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North Sea palaeogeographical reconstructions for the last 1 Ma

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Abstract

The landscape evolution of the southern North Sea basin is complex and has left a geographically varying record of marine, lacustrine, fluvial and glacial sedimentation and erosion. Quaternary climatic history, which importantly included glaciation, combined with tectonics gave rise to cyclic and non-cyclic changes of sedimentation and erosion patterns. Large-scale landscape reorganisations left strong imprints in the preserved record, and are important for the detail that palaeogeographical reconstructions for the North Sea area can achieve. In the spirit of the North Sea Prehistory Research and Management Framework (NSPRMF; Peeters et al., 2009), this paper provides background geological information regarding the North Sea. It summarises current stratigraphical and chronological frameworks and provides an overview of sedimentary environments. As we go back in time, the understanding of Quaternary palaeo-environmental evolution in the North Sea basin during the last 1 million years becomes decreasingly accurate, with degree of preservation and accuracy of age control equally important controls. Comparing palaeogeographical reconstructions for the Middle Pleistocene, the last interglacial-glacial cycle and the period following the Last Glacial Maximum illustrates this. More importantly, a series of palaeogeographical maps provide an account of basin-scale landscape change, which provides an overall framework for comparing landscape situations through time.

Keywords: palaeogeography, archaeology, southern North Sea, Quaternary

Introduction

What makes palaeogeographical reconstructions of Quaternary landscapes in the North Sea region special is the availability of a relatively vast and detailed record of rather evenly distributed sedimentary data from a variety of terrestrial and marine settings. With the relatively young age and completeness of the record comes considerable heterogeneity in depositional environments, which complicates large-scale palaeogeographical reconstruction. As the upper unit in the sedimentary sequence of the North Sea region, the Quaternary has been subject to more research than the older, underlying units, particularly onshore. The record distilled from this research is not only more complete and detailed than that of earlier periods, its architectural relationships are also better constrained by age control. The Quaternary record tells a story of dramatic climatic oscillations during the last 1 Ma. Vast expanding and receding ice sheets extended into our study area during at least three periods ('Anglian/Elsterian', 'Wolstonian/Saalian' and 'Devensian/Weichselian'). Areas even farther north saw glaciation every glacial half cycle. Various erosion-dominated glacial processes had a negative effect on the survival of palaeolandscapes and strongly influenced the broader geographical connections to the surrounding world. Furthermore, climatic oscillations have driven major changes to the physical and biological landscape. These developments have at times opened up and at times constrained the possibilities of human occupation in the Pleistocene and Early Holocene as the area cycled repeatedly through stages of sea-level lowstand, transgression, highstand and fall (Cohen et al., 2012). It is more than likely that consecutive palaeolandscape changes are reflected in the archaeological record of the study area (e.g. Preece & Parfitt, 2012).

In an overall setting of continuous Quaternary landscape change and spatially changing preservation conditions (resulting from glaciation impacts superimposed on tectonics), the archaeological record shows humans to have been present as a migratory species, evolving rapidly to make optimal use of a wide range of habitats in the North Sea area. Human evolution from the Early-to-Middle to Late Palaeolithic occurred over the same time span as the glaciation-dominated landscape evolution (e.g. Parfitt et al., 2010; Candy et al., 2011). In the last 20,000 years, the ameliorating post-glacial climate and a rising sea jointly set the stage for rapid migration and changing occupation by Late-Palaeolithic and Mesolithic modern humans. They adjusted to a landscape that gradually transformed from fully terrestrial to increasingly coastal in nature, before being forced out following marine inundation.

For many of the sedimentary environments and ecosystems of the ice ages, modern analogues are flawed at best. The original landscapes have undergone significant progressive geomorphological change, with coastlines and drainage configurations of the present and last interglacial differing dramatically from those in earlier times. Nevertheless, some interglacial settings compare more favourably to each other than others in terms of landscape configurations, and some glacial cycles are more similar than others in terms of severity and impact on preservation. To make full palaeo-anthropological use of the geological record, palaeolandscape mappers must be thoroughly familiar with stratigraphical and chronological frameworks, and must have insight into large- and small-scale geographical changes over the studied time frame.

This paper provides an overview of the stratigraphic and chronological frameworks for the last 1 Ma, a state-of-the-art inventory of palaeoenvironmental change and landscape development, and a discussion of the continuity of the record within the context of palaeogeographical reconstructions. It addresses the information and ideas incorporated in recent reconstructions for the oldest time frames in the last 1 Ma, both by intercomparison and by seeking analogues in well-known Holocene landscapes.

Climate and tectonics

Ice ages and marine isotope stages

Continuous records of Quaternary time are available from cores collected from the deep ocean and the Antarctic ice sheet (Fig. 1). For the last 120,000 years, the Greenland ice sheet provides an additional high-resolution record, of particular relevance to the North Atlantic and the study area (e.g. Lowe et al., 2008; Renssen et al., 2012). Oxygen-isotope signals in ice cores and ocean-floor sediments record global, orbitally forced climatic variations. Observed oxygen-isotope cyclicity is mirrored between the ocean and ice-core records, thus bearing information on climate as reflected in global sea-level and ice-volume changes.

The $^{18}O/^{16}O$ ratio is conventionally normalised against a standard sample, resulting in the parameter $\delta^{18}O$. High values of $\delta^{18}O$ indicate large ice volumes during cold lowstand periods known as glacials, and low values signify warm highstand periods known as interglacials (Fig. 1). In the standard subdivisions of $\delta^{18}O$ records in *marine isotope stages* (MIS), interglacials are assigned odd and glacials even numbers. The MIS ages are constrained by dated palaeomagnetic reversals and volcanic tephras, and systematic orbital cyclicity is used to further constrain ages between these tie points (e.g. Lourens et al., 1996; Lisiecki & Raymo, 2005). The MIS scheme and its dating serves as a global target curve to correlate (not equate!) stratigraphic units from more discontinuous shallow marine, terrestrial and glacial environments too.

The MIS stack provides a globally integrated signal for the growth and decay of major ice volumes, with the European ice sheets accounting for 15–25% of the global ice-volume variability (e.g. Peltier, 2004). The timing and rate at which European ice sheets grew and decayed differs slightly from those of other ice sheets, notably from the much larger and slower moving one on North America (55–75%). The Scandinavian and British ice sheets reached their maximum extents at 30–25 ka, well before the global Last Glacial Maximum (LGM) around 21 ka, and were relatively quick to melt (e.g. Sejrup et al., 2009; Carlson & Clark, 2012; Hughes et al., 2013). The explanation for the earlier timing is to be sought in the vicinity of the North Atlantic and its warm currents, and applies to earlier cycles too.

The oldest known presence of humans in northwest Europe dates from the transition of the Early to the Middle Pleistocene, when the Earth's climatic system saw profound change in its cyclicity. The latter has become known as the 'mid-Pleistocene revolution' (Berger & Jansen, 1994) or, less prosaically, the 'mid-Pleistocene transition' (Head et al., 2008). In its broadest definition, this interval extends from about 1.2 Ma to 500 ka, thus spanning considerable time on either side of the internationally defined Early/Middle-Pleistocene boundary at 781 ka (Fig. 1). During the transition, glacial–interglacial cyclicity changed from an orbital-obliquity-paced 41-ka rhythm (i.e. relatively short glacials and comparatively long interglacials) to a slower 100-ka rhythm of much longer glacials alternating with relatively shorter duration interglacials. No evidence has been found for human presence in the North Sea region from before the mid-Pleistocene transition began (Ashton et al., 2011). This absence cannot be attributed to climate or palaeogeography because in temperate stages both would have been as hospitable before the mid-Pleistocene transition as they were during it.

During the Late Pliocene and Early Pleistocene, sea-level minima were not more than 70 m below preceding highstands.

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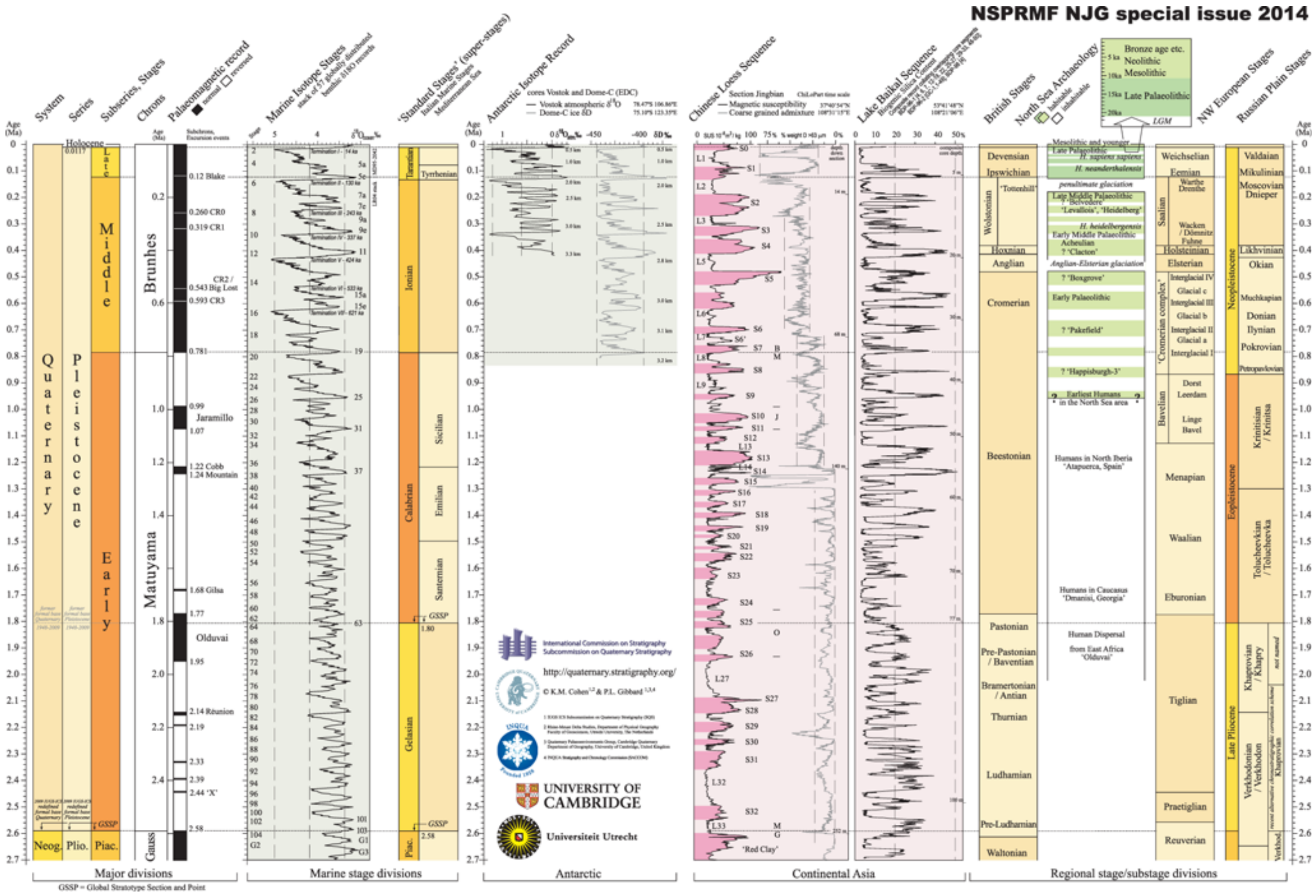

Fig. 1. Chronostratigraphical correlation table for the Quaternary (after Gibbard & Cohen, 2008; modified/updated 2009–2013, http://quaternary.stratigraphy.org/charts.

On the transition to the Middle Pleistocene, maximum continental ice volumes and associated high-to-lowstand amplitudes increased significantly. From MIS 22 (c. 800 ka) onwards, glacial sea level appears to have fallen as much as ∼150 m below interglacial levels. These maximum amplitudes were reached for some lowstands within the Cromerian Complex (MIS 20?, MIS 16?), for the Anglian (Elsterian; MIS 12) and for the end of the Saalian (MIS 6). The last glacial lowstand peaked at c. −120 m, some 21,000 years ago, within MIS 2. All maximum lowstands occurred relatively late in the glacials, out of phase with deglaciation in northwest Europe. Relatively early onsets of deglaciation in northwest Europe exposed areas to enhanced input of glacially derived sediment while sea level was still falling in the cooling limb of glacial cycles. Regional climatological effects (relative continentality, also seen in the palynological records, e.g. Turner, 1996) and altered functioning of sedimentary systems in these deglaciated but still 'arctic' areas had major effects on the proglacial and periglacial landscapes of the southern North Sea basin (e.g. Roebroeks et al., 2011). These developments influenced Palaeolithic archaeology in two ways, which we regard as being of equal importance: (1) they affected the routes for human migration and settlement, and the trapping of archaeological record at times of *postglacial and interglacial* recolonisation of our latitudes by palaeohumans, and (2) they have affected the long-term preservation of archaeological record within interglacial deposits at times of *post-interglacial* habitat deterioration and local extinction of palaeohumans (e.g. Cohen et al., 2012).

Tectonics and glacio-isostasy

The relatively large thickness and completeness of the fill of the North Sea basin, a setting favourable for palaeogeographical mapping, are the result of steady, long-term tectonic subsidence. Averaged over multiple glacial cycles, the basin centre has subsided at rates up to 0.3 m/1000 yr (e.g. Kooi et al., 1998). The degree of subsidence is a function of crustal stress fields between the Alps and the North Atlantic mid-oceanic ridge, which caused reactivation of a Triassic–Jurassic rift system early in the Miocene (25–20 Ma). Quaternary depocentres in the southern North Sea have hosted terrestrial lowland environments such as river and delta plains that from time to time experienced marine inundation (e.g. Rijsdijk et al., 2005; Hijma et al., 2012). The basin margins appear tectonically stable and are marked by near-zero net subsidence/uplift areas

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that form the hinge zone of the basin. This hinge zone has received vast amounts of sediment, delivered by rivers originating in upstream areas of uplift. Part of this mostly fluvial input has been stored along the basin margin, in particular in the Lower Rhine Embayment where the rivers Rhine and Meuse enter the North Sea basin. Here, a patchy, dissected and terraced, but still relatively complete, Quaternary record exists. Reconstructions of the positions of the rim of the basin (i.e. the basin hinge line), and the boundary between long-term net subsiding and net uplifting substrate, are based on the occurrence and internal architecture of the terraced Quaternary record (e.g. van den Berg et al., 1994; Houtgast & van Balen, 2000; Meyer & Stets, 2002; Schäfer et al., 2005; Van Balen et al., 2005; Boenigk & Frechen, 2006). The greater part of the fluvially delivered sediment has been transported well into the North Sea basin (Fig. 2).

For Palaeolithic archaeological prospection in particular, the tectonic setting matters, through its impact on spatial patterns of preservation *and* the depths at which deposits from hominin-favoured habitats would preserve (Cohen et al., 2012).

