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The history of the major rivers of southern Britain during the Tertiary

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Abstract: The evolution of the drainage system of lowland Britain is discussed on the basis of available geological evidence, including that from terrestrial sites and that which has more recently become available from offshore exploration of the North Sea, the English and Bristol Channels, and the Irish Sea. Tertiary stratigraphy throws considerable light on landform and river development. Paleocene destruction of a chalk cover, which seems to have been incomplete in western Britain, was accompanied by basin sedimentation under a tropical climate. The major elements, the Thames, Solent, Hampshire (?proto-Avon) river, Irish Sea river and possibly an early Trent river, existed almost throughout the Cenozoic. The influence of Atlantic rifting and thermal doming in NW Britain appears to have been stronger and more temporally focused than the persistent flexuring that determined and maintained Tertiary drainage lines in the SE. Here also the folded Mesozoic terrains on the surface contrast with the more dominant block-faulted relief of the Palaeozoic 'oldlands'. The rivers of the SE can be shown to have extended or reduced their lengths in response to relative sea-level change and gentle warping. Drainage antecedence, the destruction of the Solent system and the breaching of the English Channel are also evident. By contrast, the major river systems of the west are now entirely submerged. Long-term stability of the drainage pattern reflects a persistent tectonic regime in the south, with a subdued low-relief landscape having a weathered regolith and dense vegetation cover. Meandering river channels and alluvial styles predominated, although channel forms varied according to sediment load, slope and discharge variability. Coarse gravel-dominated accumulations are rare and localized. Chemically stable lithologies dominate the clastic component throughout. It is apparent that the deeply incised river valleys seen today are related to high, predominantly coarse sediment yields, encouraged by substantial, rapid climate changes in the Pleistocene. This emphasizes the significance of mechanical compared with chemical weathering for the rate and nature of landscape dissection, and the modifications that have arisen as a result of glaciation, frost-climate weathering, rapidly changing climates and sea levels. The stratigraphical evidence here reviewed is at variance with older, largely geomorphologically based landform evolution models ('denudational chronology'), but gives considerable support to the recent proposals emphasizing the significance of Paleocene erosion, and enduring low-relief landscapes and drainage systems evolving alongside fold development during the Paleogene. Given the depobasin evidence now available, postulated fluvially active episodes can, and must, be linked to contemporaneous deposition. Some at least of the many controversies involving the identity of erosion surfaces, the dating of them using only residual deposits and weathering mantles, and the selection of particular Tertiary episodes as ones of landscape development can now be resolved.

Keywords: Tertiary, rivers, stream sediments, drainage, landscapes.

Long-term drainage and landscape evolution have been important research foci for over a century. In southern Britain, investigations have centred on drainage evolution and its contribution to a 'denudational chronology' geomorphological school, which reached its acme with the publication of Wooldridge & Linton's work *Structure, Surface and Drainage in South-east England* (Wooldridge & Linton 1939, 1955). Despite some criticisms (Pinchemel 1954) the conclusions reached therein reigned largely supreme until the 1970s when a new generation of researchers began questioning the conclusions on the basis of new evidence becoming available from increasingly sophisticated investigation of tectonic history (e.g. Ziegler 1987, 1994), sedimentology (e.g. Plint 1983*a*) and pedology (e.g. Catt 1983; Green 1985). The results continue to provoke reassessments of the geomorphology of southern England (Jones 1980, 1981, 1999*a,b*) and beyond (e.g. Walsh *et al*. 1987, 1996; Walsh 1999; Mignón & Goudie 2001).

The approaches of Wooldridge & Linton (1939, 1955) and their immediate followers were essentially underpinned by three concepts.

(1) Geomorphology could use deduction and inference to erect a history of landform development using evidence from landforms themselves to fill an apparent gap in Earth history after the rock record ceased. Only later on did the focus shift to a detailed reconstruction of processes and the stratigraphy of 'superficial' deposits.

(2) The Davisian cycle of erosion was the persuasive theoretical basis available for interpretation. In this, uplift was followed by progressive erosion and stream adjustment to geological 'structure' (including lithological outcrop) as relief reduced to an eventual peneplain (summarized by Davis 1909).

(3) Sea levels changed; this could include progressively falling base levels, and might involve marine onlap and offlap at particular periods. Ideas concerning superimposition from a chalk cover and the development of marine shorelines came to Britain from the work of Johnson (1919, 1931).

Thus the evidence that Wooldridge & Linton and their followers made use of was primarily geomorphological. This included accordance of hill summits to identify former marine surfaces or peneplains, relationships between stream courses and structural elements to distinguish between surface types and to reconstruct drainage evolution over time, and field mapping of planation surfaces and related features. In the three decades following initial publication of Wooldridge & Linton's model, there followed a whole series of regional studies focusing on individual drainage basins or escarpment–backslope blocks and, generally speaking, upon episodic incision with a falling base level and on planation under hypothesized marine and fluvial conditions (e.g. Sparks 1949; Clayton 1953; Yates 1956; Everard 1957; Johnson & Rice 1961; Kidson 1962; Brunsden 1963). A similar effort was made to map and interpret surfaces in upland areas of western Britain, with recognition of marine or subaerial surfaces at higher levels (e.g. Hollingworth 1938; Balchin 1952; Jones 1952; Brown 1960*a,b*; George 1961), although with conflicting interpretations in the absence of related deposits.

Later research was able to involve a greater concentration on, and technical knowledge of, residual deposits and weathering products associated with particular surfaces (Clark *et al*. 1967; Summerfield & Goudie 1980; Catt 1983; Green 1985; Moffat & Catt 1986; Ulyott *et al*. 1998). In general, these studies have thrown considerable doubt on the earlier Wooldridge & Linton model, as weathering products, like the widespread Clay-with-flints on the Chalk, have not proved to be what they initially seemed. Further north and west, residual deposits and Tertiary outliers have been carefully examined. Again, conclusions from such studies conflict with earlier assumptions (Battiau-Queney 1984; Walsh *et al*. 1987, 1996; Walsh 1999). Finally, detailed mapping of surfaces and the interpretation of drainage patterns has suggested some convincing alternatives to the Wooldridge & Linton model (see Pinchemel 1954; Small 1964, 1980; Jones 1980, 1983, 1999*a*).

Given also the new mobile tectonic framework made available through developments in plate tectonics, and new information derived from exploration of the shelf sea floor, evidence has been growing that the erosional landscape has inherited substantial elements from throughout the Cenozoic beginning in the Paleocene and incorporating earlier elements in the west (George 1974; Chadwick 1993; Jones 1999*a*). Thus any study of the evolution of the major drainage elements of the southern British Isles must begin at the latest with the Paleogene or even earlier in the Palaeozoic 'oldlands' where a Chalk cover may not have been complete (see George (1974) and Walsh (1999) for discussions).

Furthermore, although the recent concentration on residuals and surfaces is fully understandable, it appears timely to reconsider the evidence provided by larger known bodies of Tertiary sediment. Erosion and depositional systems are necessarily linked, with the latter able to provide key information on the timing, environment and extent of the former. It appears that whereas the basal unconformities of Tertiary formations and epochs have been projected to indicate erosion levels (e.g. the variously termed sub-Eocene, early Tertiary, sub-Paleocene, sub-Oligocene surfaces recently incorporated into polygenetic models by Jones (1999*a*)), the diagnostic potential provided by the major bodies of Tertiary sediments has not been adequately developed. There is now sufficient evidence to assess river development from the standpoint of fluvial sedimentology and provenance, rather than surface morphology alone. Based on the location of deposits and their provenance, it is possible to indicate broad drainage lines (commonly called 'proto-' river systems), although not with very great detail. In some instances, sediments allow former channel types and depositional styles to be suggested, and they may also be indicative of erosional energy and weathering regime in the catchments that supplied them. A similar approach was successfully adopted for a synthesis of NW European drainage history of the last 3 Ma by Gibbard (1988). The same approach is applied here, with the effects of supplementing or modifying earlier conclusions drawn largely from erosion surfaces and residual deposits.

Tectonic and structural background

Two major tectonic influences have affected the NW European continent during the Cenozoic: fragmentation of the Eurasian–North American plate and Alpine orogenesis. The interplay of these two processes has resulted in great complexity of both structural and depositional patterns. In essence, these two processes work in opposing ways, i.e. the break-up of the northern hemisphere plate produces tensional or extensional features whereas Alpine mountain building, arising from continent-to-continent collision between the Eurasian and African plates, produces compressional features (see Ziegler 1978, 1987, 1994; Dewey 2000). Active tectonics led to widespread reactivation of older structures, particularly those of Variscan origin (Fig. 1).

Particularly important for British landscape development was rifting of the Greenland–European plate in the early Paleocene. This caused thermal uplift of Scotland and the East Shetland platform and volcanic activity. This activity and uplift was attributed to magmatic underplating resulting from a mantle plume that occurred beneath northern Britain during the early Tertiary (Brodie & White 1994). After about 54 Ma opening of the North Atlantic by sea-floor spreading resulted in the westwards movement of the magmatic plume from beneath the continent, leaving northern Britain uplifted to the present (Blundell 2002). However, in southern Britain extensional development involving Variscan structures initially led to the development of depobasins that were later deformed by northwards transmission of lithospheric stresses generated during Alpine orogenesis (Chadwick 1993; Hawkes *et al*. 1998; Dewey 2000).

After early Tertiary fragmentation of the Eurasian–North American crustal plate, the rift system of the North Sea Basin became inactive. Ziegler & Louwerens (1979) concluded that after the continental separation the crustal relaxation resulted in continued uniform basinal subsidence, which followed from a pre-existing pattern of differential subsidence initiated in the Jurassic (Ziegler 1978, 1987, 1994; Ziegler & Louwerens 1979).

