1. Introduction

The recognition that the present landscape is a product of the long-term interaction of tectonics and climate is one of the fundamental concepts in historical geoscience. Determining the response of the environment to these changes has been further emphasised by attempts to understand the relationship between rates of tectonic activity and sedimentation or erosion and the interplay of these factors with climate change (e.g. Cloetingh et al., 2005). Moreover, the dynamic linkage of erosion and tectonics results in major impacts on changes of the Earth’s climate through the evolution of major continental topography and vice versa.

The form of the Earth’s topography actually results from the net interaction of processes operating at a wide range of time scales. These include long- and short-term tectonic uplift, subsidence, phases of glaciation, and climatic and environmental changes. In northern Europe, these processes, operating simultaneously through the Cenozoic, have left a record of changing conditions that have determined the form of the present landscape. The emphasis recently has been on relatively short-term interactions involving quasi-simultaneous uplift followed shortly by incision, paced alongside Late Pleistocene marine isotope stages, and interacting with climatic fluctuations. Here we take a longer view, that of Cenozoic uplift and tectonics results in major impacts on changes of the Earth’s climate through the evolution of major continental topography and vice versa.

The Cenozoic fill of the North Sea basin has been the subject of especially intense investigation during the last 40 years as a consequence of the discovery of major oil and gas reserves in the North Sea Basin depocentre, north of the Dogger Bank. Fragmentation of the North-west European Basin in the Quaternary led to the formation of the Baltic Sea, but this depression, by contrast, originates from a combination of fluvial and later glacial erosion initiated in the Oligocene (cf. below).

In contrast to the North Sea, the Baltic Sea occupies an enclosed epicontinental depression between the Scandinavian Peninsula, Finland, the Baltic countries, and the North European Plain (Fig. 1). It stretches from 53°N to 66°N latitude and from 10°E to 30°E longitude. The sea is linked to the Atlantic Ocean and the North Sea, between the Danish islands and the Kattegat via the straits of Øresund, the Great Belt and the Little Belt. Geologically the Baltic Sea resembles a river valley complex, with two tributaries, the Gulf of Finland and Gulf of Bothnia. Geological surveys show that before the formation of the Baltic Sea, a wide plain was occupied by a substantial river termed the Eridanos or Baltic River system (cf. below). In contrast to the North Sea, the Baltic basin today contains a maximum of ca. 100 m of sediment, although in the south-west the basin may contain especially intense investigation during the last 40 years as a consequence of the discovery of major oil and gas reserves in the North Sea Basin depocentre, north of the Dogger Bank. Fragmentation of the North-west European Basin in the Quaternary led to the formation of the Baltic Sea, but this depression, by contrast, originates from a combination of fluvial and later glacial erosion initiated in the Oligocene (cf. below).

The evolution of the North Sea basin region throughout the Cenozoic occurred against a tectonic regime resulting from the fragmentation of the Eurasian-North American plate, and Alpine orogenesis (Knox et al., 2010; Cloetingh et al., 2005).
The break-up of the northern hemisphere plate, along the North Atlantic mid-ocean ridge spreading centre, gave rise to tensional or extensional features, whereas Alpine mountain building, arising from continental collision between the Eurasian and African plates, produces compressional features. Although the North Atlantic margins had been regarded as ‘passive’ (cf. Ziegler, 1978; 1987; 1994; Dewey, 2000; Knox et al., 2010; Anell et al., 2009), active tectonics led to widespread reactivation of older structures, particularly those of Variscan origin, with the Norwegian Atlantic coastal area undergoing substantial vertical movements during the Cenozoic (Cloetingh et al., 1990) (Fig. 1). The interplay between these two processes resulted in structural and depositional palaeogeographical changes through the period (Cloetingh et al., 2005).

2.1. Paleocene

Following the end of the Cretaceous, the North Sea region saw carbonate sedimentation continue into the Early Paleocene Danian Stage. However, regional uplift occurred arising from underplating of the continent associated with the rise of the Iceland mantle plume combined with north-westward-directed compressional stresses (e.g. Brodie & White, 1994; Ziegler & Dezes, 2007; Hillis et al., 2008). This late Early Paleocene uplift (the ‘Laramide’ Phase) was followed by a second period of regional uplift in the latest Paleocene, shortly before the continental suture formed between Greenland and Scotland. Significant uplift of Scandinavia also occurred periodically throughout the Paleogene (Clausen et al., 2000) giving rise to drainage directed to the south and southwest. Likewise, uplift events of the East Shetland Platform and the Scottish Highlands, led to the development of drainage aligned towards the east (Hall & Bishop, 2002). This resulted in discharge of substantial sand-rich sediment into the Northern North Sea basin and over 1000 m-thick sedimentation in the Outer Moray Firth Basin during the Late Paleocene and earliest Eocene interval (e.g. White & Lowell, 1997; Anell et al., 2012).

According to Hall et al. (2015), stable isotope ratios in kaolin from weathered clasts in quartzite- and flint-bearing fluvial gravels and from clay-rich saprolites, developed in igneous rocks, indicate weathering in north-east Scotland took place under Paleogene humid tropical climates. A substantial landmass area was actively dissected by both mechanical and chemical, subaerial denudational processes, with recycling of a thick weathering mantle material arising from long exposure (Gibbard & Lewin, 2003). Correlation with offshore sediments indicates that the Buchan Gravels were deposited by the rivers that supplied the western North Sea Paleocene–Early Eocene deep-water sand fans.

By the Late Paleocene Thanetian Stage, the sea had extended over much of eastern England, with the coastline aligned north–south down the eastern side of the modern Pennines (Knox, 1996;
The Thanetian sediments of the southern margin are mostly of shallow-marine slightly glauconitic sands, restricted to the eastern part of the London Basin but with equivalents in Belgium and the Paris Basin. Throughout much of southern North Sea region land areas were of low relief, with south-eastwards-aligned drainage in SE England (Murray, 1992), guided by general subsidence of the area. The continental deposits to the east indicate that continued relative uplift of the North Polish Platform was occurring at the time.

During this time the rivers apparently adopted flow channels dominated by sands with fine-grained abandoned channel fills. Mottled clays, pedologically modified and associated lignitic units, and sedimentation typically found in vertically-accreted floodplain sequences, are associated with fining-upward channel fills and point-bar accumulations in the Thames Basin. The clay-clast breccias typify meandering river sediments in tropical regions (Miall, 1996). Where the rivers have cohesive banks and densely-vegetated floodplains, they predominantly transport fines, but also coherent blocks of bank material eroded during floods (Gibbard & Lewin, 2003).

