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Quaternary evolution of the North Sea and the English Channel

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Abstract

The island of Britain is surrounded by a 'moat' of water, of which the English Channel and the North Sea are two major components. This talk described some major events that occurred to shape these seaways and, in particular, the evidence preserved on the Channel seabed. Here a system of valleys occurs that was carved by the westward-flowing Channel River. At its maximum in the last glacial period this river was larger than any other river in Europe today. It carried water not only from the rivers currently entering the Channel, but also from rivers flowing into the southern North Sea. Today the Holocene is characterised by limited glaciation and therefore high sea level. However, for much of the time, global sea level was lower, exposing shallow areas as dry land.

Throughout the last 2–3Ma, the build-up and decay of ice sheets on the continents have driven spectacular changes of global sea level. Driven by climatic fluctuations, these sea-level changes resulted in cycles of emergence and submergence of the Channel floor. About 500,000 years ago the English Channel and the North Sea were flooded, as they are today, but unlike today there was a substantial land barrier, the Weald–Artois ridge, that linked Britain to the European continent. During cold periods up to 500,000 years ago the two seas were drained by separate river systems: the Channel River, aligned along the Channel basin's axis, drained towards the Atlantic Ocean, while in the North Sea the major rivers flowed northward.

Although there were earlier events, the first major extension of a continental-scale ice sheet into lowland central Europe and Britain occurred c. *450,000 years ago (the Anglian advance). Critically, this ice advanced across the emergent North Sea floor from the mountains of southern Scandinavia and Scotland, blocking the northward-flowing rivers and causing an immense glacial lake to develop in the basin south of the ice front. Once dammed, the water that continued flowing from most of western Europe's rivers caused the lake level to rise. The substantial land barrier of the Weald–Artois anticline held up the water and it was this barrier that was overtopped and breached. The narrow waterway thus formed became the Dover Strait (a.k.a. Pas de Calais), linking the North Sea to the English Channel.*

The breaching of the ridge to form the Dover Strait was critical to the evolution of the Channel from then onward, up to the present. It forced the rivers Thames and Scheldt to flow through the new Dover Strait and into the Channel River. This drainage system continued to evolve for the next 200,000 years, but events were brought to a climax some 160,000 years ago when a second major continental-scale glaciation occurred (known as the Saalian advance). The resulting megafloods sealed Britain's fate: during high sea-level periods it would henceforth be an island.

The implications of such striking geographical changes for plant and animal — including human — migration are profound, resulting, among other things, in the impoverishment of British flora and fauna during warm periods such as today's British climate, but providing a major route between the Continent and Britain during glacial periods. In addition, the rapid release of huge volumes of fresh water in megafloods into the Atlantic Ocean could have triggered changes in oceanic circulation, which, in turn, could have affected the climate of the whole North Atlantic region.

[OUGS Canterbury Symposium: Marine Geotales; original transcription by Dick Millard from the seminar recording; written up by Prof. Gibbard and Dr Cohen]

Introduction

The Quaternary evolution of the North Sea and the English Channel is a history of change of drainage systems, and the interaction of these drainage systems with glaciation, sea level, and climate change and tectonics. For Britain, the development of a sea that separates our island from the Continent is central to the evolution, as it includes not only the formation of the Strait of Dover, but also the evolution of the North Sea and the English Channel. The drainage system history begins in the Neogene. The process of connection of North Sea and English Channel commenced in the Middle Pleistocene. The OUGS lecture and this article summarising that lecture, spans the full development. Key references are provided in the captions of the selected figures.

The Quaternary Period in which we live today spans 2.6 million years and includes very high-frequency change, indeed the main characteristic of this period is climate change. During the Last Glacial Maximum (or LGM) ice sheets in the Northern Hemisphere extended across the continents into what are today temperate regions. The ice sheets, like the Fennoscandian ice sheet, the small ice sheets on the British Isles, the large Laurentide ice sheet on North America (the largest ice sheet on Earth) were present at maximum extent *c.* 20,000 years ago only and receded up to *c.* 8,000 years ago. In Britain, the ice extended as far south as the English Midlands and the northern coast of Norfolk. In fact, we are still living in an ice age, you might think, for even today there is ice over Greenland, indicating that we are still very much in 'the' Ice Age; and, of course, we humans are products of that Ice Age.

It is well established that during glacials, the accumulation of ice on the land caused lowering of the global ocean. During the Last Glacial Maximum, for example, the global ocean level stood at 120m below present level. This caused the continental shelves around Britain in particular — but around the rest of the continents as well — to be mostly exposed, and therefore Britain was not an island as little as *c.* 9,000 years ago, well into the Early Holocene (the current interglacial). With the melting of ice on

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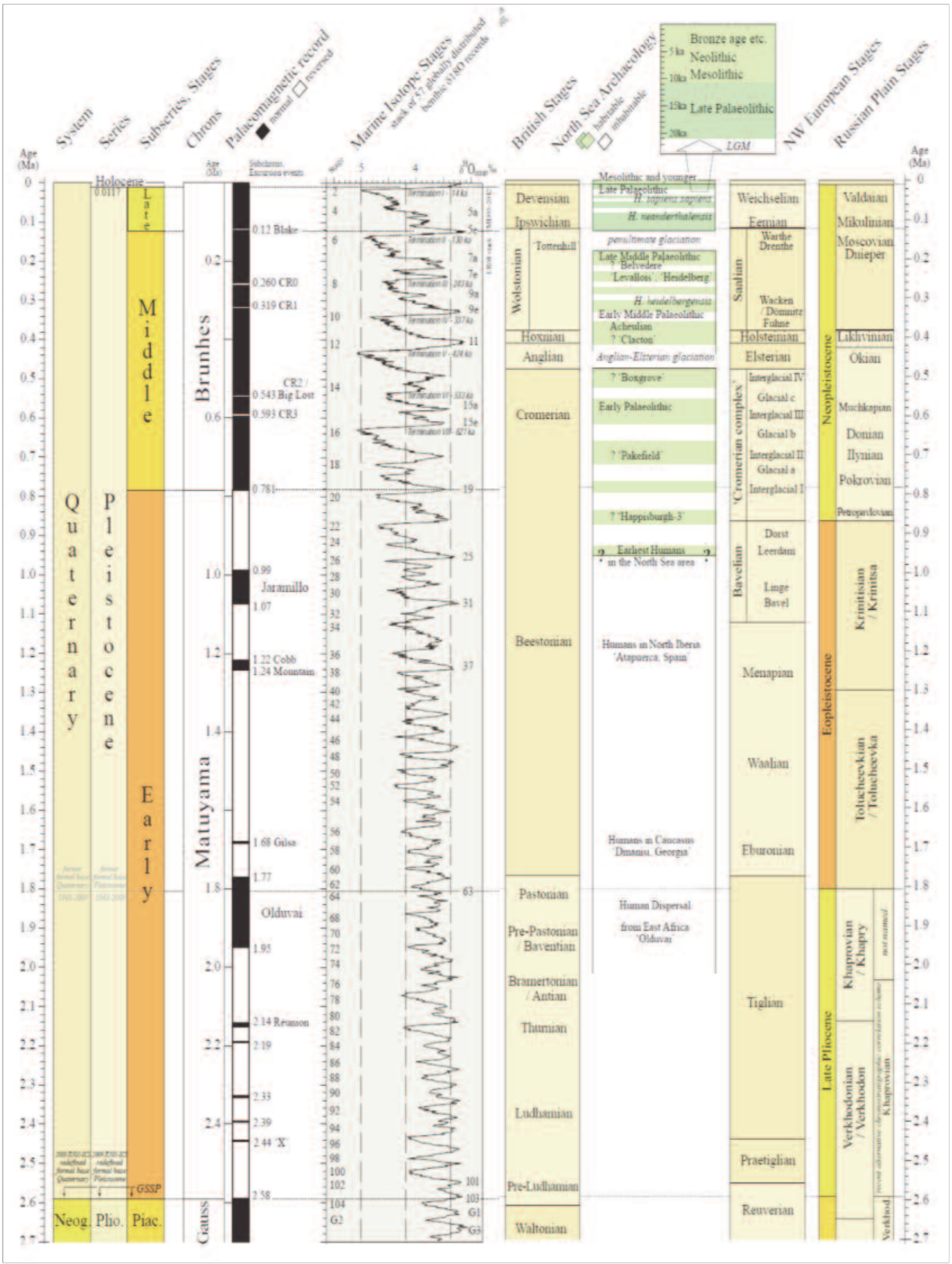


Figure 1 Chronostratigraphical correlation chart for the Quaternary, showing global divisions (IUGS International Commision on Stratigraphy), marine oxygen isotope stages from the marine record (Lisiecki and Raymo 2005), and further division schemes, including that of the regional British Stages (based on Gibbard and Cohen 2008; ICS Subcommission on Quaternary Stratigraphy).

sediment cores is critically important. It is based on measurement of the $^{18}O/^{16}O$ oxygen isotope ratio recorded in Foraminifera (value expressed as ‰ deviation to a modern seawater standard). Those data show each prolonged climate oscillation within the last 2.6 million years of the Quaternary as a continuous and well globally averaged signal. The scale of these oscillations can be seen to have increased as we approach the present day. Notably for the youngest 800,000 years, a marked increase in the intensity of climate oscillation is indicated. The time interval over which this change occurs has been termed the Middle Pleistocene transition (*c.* 1.2–0.8Ma). So, especially in the youngest part of the Pleistocene, several major northern hemisphere glaciations are evident, each separated by interglacials, or temperate periods. In these last 800,000 years, each glacial cycle shows a saw-tooth pattern, in which glacial maxima recurred every 100,000 years.