The Channel may have had a similar origin, according to Smith & Curry (1975), in that ocean crust may possibly have been formed here, but that events affecting the NW European continent may have deflected this zone southeastwards beneath the land mass. Inversion events can be equated to four progressive deformation stages recognized by Ford *et al*. (1999) (summarized by Blundell (2002)) in the North Alpine Foreland Basin. The first is Laramide tectonism in the early–mid-Paleocene, which caused mild inversion movements in the Celtic Sea, Western Approaches and the Channel region (Ziegler 1978, 1987, 1994). This was followed in the mid-Eocene by uplift of the Weald and Celtic Sea basins, and subsidence of the London and Hampshire–Dieppe basins. Uplift and folding of Eocene strata also occurred on the Isle of Wight (Gale *et al*. 1999). Later uplift in post-Eocene times related to Alpine compression reached a peak in the mid–late Miocene, with tectonic activity continuing intermittently into the Pliocene and even the Pleistocene resulting in inversion of major Mesozoic basins, including the Hampshire–Dieppe and Channel basins and the Bristol

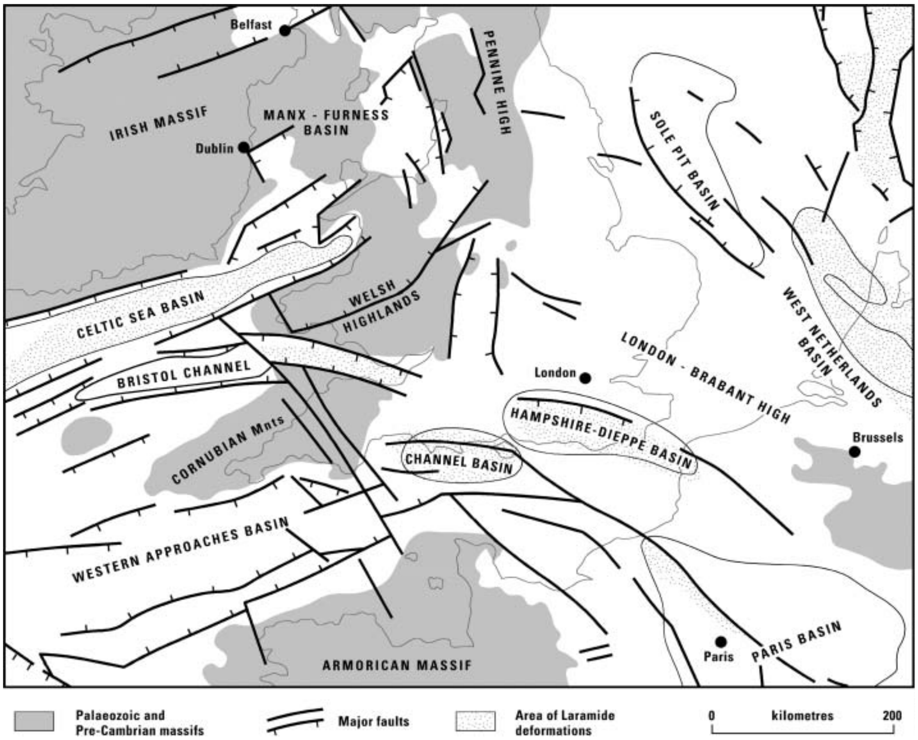

Fig. 1. Tectonic map of the British region in the early Paleogene (modified after Ziegler 1987, 1994).

Channel and Western Approaches Trough, and updoming of the Pays de Bray Anticline in the Paris Basin and the Weald–Artois Anticline (Ziegler 1978, 1987, 1994; Blundell 2002). Uplift of basement block massifs, particularly aligned along the western and northern part of the region, also occurred during these phases. This was accompanied by rapid subsidence of local pull-apart basins during the Oligocene, such as the Lough Neagh Basin in Northern Ireland, the Cardigan Bay Basin and in Devon (Lake & Karner 1987), which occurred as a consequence of short-lived wrench faulting along the NW–SE-aligned Sticklepath–Lustleigh system. Blundell (2002) considered that the post-Miocene uplift of southern Britain cannot be attributed to basin inversion but more probably resulted from compensatory isostatic rebound following denudational offloading, possibly accompanied by strain release. However, according to Japsen & Chalmers (2000), uplift during the Neogene fits a pattern of late Cenozoic intraplate uplift that is known from around the North Atlantic.

The loss of Mesozoic rocks that once covered large areas of western and northern Britain has been the subject of extended discussion. The pulsed uplift resulting from periodic magma injection, noted above, resulted in surface rejuvenation, producing substantial siliclastic deposition in the North Sea between 54 and 62 Ma, as described by White & Lowell (1997). These workers' fission-track and vitrinite reflectance data have been confirmed by Green (1986, 1989), Lewis *et al*. (1992) and Rowley & White (1998), who concluded that denudation of the eastern Irish Sea Basin resulted in between 1.5 and 3 km of exhumation with attendant removal of surface rock cover in the early Tertiary. Moreover, fission-track studies have shown evidence for a mid-Cenozoic cooling event that began *c*. 30 Ma that may have caused a further 1 km of denudation along the NW European continental margin resulting from changes in mantle heat flow (Rohrman *et al*. 1995; Japsen *et al*. 2002; Cunningham *et al*. 2003). This relief creation and erosional activity was much more pronounced in the north than further south and later in the Tertiary (see Bowman 1998; Blundell 2002), which reflects the position of the magmatic plume and its movement west as the North Atlantic opened. This process has been invoked to explain the early Tertiary history of Britain by Cope (1994), for example (but see also George 1974). Cope suggested that uplift centred on NW Britain may explain the southeastwards tilt of the English–Welsh block, attributed to a Cretaceous-aged hotspot centred on the Irish Sea. Such a hotspot would have led to the injection of igneous material below the surface causing dome-like uplift of an area 500 km in diameter. The resulting updomed area has been particularly deeply eroded but its effect is thought by Cope (1994, 1995) to explain the alignment of the modern lowland British drainage pattern, albeit modified by Pleistocene glaciation, although this is not universally accepted (Thomson 1995).

By far the largest Cenozoic basin is the NW European Basin, which extends from Poland to the northern North Sea. This basin had become stabilized by the Miocene and subsequently subsided in an irregular manner (Ziegler 1978, 1994; Japsen *et al*. 2002). This, together with the North Sea Basin, received huge volumes of sediment during the Cenozoic, particularly during the Paleogene. This basin is estimated to contain up to 3500 m of sediment for the whole period (Ziegler 1978) compared with a thickness of over 1000 m from the Quaternary alone.

Palaeogeographical setting

At the beginning of the Paleogene Britain stood at latitude 40°N, 12°S of its position today (Irving 1967; Daley 1999). The Earth's climate, which had been extremely warm during the Cretaceous 'hot-house', continued to be both warm and without the extreme fluctuations of the later Quaternary (Wolfe 1978). An overall, long-term trend of cooling climates through the Tertiary is first seen in changing floral assemblages from late in the early Eocene (Collinson *et al*. 1981; Daley 1999; Collinson & Cleal 2001*a*) culminating in the warm-temperate climate of the late Neogene (Zagwijn & Hager 1987; Zagwijn 1992).

Immediately before the Paleogene, the British region was submerged beneath the shallow Late Cretaceous Chalk sea. Some areas probably remained emergent, as in Wales, Scotland and Fennoscandia, but were of low relief. Emergence became more general by the Maastrichtian (Late Cretaceous), and by the Danian (Early Paleocene) was widespread (Murray 1992). This change was accompanied by a replacement of the longstanding deposition of marine carbonates by clastic sediments (Curry *et al*. 1978). This is attributed to increased erosion of both the emergent and submergent regions consequent on the widespread uplift associated with the opening of the North Atlantic region in late Paleocene times (Boulter & Kvacek 1989), mentioned above. Compared with this Late Cretaceous–Early Tertiary uplift and erosion, later Oligocene and Miocene events appear to have been relatively mild (Lewis *et al*. 1992), regionally restricted (Green *et al*. 2001) and related to basin compression and inversion (Chadwick 1993; Hawkes *et al*. 1998; Dewey 2000; Blundell 2002).

From the beginning of the Tertiary, Britain was surrounded by depositional basins. To the west the Atlantic Ocean–Greenland Sea basin began to open, with its periodic connections to the Channel, Paris and Western Approaches basins in the south (Pomerol 1973; Kent 1975; Thiry & Dupois 1998; Daley 1999). The long-established North Sea Basin, already referred to, lay to the east. Finally, the extension of the northern North Sea Basin to the east was the west–east-oriented NW European Basin that extended into modern Poland (Ziegler 1978, 1987). This basin also formed a major depositional feature throughout the Tertiary and early Pleistocene (Gibbard 1988).

The Tertiary deposits of lowland Britain, particularly those of the Paleogene in the main depositional Hampshire–Dieppe and London basins, characteristically record alternating transgression and regression sequences that have been attributed to global eustatic sea-level cycles (Plint 1983*b*, 1988; Haq *et al*. 1987; Neal 1996; Fig. 2). Pulsed tectonism has also been invoked (Knox 1996). Although initially restricted to the eastern end of the London Basin, later transgressions became more extensive, some reaching the Hampshire–Dieppe Basin. Over 20 such transgressions have so far been identified (Daley 1999, fig. 2.6). The older Eocene strata (London Clay, Bracklesham Group, Barton Group) represent major transgressive periods, involving several individual transgressive events. By contrast, few are found in the non-marine Solent Group of the Hampshire region (Daley 1999). Overall the sea level through the Cenozoic parallels the level of global temperature (Miller *et al*. 1987), showing a long-term downward trend that culminates in the glacioeustatic lowstands that typify the Quaternary (Fig. 2). The sea-level record represented in the British sequences reflects the interplay of the long-term trend with substantial eustatically driven oscillations, themselves modified by local tectonic activity. Attempts to relate the local sea-level record to global curves (e.g. Plint 1988) are hindered by the need to untangle these interacting drives.

The Tertiary sequences in southern Britain are summarized in Figure 3.

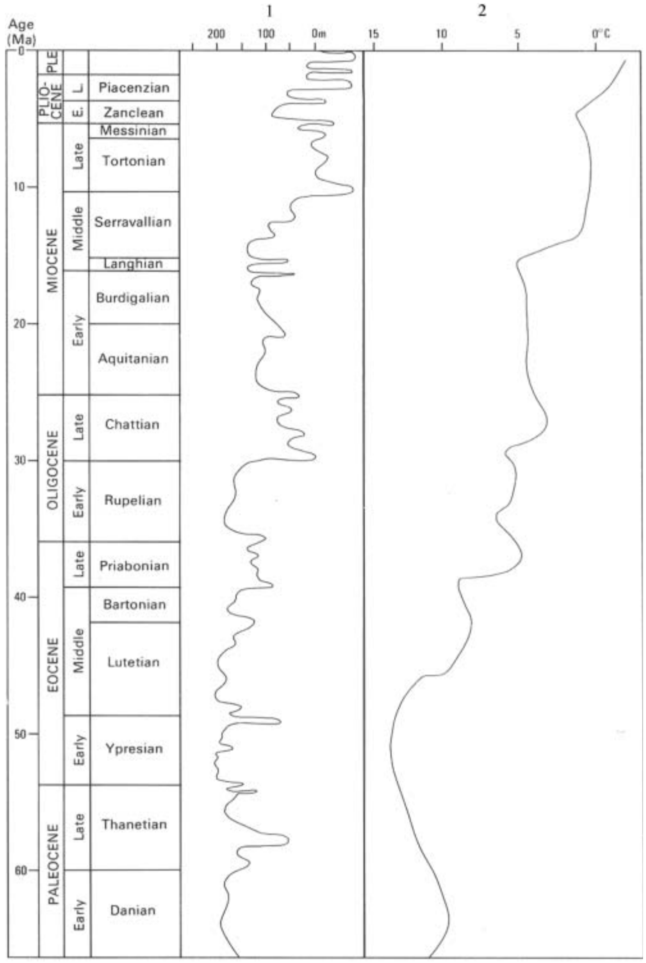

Fig. 2. Eustatic sea-level curve (1) and ocean bottom water temperature (2) during the Tertiary (after Savin 1977; Haq *et al*. 1987).

