Palaeolithic Chapter - Technical Appendix:

Sea-level Change, Palaeo-Environmental Change and Preservation Issues.

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The aim of this appendix is to provide supplementary detail on significant sea-level and palaeo-environmental changes occurring throughout the British Palaeolithic which it was not possible to include within the chapter in the Resource Assessment. It will discuss controls on sea-level, the principles of reconstructing past sea-level and palaeo-geography and then provide brief chronological overviews of the pattern of sea-level and associated palaeo-environmental changes occurring through the Palaeolithic. These dramatic environmental and climatic shifts not only transformed the past landscape but exerted a major control on the preservation of archaeological and palaeo-environmental deposits on the coast and continental shelf. Therefore this appendix will also provide a brief regional overview of likely preservation conditions around Britain.

Controls on sea-level

Sea-level changes that took place during the Palaeolithic were primarily driven by three processes.

First, addition or removal of water from the oceans on a global scale as continental ice sheets grew or shrank (*glacio-eustasy*) in response to alternating glacial and interglacial cycles. Peak glacial lowering has been estimated to be of the order of 120m below present sea-level, with interglacial highstands similar to the present, or higher by up to 6-9m (Rohling et al. 2009). Rates of changes were potentially rapid, of the order of several centimetres per year.

Second, isostatic uplift or subsidence of the terrestrial crust induced by changes in the weight of the ice sheets which modified (i.e. accentuated or reduced) the effect of glacio-eustatic changes on a regional-scale (*glacio-isostasy*). As ice sheets grew, their weight depressed the crust beneath them with areas closest to the centre of the sheet, and hence under the greatest mass, experiencing the largest depression (in some instances below contemporary sea-level). During deglaciation, the weight was released and the underlying crust rebounded at a rate faster than the meltwater-induced glacio-eustatic rise creating a pattern of RSL fall. On the margins of the ice sheets, crustal depression was also induced by the weight of the ice. However, as the ice was thinner than at the centre, isostatic rebound was only able to dominate the initial stages of deglaciation, whereupon it was overtaken by the global glacio-eustatic rise. This resulted in a RSL history of an initial fall to a lowstand and then a rise, often referred to as a J-shaped sea-level curve. In some instances, the rise may have continued to a short-lived highstand that was then terminated by another RSL fall brought about by residual isostatic rebound. Finally, areas outside or on the periphery of the ice sheet were uplifted during glaciation to compensate for the depression under the ice sheet and held there for as long as the ice was present (the *forebulge* effect). The net result was that when the ice retreated they experienced rising sea-levels brought about by rising glacio-eustatic sea-level and the local collapse of the forebulge as it migrated back into the centre of isostatic recovery.

All three types of RSL history can be observed around the British Isles during the postglacial transition from the Last Glacial Maximum (LGM) to the Holocene interglacial. Scotland and the north of Ireland, due to their position under the bulk of the British ice sheet is dominated by isostatic rebound and characterized by falling and J-shaped RSL curves. England, Wales and the south of Ireland however, largely experienced RSL rise with any isostatically-induced fluctuations/reversals occurring below present sea-level (Shennan et al. 2002; 2006; Brooks et al. 2008). Similar patterns probably characterized earlier (i.e. pre-LGM) periods with the exact pattern of RSL change dependant on ice sheet size and growth/decay history.

Third, more minor contributions were driven by crustal uplift or subsidence in response to tectonic forces. Of particular note is the subsidence of the North Sea Basin, which has experienced average subsidence of 0.4m per thousand years over the past 730,000 years (Cameron 1992). Conversely, the region surrounding the English Channel appears to have experienced uplift through the Quaternary at rates averaging 0.1m per thousand years (Lagarde et al. 2003).

Reconstructing past sea-level and palaeo-geographic change

The pattern of past sea-level change can be built up from two main sources:

1) Dated geological, sedimentological or biological features with a known relationship to past sea-level
2) Numerical models of the Earth's response to ice loading calibrated with observed indicators of past sea-level.

Each source has its own advantages and disadvantages. The advantages of dated features is that they can potentially provide a quantitative reconstruction of past sea-level for a given place and time. Their accuracy depends heavily on the nature of the feature. Some, such as submerged tree stumps or raised marine shells, provide only upper or lower limits on past sea-level. Others, provide a quantifiable relationship to past sea-level, or even a given tide level. This latter category, commonly referred to as Sea-Level Index Points (SLIPs), include microorganisms such as diatoms and foraminiferal communities with very specific habitat requirements (e.g. saltwater, brackish, freshwater). While SLIPs and limits are highly useful, the estimates they provide are generally only applicable locally (i.e. less than several tens of kilometres) due to spatial variations in sea-level history caused by differential isostatic loading/rebound. Moreover, each datapoint provides only a snapshot for a given time. Long time series records require multiple datapoints which may not always be available (Brooks 2007; Brooks et al. 2008).

In contrast, GIA models cover much larger areas (e.g. the entire British Isles) and allow continuous histories of past sea-level change to be generated from anywhere within the model coverage. The main disadvantage of these are observable misfits between model predictions and sea-level indicators (see Edwards et al. 2008, McCabe 2008 for an example from Ireland). However, the models have undergone considerable refinements over the past 15 years. For the British Isles this can be seen in a progression from the models developed by Lambeck et al (1995), to those used by Peltier et al. (2002), Shennan et al (2002) and to the most recent improvements developed by Milne et al (2006). For example, the most recent models are corrected for topography beneath the simulated ice sheets, a fact not taken into account in earlier interactions, which consequently suffered from overestimates in the weight of ice (Shennan et al. 2006). Overall, while the models can generally simulate the overall regional scale RSL well, there are questions over how well this translates to a local scale.

