palaeolithic implements (e.g. Flemming, 1998; Scarre, 1984; Smith & Bonsall, 1991 respectively). These are somewhat limited in that this sort of data can only provide a qualitative estimate of the sea level trend (i.e rising or falling sea level).

More accurate archaeological indicators of sea level change consist of dated examples of artefacts or structures designed specifically for use on the foreshore or the intertidal zone. Slipways, harbour constructions, fish traps, fish tanks or salt extraction sites can be, and have been, used to provide estimates as to the position of the past shorelines (Blackman, 1973; Pirazzoli, 1996; Scarre, 1994; Flemming, 1998).

For example, a series of submerged slipways in the port of Apollonia has been used to estimate a local relative sea level rise of 2m. This measurement has been inferred on the basis that any less depth at the base of the slips would have restricted access to all but very small ships, while any greater depth would have reduced the dry length of the slips to too great an extent (Blackman, 1973).

In terms of accuracy, the estimates of past mean sea level as inferred from these indicators tend to be of the order of several metres. This is primarily a consequence of the fact that their relationship to the past shoreline is rarely exactly known, but can be estimated on the basis of the function of the particular indicator. However, it must be remembered though that many of these sites need not necessarily lie on the shoreline proper, but could be situated in estuaries or inlets, or could even be linked to the sea by canals (Scarre, 1984). Furthermore, it should also be kept in mind that harbour structures may not be complete. For example, the present day submergence of a quay or breakwater could be as much due to the loss of the upper parts of the structure rather than a local change in sea level (Blackman, 1973). Exceptions, to these do occur and in particular in areas with very low “micro-“ tidal regimes such as the Mediterranean. Here tidal erosion notches (see Section 2.3.2.1) can be cut in specific maritime features (e.g. quay and harbour walls) providing a sea level at an inferred date (Blackman, 1973). However, this further highlights one of the key issues of sea level indicators i.e. the ability to date them.

2.3.3 Dating sea level indicators

The construction of a record of sea level change over time, whichever of the indicators described in Section 2.3.2 are used, requires accurate dating. There are a number of available methods that can be brought to bear, depending on the nature of the indicator in question. Frequently used methods include radiocarbon dating; both conventional ^{14}C and the newer AMS (Accelerator Mass Spectrometry) method; Uranium series dating, tephrachronology and dendrochronology.

However, dating the sea level indicators may also present a number of interpretative difficulties as each method has its own inherent errors margins. Radiocarbon dates for example deviate from calendar years as a result of temporal variations in atmospheric carbon. This deviation increases over time by the last glacial maximum can be as much as 3000 years (Bard et al, 1990). In addition, radiocarbon dates do not provide an exact figure, but an estimate to within 2 standard deviations. Similarly, although Uranium series dating does not need calibration in the same way as radiocarbon dates, uncertainties do creep in the further back in time one goes (Chappell & Shackleton, 1986; Pirazzoli, 1996; Kearney, 2001).

It is beyond the scope of this review to demonstrate multiple dating techniques, and cover their respective advantages and disadvantages in detail. More detail on the relevant dating methods can be found in a number of texts, such as Aitken (1990) and Taylor & Aitken (1997). What should be taken away from this brief discussion is that there are errors inherent in most dating methods and these will have an impact on the resulting sea level record, as will be demonstrated in the following section.

2.3.4 Displaying past sea level change

The creation of a sea level record, or sea level curve, requires a sequence of index points (i.e. sea level indicators) whose age, location, altitude (relative to a modern datum) and indicative meaning (a quantified vertical relationship within a former tidal frame – i.e. their relation to former sea levels) is known (Edwards & Horton, 2000). These can then be plotted such that the elevation or depth of the indicator is on the vertical axis, and its date on the horizontal axis. However, sections 2.3.2 and 2.3.3 have highlighted the fact that significant variations may exist with respect to the position of the indicators relative to sea level, and the dating techniques. Collectively, these can be termed '*age-height errors*'. Curves should therefore be drawn with this in mind, and error bars or error bands should be used to represent both the height range and the date estimate of each index point (Shennan & Tooley, 1987; Pirazzoli, 1996).

As the creation of a sea level curve is a subjective interpretation on the part of an author of a number of observed index points, simply depicting sea level with a single line represents a poor summary of the situation and represents the interpretation of the observations by the curve's author for their own purposes. This does not provide the reader with the information that will allow them to draw their own conclusions out of the original data, or indeed gain a sense of the uncertainties involved (Pirazzoli, 1991). Figure 29 represents an example of this. Although the data in question is the same for both curves, with the exception that the Bard et al (1990) curve is calibrated, the potential age height errors are hidden in one curve but not the other.

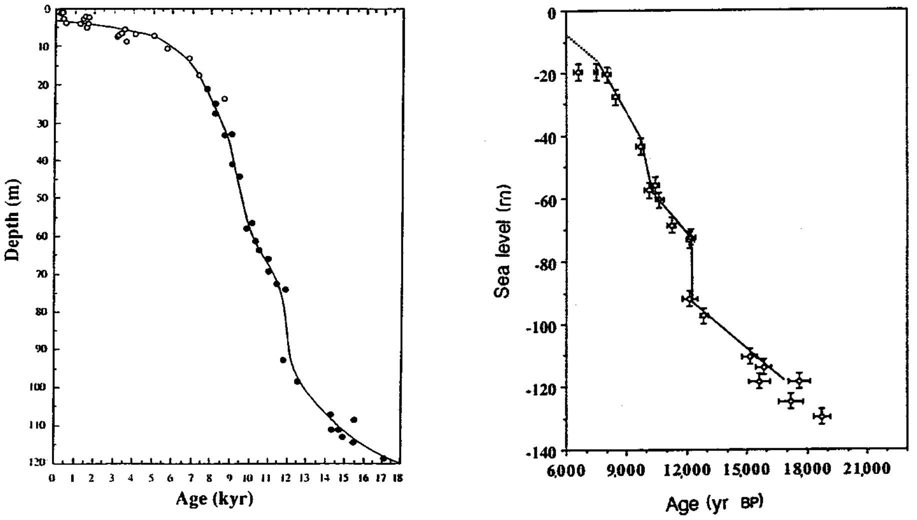


Figure 29. Glacio-eustatic sea level inferred from Barbados coral reefs. In the curve on the left the potential age height errors are hidden while in the curve on the right they are illustrated through the use of error bars (modified from Fairbanks, 1989; modified from Bard et al, 1990).

The age-height errors within an individual sea level curve can have a significant impact on any resulting palaeogeographic reconstructions in that the reconstructed shoreline position can vary from anywhere between several tens of metres to tens of kilometres depending on the gradient of the coastal area under reconstructed, and the magnitude of the errors within the sea level data (see Section 2.5).

2.4 Numerical Models and Predicting Past Sea Level Change

2.4.1 Background

Ideally, all investigations of past sea level change would be based on observations of relative sea level indicators. However, as Section 2.3.1 has indicated, these are not always available, especially with respect to the earlier phases of the Quaternary. Further, as Sections 2.2.3 and 2.3.2.4 illustrate, global glacio-eustatic changes inferred from proxies such as the oxygen isotope record represent only an approximation of past sea level change. A number of Glacial Isostatic Adjustment (GIA) models have therefore been developed to fill in the gaps in the record, by providing predictions of past sea level change and the position of palaeo-shorelines by taking into account both the key eustatic and isostatic variables. The construction of these models therefore requires the following information:

- A model of the glacio-eustatic term.
- A model of the Earth's rheology and its response to changing surface loads, both through isostasy and geoidal fluctuations.
- A detailed description of the growth and decay of the ice sheets.

Not all the processes discussed in Section 2.2.2 to 2.2.5 are included in these models. The reason for this is that the complexity of the sea level change process is such that some degree of simplification is necessary in order to allow its modelling. The scale of the models (e.g. Lambeck, 1993a, b; 1995; Peltier, 1998) also tends to be regional and global rather than local and as a result the factors modelled tend to be those that operate over larger spatial and temporal scales. It has in fact been explicitly stated that the basic models assume that the exchange of surface loads takes place entirely between ice sheets and oceans, that ice and water density are constant and that the effect of other contributions to sea level change, such as thermal expansion and tectonics are ignored (Lambeck et al, 2003).

The two main research groups involved in this field are based at the Australian National University (ANU) and the University of Toronto, with the former tackling mainly regional situations (e.g. the British Isles) and the latter approaching the problem from a more global perspective. Key figures in these groups include Kurt Lambeck (ANU) and Richard Peltier (Toronto). The basis of both of their approaches is the sea level equation formulated by Farrell and Clark (1976), the solution of which makes possible the computing of sea level given a known ocean and ice load (Mitrovica, 2003). However, differences do exist in the ways this solution is accomplished, for instance over the use of different algorithms in analysing the migration of shorelines over time (Mitrovica, 2003). Several of the differences between the two groups have been highlighted in a recent debate sparked off by Peltier’s (2002b) comment that the ANU group’s approach was based on ‘faulty logic’ and ‘invalid notions’, a claim which has inevitably been refuted by the ANU and independent authors (Lambeck et al, 2002c and Mitrovica, 2003 respectively).

In terms of comparing the work of the two research groups, analysis of the theories and methods of the ANU group by independent researchers has lead to the claim that their approach is significantly more accurate than that used by Peltier (e.g. 1994; 1998) and his co-workers (Lambeck et al, 2003). At the time of writing however, a reply from the Toronto group has not been published.

2.4.2 Basic Principle

The basic principle governing the GIA models is as follows. As relative sea level change is an outcome of the interplay between the eustatic and isostatic processes described in Sections 2.2.3 and 2.2.4, the observed sea level record has the potential to provide information on each of them. This stems from the feedback process implicit in Section 2.2.3.2 – sea level change is dependent on the Earth's responses to variations in surface load, which in turn are partly a function of changes in ocean volume (Clark, 1980; Lambeck et al, 2003; Mitrovica, 2003). More specifically the observed sea level record provides information which constrains the ice and earth models used in the interpolation process (Johnston & Lambeck, 2000). The fact that sea level records are available from a number of different regions and thus may reflect the dominance of different isostatic or eustatic influences (see Figure 9) means that it is possible to separate out the above parameters to some extent and examine their effects separately (Nakada & Lambeck, 1988). Numerical modelling of ice sheets, water distribution and isostatic rebound then provides a picture of changing land surfaces over time onto which the glacio-eustatic function can be applied.

Each of the above parameters will now be examined in greater detail.

2.4.3 The Glacio-eustatic Term

Glacio-eustasy is the only ocean volume altering input included in these models, for the reason that other inputs tend to add relatively little to volumetric changes (see section 2.2.3.1). It is worth pointing out, that for this reason much of the literature concerning numerical modelling tends to use the term 'eustatic' synonymously with 'glacio-eustasy' (see Milne et al's (2002) comments in section 2.2.3.1).

Published estimates of the ice volume equivalent sea level change since the last glacial maximum range from as high as 163 metres to as low as 102 metres, though the most common adopted measurements fall between 116 and 140 metres (Chappell & Shackleton, 1986; Fairbanks, 1989; Clark & Mix, 2002; Lambeck et al, 2002b). In particular, the most recent published estimates of the ice volume equivalent sea level change since the LGM are 130 to 135m (Yokoyama et al, 2000; Lambeck et al 2002c, Mitrovica, 2003), although Siddall et al (in prep) will again push this value back down to 125 m.

This variation is the result of many different studies operating in different areas where varying isostatic, tectonic and geoidal contributions or differing interpretations of the sea level indicators may have skewed the samples (Lambeck, 1996; Pirazzoli, 1996). Even regions far from the centres of glaciation will be affected to some extent by isostatic and geoidal fluctuations. The best estimates of glacio-eustatic change are therefore based on regions where local tectonic and isostatic movements are believed to be minimal or insignificant, or where corrections can be made for these movements (Lambeck, 1996; Lambeck & Chappell, 2001). Commonly used examples include records from Barbados (Fairbanks, 1989), the Huon Peninsula (Chappell & Shackleton, 1986), the Bonaparte Gulf (Yokoyama et al, 2000) and the oxygen isotope (OI) record (Shackleton, 1987; van Andel & Tzedakis, 1996, e.g. Figure 30).

While these eustatic sea level measurements are not truly globally applicable (see section 2.2.3.1), they are critical for constraining the glacio-eustatic volumes input into the modelling process (Scourse & Austin, 2002). Care should also be taken with the OI record as evidence from different cores may be affected by local variations in temperature and salinity, which will in turn affect the ratio of O^{18} to O^{16}.

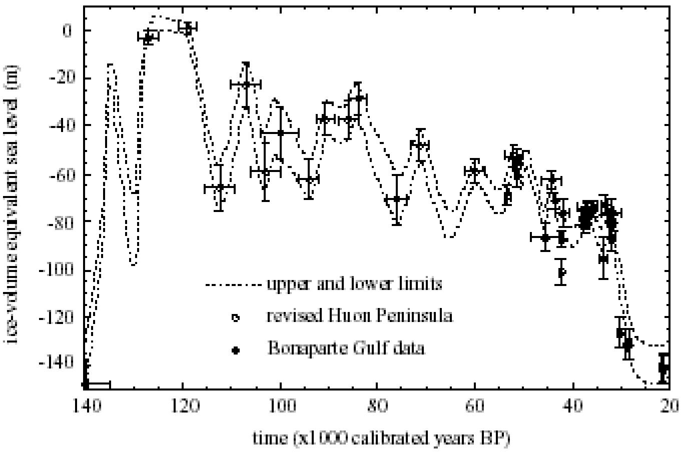


Figure 30 Ice volume equivalent sea level change for the last 140,000 years obtained from raised coral reefs on the Huon Peninsula and sediments from the Bonaparte Gulf. Note the variation between upper and lower limits of the sea level observations (from Lambeck et al, 2002b)

2.4.4 Earth rheology

As explained in section 2.4.1, models of the Earth's response to surface loading revolve around the idea of an elastically deforming lithosphere floating on top of a viscous mantle. The main questions in relation to interpolation models focus on the depth dependency of the mantle viscosity and whether this viscosity is laterally uniform. Seismic studies and analysis of glacial rebound from observed sea level records have tended to indicate that viscosity is indeed depth dependent, with an average lower mantle (below 670km) viscosity that is between 50 and 100 times greater than that of the upper mantle. The significance of this is that ice sheets tend to only stress the upper mantle, however, meltwater loading, given the size of the oceans, is much greater in extent and thus stresses the lower mantle as well. Both layers therefore need to be taken into account. Simple models of glacial rebound therefore tend to use a three-layer model with a lithosphere of between 60-100 km thick, an upper mantle of viscosity of between 2 to 5 x 10^{20} Pa s, and a lower mantle of viscosity 2 to 50 x 10^{21} Pa s (Johnston, 1995; Lambeck, 1996; Peltier, 1998; Lambeck & Chappell, 2001; Milne et al, 2002). In some instances, models with up to five layers (lithosphere, upper mantle 1, upper mantle 2, transition zone, lower mantle) have been used (e.g. Lambeck, 1995). However, in most cases the 3 layer model appears to be adequate. The choice of mantle parameters is obtained by iterating, or searching for solutions whereby predicted and observed sea level changes qualitatively agree with each other. This choice of parameters is important as different lithospheric thickness and mantle viscosities will respond differently to changing loads, thus leading to different predictions of isostatic rebound. Individual modellers do however use different parameters in their models, and as a consequence, differences can appear in their predictions. For example, recent modelling of the isostatic adjustment of the British Isles has made use of a modified version of Peltier's ICE 4G (VM2) model with a lithosphere of 90km and mantle parameters of 4 x 10^{20} Pa s (upper mantle) and 2 x 10^{21} Pa s (lower mantle) (Peltier et al, 2002; Shennan et al, 2002). This contrasts somewhat with the parameters adopted by Lambeck as set out in Table 3 below, which are similar for the upper mantle, but include a thinner lithosphere and more viscous lower mantle.

Recent studies have indicated that lateral variations in mantle viscosity and lithospheric thickness do exist (see Table 3). These general variations can be translated to regions so that, for instance, mantle viscosity beneath continental margin Australia will be less than that of northern Europe (Lambeck et al, 2002b).

Model	H_1 (km)	Upper Mantle η_{um} (x 10^{20} Pa s)	Lower Mantle η_{lm} (x 10^{21} Pa s)
Continental mantle	65-85	3-5	5 - 30
Continental margin mantle	65-80	1.5-2.5	5 - 30
Oceanic mantle	~50	~1	(10)
Values for specific regions as estimated from sea level observations			
Australia	70-80	2-3	5 - 30
Australia	75-90	1.5-2.5	(10)
Scandinavia	65-85	3-4	6 - 13
British Isles	65-70	4-5	7 - 13
Northwest Europe	(65)	2-5	10 - 30
South Pacific	~50	1	(10)

Table 3. Lateral variations in lithospheric thickness (H_1), upper mantle viscosity (η_{um}) and lower mantle viscosity (η_{lm}). Estimates have been obtained by different authors at different times, hence the multiple Australian results (after Lambeck & Chappell, 2001; Lambeck et al, 2002b).

Until very recently though, no models took account of this spatial variation and as a result, rheological parameters were back calculated from the available sea level data in each region under study (Lambeck, 1996; Lambeck & Chappell, 2001). The latest approaches however, model isostatic predictions for a range of Earth models that have been obtained from regions where mantle parameters have been estimated from observed sea level change (Lambeck et al, 2002b).

2.4.5 Surface Load (ice sheets and oceans) Models

Tied into these rheological models is information concerning the size and distributions of the Earth's ice sheets and oceans as these determine the extent and position of the isostatic movements. Analysis of glaciological and geological features such as moraines, drumlins and erratics allow estimates of ice sheet limits and the pattern of retreat since the last glacial maximum to be made (Lambeck, 1993a; 1993b; Lambeck & Chappell, 2001). Only the pattern of retreat is known since the retreating ice will have destroyed most evidence of the ice advance. Analysis of oxygen isotope samples does however provide some indication as to the broad trend of advance as well as retreat. The extent of the ice sheets at the LGM is relatively well understood (e.g. Bowen et al, 2002), with the major contributions to sea level change coming from the American ice sheets - the Laurentide, Cordeilleran and Innuitian, the European ones – the British and Scandinavian, and the Antarctic. Evidence also points to the existence of an ice sheet over the Barents Sea and possibly the Kara Sea (Clark & Mix, 2002).

Uncertainties though, arise over the thickness of the ice sheets. In some areas, it can be measured off nunataks, however, where these are not present estimates must be made based on snow supply, ablation and the nature of the rock-ice interface (Nakada & Lambeck, 1988; Lambeck & Chappell, 2001). In some instances, a constant scale factor may have to be applied to the estimated ice sheet thickness and iterated until a solution is found that is in good agreement with the observed evidence of glacial limits (Lambeck 1993a). Alternatively, assuming that mantle parameters and Earth rheology are known, it is possible to numerically calculate ice sheet extent and size from observed sea level data (Johnston & Lambeck, 2000).

Ice sheets are not solely restricted to land; floating and grounded marine based sheets also exist. Contributions from floating ice to the hydro-isostatic term do not need to be included, as they have already contributed their mass to the volume of ocean water. Grounded marine ice sheets however, will exert pressure directly on the lithosphere and upper mantle, and should be treated in the same way as land based ones. However, ice sheets do experience stages of floating and grounding, and thus it is necessary to calculate the amount of floating ice at each epoch (Lambeck et al, 2003).

In all cases, the effects of ice sheets far from the study area, as well as those close to and within it must be taken into account. While near field ice sheets are likely to contribute to sea level change through glacio-isostasy, ice sheets further away will contribute to the glacio-eustatic change in sea level, and hence, hydro-isostatically as well. In the case of the North Sea basin, the general scheme is uplift and falling sea levels in the northern sector (Scotland, Sweden, Norway and North Denmark) with subsidence and rising sea levels in the southern sector (England, Belgium, the Netherlands, South Denmark) (Figure 18). Large areas of the North Sea floor are likely to be subsiding as well due to the collapse of the glacial forebulge (Lambeck, 1993a, b, 1995; Lambeck et al, 1998; Kiden et al, 2002; Shennan & Horton, 2002).

Furthermore, rebound models must take into account the effects of glacial loading prior to the onset of deglaciation. With respect to the Late Pleistocene this means knowledge of the size and distribution of the ice sheets before the LGM. The starting point for the ice sheet history is therefore usually taken to be the Last Interglacial Stage (OIS 5e – c. 128 to 118 Kyr BP), and it is assumed that at this point in time the planet was at isostatic equilibrium (Lambeck et al, 2003). Given the lack of glaciological evidence for this, oxygen isotope data (e.g. Chappell & Shackleton, 1986; Shackleton, 1987) must be used to provide an approximation of the situation. This is necessary because the maximum extent of the ice sheets may not have persisted long enough for the mantle to reach a state of hydrostatic equilibrium. Consequently models which assume isostatic rebound beginning from a hydrostatically stable position may lead to overestimations of uplift and thus inaccurate sea level predictions (Lambeck, 1993a).

With respect to the distribution of the meltwater load over time, care must be taken to ensure that the migration of shorelines due to relative sea level rise is included, as this will affect the extent of the hydro-isostatic contribution through the distribution of meltwater. Fixed coastline models will tend to underestimate this contribution since a point close to the coastline will remain so throughout the deglaciation period. In reality, the movement of shorelines could result in it being ten or hundreds of kilometres from shore for much of the deglaciation and therefore subject to a greater water load and therefore a larger hydro-isostatic effect (see section 2.2.4.2: Johnston, 1995). Shoreline changes due to the position of grounded marine ice also need to be taken into account. Ice, being more massive, will displace water, hence there will be areas that might otherwise be inundated (i.e they lie below local relative sea level), but are covered by ice and thus should not be included in the water load term (Lambeck et al, 2003).

Recent studies also take into account the effects of what Milne has described as ‘water dumping’ (Mitrovica, 2003) and Peltier as ‘implicit ice’ (Peltier, 1998, 2002a). Essentially, the disappearance of a marine ice sheet leaves behind a ‘hole’ which serves as accommodation space for meltwater. Therefore, additional ice melting has to be included in the models to reconcile this fact with the above constraints on glacio-eustatic change (Mitrovica, 2003).

2.4.6 Solution of the models

The solution of these models takes the form of an iterative procedure whereby a range of earth parameters and ice and meltwater models are modelled in search of an optimum solution (Lambeck, 1993a, b; 1995; Lambeck et al, 2003). As stated earlier, glaciological and observed sea level evidence are used to constrain the parameters of the ice and earth models, and in addition, the observed sea level evidence may be compared to the predicted results. This allows iterative fine tuning of the parameters and thus ensures a better fit, and hence a more accurate model, between the observations and predictions. More detailed accounts of this process can be found in the literature produced by the various modellers (e.g. Lambeck, 1993a,b; Lambeck et al, 2003; Milne et al, 2002; Peltier, 1994; 1998). Figures 31, 32, 33 display different palaeo-shoreline predictions for North West Europe made using a variety of GIA models.

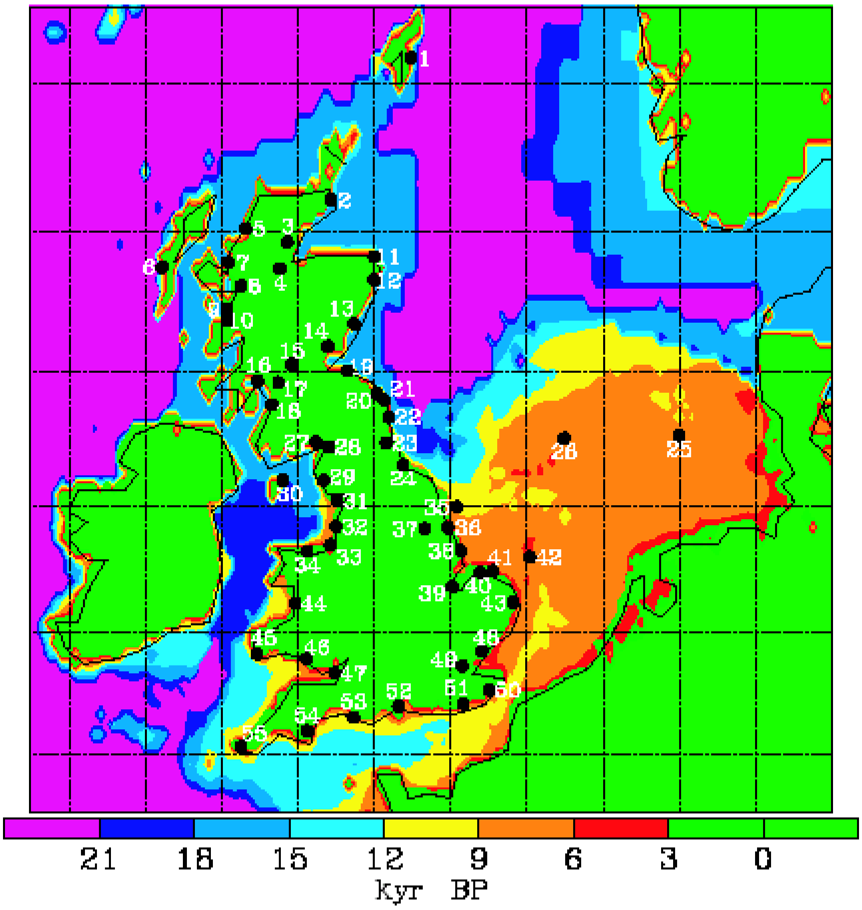


Figure 31. GIA model reconstruction of palaeo-shorelines (a.k.a. submergence history) and ice extents for North West Europe from 22 ka (C^{14}) BP till present (from Peltier et al., 2002).

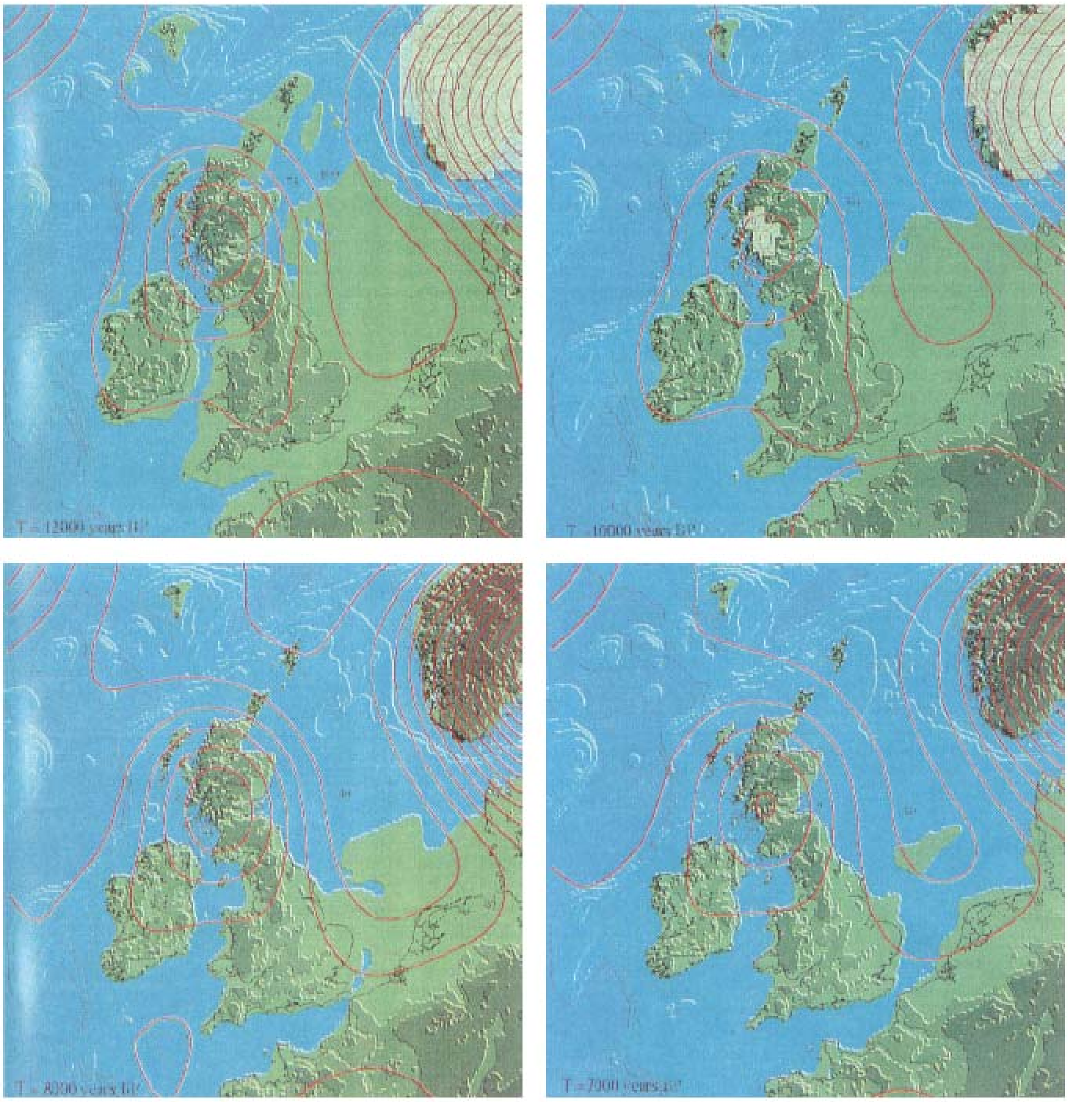


Figure 32. GIA model reconstruction of palaeo-shorelines and ice extents for North West Europe from 12 till 7 ka (C^{14}) BP. Red lines are isobases representing the degree of isostatic uplift and subsidence (from Lambeck, 1995).

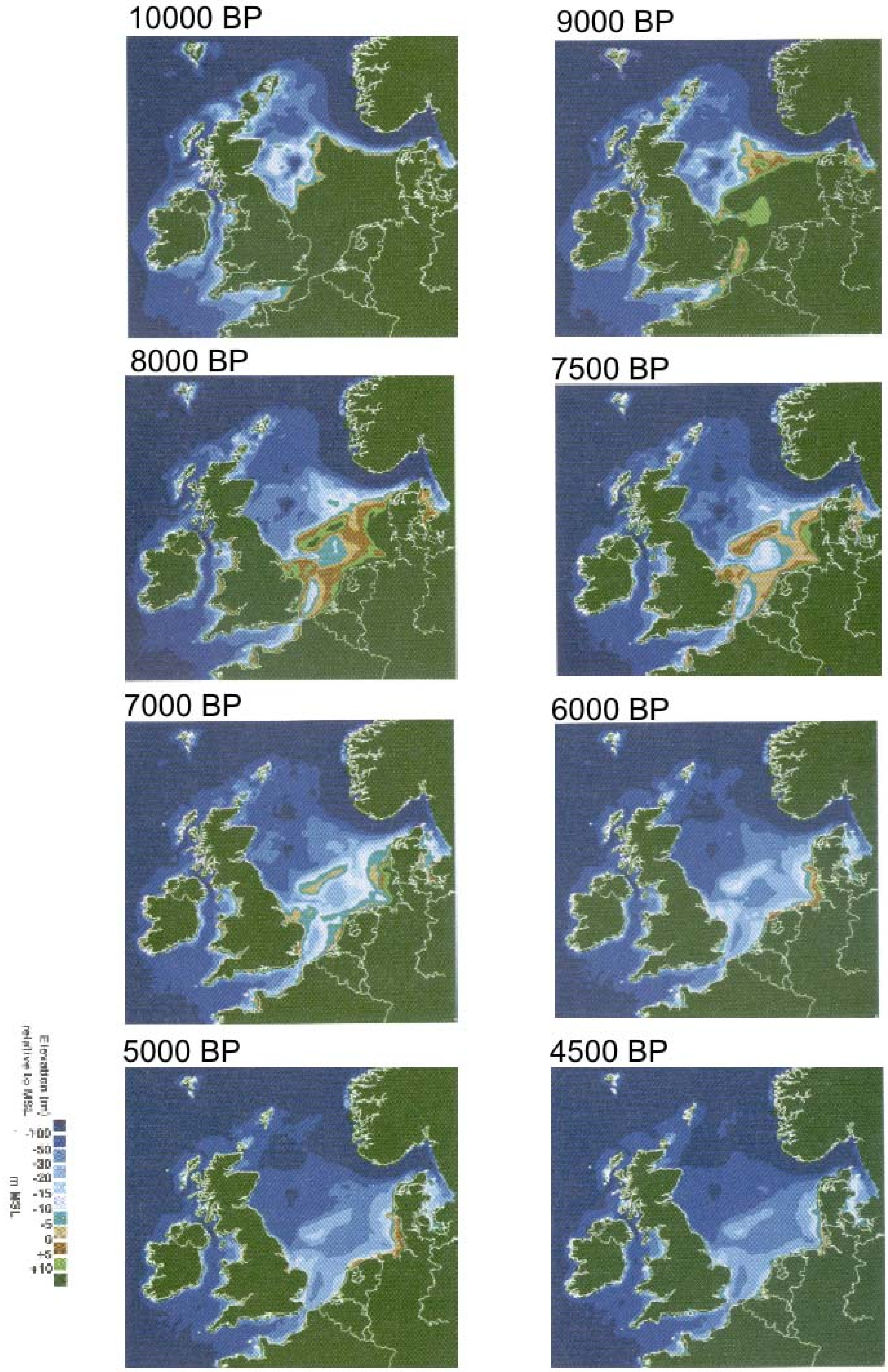


Figure 33. GIA model reconstruction of palaeo-shorelines and ice extents for North West Europe from 10 till 4 Kyr (C^{14}) BP. The colour coded contours represent elevation in metres relative to mean sea level (from Shennen et al, 2000b).

2.4.7 Effectiveness of the models

In plan view the difference between models can be clearly seen if one compares the 12 ka C14 BP model of Peltier et al. (2002 and see Figure 30) with Lambeck (1995 and see Figure 31). The palaeo-shorelines in the former (yellow – turquoise boundary) extend well in to the English Channel, extends as far North as the Firth of Forth in the North Sea and isolates the Shetland Isles. By comparison the Lambeck model has palaeo-shorelines that are located towards the entrance of the English Channel, extand as far north as the Moray Firth in the North Sea and encompass the "Shetland Isles" as part of a single land mass.

In terms of comparison with measured relative sea level curves obtained from UK shores these numerical models do provide good fits (see Figure 34), yet a unique solution has still to be developed that agrees with all the available sea level observations (Shennan & Horton, 2002).

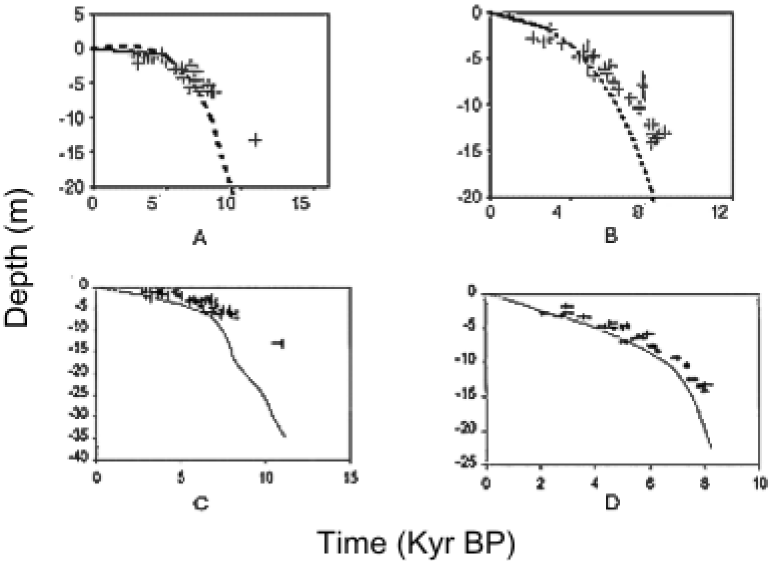


Figure 34 Comparisons of observations (index points) and predictions (lines) of sea level from the Tees estuary (A and C) and Lincolnshire (B and D). Predictions for A and B are based on Lambeck's (1995 model), and predictions for C and D are based on Peltier et al's (2002) modified ICE4G(VM2) model with a lithosphere of 90km (modified from Shennan et al, 2000a; Shennan & Horton, 2002).

McCabe (1997) for instance has pointed out that the numerical predictions for the Western Irish Sea basin do not match the sedimentological and glaciological evidence, while Plag et al (1996) draw attention to the existence of a number of unexpectedly low submerged shorelines, such as the –100m features on the Hebridean Shelf, the central Celtic Sea and the Viking Bank. These all date to c. 11,000 BP and exhibit crustal adjustment that is greater than predicted by the numerical models. In general, on a regional scale the models tend to underestimate sea level and discrepancies between observations tend to be greatest for areas under the thickest ice, or where ice limits or volumes are least well known (Shennan et al, 2000a; Shennan & Horton, 2002).

The problem has partly arisen as a result of the fact that modellers tend to pick certain factors to go into the models while ignoring others. As mentioned in section 2.4.1, only long term and large-scale influences on sea level tend to be examined.

The results of this are especially clear in that the models tend not to be able to predict short duration (c. 1000 to 2000 years), high amplitude events, such as rapidly migrating marginal bulges close to the former ice sheets (Plag et al, 1996). The situation is rendered even more problematic by the fact that certain parameters such as ice sheet thickness, lithospheric thickness and mantle viscosities are still not yet exactly known, as described in Section 2.4.4 and Table 3.

In defence of the models, they are still works in progress and some simplification of the situation is necessary to enable their construction. Once certain parameters are understood, other parameters can brought in. For instance, recent attempts have been made to integrate Lambeck's (1993a,b; 1995) models with new offshore sea level data and models of Holocene tidal regime changes in the western North Sea (Shennan et al, 2000b) while previously ignored factors such as lateral variation in the mantle are now being incorporated into the latest models (Lambeck et al, 2002b). In addition, the criticisms of McCabe (1997) can been countered by questioning his interpretation of sedimentological evidence rather than altering the GIA model (Lambeck & Purcell, 2001). In any case, once the basic structure of the models has been constructed, refining them is possible as more evidence becomes available. This can be seen with respect to the ice models (e.g. Johnston & Lambeck, 2000), and earth rheologies. Note the differences in mantle parameters between Lambeck's (1993a,b; 1995) earlier models and the more recently updated ones (e.g. Lambeck et al, 1998). The former make use of a lithosphere 65km thick, a upper mantle of (4-5)x10^{20} Pa s and a lower mantle of one magnitude greater viscosity, while the revised parameters are respectively; 65-85km, (3-4)x x10^{20} Pa s and one magnitude greater. Indeed, the need for refining and improving the models is recognised by the modellers themselves. Peltier, for example has mentioned that the latest fully developed numerical models (ICE-4G(VM2)) constructed by the Toronto group are not exact and incontestable representations of glacially induced sea level change (Peltier, 2002a).

However, in the absence of reliable relative sea level records going back to the LGM, these predictive models represent the only way of reconstructing formerly exposed continental shelves and thus placing the relevant archaeology within a reasonably accurate palaeogeographic context.

2.5 Comparing Sea Level Data and Palaeo-geographic Reconstructions

2.5.1 Introduction

The information presented in Sections 2.2 to 2.4 suggests that there is an intrinsic dilemma in the creation of regional scale palaeo-geographic maps. Fundamentally the best reconstructions would be based either on the combination of direct geological interpretation of coastal sedimentary facies and a local relative sea-level curve. However, inherent variability of sea-level change and subsequent sedimentological response makes the extrapolation of, or conflation of local sea-level curves to create a regional scale map difficult, if not currently impossible. By contrast GIA models give the regional scale but depending on the precise formulae used and the inevitably guestimated vales for rheological and loading factors result in a reduction in accuracy and a lack of agreement in palaeo-shoreline position. Further, both of these methods breakdown when looking at pre LGM events as the necessary lithological /glaciological records e.t.c. are just not available.

Section 2.5 therefore demonstrates how different sources of sea level data can result in the creation of varying palaeo-geographic reconstructions for the same times and places. Though the vertical differences in sea level between different datasets may seem small, around a few metres usually, if one takes into account the fact that a sea level change of this magnitude has the potential to flood or expose a very large area of low gradient land, the resulting landscape can look very different.

The majority of the discussion will focus on palaeo-shoreline reconstructions, however the impact of topographical and morphological changes on reconstruction will briefly be touched on. The main issue that will be considered is the magnitude of the error that exists within, and between, sources of information used in palaeo-geographic reconstructions. An appreciation of this should create a greater awareness of the accuracy and applicability of different sources of sea level data and different approaches to reconstruction. To this end, digital reconstructions of the palaeo-shorelines of North West Europe (based on a variety of data) are compared.

Highlighting the error margins inherent in a data set is not a new idea. This type of perspective has been advanced to an extent with respect to the construction of sea level curves from observed evidence. Given that sea level indicators tend to fall within a range of age and height estimates rather than a single definitive value (see Section 2.3.4), some uncertainties are likely to be involved in the creation of a sea level record for a particular time or place. The process of creating a sea level record from isolated pieces of evidence in turn is a subjective exercise of interpretation. Thus the depiction of sea level fluctuations with a single line rather than error bands or error bars provides a poor summary of the situation and represents the interpretation of the observations by the curve’s author for their own purposes, rather than a completely objective picture of sea level change (See Figure 29: and Shennan & Tooley, 1987; Pirazzoli, 1991; 1996).

Previous work has also illustrated the difficulty of using inaccurate data on which to base reconstructions. Marcus & Newman (1983) outlined the problems associated with using glacio-eustatic data as the sole measure of palaeo-shoreline position, namely that it neglected the impact of other forcing factors on shoreline position, such as the tectonic and isostatic movements of the crust. This chapter will attempt to take this sort of approach further by addressing other possible sources of inaccuracy and quantifying the margins of error.

2.5.2 Palaeogeographic reconstructions: Practical Issues

The most widely used method of palaeo-geographic reconstruction involves combining a record of sea level change - a sea level curve - with a topographic time horizon - typically present-day continental shelf bathymetry - to create a palaeocoastline map. This requires the consideration of three crucial factors:

- The choice of sea level curve used in the reconstruction
- The choice of topographic time horizon used in the reconstruction
- The resolution of the topographic time horizon data used in the reconstruction

2.5.2.1 The choice of sea level curve used in the reconstruction

There are three primary categories of sea level data that can be used in reconstruction of past landscapes: global glacio-eustatic curves; glacio-isostatic adjustment models and relative sea-level curves. As described in Section 2.2.3.1 glacio-eustatic curves provide a measure of global ocean volume change rather than global mean sea level change. Examples include the Fairbanks (1989) and Bard et al (1990) curves obtained from offshore Barbadian coral reefs (see Figure 29), oxygen isotope based curves, such as Shackleton (1987) and more recently curves based on Red Sea foraminifera (e.g. Rohling et al, 1998; Siddall et al, 2003 – see Figures 26 - 28). However, as relative sea level is controlled by a number of additional factors, such as glacio- and hydro-isostasy (Lambeck & Chappell, 2001; Pirazzoli, 1996), the use of glacio-eustatic curves tends to oversimplify palaeo-geographic reconstructions. This is especially pertinent in formerly glaciated regions such as North-West Europe, where fluctuations in ice sheet size and distribution have resulted in relative sea level varying significantly within a fairly restricted (i.e. several hundred km) area. Furthermore, the differential impact of sea level modifiers in different areas means that a degree of variation exists between eustatic curves obtained from different regions, and hence each curve will provide a slightly different approximation of global change (e.g. compare Figure 28 and Figure 30).

As we have seen in Section 2.4 glacio-isostatic adjustment models infer continental shelf exposure on the basis of mathematical models of the Earth’s crustal response to shifting ice and meltwater loads (*glacio-* and *hydro-isostasy*) in conjunction with glacio-eustatic sea level change. The development of these models is inevitably an iterative process and at present there is no definitive model. The GIA models are again intrinsically limited as they do not extend beyond the Last Glacial Maximum due to a lack of data on ice sheet extents. Recently however, palaeoclimate simulations which make use of GIA model predicted shorelines have been constructed for Oxygen Isotope Stage 3 (60-24kaBP), just prior to the LGM (Barron et al, 2003, Lambeck et al, 2002b). These shoreline models were based on the Lambeck models from the LGM for north-west Europe with supplementary data for the Mediterranean (van Andel & Shackleton, 1982; Shackleton et al, 1984). However, the lack of relative sea-level curves for this period makes it difficult to assess the efficacy of such an approach. It is worth noting that Flemming (2002) has suggested that GIA reconstructions for the post-LGM and Holocene may be applicable to the final phases of each of the last major glaciations on the basis that the patterns of isostatic depression and uplift in conjunction with glacio-eustatic sea level change at the end of each long cycle of glaciation (c. 100,000 years) and deglaciation (c. 20,000) would be similar. This suggestion has yet to be investigated in detail, yet if correct; it would prove to be of great assistance in reconstructing pre-LGM shorelines.

Finally, relative sea level curves, obtained directly from past sea level indicators (e.g. dated corals, foraminifera or archaeological material: Section 2.3.2) represent the most accurate way of reconstructing past coastlines for a particular region (e.g. Edwards, 2001; Edwards & Horton, 2000). This is because they reflect the local impact of eustatic isostatic and tectonic variables. In particular the impact of tectonic uplifts, which appears small on very short timescales (>1mm/yr), may be very significant over very long term (i.e. tens to hundreds of thousands of years) changes in palaeo-geography (Long 2003). Furthermore, when using relative sea-level curves one has to take into account the indicative meaning of the indicators. This is especially important in the case of sea level indicators which are sensitive to particular parts of the tidal cycle, such as foraminifera (Edwards, 2001; Edwards & Horton, 2000).

These curves tend to be spatially restrictive due to the unique local interactions of multiple sea level modifiers, and should therefore not be applied uncritically to large regions. Unfortunately, the vast majority of these curves do not extend back further than the Early Holocene, and even within the Holocene adverse preservational conditions mean that in many areas evidence of past sea levels does not exist locally. In these instances the only recourse is to use glacio-eustatic data or GIA models.

With respect to all the three data sources it should be remembered that all sea level data contains some inherent errors. These result from variations in the position of sea level indicators relative to sea level, and the dating techniques used on them (Shennan & Tooley, 1987; Pirazzoli, 1996). As will be demonstrated in sections 2.5.5.1 to 2.5.5.6 these '*age-height errors*' can potentially lead to significant variations in palaeo-coastline position.

2.5.2.2 The choice of topographic time horizon used in the reconstruction

All of the reconstructions reviewed as part of this exercise assumed that present day bathymetry is equivalent to the pre-transgression topography, although several did allude to the fallacy of this assumption (Coles, 1998; Shennan et al, 2000). In reality, syn-transgressive processes may have altered the coastal geomorphology, while post-transgressive processes of sedimentation and erosion could have further modified the submerged land surface in the interim (see Section 4). Conventional seismic techniques means that data can be relatively easily retrieved from sections that have been buried during the transgressive process, however, it will obviously never be possible to retrieve data on surfaces that have subsequently been eroded. Ideally, seismic investigations (in conjunction with borehole data) should be used to identify a chronostratigraphic time horizon appropriate to the period being reconstructed and this can be successfully done on local scales (e.g. reconstructions of the Arun and Solent rivers as part of PD3277, PD3543 and PD3364 respectively). However the feasibility of accomplishing this on a wide scale will require the integration of much more widespread (inevitably industry and military datasets). An interim alternative is to use incised bedrock surfaces to provide an effective maximum depth topographic time horizon. This could be used in conjunction with the bathymetric surface to provide a lower and medial limit on reconstructions (see Section 2.5.5.8). Although these problems have been recognized before (e.g. Coles, 1998; Shennan et al, 2000), the scale of the inaccuracies and possible solutions have yet to be discussed to any significant degree. Therefore section 2.5.5.8 will attempt to rectify this situation to a limited extent.

2.5.2.3 The resolution of topographic time horizon data used in the reconstruction

The resolution of the input topographic time horizon data is also an important factor in determining what the final reconstruction actually looks like. This problem is often exacerbated when using Digital Elevation Models, as these tend to interpolate between data points on the basis of a particular mathematical or statistical algorithm (Hageman & Bennett, 2000). Lower resolution data will tend to smooth out relief, thus removing any topographic extremes. Other common problems include the creation of ‘terraces’ on contour lines used for interpolation and the creation of large areas of monotonous slope in low lying areas due to a lack of data points (Verhagen, 2000). The resolution of the first order topographic time horizon data (bathymetry) varies depending on the scale at which the area in question was surveyed. For example, until the advent of satellite altimetry of the ocean bathymetry, all bathymetric surveys had to be undertaken by 2D echosounder equipped survey ships. Their coverage of the seabed was uneven and surveyed areas could be as much as hundreds of kilometres apart. This data was synthesised to produce a global 5’ data grid for the globe (ETOPO-5 data: Figure 35) which is freely available to all interested parties (Smith & Sandwell, 1997). However, the development, and use of satellite altimetry calibrated against the extant 2D echosounder survey data made possible the creation of a global digital bathymetric data source at 2’ grid spacing (ETOPO-2 data: and Sandwell & Smith, 2003).

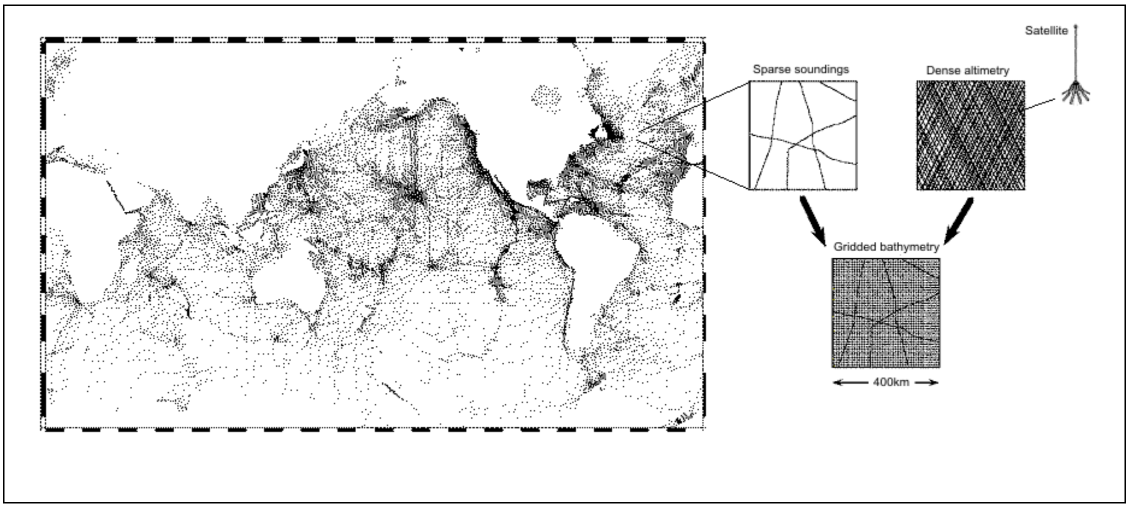


Figure 35. General principles underpinning the creation of digital bathymetric maps. Low resolution ship soundings are combined with high resolution satellite altimetry to produced a high resolution gridded bathymetric surface (modified from Sandwell & Smith, 2003)

On a regional level data sources such as the UKHO can provide bathymetric data on variable scales (from a very high resolution sub-metre bins swath bathymetry to course decametre 2D echosounder grids) depending on the location, ports and key navigational routes being generally surveyed at a much higher data density let alone more frequently. Current sub-bottom data will always be 2D in nature and thus will tend to provide coarser spatial resolution of the bedrock horizon by comparison to swath bathymetry and in many cases the high density 2D survey data owned by the UKHO. For instance, the aggregate industry typically acquire regional sub-bottom data as part of the prospection process but rarely if ever at line spacings of less than 100 m and in places this can be as coarse as 250 to 500 m. Conversely, pipeline or installation site surveys may provide higher density data but over much more restricted spatial areas. Organisations such as the BGS do provide syntheses of sub-bottom work in the form of bedrock contour maps of certain sections of the UK continental shelf but frequently the original data density is still quite large (100's to 1000's metres).

Whatever the source, taking in to account data density will be essential for all palaeo-geographic reconstructions as low resolution data can result in misrepresentations of past topography and less obviously, differences in shoreline position (see Section 2.5.5.7).

2.5.3 Sources of Sea Level Data

For the assessment of palaeo-geographic reconstructions a wide variety of sea-level sources have been consulted. The sources can be divided into post-Last Glacial Maximum and pre-Last Glacial Maximum:

2.5.3.1 Post-Last Glacial Maximum

Bard et al (1990) is a sea level curve derived from the dating of offshore coral reefs in Barbados. It extends from the LGM till the mid-Holocene (see Figure 36). It is essentially a version of the Fairbanks (1989) curve calibrated using the Uranium-thorium (U-Th) dating method rather than conventional radiocarbon dating. The Fairbanks curve was claimed to provide a measure of global glacio-eustatic change as Barbados was deemed sufficiently far from the continental ice sheets to be minimally affected by isostatic factors, and a correction was applied to account for local tectonic uplift of c.34cm kyr^{-1} (Fairbanks, 1989). The inherent height error within this curve is estimated to be +/- 2.5m and results from the habitat range of the corals (*Acropora palmata*) used as sea level indicators (Bard et al, 1990).

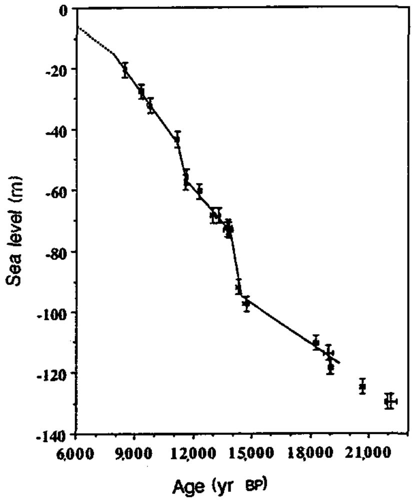


Figure 36. Global glacio-eustatic change since the LGM (modified from Bard et al, 1990).

Lambeck et al (2002b) can be considered to be a more reasonable approximation of global glacio-eustatic change than the Barbadian coral reef record. Rather than simply being based on the information from one area, it is based on 6 areas, including the Barbados reefs and Huon Peninsula terrace records, and has been corrected for isostasy. This curve also extends from the LGM to the mid-Holocene (Figure 37). To avoid confusion with another sea level curve also obtained from this article (see below), this data will be referred to in the rest of this document as Lambeck et al (2002b:Post-LGM).

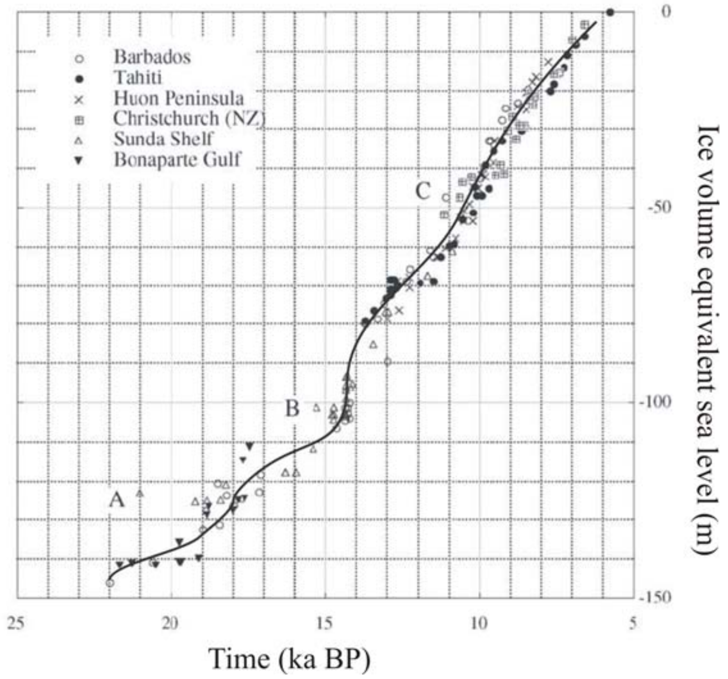


Figure 37. Post-LGM global sea level record obtained from 6 different regions and isostatically corrected (modified from Lambeck et al, 2002b)

Waller & Long (2003) is a regional relative sea level curve obtained using bio- and lithostratigraphical data for the Solent region in southern England. It is solely Holocene in scope (Figure 38).

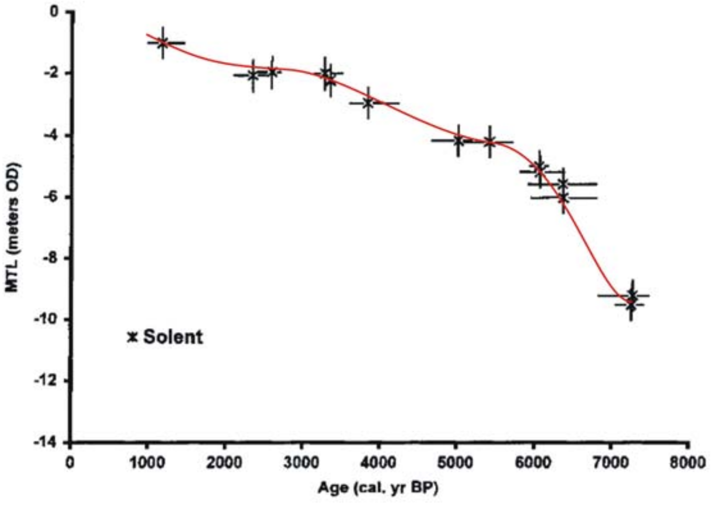


Figure 38. Holocene regional relative sea level curve for the Solent (modified from Waller & Long, 2003)

2.5.3.2 Pre-Last Glacial Maximum

Chappell & Shackleton (1986) is a sea level curve obtained from the Huon Peninsula coral terraces (Figure 39). It has been corrected for local tectonic uplift and scaled to an orbitally tuned timescale to correct uncertainties in the original U-Th dates. It represents an approximation of global glacio-eustatic change. In the original article (Chappell & Shackleton, 1986) it is referred to as HP2.

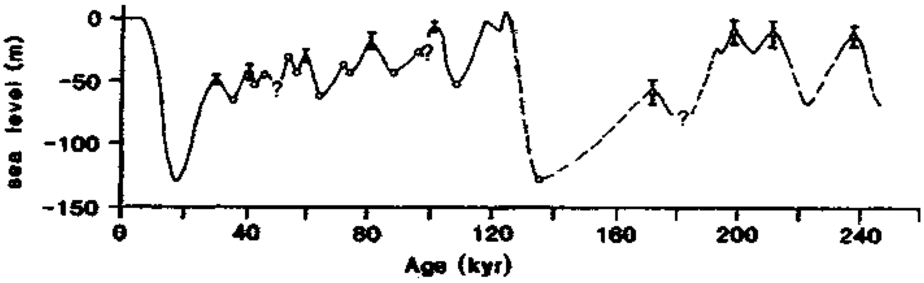


Figure 39. Pre-LGM sea level record from the Huon Peninsula (modified from Chappell and Shackleton, 1986)

Another curve obtained from Lambeck et al (2002b) is also based on relative sea level data from the Huon Peninsula coral terraces and sediment cores from the Bonaparte Gulf (Australia). For the construction of this curve, the Huon Peninsula data was re-evaluated to identify and resolve any inconsistencies in the original terrace data (Lambeck et al, 2002b). This curve has not been corrected for isostatic influences and extends from 140 kBP to the LGM (see Figure 40). To avoid confusion with the other sea level curve also obtained from this article (see above), this data will be referred to in the rest of this document as Lambeck et al (2002b: Pre-LGM).

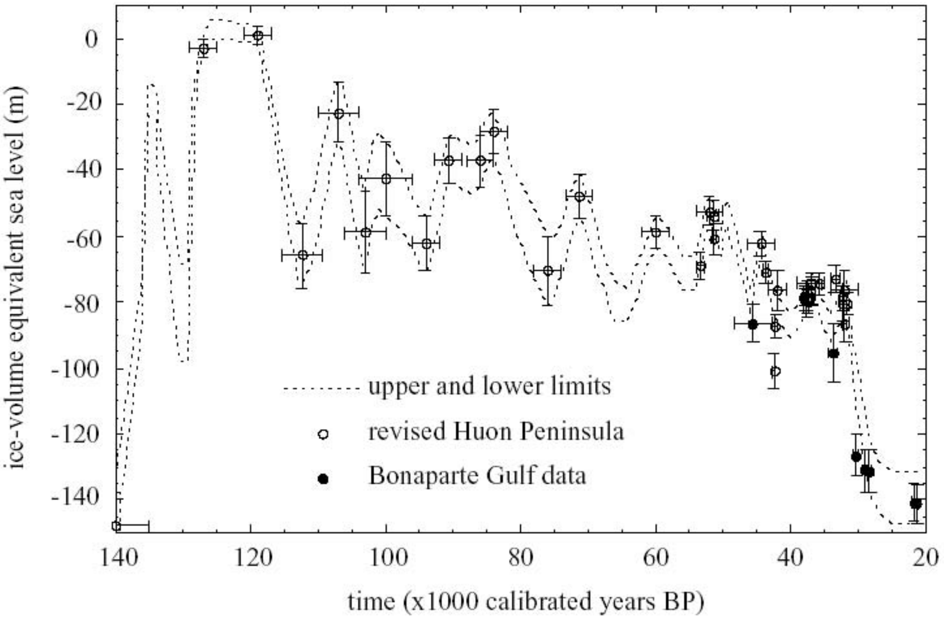


Figure 40. Pre-LGM sea level record from the Huon Peninsula and Bonaparte Gulf. Note the range of variability that exists between the upper and lower limits of the curve (from Lambeck et al, 2002b)

Chappell et al (1996) consists of a re-sampling and re-dating of the Huon peninsula coral terraces (Figure 41) to provide a closer correlation with the glacio-eustatic record derived from the oceanic foraminiferal record (Shackleton, 1987). This was undertaken after it was noted that large (up to 20-40m) discrepancies in sea level existed between the oceanic foraminiferal record of Shackleton (1987), and the HP2 curve of Chappell and Shackleton (1986).

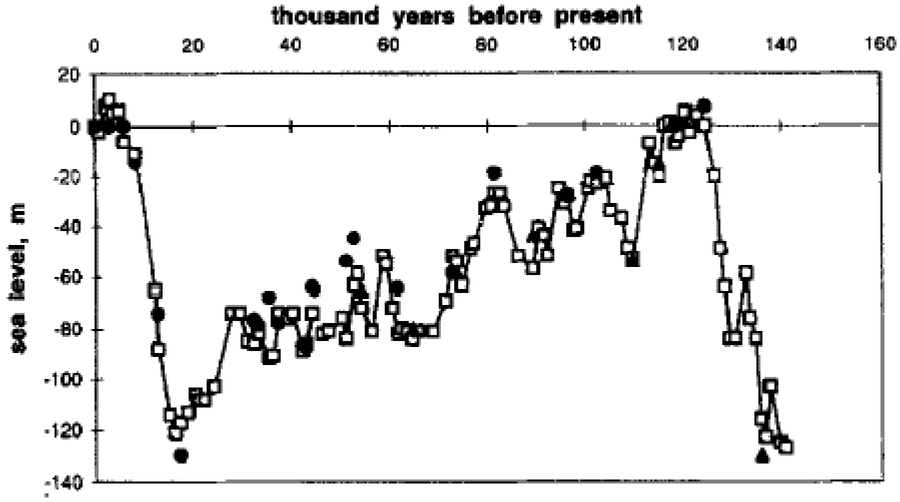


Figure 41. Pre-LGM sea level record from the Huon Peninsula after re-sampling and re-dating. Black dots refer to terrace data. White squares refer to the oceanic isotope record of Shackleton (1987) (from Chappell et al, 1996).

Rohling et al (1998) is a glacio-eustatic sea level curve derived from Red Sea salinity data (see section 2.3.2.4). The technique was used only to derive estimates of global glacio-eustatic lowstands (Figure 42). The highstands and sea level curve till 200 ka were derived from available coral reef terrace and oxygen isotope data (e.g. Pirazzoli et al, 1993; Bard et al, 1996).