Over northern Britain and Scandinavia, ice sheets developed during these glacial half cycles. The timing and magnitude of the maximum extent of the 'glaciations' of Britain, Scandinavia and the surrounding shelves matches broadly (but does not correlate precisely) to the glacial maxima in the marine isotope record. Interspersed between those glaciations were interglacials comparable to the Holocene. By 'comparable' we mean with climate, sea level, vegetation cover and animal communities similar to those found today. Obviously there has been change through that period and physical changes of the landscape and of biota have occurred in concert. Landscape evolution and biological evolution together have led to differences between the flora and fauna of older and younger glacials and interglacials, which helps us to recognise and attribute sediments from subsequent glacial and interglacial periods.

Here we present a palaeogeographical overview of the last three million years, and this includes the periods before, during and after the formation of the Dover Strait. We feel the formation

land, at the end of every glacial and well into the interglacial, the sea level rises to a level as we see today. Indeed, sea-level change is a critical point in understanding the development of the North Sea and English Channel and will recur in our discussion of their drainage evolution. Associated with the sea-level climate change are massive biotal changes. This involved the migration of the whole biota — plants and animals — being driven by repeating glacial-interglacial cycles (Fig. 1).

The latest plot of the division of time during the Quaternary shows that there are a number of different ways in which we can define the period. Herein the marine isotope curve from deep-sea of the Dover Strait is a very critical change for Britain because clearly it had enormous implications, not just in terms of our separation from the Continent but also because it provides a boundary that plants and animals cannot cross — and that includes humans, especially when the ferries aren't running — so that is a turning point in the history of this region. Following from that, we discuss the tectonic and geomorphological setting (if you like, the dynamic tectonic-geomorphological interaction), sedimentary and palaeoenvironmental records and the reconstructed landscapes and processes that operated during this period.

The Late Pliocene to Early Pleistocene, 3 to 1 million years ago: the initial drainage pattern

We begin by discussing a map showing tectonic structural elements in Western Europe, summarising a reconstruction by Ziegler (1978). It shows three major tectonic components to have affected the distribution of land and sea, the drainage and also the glaciations in our study area. This inherited geological setting underlies the whole of the further story.

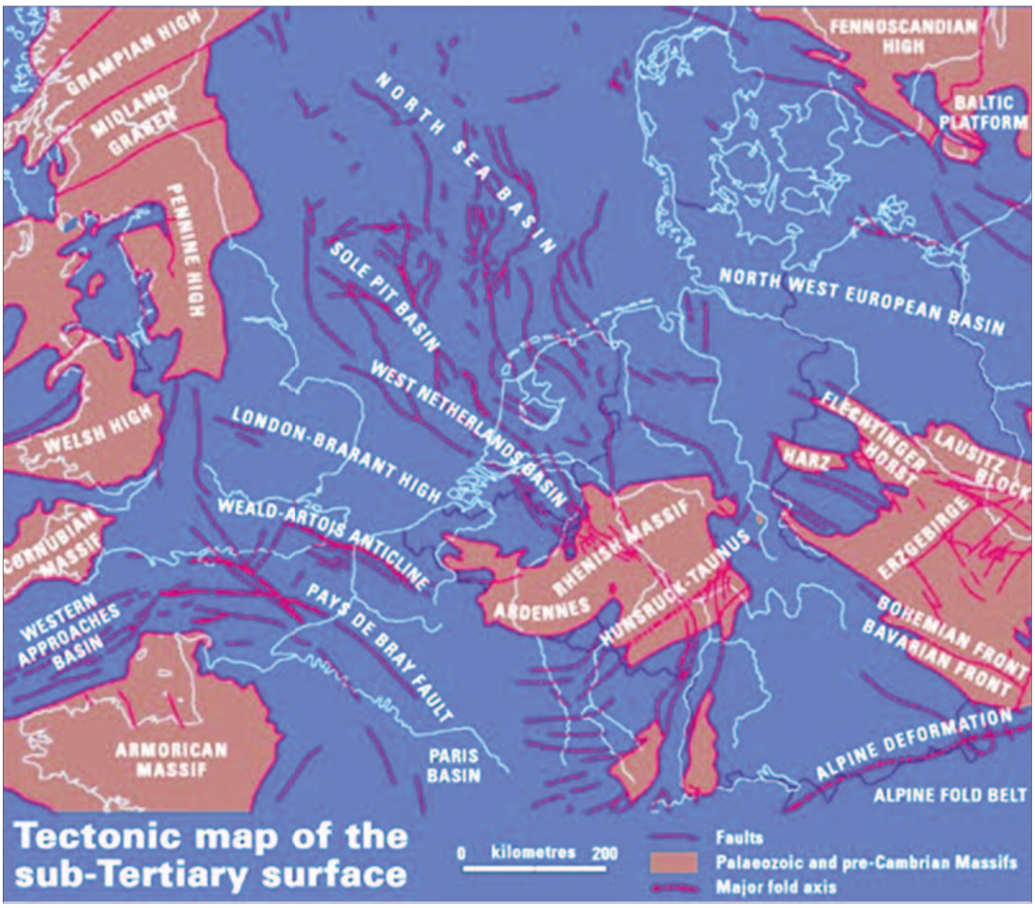
Figure 2, in orange, shows a series of massifs or crystalline blocks along the western side of the Eurasian continent (e.g. Welsh High), continuing into France (Armorican Massif). These crystalline basement areas represent uplifted blocks. There is also the important Fennoscandian High underlying Scandinavia; and similar structures forming the Rhenish Massif, the Ardennes and the Hunsrück, etc., and then to the northern Alps. These rigid blocks are mostly composed of Palaeozoic rocks. Younger geological areas between these blocks show very strong tectonic alignments. The most obvious is that aligned down the central North Sea, through the Netherlands, through the Rhenish Massif and then down the Rhine rift valley towards the Alps. This is a failed continental suture along which in a much earlier past (in the Mesozoic, when the Atlantic Ocean was opening) the continent could have rifted apart (but did not). It is still an active tectonic area: in 1992 a magnitude 5.8 earthquake occurred in the south-east Netherlands along a main fault in this suture. A parallel structure is a very large transform fault (the Fécamp Fault), which runs through the Paris Basin, continues into the Isle of Wight as the monocline and around into the Western Approaches Basin area. This gives a north-east/south-west alignment, which is associated with the opening of the Atlantic Ocean, causing uplift along the western margin. At right angles to this, are the Alpine deformation structures associated with the orogenesis of the Alps — the closing of the Mediterranean and the movement of Africa towards the European continent. This has given us a whole series of structures in a broadly east–west orientation, including the North West European Basin, which runs through Denmark, north Germany and into Poland. A particular one to note is the Weald–Artois anticline, because it links the British Isles with the Paris Basin structure and, with the London-Brabant High, underlies the zone of land that linked the British Isles area with the Continent throughout much of the Pleistocene.

Figure 3 (*overleaf*) shows the palaeogeography of three million years ago. It was originally drawn in 1988 and there are minor changes since, but the critical feature to note is that the North Sea and English Channel are not linked. They are separated by a major continental-scale 'interfluve' upland area. North of the interfluve, there is the London Basin area, drained by the Thames, which had headlands in North Wales at this time.

The structurally controlled, sub-parallel alignment of the drainage systems is noteworthy. This is because of the upland topography that during the Neogene had developed in response to uplift on the western side of Britain, in contrast to the lowland and shelf sea situation in the subsiding North Sea Basin. The latter area was a major ocean-connected shelf-sea embayment where shallow marine and deltaic sediments accumulated. South of the North Sea, drainage from the Weald towards the south is aligned into the Channel, including the major Solent River, originally identified by Clement Reid in the late 19th century.

On the continental side of the North Sea, a series of river systems can be seen. Minor river systems in Belgium, the Scheldt (or *Schelde*) and its associate streams, continue like those on the British side of the Weald, and the larger rivers Meuse (*Maas*) and Rhine (*Rhein*, *Rijn*) join from the south-east. Note that important Alpine-foreland headwaters of the Rhine only linked to the downstream parts of the system at *c.* 2.6Ma (before that time, the

Figure 2 Tectonic map of the sub-Tertiary surface (after Ziegler 1978; Gibbard 1988).