In terms of spatial coverage, RSL data is spread relatively evenly across the British Isles (Shennan et al. 2006). There are over 2000 observations/records of which approximately 1250 were validated index points (Brooks 2007). Data points from the surrounding continental shelf are much sparser and tend to only constrain the shallower portions of RSL signal (i.e. there are relatively few indicators of sea-level change from depths below -20m) (Shennan et al. 2002).

In terms of temporal distribution, the vast majority of RSL records postdate 10 ka (Shennan et al. 2002) with many of the oldest records coming from areas such as Arisaig (Scotland), where RSL never fell below modern levels (Shennan et al. 2006). Older data from submerged shelves are particularly rare. For example, Ward et al. (2006) identified only 9 pre-Holocene dates from sedimentary contexts in the southern North Sea, with the oldest date limited to 14 ka. Moreover, they also identified that the stratigraphic context of many of these submerged samples is often poorly constrained, leading to increased uncertainties in the reconstructed elevations of past sea-level. This distribution is further substantiated by the peat database held by English Heritage (Hazell 2008). Of the c. 340 sites recorded in the database, only 13 had dates or interpretations (based on stratigraphy or fossil remains) that indicated a pre-Holocene age.

Some RSL data have survived from the pre-LGM, chiefly in the form of raised beaches and marine deposits. Examples of these are known along the south coast of England and are particularly clear on the Hampshire-Sussex coastal plain. While the exact chronological sequence of these deposits has yet to be finalized, it has been suggested that they were laid down during interglacial highstands in MIS5e, 7, 9 and possibly 11 and 13 (Bates et al. 2003). Lowstand estimates for the pre-LGM are still poorly known. There are deposits and geomorphologic features offshore (e.g. deltaic sediments and palaeo-channels) which show that sea-levels were lower but the precise shelf extent and pattern of flooding/retreat cannot currently be reconstructed.

Since GIA models are calibrated against RSL data, the lack of pre-LGM data prevents their extension into the pre-LGM. Moreover, their use prior to the LGM is also hindered by uncertainties in ice sheet size and deglaciation history and the resultant complex interplay of glacio-eustatic changes and isostatic movements. Even within the post-LGM, the lack of older data from deeper shelf contexts (i.e. >20-30m water depth) results in greater uncertainty for the earliest sections of the modelled RSL histories.

Going from modelled or evidence based sea-level curves to reconstructing palaeo-geographic changes requires the combining the palaeo-sea-level record with a topographic time horizon (see full discussion in Westley et al. 2004). The most frequently used topographic surface is modern bathymetry, largely due to the fact that it is readily accessible. However, in most instances, processes of sedimentation and erosion accompanying and following marine transgression will have modified the continental shelf surface such that modern bathymetry does not correspond exactly to the topography of the shelf when it was subaerially exposed. For instance, on many shelves, valleys cut by rivers flowing across the shelf during lowstands are not visible on modern bathymetric maps as they have been infilled by marine sediment.

In situations where the palaeo-land surface has been buried, conventional seismic techniques (sub-bottom profiling) and boreholes or cores can be used to retrieve data from beneath the seabed. This then allows the identification of a chronostratigraphic time horizon appropriate to the period and the production of an accurate palaeo-geographic reconstruction. This has been done successfully on regional scales (e.g. Fitch et al 2005). However, the production of such reconstructions across for the entire British shelf is currently not possible as the fragmentary nature and poorly constrained chronology of the offshore Pleistocene record, coupled with uneven distribution of geophysical and geotechnical data, means that continuous shelf-scale palaeo-landsurfaces for a given period cannot be detected or may not even exist. Continued offshore work (e.g. Wessex Archaeology 2008; 2009) will redress this to some extent. Conversely, it will never be possible to retrieve data on surfaces that have been eroded either during or after transgression and there may be little choice in these situations but to use modern bathymetry.

Sea-level change around the British Isles during the Palaeolithic

The sections below summarize Palaeolithic sea-levels and coastline change taking a broad regional sweep and dividing it up into pre- and post-LGM as a result of data biases, namely that pre-LGM data on sea-level change is relatively sparse (see above). All shelf-scale reconstructions presently use modern bathymetry as an approximation of the past land surface despite potential modification (i.e. erosion or burial) since it was subaerially exposed. This is presently necessary because evidence of Palaeolithic land surfaces is fragmentary and contiguous shelf-scale palaeo-landscapes have yet to be reconstructed.

LGM and postglacial

During the LGM, an ice sheet extended over the British Isles, with the exception of southern and eastern England, and isostatically depressed the crust beneath it. Consequently, shelf exposure in the most heavily glaciated areas (primarily Scotland and Ireland) was similar to the present, despite a global glacio-eustatic fall of ~120m. By contrast, the unglaciated shallow shelves around England were exposed by the eustatic fall such that large tracts of the North Sea were subaerial, as were the English Channel and Celtic Sea. Shelf exposure was also enhanced by the creation of a glacial forebulge which extended into the aforementioned areas, raising the crust even higher above contemporary sea-level (Lambeck 1995).