### 2.2. Eocene

The opening of the North Atlantic Ocean basin was accompanied by renewed thermal subsidence of the North-west European Basin. This initiated more widely distributed, thick Eocene successions, the principal depositories being the Viking Graben, the central North Sea and northern Germany. Eastwards progradation from the western margin of the basin also occurred in the southern North Sea. Widespread deposition in this region of London Clay occurred during the Ypresian, supplied to the basinal areas by the rivers from the north and west (Fig. 3). The products of the continued earlier weathering replaced the major erosion phases seen earlier. This clay-dominated deposition was terminated by a rapid expansion of fluvial delta complexes towards the east in the late Ypresian-Lutetian (early Middle Eocene), the sediments consisting of cross-beded sands, with thin clay or silt partings and thin pebble beds, becoming considerably coarser towards the west (Knox et al., 2010).

The early Eocene climate of the region was very warm, the land to the north, west and south supporting dense tropical to subtropical and warm-temperate forests, with mangrove swamps on the coasts (e.g. Reid & Chandler, 1933; Anderton, 2000; Collinson & Cleal, 2001b). In higher regions to the west, north and east an ‘upland flora’ may have flourished, but temperate elements were also well represented (e.g. Daley, 1972). According to Daley (1972) the flora shows strong general affinities with today’s Malay Peninsula, characterised by high levels of precipitation and environmental stability. The nature of the land surface during the early Eocene appears to have continued to be subdued (e.g. Wells & Kirkaldy, 1966; Daley, 1972). The region was characterised by slow subaerial degradation under conditions of intense chemical weathering. The vast volumes of clay owe their origin to extended weathering in the catchments of rivers flowing from the more distant, higher-ground areas (Gibbard & Lewin, 2003).

During the later Paleogene the Baltic region may have been occupied by the sea (Kramarska et al., 2004; Kramarska, 2006). A northerly origin of epidote-rich heavy-mineral assemblages
in the associated sands implies derivation from the Devonian sandstones of the northern Baltic States (cf. Rattas & Kalm, 2001) which were land at this time. Uplift of the southern and western basin margins brought this sedimentation phase to a close in latest Ypresian times with a major influx of sand into the southern basin-marginal areas. This sediment is thought to reflect uplift associated to renewed convergence of the African and European plates, at ca. 51 Ma (Dewey & Windley, 1988). Further uplift continued into the early Lutetian in the southern North Sea, with the replacement of marine by paralic facies on the North Polish Platform, and a loss of the connection with the eastern Atlantic. Later subsidence of the southern and western marginal highs followed, leading to progressive transgression of the southern and south-western margins and a return to predominantly fine-grained sedimentation (Knox et al., 2010).

Significant palaeogeographical changes during the late Middle Eocene occurred as a consequence of uplift of western Britain and France (Fig. 4). These changes were superimposed on a eustatic sea-level fall. Along the western North Sea basin margin, shallow-marine sands extended eastwards beyond the Sole Pit inversion zone. Clay deposition was brought to an end by a rapid expansion of fluvial delta complexes towards the east in the late Ypresian – Lutetian (early Middle Eocene) (Wells & Kirkaldy, 1966; Anderton, 2000). There is some disagreement concerning the situation in the Baltic region. Whilst it is generally considered that the region was submerged by a Baltic Seaway, (King, 2008 in Knox et al., 2010), others (e.g. Jaworowski, 1987) point to the deposition of amber-bearing sands in northern Poland which indicate a south-eastwards delta that prograded from the Fennoscandian landmass during the late Eocene. This input suggests a possible Baltic River system precursor (cf. below). The latest Eocene was marked by regional uplift associated with the Pyrenean tectonic phase. This uplift was accompanied by local inversion of Mesozoic basins, which led to widespread marine regression from marginal areas.

2.3. Oligocene

The transition from the Eocene to the Oligocene is associated with a marked change in the pattern of uplift and subsidence in northwest Europe, reflecting a change in the regional stress regime. The complex pattern of sedimentation that characterised the Eocene was replaced by a more uniform pattern of basin-centred sedimentation. This change arose as a consequence of uplift of the western and north-eastern basinal margins (Knox et al., 2010).

Following Early Eocene crustal separation, the Mid-Norway margin was partly inverted during the Late Eocene–Early Oligocene, from the Oligocene onward resulting in the nearshore areas being uplifted and deeply truncated (Holtedahl, 1953; Doré & Jensen, 1996; Clausen et al., 2000; Cloetingh et al., 2005). In Scandinavia, as in the Paleocene and the main sediment provenance were to the north and northeast during the Oligocene in contrast to the Eocene when the sediment was principally derived from the west (Clausen et al., 2000). In the Baltic region, combined uplift and southward tilting of the Fennoscandian Platform resulted in the establishment of a north to south palaeoslope exposing land areas that provided a new sediment source. This uplift is reflected in a marked change from eastward to predominantly massive westward progradation in the

Figure 3. Early Eocene (middle Ypresian) palaeogeography, modified from Gibbard & Lewin (2003) and from Knox et al. (2010).
Filling the North Sea Basin

North Sea (Clausen et al., 2000; Huuse, 2002); sediments entered from the east rather than the west. The hiatus at the Eocene-Oligocene boundary in Belgium and other marginal successions is considered to result from regional uplift and inversion associated with the Pyrenean tectonic phase (Knox et al., 2010).

During the Early Oligocene the eastern North Sea was occupied by southwards prograding deltaic deposits (Schiøler et al., 2007), reflecting the first evidence for the uplift of southernmost Norway which was subjected to substantial erosion at this time (Michelsen & Nielsen, 1993; Michelsen et al., 1998; Rundberg & Eidvin, 2005; Rasmussen, 2004). This initiated a marked change in sedimentation pattern (Anell et al., 2012). The uplift was associated with uplift in eastern areas of Scandinavia at that time, since amphibole and epidote-dominated sands occurred initially in the lowermost Oligocene sediments of north-west Poland (Kosmowska-Ceranowicz, 1988). The similarity of this heavy-mineral assemblage with that reported from the lowermost Oligocene of the Viborg Formation of Denmark (Vinken, 1988) suggests derivation from southern Sweden. This, combined with continued influx of epidote-rich sands from the north-east, resulted in deposition of epidote-rich sands on the Polish Platform (Morton et al., 1988).