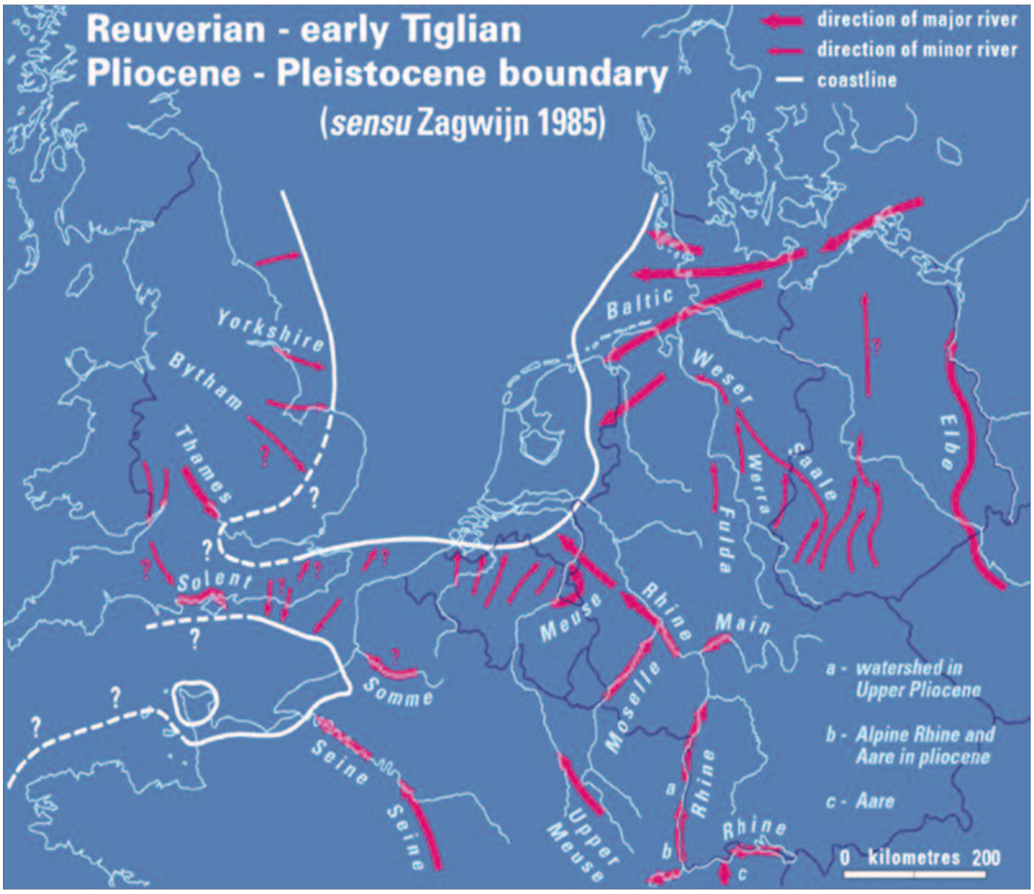


Figure 3 Drainage and palaeogeography at the beginning of the Pleistocene (after Gibbard 1988).

alpine reaches were part of the Rhône system and drained into the Mediterranean). The major drainage system at this time, much bigger than the Rhine today, was the Baltic River System, sometimes referred to as the Eridanos River. This major river ceased to exist over the course of the Pleistocene, but it had been active throughout the Neogene, building out its delta and feeding the North Sea shelf seas with sediment, filling more and more of the accommodation space and pushing the coastlines of the embayment north-westward. As tributaries, this river included precursors of the rivers Elbe (draining from Czechoslovakia) and Weser (central Germany).

In the Channel region, the Somme and the Seine were already in existence. At this time, the Seine's course included headwaters in the Massif Central. Uplift of the Massif Central, as a consequence of Alpine earth movements, caused the headwaters of the Seine to be diverted to become the headwaters of the Loire, so the Seine was effectively beheaded by this time.

From this palaeogeographical setting, in the British sequence there are Plio/Pleistocene marine sediments in East Anglia (Fig. 4, *opposite*), the so-called crags. These extend relatively far inland and up to quite high levels. In Hertfordshire they occur up to 120m above present sea level, so there must have been uplift of the western region of Britain in the youngest 3Ma. Farther east, these deposits occur at sea level and below offshore. They underlie the North Sea and the same type of system occurs on the Flemish-Dutch side within the Westkapelle Ground and Maassluis Formations (offshore and onshore, respectively). As shown by the section across the North Sea from East Anglia to near IJmuiden in the Netherlands, a substantial sedimentary wedge underlies the North Sea, reaching more than 600m thickness underneath the coastal Netherlands (Fig. 4). On the British side, the Crag Group sediments are very thin by comparison. This distribution reflects the differences in subsidence regime between the English and Belgian sectors of the Southern Bight, and the Dutch sector of the North Sea (echoing the structural alignments in Fig. 2). The Crag deposits were laid down about 2.3 or 2.4 million years ago when the Thames Basin was occupied by the sea. As time advanced into the Early Pleistocene, there was a progressive migration of the coastline towards the north. This has been tracked by the offshore mapping using the very detailed seismic techniques now available. This progressive migration of the coastline northward is mainly a result of input of fluvial sediments by rivers around the North Sea Basin, but in particular by input of sediment from the Baltic System.

The Baltic River system (the Eridanos), would probably still exist today if major glaciations had not occurred in the Middle Pleistocene. In the Early Pleistocene, the Eridanos was draining most of Fennoscandia and draining the Baltic states and adjacent portions of Russia (Fig. 5, *opposite*). The Baltic Sea area, in the Early Pleistocene was a river system, not the marine embayment it is today. This is confirmed by the massive volumes of river-delivered sediment in the central and northern North Sea. From the Pliocene/Early Pleistocene boundary onwards, in the northern North Sea we see the presence of an ice sheet on nearby Norwegian Scandinavia, as iceberg scours in seismics and as occasional dropstones in otherwise ordinary shallow marine deposits. At the same time, the Baltic River system migrated out into the North Sea and here you see the tracks of floating icebergs from floating ice present in Norway *c.* 2.5 million years ago. They track southwards: the currents would still carry ice in that direction if we had floating ice up there today (Fig. 6, *page 68*).

Beginning of Middle Pleistocene, up to 500,000 years ago: the 'Cromerian Complex'

The second period considered here is termed the 'Cromerian Complex' Stage of the end of the Early to the early Middle Pleistocene, beginning roughly one million years ago (*see* Fig. 1; Middle Pleistocene transition) and running up to the Anglian glaciation (that began *c.* 470,000 years ago). As already mentioned, during this time period, the glacial-interglacial climate oscillations were more profound than before, and this led to the development of more substantial ice sheets in northern Europe, North America and elsewhere.

There probably were glaciations in the Alps and of north Wales and certainly in Scandinavia at this time. The first of the really extensive glaciations is the so-called Don glaciation, named after

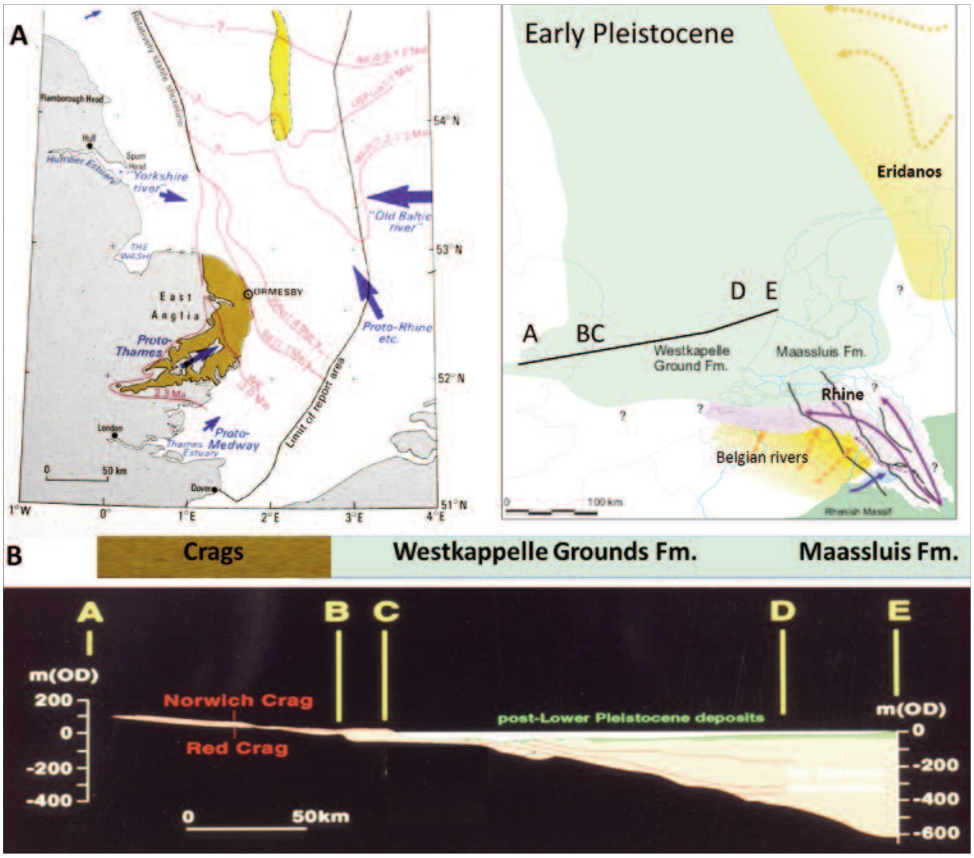


Figure 4 (A) The mapping of the Crag Group sediments and Early Pleistocene coastline migration in the British sector of the North Sea (from Cameron et al. *1992), and for the Netherlands' offshore and onshore parts of the basin (from Westerhoff 2009); (B) W–E cross-section through the Quaternary of East Anglia and the southern North Sea (teaching material © P. L. Gibbard).*

the Don Valley in Russia, about 650,000 years ago. However, before the Anglian, ice sheets did not manage to cover our region of interest. Indirectly and marginally, the Cromerian Complex glaciations did affect the study area; directly they did not yet do so. Figures 7 (*overleaf*) and 8 (*page 69*) thus show the geographical setting of the region before major glaciations occurred and affected the lowlands of the south of Britain and the south of the North Sea. They carry less detail in the Middle Pleistocene glaciated north than in the unglaciated south.