Paleocene

Much of what is now Britain became emergent during the early Paleogene (Daley 1999; Anderton 2000); the maximum uplift occurred in the NW, causing a regional tilt towards the east and SE (Murray 1992). Indeed, the form of the modern landmass was already identifiable (Lovell 1977), in contrast to conditions during the Late Cretaceous submergence. Where it existed, the extensive Chalk cover was being actively dissected by both mechanical and chemical subaerial denudational processes to produce a residuum of flints. Where the substrate beneath the Chalk was exposed it was subjected to active erosion, and older rocks were also being removed and transported. These included the crystalline basement rocks of the massif areas of the SW Peninsula, Scotland, Wales and Brittany, which were subjected to block-faulting. The nature of the landscape of these massifs is unknown but it seems likely that they reached significant altitudes or were undergoing continual uplift to judge from the thick sequences of Paleocene arenites preserved in the adjacent basins (Daley 1999). However, much of England was of low relief, with southeastward-aligned drainage (Murray 1992), encouraged by general subsidence of the SE (Fig. 4). The derivation of thick weathering mantle material suggests that long exposure rather than rapid uplift was required to develop the considerable volumes of chemically weathered materials produced during the Tertiary. In the Late Paleocene, southern central and SE Britain were lowlying and readily inundated by marine transgressions from the east (Murray 1992), which resulted in the Paleogene deposits being laid down across the region. This thick, mainly clastic sedimentary sequence was almost certainly accom-

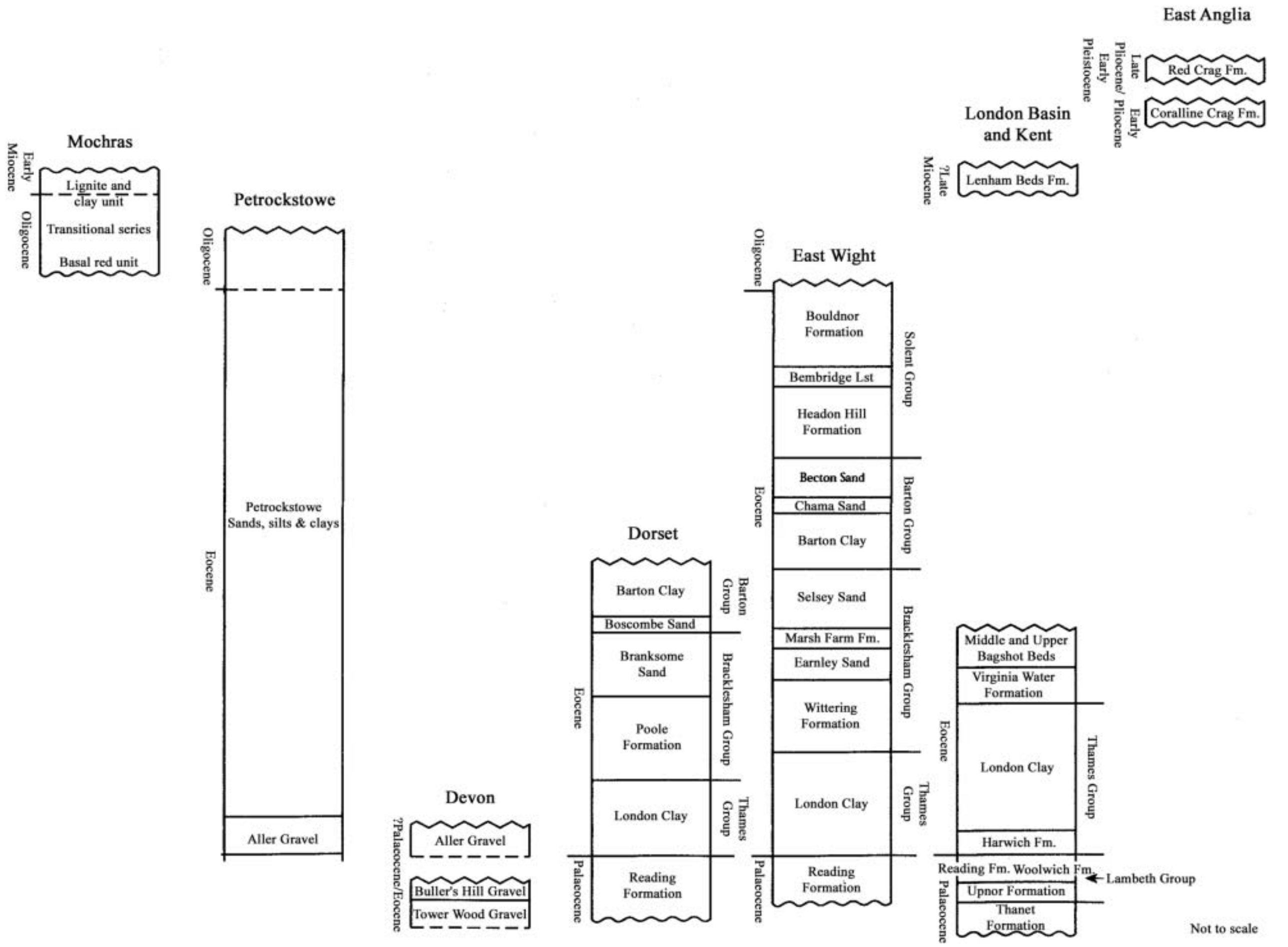

Fig. 3. Summary of the main Tertiary sequences in lowland Britain, showing the major lithostratigraphical units (modified from Daley & Balson 1999).

panied by marked subsidence for millions of years (Pomerol 1973).

The earliest Tertiary deposit in Britain is the marine Thanet Sand Formation (Thanetian), a series of slightly glauconitic sands that rest directly on the eroded transgressive surface on Chalk, restricted to the eastern part of the London Basin but with equivalents in Belgium and the Paris Basin (Fig. 3). This formation is overlain by the Lambeth Group, which includes the Woolwich Formation, a series of laguno-marine sediments that pass westwards into the Reading Formation. The latter are a series of clays and associated sediments of fluvial origin that accumulated in a deltaic complex (Wells & Kirkaldy 1966; Anderton 2000).

At least one major river, sometimes referred to as the 'Eocene Mississippi' or 'Amazon' (e.g. Wooldridge & Gill 1925; Wooldridge & Ewing 1935; Wells & Kirkaldy 1966) but more realistically a proto-Thames system, entered the London Basin in the area of the modern Chilterns from Hertfordshire, Middlesex, Buckinghamshire and Berkshire. Here cross-stratified gravels and sands, accompanied by silty clay lenticular channel fills associated with inwashed plant material and frequent clay-clast breccias, occur (e.g. Crane & Golding 1991). Such breccias could have originated from bank undercutting during channel migration (Wells & Kirkaldy 1966). Exotic clast assemblages, including quartz and lydites, the latter derived from rocks of Early Cretaceous and Late Jurassic age of the NW (Wooldridge & Gill 1925; Wooldridge & Ewing 1935), are also found. They are associated with mottled clays representing weathered, low-energy floodplain accretionary sediments and locally with lignite units up to 1 m thick (Hester 1965). Smaller tributaries may also have contributed to the delta complex from the north, west and even possibly the SW. These predominantly fining-upward type sequences clearly indicate the occurrence in Reading times (late Thanetian, *c.* 55 Ma ago) of at least one substantial, probably actively meandering proto-Thames river from the NW (Hester 1965), possibly rejuvenated by contemporary earth movements. This was transporting pebbly sand to clay-sized material and forming a major delta complex (Fig. 4).

Reading facies-type sediments also occur in the Hampshire–Dieppe Basin (Fig. 3). Here they comprise thin transgressive pebbly sands, resting on Chalk, overlain by sands and mottled clays (Hester 1965; Anderton 2000), deposited by rivers from the west and SW. This is, in principle, the first evidence of a proto-Solent River system. Heavy-mineral analysis of the sands clearly indicates a possible Armorican contribution at this time (Morton 1982) but according to Daley (1972) they are unlikely to be of fluvial origin because 'the latter was periodically separated from Britain'. Deposited during regression of the sea, the Reading Formation of the Isle of Wight, the central Channel and mainland localities such as Felpham (Bone 1986; Collinson & Cleal, 2001*a*) predominantly comprises mottled multicoloured clays; the coloration is thought to result from subaerial weathering (Buurman 1975, 1980; Daley 1999). Although these sediments may in places be of lagoonal origin (Ellison 1983), it is generally more likely that they represent floodplain vertical accretion complexes that have been periodically affected by pedogenesis to produce hydromorphic gley soils of fluvial to fluviomarine origin. These soils formed under a warm climate with a distinct rainy season (Buurman 1975, 1980). Associated channel-fill sandy clay breccia and lignite are known from Sussex and the Central Channel. At the former a diverse flora, including trees in growth position, indicates a dense floodplain swamp forest of warm, seasonally humid climate, comparable with those of the modern southeastern USA (Collinson, in Bone 1986; Collinson & Cleal 2001*a*). Further west at Studland Bay, the Reading Formation comprises fluvial channel-fill current-bedded granular sands containing fragmentary plant material (Daley 1999).

It therefore appears that the Thanetian was the first period when substantial evidence of significant fluvial activity is represented in both the Hampshire–Dieppe and London basins (Fig. 4). Palaeocurrents and provenance indicators suggest drainage alignment towards the SE. In both regions the rivers seem to have adopted flow channels dominated by sands with clay-plug type abandoned channel fills and notably clay-clast breccias in the London region. The multicoloured 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 typify meandering river sediments in tropical regions (Miall 1996). Here rivers have cohesive banks, densely vegetated floodplains, and predominantly transport fine material but also coarser sediment during floods. Both the proto-rivers Solent and Thames and others were already present at this time. Their preservation and disposition, in the uppermost parts of the sequence, indicate that they may have been extending their courses seaward to follow the regressing sea.