The first major sea-level fall resulting from the Oi-1 cooling event (De Man et al., 2004) led to widespread erosion of the previously deposited Early Oligocene marginal sediments. Substantial glacio-eustatic sea-level fall (Michelsen et al., 1998) at the Early-Late Oligocene (Rupelian-Chattian) boundary, accompanied by renewed tectonic activity, was superimposed on the palaeanoecological changes already initiated at the Eocene-Oligocene boundary (cf. Vandenberghe et al., 2012; Vandenberghe et al., 2014; Pekar & Miller, 1996; Fig. 5). Uplift and sea-level fall resulted in emergence of the entire Fennoscandian platform (Knox et al., 2010). This major regression phase, which saw large previously submerged areas exposed subaerially, allowed the extension of rivers across previously submerged marginal areas. The absence of any major sediment influx along the western North Sea Basin margin during the Late Oligocene indicates that the land area maintained a low relief (Gibbard & Lewin, 2003) (Fig. 5).

The prevailing climate during the Early Oligocene was generally seasonally wet, hot, and tropical (Wilkinson, in Edwards & Freshney, 1982), although cooler conditions may have occurred on the higher areas (Tappin et al., 1994). This palaeogeographical pattern continued through the later, Neogene sea-level hightstands.

2.4. Neogene

Substantial evidence for widespread Neogene uplift and tectonics around the northern Atlantic (e.g. Chalmers & Cloetingh, 2000; Japsen & Chalmers, 2000), occurring contemporaneously with increased subsidence and sedimentation in adjacent basins, has been established (Cloetingh et al., 1990, 2005). Throughout much of the southern North Sea basin margin the base of the Miocene is marked by a hiatus, thought to result from a combination of tectonic activity related to the mid- to late Miocene Savian Alpine phase and eustatic sea-level fall caused by the increased volumes of polar ice caps, particularly in Antarctica. The Savian phase was also marked by renewed inversion of the Sole Pit Basin (Van

Figure 4. Early Eocene (late Ypresian) palaeogeography, modified from Knox et al. (2010).
Hoorn, 1987) and the Sorgenfrei-Tornquist Zone (Rasmussen, 2009), by inversion on the southern flank of the Ringkøbing-Fyn High and in the Danish Central Graben (Rasmussen, 2009; King, 2006; Knox et al., 2010). It is probable that the Weald and Cleveland basins were also affected by inversion at this time. Although it has been suggested that the Weald Basin was substantially inverted during the Pyrenean (latest Eocene) tectonic phase (e.g. Ziegler, 1990; Ziegler & Dézes, 2007). The timing is still debated (cf. King, 2006). The presence of Neogene marine sediments at an elevation of 180 m on the southern flank of the Weald anticline indicates relatively recent uplift in the Pliocene or Pleistocene. Similarly the occurrence of late Pliocene marine sediments at altitudes of up to 180 m a.s.l. on the margins of the London Basin (West, 1972; Balson, 1999) implies Early Pleistocene uplift of western and north-western Britain (cf. Gibbard, 1988).

Within the North-west European Basin the Oligocene-Miocene unconformity is less distinct in the east than in the west, reflecting enhanced subsidence following the Savian tectonic phase. Increased sediment supply in the eastern basinal area, and especially in the North European Basin, was associated with the development of a Baltic River (Fig. 6). The catchment of this major river system included much of Fennoscandia, the Baltic States and westernmost Russia. Heavy-mineral evidence from the Polish succession shows a marked reduction in the epidote-bearing sand input from the Oligocene into the Miocene (Vinken, 1988; Kramarska, 2006; Knox et al., 2010). The amphibole and epidote-rich sands that had been deposited in the north-western Polish area during earliest Oligocene times are found further west in the Miocene (Vinken, 1988), indicating that the Baltic River flowed westwards along the trend of the present-day southern Baltic Sea basin (Fig. 6). This is consistent with Bijlsma’s (1981) record of the stratigraphic and geographical distribution of the distinctive Baltic Gravel Assemblage (cf. also Overeem et al., 2001), which largely consists of sedimentary rock types derived from the Lower Palaeozoic rocks of southern Scandinavia. There was a marked progradation across the Danish Shelf in the Early Miocene as a result of uplift and inversion combined with deposition of deltaic sediments of the Ribe, Bastrup and Odderup formations in the part of the North Sea basin beneath modern Denmark (Rasmussen, 2004). Heavy mineral studies demonstrate that the source area for the sand-rich deltas were present-day Finland, Sweden and particularly southern Norway and Sweden (Knudsen et al., 2005; Husee, 2002; Knox et al., 2010). Coastal progradation also took place to the south following uplift of the Bohemian Massif and, to a lesser extent, in the Lower Rhine Graben (Fig. 6). The climate during most of the Early Miocene was changing from cool to warm temperate and frost was rare in the lowland areas (Rasmussen et al., 2008).

The thick fluvial and associated sequences of the Lower Rhine Embayment (e.g. Schäfer et al., 2004) in western Germany, the Leipzig region of Eastern Germany, and the Belchatow region of Poland accumulated at this time. Although by no means restricted to the Neogene, the widespread sequences include brown coals or lignites. The fluvial sands and gravels, together with organic-rich clay beds, indicate that meandering rivers systems, associated with extensive and long-lasting peat accumulations, dominate the Neogene accumulations (e.g. Gleise, 1971; Eissmann, 2002).

Figure 5. Late Oligocene (middle Chattian) palaeogeography, modified from Gibbard & Lewin (2003) and Knox et al. (2010).
Channel-belt sediments dominated only part of the floodplain areas. Such sequences represent lowland deposition in partially coastal deltaic situations, particularly during the Mio-Pliocene of the Lower Rhine Embayment area, with fluvial progradation arriving in the Netherlands during the Tortonian (Martinius & Van den Berg 2011; Wong et al., 2007), the rivers draining subdued topography in central Europe.

There is little information available for the western basin margin because of later Neogene uplift and erosion. However, the reworked marine Miocene fossils in phosphatic 'lag' gravels in East Anglia (Balson, 1990, 1999) suggest that sedimentation may have extended into south-east England, whilst westerly fine-clastic input from the proto-Forth and Tyne-Tees rivers is recorded in the Central North Sea (Gatliff et al., 1994).