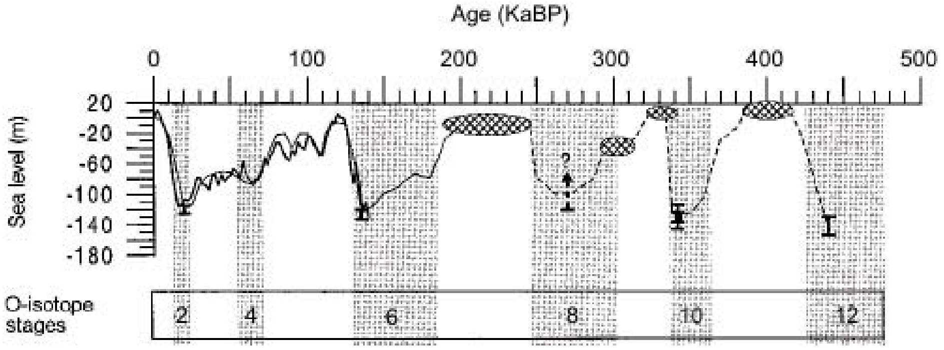


Figure 42. Pre-LGM glacio-eustatic sea level change inferred from Red Sea salinity data. Error bars represent the range of estimates of lowstands estimated from the salinity data, hatched ovals are highstand ranges derived from coral terrace and isotope data (modified from Rohling et al, 1998).

Finally, Siddall et al (2003) is the latest version for the sea level curve based on the Red Sea salinity data (Figure 43). It claims to provide much greater accuracy (+/- 12m) and greater resolution (centennial scale) between 25,000 and 70,000 years ago (Figure 44).

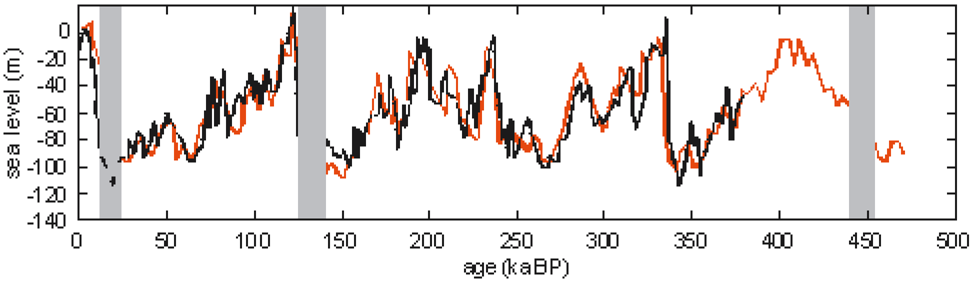


Figure 43. Pre-LGM glacio-eustatic sea level change inferred from Red Sea salinity data (from Siddall et al, 2003).

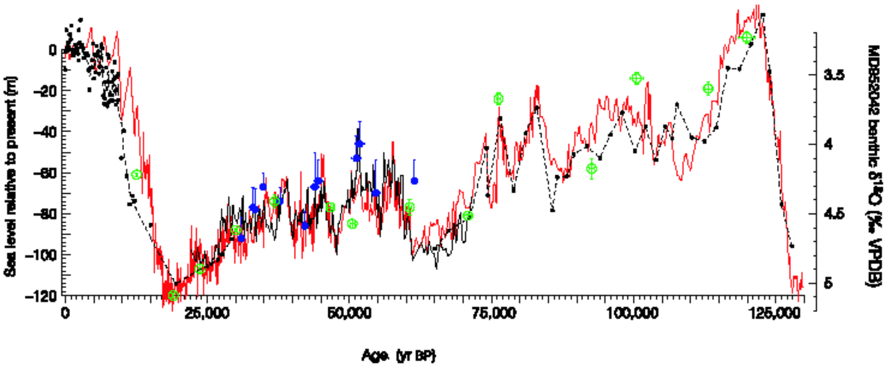


Figure 44. Reconstruction of sea level from Red Sea salinity data between 130 and 0 ka BP. The section of the curve between 25 and 70 ka BP is of centennial scale resolution. Green and blue dots represent coral terrace data included for comparison (modified from Siddall, 2003).

2.5.4 Methodology

Testing of the inherent errors involved with palaeo-geographic reconstructions was undertaken using the following methodology:

- Sea level positions were obtained from the data sets presented in Section 2.5.3.1 and 2.5.3.2 either directly from the text (e.g. Rohling et al, 1998), or tables accompanying the text (e.g. Chappell & Shackleton, 1986). If this was not possible, they were then read off the sea level curves that accompanied each article (e.g. Lambeck et al, 2002b).
- Sea level positions were then are applied to the present day bathymetry of North West Europe. The base dataset of present day bathymetry was obtained from the ETOPO-2 database of global elevations. This database was constructed using satellite altimetry and has a resolution of 2 minutes of latitude and longitude (1 minute of latitude = 1 nautical mile = 1.852km).

- The sea level positions and bathymetric data were inputted into Surfer 8, a contouring package. This allowed visual representations of approximate shoreline position to be calculated for particular times and sea level curves (Figure 45).
- Digitising the data also enabled calculations of the differences (in km) between particular shorelines to be made.

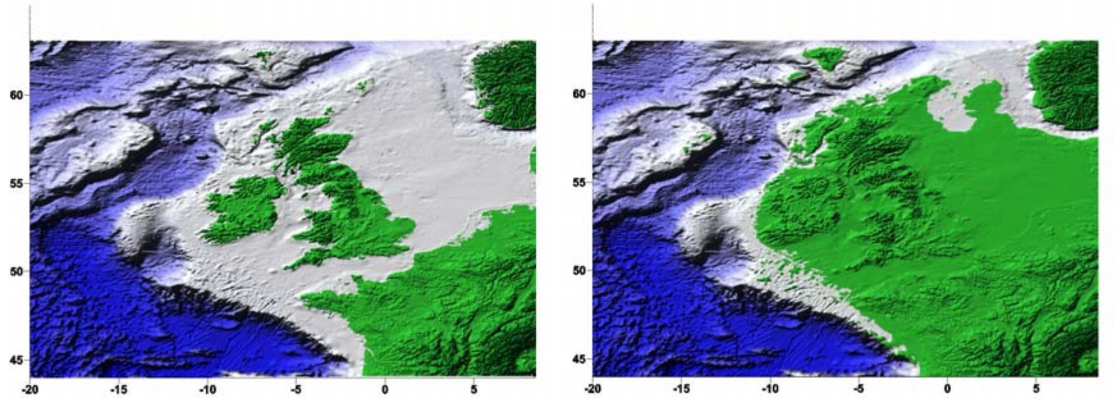


Figure 45. Example of digital reconstructions created using the Surfer 8 program. Image on left shows the present day configuration of North-West European shorelines. Image on right shows the shoreline position at –120m, the value often quoted for the global glacio-eustatic sea level fall at the LGM on the basis of Fairbanks (1989). Scales indicate latitude and longitude in decimal degrees, with negative values equating to degrees west of the meridian.

Following the above method it was then possible to make the following comparisons:

- Bard et al (1990) versus Lambeck et al (2002b: Post LGM). To provide an indication of the level of variability between two curves which purport to demonstrate global glacio-eustatic change, though it should be acknowledged that Lambeck et al (2002b: Post-LGM) provides a better approximation. It should also highlight the impact of isostatic variables, even in areas where they are considered minimal. A similar exercise will be performed for the pre-LGM data using Siddall et al (2003) and Lambeck et al (2002b: Pre-LGM). This will be demonstrated in Section 2.5.5.1.
- Rohling et al (1998) versus Bard et al (1990). To highlight the error margins within and between individual data set. – Section 2.5.5.2.
- Chappell & Shackleton (1986) versus Chappell et al (1996). To demonstrate how a seemingly secure sea level record can be modified significantly as additional data becomes available. – 2.5.5.3.
- The effect of tectonic influences on shoreline position is demonstrated by applying an estimate for long term regional (southern Britain) crustal uplift to Siddall et al (2003), and comparing it to a version of itself that has no uplift correction. This correction has been estimated at between 0.070 and 0.087 $mmyr^{-1}$ since OIS 12 (440 ka: Maddy et al, 2001), therefore a value of 0.0785 $mmyr^{-1}$ is used. – 2.5.5.4.
- The difference resulting from the use of glacio-isostatic-adjustment (GIA) models compared to eustatic curves is demonstrated by comparing palaeo-

geographic reconstructions from Lambeck & Purcell (2001) and Lambeck et al (2002b: Post LGM). – 2.5.5.5.

- The differences resulting from use of global glacio-eustatic curves and local regional sea level data is demonstrated by applying Lambeck et al (2002b: Post LGM) and a local curve (Waller & Long, 2003) to a local context: the West Solent (southern England). – 2.5.5.6.
- In situations where the palaeo-shoreline position fell within a range of values (e.g. Chappell et al, 1996), the average of the upper and lower limits was plotted.

Finally, the impact of maintaining a constant sea-level curve but a variable topographic time horizon is considered by comparing:

- Two different bathymetric surfaces; ETOPO-5 (resolution of 5 minutes of latitude/longitude) and ETOPO-2 (resolution of 2 minutes of latitude/longitude) will be applied to the same sea level data (Lambeck & Purcell, 2001: GIA model) to demonstrate the impact that resolution can have on shoreline variability. – 2.5.5.7
- Two different surfaces in the English Channel will be combined with the same sea level curve. These are the present-day bathymetric surface and the rockhead contours (base of the Quaternary sequence). This should provide an indication of the margin of error that can result from long term processes of sedimentation and erosion. - 2.5.5.8
- To facilitate comparison, the average of the upper and lower limits of the English Channel bathymetry and bedrock surfaces was also plotted. – 2.5.5.8

It must be stressed that the reconstructions produced by this exercise are approximate and should not be considered to as accurate enough to be applicable to underwater work. There are several reasons for this:

- These reconstructions primarily make use of present day bathymetry, which is itself only an approximation of the pre-transgression landsurface.
- In the instances where sea level data had to be obtained directly from sea level curves, variations of the order of a meter can result from interpretation by different individuals. In effect the scale of the curve and the thickness of the lines can lead to minor errors.
- The resolution of the bathymetric data (2 minutes of latitude or longitude, or c. 3.6km) is insufficient for more than general overviews at a continental scale.

However, the accuracy of the reconstructions is sufficient to enable comparison to be made between data sets, thus illustrating some of the practical issues involved in reconstructing submerged landscapes.

2.5.5 Results

2.5.5.1 Differences between glacio-eustatic approximations

Reconstructions for before and after the Last Glacial Maximum (LGM) will be examined separately. For the post-LGM comparison a series of c. 2000 year time steps was undertaken (Table 4):

Date (ka BP)	Sea level altitude (Bard et al, 1990)	Sea level altitude (Lambeck et al, 2002b: Post-LGM)	Maximum shoreline difference	Minimum shoreline difference
22	-130m	-146m	69.9km	0.2km
18	-112m	-125m	69.6km	1.2km
16	-102m	-113m	122km	0.6km
14	-81m	-87m	44.1km	0.3km
12	-60m	-66m	38.7km	0.6km
10	-36m	-45m	115.6km	0.3km
8	-16m	-18m	3.6km	0.2km
6	-6m	-2m	90.3km	0.1km

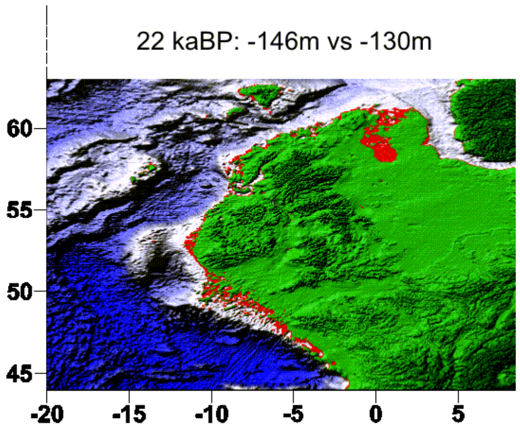
Table 4: Shoreline differences in kilometres between two different post-LGM eustatic curves applied to the bathymetry of the North-west European continental shelf

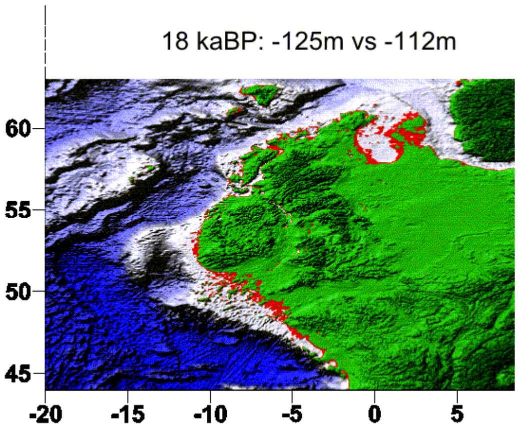
A brief glance at the maps overleaf (Figure 46) might give the impression that the differences in shoreline position are not that significant. However, quantification of the variability indicates that height differences of up to 16m can result in reconstructed palaeo-shorelines being positioned between 1 and 115 km apart.

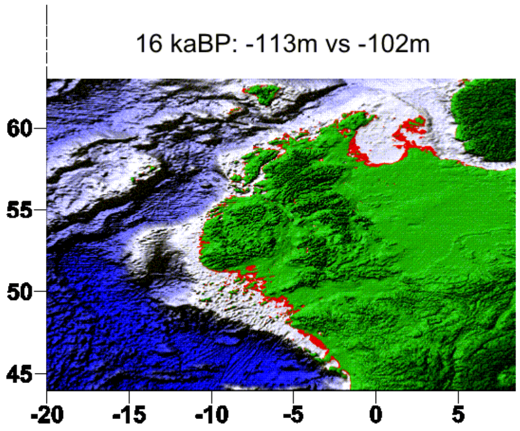
In addition to the problem of different shoreline positions, application of different sea level curves can lead to the creation of very different coastal morphologies depending on the nature of the bathymetric surface being transgressed. Note for example the large (c. 100km by 250-300km) embayment which appears in the northern North Sea at 22ka BP if Bard et al (1990) is used, but which is not present in the same period if Lambeck et al (2002b: Post-LGM) is used. Another significant feature is the presence or absence of islands (note in particular the western edge of the shelf) depending on which curve is used. To some extent variability is reduced if the difference between shorelines is minimized, as demonstrated by the maximum value for 8 ka BP – 3.6 km. However, it also depends on the gradient of the bathymetric surface that the shorelines cross. For example, there is a maximum difference of 38 km between the shorelines for 12 ka BP, which differ by 6 metres of vertical height. However, there is a maximum difference of 90 km for 6 ka BP even though the shorelines are only 4 vertical metres apart. This is created by the existence of a large shallow water, low gradient surface extending west off the Cotentin Peninsula.

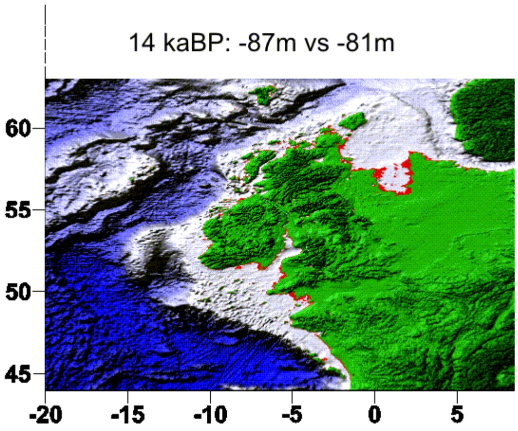
Overall, Lambeck et al (2002b: Post-LGM) consistently overestimates the palaeo-shoreline position relative to Bard et al (1990), except for the final reconstruction in which the reverse takes place.

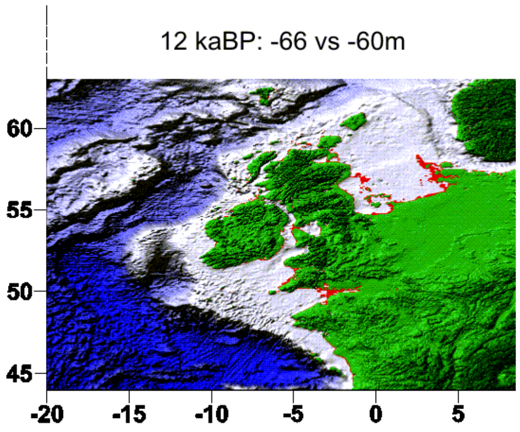
Figure 46 (Overleaf). Comparison of palaeographic reconstructions created using different approximations of glacio-eustatic change. The red shoreline represents that of Lambeck et al (2002b: Post-LGM), and the green shoreline that of Bard et al (1990). The exception is the image for 6 ka BP, where the shoreline colours are reversed (i.e. red =Bard et al (1990); green = Lambeck et al (2002b: Post-LGM).

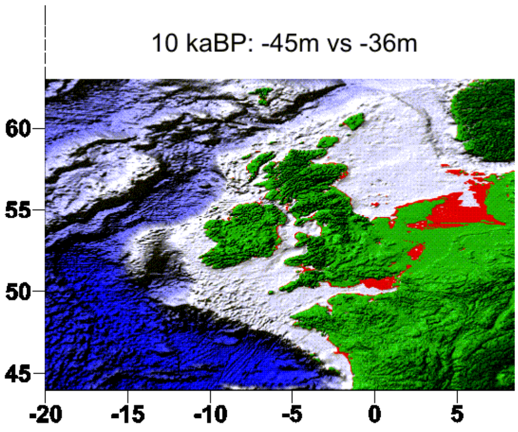

22 kaBP: -146m vs -130m

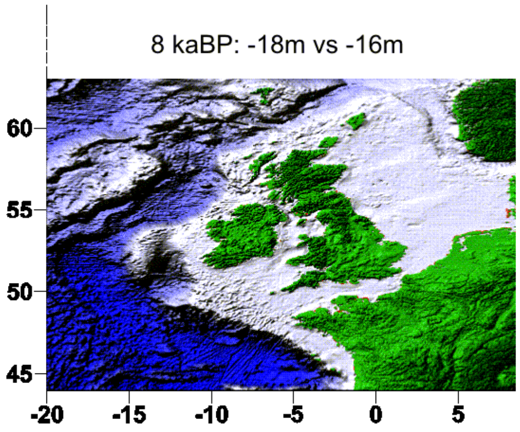

18 kaBP: -125m vs -112m

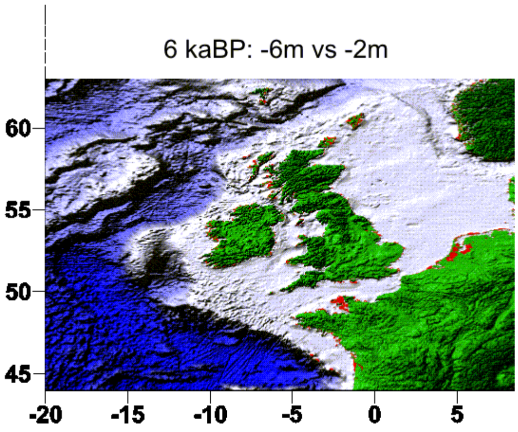

16 kaBP: -113m vs -102m


14 kaBP: -87m vs -81m


12 kaBP: -66 vs -60m


10 kaBP: -45m vs -36m


8 kaBP: -18m vs -16m


6 kaBP: -6m vs -2m

For the pre-LGM (65 to 33 ka BP) time steps of between 7000 and 2000 years between were digitally reconstructed and compared (Table 5):

Date (kBP)	Sea level altitude (Siddall et al, 2003)	Sea level altitude (Lambeck et al, 2002b: Pre-LGM)	Maximum shoreline difference	Minimum shoreline difference
65	-99m	-80m	103km	1km
60	-91m	-59m	235km	1.9km
55	-81m	-73m	68.8km	8.3km
51	-64m	-58m	31.6km	0.3km
46	-83m	-80m	27.3km	0.4km
44	-67m	-63.5m	46.4km	0.2km
40	-92m	-88m	146km	0.4km
33	-75m	-78.5m	32.7km	0.2km

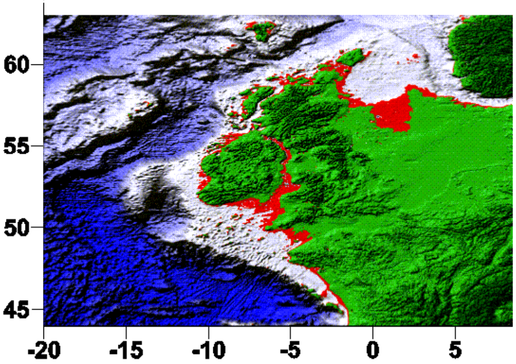
Table 5: Shoreline differences in kilometres between two different pre-LGM eustatic curves applied to the bathymetry of the North-west European continental shelf

As with the post-LGM reconstructions, major differences in shoreline position result from the application of different sea level data. This is most apparent in the reconstructions for 65 and 60 kaBP which offer radically different palaeo-coastlines. However, from then on there appears to be better overall correlation between the 2 curves, with shoreline differences ranging from 69 km to less than a kilometre. The large value of 146 km for 40 ka BP was created by the presence of a large embayment in the northern North Sea, when the –88m was used, but which was absent with the deeper shoreline (-92m). On the basis of this exercise, it seems that differences of this magnitude represent the best case scenario for this sort of data. As before, one curve (Siddall et al, (2003) in this case) consistently overestimates the other, except for one instance (35 kaBP) where the reverse situation occurs.

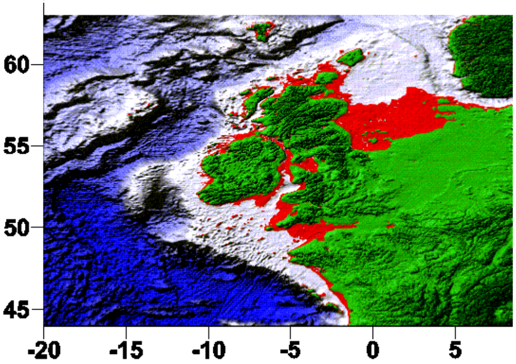
It is worth remembering that the data from the curves analysed above was an average of the inherent error margins. These mean that shoreline positions can potentially vary within a range. The magnitude of this range will now be examined.

Figure 47 Overleaf. Comparison of palaeographic reconstructions created using different approximations of glacio-eustatic change. The green shoreline represents that of Lambeck et al (2002b: Pre-LGM), and the red shoreline that of Siddall et al (2003). The exception is the image for 35 kaBP, where the shoreline colours are reversed (i.e. red =Lambeck et al (2002b: Pre-LGM); green = Siddall et al (2003).

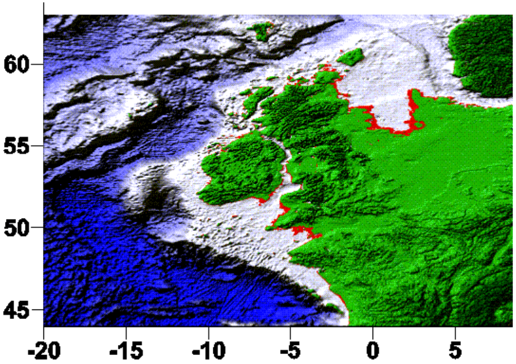
65 kaBP: -80m vs -99m



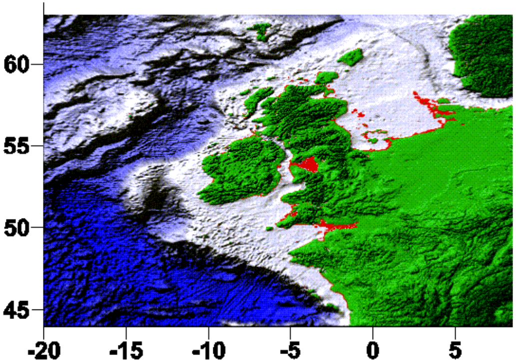
60 kaBP: -59m vs -91m



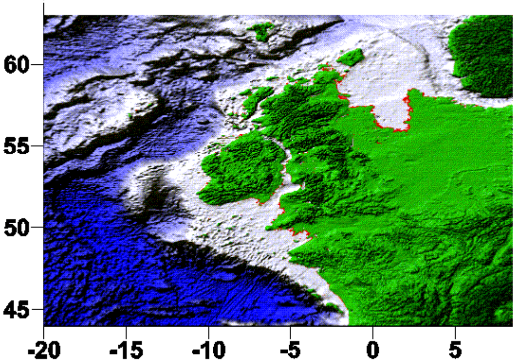
55 kaBP: -73m vs 81m



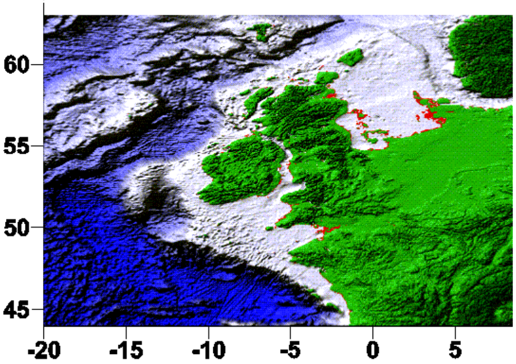
51 kaBP: -58m vs -64m



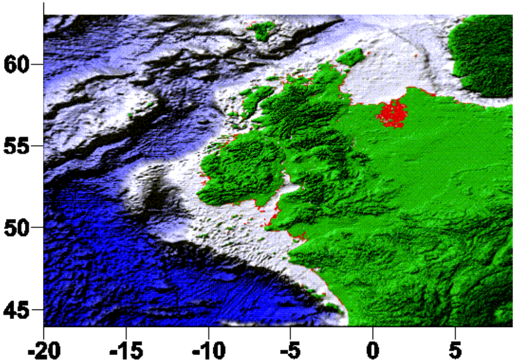
46 kaBP: -80m vs -83m



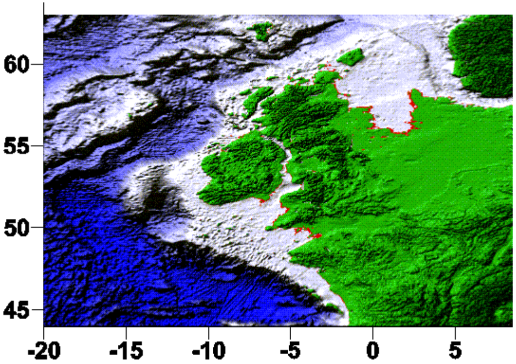
44 kaBP: -63.5m vs -67m



40 kaBP: -88m vs -92m



35 kaBP: -78.5m vs -75m



2.5.5.2 Error margins within a data set

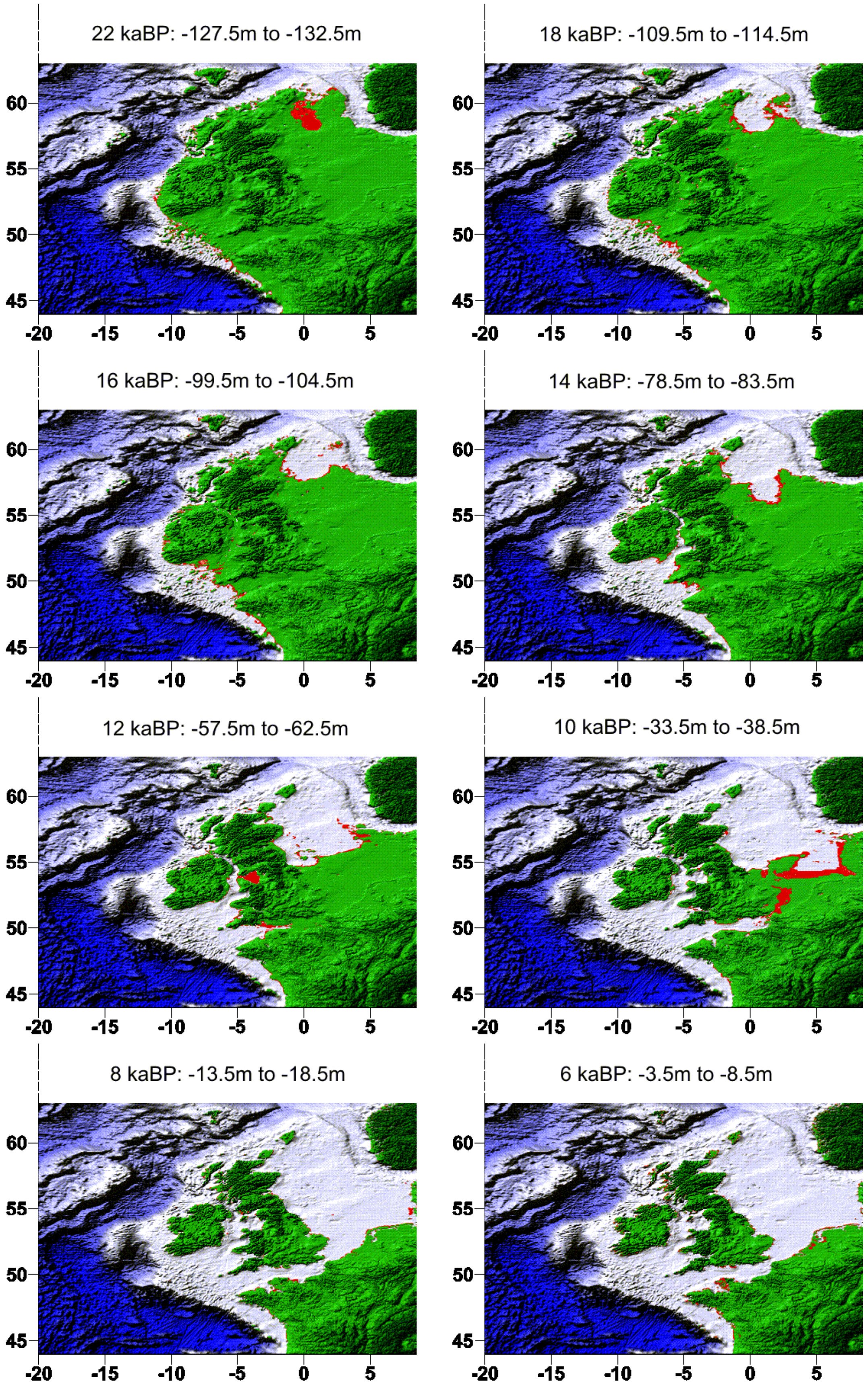
A number of the eustatic curves did provide error bars on their data. The following reconstructions aim to illustrate the impact such error bands on shoreline reconstruction for the NW European continental shelf. Again the post- and pre-Last Glacial Maximum (LGM) conditions will be examined separately. For the post-LGM comparison a series of c. 2000 year time steps was undertaken (Table 6):

Date (ka BP)	Sea level altitude range (Bard et al, 1990)	Maximum shoreline difference	Minimum shoreline difference
22	-127.5 to -132.5 m	29.5 km	0.1 km
18	-109.5 to –114.5 m	43.7 km	0.2 km
16	-99.5 to –104.5 m	59.6 km	0.2 km
14	-78.5 to -83.5 m	26.4 km	0.4 km
12	-57.5 to –62.5 m	38.1 km	0.3 km
10	-33.5 to -38.5 m	120.6 km	0.1 km
8	-13.5 to –18.5 m	12.9 km	0.1 km
6	-3.5 to –8.5 m	89 km	0.1 km

Table 6: Shoreline differences in kilometres between the maximum and minimum post-LGM eustatic sea level curve values of Bard et al (1990) applied to the bathymetry of the North-west European continental shelf

Error margins in the Bard et al (1990) sea level curve were +/-2.5 m, giving a total error range of 5 m. Overall, compared to the variations between different curves (see Section 2.5.5.1), the palaeo-shorelines, were generally closer to each other, though maximum differences were still of the order of several tens of kilometres (Figure 48). Nevertheless, significant shoreline variability was again possible in areas of low gradient local topography. Again, note the presence of the large bay at 22 ka BP when the minimum error value was used, and its absence when the maximum value was used. Further large differences are noticeable in the central North Sea at 10 ka BP and North-West England at 12 ka BP, and off the Cotentin Peninsula at 6 ka BP.

Figure 48 Overleaf. Palaeogeographic reconstructions demonstrating shoreline variability resulting from the error margins within a data set. Sea level information is from Bard et al (1990). The red shoreline represents the lowest end of the error margin (i.e. the greatest lowstand value), while the green shoreline is the highest end of the error margin (i.e. the minimum lowstand value).


22 kaBP: -127.5m to -132.5m
18 kaBP: -109.5m to -114.5m
16 kaBP: -99.5m to -104.5m
14 kaBP: -78.5m to -83.5m
12 kaBP: -57.5m to -62.5m
10 kaBP: -33.5m to -38.5m
8 kaBP: -13.5m to -18.5m
6 kaBP: -3.5m to -8.5m
60
55
50
45
-20
-15
-10
-5
0
5

For the pre-LGM single eustatic curve error comparison time steps of between 70 ka and 135 ka were taken, as these represent the major lowstand events between 440 ka BP and 135 ka BP – Table 7:

Date (ka BP)	Sea level altitude range (Rohling et al, 1998)	Maximum shoreline difference	Minimum shoreline difference
440	-150 to -128 m	74.2 km	2.2 km
340	-143 to -113 m	419.5 km	0.6 km
270	-128 to –112 m	74.6 km	1.6 km
135	-131 to –119 m	252.8 km	0.3 km

Table 7: Shoreline differences in kilometres between the maximum and minimum post-LGM eustatic sea level curve values of Rohling et al (1998) applied to the bathymetry of the North-west European continental shelf

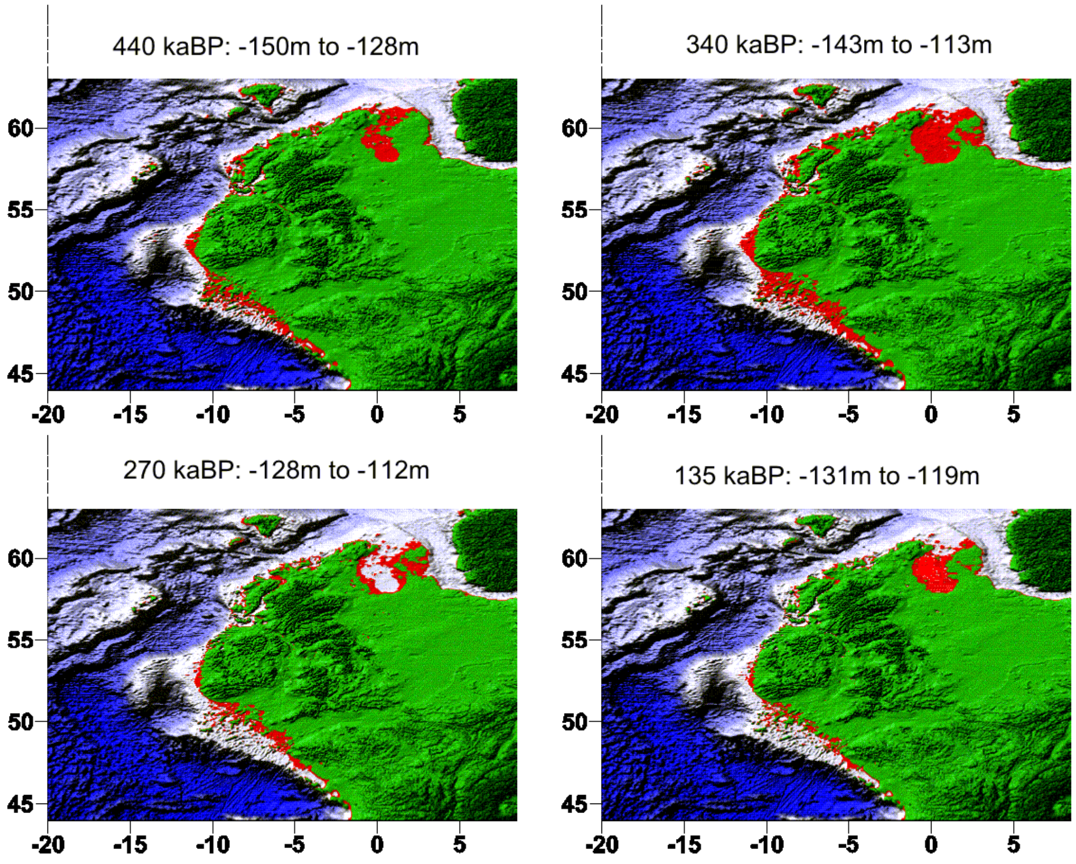


Figure 49. Palaeo-geographic reconstructions demonstrating shoreline variability resulting from the error margins within a data set. Sea level information is from Rohling et al (1998). The red shoreline represents the lowest end of the error margin (i.e. the greatest lowstand value), while the green shoreline is the highest end of the error margin (i.e. the minimum lowstand value).

In contrast to the post-LGM reconstructions, the error margins in this sea level curve are not constant, but vary from +/- 8 m to up to +/- 15 m. The fact that the error margins are, on the whole larger, means that the differences in shoreline position are generally more dramatic, up to several hundred km in some instances. These extreme results are created by the presence or absence of the northern North Sea embayment 340 and 135 ka BP (Figure 49). Also, despite the very large vertical difference between some of these shorelines, horizontal differences could still range within a few kilometres. These were created in areas where bathymetry was very steep. The more common shoreline differences tend to be of the order of several tens of kilometres. Once again, another major feature is the almost archipelago-like nature of the western shoreline when the upper end of the error margin is used. Even though the shoreline differences in this region may appear relatively small, especially in comparison to the northern North Sea situation, the differences are routinely of the order of several tens of kilometres up to over a hundred kilometres.

2.5.5.3 The effect of new data on a eustatic curve

Comparison of Chappell & Shackleton (1986) and Chappell et al (1996) show the difference in data as provided by the same authors a decade apart (Table 8):

Date (ka BP)	Sea level altitude (Chappell & Shackleton, 1986)	Sea level altitude (Chappell et al, 1996)	Maximum shoreline difference	Minimum shoreline difference
72	-36 m	-58.5 m	292.6 km	0.5 km
44	-45 m	-65 m	477.2 km	0.6 km
42	-52 m	-87.5 m	393.3 km	1.4 km
35	-65 m	-68 m	47.5 km	0.3 km

Table 8: Shoreline differences in kilometres between the two eustatic curves created by the same research but a decade apart, as applied to the bathymetry of the North-west European continental shelf

It is clear from these reconstructions (Figure 50) that significant changes in shoreline position and indeed the entire character of the coastline are possible in these circumstances. The greatest changes are once again visible in areas of low gradient, such as the central North Sea and English Channel. Shoreline variation again varies laterally but with maximum errors between c. 50 km and c. 300 km.

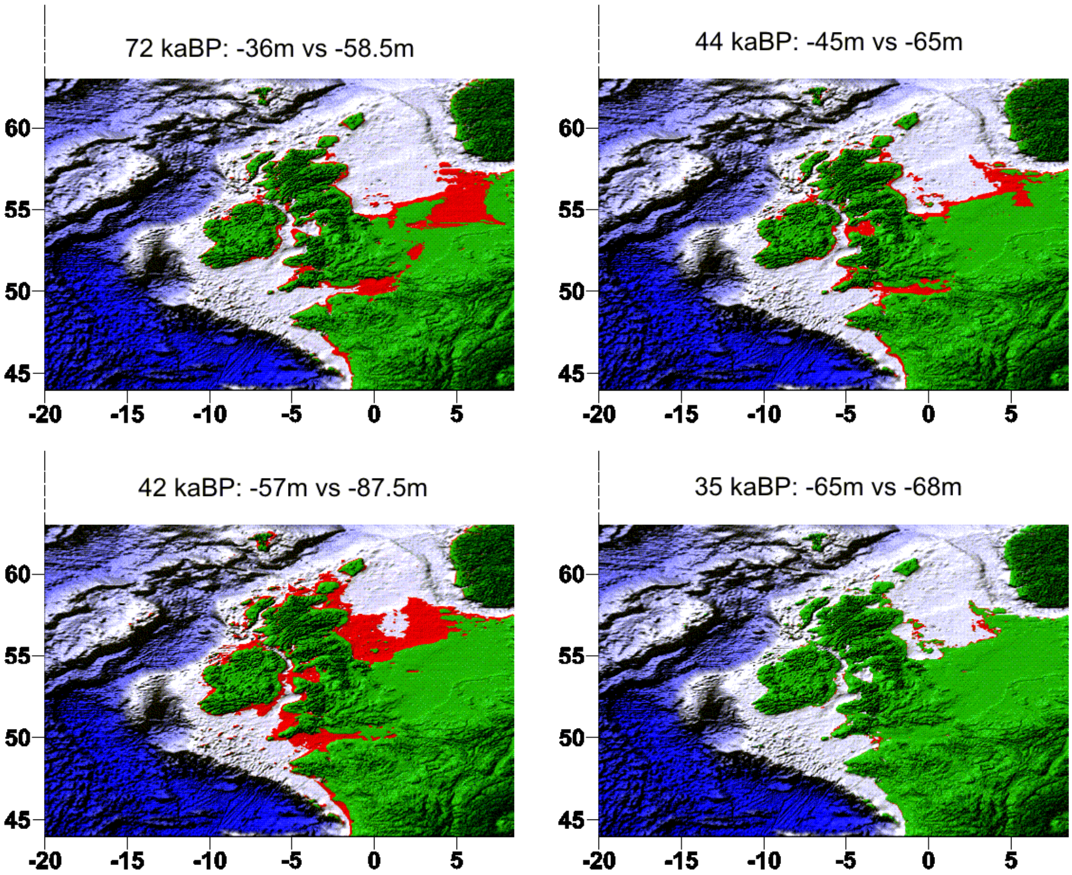


Figure 50. Differences in palaeo-geographic reconstruction resulting from the use of improved data. Green shorelines are from Chappell & Shackleton (1986), red shorelines are from Chappell et al (1996).

2.5.5.4 Long Term Tectonic influences

Tectonic influences were tested using a constant eustatic sea level curve, but with and without correction for long term uplift (Table 9):

Date (ka BP)	Sea level altitude (Siddall et al, 2003) (No uplift correction)	Sea level altitude (Siddall et al, 2003) (With uplift correction)	Degree of uplift (After Maddy et al, 2001)	Maximum shoreline difference	Minimum shoreline difference
350	-67 m	-94.48 m	27.475 m	225.7 km	1.9 km
300	-67.6 m	-91.15 m	23.55 m	178.3 km	1.3 km
250	-92.6 m	-112.23 m	19.625 m	400.1 km	1.4 km
200	-11 m	-26.7 m	15.7 m	109.6 km	0.3 km
150	-94 m	-105.78 m	11.775 m	306 km	0.7 km
100	-49.5 m	-57.35 m	7.85 m	152.5 km	0.4 km
50	-59.4 m	-63.33 m	3.926 m	187.3 km	0.6 km
22	-99.7 m	-101.43 m	1.727 m	66.3 km	0.1 km

Table 9: Shoreline differences in kilometres between the same eustatic curve (Siddall et al., 2003) but with variable long term uplift applied (no uplift vs uplift of 0.0785 mmyr^{-1}).

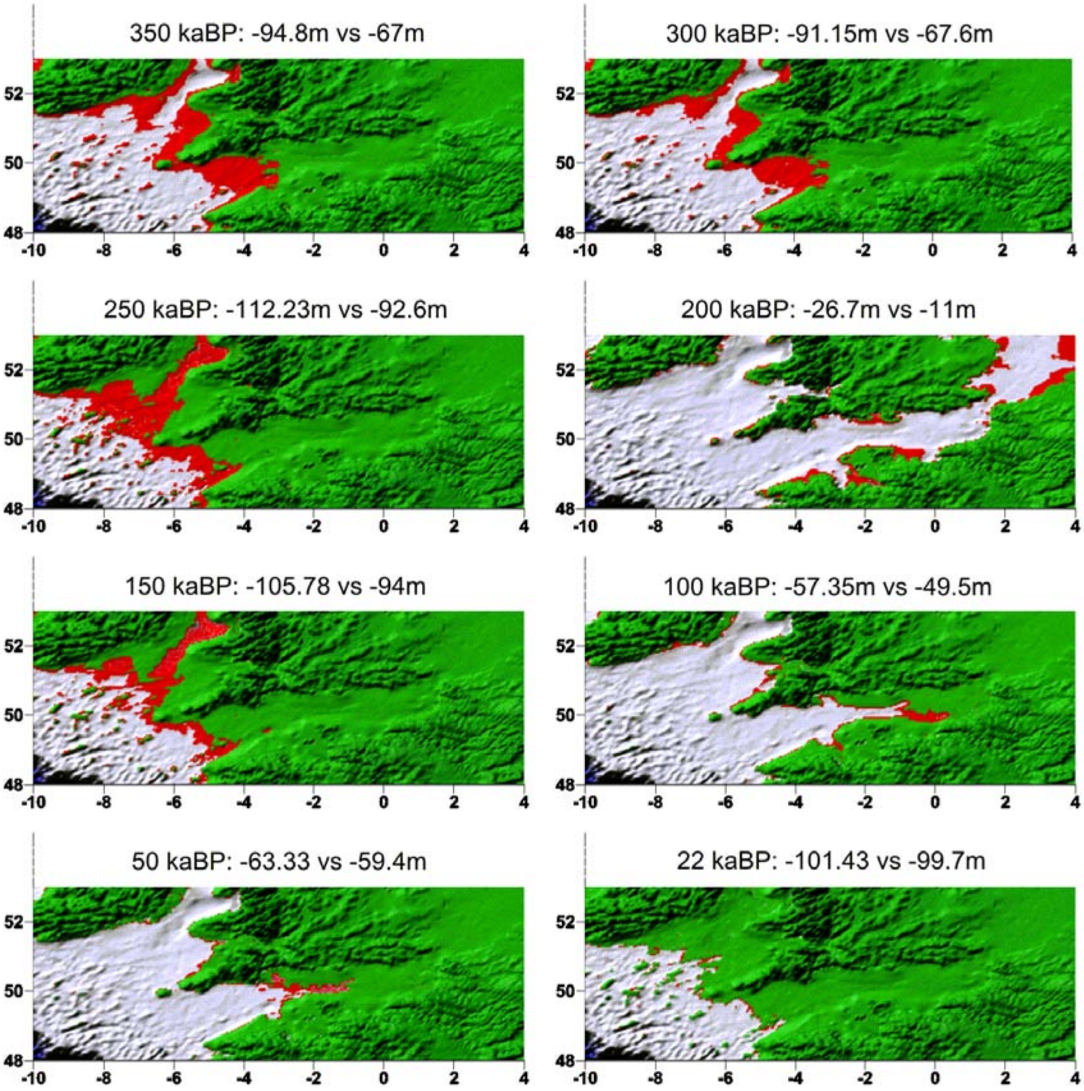


Figure 51. Palaeo-geographic reconstructions compared to highlight shoreline variability resulting from long tern tectonic uplift. Sea level data is from Siddall et al (2003). Red shoreline has is not corrected for uplift, green shoreline is corrected for an uplift of 0.0785 mmyr^{-1} (Maddy et al, 2001).

For these reconstructions, only the English Channel and southern Bight of the North Sea have been digitised as the uplift correction used in this exercise has only been calculated for southern England (Figure 51). It has thus been assumed to be only regionally valid. The overall pattern is that the degree of shoreline difference is greatest the further back in time one goes. This is unsurprising as the magnitude of uplift and its long term constant nature are such that older areas have been uplifted further. However, even within the last 50,000 years differences of up to c. 180 km are possible, resulting from the English Channel taking the form of an embayment at the lower shoreline (-63 m in this case) and extending almost as far as the Isle of Wight with the upper shoreline (-59.4 m: Figure 51). Very large differences were also notable in the Celtic Sea, with shorelines characterised by the presence or absence of a large channel extending up into the Irish Sea at 250 and 150 ka BP.

2.5.5.5 GIA models versus glacio-eustatic curves

The GIA-based reconstructions were constructed by digitising and incorporating relative sea level isobases obtained from Lambeck & Purcell (2001) into the base map of North West European shelf bathymetry (Figure 52).

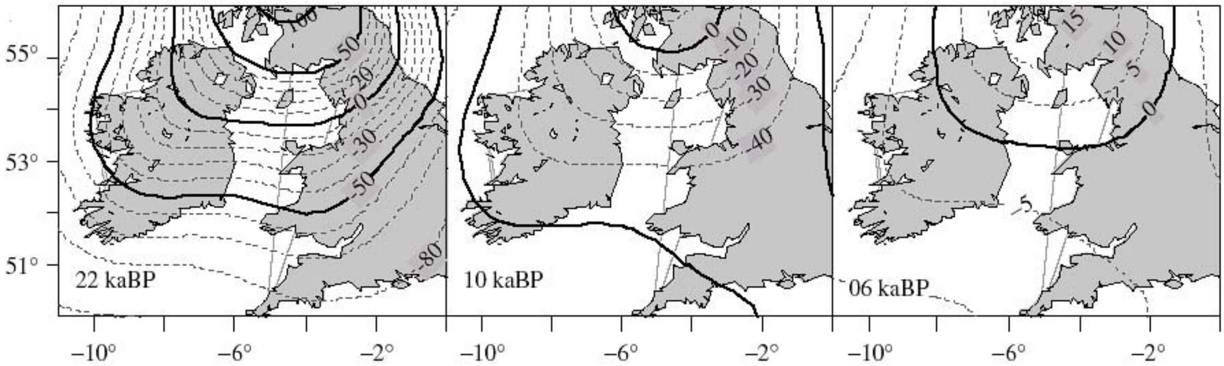


Figure 52. Predicted relative sea level change for the Irish sea region in response to contributions from the melting of the British, North-West European, American and Antarctic ice sheets (from Lambeck & Purcell, 2001)

As the information in this article was based on an uncalibrated C^{14} timescale, it was calibrated using the online CalPal program (provided by the University of Cologne Radiocarbon Laboratory http://www.calpal-online.de/index.html) to allow comparison with the calibrated sea level curves used in this exercise. The shorelines created from the GIA model were then compared with the sea level data from Lambeck et al (2002b) (both pre- and post-LGM in this instance) as this was assumed to provide a reasonable estimate of global glacio-eustatic change (Table 10 and Figure 53).

Date (uncal ka BP)	Calibrated date (ka BP)	Sea level altitude (Lambeck et al, 2002b)	Maximum shoreline difference	Minimum shoreline difference
22	25.6	-146 m	560.8 km	33.7 km
10	11.5	-62 m	289 km	7.1 km
6	6.8	-8 m	19.1 km	0.1 km

Table 10: Shoreline differences in kilometres between the GIA reconstruction of Lambeck & Purcell (2001) and the eustatic curve of Lambeck et al (2002b).

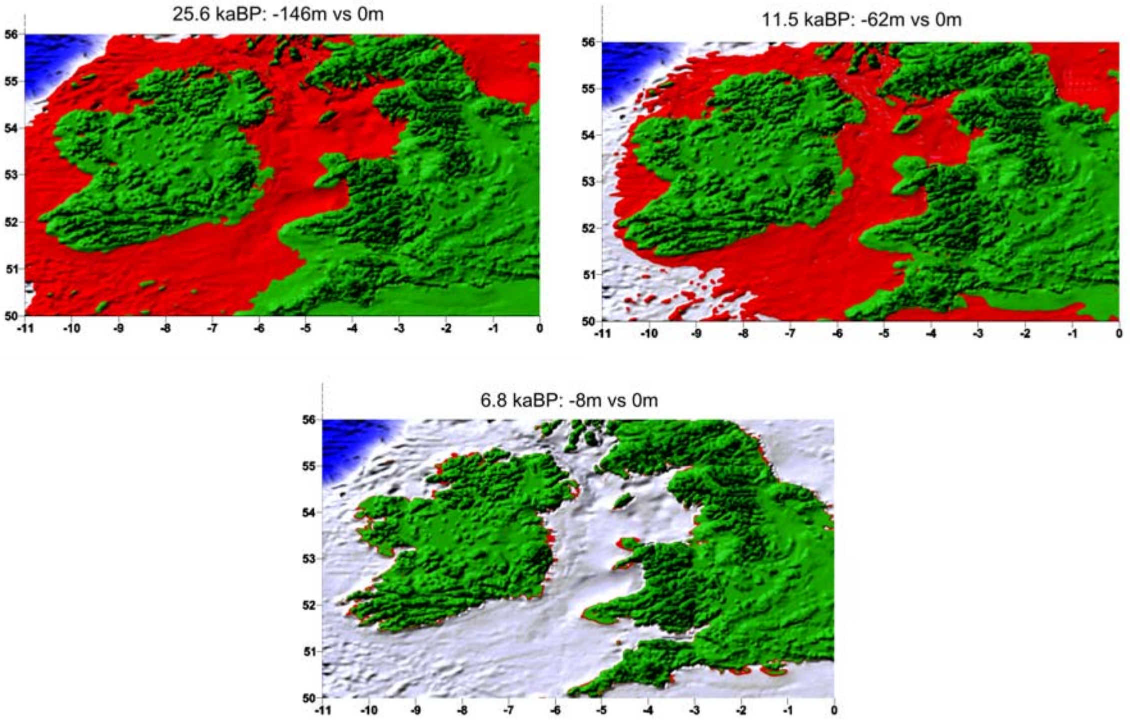


Figure 53. Comparison of palaeo-geographic reconstructions created with GIA models and global glacio-eustatic curves. Green shoreline represents the GIA model-based reconstruction of Lambeck & Purcell (2001). Red shoreline represents glacio-eustatic curve of Lambeck et al (2002b). The positions of the British and Irish ice sheets have been omitted for the sake of clarity.

It is clear from this that the use of global-glacio eustatic curves as the sole basis for a palaeo-geographic reconstruction will lead to significant errors in areas under the influence of major continental ice sheets (Figure 53). The errors are most pronounced when the sheets are large and accreting or melting. This is because the changing distribution of ice mass can cause the crust to uplift or downwarp significantly over a timescale of several thousand years. The errors are such that differences in shoreline position are not simply a case of movement of several kilometres in one direction. Rather, an entirely different picture of the palaeo-landscape is possible depending on whether isostasy has been taken into account. Note in Figure 53 that current islands of Britain and Ireland are part of a single landmass until the early Holocene, if the glacio-eustatic based reconstruction is to believed. In reality, isostatic factors would have meant that they were separated far earlier. Overall, the differences are greatest when the ice sheets are at their greatest extent (25.6 ka BP in this instance). However, there still are significant differences when the ice sheets have largely disappeared. This is the result of the lag between the isostatic response and ice sheet growth and decay (11.5 ka BP). Finally, several thousand years after the ice load has disappeared, on-going isostatic adjustments have now slowed down to the point where closer correlations to glacio-eustatic sea level change can be noticed (6.8 ka BP).

2.5.5.6 Regional relative sea level curves versus global glacio-eustatic curves

In order to compare the actual ability of a eustatic curve to predict local sea level variation and ultimately shoreline position, the eustatic curve of Lambeck et al (2002b:Post-LGM) was compared with the local relative sea level curve of Waller & Long for the Solent region (Table 11 and Figure 54). A 2D bathymetric dataset provided by New Forest District Council from the mouth of the Lymington river was used to provide the stratigraphic time horizon.

Date (ka BP)	Sea level altitude (Waller & Long, 2003)	Sea level altitude (Lambeck et al, 2002b)	Maximum shoreline difference	Minimum shoreline difference
7	-9m	-9m	0m	0m
6	-5m	-2m	1125m	23m
5	-4m	0m	>1600m	34m

Table 11: Shoreline differences in metres between the GIA reconstruction of Lambeck et al (2002b) and the local relative sea level curve (Solent region) of Waller & Long (2003).

The reconstructions depicted in Figure 54 demonstrate that different shoreline position can result depending on whether regional relative sea level curves or global eustatic curves are used. Overall, the differences are the smallest out of all the data sources analysed so far, ranging from over 1.6 km (5 Ka BP) to no difference at al (7 Ka BP). These differences are the cumulative result of local isostatic, tectonic, geoidal, steric & sedimentary modifications to the global glacio-eustatic signal. It should be noted that the impact of these modifications will vary over time and space. For instance, in this area (West Solent) isostatic adjustment will have been less than that of an area close to the Last Glacial ice sheets. In addition, by this stage in time (i.e. mid-Holocene) the magnitude of the local isostatic response had probably decreased to the point where global glacio-eustasy dominated the local trend of relative sea level change.

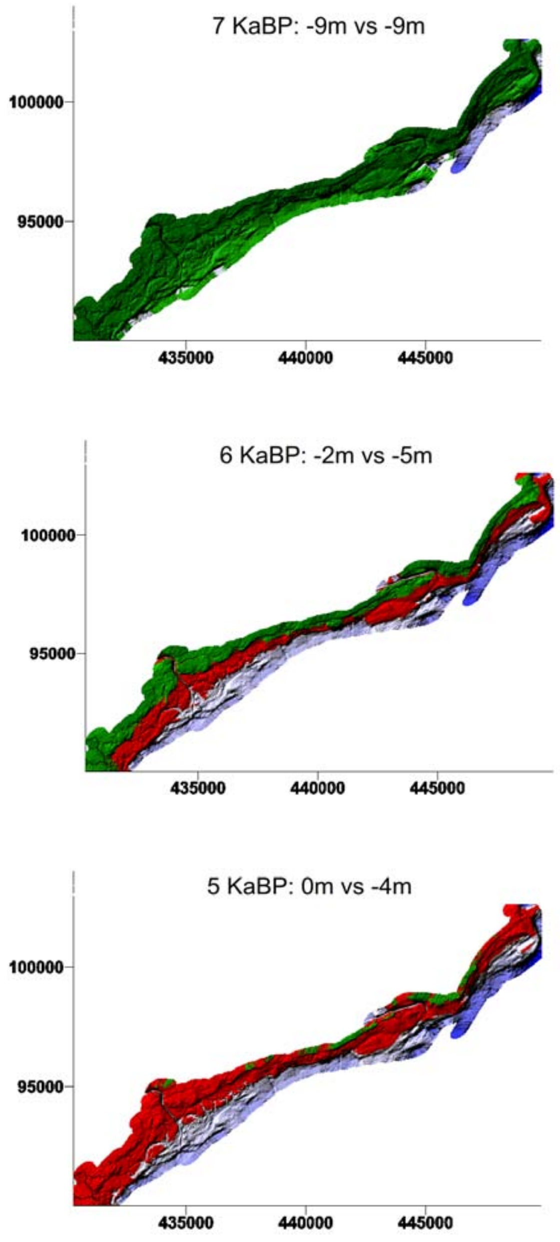


Figure 54. Comparison of palaeogeographic reconstructions created using regional relative sea level curves and global glacio-eustatic curves. Green shoreline represents glacio-eustatic curve of Lambeck et al (2002b:Post-LGM). Red shoreline represents the regional relative sea level curve of Long & Waller (2003).

2.5.5.7 Issues of Resolution

The impact of input data resolution on palaeo-geographic reconstructions is illustrated in the image below (Figure 55). In this instances, shorelines from a GIA model (Lambeck & Purcell, 2001) have been applied to a high resolution (ETOPO-2) and low resolution (ETOPO-5) bathymetric surface.

In these images it is possible to see distinct differences in palaeo-shoreline position. According to the ETOPO-5 reconstruction, there appears to be more land off south-east Ireland, west Wales and south-west England. In addition, the ETOPO-2 reconstruction has a number of islands in the Celtic Sea, which are not present in the ETOPO-5 reconstruction.

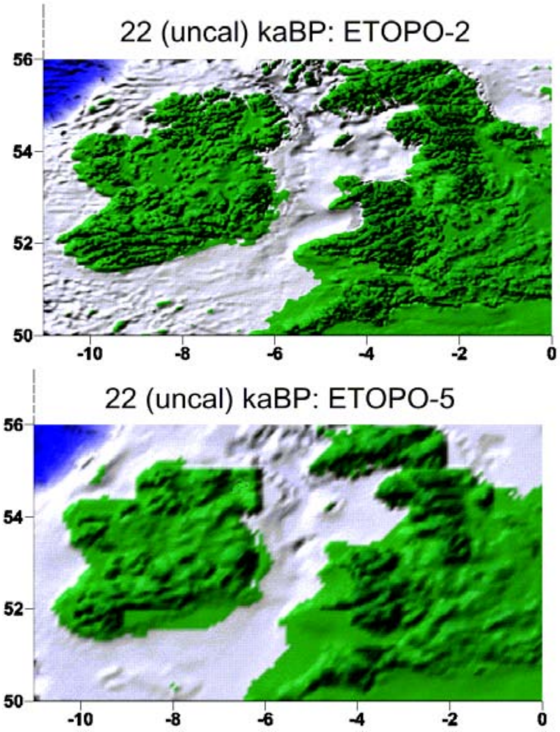


Figure 55. Comparison of palaeo-shoreline position variability resulting from the use of different resolution bathymetric and topographic data. Image on the left uses ETOPO-2 data, image on the right uses ETOPO-5 data. Shorelines are from Lambeck & Purcell (2001) – 22 (uncal) kaBP. For the sake of clarity, the British Ice Sheet has been removed.

2.5.5.8 Topographic time horizon variability

The area chosen in order to look at the impact of picking an alternative topographic time horizon to the seabed bathymetry was located between 2 degrees East and 2 degrees West, and between 50 and 51 degrees North, an area encompassing the Dover Straits to the Isle of Wight (Figure 56).

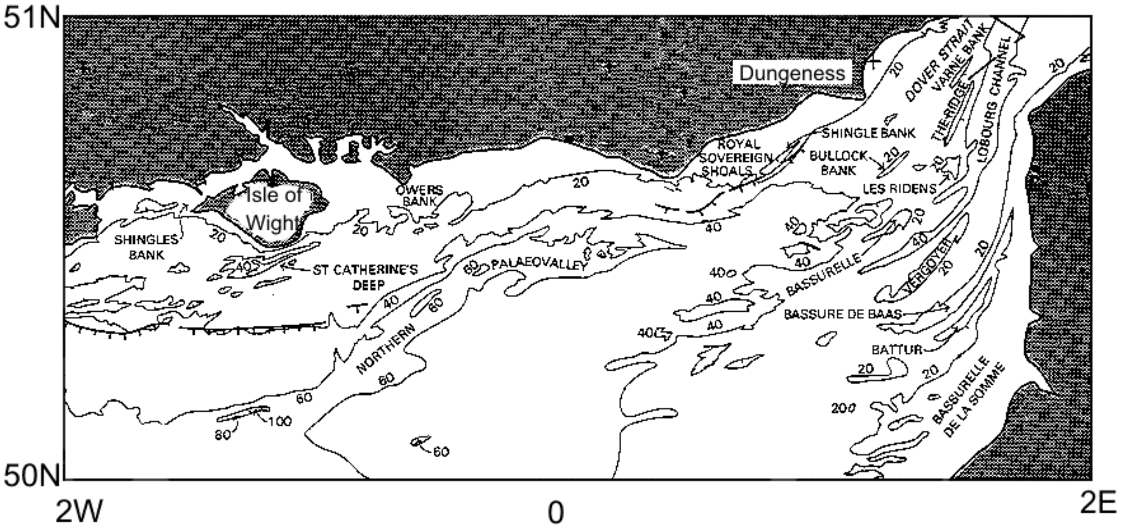


Figure 56. The present day bathymetry of the Wight-Dungeness area. Depths are in metres below sea level (modified from Hamblin et al, 1992).

The surfaces compared were the modern bathymetric surface (Figure 56) and the depth to the base of the Quaternary sequence (rockhead contours: Figure 57). This latter surface was obtained by combining bathymetric depths with measurements of sediment infill. The information was digitised from the British Geological Survey’s 1:250000 series maps of seabed sediments and Quaternary geology.

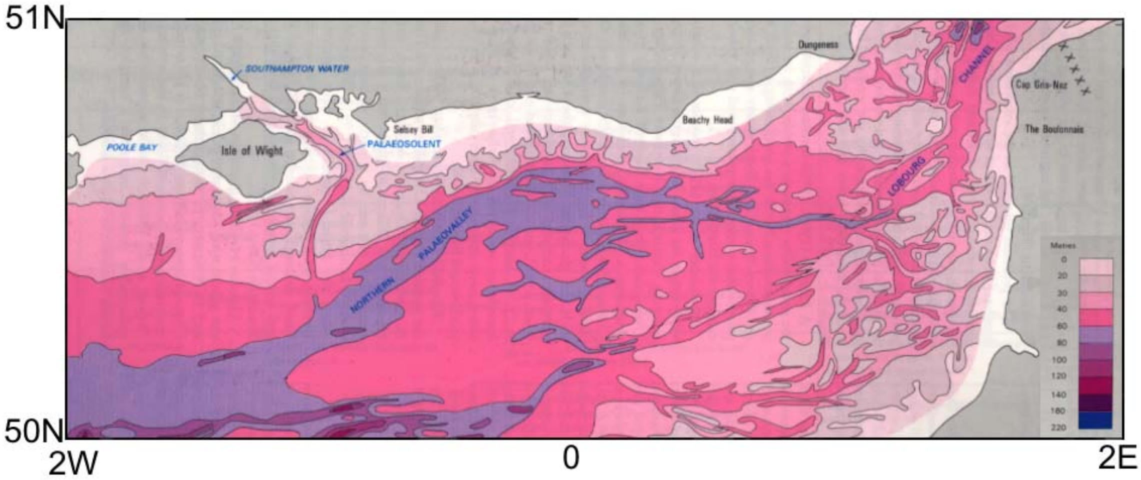


Figure 57. Depth (in metres) to base of the Quaternary – bedrock - in the Wight-Dungeness area (modified from Hamblin et al, 1992).