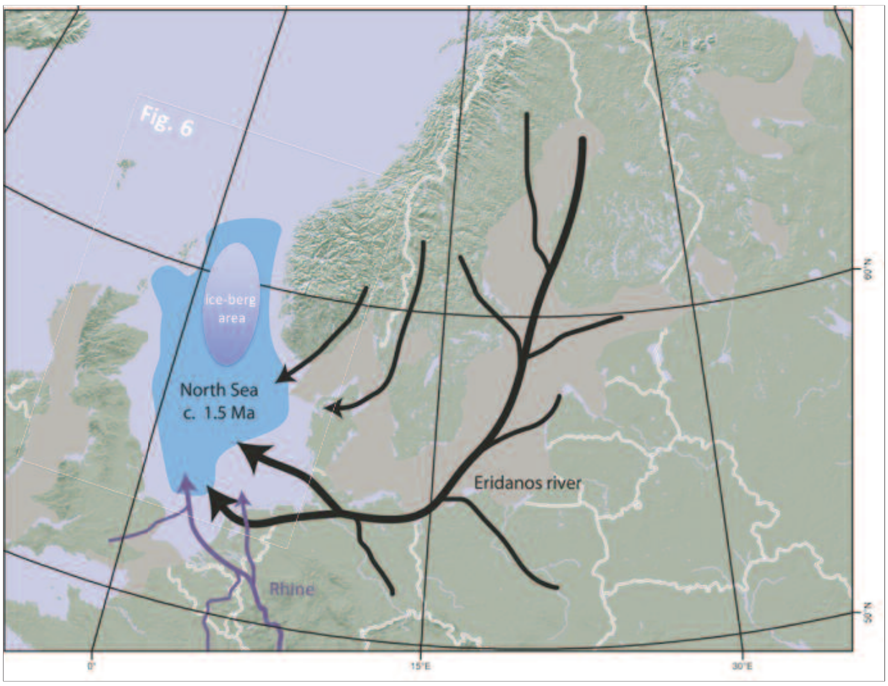
By the time of the Middle Pleistocene, the Rhine had become a significantly more important element in the southern North Sea region. The protruded Rhine deltaic complex by this time had filled the whole of the central and southern North Sea. Particularly at low sea-level stands, the southern North Sea became a major lowland area. To the south, the interfluve formed by the Weald–Artois anticlinal structure continued to be present. In the south-west, this structure of the major drainage lines still occurred, including the Thames and its tributaries from the Weald, drainage from the western side of Britain (the Midlands), possibly a Yorkshire River and rivers farther north (though these are poorly represented). On the eastern side of the North Sea, the northern (Baltic) river system by this time appears to have lost the connection to the Fennoscandian and Baltic headwaters. This implies that at this time the Baltic had been formed, as a consequence of intensified glacial erosion by the more substantial ice-sheets. Nevertheless, along this northern course within the North European Basin (*see* Fig. 2), major input occurred from Scandinavian glacial outwash, adding to the water and sediment discharge of Elbe and Weser, and in the North Sea area mixing with that of Rhine, Meuse, Scheldt and Thames.

South of the Weald–Artois interfluve the drainage systems were in the same positions as before. On the British side of the Channel, the Solent River remained a major input from the Hampshire Basin. On the southern side of the Channel, the Seine and the Somme occurred, and together with the British rivers entered the substantial Channel River system (or *Fleuve Manche*), which occurred on the floor of the basin during low sea-level stands. This Channel River would play a crucial receiving role in the drainage evolution of the region subsequently.

Ancient humans in the landscape of the 'Cromerian Complex'

At this point it is important to stress that the drainage systems and the palaeogeography described so far have been predominantly the sort that occurs during 'low-stand', or cold and glaciated periods (i.e. as shown in Fig. 7). However, intervening between the glacial, or cold-climate intervals there are also interglacial periods, like that in which we live today, which are temperate and warm (i.e. as shown in Fig. 8). Recent studies have shown the distribution of

Figure 5 Extent of the Eridanos river system in the Early Pleistocene (from Cohen et al. *2014).*



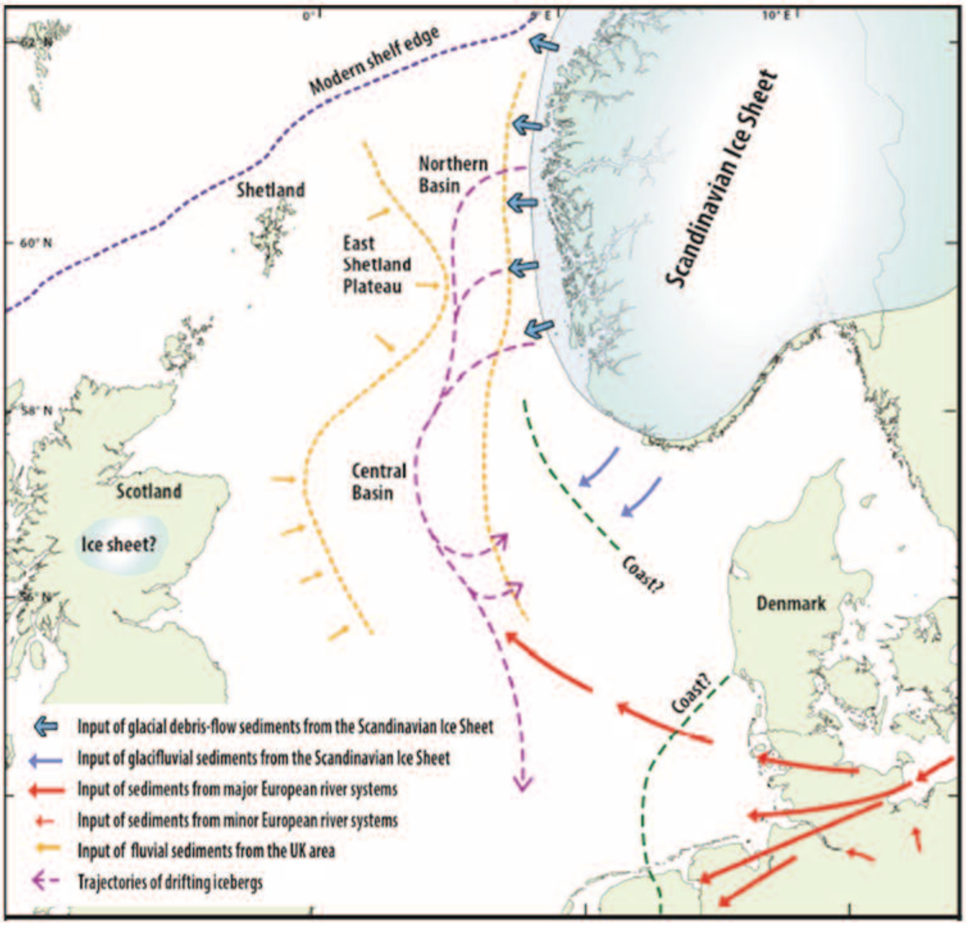
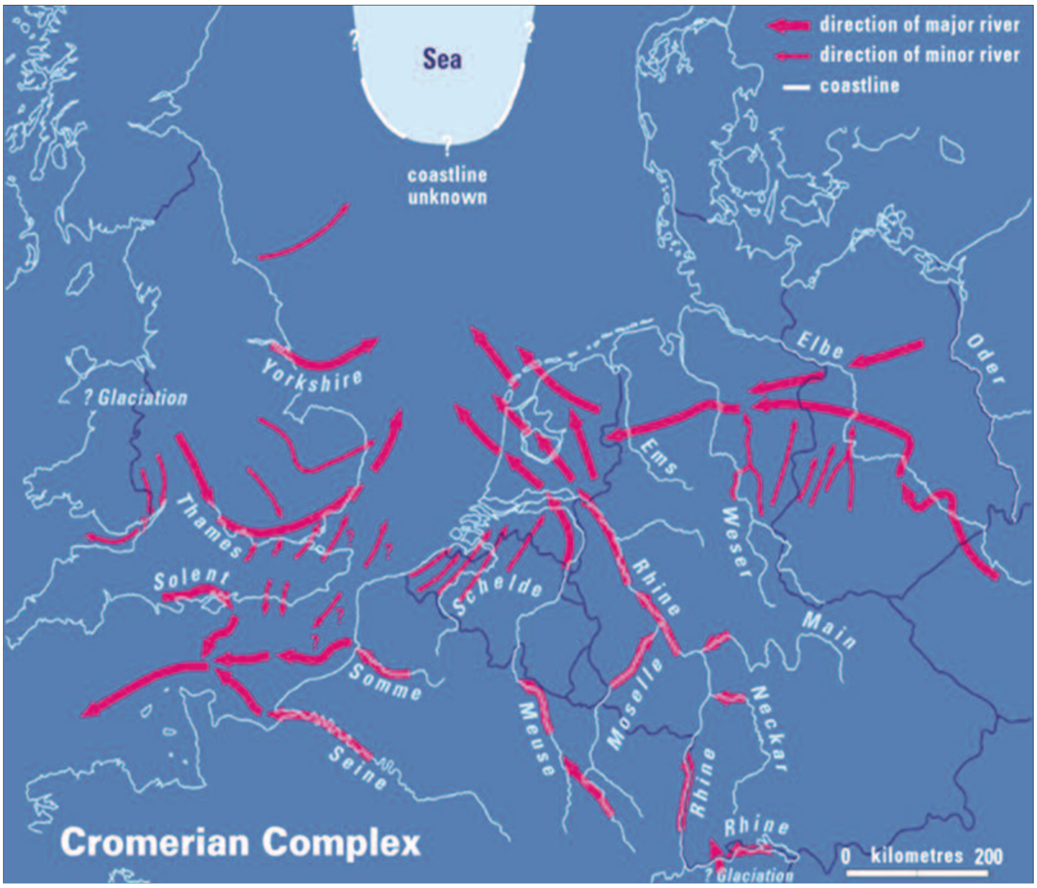


Figure 6 Early Pleistocene glacial evidence in the northern North Sea, off the Baltic River delta front (from Ottesen et al. *2014).*

Figure 7 Drainage and palaeogeography at low-stands during the Cromerian Complex Stage (after Gibbard 1988).



humans (or hominins, as not all were *Homo sapiens*), who were able to colonise our region. For example, two particular sites have been identified on the East Anglian coast — Pakefield and Happisburgh on the Norfolk coast have shown evidence of human occupation in two interglacial intervals between *c.* 600,000 and 750,000 years ago. There may be more sites forthcoming.