Eocene

Early Eocene

The Eocene opens with renewed significant marine transgression from the east resulting in deposition of Thames Group sediments, the thickest and most extensive of which is the London Clay Formation (Fig. 3), deposited during the Early Eocene Ypresian Stage (Daley 1999; Anderton 2000). During this period, submergence was most extensive towards the west and linked the London and Hampshire–Dieppe basins (Fig. 5) (Davis & Elliott 1957; King 1981). At least five transgression–regression cycles are represented, reflecting periods of sea-level rise followed by shallowing and coastline progradation (Plint 1988; Anderton 2000). Thin, marginal sand and silt-dominated sediments are rare in the London Basin but are found in the Hampshire–Dieppe Basin in Dorset and western Hampshire, where they were subjected to pedogenesis.

During deposition of the London Clay, the regional climate was very warm, the surrounding land to the north, west and south supporting dense tropical to subtropical and warm-temperate forests, with mangrove swamps on the coasts (Reid & Chandler 1933; Anderton 2000; Collinson & Cleal 2001*b*). Inland an ‘upland flora’ may have flourished, but temperate elements were also well represented in the shallow marine sediments (Daley 1972). The overall character of the flora shows affinities with the present-day Malay Pensinsula, characterized by high levels of precipitation and environmental stability (Daley 1972).

The nature of the land surface during London Clay times is poorly known but appears to have continued to be subdued with wide plains and no mountains in Wales (e.g. Wells & Kirkaldy 1966; Daley 1972). The major erosion phases seen earlier had ceased and instead had given way to overall slow degradation of exposed surfaces subjected to intense chemical weathering. This is seen 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. Only limited evidence of actual channel systems is known at present. However, continual influx of river water has been invoked to explain the low-diversity foraminiferal assemblage in the Hampshire–Dieppe Basin by Murray & Wright (1974). In addition, incised fluvial channels, formed during local sea-level lowstands and then infilled by estuarine deposits during subsequent marine transgression, are recorded from the Portsmouth and Whitecliff members across the basin (Plint 1988). Davis & Elliot (1957) recognized that the basal pebble beds of the Hampshire basin region were derived from the SW, presumably by rivers (Fig. 5). Those workers envisaged several smaller streams flowing northwards.

Late Early–early Mid-Eocene

London Clay deposition was brought to an end by a rapid expansion of fluvial delta complexes towards the east in the late Ypresian–Lutetian (early Mid-Eocene) (Fig. 6). In the London Basin 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 (Fig. 3). The latter are marine in the east, but to the west represent a vast delta complex (Wells & Kirkaldy 1966; Anderton 2000). The sediments are similar to the Reading deposits, consisting 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 NW, which encouraged river incision and potentially increased discharges of coarser terrigenous sediments. No later Paleogene fluvial or estuarine sediments are found in the London Basin.

In the Hampshire–Dieppe Basin the London Clay is succeeded by the Bracklesham Group sequences (Fig. 3); in particular by the coarse cross-bedded fluvial sands of the Poole Formation in the western part of the basin, e.g. around Wareham, that span the latest Ypresian (or ‘Cuisian’) to mid-Lutetian stages (see Curry *et al*. 1977). These sands pass laterally eastwards into silts and fine sands of estuarine and marine origin. The basal sands, such as those exposed at Studland Bay, Dorset, together with those of the Bournemouth cliffs, Wareham and the Isle of Wight, characteristically occur in fining-upward cycles that pass upwards into lignitic sands and fine material rich in plant remains (Fig. 6; Plint 1983*a*; Daley 1999). Plint (1983*a*) interpreted these sequences as representing actively meandering sand-bed rivers, but with affinities to those of sandy braided streams. The progressive westward coarsening of these deposits is accompanied by a pebble composition that includes exotic clasts such as abundant vein quartz, black chert, silicified limestone and siltstone, all derived from Palaeozoic rocks but possibly reworked from the Wealden (Plint 1982). The architecture of the sequences suggests fluctuating, potentially seasonally varied discharge, and this accords well with the predicted tropical to subtropical climate (Smith *et al*. 1973) and a dense and diverse tropical to subtropical vegetation (Daley 1972, 1999).

Further west, beyond the margins of the Hampshire–Dieppe

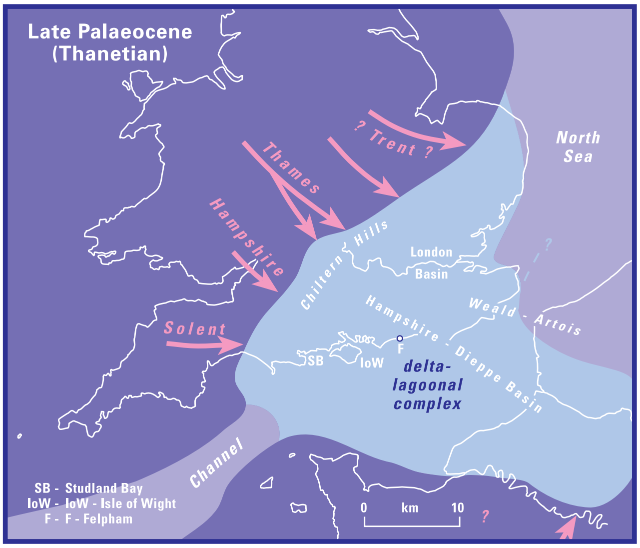

Fig. 4. Palaeogeography of the Late Paleocene Thanetian Stage (modified from Bignot 1972; Murray 1992; J. P. Lautridou, pers. comm.).

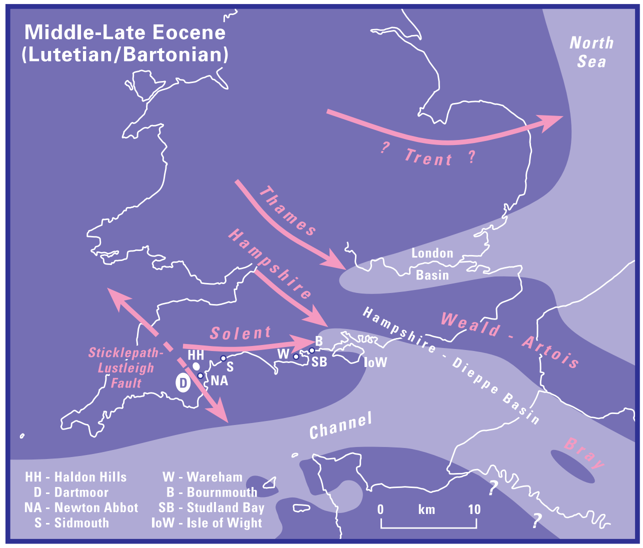

Fig. 6. Palaeogeography of the Mid–Late Eocene Lutetian–Bartonian Stages (modified from Bignot *et al*. 1968; Larsonneur 1972; Pomerol 1973; Plint 1982; Murray 1992).

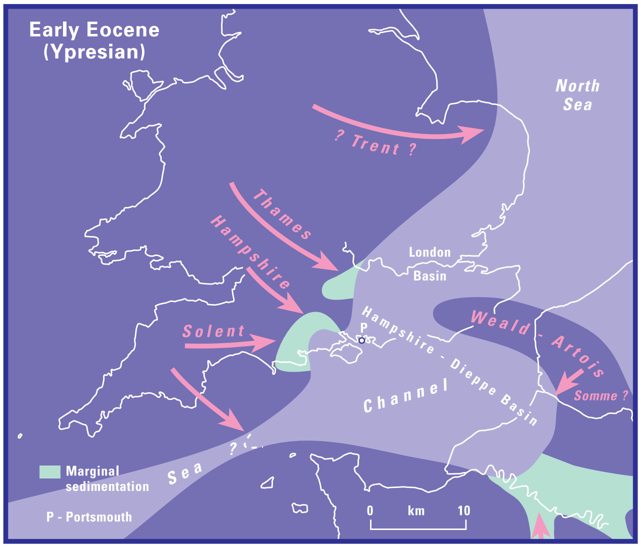

Fig. 5. Palaeogeography of the Early Eocene Ypresian Stage (modified from Davis & Elliott 1957; Bignot 1972; Pomerol 1973; Murray 1992; Anderton 2000; J. P. Lautridou, pers. comm.).

Basin, outliers of coarse gravels provide considerable insight into the early Paleocene drainage and environment of SW England. At Blackdown and Bincombe in Dorset, a conglomeratic facies of the Middle Eocene Bracklesham Group (Daley 1999) occurs. These crudely bedded, clast-supported gravels appear to be the upstream equivalent of those at Wareham (Plint 1982) and again include a range of exotic lithologies derived from Paleozoic source rocks. The coarse nature and bedding structures in the gravels have resulted in their being interpreted as high-energy fluvial deposits; Plint (1982) attributed them to alluvial fan-type deposits associated with local fault movements. However, if they were solely a local phenomenon, that would not explain their exotic pebble components (see Daley 1999). It is therefore more likely that they represent derivation from a gravel river-type accumulation tributary to a major eastward-flowing river, i.e. the Solent River, from Devon, possibly augmented by dissection of tributaries additionally supplying locally derived materials (Figs 6 and 7).

The Haldon Formation gravel in Devon apparently represents an upstream equivalent of the Poole Formation (Fig. 3). These gravels, described by Hamblin (1973) and Edwards & Freshney (1982), comprise two members. The lower, Tower Wood Gravel is a flint gravel comprising unabraded clasts in a clay-dominated matrix, the latter being ‘a well-ordered kaolinite with little ball clay kaolinite and illite’ (Hamblin 1973). It is interpreted as a weathering residue, derived from a former cover of Chalk that may have reached as much as 200–300 m thick. However, heavy minerals indicate that the clay was derived from the Dartmoor Granite, west of the Haldon Hills, and probably accumulated post-depositionally in the interclast voids.