For ease of analysis the area was split in two down the 0° line of longitude. The area to its west will be known as the Wight area, and the area to its right will be known as the Dungeness area (Figure 58).

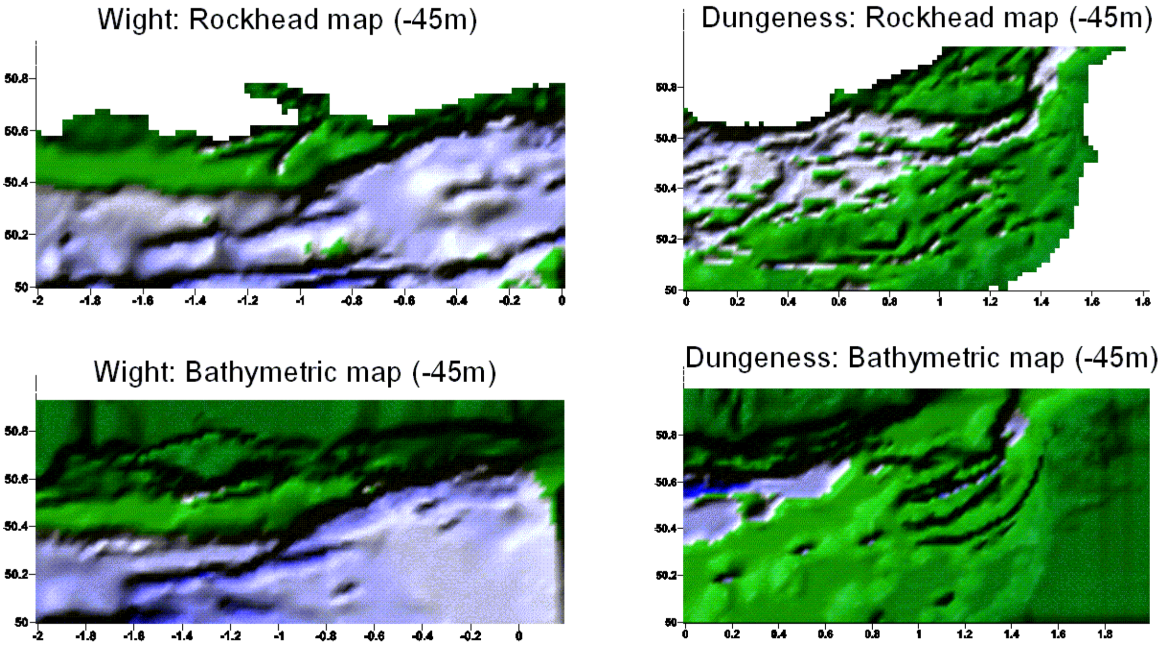


Figure 58. Digital maps of bathymetric and rockhead surfaces for the Wight and Dungeness regions. Sea levels have been nominally placed at –45m. X and Y axes show latitude and longitude in decimal degrees.

A visual inspection of these reconstructions would indicate that some differences in shoreline position are apparent, most obviously in the Dungeness region, where they may be of the order of several kilometres to tens of kilometres. Differences do occur in the Wight area, but are more subtle and are less obvious from these reconstructions. Consequently 6 transects running from north to south were taken across each of these two areas, for both the bathymetric surface and the rockhead contours. These have been compared in Figures 59 and 60 and provide a better indication of the degree of difference between the two surfaces.

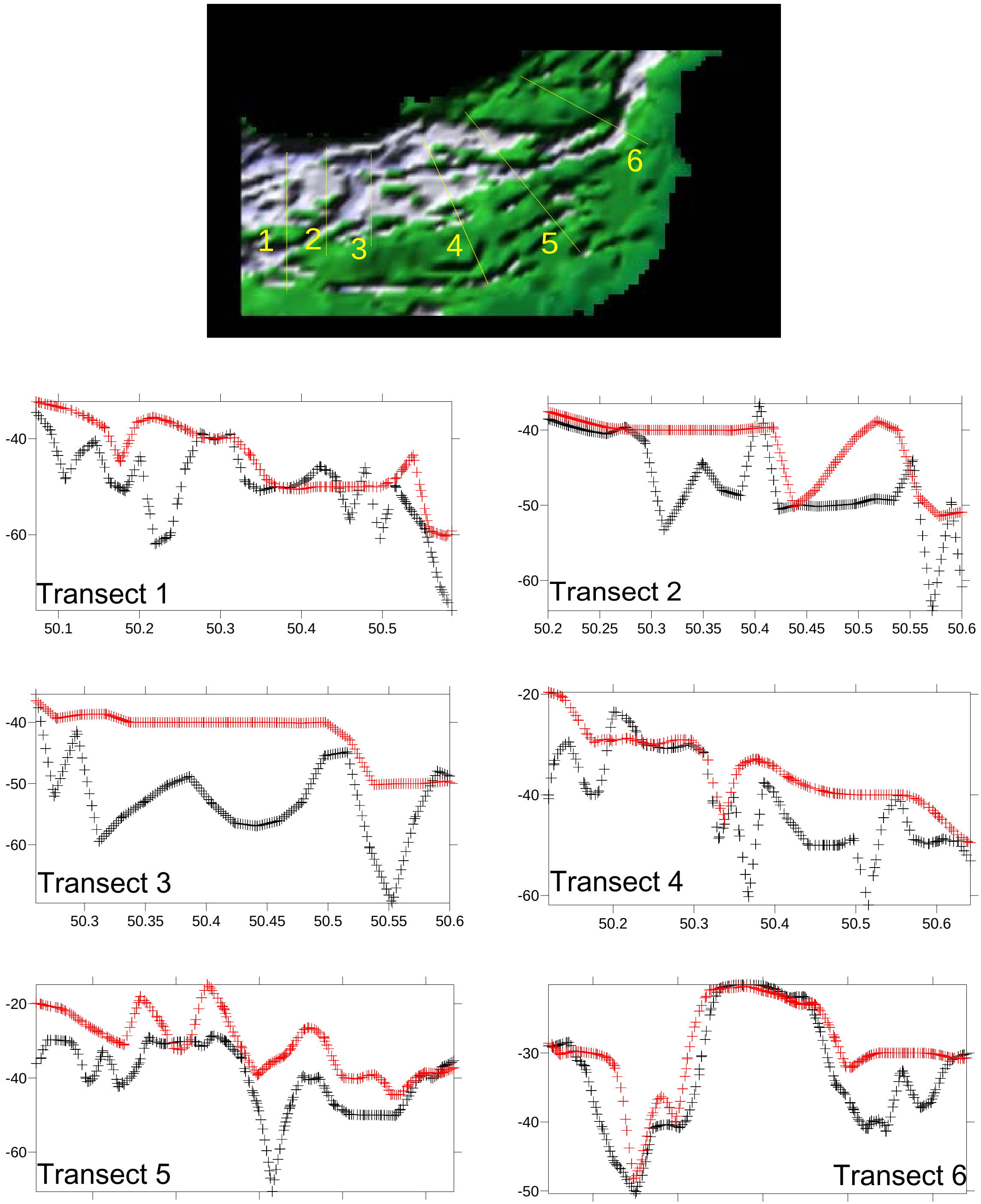


Figure 59. Comparison of rockhead and bathymetric surfaces along selected transects in the Dungeness region. The transect locations are provided by the digital bathymetric surface at the top of the figure. On the graphs, red lines indicate the modern bathymetric surface and black lines the rockhead surface. Y axis depicts metres below present sea level. X axis shows latitude in decimal degrees.

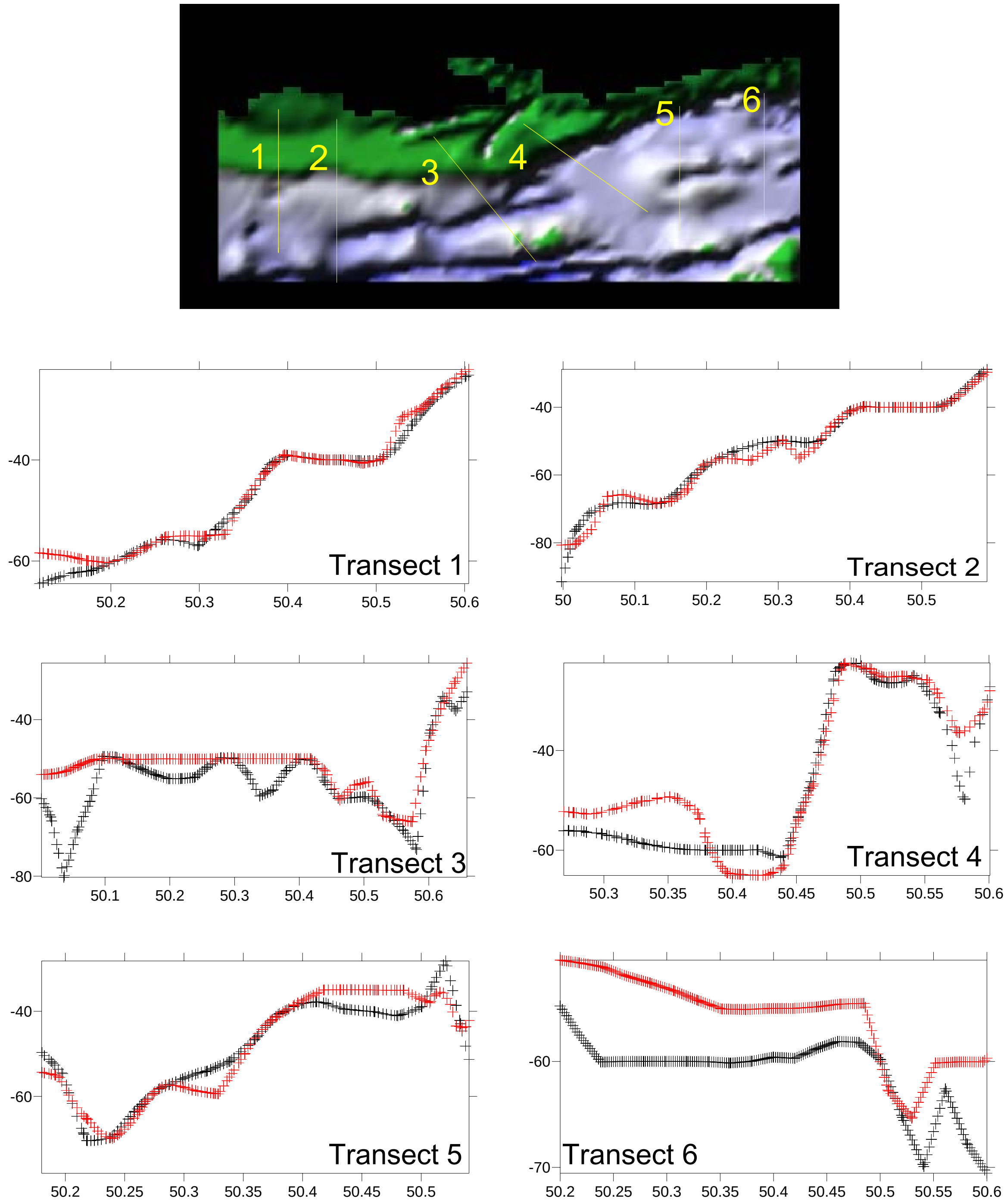


Figure 60. Comparison of rockhead and bathymetric surfaces along selected transects in the Wight region. The transect locations are provided by the digital bathymetric surface at the tope of the figure. On the graphs, red lines indicate the modern bathymetric surface and black lines the rockhead surface. Y axis depicts metres below present sea level. X axis shows latitude in decimal degrees.

It is apparent from Figures 59 and 60 that the difference between the modern bathymetric surface and the bedrock horizon can vary significantly over a relatively restricted region (in this case c.432 km by c.108 km). The vertical differences between the surfaces can range from greater than 20m (Dungeness Transect 3) to no appreciable differences on this scale (Wight Transect 1). This can lead to variations in the actual topography of the reconstructed landscape. In this instance, it is apparent that a number of palaeo-valleys appear to be infilled (e.g. Wight Transect 3, Dungeness Transect 1) while the close correlation between the surface most likely relates to the transgressive erosion of the former landsurface by the post-LGM sea level rise (Reynaud et al, 2002). Overall, differences appear to be more significant in the Dungeness region than the Wight region, where only 1 transect (number 6) revealed consistent significant differences between the two surfaces along most of the transect. The use of different surfaces also resulted in the creation of different shoreline configurations (Figures 61 and 62 and Tables 12 and 13). These palaeo-shoreline maps were produced by overlaying 3 contour maps of the Wight and Dungeness regions; the modern bathymetric surface, the rockhead surface and an intermediate surface created by calculating the mid-point altitude between the two other surfaces for each nodal point. Mean sea-level was dropped by -25 m, -35 m and – 45 m respectively.

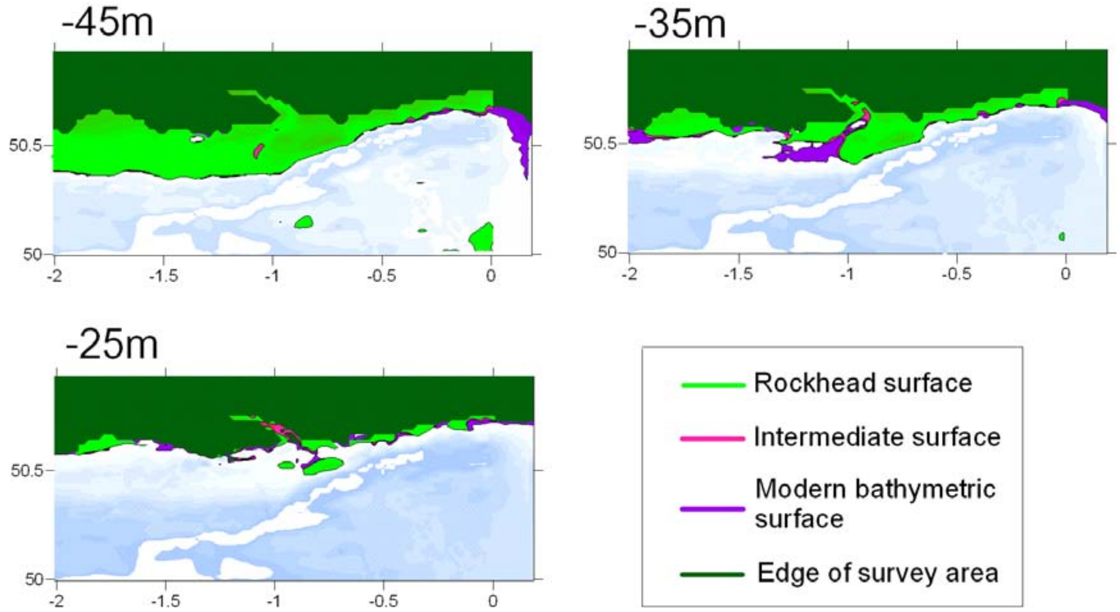


Figure 61. Overlaid shorelines produced by different bathymetric surfaces for the Wight region. The edge of the survey area indicates the limit of the known rockhead contours, and hence for this exercise the limits of the data. To some extent it approximates the present shoreline

Depth (mbsl)	Maximum shoreline distance (rockhead to intermediate)	Maximum shoreline distance (intermediate to bathymetry)	Maximum shoreline distance (rockhead to bathymetry)	Minimum shoreline distance (rockhead to intermediate)	Minimum shoreline distance (intermediate to bathymetry)	Minimum shoreline distance (rockhead to bathymetry)
-45	1.4 km	1.2 km	2.6 km	-	-	< 0.1km
-35	18.2 km	18.2 km	36.4 km	-	-	< 0.1km
-25	1.1 km	3.4 km	4.5 km	-	-	< 0.1km

Table 12: Shoreline differences in metres between three topographic time horizons (bathymetry, bedrock and a mid-point surface) for the Wight region. MSL has been nominally dropped by -25 m, -35 m and – 45 m respectively.

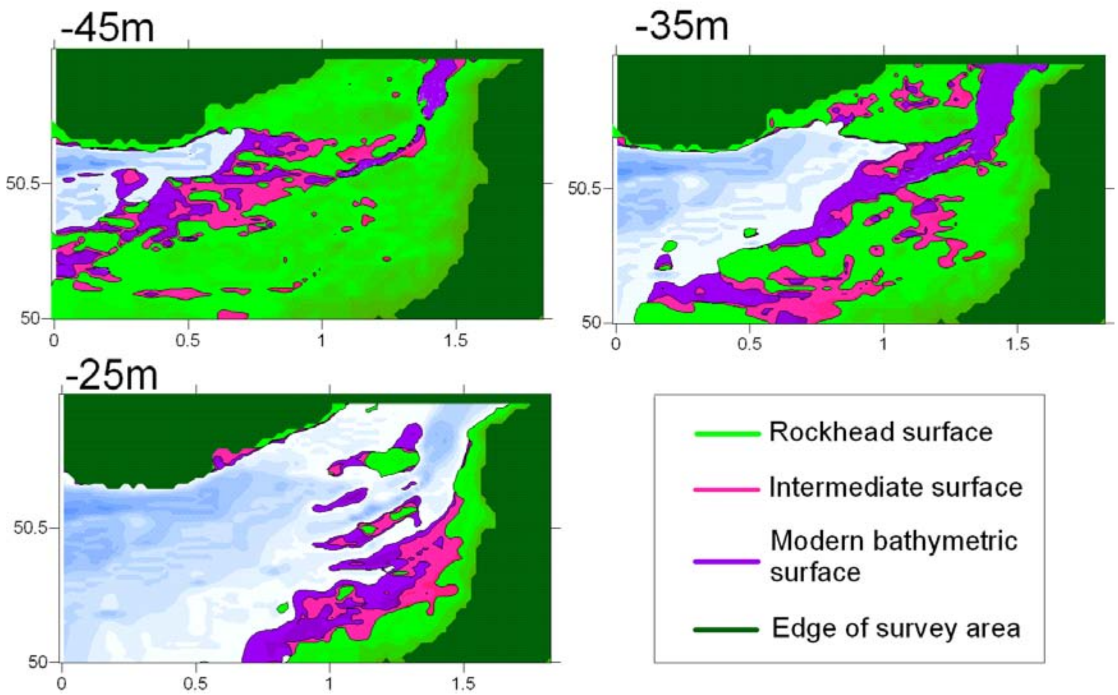


Figure 62. Overlaid shorelines produced by different bathymetric surfaces for the Dungeness region. The edge of the survey area indicates the limit of the known rockhead contours, and hence for this exercise the limits of the data and represents the present shoreline.

Depth (mbsl)	Maximum shoreline distance (rockhead to intermediate)	Maximum shoreline distance (intermediate to bathymetry)	Maximum shoreline distance (rockhead to bathymetry)	Minimum shoreline distance (rockhead to intermediate)	Minimum shoreline distance (intermediate to bathymetry)	Minimum shoreline distance (rockhead to bathymetry)
-45	19.6 km	20 km	39.6 km	0.1 km	-	0.1km
-35	37.2 km	25.9 km	63.1 km	-	-	< 0.1km
-25	13.4 km	17.9 km	31.3 km	-	-	< 0.1km

Table 13: Shoreline differences in metres between three topographic time horizons (bathymetry, bedrock and a mid-point surface) for the Dungeness region. MSL has been nominally dropped by -25 m, -35 m and – 45 m respectively.

It is clear from the figures that shoreline configurations can vary radically (e.g. Dungeness) or relatively little (e.g. Wight). Maximum and minimum shoreline position differences ranged from over 60 km to less than 100 metres. In fact, in most instances the minimum distances were so small as to be almost negligible given the scale of the area, in these instances they were assumed to be less than 100m as the scale does not really permit any measurements smaller than this. The implications of these differences are most marked in the -35 m metre comparison for the Dungeness area where we have connectivity between the current European mainland and Britain if the modern bathymetry is used whereas the island status of Britain occurs for both the intermediate and the rockhead horizons.

2.6 Discussion

The creation and analysis of these maps raises a number of relevant issues.

- Significant variability in shoreline position can result even when the difference between two curves, or the error margins within a curve appears small (e.g. several metres). The effect of this largely depends on the gradient of the surface being transgressed. On a continental scale, the variations do not appear particularly significant. However, if the actual differences in shoreline position are quantified, they can range from 1 to over 100 km. In terms of the discussion of large-scale migration or habitation patterns, or indeed creating a reasonably accurate sense of palaeo-geographic space, this magnitude of error is not particularly significant. Conversely, if these reconstructions are used for potential site prospection, these reconstructions are simply not accurate enough.

- A great deal of variability can result from the use of different curves, or data obtained from different sources as demonstrated by the comparison of GIA model, local relative sea level curves and global glacio-eustatic curves. A greater and more widespread understanding of the advantages and disadvantages of each particular type of sea level data is necessary.

- Error margins tend to increase the further back in time one goes. Note the comparison of shoreline differences in section 2.5.5.2. While the +/- 2.5 m error margin of Bard et al (1990) resulted in differences of up to 120 km, those of Rohling (up to 30m error) could create differences that were almost four times as great. Even the highest resolution pre-LGM glacio-eustatic curve currently available (Siddall, 2003) has a +/- 12m error margin. The implications of this are that for the earlier periods of prehistory, shoreline reconstruction are likely to be less accurate and rather more difficult than the later periods. Most of the error margins of this magnitude can be glossed over when discussing large scale issues, though some of the more extreme results should be taken into consideration.

- The use of lower resolution data can lead to significant differences in shoreline configuration and position. Researchers should bear this in mind and use data of appropriate resolution to their work. Ideally the data of the highest resolution should be used. If this is not available, then lower resolution data can be used, but only if its limitations and applicability are taken into account. ETOPO-2 and ETOPO-5 data, for example is far too coarse to examining anything smaller than a global or regional scale (i.e. tens of kilometres or more). It should also be remembered that that data on a single map may have been drawn at several different scales, and researchers should take this into account when using it.

- Regional relative sea level curves and GIA models provide the closest approximations to the situation in the past. However, they too suffer from their own limitations such as a limited range prior to the LGM (GIA models and regional curves) and poor large scale coverage (regional curves).

- Even in regions regarded as tectonically stable such as southern England, very slow long term trends of uplift and subsidence can create major differences in palaeo-shoreline reconstruction depending on whether these are taken into account. Although their effects are relatively small for more recent periods, they are more significant the further back one goes in the past. Accounting for them is therefore very important when considering the development of palaeo-geography on scales of hundreds of thousands of years.

- Although modern bathymetry can correlate to surfaces relating to earlier periods, in many instance there may be a significant difference (up to c. > 20 m) between them. This can lead to inaccurate representations of shoreline positions (up to 60 km difference) and past topography can be markedly mis-interpreted. The bedrock horizon represents a minimum value that could be used in reconstruction. However, modern bathymetry does not represent a maximum value as processes of erosion may have reduced its height over time.

Most of these above issues are rarely questioned when reconstructions of past landscapes are made. Maps tend to be created and presented as faithful representations despite the fact that the complexities of palaeo-geographic change have been glossed over, and assumptions have been made about the nature of the input data. The result is that reconstructions often depart significantly from each other (Section 2.1).

This is not entirely the fault of their authors. In many instances there is often no alternative but to use certain types of data, such as glacio-eustatic curves, in the absence of other categories of evidence. This is not to say that all previous work should be discarded, and regarded as a totally unrepresentative image of the past. Rather, by developing some measure of recognition of the error margins involved in existing representations their use can still be a worthwhile exercise.

Future work should also consider the nature of the input data before simply applying sea level data uncritically. For instance, GIA models have become increasingly popular in recent years (e.g. Coles, 1998; Flemming, 2002), but rather than simply adopting them wholesale, it is essential that the issues surrounding them are known, such as, whether they apply in all instances (e.g. McCabe, 1997), or whether the ANU models are more accurate than the University of Toronto’s (Lambeck et al, 2003) or vice versa. In addition, these reconstructions are only available for regions that have been studied by the GIA modellers. Constructing such models independently tends to be beyond the resources of most archaeological organisations.

In any case, improving existing reconstructions of submerged landscapes is essential if archaeologists wish to take their study to the next level - that of actually locating and excavating evidence from the sea bed. Given the expensive and time consuming nature of underwater survey, an accurate picture of the past landscape and possibly the location of probable sites will be necessary, to make the prospect of systematic underwater work a reality. The study of these areas on a smaller scale (i.e. not simply looking at broad processes of colonization or migration) will also require a far more detailed knowledge of the landscape than is currently available. This may in turn require detailed information on local sea level changes and accompanying landscape evolution. This will be discussed further in Section 4, while the above proposals will be reviewed at the end of the entire document, and modified if necessary on the basis of the results of the following Themes.

3. Theme 2: The Nature of the Pre-submergence Archaeological Deposits

3.1 Introduction

3.1.1 Rationale

Having examined issues of the palaeo-geographic contexts that past hominids may have occupied, attention must now be turned to the nature of the evidence they left behind. As relatively few sites (when compared to the terrestrial record) are known from the Northwest European continental shelf (see Section 3.6), it will be necessary to extend the known terrestrial record offshore to provide some idea of the nature of the submerged archaeology. The use of terrestrial evidence as an analogue for the underwater deposits is not a new idea; note for instance Coles's (1998; 2000) speculative reconstructions of 'Doggerland' (the exposed North Sea basin), which were based on terrestrial material from Britain and continental Europe. This method is justified on the basis of similarities in material culture, and moreover broadly contemporaneous shifts in material culture, on both sides of the North Sea and English Channel regions (Coles, 1998; 2000, Housley et al, 1997; White & Schreve, 2000). These similarities are observable from the earliest periods of prehistory, for instance the presence of the Lower Palaeolithic 'Clactonian' and 'Acheulean' toolkits in Britain and Germany, and Britain and France, respectively, through to the latest periods; note for example the presence of early Mesolithic Maglemosian tool forms in both Britain and Scandinavia (Coles, 1998; Mithen, 1999; White & Schreve, 2000).

This therefore implies a network of contacts, either in the form of the movement of people, or the transmission of ideas across the presently submerged regions. The existence of these contacts at times in which relative sea levels were low in turn argues for the occupation and exploitation of these regions by the groups creating the archaeological record in continental Europe and the British Isles.

This section will therefore review both the known terrestrial and submerged records of Northwest Europe. Particular topics to be focused on consist of the following:

- The location of the archaeological deposits
- The composition of the archaeological deposits
- The state of the archaeological deposits
- The information regarding past societies that can be obtained from the archaeological material

An overview of these issues will provide an indication of the archaeological potential of the existing terrestrial record, and hence go some way towards highlighting the potential of the submerged evidence. Each of these topics will now be discussed briefly in turn.

3.1.2 The location of the archaeological deposits

A secure understanding of the relationship between topography, ecology, geography and the archaeological material is essential if predictive models of site location are to be constructed. This is necessitated by the fact that predictive modelling is based on the principle that sites tend to recur in environmental settings favourable to human occupation and use (Brandt et al, 1992; Wescott & Brandon, 2000). Knowledge of terrestrial patterns of site location could be applied to the seabed, assuming of course that the submerged palaeo-land surface can be reconstructed, and that the hominids, which occupied the presently submerged area, followed similar settlement patterns to their terrestrial counterparts.

In addition it must be remembered that the environmental setting of a site may also have an influence on the sorts of post-deposition taphonomic processes that will operate on the archaeological material. For instance, it might be expected that many sites will be found in river valleys, as the presence of fresh water would have made them attractive for human settlement. However, concentrations of artefacts in river valleys may also be the result of their incorporation into river gravel terraces by natural processes of fluvial erosion and deposition (Wymer, 1992).

Finally, distributions of archaeological sites may also be the result of patterns of archaeological research (Rigaud & Simek, 1987), industrial work, such as gravel extraction (Hosfield, 1999) and or the activities of avid collectors of artefacts (Ashton & Lewis 2002). Hosfield (1999), for instance, has correlated the existence of dense findspots of Lower Palaeolithic material with areas of extensive aggregates extraction in the Hampshire basin.

This review will therefore highlight any patterns that are immediately apparent from a broad scale overview of the available literature. The potential of these patterns for use in predictive modelling will be examined as part of Section 5.

3.1.3 The composition of the archaeological deposits

Certain classes of archaeological material have the ability to shed light on different aspects of the societies under study. Tools for instance may provide information as to technical abilities, or subsistence practices, while art or ornamental objects can serve to illuminate aspects of social life. For example, the discovery of spears from a number of Lower and Middle Palaeolithic contexts, such as Clacton and Lehringen help substantiate the view that these hominids were hunters rather than scavengers (Mellars, 1996).

This review will therefore look at the available terrestrial material to identify the kind of evidence that is likely to be encountered on or under the seabed. However, it must be remembered that underwater preservational conditions are different to those on land, and consequently the composition of underwater deposits may not be analogous to those found on dry land.

3.1.4 The state of the archaeological deposits

In this instance the state of a deposit can be taken to mean the degree of post depositional reworking it has suffered. The importance of this lies in the fact that the state of an archaeological deposit has a bearing on its interpretative value and hence, archaeological potential.

Studies of taphonomic processes (e.g. Schiffer, 1983; 1987) have highlighted the fact that deposits of material culture rarely survive intact or maintain their spatial integrity over the millennia between deposition and discovery. With respect to the study of submerged landscapes it is worth considering the various categories of evidence that may be encountered on the continental shelves. This arises from the fact that any submerged material may have been disturbed or altered by marine as well as terrestrial site formation processes.

For the purposes of classification, the following definitions will be used in this paper:

- Primary context sites are assemblages in which the artefacts are still located on the past land surface (be it currently buried or exposed) on which they were deposited. This does not mean to say that the artefacts are exactly at their point of deposition, merely that the overall artefact movement caused by intervening taphonomic processes is small on a regional (i.e. beyond the confines of an individual site) scale (Schiffer, 1987). Since the spatial relationships between artefacts will not have been altered to a significant degree, the best examples of these contexts have the potential to provide 'snapshots', or very finely detailed images, of past behaviour (Gamble, 1999). This allows detailed interpretations of tool manufacturing techniques, subsistence behaviour, settlement strategies and social lives to be made. These sites will be discussed in section 3.3.

- Secondary context sites are those in which artefacts have been derived or moved from their original point of deposition by environmental processes (Hosfield, 1999; Schiffer, 1987). To quote Gamble (1999:114):

"at best they are findspots with differing numbers of items which were gathered from a number of old land-surfaces, at different times and from a range of distances."

With respect to the archaeological deposits under study, the most widespread form of secondary context consists of artefact bearing fluvial sediments typically associated with terrace landforms. These form as a result of the lateral movement and downcutting of rivers over the course of a glacial/interglacial cycle (Bridgland et al, 1995). Secondary contexts may also form as a result of other geological processes, such as permafrost action, glacial movement and solifluction. For example, as glaciers move across a land surface, they pick up and incorporate large bodies of sediment. As they retreat this material is redeposited in the form of moraines. Any archaeological material within these sediment bodies will therefore be removed from its point of origin and can potentially be deposited hundreds of kilometres away (Schiffer, 1987). Marine syn- and post-transgressive processes also have the potential to turn primary context sites into secondary context assemblages.

This review will focus primarily on fluvial sediments, as these are the most prevalent form of secondary context in early prehistory, but will touch briefly on other secondary contexts formed by marine processes.

"more Palaeoliths are found on the deposits underlying river terraces than any other context. For the most part, they are not in primary context, but derived from river beaches, old land surfaces and even earlier reworked terrace deposits" (Wymer, 1999:21)

Evidence from secondary context terrace sediments is both spatially and temporally coarse in that the artefacts within a given river system may represent a sample derived from an area of several tens or hundreds of square kilometres, over a period of up to tens of thousands of years. While these were once regarded simply as providing a source of artefacts for typological comparison and also providing broad indications of hominid presence or absence, recent work (e.g. Hosfield, 1999; 2001, 2004; Ashton & Lewis, 2002) has demonstrated that they have the potential to provide information as to long term patterns of hominid demography and land use. Ashton and Lewis (2002) in particular have used evidence from the terraces of the Middle Thames Valley to demonstrate that British hominid populations appeared to decline from OIS (Oxygen Isotope Stage) 10 onwards with a possible absence from OIS 6 till OIS 4 (see Figure 64 for chronological subdivisions). These sites will be discussed in section 3.4.

- With respect to the investigation of submerged landscapes, it is worth considering a third category – ‘tertiary contexts’ (Figure 63). These represent terrestrially formed secondary contexts assemblages that have been modified as a result of either syn- or post-transgressive processes. Essentially, the processes that accompany, and follow, marine transgressions, may further rework assemblages that are already in secondary context, such as fluvial terraces. This is a new classification formulated on the basis that much of the early prehistoric record is composed of terrestrially formed secondary context sites (Wymer, 1999), and consequently, the submerged archaeological record may contain a large number of these deposits, a significant proportion of which may have undergone reworking during, and after transgression. The fact that multiple marine transgressions and regression have taken place over the Pleistocene (Chappell & Shackleton, 1986; Rohling, 1998) serves to highlight the fact that presently submerged archaeological deposits may have undergone significant reworking. These contexts have yet to be studied in any detail and their archaeological potential remains to be determined. These will be discussed in section 3.5.

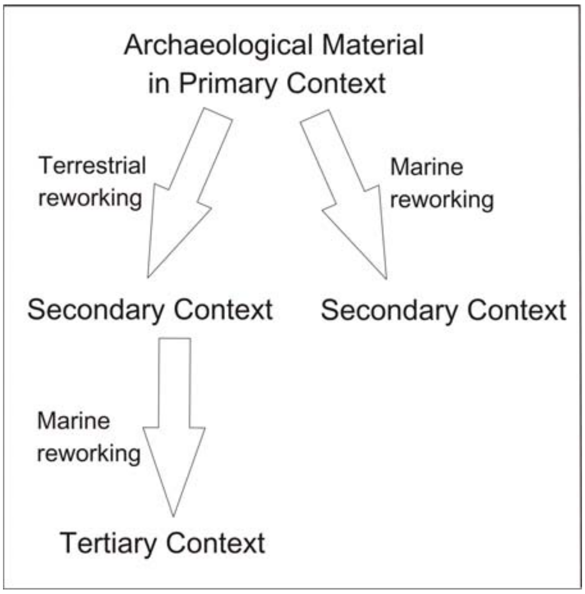


Figure 63. Diagram illustrating the progression from primary to secondary to tertiary context that will be adopted in this document. The term ‘marine reworking’ encompasses both syn- and post-transgressive processes.

3.1.5 Interpretation of the archaeological material

Assessing the archaeological potential of continental shelves will involve an understanding of what the relevant material can reveal about past societies. To this end, this review will highlight the existing interpretations that have arisen out of decades of studying the terrestrial (see section 3.2 to 3.4), and to some extent the submerged records (see section 3.6) of North West Europe. Where possible, it will also draw attention to questions and areas that could be investigated by evidence from submerged contexts. This is particularly relevant given that submerged contexts could potentially provide both additional, and totally new, evidence, compared to what is currently found in terrestrial contexts. This arises from the fact that submerged landscapes are likely to contain two broad categories of evidence:

- Sites that are direct analogues to those of the same period that are currently found in terrestrial contexts. These represent inland use of the landscape before it was submerged.
- Sites located on, or near, a coastline for the purposes of occupation or interaction with, or exploitation of the maritime environment. The submergence of Palaeolithic coastlines means that barring occasional exceptions, these sites have no direct contemporary analogues in the terrestrial contexts investigated today.

Particular research questions relevant to submerged landscapes therefore include the timing and nature of inland and coastal migration routes, the antiquity and nature of marine exploitation and the role of these presently submerged regions within the wider geographical context of the past landscape (Coles, 1998; Flemming, 1998; Erlandson, 2001).

3.1.6 Chronological focus

In this review, for the purposes of analysis, the archaeological record will be broken down chronologically as follows (see Figure 64):

- Lower Palaeolithic – 500 to 300 ka BP
- Middle Palaeolithic – 300 to 40 ka BP
- Upper Palaeolithic – 40 to 10 ka BP
- Mesolithic – 11 to 5 ka BP

All dates will be expressed in calendar years unless explicitly stated.

The divisions have been made on the basis of the following:

- Archaeological evidence strongly suggests that the large-scale occupation of North West Europe did not occur until OIS 13 (528 - 478 ka BP) though brief ephemeral ‘pioneer’ incursions may have been made before this point in time (Roebroeks & Van Kolfschoten, 1994; 1995).
- The archaeological record of lithic tool types retains remarkable unity and stability across Europe until the emergence of the prepared core, or Levallois, technique of tool manufacture in OIS 8 (301 - 242 ka BP). In addition, the period from c.300 ka on sees the appearance of ‘proto-Neanderthal’ traits in the hominid population of Europe. The conventional beginning of the Middle Palaeolithic is therefore usually given as sometime between 250 (Mellars, 1996) and 300 ka BP(Gamble & Roebroeks, 1999). In this review the earlier date will be adopted.
- Around 40 ka BP, anatomically modern humans and their associated material culture appear in the European archaeological record. This marks a significant change in terms of both material culture and hominid behaviour (Klein, 1999).
- The start of the Mesolithic is traditionally associated with the Pleistocene-Holocene transition (c. 11 ka BP in calendar years, but 10 ka BP in radiocarbon years) and its end with the ‘Neolithic revolution’ and the replacement of the

hunter-gatherer way of life by settled agriculture (c.6 to 5 ka BP in North West Europe) (Champion et al, 1984; Mithen, 1999).

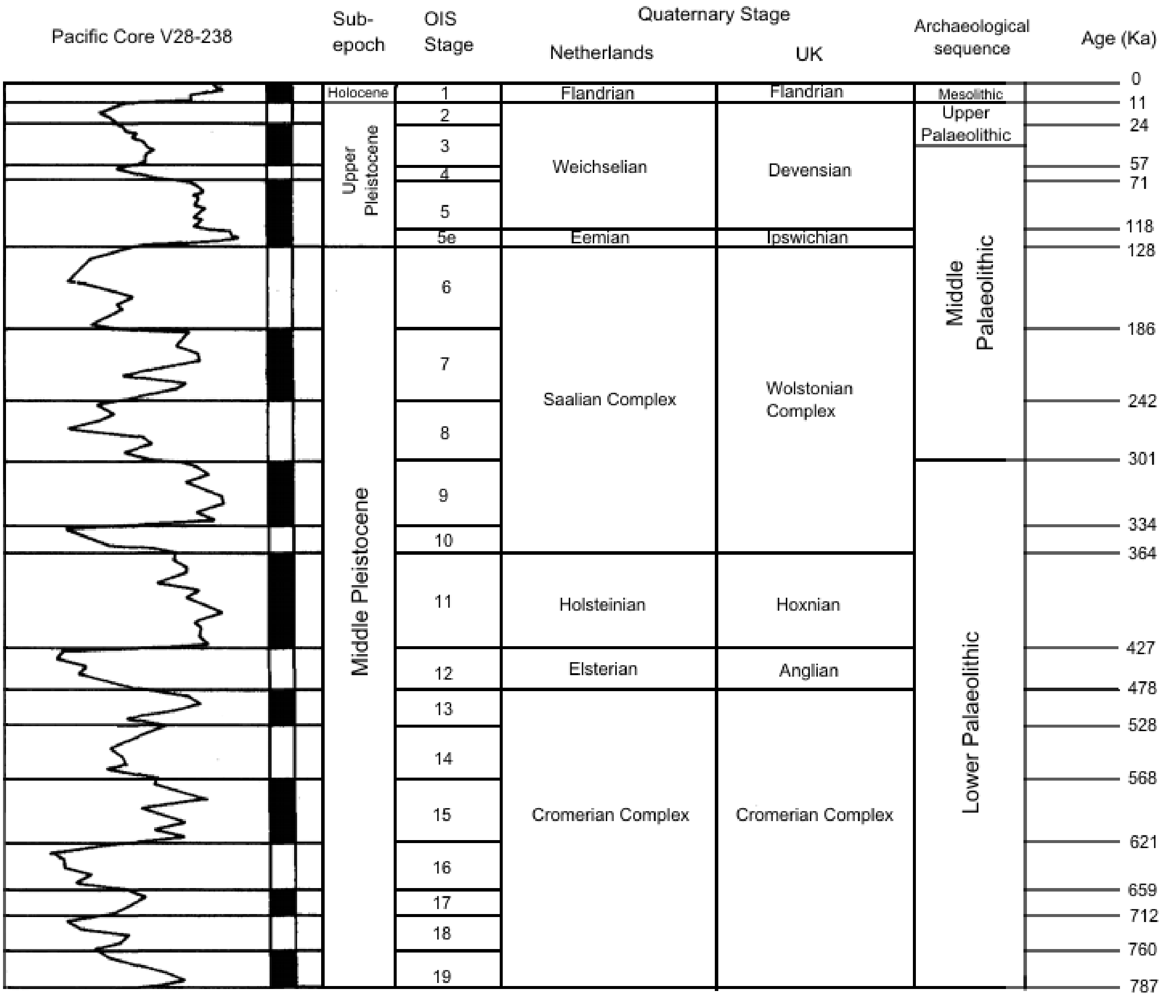


Figure 64. Chronological overview. Dark band represent warm stages, white bands represent cold stages (after Gamble, 1999; Roberts & Parfitt, 1999; Wymer, 1999)

3.1.7 Spatial focus

The archaeological records of the following countries will be examined: Great Britain, France, Holland, Belgium, Germany, Denmark, Norway, and Sweden. The choice has been made on the basis that they surround the submerged landscapes in question (the English Channel and North Sea) and thus there is a high probability that the underwater archaeological evidence will be similar to that from the aforementioned terrestrial regions.

3.2 Environmental Background

3.2.1 Overview

The long-term and large-scale environmental backdrop to these periods is provided by the alternation of global climate between glacial and interglacial phases initiated by variations in the Earth’s orbit, rate of rotation and axial tilt (the Milankovitch cycle: Zachos et al, 2001).

Glacial stages are characterised by decreased temperatures, the growth of ice sheets, and decreases in global ocean volume resulting in changes in palaeo-coastline configuration (see Section 2 for full discussion of sea level change). Three major glacial phases affecting North West Europe have been identified which fall within the relevant chronological period; the Anglian/Elsterian, the Wolstonian/Saalian and the Devensian/Weichsalian (Figure 64: Woodcock, 2000). Of these, the most extensive ice cover occurred in the Anglian, extending in the south as far as the Celtic Sea, the Thames and the Severn estuary, and linking up with the Scandinavian ice sheet across the southern and central North Sea (Gibbard, 1988; Huuse & Lykke-Andersen, 2000; Woodcock, 2000). The Wolstonian ice sheet is somewhat more difficult to trace, though it likely did not extend further south than the Anglian one. The presence of pre-Devensian glacial till overlying Hoxnian deposits in the central North Sea does indicate an offshore extension of this sheet, and it too probably connected to the Scandinavian ice sheet (Gibbard, 1988). Furthermore, extensive erosional surfaces in the North Sea have been attributed to action of these ice sheets (Woodcock, 2000). The Devensian sheet is somewhat smaller than its earlier counterparts, extending only as far south as southern Ireland and Wales, with a tongue of ice extending down from North East England into the North Sea off East Anglia (Figure 65). Some debate exists over whether it connected with its Scandinavian counterparts across the North Sea, with a number of researchers inferring a connection across the northern North Sea on the basis of subglacial valleys believed to date to this time (e.g. Ehlers & Wingfield, 1991; Sejrup et al, 1998), while others see the lack of glacial sediments in this area as proof that a connection did not exist at the LGM (e.g. Long et al, 1986; Huuse & Lykke-Andersen, 2000). Recent geochronologic dating however, suggests that there was no connection across the North Sea during the LGM, but a connection may existed prior to earlier in the Weichsalian, possibly around 40 ka (Bowen et al, 2002).

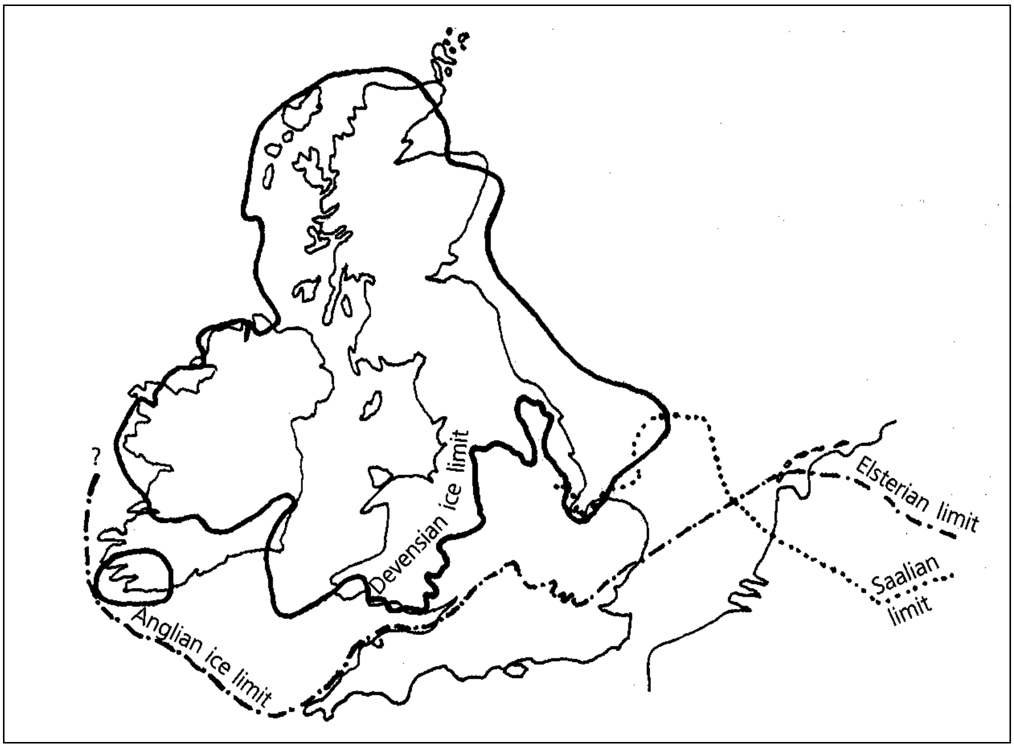


Figure 65. Approximate maximum ice limits of the Anglian and Wolstonian ice limits, and the LGM Devensian ice limits in relation to present day British shorelines. A connection between the British and Scandinavian ice sheets across the northern North Sea probably existed earlier in the Devensian (modified from Woodcock, 2000).

In terms of ecology, in North West Europe, this led to a reduction in tree cover and the replacement of woodland by open environments such as steppe tundra. The reverse is true of interglacial cycles – temperatures increased; ice sheets melted, eustatic sea levels rose and trees replaced the open steppic environments (Bell & Walker, 1992). On a smaller scale (i.e. tens to hundreds of kilometres) there will have been regional variations with respect to the composition and distribution of the flora and fauna, seasonality, temperature ranges and precipitation. Note for instance the argument that south-west France provided a 'glacial refugia' for both animals and humans during the Last Glacial Maximum (LGM) due to its greater productivity, reduced seasonality and higher temperatures compared to the more northerly areas of the continent (Housley et al, 1997; Jochim, 1987).

In addition, climatic amelioration along a west-east axis has also been suggested (Vandenberghe et al, 1998; Gamble, 1999). This amelioration takes the form of reduced seasonality and sometimes, increased precipitation in areas in the vicinity of the oceans. This 'maritime' climate results from the greater specific heat capacity of the oceans compared to the land. Water takes on, and gives up, heat slower than the land. For instance, in the continental interior heat taken on in the summer is quickly lost during the winter. Consequently, due to this moderating influence, areas in proximity to the coast have warmer winters and cooler summers than those located in the continental interior (Goudie, 2001). For example, at 13 to 12.5 (C^{14}) ka BPa difference of 7°C in the mean temperature of the warmest month between southern England and southern Sweden has been interpreted as the moderating of the cooling effect of the Scandinavian ice sheet by warm North Atlantic surface water

(Vandenberghe et al, 1998). It should be noted though that this ameliorating effect can be 'turned off' in exceptional circumstances. During the Younger Dryas (11 – 10 (C^{14}) ka BP), extended winter sea ice cover in the North Atlantic in conjunction with onshore westerly winds resulted in influxes of cold dry air to coastal areas resulting in a modification of the ameliorating trend to the point where even coastal areas such as Ireland exhibited annual temperature ranges of 30 to 34°C, a value that is normally associated with a continental climatic signature, and one that was comparable to contemporary values for areas in the continental interior, such as Poland. As a point of comparison, the present day annual temperature range for Ireland is between 9 and 11°C (Isarin et al, 1998).

The Younger Dryas cold phase also provides an example of the short term climatic fluctuations that exist within the long term glacial/interglacial cycles. Ice cores from Greenland suggest the majority of its transition to the Holocene warm phase took place at around 11.7 ka BP, when annual surface temperatures increased by as much as 5 to 10°C within the space of 20 years (Taylor et al, 1997; Taylor, 1999). In fact these short-term high amplitude fluctuations occurred regularly over the past hundred thousand years, resulting in temperature changes of up to 7°C above the intervening cold spells (Figure 66). These third order Dansgaard/Oeschger (D/O) oscillations were in turn superimposed on top of a second order cycle of interstadials (warm phases) and stadials (cold phases), each of which could potentially last several thousand years (Van Andel, 2003). These events were in turn nested within the first order sequence of glacial/interglacial cycles.

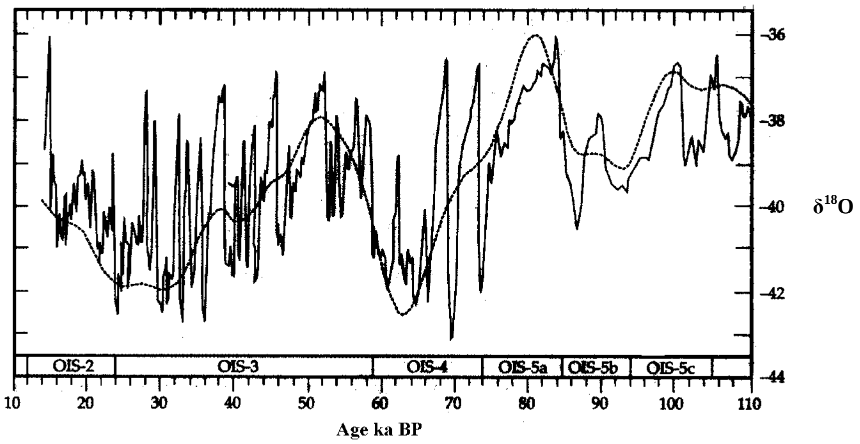


Figure 66. High-frequency high amplitude climate changes occurring over the past 100,000 years as inferred from Greenland ice cores. The smooth curve depicts the general climatic trend, while the jagged profile depicts the changes in δ^{18}O recorded in the ice. Greater values of δ^{18}O indicate cold stages (after Van Andel, 2003).

3.2.2 Implications for submerged landscape research

Glaciation provides a limiting or boundary variable to consider when assessing areas that might contain archaeological material. In effect, areas covered by glaciers will be uninhabitable and thus contain little or no archaeological material. Furthermore, any artefacts deposited prior to glaciation are likely to have been destroyed or intensively damaged by the ice advance, while sites will be converted from primary to secondary contexts (Flemming, 2002). Indeed the extent of reworking it such that Gibbard (1988) has described it as 'total landscape remodelling'. Therefore, looking at the available data on glacial limits and shoreline positions, submerged landscapes of varying archaeological potential in the study area can be defined. These are as follows:

- The coast of Scotland. Due to isostatic uplift, any areas occupied by humans since the retreat of the ice sheets will have been elevated beyond mean sea level rather than being submerged. In addition, there is no evidence for a pre-Holocene occupation of Scotland.
- The North Sea. Any material dating from prior to the LGM may well have been disturbed or destroyed by the impact of the Anglian, Wolstonian and Devensian ice sheets, except in the most southerly parts of the area (the Southern Bight). These sheets will also have rendered this area uninhabitable for long periods of time. Hence the majority of material found here is likely to date to the Late Pleistocene and Holocene after the ice sheets had retreated.
- The English Channel. This area is free of glacial action and hence may have been occupied during glacial periods. In addition its archaeological deposits will not have been directly affected by destructive glacial processes.

A further aspect to consider is the impact of shorter term events such as interstadials, stadials and D/O events on sea level change, and palaeo-coastline position. While they are known to have an impact on the magnitude and extent of ice sheets (Van Andel, 2003), their effect on shoreline position has not been addressed to a significant extent. The latest glacio-eustatic curves (Siddall et al, 2003) do provide a high resolution picture of rapid global fluctuations in sea level, but these have yet to be correlated with specific climatic events. However, the isostatic effects of these short term fluctuations have not been considered in great detail. The implications of this are that snapshot reconstructions of shoreline position similar to those presented in Section 2 represented only a partial representation of the total situation, in that between each snapshot, rapid sea level fluctuations of several meters could have changed the coastline configuration by as much as several tens of kilometres.

3.3 Archaeological Material in Primary Context

3.3.1 Background

As stated in section 3.1.4 assemblages in primary context are those in which the archaeological material has not been modified or disturbed to any significant extent by post-depositional taphonomic processes. With respect to the periods in question a useful test of this is whether the lithic material can be refitted, assuming that knapping took place on site (Figure 67: Gamble, 1986; Schick, 1986).

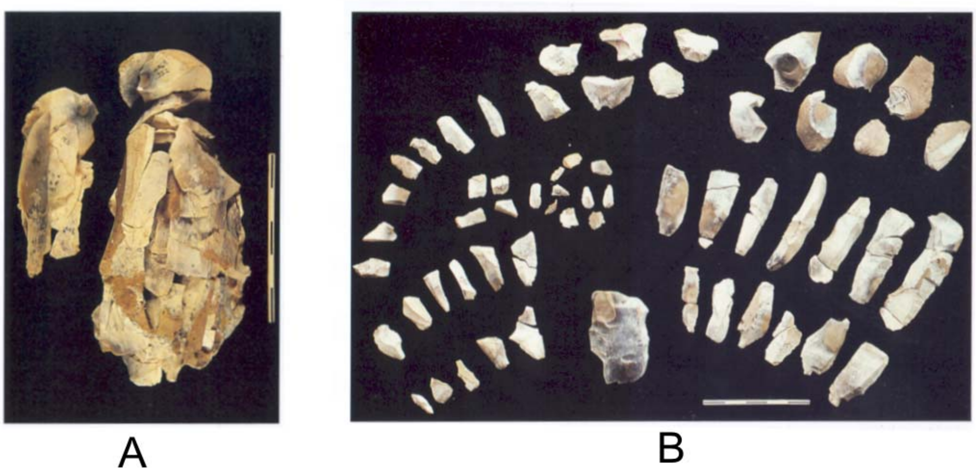


Figure 67. A) Refitted Upper Palaeolithic blade core. B) Exploded view of the same core showing the original core and detached flakes and blades. Refitting represents a useful way of ascertaining if a site is in primary context (after Barton, 1997)

Archaeological evidence from primary contexts from the Lower Palaeolithic to the Mesolithic consists primarily of some, or all, of the following (Wymer, 1976, 1982; Gamble, 1986, 1999; Champion et al, 1994; Klein, 1999):

- Stone tools and débitage.
- Bone tools and other worked items.
- Unmodified or cut-marked bone, both hominid and animal.
- In exceptional circumstances (e.g. waterlogging), other organic material, such as wood, may be preserved.
- Art. This consists of parietal (wall) art and also mobile decorated or ornamental objects. It is restricted to the Upper Palaeolithic and Mesolithic.
- Structures. Evidence consists either of postholes or the foundations of the structure in question.
- Hearths.

The importance of primary context evidence is that it provides a fine-grained picture of past lifeways, hence the frequent use of the terms ‘snapshot’ or ’15 minute episode’ (e.g. Gamble, 1999) when describing exceptionally preserved examples of these contexts. In reality, the time span of the depositional processes may range from a matter of minutes to a period of months or years. Therefore, while a primary context site may be spatially coherent, it must be remembered that it could represent something of a temporal palimpsest. For instance, where detailed dating, or stratigraphic separation is not available, a large dense accumulation of archaeological material could represent a single long term occupation, or the abandonment and reuse of the site over a longer period of time.

Primary context sites are also important in that in some cases biological evidence such as pollen, molluscs, insects and small vertebrates may be preserved. These provide material that can often be dated and provides information on the palaeo-environment (Wymer, 1976).

Individual primary context sites can potentially provide great detail on technology, subsistence patterns and social organisation within the context of a particular group at particular place and time. For example, an examination of the relative frequencies of certain artefact forms (assuming their functions are known) could allow interpretations to be made as to whether a particular locale had functional or social significance within the wider landscape. However the elucidation of broader temporal and spatial patterns requires these sites to be looked at in conjunction with evidence from other primary contexts and also the available secondary context evidence. Specific examples of primary context sites and their interpretation will be discussed in the following sections.

3.3.2 The Lower Palaeolithic

3.3.2.1 Hominid species

Fossils from the Lower Palaeolithic tend to be attributed to *Homo heidelbergensis*; the generic term given to the early European populations (Klein, 1999; Lewin, 1999; Gamble, 1999). There is some debate over the use of the term *H. heidelbergensis* in that the specimens so far discovered exhibit varying degrees of similarity with preceding *Homo ergaster* and later *Homo neanderthalis* populations. Klein (1999) for instance makes use of the term 'early *H. neanderthalis*' in preference to *H. heidelbergensis*. In general though, *H. heidelbergensis* is primarily used as a chronological definition, in that it encompasses the various European specimens that date from the first large-scale occupation of Europe (c.500 ka BP) till the appearance of 'proto - Neanderthals' from about 300 ka onwards (Mellars, 1996).

Remains have been found at a number of sites including Boxgrove (Britain), Mauer and Bilzingsleben (both Germany) (Bosinski, 1995; Mania, 1995; Roberts et al, 1994).

3.3.2.2 Archaeological evidence

The most common form of evidence consists of scatters or concentrations of stone artefacts, débitage and faunal remains. Assemblages have often been classified on the basis of whether they contain the classic type fossil of the Lower Palaeolithic – the Acheulean hand axe (Figure 68). Assemblages without these tools have often been assigned to separate technological traditions, such as the Clactonian or proto-Mousterian (Klein, 1999). Evidence suggests that there is a continental divide running north-west to south-east roughly corresponding to the course of the Rhine, with handaxe bearing assemblages restricted to the southern and western regions, and non-handaxe assemblages restricted to northern and eastern areas (White, 2000; White & Schreve, 2000). Questions have arisen as to whether this is evidence of separate groups of hominids with different levels of social learning (e.g. Mithen, 1994), hominid planning behaviour (e.g. Wenban-Smith, 1998), a reflection of different activities (e.g. Ashton & McNabb, 1994) or a factor of local raw material availability (e.g. Ashton, 1998) (see White (2000) for an overview of this debate).

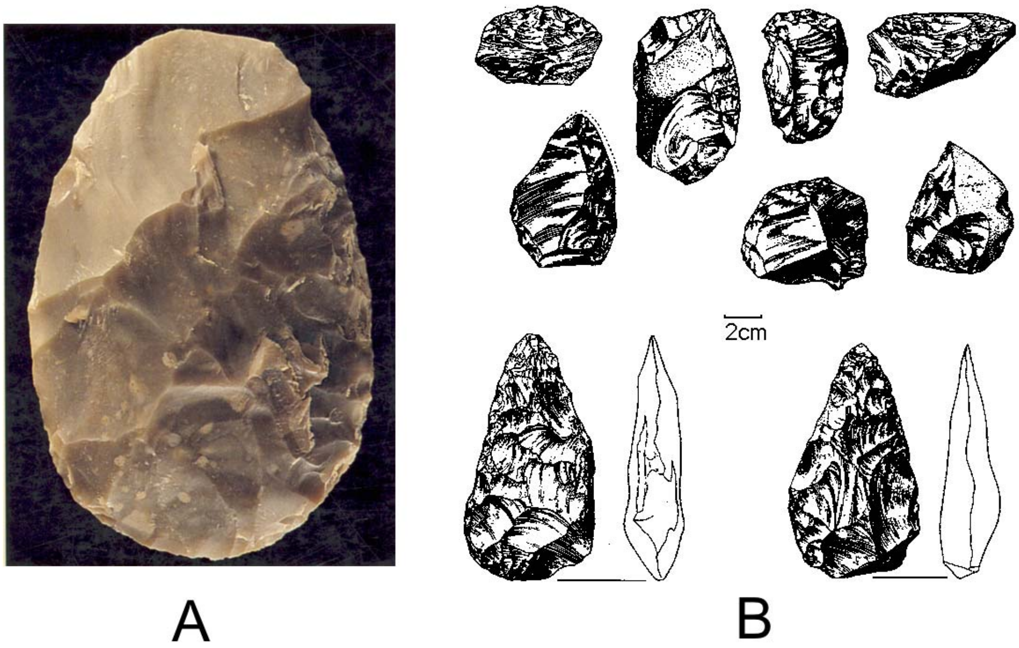


Figure 68. A) Ovate handaxes from the site of Boxgrove, southern England. B) Selection of Acheulean tools: scapers (top) and handaxes (bottom) (after Barton, 1997)

The dominance of stone artefacts in the archaeological record is as much a reflection of their durability as hominid raw material preferences. Artefacts made on other raw materials have been preserved in a number of instances. A number of rhino and elephant bones that have flaked in much the same way one would knapp a flint nodule were recovered from Bilzingsleben, while among the best known examples of preserved organic artefacts are the wooden spears from Clacton (Britain) and Schöningen (Germany: Figure 69 - Klein, 1999; Gamble, 1999). In terms of recovery, organic artefacts tend to be less common than in later periods.

Figure 69. 2.3m long spear from Schöningen, Germany. The preservation of wooden objects from this period is rare, except in exceptional circumstances, such as this (from Barton, 1997).

Organic evidence though is often preserved in the form of the remains of animals. If the environmental tolerances of the species in question are known, they can be used as proxy indicators of palaeoclimate and to some extent, chronology. For example, in Britain each of the four post-Anglian (OIS 12) interglacial stages, is characterised by its own distinctive mammalian faunal grouping. Stage 11, the first of these interglacials, for instance, is characterised by the presence of cave bear (*Ursus spelaeus*) and a large subspecies of fallow deer (*Dama dama clactoniana*). The presence of these species at the primary context sites of Hoxne and Swanscombe (both Britain) places them both within this interglacial (Schreve, 2001). These and other members of the faunal assemblage such as the rabbit, horse and pine vole, also indicate that conditions were as warm as today's during this period. In addition, at Swanscombe, changes in the faunal assemblage over time can be observed, with numbers of woodland species such as *D. d. clactoniana* decreasing, and grassland taxa such as horse increasing. This implies an ecological shift within the interglacial from closed to more open environments (Schreve, 2001). Should these mammal remains bear cut marks or evidence of human modification, they can provide indications as to the subsistence patterns of these hominids.

Evidence for built structures in this period is somewhat equivocal. Several sites have concentrations of artefacts and other debris that could mark the position of huts or shelters. At Bilzingsleben for instance, three semi circular concentrations of travertine blocks and animal bones have interpreted as weights to hold down structures, possibly windbreaks or shelters of some sort (Mania, 1995). An alternative interpretation however, has suggested that these concentrations may in fact be the result of deposition of material around trees, rather than shelters (Gamble, 1999). This particular site will be discussed further in the next section.

3.3.2.3 Sites

A number of well-preserved sites in primary context do exist for this period. These can occur when low energy fluvial or lacustrine sediment are deposited over archaeological material. Examples of this include Miesenheim I (Germany) and Hoxne (Britain). The low energy nature of the process means that the artefacts maintain their spatial relationships, while the deposited sediment serves to protect the material from destructive taphonomic processes. Similarly, evidence can also be preserved in situ through burial by wind blown loess. Examples include the Karlich site in Germany and Cagny-la-Garenne in France (Wymer, 1976; Bosinski, 1995; Gamble, 1999). Three examples of primary context sites are listed below. They have been chosen on the basis that they illustrate the various settings in which exceptional preservation can occur.

- *Boxgrove (Britain) – Primary Context Coastal Site – OIS 13 – c. 500ka BP*

The site of Boxgrove in southern England represents an example of a coastal site in primary context. At present it is situated on a raised beach some 10km from the current shoreline. At the time of deposition of the main in situ assemblage, the surrounding environment would have consisted of lagoonal mudflats created by marine regression (Figure 70).