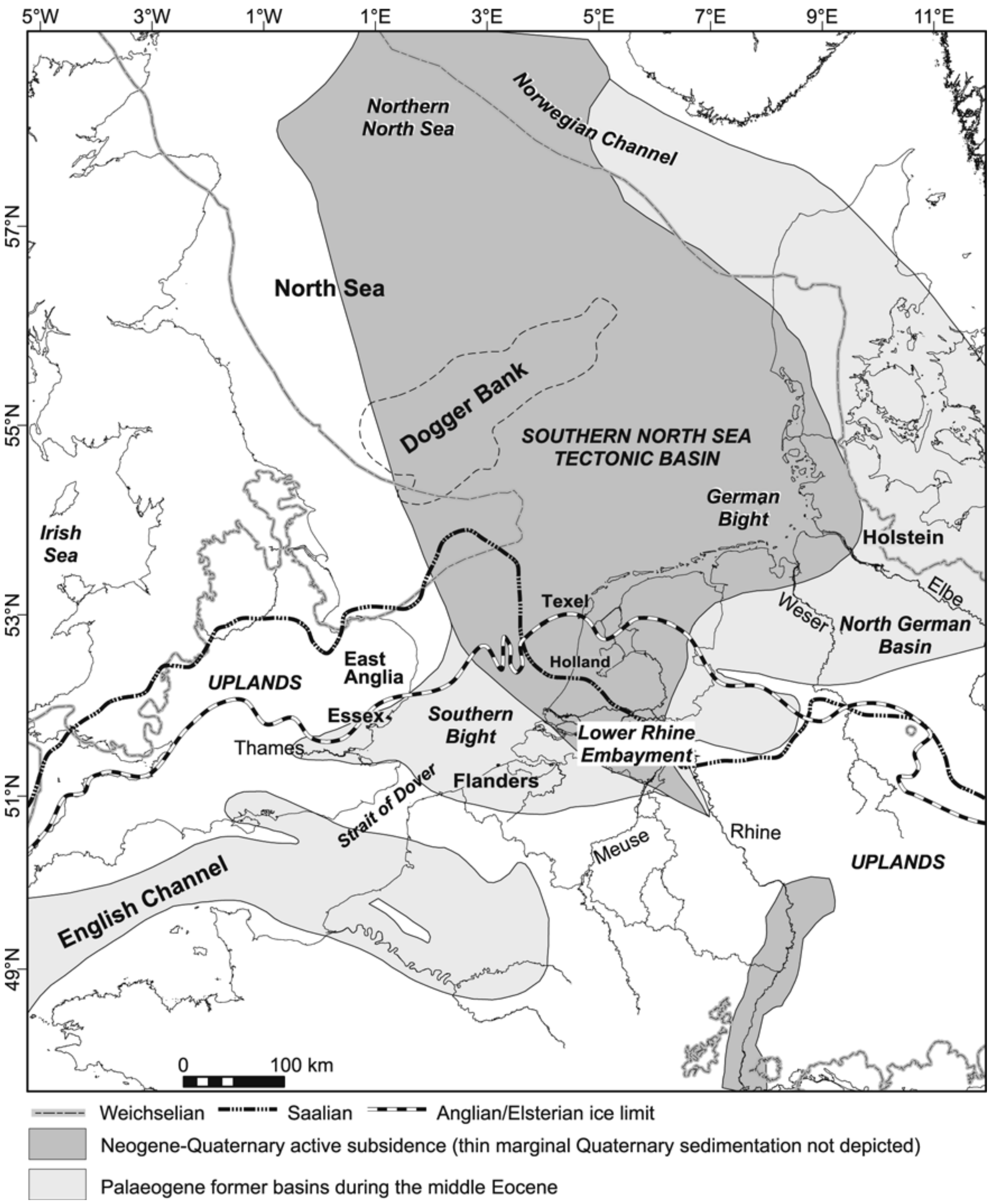

Fig. 2. Quaternary tectonic and glaciation setting of the North Sea area (after Hijma et al., 2012).

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For archaeological research and heritage management in the southern North Sea, it is important to realise that the main hinge line separating the Quaternary subsiding tectonic basin from the British–Southern Bight–Belgian older shoulder runs diagonally southeast–northwest through an offshore area between Holland and East Anglia (Fig. 2). In the depocentre, the seafloor substrate is dominated by a thick sequence of fluvial sands deposited by the Rhine and by North German rivers, which have long had their deltas in the present-day North Sea. For this now submerged area, terrestrial lowstand palaeolandscapes would have been comparable to those of the adjacent onshore Netherlands and northern Germany. Outside the North Sea basin proper (Fig. 2), the area between Flanders and East Anglia has been marked by mild uplift. Typical past landscapes would have been similar to palaeolandscapes as reconstructed for onshore Essex and Flanders, and the Southern Bight of the North Sea is underlain by Pleistocene-denudated Paleogene geology (Hijma et al., 2012). Even further south, the Strait of Dover crosscuts the currently inactive Weald–Artois anticlinal structure, with Mesozoic seafloor subcrop. This southern tip of the North Sea lies outside the North Sea tectonic basin. Note that the exact position of the hinge line is difficult to define and pin-point, and the position of the hinge line in the last 1 Ma may not have been exactly that of the last 250 ka or the last 2.5 Ma. One may prefer the term 'hinge zone' for that reason. This does not affect the general notion that the Southern Bight and Dover Strait in general are outside the tectonic subsidence area that is the North Sea Basin.

In addition, so-called glacial isostatic adjustment (GIA) forms a second mode of differential vertical crustal movement, operating at the same time scales as the glacial–interglacial cyclicity, driven by the growth and decay of ice-sheets and the associated changes in mass distribution over the earth surface. This induces oscillations in crustal warping that are more or less in phase with the climate and sea-level cycles. Owing to the visco-elastic nature of GIA, part of the adjustment is direct, part is stepped-delayed (e.g. Peltier, 2004; Lambeck et al., 2006; Steffen & Wu, 2011). During each glaciation, the crust below the ice sheet is depressed by the weight of ice up to 3 km thick (Fig. 3). In compensation, the peripheral area around the area of crustal depression experiences upwarping (forebulging). During deglaciation, and for some continued relaxation time thereafter, the suppressed areas rebound while in the periphery the forebulge collapses. The loading and unloading of shelf areas with the weight of sea water causes further perturbating warping effects (hydro-isostasy). Glacio and hydro-isostasy together controlled the timing and speed of transgression, the positioning of migrating coastlines of specific times and the depths at which sedimentary indicators of former sea levels from along palaeocoastlines are found preserved today (e.g. Lambeck, 1995; Sturt et al., 2013), of relevance to Palaeolithic and Mesolithic submerged archaeology alike.

A further phenomenon related to GIA is the gravity effect of the presence of ice sheets and deepening oceanic water bodies. Regional accumulation of mass affects the geoid and increases the elevation of large ice-proximal water bodies relative to those of their distal counterparts. In the North Sea, the lowstand associated with the LGM was not at the global −120 m, but some tens of metres higher (e.g. Peltier, 2004; Steffen & Wu, 2011). The vertical positions at which palaeo-coastlines are currently encountered is controlled by syn-depositional geodetic and post-depositional GIA effects combined, complicating the environmental and palaeolandscape reconstructions for the North Sea area, during the last deglaciation (e.g. Lambeck, 1995) and during earlier glacial–interglacial cycles (e.g. Lambeck et al., 2006).

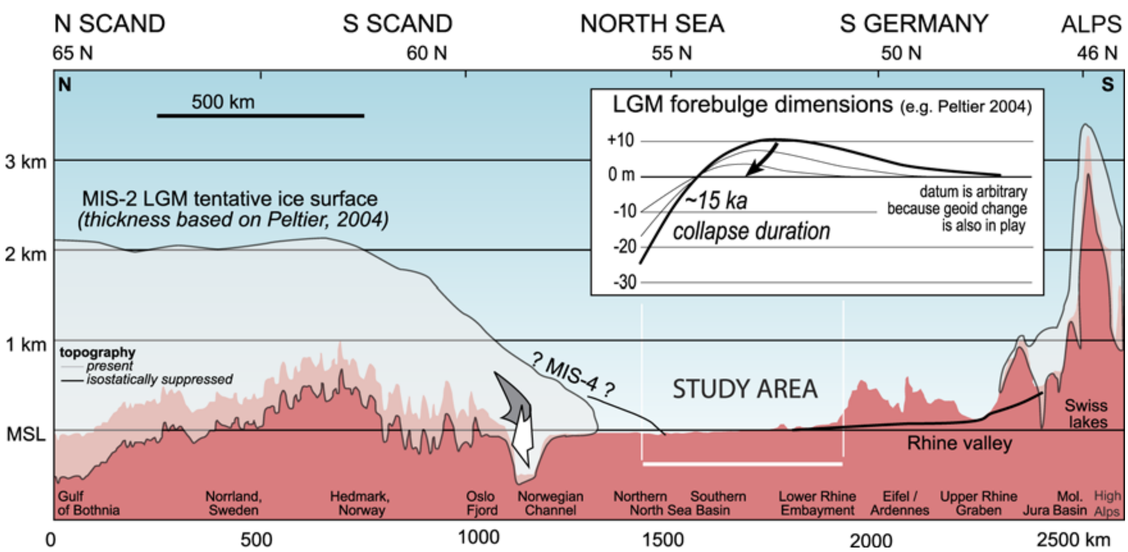

Fig. 3. Cartoon illustrating the ice thickness and GIA magnitude for Scandinavia, the North Sea basin and the periglacial foreland of northwest Europe (after Cohen et al., 2009; abridged).

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GIA explains both the complex patterns and the differential timing of Holocene transgression along the North Sea coast, as seen along Britain and from Flanders to the German Bight. The magnitude of warping varies spatially and causes palaeocoastlines of the same early Holocene age to differ many metres in elevation when traversing the study area (Vink et al., 2007). These processes and conditions will have differed between glacial cycles, but in general the farther south within the study area, the more comparable the spatial patterns of GIA between successive larger glaciations. GIA in these distal ice-peripheral areas is relatively strongly affected by crustal properties that have remained constant through time, such as the presence of major fault systems bounding the North Sea basin (Lambeck et al., 2006). In ice-proximal northerly peripheral regions, variation in ice-load patterns makes GIA patterns differ more strongly from one glaciation to the next. Asymmetry of the peripheral forebulge (inset of Fig. 3) causes this. Particularly when geoid-change is accounted for in the datum to which the forebulge vertical displacements are expressed, it shows a restricted area of steep northern flank, a somewhat broader area with the warping crest and a much-stretched southward-decaying tail. Ice-mass differences between glacials change the centroid-position of the steep flank much more than they change it for the broader crest zone, and they hardly affect the centroid of the gentle southern flank.

GIA is, again, a process that affected *post-glacial* migration and recolonisation as well as long-term preservation, of relevance to the Palaeolithic of past interglacials (e.g. Hijma et al., 2012; Cohen et al., 2012), in very similar ways as it is affecting the latest Palaeolithic and Mesolithic archaeology of the current interglacial (e.g. Lambeck, 1995; Smith et al., 2011; Sturt et al., 2013), as well as younger coastal plain as well as even younger coastal-plain accumulation and archaeology (Kiden et al., 2002; Cohen, 2005; Gouw & Erkens, 2007; Hijma & Cohen, 2011).

Patterns of differential crustal movement have strongly influenced the preservation of lowland depositional records, especially over periods of 10^4 to 10^6 years. Long-term subsidence creates conditions favourable to the preservation of interglacial deposits with possible archaeological remains over many subsequent glacial–interglacial cycles. In these types of settings, Early Palaeolithic sites can still be discovered today.

Before 500 ka, glaciations were not able to overprint the effects of tectonics and glacio-isostasy on the overall landscape. Various lowland environments aligned to subsidence depocentres and maintained relatively stable positions during the Cromerian Complex Stage between 1 Ma and 500 ka ago (Fig. 1). In highstand interglacial stages, this explains aspects of accumulation and preservation of the Early Palaeolithic record along the North Sea's southern shores (Cohen et al., 2012). In lowstand glacial stages, the strong tectonic control on valley positioning made that major valley diversions were exceptional events. From 500 ka onward, however, the effects of extreme glaciations began to dominate those related to long-term subsidence. Direct and indirect glaciation impacts led to disruption and rerouting of river systems into and within the basin, thus providing strong control of the location of depositional systems, especially during the Anglian and Saalian glacial maxima (Gibbard, 1988; Busschers et al., 2007, 2008; Hijma et al., 2012).

Glacially disturbed valley networks traverse and skim tectonic depocentres and uplifting areas rather than following differential-subsidence-controlled paths. Although the positioning of depositional centres associated with major valleys and river mouths was no longer tectonically controlled, vertical crustal movements continued to control preservation. The resulting record consists of buried deposits in areas of subsidence (e.g. Busschers et al., 2007) and preserved terraces along the basin rim, where uplift made interfluve areas out of former valley floors (e.g. Boenigk & Frechen, 2006). These contain Palaeolithic records, which require comparison and correlation to independently dated coastal and offshore sites (e.g. Parfitt et al., 2005, 2010; Preece & Parfitt, 2012) to develop and test theories on migration patterns, habitat tracking and palaeohuman evolution (e.g. Hopkinson, 2007; Hublin, 2009; Cohen et al., 2012).

Regional stratigraphic frameworks

Chronostratigraphic division schemes

Seventeen major phases of alternating cold and temperate climate have been recognised in the terrestrial and shallow-marine record of the North Sea basin. Not all of them can be linked to a single MIS (Fig. 1; NW European Stages). Most glacials and interglacials are marked by multiple climate-driven phases of shorter duration (e.g. Lowe et al., 2008): relatively cold stadials and relatively warm interstadials. The Greenland ice-core record of the Late Pleistocene corroborates the subdivision made on the basis of the oceanic sediment-based isotopic record. The Greenland ice core also shows sub-Milankovitch oscillations that were relatively strong in amplitude and rather quick in alternation: several degrees of abrupt warming followed by slow cooling, over periods spanning between 500 and 2000 years (e.g. Lowe et al., 2008).

The last two glacials (Britain: the Wolstonian 'Tottenhill' substage and the Devensian; the Netherlands and Germany: the Saalian Drenthe substage and the Weichselian; southern North Sea: Saalian Drenthe substage, Last Glacial; Fig. 1) are most easily linked to the MIS record and correlated between sub-regions. For glacials and interglacials before (Britain: during the Anglian and Early Wolstonian; the Netherlands: Elsterian and Early Saalian; southern North Sea: Anglian and Early Saalian) linkage has been less easy. Linkage relies on stratigraphical reasoning, which combines arguments of biostratigraphic correlation with lithostratigraphic tracing, and aims to correlate records in the North Sea towards sites with

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numerical age constraints (e.g. Litt, 2007; but sites with direct dating evidence are sparse) and to sites that directly recorded marine oxygen isotope signals (e.g. Toucanne et al., 2009; but this requires tracing of signal over relatively long distances).

In the stratigraphical framework, the northwest European Holsteinian interglacial stage may be associated with either MIS 9 or MIS 11, whereas the British equivalent, the Hoxnian, correlates to a part of MIS 11 (most likely MIS 11c). The pollen-based palynological signals in deposits of these two interglacials are very similar in the North Sea region, which hinders stratigraphical correlations based on that type of information alone. This includes correlation to glacial–interglacial sequences in the Netherlands and the Lower Rhine Embayment (e.g. Zagwijn & van Staalduijnen, 1975; Kukla, 1978) and North Germany (e.g. Geyh & Müller, 2005), tracing of glaciogenic sedimentary signals to the shelf and deep-sea record of the coast of Norway and Scotland (e.g. Sejrup et al., 2009), and proglacial tracing of sedimentary signals to the shelf and deep-sea record of the English Channel and the Western Approaches (Toucanne et al., 2009). Subglacially produced tills in the North Sea basin can also be tied to sequences of terraced river deposits that show mineralogical changes through time, induced by river course changes, and include several dated marker beds left by volcanic events (Boenigk & Frechen, 2006). Figure 1 contains our currently preferred correlations, but several issues remain unresolved, in part because direct dating evidence is sparse. This sparseness complicates open archaeological questions on the timing and nature of Lower to Middle Palaeolithic behavioural and evolutionary changes (Hopkinson, 2007).

