The southern North Sea? Rhine-Thames land!

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A series of three papers dealing with the closely interlinked topics of Holocene and Pleistocene geological evolution of the Southern North Sea – also dubbed Rhine-Thames land - is presented here. For this summary it is best to start with the paper that appeared last (Hijma *et al.,* 2012), which deals with landscape change in the last million years and the wider Southern North Sea region. To paleohumans back then and to us modern man today, the landscape of the North Sea region looked vastly different one million years ago. A landbridge connected England to Belgium and the rest of continental Europe. Since then, however, several cycles of melt waters from land ice have stripped the terrestrial landscape of the land bridge, allowing the sea to enter the area in interglacials. The paper links Quaternary Geological research questions on timing and rates of landbridge lowering and removal to research questions in archaeology, on dispersal of paleohumans from refugia and behavioural evolutionary adaptions to living in temperate habitats. Quaternary scientists need to be able to situate a large number and wide variety of observations and finds from the North Sea in their proper geological setting in order to translate these finds into information about past landscapes and their inhabitants (e.g. Gaffney et al., 2009). The North Sea area is a critical region to answer some major open questions in the fields of palaeoanthropology and Pleistocene studies as NW Europe was at the edge of hominin expansion during its evolutionary stages through the Pleistocene (e.g. Parfitt *et al.*, 2005; Roebroeks, 2005; Parfitt *et al.*, 2010). As the archaeological richness of the Rhine-Thames part of the North Sea is becoming more and more evident, studies providing proper regional geological context for all stages of the Palaeolithic are needed. The increasingly larger volumes of Pleistocene sediments that are mined from the North Sea, in particular for sand extraction, makes this even more important. A spectacular example is the rare find of a Neanderthal skull fragment from off the coast of the Netherlands (Hublin *et al.*, 2009). Comparatively little was known about the geological setting of the fossil. Local stratigraphical context is missing, and the Pleistocene landscape context is only known in broad and general terms.

The Hijma *et al.* (2012) paper provides a regional framework to place sites from older and younger Palaeolithic periods in a continuous landscape evolutionary framework. The paper integrated geological data from the Belgian, Dutch and British onshore and offshore, and visualizes this for critical periods as palaeogeographical scenario maps (Figures 1,2). Two of these maps contrast the situation in the interglacials of the Middle Pleistocene, before and after the Anglian/Elsterian glaciation. Before this glaciation (in the Pleistocene up to 500,000 years ago) a wide land bridge existed between England and Belgium even during marine highstands. The land bridge was much narrower, but not yet fully removed and not yet lowered to below sea level on its northern flank, in the interglacials of the period after 500,000 years ago, up to the Saalian glaciation (150,000 years ago) at the end of the Middle Pleistocene. Erosive action by melt water from this ice age finished the job of removing the land bridge, and replaced it with an axial valley that connected rivers from the North Sea to those of the English Channel. A third map shows the Strait of Dover, Southern Bight and more northerly parts of the North Sea first fully connected during the sea level high stand of the last interglacial (Eemian, 120,000 years ago). A fourth maps shows the axial valley re-emerged with sea level high stand of the Last Glacial, with the rivers Rhine, Thames, Meuse and Scheldt all joined and routed south as the so-called Channel River. For archaeology, the differences in river network, coastal configuration and erosion base owing to the stage wise removal of high stand situations have strong archaeological implications via (i) changes migration routes of herds of herbivores on which hominins preyed, (ii) changes in availability of flint raw materials in England, northern France and Belgium, and (iii) progressively deepening valleys and increasing loess sedimentation changing the ways in which archeological sites form and preserve (site taphonomy). Geologically, it provides 10 cross-sections that allow to trace several generations of Late Pleistocene valley systems of the Rhine towards the British-Belgian sector and the Strait of Dover: connecting the datable depositional record of the Quaternary North Sea basin into the geomorphological traceable record in Tertiary and Mesozoic substrate of the former landbridge.

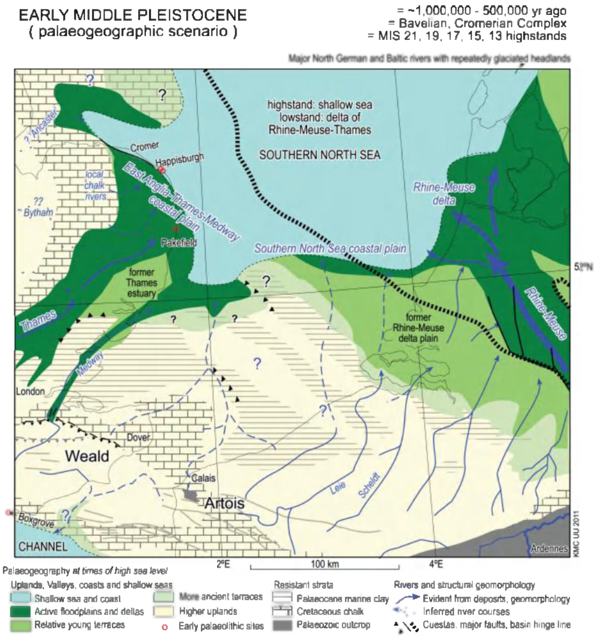

Figure 1. An interglacial highstand situation during the early Middle Pleistocene as repeatedly occurring between 1 and 0.5 Ma (i.e. ‘Bavelian, Cromerian Complex’; MIS 21, 19, 17, 15, 13) showing repeatedly glaciated headlands.