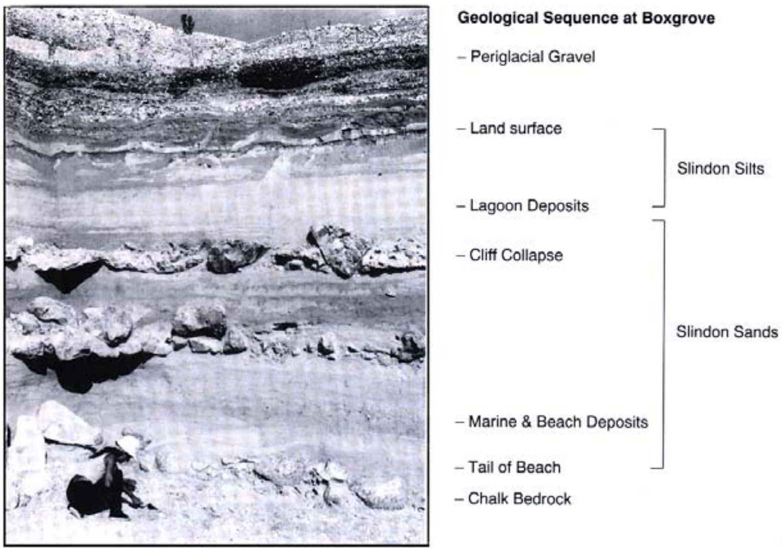


Figure 70. Stratigraphic section and geological sequence at Boxgrove. This highlights the coastal nature of the site (from Barton, 1997).

Earlier levels at the site do contain several flakes, handaxes and butchered bones that appear to have been discarded in what was then the intertidal zone. The site is located at the base of a chalk sea cliff, and consists of several discrete lithic and bone scatters, which imply on site flint knapping and animal butchery. The source of the flint appears to have been the aforementioned sea cliff. Refitting and use wear analysis point to the fact that handaxes were manufactured on site, used to butcher animal carcasses and then discarded. In addition to the animal remains, a *H. heidelbergensis* tibia and two teeth have been recovered. Although fish bones have been recovered from the site, it is not known if these were part of the hominid diet or introduced to the site by natural processes (Roberts et al, 1994; Stringer et al, 1998; Roberts & Parfitt, 1999).

- *Bilzingsleben (Germany) – Primary Context Terrestrial Site – OIS 11*

The site of Bilzingsleben (North Germany) was situated on the shore of a shallow lake. The remains of freshwater fish are present as are the remains of larger mammals. These have been attributed to the subsistence practices of the hominids occupying the site. Several concentrations of material have been interpreted as semi circular dwelling structures, each of which is associated with a hearth. Other concentrations of material have been interpreted as workshop areas with anvils of stone or bone. The lithic industry includes flake tools, choppers but no Acheulean handaxes. In addition to stone, wood and bone artefacts, the remains of three hominids are also present. This site has been interpreted as the home base for a group of these hominids for some time (Mania, 1995). An alternative interpretation however sees the site as the product of the reuse of this particular locale over many years and visits, possibly as a result of its affordances. According to this perspective, the anvils were the focus of social and technical activity, while the apparent ‘structures’ were the product of concentrations of material around trees. The site is thus seen more as series of gatherings rather than built campsite (Gamble, 1999). At present, the archaeological evidence does not support one argument over the other.

- *Hoxne (Britain) – Primary Context Terrestrial Site - OIS 9 or OIS 11*

  At the time of occupation the site was located on a lakeshore. This location resulted in the archaeological deposit being sealed in fine-grained lacustrine sediment which ensured its preservation in primary context. Dating of the site is somewhat uncertain, with thermoluminescence (TL) dating of burnt flint (298+/-16 ka BP and 330+/-27 ka BP), uranium series (U-Th) and electron spin resonance (ESR) (average of 319+/-38 ka BP) placing the archaeology in OIS 9, but biostratigraphical considerations suggesting a date of OIS 11. In terms of the archaeological material, handaxes and flakes have been found, as have the remains of various mammalian bones and teeth, some of which bear cut marks. Stone clusters and a stone 'emplacement' have been regarded by some as early evidence of built structures (Singer et al, 1993; Wymer, 1999).

The majority of the primary context archaeological evidence for the Lower Palaeolithic occupation of Europe is found near water sources, such as streams or lakeshores; examples include the aforementioned sites of Bilzingsleben, Hoxne, and others such as Swanscombe (Britain) and Miesenheim I (Germany) (Bosinski, 1995; Mania, 1995; Gamble, 1999).

"Open fluviolacustrine habitats with diverse and abundant resources were extensively targeted by Middle Pleistocene hominids." (White, 2000:49)

To some extent, this can be attributed to hominid choice. These areas would have been preferred due to the presence of fresh water, raw material (e.g. flint eroding out of river banks), and other animals. In addition, rivers may have facilitated movement around the landscape (Wymer, 1982, 1992, 1999). This preference is substantiated by its recurrence in similar patterns across the world. The Rift Valley of East Africa, for instance is home to a number of well known lakeside sites occupied by early hominids, such as Olduvai Gorge, Koobi Fora and the Turkana Basin sites (Wymer, 1976, 1982; Rogers et al, 1994; Klein, 1999). However, site formation processes are also likely to have played a part in creating this pattern, in that low energy fluvial or lacustrine sedimentation represents an ideal context for fine-grained preservation. Areas on the edges of abandoned channels or oxbow lakes are regarded as particularly amenable to preservation of primary context as they are still located on the floodplain, but far enough away from the main stream that they escape erosion at a later date (Wymer, 1992).

The vast majority of sites also appear to be located in the open air. Whether this is entirely the result of hominid preference is uncertain since it has been pointed out that most caves from this period have collapsed and their deposits eroded or scoured away (Wymer, 1982; Klein, 1999).

With the exception of Boxgrove, coastal sites in primary context are not known for North West Europe. Worldwide, a number of sites do exist which have been interpreted as possible examples of early coastal exploitation. The closest one to the study region is Terra Amata (c.300 to 250 ka BP), which is located on the French Mediterranean coast and which contains shellfish and fish remains in association with various lithic implements (Erlandson, 2001).

Although primary context sites do exist for the Lower Palaeolithic, they tend to be rather rare, especially when compared to the sheer quantity of archaeological material obtained from river gravel deposits. In Britain, there are only 11 primary context sites for this period compared to the several hundred derived assemblages. These 11 sites are Boxgrove, Clacton, Swanscombe, Hoxne, High Lodge, Stoke Newington, Barnham, Red Barns, South Woodford, Dartford Heath, West Stow (Wymer, 1992, 1999).

Indeed in Scandinavia, no primary context assemblages have been discovered though some evidence in secondary context has been attributed to this period. In this area the original sites are likely to have been disturbed by a combination of glacial movement, periglacial activity and fluvial processes (Hølm & Larsson, 1995).

3.3.2.4 Interpretation

Claims have been made for a hominid presence in North West Europe as early as 1 million years ago (Roebroeks & Van Kolfschoten, 1995; Klein, 1999). However, the bulk of sites dated to this period suffer from either a lack of hominid remains, the exception being Atapuerca TD6 (Spain), which is in any case outside the study area, or the possibility that the artefactural evidence may be the product of natural forces rather than hominid manufacture (Roebroeks & Van Kolfschoten, 1994; 1995).

The earliest undisputed evidence for a hominid occupation appears in OIS stage 13 (538-478 ka BP). Sites from this period are found in both primary and secondary contexts, while human remains and undisputable artefacts such as Acheulean handaxes are common. Earlier sites do occur sporadically in southern Europe, notably Atapuerca, Orce (both Spain) and Ceprano (Italy) which date to between 1 Myr and 700 ka BP. Overall the pattern seems to be one of restriction to warmer southern European climes with possible sporadic excursions north, until 500 ka when the large scale colonization of more northerly European latitudes (Gamble, 1999).

In terms of the occupation of the most northwesterly part of the continent (i.e. Britain) a pattern emerges after 500 ka. Clactonian, or assemblages without handaxes, appear in the initial stages of OIS 11(Hoxnian) and OIS 9 (Purfleet) interglacials before being replaced by Acheulean (handaxe bearing) assemblages, followed by a subsequent lack of archaeological material during the glacial maxima of OIS 10 and 8 (White & Schreve, 2000). White and Schreve (2000) have interpreted this patterning as the result of separate pulses of colonization following the abandonment of Britain during glacial maxima, with Clactonian populations arriving in Britain from northern and central Europe in the early parts of interglacials before being replaced by Acheulean populations from the south. Various explanations for this patterning have been proposed, notably the presence of physical, ecological or social barriers that allowed one population access to Britain before the other (White & Schreve, 2000). This scenario is plausible but not entirely certain, as various other arguments have also been proposed to explain the difference between the Clactonian and the Acheulean, notably Ashton’s (1998) suggestion that the presence or absence of handaxes reflects the suitability of local raw material and the particular focus of hominid activity.

It is likely that these hominids were hunters. Evidence for this comes in the form of the Clacton and Schoeningen spears and the presence of cut marks appearing on animal bones before the gnaw marks of non-human carnivores, thus implying the prey animal was initially killed and butchered by hominids (Roberts & Parfitt, 1999). In terms of function, use wear analysis has indicated that stone tools were used on a variety of raw material including bone, antler, meat, plant material and wood. One to one correlations between tool types and functions are still somewhat speculative though experiments have illustrated the usefulness of the handaxe as a butchery implement (Schick & Toth, 1993).

With respect to the occupation and exploitation of coastal and aquatic environments very little is known. A number of sites do contain the remains of fish and shellfish, though whether hominids or other animals brought these in has yet to be determined. The Boxgrove site is situated on a beach; however whether this was for a coastal or maritime reason, or simply that flint was easily obtainable from the cliff is uncertain. In general, primary context sites from this period have been able to shed light on hominid subsistence practices (e.g. via the cut marked bones from Boxgrove and Hoxne), their technical abilities (e.g. via the in situ flint scatters at Boxgrove) and also to some extent their planning aptitude and use of resources. For instance, the presence of discarded handaxes in mint condition at Boxgrove implies that their construction and use was something of an immediate term response to a need, in this case animal butchery, rather than them being curated tools that were transported about the landscape (White, 2000).

3.3.2.5 Implications for submerged landscape research

The undisputed presence of hominids in Britain as early as OIS 13 argues strongly for an occupation of the submerged landscapes in question, when they were exposed during the Middle Pleistocene, and implies they played a role in the colonization of Britain given the lack of evidence for watercraft in this period. For instance, an investigation of these areas could serve to confirm or deny White and Schreve's (2000) suggestion that the Clactonian and Acheulean toolkits in Britain represent the archaeological signature of separate pulses of colonization and migration by hominids from central and eastern Europe (Clactonian) and southern and southwest Europe (Acheulean).

Based on the distribution of known terrestrial sites, prime areas to undertake site prospection would be situated close to water sources, such as rivers, lakes or springs. This is most likely a factor of hominid preference for these areas and the high preservation potential of low energy fluvial sediments. The anaerobic environment of the seabed sediment could potentially enable the preservation of organic remains. These would enhance existing palaeoenvironmental records, while any organic artefacts would fill in some of the vast gaps in the current evidence. The survival of stone artefacts from the Lower Palaeolithic in submerged contexts is more certain though, with the recent discovery of three Acheulean handaxes in 8m of water in Table Bay, South Africa (Flemming, 1998; Werz & Flemming, 2001). The existence of coastal sites (e.g. Boxgrove) certainly indicates that hominids were not avoiding the littoral zone. More evidence from the coastal zone would go some way to determining the reason they were there. Possibilities include the coast as a route for migration (e.g. Stringer, 2000) or a source of resources (Erlandson, 2001).

3.3.3 Middle Palaeolithic

3.3.3.1 Hominid species

The Middle Palaeolithic is characterised by the appearance of Neanderthals (*Homo neanderthalis*), the descendants of the *H. heidelbergensis* populations of Europe (Lewin, 1999). Specimens exhibiting the 'classic' Neanderthal physiology do not appear until OIS 5 (127 to 71 ka BP), however the specimens dated to before this time can be thought of as 'proto-Neanderthals' or transitional specimens in the evolutionary progression from *H. heidelbergensis* to *H. neanderthalis* (Mellars, 1996; Klein, 1999).

3.3.3.2 Archaeological Evidence

As in the preceding period, lithic implements, debitage and faunal material dominate the archaeological record. The classic knapping technique of the Middle Palaeolithic is known as ‘Levallois’. This involves the shaping and modification of a lithic core so as to control the size and shape of the subsequently struck flakes (Bordes, 1980; Schick & Toth, 1993). Tool industries of the Middle Palaeolithic, such as the Mousterian, tend to be characterized by a reduction in the numbers of large bifacial tools such as Acheulean handaxes, an increased emphasis on flake tools often made using the Levallois technique, such as the bout coupe handaxe (Figure 71). Retouching of flakes and other tools was also a common practice designed to resharpen blunted edges (Dibble & Rolland, 1990).

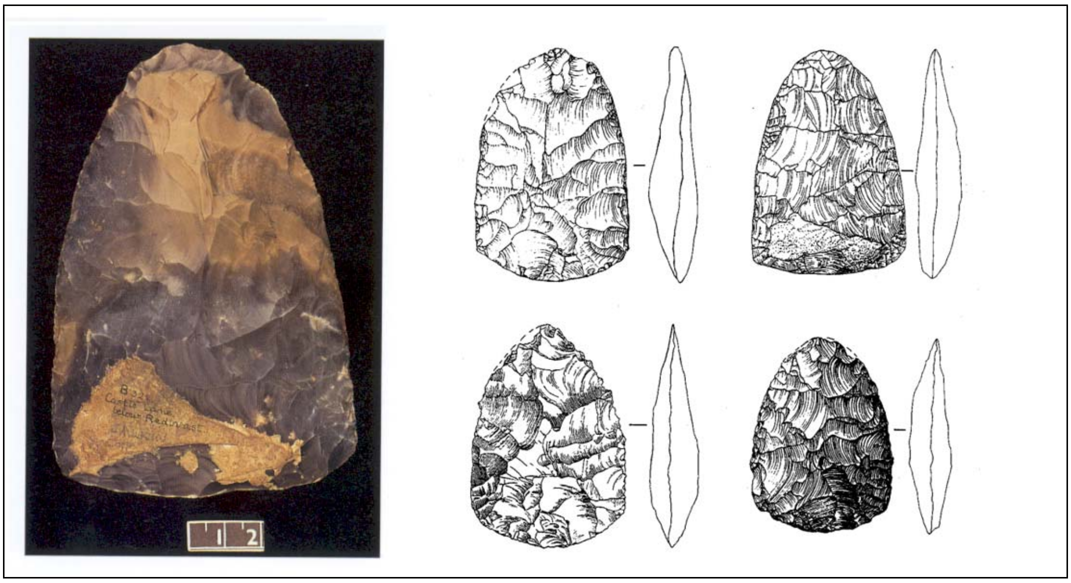


Figure 71. Mousterian or bout coupé handaxes commonly found in the Middle Palaeolithic of southern England (after Barton, 1997; Mellars, 1996).

Microwear analysis has suggested functions for certain classes of tool form. Notches and denticulates appear to have been used mainly on wood, while sidescrapers and points were used on both wood and flesh. There is no equivocal evidence for hafted tools, however marks and striations on some points could indicate friction caused by hafting while impact fractures on some pieces, such as those from the site of La Cotte de St Brelade (Jersey), strongly hint that they were used as weapon tips or projectile points (Callow, 1986).

Exceptional instances of preservation have resulted in the survival of artefacts made of organic raw materials. The German site of Lehringen for example has produced a 2.4m long wooden spear, while some 30 tools made on mammoth bone have been recovered from the site of Salzgitter Lebenstedt (Klein, 1999; Roebroeks & Tuffreau, 1999; Gaudzinski & Roebroeks, 2000).

As before, faunal remains have the potential to inform us about palaeo-ecology; and should they have been accumulated and utilised by past hominids, provide information as to their subsistence organisation. Mauran (France) for instance is almost entirely composed of prime age bison, thus implying that some sort of selective hunting strategy was in operation, while La Cotte de St. Brelade has strong indications of specialization in rhino and mammoth (Scott, 1980; Mellars, 1996).

Deliberate burials are one facet of evidence that serve to distinguish this period from the preceding one. Examples include the sites of Le Moustier, La Chapelle-aux-Saints and La Ferrassie (all France - Gamble & Roebroeks, 1999). Whether these involved ritual or ceremony is uncertain as the grave goods are no different to the artefacts that constitute conventional assemblages.

3.3.3.3 Sites

On a continental scale, sites in primary contexts are more common than in the Lower Palaeolithic. Southwest France for instance has over fifty cave and rockshelter sites and several hundred open air sites (Mellars, 1996). However, this pattern does not apply to all regions. As before, Scandinavia lacks any such sites, while Britain has less than ten. The lack of such sites in Britain is partially the result of the fact that there appears to be a break in occupation between 180 and 60 ka (AHOB, 2003; Ashton & Lewis, 2002) as well as the reworking of the primary context evidence by fluvial and other taphonomic processes.

In terms of site location patterns, many Middle Palaeolithic sites are found in rockshelters or caves. This may be a reflection of archaeological research as much as than hominid preference in that cave sites are preferentially investigated as they are more obvious sources of archaeological material than open air locations. This results from the fact that discovery of open air sites tends to be fortuitous, while caves and rockshelters are rather more obvious places to look for archaeological material (Rigaud & Simek, 1987; Bocquet-Appel & Demars, 2000). In addition, the sheltered environment of a cave is more likely to protect archaeological material from disturbance than exposed open ground.

However, even within this research driven pattern, concentrations of cave sites do exhibit distinct patterns of land use. They tend to be concentrated in limestone, though this is almost certainly a function of geology as much as hominid choice. In southwest France in particular, occupied caves are found in main river valleys, and especially in tributary valleys. This has been interpreted as a preference for narrow, sheltered micro-habitats with access to wider resources on the major floodplains. Further factors determining site location in this area include the proximity to good quality flint and exposure to sunlight. To this end, the majority of caves are located on south facing slopes to maximise the amount of light they receive and also because the local prevailing cold winds blow from the north (Mellars, 1996).

Cave sites also exist closer to submerged landscapes under study such as Spy (Belgium) and Feldhofer (Germany - Roebroeks & Tuffreau, 1999). In Northern France though, cave occupation is much rarer, though as Roebroeks and Tuffreau (1999) have pointed out, this may be more to do with the obscuring of caves by thick loess cover. Two examples of cave sites are described below:

- *La Cotte de St. Brelade (Jersey) – OIS 7 – c. 238 ka BP.*

At present the cave is located on the coast at the foot of a cliff (Figure 72). At the time of occupation, low sea levels would have ensured that the surrounding region was an exposed steppe.

Figure 72. Present day setting of La Cotte de St Brelade, Jersey, showing the cliff and cave (from Gamble, 1999).

TL dating of flint artefacts has provided an initial timing of occupation of c. 238 ka BP (Callow & Cornford, 1986; Roebroeks & Tuffreau, 1999). Evidence, in the form of a long sequence of artefacts and faunal remains from OIS 7 till the last glacial stage, indicates the reuse of this locale periodically over the long term. Of particular importance is the material from Layers 3 and 6. In these layers, faunal remains are composed solely of mammoth or rhino remains, which appear to have been stacked into organized piles against the cave wall. Layer 6 for instance has stacked mammoth scapulae with a rhino skull placed on top, while Layer 3 contains a concentration of skulls without their accompanying parts (Figure 73).

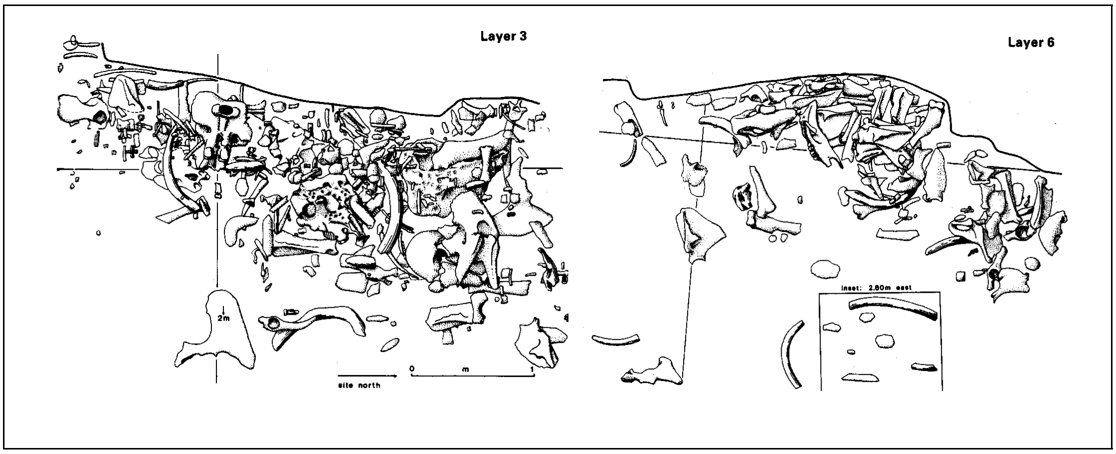


Figure 73. Faunal remains from Layers 3 and 6 at La Cotte de St Brelade (after Scott, 1986)

This, in conjunction with cut marks on the bones, implies hominid accumulation of the remains. There are indications that these concentrations represent rapid rather than long term accumulations, notably the lack of weathering on many bones (implying rapid post depositional sedimentation), and that most of the remains are in direct contact and not separated by sediment and other debris. Exceptional preservation in this instance is the result of rapid covering of the remains by loess. These deposits have been interpreted as the product of a mass drive of animals over the cliff behind and their subsequent butchery (Scott, 1980; 1986). The importance of this site lies in the evidence it provides to support the view that hunting was practised in this period and the utilisation of particular landscape features to aid in this practise. The assemblage also contains lithic points, some of which appear to have impact fractures (Scott, 1980; Callow, 1986).

- *Pontnewydd (Wales) – OIS 7*

The site is located in a limestone valley approximately 10km from the present coast of north Wales. It represents the most northerly extent of the Neanderthal world uncovered so far. The lithic assemblage consists of recognisable tools, such as handaxes, and debitage. In total around 330 artefacts have been recovered. Analysis of these remains has indicated the use of the Levallois technique. TL dating of a burnt flint has provided a date of 200 +/- 25 ka BP. Organic remains have been preserved; the faunal assemblage includes roe deer and reindeer, however, whether were brought in by the hominid occupants of the cave is not certain. In addition, the cave has also produced 7 hominid teeth and mandible fragments, which are said to exhibit Neanderthal features. The significance of Pontnewydd also lies in the fact that provides the earliest evidence of a hominid presence in the upland regions of Britain. The site has been interpreted as a short term, possibly seasonal, hunting occupation. Analysis of this site is rather limited as debris flows into the cave have disturbed the spatial integrity of the remains and possibly introduced some of them (Green, 1984). Pontnewydd therefore provides an example of a primary context site in which the elucidation of a snapshot of past lifeways is not possible, but still provides valuable information on past hominids.

Open air sites are again located both near water sources, be they springs, lakes or rivers. They are however also found in areas further away from water, such as interfluves and also in upland regions. To again use southwest France as an example, the densest concentrations of, and generally, richest open air sites coincide with the high portions of the interfluve locales between areas of dense cave occupation in river valleys (Mellars, 1996). Smaller (both in terms of their size and quantity of archaeological material) sites meanwhile are distributed across high and low areas, both on slopes and also within the floodplains of the river catchments. These distributions should not be taken at face value though, as it has been pointed out their discovery is due in large part to exposure by modern agriculture, and their concealment to local geology and vegetation (Mellars, 1996). It does seem to point to the occupation and use of large areas of the landscape rather than small localized territories.

A number of open air sites are also known from closer to the study region:

- *Maastricht-Belvedere (Netherlands) – OIS 7.*

  Burnt flints have provided a TL date of 250 +/-22 ka BP. The site was located by a river and was partially preserved in fine grained fluvial sediments. Site J at this locale was preserved by wind blown loess. The assemblage includes the remains of both small and large animals and a large quantity of lithics and debitage. Refitting experiments have clearly demonstrated the in situ nature of the assemblage (Gamble, 1999; Roebroeks & Tuffreau, 1999).

- *Biache-St.Vaast (France) – OIS 6.*

  TL dates on burnt flint point to a date of 175 +/- 13 ka BP. The site lies on a fluvial deposit and is covered by loess sediment. The assemblage contains many lithic artefacts, a large number of faunal remains, dominated primarily by large mammals such as bovids, bears and rhinoceros, and two fragmentary hominid skulls. (Roebroeks & Tuffreau, 1999).

- *Lynford Quarry (England) – OIS 4*

  This open air site was located and excavated very recently, hence a published account is not yet available. A preliminary interpretation suggests it was a Neanderthal butchery site situated by a pond. Some 30 Mousterian handaxes and over 500 other worked flint artefacts have been recovered along with the remains of 9 mammoths, a reindeer, a woolly rhino and a brown bear. Preservation at this site is exceptional; with the remains of various species of insects and flora providing a detailed palaeoenvironmental record for this findspot. OSL dates on organic sediments have pointed to a date of between 64,000 to 67,000 ka (English Heritage, 2003; Norfolk Archaeology Unit, 2002).

Sites situated on the coast for the purpose of exploiting the maritime environment are not known for this region. However, while quite rare, these sorts of sites do exist for other areas. Notable examples are Vanguard Cave (Gibraltar) and Abdur (Eritrea) (Barton et al, 1999; Walter et al, 2000). Erlandson (2001) provides a comprehensive overview of these sites.

3.3.3.4 Interpretation

The Middle Palaeolithic is characterised by the emergence of the Neanderthals, an indigenous development of the *H. heidelbergensis* populations of Europe and by the development of a new and complex set of knapping techniques that involved extensive core preparation (Mellars, 1996; Klein, 1999).

A number of well preserved primary context sites in both open air and sheltered (cave and rockshelters) locales are known for this period. Note for example the dense concentration of sites in the limestone plateau of southwest France (Turq, 1999). The widespread occupation of the latter does seem to mark a break from the preceding Lower Palaeolithic, though this may be as much a function of preservation (section 3.2.3) as hominid preference.

Well preserved primary context sites include Combe Grenal, the Grotte Vaufrey and La Micoque (all France). Further north examples include La Cotte de St Brelade (Jersey), and Pontnewydd Cave (Wales - Green, 1984; Callow & Cornford, 1986; Mellars, 1996).

In much the same way as in the preceding period, primary context sites are often located in riverine environments such as Maastricht-Belvedere (Netherlands) and Salzgitter-Lebenstedt (Germany) (Gaudzinski & Roebroeks, 2000). Sites also tend to be located near other water sources, such as ponds and lakes; examples being Lehringen (Germany) and Lynford Quarry (England - Roebroeks & Tuffreau, 1999; Norfolk Archaeology Unit, 2002). As before, it is likely that the occupation of these locales was conditioned by hominid preference, in that they afforded abundant food and water, but also by the high preservational potential of these environments. In terms of contexts affording high preservation, loess areas should also be considered.

Cave sites have tended to be interpreted as living areas or base camps. The number of archaeological layers at many sites reflects the fact that these locations were favoured locations and reused by hominid groups over the timespans of thousands of years (Mellars, 1996). Open air sites may have been camps, kill sites, butchery sites, workshop sites or may have incorporated all functions. Analysis of the patterning of the various site types in southwest France has pointed out that workshop sites tend to be located on or near flint sources while mixed activity open air sites are systemically situated in the higher parts of the interfluves where observation of the surrounding valleys and micro regions could be performed (Turq, 1999).

Analysis of lithic raw material found at these sites provides an indication as to the movement patterns of these people. Studies from southwestern France indicate that the bulk (70-98%) of the material came from less than 5km away, while less than 5% was from distances of 30km or more (Mellars, 1996). This implies relatively restricted geographical ranges compared to the societies of later periods (see section 3.3.4.4).

3.3.3.5 Implications for submerged landscape research

The continuing presence of hominids in Britain and continental Europe from OIS 13 till the end of OIS 7, combined with contemporaneous shifts in lithic technology in both areas, notably the development of the Levallois technique, strongly argues for the movement of hominids across the North Sea and English Channel regions. Given the lack of evidence of watercraft in this period, it must be assumed that this movement took place at times of low relative sea level when these areas were exposed as dry land. Furthermore given the size of the areas concerned and the likelihood that the societies in question would not have conceived of Britain and Europe as two separate geographical areas, this process of movement would have probably been part of a longer-term occupation of the presently submerged areas (White & Schreve, 2000).

In particular, the occupation of these currently submerged areas between 180 and 60 ka BP, would raise further questions of why Britain appears to have been abandoned at this point in time.

In terms of site distribution, a similar pattern to that described for the Lower Palaeolithic (see section 3.3.3.5) is recognizable, with potentially well preserved open air sites occurring near water sources, such as rivers, lakes and ponds due to the twin processes of hominid preference and enhanced preservation in low energy fluvial or lacustrine sediment. However, for this period, additional areas to consider would be those in which the solid geology affords high potentials of cave or rockshelter formation. Smaller, more ephemeral deposits may exist in upland and interfluve locations. Whether these locations can be predicted underwater with any degree of certainty is not known, since even on land they tend to be chance finds.

Finally, as with all other periods of submerged archaeology, the possibility that enhanced preservation of organics remains and artefacts must be considered.

3.3.4 Upper Palaeolithic

3.3.4.1 Hominid species

Around 40 ka BP, anatomically modern humans (*Homo sapiens sapiens*) appear in Europe. The balance of evidence suggests they were part of a population dispersal out of Africa rather than an indigenous evolutionary development of the Neanderthals. The 2 species co-existed for a period of time until around 27 ka BP– the date of the latest Neanderthal deposits (d’Errico et al, 1998). How and why the Neanderthals became extinct is not entirely certain though genetic differences between the two populations suggest that interbreeding was not possible (Klein, 1999; Lewin, 1999).

3.3.4.2 Archaeological Evidence

The Middle to Upper Palaeolithic transition has often been seen as marking something of a ‘revolution’ in the archaeological record. The period sees the proliferation of certain techniques of flint knapping, notably the use of blades, increased standardization of tool forms and also greater industrial variability in both time and space. This is evident in the proliferation of regional and chronological techno-complexes, examples being the Aurignacian, Gravettian, Magdalenian and Creswellian, to name but a few (Champion et al, 1984; Gamble, 1986; Barton, 1997; Mussi et al, 2000).

The use of non-lithic raw materials also becomes more common. While examples of worked bone do exist from the earlier periods, the Upper Palaeolithic witnesses a veritable explosion of tools, implements and ornamental objects made on bone, antler and ivory (Figure 74 - Gamble, 1986). In exceptional circumstances, wooden artefacts have also been preserved. The wet conditions at the site of Stellmoor (Germany) for example have preserved 105 arrow shafts and fragments dating to the final phase of the Upper Palaeolithic (Bokelmann, 1991).

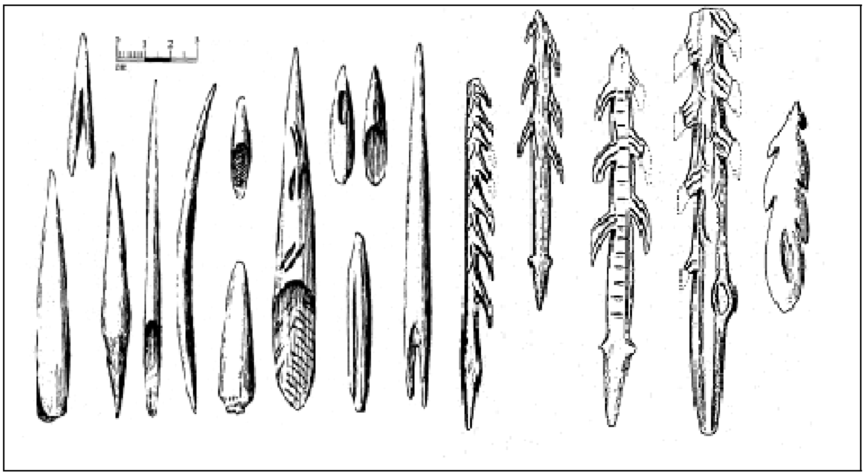


Figure 74. Selection of Upper Palaeolithic implements made on bone and antler. They range from simple points, on the left to more complex harpoons, on the right (from Peterkin, 1993)

A major difference between the Upper Palaeolithic record and that of the Lower and Middle Palaeolithic is the existence of art. This comes in the form of either parietal, or wall, art – such as the cave paintings at Lascaux, Chauvet and Cosquer - and portable carved or engraved objects. Animal teeth and shell that have been pierced for suspension also occur in many sites and have been interpreted as decorative or ornamental objects (Champion et al, 1984; Klein, 1999).

Structures are also apparent at a number of open air sites across Europe. Gonnersdorf and Andernach (Germany) for example have post holes, boiling pits and internal fireplaces which imply substantial dwelling structures, while evidence of tent like structures with outside hearths have been inferred for the sites of Pincevent and Verberie (France - Audouze, 1987; Barton, 1999).

3.3.4.3 Sites

In contrast to the earlier periods, quite literally hundreds of primary context Upper Palaeolithic sites are known from across North West Europe.

Where local geology permits, caves and rockshelters continue to be intensively occupied. Examples include Kent's Cavern (Britain), Peterfels Cave (Germany) and Trou Magrite (Belgium - Albrecht, 1983; Dewez, 1986; Barton, 1999).

Open air sites however, are more common than in the preceding period and in some instances have evidence of substantial and repeated occupations. This could be an accident of preservation (i.e. there has been less time for destructive taphonomic processes to operate compared to the earlier periods), though the unequivocal presence of structures at a number of them (see below) does highlight the ability of anatomically modern humans to create their own shelter and thus be less dependent on the distribution of natural cavities.

Once again a number of well preserved open air sites are known from around natural water sources. Riverside locations include sites such as Pincevent and Etiolles (Audouze, 1987), while there are also a number of sites situated on lakeshores. This is especially true of the Late Upper Palaeolithic sites in Scandinavia, which are often situated near the inlets and outlets of lakes (e.g. Trollesgave (Denmark)). The location of these latter sites has been interpreted as an indication that these groups were fishing (Fischer, 1991; Larsson, 1991). As before though the presence of sites near water probably relates to hominid preference and preservational factors.

Hunting strategies are also inferred to have conditioned site location to some extent. The south German sites of Peterfels, Kesserloch and Schaffhausen are situated adjacent to narrow tunnel valleys into which herds of reindeer were driven and slaughtered (Albrecht, 1983). Closer to the study area, similar patterns are evident in the Ahrensburg tunnel valley (Schleswig-Holstein, North Germany). The site of Miendorf is situated between 2 small lakes, while the site of Stellmoor is located between a lakeshore and the steep sides of the valley. Both locations form ideal bottlenecks for driving and then ambushing reindeer herds (Bokelmann, 1991; Bratlund, 1991). Similarly, settlement patterns at Cheddar Gorge (Britain) could have been influenced by these factors, as there is a concentration of sites in association with narrow canyon-like topography suitable for corralling or driving animals (Barton, 1999). Alternatively, sites near river fords can either be seen to have been located there to take advantage of migrating salmon or reindeer herds, which would have been vulnerable when crossing these rivers (White, 1989).

In general, it seems that areas of significant relief are prime areas for site prospection, for the reasons described above (shelter and hunting), but also in that these areas represent points from which a range of diverse biotopes (e.g. upland plateaus and lowland floodplains) could be readily accessed (Rozoy, 1998).

This is not to say that upland areas were totally avoided. For instance, the site of Ville St. Jacques (France) is located on the edge of a plateau in the Paris Basin, unlike the majority of sites in this area (e.g. Etiolles, Pincevent, Marsangy) which are positioned in the river valleys. The relative rarity of these sorts of sites compared to the cave and valley sites above is probably a function of the overwhelming focus of archaeological research on cave and valley sites to the detriment of other loci of settlement, and the higher incidence of plough damage to upland sites, which are not protected by layers of fluvial sediment (Rigaud & Simek, 1987; Audouze & Enloe, 1991).

The distribution of high quality flint outcrops can also be seen as influencing regional settlement patterns. For instance, the current archaeological record suggests that Brittany was far less densely occupied in the post Last Glacial Maximum (LGM – c. 22 ka BP) re-colonization of northern Europe than other areas. This has been interpreted as a reluctance to visit it because it lacks high quality flint (Rozoy, 1998).

These factors though are not universally applicable, given the element of human choice involved in weighing up the pros and cons of a particular location.

The site of Pincevent for example is located some 30km from a high quality flint source. Its rich reindeer dominated faunal assemblage though implies that the priority at this location was the hunting of reindeer. In contrast, the site of Etiolles (around 35km from Pincevent) exhibits a reverse priority with the assemblage including numerous large high quality flint nodules but a relatively small faunal assemblage (Audouze & Enloe, 1991).

Coastal sites are not apparent for this period and region. However, the existence of evidence inland of journeys to the coast, such as perforated sea shells and artistic images of sea fauna strongly implies that the lack of sites is more a function of the submergence of the coastline by the postglacial sea level rise (Figure 75) (see Cleyet-Merle & Madeleine, 1995; Erlandson, 2001 for a comprehensive review).

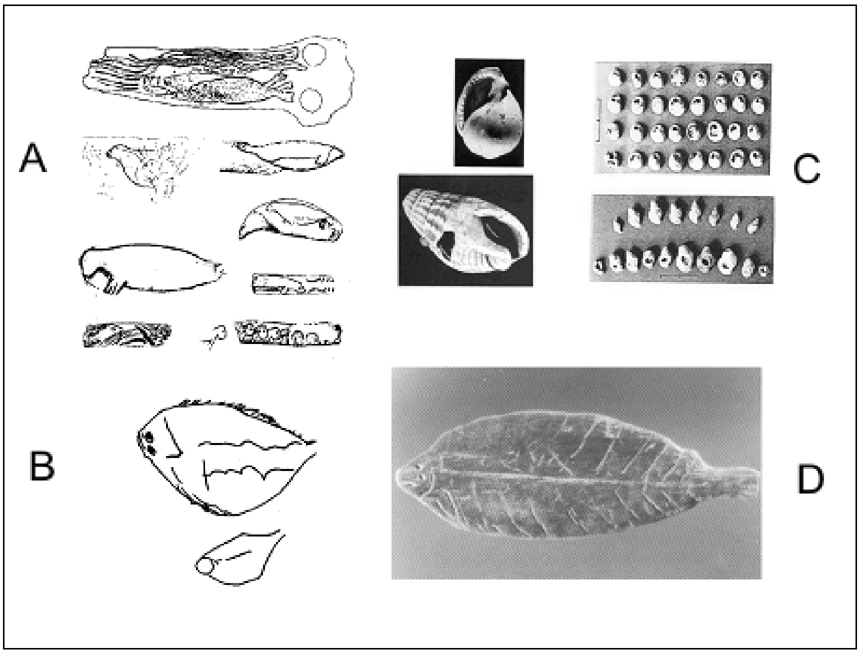


Figure 75. Artistic evidence of coastal knowledge in the Upper Palaeolithic. A) Depictions of seals on various art objects. B) Engraved flat fish from the walls of Le Mas d'Azil cave, France. C) Perforated ornamental shells. D) Mobile engraving of a flat fish from Lespuge, France.(from Cleyet-Merle & Madeline, 1995; Stiner, 1999).

Some examples of primary context sites now follow:

- *Gough's Cave (Britain) - Inland cave site - OIS2*

The site is located in the Cheddar Gorge (Somerset), where several other sites of the same period are also situated. Various dates have been obtained for the site, ranging from 12.8 to 11.8 ka (C^{14}) BP. If the earliest date is accepted, then it provides the earliest date for the post-glacial re-colonization of Britain. The lithic assemblage has been assigned to the Creswellian, a British variant of the wider European Magdalenian tradition and is characterized by the presence of distinctive trapezoidal backed blades (Figure 76: Cheddar points - Barton, 1999).

Figure 76. Cheddar points from Gough's Cave, England. The longest measures 6cm (from Barton, 1997).

Sourcing the flint to Wiltshire (some 60km away) has provided some clues as to the mobility patterns of the cave's occupants. The long distance patterns are substantiated by the presence of non-local seashells and Baltic amber, the nearest source of which is the North Sea coast, which would have been some 300 to 400km away at the time. The remainder of the material culture includes ivory rods, antler batons, bone needles and awls similar to those found in contemporary sites across North West Europe. The faunal assemblage contains the remains of both small (e.g. hare) and large mammals (e.g. red deer and wild horse). It seems the topography of the gorge may have been a factor in site location in that it forms a narrow winding canyon well suited to driving animals, just beyond the cave.

The presence of whooper swan in the assemblage, a migratory species, implies that the cave was a winter site. Whether it was a specialised ‘task site’ or ‘residential site’ remains to be determined at some point. Finally, Gough’s Cave has also produced the remains of at least three adults and two children. Cut marks on the bones indicate that post-mortem dismemberment and defleshing of the remains took place. This has been interpreted as evidence for cannibalism or the existence or a two stage burial practice (Currant, 1991; Barton, 1999).

- *Oldeholtwolde (Netherlands) – Inland open air site - OIS 2*

The site is located in the Tjonger Valley of the north west Netherlands and is attributed on the basis of typology to the Hamburgian culture. At the time of occupation the site would have been located on a stream bank. C^{14} dating has provided an Allerød date of c. 11.5 ka (C^{14}) BP. The site consists of a central hearth surrounded by a scatter of some 10,400 flint artefacts. These include cores, debitage and recognized tool forms. Refitting of many of the pieces has demonstrated the in situ nature of the assemblage. No organic remains have been preserved. The site has been interpreted as a short term - possibly as little as two to three weeks - occupation by a small group, most likely a nuclear family. The proportions of artefacts do not however provide any information as to whether this site had a specialized function (Stapert et al, 1986). The evidence from this site is rather less spectacular than that from Gough’s Cave described above. Nevertheless it highlights the variation that exists between assemblages as a result of both cultural and natural site formation and evolution processes.

- *Pincevent (France) – Inland open air site – OIS 2*

The site of Pincevent is situated in the Paris Basin region of northern France. It consists of several hearths, lithic scatters and a reindeer dominated faunal assemblage. Organic artefacts are sparse, and consist of a few batons, awls, needles and points made on bone. It is located, as are the majority of contemporary sites in the Paris Basin, on a low river terrace, a few kilometres from the confluence of two rivers and close to a ford. The site contains some 12 occupation units, many of which are stratigraphically independent but spatially repetitive, thus implying the reuse of this site over time. A number of C^{14} dates have been obtained from the various layers, ranging from c. 12.3 to 10.9 ka (C^{14}) BP. Frequent flooding has ensured the rapid burial and thus exceptional preservation of the living floors. Patches of low numbers of artefacts situated to one side of the hearths have been interpreted as position of light tent-like structures. Pincevent has been interpreted as a site geared primarily towards the processing of reindeer that were probably killed nearby, as mentioned in section 3.3.4.3, this function took precedence over local deficiencies in other resources (Audouze, 1987; Audouze & Enloe, 1991).

3.3.4.4 Interpretation

Settlement patterns between the Middle and Upper Palaeolithic exhibit a degree of continuity in that similar locales continue to be occupied, notably caves, rockshelters, river valleys and lakeshores. However, there is also a certain amount of variation between the two periods in that more substantial and complex open air sites are known for the later period. This could be interpreted as an accident of preservation or the greater ability of Upper Palaeolithic people to mitigate the surrounding environment by building their own shelters.

On a continental scale sites as far north as Wales are known before the advent of the LGM, Paviland Cave (Wales) for instance is dated to c. 26 ka BP(Barton, 1999). On the whole, settlement in the north west of the region (i.e. Britain and Scandinavia) though is rather more sporadic than in the more southerly regions (e.g France) and Central Europe (Mussi et al, 2000). This pattern was disrupted by the climatic and environmental downturn of the last glacial stage which is often believed to have led to the near total depopulation of the Western Europe above latitude 50°N (Tolan-Smith, 1998; Housley *et al*, 1997). Evidence suggests that the inhabitants of these areas made their way to two refugia located in Franco-Cantabria (southwest France and northern Spain - Jochim, 1987) and the Central Russian Plain (Soffer, 1985). Both these areas have evidence of continuous occupation throughout the Upper Palaeolithic, which furthermore appears to increase through the period concerned (Jochim, 1987). The reasoning behind proposing these areas as refugia hinges on their greater productivity, resource diversity and milder climate relative to northern Europe.

This occupational hiatus is evidenced by the lack of sites in Britain and Belgium between 25 and 14 ka (C^{14}) BP and only 5 sites dating to this period in Germany (Jochim, 1987; Housley *et al*, 1997; Street & Terberger, 1999). It was from these refugia therefore, that human groups emerged to reoccupy the northerly latitudes of the continent in the postglacial, with radiocarbon dates suggesting that the process of recolonization began around 14 ka (C^{14}) BP with the appearance of Magdalenian groups in the Upper Rhine valley and Britain and Scandinavia - occupied from 12.8 and 12.5 ka (C^{14}) BP respectively (Housley *et al*, 1997).

In terms of the subsistence organisation the societies of the European Upper Palaeolithic appear to have been that of mobile hunter-gatherers. Faunal assemblages from across western Europe have indicated that a diverse range of species ranging from salmon (Jochim, 1987) to reindeer (Boyle, 1993) were hunted. While differences in prey choice do exist between different regions resulting from the varying spatial distribution of the animals, there seemed to have been a common continental focus in that the primary prey category was big game, specifically large herbivores such as reindeer, red deer, horse, bison, aurochs, ibex and saiga.

Climatic shifts in the post glacial, notably the replacement of the steppe tundra environment by closed forests are believed to have altered this system such that it was modified to a more diverse strategy that sought to incorporate a wider range of resources into the diet such as small game and aquatic resources.

The distances travelled by these people through the landscape as part of their mobile lifestyle are thought to have been quite large, up to several hundred kilometres in some instances, as evidenced from sourceable objects such as flint and sea shells (Rozoy, 1998; Barton, 1999).

3.3.4.5 Implications for submerged landscape research

The investigation of submerged archaeological sites is particularly pertinent to the Upper Palaeolithic given that there is evidence inland of contact with the coast but yet these very coastlines are missing from the present archaeological record (Cleyet-Merle & Madeleine, 1995; Erlandson, 2001). Questions to be focused on for this period would therefore concern the antiquity and development of the coastal adaptation. The possibility of either separate coastal and inland populations, or the seasonal movement of people between the two regions would add an extra dimension to what is presently known of the social system of the time. The possibility of a coastal Upper Palaeolithic presence also has implications for the routes taken in the recolonisation of Northern Europe after the LGM, for instance via the western coast of the continent rather than through Northern France and Germany as is frequently assumed (e.g. Housley, et al, 1997). Alternatively, given the ameliorating effect of the coastal climate, it might be worth investigating the possibility that the coastline of the northern sector of the continent was occupied during the LGM, rather than the near total abandonment scenario that is generally envisaged.

A small quantity of archaeological evidence from the seabed can be assigned to submerged regions in question, notably the Viking Bergen core and the Leman and Ower point (see section 3.6.2). In addition, similarities in material culture between Britain and the continent imply contact across the presently submerged regions, an thus a human presence in these areas.

With respect to site prospection, as before, likely areas to look for sites would be river valleys, lakeshores, cave bearing geological strata and areas with high quality flint sources. In particular, narrow valleys similar to the Cheddar Gorge and Ahrensburgian tunnel valleys may have held a particular attraction for the reindeer hunters of the Late Palaeolithic. Coles (1998) in fact has pointed out the existence of a number of submerged sub-glacial incisions or tunnel valleys, to the north of the present day Dogger Bank, and also off the East Coast of Scotland, that may have been amenable to settlement when this land was exposed.

3.3.5 Mesolithic

3.3.5.1 Hominid species

By this stage, anatomically modern humans (*Homo sapiens sapiens*) are the sole hominid species present in Europe, and indeed the world (Klein, 1999; Lewin, 1999).

3.3.5.2 Archaeological evidence

In terms of technology, the distinctive hallmark of the Mesolithic is the microlith; a small shaped blade designed to be fitted into a haft to form a composite tool. Microliths are known in the Upper Palaeolithic and their use increases over time, to the point where they represent the dominant tool form of the Mesolithic (Figure 77). Beyond this, evidence tends to be very similar to the Upper Palaeolithic; primarily scatters of stone, bone and other tools (Price, 1991). There is a significant degree of regional variability both in time and space. In Britain for instance, early Mesolithic sites are dominated by so called ‘broad blade’ assemblages containing relatively large isosceles triangle shaped microliths. After 8.5 ka BP, there is a shift from these larger microliths to smaller ones, taking a variety of forms ranging from scalene triangles to needle points (Mithen, 1999). In France, regional variants include the Sauveterrian, the Tardenosian, the Beaugencien and the Ardennien, to name but a few (Rozoy, 1998).

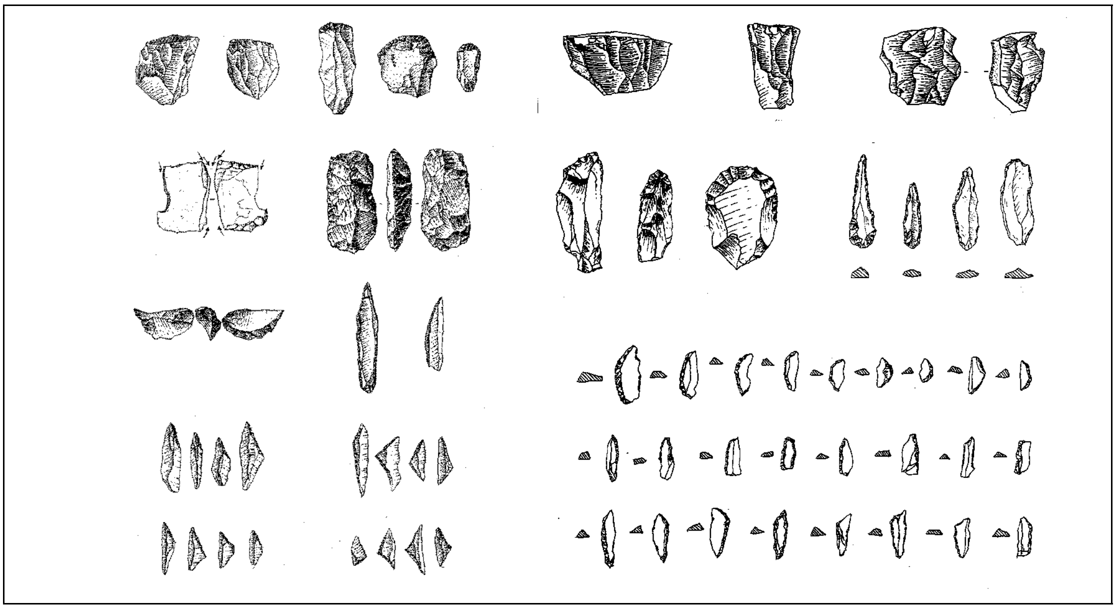


Figure 77. Selection of Mesolithic tools including cores, scrapers, borers, burins, bladelets and microliths (from Mithen, 1999).

There is greater evidence for structures in this period, usually in the form of post holes. Examples include Mt. Sandel (Ireland), East Barns (Scotland) and Howick (England - Mithen, 1999; Gooder, 2003; Waddington, 2003).

A difference with the earlier periods is that middens become more prevalent. These consist of waste heaps of shells, faunal remains and artefacts, and are known predominantly from coastal locations. Towards the end of the sequence, Neolithic traits start to appear. Pottery for example is used by the late Mesolithic (6.6-5.2 ka BP) Ertebølle culture of Scandinavia and the Swifterbant group of the Low Countries (Price, 1991, Louwe Kooijmans, 1999).

Organic artefacts also appear in a number of sites, such as pierced shells, antler mattock and bone points and harpoons (Figure 78). In exceptional circumstances, such as waterlogging, wooden artefacts may also be preserved (Andersen, 1985).

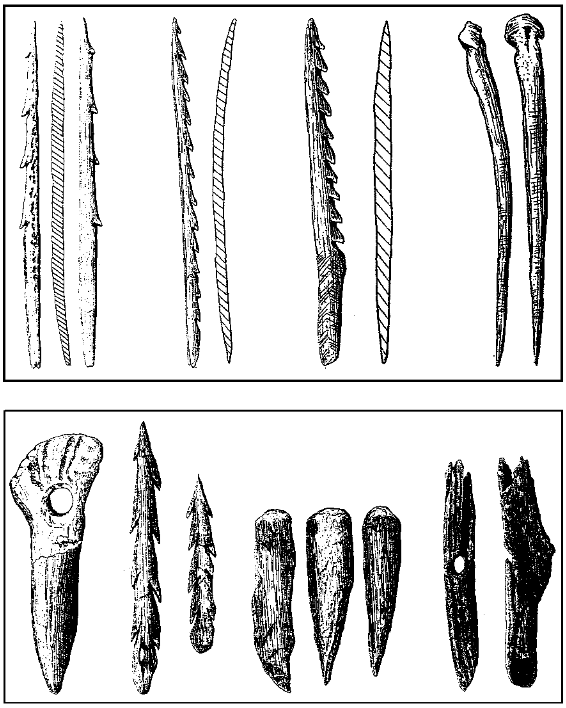


Figure 78. Organic artefacts from Mesolithic contexts. Top row: barbed antler points and a bone pin. Bottom row: Mattock heads, bone harpoons and ‘limpet scoops’ (from Mithen, 1999)

3.3.5.3 Sites

As in the Upper Palaeolithic and in contrast to the Lower and Middle Palaeolithic, hundreds of primary context sites are known for this period.

The majority of Mesolithic sites excavated so far appear to be open air. A major difference when compared to the Upper Palaeolithic is that coastal settlement is now apparent. Shell middens proliferate, and sites with material culture associated with maritime activities such as fish traps, boats and fishhooks become far more common. This however could be related to the submergence of earlier coastal settlements by rising relative sea levels (Bailey, 1983). Some of the best preserved examples of the Mesolithic coastal lifestyle come from southern Scandinavia. For example:

- *Tybrind Vig (Denmark) – 6.6 to 5.2 ka BP(uncal)*

Postglacial relative sea level rise has resulted in the inundation of this site. Submergence though has resulted in remarkable preservation conditions.

The site is located at a water depth of 2-3m and is about 250m from the modern shoreline. At the time of occupation it would have been a multi-seasonal site situated on the coast. The exceptional preservation conditions have resulted in a very rich collection of organic artefacts including the remains of 3 canoes, 14 paddles (four of which are decorated), fishhooks, leisters and a fragment of fishing line (Figure 79).

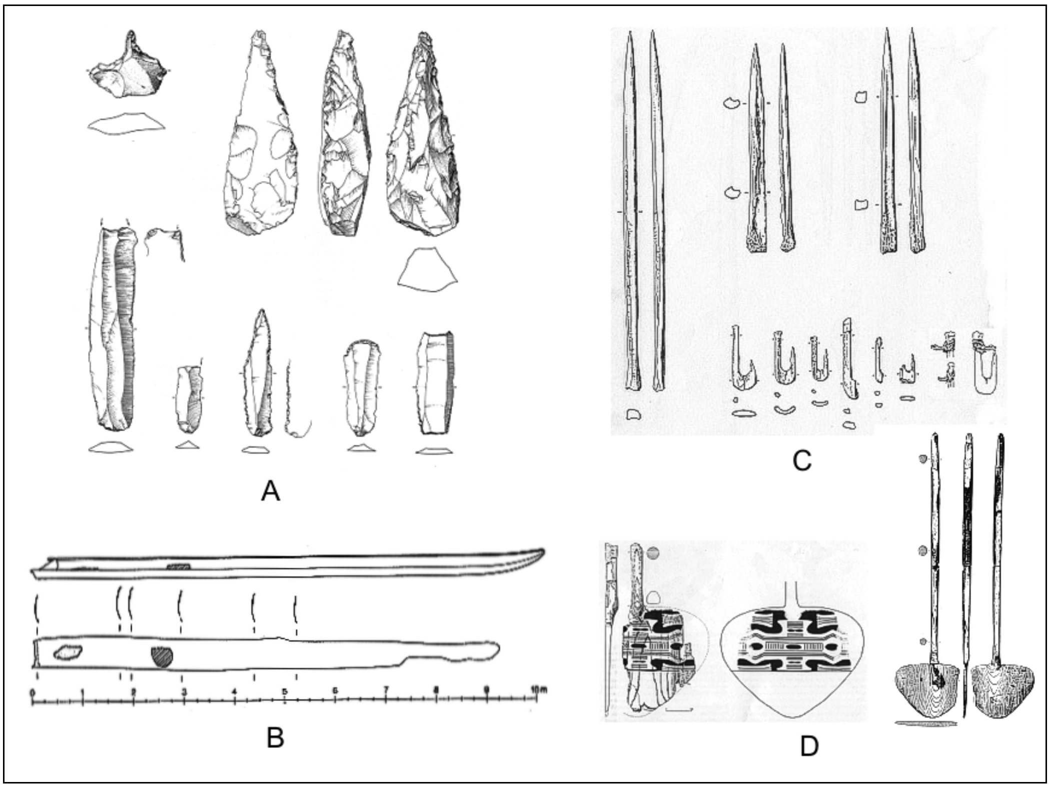


Figure 79. Selection of finds from the underwater excavation at Tybrind Vig. A) Lithic implements. B) 9.5m long canoe. C) Organic artefacts including bone points and bone fishhooks. D) Paddles, both decorated and plain examples. Artefacts are not to scale (after Andersen, 1985)

Faunal remains consist of a combination of marine and terrestrial species including both large and small mammals, molluscs and fish. In addition, the remains of a woman and a small child were found in a burial pit. The significance of the site lies in both its spectacularly preserved organic inventory and the fact it was the first submerged prehistoric settlement to be systematically excavated in North West Europe (Figure 80 - Andersen, 1985; Malm, 1995).

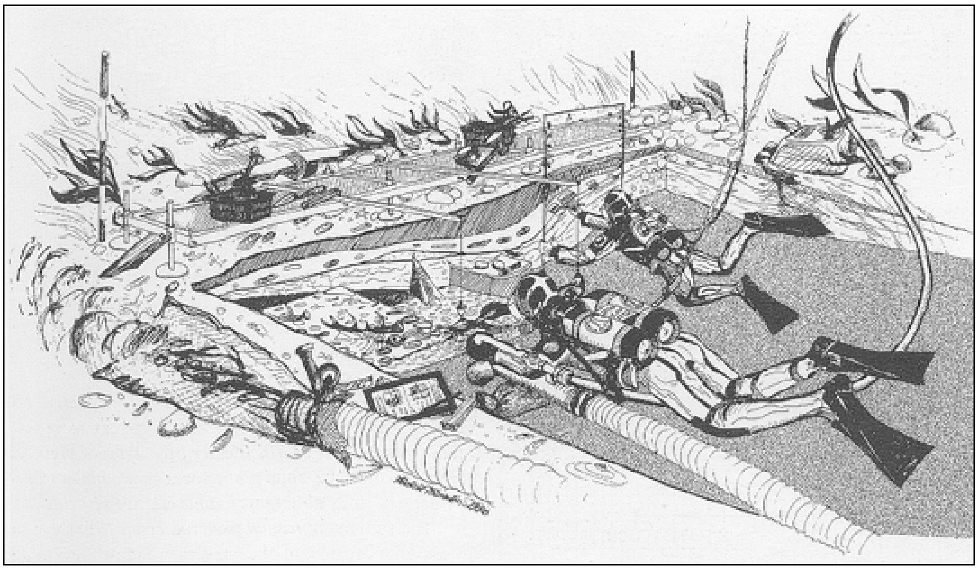


Figure 80. Artist’s impression of underwater excavations at Tybrind Vig (from Malm, 1995)

The use of inland areas still continues, with sites located by rivers, lakes (e.g. Star Carr, England) and so on, while many sites are located in areas of high relief, presumably to provide views of the surrounding landscape and for the particular resources that the uplands afford. This appears to be the case for the Mesolithic of northern England, with many sites located on ridges, hills and valley heads (Kvamme & Jochim, 1985). Examples of inland sites include:

- *Téviec and Hoëdic (France) – 7.7 to 5.3ka BP*

Both these sites are presently located on small islands in the Bay of Quiberon (Brittany). They both contain shell middens, abundant microlithic industries and rich cemeteries. Téviec has ten graves containing 23 individuals, while Hoëdic has 9 graves containing 14 individuals. These remains in fact constitute two thirds of the burials from the French Mesolithic. Grave goods, including perforated shells, red deer antler, bone pins and flint implements are common (Figure 81). A number of AMS dates have recently been obtained from the human remains. Dates from Téviec cluster around 7.2 ka BP while those from Hoëdic are spread between 7.3 and 6.5 ka BP with outliers at c. 7.8 and 5.3 ka BP.

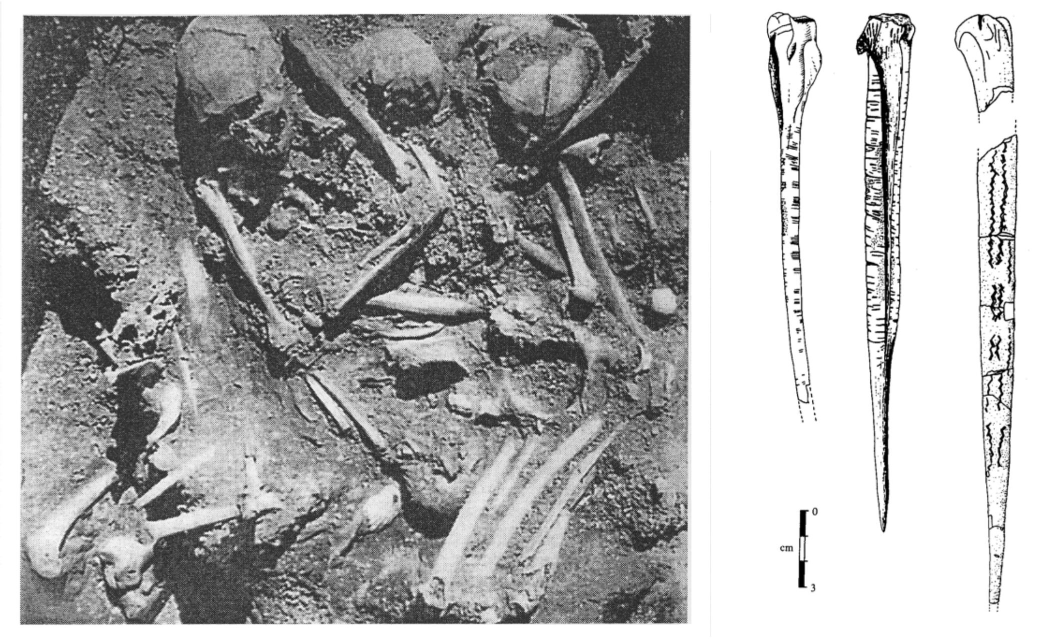


Figure 81. Burial from Téviec (left) and bone pins from Téviec and Hoëdic (right) (from Schulting, 1996).

At the time of occupation, when the local relative sea level was lower, the islands would have been high points on a coastal plain. Téviec would have been 1km from the shoreline, while Hoëdic would have been 2km from the shoreline at the time of the first burial. However, by the time of its latest burial, sea level changes would have ensured that its position in relation to the coastline would have been relatively similar to the present (Schulting, 1996; Schulting & Richards, 2001).

Data from the midden deposits has indicated the sites may have been occupied for most of the year and that the inhabitants subsisted on a diverse set of resources which included both marine and terrestrial fauna. This has recently been substantiated by isotope analysis of human remains from both of the sites which have indicated that the inhabitants of Hoëdic derived some 70 to 80% of their protein from the sea while those from Téviec had a diet based on roughly equal proportions of both protein sources (Schulting, 1996; Schulting & Richards, 2001).