By contrast, the overlying Buller’s Hill unit (*sensu* Hamblin 1973) is a clast-supported flint gravel in a sandy clay matrix. Its pebble assemblage includes a range of exotic lithologies including quartz, tourmaline and quartzite, as well as thermally altered Carboniferous shale and chert. The associated heavy-mineral suite is particularly rich in tourmaline and is again of granitic origin. However, unlike that in the Tower Wood unit beneath, the clay occurs as both ordered and disordered kaolinite, with more illite. Taking the evidence altogether, Hamblin (1973) concluded that the gravels accumulated under periodic high-energy sheet-floods, alternating with dry-seasonal conditions of low-energy flow or even complete desiccation. These flash-type floods are often typical of arid or semi-arid areas (see Jones 1977). The Buller’s Hill unit therefore represents an eastward-flowing braided fluvial system; the material was derived from the Dartmoor Granite complex and its aureole, as well as weathered Palaeozoic rocks (Hamblin 1973; Daley 1999). In addition to the sedimentological evidence, the predominance of abundant kaolinite indicates that the contemporaneous weathering occurred under a savannah climate with intermittent dry periods, as the clay mineral is characteristic of savannah lateritic soil processes. Similar sediments, overlying a laterite soil and an associated silcrete horizon, are known from the Sidmouth area (Isaac 1979).

Like the Buller’s Hill Gravel, the Aller Gravel found south of

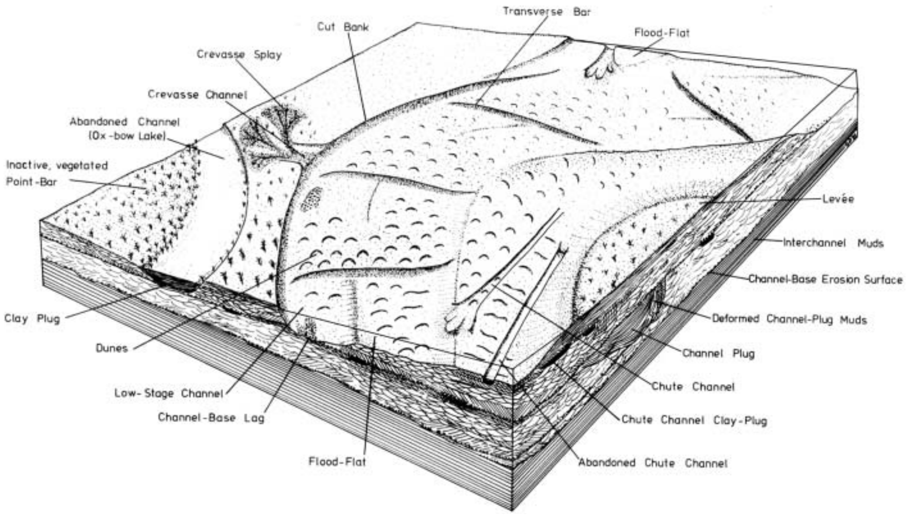

Fig. 7. Hypothetical 3D sequence model for point bars in the Mid-Eocene Poole Formation of Dorset (after Plint 1983*a*).

Newton Abbott, Devon, provides additional evidence of early Paleocene fluvial activity in SW England. This 25–30 m thick sequence of cross-bedded and channelled flint gravels and sands, the lenticular nature and horizontally bedding structure of the matrix-supported gravel and sand, together with the large clast size variability, frequent erosion surfaces, etc. all indicate deposition in a braided fluvial complex. The pebble assemblage again confirms derivation from the SW, as it includes aureole as well as rocks from the Dartmoor Granite itself, together with unmetamorphosed Carboniferous rocks of north or northwestern origin (Daley 1999).

Late Mid-Eocene–Late Eocene

In SW England a series of isolated, enclosed basins occur along the line of the major NW–SE-trending Sticklepath–Lustleigh wrench fault. They include the Bovey, Petrockstowe and the minor Dutson Basin on land and the Stanley Bank Basin beneath the Bristol Channel. The Bovey Basin is the largest of these features, all of which are infilled by terrestrial, largely fluvial sediments. The predominently argillaceous sediments of the Bovey Formation are underlain by the Aller Gravel, discussed above. Here, however, they are overlain by a complex, highly variable sequence that is over 1000 m thick, described by Edwards & Freshney (1982). The upper 300 m of these sediments are certainly of Oligocene age (see below) and are exposed in quarries from which the koalinite-rich clay is extracted. However, the lower 700 m thick unexposed part of the sequence (the lower Bovey Formation) is of Eocene age and represents accumulation in the fault-bounded trough during which sedimentation kept pace with subsidence (Edwards 1976). The sediments comprise silts, sand, gravel and, often lenticular, silty clay, comparable with similar sediments in the Petrockstowe basin, where the bulk of the deposits are Eocene (Edwards & Freshney 1982). At Petrockstowe the basal sediments are again braided stream gravels, derived from the Dartmoor Massif and overlain by a series of upward-fining cyclic sequences of sands to fine material, seatearths and deeply weathered palaeosols (Edwards & Freshney 1982). These channel to floodplain sediment cycles typify an active-meandering river, sands- to fine material-dominated active- to stable-meandering or even in part anastomosing system with stable floodplain surfaces, cut-off meander channel fills, etc. However, the cyclicity is partly attributed to subsidence. Here the sediments fine in a north-westerly direction, indicating that the river was flowing into the Stanley Bank Basin towards the Bristol Channel (Edwards & Freshney 1982; Tappin *et al*. 1994), the latter appearing as a landscape element for the first time at this stage. Comparable sediments are also known from the St. George's Channel Basin beneath the Irish Sea (Tappin *et al*. 1994; see below). In contrast, the Bovey Basin stream flowed to the SSE (Fig. 5), showing that by this time the upper headwaters of the Solent River had been severed by movement of the Sticklepath–Lustleigh Fault (Edwards & Freshney 1982). A comparable deep infilled basin, the Bassin de Rennes, occurs in Brittany.

The later Mid–Late Eocene (late Lutetian, Bartonian–Priabonian) saw the continued sedimentation of freshwater and estuarine sediments in the western part of the Hampshire–Dieppe Basin. The extensive estuarine Boscombe Sand (Barton Formation) in the Hampshire–Dorset area (Fig. 3), reflects deposition in a tidal channel environment that interfingers with beach conglomerates (Plint 1983*a*, 1988). Fluvial deposits of Bartonian age are apparently unknown but deposition of the Headon Hill Formation (Solent Group) above occurred in near-coastal situations, including brackish lagoons, freshwater stream and shallow alkaline lakes in a low-energy embayment (Fig. 8). The sediments include lacustrine freshwater limestones, silts, marls, occasional sands and local lignite (Daley 1999; Anderton 2000). In places, fossil variegated palaeosols, formed under conditions of highly seasonal wetting and drying, also occur (Huggett *et al*. 2001). Although local stream input is represented, no large-scale fluvial activity is apparently recorded.

The youngest Eocene sediment in the Hampshire–Dieppe Basin is the Bembridge Limestone. This highly fossiliferous muddy limestone complex represents deposition in a series of pools and lakes with a limited local catchment surrounded by dense forest (Collinson & Cleal 2001*c*) under a subtropical or warm-temperate climate (Daley 1999). Although there is again no direct evidence of substantial fluvial activity at the Isle of Wight sites, it is highly probable that the Solent, and possibly a Hampshire (?proto-Avon) river, continued to flow at some distance, as sedimentation continued into the early Oligocene Bembridge Marls (see below), which reflect deposition in a sluggish-water estuary (Collinson 1983). The lack of fluvial sediment implies either that discharges and/or sediment supply were low, which reinforces the conclusion that southern English

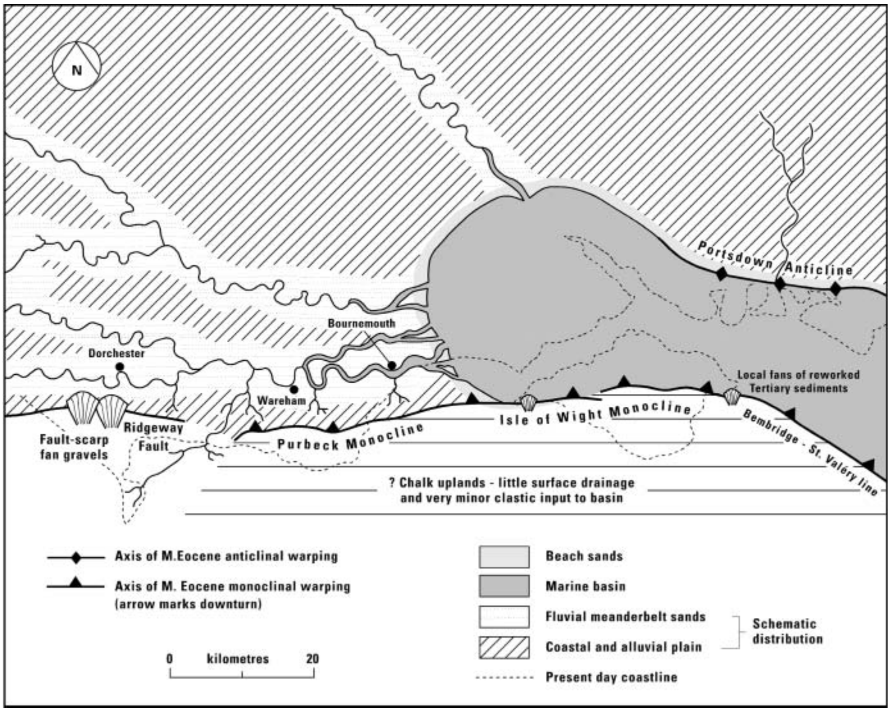

Fig. 8. Generalized palaeogeography of the western Hampshire–Dieppe Basin during deposition of the Bracklesham Group (modified after Plint 1983*a*).

landscapes remained subdued, with stable, densely vegetated surfaces during this interval.

Oligocene

The Oligocene begins in the Isle of Wight area with sedimentation of the Rupelian-age Bouldnor Formation (Fig. 3), the lowest member of which, the Bembridge Marls Member, continues from the Eocene. The Bouldnor sequence predominantly comprises black, green or grey silts that include plant and animal fossils of fresh- to brackish-water environments (Daley 1972). The overall sedimentology suggests deposition in a low-energy estuarine or floodplain complex, 'the upper reaches of which were sufficiently river-influenced and isolated from the sea to have experienced near- or truly freshwater conditions' (Daley 1999, p. 148) in what was in all probability the proto-Solent River. The palaeobotanical investigations from the Bouldnor Formation are significant in that they demonstrate a distinct shift from the post-Bartonian subtropical to very warm-temperate conditions to cooler climate (Machin 1971; Collinson 1983; Collinson & Cleal 2001*c*). The flora records a remarkable assemblage of aquatic and paludal plants inhabiting a lush local environment, with a hinterland of more open vegetation with trees including *Pinus* and *Sequoiadendron* that contrasts markedly with the dense tropical-type forest of the Eocene.