A widespread transgression took place during Mid-Miocene times, with marine facies extending over much of the Danish Shelf as far as south-west Poland (Fig. 6). This transgression was driven by a eustatic sea-level rise associated with the Mid-Miocene climatic optimum (~17 to 14 Ma; Zachos et al., 2001), but in the south-eastern embayment of the North Sea it appears to have been enhanced by subsidence associated with increased southward tilting of the Fennoscandian Platform. In the northern and eastern Polish areas, there was a marked increase in the area of non-marine sedimentation, with increased fluvial supply mainly from the east and north-east (Knox et al., 2010).

A distinct change in the tectonic regime of the North Sea region occurred during the late Mid-Miocene, with accelerated uplift of Britain and Fennoscandia (Knox et al., 2010). This uplift apparently reflected the culmination of the tectonic regime change that had begun earlier in the Oligocene possibly driven by mantle processes (Cloetingh et al., 2005). Uplift of Fennoscandia, coupled with a marked deterioration in climate, led to a major increase in sediment supply to the south-eastern embayment of the North Sea via the Baltic River (Overeem et al., 2001), although sediment did not reach the southern North Sea until the Late Miocene (Knox et al., 2010; Rasmussen & Dybkjaer, 2014; Thöle et al., 2014). The South Swedish Dome also appears to have undergone relative uplift (Japsen & Bidstrup, 1999; Japsen & Chalmers, 2000; Lidmar-Bergström & Näslund, 2002; Japsen et al., 2007), while subsidence accelerated in the North Sea region (Fig. 6).

According to Lidmar-Bergström et al. (2000), the relict ‘Palaeic surface’ of Scandinavia (Reusch, 1901) consists of high plains and broad valleys above 800 m a.s.l. Ancient exhumed surfaces occur on the flanks of the domal uplift. According to Rohrman et al. (1995) southwestern Norway was uplifted by as much as 2 km during Neogene times. This uplift may be a continuation of updoming initiated in the Paleogene, associated with the opening of the North-east Atlantic Ocean, taking surfaces to levels nowadays at 1200 m, although it might have been initiated earlier in the Late Eocene-Early Oligocene. Consequent fluvial incision gave rise to valley incision as much as 300 m deep (Medvedev & Hartz, 2015), probably enhanced by a change to cool and wet climate in the Pliocene, and thus enhanced delivery of sediment to alluvial systems down-valley. A consequence of the uplift and climatic deterioration was increased sedimentation in the neighbouring basins beginning in the Miocene (Jordt et al., 1995). Continued incision to a depth of as much as 2 km below
the palaeosurfaces is attributed to further climatic deterioration in the Quaternary when fluvial and glacial erosion resulted in 0.8 km uplift of rocks and up to a 0.5 km rise of local topography according to Medvedev & Hartz (2015). This was accompanied by further increased sedimentation in surrounding basins (Cloetingh et al., 2005).

The pattern of uplift and subsidence established at that time has persisted to the present day, with a 1500 m-thick accumulation of sediment in the central North Sea since the Mid-Miocene. A widespread planation surface of presumed middle Miocene age (‘Reskajeage surface’) is recognised across western Britain and beyond (Walsh et al., 1987, 1996; Walsh, 1999). In north-east Scotland kaolin weathering took place in the middle Miocene under temperatures of 15 ± 5 °C (Hall et al., 2015). According to Rasmussen & Dybkjaer (2014) modern analogues of the Danish Miocene river systems are known from modern south-west India and therefore confirm that warm climates predominated. Despite this there is no suggestion that a monsoon-type climate prevailed, rather that simply high precipitation relative to today occurred.

Uplift along the Weald-Artois axis appears to have finally led to closure of the Channel Seaway linking the North Sea southwards to the eastern Atlantic Ocean. The Baltic River deposits, characterised by the Baltic Gravel Assemblage, extended farther west during the Late Miocene (Bijlsma, 1981) flowing directly into north Germany under conditions of relatively rising sea level (Thøle et al., 2014). The substantial uplift, to which has been attributed a marked incision of river valley systems through the period, particularly in the Weald, (e.g. Jones, 1980; 1999a, b), is not confirmed by the sedimentary record (Gibbard & Lewin, 2003). Indeed the lack of major thicknesses of Neogene clastic sediments, in general, suggests that incision was not that intense throughout much of the region.

Relative sea level is generally thought to have continued rising into the Early Pliocene (Fig. 7) (cf. Knox et al., 2010). During this time the Weald-Artois land-barrier might have been temporarily overtopped (cf. above) (e.g. van Vliet-Lanoë et al., 1998; Balson, 1999). The North Sea Basin experienced increased subsidence (cf. Cloetingh et al., 2005), whilst sedimentation continued to be dominated by the Baltic River, which supplied vast amounts of sediment to the south-eastern embayment, leading to continued offshore progradation (Overeem et al., 2001; Kuhlmann & Wong, 2008; Thøle et al., 2014). Elsewhere, the effects of relative sea-level rise were countered by continued uplift, most notably of the Scottish source areas, as shown by a major phase of southward land progradation. Shortly after, the shelf underwent uplift and erosion associated with a major phase of exhumation of Fennoscandia including the continued rise of the South Swedish Dome and southern Norway (Japsen & Chalmers, 2000; Lidmar-Bergström & Näslund, 2002; Japsen et al., 2002, 2007; Cloetingh et al., 2005). Discussions regarding the potential interplay of uplift and climatic deterioration of the Scandinavian mountains is still unresolved (e.g. Anell et al., 2009, 2012) but it is likely, given the influx of coarse clastic materials (Rundberg & Smalley, 1989), that glaciation was already established in the Norwegian mountains in Pliocene times (Ehlers et al., 2011; Medvedev & Hartz, 2015). The formation of the major elements of the preglacial landscape of Scotland, is thought to have occurred under the regime of warm to temperate humid climates during the
Neogene (Hall & Bishop, 2002). The drainage system during the Pliocene was of braided character, depositing quartz-dominated gravels and sands derived from the west to north-west (Kesel & Gemmell, 1981; Hall et al., 2015). The occurrence of chemically resistant minerals and lithologies, such as quartz and flint, derived by long-term weathering under moist, warm-temperate climates, typify the fluvial bed products in the Miocene and Pliocene across the region, from the Baltic river system to the rivers of central Germany (Gibbard, 1988; Gibbard & Lewin, 2009) (Fig. 7). Indeed it appears that the foundations of the modern drainage system of northwestern Europe were laid in the Miocene under a persistent tectonic regime, with a subdued low-relief landscape having a weathered regolith and dense vegetation cover. In general, these early rivers occupied shallow valleys.