- *Jardinga (Netherlands) – 7.4 –7 ka BP*

The site is located in the valley of the Tjonger River, an area known for its concentration of Late Palaeolithic sites. Fewer Mesolithic sites are known from the area, though there are a great deal of surface finds that have yet to be dated and which may enhance existing knowledge of the Mesolithic activity in this area. Jardinga consists of a concentration of some 66 cut marked and broken aurochs bones, a red deer rib fragment, 6 flint artefacts and 8 pieces of wood. Two sets of radiocarbon dates have been obtained from the bones, implying 2 separate occupations – one at c. 7400 yr BP, and another between 7250 and 7050 yr BP. The lack of weathering on the bones indicates they were rapidly buried in the sediment after deposition and highlights the in situ nature of the assemblage. This is further substantiated by the completeness of certain small skeletal elements, such as the foot bones of the aurochs, which might be expected to have been dispersed if the remains had undergone a degree of post depositional reworking. The site has been interpreted as a kill and primary butchery site on 2 separate occasions in the Late Mesolithic. Its location is probably chosen so as to hunt animals when they came to the river to drink. In addition the open areas around the river would have been more attractive to large herbivores than the surrounding closed forest, which in turn would have made it attractive to hunters (Prummel et al, 2002). While the deposit is far less spectacular than those of the sites mentioned above, it does provide detailed insights into a particular facet of a local subsistence strategy.

3.3.5.4 Interpretation

Settlement patterns in the Mesolithic are diverse and sites are found in a variety of locales. Caves and rockshelters, while still occupied (e.g. Ulva Cave, Scotland) form a smaller proportion of the total site types due to the proliferation of open air sites. Settlement continues on lakeshores (e.g Star Carr, England) and in river valleys (e.g. Noyen-sur-Seine, France), while many sites are also found in upland areas, presumably for the views and resources they afforded (Kvamme & Jochim, 1985; Whittle, 1996; Mellars & Dark, 1998). On a continental scale, an absence of evidence from large areas of central and south east Europe may indicate a reluctance to inhabit large heavily wooded lowland areas that lacked natural openings created by rivers, lakes and marshes (Whittle, 1996). The main break from all the earlier periods of prehistory is the appearance and spread of large numbers of coastal sites. It has yet to be ascertained whether this marks the development of a new subsistence-settlement pattern, or simply the first archaeologically visible manifestation of this phenomena, the earlier examples having been submerged by sea level rise (Bailey, 1983).

The Mesolithic is characterised by broad-spectrum economies. Sites from a variety of diverse areas ranging from Tybrind Vig (Denmark), Freisack (Germany) and Ulva Cave (Scotland), contain evidence of a wide range of foods including shellfish, fish, marine mammals, terrestrial big and small game and edible plants (Price, 1985; Gramsch & Kloss, 1985; Andersen, 1985; Russell *et al*, 1995). In particular, shell middens proliferate in coastal regions, with numerous examples turning up on the Atlantic coasts of France, Scotland and Scandinavia (Bailey, 1983; Andersen 1995; Russell et al, 1995). These have been taken as evidence of the intensified use of the maritime environment described above. If one takes the position that the intensification of coastal occupation is primarily a Holocene event, then the impetus behind this behavioural shift is usually attributed to the continental scale climate changes initiated in the Late Glacial, namely increased temperatures and the replacement of open steppe tundra with closed forest environments, leading to the disappearance of the large herds of grazing herbivores, such as reindeer.

The hunter-gatherer lifestyle does continue, though in some instances mobility can be seen to be decreasing. The rich coastal resources of the Danish archipelago for instance have been seen as providing a stable resource base, which in turn promoted a more sedentary lifestyle (Woodman, 1985).

The adoption of agriculture and the so-called ‘Neolithic revolution’ appeared around 6 to 5 ka BP. Whether or not it was brought in by migrating people, indigenously developed or came about through a combination of the aforementioned factors is not certain. It was not however, universally adopted at the same time. For example, people in Scandinavia maintained a hunter-gatherer lifestyle for a thousand years after the adoption of farming in neighbouring Germany (Whittle, 1996).

3.3.5.5 Implications for submerged landscape research

Again similarities in material culture in both Britain and continental Europe suggest the existence of contacts across the presently submerged landscapes. Archaeological evidence from the submerged areas would therefore help ascertain the nature of these contacts. Were they constituted largely by the movement of people and ideas (i.e. migration and cultural transmission), or was there a continuity in population across the North Sea and English Channel; in other words, long-term habitation in the manner suggested by Coles (1998). Determination of this would go some way to addressing the ‘landbridge question’ (see section 1.3) which currently dominates archaeology.

The Mesolithic also differs from earlier periods in that submerged sites have been located and excavated. Examples include Bouldnor Cliff (England: see section 3.6.2) and Tybrind Vig (Denmark) (see section 3.3.5.3). Sites on land meanwhile are distributed widely across the landscape, possibly as a result of human choice and the fact that there has been less time for post-depositional processes to remove or rework them compared to earlier periods. The sorts of questions that could be looked at in relation to submerged Mesolithic archaeology are similar to those for the Upper Palaeolithic mentioned in section 3.3.4.5, namely the antiquity of large scale maritime exploitation and the nature and extent of coastal occupation. In fact, the rich and complex coastal occupation of south Scandinavia was in fact one of the main lines of evidence that served to demonstrate that the Mesolithic was more than an impoverished relation sandwiched between the art rich Upper Palaeolithic and the farmers of the Neolithic (Price, 1991). This again places a premium in locating the submerged shorelines. Finally, the known existence of a substantial coastal occupation, in conjunction with the Holocene transgression would also make this period ideal for looking at hunter-gatherer responses to sea level change, and assessing whether there was rapid abandonment in the face of inundation, or whether adaptation to new environments took place as well. This may in turn have implications for the adoption of a new way of life (settled agriculture) in around the mid-Holocene.

3.4 Secondary Contexts

3.4.1 Overview

As stated in section 3.1.4 the most prevalent form of secondary context for the periods concerned are river terrace sediments. These take the form of ‘staircases’ arranged with the oldest deposits at the top of the sequence (see Figure 82). Essentially, terrace formation is brought about by incision into the bedrock over which the river runs. Over the timescales in question (10,000 to 1,000,000 years) the causes of this process are external to the river system, notably climate change and tectonic or isostatic uplift. Climate affects the river discharge and sediment supply, which in turn leads to variable degrees of sedimentation or erosion, while the actual formation of the staircase requires progressive uplift of the land surface (Bridgland, 1995; Maddy et al, 2001). This is highlighted by the fact that terrace staircase sequences do not form in areas experiencing crustal subsidence. The lower Rhine for instance, situated in the subsiding southern portion of the North Sea Basin, has formed an aggradationally stacked sequence of deposits rather than terraces, while its upper reaches, located in the uplifting continental interior, are characterised by extensive terrace sequences (Bridgland, 2000).

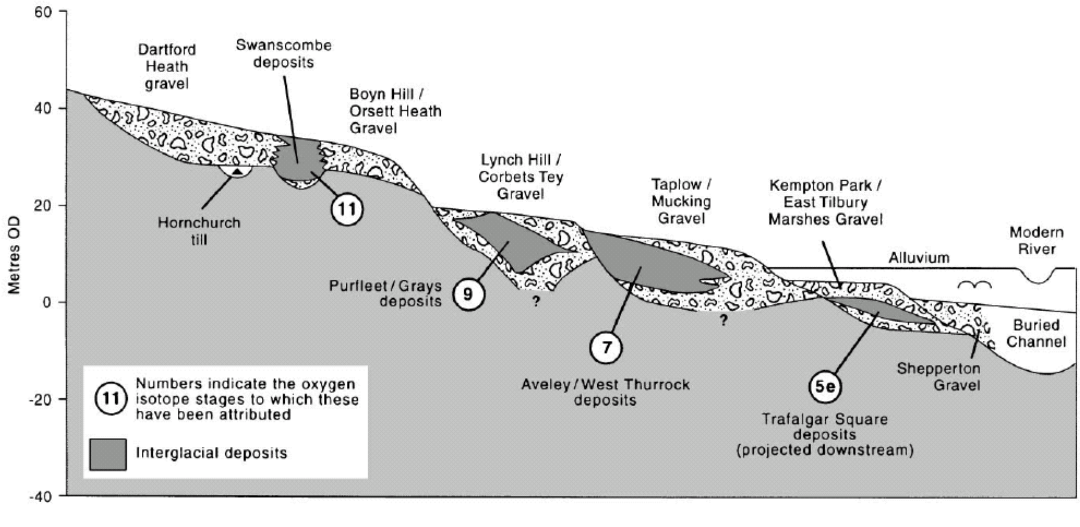


Figure 82. Idealized terrace staircase for the Thames valley (from Bridgland, 2000).

Recent models (e.g. Bridgland, 2000; Maddy et al, 2001) have illustrated the climatically driven aspect of this process in terms of a six-stage sequence (see Figure 83).

- Stage 1) – *Fluvial incision.* [Glacial to interglacial transition, warming trend]

  Sediment supply is reduced as increasing vegetation cover stabilizes valley slopes. Stream power is increased by the release of water from glaciers and frozen ground. Climatic instability also results in a higher incidence of high frequency/high magnitude rainfall events which in turn increase stream power. The combination of reduced sediment supply and increased stream power promotes erosion.

- Stage 2) – *Aggradation.* [Glacial to interglacial transition, warming trend]

  Fluvial incision in stage 1 creates accommodation space which is filled by the deposition of pre-existing terrace sediment. This occurs primarily in the lower reaches of rivers

- Stage 3) – *Stable.* [Interglacial stage, stable and warm]

  Fine grained, low energy interglacial flood deposits are overlain on the gravels deposited in stage 2.

- Stage 4) – *Erosion.* [Interglacial to glacial transition, cooling trend]

  Climatic instability in the early stages of the transition may promote high energy flooding events, thus resulting in an initial phase of erosion.

- Stage 5) – *Aggradation*. [Interglacial to glacial transition, cooling trend]

  Decreases in vegetation and increased freeze thaw weathering promote the movement of sediment from valley slopes to the valley floor. Climatic instabilities once again promote high frequency/high magnitude rainfall events thus increasing stream power. This, combined with the high sediment supply leads to substantial aggradation.

- Stage 6) – *Stable*. [Glacial stage, stable and cold]

  A large quantity of potential discharge is locked up as permafrost and ice. The rainfall events of stage 5 are reduced, further decreasing the flood frequency. Activity tends to be small scale and high frequency – e.g. the redistribution of stored sediment by an annual flood.

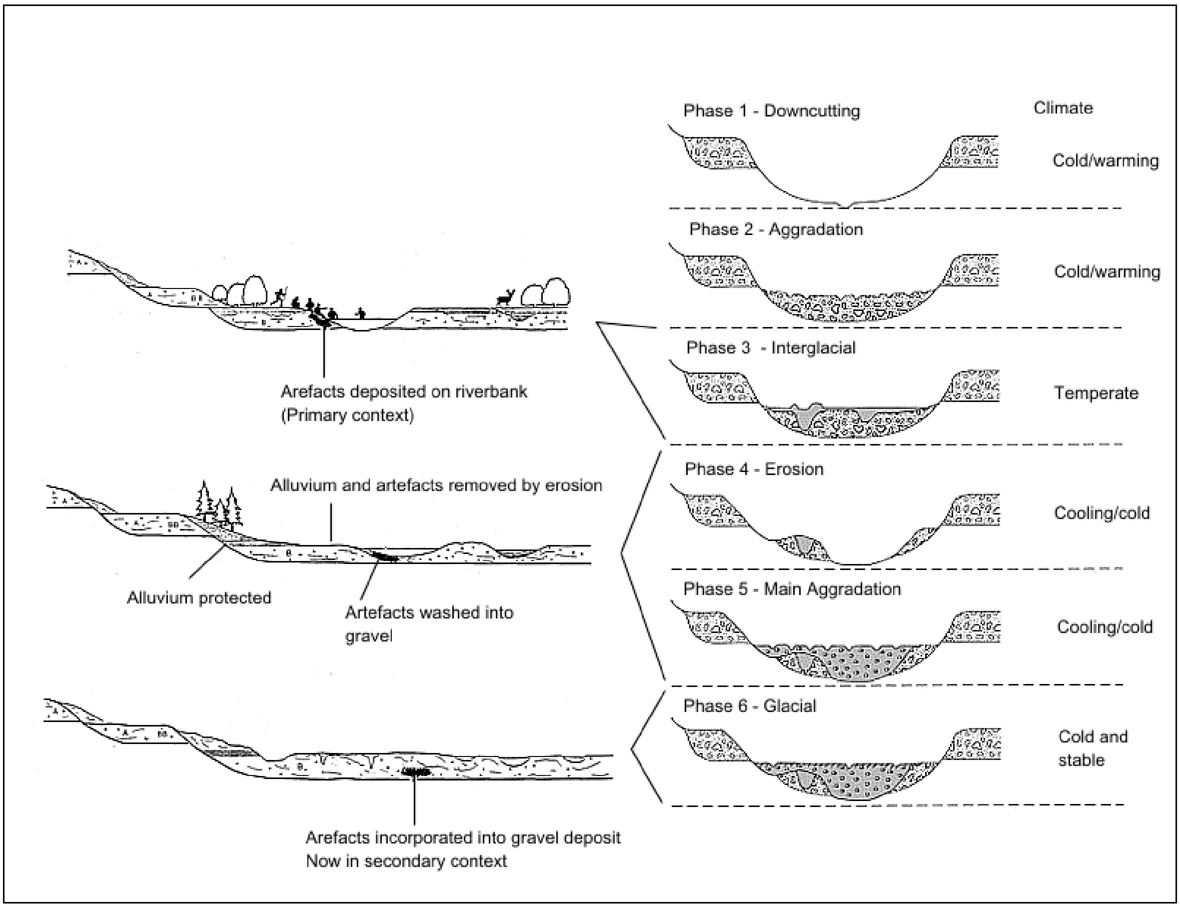


Figure 83. Formation of secondary context archaeological deposits (left) as part of a six-stage model of climatically induced terrace formation (right) (modified from Bridgland, 2000 and Wymer, 1999).

Any archaeological material situated on valley slopes and floodplains can be considered as a form of sediment and thus subject to the above processes of erosion and aggradation. The upshot is that artefacts may be redistributed up to tens of kilometres from their point of origin, and the spatial and temporal relationships between artefacts from each individual site will be lost. Conversely, this does mean that the artefacts within a single terrace unit are a reflection of a wide variety of activities over a long (tens of thousands of years) period of time, and they can be compared with the material from older or younger units (Ashton & Lewis, 2002). This makes them particularly amenable to looking at the long term spatial structure of lithic distributions about a landscape with the ultimate aim of elucidating demographic trends and landscape exploitation strategies on a macroscale (i.e. hundreds of kilometres and tens of thousands of years) level (e.g. Ashton & Lewis, 2002; Hosfield, 1999; 2001). Note for instance Ashton and Lewis's (2002) use of Thames gravel terraces to infer regional population dynamics over OIS stages 13 to 5.

The issue of sites in secondary context fluvial gravels has only really been applied to the Lower and Middle Palaeolithic periods. As described above, terrace gravels form as a result of the movement and downcutting of rivers over the course of a glacial/interglacial cycle (Bridgland, 1995). The preponderance of secondary contexts in earlier periods is a consequence of the actions of multiple examples of these events. Since the start of the Upper Palaeolithic there has only been a single glacial to interglacial transition, thus there has been far less time for multiple terraces to form. In fact the time span of each gravel terrace is estimated to be between 70 and 100,000 years (Hosfield, 1999). In comparison the Upper Palaeolithic spans only 30,000 years and the Mesolithic 4,000 years. The sheer number of primary context sites from these two periods has meant that disturbed and derived assemblages have never been examined to the same degree as in earlier periods. Indeed, an examination of the relevant literature would reveal that the question of the potential of secondary context deposits is simply not an issue discussed by Upper Palaeolithic and Mesolithic specialists.

The point in time at which deposits were forming in the postglacial (Stages 1 and 2 above) also coincides with the large scale de-population of northern Europe between the LGM and the Bölling interstadial described in section 3.3.4.4. Consequently there would simply have been far less archaeological material available for reworking by fluvial process (Wenban-Smith, 2002).

Individual gravel terraces may also contain lenses of finer sediment which could reflect periods of lower energy activity, and it is possible that primary context archaeology and biological material may be preserved in them (Wenban-Smith, 2002). The lower loam layers at Swanscombe (England) for example contain a core and flake industry in primary context, while the gravel layers overlaying them contain derived artefacts (Wymer, 1999). Figure 84 illustrates this phenomenon in relation to the archaeological deposits in the Cagny area (France).

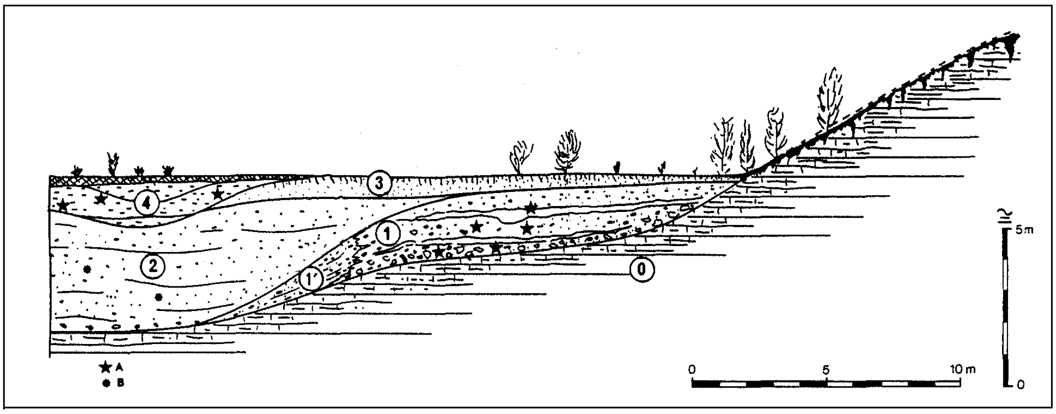


Figure 84. Idealized section through terrace complex in the Cagny area. (A) Undisturbed Palaeolithic sites. (B) Reworked Palaeolithic artefacts. (0) Bedrock. (1) Chalky slope deposits with interstratified bed of calcareous fluvial silts. (1’) Calcareous fluvial gravels. (1 & 1’: Early glacial sedimentation). (2) Coarse sedimentation in periglacial environment (Full glacial sedimentation). (3 & 4) Calcareous fine fluvial silts (Interglacial sedimentation). (5) Brown leached soil (Interglacial). Note the presence of both reworked and undisturbed sites within the same terrace complex (modified from Tuffreau & Antoine, 1995).

3.4.2 Secondary context terrace sites

A large proportion of the archaeological evidence for the Lower and Middle Palaeolithic comes from derived or secondary contexts. For instance, the record for Britain is made up of around 16 primary context assemblages and several hundred secondary context collections, which take the form of fluvial gravel terraces (Hosfield, 1999; Wymer, 1999). Lower Palaeolithic findspots in Britain therefore tend to be concentrated along the Thames Valley, the Hampshire rivers and the Ouse valleys (Wymer, 1999). Similar patterns are present in continental Europe with concentrations in the Rhine and Somme valleys (Wymer, 1982; Bosinski, 1995; Tuffreau & Antoine, 1995). Examples of secondary context sites from North West Europe include:

- *Mauer (Germany) – OIS 13.*

  The site was located on an aggrading river bank, onto which animal bones and a hominid mandible were washed. Some struck lithics were found in the deposit, however it is more likely they were created by natural forces than human action (Bosinski, 1995).

- *Abbeville: Stade and Champ de Mars sites (France) – OIS 13.*

  These gravel terraces are located 33m above the bedrock of the present day river valley. Numerous Acheulean handaxes and bifaces have been recovered from them (Tuffreau & Antoine, 1995).

- *St Acheul: Rue de Cagny site (France) – OIS 11 to 12*

  The stratigraphic sequence at this site contains both gravel and fine-grained fluvial deposits. The gravels have produced large numbers of lithic artefacts including handaxes, flake tools, notches and denticulates. The lower parts of the finer grained deposits have also produced around 220 handaxes (Tuffreau & Antoine, 1995).

- *Thurrock – OIS 10*

  No handaxes are known from this site. However, large numbers of cores and flakes have been recovered. Few are in mint condition, indicating a degree of post depositional reworking. The site is situated in a terrace some 14m OD which has been assigned to OIS 10. Artefacts occur at all levels within 1.5 to 2m of gravel (Wymer, 1999).

- *Great Pan Farm (Isle of Wight) – OIS 7*

  This site has produced over 50 handaxes, at least one of which is of bout coupé form, two Levallois flakes and some cores from a gravel pit situated on a terrace some 8 metres above the present surface of the river Medina (Wymer, 1999).

3.4.3 Relevance to submerged landscape research

Today's rivers represent only the upper reaches of palaeo-rivers that would have drained North West Europe during the Pleistocene. At times of low sea level, these rivers would have extended across the exposed continental shelf (Figure 85) (Bridgland, 2002; Gibbard & Latridou, 2003).

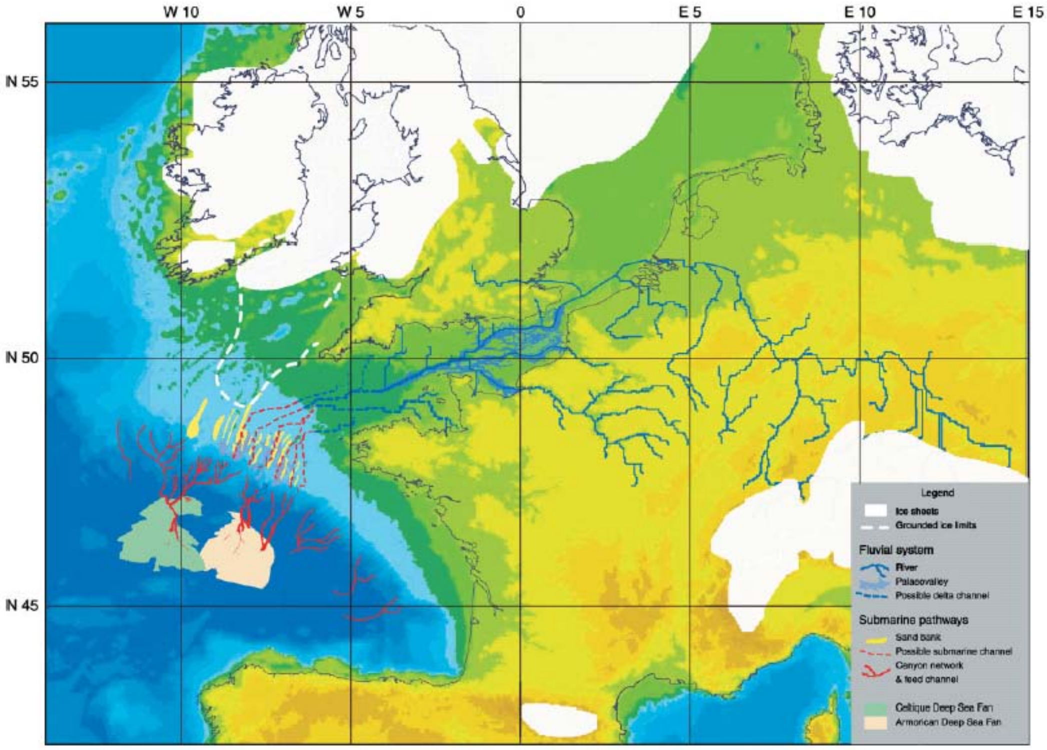


Figure 85. Reconstruction of the exposed shelf and palaeo- rivers at the LGM lowstand and their course through the present day English Channel region. Shorelines have been modified to account for isostatic influences (modified from Bourillet et al, 2003).

Surveys of the seabed and sub-seabed stratigraphy have identified a number of palaeo-channels (see Figure 86, 87) (e.g. Bridgland et al, 1993; Velegrakis et al, 1999). Comprehensive reviews of these palaeo-channels and palaeorivers can be found in Gibbard (1988), Bridgland (2002) and Antoine et al (2003).

Palaeo-channels can also be produced by forces other than fluvial erosion. Deeply incised submerged palaeo-valleys on the North West European shelf, are currently the subject of significant debate with current theories of formation including steady meltwater erosion, glacial erosion, tidal scour, catastrophic meltwater outbursts, lowstand fluvial erosion or aggradation of delta channels (Huuse & Lykke-Andersen, 2000; Kluiving et al, 2003). Recent work suggests a combination of glacial erosion and steady subglacial meltwater erosion is the likely cause (Huuse & Lykke-Andersen, 2000). In any case, many of the palaeo-valleys in the North Sea will not have been produced by fluvial processes and hence will not have formed the terrace sequences seen elsewhere in the region. Although disputed by Flemming (2002) on the basis of the extent of re-working, it is still probable that these glacio-fluvial systems will have re-worked and re-deposited archaeological material both within channels and in ice proximal locations. Although much deeper in the section (100-200 m below seabed) and inevitably heavily spatially and temporally mixed they may still represent locations of secondary context material.

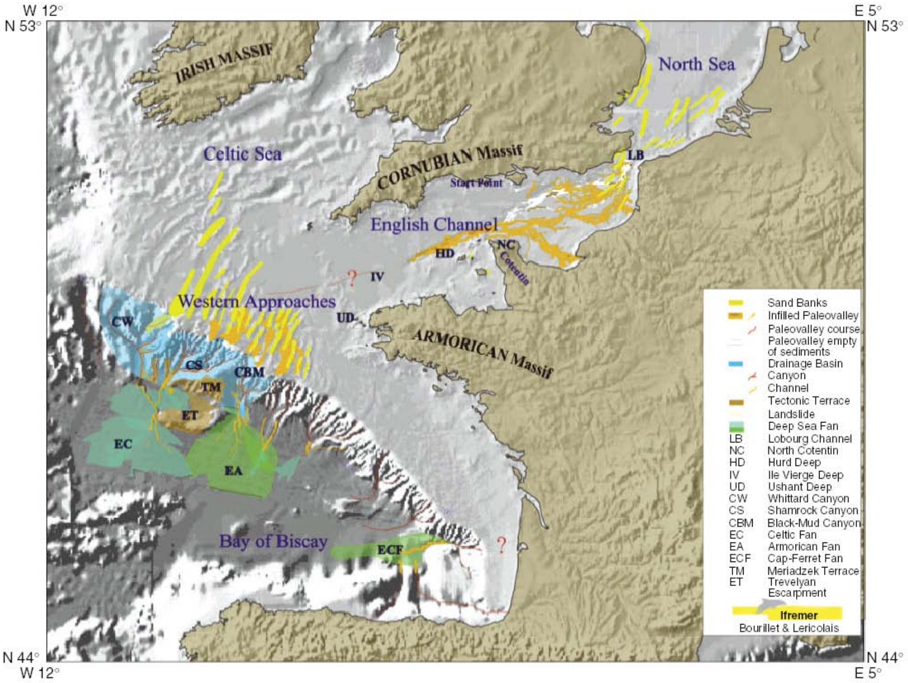


Figure 86. Quaternary palaeochannels in the English Channel and Western Approaches (from Lericolais et al, 2003).

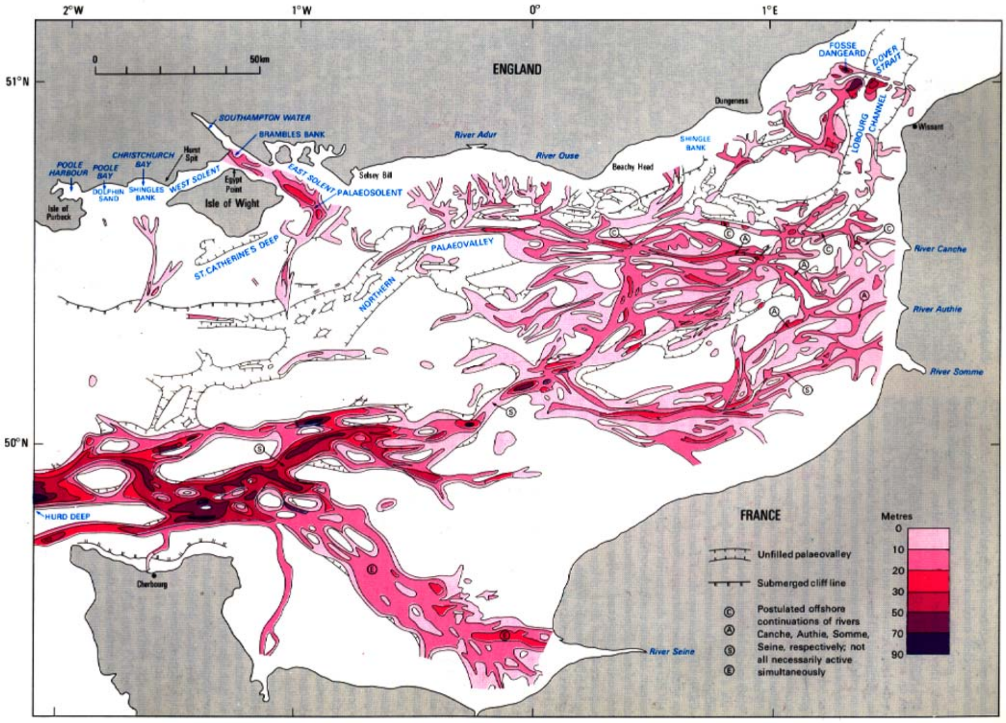


Figure 87. Close up of Quaternary palaeo-channels in the Eastern English Channel (from Hamblin et al, 1992).

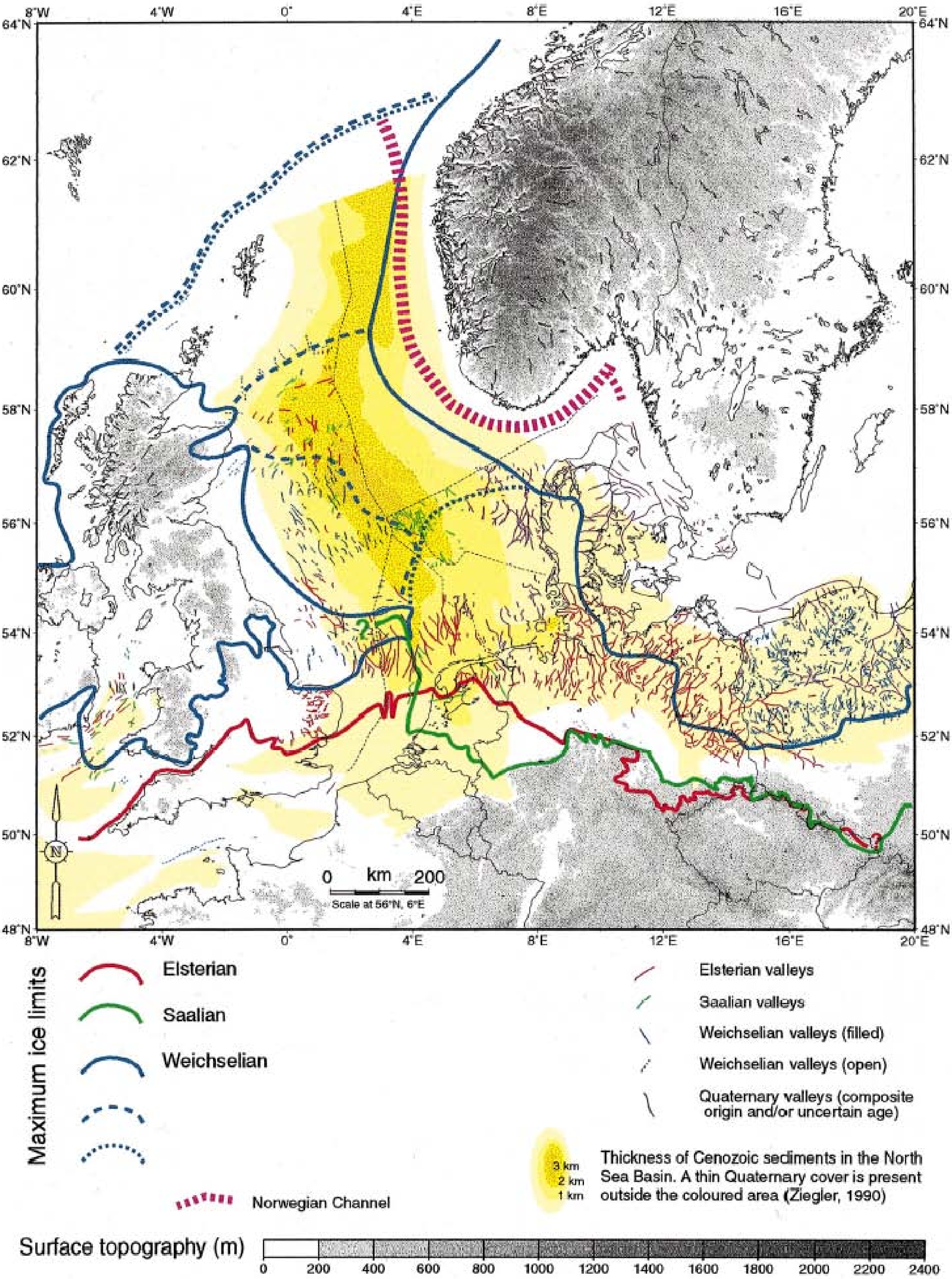


Figure 88. Quaternary palaeovalleys in the North Sea. The blue dotted ice limits indicate alternative perspectives on the Weichsalian ice limits which infer a connection between the British and Scandinavian ice sheets (after Huuse & Lykke-Andersen, 2000).

The implications are that if hominids did occupy these submerged landscapes at various points in time since OIS 13, there is potentially a wealth of archaeological information in secondary contexts locked up in the terrace and channel deposits associated with these fluvial and glacio-fluvial palaeo-channels. This information could be of great use in understanding long term land-use strategies and hominid demography across the English Channel and North Sea plain. In addition, the fluvial records may be of great assistance in reconstructing palaeo-environmental conditions and palaeo-climatic fluctuations (Bridgland, 2002). However, before these goals can be realized, two main issues have to be considered.

The first is that, while submerged palaeo-channels and river terraces are known to exist in the study area, it should not be automatically assumed that the presence of the former necessarily precludes the existence of the latter. As stated in section 3.4.1 they require long term tectonic uplift to form and thus do not exist in subsiding areas, such as the Lower Rhine (Bridgland, 2000). They are however known to be present in the outer Thames estuary (Figure 89) (Bridgland et al, 1993), which is located just outside of the subsiding portion of the North Sea.

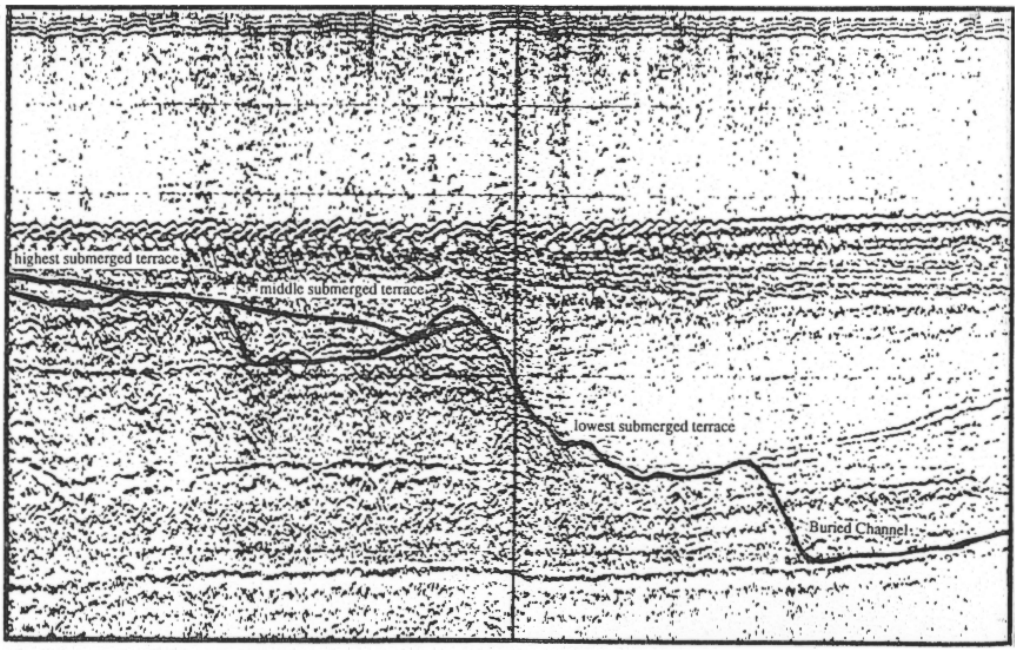


Figure 89. Seismic profile of the submerged Thames-Medway Valley. Image has been annotated to highlight the three river terraces and the buried channel (from Bridgland et al, 1993). Note no scale in original paper.

Other areas of uplift include the south coast of England, as indicated by the presence of raised beaches (Bridgland, 2000), hence raising the possibility that terraces exist in the English Channel. However, geological investigation suggests that terraces appear to be absent through much of the area. This contrasts somewhat with the terrestrial evidence for this region which is characterised by a number of terraces (e.g. the Solent terrace sequence). This absence is most pronounced in the larger palaeovalleys, such as the Lobourg Channel and Northern Palaeovalley, though sediments may be preserved in some of the smaller channels due the protection their banks afforded. The absence of terraces has been attributed to their destruction and reworking by marine transgression during each phase of sea level rise (Hamblin et al, 1992). There are some exceptions to this though, in that several well developed gravel terraces are known to exist in the offshore buried channels of the Arun Rivur, and the East Solent (Velgrakis et al, 1999). Sediment from terraces reworked by marine processes would currently be distributed about the Channel floor and therefore may represent an example of a tertiary context (see section 3.5).

Clearly, rather than simply assuming that palaeo-channels and terrace deposits go hand in hand, we have to ascertain first whether deposits would have actually formed, and then whether they have been preserved. In areas where terraces do exist, these relict fluvial gravels are the kinds of deposit targeted by the marine aggregates industry (Selby, 1992). Thus a secure understanding of their location, evolution and also archaeological potential will be crucial in developing a sensible and practical research and legislative strategy to enable their utilization by both the archaeological community and aggregates industry.

In addition to terrestrially formed secondary contexts, we also have to consider that the impact of transgression may be such that the primary contexts described in section 3.3 may have been reworked by marine processes into secondary contexts. Little is known about the nature of these deposits, and they will be examined further in Section 4. However, their interpretative potential is likely to be similar to that of the fluvial secondary contexts described above. If a sufficiently large sample can be obtained they may provide evidence geared to answering long term and landscape scale questions.

3.5 Archaeological Material in Tertiary Context

The category of tertiary contexts is proposed on the basis that much of the submerged record may consist of terrestrially formed secondary contexts that have been reworked by marine processes.

A number of regions of potential tertiary contexts can be identified on the North Western European shelf. These consist of areas of known sediment movement and can be identified from the presence of particular bedforms. Various types of these are known from the study regions, notably sand ribbons, sand waves, sand banks and gravel waves (see Figures 90 and 91: Cameron et al, 1992; Hamblin et al, 1992).

Many of these would have formed when rising sea levels reworked fluvially or glacially deposited sediments, but other examples may have formed more recently due to tidal action and wave currents. Areas of particular potential may be located in the vicinity of palaeo-valleys, as their fluvial terrace deposits may well have provided the sediment supply for both syn- and post-transgressive processes. The extent of reworking is likely to range from the formation of a sea bed lag to the total modification of the deposit, depending on factors such as the composition of the sediment, the amount of times it has suffered transgression and regression and the local hydrodynamic regime (Selby, 1992). It has been suggested that with the exception of the gravel waves between the South Falls and the Sandettie Banks (see Figure 91), most relict Pleistocene fluvial and glacial gravel deposits in the southern North Sea have not been reworked to a significant degree despite the presence of strong tidal currents (Cameron et al, 1992). If this were true it would enhance the archaeological potential of these deposits. As the exact nature of what a archaeological tertiary context looks like is unknown at present, their ability to aid in research questions is uncertain. Nevertheless, they should be able to at last provide indications of hominid presence or absence within a given area, at a particular time, if the artefacts can be dated. Therefore, in some ways they occupy the niche previously occupied by secondary contexts (see section 3.1.4) before they were found to be of use with respect to addressing long term patterns of hominid demography (e.g. Ashton & Lewis, 2002). Given this precedent, it would be prudent to not to designate these deposits as being of little use to current archaeological work as they may be valuable to future research.

Figures 90 and 91 illustrate the distribution of known areas of sediment movement. The archaeological potential of these deposits will be discussed further once marine taphonomic processes have been investigated further in Section 4.1 and 4.2.

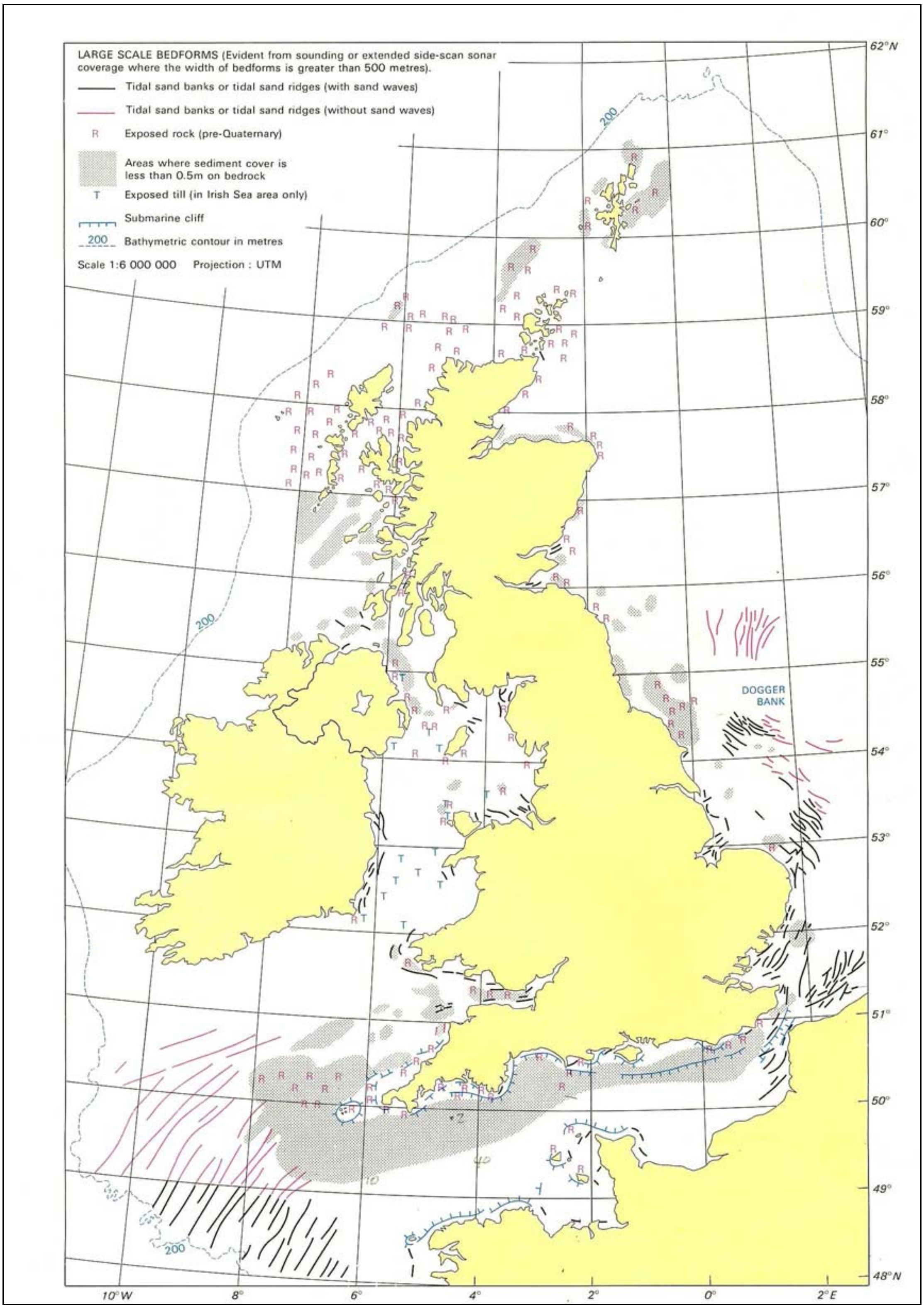


Figure 90. Areas of known sediment movement and hence potential tertiary contexts. Map shows large scale (width > than 500m) bedforms. Particular features to note are areas of thin, or no sediment cover, over bedrock, thus implying significant marine erosion. Archaeological sites in this area are most likely to take the form of marine formed secondary contexts or tertiary contexts (from Rippon, 1987).

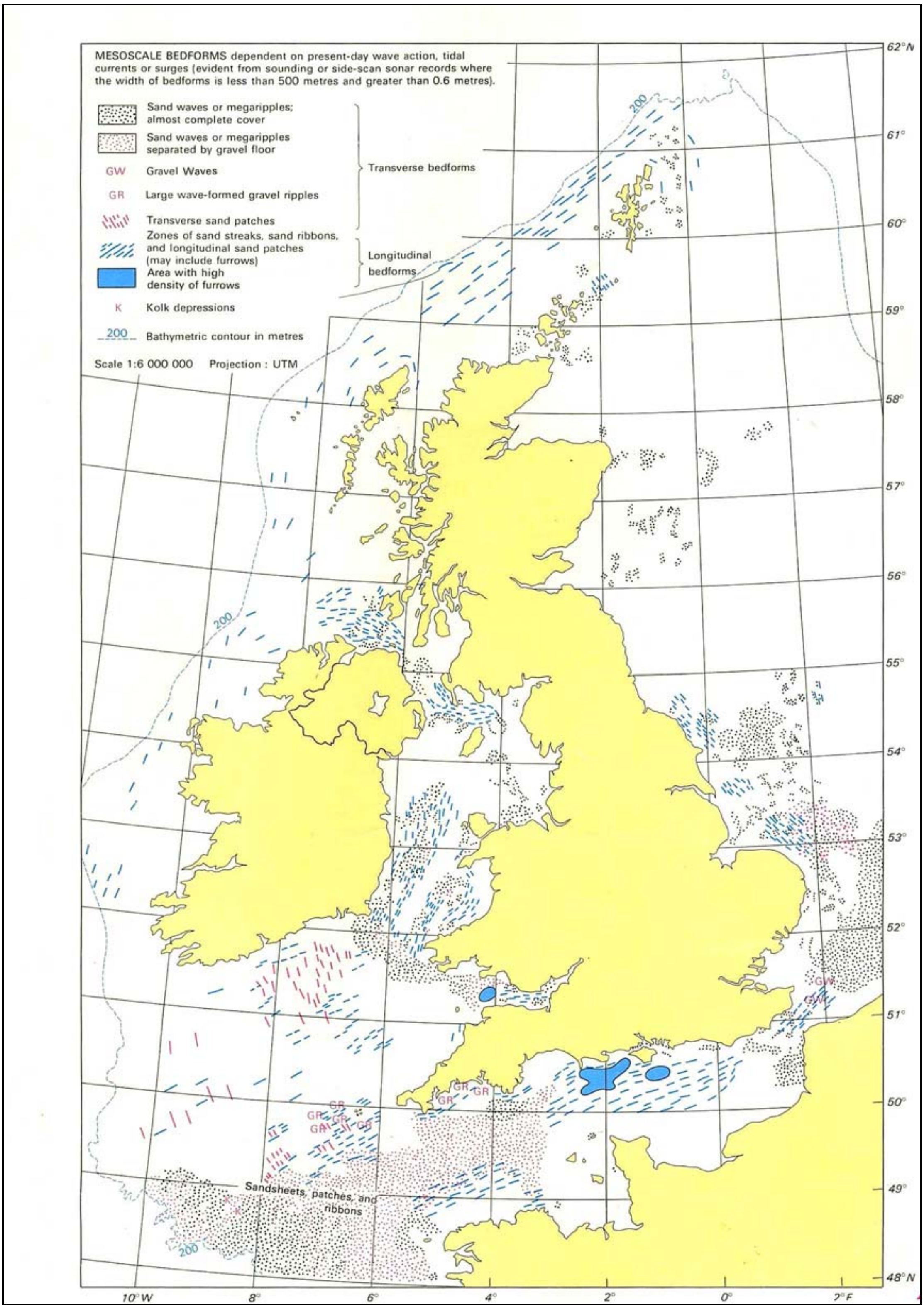


Figure 91. Areas of known sediment movement, and hence potential tertiary contexts. Map shows mesoscale (than 0.6m <width < than 500m) bedforms. Particular features to note are areas of gravel waves and gravel ripples. These imply that current movements are strong may be strong enough to rework and displace archaeological material (from Rippon, 1987).

3.6 Submerged Contexts

3.6.1 Background

Some submerged evidence for these periods has actually been located in the North Sea and English Channel regions (see Flemming, 2002 for a comprehensive review). Some of it comes from relatively secure stratigraphic and spatial contexts, and can be dated. For the purposes of this section these will be classified as sites. In addition, there are also substantial collections of material, often obtained inadvertently by dredging or trawling. These have not been classified as 'sites' on the basis that the exact provenance and dating of the material culture are not securely known. Figure 92 illustrates the distribution of these sites and collections.

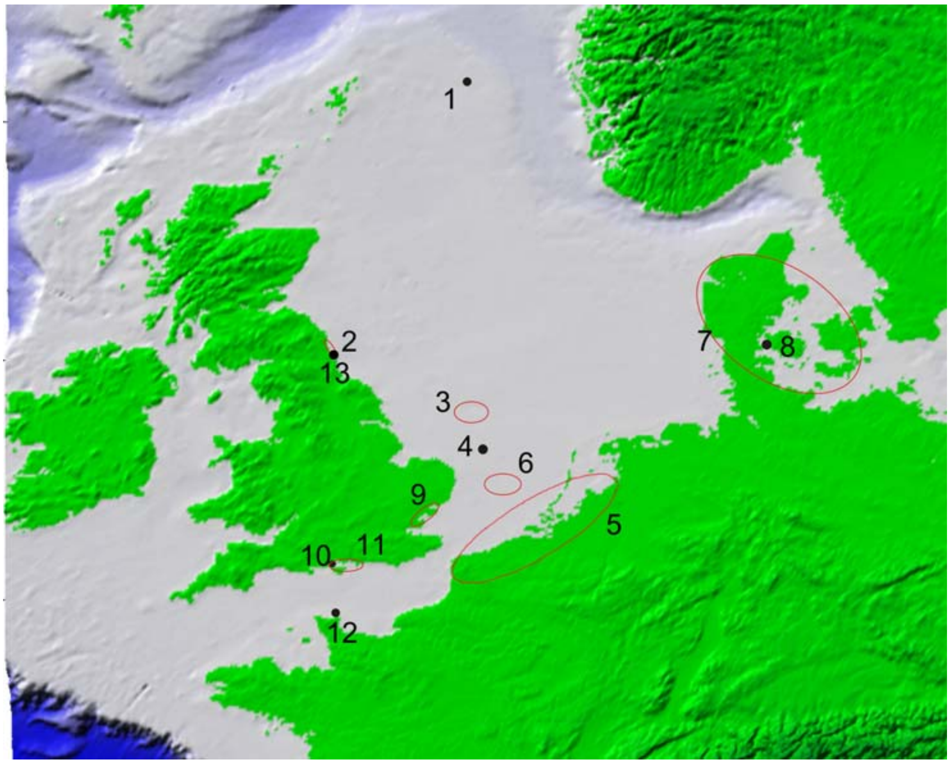


Figure 92. Location of submerged sites and collections mentioned in the text. Black dots = individual sites. Open ellipses = collections or large concentrations of individual sites. (1). Viking Bank Core. (2) Northeast of England. (3) Dogger Bank. (4) Leman and Ower point. (5) Various collections of finds from Dutch and Belgian waters. (6) Brown Ridge. (7) Various Scandinavian sites. (8) Tybrind Vig. (9) Essex Coast. (10) Bouldnor Cliff. (11) The Solent. (12) Fermanville (13) Gateshead.

3.6.2 Sites

- *Viking Bank*

A worked flint has been recovered from a vibrocore taken from the Viking Bank area of the North Sea at a depth of 143m. It has been attributed typologically to the Upper Palaeolithic but its exact function is unknown, as it is broken and incomplete. The flint itself is believed to have derived from a terrestrial archaeological site prior to marine transgression and then became incorporated into a layer of Holocene sediment. Geological investigations of the seabed sediment indicate that this area was transgressed by 9 ka BP, thus providing a minimum age for any terrestrial archaeological sites in the area (Long et al, 1986).

- *Bouldnor Cliff*

An early Mesolithic site has been located and excavated at Bouldnor Cliff in the Solent. The site is located at the base of an underwater cliff in 11m of water and has produced over 300 worked flints. Dendrochronological dating of timber from the remains of a submerged forest associated has provided dates of c.8 to 8.5 ka BP (Momber, 2000, 2001).

Work is currently being undertaken by the Hampshire and Wight Trust for Maritime Archaeology (http://www.soc.soton.ac.uk/HWTMA/).

- *Fermanville, Cherbourg*

Levallois-Mousterian tools dating to c. 45 ka BP have been found eroding out of peat deposits in a water depth of 25m. The peat beds appear to form the sides of a gully which has been interpreted as a submerged stream bed (Flemming, 1998, 2002).

- *Scandinavia*

Quite literally hundreds of late Palaeolithic, Mesolithic and Neolithic sites have been located in the waters off southern Scandinavia. These range from scatters of worked flints (Figure 93) situated on the seabed surface to full scale settlements, such as Tybrind Vig (see section 3.3.5.3), embedded in the sediment. To go into the details of these sites would require an entire separate review. For more information, see Pedersen et al (1997) and Fischer (1995a). Both volumes contain comprehensive overviews of the areas in question.

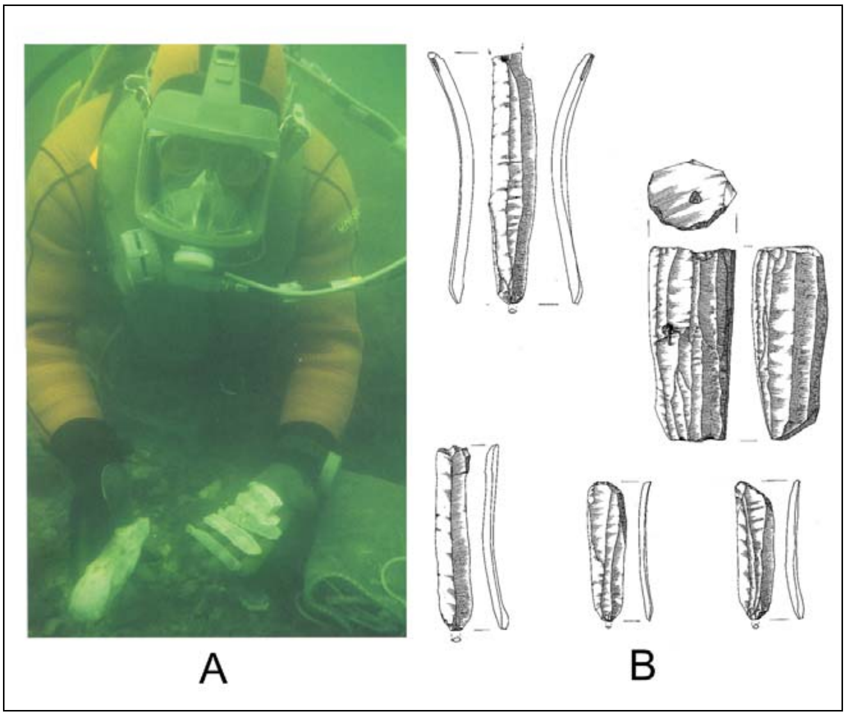


Figure 93. A) Collection of lithic artefacts from the underwater site of Stavreshoved (Denmark). B) Examples of the blades and cores recovered from the Stavreshoved site (after Pedersen et al, 1997)

- *Leman and Ower Bank*

In 1931 the trawler *Colinda* dredged up a barbed bone weapon tip that was embedded in a lump of peat from about 36m water depth (Figure 94). The point is similar to many examples from the late Upper Palaeolithic terrestrial record and is AMS dated to c.11,740 +/-150 BP(Smith & Bonsall, 1991; Coles, 1998; Barton, 1999).

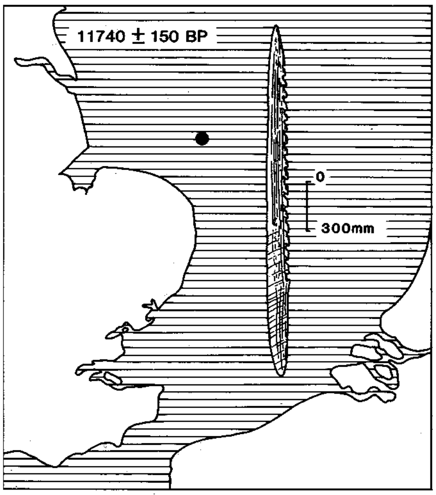


Figure 94. The Leman and Ower point and the location from where it was recovered (from Smith, 1992)

- *Gateshead*

In 2003 a number of lithic artefacts were recovered by scuba divers from the waters off Tynemouth. These range from Early Mesolithic (10 to 8.5 ka BP) pieces recovered from 6-8m of water to Late Mesolithic (8.5 to 5 ka BP) material from the intertidal zone to 4m depth. The artefacts include flakes, blades, scrapers and cores and appear to be water rolled. They are believed to have been originally deposited on the presently submerged Mesolithic shoreline (SALT, 2003).

3.6.3 Collections of material from insecure contexts

- *Brown Ridge and Dogger Bank*

Quite literally hundreds of worked flint, bone artefacts and tonnes of Pleistocene faunal remains have been dredged up by fishermen from these areas of the North Sea (Flemming, 2002). Beyond the general location of these areas, little is known about their stratigraphic context, and the spatial patterning of the assemblages.

- *The Solent*

Peat beds in the Solent are a rich source of lithics. With the exception of Bouldnor Cliff though, little is known about the context of these lithics as they tend to be obtained by dredging (Momber, 2000).

- *Dutch and Belgian waters*

A similar situation to the above is known in Holland and Belgium where dredging operations and harbour constructions have uncovered large numbers of flint artefacts (Flemming, 2002).

- *Essex Coast*

Surveys in the intertidal zone along the coast have resulted in the collection of several hundred lithics, many of them Mesolithic. Denser scatters of Mesolithic implements are known from two sites – Crouch Site 4 and Blackwater Site 3. Both these have been interpreted as inland sites located adjacent to freshwater stream well inland of the tidal limit. The artefacts were then covered by sediment as the sites were inundated. Their exposure and discovery is attributed to the recent erosion of the sediment at these locations (Wilkinson & Murphy, 1995; Fulford et al, 1997).

- *North East Coast of England*

A submerged forest is known to exist in the waters off Hartlepool. While the bulk of it is underwater, parts of it can be observed at very low tide. Investigation of these areas has resulted in the collection of a number of worked flints, including cores, debitage, microliths and microburins from peat bed associated with the forest. The artefacts were typologically assigned to the Maglemose, an early Mesolithic technocomplex (Trechmann, 1936; Fulford et al, 1997).

Much of this material finds its way into private collections or local or regional museums, both in Britain and the Low Countries (Flemming, 2002), and as a result the information on them is rather diverse and spread out. In this country at least, this situation is currently being remedied by Wessex Archaeology's ALSF project *"Artefacts from the Sea"* which is designed to enhance information in the existing Sites and Monuments Records (Wessex Archaeology, 2003).

3.7 Summary and Discussion

Any review or assessment of archaeological potential should entail an understanding of the type of archaeological material that might be encountered, its state of preservation and its interpretative potential. To this end this chapter has highlighted the following:

- Broad-scale patterns can be detected in the archaeological record of the areas adjacent to the North Sea and English Channel regions. The implication is that the patterns apply to these submerged landscapes as well to a certain extent, and thus should provide some indication as to the sorts of prehistoric archaeology that are likely to be encountered on, or below, the seabed.

- Glaciation has provided certain limits on the distribution of archaeological material. Large areas of the central and northern North Sea have suffered extensively destructive glacial erosive processes and therefore are unlikely to contain a great deal of useful archaeological material from prior to the Last Glacial Maximum. They may however be a rich source of post-LGM material. The southern North Sea and English Channel though may have been less intensively affected and hence are more likely to contain a variety of deposits possibly dating back as far as 500 ka BP.

- Sites are found in a variety of location at different points in time. With respect to hominid preference, worthwhile areas of potential appear to be located in river valleys. Lakeshores also appear to be attractive areas, especially in the earlier periods while areas with geology susceptible to cave formation should also be considered. On a finer scale, settlement patterns are also likely to be determined by the distribution of both raw material, such as flint, and subsistence activities or resources, such as topographically based hunting strategies.

- In terms of preservation, there is likely to be a continuum ranging from significantly reworked deposits to sites in which the archaeology has maintained nearly the same spatial integrity since the time of deposition. Work on these primary and secondary contexts on land has revealed that both sorts of deposits can provide very useful insights into past societies. A large part of the secondary context evidence will be contained in preserved fluvial river terraces, examples of which are known underwater. However, marine and transgressive reworking may have lead to the creation of secondary contexts as well. Developing an understanding of the potential of these contexts is important, especially with respect to Upper Palaeolithic and Mesolithic research, which at this point in time, have not really had to contend with this issue.

- The dynamic nature of the marine environment necessitates the consideration of a third category – tertiary contexts. These represent reworked terrestrially formed secondary contexts. Their archaeological potential is uncertain but it should not be discounted until further research has been undertaken. At present, potential areas of tertiary context are areas of significant sediment movement (inferred on the basis of bedforms) in the vicinity of possible terrestrial secondary contexts (e.g. fluvial terraces) which may have provided a sediment supply during and after phases of transgression.

- The impact of short-term climatic fluctuations such as Dansgaard/Oeschger oscillations on sea level and transgressive events has to be examined further as they are likely to have an influence on shoreline position. Rapids oscillations of sea level within glacial/interglacial cycles may also enhance the marine reworking of archaeological material and reduce the possibility of finding in situ primary contexts exist.

- In terms of the actual material culture, the most common forms of evidence are scatters of worked stone and bone. However, given the anaerobic environments underwater, preservation may be considerably enhanced, and this could lead to the possibility that organic artefacts, such as those made on wood, may also be found. Better organic preservation could provide evidence which would enhance our knowledge of past societies both in terms of the material culture they possessed, which in turn could allow insights into their social lives, and the palaeo-environments they inhabited.

- Submerged prehistoric archaeological evidence can potentially assist in a number of current research questions. Among these are the ‘traditional’ questions concerning patterns of colonization and migration, notably the timing and entry of hominids into Britain and the routes they took. However, integrated with this should be a more secure understanding of how this process took place, and the role that the long-term occupation of areas such as the North Sea played in it. Further important questions concern the development and extent of coastal occupation throughout prehistory, a subject which the terrestrial record in isolation cannot address to a significant degree, and the impact of sea level change on past societies.

It should be stressed that this is not a predictive model. Sites have been looked at only in very general terms and the relationships between resources, topography, site location and so on have not been quantified or examined on local scales. Whether or not this information can be integrated into a predictive modelled will be discussed in Section 5. Furthermore, the syn- and post-transgressive processes acting on the archaeological material have not yet been brought into the equation. In the light of the dynamism of the marine environment, and the probability that it will have resulted in the creation of many secondary and tertiary context assemblages, an enhanced understanding of the way in which it does this is necessary. Consequently, the next Section (4), will attempt to address this issue.

4. Theme 3: The modification of continental shelf archaeology by transgression and regression

The previous chapters have described the issues involved in reconstructing submerged landscapes (Section 2: Theme 1) and examined the potential of submerged archaeological material (Section 3: Theme 2). The intention of this chapter is to assess the impact that the process of transgression and regression during the sea level cycle have on both landscapes and deposits of archaeological material.

Critical to this discussion are concepts of scale. This is highlighted by the fact that continental shelves are exceedingly dynamic areas, with the capacity to change on a range of temporal and spatial scales ranging from millimetres and microseconds to thousands of kilometres and millions of years (Figure 95: Sternberg and Newell, 1999; Schwarzer et al, 2003).