Deglaciation began in earnest from 20–19ka on with England and its adjacent shelves largely ice free from 18–17ka on (Bowen et al. 2002; Shennan et al. 2006). As the ice melted, ocean volumes increased and glacial loading decreased. Areas under the ice, primarily in Scotland, the northern North Sea and Irish Sea, were initially flooded but then subsequently uplifted faster than the glacio-eustatic rise, resulting in shelf exposure. Outside the area of maximal ice loading, an initial period of slow RSL rise or stability was followed by rapid RSL rise. This stemmed from a lag between isostatic response and ice loading such that the greatest forebulge uplift took place after the ice sheets had reached their maximum extent. In addition, the gravitational attraction of the ice sheets reduced as they shrank, decreasing water levels close to them by up to several metres. The net effect was that crustal uplift kept pace with the glacio-eustatic rise such that shorelines remained relatively stable or retreated slowly.

The length of this period of stability varies depending on the reconstruction used. Lambeck (1995) places it between ~21.5–14ka, Coles (1998) indicates it took place between 16–15ka, while both Milne (2002) and Peltier et al (2002) indicate faster shoreline retreat from 15ka onwards. The subsequent period of rapid RSL rise was driven by forebulge collapse combined with continuously rising eustatic sea level and was further exacerbated at 14ka by a rapid 20m-equivalent meltwater pulse from the decaying continental ice sheets (Stanford et al. 2006).

The resulting retreat was not uniform. For example, a large embayment was rapidly created off north east England while the remainder of the North Sea shoreline retreated slowly back from the Norwegian trench. By the end of the Palaeolithic, although the subaerial shelf was reduced, most of the Central and Southern North Seas were still exposed and bounded by a coastline that linked Jutland to north east England. At the same time, the English Channel was initially transformed into a large embayment that expanded eastwards and ultimately became an extended marine channel. However, this had not reached the Dover Straits by 11.5ka, and a terrestrial connection to the Continent was still maintained. Subaerial shelves also extended the south coast such that the Isle of Wight was linked to the mainland and the Solent was a fluvial valley rather than a marine waterway. To the west, the shorelines of the Celtic and Irish Seas retreated away from the deep (>100m) Celtic Trough towards Britain and Ireland with the shelf largely flooded by the end of the Palaeolithic and exposed areas restricted to fringes around the modern coast and within modern bays and estuaries (e.g. Bristol Channel, Morecambe Bay). Whether or not Ireland and Britain were connected is still uncertain. While some models (e.g. Lambeck 1995; Brooks et al. 2008) suggest a terrestrial connection, this may only have been a few metres above sea level and subject to flooding by storm waves, high tides and the large meltwater influxes from the retreating ice (Edwards & Brooks 2008).

For all areas, tidal amplification was likely as the coastline retreated from the shelf edge and may have resulted in the transformation of wave-dominated coastlines (e.g. beaches, barriers and deltas) to tide-dominated landforms such as mudflats, saltmarsh and estuaries. The precise pattern of change was also determined heavily by local factors such as bathymetry, sediment availability and the rate of sea-level rise. For example, slow rates of rise may have promoted marsh formation while fast rates may have resulted in marsh drowning and loss.

Pre-LGM

The pre-LGM (800–24ka) is marked by a succession of alternating interglacials and glacials accompanied by sea-level rise and fall. Insufficient evidence exists to reconstruct a detailed history of sea-level and palaeogeographic change; only coarse qualitative reconstructions are possible.

During the earliest known occupation of Britain (c. 800–500ka), the southern North Sea was infilled by the Eridanos delta, a vast formation created by sediment input from several major rivers including the Rhine, Maas, Scheldt and Thames (Gibbard 1995). Consequently, Britain remained a peninsula despite fluctuations in sea-level that have been tentatively correlated with global glacial/interglacial transitions (Funnell 1995; Lee et al. 2006). By the late Cromerian/MIS 13 interglacial (c.500ka) global ocean volume had risen to c.10–20m below present (Rohling et al. 2009). Together with continued subsidence of the southern North Sea, this resulted in submergence of much of the delta. However, the terrestrial connection was not completely broken as suggested by similarities in faunal assemblages from Britain and the Continent (Funnell 1995).

Global sea-levels fell in the Anglian/MIS12 glacial to c.-120m, a consequence of the onset of continental glaciation evidenced in Britain by an ice sheet that reached as far south as the Thames. While this implies that large portions of the shelf were subaerial, in reality the extent of habitable land was reduced as the ice extended across much of the North and Celtic Seas. In addition, most of the unglaciated southern North Sea was covered by a proglacial lake trapped between the ice margin and a chalk ridge spanning the Dover Straits (Gibbard 1995).

This pattern of rising and falling global sea-level coincident with global climate changes continued throughout the Palaeolithic. Therefore, maximum exposure of unglaciated shelves occurred during, or immediately after glacial maxima due to the global-eustatic fall and forebulge uplift. Maximum pre-LGM exposure can therefore be expected during MIS 12, 10, 8, 6 and 4-3, glacial periods characterized by the ice sheet growth and low (~-90 to -120m) global eustatic sea-levels (Rohling et al. 2009). In each cold stage, the exact distribution of exposed and habitable land depended on the interaction between glacio-eustasy, isostasy and the extensions of ice onto the shelf.