On a different level, but equally uncertain, are the precise timing of the onset of the last interglacial and its duration, as registered in pollen records across terrestrial Europe. The broad correlation of the Eemian/Ipswichian to the beginning of MIS 5 (substage MIS-5e) is universally accepted (Fig. 1). The precise onset of the Eemian (base of pollenzone E1), however, somewhat lagged the start of MIS 5 (mid-point Termination II, Fig. 1) and may be diachronic across Atlantic Europe (e.g. Sánchez-Goñi et al., 1999; Sier et al., 2011). The timing of *regional* maximum transgression of the North Sea also lags behind that of the *global* eustatic sea-level curve owing to glacio-isostatic adjustments in the periphery of the Scandinavian-British ice sheet (e.g. Lambeck et al., 2006) and to North Atlantic ocean-siphoning effects (e.g. Mitrovica & Milne, 2002). By influencing the regional climate, Late Saalian and Eemian regional developments in Greenland and the North Atlantic presumably delayed the interglacial climatic optimum relative to the global average signal, following similar mechanisms as in the Holocene (Renssen et al., 2012), by at least the amount of lag time observed for the Holocene (2000 years), and given the instability of the Eemian Greenland ice sheet (NEEM community members, 2013) potentially longer. This will have controlled the regional vegetational development of the study area, used as a means of time control, stage-wise *within* the Eemian (e.g. pollenzones E1 to E6). The timing of the transgression further affected the regional climatic gradients and the distributions of sedimentary environments, in ways similar to those seen during the Holocene. The question is how the yet unknown lengths of regional climate-change and transgression delays (i.e. the degree to which these differed for the Eemian relative to the Holocene) propagate into and complicate palaeogeographical intercomparison of the last interglacial and the Holocene for the North Sea region. The simple approach has been to portray the Eemian as a clone of the Holocene. If both the climatic and the transgressive transitions in the Eemian of northwestern Europe occurred longer after the globally recognised beginning of the last interglacial (Termination II in Fig. 1) than their equivalent transitions did in the Holocene (following Termination I), this would be hard to identify in the current record because of numeric dating accuracy. Yet our current global climate-system understanding does predict this to be the case (text and references above). Uncertainty in the timing of climate change and transgression propagates to studies of Neanderthal habitat tracking and migration pathways in the North Sea basin, and between mainland Europe and Britain. It sets palaeogeographical reconstruction challenges that exceed the resolution that the currently established chronostratigraphical approaches (i.e. Fig. 1) can provide.

Lithostratigraphic division schemes

In the past decade, the various (national) lithostratigraphic subdivision schemes for the southern North Sea basin and its surrounding countries have been modified considerably (e.g. Doppert et al., 1975; van Adrichem Boogaert & Kouwe, 1993; Bowen, 1999; Gullentops et al., 2001; Laga et al., 2001; McMillan, 2002, 2005; Ebbing et al., 2003; Westerhoff et al., 2003; Rijsdijk et al., 2005; Weerts et al., 2005). Differences between these schemes exist for various reasons.

First, onshore lithostratigraphic systems are difficult to correlate with offshore seismostratigraphic units. Second, the politico-geographical division of the North Sea continental shelf is a complicating factor. Even the originally common scheme developed by the British, Belgian, Dutch, German and Danish geological surveys while jointly mapping the North Sea has been abandoned by some partners. Third, researchers have worked with and have chosen to formalise division schemes on different scales, which is understandable given the differences in geological setting. Many deposits that rank as 'Formations' in the British system, for example, equate to 'Members' in the Dutch system (Westerhoff et al., 2003), and also between onshore and offshore schemes different hierarchical slotting decisions are made. Quite a few of these lithostratigraphic units are specifically associated with remnants of various landscapes formed at different times. Seismo-lithostratigraphic 'Formations' recognised offshore, on the other hand, are particularly inclusive. They match the

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scale of onshore Dutch 'Formations' and 'Subgroups' and onshore British 'Subgroups' and 'Groups'.

A final reason for regional differences in schemes and for correlation problems between onshore and offshore litho- (seismo-) stratigraphic units applies only to deposits in the older part of the Quaternary. There is a loss of discriminating lithological detail when units are traced from the basin margin (river valley) to the basin centre (alternating submerged shallow-marine environments and emerged fluvial plains) because the deposits of multiple sources become increasingly mixed and consequently lose many of their unique provenance-indicative fingerprints. The higher rates of subsidence near the basin depocentre increase the chance that multiple erosional levels are preserved. Towards the basin margins, recycling is increasingly severe, with fewer and fewer recycling episodes being preserved in separate layers. In areas with little or no net deposition, an amalgamated record of multiple recycling events is commonly all that remains, making it difficult to reconstruct palaeogeography.

Landforms and other morpho-sedimentary features

For a thorough understanding of human presence in relation to palaeolandscapes, the various preserved and buried landforms from glacial and interglacial times must be considered in light of their overall palaeogeographical settings. For Palaeolithic and Mesolithic archaeology and palaeogeography, periglacial and interglacial features are the most relevant because they are the most likely to hold archaeological content. Full glacial environments are mainly important as basin-wide markers bounding intervals and placing constraints on features left during milder stages.

Features from glacial times

The harshest Pleistocene glacials caused erosion and widespread reworking, creating and mobilising sediment. The North Sea area was (partly) covered by land ice for only a brief part of these glacials. For a much larger part of the time, terrestrial 'periglacial' conditions were dominant. Near the depocentre, the glacial depositional record is relatively complete, which is of particular significance to the study of the Early and Middle Palaeolithic.

Sub-glacial landforms: These include depositional ('till sheets') and erosional features (tunnel valleys, tongue basins). The former occupy laterally extensive areas throughout the glaciated region. The latter are elongated and remarkably deep features presumably formed by pressurised, super-cooled sub-glacial flows of water controlled by ice-sheet hydrology (e.g. Moreau et al., 2012). Relatively small-scale tunnel valleys occur on Chalk bedrock of East Anglia (Anglian age; Woodland, 1970) and immediately offshore (Anglian/Wolstonian/Devensian age). Up to seven generations (from up to five glacial cycles, MIS 12 to MIS 4; Stewart & Lonergan, 2011) have been recognised in the North Sea, where they are much larger. The largest of the tunnel valleys (Anglian/Elsterian age) are infilled by glacio-lacustrine sediments that accumulated during deglaciation, and by lacustrine and marine deposits from post-glacial times (Laban, 1995; Lee et al., 2012; Moreau et al., 2012). The valleys are therefore important containers of palaeoenvironmental information. Positive-relief sub-glacial landforms (e.g. eskers), which may have been temporary palaeosurfaces, are relatively rare in the North Sea basin.

Ice-marginal landforms: These features form immediately next to ice margins. They are most strongly developed where land ice reached its maximum extent and near former ice limits associated with temporary re-advances, but occur all over formerly glaciated areas. The distribution of depositional positive-relief features (ice-pushed ridges, deltas, delta-moraines, ice-marginal fans and kames, sandar) – especially where associated with erosional subglacial ice-marginal landforms such as tongue basins (see above) – can be used in reconstructions of past ice-margin changes. Large-scale Saalian morainic and ice-pushed ridges mark terrestrial still-stand positions at several sites across the North Sea basin (e.g. van den Berg & Beets, 1987; Busschers et al., 2008). Where the ice fronts were submerged, sediment-rich meltwater created deltas or fan-like accumulations that form ridge-like delta-moraines where coalesced, such as in the Anglian of Norfolk (Cromer Ridge; Gibbard & van der Vegt, 2012). Depressions created by ice scour tend to occur upstream of ice-pushed constructional landforms. In some aspects they are comparable to the tunnel valleys discussed above, but their relation with surrounding ice-pushed ridge topography signals a different genesis (pushing material towards the sides, e.g. van den Berg & Beets, 1987, rather than eroding it and moving it longitudinally). In the North Sea, most Anglian and Saalian ice-marginal landforms have been eroded by processes associated with deglaciation and periglacial stages, and locally by Devensian ice. The scant and discontinuous morphological evidence for ice-margin positions is a major obstacle in Quaternary palaeogeographical studies of the North Sea area.

Proglacial features: Continental ice sheets have released considerable volumes of meltwater and sediment into the North Sea area. Outwash systems, such as sandar fans and ice-marginal rivers, formed during advance as well as recession. When meltwater could not freely drain, it ponded to form proglacial lakes, in which case the outwash systems developed into fan-deltaic and subaquatic variants. Direct blockage and proglacial ponding also affected rivers that flowed towards the ice front in northerly directions. To the east (e.g. Winsemann et al., 2004) and west (e.g. Gibbard, 1995) of the present-day North Sea, river valleys relatively close to the ice front were temporarily occupied by proglacial or ice-dammed lakes. The largest-scale ponding occurred when Scandinavian and British ice fronts joined and blocked northward meltwater drainage. Allegedly, the largest proglacial lake thus formed occupied much of the southern North Sea basin during part of the

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Anglian/Elsterian Stage (Fig. 4). Its existence and size are primarily inferred from erosional geomorphological evidence, however, and direct evidence in the form of fine-grained lacustrine facies has never been found in the North Sea basin proper. Poor preservation of proglacial sedimentary evidence is a major problem in studies on North Sea glaciations older than 150,000 years. Although it is thought that lakes formed along the ice margin of all the major glaciations, and changed in response to the ice-margin mobility through time, all existing reconstructions are highly speculative (Murton & Murton, 2012).

Preservation of glacio-lacustrine deposits differs strongly for the two end-member types of proglacial lake that exist. Whereas many sub-glacially eroded features contain distal glacio-lacustrine infill (commonly continuing upward into postglacial fill), proglacial lakes from times of maximum glaciation left a predominantly erosional record. Water levels in these latter lakes were unstable because the outlet levels changed continuously following short-lived phases of maximum lake level and extent. Partial lake drainage during ice-margin reconfigurations at maximum glaciation and during initial deglaciation stages reduced water depths and reduced the areal extent of lakes south of the ice front. Where distal lake beds fell dry, newly established fluvial channels caused widespread erosion of the accumulated lake deposits. Former lake shorelines and abandoned lake deltas are heavily dissected, if at all present, and terraces formed during lake stages cannot easily be distinguished from normal fluvial terraces produced in the same river valleys. Sediment provenance in wide river plains and shallow-lake braided-river delta plains is the same, sediment body thickness is very similar and sedimentological structures in part of the deposits may be differentiating, but to prove that demands very detailed study in multiple large outcrops (i.e. monitoring exposures in active quarries over years). Tracing sedimentary units downstream may be a way to distinguish 'continuous' valley trains from 'widening and terminating' delta lobes (Cohen et al., 2005; Busschers et al., 2008), but to do so across the hinge zone means switching from terrace record (dissected exposures) to buried deposits (boreholes), which in the case of the study area are in turn deformed by ice-margin activity (displaced, glacio-tectonised exposures), again complicating matters. The incomplete record

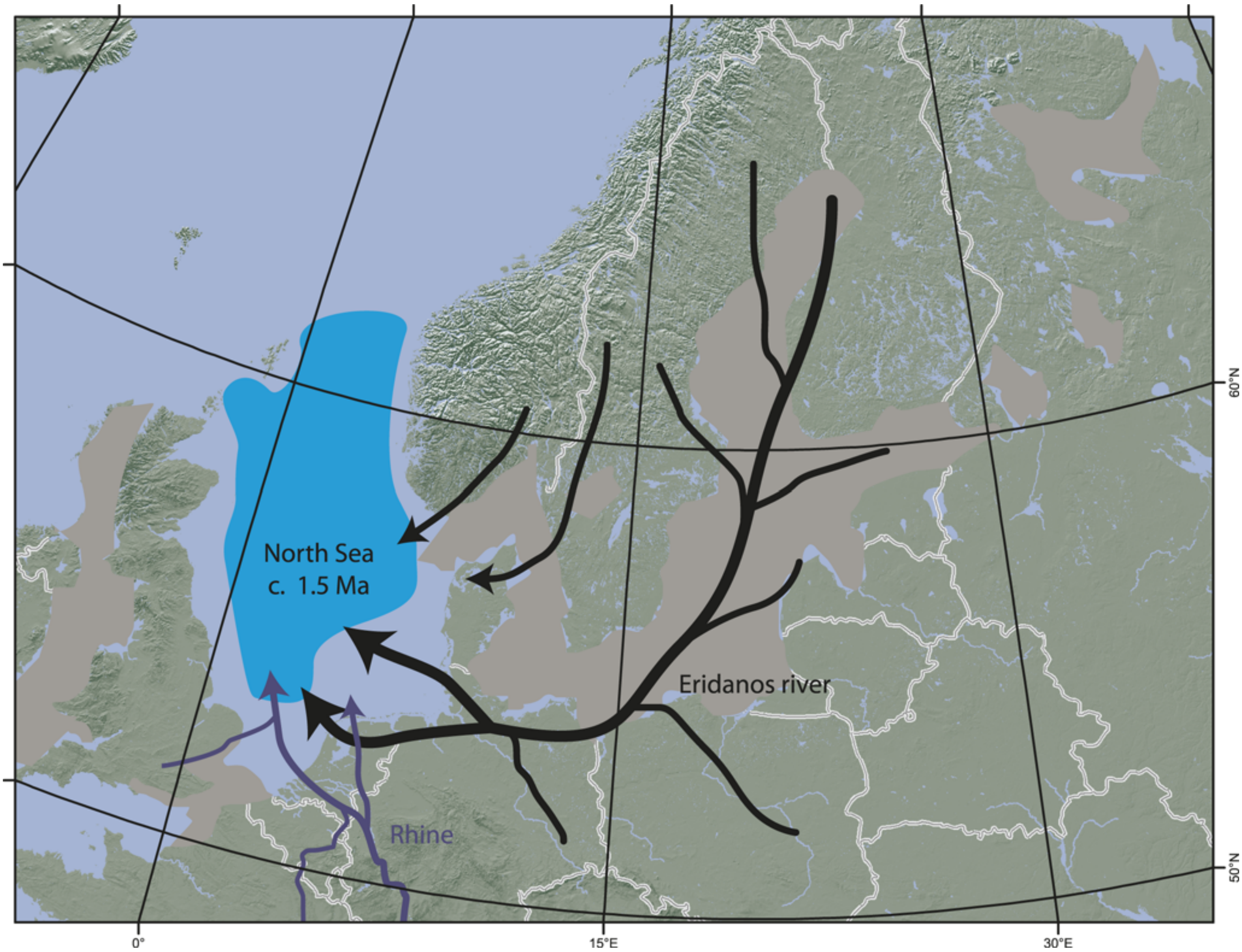

Fig. 4. Drainage basin and delta of the Miocene–Pliocene–Early Pleistocene Eridanos river system (after Overeem et al., 2001). Background map depicts former terrestrial environment in Middle-Pleistocene-glacial excavated areas that are nowadays seas.

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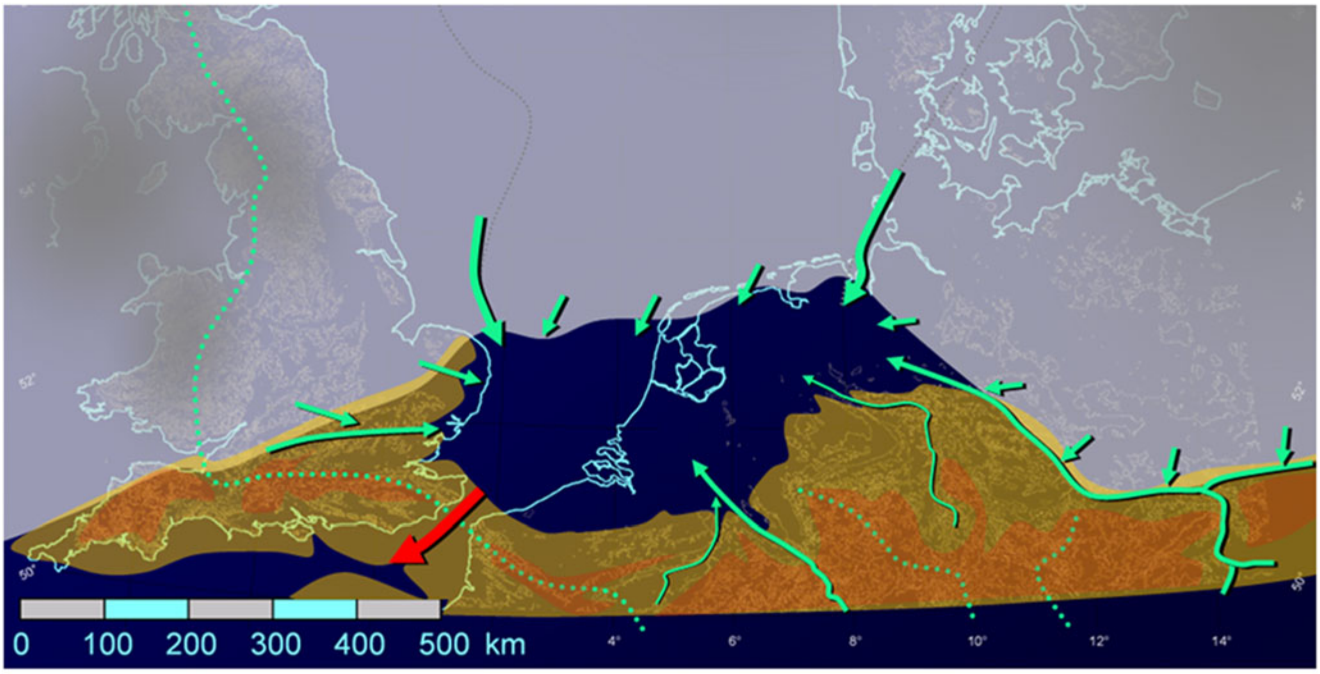
of proglacial features, increasingly fragmentary for older glaciations, thus complicates palaeogeographical reconstructions and has limited reconstructions for, for example, the Anglian to the conceptual level (Fig. 5).