2.5. Pleistocene

Subsequent early Pleistocene uplift of western, north-western and northern Britain caused a relative displacement of ca. 180 m between the western London Basin and the Suffolk coast (Mathers & Zalasiewicz, 1988). The resulting regression allowed the east and north-eastwards expansion of the River Thames system to occupy the basin vacated by the sea (Gibbard, 1988). Further north-east, precursors of the Trent, Humber and Tyne-Tees were present (Cameron et al., 1992), as well as off the eastern Scottish coast. Likewise in the Early Pleistocene the Eridanos (Baltic) River delta complex continued to expand west and later north-westwards in the Netherlands’ North Sea sector (Fig. 8). During this time the depositional evolution was strongly influenced by climatic variations and resulting sea-level changes (Funnell, 1996; Overeem et al., 2001; Kuhlmann & Wong, 2008; Thöle et al., 2014). Glaciation occurred periodically in the region from the Plio-Pleistocene boundary times and through the later Pleistocene (Thierens et al., 2012; Ottesen et al., 2014; Sejrup et al., 1995) causing landscape remodelling and frequent reorganisation of drainage systems on adjacent land areas (cf. Gibbard & Cohen, 2015; Cohen et al., 2014). During the Middle to Late Pleistocene river incision greatly increased apparently in response to the increasing severity and longer duration of cold climates (Gibbard & Lewin, 2009).

By the early Middle Pleistocene (ca. 1 million years ago), the glacial-interglacial climate oscillations became more profound than previously leading to the development of substantial ice sheets in the Alps, Scandinavia, Wales and Scotland at this time (Head & Gibbard, 2015). Although glaciation had advanced into the lowland regions surrounding the Baltic by ca. 650 ka, it was not until the Anglian (Elsterian) Stage that ice sheets overrode the North Sea basin, southern Britain and northern Germany (Ehlers et al., 2011) (Fig. 9).

By the Middle Pleistocene, the Rhine had become an important element in the southern North Sea region as its catchment progressively increased. The Rhine deltaic complex by this time had filled the central and southern North Sea, the southern North Sea having become a land area. To the south, the Weald-Artois anticlinal structure formed a substantial barrier separating the North Sea from the Channel. North of this structure the major drainage lines entered the North Sea basin. On the eastern side, the northern (Eridanos or Baltic) river system had lost the connection to the Fennoscandian and Baltic headwaters. This implies that the Baltic basin had been formed, probably by

![Figure 8. Pre-glacial Pleistocene palaeogeography, modified from Gibbard (1988), Knox et al. (2010) and Thöle et al. (2014).](image)
intensified ice-sheet erosion. Nevertheless, major input sediment occurred along this course within the North European Basin, from Scandinavia, the Baltic States and the north German rivers, and in the North Sea area with the Rhine, Meuse, Scheldt and Thames. This input during the Middle Pleistocene was also potentially increased by the accelerated uplift of the Ardennes-Rhenish massif by up to 600 m which had begun in the Miocene (Van Balen et al., 2000, 2005). Sediment accumulated in the Roer Valley Graben which had subsided by a similar order.

South of the Weald-Artois interfluve the drainage systems, the rivers of northern France, especially the Seine, joined those from Britain to form the substantial Channel River system (or Fleuve Manche) which occurred on the floor of the basin during low sea-level stands.

A major change occurred ca. 450 ka ago in the Anglian (Elsterian) Stage (Fig. 9). During this glaciation ice from southern Norway crossed the North Sea and overrode easternmost Britain to deposit a complex of glacial sediments (Gibbard, 1995). This complex includes not only diamicton but glaciolacustrine sediments, including stratified diamictons that accumulated beneath a floating ice-front (Lunkka, 1994; Gibbard & van der Vegt, 2012), these sediments indicating the occurrence of a massive proglacial lake in the unglaciated southern North Sea basin (Gibbard, 1988, 1995; Cohen et al., 2014). This ice sheet across the basin blocked the drainage systems, whilst the topographic barrier to the south (Weald-Artois anticline) between Kent and northern France, caused an extensive lake to form (Belt, 1874; Gullentops, 1974; Gibbard, 1988, 1995, 2007; Hijma et al., 2012; Cohen et al., 2014).

The overspill of this lake occurred at what is now the Straits of Dover (Pas de Calais). A saddle-like topographic feature on the Chalk topography, on the drainage divide presumably functioned as the threshold over which overspill occurred. To the north, the lake water level behind this saddle reached a maximum of ca. 30 m above present sea level. Overspill of the lake initiated a spillway that was rapidly incised, huge quantities of sediment being evacuated southwards into the Channel river, the finest material being transported onto the lower shelf, the shelf front and ultimately the abyssal fans on the adjacent Atlantic Ocean floor.

However, the dramatic erosion of the Straits of Dover area is not thought to have taken place during one, but two major glacially-driven erosional episodes. Although substantial erosion took place during the Anglian glaciation, it is now known that it took a second major glaciation of the southern North Sea, comparable in extent to the Anglian, to form a second proglacial lake which restarted the retrogressive erosion, to complete the connection of the North Sea and English Channel drainage (Gupta et al., 2007; Gibbard, 2007; Hijma et al., 2012; Cohen et al., 2014).

This second event occurred ca. 160 ka ago during the Saalian (= Wolstonian) Stage glaciation (within MIS 6). During this phase British and Scandinavian ice lobes again met across the North Sea (Ehlers & Gibbard, 2004). On the Netherlands’ side, the Saalian glaciation reached further south than any previous glaciation. To the south of the ice-front a topographic ridge across the southern North Sea occurred contemporaneously with braided-river deltaic features from the ice-marginal river Rhine (Busschers et al., 2008). A similar delta complex is seen in western
Belgium (Mathys, 2009). These deltas formed in a glacial lake, the water level of which is estimated at a maximum of ca. +5 m. Mapping of the North Sea floor between the Netherlands and Britain has demonstrated the continuity of this Saalian ice-limit across the North Sea basin. Also, the abyssal record off the English Channel continental slope shows sediment delivery peaks in MIS 6 (at ca. 160 ka ago) that rival that of MIS 12 (at ca. 450 ka) (Toucanne et al., 2009). This evidence demonstrates the contemporaneous occurrence of a lake during the Drenthe Substage maximum glaciation in the Saalian (and equivalent part of the Wolstonian).