Climate and sea-level also fluctuated within individual glacials and interglacials. This is exemplified by evidence of millennial-scale climate changes through MIS2–4 (Shackleton et al. 2000; NGRIP 2004), which in turn may have created sea-level oscillations of metres to tens of metres (Chappell 2002; Siddall et al. 2003). Even larger fluctuations have been noted in earlier periods. The Aveley/MIS 7 interglacial, for example, includes multiple highstands and a sea-level fall of at least 60m during substage MIS 7d (Dutton et al. 2009; Rohling et al. 2009), which is also evidenced on the south coast of England by terrace formation in the Solent and Arun river systems (Bates et al. 2010). The magnitude of both millennial-scale and longer-term sea level changes implies considerable fluctuations in ice sheet size, likely resulting in local to regional-scale isostatic deformation on top of the glacio-eustatic changes. Consequently, their impact on British palaeogeography cannot be quantifiably reconstructed at present and we can expect considerable complexity in coastal geography and the opening/closure of seaways throughout both glacial and interglacial periods.

Broadly speaking, deglaciation resulted in sea-level rise, shelf flooding, coastal retreat and the transformation of fluvial valleys into estuaries. As in the post-LGM, the magnitude and rate of change depended on the interaction between glacio-eustasy and isostasy, being eustatically dominated further from the ice sheets and possibly first experiencing a sea-level fall, stillstand or slow rise followed by a rapid rise closer to the ice margins. Conversely, areas under greatest ice cover experienced uplift and shelf exposure. Sea-level and shelf flooding peaked during interglacial maxima (MIS 13, 11, 9, 7 and 5e), reducing shelves to fringes of modern coasts, as evidenced by raised marine deposits and beaches in areas such as East Anglia, Sussex, Essex, the Thames basin and northern France (Bates et al. 2003). Highstand separation of Britain from the Continent could have occurred as early as the Hoxnian/MIS 11 interglacial when rising sea-levels penetrated the Dover Straits chalk ridge through a gap previously eroded by outflow from the Anglian/MIS 12 proglacial lake (Gibbard 1995). Isolation was aided by the fact that the Eridanos delta was by then moribund and subsiding (Funnell 1995). However, faunal and archaeological evidence suggest that a terrestrial connection across the southern North Sea was maintained for at least parts of the Hoxnian/MIS 11, Purfleet/MIS 9 and Aveley/MIS 7 interglacials. For instance before or after sea-level had reached their maximum levels but while the climate was still warm, or alternatively during substage level fluctuations such as MIS 7d (White & Schreve 2000). The Ipswichian/MIS 5e interglacial, however, has unequivocal evidence for a marine seaway linking the Channel and North Sea (Meijer & Preece 1995).

Highstands also resulted in sea cliff formation, as evidenced by onshore palaeoclifflines, with magnitude of retreat during interglacial highstands (lasting several thousand years on average) reaching up to several kilometres, though rates would have varied with wave exposure and geological composition (e.g. Sussex coast is chalk, East Anglia is till) (Trenhaile 2002; Dong & Guzzetti 2005). Islands may also have formed during periods of high sea-level, originating as isolated high terrain with the surroundings submerged by the rising sea (e.g. the Dogger Bank in the Early Holocene), from marine depositional processes (e.g. the Wadden Isles) or from peninsulas separated from the mainland by erosional activity (e.g. Britain as a whole) (Behre 2007).

The final point to emphasize is that highstand and lowstands represent extreme situations. For most of the Palaeolithic, ice sheet extents, sea-levels and palaeogeography were between the two, albeit biased towards glacial conditions and lowered sea-level; on a global scale typical less than -20m for the last 500ka (Rohling et al. 2009). Although this would have been modified by glacio-isostatic effects, it indicates that the exposure of hundreds of square kilometres of shallow shelf around Britain was the norm rather than the exception. The largest exposures of habitable shelf probably occurred prior to glacial maxima, when sea-levels were falling but before shelves were ice covered or transformed into polar desert, or after deglaciation, when shelves were ice-free but before not yet inundated.

Palaeo-landscape and palaeo-environmental change during the Palaeolithic

This section provides background information regarding the shelf environment, with a focus on landscape developments during the Palaeolithic.

The oldest archaeological finds in Britain come from Pakefield and Happisburgh, both located on the East Anglian coast in association with the Cromer Forest Bed formation (Parfitt et al. 2005, 2010). Both sites occur in fluvio-estuarine sediments representing temperate lowland, valley-side occurrences in near-coastal situations (Lee et al. 2006) which predate the most extensive of the British glaciations, the Anglian/MIS 12. This glaciation also extended onto the surrounding shelf, creating a marked erosional surface, profoundly modifying the pre-existing landscapes and the palaeodrainage patterns, for example, destroying the Bytham river, which had previously drained the Midlands and East Anglia, and pushing the Thames south to its present position (Rose 2009).

The Cromer Forest Bed occurrences are part of an extensive series of fluvial and related sediments that extend under the southern North Sea (West 1980; Cameron et al. 1992). This formation forms part of the massive Eridanos fluvio-deltaic system that largely accumulated during cold periods when the sea-level was low, although interglacial high sea-level stands are recorded, as at the Happisburgh locality. By their nature these sequences represent intermittent sedimentation, with substantial hiatuses representing sea level and channel shifts. In common with most terrestrial depositional environments, they thus provide a fragmentary record of occupation by humans and other biota. Palaeoecological data (e.g. beetles, pollen, plant remains and fauna) indicate that the environment during the earliest occupation (c.900–800ka) was similar to southern Scandinavia and dominated by boreal forest (e.g. pine, spruce) (Parfitt et al. 2010). Late phases of pre-Anglian/MIS12 occupation took place under milder Mediterranean-type climates, characterized by marsh, oak woodland and open grassland which supported a diverse range of mammals such as elephants, hippos and deer (Coope 2006; Parfitt et al. 2005). During these periods, subaerial shelves formed seamless low-lying extensions of the reconstructed onshore environments, and hence similar conditions likely prevailed.