Periglacial river valleys: During lowstands, lakes and rivers occupied the lowest parts of the landscape, and regional groundwater tables in the adjacent lowlands were within a few metres of the surface, well above coeval sea level. The North Sea floor during glaciation maxima was a polar landscape dissected by rivers. Its hydrology was affected not only by precipitation and groundwater flow, but also by permafrost (year-round frozen substrate) development and melt. Abundant mammoth bones and other mammal skeletal remains dredged from the North Sea floor (e.g. van Kolfschoten & Laban, 1995) are evidence of less hostile circumstances and indicate that the most severe polar-desert conditions were relatively short-lived. For much of the periglacial times, the present-day North Sea probably was a dry grassy steppe-tundra, perhaps with patches of boreal forest at times. It is likely that the river valleys were hospitable sanctuaries for herds of mammals during the harshest times, providing drinking water, and being slightly warmer and more fertile than the surrounding upland. Repeated sea-level (base-level) fall during the past 1 Ma is reflected in river incision and in increased denudation of emergent surfaces. Sediment removed from periglacial land areas was deposited in shrinking and expanding marine basins. Close to the coast, valley gradients were gentle, valleys wide and river incision was limited. The dominance of stacked braid-belt architectures throughout the basin, evidence of extensive reworking rather than just incision or aggradation (e.g. Busschers et al., 2007; Hijma & Cohen, 2011), suggests the 'low-shouldered, delta-capped' palaeovalleys and associated *in situ* archaeological remnants to have a relatively high preservation potential, at least below present onshore areas. Offshore along the North Sea's erosive exit route across Southern Bight basin shoulder terrain preservation of the palaeovalley units is far less favourable (e.g. Hijma et al., 2012). In these areas, relatively coarse reworked lag deposits lay at relatively shallow depths below the seafloor, within reach of dredging



"6. One of the principal effects of this great advance and accumulation of ice, not yet taken into consideration by geologists, was an interruption to the drainage of all countries whose rivers flowed northwards. [...] In western Europe this interference with the drainage of the land took place [...]. All the rivers of northern Germany must have been dammed back by the ice descending from the Scandinavian mountains. One of the most important changes was effected in the German Ocean [the North Sea]. Its northern half was filled with ice, from the mountains of Norway and Sweden, from Scotland and northern England. As we know that at this time the Straits of Dover did not exist, it is evident that the southern portion of the bed of the German Ocean must have been filled by a great fresh-water lake, varying in extent during the advance and retreat of the ice, into which flowed all the water of the melting ice, and all the rivers that now run into the same area." Thomas Belt, *Nature*, May 14, 1874, pp 25-26.

Fig. 5. Proglacial lake extent leading to initial breaching of the Strait of Dover, as envisaged for the early stages of maximum Anglian glaciation (from Cohen et al., 2005; Gibbard, 2007). With a quote from Belt (1874).

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(e.g. Hijma et al., 2012), which paradoxically have produced a richer *ex situ* paleontological and Palaeolithic record than better preserved periglacial areas to the north (e.g. Mol et al., 2006). Further west into the southern North Sea, in the hinge zone and outside the North Sea basin, localised palaeovalley infill from British river systems have been encountered below gravel lags from the youngest stages (e.g. Bridgland & D'Olier, 1995), which may well host a complementary record to the bone-gravel-lag from the Lower Rhine in the North Sea.

Periglacial landscapes outside valleys: Permafrost was common in areas exposed to terrestrial processes during low-stand conditions. Seasonal freezing and thawing gave rise to complex suites of depositional and erosional landforms. Typically, the erosional forms reflect the removal of material by wind, water and mass-flow processes, especially where and when vegetation cover was patchy or absent. Frost-dominated processes acted on the different substrates in different ways. Chalk, for example, is susceptible to mass flow and to cold-water dissolution under periglacial conditions. Dry valleys, dolines and solutional pipes are common. Arenaceous Pliocene and Early Pleistocene terrains are prone to deflation. Clayey intercalations are not deflated easily, which in the lowlands of the south-west Netherlands left Early Pleistocene plateaux with a Middle to Late Pleistocene periglacial veneer (Westerhoff et al., 2009). Where undercut by migrating channels in valleys, periglacial freezing cycles and meltwater production on steepened hill slopes promoted mass wasting of the clayey strata. On the depositional side, wind-blown dust (loess) and sand accumulated across extensive regions. In the North Sea basin, sandy aeolian deposits are widespread, derived in part from nearby sources in local periglacial river systems (e.g. van Huissteden et al., 2000). The southern rim of the North Sea basin is the northern edge of the European loess belt. Here, silt is the dominant wind-blown deposit, originating from the fluvial plains of the larger rivers (e.g. Antoine et al., 2003).

The periglacial interfluve landscape provided the initial conditions for soil and hydrological and vegetation and faunal developments each time the climate ameliorated from cold to temperate. There was a direct control on human habitats in terrestrial settings outside deltas and coastal plains (see below). For Palaeolithic and Mesolithic archaeology in and around the North Sea, the periglacial geomorphological activity in the interfluve areas further caused (1) fresh substrate to be exposed at accessible locations along secondary drainage systems (local rivers, brooks, doline lakes, hollows, small caves) and landmark landforms (plateau areas, low cuesta escarpments), and (2) cold-stage aeolian and colluvial cover to be developed over temperate stage surfaces. Typically, the temperate stages inherit the periglacial interfluve drainage networks and substrate exposures. This has enabled humans to trace discoveries of suitable quantities of flint in gravels of active rivers upstream to the substrate source areas where these were entrained from older terrace gravels (coarser grained strata from older terraces) and even to the original bedrock sources itself. Whereas proglacial activity and big river activity have altered the long-distance migration paths of palaeohumans in a progressive way (next section), interfluve activity in equally progressive ways affected resource accessibility around and in the youngest eroded parts of the southern North Sea (Cohen et al., 2012; Hijma et al., 2012). The aeolian and colluvial periglacial cover of temperate surfaces is an important element of the local preservation of archaeology. Progressive changes in the effectiveness of especially aeolian cover (notably in relation to growth of the Channel River) affect site taphonomy and differences therein between upwind England and downwind continental Europe (Hijma et al., 2012). Such differences, however, would hold more strongly for upland areas surrounding the North Sea and the English Channel, than for the buried landscapes below the Southern North Sea floor (that we see as source region for loess predominantly), within the ecotone of habitat availability (Parfitt et al., 2010).

Features from temperate (interglacial) times

After each glaciation, climate amelioration and associated sea-level rise forced significant faunal and vegetation changes, as well as dramatic modification of hydrological regimes. The rising sea transformed large terrestrial areas into open sea and coastal zones. In areas not submerged, depositional styles of river valleys changed, and soil-formation processes intensified. Erosion and reworking were less widespread during interglacials than under periglacial conditions, but few interglacial terrestrial deposits survive in the long term. They are easily and preferentially eroded during subsequent glacials, making interglacial (and interstadial) palaeolandscapes and *in situ* archaeological remnants rare in comparison to their periglacial counterparts, but exceptions exist. Holocene deposits are one such exception, of course, because they are part of a still accumulating interglacial record. Over time scales longer than an interglacial, only the deepest fills of tidal, estuarine and fluvial channels have relatively high preservation potential. This also stretches to buried drowned valleys, of which the relatively early and deepest drowned segments in the highstand coastal zone (Hijma & Cohen, 2011) may have better odds of survival than segments farther inland (e.g. Busschers et al., 2007) and seaward (Hijma et al., 2012). In the southern North Sea, this is of demonstrated relevance for near-coastal Mesolithic site coverage (Weerts et al., 2012; Moree & Sier, 2014) and may also be of relevance in research on Palaeolithic interglacial re-dispersal routes (cf. Cohen et al., 2012).

Interglacial deposits filling glacial-scour features: Interglacial landforms and deposits preserved in deep glacial-scour features, limited to those warm periods that immediately followed the few episodes of glaciation of the North Sea area, tend to be preserved. Where such features host subaquatic deposits that accumulated in metres-deep lake waters, this provides excellent by-proxy records for palaeoenvironmental reconstruction. The deposits have hence

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been targeted in the past by Quaternary stratigraphers and many studied locations have become classic sites (being the namesakes of many of the regional stratigraphic units in Fig. 1). It is unlikely that humans lived in these infilling glacial-scour features. For archaeology the palaeoenvironmental information is of contextual importance only, unless lakeshore deposits have also been preserved. In areas that are initially lake but were later transgressed by the sea, the odds for preservation of deposits from lake shore settings are relatively high. This would hold for most such lakes in the present North Sea region (e.g. Briggs et al., 2007; Murton & Murton, 2012) and could also hold for Eemian equivalent environments at depth below the Holocene coastal plain (e.g. Peeters et al., 2014).

The seafloor: On transgression and inundation by the North Sea, newly submerged areas became subject to tidal currents and to wave action, and were obviously no longer inhabitable palaeolandscapes. Sandy substrates were most easily reworked by currents and waves into bank features (see Cooper et al., 2008 for an overview). Fields of sand waves, ubiquitous in the present-day North Sea, must have been common during each highstand. Sand-wave migration and shoreface erosion left ravinement surfaces, lags of coarse clasts that may include archaeological artefacts and mammal remains. The ravinement surface of the last interglacial is an important stratigraphical marker under the North Sea. Mollusc assemblages of the Holocene, Eemian and older interglacial North Seas differ in composition, aiding their stratigraphical distinction (e.g. Meijer & Preece, 1995; Rijsdijk et al., 2013). For archaeology, it is mostly the degree to which marine ravinement eroded terrestrial palaeosurfaces that matters. Over considerable areas of North Sea floor, the Holocene marine ravinement did erode the inherited Last Glacial periglacial surface and Early Holocene soils within them. There are, however, considerable areas where in the first stages of transgression sedimentation had dominated, and Early Holocene soil and covering peats have been preserved at some depth (typically 1–4 m) below the seafloor. In such areas, the surfaces stand a chance of escaping future marine reworking because the reworking is restricted in depth and only affects the transgressive cover. In these cases it is not the erosion-scarred seafloor that is the drowned landscape, but a more pristine, better protected buried landscape found somewhere below the seafloor (Ward & Larcombe, 2008; Weerts et al., 2012; Moree & Sier, 2014).

Coastal features and the drowned landscape below: In the highly dynamic environments of the coastal zone, preservation of transgressed surfaces is a function of sediment supply at the time of transgression, besides eventual water depth in the subsequent highstand stage. This appears to hold both for sand-dominated systems such as the Holland Barrier coast (Beets & van der Spek, 2000) and for extensive mixed-load river mouth areas that indent, underlay and dissect it, where the lowstand surface was covered with fines as part of the transgressive developments (Hijma & Cohen, 2011). The modern Dutch barrier coast, formed from the Middle Holocene onward, owes its position and width in part to the abundance of fluvial Pleistocene sand reworked shoreward from the low-gradient offshore North Sea floor. Near the coastline, erosion was partly a function of the shoreface and nearshore gradient. Steep gradients render a coast vulnerable to wave attack and destruction of palaeosurfaces.

The present North Sea coast of East Anglia down to the Thames Estuary, with its cliffs, bluffs and estuaries that originated from drowned valleys, differs from that of Flanders, Holland, the Wadden Islands and large parts of the German Bight. From northwest France to Denmark, the coast of mainland Europe is fringed by a series of sandy barriers that protect muddy back-barrier lagoons, swampy deltas, tidal inlets and estuaries resulting from marine incursions. However, the Weser and Elbe estuaries can be viewed as estuaries in drowned (Pleistocene) valleys. These latter estuaries formed in deeply incised valleys in the Saalian till.

Large parts of the lowland on the continental European side of the North Sea contain remnants of former back-barrier coastal landscapes (tidal basin, lagoon, marsh and peatland). The Pleistocene substrate of the western and northern Netherlands shows the marks of a tidally modified fluvial palaeolandscape that extends far, but discontinuously, below the North Sea, all the way to the Dogger Bank (Fig. 2; Gaffney et al., 2007). Although coastal processes such as shoreface erosion and tidal-inlet scouring have modified the drowned fluvial palaeolandscape, large-scale palaeosurface patterns have survived in many places. The inherited Pleistocene morphology has influenced the development and spatial distribution of archaeologically relevant coastal features such as barriers, beach plains and river outlets. All rivers in the North Sea area have been strongly affected by Holocene sea-level rise. It changed patterns of fluvial sedimentation up to c. 150 km from the coast in the low-gradient bigger rivers, played a role in the formation and demise of distributaries (and thus sediment delivery to the coast; Beets & van de Spek, 2000; Berendsen & Stouthamer, 2000; Hijma & Cohen, 2012), and governed peat formation in active and abandoned alluvial plains (and thus accommodation and preservation of palaeosurfaces and sedimentary layers including any contained archaeology and palaeoenvironmental information; Cohen, 2005; Gouw & Erkens, 2007). This also took place in earlier interglacials (e.g. Busschers et al., 2007).

Estuaries and tidal inlets can scour to depths many tens of metres below sea level. Estuaries and tidal inlets along the modern Netherlands coast in their present form result from Medieval storm surges, and many do not have a strong valley-inherited morphology. Most of them have very limited direct spatial relations with equivalent palaeoenvironments from older stages. Unlike these modern features, Early to Middle Holocene estuaries did occupy valley-inherited positions (e.g. Beets & van der Spek, 2000; Vos et al., 2011; Hijma & Cohen, 2011), and these environments contain the

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mesolithic wetland archaeological record (Verhart, 1988; Weerts et al., 2012; Moree & Sier, 2014). In the later Holocene, however, deltaic avulsions have successively shifted river-mouth positions (Berendsen & Stouthamer, 2000), at first away from inherited positions and in some cases returning later on.

As on the Belgian–Netherlands side, the deepest parts of English fills have the best chance of survival. Preserved bases of older generations of estuarine and inlet fills provide palaeogeographically relevant information, and may hold archaeological and palaeontological material. In the Southern Bight, the estuaries along the Essex coast are of a different nature to those on the Flemish–Dutch side. The British estuaries have transformed from valley into estuary, and back, several times over multiple glacial–interglacial cycles. In the absence of major subsidence, sediments of older stages have been preserved as terraces along the valley margins (e.g. Roe & Preece, 2011). Estuaries are amongst the richest coastal habitats in terms of readily available nutrition and palaeohumans may well have exploited them since relatively early in their evolutionary history (Cohen et al., 2012, and sources therein).

On the British side of the North Sea, coasts with cliff and bluff erosion that irreversibly exposes older strata are common. Their formation is driven by storm-related wave action and by precipitation-related destabilisation of rock or sediment. Palaeo-cliff lines (currently submerged as well as inland) indicate that final highstand features may survive during subsequent glacials. They are excellent palaeo-coastline indicators. Cliff-line retreat during interglacial highstands (lasting some 10,000 years on average) was several kilometres, judging from present retreat rates. Rates differ with the cliff's geological composition (Weald–Artois: chalk; East Anglia: till) and exposure to waves. The higher parts of these cliffs are also denuded under periglacial circumstances, while colluvium accumulates at their base. The repeated alternation of marine and periglacial conditions may have promoted long-term cliff retreat. In the depocentre part of the North Sea therefore, palaeocliffs should not be expected to be a common feature. In the Southern Bight, former cliff lines can be projected seaward from the present position and possibly explain concentrations of finds from within the marine ravinement bed. Where cliff retreat exposes older interglacial strata, potentially archaeologically relevant units and palaeosurfaces become newly exposed (e.g. East Anglia; Parfitt et al., 2010). Where palaeo-cliff lines formed in flint-containing material, they are archeologically relevant from a natural-resource perspective (e.g. southern England; Bates et al., 1997).