The opening of the Dover Strait initiated diversion of the rivers (Gullentops, 1974; Gibbard, 1988). Following drainage of the Anglian glacial lake, the Belgian rivers and the Thames, were redirected into the Channel River. However, it was not until after drainage of the lake formed in the subsequent Saalian glaciation that the Rhine and Meuse were realigned to the south where they joined the rivers through the Dover Straits (Busschers et al., 2008; Hijma et al., 2012). The glacioeustatic sea-level fall at the transition to the last glacial (Weichselian/Devensian Stage), allowed the Dover Straits to be reoccupied by this substantial river system. Periodically the Rhine-Thames Channel River also carried meltwater from the British and Scandinavian ice sheets, although this was episodic, for most of the time the outwash drained northwards.

As noted above, the Baltic basin was probably initiated by intense glacial erosion that began late in the Early Pleistocene (ca. 1.2 Ma) based on the occurrence of glacial erratics in the Netherlands Hattem Beds (Zandstra, 1971) and in early Middle Pleistocene glacial diamictics in Poland, the Baltic States and the Russian plain (Marks, 2004; Ehlers & Gibbard, 2004). The earliest marine sediments preserved in the Baltic basin are of Holsteinian (i.e. late Middle Pleistocene, ca. 380 ka) age. They are known from northern Germany, Poland, Kaliningrad Oblast and as far north as the Bay of Riga (Marks & Pavlovskaya, 2003).

3. Fluvial styles through the Cenozoic

It is possible in general terms to suggest some conclusions about the changing river networks and styles of fluvial sedimentation as the North Sea area developed. These styles reflect the tectonics and climates at particular times, though linkage to single causative factors is seldom possible. For example, high-energy river discharges may reflect both steep catchment gradients (relating to uplift), but also high runoff, both of which may be linked to the other for high relief areas.

3.1. Paleocene

A major proto-Thames system evolved in the London Basin (e.g. Wells & Kirkaldy, 1966; Wooldridge & Gill, 1925; Wooldridge & Ewing, 1935) in the late Thanetian. Its low-energy clay-dominated, floodplain accretionary sediments, locally with lignite units up to 1 m thick (Hester, 1965), occur as predominantly fining-upward sequences formed by a series of meandering rivers. The river was transporting pebbly sand to clay-sized material and forming a major delta complex. The flow channel itself was dominated by sands, with clay-plug type abandoned channel fills and notably clay-clast breccias. The multi-coloured mottled clays, pedologically-modified and associated lignitic units, and sedimentation typically found in vertically-accreted floodplain sequences, are associated with fining-upward channel fills and point-bar accumulations. The clay-clast breccias are said to typify meandering river sediments in tropical regions (Miall, 1996), but low-energy humid environments more generally (sub-tropical and temperate) show similar characteristics. Here rivers have cohesive banks, densely-vegetated floodplains, and predominantly transport fines but also clay clasts during floods.

3.2. Eocene

The nature of the land surface during London Clay times is poorly known but appears to have remained subdued with wide plains (e.g. Wells & Kirkaldy, 1966; Daley, 1972). Slow degradation of exposed surfaces subjected to intense chemical weathering is reflected in the vast volumes of clay which may have been produced by extended earlier weathering and supplied to the basinal areas by the rivers from the north and west.

London Clay deposition ended with the rapid expansion of fluvial delta complexes towards the east in the late Ypresian–Lutetian (early Middle Eocene) times. This transition is signalled by the sand-silt alternations of the Claygate Beds and the subsequent accumulation of the overlying Virginia Water-Bagshot Formation sands in the west representing a vast delta complex (Wells & Kirkaldy, 1966; Anderton, 2000). The sediments consist of cross-bedded sands, with thin clay or silt partings and thin pebble beds, becoming considerably coarser towards their western limit. This transition from the London Clay to the overlying sands may reflect either depression of the basin, or uplift of the hinterland further west and north-west, which encouraged river incision and potentially increased catchment yields of coarser terrigenous sediments. No later Paleogene fluvial or estuarine sediments occur in the London Basin.

3.3. Oligocene

No younger Paleogene sediments are known from the London Basin, but they do occur in the Hampshire-Dieppe Basin and further west. Here palaeobotanical investigations demonstrate a distinct shift from the post-Bartonian subtropical/very warm temperate conditions to cooler climate (Machin, 1971; Collinson, 1983; Collinson & Cleal, 2001a/b). Fluvial sediments in Denmark draining the southern Scandinavian peninsula have been thought to adopt a braided form. Massive fluvial sand was deposited in the basinal setting during the Upper Oligocene which led to substantial westward shoreline migration (Rasmussen, 1998). In the lower Rhine system, by contrast, fluvial sands and gravels, together with intercalated organic-rich clay beds, were laid down by meandering rivers (e.g. Eissmann, 2002). These sequences represent lowland deposition in partially coastal deltaic situations, particularly during the Mio-Pliocene of the Lower Rhine Embayment area (Gleise, 1971; Gleise & Hager, 1978; Zagwijn, 1989; Zagwijn & Hager, 1987), the rivers draining subdued topography in central Europe.

3.4. Neogene and Quaternary

In situ Miocene deposits are virtually absent from Britain, whereas they are present in neighbouring continental countries, including Germany, Poland and the Netherlands. In the Central North Sea, westward input of fine-clastics from precursors of NE English and Scottish rivers occurred (Gatilov et al., 1994). These sediments joined the substantial input from the prograding Baltic (‘Eridanos’) deltaic system from the south and south-east, first seen in late Miocene times (Zagwijn, 1974; 1979; Cameron et al., 1992; Funnell, 1996; Huuse, 2002; Overeem et al., 2001; Rasmussen et al., 2006; Thöle et al., 2014). The deposits of this river system are generally not exposed in the North Sea region, but in Lithuania equivalent deposits spanning the late Miocene to Middle Pleistocene occur in the south-east and in neighbouring Russia (Kaliningrad Oblast) and Belorussia. Here the Pliocene-Age Anyksiai Formation is overlain by the Early Pleistocene Daumantai Formation, both of which comprise quartz sands with subordinate silt, clay and lignite channel fills. The Anyksiai Formation (Upper Pliocene) is characterised by a `Neogene-continental' heavy-mineral assemblage, which comprises maximum values of stable minerals including quartz (95%), zircon (3.4%), staurolite (6.7%), iron oxides and hydroxides (9.6%).