To the west in the Irish–Celtic Sea region there are a series of downfaulted basin structures infilled with sediments of late Paleogene to early Neogene age. These basins owe their origin to basin inversion during the post-Maastrichtian (latest Cretaceous) to pre-Mid-Eocene period (see Tucker & Arker 1987). They include the St. George's Channel Basin, the North and South Celtic Sea basins, the Bristol Channel Basin, the Stanley Bank Basin and the Cardigan Bay Basin (Tappin *et al*. 1994). They were infilled, particularly in the north and east, mainly by fluvial and related deposits. The sequences are best known from the Mochras borehole in the Cardigan Bay Basin, and from the well-known onshore basins at Petrockstowe and Bovey Tracey in Devon. The former has been described in detail by O'Sullivan (1971, 1979) and summarized by Dobson & Whittington (1987) and Tappin *et al.* (1994). All agree that the repeating sand, silt, clay and lignite fining-upward sequences represent fluvial floodplain complexes (Fig. 9). These fining-upward cycles are thought to represent relatively short periods of sedimentation punctuated by long phases of pedogenesis under moist swampy forested conditions (Dobson & Whittington 1987). Seasonal water-table variation is invoked to account for the formation of characteristic gley soils. Lateral reworking resulting from active stream channel meandering is rare. The sediment cycles include sharp-based sand beds, interpreted as crevasse splays, and basal coarsening-upward sheets immediately predating a fining-upward accumulation, interpreted as levee deposits (Dobson & Whittington 1987). Overall this facies architecture resembles those of a sand-bed anastomosing or meandering channel model. These sequences have been compared with those infilling the substantial Lough Neagh Basin in Northern Ireland, which is also thought to be part of the same river system (Wilkinson *et al*. 1980; Murray 1992).

Associated with these predominantly fine sediment sequences in north Wales is a characteristic facies of conglomerates interpreted as representing mass flow deposits or alluvial fans (Fig. 9). These fans initiated on steep slopes, possibly generated by movement on the adjacent faults, and involved transport of debris flows of varied energy types. Some of the flows were sufficiently fluid to have resulted in transport of soft, deeply weathered clasts periodically derived from the adjacent massif and extending out onto the river floodplain (Dobson & Whittington 1987). Although deposition in the Irish Sea region basins was predominantly terrestrial, the South Celtic Sea Basin includes micaceous, glauconite-rich sands and in the basal part carbonaceous materials interpreted as being of marginal-marine origin, implying deposition at the mouth of a substantial Irish Sea river system (Fig. 10).

As noted above, the upper 300 m of the Petrockstowe and Bovey Basin infills (the middle and upper Bovey Formation) are

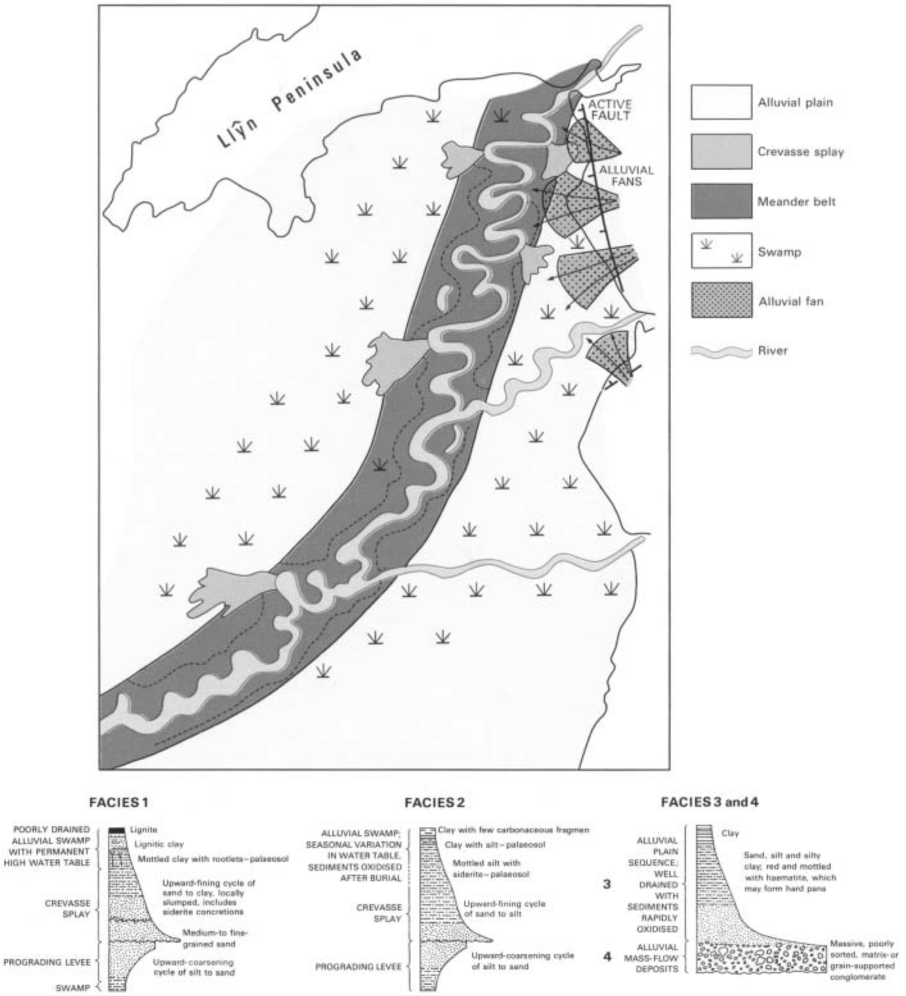

Fig. 9. Simplified reconstruction and vertical sequence sediment profiles from the late Oligocene–early Miocene of Cardigan Bay. The depositional model represents a high-sinuosity river system with swamp-dominated floodplains, formed by overbank deposits. Course modification arose from crevasse splays. The sediment facies assemblages represent fining-upward, channel to floodplain cycles 1–2 m thick. They terminate as follows: 1, perennial swamps with gleyed soils; 2, penecontemporaneous swamps with seasonal water-table variation; 3, fine-sediment accumulations associated with coarse-grained conglomeratic material (facies 4), thought to represent well-drained floodplains. Facies 3 and 4 are restricted to the basal part of the succession (after Dobson & Whittington 1987).

certainly of Oligocene age and comprise cyclic sequences of sand and carbonaceous clay complexes deposited predominantly on river floodplains, remarkably similar to those described from Cardigan Bay, and short-term lakes (Edwards & Freshney 1982). The sands represent channel fills, occasionally associated with local brecciated horizons, thought to result from reworking of desiccated floodplain clays. In parts, channels cut into underlying clay beds include intraformational breccias of clay clasts in a clay matrix, interpreted as a result of channel bank undercutting. Meanwhile, presumably floodplain vertically accreted accumulations of koalinite-rich clays, associated with rootlet beds and local soils, and backswamp lignite units are frequent. But most of the 'lignite' is of detrital origin, being composed of reworked *Sequoia* macrofossils derived from the surrounding dense upland forests (Edwards & Freshney 1982). Overall the streams are thought to have adopted a meandering mode, as vertical-accretionary fine-sediment sequences predominate, but there is also distinct evidence of point-bar, crevasse splay and levee facies. Some of the accumulations, particularly those in the actively subsiding basins, may have adopted an anastomosing form. However, the predominance of clays in the Petrockstowe and Bovey basins again suggests that the SW Peninsula landscape was relatively subdued (see Walsh *et al*. 1987), although they could have been derived from older sequences. The clays were derived from the decomposition of the Dartmoor Granite. The rivers flowed in opposite directions (Fig. 10); the Petrockstowe river continued to flow northwestwards whereas the Bovey basin river flowed SSE towards the Channel (Edwards & Freshney 1982).

These deposits were laid down under a seasonally wet, generally hot climate, which was of subtropical aspect (Wilkinson in Edwards & Freshney 1982), although cooler conditions may have occurred in the higher areas such as Dartmoor (Tappin *et al*. 1994). However, marked climate change at the onset of the late Oligocene Chattian Stage is indicated by substantial cooling in North Sea molluscs (Buchardt 1978). This is accompanied by a eustatic sea-level fall of over 100 m (Haq *et al*. 1987: Fig. 2), related to glaciation in Antarctica (Miller *et al*. 1987). This gave rise to a major regression phase, which saw large previously submerged areas exposed subaerially, allowing the extension of rivers such as the Thames (Anderton 2000) and the Irish Sea river, mentioned above (Fig. 10).

Miocene and Pliocene (Neogene)

The later Oligocene to mid-Miocene saw the main phases of the Alpine (Helvetic) Orogeny, which was represented in the British region by inversion of the Celtic Sea, Irish Sea, Bristol Channel, Western Approaches, English Channel and Paris basins (Ziegler 1987; Evans 1990; Chadwick 1993; Cope 1994; Tappin *et al*. 1994; Blundell 2002). Subsidence continued in the North Sea, whereas Fennoscandia, Wales and Scotland were uplifted (Murray 1992). Equally, there was uplift of Exmoor (Straw 1995)

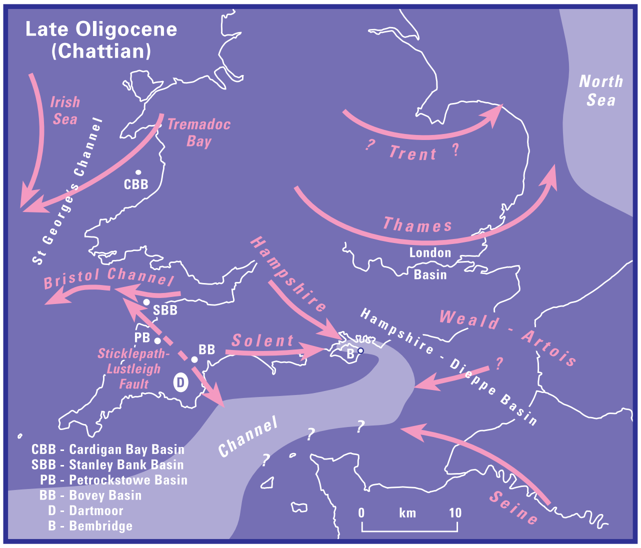

Fig. 10. Palaeogeography of the late Oligocene Chattian Stage (modified from Bignot 1972; Pomerol 1973; Murray 1992; Anderton 2000).