Inland interglacial features: During temperate periods, the landscape of western Europe was characterised by the establishment of a dense broad-leaf forest that colonised interfluve and valley areas alike (e.g. West, 1989, 1996). The biodiversity of both fauna and flora increased markedly during each phase of climate amelioration. Interglacial mammalian assemblages typically included a wide range of taxa, many of which are now associated with warmer regions. Abundant remains of beaver, aurochs, deer, elephant, bear, rhinoceros, hyena and lion have been found in units from different interglacials (e.g. Schreve, 2001; Schreve & Bridgland, 2002). Preserved records of small rodents and freshwater molluscs are useful in providing time frames for these units, also in fluvially and marine reworked contexts (e.g. Mayhew et al., 2014). The bones of birds, fish and amphibians are important palaeoenvironmental indicators too (e.g. Joordens et al., 2009; Finlayson et al., 2011). Representatives of the genus *Homo* were widespread throughout the region during several warmer phases. In addition to the biota, preserved forest-type palaeosols and remnants of peat blankets are diagnostic of interglacial conditions (e.g. Zagwijn, 1996; Stremme, 1998; Turner, 2000). They reflect inland palaeolandscapes that were remarkably stable. The interglacial land surface was either cloaked in dense vegetation on rich forest soils or covered by peat blankets in areas with poor drainage, generally preventing soil erosion and slope instability. Flood response in rivers was mitigated because precipitation was trapped rather than discharged directly in the form of runoff. Most rivers occupied stable channels between wooded floodplains, flooded only following snowmelt and rain storms in the hinterland (e.g. Busschers et al., 2007; Lewin & Gibbard, 2010; Peeters et al., 2014).

Periods of stability, marking the warmest parts of interglacials, were preceded and followed by phases of steady change, related to climate amelioration and deterioration. Records of regional vegetation succession and accompanying faunal colonisation and decolonisation form some of the clearest evidence of changing palaeolandscape dynamics. The permanent loss of some taxa and the arrival of new forms has been used as an effective means of discriminating between past interglacials. As man is a terrestrial species, all these inland matters affected archaeology in numerous ways while the rivers were creating their sedimentary record (syn-depositional, short-term preservation; cf. Cohen et al., 2012). For long-term preservation, it then matters what marine drowning and glaciation have done to the fluvial deposits (post-depositional, long-term preservation), which has been reviewed above.

Long-term developments

With every climate cycle, similar glacial and interglacial depositional environments, hydrological conditions and regional vegetation patterns returned. The distribution of these environments, conditions and patterns differed strongly between succeeding cycles, however, reflecting major long-term changes in drainage configuration and overall palaeogeography. Unlike Quaternary climate, sea-level change and vegetation history, landscape evolution has been far from cyclic. This is particularly true for the North Sea basin during the last 1 Ma. Before that time, the alternating landscape patterns between successive lowstands and highstands showed dynamic equilibrium, with main river systems and coastlines occupying very similar positions in equivalent phases

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of different glacial cycles (e.g. Westerhoff et al., 2009). Since 1 Ma, repeated glaciations have altered the landscape step by step, diverting rivers, rerouting sediment and forcing coastline reconfiguration. Negatively put, this means that modern drainage, topography and bathymetry in the North Sea basin are hardly indicative for valley positions and landscape structures older than c. 150,000 years. Positively, it means that virtually every location within the North Sea basin has seen valley–floodplain systems functioning, reworking and depositing for part of the time between 1 Ma and 150 ka, creating a patchy and discontinuous record in space that covers time intervals relatively evenly.

Critical tipping points in the development of the North Sea landscape were exceeded when Anglian and Saalian ice sheets reached their maximum extents. Many large-scale changes were irreversible, forcing a progressive development. Each substantial glaciation since the Middle Pleistocene has induced further drainage diversion and catastrophic erosion-related landscape changes. The North Sea examples below show that whereas the Quaternary climate, sea-level and vegetation history is cyclic, landscape evolution is far from cyclic. Progressive, irreversible changes occurred not just in the North Sea area, but hold for the full margins of terrestrial maximum-glaciation ice sheets across Europe (e.g. Fig. 4): the Irish Sea, the British Midlands, northern Germany and the peri-Baltic region.

Loss of the Eridanos river system

A major Middle-Pleistocene development in the North Sea area was the demise of the large Eridanos river system (Fig. 4). The Eridanos system existed in the Miocene, Pliocene and Early Pleistocene. Its drainage basin extended as far east as the modern Baltic Sea and Finland, into the headlands of the large Russian rivers Volga and Dnieper today. Increasingly severe glacial minima following the Mid-Pleistocene climatic transition, associated with progressively more extensive glaciations, brought about major changes in these upstream parts of the Eridanos tributary network. Erratic Scandinavian gravel first arrived late in the Early Pleistocene (Doppert et al. 1975; Bijlsma, 1981; Gibbard, 1988), not long before most source areas were lost, strongly reducing northern fluvial sediment supply to the North Sea area.

From then on, northern Germany was occupied by ice-marginal river systems each time the Baltic Sea area was covered by ice, delivering smaller but still considerable amounts of sediment to the southern North Sea basin. During interglacials and glacials with relatively minor glaciation, however, the North Sea no longer received major fluxes of sediment from easterly sources. The reduction in sediment supply had a significant long-term impact on the central North Sea area. By c. 1 Ma, Eridanos sediment had filled sizable parts of the available accommodation space and successive highstand coastlines were located far seaward of today's Wadden Islands (Overeem et al., 2001). After 1 Ma, a growing sediment deficit moved the highstand coastline south and east, increasingly close to its present-day position. Zagwijn (1974, 1979) dubbed this highstand situation 'Ur-Frisia'. It is synchronous to the 'Costa del Cromer' dubbed-situation (Roebroeks, 2005) of the earliest known human presence in the area.

In the south of the former Eridanos depocentre, the loss of northern and eastern sediment supply was compensated by enhanced sediment influx from the Rhine, which transported ever more and coarser sand and gravel liberated from central Europe during increasingly severe glaciations. The Rhine supplied enough material to balance subsidence and to create a delta plain in the western Netherlands depocentre during every interglacial of the last 1 Ma, not unlike what happened in the preceding 1 Ma. Meanwhile, the Rhine was relocating its centre of deposition from a western position in the present North Sea towards the northwest Netherlands. Halfway through the Middle Pleistocene, it had completely avulsed to the northern Netherlands (Busschers et al., 2008).

The loss of the Eridanos sediment source mattered for coastal configurations of the northern Netherlands region and adjacent areas, especially in the Cromerian Complex Stage (roughly 1 Ma to 0.5 Ma). These coastal configurations changed at the time of the oldest known interglacial coastal presence of Palaeolithic humans along the southern North Sea rim. Highstand coastlines were located farther north and west from the present-day coastline early in the Cromerian Complex than towards the end of it (Zagwijn, 1974). On the English side of the North Sea, where the oldest European Palaeolithic sites have been found (Parfitt et al., 2010), the reverse is true. Up to the Anglian glaciation, the coastal plain of East Anglia returned to more or less the same position during every interglacial cycle within the Cromerian Complex (Cohen et al., 2012).

Creation of the Dover Strait drainage outlet

High-resolution bathymetric data have spawned renewed interest in the genesis of shelf-valley systems in the English Channel and in the origin of the Dover Strait (e.g. Gupta et al., 2007; Gibbard, 2007; Mellett et al., 2013). Spillage of vast volumes of accumulated meltwater from proglacial lakes carved out the later sea strait and left the enigmatic scars still visible on the English Channel floor today (Belt, 1874; Gibbard, 1988). It induced severe proglacial erosion and meant that the Channel River (Fleuve Manche), the shelf region of the Western Approaches and the abyssal fans below it were fed more water and sediment than before (e.g. Toucanne et al., 2009). Following the opening of the Strait of Dover, the area between southwest Britain and mainland Europe stopped delivering sediment to the North Sea depocentre, at least during lowstands. The present-day shallow-marine and coastal regimes in the Southern Bight, with cliffs, estuaries, ravinement surfaces and other features (see the section on features from temperate (interglacial) times above), owe their existence to the (pro)glacial erosion triggering the opening of the Dover Strait.

Although theories on the timing and pacing of the opening of the Strait still have to be substantiated by other than erosional geomorphological evidence, the hypothesis that this started in the Anglian and is related to massive spillage of proglacial water from the North Sea Basin towards the south (Gibbard, 1988, 1995) has far-reaching bearings on northwest Europe's Middle and Late-Pleistocene archaeological record and on the history of man as inferred from it. These bearings are not found as much in the would-be catastrophic events, which are attributed a key role in the formation of the Strait of Dover in some versions of the hypothesis (e.g. Gupta et al., 2007), and neither are they found in the interpretation that it must all have happened during a specific single glaciation (e.g. Belt, 1874), or must have happened as a stepwise process spread over more than one glaciation (Busschers et al., 2008; Hijma et al., 2012). Rather, they come from the simple concept (*not* hypothesis) that terrestrial upland in the Strait of Dover and Southern Bight disappeared in the Middle Pleistocene and was replaced by a new exit route for river waters and entrance route for marine waters into this region outside the North Sea Basin proper (i.e. an open Strait of Dover).

As it stands, it appears that the Dover Strait became the permanent fluvial exit route for the Thames much earlier in the Middle Pleistocene than for the Rhine, and that marine exchange between the English Channel and the North Sea was strong in the Eemian, and much smaller or absent in the preceding interglacials (Meijer & Preece, 1995; Hijma et al., 2012). As this appears to have happened 'halfway' through the period of Palaeolithic occupancy in the North Sea region, it not only affects distribution of coastal archaeology from during the younger half of the archaeological record, but also comparison of sites and distribution across the period. Understanding the palaeogeographical change is vital in separating human-evolutionary from landscape-related aspects in the routes of re-dispersal between successive temperate intervals and overall distribution of palaeo-humans (Hijma et al., 2012). Timing the palaeogeographical change is vital to understanding whether behavioural changes as inferred from archaeological records occurred independently from the large-scale landscape changes or not (e.g. Cohen et al., 2012). Importantly, further carving and deepening of the opened Dover Strait continued in the last glacial (Antoine et al., 2003; Hijma et al., 2012; Mellett et al., 2013; Rijsdijk et al., 2013), at the time of Neanderthal presence in the region (Hublin et al., 2009). From that time onwards there is a noticeable increase in aeolian deposition and loess-related archaeology from the grown, permanent Channel River (see the section on features from glacial times above).

Shifting interglacial coastlines

Coastal processes in younger glacial–interglacial cycles were strongly influenced by the footprint of glaciations of the North Sea basin itself, and by extra-basinal developments related to the opening of the Dover Strait and the shifting of Rhine depocentres after the loss of the Eridanos. First, glaciations accentuated the topography that would later be inundated by postglacial transgressive seas. Regional and local highs, for example, were future coastal headlands, and glacial basins transformed into embayments. On a larger scale, the scouring in the Strait of Dover area, and the subsequent establishment of river valleys extending into the English Channel, brought extra transgressive pathways and altered the tidal circulation and amplification patterns during highstands (Uehara et al., 2006; Smith et al., 2011). Whilst all river mouths and coasts were transgressed 'from the north' before these changes, southern river systems in youngest cycles were transgressed 'from the south', through the Strait of Dover. Along coastal re-dispersal routes, migration of groups of palaeohumans will have changed in response to these palaeogeographical changes (Cohen et al., 2012).

Accurate reconstruction of interglacial coastlines during transgression, highstand and sea-level fall is difficult. For rapid transgressions, typical of early deglaciation phases, coastline positions can be regarded as the intersection of reconstructed water-level and basin-floor topography. Complications related to river-mouth configuration and coastal sedimentation are then ignored. For highstands, the volume and distribution of sediment that is mobilised and transported towards the coastal zone (from onshore and offshore) and the duration of the highstand are major factors determining the coastal configuration. Great volumes of sediment have been transported toward coasts and into estuaries along partly unknown sediment-transport pathways generated by cross-shore (storm) wave fields and longshore and cross-shore tidal currents. Much of the sediment was derived from the seabed (i.e. inherited lowstand glacial, fluvioglacial and periglacial sediment; see the section on landforms and other morpho-sedimentary features above) and from eroding headlands, but additional material was provided from onshore sources by rivers.

In the tectonically subsiding parts of the North Sea area, ice-marginal headlands have played a prominent and recurrent role in controlling the position of successive highstand barrier systems. The promontory related to the overridden ice-marginal feature between Texel (in the northwest Netherlands) and the Dogger Bank was present in the Eemian as well as the Holocene. The ice-marginal structure forms the shallowest area of the North Sea between mainland Europe and Britain, and must have been a land bridge in latest Saalian (c. 130,000 years ago) and Lateglacial/earliest Holocene times (up to c. 9000 years ago), as rising sea level drowned the continent. During lowstands, it was the divide between 'Rhine/Meuse' and 'Elbe/Weser' drainage. The modern, slightly concave coastline of the western Netherlands is the result of progressive promontory erosion in the last interglacial and the Holocene, combined with complete infilling of embayments with peat and remobilised clastic sediment during the Eemian (marginal marine), Weichselian (falling-stage deltaic) and Holocene (marginal marine). Promontory erosion was interrupted during the last lowstand,

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but major remobilisation of sand by periglacial fluvial and polar-desert (aeolian) processes had its own indirect effect on Holocene barrier formation, explaining part of the differences between Eemian and Holocene coastal configurations. Clearly, inherited topography is in fact quite short-lived as the dominant control on transgressive coasts. Sediment supply and redistribution are the main controls during highstands and falling base level. In the basin, the control of sedimentary activity is helped by background tectonic subsidence, which makes promontories sink and stimulates new deposition. For coastal areas to the south of the North Sea depocentre (notably in southeast England and Flanders), topographic inheritance has been the main control during transgressions and highstands, and fluvial erosion the main control during lowstands. In this part of the study area, highstand coastal configurations show ever deeper estuaries and increased inland tidal reach. The positions of most valleys (estuaries when drowned), however, has remained unchanged from one interglacial to the next.

Palaeogeographical mapping at different resolutions

Three palaeogeographical reconstructions for the southern North Sea (Middle Pleistocene, Hijma et al., 2012; Late Pleistocene, Lambeck et al., 2006; Holocene, Vos & de Vries, 2013) show how an increasingly incomplete record going back in time reduces the maximum spatial resolution possible. The same is true for the temporal resolution (amount of time in between, or time interval represented by, reconstructions). Datable material becomes increasingly sparse in older units, and techniques for independent dating of terrestrial deposits older than c. 30,000 years have generally not been available. All palaeogeographical maps also have to overcome the problem of missing records, requiring interpolation and thus introducing uncertainty.

Reconstructions for the Middle Pleistocene (Fig. 6) provide overviews of landscape changes at a basin scale and over hundreds of thousands of years. They visualise long-term progressive palaeogeographical developments rather than detailed changes through time, which cannot be resolved with the data and methods available. The maps show the contrast between typical interglacial palaeogeography at the time of earliest Palaeolithic hominin presence in the North Sea area, before 500 ka, and typical interglacial palaeotopography after 500 ka (Peeters et al., 2009; Hijma et al., 2012). They are based on geological and geomorphological maps made for different purposes, and on state-of-the-art topographical and bathymetric datasets. Even though glacial periods are not visualised here, their inferred effects were used to reconstruct and explain the differences in successive interglacial configurations.