In central France, there are sites that could be older: some claimed to be as much as a million years old. Around the Mediterranean, similar aged and older sites are known. This would be the refuge area from which Britain was recolonised in some of the Cromerian Complex interglacials. The major Weald–Artois land bridge or link between the Boulonnais [the central land area in Fig. 8] and Sussex, Kent and south-east England was still an important landscape element during this interval. It is a predominantly chalk ridge, no doubt, carrying its own streams (Fig. 8). In the Chalk, bands of flint occur and where these eroded (cliffs, gravel beaches, river valleys) they provided a rich lithic resource for tool-making hominins.

In Britain, the most important site from this period is Boxgrove, near Chichester in Sussex. The deposits at this site represent an interglacial period, fairly late before the arrival of the ice at *c.* 450,000 years ago. It is especially important since it yielded the earliest find of human fossil bone in Britain to date. The site is associated with a fossil beach complex, which can be identified in Hampshire and on the Isle of Wight. This locality occurred at the mouth or estuary of the Solent River system. Basically, by the Cromerian Complex interval there is evidence of human occupation of the area during the interglacials, although the glacials were probably too cold for human occupation. Almost all these localities are coastal sites, at least as far north as around Britain — the late Cromerian Complex site at Boxgrove along the English Channel, and the earlier Cromerian Complex sites at Pakefield and Happisburgh along the North Sea (Fig. 8).

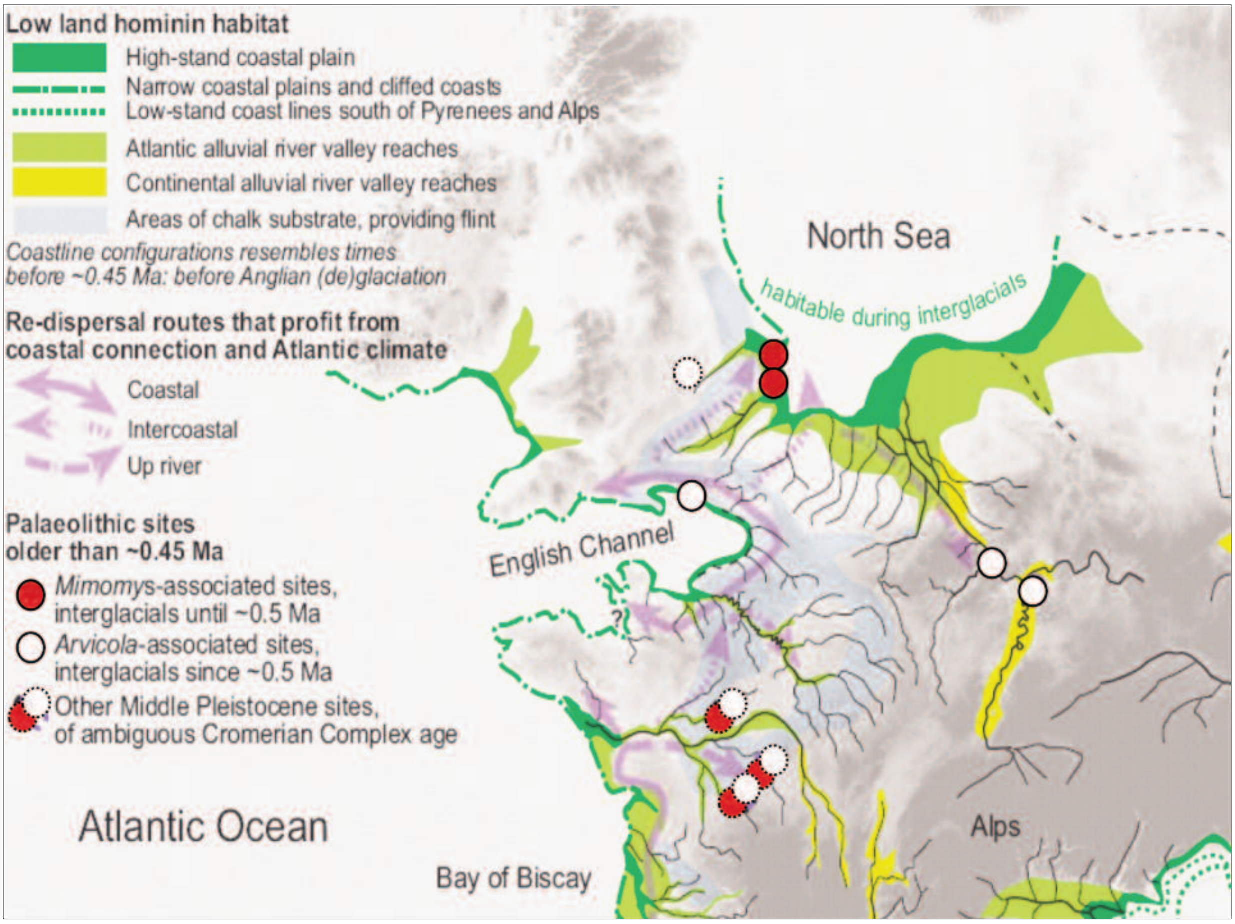


Figure 8 Coastlines and palaeogeography at high-stands during the Cromerian Compex, including presumed dispersion routes of hominins (after Cohen et al. *2012).*

Channel River, Continental shelf and Ocean floor

When the coastal and emerged seafloor environments of the Channel and North Sea are compared, it is important to understand that the geology of the English Channel is very different to that of the North Sea. The latter is a subsidence area and depocentre (*see* Fig. 4). By contrast, the Channel is floored mostly by Mesozoic and Paleogene bedrock, through which a complex of channels have been incised (Fig. 9, *overleaf*). The largest of these channels is the so-called Northern Palaeovalley. It merges with palaeovalleys of the Somme and the Seine and continues as the joined Median Palaeovalley across the deeper shelf region of the Western Channel. The confluence of all the Eastern river systems was important for incision and river terrace formation of the Southern English and Northern French rivers. At sea-level low-stands, the river entered the Atlantic Ocean between Cornwall and Britany.

From there, the sedimentary system continues as a complex of submarine canyon-like features passing sediment down the continental slope and on to the Bay of Biscay ocean floor, where there are two major abyssal fans. These fans build up as a consequence of sediment delivery down the English Channel and also down the Celtic or Irish Sea. This abyssal record has become known in recent years, since it was cored by our French colleagues (Toucanne *et al.* 2009). The relatively continuous deep-sea records from this area are critical because they provide a direct way to link Marine Isotope Stages (MIS) and pulsed sediment delivery from Britain and the Continent to the abyss. This record reaches back 1.2 million years. It shows increased sediment delivery during the glacials of the Cromerian Complex (even-numbered MIS 22 to 14). Then, from MIS 12 onwards, within glacial periods it shows major extra increases in sediment delivery (amplified amounts), from the Channel River and the shelf edge regions to the abyssal fans. This signals that a critical change occurred *c.* 450,000 years ago: For the first time, we see glaciation right across this whole region, recorded at the very downstream end of the English Channel drainage system. This tipping point in the record marks the first glaciation that directly affected the English Channel and southern Britain. This glacial period is known as the Anglian Stage.

The Anglian, 450,000 years ago: opening of the Dover Strait begins

Critically important sedimentary evidence of the glaciation covering most of Britain *c.* 450,000 years ago exists across East Anglia. The oldest glacial diamicton is the so-called Happisburgh Diamicton (Fig. 10A, *overleaf*). It has a characteristic grey colour, and contains mostly local lithologies and silt derived from the floor of the North Sea. It was deposited by ice that crossed the North Sea. It contains very characteristic crystalline rocks, including, in particular, larvikite and rhomb porphyry, which are erratics derived from the Oslofjord area of southern Norway. During this initial stage of the glaciation the ice rode up on to the British landmass and deposited this material. It is overlain by lacustrine meltwater sediments.