Holocene drowning of the North Sea

The largest river in the southern North Sea is the Rhine-Meuse system. The paper by Hijma and Cohen (2011) describes the transition from Late Pleistocene valley to Holocene delta plain of this system, onshore and offshore of the present coast. The critical period in this transition was the time between 9000 and 6000 years ago. A series of palaeo-geographical maps is presented, based on mapping and dating at very high data densities and completely covering the system – reaching a level of detail unsurpassed in the world. The map series shows a Rhine-Meuse-Scheldt estuary offshore of Rotterdam at 9000 years, which rapidly drowns and shifts landwards, loses the Scheldt as a feeding river, starts to lose the Rhine too, develops a muddy and organic backfill and embryonic barrier systems, exports sediment to the coastal barrier system and tidal inlets to the north of the drowning estuary. All of this happens over a time period of 2500 years, leading up to stabilisation of barrier coastal system around 6000 years ago. This resolves the transgressive stage of coastal evolution of the North Sea to similar level of detail and process explanation as the later Holocene stages. To have closed this former knowledge gap is especially important because it allows studying landscape evolution of the North Sea’s river valleys from the last ice age to its river mouths and coasts of the Holocene in a continuum.

The position of the Rhine-Meuse-Scheldt system on the wide, low-gradient continental shelf that the North Sea basin provides is of particular importance. It has made that base-level changes is a dominant control on sedimentation for relative short periods of time within glacial cycles only, and kicks in relative late in the interglacial. Plenty of accommodation space is left to fill by terrestrial deposition by rivers, and the system can be seen to go through changes in sedimentary style in response to hinterland climatic changes. This holds for full glacial conditions of the Last Glacial Maximum and times before; with beginning warming in the Late-glacial, and with continued warming of the Early Holocene, and the later North Sea floor and coastal plain base overly considerable preserved valley surface area from each of these time periods.

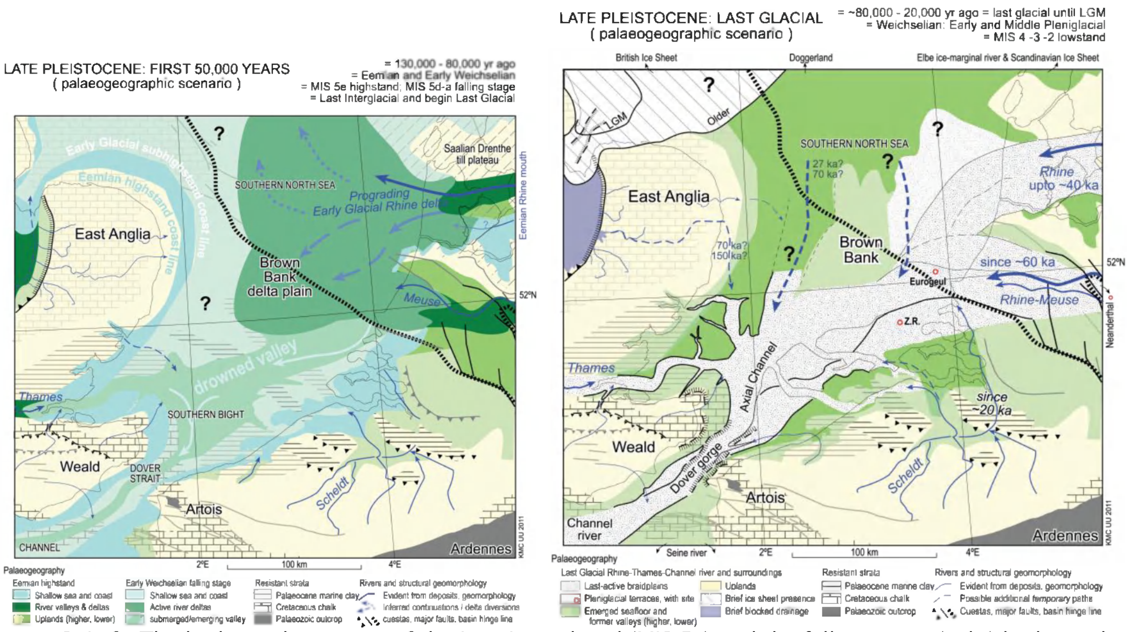

Figure 2. Left: The highstand situation of the Last Interglacial (MIS 5e) and the falling stage (sub-) highstands of the Early Weichselian (MIS 5d-a). The map is representative for the lateMiddle Palaeolithic (130-80 ka ago). Right: The lowstand situation for thecoldest part of the Late Pleistocene, the Weichselian Early and Middle Pleniglacial, up to the Last Glacial Maximum (_80-20 ka ago).