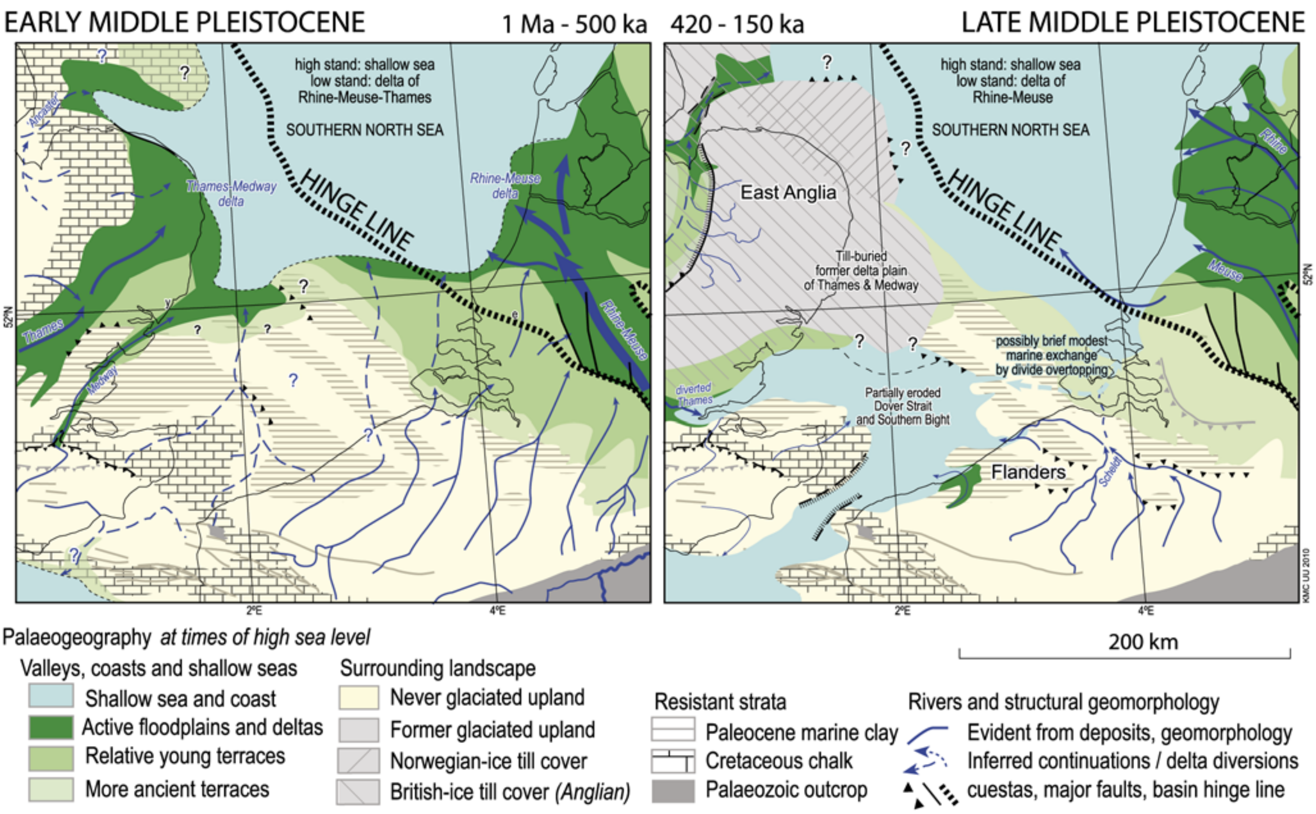

Fig. 6. Example palaeogeographical scenario maps for the Middle Pleistocene. A) interglacial highstands of the Cromerian Complex Stage; B) interglacial highstands from between the Anglian (Britain) and Saalian (continental Europe) stage main glaciations (from Hijma et al., 2012; after earlier versions contributed to the NSPRMF, Peeters et al., 2009).

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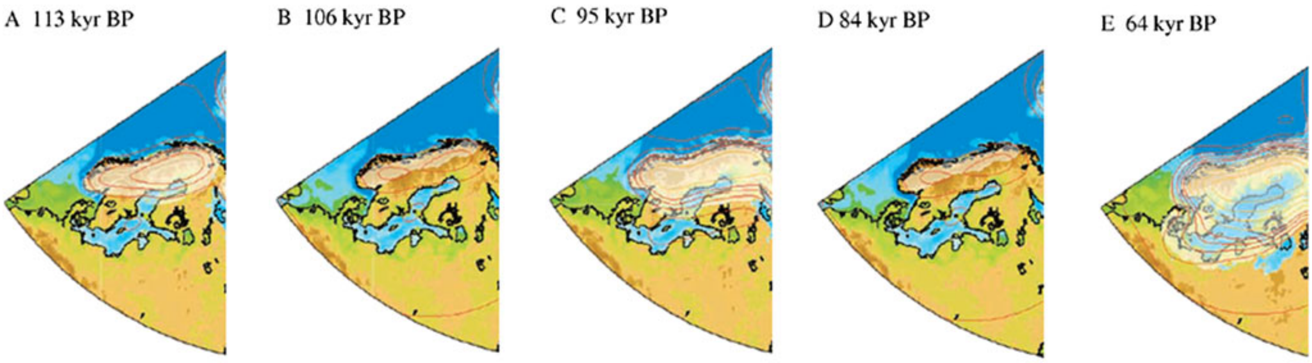

Fig. 7. Example palaeogeographical map series for the Late Pleistocene: output of GIA modelling (from Lambeck et al., 2006; the original output also covers Russia).

In the so-called 'scenario maps' for different sets of interglacials there is considerable uncertainty about the precise positions of primary features such as coastlines and drainage divides. Two types of uncertainty are in play. Most depositional features can easily be linked to past palaeolandscapes, and the uncertainty is mainly related to age attribution. As new dating evidence becomes available, a feature may appear in a reconstruction for a preceding or subsequent period. Where erosion has removed parts of the landscape record, geomorphological reasoning is needed. Process-attribution uncertainty, the main obstacle in reconstructing erosion, is the other type. It is caused by poor knowledge of the rates and magnitudes at which erosional processes have operated in the past, especially the processes in the glacial periods that are skipped in the visualisations. Simply doing more mapping and more dating cannot overcome this as one cannot sample what is gone. When combined with geomorphological modelling, provenancing palaeo-sediment fluxes, and comparison of eroded and received volumes along the chain of source and sink areas involved, it might yield the necessary constraining information on magnitudes and rates.

The example reconstructions for the Late Pleistocene (Lambeck et al., 2006; Fig. 7) concern visualisations of GIA modelling output. Many more papers with such GIA-modelling generated reconstructions exist, especially for the post-LGM time frame (e.g. Sturt et al., 2013, for the study area). This displays the fast developments and considerable improvements on the numeric geophysical solutions and sea-level calibration aspects of the GIA modelling. Development and improvement on the palaeotopography, bathymetry and landscape-reconstruction aspect in the modelling appear to be slower. GIA modelling output provides an overview of landscape change over tens of thousands of years, and typical published output focuses on shifting land–ice and land–sea boundaries. The models use ice-limit reconstructions for successive stages of glaciation and deglaciation to geographically position and constrain nearby ice masses, and they are useful in reconstructing past coastlines. The models calibrate palaeo-sea levels and vertical land movements to regional datasets of sea-level index points (and similar data for ice-lake levels). Palaeocoastlines are calculated from the intersection of reconstructed relative sea levels and present-day land and seabed elevation. Erosion- and sedimentation-related changes in this elevation are not accounted for, producing artefacts in maps. The Dogger Bank hill (cf. Gaffney et al., 2007), an ice-marginal feature formed during the Last Glacial (e.g. Laban, 1995), appears as an island in reconstructions for the last interglacial (e.g. Fig. 7), which *preceded* the Last Glacial and the creation of the hills. Similarly, Late-Holocene coastal barriers feature as ridges in most reconstructions for *early* Holocene landscapes and coast lines (e.g. Lambeck, 1995; Sturt et al., 2013). Deployed to the scale of our study area, typical GIA-modelling data need to be supplemented with reconstructed digital topography for past situations ('palaeo-DEMs'), if they are to produce accurate coastline configurations.

Reconstructions for the Holocene provide an overview of the landscape over thousands of years, typically at time steps of 500–1000 years (e.g. Berendsen & Stouthamer, 2000; Hijma & Cohen, 2011; Vos et al., 2011). The example in Fig. 8 is taken from a series of palaeogeographical maps (Vos & de Vries, 2013) showing landscape changes driven by coastal-marine and fluvial sedimentary processes, climate change, hydrological conditions and vegetation (swamps and bogs), with an increasing influence of humans. As for the example for the Middle Pleistocene, these Holocene reconstructions are a product of data synthesis and integration 'in the palaeogeographer's mind'. From the GIA modelling, the Holocene reconstructions have taken over the notion of the differences in palaeo-coastline *depth* between southern and northern parts of the study area (Lambeck, 1995; Kiden et al., 2002; Vink et al., 2007; Sturt et al., 2013). They have not taken over the by-product coastline positions that GIA models provide. Instead, much effort was put into correcting for erosion and deposition through the various stages since the LGM and stepwise through the Holocene, especially in the coastal zones. As an example, for each Holocene tidal channel a trade-off decision had to be made on whether it followed a 'new' independent path or an 'inherited' pre-existent path

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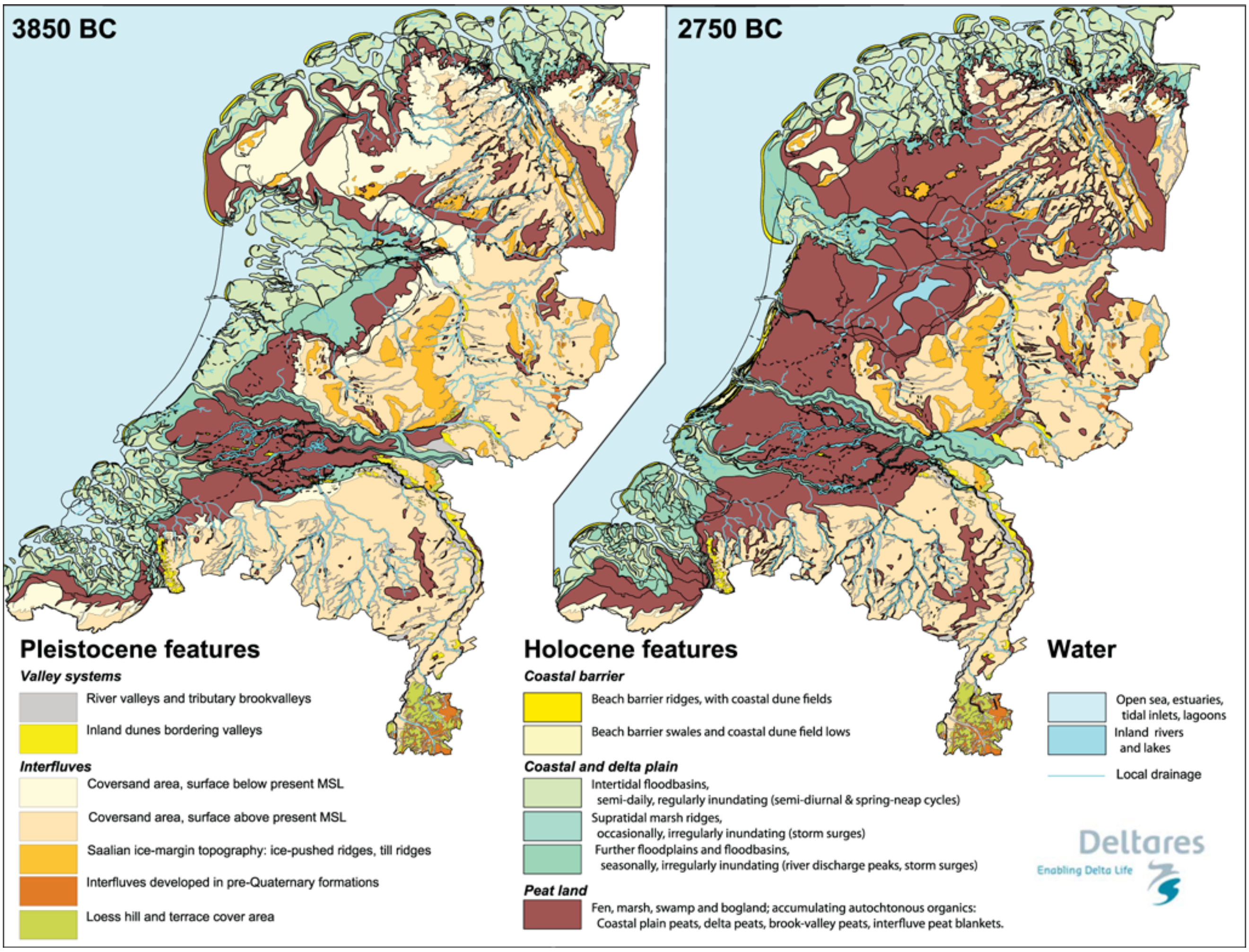

Fig. 8. Example palaeogeographical maps for the Holocene: reconstructions for 3850 BC and 2750 BC (i.e. 5800 and 4700 cal BP), selected from a series of ten such maps (after Vos et al., 2011; Vos & de Vries, 2013; second-generation maps; www.archeologieinnederland.nl).

(Vos, 2013). Virtually all Middle-Holocene tidal-inlet channels (see the section on features from temperate (interglacial) times above; systems active between 8.5 and 4 ka ago) are interpreted as having exploited paths inherited from local rivers (i.e. last-glacial periglacial interfluve features; see the section on features from glacial times above). In contrast, many Late Holocene tidal inlets along the Dutch coast appear to occupy 'new' positions, but not all. The insight into channel-position inheritance in the Middle Holocene transgressive situation is of relevance for archaeological predictions regarding the buried postglacial landscape. Positions of millennia-younger systems can be of use to predict where Mesolithic drowned local valley systems were located. The fringes of these systems may have survived younger tidal erosion and predict where archaeological sites may be present at depth below sediment and water in the coastal zone. Furthermore, knowing where the Mesolithic channels were means knowing where the post-LGM interfluves were and this, in turn, allows separation of these two palaeo-environments in assessments of preserved surface.

Future perspectives

Excellent time control and data density, achieved for the Holocene of the Netherlands, have allowed the production of reconstructions for narrowly defined time intervals. The Late Pleistocene GIA-modelled palaeogeographies are also for narrowly defined intervals, but they include much more uncertainty because they tend to use uncleaned modern topographic and bathymetric data, which are indirect data when past topography is concerned. The Middle Pleistocene examples, in contrast, are for 'interglacial highstand' situations, thought to have repeated themselves a couple of times within the broad time slices that the maps represent. While thus avoiding the problem of having to assign a narrowly defined age where there are no methods to resolve it, this approach blurs local detail in the few areas on the map where well-developed sequences are preserved that would allow for reconstruction at higher temporal resolution. Resolving the particularities of the correlation of the suites of continental European Elsterian *s.l.* and Holsteinian *s.l.* sites to the Anglian and Hoxnian British stages is needed to improve the Middle Pleistocene palaeogeography of the

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Middle Palaeolithic archaeological horizons and the glacial breaks between them. This will also be needed to connect archaeology from along past North Sea shores to terrestrial counterpart sites from this period.

None of the presented palaeogeographical reconstructions for the Middle Pleistocene, the Late Pleistocene and the Holocene indicate which parts of the visualised landscapes have been preserved. Assessments of preservation and associated uncertainty are left to the reader or expert interpreter. Overlaying palaeogeographical reconstructions with distribution maps of geological units is a useful assessment tool, provided that lithostratigraphic schemes in geological mapping are not too 'all inclusive'. Quests to separate chronostratigraphy from lithostratigraphy in mapping the Pleistocene of the North Sea basin should guard against the production of broad container units of uniform lithogenesis, and instead should strive for resolving the larger-scale internal architecture of such units. Architectural subdivision of the Dutch Kreftenheye Formation (Late Pleistocene to early Holocene fluvial sediments) into its constituent palaeovalley fills (Busschers et al., 2007; Hijma et al., 2012) is a recent example of such practice.

Seismic data (e.g. van Heteren et al., 2014) can assist greatly in the architectural subdivision of lithologically uniform stratigraphic units. It is believed that particularly for the Middle Pleistocene between the MIS-12 and MIS-6 glaciations, critical information to solve relative dating problems can be unveiled with more sophisticated offshore geological mapping of the North Sea floor, especially when also applied in areas *between* tunnel valley features (on which much of the mapping work so far has focused; e.g. Stewart & Lonergan, 2011; Moreau et al., 2012; van der Vegt et al., 2012). As an increasing number of such products become available, palaeogeographical maps will suffer less and less from overprinting by younger geomorphological activity and poor reproducibility.