Associated with the diamicton are glacial lake sediments (Fig. 10B). Sometimes these characteristically laminated deposits are called 'varves', but technically they are rhythmites, because varves are laid down annually. If it cannot be demonstrated that they were laid down annually, although they are probably annual,

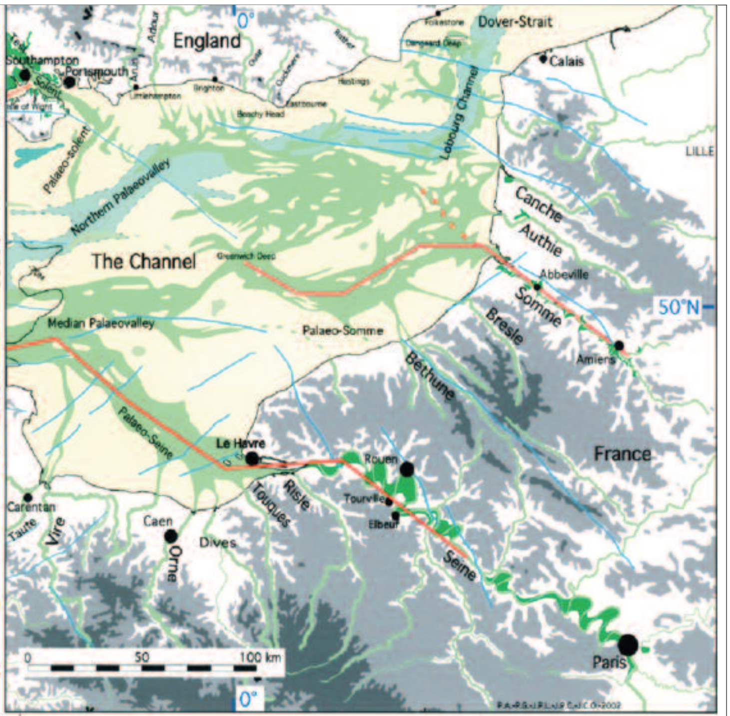
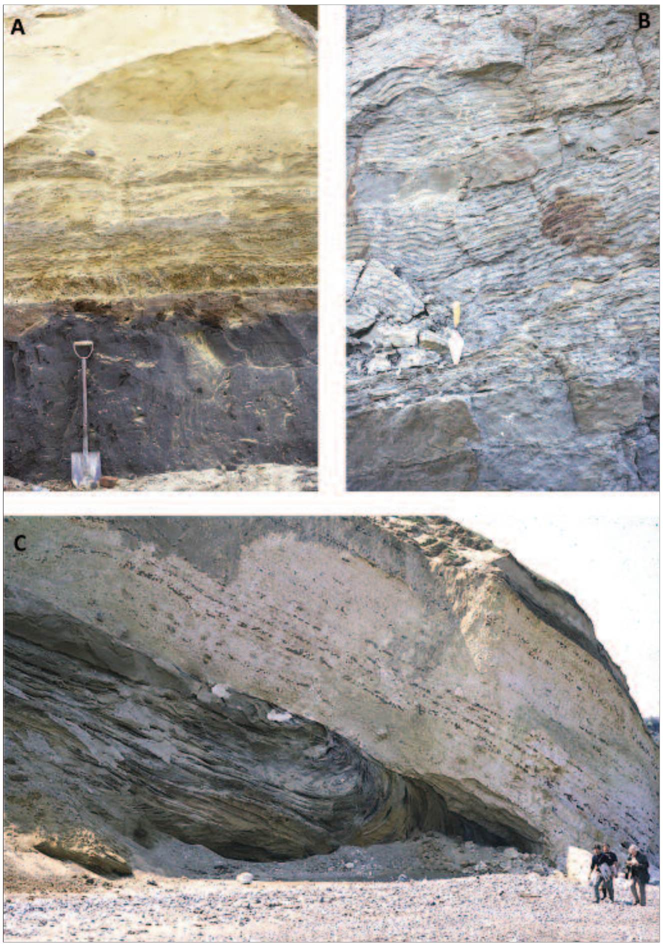


Figure 9 The Channel River drainage system (from Antoine et al. 2003).

Figure 10 Photographs of glaciogenic deposits of Anglian age from the base of cliff sections at Happisburgh and Sidestrand, Norfolk coast: (A) North Sea Drift Formation, Happisburgh Diamicton Member and overlying outwash sand; (B) Rhythmite (varved) glacio-lacustrine laminated deposits grading to waterlain melt till at the base; (C) Glaciotectonic thrusted block of Chalk (flint banding in place) (spade, trowel, people for scale; photographs by P. L. Gibbard).



the complication is avoided by using the more general term rhythmites, or laminated sediments. Associated with these ice-front, lake-rim sediments are stratified diamictons. Diamicton laid down on the land under a glacier is normally massive. Therefore when a glacial diamicton is stratified, another explanation must be sought. The explanation here is that the diamicton was laid down from floating ice, i.e. its occurrence indicates an ice front terminating in a meltwater-ponded foreland. The wet ice-margin deposition is also accompanied by glacial tectonics, a text-book example of which is the Sidestrand thrust block (Fig. 10C). The direction of overthrusting of this block and many like it in the Norfolk cliffs is an indication of ice advance from across the North Sea and, because of the erratic clasts, likely all the way from Norway.

The advance of the ice sheet across the North Sea produced the inevitable. If all the drainage systems were blocked by ice from Scandinavia entering Britain, the water was prevented from escaping to the sea. The presence of upland topography (Weald–Artois anticline, *see* Fig. 2) between Kent and northern France (*see* Fig. 8) caused an extensive lake to form between the ice sheet in the north and the land barrier in the south. The water-laid deposits from along the ice front at Happisburgh, would be from a north-western corner within the massive lake.

At a lowest point along the southern rim of the lake, it ought to overspill, and this would have happened into what is now the Strait of Dover (*Pas de Calais*). This idea, originally by Thomas Belt (1874, a letter published in *Nature*, and discussed in correspondence between Alfred Wallace and Charles Darwin), explains the major change in palaeogeography seen before and after the Anglian glaciation (Fig. 11, *opposite*), and connects the glacial sedimentary evidence of East Anglia, the geomorphology encountered in the Dover Strait, and that from the abyssal fans off the English Channel.

Just before the proglacial lake ponded and overspill began, the still very similar morphology and elevation of the periglacial chalk landscape of Kent and across to Picardy in France, was

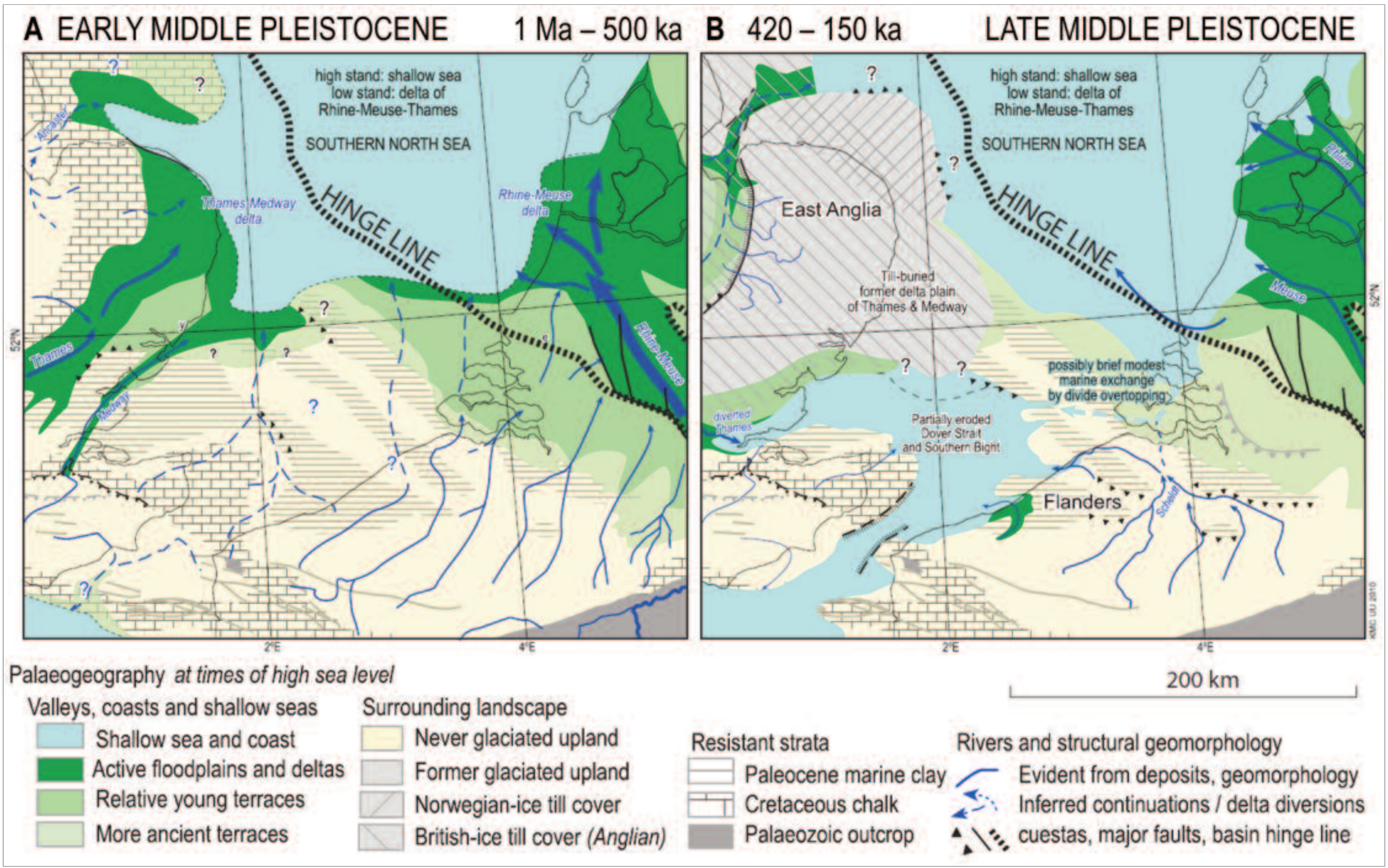


Figure 11 Contrasting palaeogeography (high-stand situations) before and after 450ka (scenario maps from Hijma et al*. 2012; Cohen* et al*. 2014).*

continuous from Dover to Calais on the two sides of the Strait — also in elevation. A saddle-like topographic feature in the Chalk hill topography, along the drainage divide separating local rivers draining to the north and the south, would have functioned as the sill for the spillage. To the north, the lake maintained a water level held up by the elevation of this saddle. Estimates of its height are tentative — as it is now eroded — but it should be below the lowest such saddles surviving in adjacent Kent and Picardy, and lows in the topography of the Holocene backset cliff section on either side of the channel give some handle on this elevation. Figure 12 (*overleaf*) shows the extent of the Anglian lake, assuming a former Dover Strait saddle at *c.* 30m above present sea level.