An important Middle Pleistocene development in the North Sea area was the loss of the Eridanos River, a system that reached east into the modern Baltic. During the Middle Pleistocene transition, the headlands of the Eridanos system were demolished by repeating, and progressively more severe, glaciations. Demolition was completed in the Anglian/MIS 12 when advancing ice from Scandinavia and northern Britain overrode its deposits, remodelled the drainage system and ended a long period of net northwards regression of the North Sea coast (Gibbard 1988; Rose 2009). Glaciation brought an end to the temperate conditions of the preceding interglacials with the peak Anglian/MIS 12 characterized by periglacial conditions, extended ice sheets (both on land and onto the North and Irish Sea shelves) and the formation of a massive pro-glacial lake in the southern North Sea (Gibbard 1995) as outflow from the Rhine, Thames, and Meuse rivers was blocked to the north by the ice and the south by the Dover chalk ridge. Note however, that while peak glaciations created exceedingly harsh Arctic or periglacial environments, the transitional periods leading into and out of the peak glacial were less cold though not fully temperate, characterised by, for instance, boreal environments.

The formation of the North Sea pro-glacial lake had profound implications for the landscape development of both on and offshore areas of the North Sea and English Channel alike. Specifically, this has renewed interest in the genesis of shelf valley systems in the English Channel and the origin of Dover Strait generated by the availability of high-resolution bathymetric data (Gupta et al. 2007), as well as lithological and dating evidence collected from on-land localities. The data suggest that pro-glacial lakes covering the southern North Sea and part of the Netherlands formed during the largest glaciations (Anglian/MIS 12, late Wolstonian/MIS 6) before the Dover Strait had eroded to below mean sea level. The origin of the erosion in the Dover Strait results from the spillage of accumulated meltwaters from such lakes, carving the sea strait and the palaeochannels on the Channel floor (Gibbard 1995; Toucanne et al. 2009). Prior to this the Thames, Rhine, Scheldt and Maas had drained northwards into the North Sea, however, the breach and the progressive southward diversion of the rivers by encroaching ice sheets resulted in the formation of a drainage corridor into the English Channel. The exact timing of this diversion is still uncertain but probably dates to between MIS12-6 (Gibbard 1995; Bridgland 2002; Toucanne et al. 2009). The implications of these insights for an understanding of the Middle/Late Pleistocene archaeological record in north west Europe are far reaching since they indicate periods when Britain was connected and subsequently disconnected from the Continent by sea level change and fluvial activity and therefore open to migration across exposed the exposed shelf.

The Anglian/MIS 12 was followed by an extended temperate period, the Hoxnian/MIS 11, characterised by a warm climate, with a mixture of open and forested environments and warm temperate fauna (Stringer 2006). The extent of shelf exposed during this period was quite limited as a consequence of high sea levels and is reflected by raised beaches on either side of the English Channel (Bates et al. 2003) and marine sediments overlying Anglian/MIS 12 glacial deposits in East Anglia (Gibbard et al. 1991; Ventris 1996).

The following Wolstonian Stage (broadly equivalent to MIS 11b–6) has been repeatedly noted as a critical interval in the landscape evolution of lowland England during which the modern drainage system was established (Gibbard 1991). Subsequent Ipswichian/MIS 5e interglacial sequences, occurring at or close to modern floodplain level in river valleys throughout the region, confirm that the present drainage system was in place by this time. Major glaciation in the Wolstonian/MIS 11b–6 is confirmed by various cold stage and glacial accumulations post-dating the Hoxnian/MIS11, with the most extensive glaciation (including offshore extensions of ice into the North and Irish Seas and formation of a pro-glacial lake in the former) confined to the late Wolstonian/MIS 6 (Toucanne et al. 2009). Subsequent valley evolution, incision and accompanying fluvial sediment deposition is indicated, both on and offshore, throughout the region. Although this interval is predominantly represented by fluvial and periglacial activity that occurred under cold, stadial climates, it was also punctuated by milder events, such as the Purfleet/MIS 9 and Aveley/MIS 7 intervals, during which temperate flora and fauna were present (Schreve 2001; Gibbard et al. 2009).

The apparent absence of humans from Britain during the Ipswichian/MIS 5e interglacial has been repeatedly noted and is often interpreted as a reflection of the fact that all terrestrial connections to the Continent were severed by higher than present sea-levels before hominins reached the coast (White & Schreve 2000). Nonetheless, the possibility of occupation should not be completely ruled out particularly in the light of recent finds from Dartford which suggest a hominin presence during MIS 5d–c, a period previously believed to lack archaeological evidence (Wenban-Smith 2010).

The third substantial division of the Palaeolithic record (the Devensian/MIS5d–1) spans the Late Pleistocene to earliest Holocene. Throughout lowland Britain, this period was marked again by predominantly cold climate sedimentation intermittently in river valleys (e.g. Briant et al. 2005), and this again might be expected to continue offshore during lowstand phases. The interfluves were subjected to prolonged and intense periglacial climates and therefore weathering. Mass movements, and in particular aeolian activity, were significant especially during the Late Glacial.