Conclusions

The Quaternary climatic history in the North Sea region importantly included direct effects of glaciation. Combined with tectonics this has given rise to cyclic and non-cyclic changes of sedimentation and erosion patterns. Trends in geological preservation and inheritance of large-scale landscape structures left strong imprints in the record, and are major controls on the detail that palaeogeographical reconstructions for the North Sea area can achieve. In performing palaeogeographical reconstructions, dealing with the degree of preservation is equally important as dealing with the accuracy of age control.

For Palaeolithic archaeology of past temperate half-cycles, Quaternary geological-geomorphological reconstructions matter in two ways:

1. Paleohuman migrations in *post-glacial* times, coincident with climatic amelioration and transgressions, occurred in a landscape with a strong inheritance imprint from geomorphological activity in preceding glacials. With every interglacial, the opportunities for palaeohuman landscape exploitation were altered, in some instances dramatically progressively, in other instances more gradually but also progressively. From the landscape 'routing' viewpoint, subsequent interglacials differ more strongly than from climatic or vegetation 'habitat' viewpoints. Palaeogeographical map series illustrate the differences very well.

2. Glacial and periglacial conditions from times *following interglacials* control 'long-term' preservation of archaeology, i.e. over 100,000 years and longer, by repeated glacial–interglacial cycles. Because of progressive landscape developments, the way that post-interglacial preservation worked out has changed through time. This co-affects archaeological differences between interglacials and is a factor to consider besides evolutionary, behavioural and tolerance changes and normal loss of sites back in time. The latest Paleolithic and Mesolithic archaeology is only one half-cycle young and its preservation is not yet fully affected by the processes above.

Palaeogeographical maps for the North Sea area are a useful but imperfect visualisation of landscape development through time. Their construction requires the integration of various types of geological data, collected and documented within stratigraphic frameworks that may not be ideally suited to palaeolandscape research. Where geological maps summarise the distribution and ages of preserved sediment and rock (with poor time control and poor architectural detail in many cases), palaeogeographical maps also give a reconstruction of non-preserved parts of the landscape (adding additional uncertainty). Intercomparison of three example map sets for Middle-Pleistocene, Late-Pleistocene and Holocene times show the temporal and spatial resolutions that can nowadays be achieved for the successive time periods. Jointly, the maps indicate that palaeogeographical development has been progressive rather than cyclic.

To optimise palaeogeographical reconstruction in future research, the field would benefit from (digital) integration of specialised geological mapping (paying particular attention to sedimentary environments and palaeotopography), GIA modelling and state-of-the-art age control. As databases are increasingly digitised and computing power increases, automated combination of large diverse datasets will become feasible, allowing map makers to show how palaeotopography has co-evolved with sea-level variation, ice-sheet growth and decay, geoid change and surface warping. This will be a major step towards producing palaeogeographical maps that can be interrogated and adjusted easily, and be reproduced independently. Knowing the degree of preservation of past landscapes is as important as being able to date past landscapes with sufficient accuracy.

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References

Antoine, P., Catt, J., Lautridou, J.P. & Sommé, J., 2003. The loess and coversands of northern France and southern England. Journal of Quaternary Science 18: 309-318.

Ashton, N., Lewis, S.G. & Stringer, C., (eds), 2011. The Ancient Human Occupation of Britain. Developments in Quaternary Science 14: 11-22.

Bates, M.R., Parfitt, S.A. & Roberts, M.B., 1997. The chronology, palaeogeography and archaeological significance of the marine Quaternary record of the west Sussex coastal plain, southern England, U.K. Quaternary Science Reviews 16, 1227-1252.

Beets, D.J. & van der Spek, A.J., 2000. The Holocene evolution of the barrier and back-barrier basins of Belgium and the Netherlands as a function of late Weichselian morphology, relative sea-level rise and sediment supply. Geologie en Mijnbouw 79: 3-16.

Belt, T., 1874. The Glacial Period, Nature, 10 (May 14): 25-26.

Berendsen, H.J.A. & Stouthamer, E., 2000. Late Weichselian and Holocene palaeogeography of the Rhine–Meuse delta, The Netherlands. Palaeogeography, Palaeoclimatology, Palaeoecology 161: 311-335.

Berger, W.H. & Jansen, E., 1994. Mid-Pleistocene Climate Shift – The Nansen Connection. *In*: Johannessen, O.M., Muench, R.D. & Overland, J.E. (eds): The polar oceans and their role in shaping the global environment. Geophysical Monograph 85. American Geophysical Union: 295-311.

Bijlsma, S. 1981. Fluvial sedimentation from the Fennoscandian area into the north-west European basin during the late Cenozoic. Geologie en Mijnbouw 60: 337-345.

Boenigk, W. & Frechen, M., 2006. The Pliocene and Quaternary fluvial archives of the Rhine system. Quaternary Science Reviews 25: 550-574.

Bowen, D.Q. (ed.), 1999. A revised correlation of Quaternary deposits in the British Isles. Geological Society of London Special Report No 23, 174 pp.

Bridgland, D.R. & D'Ollier, B., 1995. The Pleistocene evolution of the Thames and Rhine drainage systems in the southern North Sea Basin. *In*: Preece, R.C. (ed.): Island Britain: A Quaternary Perspective, Geological Society, Special Publication 96: 27-45.

Briggs, K., Thomson, K. & Gaffney, V., 2007. A geomorphological investigation of submerged depositional features within the Outer Silver Pit, southern North Sea. *In:* Gaffney, V.L., Thomson, K., & Fitch, S. (eds): Mapping Doggerland: the Mesolithic landscapes of the southern North Sea. Archaeopress (Oxford).

Busschers, F.S., Kasse, C., van Balen, R.T., Vandenberghe, J., Cohen, K.M., Weerts, H.J.T., Wallinga, J. & Bunnik, F.P.M., 2007. Late Pleistocene evolution of the Rhine–Meuse system in the southern North Sea basin: imprints of climate change, sea-level oscillation and glacio-isostacy. Quaternary Science Reviews 26: 3216-3248.

Busschers, F.S., van Balen, R.T., Cohen, K.M., Kasse, C., Weerts, H.J., Wallinga, J. & Bunnik, F.P., 2008. Response of the Rhine–Meuse fluvial system to Saalian ice-sheet dynamics. Boreas 37: 377-398.

Candy, I., Silva, B. & Lee, J., 2011 Climates of the early Middle Pleistocene in Britain: Environments of the Earliest Humans in Northern Europe. *In*: Ashton, N., Lewis, S.G. & Stringer, C. (eds): The Ancient Human Occupation of Britain. Developments in Quaternary Science 14: 11-22.

Carlson, A.E. & Clark, P.U., 2012. Ice sheet sources of sea level rise and freshwater discharge during the last deglaciation. Reviews of Geophysics 50: RG4007.

Cohen, K.M., 2005. 3D geostatistical interpolation and geological interpretation of paleo–groundwater rise in the Holocene Coastal Prism in the Netherlands. *In:* Giosan, L. & Bhattacharaya, J.P. (eds): River Deltas: Concepts, models, and examples. Society for Sedimentary Geology (Tulsa, Oklahoma): 341-364.

Cohen, K.M., Gibbard, P.L. & Busschers, F.S., 2005. Stratigraphical implications of an elsterian pro-glacial 'north sea' lake. *In:* Dehnert, A. & Preusser, F. (eds): INQUA-SEQS Meeting Volume of Abstracts. INQUA-SEQS (Bern).

Cohen, K.M., Stouthamer, E., Hoek, W.Z., Berendsen, H.J.A. & Kempen, H.F.J., 2009. Zand in banen: zanddieptekaarten van het Rivierengebied en het IJsseldal in de provincies Gelderland en Overijssel. Provincie Gelderland/Universiteit Utrecht (Utrecht): 130 pp.

Cohen, K.M., MacDonald, K., Joordens, J.C., Roebroeks, W. & Gibbard, P.L., 2012. The earliest occupation of north-west Europe: a coastal perspective. Quaternary International 271: 70-83.

Cooper, W.S., Townend, I.H. & Balson, P.S., 2008. A synthesis of current knowledge on the genesis of the Great Yarmouth and Norfolk Bank Systems. The Crown Estate (London): 69 pp. ISBN: 978-0-9553427-8-3.

Doppert, J.W.Ch., Ruegg, G.H.J., van Staalduinen, C.J., Zagwijn, W.H. & Zandstra, J.G., 1975. Formaties van het Kwartair and Boven Tertiair in Nederland. *In:* Zagwijn, W.H. & van Staalduinen, C.J. (eds): Toelichting bij geologische overzichtskaarten van Nederland. Rijks Geologische Dienst (Haarlem): 11-56.

Ebbing, J.H.J., Weerts, H.J.T. & Westerhoff, W.E., 2003. Towards an integrated land-sea stratigraphy of the Netherlands. Quaternary Science Reviews 22: 1579-1587.

Finlayson, C., Carrión, J., Brown, K., Finlayson, G., Sánchez-Marco, A., Fa, D., Rodríguez-Vidal, J., Fernández, S., Fierro, E., Bernal-Gómez, M., & Giles-Pacheco, F., 2011. The *Homo* habitat niche: using the avian fossil record to depict ecological characteristics of Palaeolithic Eurasian hominins. Quaternary Science Reviews 30: 1525-1532.

Gaffney, V.L., Thomson, K. & Fitch, S. (eds), 2007. Mapping Doggerland: the Mesolithic landscapes of the southern North Sea. Archaeopress (Oxford).

Geyh, M.A. & Müller, H., 2005. Numerical ^{230}Th/U dating and a palynological review of the Holsteinian/Hoxnian Interglacial. Quaternary Science Reviews 24: 1861-1872.

Gibbard, P.L., 1988. The history of the great north-west European rivers during the past three million years. Philosophical Transactions of the Royal Society of London B318: 559-602.

Gibbard, P.L., 1995. The formation of the Strait of Dover. *In:* Preece, R. C. (ed.): Island Britain: A Quaternary Perspective. Geological Society, London, Special Publications 96: 15-26.

Gibbard, P.L., 2007. Palaeogeography: Europe cut a drift. Nature 448: 259-260.

Gibbard, P.L. & Cohen, K.M., 2008. Global chronostratigraphical correlation table for the last 2.7 million years. Episodes 31: 243-247.

Gibbard, P.L. & van der Vegt, P., 2012. The genesis and significance of the Middle Pleistocene glacial meltwater and associated deposits. *In:* Dixon, R. & Markham, C. (eds): A celebration of Suffolk Geology: GeoSuffolk 10th Anniversary Volume. Geoscience Suffolk (Ipswich): 303-326.

Gouw, M.J.P. & Erkens, G., 2007. Architecture of the Holocene Rhine–Meuse delta (the Netherlands) – A result of changing external controls. Netherlands Journal of Geosciences – Geologie en Mijnbouw 86: 23-54.

Gullentops, F., Bogemans, F., de Moor, G., Paulissen, E. & Pissart, A., 2001. Quaternary lithostratigraphic units (Belgium). Geologica Belgica 4: 153-164.

Gupta, S., Collier, J.S., Palmer-Felgate, A. & Potter, G., 2007. Catastrophic flooding origin of shelf valley systems in the English Channel. Nature 448: 342-345.

Head, M.J., Pillans, B. & Farquhar, S.A., 2008. The Early–Middle Pleistocene Transition: characterization and proposed guide for the defining boundary. Episodes 31: 255-259.

Hijma, M.P. & Cohen, K.M., 2011. Holocene transgression of the Rhine river mouth area, The Netherlands/Southern North Sea: palaeogeography and sequence stratigraphy. Sedimentology 58: 1453-1485.

Hijma, M.P., Cohen, K.M., Roebroeks, W., Westerhoff, W.E. & Busschers, F.S., 2012. Pleistocene Rhine–Thames landscapes: geological background for hominin occupation of the southern North Sea region. Journal of Quaternary Science 27: 17-39.

Hopkinson, T., 2007. The transition from the Lower to the Middle Palaeolithic in Europe and the incorporation of difference. Antiquity 81: 294-307.

Houtgast, R.F. & van Balen, R.T., 2000. Neotectonics of the Roer Valley Rift System, the Netherlands. Global and Planetary Change 27: 131-146.

Hublin, J.-J., 2009. The origin of Neandertals. Proceedings of the National Academy of Sciences 106: 16022-16027.

Hublin, J.-J., Weston, D., Gunz, P., Richards, M., Roebroeks, W., Glimmerveen, J. Anthonis, L., 2009. Out of the North Sea: the Zeeland Ridges Neandertal. Journal of Human Evolution 57: 777-785.

Hughes, P.D., Gibbard, P.L. & Ehlers, J., 2013. Timing of glaciation during the last glacial cycle: evaluating the concept of a global 'Last Glacial Maximum' (LGM). Earth Science Reviews 125: 171-198.

Joordens, J.C.A., Wesselingh, F.P., de Vos, J., Vonhof, H.B. & Kroon, D. 2009. Relevance of aquatic environments for hominins: a case study from Trinil (Java, Indonesia). Journal of Human Evolution 57: 656-671.

Kiden, P., Denys, L. & Johnston, P., 2002. Late Quaternary sea-level change and isostatic and tectonic land movements along the Belgian–Dutch North Sea coast: geological data and model results. Journal of Quaternary Science 17: 535-546.

Kooi, H., Johnston, P., Lambeck, K., Smither, C. & Molendijk, R., 1998. Geological causes of recent (~100 yr) vertical land movement in the Netherlands. Tectonophysics 299: 297-316.

Kukla, G., 1978. The Classical European Glacial Stages: Correlation with Deep-Sea Sediments. Transactions of the Nebraska Academy of Sciences and Affiliated Societies VI (Paper 334): 57–93.

Laban, C., 1995. The Pleistocene glaciations in the Dutch sec- tor of the North Sea: a synthesis of sedimentary and seismic data. PhD thesis, University of Amsterdam: 194 pp.

Laga, P., Louwye, S. & Geets, S., 2001. Paleogene and Neogene lithostratigraphic units (Belgium). Geologica Belgica 4: 135-152.

Lambeck, K., 1995. Late Devensian and Holocene shorelines of the British Isles and North Sea from models of glacio-hydro-isostatic rebound. Journal of the Geological Society – London 152: 437-448.

Lambeck, K., Purcell, A., Funder, S., Kjær, K.H., Larsen, E. & Moller, P., 2006. Constraints on the Late Saalian to early Middle Weichselian ice sheet of Eurasia from field data and rebound modelling. Boreas 35: 539-575.

Lee, J.R., Busschers, F.S. & Sejrup, H.P., 2012. Pre-Weichselian Quaternary glaciations of the British Isles, The Netherlands, Norway and adjacent marine areas south of 68 N: implications for long-term ice sheet development in northern Europe. Quaternary Science Reviews 44: 213-228.

Lewin, J. & Gibbard, P.L. 2010. Quaternary river terraces in England: forms, sediments and processes. Geomorphology 120: 293-311.

Lisiecki, L.E. & Raymo, M.E. 2005. A Pliocene–Pleistocene stack of 57 globally distributed benthic δ180 records. Paleoceanography 20: PA1003.

Litt, T., 2007. Introduction: Climate, vegetation and mammalian faunas in Europe during Middle Peistocene interglacials (MIS 7, 9, 11). *In:* Sirocko, F., Claussen, M., Sánchez-Goñi, M.F. & Litt, T. (eds): The Climate of Past Interglacials. Developments in Quaternary Sciences 7: 351-357.

Lourens, L.J., Antonarakou, A., Hilgen, F.J., van Hoof, A.A.M., Vergnaud-Grazzini, C. & Zachariasse, W.J., 1996. Evaluation of the Plio-Pleistocene astronomical timescale. Paleoceanography 11: 391-413.

Lowe, J.J., Rasmussen, S.O., Björck, S., Hoek, W.Z., Steffensen, J.P., Walker, M.J.C., Yu, Z.C. & the INTIMATE group, 2008. Synchronisation of palaeoenvironmental events in the North Atlantic region during the Last Termination: a revised protocol recommended by the INTIMATE group. Quaternary Science Reviews 27: 6-17.

Mayhew, D.F., Dieleman, F.E., Slupik, A.A., van den Hoek Ostende, L.W. & Reumer, J.W.F., 2014. Small mammal assemblages from the Quaternary succession at Moriaanshoofd (Zeeland, the Netherlands) and their significance for correlating the Oosterschelde fauna. Netherlands Journal of Geosciences: doi:10.1017/njg.2014.6.