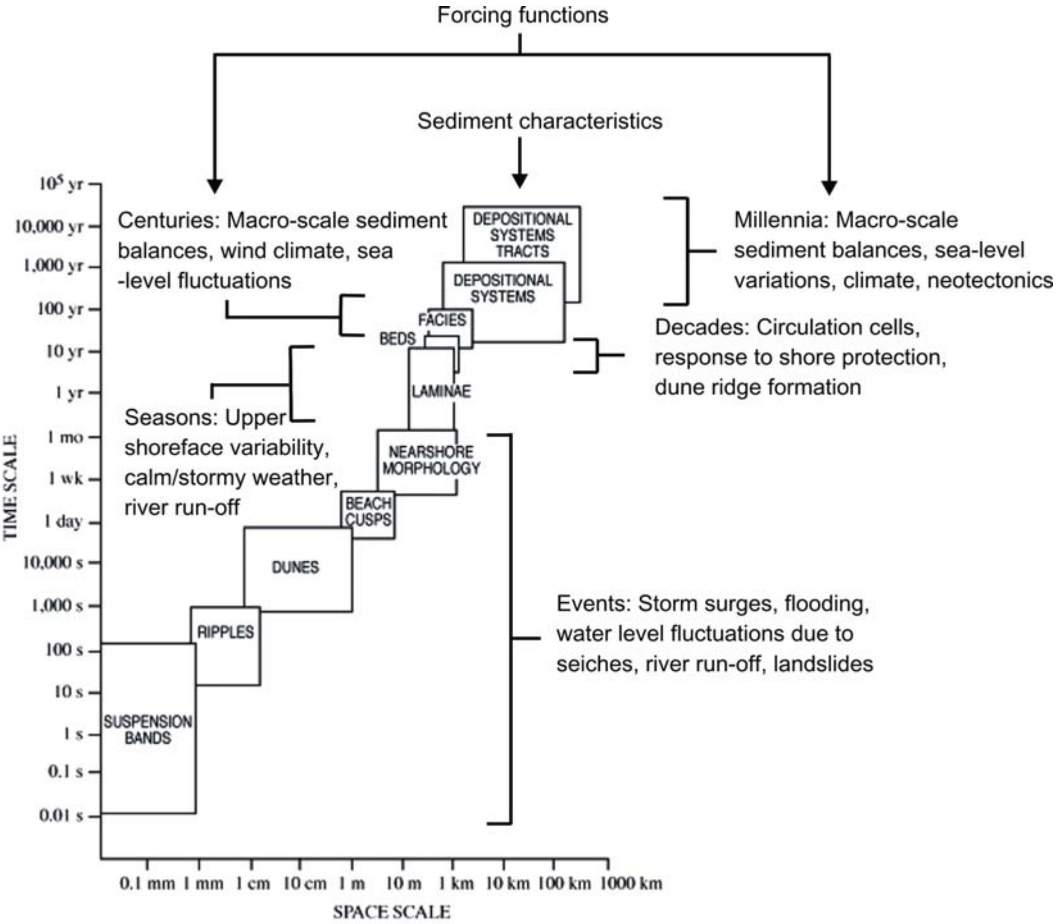


Figure 95. Timescale of forces operating in coastal evolution and the characteristic sedimentary features they create (modified from Schwarzer, 2003; Sternberg & Newell, 1999)

Processes operating at different scales have the potential to affect archaeological material in different ways and also provide information which may be suited to addressing particular research questions (see Section 3: Theme 2 for a discussion of primary versus secondary contexts).

This document is therefore divided into two parts Section 4.1 seeks to understand large scale responses of coastlines and continental shelves to marine transgression and regression while Section 4.2 examines the responses of individual deposits of archaeological material to transgressive and regressive forces. Section 4.1 should therefore assist in addressing some of the issues involved in the large scale reconstruction of submerged landscapes while Section 4.2 has a role in assessing the extent of reworking that individual deposits of archaeological material are likely to be subject to.

4.1 Shoreline and Continental Shelf Responses

4.1.1. Introduction

An examination of the available literature and techniques of palaeogeographic reconstruction have highlighted that most attempts make use of present day seabed bathymetry (Section 2.5). However, questions have been raised as to whether the present-day seabed is an accurate representation of the sub-aerial landscape at sea level lowstands (Section 2.5) or whether it has been significantly modified (buried, eroded or reworked) by cycles of sea level change. Modification of the landscape could occur as a result of processes operating sub-aerially prior to transgression, during transgression (syn-transgressive), during regression (syn-regressive) and after trans- or regression (post-trans- or regressive). This final stage is commonly referred to as a ‘stillstand’. It is outside the scope of this project to consider the processes operating sub-aerially when the continental shelf is exposed because of marine regression. The aims of this chapter therefore are to:

- Determine the impact of transgressive and regressive processes on shoreline morphology both during, and after transgression and regression.
- Determine the impact of marine processes on the continental shelf, both during, and after transgression and regression.

An examination of the impact of transgressive processes on shoreline and shelf morphology should demonstrate the extent of modification, thus determining how close an analogue the present day shelf is to the sub-aerial lowstand landscape. The impact of regressive processes will also have to be looked at since sea level has undergone multiple large scale fluctuations over the Quaternary. Hence any archaeological landscapes dating from prior to the Last Glacial Maximum (LGM) lowstand may have been modified by regressive as well as transgressive processes.

The issue of trans- and regressive modification of the landscape has been recognised by a number of researchers (e.g. Garrison, 1991; Coles, 1998; Shennan et al, 2000). However, its effects have rarely been considered when reconstructing the extent of past coastlines. Section 2 (Theme 1) has highlighted the error margins in shoreline position that could result from this. Unfortunately, most reconstructions simply use present day sea floor bathymetry as an analogue to that of the past landsurface (e.g. Lambeck, 1995; Shennan et al, 2000). Again, this approach is perfectly acceptable if all that is required is a broad sense of palaeogeographic space, but we have to question whether it provides a level of accuracy sufficient for more regional and local archaeological research of continental shelves, especially in areas that may have suffered significant erosion or deposition during and after transgression.

The situation is somewhat better when it comes to reconstructing the actual pre-submergence makeup of the past landsurface (i.e. its geomorphology and topography). A number of researchers (e.g. Bridgland, 2002; Catteno & Steel, 2002; Bourillet et al, 2003) have focused intensively on this subject, and consequently there does exist a substantial body of work concerning the extent of large scale subaerially formed features on the shelf. This work is overwhelmingly geological in focus, (e.g. Cameron et al, 1992; Hamblin, 1992), but elements have been adopted by archaeologists in order to present a more realistic picture of emergent shelves at lowstands (e.g. Coles, 1998; Flemming, 2002). From a purely archaeological point of view, this situation has arisen as a result of the general lack of interest in submerged areas, and the fact that existing work has focussed on specific sites, rather than landscapes, where detailed, but very localized, reconstructions can be made (e.g. Geddes et al, 1983) or very broad studies where a rough outline of the position of past coastlines is all that is required (see Section 2.1).

This is not to say that archaeologists are unaware of, or are lagging behind the geological community. In fact, it is only fairly recently that very detailed geological reconstructions of past shelves and changes induced by transgressions and regression have come about (e.g. Bridgland, 2002; Bourillet et al, 2003; Reynaud, 2003; Van der Molen et al, 2004). Consequently, geological evidence from shelves is still incomplete and gaps do exist in the understanding of their past nature. This is illustrated by the initiation of two major International Geological Correlation Program (IGCP) Projects; Project 396 – *The record of continental shelves during the Quaternary, their interpretation, correlation and applications* - which ran from 1996 to 2000 (Yim, 2000), and its follow up; Project 494 – *Continental shelves during the Last Glacial Cycle: knowledge and applications* (2001-2005: Yim et al, 2002). Among the aims of these projects were the investigation of palaeoenvironmental changes on continental shelves and the impact of sea level change (Yim et al, 2002). Clearly, there is still a great deal of work to be done which will aid future palaeo-landscape reconstruction and which in turn will facilitate archaeological research, and furthermore, this also illustrates the value that the continental shelves have to other disciplines.

In addition to these recent studies of the impact of past sea level change on the shelf, a number of models have recently been developed to assess coastal evolution in the face of present day sea level rise (e.g. Carter & Woodroffe, 1994b; Pethick, 2001). Although present day processes or environments may not be exact analogues to those of the past, these models may provide indications of the sorts of coastal changes that could have potentially taken place in the past but which are not preserved in the stratigraphic record.

From the archaeological perspective, its is worth reviewing why the misconception that marine transgressions simply flood a landscape, leaving it broadly unchanged, thus allowing modern continental shelf topography to be used as a representation of the past landsurface, may have arisen (Stride, 1982). One reason is the terminology that surrounds continental shelves. Shelves are frequently described as ‘relict’; however this should not be taken to mean that they are fossilized or unchanged landscapes. Use of the term ‘relict’ was first applied by Emery (1968) on the basis that shelf surface sediments appeared to have been deposited prior to the mid-Holocene highstand in sea level, and that they thus represented deposits created at times of lower sea level (Stride, 1982). ‘Relict’ in this case is a chronological definition and does not preclude the possibility that these sediments were reworked, both by the transgressive event itself and post-transgressive processes, thus altering the geomorphology and topography of the original terrestrial landscape (Emery, 1968; Stride 1982).

"Relict sediments can be identified by and defined by their anomalous composition, grain size, and grain surfaces, even though they may have been moved about in response to their new environments" (Emery, 1968:446)

In all fairness, structural features may be defined as 'relict' in the sense that they have been inherited from an earlier time period, and while examples of these may exist on continental shelves; it is inaccurate to think of shelves entirely in this fashion.

The difficulty lies in the fact that the difference between the two definitions is rarely explicitly expressed in the literature and consequently care should be taken. In reality, studies have indicated that deposits on continental shelves do in fact respond to modern hydrological processes, and thus the notion of the continental shelves as an untouched landscape is rendered invalid (Stride, 1982; Swift & Thorne, 1991; Nittrouer & Wright, 1994).

"Modern shelves are, to a greater or lesser extent, relict in the sense that pre-Holocene sediment is exposed and is being current-reworked" (Leeder, 1999:444)

Admittedly, there are cases in which the present-day seabed has provided a reasonably accurate analogue to the past landscape. The Danish 'fishing site' predictive model (see Section 4) was based on correlating present-day bathymetric contours with the most suitable topographic locations for fishing with standing gear and proved remarkably effective in locating archaeological material. Even so, there were occasions where the relief of the original prehistoric landscape was obscured by more recent sediments, thus reducing the effectiveness of the predictive approach based on modern bathymetry (Fischer, 1995b; Fischer & Pedersen, 1997). Furthermore, bathymetric models may be useful in sediment starved areas, such as the limestone regions of North-West Florida, where a paucity of clastic erosional material and resulting low sedimentation rate means that terrestrial features (e.g. sinkholes and river channels) can still be visually identified underwater (Figure 96: Dunbar et al, 1991).

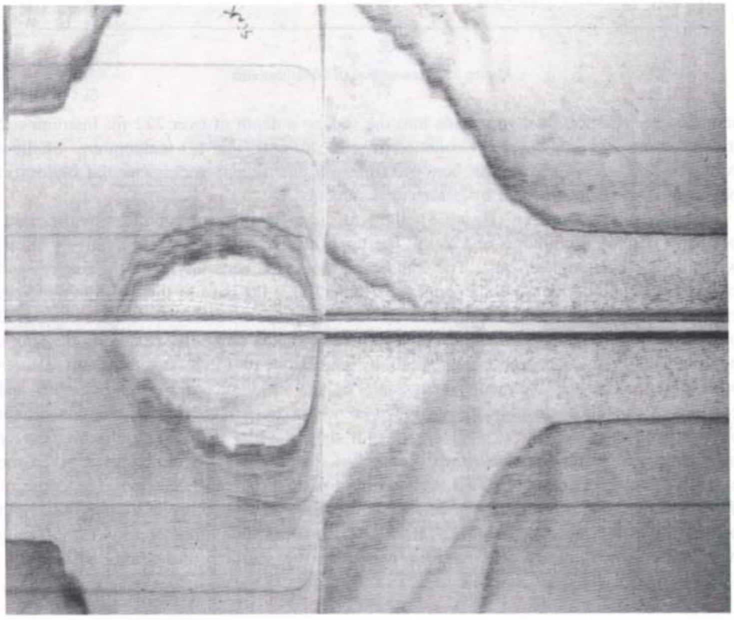


Figure 96. Sidescan sonar image of a karstic sinkhole in 175m water depth off North-West Florida (from Garrison, 1991).

Recent advances in sonar technology, and in particular swath bathymetry, means that very high resolution imagery of shelf topography is now available for palaeo-landscape and archaeological interpretation and is beginning to be used widely (e.g. Fedje & Josenhans, 2000; Mandryk et al, 2001 - Figure 97). However, the archaeological usefulness of such data is reliant upon a well preserved yet exposed pre-submergent land surface being present. It is therefore essential to identify if the sheltered archipelago environments, such as the south Scandinavian situation, or a sediment starved karstic area, as in north-west Florida, are typical of shelf conditions.

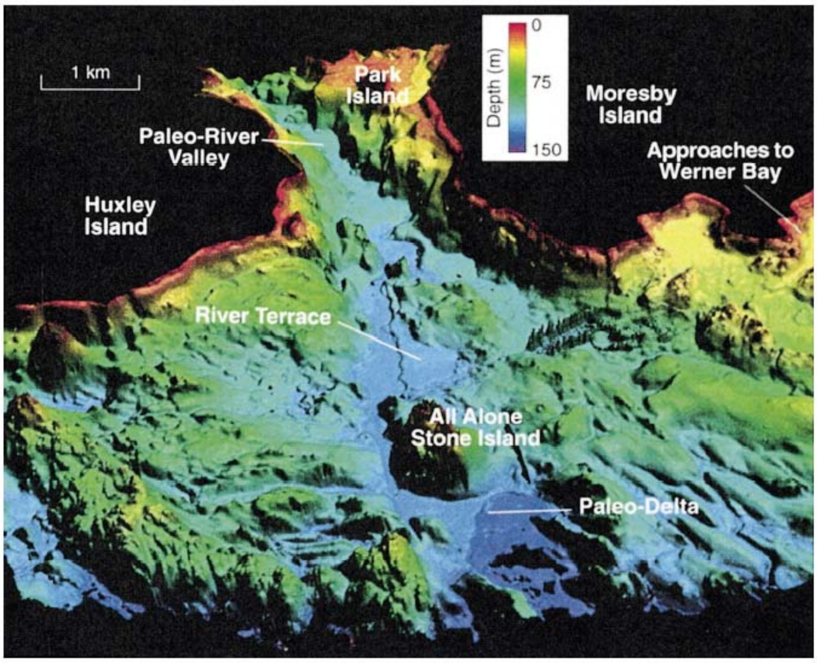


Figure 97. Multibeam bathymetry map of the southern Juan Perez Strait (British Columbia, Canada) processed into a digital terrain model. The data has a spatial accuracy of +/- 1m. Note the identification of geomorphic features created at sea level lowstands (e.g. palaeo-delta) (from Mandryk et al, 2001)

Many parts of the continental shelf are characterised by significant accumulation of syn- and post-transgressive sediments. This can be seen in some sections of the submerged English Channel river systems (see Section 3.4.3). For example Figure 98 represents a sub-bottom boomer profile from the outer section of the Arun River system, showing in excess of 17 m of unconsolidated Holocene sedimentary fill. This results in a significant smoothing of the seabed contours in this locality (Figure 99) by comparison to the obviously incised palaeo-channel described by the bedrock surface (Figure 99). The full history of this sequence is currently being explored as part of PD3363 in collaboration of the more extensive surface and sub-surface studies of upstream parts of the submerged Arun river system (PD3277) and Wessex Archaeology.

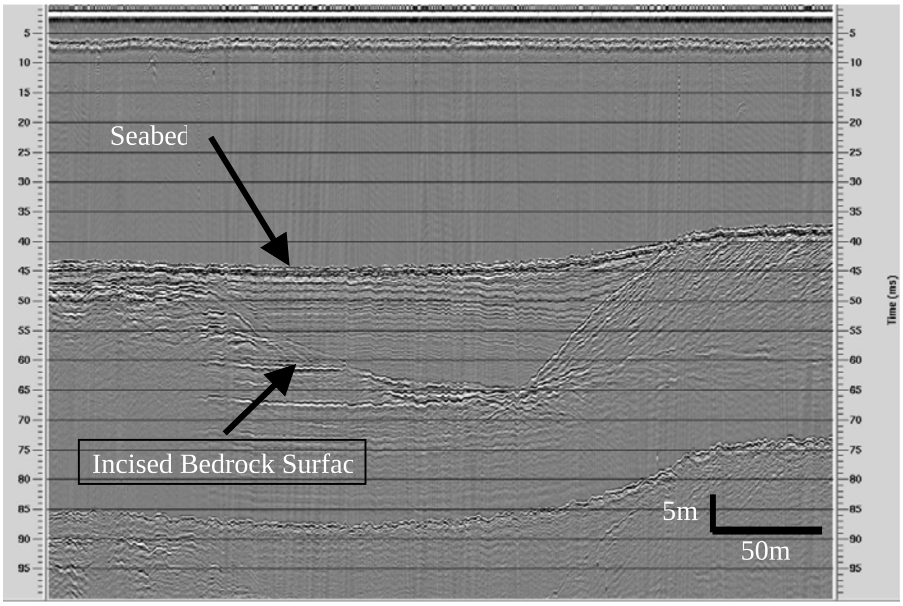


Figure 98. Seismic section of buried palaeo-channel associated with outer sections of the submerged Arun palaeo-valley showing seabed and incised bedrock horizons. Data courtesy of Wessex Archaeology.

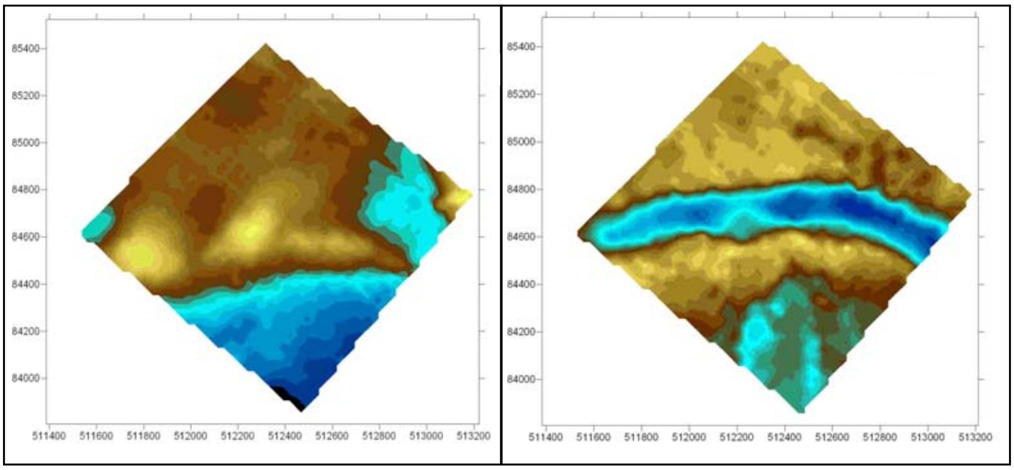


Figure 99. Contour maps based on the interpretation of seismic data from the outer section of submerged Arun palaeo-valley. The clear channel identified in the bedrock contour map on the right is not identifiable in the seabed bathymetry shown on the left. Each square represents an identical 1 km block.

4.1.2 Geomorphological Responses to Sea Level Change on Shores and Shelves

Studies of continental shelves have indicated that over geological timescales (i.e millions of years) their physical environment assumes the form of a predictable 'regime' (Swift & Thorne, 1991; Thorne & Swift, 1991). This is illustrated by the characteristic shelf-slope configuration developed by all shelves (Figure 100). This consists of relatively steep slopes close to the shoreline. They then slope gently (average gradient of 1 in 500) down to the shelf break, whereupon they drop rapidly (average gradient of 1 in 20) down the depths of the ocean basin (Pickard & Emery, 1990; Swift & Thorne, 1991). This profile is the result of a dynamic equilibrium created by the complex interactions of five variables on sub-geological timescales.

These variables are:

- Rate of sediment input from landward sources
- Type of sediment input
- Rate and direction of relative sea level change
- Rate of dispersive sediment transport
- Variations in the fluid power of shelf currents

These variables vary the rate and magnitude of sediment deposition on the shelf through sediment supply and the fluid power available to remove it. As the system is in dynamic equilibrium, any change in one variable, results in a change in the sedimentary regime, such that the change is compensated for by an adjustment of one of the other variables. Consequently, sediment accumulates up to the point at which wave energy is sufficient to mobilize it (wave base). As wave base is approached, the ratio of sediment deposited to sediment bypassed decreases. Given that vertical aggradation is no longer possible, the locus of deposition shifts seaward to the forward face of the sediment pile to form the continental slope – a steeply sloping surface dominated by gravity driven processes, thus forming the characteristic equilibrium shelf profile (Swift & Thorne, 1991). The overall seaward deepening profile is a consequence of the fact that sediment input is higher closer to the shore, as a result of fluvial discharge and coastal erosion, and that wave energy decreases as the waves propagate landward and hence wave base operates at a lesser depth than further seaward on the shelf. Continual subsidence resulting from the accumulated weight of sediment allows the continual aggradation of sediment up to wave base (Swift & Thorne, 1991).

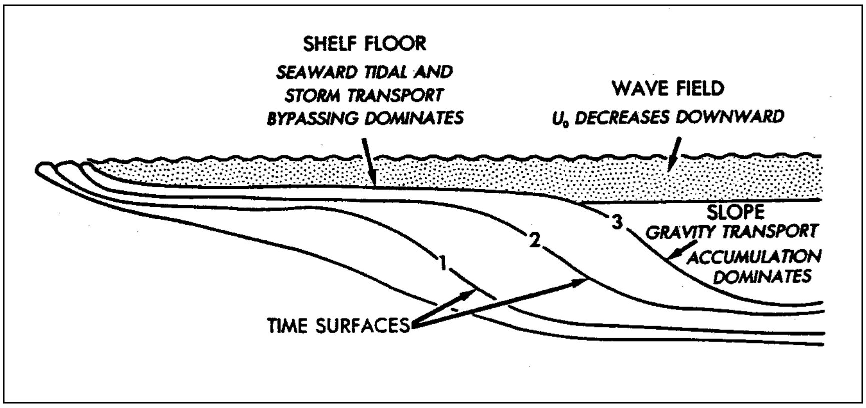


Figure 100. Schematic illustration of the long term evolution of a shelf and the components of the classic shelf profile (from Swift & Throne, 1991).

From the perspective of archaeological research, or indeed palaeo-landscape reconstruction, the temporal and spatial scales of interest are somewhat smaller than those of large-scale shelf studies, at most usually involving thousands to tens of thousands of years and tens to hundreds of kilometres. Thus, at these scales, it is the changes amongst the above five variables that are important rather than the very long term equilibrium of the shelf surface.

Generic models of stratigraphic system variability in response to the sea level cycle (and hence on a temporal and spatial scale relevant to archaeology) identifies a series of lowstand, highstand, transgressive system tracts (e.g. Woodroffe, 2003 - Figure 101).

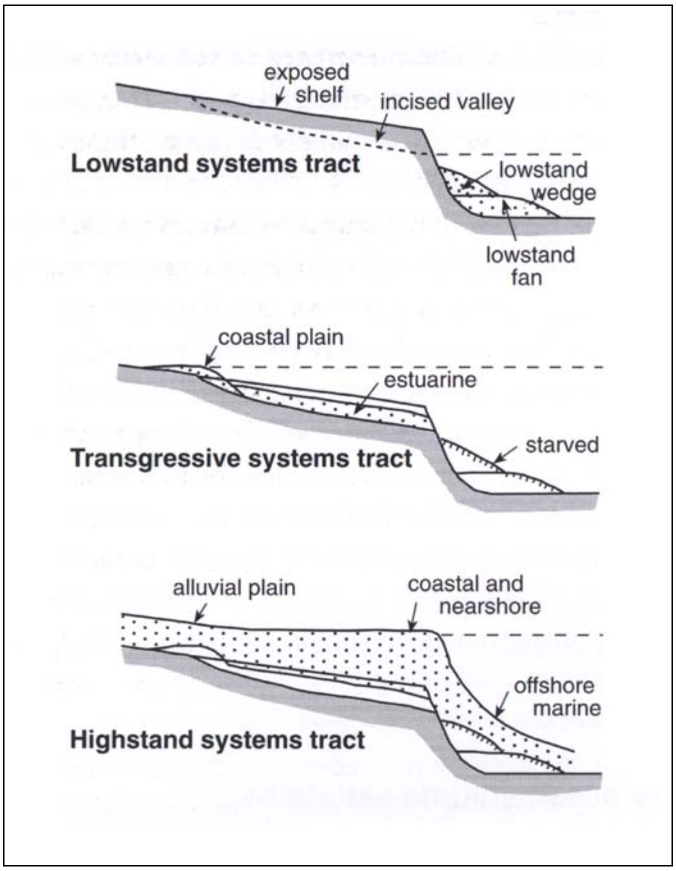


Figure 101. Illustration of the development of different depositional systems, and hence different coastal geomorphology under changing conditions of sea level (after Woodroffe, 2003).

In order to understand the process by which these system tracts develop, it is necessary to investigate the actual role of sea level change, and equally importantly, sediment supply in determining the nature of the shelf deposition regime. This interplay results in the formation of one of two basic regimes (Figure 104):

- *Supply dominated regimes (regressive depositional systems)*

  Under these circumstances, the rate of sediment input is greater than the rate of sea level rise and the ability of marine processes to remove it. In essence the supply of sediment exceeds the quantity of available accommodation space. This can be created either by an excess of sediment input, or a relative sea level fall which creates a decrease in local accommodation space. In the former case, progradational regression may take place, while in the latter case forced regression takes place (see Section 2.2.5 for detail). The deposits laid down by these regimes are thick, fine grained and homogenous, and are known as regressive depositional systems.

- *Accommodation dominated regimes (transgressive depositional systems)*

In contrast, in these regimes the rate of sea level rise and effect of marine processes exceeds the rate of sediment input. Thus accommodation exceeds supply and either forced or erosional transgression may take place depending on whether the dominant factor is sea level rise or sediment supply (see Section 2.2.5 for detail). The resulting transgressive depositional systems are thin, coarse grained and heterogeneous.

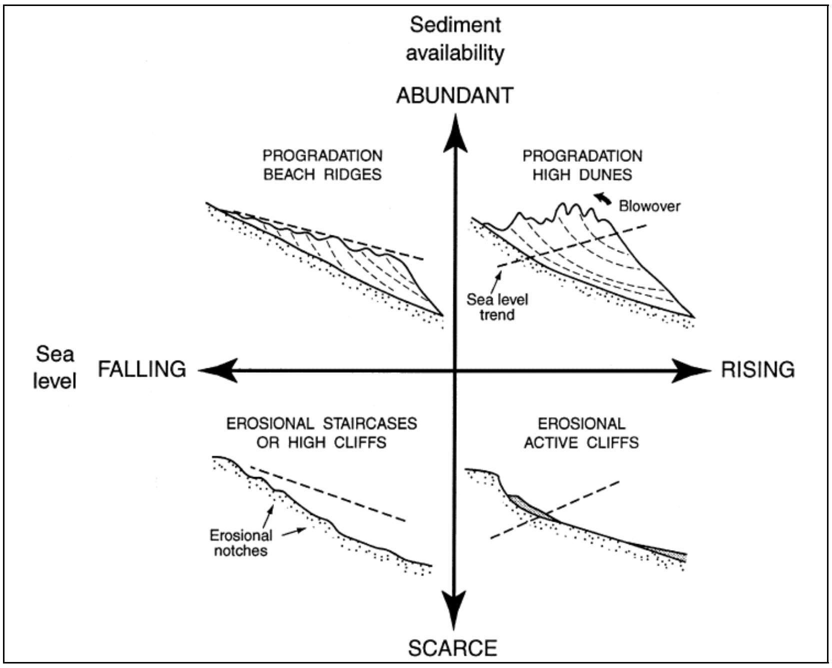


Figure 102. Response of coastlines to the interaction between sediment supply and relative sea level. Note that progradation can occur under conditions of rising sea level provided there is an abundant sediment supply, while transgression (represented here by erosion) is possible under falling sea levels if the sediment supply is scarce. The top two cases represent supply dominated regimes, while the bottom two depict accommodation dominated regimes (from Hansom, 2001).

Clearly the dynamics of sea level change in conjunction with sediment availability and accommodation space plays an important role in determining the nature of coastal and shelf sedimentation, and hence the geomorphology of shelf and coastal sedimentary bodies within the overall shelf equilibrium profile (Swift & Thorne, 1991; Thorne & Swift, 1991; Hoselmann & Streif, 2004). This has been illustrated by recent modelling experiments which investigated the impact of basin-scale bathymetric changes in response to differing rates of sea level change (Van der Molen et al, 2004). Van der Molen et al’s computations focus on the basin-scale evolution of the seabed (hundreds of kilometres), span several tens of thousands of years, and represent various scenarios of sea-level change. Morphological features with length scales of tidal sandbanks and smaller were not included. Their results show that the basin will export sediment and deepen. Also, it will expand by the accumulation of eroded sediment in deeper waters. The deepening causes reduction of the flow velocities and the net sediment transport, resulting in decreasing rates of morphodynamic evolution. The feedback of the developing bed levels to the water motion is dominated by the increase in water depth, and much less by the seabed topography. Externally prescribed changes in sea level change the wavelengths of the tide and the seabed pattern and thus also change the speed of the morphodynamical evolution.

The effect of two additional factors, namely geological inheritance and climatic or oceanographic factors, also have to be considered in shelf and shoreline evolution (Carter & Woodroffe, 1994; Forbes & Syvitski, 1994; Hansom, 2001; Catteneo & Steel, 2002). Geological inheritance refers to the geological and topographic makeup of the landscape in question that has been created by various land-forming processes operating over the course of geological time (Roy et al, 1994). This includes factors such as gradient and lithology (Roy et al, 1994; Hansom, 2001). Climatic and oceanographic conditions refer to factors such as the local wave and tidal regime. The importance of these is that they control the local sediment transport pattern.

These processes (sea level change, sediment supply, geological inheritance and oceanographic conditions) operate over a series of timescales ranging from events (e.g. storm surges and landslides) to millennia (e.g. glacio-eustatic sea level change) (Schwarzer et al, 2003 - see Figure 95 for summary). The balance between these influences is such that changes in each of them have the potential to create changes in coastal morphology and shelf facies geometry (Swift & Thorne, 1991; Swift et al, 1991; Forbes & Syvitski, 1994). For instance, basin widening and increased fetch resulting from a sea level rise could potentially alter oceanographic factors, such as tidal current strength. Further modifications to current patterns could result from the changing coastal configurations and bathymetric shifts creating differing interactions between waves, sea floor and coastline. In addition, changes in sea level may also result in differential access to sediment sources and rates of supply. The aforementioned changes in current strength may in turn modify the rate of erosion (Forbes & Syvitski, 1994; Catteneo & Steel, 2002).

In summary, the dynamics of shoreline change and resulting stratigraphy of the transgressive and regressive deposits, and hence the makeup of the present continental shelf surface, is strongly dependent on the rate and sense of sea level change relative to sediment supply, basin physiography and energy distribution (Swift & Thorne, 1991; Catteneo & Steel, 2002).

The following sections will examine how coasts and shelves respond to transgression and regression, and how this may be reflected geomorphologically and stratigraphically. Although coastlines are an integral part of the continental shelf they will be discussed separately in this document. This results from the fact that marine processes and oceanographic conditions in coastal waters differ markedly from those operating further out to sea. These differences result from the relative shallowness of the water in coastal areas, the presence of the shoreline as a boundary to flow and the effects of fluvial input in coastal waters (Pickard & Emery, 1990). Further, the coastal environment will inevitably occur at all locations on the shelf at different times during the transgressive-regressive cycle and so can play a major role in the development of the whole shelf. Finally, as described in Section 1 the coastal zone may represent a key environment for Hominid evolution and hence require careful study.

For the purposes of this document, the shoreline, or coastline will be considered the point from the high water mark to the lower end of the shoreface, also known as the nearshore area (20 to 30m water depth: Leeder, 1999; Harris & Wiberg 2002), and the continental shelf the area from this point to the shelf break (Figure 103). This division has been chosen on the basis that below the depth of the shoreface, forces induced by wave action under ambient conditions cease to dominate sedimentary processes. It should be noted that the coast includes more than just beaches and cliffs, but also geomorphological features such as deltas, estuaries and lagoons.

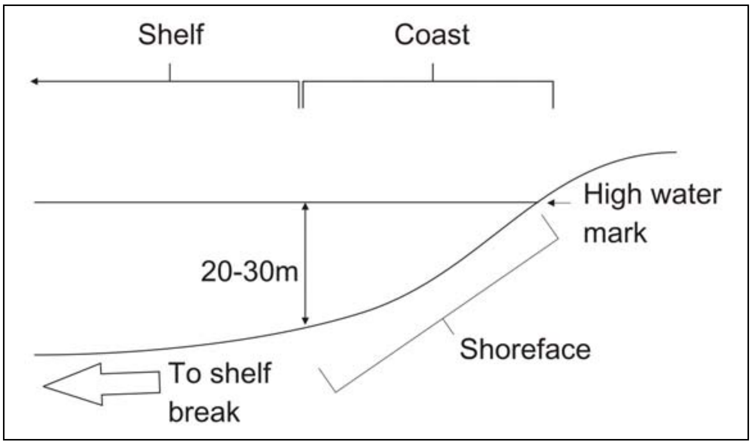


Figure 103. Division of coast and shelf adopted in this document

4.1.3 Response of Fluvial Systems to Sea Level Change

Prior to describing the effects of sea level change on coasts and shelves it is important to recognise that the effects of sea level change may reach an appreciable distance inland of the coastal margin. This effect can be particularly seen within fluvial systems which are in turn key in terms of both their importance in the evolution of terrestrial landscapes (Blum & Törnqvist, 2000), and from a strictly archaeological perspective, the advantages they afford for utilization and settlement by past humans (see Section 3: Theme 2). Blum & Törnqvist (2000) suggest that the landward limit of influence (defined as the intersection between the modern floodplain and the floodplain surface from the Last Glacial Maximum (c. 20 ka) lowstand – Figure 104) can vary from at least 300 – 400 km for low gradient, high sediment supply river systems to c. 40 km for steep gradient low sediment supply systems.

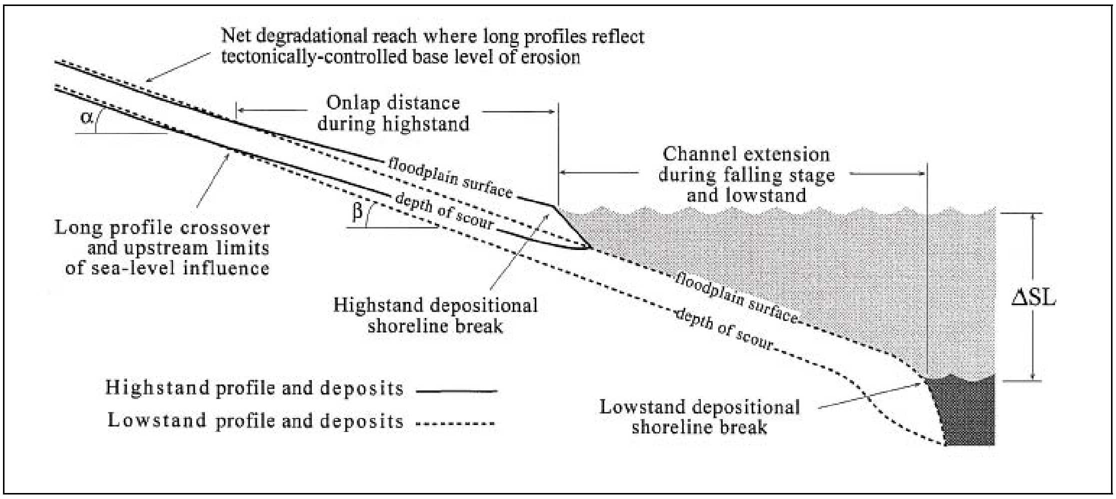


Figure 104. Schematic diagram showing the long profile response of a river system to sea level fall (from Blum & Törnqvist, 2000).

The major control of sea level change on fluvial system evolution is through its direct control on the altitude of a river systems base level; the imaginary horizontal surface to which subaerial erosion proceeds (Schumm, 1993). Riverine systems respond rapidly to changing base levels so the extent of fluvial material on the continental shelf is frequently related to the fluctuation in relative sea level. During lowstands fluvial systems (frequently enhanced by the high discharge rates associated with proglacial rivers) can extend all the way to the shelf edge (Bridgeland, 2000; 2002). This may result in the erosion of extensive drainage networks into the pre-existing shelf sediments or basement material and the deposition of associated sub-aerial facies (Gibbard & Latridou, 2003 and Section 3.4.3).

In addition, the drop in base level caused by sea level fall instigates deeper incision as the river seeks to return to its equilibrium profile (Figure 104). However, it should be noted that incision can be retarded to an extent if rates of sediment supply are high (Blum & Törnqvist, 2000). This resulting increase in gradient has also been postulated as the mechanism behind fluvial systems switching from meandering to braided patterns. In reality, studies suggest that other factors, notably increased sediment loads, higher discharge and channel bank instability may have more important, and consequently channel gradient changes cannot be seen as the sole driver behind this switch (Leigh et al, 2004).

As described by Blum & Törnqvist (2000) sea-level rise results in channel shortening, decreases in the distance over which sediments can be stored and, in most cases, flattening of the channel slope. Discharge is conserved, but reductions in slope will result in corresponding downstream decreases in stream power and sediment transport rates. These conditions result in net valley aggradation which in turn can affect channel geometry. However, even within long periods of overall net valley aggradation driven by sea-level rise (time-scales of 10^3 – 10^4 years) significant intervals of incision and/or sediment bypass can occur if sediment supply decreases relative to stream power.

In general, a degree of debate does exist over the importance of base level changes in fluvial systems. This arises from the fact that the major base level changes occurring over the Quaternary were glacio-eustatic in origin, and consequently, their effects are difficult to distinguish from those of other factors, for instance, changes in discharge and sediment load that occurred during glacial phases alongside the glacio-eustatic fall (Miall, 1996). Space does not permit an in-depth discussion of this subject, as it would require an entirely separate review, such as has been undertaken by Miall (1996) and Blum & Törnqvist (2000).

4.1.4 Coastal Responses to Sea Level Change

In this section the impact of sea level change on coasts will be presented with respect to particular coastal features and landforms.

4.1.4.1 Deltas

Deltas are seaward protruding constructional coastal landforms that represent the accumulation of fluvial sediment in river mouths (Swift et al, 1991; Dalrymple et al, 1992; Davis Jr. & Fitzgerald, 2004 – Figure 105).

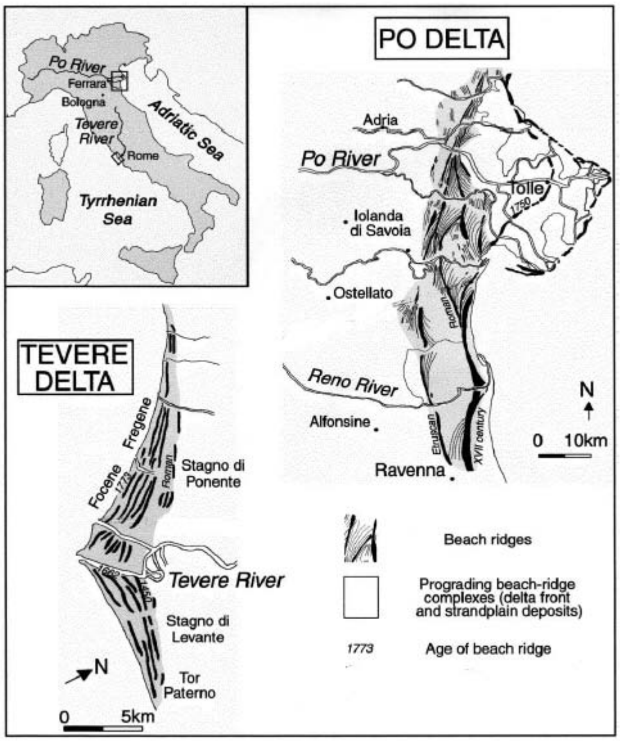


Figure 105. Plan view of two Italian delta systems, the Tevere and the Po (from Amorisi & Milli, 2001)

They form under supply dominated regimes, in that the accumulation of fluvially supplied sediment is greater than the ability of marine processes to rework and remove it, thus resulting in the progradation of shorelines (Swift et al, 1991; Suter, 1994). Hence they can be considered regressive depositional systems. The morphology of individual deltas is to a large extent controlled by the local oceanographic conditions as well as local relative sea level change, sediment supply and the fluvial regime (Figure 106).

The impact of waves on deltas systems results in the redistribution of sediment carried by the effluent jets issuing from the delta mouth. In areas of high wave power relative to river discharge, deltas are much more linear in plan form and spread parallel to the coast. Longshore transport of sand from the delta mouth may also result in the creation of barriers away from the delta mouth. Deltas in macrotidal (>4m) environments however, are shaped by the bi-directional passage of the tidal current and consequently are characterised by funnel shaped mouths and linear (i.e. shore-normal) tidal shoals and extensive tidal flats (Leeder, 1999; Davis Jr. & Fitzgerald, 2004).

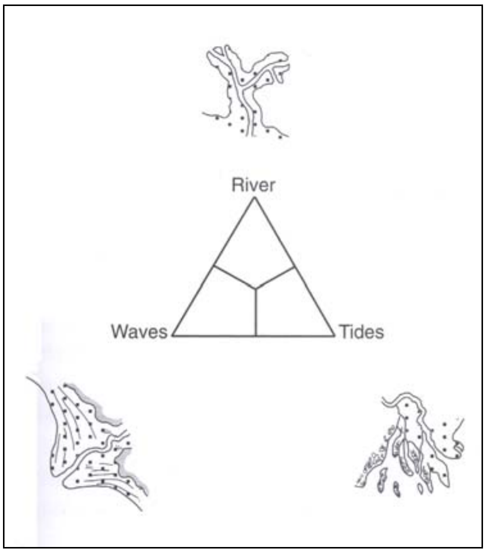


Figure 106. Generalized view of the impact of wave, tidal and fluvial processes on delta morphology (from Woodroffe, 2003).

As sea levels change, so too do deltas. In fact glacio-eustatic fluctuations are recognised as the major control on sedimentation and hence the main influence on the stratigraphic evolution of deltaic systems (Amorosi & Milli, 2001). Each particular phase of the sea level cycle is reflected in delta morphology. Falling sea levels result in rapid progradation across the shelf as accommodation space decreases. Conversely, a reduction in accommodation space results in the deposits being relatively thin and stacked progradationally. Furthermore, as shelf width decreases, so too does across-shelf wave attenuation resulting in increasing wave domination on delta morphology. Meanwhile the extension of rivers across the shelf cuts across pre-existing deltaic sediments.

At lowstands, deltas are located at or near the shelf edge. At this point in space and time, increasing accommodation space caused by the decreased rate of sea level fall, increasing subsidence and increasing sea floor gradient lead to a different depostional style. Lowstands systems tracts therefore tend to be thick and aggradationally (vertically) stacked. Downslope movements induced by turbidity currents are also common. When sea levels begin to rise again, deltas retrograde into incised valleys. They do however, prograde seaward when sea level rise slows or during stillstands. Consequently, transgressive deltas deposits are thin (<10m) and backstepping (retrogradationally stacked). In addition, the creation of embayments results in amplification of the tidal wave and hence increasing tidal domination. At highstands, deltas once again prograde seaward. This is the current global situation (Suter, 1994).

During the majority of the post-LGM period, the rate of sea level change was too great for deltas to form. Essentially, the rise in sea level created accommodation space that could not be filled by the contemporary sediment supply and thus estuaries formed where rivers met the sea. It was only when the rate of rise slowed down in the mid-Holocene that active accumulation could take place (Stanley & Warne, 1994; Davis Jr. & Fitzgerald, 2004).

4.1.4.2 Estuaries

Estuaries represent the seaward portion of drowned valley systems that are influenced by wave, tidal and fluvial processes (Dalrymple et al, 1992 – Figure 107).

They form under accommodation dominated regimes in that sediment delivered by fluvial or marine processes is insufficient to fill the accommodation space created by rising sea level, or in the case of stillstands, to compensate for removal by marine processes (Swift & Thorne, 1991). Consequently, another characteristic feature of estuaries is that they receive sediment from both fluvial and marine sources (Dalrymple et al, 1992).

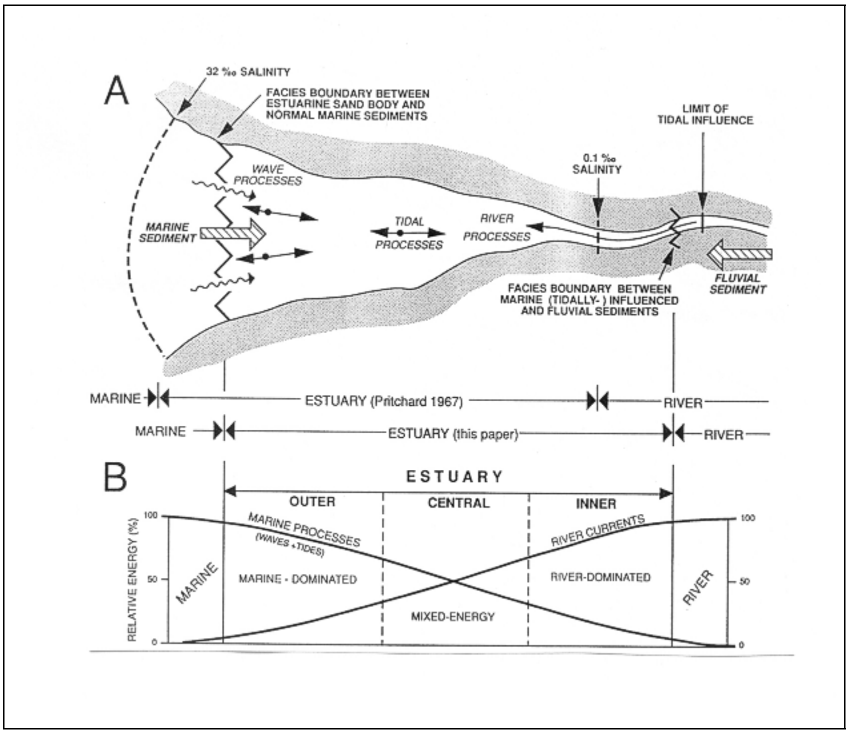


Figure 107. A) Schematic plan view of an estuary showing the generalized transport patterns. B) Schematic diagram showing the interactions between marine and fluvial processes in an estuary (from Dalrymple et al, 1992).

Estuaries tend to be classified as either tide dominated or wave dominated. The former occur along coasts with high tidal ranges and large tidal prisms while the latter are found in areas of reduced tidal range and on barrier coasts (Davis Jr. & Fitzgerald, 2004). Wave-dominated or microtidal estuaries tend to be dendritic in form while tide dominated estuaries are funnel shaped as a result of the penetration of tidal energy further up the estuary than wave energy (Swift et al, 1991; Dalrymple et al, 1992). Tide domination also results in the formation of elongate bars along the estuary mouth while wave domination leads to the formation of bars or barriers across the mouth (Dalrymple et al, 1992 – Figure 108).

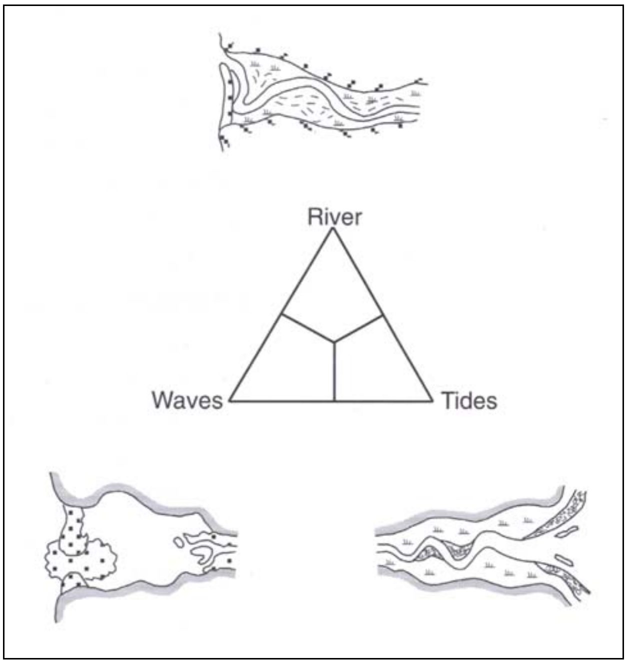


Figure 108. Generalized view of the impact of wave, tidal and fluvial processes on estuary morphology (from Woodroffe, 2003).

These ‘end member cases’ however, are usually modified by local factors like relative sea level rise, geological history and local oceanographic conditions such that different estuaries exhibit varying degrees of morphological deviation from the models (Dalrymple et al, 1992).

The estuarine response to constant sea level rise tends to take the form of an upward and landward ‘stratigraphic roll-over’ translation (Long et al, 2000; Pethick, 2001). Intertidal sediments are eroded from the outer reaches of the estuary by marine processes as wave propagation increases due to increasing water depth. This also results in the retreat of the saltmarsh/mudflat boundary (landward movement). These are then moved landward to the inner estuary and redeposited in the intertidal zone thus elevating the mudflat and marsh surfaces (upward movement). The end result is that the estuary channel and its associated landforms migrate landward as a unit with relatively little morphological change provided the sea level rise remains constant (Dalrymple et al, 1992; Long et al, 2000; Pethick, 2001). Models developed in response to present day sea level rise (6mm/yr) suggest that the rate of estuarine migration is 8 metres a year (Pethick, 2001). However, if the rate of sea level change is modified, then changes in estuary response can take place. For example, estuaries in southern England exhibited a pattern of upward and seaward (rather than landward) migration of intertidal and sub-tidal environments during the Mid-Holocene in response to a slowing in the rate of relative sea rise (Long et al, 2000).

Further changes may take place if external variables such as sediment supply, river inflow, tidal range and wave climate are modified by, or along with, the sea level change. In these instances other morphologic changes would occur in conjunction with the rollover response, such as, a local increase in tidal range leading to an estuary’s morphology changing to a more tide dominated configuration (Dalrymple et al, 1992; Chappell & Woodroffe, 1994). For example, a switch from tide to wave domination during the mid to late Holocene transgression resulted in the development of coarse grained barriers and spits in the mouth of the Delaware Bay estuary (Fletcher et al, 1990).

Finally, under regressive conditions, that is if either sea level rise reverses or slows to a point at which sediment supply exceeds the rate of creation of accommodation, estuaries will infill and form deltas, if sediment is supplied fluvially, or straight prograding coasts, if sediment is supplied by marine processes (Dalrymple et al, 1992 – Figure 109).

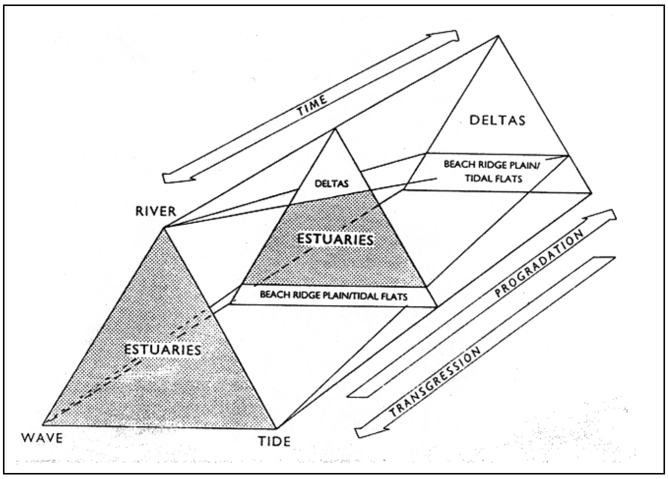


Figure 109. Diagram indicating the transition from estuary to delta or prograding coast depending on local wave and tide climates and the rate of transgression or regression (from Dalrymple et al, 1992)

4.1.4.3 Saltmarshes

Saltmarshes are defined as being the part of the high intertidal zone dominated by halophytic vegetation, such as the *Spartina* species of grasses that are regularly flooded by the sea (Allen, 1990; 2000; Davis Jr. & Fitzgerald, 2004). They are common features on low energy open coasts or in the inner protected areas of estuaries (Figure 110). The actual physical environment of a marsh depends on a number of local factors, notably local tidal range and relative sea level change (Davis Jr. & Fitzgerald, 2004). Tidal range in particular determines the altitudinal limits of the marsh and its extent landwards and seawards. Note for example that marshes tend to exist within 1m of high tide (Allen, 2000, Davis Jr. & Fitzgerald, 2004). Consequently, modifications to the tidal regime as sea level changes lead to changes in the size and extent of the marsh.

Saltmarshes represent highly effective sediment traps, and should the sediment they sequester be capable of meeting the increase in accommodation space created by a sea level rise, they can effectively inhibit forced transgression, by growing upwards at the same as sea level rise. However, rapid changes in sea level can result in their drowning. During stillstands or slow rises in sea level, organic sediment builds from the decomposition of marsh plants builds up thus prompting the growth of peat which can prograde seawards, resulting in a progradational regression of the coastline (Allen, 2000, Long et al, 2000; Streif, 2004).

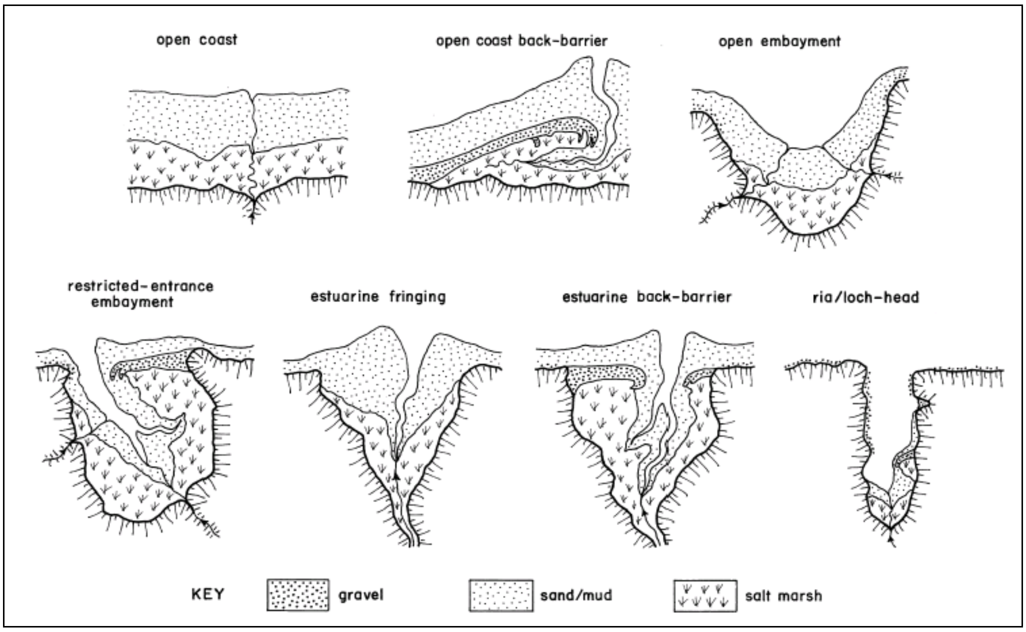


Figure 110. Geomorphological classification of salt marshes (from Allen, 2000).

4.1.4.4 Barriers

Barriers are elongate wave built accumulations of sediment that form parallel to the shoreline. They are characterised by the existence of oceanic and lagoonal shorelines and can range from less than a hundred metres to several kilometres in width, though their exact makeup varies with local sediment availability (Figure 111).

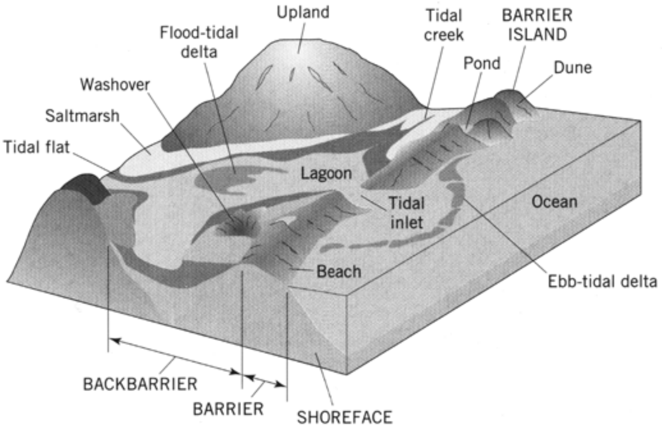


Figure 111. Idealized view of a barrier system (from Davis Jr. & Fitzgerald, 2004)

Types of barriers include spits, which are attached to the mainland at one end, welded barriers, which are attached at both ends, and barrier islands, which are totally detached (Swift et al, 1991; Davis Jr. & Fitzgerald, 2004). They form under accommodation dominated regimes where sediment supply is less than can be accommodated by compaction or rising sea levels, and can thus be reworked and transported by storm or tidal currents (Swift et al, 1991).

The development of barriers is a complex response to gradient, sediment supply, oceanographic conditions and rate of relative sea level change (Roy et al, 1994). They originate in a number of ways depending on the interplay between these factors. One way is as a result of the detachment of mainland beaches during transgression. This occurs when beaches are nourished by littoral drift and can thus keep pace with sea level rise by accreting upwards. However, the back barrier area behind them is sediment starved and starts to flood where it abuts an estuary. Over time the resulting lagoon increases in size and the beach gradually detaches to form a barrier (Swift et al, 1991). Alternatively, they can form as a result of the vertical accretion of offshore bars. Finally, spits may build up in areas of significant longshore transport where the presence of headlands results in the deposition of sediment through wave deflection and the slowing down of the longshore current. These spits may in turn be breached by storms to form individual islands (Davis Jr. & Fitzgerald, 2004).

On microtidal (<2m) or wave dominated coasts, barrier systems tend to be elongated and continuous. As tidal range increases, barriers shorten and tidal inlet width decreases to the point where the barriers disappear altogether on macrotidal coasts and the sediments that would form the barriers is distributed about the sea floor. In these areas coastal morphology generally consists of shore normal tidal channels and open estuaries (Swift et al, 1991). Hence modifications to the tidal regime by changes in sea level have the ability to alter barrier morphology.

Barriers tend to respond in one of three ways to sea level rise (Swift et al, 1991; Cooper, 1994); by erosion, overstepping (the barrier remains in situ) or translating (also known as ‘barrier rollover’ - Figure 112). Barrier rollover results from the washover of sediment from the shoreface to the backbarrier either from both storm and fair weather wave action (Swift et al, 1991). Thus the entire barrier is reworked over the course of the transgressive event, but is maintained without loss of material.

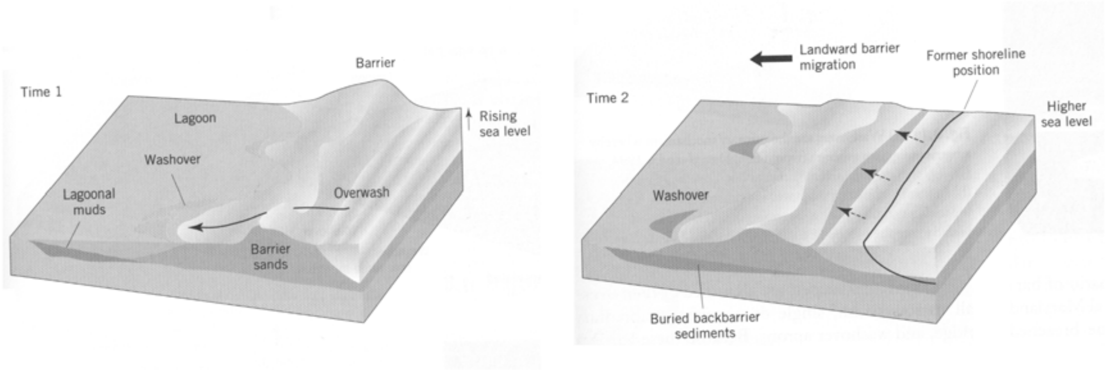


Figure 112. Response of a barrier to sea level rise by barrier rollover (from Davis Jr. & Fitzgerald, 2004)

In erosive situations, although the same cross sectional process is maintained, material eroded from the shoreface is moved seaward and deposited below wave base in the nearshore zone, resulting in the profile moving upward in relation to the sea level rise. Overstepping however drowns the barrier, thus creating a relict landform (Cooper, 1994). Integral to each of these responses is the rate of relative sea level change. Under conditions of rapid rise, overstepping and drowning are more likely, while erosional and translational responses are more likely under conditions of slower rise, which gives the barrier sufficient time to adjust to the changing regime parameters. As always, the exact nature of the adjustment will depend on local geology, antecedent topography and sediment supply (Cooper, 1994). Both overstepping and barrier migration are known to have taken place in different areas during the Holocene sea level rise. This can be illustrated by investigations of the shelf environment which reveal that in some areas barriers are replaced in the stratigraphic sequence by erosional, or ravinement surfaces, resulting from shoreface retreat (Niedoroda et al, 1985; Swift et al, 1991) while, in a number of other areas relict barriers are known to exist on the continental shelf, most likely as a result of barrier overstepping (e.g. Forbes et al, 1995, Oldale, 1995 - Figure 113).

When viewed over timescales of several thousand years, barrier migration is continuous in the face of rising sea level. However on timescales shorter than this, movement may have ceased and progradation resumed as the rate of sea level rise slowed or halted (Swift et al, 1991).

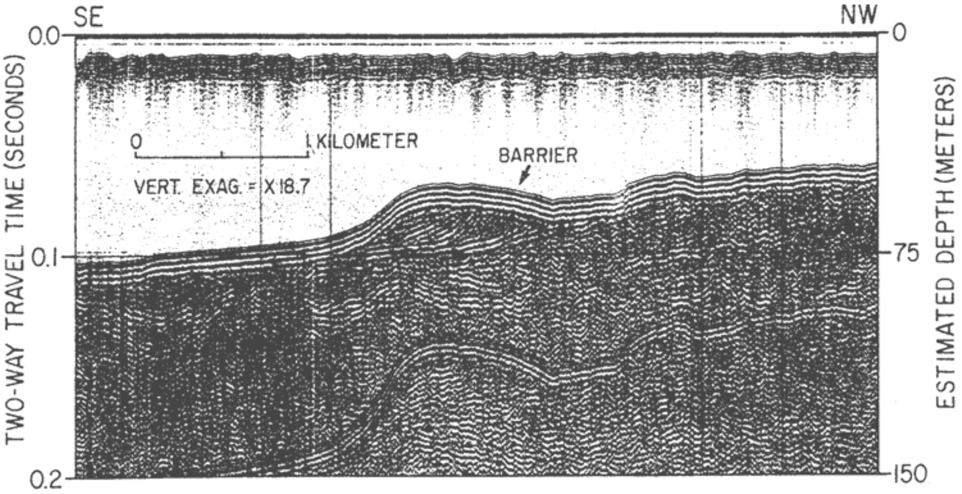


Figure 113. Seismic profile showing a drowned barrier spit located in 50-70m water depth on the North American shelf off Massachusetts. Preservation of the barrier has been attributed to its large size (>20m thick), rapid rate of sea level rise and an abundant sediment supply (from Oldale, 1985)

4.1.4.5 Lagoons

Lagoons are coastal bays that have become restricted by the presence of a barrier (see Section 4.1.4.4). They differ from estuaries in that they have little or no freshwater input and are further distinguished on the basis that the presence of the barrier reduces significant tidal changes. They form where an embayment, and a mechanism for isolating it, such as a spit or barrier, exist (Davis Jr. & Fitzgerald, 2004 – Figure 111). Lagoons themselves may be a response to sea level rise. They form when rising sea levels inundate low lying land behind ridges or dunes, or when barriers grow because of sea level rise (see section 4.1.4.4). Lagoon size and shape is largely a function of local gradient and the extent of sea level rise (Cooper, 1994). During stillstands the restrictive nature of lagoons is such that they infill with sediment, evolving to a marsh or deltaic plain through which rivers drain. Sea level change however modifies this pattern. The response of a lagoon to sea level rise depends largely on the response of the enclosing barrier to sea level rise (see section 4.1.4.4 for further discussion). A landward migrating barrier could result in the landward translation of the lagoon as well, thus maintaining a constant volume, while a vertically accreting barrier may lead to an increase in lagoon volume thus slowing the rate of infill (Cooper, 1994). However the destruction or drowning of barriers by rapid sea level rise results in the loss of the lagoon and its particular environment.

4.1.4.6 Paraglacial Coasts

Glaciated coasts are those whose coastal morphology has been sculpted by the action of glaciers, thus resulting in the occurrence of distinctive features such as drumlins, moraines, fjords, outwash sands and gravels (Davis Jr. & Fitzgerald, 2004; Forbes & Syvitski, 1994). In these situations sediment sources and supply tend to be highly localized and dependent on the former location of glaciers. Hence, the primary impact of sea level rise is that it determines the availability of sediments and the timing and location of sediment reworking. While this is a role common to all coasts, it is somewhat enhanced in paraglacial settings given the localized nature of the sediment supply (Forbes & Syvitski, 1994; Ballantyne, 2002).