The climatic history of Early Devensian time (*c*.115-50ka) is marked by a rapid increase in global ice volume. Ice volumes fluctuated through MIS 5d–a and are mirrored by marked local temperature changes, but climatic deterioration into MIS 4, at *c*.75ka reflects the build up of continental ice masses and complementary sea-level fall (Aalbersberg & Litt 1998). The Middle and Late Devensian (c.60–11.5ka) climate is recorded in detail by local temperature estimates from beetle faunas, pollen records and regional inferences from ice and deep-sea cores. These show that climate oscillated throughout MIS 3 between short lived (several thousand year max.) cold stadial and warm interstadial phases (Guiter et al. 2003; Van Andel 2003). During interstadials, tree populations increased without peaking to full interglacial levels, as warmth and moisture did not reach the requisite intensity. Instead, warm steppe or temperate grassland interspersed with smaller stands of trees may have dominated. During stadials, tree cover gave way to open steppe or tundra. Open grasslands/steppe was dominated by grazers (e.g. horse, bison, reindeer, mammoth and woolly rhino), while woodlands were home to more solitary browsers (e.g. red and roe deer). Considering that vegetation patterns fluctuated rapidly between stadials and interstadials throughout the Devensian, fauna consisted of mixed communities with differing proportions of species depending on climatic conditions, for instance with cold-adapted types dominating during stadials. Direct evidence of MIS 3 shelf fauna, such as horse, mammoth and reindeer, has also been obtained via specimens recovered from the North Sea (Mol et al. 2008).

Subsequently, climate deteriorated again to a low point at 24–21ka: the Last Glacial Maximum/MIS 2 (or Dimlington Stadial in British terminology). This marks the climax of the Devensian glacial period, and is the probable age of its maximum ice limit in most areas. During this period the British ice was no longer sufficiently extensive to join the Scandinavian ice sheet across the North Sea basin, although they were confluent at c.30–25ka (Carr et al. 2006; Sejrup 2009). Instead, lowered sea level left a wide plain affected by permafrost and periglacial processes over much of the southern and central North Sea basin. Further north, deeper parts of the basin retained marine water, but with a cover of sea ice (Coles 1998; Huijzer & Vandenberge 1998).

The Devensian ice sheet never reached the same extent as its Middle Pleistocene precursors, but it modified drainage patterns in analogous ways. The rivers Thames, Rhine, Meuse and Scheldt again flowed from the North Sea basin via the Dover Strait into the Channel River, whereas drainage from the English Midlands was blocked by ice to form pro-glacial lakes in eastern England (Bateman et al. 2007). Ice also advanced into the Irish Sea, covering most of Wales and Ireland (Bowen et al. 2002). Near the ice front, winds concentrated cover-sand or silt-grade loess sediment, whilst extensive permafrost developed over most of the ice-free area of southern England, only the south west peninsula of England being spared its severest effects. Ice-free shelves were probably reduced to periglacial or polar desert inhabited by few large mammals (Coles 1998).

The melting of the ice between 19-15ka was spasmodic and reflected in both on and offshore records (e.g. Coope et al. 1998; Zaragosi et al. 2001). A Windermere Interstadial (the Bølling/Allerød in north west European terminology) between 15-12.9ka, intervened between the main Dimlington Stadial and the subsequent Loch Lomond (north west Europe, Younger Dryas) Stadial (Hill et al. 2008). By 12.5ka, the climate of England, Wales and their adjacent exposed shelves was as warm as it is today, although more continental in character, with dominant vegetation consisting of light woodland and parkland, a change from the steppe and tundra environments typical of the stadial events on either side (Coles 1998; Rochon et al. 1998). During the Loch Lomond Stadial, from 12.9-11.5ka, a large ice mass developed in the west Scottish mountains, and smaller cirque and valley glaciers in the uplands of southern Scotland, north west England, Ireland and Wales. Exposed shelves therefore escaped direct glaciation, however, as with terrestrial areas outside the Loch Lomond ice limits, they experienced a new phase of periglaciation that was overprinted on that from earlier events (Bell & Walker 2005).

Regional preservation conditions

The following sections give a broad regional overview of the likely preservation conditions off Britain, highlighting areas where Pleistocene deposits or archaeological material are known to be preserved or absent. See Strategic Environment Assessment (SEA) documents for more detailed discussion (Flemming 2002; 2003; 2004; 2005; Wickham-Jones & Dawson 2006; Maritime Archaeology Ltd 2007).

Scotland and the northern North Sea

The northern North Sea probably has a heavily truncated submerged archaeological record resulting from glaciation, sea level change and coastal/marine erosion. During maximal glaciation, the shelf was covered by ice sheets originating in the Scottish Highlands and Scandinavia. Proximity to the ice created a resource-poor polar desert, except perhaps on unglaciated coastlines where fish and marine mammals could have survived. Consequently, this would have been an unattractive area for settlement, except possibly during intervals of ice retreat. However, archaeological material deposited prior to glaciation was overrun by the advancing ice and probably destroyed/reworked. This is substantiated by the lack of unequivocal pre-Late Glacial archaeology in Scotland and Scandinavia as most evidence of an earlier occupation was probably destroyed by the Devensian/MIS 2 ice advance. Nonetheless, the survival of isolated pockets, for example in caves, should not be entirely ruled out (Flemming 2004). These patterns are reflected in shelf geology, whereby the vast majority of the Quaternary sequence comprises subglacial, proglacial and glacio-marine deposits. In general, shelf sediments are discontinuous around Scotland, locally thick in depressions and infilled channels, but thin and absent in other areas where exposed bedrock forms the seabed (Andrews et al. 1990; Fyfe et al. 1993; Stoker et al. 1993). Consequently, the vast majority of preserved landscapes probably postdate the post-LGM.