McMillan, A.A., 2002. Onshore Quaternary geological surveys in the 21st century – a perspective from the British Geological Survey. Quaternary Science Reviews 21: 889-899.

McMillan, A.A., 2005. A provisional Quaternary and Neogene lithostratigraphical framework for Great Britain. Netherlands Journal of Geosciences 84: 87-107.

Meijer, T. & Preece, R.C., 1995. Malacological evidence relating to the insularity of the British Isles during the Quaternary. Geological Society, London, Special Publications 96: 89-110.

Mellett, C.L., Hodgson, D.M., Plater, A.J., Mauz, B., Selby, I. & Lang, A., 2013. Denudation of the continental shelf between Britain and France at the glacial–interglacial timescale. Geomorphology 203: 79-96.

Meyer, W. & Stets, J., 2002. Pleistocene to recent tectonics in the Rhenish Massif (Germany). Netherlands Journal of Geosciences 81: 217-222.

Mitrovica, J.X. & Milne, G.A., 2002. On the origin of late Holocene sea-level highstands within equatorial basins. Quaternary Science Reviews 21: 2179-2190.

Mol, D., Post, K., Reumer, J.W., van der Plicht, J., de Vos, J., van Geel, B., van Reenen, G., Pals, J.P. & Glimmerveen, J. 2006. The Eurogeul — first report of the palaeontological, palynological and archaeological investigations of this part of the North Sea. Quaternary International 142: 178-185.

Moreau, J., Huuse, M., Janszen, A., van der Vegt, P., Gibbard, P.L., & Moscariello, A., 2012. The glaciogenic unconformity of the southern North Sea. Geological Society, London, Special Publications 368: 99-110.

Moree, J.M. & Sier, M.M. (eds), 2014. Twintig meter diep! Mesolithische bewoning in de Yangtzehaven-Maasvlakte te Rotterdam. Landschapsontwikkeling en bewoning in het Vroeg Holoceen. BOORrapporten 523, BOOR Rotterdam: c. 360 pp (*in press*, *exp. 2014*).

Murton, D.K. & Murton, J.B., 2012. Middle and Late Pleistocene glacial lakes of lowland Britain and the southern North Sea Basin. Quaternary International 260: 115-142.

https://doi.org/10.1017/njg.2014.12 Published online by Cambridge University Press

NEEM community members, 2013. Eemian interglacial reconstructed from a Greenland folded ice core. Nature 493: 489-494.

Overeem, I., Weltje, G.J., Bishop-Kay, C. & Kroonenberg, S.B., 2001. The Late Cenozoic Eridanos delta system in the southern North Sea Basin: a climate signal in sediment supply? Basin Research 13: 293-312

Parfitt, S.A., Barendregt, R.W., Breda, M., Candy, I., Collins, M.J., Coope, G.R., Durbidge, P., Field, M.H., Lee, J.R., Lister, A.M., Mutch, R., Penkman, K.E.H., Preece, R.C., Rose, J., Stringer, C.B., Symmons, R., Whittaker, J.E., Wymer, J.J. & Stuart, A.J., 2005. The earliest record of human activity in northern Europe. Nature 438: 1008-1012.

Parfitt, S.A., Ashton, N., Lewis, S.G., Abel, R.L., Coope, G.R., Field, M.H., Gale, R., Hoare, P.G., Larkin, N.R., Lewis, M.D., Karloukovski, V., Maher, B.A., Peglar, S.M., Preece, R.C., Whittaker, J.E. & Stringer, C.B., 2010. Early Pleistocene human occupation at the edge of the boreal zone in northwest Europe. Nature 466: 229-233.

Peeters, H., Murphy, P. & Flemming, N. (eds), 2009. North Sea Prehistory Research and Management Framework (NSPRMF) 2009. Rijksdienst voor het Cultureel Erfgoed/English Heritage (Amersfoort): 40 pp.

Peeters, J., Busschers, F.S. & Stouthamer, E., 2014. Fluvial evolution of the Rhine during the last interglacial–glacial cycle in the southern North Sea basin: A review and look forward. Quaternary International. http://dx.doi.org/10.1016/j.quaint.2014.03.024.

Peltier, W.R., 2004. Global glacial isostasy and the surface of the ice-age Earth: The ICE-5G (VM2) model and GRACE. Annual Review of Earth and Planetary Sciences 32: 111-149. Publication 42: 109-124.

Preece, R.C. & Parfitt, S., 2012. The Early and early Middle Pleistocene context of human occupation and lowland glaciation in Britain and northern Europe. Quaternary International 271: 6-28.

Renssen, H., Seppä, H., Crosta, X., Goosse, H. & Roche, D.M., 2012. Global characterization of the Holocene Thermal Maximum. Quaternary Science Reviews 48: 7-19.

Rijsdijk, K.F., Passchier, S., Weerts, H.J.T., Laban, C., van Leeuwen, R.J.W. & Ebbing, J.H.J. 2005. Revised Upper Cenozoic stratigraphy of the Dutch sector of the North Sea Basin: towards an integrated lithostratigraphic, seismostratigraphic and allostratigraphic approach. Netherlands Journal of Geosciences 84: 129-146.

Rijsdijk, K.F., Kroon, I.C., Meijer, T., Passchier, S., van Dijk, T.A.G.P., Bunnik, F.P.M. & Janse, A.C., 2013. Reconstructing Quaternary Rhine–Meuse dynamics in the southern North Sea: architecture, seismo-lithofacies associations and malacological biozonation. Journal of Quaternary Science 28: 453-466.

Roe, H.M. & Preece, R.C., 2011. Incised palaeo-channels of the late Middle Pleistocene Thames: age, origins and implications for fluvial palaeogeography and sea-level reconstruction in the southern North Sea basin. Quaternary Science Reviews 30: 2498-2519.

Roebroeks, W., 2005. Archaeology: life on the Costa del Cromer. Nature 438: 921-922.

Roebroeks, W., Hublin, J.-J. & MacDonald, K., 2011. Continuities and Discontinuities in Neanderthal Presence: A Closer Look at Northwestern Europe. *In:* Ashton, N., Lewis, S.G. & Stringer, C. (eds): The Ancient Human Occupation of Britain. Developments in Quaternary Science 14: 113-124.

Sánchez-Goñi, M.F., Eynaud, F., Turon, J.L. & Shackleton, N.J., 1999. High resolution palynological record off the Iberian margin: direct land-sea correlation for the Last Interglacial complex. Earth and Planetary Science Letters 171: 123-137.

Schäfer, A., Utescher, T., Klett, M. & Valdivia-Manchego, M., 2005. The Cenozoic Lower Rhine Basin – rifting, sedimentation, and cyclic stratigraphy. International Journal of Earth Sciences 94: 621-639.

Schreve, D.C., 2001. Differentiation of the British late Middle Pleistocene interglacials: the evidence from mammalian biostratigraphy. Quaternary Science Reviews 20: 1693-1705.

Schreve, D.C., & Bridgland, D.R., 2002. Correlation of English and German Middle Pleistocene fluvial sequences based on mammalian biostratigraphy. Netherlands Journal of Geosciences 81: 357-374.

Sejrup, H.P., Nygård, A., Hall, A.M. & Haflidason, H., 2009. Middle and Late Weichselian (Devensian) glaciation history of south-western Norway, North Sea and eastern UK. Quaternary Science Reviews 28: 370-380.

Sier, M.J., Roebroeks, W., Bakels, C.C., Dekkers, M.J., Brühl, E., de Loecker, D., Gaudzinski-Windheuser, S., Hesse, N., Jagich, A., Kindler, L., Kuijper, W.J., Laurat, T., Mücher, H.J., Penkman, K.E.H., Richter, D. & van Hinsbergen, D.J., 2011. Direct terrestrial–marine correlation demonstrates surprisingly late onset of the last interglacial in central Europe. Quaternary Research 75: 213-218.

Smith, D.E., Harrison, S., Firth, C.R. & Jordan, J.T., 2011. The early Holocene sea level rise. Quaternary Science Reviews 30: 1846-1860.

Steffen, H. & Wu, P., 2011. Glacial isostatic adjustment in Fennoscandia — a review of data and modeling. Journal of Geodynamics 52: 169-204.

Stewart, M.A. & Lonergan, L., 2011. Seven glacial cycles in the middle-late Pleistocene of northwest Europe: Geomorphic evidence from buried tunnel valleys. Geology 39: 283-286.

Stremme, H.E., 1998. Correlation of Quaternary pedostratigraphy from western to eastern Europe. Catena 34: 105-112.

Sturt, F., Garrow, D. & Bradley, S., 2013. New models of North West European Holocene palaeogeography and inundation. Journal of Archaeological Science 40: 3963-3976.

Toucanne, S., Zaragosi, S., Bourillet, J.F., Gibbard, P.L., Eynaud, F., Giraudeau, J., Turon, J.L, Cremer, M., Cortijo, E., Martinez, P. & Rossignol, L., 2009. A 1.2 Ma record of glaciation and fluvial discharge from the West European Atlantic margin. Quaternary Science Reviews 28: 2974-2981.

Turner, C. (ed.), 1996. The early Middle Pleistocene in Europe. Balkema (Rotterdam): 319 pp.

Turner, C., 2000. The Eemian interglacial in the north European plain and adjacent areas. Geologie en Mijnbouw 79: 217-232.

Uehara, K., Scourse, J.D., Horsburgh, K.J., Lambeck, K. & Purcell, A.P., 2006. Tidal evolution of the northwest European shelf areas from the Last Glacial Maximum to the present. Journal of Geophysical Research 111: C09025.

van Adrichem Boogaert, H.A. & Kouwe, W.F.P. (eds), 1997. Stratigraphic nomenclature of the Netherlands, revision and update by RGD and NOGEPA. Mededelingen Rijks Geologische Dienst 50: 39 pp.

van Balen, R.T., Houtgast, R.F. & Cloetingh, S.A.P.L., 2005. Neotectonics of The Netherlands: a review. Quaternary Science Reviews 24: 439-454.

van den Berg, M.W. & Beets, D.J., 1987. Saalian glacial deposits and morphology in The Netherlands. *In:* van der Meer, J.J.M. (ed.): Tills and Glaciotectonics. Balkema (Rotterdam): 235-251.

van den Berg, M.W., Groenewoud, W., Lorenz, G.K., Brus, D.J. & Kroonenberg, S.B., 1994. Patterns and velocities of recent crustal movements in the Dutch part of the Roer Valley rift system. Geologie en Mijnbouw 73: 157-168.

van der Vegt, P., Janszen, A. & Moscariello, A., 2012. Tunnel valleys: current knowledge and future perspectives. Geological Society, London, Special Publications 368: 75-97.

van Heteren, S., Meekes, J.A.C., Bakker, M.A.J., Gaffney, V., Fitch, S., Gearey, B.R. & Paap, B.F., 2014. Reconstructing North Sea palaeolandscapes from 3D and high-density 2D seismic data: An overview. Netherlands Journal of Geosciences 1-12.

van Huissteden, J.K., Vandenberghe, J., van der Hammen, T. & Laan, W., 2000. Fluvial and aeolian interaction under permafrost conditions: Weichselian Late Pleniglacial, Twente, eastern Netherlands. Catena 40: 307-321.

van Kolfschoten, T. & Laban, C., 1995. Pleistocene terrestrial mammal faunas from the North Sea. Mededelingen Rijks Geologische Dienst 52: 135-151.

Verhart, L.B.M., 1988. Mesolithic barbed points and other implements from Europoort, the Netherlands. Oudheidkundige mededelingen uit het Rijksmuseum van Oudheden te Leiden 68: 145-194.

Vink, A., Steffen, H., Reinhardt, L. & Kaufmann, G., 2007. Holocene relative sealevel change, isostatic subsidence and the radial viscosity structure of the mantle of northwest Europe (Belgium, the Netherlands, Germany, southern North Sea). Quaternary Science Reviews 26: 3249-3275.

Vos, P.C., 2013. The compilation of the Holocene palaeogeographical maps of the Netherlands. Deltares (Utrecht): 41 pp, www.archeologieinnederland.nl, last accessed on 13 February 2014.

Vos, P.C. & de Vries, S., 2013. 2e generatie palaeogeografische kaarten van Nederland (versie 2.0). Deltares (Utrecht), www.archeologieinnederland.nl, last accessed on 13 February 2014.

Vos, P.C., Bazelmans, J., Weerts, H.J.T. & van der Meulen, M. (eds), 2011. Atlas van Nederland in het Holoceen. Bert Bakker (Amsterdam): 94 pp.

Ward, I. & Larcombe, P., 2008. Determining the preservation rating of submerged archaeology in the post-glacial southern North Sea: a first-order geomorphological approach. Environmental Archaeology 13: 59-83.

Weerts, H.J.T., Westerhoff, W.E., Cleveringa, P., Bierkens, M.F.P., Veldkamp, J.G. & Rijsdijk, K.F., 2005. Quaternary geological mapping of the lowlands of The Netherlands, a 21st century perspective. Quaternary International 133: 159-178.

Weerts, H.J.T., Otte, A., Smit, B., Vos, P., Schiltmans, D., Waldus, W. & Borst, W., 2012. Finding the Needle in the Haystack by Using Knowledge of Mesolithic Human Adaptation in a Drowning Delta. *In:* Bebermeier, W., Hebenstreit, H., Kaiser, E. & Krause, J. (eds): Landscape Archaeology. eTopoi Journal for Ancient Studies, Special Volume 3: 17-24.

West, R.G., 1989. The use of type localities and type sections in the Quaternary, with especial reference to East Anglia. *In:* Rose, J. & Schlüchter, C. (eds): Quaternary Type sections: Imagination or Reality? Balkema (Rotterdam): 3-10.

West, R.G., 1996. Outline of the stratigraphy and vegetational history of the Cromer Forest-bed Formation. *In:* Turner, C. (ed.): The early Middle Pleistocene in Europe. Balkema (Rotterdam): 1-8.

Westerhoff, W.E., Wong, Th.E. & de Mulder, E.F.J., 2003. Opbouw van de ondergrond. Deel 3. *In:* de Mulder, E.F.J., Geluk, M.C., Ritsema, I., Westerhoff, W.E. & Wong, Th.E. (eds): De ondergrond van Nederland. Netherlands Institute of Applied Geoscience TNO – National Geological Survey. Peeters (Herent): 249-352.

Westerhoff, W.E., Weerts, H.J.T. & Menkovic, A., 2009. The evolution of the lower Rhine–Meuse system during the Early Pleistocene. *In:* Westerhoff, W.E. (ed.): Stratigraphy and sedimentary evolution: The lower Rhine–Meuse system during the Late Pliocene and Early Pleistocene (southern North Sea Basin). Geology of the Netherlands 2: 121-147.

Winsemann, J., Asprion, U. & Meyer, T., 2004. Sequence analysis of early Saalian glacial lake deposits (NW Germany): evidence of local ice margin retreat and associated calving processes. Sedimentary Geology 165: 223-251.

Woodland, A.W., 1970. The buried tunnel-valleys of East Anglia. Proceedings of the Yorkshire Geological and Polytechnic Society 37: 521-578.

Zagwijn, W.H., 1974. Palaeogeographic evolution of the Netherlands during the Quaternary. Geologie en Mijnbouw 53: 369-385.

Zagwijn, W.H. 1979. Early and Middle Pleistocene coastlines in the southern North Sea Basin. *In:* Oele, E., Schüttenhelm, R.T.E. & Wiggers, A.J. (eds): The Quaternary History of the North Sea. Acta Universitas Upsalliensis Symposium Universitas Upsalliensis Annum Quingentesimum Celebrantis 2: 31-42.

Zagwijn, W.H., 1996. An analysis of Eemian climate in western and central Europe. Quaternary Science Reviews 15: 451-469.

Zagwijn, W.H. & van Staalduinen, C.J. (eds), 1975. Toelichting bij geologische overzichtskaarten van Nederland. Rijks Geologische Dienst (Haarlem): 134 pp.

https://doi.org/10.1017/njg.2014.12 Published online by Cambridge University Press