Once Anglian lake overspillage set in, it began to erode the chalk ridge, and a spillway channel incised, deepened and widened the saddle. With proceeding erosion, the saddle position retrograded northward and at some point in this process, it no longer was held up by Chalk, but by the younger Paleogene deposits such as the London Clay. The bedrock geology of the stripped floor of the Strait of Dover today indicates the location off Belgium, where the retreating saddle would have changed substrate. Projecting the seafloor geology (at 30m to 50m depth today) upwards to the level of the former saddle and the modern cliff tops, indicates some 70m of Chalk bedrock to have been eroded since the Anglian began, more than some 32km wide. Similarly, some 45m of Paleogene 'bedrock' has been eroded, more than 180km wide — representing an even larger volume. Such quantities of sediment are not found in the North Sea deposits to the north, and therefore the majority must have been evacuated southward, via the Channel River and ended up in the lower shelf, shelf front and abyssal fans.

The Saalian (Wolstonian), culminating 160,000 years ago: opening of Dover Strait completed

Importantly, this dramatic erosion of the Strait of Dover area is not thought to have taken place during one, but during two major episodes of glacial erosion. In the first, 450,000 years ago and associated with the Anglian glaciation, substantial erosion took place there, but time was insufficient for removal of all the bedrock ridge structure. This is the reason why a remaining land bridge, which the sea levels during the interglacials after the Anglian (such as that of the Hoxnian, *see* Fig. 1) could hardly overtop, is depicted in the scenario maps in Figure 11. It took a second major glaciation of the southern North Sea, rivalling that of the Anglian in extent (Fig. 13, *overleaf*), to form a proglacial lake again, restarting the retrograding proglacial erosion process, and finishing the job of fully connecting the North Sea and English Channel drainage.

This second event occurred 160,000 years ago during the glaciation termed Wolstonian in Britain and Saalian in the Netherlands (within MIS 6; *see* Fig. 1). During this phase, British ice lobes reaching as far south as the Fenland in eastern England met once again with Scandinavian lobes coming down across the North Sea. On the Dutch side of the North Sea Basin, the Saalian glaciation reached farther south than any glaciation before (what the Anglian glaciation did on the British side). It reached a maximum limit across the centre of the country almost to the River Rhine, which formed an ice-marginal stream of the Saalian ice sheet (just like the Anglian ice did with the Thames).

An important indication that at the beginning of the Saalian glaciation a topographic ridge still existed across the southern North Sea to the south of the ice-front are the contemporaneous

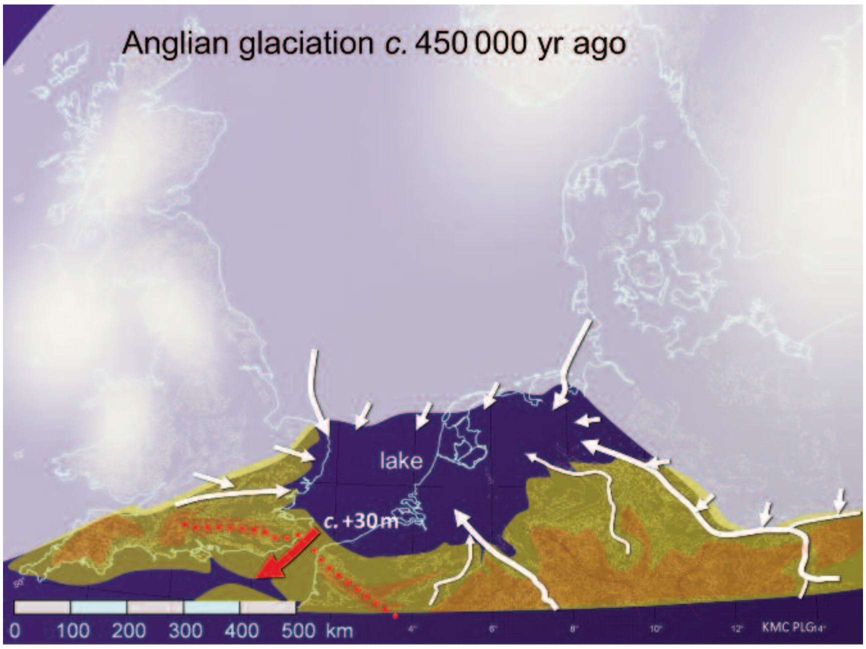


Figure 12 Proglacial lake extent as envisaged for early stages of the Anglian, leading to initial breaching of the Strait of Dover (after Gibbard 1995; Cohen et al. *2005; Gibbard 2007; Cohen* et al. *2014).*

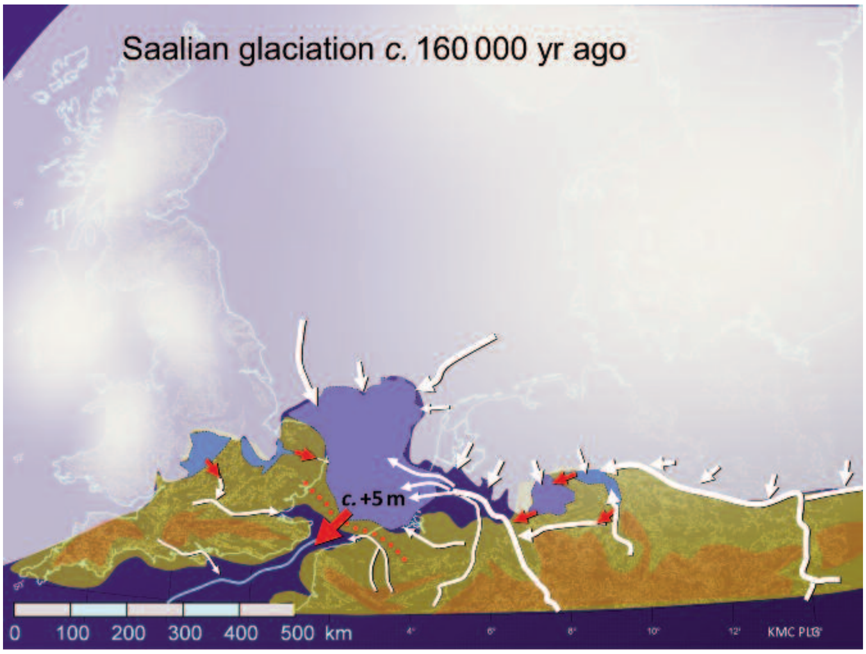


Figure 13 Proglacial lake extent as envisaged for the Drenthe Substage of the Saalian, completing the breaching of the Strait of Dover (produced for OUGS symposium and for this publication, to complement Fig. 12; it incorporates reconstructions for the Saalian ice front from Busschers et al. *2008 (Netherlands); Meinsen* et al. *2011 (Germany), Moreau* et al. *2012 and Hijma* et al. *2012 (southern North Sea) and from Gibbard* et al. *2009 for the Wolstonian of East Anglia).*

braided-river deltaic features from the ice-marginal River Rhine. This delta must have formed in a standing body of water, so there is evidence for a proglacial lake. The elevation can be traced in the geological mapping of the western Netherlands, and grades to a base level estimated at *c.* +5m (after accounting for background subsidence in this part of the basin, e.g. *see* Fig. 4). By coincidence, the Saalian ice-lake delta terminates near the present coast. Dissecting features from subsequent stages signal effective base levels at least 10m deeper, showing that erosion quickly proceeded. These can be traced across the North Sea floor (*compare* Fig. 11B with Fig. 14A). Mapping of the North Sea floor between the Netherlands and Britain has recently been updated using seismic geophysical methods, showing the Saalian ice-limit and showing clinoforms next to it, from glacial outwash deltas into the same lake (at comparable depths of preservation as the Rhine lake delta). Also, the abyssal record off the English Channel continental slope shows a sediment delivery peak in MIS 6 (at *c.* 160,000 years ago) that rivals that of MIS 12 (at *c.* 450,000 years). All of this is strong evidence for the contemporaneous occurrence of a lake during maximum glaciation Drenthe Substage in the Saalian (and equivalent part of the Wolstonian).

If the Saalian and Anglian ice lakes are compared, there are differences in the precise positions of the ice limit, and there is a difference in the elevation to which each lake would fill and spill over. Despite this, essentially the Saalian spillway erosion is envisaged to have continued where Anglian overspillage had stopped.