Of this landscape, little is known to be left beyond large robust features such as moraines which formed during ice retreat. These constituted the landscape on which postglacial migrants could have settled, but their upper surfaces (i.e. those most likely to be artefact bearing) are the most susceptible to erosion during and after marine transgression. Marine erosion is particularly strong as much of the area is subject to high wave energy, while strong tidal currents also exist, such as in the straits between islands. This, in conjunction with low sediment input from land, means that much of the postglacial landscape has probably been reworked into the modern seabed.

This implies that large swathes of the shelf were swept clear of palaeolandscape and associated archaeological evidence, firstly by the ice as it expanded, secondly by erosion associated with marine transgression, and finally by strong modern wave and tidal currents. Any surviving artefacts would exist in reworked deposits removed from their original contexts and associated evidence. An example of this is the worked flint cored from the Viking-Bergen bank and located within a lag deposit created by marine transgression (Long et al. 1986). Higher potential areas, where in situ material could survive, consist of sheltered environments such as caves, gullies, sea lochs and natural sediment traps, examples of which are located around the modern isles, particularly on their leeward sides (Flemming 2003). Substantiating evidence for this consists of submerged peats off the Hebrides, Orkneys and Shetlands (Stoker *et al.* 1993) and animal bones trawled from parts of the shelf (Flemming 2003; Wickham-Jones & Dawson 2006). Other possible areas include infilled depressions on the shelf, though material here could be so deeply buried that it remains inaccessible to modern archaeological techniques.

Irish Sea

The situation in the Irish Sea is broadly similar to the northern North Sea as it too was overridden by LGM ice. Nonetheless, the possibility of preserved palaeolandsurfaces should not be completely discounted especially given that there are terrestrial sequences on either side of the Irish Sea which have survived glaciation. For example, High Lodge (Norfolk), survived the Anglian/MIS 12 glaciation as a vast intact ice-transported erratic (Stringer 2006) and Aghnadarragh (County Antrim), contains a set of MIS 3 peats, sediments and associated faunal remains stratified between two glacial till deposits (McCabe et al. 1987). Evidence of formerly exposed land does exist on the Irish Sea seabed in the form of relict periglacial features and outwash plain channels between 53–55°N (Jackson et al. 1995). In addition, intertidal and submerged peat and forests are known on the Northern Irish and Welsh coasts (Flemming 2005; McErlean et al. 2002; Whitehouse et al. 2008), the Bristol Channel - where intertidal Palaeolithic artefacts have also been identified (Bell & Neumann 1997) - and off the Merseyside and Lancashire coasts where at least one deposit (Heysham Harbour), reportedly contains Late Glacial fauna (Hazell 2008). It is these inshore waters with sheltered bays and loughs that have the most archaeological potential. Large depressions, such as glacially incised valleys may also hold sediments dating to times when the landscape was subaerial. However, they are presently buried by tens of metres of marine sediment, rendering any archaeological deposits invisible (Flemming 2005).

Central & Southern North Sea

Although tracts of the central and southern North Sea basin were glaciated, a trend of tectonic subsidence coupled with significant fluvial input and a more sheltered environment than the northern North Sea has allowed accumulation of a thicker sedimentary sequence. Approximately 80% of this comprises of deltaic sediments built up prior to the Anglian/MIS 12. The uppermost levels of the deltaic deposit, the Yarmouth Roads formation, are the remnants of a wetland plain created by the expansion of the Eridanos delta. Evidence for this consists of terrestrial and intertidal sediments with plant remains, freshwater microfossils and peat (Cameron et al. 1992; Gatliff et al. 1994). Onshore, these deposits have been correlated with the Cromer Forest-Bed and Wroxham Crag formations which crop out along the Norfolk coast and contain in situ Palaeolithic artefacts at Pakefield and Happisburgh (Hazell 2008; Wessex Archaeology 2008; Parfitt et al. 2005). Therefore, there is a strong possibility that the upper levels of the Yarmouth Roads formation contain early Palaeolithic material. However, this is offset somewhat by the absence of this formation across parts of the North Sea (e.g. much of the southern Bight with the exception of palaeovalley infills and north of ~56°N). On a more local scale, recent surveys found no evidence of submerged Cromer Forest Bed or Wroxham Crag formations off Happisburgh; off Pakefield only the Wroxham Crag formation was found to be present (Wessex Archaeology 2008). Moreover, while there are instances where the Yarmouth Roads formation crops out at, or close to, the seabed, there are large areas where its archaeological potential is limited by burial beneath metres to tens of metres of later deposits.

The remaining 20% of the Quaternary sequence is composed of fragmented, transgressive/regressive non-deltaic sediments laid down during the climatic fluctuations of the Middle to Late Pleistocene and early Holocene. In contrast to the thick and extensive deltaic deposits, these non-deltaic elements are fragmentary, discontinuous and vary in thickness and extent due to successive cycles of glaciation, inundation and subaerial exposure. Pockets of preservation evidence a range of environments including marine, subglacial, intertidal and fully terrestrial (Cameron et al. 1992). Important deposits are the Brown Bank, Elbow, Twente and Dogger Bank formations which date to MIS 2–4 and are respectively lagoon, tidal flat, periglacial aeolian and lagoonal/lacustrine sediments. Importantly, submerged peat deposits are known from the Brown Bank, Elbow and Dogger Bank localities, demonstrating the preservation of terrestrial or wetland deposits (Cameron et al. 1992; Gatliff et al. 1994; Balson et al. 2002). Although it is these intertidal and terrestrial deposits that are often most attractive to archaeologists, marine deposits should not be ignored as they could provide datable horizons that would facilitate correlation with the extant Quaternary chronostratigraphic framework.