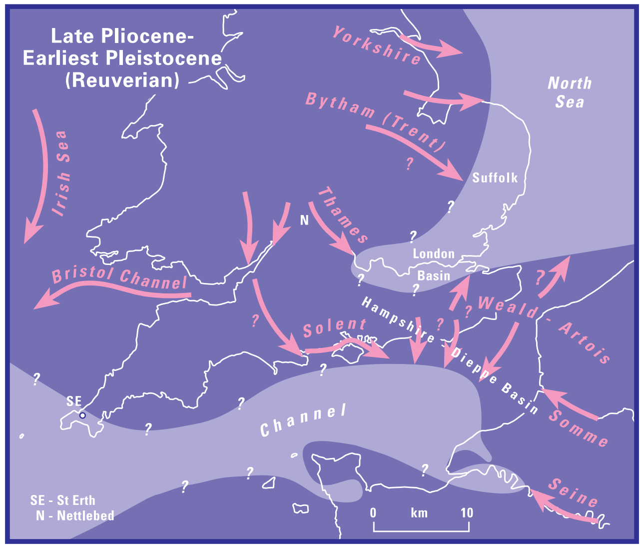

Fig. 12. Palaeogeography of the Late Pliocene–earliest Pleistocene, Reuverian Stage (modified from Bignot 1972; Larsonneur 1972; Gibbard 1988; F. Quesnel, pers. comm.).

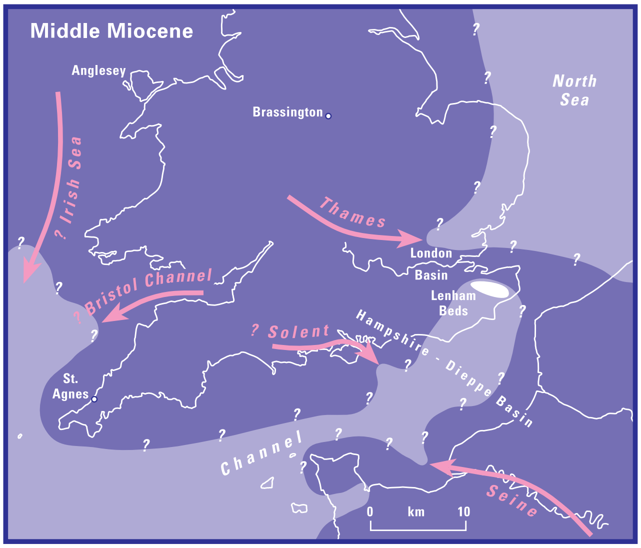

Fig. 11. Hypothetical palaeogeography of the Mid–Late Miocene (modified from Bignot 1972; Larsonneur 1972).

in the SW, and the Weald–Artois Anticline of the order of *c.* 180 m (West 1972) in the SE.

Apart from the thin, localized aeolian and colluvial deposits of the St. Agnes Outlier, in Cornwall (Walsh *et al.* 1987), Anglesey (Walsh *et al.* 1996) and the Brassington Formation doline infillings in Derbyshire (Boulter 1971; Walsh *et al.* 1987; Collinson & Cleal 2001*c*), onland *in situ* Miocene deposits in Britain are virtually absent, although Chandler (1964) considered that the Bovey Formation might continue into the Miocene (Fig. 11). This contrasts strongly with the finds in neighbouring continental countries, including northern France and more particularly Germany, Poland and the Netherlands. Although there can be little doubt that rivers continued to flow in Britain throughout the Neogene, it is only in the offshore regions that unequivocal evidence occurs. The clearest example is the continued fluvial sedimentation into the Early Miocene, demonstrated in the Mochras borehole, noted above. Similarly, westerly fine-clastic input from the proto-Forth and Tyne–Tees rivers is recorded in the Central North Sea (Gatliff *et al.* 1994). This is joined by more substantial input from the prograding Ur-Frisia (also termed ‘Eridanos’) deltaic system from the south and SE, first seen in late Miocene times. These deltas, derived from the Baltic River, the Rhine and the Maas, prograde progressively through the Pliocene, eventually coalescing to form a massive delta plain that occupied the southern North Sea region by the Early Pleistocene (Zagwijn 1974, 1979; Cameron *et al.* 1992; Huuse *et al.* 2001; Overeem *et al.* 2002).

In stark contrast to the lack of Neogene fluvial deposits in Britain stand the thick fluvial and associated sequences of the Lower Rhine Embayment in western Germany and the Netherlands, the Leipzig region of Eastern Germany and the Belchatow region of Poland. Although by no means restricted to the Neogene, these economically important sequences include brown coals or lignites, which underlie large areas and include substantial fluvial sequences of this age. Fluvial sands and gravels, together with organic-rich clay beds, indicate that meandering river systems, associated with extensive and long-lasting peat accumulations, dominate the Neogene accumulations (e.g. Gleise 1971; 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 & Hager 1987; Zagwijn 1989), the rivers draining subdued topography in central Europe. The detailed palaeobotanical investigations are beyond the scope of this paper, but suggest extensive, diverse, densely forested environments that indicate subtropical periods that alternate with temperate ones, characterized by an ‘arcto-Tertiary flora’ dominated by deciduous temperate forest (Zagwijn & Hager 1987; Zagwijn 1992). During the Pliocene the warm-temperate arcto-Tertiary flora became predominant (Zagwijn 1992; Eissmann 2002). Indeed, in eastern Germany an almost continuous sequence of floral assemblages from the Eocene to the Pliocene is represented.

Neogene fluvial sediments also occur in the Channel region.

Here the early Pliocene quartz-rich Lozère Sands in the Lower Seine Valley area (Cavelier & Kuntz 1974; Kuntz & Lautridou 1974; Lautridou 1985; Tourenq *et al*. 1991; Cavelier *et al*. 1995; Tourenq & Pomerol 1995) were deposited by a substantial proto-Seine river flowing northwestwards from the Massif Central. During eustatic sea-level lowstands the Seine turned southwestwards in the Channel to enter the sea west of the Cotentin (Pomerol 1973; Lericolais 1997; Lautridou *et al*. 1999). The Solent River apparently joined the proto-Seine and thus initiated the eastern Channel fluvial system during this interval (see Pomerol 1973). Further SW, Guillocheau *et al.* (1998) and van Vliet-Lanoë *et al.* (1998) have suggested that the 'Red Sands' of Brittany are of Late Miocene to early Pleistocene age. These 'Red Sands' fill shallow valleys in the Armorican Massif and represent local meandering to braided stream systems.

Extensive marine transgression occurred in the early and mid-Miocene (see Zagwijn & Hager 1987) but deposits of this age are poorly represented in the British Isles region. Only phosphatic 'lag' gravels occur within the Pliocene Coralline Crag Formation in Suffolk (Balson 1990, 1999) and the late Miocene Lenham Beds that occur in solution pipes in the Chalk surface of the Weald (Balson 1999) (Figs 3 & 11). The latter, a series of ferruginous shelly sands, are the only preserved *in situ* product of the late Miocene–early Pliocene marine transgression. This transgression entered the area from the west (i.e. the Channel), not the north; the Weald–Artois Anticline ridge continued to form a major barrier between the two basins throughout the period (Balson 1999; but see Funnell 1996). Thus the southern North Sea remained a semi-enclosed basin that periodically inundated parts of eastern England. This late Miocene transgression has often been invoked to explain the development and superimposition of the modern drainage system in southern England (e.g. Wooldridge & Linton 1939, 1955). However, it is now generally accepted that any Neogene transgression was markedly less extensive in England than previously thought (Figs 11 and 12). For example, Cornubia was not submerged (except the extreme southwestern point where the Early Pleistocene St. Erth Beds were deposited), and therefore the inundation was of limited importance to the drainage evolution (Jones 1980, 1981, 1999*a*; Walsh *et al*. 1987; Walsh 1999). Instead, a widespread planation surface of presumed mid-Miocene age ('Reskajeage surface') is recognized across western Britain, western Wales, Ireland and potentially northern France (Walsh *et al*. 1987, 1996; Walsh 1999). Of greater significance was the substantial uplift noted above, which Jones (1980, 1999*a*, 1999*b*) saw as resulting in substantial incision of river valley systems through the period, particularly in the Weald (see Jones 1999*b*). However, it should be stressed that this incision is not confirmed by the sedimentary record. The absence of substantial accumulations of Neogene clastic sediments suggests that incision was not as intense as previously thought. This should be seen against a background of the lack of accommodation space, followed by intense later Pleistocene incision.

Late Pliocene to earliest Pleistocene (*c*. 3–2 Ma) fluvial sediments are very restricted in extent in Britain. At this time the London Basin was initially submerged beneath the sea (Fig. 12). Fossiliferous sands, with a lithology and fauna comparable with the Red Crag Formation of Suffolk (Fig. 3), occur at heights of up to 180 m above sea level on both the north and south sides of the London Basin (West 1972; Balson 1999). Subsequent early Pleistocene uplift of western and northwestern Britain caused a relative displacement of *c*.180 m between the western London Basin and the Suffolk coast (Mathers & Zalasiewicz 1988). The resulting regression allowed the eastward and northeastward expansion of the River Thames system to occupy the basin vacated by the sea (Gibbard 1988). Similarly, the Solent system rivers extended their courses in the Hampshire–Dieppe Basin. This development is indicated by gravel and sand accumulations of the Nettlebed and Pebble Gravel Formations in the London Basin (Gibbard 1999) and Older Gravel Formation in the Hampshire–Dieppe Basin (Gibbard & Allen 1995; Gibbard & Preece 1999). Further NE, precursors of the Trent, Humber and Tyne–Tees were present (Cameron *et al*. 1992), and in the west rivers were re-established in the downfaulted Bristol Channel and Irish Sea basins (see Tappin *et al*. 1994). Similar evidence is seen in the Seine system of northern France (see Lautridou *et al*. 1999; Antoine *et al*. 2000, 2003) and the Belgian rivers (e.g. Gibbard 1988).

Synthesis

Following the present review of evidence derived from Tertiary sedimentation patterns, it seems advisable to adjust the perspectives provided by the more exclusive reliance on morphological evidence in a number of significant respects. Viewing drainage and land surface evolution as a component of a coupled erosion and depositional system, it is to be expected that the nature of erosional activity will be reflected in depobasins, which will also contain evidence of terrestrial environments (such as the nature of landmass-yielded sediment and alluvial sedimentation style) that is simply not available from analysis of fragmented erosion surfaces and their *in situ* residual deposits. This is amply illustrated in the considerable body of geological research that has been reviewed here.