That erosion of the land bridge stopped suddenly towards the end of the Saalian is found in two particular characteristics. The first is that the ice-lake would have no longer used the southward spillway, as soon as the Scottish and Norwegian ice masses up north were no longer coalescent. At that point in the deglaciation history of the Anglian, the North Sea ice lake would have quickly drained northward, rapidly dropping the lake level and exposing a good part of the former proglacial lake floor as dead-ice terrestrial landscape. The second characteristic is the diversion of the River Thames, caused by expanding British ice lobes in the Anglian following deposition of the Happisburgh Diamicton. These glacial events over Essex and Suffolk positioned the new Thames Valley south of where the saddle would survive, and covered up pre-diversion valley pathways across the land bridge with considerable thickness of 'Lowestoft Formation' tills (*see* Fig. 11B). The two events together explain that once Anglian lake spillage ceased, there was no substantial post-Anglian river system that kept the land bridge under attack. So, during the second major glaciation, some 300,000 years after the first, proglacial spillway erosion could resume and finally destroy the remnants of the land bridge and fully connect the North Sea to the English Channel.

A last important difference to note is that in composition and erodibility the saddles holding up the Anglian/Elsterian and the Saalian lakes are not comparable. The land bridge present in Saalian/Wolstonian was much lower and narrower than that during the Anglian. It was no longer made of Chalk, but of London Clay (or similar Tertiary sediments). The ridge was therefore more easily eroded. It is likely that the final stages of the destruction of this land bridge were really rapid and potentially dramatic. The lake may have not simply drained, but flushed out southward into the Channel River. There is good geomorphological indication for a catastrophic magnitude of this event in Gupta *et al*.'s 2007 paper in *Nature*. This shows detailed bathymetric mapping of the English Channel in which a deeply incised channel (the Northern Palaeochannel) includes streamlined islands cut into Chalk bedrock. The islands are streamlined with some younger drainage carved into them. This morphology indicates very fast flowing water, which almost certainly resulted from the breaching of the last remaining part of the land bridge, producing very fast erosion. Finding other than geomorphological evidence in the English Channel is difficult because it has all been stripped of sediment.

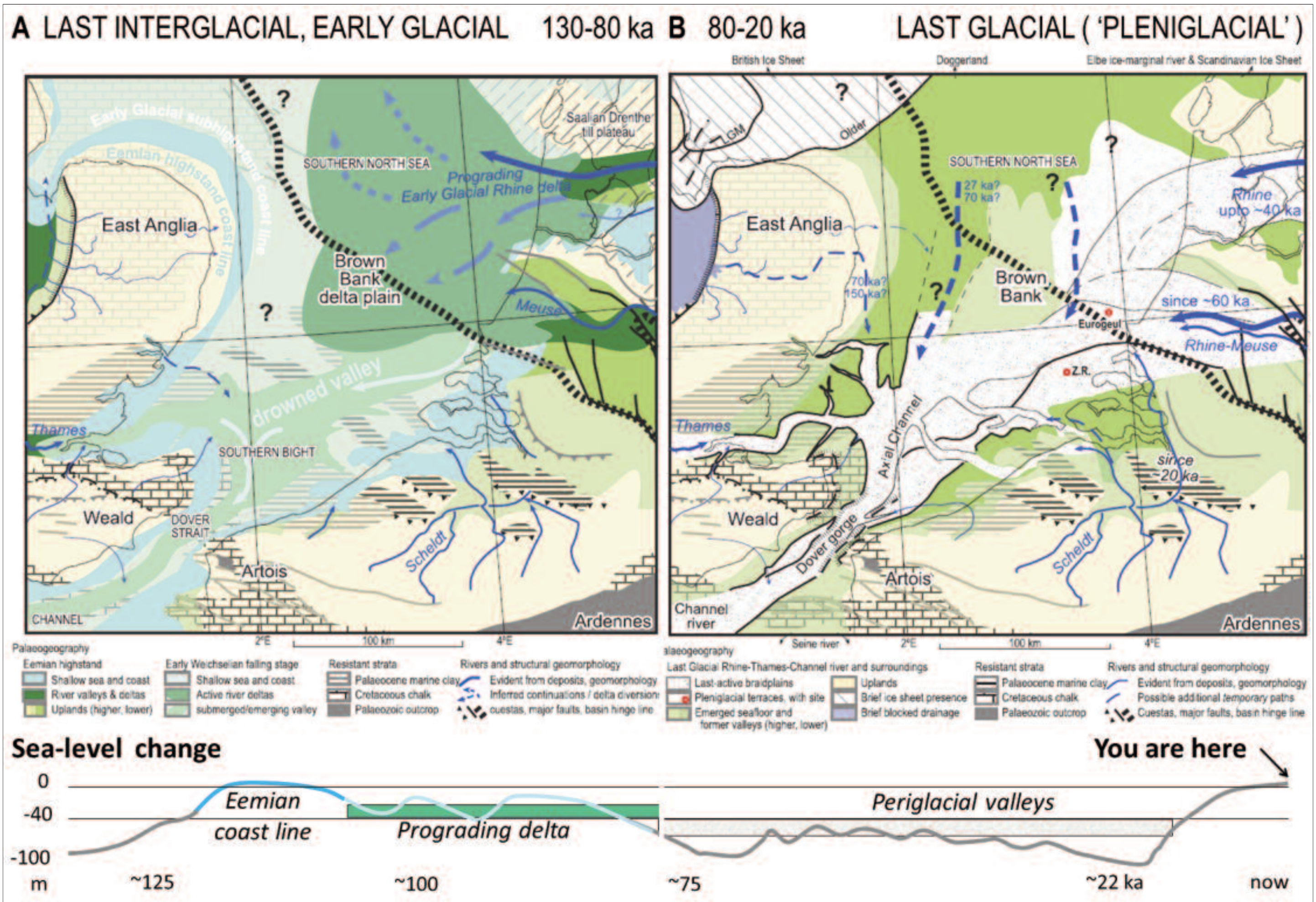
So, there was potentially a catastrophic flood, but this is not the principal point in this review. The main point is that the full opening of the Strait of Dover is the result of major big glaciations, with two proglacial lakes in the Anglian and in the Saalian/Wolstonian phases. Each of them must have existed for perhaps 5,000 or 10,000 years, during which time excess water gently spilled over the bounding barrier, before that barrier was finally removed. It is interesting to note that the cold periods between the Anglian (Elsterian) and Wolstonian (Saalian) (i.e. MIS 10 and 8) seem to have been characterised by less-extensive glaciation, the drainage of the southern North Sea region apparently remaining unmodified throughout this interval.

The opening of the Strait of Dover is portrayed as a story of glacial erosion, in the absence of man, but it is linked to the interglacial situations that are of great importance to the Palaeolithic archaeologist. From *c.* 800,000 years ago, episodic human occupation of the region had begun. At that time the land bridge provided a crucial link between what is now Britain and what is now the Continent. In the time between the Anglian and Saalian glaciations — 'the interbellum' — humans were also present in the region, while the land bridge had altered but, critically, not disappeared. Different paths for migrations and access to lithic resources were available to humans after the Anglian than were available before it (*compare* Fig. 11B to Figs 8 and 11A).

The Late Pleistocene, Holocene, and future: aftermath of the opened Dover Strait

Following the Saalian glaciation, the Last Interglacial began *c.* 130,000 years ago. This was the first time that the Southern Bight of the North Sea had a coastal outline that is comparable to that of the Holocene. Last Interglacial humans (Neanderthals at this stage of human evolution in our area) occupied continental Europe, but no humans appear to have been living in England. This was because they were unable to cross the seaway that, in this interglacial, first formed a significant barrier. Although the Last Interglacial was relatively short (*c.* 12ka, the sea-level high-stand lasting just *c.* 6ka), it was followed by slow sea-level fall with the Rhine delta building out into the North Sea (Fig. 14). As the sea-level fall proceeded into the last glacial, finally the first glacial occurred where a river larger than the Thames passed through the Dover Strait for the entire duration of the sea-level

Figure 14 Palaeogeography during the last glacial cycle, sea-level high-stands in the first half, and sea-level low-stand in the part after 80ka (scenario maps from Hijma et al. *2012; tentative sea-level curve for the periods added by the authors).*



low-stand (*c.* 100 ka). This Rhine-Thames river made use of a gorge-like valley that it had inherited from the Saalian glaciation. During shorter periods within the Last Glacial, meltwater from British and Scandinavian ice fronts well to the north of the study area would also have spilled south towards the study area, but this was probably only episodically, and for most of the time that outwash drained north. If we disregard the brief episodes of maximum glaciation and ignore periods of sea-level high-stands, then it is already 450,000 years ago that the Thames became connected to the Channel River, but it is only 130,000 or so that the Meuse and Rhine did so.

Now, what about the future? When a next glaciation, with ice coverage comparable in coverage to that of the Anglian occurs, no glacial lake will be formed. The North Sea and the Channel of the future will certainly look different from today; how different will depend on the erosion and deposition around our coasts. For example, the Dover Strait might be expected to be progressively widened by erosion during sea-level high-stands.

The final critical point is that this presentation is entitled ‘Quaternary evolution’: ice ages come and go, climates oscillate between cold and warm, and vegetation migrates and more or less regenerates in each interglacial. However, what is not the same is the landscape, because there is erosion as well as deposition during each glaciation, the effects of which are not repaired in non-subsiding areas. The landscape of the future will be inherited from our situation today and its evolution will proceed from there. The Strait of Dover provides graphic evidence of this.

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