Further indicators of preservation are the collections of Pleistocene fauna and Palaeolithic artefacts obtained from off the Dutch and East Anglian coasts (see Case Study in section 1.1;

Flemming 2002; Mol et al. 2008; Wessex Archaeology 2009). Within the Dogger Bank, high-resolution seismic records have imaged more detailed aspects of the buried and preserved palaeolandscape, such as an infilled late Devensian proglacial valley that is overlain by a complex Holocene river system and associated sediments which in turn may have developed into an estuarine environment within rising sea-levels (Fitch et al. 2005). In general, these reconstructions show that the slopes and depressions surrounding the Dogger Bank contained environments favoured by past humans (river valleys and marshland) during the Mesolithic and possibly also the Palaeolithic and are therefore indicative of an area of high archaeological potential (Gaffney et al. 2007).

Other areas of high potential are palaeovalley infills such as the Swarte Bank formation, a late Anglian/MIS 12 set of glacio-fluvial and glacio-lacustrine sequences (Cameron et al. 1992). If these valley fills were deposited after ice retreat, then archaeological evidence of hominin use may be preserved. However, if they were deposited subglacially (Praeg 2003), then they are unlikely to contain archaeological evidence. Gravel deposits associated with palaeo-river systems have also been detected offshore (e.g. Thames-Medway: Bridgland and D'Olier 1995). If these formed in a similar manner to those on land, they could potentially contain secondary context archaeological material, preserved lenses of in situ material and important geological or palaeoenvironmental evidence (Bridgland 2002; Wenban-Smith 2002). However, there are considerable challenges in correlating marine deposits with the terrestrial terrace sequence and hence their dating is still unclear, as is their history of formation and modification by both marine and terrestrial processes (Bates et al. 2007). Consequently, while the broad category of offshore gravel deposits associated with palaeo-river systems can be regarded as having high potential, assigning this value to an individual deposit is currently difficult unless there is associated evidence which can confirm its age and origin.

Finally, although wave action is reduced in the sheltered southern North Sea compared to open Atlantic coasts, it can still mobilize sediment particularly where there are strong tidal currents. Consequently, archaeological sites exposed on the seabed are unlikely still to be in primary context, although buried sites may still be. This is reflected by the fact a large proportion of modern marine sands consist of Pleistocene sediments that were reworked in the early stages of the Holocene transgression (Cameron et al*.* 1992).

English Channel

The English Channel was never glaciated, and therefore this constraint on archaeological preservation no longer applies. Nonetheless, strong wave action and tidal currents, in addition to coastal erosion accompanying marine transgression, mean that much of the its seabed consists of a thin coarse sand and gravel lag over bedrock, locally overlaid by fine sediments (Evans et al. 1990). In this situation, most archaeological material will occur in reworked contexts. Exceptions could occur in the deeper (up to several tens of metres thickness) deposits which infill the extensive palaeovalley network incised by the lowstand Channel River system and associated tributaries. In several instances, peats, pollen, estuarine and intertidal sediments have been found associated with these palaeovalleys (Hamblin et al. 1992), though most of currently recognised material is early Holocene in date, such as at Bouldnor Cliff (Isle of Wight) and the palaeo-Arun valley (Sussex) (Momber 2000; Wessex Archaeology 2008). A potentially Ipswichian/MIS 5e peat has also been recovered in boreholes from Pennington Marshes on the northern flank of the

Solent (Hazell 2008) substantiating indications of high preservation potential provided by Palaeolithic artefacts dredged from this area (Wessex Archaeology 2004).

Also associated with palaeovalleys are gravel deposits laid down by lowstand rivers and potentially containing artefacts in secondary context and finer grained lenses with potential in situ archaeology and palaeoenvironmental evidence (Wenban-Smith 2002). However, the caveat previously described in reference to the southern North Sea still applies; while the broad category of deposits may be considered as having high potential, classification of individual deposits is currently not possible without detailed dating, correlation and taphonomic data (see also Bates et al. 2007).

The complexity of site formation processes is illustrated by differences in preservation between different palaeovalleys. It is notable that the largest examples in the area, the Lobourg and Northern palaeovalleys (up to 20km wide), are largely empty of sediment. By contrast, smaller submerged extensions of modern river systems, (e.g. the palaeo-Arun) are infilled with up to tens of metres of Pleistocene deposits. This has been interpreted as resulting from the increased shelter afforded by smaller channels during transgression compared to the more open expanses of the larger river systems (Hamblin et al. 1992). In addition, there are also much shallower (c.3m) buried channels, such as at Selsey, containing interglacial sediments. These smaller channels were marginal to the main drainage valley and record shorter intervals of infilling. In these situations, the complexity of preservation/erosion patterns brought about by the rate and direction of sea-level change, inherited geomorphology and interplay between fluvial and marine processes is illustrated by the fact that several channels situated within a restricted area contain sediments dating to different interglacials at broadly the same altitude (Bates et al. 2007).

A palaeolandscape feature that has received less attention, possibly due to the more obvious expression of the palaeovalleys on the seafloor, is the coastline. It is possible to trace features such as clifflines, beaches or shore platforms using high-resolution bathymetric and seismic data, though as with fluvial and other terrestrial deposits this is reliant on their survival through repeated episodes of submerged and emergence. In this context, it is interesting that some gravel deposits in the Channel have been interpreted as relict storm beaches rather than fluvial terraces (Wenban-Smith 2002). If associated with datable material, then such features could provide important constraints on low sea-level stands. However, this represents an area that is in need of greater research.

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