The overlying Daumantai Formation is represented by fine-grained sand, silt clay with interlayers of silt, and more rarely by interbedded clay and sand. Organic material and wood characteristically also occur in the Daumantai deposits. Unstable heavy minerals of the magnetite-garnet-amphibole association characteristically occur at low frequencies in the Daumantai sands, indicating that during their formation input of Scandinavian material took place. The implication of this is that during the Daumantai period the supply of Scandinavian erratic material increased as a result of glaciation in headwater areas (Satkunas, 1998).

According to Thöle et al. (2014) in the latest Miocene, the Baltic River delta was dominated by flow from the east, including increasing input from the North German rivers. Although Burger
(2001) distinguished three heavy mineral assemblages in the Late Miocene deposits, reflecting different river system sources, only southern Norway could be specifically identified. Apart from the Scandinavian provenances, this author noted a potential increased contribution from the south-east, i.e. eastern Germany, Poland and the Czech Republic. Thöle et al. (2014) note that uplift of the Western Carpathian and Eastern Sudetes occurred at this time (Badura & Przybyski, 2004), initiating major reorganisation of the drainage system. This resulted in re-alignment of the formerly southward-directed drainage northwards to the North Sea Basin, the Carpathians and Sudetic rivers most probably becoming southbank tributaries of the Baltic River System (Badura & Przybyski, 2004).

In detail the sediments comprise sands and fine gravel with subordinate fine-grained sediment laminae predominant. The former occur as incomplete fining-upward cycles filling shallow channel-like depressions often dissecting elongate stratified sand and silt horizontally-bedded units. Occasional fills of silt, and more rarely, silty clay occur in elongate lenticular form. Associated with these fine sediments are peat-like lignite beds, especially in the pre-Quaternary strata. Overall the facies association resembles that of a sand-dominated multiple-channelled braided river.

Coarse-grained sediments from the upper units and some of the river deposits show evidence for different source area composition. The shift from warm Pliocene towards cold, Pleistocene climate conditions and the intensification of glaciation in the Baltic River catchment are also seen in the equivalent sediments in the Nethelands where this is expressed by the increase of unweathered illite and a decrease of smectite and kaolinite content (Kuhlmann et al., 2004). The progressive gradual reduction in the inherited regolith thickness through the course of Pliocene to Early Holocene time resulted in expanding areas where pre-Tertiary and pre-Mesozoic bedrock became exposed. These began contributing minerals to the fluvial sediments.

The vegetational evidence indicates a predominantly coniferous-forested landscape. However, species-rich forests probably continued during the Anyksiai time; certain intervals of steppe-forest occurred, probably reflecting periods of climatic deterioration. By contrast, vegetation during deposition of the Daumantai deposits was characterized by temperate forests indicating a cool, humid climate.

Sediment production from the Fennoscandian shield peaked during the cold and highly fluctuating climate of the Late Pliocene–Pleistocene. Although a tectonic uplift component has been proposed by many authors (Japsen & Chalmers, 2000; Overeerem et al., 2001; Dahlgren et al., 2005; Stoker et al., 2005), Golczkowski et al. (2012) suggest that the Plio-Pleistocene erosion history of Scandinavia (and therefore of offshore sedimentation) is dominated by the increase of unweathered illite and a decrease of smectite and kaolinite content (Kuhlmann et al., 2004). The progressive gradual reduction in the inherited regolith thickness through the course of Pliocene to Early Holocene time resulted in expanding areas where pre-Tertiary and pre-Mesozoic bedrock became exposed. These began contributing minerals to the fluvial sediments. This appears to relate to the subdued relief that seems to have prevailed, to stability of regolith and its replacement under a dense vegetation cover, and to predominance of fine particulate materials in transport. From the British side of the North Sea, it is clear that during certain periods, e.g. the late Ypresian to Lutetian or the middle Thanetian, the rivers were predominantly transporting clastics, sand and silt derived from destruction of the upland of hinterland to the west, particularly Palaeozoic and Pre-Cambrian massifs, resulting in great expansions of sand-rich deltas. This is perhaps analogous to some tropical rivers today, like the Andean headwaters of the Amazon, whereas the river’s cratonic tributaries are more typically meandering but respond to variations in sediment load (Constantine et al., 2014).

Comparison with the impact of the cold-climates of the later Pleistocene with periglacial conditions, frost-weathered bedrock and seasonally-focused runoff, are likely to have dominated extra-glacial landforming processes, in particular being responsible for bedrock incision. The relatively brief episodes of glaciation within cold periods, in the peripheral regions, were potentially aggradational, and interglacial periods were broadly ones of quiescence (Gibbard & Lewin, 2009; van Huissteden et al., 2013). Whilst this picture might be biased by the record preserved principally from river valley environments, coastal or deltaic areas were less quiet in erosional/depositional terms during temperate-climate events.

4. Discussion and Synthesis

Through the last 60 My the southern North Sea has migrated from 42° to 52° North resulting in the region passing through a range of climatic zones from tropical to temperate climates (van Hinsbergen et al., 2014). Meandering streams dominate throughout the pre-Quaternary period in lowland areas of the North Sea region, the evidence conforming generally to Maill’s (1996) models for rivers in seasonal tropical/sub-tropical/warm-temperate situations. Although their form will inevitably have varied locally depending on materials in transport, discharge variability and variations in slope, the overall stability in fluvial form is striking across the lowland regions before the second half of the Pleistocene. This appears to relate to the subdued relief that seems to have prevailed, to stability of regolith and its replacement under a dense vegetation cover, and to predominance of fine particulate materials in transport. From the British side of the North Sea, it is clear that during certain periods, e.g. the late Ypresian to Lutetian or the middle Thanetian, the rivers were predominantly transporting clastics, sand and silt derived from destruction of the upland of hinterland to the west, particularly Palaeozoic and Pre-Cambrian massifs, resulting in great expansions of sand-rich deltas. This is perhaps analogous to some tropical rivers today, like the Andean headwaters of the Amazon, whereas the river’s cratonic tributaries are more typically meandering but respond to variations in sediment load (Constantine et al., 2014).