For the transgression, it is shown that the base of the coastal prism records three stages. (i) From the millennium before 8.45 ka BP, deltaic fluvial environments of extensive wetlands bury Late-glacial and Early Holocene valley parts. (ii) The millennium after 8.45 ka begins with a rapid drowning event. Thereafter, marked erosion in the coastal zone, an embryonic barrier system that stepped back many kilometers, increasing tidal amplitudes in the estuaries, and bay-head delta development in upper estuarine environments are seen. (iii) The period between 7.5 and 6.3 ka BP saw the Rhine step backward and divert away from this former mouth through multiple avulsion, and eventually saw the coastal barrier system stabilize its position, marking the high stand to have commenced.

Sea level jumping 8,450 years ago
The paper by Hijma and Cohen (2010) describes the evidence for the pulse of accelerated sea-level rise that occurred at 8.45 ka. Both the timing and the magnitude of this sea-level jump were quantified directly from precise sea-level data harvested from the Rhine delta. Evidence from terrestrial, glacial, and global climate model reconstructions suggests that this sea-level jump was caused by huge amounts of meltwater release in the final stages of existence of proglacial lake Agassiz in North-America. Drainage of this lake in front of the melting Laurentide ice sheet is nowadays widely regarded to have caused the 8.2 ka cooling event, that was particularly significant in the Northern Hemisphere (see Törnqvist en Hijma, 2012 for a recent overview). The chronology of the meltwater pulse, however, so far had been based on marine data of limited dating accuracy, which had placed it at ca. 8470 ± 300 yr. The data from Rotterdam, observed at considerable distance from the release site, specify abrupt sea-level rise to have commenced 8450 ± 44 yr ago and shows sea level markers from before and after the jump to be separated 4 meters vertically.

Between 8500 to 8300 years ago, sea level is shown to have jumped a 2.11 ± 0.89 m, in addition to background relative sea-level rise over that two century period (1.95 ± 0.74 m). In other words: in the North Sea basin, in these special centuries sea level rise was double that of what was seen in the centuries before and after. Considerable areas of land transformed to shallow sea at this time. Full marine connection between the Southern Bight and German Bight was established, and the wave and tidal regime as we know it today spun up. The temporal acceleration of the sea-level jump catalyzed these transformations from subaerial to drowned conditions. The event set back coast lines and river mouths, and is recorded as the transgressive surface at the base of the Rhine-Meuse coastal prism. Due to the event-nature of the sea level jump, the diachroneity of this transgressive surface is strongly suppressed in the critical area of the later coastal zone. The four meters of very rapid rise were followed by some 10 meters of gradually decelerating further rise in the millennia – which drowned the basal transgressive contact relatively deep, preserving it relative widely.

Corrected for gravitational effects with distance to release site, the magnitude at Rotterdam translates to a global-averaged eustatic sea-level jump that is double the size of previous estimates (3.0 ± 1.2 m versus 0.4–1.4 m). The discrepancy suggests either a coeval Antarctic contribution or, more likely, a previous underestimate of the total American lake drainage. Besides the global climatological and sea level signal links, the event is of circum-oceanic stratigraphical relevance deltaic and coastal successions worldwide, event to the extent that jump's transgressive contact is of use in formally dividing the Early Holocene from the Middle Holocene (Hijma en Cohen, 2010; Cohen en Hijma, 2013). Reference to the sea-level acceleration results since 2010 includes the IPCC fifth assessment report, prospection and discovery of Early Mesolithic sites below Rotterdam harbour extension (Weerts et al., 2012), and renewed attention to the time-depth interval in Asian deltas, notably that of the Yangtze (Wang et al., 2013).

Continuous geological coverage
The series of papers address critical time-periods that together describe the coming into existence of the North Sea as we know it today. This provide a considerably updated framework for the macro-evolution of the North Sea during the last million years. In our appreciation, older macro-evolutionary overviews in the past often suffered from gaps. Late Pleistocene chapters would cover the glacial maximum predominantly and Holocene chapters the last 6000 years. Early Holocene terrestrial conditions were not considered to be relevant for sedimentation. Understanding of the Holocene transgression of the North Sea was underdeveloped and projection rather than based on mapping. The papers avoid such gaps. Clouds of sea-level rise data were collected from before, from during and from after the sea-level jump in the 2010 paper. The full transition from glacial river valley, through adaptive phases of climatic amelioration of the glacial-interglacial transition, through transgressive estuarine situations, to the eventual barrier coast and delta plain is described as a continuous story in the 2011 paper, highlighting aspects of geological-geomorphological inheritance in the development besides external changes. The progressive nature of the erosive transformation of the Belgian-English landscape to the Southern Bight open sea is highlighted in the 2012 paper.

Such efforts enable next steps of research, such as studying rates of coastal processes under considerable sea-level rise (e.g. for coastal geomorphologists), regional geological correlation and comparison along the North Sea (e.g. for stratigraphers), and the merging of terrestrial and offshore geological frameworks (e.g. for paleolithic archeologists). Furthermore, the publications have renewed international attention for the Southern North Sea region as a geological reference area for shelf, delta and sea-level research. Lastly, the papers contain new insights that are provoking and renewing research cooperation between onshore and offshore groups from the countries around the North Sea.

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