It is worth noting at this point that glacial deposits (typically sub-glacial, pro-glacial and glacimarine) related to the growth and decay of ice sheets dominate many mid-latitude and high-latitude shelves and are hence worthy of discussion here. Subglacial sediments are deposited beneath grounded glaciers and ice sheets; proglacial deposits are dominated by high discharge, potentially, high sediment laden, fluvio-glacial channels either cutting into exposed terrestrial environments or directly into the ocean; and finally glacimarine sediments can be defined as being deposited from grounded tidewater ice fronts, floating glacier tongues, ice shelves and icebergs. These patterns of sedimentation vary in three-dimensions (i.e. both orthogonal and parallel to an ice front) and are controlled by the interaction of five factors: pre-existing shelf geometry; variability in the spatial and temporal pattern of ice sheet growth and decay; glacio-eustatic cycles and isostatic crustal response; and post-depositional current re-working. Simply, in proximal locations to the sediment source, steep gradients in grain-size variability can be identified in all dimensions. By comparison at distal localities, depositional environments become more homogeneous over larger areas.

This basic facies architecture described above is spatially related to the location of the ice front. Naturally over timescales of 1000’s – 10,000’s of years the location of these depositional environments will migrate with the growth and decay of ice sheets. Further, their potential for preservation (i.e. the combined threat of reworking or burial) will be dictated by the associated fluctuation in relative sea-level at any one site. During the major growth phases of continental ice sheets, the ice front can coincide with the shelf edge resulting in the deposition of large volumes of sediment across the shelf and can even result in active shelf progradation.

During these periods of advance individual ice streams may also be capable of excavating large cross-shelf valleys, frequently U-shaped in cross-section, several hundreds of metres deep and several kilometres across (Huuse & Lykke-Andersen, 2000 – see Section 3.4.3). Many of these features are pre-Quaternary in age and probably represent poly-phase erosion enhanced by contemporaneous uplift. These channels frequently represent local depo-centres for glacially derived sediment. During retreat proximal zone processes will replace ice-contact depositional styles (Figure 114). Further, during retreat, oceanic waters will penetrate onto the shelf, increasing long-shelf sediment dispersion whilst the increase in shelf width in response to marine incursion will increase both tidal and wind induced erosion.

It should be noted that during the Pleistocene this temporal variability in ice sheet growth and decay has been predominant on the mid-latitude northern European and

North American shelves. By comparison the high latitude, Antarctic and Greenland ice sheets, underwent very little areal or volumetric change, at least during this last glacial cycle.

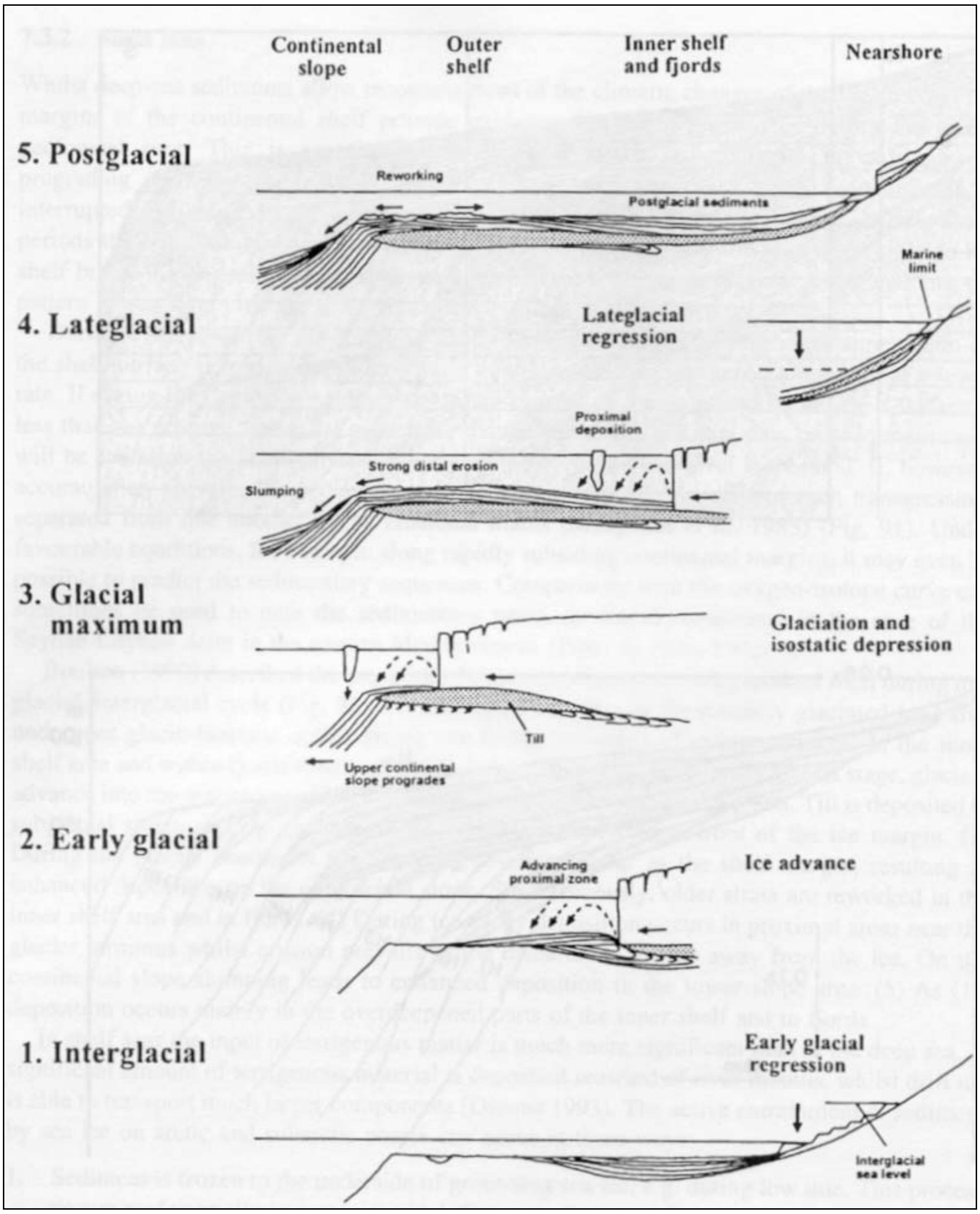


Figure 114. Model of glaciomarine depositional variation in space and time over the course of one glacial cycle. The relative changes in sea level are indicated (After Boulton, 1990).

4.1.4.7 Strandplains

Strandplains are a form of regressive depositional system that develop on the flanks of wave dominated deltas (Swift et al, 1991). They range in length from 5-100 km along shore, 1-30 km in width while their deposits are 10 to 20m thick. Although they are indicative of regressive depositional systems, they can form even when sea level is rising, provided the local sediment source exceeds the accommodation created by the sea level rise. This category is known as ‘rising sea level strandplains’ and contrasts with ‘falling sea level strandplains’ which form during sea level falls (Swift et al, 1991). The progradation of strandplains is episodic, with successive parallel beach ridges added as storms erode sediment from the nearby delta and entrain it within the local littoral currents. In areas of coarse sediment, strandplains are formed by sets of storm beaches, or gravel ridges (Swift et al, 1991).

4.1.4.8 Rocky Shores and Hard Coasts

The previous sections have focussed on depositional coastlines with a relatively abundant sediment supply. This section addresses rocky or hard coasts. These rugged shoreline types form on active continental margins characterised by seismicity, coastal mountain ranges, volcanism and narrow shelves or where the structural grain of the land is such as that it is readily exposed by the longshore removal and transport of sediment (Griggs & Trenhaile, 1994). In these situations, sediment availability is relatively low due to the difficulty of eroding the shoreline. Although erosion is difficult, it is not impossible given enough time and sufficient wave strength. Rising relative sea level therefore results in simple transgression, the effects of which depend on the gradient of the surface being flooded, the local wave climate, local geology and the rate of rise. These serve to determine the erosive impact that the sea has on the coastline in that they determine the strength of the waves, the strength of the rock and the duration for which the waves impact on the shore. This can lead to the development of wave cut notches and platforms which can indicate the position of a shoreline usually at a time of stillstands or very slow rises in sea level (Trenhaile, 2002 – see Section 2.3.2.1). It has been suggested that wave erosion may have been particularly effective during the early stages of interglacials and interstadials when sea levels were rising, and the rocky formations had suffered frost shattering during the preceding cold stages (Trenhaile, 2002). The scree formed by the frost weathering may have protected the main body of the cliff during the early stages of the transgression. The degree of protection it afforded may in turn have affected the impact that the transgression had on the rocky substrate (Figure 115).

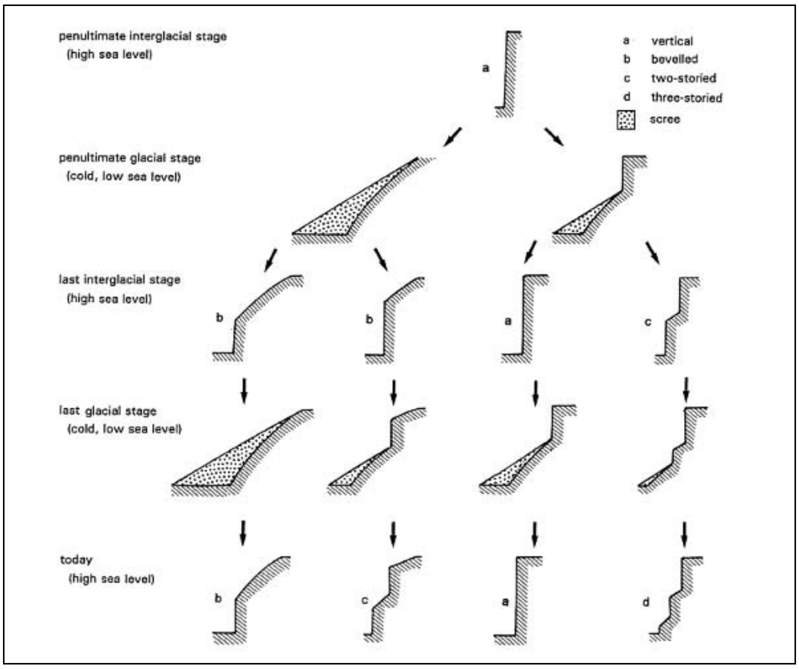


Figure 115. Diagram showing cliff evolution over the course of 2 glacial/interglacial cycles on mid to high latitude coasts. Scree formed during glacial phase was removed by marine erosion. The final morphology of the cliff is determined by the rate of wave erosion and the extent of scree cover protecting the cliff (from Trenhaile, 2002).

In fact, the degree of erosion over the course of one glacial/interglacial cycle has been estimated, on the basis of modelling, at between 1 and 3km (Trenhaile, 2002). More rapid rises are unable to rework the lithified surface and thus the existing shoreface therefore breaks up into a series of rock defended sand bodies, and bays (Swift et al, 1991). Whether or not embayments develop along these areas is determined largely by the extent and steepness of bedrock outcrops, with frequency increasing in areas with steeper and less easily erodable substrates (Roy et al, 1994; Trenhaile, 2002).

4.1.5 Continental Shelf Processes

At highstands and at offshore locations (beyond ambient wave base: see Section 4.1.2) during the transgressive/regressive phase there is the potential for reworking of shelf deposits and the deposition of new deposits. It is therefore important to appreciate the nature of the driving forces controlling sediment transport on continental shelves. This section will therefore discuss the nature of the processes operating from the shoreface down to the shelf break. This should further substantiate the view that present day sea floor bathymetry is not an unequivocal representation of the sub-aerial palaeo-landscape.

Currents on the continental shelf can be divided into three main categories; tidal currents, meteorological currents and density currents (Figure 116: Nittrouer & Wright, 1994; Leeder, 1999).

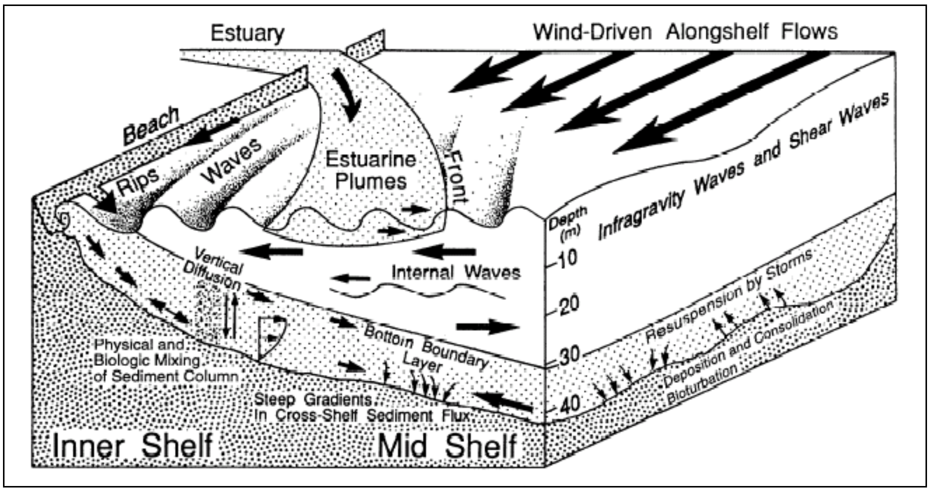


Figure 116. Summary of physical processes responsible for sediment transport on continental shelves (from Nittrouer & Wright, 1994)

4.1.5.1 Tidal Currents

Tidal currents are produced by the semi-diurnal tidal wave created by the gravitational influences of the sun and moon. As the oceanic tidal wave reaches the shelf break, it decelerates due to the reduction in water depth. This in turn increases the amplitude of the tidal wave and enhances the resulting tidal current (Howarth, 1982; Leeder, 1999). Further modifications to tidal strength also result from local basin morphology; amplification for instance may result from reductions in basin depth and width, or resonance whereby the natural oscillation of the sea coincides with the tidal period (Howarth, 1982). In general, the strength of the tidal stream decreases with depth to the point that its strength at 100m depth is half that at 1m depth (Hamblin et al, 1992), but still maintains velocities capable of re-working shelf sediments. For example, bottom current measurements in the Celtic Sea have demonstrated velocities of 1 ms^{-1} at a depth of 165m during spring tides. Furthermore, the circulation of large sand dunes confirms that these currents are mobilizing sediment (Berné et al, 1998). As tidal currents are bi-directional, it is the stronger of the peak ebb or flood tide which determines the net sediment transport direction (Stride, 1982). Shelves whose sediment transport pathways are determined largely by these forces are known as tide dominated shelves. Examples include the North Sea and English Channel areas (Reynaud et al, 2003).

Where tides dominate on shelves the tidal current transport path controls the distribution of grain size, bedforms and facies. In this case there is a generally recognised trend of decreasing grain size down the tidal current path, for example from gravel to coarse sand, to mud, all dependent on the sediment supply. In the older literature this tidally controlled distribution is known as a *nearshore sediment prism* with sand deposited in the nearshore and mud deposited in deeper waters. The complete tidal current path also shows a predictable sequence of bedforms (see Section 4.1.5.4), but the precise type depends on whether the sand supply is high or low. Bedform size decreases towards the end of the tidal current path with small sand waves, sand patches, and then mud deposition. Often the down current reduction in flow strength accompanies an increase in water depth, and in this instance, grain size decreases with increasing water depth. Although mud zones are usually located at the ends of tidal current transport paths, mud can accumulate in a variety of positions on shelves, as a response to the interaction of wind-drift and ocean circulation patterns.

4.1.5.2 Meteorological Currents

Meteorological currents are those produced by wind forcing. Wind, or weather dominated shelves are those on which sediment transport is largely controlled by wind or storm induced currents. On these shelves, tidal ranges tend to be less than 1m, and tidal currents are weak; less than 0.3 ms^{-1} (Leeder, 1999). For example, off north-eastern Denmark temporary wind induced currents can reach near surface speeds of 2 ms^{-1}, enough to induce sand wave formation in an area where tidal current speeds only reach 0.25 ms^{-1} (Johnson et al, 1982).

It is a misconception that the effect of wave induced sediment movements only takes place in relatively shallow areas (Stride, 1982). Recent research has demonstrated that storm currents can actually affect the seabed at depths of over a hundred metres (e.g. Berné et al, 1998) with storm wave generated bedforms having been observed at depths of up to 140m in the Celtic Sea (Reynaud et al, 2003) and 200m on the Oregon shelf (Leeder, 1999). However, it is only the largest storms that can affect the seabed at the outer shelf margin. In general on weather dominated shelves there is an offshore decrease in grain size, although reworking of relict sediments commonly gives a mixed sediment.

It should be noted that most shelves do exhibit a mixture of two forces in time and space (Leeder, 1999). For instance, tidal currents alone have the potential to move sand, and sometimes gravel, in strongly tidal areas of the shelf. In conjunction with storm and wind currents though, sediment can be moved over most parts of the shelf (Johnson et al, 1982). Alternatively, storm induced currents may temporarily reverse the net direction and rate of sediment transport (Johnson et al, 1982). In tidal areas, the main offshore effect of storm waves tends to be an increase in sand transport rates in the direction of the dominant tidal current (Stride, 1982). Both tide and meteorological currents may in turn alter the direction of density currents (see Section 4.1.5.2).

4.1.5.3 Density Currents

In addition to the key role played by tide and wind induced activity on the movement of sediment on the continental shelf a variety of other oceanic factors also play a role, which will vary in their importance along a given continental margin. These additional factors can be grouped into large-scale ocean currents, upwelling/downwelling events and internal tides and waves (Figure 116). The type, the occurrence and intensity of various ocean currents off any continent vary systematically in relation to the eastern and western margins of the ocean basins. Simply, the density driven ocean scale currents tend to be narrow and intense on the western boundary of oceans; e.g. the Gulf stream can locally be as little as 50 km wide and near the surface attains velocities which can range from 1 ms^{-1} to 3 ms^{-1}. Conversely, eastern boundary currents are relatively broad and weak; e.g. the California Current can be as wide as 1000 km and surface flows are typically < 0.25 ms^{-1}. The meandering of such currents adjacent to the shelf break results in both the movement of suspended material within the water column (thus controlling its final place of deposition) and the migration of bed load sediment. In addition, to displacing water by meandering, such currents produces eddies which can replace coastal water with offshore water, thus further complicating the dispersal patterns of sediment.

The influence of these currents can be demonstrated by the distribution of sediment and bedform types on the Spanish Gulf of Cadiz shelf. Here the North Atlantic Surficial Water (NASW) currents flowing southeastward across the Cadiz shelf toward the Strait of Gibraltar dominate sediment distribution. Even inner shelf sandy facies formed by wave activity are modified by the NASW currents to form a belt of sand dunes at 10-20 m water depth. The NASW also dictates the south-easterly progradation of a mid-shelf Holocene mud facies. Further, increased NASW current speeds near the Strait of Gibraltar and the strong Mediterranean Outflow Water currents that are also present at this site, result in a lack of mud deposition and the development of a reworked transgressive sand dune facies across the entire southernmost shelf. It should be noted that such ocean scale currents are significantly affected by local morphological controls (e.g. tectonically induced bedrock highs) which can result in the patchy development of sedimentary facies and bedform variability particularly on the inner shelf.

Landward upwelling and seaward downwelling events can also cause the transportation and deposition of fine grained sediments. For instance, upwelling flows of over 0.1 ms^{-1} are dominant within the bottom layer of the outer shelf off northwest Africa, sufficient to move unconsolidated muds and sands. Consequently, complex patterns of across-shelf particulate transport have been observed for upwelling systems as water motion is 3-dimensional (along-shelf, across-shelf and vertically).

Finally, internal tides and waves propagate along density interfaces and within pycnoclines and they are common in the main and seasonal thermocline of the world’s oceans. If the seasonal or permanent thermocline intersects the shelf, these internal features, propagating in the thermocline, can interact with the bed and thus affect sedimentation. As these features are only present under seasonally stratified conditions for some 6-8 months per annum their effect may appear small, but the net effect over geological timescales could be significant. As flows associated with internal tides are oscillatory, both landward and seaward flows occur. When the ratio of the bottom slope is less than unity, as internal waves move across a sloping bottom, they may break and generate internal surf, which could further entrain sediment for transport. Frequently, these internally derived currents interact with tidal and/or wave activity to further enhance sediment movement. Flow velocities associated with internal waves can exceed 0.3 – 0.4 ms^{-1} and are frequently superimposed on other local currents. These velocities are sufficient to significantly affect cross-shelf transport, and may be capable of forming large-scale bedforms with wavelengths of several kilometres.

For the outer shelf of the Celtic Sea, internal waves have been observed to propagate both on-shelf and off-shelf (Heathershaw et al., 1987). These authors suggest that the shelf break actually represents a bedload parting zone. Net movements are off-shelf just below the shelf break and on-shelf immediately behind it. Further, on-shelf the predicted net sediment movements are again off-shelf suggesting a broad zone of convergence extending some 10 km behind the shelf break.

4.1.5.4 Impact of shelf currents

The existence of currents and their impact on present day seabed sediment on the continental shelf floor can be demonstrated by the existence of bedforms:

“Bedforms are an integrated response to all water movements that have been operative during quite a long period” (Johnson et al, 1982:89)

These form in areas that have a source of mobile sediment, either from the seabed, fluvial sources or coastal erosion, and currents of sufficient strength to mobilize it (Belderson et al, 1982; Johnson et al, 1982; Dyer & Huntley, 1999).

Typical features on continental shelves include: sand ribbons, dunes, sheets and ridges and banks. Sand ribbons, can be up to 20km long, 200m wide, and 100m thick and occur on coarse sand and gravel substrates in water depths of 20 - 100m. Dunes can be up to 15m high, have a wavelengths of 600m and occur in very high energy tidal environments, but tend to be absent in nearshore areas where wave activity is high as waves, especially during storms, as these tend to reduce dune height and wavelength (Leeder, 1999). Sheets are relatively thin (up to 12m) but extensive areas (up to 1000km) of sediment laid down by tidal currents. They can be formed from mud, sand or gravel with their grain size being determined by mean spring peak tidal current speeds (Stride et al, 1982). Gravel sheets in particular include clasts of up to boulder size reworked from Pleistocene terrestrial deposits by the early Holocene and transgression and later tidal current activity. The deposition of these extensive facies occurs when current strength decreases to the point at which sediment transport is no longer possible (Stride et al, 1982).

Finally, sand banks form in nearly all shallow tidal seas provided there is a supply of sand, and currents exceed about 0.5 ms^{-1}. Sand ridges are particularly elongated banks. On open shelves these features can be up to 80km long, 13km wide and tens of metres in height with wavelengths of 3 to 12km (Dyer & Huntley, 1999). They in turn may be covered by active smaller features such as dunes (Leeder, 1999). Although they tend to be composed of sand, where currents are sufficiently strong gravel banks may form. Banks and ridges form in a range of depths, from shallow water estuary mouths to depths of more than 150m on the outer shelf, and tend to occur in parallel to one another in groups (Berné et al, 1998; Dyer & Huntley, 1999; Stride et al, 1982).

A number of different classes of bank and ridge exist, including; open shelf ridges, tidal delta ridges and headland associated ridges. Morphological and evolutionary differences between these classes come about as result of the varying hydrodynamic circumstances in each situation. Changes in sea level have been frequently associated with the formation and maintenance of sand banks (see Section 4.1.5.5).

The smaller of these bedforms tend to be more indicative of short term events, such as storms (Johnson et al, 1982). Whereas the larger features highlight the effect that currents may have had on the morphology and topography of submerged palaeo-landscapes over the long term. This is because larger features respond more slowly to changes in the hydrodynamic regime and thus are a better representation of long term change.

4.1.5.5 Impact of transgression and regression on shelf processes

If sea level change accompanies transgression and regression, it may have a significant impact on regional and local tidal regimes and wave climates, and in turn these will affect the transport patterns of sediment around the coasts and on shelves, and therefore, the evolution of coastal and shelf geomorphology on timescales of thousands to tens of thousands of years (Van der Molen & van Dijck, 2000; Van der Molen, 2002). Modification of tidal regimes and wave climates by sea level change comes about because the resultant bathymetric shifts modify currents strengths by increases or decreases in bottom friction (a function of depth) while coastline changes may divert or deflect existing currents. Further impacts resulting from sea level change are changes in the tidal range and tidal prism due to modifications to basin morphology (Scourse & Austin, 1995; Shennan et al, 2000).

Numerical modelling of these forces can provide reasonably effective simulations of past changes in both tidal regime and wave climate in response to sea level change (e.g. Scourse & Austin, 1995). For example: Holocene changes in sea level around the British Isles appear to have led to relatively minor changes in areas where the tidal wave propagates progressively and without entering shallow water in regions such as Northern Scotland. Conversely, major changes are apparent further South where the opening of the straits of Dover resulted in the conversion of the Southern Bight from a quiet microtidal sea, to one with a larger tidal range (>2m) subject to tidal scouring (Austin, 1991; Van der Molen & de Swart, 2001a). Concomitant with these changes were modifications to the strength and direction of sediment transport, notably a switch from onshore transport towards the Low Countries before 6 (C^{14}) ka BP to alongshore transport by the present (Figure 117 - Van der Molen & van Dijck, 2000).

In terms of wave climate, modelling suggests that wind-wave conditions and associated orbital velocities and sand-transport patterns have changed over time as the basin geometry changed. The outputs of a model for the southern North Sea (Van der Molen & de Swart, 2001b) show that mean wave heights increased after 7.5 (C^{14}) ka BP with the largest changes occurring in the shallow water (Figure 118). Further, the dominant form of wave induced transport switched from suspended load to bedload transport after 6 (C^{14}) ka BP, while the overall east to west direction of the bed-load transport remained constant until the present day but decreased slightly in magnitude.

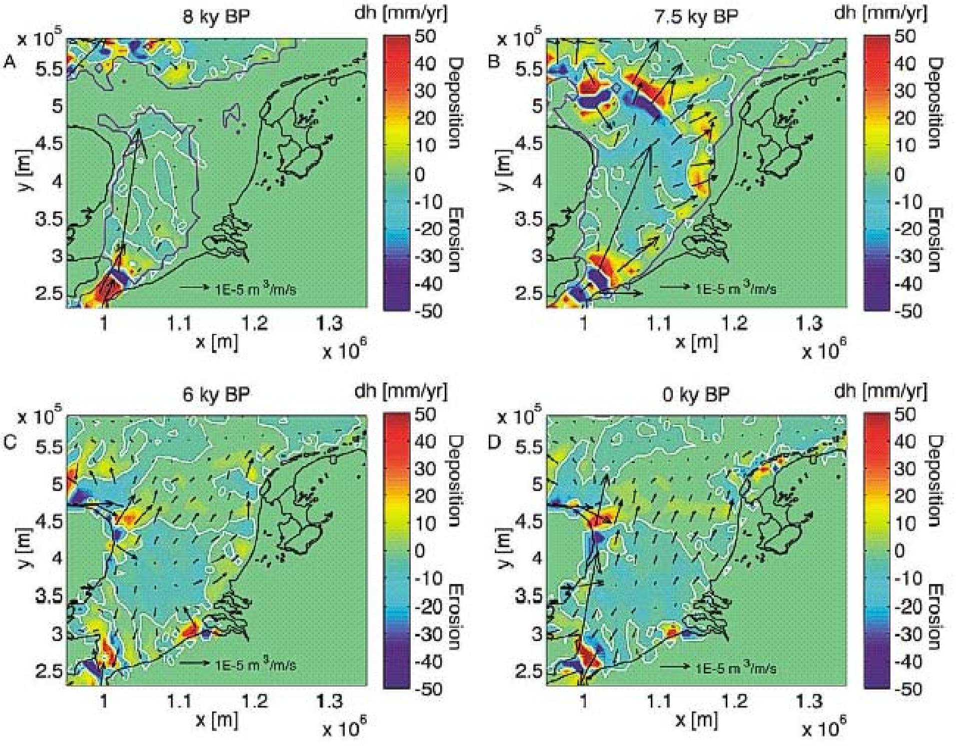


Figure 117. Sand transport patterns for the southern North Sea during the Holocene. Arrows indicate transport directions and strength (m^3/ms^{-1}), colours indicate erosion/deposition rates (mm/year) (from Van der Molen & Van Dijck, 2000).

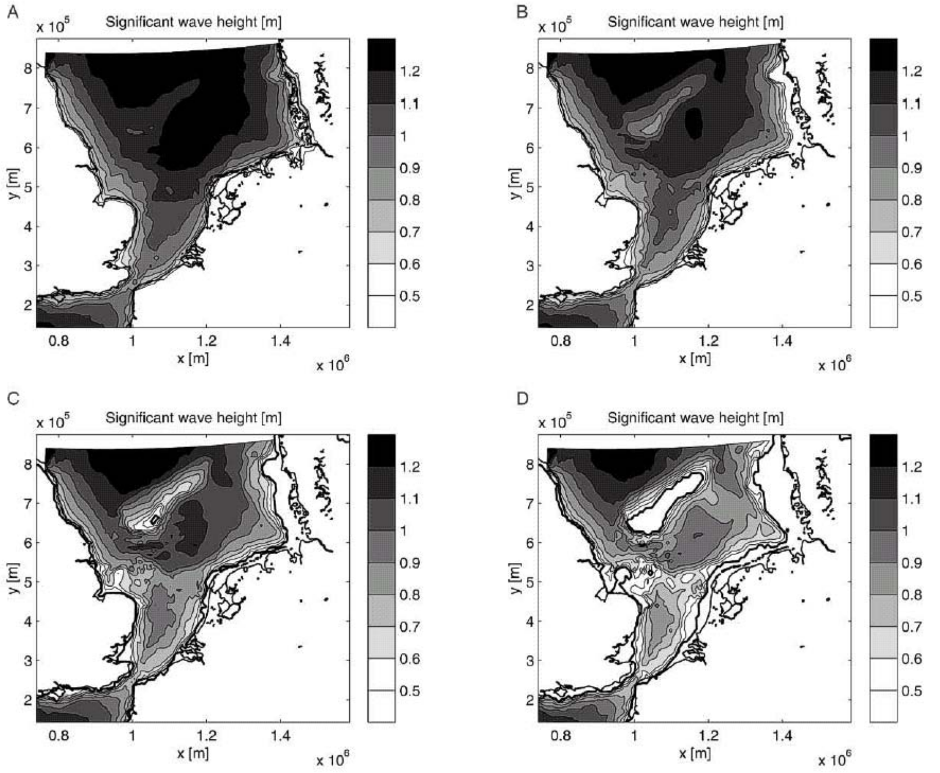


Figure 118. Results of significant wave height modelling in the North Sea for A) the present B) 6 ka BP C) 7 ka BP D) 7.5 ka BP (all dates are uncalibrated C^{14}) (from Van der Molen & de Swart, 2001b)

The products of these modifications to the hydrodynamic regime are changes in seabed morphology. Estuary mouth sand ridges for instance are interpreted as forming as a result of rising sea levels increasing tidal flow into an estuary. This increased flow in turn widens and deepens tidal channels with the eroded sediment deposited on the channel margins. Over time this sediment builds up into ridges (Dyer & Huntley, 1999). Conversely, moribund sandbanks are found in deep water, the rising sea levels of the transgression making possible the preservation of banks by removing them from zones of significant sediment movement (Dyer & Huntley, 1999).

Alternatively, a number of deep water ridges have been interpreted being created during the Postglacial transgression by the erosion and remoulding of pre-existing lowstand estuarine or deltaic deposits (Berné et al, 1998). In these cases, the eroded remains of nearshore features such as fluvio-estuarine, barrier and tidal-delta deposits are overlain by offshore dunes created by tidal action, which are in turn reworked by storm wave induced currents as the influence of constructional tidal forces wanes with depth increase caused by rising sea levels (Reynaud et al, 1999 – Figure 119).

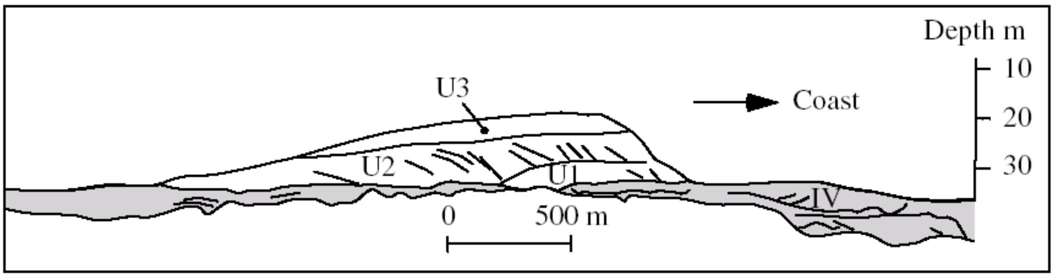


Figure 119. Cross-section of the Bassure de Baas bank (Eastern English Channel). Seismic units have been interpreted as follow: U1) Remnant of tidal delta lobes situated above and infilled valley. U2) Remnant of shoreface bank migrating coastwards under wave action. U3) Tide-dominated reworking of shoreface banks. Final stage of bank construction. Overall the bank highlights the transformation of coast and shoreface under transgressive conditions (from Reynaud et al, 2003).

4.1.6 Implications for Archaeological Studies

Archaeological work on continental shelves requires a secure grasp of palaeogeography and palaeotopography for the purposes of site prospection, cultural resource management and interpretation. This is especially important if predictive modelling is to be undertaken as many models are topographically based (see Section 5).

A review of sedimentological, geological and coastal management literature has highlighted the fact that coastline and shelf surfaces change under transgressive, regressive and stillstand regimes. Furthermore, the resulting stratigraphic record is fragmentary as in many cases processes of erosion and deposition accompanying and following transgression have obscured or destroyed much of the original sedimentary record (Streif, 2004). Therefore, there are a number of implications for archaeological research:

- Coastal and shelf surface changes under transgressive conditions are such that present bathymetry cannot be used as a direct representation of the past landscape. This is exacerbated by the modification of the shelf surface by stillstand processes.

- Care should be taken when extrapolating relatively restricted (spatially and temporally) evidence, or presenting palaeogeographic reconstructions as accurate representations.
- Sub-bottom investigations should be an essential part of archaeological investigations to enable a more secure understanding of how the landscape has changed over time.
- Topographical and morphological changes render the development of predictive models more difficult but not impossible. Certain important landscape features, (e.g. buried channels) are still present.

Future areas for research include:

- The increased integration of existing sedimentological and geological data with archaeological work to enhance existing palaeogeographic reconstructions and construct new ones.
- Increased investigation underwater using remote sensing and geophysical equipment, not simply to locate archaeological material, but to obtain information that will aid in understanding the evolution of the wider landscape.
- The possibility of using parameters other than topography to construct predictive models. Suggestions include lithic raw material (e.g. flint and chert). This approach has been tested to some extent off North West Florida (Dunbar et al, 1991). This will be discussed further in Section 5.
- This study has focused on landscape changes taking place over a single transgressive cycle. However the investigation of pre-Last Glacial Maximum deposits will require knowledge of preceding glacial and interglacial stages. A greater understanding of landscape evolution over multiple trans- and regressive cycles is necessary.

4.2 Response of Individual Deposits of Archaeological Material

4.2.1 Introduction

The previous chapters have demonstrated the possibility that archaeological material exists on continental shelves. However, as briefly outlined in Sections 3.4, 3.5 and 3.6, it is possible that syn-transgressive and regressive marine processes have modified the arrangement and makeup of the presently submerged archaeological record. This chapter seeks to further investigate the impact of these processes on individual archaeological deposits. Therefore, it aims to:

- Determine the preservation potential or likely state of the archaeological material on the seabed.
- Consider issues of temporal scale. The impact of single events (e.g. storms), versus longer-term oceanographic processes on archaeological material.

In the interests of assessing the archaeological potential of continental shelves, the extent and nature of this modification must be investigated, since, as previously stated (Section 3), deposits in primary, secondary and tertiary context have different interpretative values, in that they each are suited to addressing particular research questions. In addition, knowledge of where archaeological material is likely to have survived transgression, in a particular preservational context, may be important in designing future strategies of site prospection or cultural resource management.

A review of existing literature has indicated that approaches to the modification of archaeological material by transgression, regression and marine processes are somewhat sparse. Note for instance the following statement:

"the impact of inundation upon terrestrial sediments, a post-depositional process not hitherto relevant to Palaeolithic studies and one whose possible effects need to be considered" (Wenban-Smith, 2002:7).

The dominant perspective in much of the archaeological literature assumes that transgression will result in the destruction of sites through erosion.

"lake and sea levels have varied tremendously over the past 2 million years, and erosion during high stands has repeatedly obliterated the archaeological record where evidence for early aquatic resource use is most likely to be found" (Erlandson, 2001:300)

"with the Post-Glacial sinking and flooding of the respective coasts and deltas of the Late Glacial river systems, such diagnostic [coastal] sites may have been lost to the archaeological record due to major incision and aggregation" (Newell & Constandse-Westermann, 1996:385).

Statements such as the above tend to be based on assumptions rather than empirical evidence. However, the work that has been done on the subject of marine taphonomic processes (e.g. Flemming, 1983; Kraft et al, 1983 – Figure 120) emphasises the fact that archaeological material can survive marine transgression. This emphasis is borne out by the fact that globally, around 500 submerged archaeological sites are known (Flemming, 1998), several of which can be considered to be in primary context, for example, Tybrind Vig (Andersen, 1985).

These studies identified some basic taphonomic principles that ensured the survival or destruction of archaeological sites undergoing submergence. Destructive factors were identified as wave erosion, current erosion and ice erosion. Hence, the survival of sites occurred in situations in which these destructive influences were minimized. Key areas identified were lagoons, sheltered alluvial coasts, accumulating beaches, sea caves, karstic caves, the lee of coastal islands and coral reefs. These have been assessed in terms of wave heights, wave fetch and archaeological sites found in them (Flemming, 1983). Burial of sites to a sufficient depth in sediment, prior to transgression, such they were not affected by the passage of the erosive shoreface was also identified as a critical factor in their survival (Kraft et al, 1983). In summary, ideal conditions for preservation could be described as those that promote gentle, yet rapid burial (Dunbar et al, 1991). A further important conclusion was that while gross topography (i.e. spatial scales of 10-100km) may have created generally favourable conditions, it was the local topography (i.e. spatial scales of < 1 km) surrounding a site that determined its survival (Flemming, 1983).

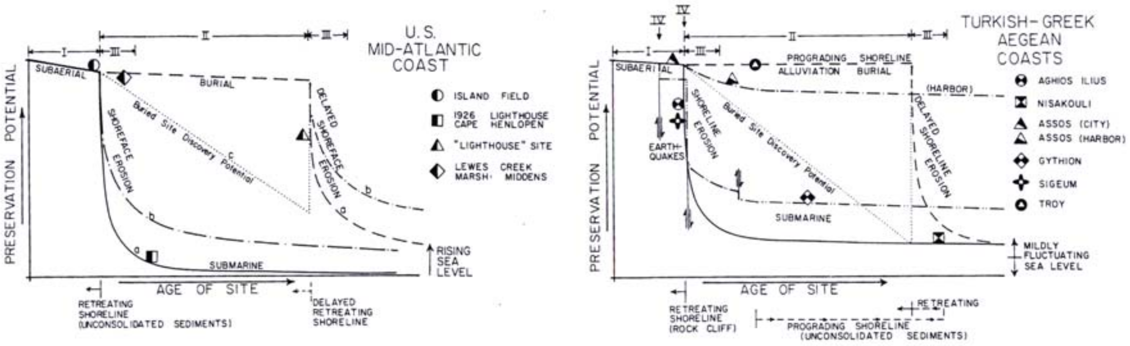


Figure 120. Kraft et al's (1983) conceptual model of submerged archaeological site preservation. Roman numerals refer to phases in the history of a coastal site. I) Subaerial degradation. II) Burial. III) Shoreline erosion. IIIa) Open ocean conditions. IIIb) Estuarine conditions. IV) Tectonic movement.

This work represented something of a starting point as prior to this, little had been done on the taphonomy of submerged terrestrial sites beyond the discussion of individual archaeological deposits (e.g. Andersen, 1980). These studies made use of a relatively small and quite diverse body of data to infer some very general principles. Kraft et al's (1983) conceptual model was based on two very different regions – the mid-Atlantic coast of the USA and the Aegean coast – while Flemming's (1983) inferences were based on a sample of sites ranging in age from the Middle Palaeolithic to the Bronze Age, and from across the globe.

This work though was not entirely comprehensive. For instance, given the small and diverse nature of the sample coupled with the temporal and spatial variability of sea level and coastline change, questions can be raised about the applicability of the general principles of site survival in all situations. Indeed, Flemming (1983) pointed out that:

"A complete study of the survival of archaeological materials would have to include the mechanism of immediate preservation at the site of occupation in the short term; the mechanism of surviving marine transgression; and the mechanism of surviving underwater for many thousands of years" (Flemming, 1983:164)

However, despite this rather promising start, the issue of marine taphonomic processes and their impact on submerged terrestrial material has not really been discussed or taken further. This paucity of recent work is illustrated by recent reviews of submerged archaeology (Flemming, 1998; 2002) which, in discussions of 'the taphonomy of submarine occupation' (Flemming, 1998:134) reference Flemming (1983) and Kraft et al (1983). This contrasts somewhat with work on site formation processes in other facets of maritime archaeology. Note for instance the updating of Muckleroy's (1978) model of shipwreck taphonomy by Ward et al (1999). It seems that there is a gap in research between studies of large scale landscape evolution (Section 4.1) and the above site specific studies that needs to be filled.

Expanding the perspective from maritime to terrestrial archaeology, some work does exist on the responses of prehistoric material to fluvial processes, such as Schick's (1986) work on East African Lower Palaeolithic material, and more recently experimental work on biface and flake distribution in Welsh rivers (Hosfield & Chambers, 2002; Hosfield, 2004). However, these sort of studies have yet to be extended to the marine situation.

As the archaeological approaches to this topic are rather limited, attention will also be turned to the areas of marine geology and sedimentology. A significant amount of research has been undertaken on the subject of sediment movement by marine processes for coastal engineering and management (e.g. Orford et al, 2002) or minerals prospection purposes (e.g. Corbett & Burell, 2001). The reasoning behind using these approaches to gain insights into the reworking of archaeological deposits is that much archaeological material, especially the lithic implements which comprise the vast majority of the prehistoric record (see Section 3: Theme 2), can be regarded simply as 'unusually shaped clasts' (Hosfield, 2004), and should theoretically respond to marine processes in similar ways to natural sedimentary particles of similar size, mass, shape and material type. Nevertheless, Schick (1986) does suggest that the unusual morphology of archaeological material relative to natural sediment, and its restricted size category within the geological range may affect its behaviour in a fluid medium, and consequently the geological studies are unlikely to provide exact analogues to the archaeological situation.

This investigation will focus primarily on coarse clastic deposits. These consist of all grains commonly classified as coarser than sand on the Wentworth scale, or greater than 2mm in diameter, ranging from granules to boulders (Pethick, 1984). This follows the terminology of Orford & Carter (1993) which, in addition to the defining 'coarse clastic', used the term gravel to refer to all material between pebble and cobble size classes (between 4 and 256 mm in diameter) (Carter & Orford, 1993; Pethick 1984). This is because bulk of the archaeological material from the periods in question, notably lithic implements, is rarely less than several centimetres in size (Schick, 1986).

Further potential departure from the situation in reality is linked to the methodology of both the archaeological and sedimentological approaches, namely the use of laboratory based flume experiments and natural field experiments. The disadvantages of using these sorts of studies is related to the general problems associated with them. Natural field experiments often have a lack of control in monitoring variables; consequently, it may be difficult to determine the exact effects of individual variables. Flume experiments meanwhile are better able to determine individual effects, but do suffer from the fact that they oversimplify complex systems (Nash & Petraglia, 1987).

Therefore, at this rather introductory stage of research, any insights drawn out of the existing body of work will not constitute unequivocal statements as to how archaeological deposits may be reworked in the coastal and shelf environments. However, they may be able to illustrate the types of general processes that should be considered when assessing the condition and location of archaeological contexts in the marine environment, and also indicate any questions which can be addressed by future research.

4.2.2 Sediment Dynamics

4.2.2.1 Basic Theoretical Principles

This section will discuss the basic concepts of sediment dynamics that are necessary to understand how archaeological material might respond under transgressive or marine conditions.

As fluid passes over a bed of sediment grains, it decelerates due to friction against the bed surface. This generates horizontal 'shear stresses' in the layer of fluid closest to the bed; the 'boundary layer'. The momentum of the moving fluid is transferred to the sediment grains by these shear stresses and exerts a force on them (Figure 121).

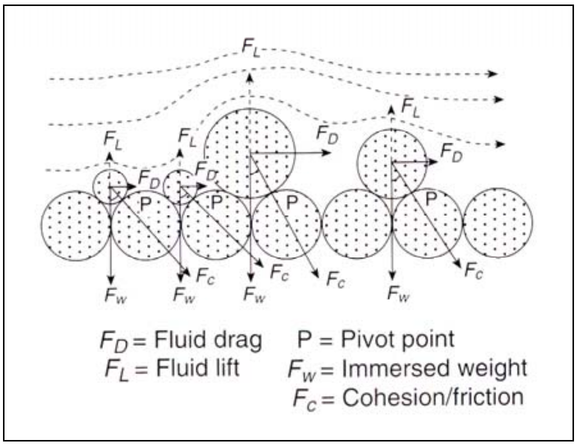


Figure 121. Summary of forces acting on sediment grains that are involved with entrainment and transport (modified from Woodroffe, 2003).

Should this force be sufficient to overcome the forces holding a grain to the rest of the bed, then it will be lifted out of the bed and over the underlying layer. The strength of these latter forces is determined largely by the grain's mass, and whether it is attracted or interlocked with other grains. The point at which grains begin to move with fluid flow is known as the 'critical threshold velocity' (Leeder, 1999). Key to this process are:

- Grain size and density
- Bottom boundary layer currents
- Type of flow
- Interactions between sediment particles

These will now be discussed in turn.

- **Grain size and density:** of each grain plays a part in determining its critical threshold velocity. Larger grains tend to have higher critical thresholds than smaller grains and hence require larger shear stresses before they move. Figure 122 provides an indication of the current velocities required to induce transport in material of different grain sizes. This effect is illustrated by the fact that around the British Isles, tidal current gravels tend to be only a few centimetres thick (though exceptions do exist in areas of strong current), while associated muds can be up to 30m thick and are potentially much more extensive, due to the weakness of currents over large areas of shelf (Stride et al, 1982). Deposition takes place as overall activity decreases to the point where grains are static for longer periods and mobile for shorter ones until they are either buried deep enough for only the most powerful water movements to affect them, or if current strength decreases sufficiently (Stride, 1982). This relatively simple relationship however, is modified by the nature of the bottom boundary currents, the nature of the flow and the effects of large scale bed morphology. The theoretical current velocity estimated to be capable of transporting coarse clastic material is of the order of c. 0.75 ms^{-1} or greater (see Figure 122 - Stride et al, 1982). It should be mentioned though, that palaeo-environmental evidence, which often forms a important component of any archaeological site, may be smaller than this coarse material. This sort of evidence includes pollen and microfossils of plants and animals. It is therefore worth bearing in mind that though a site may appear to be in primary context (i.e. the more obvious artefacts are still in situ), less visible components may have been winnowed away.

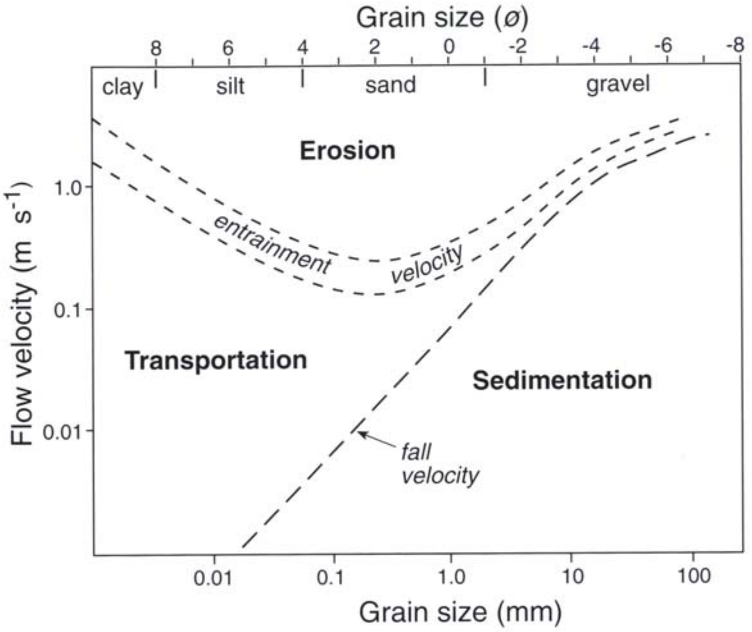


Figure 122. Hjulstroms Curve. This provides a measure of the critical entrainment velocity for material of different grain sizes (from Woodroffe, 2003).

- **Bottom boundary layer processes:** involve interactions between currents, waves, bed morphology, sediment suspension and transport. Shear stresses are a function of current velocity in that increased velocities result in higher shear stresses. Therefore shear stresses, and hence sediment movement, induced by both waves and tidal currents are depth dependent in that they decrease as depth increases (see Sections 4.1.5.1 and 4.1.5.2, Figure 123).

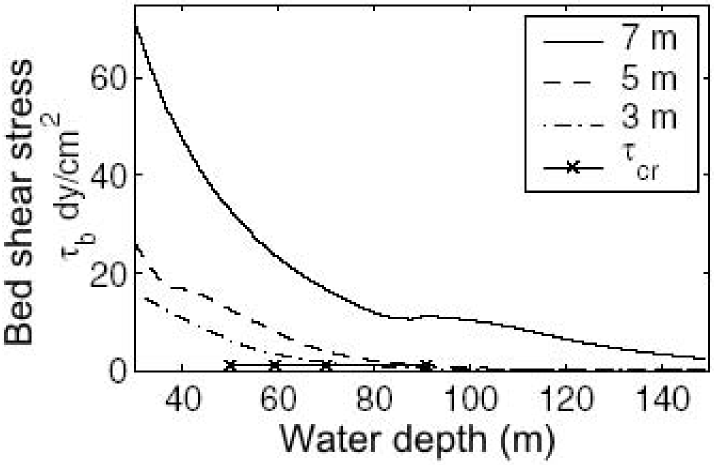


Figure 123. Bed shear stress across a continental shelf calculated for significant wave heights ranging from 3 to 7m. Note the decrease with depth in all cases (from Harris & Wiberg, 2002).

- **Type of flow:** studies of sediment movement in the marine environment suggest that the consideration of two types of flow is necessary (Leeder, 1999; Paphites et al, 2001). Firstly, unidirectional flow is essentially what was discussed at the beginning of this section. It is a flow in one direction generated by tidal or density currents that has the capacity to entrain sediment depending on current speed, sediment grain size and density. Secondly, oscillatory flow is caused by the motion of water particles under wave conditions. At the water surface, water particles move in a circular orbit. However, as depth increases, the orbit decreases exponentially (Figure 124). At the point at which depth equals one-half wavelength, there is virtually no wave induced movement of water particles. In shallow regions, the seabed may be located at less than one-half wavelength, and the orbits become progressively flattened. Consequently, at the seabed water moves in an oscillatory ('to and fro') motion (Figure 124 - Open University, 1989; Leeder, 1999; Davis Jr. & Fitzgerald, 2004).

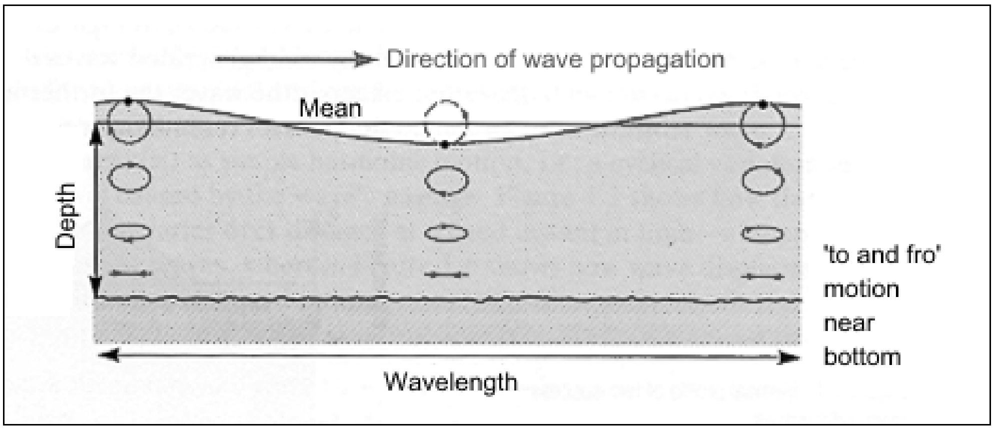


Figure 124. Diagram demonstrating the flattening of wave orbital movements in shallow water (after Open University, 1989).

Each type of flow has the potential to affect sediment grains in different ways: Assuming it is capable of entraining the sedimentary grains in question, unidirectional flow will move the grains in a single direction until it is incapable of doing so (i.e. the bed shear stress falls below the critical shear stress). Under oscillatory flow, sediment grains will move to and fro but with a net movement in the direction of propagation of the wave. This results from the fact that the orbital velocity of a wave is not the same speed in either direction (Figure 125). At wave troughs, the distance of a water particle to the seabed is reduced and concomitantly, frictional retardation by the bed is increased. Consequently, particles speeds are higher at wave crests (onshore movement) but are only maintained for short intervals of time. In contrast at wave troughs, speeds are lower (in the offshore direction) but are maintained for longer periods (Open University, 1989). This asymmetry means that both coarse and fine sediment are transported shorewards, but often the coarse fraction cannot be returned seawards (Open University, 1989). This net onshore transport of coarse material combined with net offshore transport of finer material results in cross shore segregation of sediment characterised by offshore fining (de Meijer et al, 2002).

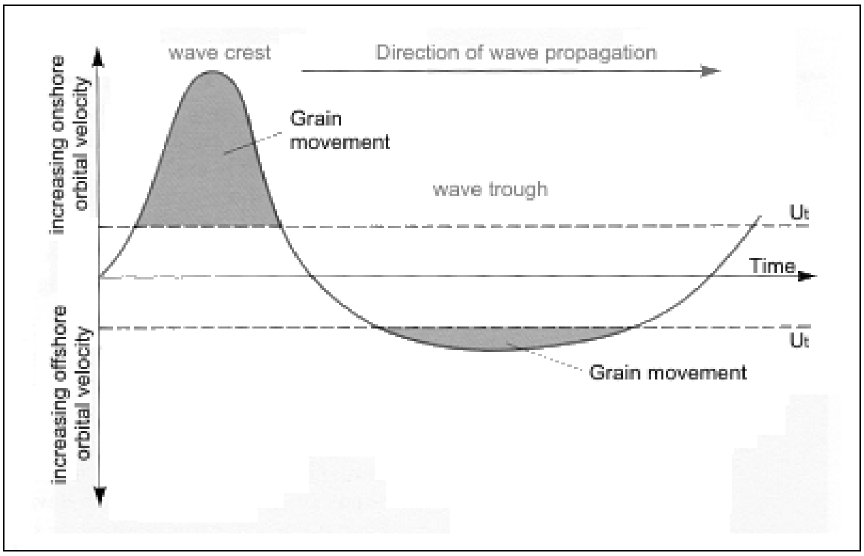


Figure 125. Asymmetry of water particle velocities associated with wave orbital motions in shallow water. Ut is the critical threshold velocity at which grains of a given size will begin to move. Grey areas represent the range of velocities for which the grains will transported (from Open University, 1989).

In most cases, these flows do not operate in isolation, but interact to produce combined shear stresses (Paphites, 2001). In general, the interaction actually reduces the threshold velocity of the sediment, and can enhance sediment transport. This happens because the oscillatory movements of waves can lift sediment into suspension at lower equivalent velocities than a steady current. Once in suspension, it can be moved by the unidirectional flows which, on their own would have been incapable of generating sufficient shear stresses to lift them off the bed (Open University, 1989). The nature of the interaction is also affected by the period of the waves. For long period waves (e.g. > 10 seconds) the two components interact in a linear fashion such that as the importance of wave action increases, the influence of unidirectional flow decreases and vice versa. Furthermore, the longer the period of the wave, the more ‘developed’ the interaction between flow and oscillation will be and hence will result in a lower threshold for sediment movement (Paphites et al, 2001). However, in shorter period (e.g. c. 5 seconds or less) waves, the thin turbulent boundary layer of the waves can actually suppress the impact of unidirectional flow thus increasing the threshold required for grain movement (Paphites et al, 2001).

- **Interaction between sediment particles and bed morphology:** it should be noted that grain size and density is not the sole control on transportability. Electrostatic forces may hold grains together, particularly in estuaries where the water chemistry promotes flocculation (the amalgamation of clay particles through electrostatic attraction: Leeder, 1999). Further, the transportation of small grains may be retarded if they shelter amongst larger particles (Hosfield, 2004). Artefacts may also be trapped in certain areas by localized modifications of the flow patterns, such as scour pits (Schick, 1986). The propensity of this to happen depends to a large extent on bed morphology. Sheltering for example is more likely to occur in a coarse grained bed than a fine grained one as the gaps between the larger particles can potentially trap smaller grains.

In addition, the composition of sediment may also have an impact on the resulting transport patterns. In mixed sediments for example, the threshold velocity of the coarser fraction tends to decrease, as they protrude further into the boundary layer. The resulting lower pivoting angles then appear to maximise the local lift and drag forces, thus facilitating its entrainment (Panagiotoupolous et al, 1994; Paphites et al, 2001; De Meijer et al, 2002).

4.2.2.2 Modes of Transport

Transport of particles takes place in 2 modes; bedload transport and suspended load transport. In the former, particles are supported intermittently by grain to grain contact, while in the latter they are supported by turbulence (Nittrouer & Wright, 1994; Leeder, 1999 - Figure 126).

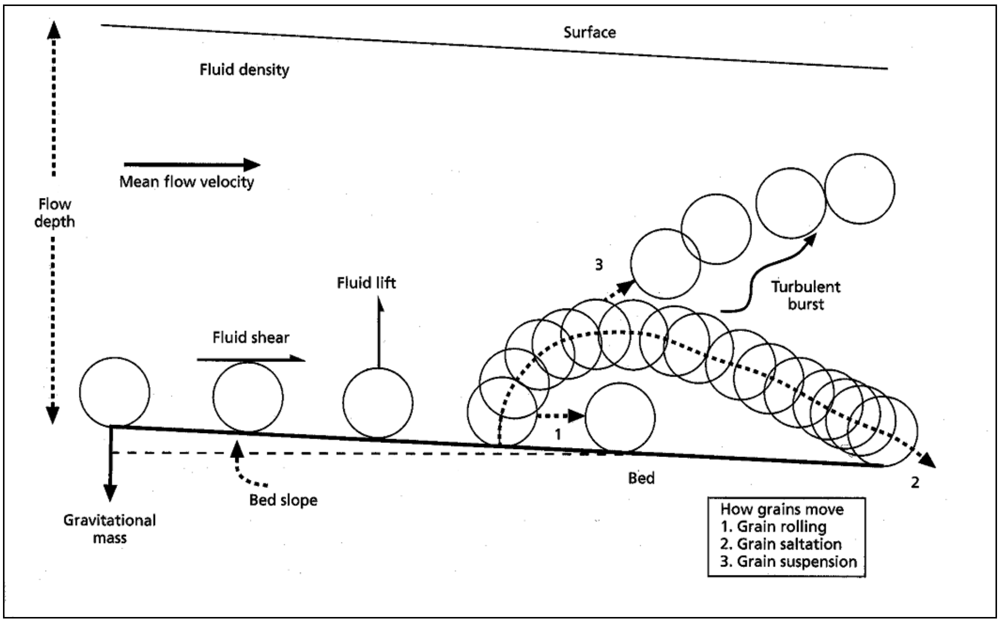


Figure 126. Grain movement under conditions of flow. Grain rolling and saltation (intermittent rising and falling of grains in conjunction with movement in a horizontal direction) constitute bedload transport. Grain suspension constitutes suspended load transport (modified from Leeder, 1999).

Coarse particles tend to be suspended less often than finer ones, due to their greater threshold velocities. The same is likely to be true of archaeological material (Schick, 1986). The movement of sediment grains tends not to be continuous, but to occur in short periods when the shear stress is sufficient to enable erosion and then transport, followed by longer periods when the particles are stationary (Hosfield, 2004). At these times it is possible for the particles to be buried beyond the range of transport processes and remain in situ (Nittrouer & Wright, 1994). This processes is complicated by the fact that differential transport of particles may occur with respect to particle size, shape and composition (de Meijer et al, 2002; Lee, 2001; Nittrouer & Wright, 1994). This means that certain particles, or particle classes may be selectively deposited, transported or buried at particular points on the shelf, thus somewhat complicating the overall pattern of sorting. Theoretically, the same should be true of archaeological material and will be discussed further in the following sections.

4.2.3 Archaeological deposits on coastlines

For the purpose of this discussion the factors to be focused on concern the proportion of sediment that is removed from the shoreline, the distance it travels, and the depth (both of water, and sediment) to which these processes operate as these should theoretically determine whether an assemblage in primary context is reworked into secondary context. The coastline or beach (Figure 127) is generally considered the most active part of the continental shelf (Emery, 1968). Forces operating here are often driven by breaking waves, each of which has the ability to move sediment (Davis Jr. & Fitzgerald, 2004). However, the diurnal tidal cycle also results in twice daily unidirectional currents flowing onshore with the flood tide and offshore with the ebb tide. Thus the exact contribution of each type of flow (i.e. the local hydrodynamic pattern) depends on the local tidal prism and local wave climate. These will be influenced by local bathymetry, shoreline morphology and geology and wind patterns (see Section 4.1.5.5).

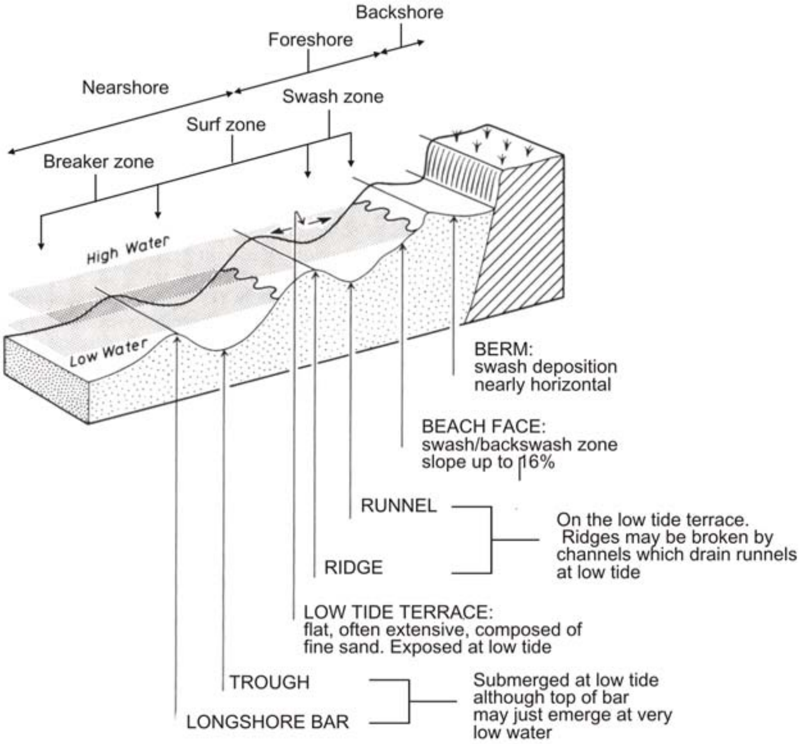


Figure 127. Idealized profile of a beach (modified from Pethick, 1984).

The gradient of the beach also influences the way sediment on it behaves. On gently sloping beaches, wave energy is gradually dissipated across a wide cross shore area, thus promoting the deposition of sediment onshore. In contrast, steep beaches tend to be erosional as the gradient reflects a significant amount of water, and hence energy, back to open water. This enhanced backwash therefore promotes removal of sediment from the beach surface (Davis Jr. & Fitzgerald, 2004). Furthermore, the gradient of the beach, in conjunction with the local tidal range, controls the amount of time for which a particular hydrodynamic zone (e.g. swash zone, surf zone) spends over a particular section of the intertidal zone. This in turn influences the degree of reworking at a given section of the beach (Jackson et al, 2002).