By contrast, during the early Ypresian, the dominant load was clay, derived from the thick weathering crusts and associated volcanic materials indicated by the high content of smectite following intense pyroclastic activity produced by Thulean flood basalts from the Iceland plume. This was associated with the opening of the Atlantic Ocean and this impacted on the whole of NW Europe (Brodie & White, 1994; Knox, 1996; Cloetingh et al., 2005; Knox et al., 2010). This was deposited as London Clay when a period of comparative structural quiescence coincided with the maximum of Paleogene marine transgression. Where channel and floodplain complex depositional sequences are preserved, e.g. the late Thanetian, a mixed load of fine granular material, together with sand, fines and locally clay-brecias was transported. In almost all the cases described, vegetation played a profoundly important role. Repeatedly descriptions of lignite (peat), which may be associated with floodplain sequences, are reported. Such rivers are more characteristic of low-migration channels bordering wetlands as found in the lower Amazon, and rivers that do not
directly fill their valleys with lateral accretion deposits (Maurice-Bourgoin et al., 2007; Lewin & Ashworth, 2014). Other restricted mineral corridors with bordering organic wetlands and lacustrine systems occupying valley floors have been reported from the Paraná system in Argentina and in Papua New Guinea (Iriondo et al., 2007; Day et al., 2008). In most cases the dense vegetation can be assumed to have greatly contributed to bank cohesion and stability, a situation typically found in tropical, sub-tropical and warm-temperate environments alike.

In Britain, identification of floodplain surfaces has been repeatedly represented by descriptions of palaeoools, mostly originating under moist, but seasonally dry conditions, e.g. in the Hampshire Basin Reading Beds (Paleocene), the Headon Hill Formation (late Middle to Late Eocene), in the Bovey Formation (Oligocene) and in the Lignite and Clay Unit (Oligocene–Early Miocene) in the Cardigan Bay Basin.

Gravel (conglomerate) accumulations are extremely rare in the regional northern European Cenozoic alluvial sequences. Whilst braided sheet-flood sequences occur in the upland regions of Britain (Gibbard & Lewin, 2003) coarse aggradations were apparently restricted to areas of high relief or active uplift such as Scotland, Norway and northern Denmark. The general persistence of subdued topography implies that rivers throughout much of the period lacked sufficient potential energy, or proximal mountain sediment sources, to generate flows capable of moving coarse materials. The implication is that even under conditions of precipitation higher than that today (e.g. Daley, 1972; Haywood et al., 2000), storm-induced floods rarely caused transport of gravel-sized material. The density of the vegetation cover throughout the region must have acted to reduce the impact of flood, supported by efficient groundwater percolation (Gibbard & Lewin, 2009). Moreover, the predominance of intense chemical weathering may have resulted in coarse gravel-sized material being absent from catchments. Nevertheless sand-dominated accumulations occur throughout the period across the region, indicating that this material, often composed predominantly of chemically stable mineral assemblages, was being transported throughout the region. This is characteristic of many humid river systems today beyond the influence of prior cold-climate weathering.

Humid rivers simply being characterized as ‘tropical’ can be misleading: in the warm inter-tropical convergence zone (ITCZ), they may receive intense but localized daily convective rainfall, with annual and daily insolation variations, and seasonal monsoons with ITCZ migration. Chemical weathering may be intense, producing clay sediments. Year to year variation may be comparatively subdued within most of the tropics, but considerable in sub-tropical monsoon regimes and cyclone-labile regions. Mid-latitude rainforest may not have the same characteristics as tropical rainforest.

Small rivers respond to intense localized rainfall; large ones respond smoothly to seasonal fluctuations. Lower water viscosity at warm temperatures reduces fine sediment transport by between 3 and 0.35% per 10° rise in temperature depending on particle size (Syvitski et al., 2014). Tropical river regimes with the present-day distribution of continents, mountains and oceans are distinctive. But without relief and with a cover of rainforest, cratonic rivers like the Congo may be low sediment-yielding (Latrubesse et al., 2005, table 2), and this is likely to have applied to the former Erdianos until tectonic uplift affected its tributaries.

In spite of the view that uplift might explain the large increase in sedimentation in the latest Cenozoic that began at ca. 2.5 Ma, comparison with later fluvial activity implies that it almost certainly reflects climatic deterioration (review in Gibbard & Lewin, 2009). A substantial change marked the beginning of the Quaternary, with glaciation extending to lower altitudes and sea-level in southern Norway and periglacial frost-dominated climates becoming established over the region. An even greater impact occurs in response to further intensification of cold climates following the Middle Pleistocene Transition (Gibbard & Lewin, 2009; Head & Gibbard, 2015). There is a Pleistocene incision question concerning drivers, feedbacks and timings. Did cold-climate and accelerated erosion lead to removal of mass, consequent tectonic uplift, and hence positive feedback with further linear incision? Some have also coupled uplift to near-contemporary late Quaternary neotectonics or glaciotectonics (Antoine et al., 2000). Or did climate and accelerated activity simply permit greater climate-driven and episodic linear erosion in elevated areas that were in any case prepared tectonically by uplift over the longer term (Antoine et al., 2007; Van Balen et al., 2000)?

Throughout much of Europe, low-relief land surfaces dominated the southern regions until the Plio-Pleistocene. The tectonic regime operating in north-west Europe remained broadly the same throughout the Cenozoic, although the progress of erosion and deposition around the North Sea Basin were sufficient to drive substantial developments throughout the period, with sediment inputs coming from different quarters and with different river styles. In the broadest terms, there has been a clockwise shift in sediment sources at first from the north-west, then Scandinavia, then to a now- disappeared Erdianos River and finally to the Rhine-Meuse system.

Today’s river valleys, deeply incised during the Pleistocene, almost certainly result from efficient erosion at such times, with high and predominantly coarse to very coarse sediment yields resulting from frost-dominated climates (cf. Anell et al., 2012; Cloetingh et al., 2005; Gibbard & Lewin, 2003, 2009). This is notwithstanding the continuing impact of regionally important factors, such as local tectonics, lithologies and relief. The general depletion of regolith generated earlier in the Neogene, faster than it could be replaced and coupled with accelerated weathering, contributed substantially to the activity and materials in transport by rivers. This change resulted from amplification of external climate and tectonic changes occurring at the time. The frequent thinnings and occasional disappearance of the vegetation cover and the altered conditions for channel-bed and valley-floor incision that accompanied these changes explain the later Pleistocene landscape dissection (Gibbard, 1988).

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6. References