In terms of impact, the most obvious aspects to consider are transport of the artefacts, and damage to the artefacts, such as through abrasion or rolling (Hosfield, 2004; Schick, 1986). Transport of the artefacts results in the transformation of primary contexts to secondary contexts, and secondary contexts into tertiary contexts while damage may make the artefacts more difficult to identify, interpret and analyse.

When considering how archaeological material on the shoreline might respond to transgression, we also have to consider whether it lies on the surface, or is buried within the coastal sediment. The reason behind this lies in the fact that burial should protect archaeological deposits from taphonomic forces (Flemming, 1983; Kraft et al, 1983).

4.2.3.1 Exposed material

As individual clasts rest on a surface (e.g. the beach face, or the shoreface), they protrude into the bottom boundary layer and are subject to cyclic loading and shear stresses as waves and tidal currents pass over them (Carter & Orford, 1993; Leeder, 1999). Archaeological material is unlikely to be an exception to this rule unless buried to a sufficient depth in the sediment (see Section 4.2.3.2). Studies of coarse-grained beaches have suggested that the transport of clasts tends to be correlated with wave height, the duration of immersion, and the long axis of the clast. The main observations of these studies now follow:

On flat sand beaches or relatively planar surfaces, individual clasts may move landward by up to 35 metres within a few hours (Carter & Orford, 1993). As individual clasts tend to then collect into surface gravel patches this leads to the possibility that archaeological material of similar size and shape may accumulate in such patches (Carter & Orford, 1993). This results from the differences in critical thresholds (see Section 4.2.2.1) of differently sized particles which in turn partially determines their transport patterns and hence position within stratigraphic sequences.

On beaches, size gradients tend to result from the asymmetry between wave uprush and backwash forces (see Figure 128). This results in preferential deposition of coarse material at the beach crest, relatively fine material in the mid-beach zone and coarser material at the seaward edge of the beach. Although this pattern may be altered by factors such as tidal cycle fluctuations, all gravel beaches will exhibit some sort of cross beach variation (Lee, 2001; Orford et al, 2002).

Particle shape may also exert an influence with disk and blade shapes moving preferentially up the beach, and more rounded forms, such as spheres and rollers moving preferentially down-beach (Lee, 2001; Orford et al, 2002). As before, this is an idealized situation (Figure 130).

On beaches with a significant coarse component, extensive grain to grain collision may occur, especially during plunging wave conditions (Carter & Orford, 1993). By implication, this suggests that archaeological material on such a beach, if exposed to wave action, may be significantly abraded.

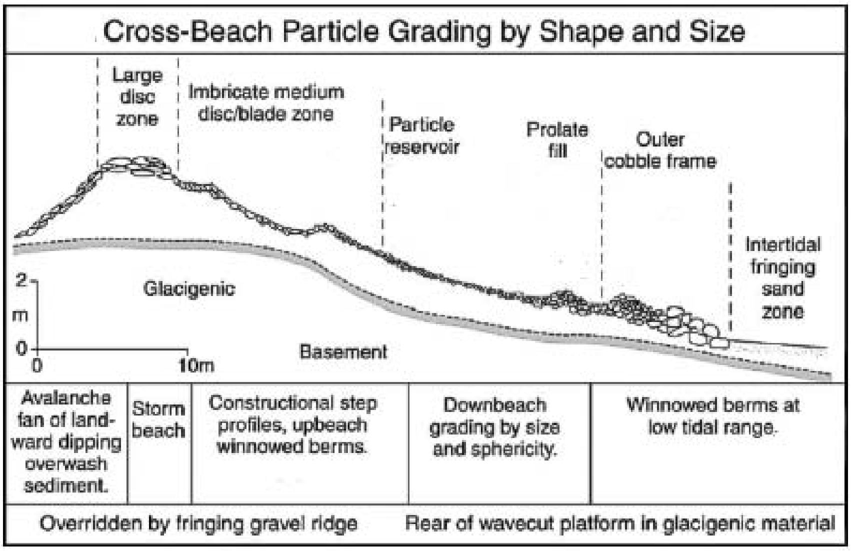


Figure 128. Idealized profile of size and shape sorting of coarse clastic particles (modified from Orford et al, 2002)

Archaeological material may however survive in relatively secure contexts on low energy beaches. In these environments, non-storm significant wave heights are less than 0.25m, beach face widths are less than 20m and significant wave heights during strong onshore winds (< 8 ms^{-1}) are less than 0.5m. This observation has been inferred on the basis that these coasts are characterised by little evidence of cyclic cross shore sediment exchange, and an inability of waves to rework micro-topographic features or beach litter (Jackson et al, 2002). By implication the same should be true of archaeological material. Note for instance that many of the areas highlighted by Flemming (1983:161-162) as being conducive to preservation of archaeological sites were characterised by 'minimal' or 'small' maximum wave heights.

Some ideas have also been advanced as to the behaviour of coarse clasts in the surf zone. In this zone, flow is dominated by breaking waves and consequently there is likely to be a large contribution from oscillatory motions (Nittrouer & Wright, 1994). While extensive research has been conducted into the dynamics of sediment motion under wave conditions, the vast majority of it has focused on fine sediment (Panagiotopoulos et al, 1994; Voropayev et al, 2003). Relatively little consideration though has been given to the movement of larger sediment particles which might more accurately mimic the behaviour of archaeological material barring some recent papers by Voropayev et al (2001; 2003) on cobble sized (6.4 to 25.6 cm diameter) material.

In general, with orbital velocities of up to 0.5 ms^{-1}, a variety of cobble responses are possible, ranging from onshore and offshore movement to steady oscillations with no net movement. The response of the cobble can be related to their size, density, initial position, the slope of the bottom, background flow and friction between the bed and the cobble. For example, where density exceeded 1.5 gcm^{-3}, no movement was observed at all in flume experiments. Complications have however been observed in the zone of breaking waves where in some instances cobbles moved onshore, but in other instances, the same cobble was trapped. This behaviour could not be explained (Voropayev et al, 2001).

Bedforms created by wave oscillations can also modify the transport patterns of individual clasts in the surf zone. For example: the migration of ripples can result in the periodic burial of clasts, effectively trapping them. This is especially the case with larger clasts (c. 20cm diameter, 3kg mass) when they are of comparable size to the ripples, though smaller ones (c. 7 to 10cm, <0.5kg mass) appear to exhibit a net onshore movement (Voropayev et al, 2003).

The cobble responses described above are not exact analogues to the behaviour of archaeological material in the surf zone, however they do provide some indications of the parameters to consider when assessing their reworking. They do highlight the fact that the interaction between the multiple factors affecting sediment movement means that the resulting distribution of particles can be difficult to predict.

A further issue to consider is that waves breaking in the surf zone set up rip and longshore currents which can move sediment parallel to the coastline. These are commonly of the order of 1 ms^{-1} or greater (Nittrouer & Wright, 1994; Open University, 1989). Observations of coarse clastic sediment on beaches have provided the following statements:

The position and form (size and shape) of coarse particles has also been argued to impact on the distance they move longshore. Experimental work suggests that particles closer to the seaward side of the beach tend to move further longshore. This is a logical conclusion since material closer to the seaward margin will be subject to a greater degree of inundation and thus more opportunities to be entrained by longshore currents (Lee, 2001).

Similar conclusions have been made for particle size in that large clasts move greater distances longshore. This seemingly simple relationship though may be modified by wave energy to the extent that it may be accentuated with increasing wave energy, but reversed with decreasing wave energy. This has been related to the sheltering of smaller grains by the larger particles which reduce their longshore velocity (Lee, 2001). However, when wave energy is reduced, larger clasts cannot be entrained, thus even with a reduced velocity smaller grains will move further. In terms of the distances moved the largest movement of gravel that has been recorded was 2km in 30 days (Lee, 2001). However, this is an exceptional result and most rates are an order of magnitude less, while in some instances virtually no movement was noted (Carter & Orford, 1993).

Particle density may also have a role as it has been observed that clasts of lower density tend to have a higher longshore transport velocity than their denser counterparts (Lee, 2001). It should also be noted that when accumulations of material occur, consideration such as group imposed controls (e.g. bed acceptance or rejection, contact stresses) should be brought to bear as these may influence subsequent sorting and entrainment (Carter & Orford, 1993).

The deposition of material entrained by longshore currents occurs where the velocity of the current decreases to the point where it is no longer to exceed the threshold of the material it carries. In many cases this occurs in particular topographic or geomorphic situations. For examples, studies of placer (heavy mineral) deposits have demonstrated that they are often best developed at points of shoreline curvature (e.g. headlands), barriers and also near river mouths where currents slow and wave action diminishes (Browne, 1994; de Meijer et al, 2002).

The above observations have been drawn out of studies which have examined material affected by multiple tidal cycles. However, very rapid events, chiefly storms can also have a significant impact, though studies suggest they often result in the rearrangement of material on a beach rather than the removal of significant quantities offshore. This rearrangement often takes the form of the removal of sediments from the beach crest and their redeposition on lower portions of the beach (Van Wellen et al, 1997). However, other authors suggest they can also cause severe beach and dune erosion, and result in significant offshore sediment transport (Schwarzer et al, 2003). The kind of impact that extreme wave erosion could have on archaeological material is graphically illustrated by the fact the concentrations of gravel, peat lumps and fossil wood from 10 to 25m water depth are often found after storm events on the barrier island beaches of German North Sea coast (Hoselmann & Streif, 2004). In either case (i.e. rearrangement or removal) the spatial and structural integrity of an archaeological site will be lost. In all cases the survival of a site will depend on the unique local interaction of wave action, tidal current, coastal substrate and morphology, weather and nature of the archaeological material itself.

In terms of the impact of transgression on exposed material, it will essentially alter its duration of inundation and thus the time it spends in the swash, surf, breaker and finally offshore zones (see Section 4.2.4). It may thus have an effect on the final sorting pattern of a deposit, though the exact effect is difficult to quantify at this point in time.

There have been some observations on the behaviour of in situ archaeological material exposed on beaches. For example, in Langstone Harbour (southern England), archaeological material ranging from Mesolithic flint implements to Roman pottery has been observed eroding out of low salt marsh cliffs on the edge of the upper foreshore (Figure 129). These have been interpreted as being in primary context when incorporated in the cliff deposit (Stage 1: Figure 129). However, cliff retreat due to wave erosion releases the artefacts onto the upper foreshore. At this point, the finer resolution of the assemblage will have been lost as some minor rearrangement has taken place but the basic horizontal spatial integrity, (though not the vertical stratigraphic relationships), remains (Stage 2: Figure 129). Wave action then results in the winnowing out of the smaller artefacts, and limited movement of the larger pieces (Stage 3: Figure 129). As coastal recession of the saltmarsh continues, the intertidal foreshore migrates shoreward. More rigorous wave action and swash then results in further reworking (Stage 4: Figure 129) with the end result that the artefacts are removed by tidal action, probably into the tidal channels of the harbour (Stage 5: Figure 129 - Allen, 2000).

In general, it seems that artefacts may survive for millennia in primary context in the cliffs. Once released from this context, they have moderate residence time at the foot of the cliffs before they are deposited on the wave cut upper foreshore platform, often with other, similarly sized material. As the foreshore is cut down, the artefacts are rapidly removed from the foreshore in into the tidal channels (Allen, 2000).

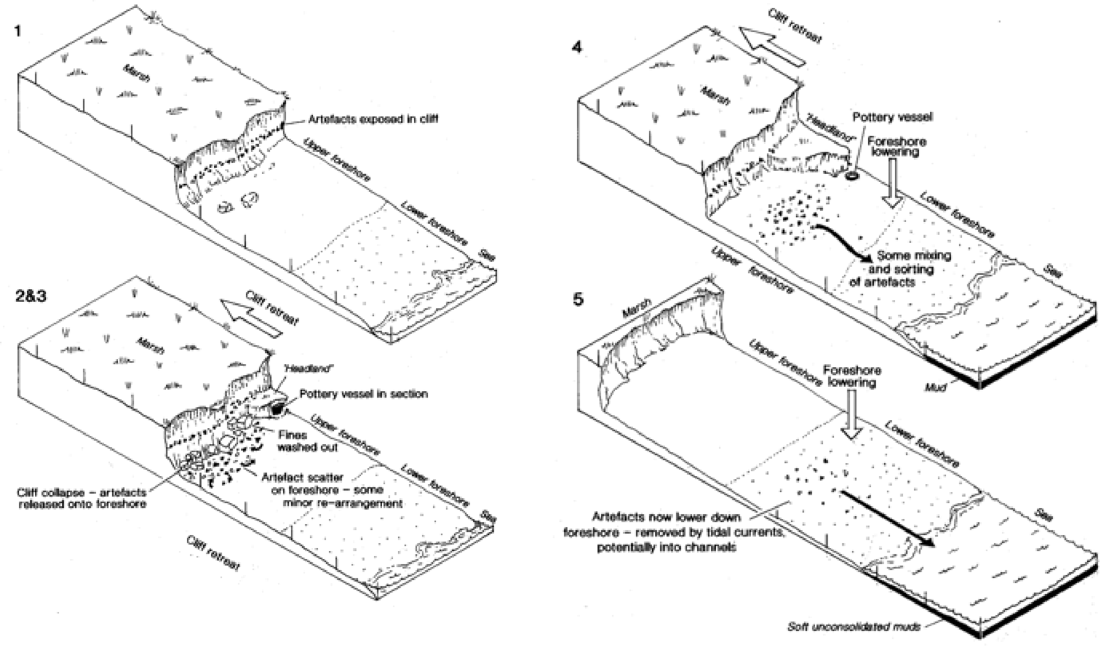


Figure 129. Diagram showing sequence of events in the reworking of primary context assemblages at Langstone Harbour. See above text for sequence of events (from Allen, 2000)

Tidal range in Langstone Harbour is around 3m (Allen, 2000). Consequently it is worth considering that there may be a significant unidirectional contribution to the local sediment transport regime. Experimental work on lithic flake scatters under conditions of unidirectional flow (river system) has demonstrated a pattern, which may also influence the sequence of events depicted in Figure 131. Freshly knapped, or in situ, scatters are characterised by a high concentrations of flakes and debitage within a relatively limited area. Consequently, high levels of interaction between the flakes, could retard transport. Therefore, the first instance of transport is characterised by reduced reworking (flakes transported <10m), but after that, each subsequent transport event increases the spread of the material, thus reducing the interaction between particles, which in turn increases the overall spread of the scatter (flakes transported >80m: Hosfield, 2004).

4.2.3.2 Buried material

In addition to material exposed on the shoreline, we must also consider the effects of transgression on material buried within beach sediment. Indeed one of the main factors when considering the likely preservation of buried deposits, is the depth to which sediment may be mobilized by wave processes in the surf zone. In sedimentological terms this can be related to the 'sediment mixing depth', which is can be thought of as follows:

> *"The vertical thickness of a layer where active sediment exchange takes place, below which lies an immobile bed"* (Ferreira et al, 2000)

The maximum mixing depth is therefore the limit of detectable erosion of the bed and controls the truncation of antecedent sedimentary structures (Sherman et al, 1994), which may contain archaeological material. The mixing depth tends to be controlled by processes that operate over the course of a few hours (Sherman et al, 1994). However, the continual operation of these short term processes on archaeological material over a longer period of time, for instance, from days to years, certainly has the potential to disrupt a primary context assemblage. Indeed, as the previous section (4.2.3.1) has highlighted, movement of coarse clasts in the surf zone can be very rapid, so even a very short term event may have a significant impact on the spatial integrity of a deposit of archaeological material.

Experimental studies have indicated that mixing depth is related to breaking wave heights and foreshore slope, with greater breaking wave heights causing increased mixing depths, and increases in slope also resulting in increased mixing depths. On steeper slopes, plunging and collapsing breakers dominate, thus resulting in higher wave energy dissipation over a relatively restricted cross shore zone, while on gentle slopes spilling breakers dominate. These dissipate the same amount of wave energy, but over a large cross-shore area, thus resulting in reduced mixing depths (Ferreira et al, 2000). Mixing depths in everyday situations tend be of the order of several centimetres to several tens of centimetres depending on breaker height and foreshore slope (Table 14 - Sherman et al, 1994; Ferreira et al, 2000; Lee, 2001).

Breaking wave height (m)	Beach face slope	Min. mixing depth (cm)	Max. mixing depth (cm)
0.37	0.11	10.6	15.0
0.34	0.11	10.6	15.0
0.37	0.11	10.6	15.0
0.64	0.10	9.9	15.0
0.49	0.10	10.3	20.0
0.80	0.14	22.0	25.0
0.49	0.11	10.7	19.0
0.60	0.10	16.0	28.5
0.81	0.10	15.3	34.7
0.61	0.12	14.4	32.0
0.85	0.14	17.2	34.6

Table 14. Experimental results from Portuguese beaches showing wave height, beach slope and maximum and minimum mixing depths (after Ferreira et al, 2000).

The influence of burial depth on the movement of coarse clasts is clearly shown by the fact that particles are 3, 5 and 66 times as mobile at the beach surface than the lowest moving sediment under conditions of high, intermediate and low prevailing wave energy conditions respectively (Lee, 2001). Clearly archaeological material buried below the maximum sediment mixing depth will be unaffected by wave and tidal processes, except under extreme storm wave conditions which may erode sediment to a greater depth.

Finally, the type of sediment in which the archaeological material is buried may also be an important consideration. Peat and associated fine grained inorganics that are buried beneath the oxic zone in particular, (Streif, 2004; Behre, 2004) are regarded as providing excellent protection, both in terms of organic preservation, and maintaining the spatial relationships between artefacts by packing them in fine grained cohesive sediment (Flemming, 2002). Key to the good preservation (certainly of wood and other fibrous material) is the inhibition of macrofaunal and microfaunal species that are so effective at degrading exposed materials. In the near anaerobic conditions of the shallow section, only soft rot and microbial erosion bacteria are a threat but these do tend to be the slowest forms of faunal degradation. This is evidenced by the dramatic preservation in peat and silt of a Bronze Age (c. 4 ka BP) timber circle ('Seahenge') in the intertidal zone on the Norfolk coast (Figure 130), and the presence of what appear to be in situ artefacts eroding out of the peat layer in the vicinity of the circle (Champion, 2000).

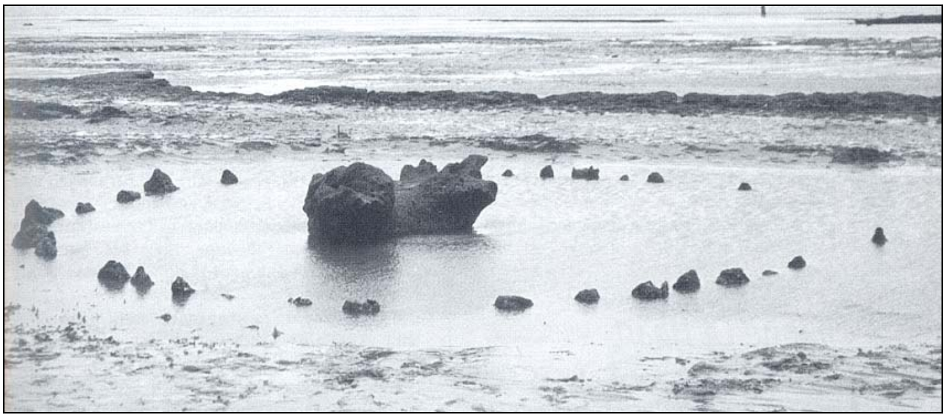


Figure 130. Bronze Age Timber circle ('Seahenge') eroding out of peat deposits on the Norfolk coast (from Champion, 2000)

4.2.4 Archaeological deposits on the shelf

As explained in Sections 4.2.2.1, more energetic waves result in higher bed shear stresses, thus resulting in entrainment from a deeper layer of sediment, in a given area, and also entrain more sediment from deeper waters than less energetic waves (Harris & Wilberg, 2002). For given surface wave conditions, the intensity and magnitude of wave induced bed shear stress diminishes rapidly as water depth increases (Harris & Wiberg, 2002). Thus, a point is reached below which the impact of waves on sediment transport is minimal; this point is known as the 'wave base'. It can be located as much as 100m in depth depending on the period of the wave (Swift & Thorne, 1991; Leeder, 1999), though does not usually extend below 20 or 30m depth (Harris & Wiberg, 2002;). Consequently, bottom boundary layer processes on the mid and outer shelf are dominated by unidirectional tidal and density currents, though storm waves may occasionally induce movement at great depths (Nittrouer & Wright, 1994).

As has been described in Section 4.1.5.4 the bulk of sediment transported on shelves is sand sized. However, where current speeds are strong enough, such as at extreme spring tides, gravel can also be moved (Johnson et al, 1982). Bedforms comprised of this material range from gravel waves ranging from several centimetres to several metres in height, which form when peak near surface mean spring current speed is greater than 0.65 – 0.7 ms^{-1} while current speeds of greater than 1.5 ms^{-1} can create 30m wide by 1m deep furrows in gravel substrates (Belderson et al, 1982; Stride et al, 1982). Furthermore, 1m high gravel waves of about 10m wavelength are known in areas of strong tidal currents and contrast with the lag gravels formed in areas of weaker current due to the winnowing away of the finer fraction. In these areas though, storm waves are capable of forming smaller gravel ripples of 20-25cm in height and 125cm in wavelength (Stride et al, 1982).

Thus, sediment transport on shelves is controlled by grain size, current velocity and depth. The movement of gravel on the shelf also suggests that archaeological deposits are unlikely to be immune from further sorting and disturbance as they move further seaward. The sort of reworking that archaeological material may encounter may be more similar to the unidirectional flows encountered in fluvial environments. Flume experiments by Schick (1986) have shown that below speeds of 0.15 ms^{-1} there in no movement in artefacts greater than 0.5 cm in diameter. At about 0.40 ms^{-1} artefacts of 1-2 cm in diameter move intermittently, while larger pieces make in place stabilizing adjustments. Increasing the speed to 0.6 ms^{-1} results in the movement, be it continuous or intermittent, of all pieces, including those up to 8cm long. Finally speeds of greater than 0.75 ms^{-1} were found to be capable of entraining all artefacts up to 15cm long and moving them continuously or nearly continuously. On this basis of these results, there is no reason to assume that archaeological material will be unaffected by the tidal currents described above.

However, these experiments also demonstrated that the movement of artefacts is not simply controlled by the velocity of the flow and their size and shape. Both Hosfield (2004) and Schick (1986) have postulated that interaction between particles (both natural and man-made) and bed morphology modifies this pattern to the extent that Hosfield (2004) observed that distribution of larger clasts is essentially random, while Schick (1986) noted that it was possible for regular patterns to be distorted. Both studies though, made the point that the movement of material is episodic rather than continuous and phase of burial or trapping may remove individual artefacts from the sedimentary regime, thus modifying the composition of the final deposit.

This observation will almost certainly apply to material on the continental shelf, for the simple reason that sediment transport is not homogenous across its surface as flow regimes vary due to the action of different forces. For example, protrusions on the seabed may redirect flow, or alternatively depressions or channels may act as conduits for particle flow (Nittrouer & Wright, 1994). Consequently certain areas may be surfaces of net erosion and others of net deposition. Indeed depressions and hollows tend to be preferential areas of deposition (Dunbar et al, 1991; Roy et al, 1994).

Consequently, archaeological material on the shelf is not going to exist in a simple system of depth dependent, and size sorting but may occur in patches dependent on localized conditions of deposition and erosion.

4.2.5 Implications for Archaeological Material

The above sections have highlighted the possible processes operating on archaeological material as it undergoes transgression. The impact of these means that the submerged continental shelf is likely to be a palimpsest of preservational variation. The implications are as follows:

- Archaeological material exposed on a beach is likely to be moved about by wave action. Hence sites exposed on a beach surface are unlikely to survive in primary context.
- On the shelf, even at great depth they may be reworked by unidirectional current flows and occasional storm wave action.
- If sites are buried to a sufficient depth of sediment they stand a far better chance of surviving in situ. However, this reduces the possibility of their discovery compared to exposed material. Recently exposed material may also have the advantage that the spatial relationships between artefacts are not too disturbed.
- Small pieces of evidence, such as palaeoenvironmental data (e.g pollen, microfauna), may well be winnowed away even if larger artefacts are only minimally disturbed.
- Secondary and tertiary assemblages are likely to be much more common. There is also a high potential that they will occur as patches of archaeological material sorted by size and type. However, this is not entirely certain given the complex responses of material to bed morphology, other particles and the combined impact of unidirectional and oscillating flows.
- Certain areas, (e.g. hollows or scour pits) may be preferential areas of deposition and trapping, and hence may represent potential areas of investigation.
- There is also a significant possibility that much of this material will be abraded and damaged and by collisions and bomardment with other particles.

Potential areas for future research to investigate could include:

- The archaeological potential of marine secondary contexts and tertiary gravels. Both Schick (1986) and Hosfield (2004) alluded to robust patterns observable in the distribution of secondary contexts material that allowed the investigation of the taphonomic processes affecting them and which may in time allow further interpretations to be made of hominid behaviour. Likewise, Allen (2000) noted that that the patterns seen in the scatters of material on the foreshore at Langstone Harbour could be compared to known primary context assemblages of the same period and the differences between them used to ask questions about ‘cultural activity, disposal practices, taphonomy and possible rearrangement by erosion’ (2000:198). Similarly, if marine secondary and tertiary contexts are commonplace in the shelf environment, then effective use will have to be made of them. Key to this will be determining research questions to which they are appropriate.
- Targetting site prospection on the basis of preservational condition. This could either take the form of investigation of areas of present erosion on the basis that it is only in these areas that archaeological material will be subject to further disturbance. Alternatively, areas of likely preservation such as deeps and hollows subject to preferential infilling could be targeted.
- Greater quantification and investigation of sediment mixing depths, especially in relation to depth of burial in archaeological sites.
- Experimental work on taphonomic processes operating on archaeological material on beaches and in the surf zone. This follows on from sedimentological

> research in coastal environments (e.g. Lee, 2001) and archaeological research in terrestrial environments (e.g. Hosfield, 2004; Schick, 1986) which has been able to demonstrate that robust patterns are deducible from disturbed archaeological material. In addition, a PhD dissertation has recently been submitted which assesses taphonomic processes on the basis of artefact abrasion and damage (Chambers, 2004). Although the full details of this were not available at the time of writing, this type of approach could be valuable in examining the marine reworking of secondary and tertiary contexts.

This preliminary investigation has highlighted that the study of marine taphonomic processes still has a long way to go. At the one end of the spectrum exists a number of specific locales inferred largely in the basis of single sites (Flemming, 1983). At the other end exist studies of coarse grained sediment movement under marine conditions. The next step will bring the two together into an analytical middle ground which may be of use to constructing models of preservational ‘hotspots’.

5. Theme 4 - Predictive Modelling of Submerged Archaeological Deposits

5.1 Introduction

Sections 2, 3 and 4 (Themes 1, 2 and 3 respectively) have highlighted the fact that submerged continental shelves are potentially rich sources of archaeological material. In the interests of managing this resource, and accessing it for the research purposes, these deposits must be located. However, underwater survey is an expensive, time consuming and complicated business. Acoustic systems can be used to locate archaeological material such as shipwrecks or past landscapes (e.g. Garrison, 1991; Praeg, 2003), but their effectiveness in locating prehistoric sites or prehistoric material such as described in Section 3 has yet to be tested. Divers, meanwhile are restricted to the shallower parts of the continental shelf, and can only spend limited amounts of time underwater. In addition, poor visibility may also hinder survey attempts, and while burial of archaeological material may promote its preservation, it may also retard its discovery (Flemming, 1983; 2002). In general, existing underwater work has indicated that even intensive searching with acoustic systems in conjunction with diver survey stands only a marginal chance of locating artefacts (Flemming, 1998).

Consequently, attention has been turned to the development of predictive models in order to facilitate the process of discovery (Bates et al, 2003; SALT, 2003). If areas of high archaeological potential (‘archaeological hot-spots’) can be determined in advance, then survey can focus intensively on these regions, hence reducing the time and expense. Furthermore, knowledge of areas of archaeological sensitivity can also provide a guide for shelf industrial concerns of where their work may affect the archaeological resource.

This document will briefly discuss the nature of existing predictive models and discuss their applicability for use in submerged environments. This discussion will take into account any conclusions drawn out of Themes 1, 2 and 3 and will attempt to provide guidelines for future use of predictive models for submerged prehistoric archaeology. This is intended to avoid the development of models based on inapplicable data or incorrect assumptions, which, if put into practice, may hinder any future attempts to access and manage the underwater resource.

5.1.1 Background

The use of predictive models in submerged landscape research has been postulated for some time. Note Flemming’s comment from 20 years ago:

“If submarine archaeological sites are to be found in the region of critical straits and land bridges we must be able to predict the approximate location of sites so as to minimise the search area, and the conditions must be known which will maximise the chance of survival of material” (Masters & Flemming, 1983:138).

However, despite the evident potential that models may have, this concept has been infrequently followed up in the intervening years. One exception to this was the predictive model created in the 1980s by Danish archaeologists to predict the location of submerged Mesolithic fishing sites (Fischer, 1995b). It arose out of the realisation that:

" [a] systematic diving survey of the entire seabed would be in practice impossible to carry out. In any case… it would take too long in relation to the tempo of destruction achieved by present day construction and raw material exploitation in the sea bed. [The] solution to this problem is model based prediction of site location" (Fischer, 1995:373).

The basis of the model was the correlation of archaeological sites with the most suitable present day localities for fishing with standing gear and fish traps. The importance of fishing in the Scandinavian Mesolithic could already be seen from existing archaeological evidence from isostatically uplifted shorelines while the information concerning the location of fishing sites was obtained by interviewing fishermen who practised traditional methods of fjord fishing with stationary fish traps. They indicated that the best places had certain topographical characteristics that facilitated the concentration of fish and minimized damage to the fish traps by wave action. Examples included the mouths of streams, places where fjords narrowed and the tips of peninsulas or headlands (Figure 131 - Fischer, 1995b; Fischer & Pedersen, 1997). The advantage of focussing on these topographical characteristics is that they can be read off depth contours on commercial undersea maps.

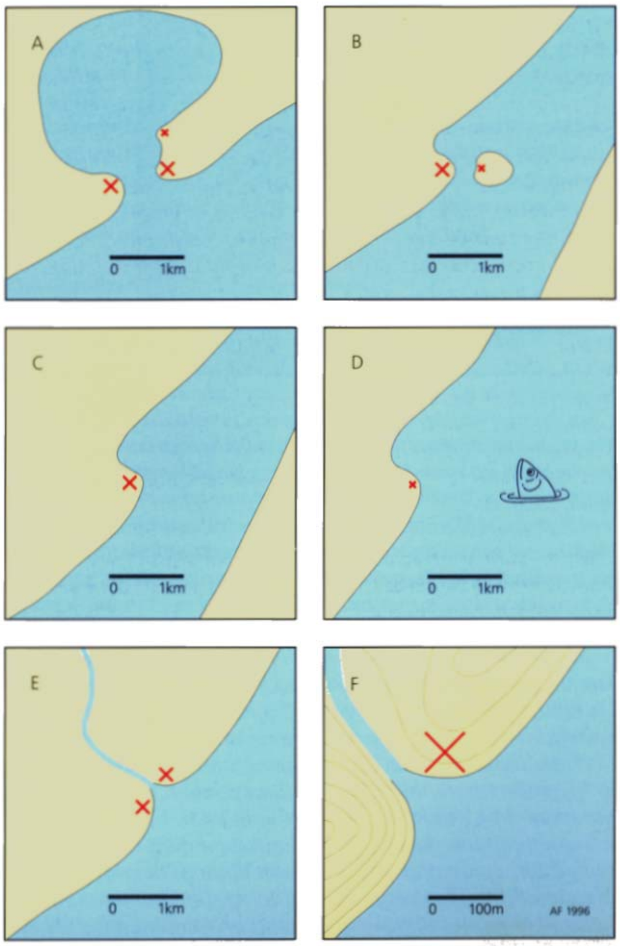


Figure 131. Sketch map of typical locations of Scandinavian Mesolithic coastal sites. A) Along narrow straits with a large hinterland on both sides of the channel. B) along narrow straits between the mainland and a small island. C) and D) on projecting headlands. In these areas the most suitable sites were in the lee of the headlands, where the impact of strong is minimized. E) and F) By major river mouths. Particularly favoured areas were located on evenly sloping terrain. In all sketches the larger X indicates a more suitable site (from Fischer & Pedersen, 1997).

Testing of the model by underwater diving surveys has highlighted its usefulness, with success rates of greater than 80% claimed in some instances (Fischer, 1995b).

The importance of the model with respect to both academic research and cultural resource management is illustrated by the fact that it greatly increased the number of known Mesolithic sites in both Swedish and Danish waters thus providing new evidence for archaeologists to work with, and also facilitated the underwater survey that preceded the construction of the A/S Storebaelt Fixed Link bridge (Pedersen et al, 1997).

Predictive surveys were also undertaken by American archaeologists in the waters off Northwest Florida (Dunbar et al, 1991). Their models were based on the correlation between terrestrial Palaeo-Indian sites, chert sources and karstic terrain features, notably rivers and sinkholes. A number of artefacts were collected by these investigations, though not in the same quantities as the Scandinavian surveys.

Unfortunately, although not within their original remits, neither approach has been tested in a variety of different submerged environments, and it is probable that they are both somewhat spatially and temporally delimited and may not provide immediate insight to environments submerged in central shelf localities. This limitation is due to the somewhat atypical interaction between sea-level change and sea-bed change in the sheltered environments investigated during the Danish study, and the karstic environment that characterises the Northwest Floridian coast. Furthermore, the only material recovered by either approach post-dates the early Holocene and thus it is questionable whether they may be applicable to earlier sites. Finally, though it is accepted than not all of the material is in primary context, there has been little discussion of the implications of this, beyond the statement that *"disturbed features and redeposited tools…[are] archaeologically less interesting sites"* (Pedersen & Fischer, 1997:119), and the mechanism behind it, beyond a general allusion to 'wave erosion' (e.g. Fischer & Pedersen, 1997).

5.1.2 Predictive Modelling in Terrestrial Contexts

It is beyond the scope of this project to provide an in-depth review of the construction and use of predictive models in terrestrial archaeology, so this section will provide only a general overview of their fundamental features and thus provide possible routes forward for the marine environment. For more detail the reader is advised to consult Judge & Sebastian (1999), or Wescott & Brandon (2000).

Predictive modelling of archaeological settlement patterns operates on the principle that human choices in positioning a site or settlement are constrained and influenced by the affordances and characteristics of the local environment (Brandt et al, 1992; Warren & Asch, 2000). Therefore, if patterns exist between site locations and one or more environmental variables or features, and if relationships between them can be ascertained, a model can be constructed that focuses on the effect of these variables in determining site location (Brandt et al, 1992).

"Prediction is …the elucidation of settlement 'rules' in a form that allows us to map locations which conform to the conditions predicted by the model for settlement" (Stančič & Veljanovskji, 2000:148).

The most commonly used variables relate to environmental factors, such as slope or distance to fresh water because they are easy to obtain from soil, geological and hydrological maps (Kamermans, 2000) or even satellite remote sensing data (e.g. Custer et al, 1986). In addition, it is known that groups of people ranging from nomadic hunter-gatherers to urbanised societies respond to environmental pressures (Brandt et al, 1992). More recently however, ideas of bringing socio-cultural variables into modelling have been advanced (Gaffney & van Leusen, 1995; Stančič & Kvamme, 1999). These variables will be discussed in more detail in section 5.1.3.

The construction of predictive models, hinges not just on the choice of variables, but also on two fundamental assumptions:

1. A knowledge of known archaeology allows the establishment of locational factors, that can be empirically tested (Stančič & Veljanovskji, 2000). Fundamental to this assumption is the idea that settlement patterns are strongly guided by environmental characteristics (Warren & Asch, 2000).

2. These environmental features can be obtained, at least indirectly, from modern maps or environmental characteristics (Duncan & Beckman, 2000; Warren & Asch, 2000).

Predictive models of archaeological site location are divided into two main categories; inductive and deductive.

- Inductive, or correlative, predictive models are the most commonly used type in archaeology (Church et al, 2000). These examine distributions of known archaeological sites and identify and quantify correlations between the site locations and particular environmental variables, or landscape features, which are selected on the basis of statistical significance (Judge & Sebastian, 1988; Church et al, 2000; Ebert, 2000). For example: sites are located on level to moderately level slopes composed of soil type A and that are within X distance from water (Church et al, 2000). The correlations are assumed to represent causality and thus, from them, predictions can be made as to the locations of sites in unsurveyed areas, if the environmental characteristics of these areas can be determined (Kamermans, 2000; Warren & Asch, 2000).

- Deductive, or exploratory predictive models are less common (Church et al, 2000; Kamermans, 2000). These attempt to predict how particular patterns of human land use will appear in the archaeological record on the basis of deductions derived from prior archaeological, historical or ethnographic information (Judge & Sebastian, 1988). For example: residential hunting sites dating to the Archaic period are located in the foothills between elevations of X to Y on moderately level slopes and within X distance of water because the resources of food (mule deer) and water are present and these resources form the most reliable subsistence base available at that time (Church et al, 2000). The distribution of known sites can then be used to evaluate the model (Kamermans, 2000).

The relative merits of each of these two approaches with respect to submerged landscapes will be discussed in Section 5.1.4. However, it should be noted that the two approaches need not be used in isolation. Indeed, many researchers actually use a combination of inductive and deductive methodology in the form of a continuous process over time whereby the model can be reformulated as new information is incorporated (Figure 132 - Kamermans & Wansleeben, 1999).

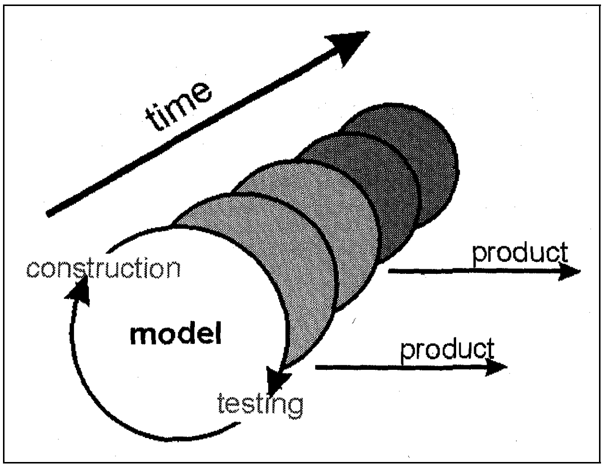


Figure 132. Constructing and testing of a model is a continuous process. While the stability and reliability of the model will probably increase over time, the intermediate results can still be useful products (from Kamermans & Wansleeden, 1999)

5.1.3 Variables Modelled

This section provides an overview of the environmental and social variables which tend to be incorporated into predictive models. Each class of variables will be discussed in isolation for the sake of clarity. However, it should be noted that the application of single classes of variables in a model may result a different prediction depending on which class is used. Consequently, most models tend to use combinations of variables (Kamermans, 2000).

5.1.3.1 Topographic variables

Measures of terrain such as slope, aspect or relief are often implicitly (in inductive models) or explicitly (deductive models) assumed to equate to measures of shelter (Church et al, 2000). Sites located in valleys may be more sheltered from wind and weather than those on the interfluves, while certain slope faces may receive more sunlight. For example: the location of sites on south and west facing slopes of river valleys in Limburg (Netherlands) has been related to Middle Palaeolithic groups sheltering from cold northerly and easterly winds (Kolen et al, 1999) while similar patterns (i.e. warmer temperatures and reduced wind chill in valleys) have been noted in the Middle Palaeolithic of southwest France (see Theme 2) (Davies et al, 2003; Mellars, 1996).

Topographic or terrain variables may also relate to the placement of sites in response to subsistence practices. Note the positioning of submerged Mesolithic sites in Scandinavia to take advantage of topographical features that were optimal places for fishing with standing gear (Fischer, 1995). Hunting strategies, and thus the archaeological sites that result from them are in some instances topographically based. A number of sites are positioned at cliff bases (e.g. La Cotte de St. Brelade: Scott, 1980) or in tunnel valleys (e.g. Peterfels - Albrecht, 1983: see Section 3.3.4.3). Many hunter gatherer sites are believed to be situated at locations which, due to their topography, provide good views of the surrounding area and thus the location of prey species. An example are the Mesolithic sites of Northern England which tend to be located on ridges, hills and valley heads (Kvamme and Jochim, 1985).

5.1.3.2 Hydrologic variables

Water is crucial to the survival of humans, plants and animals, and consequently distance to water is often one of the key resources modelled (Church et al, 2000). Examples of archaeological sites being located in close proximity to water are numerous, with concentrations of sites occurring along lakeshores, rivers and by springs. Studies of the Magdelenian occupation of the Paris Basin have indicated that the vast majority of sites are located along river valleys rather than on the plateaus between them (Audouze, 1987). An important Lower Palaeolithic site has been found in the travertine springs at Bilzingsleben in Germany (Gamble, 1999) while lakeside occupations are found in all periods and in diverse contexts ranging from the Mesolithic settlement at Star Carr (Mellars & Dark, 1998) to the Lower Palaeolithic site of Hoxne (Singer et al, 1993 - see Section 3).

5.1.3.3 Geomorphological variables

Geomorphological variables consist of various landforms which may have influenced human settlement, such as beach ridges, lagoons, estuaries, caves or rockshelters (Kamermans, 2000). Each of these may have influenced settlement patterns by providing particular advantages in different areas, for instance, caves and rockshelters provide shelter from the elements while lagoons and estuaries are often rich in resources. For example, ethnographic studies indicate that open prograding coasts in Alaska were frequently occupied in contrast to the situation in Florida, where lagoons rather than beaches tended to be settled due to their high productivity and shelter from the elements (Dunbar et al, 1991; Mason, 1991).

Soil type is also a feature that is often incorporated into models as this may influence the distribution and nature of the local vegetation. This may be more important with respect to settled farming societies rather than nomadic hunter-gatherers, as the location of fertile soil is likely to be a major influence on where crops can be grown and hence settlements located.

5.1.3.4 Resource variables

A number of resource types can be seen as influencing human settlement patterns, these can broadly be divided into food water and raw materials. Water has already been dealt with in Section 5.1.3.2, so this section will deal with the other two.

In the prehistoric period the dominant raw material that is seen to influence settlement patterns is stone. In the Aquitaine Basin of France there are open air Middle Palaeolithic sites situated near flint sources regardless of topography (Turq, 1999) while underwater investigations in Florida have been based partly on correlations between site locations and chert sources (Dunbar et al, 1991).

Similarly, with respect to food, the location of edible or even medicinal plants (Dalla Bona, 2000) may also have been important. However, as these do not preserve well in the archaeological record, their influence is uncertain. Furthermore, stone sources offer some distinct advantages for predictive modelling. Their stability means that their location is unchanged over long periods of time and hence are more easily modelled under the assumption that modern conditions are equivalent to those in the past (Section 5.1.2). Their varying spatial distributions though, do mean that models constructed for one area (e.g. a lithic rich area) may not be applicable to other (e.g., lithic-poor) areas (Church et al, 2000).

Animal bones are more commonly preserved and this has lead to suggestions that the location of certain sites was determined by their proximity to certain prey species. Note for example the contrast between the French Upper Palaeolithic sites of Etiolles and Pincevent (Audouze & Enloe, 1991) described in Section 3.3.4.3.

5.1.3.5 Social variables

The incorporation of social variables is a relatively new feature of predictive modelling and stems from the realization that settlement patterns may be more than just environmentally determined. Therefore models have to consider the creation of a symbolic, political or economic landscape by past societies and its influence on site location.

There are a number of ways of accomplishing this. One proxy has been assumed to be the distance between sites. For example, the distance between hillforts on the island of Brac (Croatia), has been assumed to be a reflection of the size of the economic territory required to support each hillfort, while the positioning of, and degree of intervisibility between, each hillfort has been related to the need to exert visual control over large territories (Stančič & Kvamme, 1999).

Alternatively, the location of sites may be also due to particular places in the landscape having ritual or social significance to past people. Neolithic monuments in the Black Mountains of Wales appear to have been situated so as to direct and focus attention on significant features of the landscape - the Black Mountains themselves and the valleys running through them (Tilley, 1994). Incorporating such variables is somewhat more difficult in the case of more archaeologically ephemeral societies, such as nomadic hunter-gatherers, which do not construct monuments, though some attempts have been made to understand how they may have bestowed symbolic attributes on the natural landscape. Boaz and Uleberg (2000) for instance have related changes in the topographic characteristics of site locations to changing perceptions of landscape caused by relative sea level change during the Mesolithic of southern Norway.

5.1.4 General Criticisms of Predictive Modelling

The above overview may have given the impression that predictive models represent an elegant and effective solution to the problems of site prospection and cultural resource management. However, a thorough assessment of the effectiveness of these models requires that any criticisms of them are taken into account.

These critiques largely concern the assumptions that are made in the modelling process (Section 5.1.2), the variables modelled (Section 5.1.3) and the misconceptions that come about through use of these models. Some of the criticisms apply to inductive models, and others to deductive models. There are also several which apply to both categories.

5.1.4.1 Critique of inductive models

Inductive predictive models rarely take into account factors which may modify or distort the archaeological record, such as post-depositional taphonomic forces. Consequently, patterns inferred from the known distribution of archaeological sites may be substantially different to the actual past patterns, thus the statistically generated correlations may result in the creation of a misleading model (Kamermans & Wansleeben, 1999; Kuna, 2000). The skewing of the model by post-depositional transformations can be mitigated if a deductive approach is taken, in that the rules governing settlement behaviour can be inferred from theoretical models of past societies rather than their observed archaeological remains.

Inductive modelling has also come under fire because it rarely provides explanations of the correlations it finds between sites and environmental variables that go further than relatively anecdotal statements (Ebert, 2000), or in some cases which are not explicitly explained at all (Church et al, 2000). This makes it difficult to determine if the inferred patterns are indeed the result of human locational tendencies, or are just an artefact of the nature of the background environment.

Essentially the main criticisms concern the data that is inputted into the model. If the correlations discovered between sites and socio-environmental variables are a valid representation of past rules of site location, then the model can be considered applicable. However, if the correlations are merely statistical artefacts created by post-depositional processes or the background environmental noise, then the usefulness of the model must be questioned.

5.1.4.2 Deductive models

In contrast to inductive models, the deductive technique derives its rules of settlement location from models of behaviour rather than statistical correlations between sites and a set of variables. This provides it with an instant advantage over inductive modelling in that it is immediately a more explanatory approach.

However, deductive models have been, criticised on the basis that they assume that the particular form of human behaviour in a given environment will create a specific pattern in the archaeological record when in reality it could create multiple different archaeological signatures (Kamermans, 2000). In addition, with respect to social variables, ascertaining the relationship between site locations and the perceived cultural, religious or symbolic properties of the landscape, which may have played a part determining the location, are not easy to deduce, and can often be a somewhat subjective exercise (Kuna, 2000).

Finally, questions have been raised over the nature of the principles of least effort, or ‘cost-distance theories’ that are often used to explain the relationship between sites and their distance to particular environmental features. According to these, more important factors in site placement will be situated closer to the site as less energy will be expended in achieving the benefit these features provide. However, as Ebert (2000) has pointed out, it is not certain that people rigidly behave in this rather mechanistic manner. Other important structuring factors may include the time taken - which may be dependent on local topography or vegetation and may not have a linear relationship with distance - rather than energy expended, to reach a feature, or the sequencing of multiple activities within a given area (Ebert, 2000).

5.1.4.3 Inductive and deductive models

One major criticism of the both categories of model concerns the use of modern data. In inductive models, relationships between site locations and easily obtainable modern environmental characteristic are commonplace, while in deductive models, deduced settlement rules are then applied to the modern landscape in an effort to predict site locations or test hypotheses concerning about site location. However, the dynamics of the environment and climate over time make this a rather tenuous assumption especially with respect to early periods of prehistory (Church et al, 2000) and as Hosfield has pointed out, this makes attempts to predict the location of early prehistoric sites (e.g. Lower and Middle Palaeolithic) on the basis of modern environmental data an “uninformative and fruitless exercise” (Hosfield, 1999:245). It is not just the dynamics of the environment that models tend to gloss over. Rules governing human-landscape interactions are often assumed to be rather inert, thus sites are continually assumed to be placed in the same position even across major time spans, regardless of changing past human ideas of settlement location. (Kamermans, 2000). On the whole predictive models tend to suffer from a rather static view of environment, society and their interaction.

This may have partly arisen due to the extensive use of predictive models in cultural resource management. Environmental planners tend only to be concerned with designating areas as archaeologically rich or archaeologically poor, with little regard to the type, period or nature of the site (Kamermans & Wansleeben, 1999). Many models therefore reflect this need.

As a result, it has been suggested that future predictive models should take into account different time periods (Kamermans & Wansleeben, 1999). The rationale behind this is that the locational preferences of societies may change over time, thus necessitating the constructing of separate models.

The choice of variables used by both types of model has also been roundly criticised. A focus on environmental variables has led to suggestions that predictive models are environmentally determinist. In reality, cultural, political, symbolic or social factors may have played as great a role in determining settlement patterns (Dalla Bona, 2000; Kuna, 2000). To some extent, attempts are being made to redress this balance. Note for example, the recent studies which explicitly incorporate social factors into their models (e.g. Stančič & Kvamme, 1999). However, as stated in Section 5.1.3.5, accomplishing this is still a relatively difficult, and often highly subjective task.

Another problem involves a failure to see some of the complexities associated with many of the variables. For example, distance to water is simply a measure of the distance of a site to the nearest water source. It takes no account of the seasonal availability and duration of the water source, its quality or whether it provides any other resources (e.g. fish), all factors which might also influence the decision of past humans to locate their sites in relation to it (Church et al, 2000; Ebert, 2000).

Related to this is the way in which past humans may have viewed each of these variables. It is unlikely that the affordances or potential offered by each variable were equally distributed, and indeed the perceived benefits of each may have changed over space and time (Dalla Bona, 2000). For example, Dalla Bona (2000) has pointed out that while water may be an important locational factor, it is unlikely that sites will be distributed evenly around a lakeshore. Certain areas within this already favourable zone may have been perceived as more, or less preferable. In effect, it is the particular combination of variables in a certain context that is important. This makes it difficult to judge which were considered important in locating sites.

Overall, it seems that the effectiveness of predictive modelling is somewhat compromised by these criticisms. Consequently, archaeological prediction in terrestrial contexts is not perfect. Predicted archaeologically rich areas may contain barren zones, while area of low potential could contain isolated, but important sites (Kuna, 2000). Nevertheless, if these shortcomings are understood and models are recognised as providing levels of confidence rather than absolute correlations between site locations and the environmental variables, they can still be flexible and powerful tools (Duncan & Beckman, 2000).

5.1.5 Model Applicability in Submerged Prehistoric Contexts

Having discussed the usefulness of conventional (i.e. terrestrial) predictive modelling approaches, attention must be turned to their applicability in submerged contexts. The main issue is whether the unique situations produced by underwater archaeological deposits, as detailed in Sections 2 – 4 (Themes 1, 2 and 3) renders these approaches more or less applicable. On these basis of these three themes and the above analysis, some ideas can be advanced:

- At present, a straightforward inductive approach based on the statistical correlation of known submerged sites with environmental variables will not be possible since such a concentration of sites is not known, with the exception of the submerged Mesolithic sites of south Scandinavia (see Section 3.6: Fischer, 1995b; Pedersen et al, 1997). However, the settlement pattern in this area may not be applicable to more exposed and open coasts such as those of the English Channel and North Sea.

- Alternatives to this therefore include an inductive approach based on the statistical correlation of known terrestrial sites with environmental variables, or a deductive approach which identifies settlement pattern rules based on the known terrestrial record. To some extent this is the approach that has been advanced in Section 3: Theme 2. Following Kamermans & Wansleeben's (1999) observation that the two types of approach are often used in tandem, there is no reason why this combined approach could not be attempted. The relationships inferred from these approaches can then be applied to the submerged environment.

Regardless of whether the two approaches are used together or in isolation, the model must overcome several major pitfalls:

- Section 4.1 made the point that large areas of the seabed are unlikely to bear a great deal of resemblance to their pre-submergence topography and geomorphology. Though there have been recent calls for modellers to take into account post-depositional processes to a greater extent (e.g. Church et al, 2000; Kamermans & Wandsleeben, 2000), predictive models still tend to rely on the assumption the environmental characteristics obtained from the present landscape will equate to those in the past (Section 5.1.2). In the light of the major landscape changes resulting from syn-and post-transgressive processes, taking post-depositional landscape modification into account will be absolutely essential. To some extent, landscape geomorphology can be reconstructed if detailed geological and geophysical surveys are undertaken and especially if sequences are dateable. On the regional scale, a wealth of evidence exists in documents such as the British Geological Survey reports for the North Sea and English Channel. Similar information is also available for the other countries surrounding these regions. On a finer scale, more detailed information is available from areas in which comprehensive surveys have been performed, such as the palaeo-Arun (Gupta et al, 2004a,b). Essentially, the techniques for reconstructing the past landscape do exist, however, they have only been applied in detail to certain areas. In these areas there may be scope for modelling. But for the shelf as a whole, much more accurate and detailed reconstructions will be necessary to enable fine scale modelling.

- Section 3 (Theme 2) has indicated that a wealth of terrestrial data exists with respect to inland occupation. However, barring the Mesolithic and later periods, the prehistoric record is characterised by an overall lack of evidence for coastal occupation. Theoretically, much of the submerged evidence should relate to coastal use or settlement, given that transgression would have meant that all parts of the presently submerged landscape would have been coastal at some point in time. This paucity of evidence would make the construction of a predictive model (either inductively or deductively) somewhat difficult, and until more evidence is located, it would have to be largely based on conjecture and assumptions about the nature of early coastal occupation (see Erlandson (2001) for an overview of this subject). Construction of a predictive model for material that would have related to inland use is somewhat more secure.

- Predictive models tend to focus on the idea of a 'site'. These are usually conceived as concentrations of archaeological material and range from extensive settlements to scatters of stone tools. The size of these features is also variable and can range from several square metres up to several hectares (Schiffer, 1987; Flemming, 1998). In any case, the usual assumption is that they will be in primary context. As Sections 3 and 4 have pointed out, a large proportion of the submerged evidence will likely take the form of reworked secondary and tertiary contexts. As these have been removed from their point of deposition, this negates traditional predictive modelling approaches that infer or deduce rules governing human choices in site location. The issue may be further complicated by the fact that these deposits may take the form of extensive collections of material situated within a substrate rather than discrete sites.

- This may result in a preservational or context guided approach whereby modelling focuses not just on where past humans would theoretically have located their sites, but on where conditions have meant that this evidence is likely to be preserved, in other words, a 'deposit' rather than 'site' based approach. For example: areas with a thick sediment cover could be assumed to have a high potential of primary and terrestrially formed secondary contexts and targeted for further investigation, while areas characterised by long term erosion could be classified as lower potential. This approach would however class secondary and tertiary contexts as a lower priority, a judgement that cannot be made on the basis of present information. Alternatively, this could be reversed in that areas of thick sediment cover could be assumed to be protected from natural reworking, and investigations focus on areas of erosion, where artefacts may be naturally exposed and may be under threat. This approach may have an advantage in that it may be able to target areas in which primary, secondary or tertiary contexts are preserved on the basis of known past and present sedimentary regimes rather than assumed human choices about a landscape which may not be possible to reconstruct.

- At this point in time it is probably worth noting an issue that has not yet been raised to any significant extent, with the exception of Flemming (1996). This is the human response to sea level change in the past. Section 4 has illustrated the complex geomorphological responses that coasts exhibit in response to sea level fluctuations, but as yet these have rarely been considered in relation past human settlement. Rather than simply reviewing the suite of environmental changes resulting from sea level change, it would be worth considering which of these operate within a temporal and spatial scale appropriate to human perception and response. An examination of human responses to sea level change has implications in terms of site formation processes, in that it represents the ‘cultural’ element of the taphonomic process (Schiffer, 1987), but also has wider resonance in terms of assessing how past societies coped and responded to changing environmental conditions. In any case, the past human response may well have resulted in the creation of distinct archaeological signatures, and therefore may be a element that is worth considering in future predictive modelling exercise.

- If a model is to be constructed, other considerations will have to include its scale and complexity. From the perspective of environmental assessment, a model that is capable of designating large areas (i.e. several kilometres to tens of kilometres) of seabed as archaeology sensitive, or archaeologically barren has attractions. However, from a purely academic or research oriented point of view, a more detailed model that focuses on different time periods or sites types (e.g. coastal sites) may be considered to be more useful. Decisions will therefore have to be made as to which line a predictive model takes.

In summary, based on the information explored in Sections 2 – 4 (Themes 1, 2 and 3), sufficient evidence currently exists to construct very large-scale (i.e. shelf scale) models or reconstructions with limits imposed by the position of palaeo-shorelines, glaciers and the patterns that exist in terrestrial contexts, similar to those done by Coles (1998). These overviews will only be accurate to within kilometres to tens of kilometres. At the other end of the scale, limited predictive models could be constructed for certain localized (i.e. kilometres or less) areas, but only if sufficient geological and sedimentological evidence is available to enable both a secure reconstruction of the palaeo-landscape to be undertaken and allow some assessment of the impact of marine processes on the distribution of archaeological material. Modelling the scale in between may be somewhat more difficult until more information becomes available. Nevertheless, some predictive models should be constructed and tested in the near future provided the ideas advanced above are taken into account, as these may provide new data that enable the construction of a next generation of more accurate models.

6. Synthesis and Summary

6.1 Overview of Themes 1 to 4

A great deal of potentially useful archaeological material exists on the continental shelves of the world. However, it is being threatened by the recent expansion of industrial concerns onto the shelf. It is therefore important, from both academic and cultural resource management perspectives, to locate and investigate this archaeological resource before it is irretrievably lost.

In an ideal world, all investigations of submerged landscapes and their potential archaeology would be based around small scale localized studies. Particular areas would be subject to high resolution surveys using bathymetric and sub-bottom seismics, core sampling and diver survey. This would enable very detailed palaeo-environmental and palaeo-geographic reconstructions to be constructed. Models (on local and regional scales) could then potentially be developed for the location of particular types of site (e.g. fishing sites), periods of site (e.g. the Mesolithic) or preservational contexts (e.g. primary contexts).

In reality, time and expense considerations render this approach highly unlikely in the near future. At present, detailed geological snapshots of certain areas do exist (e.g. the palaeo-Arun valley), as do glimpses of submerged archaeology (e.g. Bouldnor Cliff) but nothing like the intense detail that the ideal approach demands. Consequently we have to accept that a more ‘top-down’ strategy may have to be adopted. To this end, this project has performed a wide ranging review and assessment of the existing information regarding continental shelves in an effort to determine what archaeologists and other Quaternary researchers are capable of achieving at present and over the next few years.

This information was divided into 4 broad Themes, and the results of the assessment are as follows.

Theme 1: The reconstruction of submerged landscapes

- Significant flaws exist in our perception of submerged landscapes, the role they played in prehistory and the way in which they are reconstructed.
- In archaeology at least, a better understanding of sea level change and its effect on palaeo-geographic reconstruction is required. Rather than simply taking existing reconstructions at face value, their validity and applicability to the particular questions being asked must be assessed before use.
- Errors exist in all forms of sea level data, and thus result in spatial errors in the position of reconstructed palaeo-shorelines.
- The magnitude of spatial differences in shoreline position depends on the source of sea level data and the topographic time horizon, used in the reconstruction. However, in all cases, spatial errors are minimized in areas of steep topography.
- The most accurate and applicable palaeo-shoreline reconstructions require relative sea level based on local data. These reconstructions are applicable for predictive modelling or survey on a scale of kilometres or less.

- The techniques of constructing sea level curves are well established. However, in many cases the evidence required to construct them no longer exists. In these occasions coarser reconstructions may have to suffice.

- The error limits associated with the reconstruction of shelf scale landscapes have been quantified and assessed for a range of sea level curves and stratigraphic time horizons, using the North-west European continental shelf as an example.

- These regional reconstructions are suitable for providing a large scale background to archaeological research and for the initial planning stages of more localised surveys. Such reconstructions will have implications for both academic research and offshore environmental impact assessment. They are not applicable for predictive modelling or survey on a scale of kilometres or less.

Theme 2: The nature of the pre-submerged archaeological deposits

- A spatial and temporal diversity of archaeological material potentially exists in the presently submerged areas of the continental shelf.

- Large scale patterns of land use are evident in the terrestrial record which are likely to be applicable to the submerged regions.

- The submerged material will probably exist in one of three states of preservation: Primary, secondary or tertiary context.

- The research potential of secondary contexts for the Upper Palaeolithic and Mesolithic and tertiary contexts for all periods needs to be examined to a greater degree than at present.

- The potential of the submerged material lies in more than just identifying areas as ‘landbridges’ or migration corridors.

- Areas identified for further research include the antiquity and importance of coastal exploitation, and human response to sea level change. Each period and region may also have specific research questions that could be addressed by data from submerged contexts.

Theme 3: The modification of archaeological deposits by trans- and regression

- The present seabed is not an exact analogue of the lowstand landsurface

- Effective interrogation and exploitation of the submerged archaeological resource will require secure and accurate landscape reconstructions.

- The ability and techniques to achieve this are well established. The main difficulty is the time and expense required.

- A significant quantity of archaeological material will be reworked by marine processes. Understanding the processes behind this is important. Future work should attempt to examine these processes in detail. At present some tentative hypotheses and statements can be advanced on the basis of fluvial work and general studies of coarse clastic sediment dynamics.

- A more secure understanding of marine taphonomic processes may aid our understanding of the potential and location of marine secondary and tertiary contexts

Theme 4: Predictive modelling of submerged archaeological deposits

- Predictive modelling of submerged archaeological deposits is possible provided the problems described in Themes 1, 2 and 3 are addressed, especially those concerning landscape reconstruction and post-depositional taphonomic processes.
- At present, it is only really feasible where we have detailed reconstructions or knowledge of the past landscape, or a certainty that a landscape is 'relict' (in the sense of being unaffected by syn- and post-transgressive processes).
- Essential elements of the model to consider include past human choice in situating sites within the landscape and the post-depositional modification of this pattern.
- Approaches could therefore be based around investigating areas amenable to past human settlement, or areas of likely preservation or erosion. This latter approach places a premium on understanding the transgressive reworking and modification of archaeological deposits.
- Although there are gaps in the information pertaining to submerged landscapes, there is no reason why the filling of these gaps and the development of predictive models cannot be undertaken at the same time. Limited predictive modelling can, and should, be undertaken in areas where the problems described above can be addressed or overcome to a certain extent in order to gain information that will aid in filling the knowledge gaps while the models can be updated as these gaps are filled.

6.2 Dissemination

- Papers based on the information and results of this project have been presented at the following meetings, seminars and conferences:

1st Aggregates Levy Workshop. April 4th, 2003. Southampton Oceanography Centre.

UK Archaeological Science Conference. April 2nd to 5th, 2003. St. Anne's College, Oxford.

"Integrating Terrestrial and Marine Related Archaeology". English Heritage Aggregates Levy Sustainability Fund meeting. April 29th, 2003. Museum of London Archaeology Service.

"Black Boxes". May 3rd and 4th, 2003. Computer Applications and Quantitative Methods in Archaeology, UK. Department of Archaeology, University of Southampton.

"The evolutionary legacy of the Ice Ages". May 21st and 22nd, 2003. The Royal Society. (Poster Presentation).

"A re-assessment of the archaeological potential of continental shelves". ALSF day-meeting, Museum of London, 16th September 2003.

"A re-assessment of the archaeological potential of continental shelves". EH Milestone Event – invited speaker. Museum of London, October 16th 2003.

Underwater Treasures: Archaeology and Aggregates – An Academic Perspective. Presentation to the All Part Parliamentary Group for the Earth Sciences and the All Party Parliamentary for Archaeology, November 16th 2003.

“*Land & Sea: Integrating Archaeologies*”. November 1st and 2nd, 2003. Department of Archaeology, University of Southampton.

- Papers have been drafted on “the reconstruction of regional scale palaeo-landscapes” (for submission to Proceedings of the Prehistoric Society) and on “Dynamic controls on the archaeological potential of continental shelves” (for submission to Archaeological Science).
- The project also has a website hosted at the University of Southampton (http://www.arch.soton.ac.uk/Research/Aggregates/shelves-intro.htm) onto which an outline of the project, and a digital version of this document have been uploaded.
- Finally, dissemination of this work via the internet has already resulted in contact with an industrial organisation (METOC) which undertakes environmental impact assessments for major offshore construction projects. Negotiations are currently being undertaken to utilise the regional scale methods and techniques described here to identify and mitigate the potential threat of offshore construction to shelf archaeology.

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