The Wooldridge & Linton model has already been much modified. In particular, erosional surfaces are now more generally regarded as composite and in part of Paleogene origin (as discussed by Pinchemel 1954; Jones 1980, 1981, 1999*a*, 1999*b*; Small 1980; Walsh *et al*. 1987, 1996; Walsh 1999). The recent synthesis by Jones (1999*a*) identified a series of events in a 'new model of Tertiary landscape evolution'. This begins with emergence of the land from beneath the sea that began during the late Cretaceous and was completed by the early Paleocene. This was a dominating phase that provided the land surface upon which the drainage system developed. Destruction of the extensive Chalk up to 350 m thick followed, with virtually the entire cover being removed over uplifting areas (e.g. the Weald–Artois Anticline, the Channel High), under a tropical to subtropical climate. Paleocene and Eocene sediments were deposited on a polygenetic sub-Paleogene surface. By this time, the surface had a subdued relief form overlain by a weathered regolith (see Green 1985). Jones also emphasized the identity of separate morphotectonic regions differentiated to the extent that regional uniformity, specifically in chalkland areas, is unlikely (Jones 1999*a*).

The present synthesis emphasizes the persistence of coupled erosion and sedimentation during a whole series of transgressive and regressive episodes in the Paleogene rather than the separation of erosion and sedimentation periods: it appears doubtful whether periods of uplift–high relief were separated from ones of erosion–low relief in but a few stages echoing the Davisian cycle of erosion, even in modified form. Tectonic deformation occurred in pulses throughout the Paleogene, with structural basins (e.g. the London and Hampshire–Dieppe basins) becoming more strongly defined by the growth of the Weald–Artois Anticline and the Isle of Wight Monocline. Sedimentation was focused on these basins, deposition in the London Basin ending in the Eocene, presumably determined by available accommodation, but continuing into the Oligocene in the Hampshire–Dieppe Basin. There was an extensive, and probably faceted, low-relief duricrusted land surface, which in the west was episodically denuded from the Paleocene onwards, but which in the east developed on younger emergent Paleogene sediments. However, formerly postulated periods of erosion (as in the production of a mid-Tertiary peneplain and a later marine transgression) without evidence of substantial deposition appear unsupportable, and they are not reflected in the actual sedimentary record as strongly as are many other episodes.

Apart from the wealth of information now available on Tertiary rivers and their environments, perhaps the single most striking point to arise from this synthesis is the long-term stability of the fluvial system, the major elements of which were clearly already in existence in the late Paleocene. They must therefore have been established on the emerging and deforming surface at the end of the Cretaceous (see Cope 1994; Rohrman *et al*. 1995; Blundell 2002). Although this was already appreciated by Linton (1951) and Brown (1960*b*), the present assessment of river development from the standpoint of fluvial sedimentation and provenance, rather than surface morphology, unequivocally demonstrates that the major elements, the Thames, Solent, Irish Sea river and possibly an early Trent river, existed throughout the Tertiary, i.e. for at least 55 Ma and indeed on into the Pleistocene (Gibbard 1988, unpubl. data). This conclusion must be seen against a backdrop of significant, continual crustal deformation and upwarping throughout the period that continues today. It is even more notable that the Solent River has entered the Channel area in virtually the same place at periods of active erosion or sedimentation throughout this period. The Thames has, by contrast, markedly extended and reduced its course in response to external changes, a point discussed in a Pleistocene context by Gibbard & Allen (1995).

Tectonic regime has been the overriding control on the long-term stability of the drainage system. Notwithstanding the major changes that have taken place, the region has effectively remained in the same tectonic setting since the end of the Cretaceous, i.e. the opening of the North Atlantic Ocean basin, and during the later Alpine (Helvetic) Orogeny. The interaction of these processes has produced the long-term uplift of north-western block areas, the rejuvenation of Variscan structures south of the Variscan Front (from south Wales to central Kent in southern England) and the long-term continued downwarping of the North Sea. The net effect has been to cause southern Britain to tilt towards the SE throughout the Cenozoic. It has also led to repeated movement on some critical, more localized structures. Apart from the inversion of a series of basins noted above, it has driven the continual, pulsed rise of the Weald–Artois Anticline, a major structural element that has influenced the palaeogeography of SE England and in particular the drainage evolution and the seaway form virtually throughout the Tertiary (Pomerol 1973). This structure began rising in the Early Eocene Ypresian Stage, becoming a significant barrier in the Eocene Mid-Lutetian, following the London Clay sea-level highstand, and remaining so until it was breached in the Mid-Pleistocene. The barrier has conditioned the separation of the Solent and Thames drainage for 50 Ma. Moreover, drainage developed concordantly to the macro-structures and regional slopes of the elongated dome-like ridge radiating predominantly north- and southwards to enter the precursors of the North Sea and the Channel with probable antecedence operating in relation to minor folds (see Jones 1999*b*).

Similarly, the substantial Wight–Bray Monocline forms part of a major series of compressional structures that reflect reaction of deep-seated Variscan crustal structures (e.g. Ziegler 1987; Hamblin *et al*. 1992; Blundell 2002). The predominantly upward movement on this west–east- then NW–SE-trending feature has controlled the southern margin of the Solent system and of the Hampshire–Dieppe Basin throughout the Cenozoic.

Long-term consistency is seen not only as continuity of course-alignment but also of river form. Surprisingly, meandering streams predominate throughout the period and the evidence conforms generally to the models of Miall (1996) for rivers in seasonal tropical, subtropical or 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 region. This stability appears to relate to the subdued relief that seems to have prevailed, to stability of regolith resulting from dense vegetation cover, and to predominance of fine particulate materials in transport. It is clear that during certain periods, e.g. the late Ypresian to Lutetian or the mid-Thanetian, the rivers were predominantly transporting clastic material, sand and silt derived from destruction of the uplifting hinterland to the west, particularly Palaeozoic and Precambrian massifs, resulting in great expansions of sand-rich deltas. By contrast, during the early Ypresian, the dominant load was clay, derived from the thick weathering crusts, and deposited as London Clay when a period of comparative structural quiescence coincided with the maximum of Paleogene marine transgression. Similarly, there also seem to have been periods, such as during deposition of the Bouldnor Formation (Rupelian) of the Isle of Wight (Fig. 3), when only very limited volumes of fine material were in transport. Where channel and floodplain complex depositional sequences have been recorded, e.g. the Reading Beds (late Thanetian), a mixed load of fine granular material, together with sands, fine material and locally clay-breccias was being moved. 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. These sediments can arise in various ways, most commonly by *in situ* growth and accumulation in floodplain pools or hollows, where they frequently represent the end-member in fining-upward cycles, e.g. in the Bovey Basin Oligocene sequences. However, they can also originate as transported, detrital organic accumulations, such as those described by Plint (1983*a*) from Wareham, or Collinson & Cleal (2001*a*) from Felpham. In most cases the dense vegetation can be assumed to have greatly contributed to bank cohesion and stability; a situation typically found in tropical, subtropical and warm-temperate environments alike.

Floodplain surfaces are also repeatedly represented by descriptions of palaeosols, mostly originating under moist, but seasonally dry conditions, e.g. in the Hampshire Basin Reading Beds (Paleocene), the Headon Hill Formation (late Mid- to Late Eocene), in the Bovey Formation (Oligocene) and in the Lignite and Clay Unit (Oligocene–Early Miocene) in the Cardigan Bay Basin. Lateritic soil processes and silcrete formation, operating under a savannah (semi-arid) climate with intermittent dry periods and perhaps areally restricted along drainage lines, have also been reported from the early Mid-Eocene of Devon, and duricrust remnants involving a variety of parent bedrock materials are well known (Summerfield & Goudie 1980; Ulyott *et al*. 1998).

Coarser accumulations, dominated by gravels (conglomerates), are extremely rare in the regional Tertiary alluvial record. It is only in the braided sheet-flood sequences of Devon, the pebbly sands of the Reading Formation and the fluvial fan-type sequences in proximity to active faults, such as the Mochras

Fault in Cardigan Bay, the Bracklesham Group in Dorset and the Sticklepath–Lustleigh Fault in Devon, that coarse aggradations apparently occurred. Although this may be an artefact of their very low preservation potential, because such fan-type sequences are usually restricted to areas of high relief, which are later removed, it is more likely the result of general and persistent subdued topography simply lacking sufficient potential energy to generate flows capable of moving coarse detritus. This suggests that even under conditions during which precipitation was far higher than that today (see Daley 1999; Haywood *et al*. 2000), storm-induced floods were seldom able to cause substantial movement of gravel-sized material. Also to be emphasized is the density of the vegetation cover throughout, which acted to cushion flooding by removing water by evaporation, supported by efficient groundwater percolation. In addition, the predominance of intense chemical weathering through the period may have resulted in coarse gravel-sized material being relatively rare in the landscape. Where coarse clastic materials do occur they overwhelmingly comprise chemically stable lithologies, except in some local situations, such as the alluvial fans of north Wales.

As noted above, the Tertiary deposits of lowland Britain, particularly in the main depositional Hampshire–Dieppe and London basins, characteristically record alternating transgressions and regressions that have been attributed to global eustatic sea-level cycles, modified by local tectonic activity. The fluvial responses to these sea-level changes appear to parallel closely the reactions seen in British Pleistocene river systems (see Gibbard 1988), i.e. during transgressions their lower valleys are drowned by the sea, and during regressions the rivers extend their courses across the highstand sediments, in places cutting through the pre-existing marine–estuarine–deltaic sediment wedge *en route*, as they establish a graded course to the sea. Evidently, the rivers did this repeatedly throughout the period.

The general observation that, unlike nowadays, low-relief land surfaces dominated the southern British region until the Pleistocene is extremely important. Today most of the area, although not mountainous, has a considerable topography. Given that the tectonic regime currently affecting the region has remained broadly the same throughout the Tertiary, it is apparent that today's deeply incised river valleys must be the product of high, predominantly coarse to very coarse sediment yields, resulting from the substantial, rapid climate changes that characterize the Pleistocene. These climates introduced permafrost and cold-climate weathering products to river systems. The frequent thinning and occasional disappearance of the vegetation cover and the altered conditions for channel-bed and valley-floor incision that accompanied these changes explain the landscape dissection (Gibbard 1988). Although, without doubt, substantial climate change also occurred in the Tertiary, e.g. in the Oligocene, the changes apparently had less impact on long-term landscape evolution. This highlights the significance of mechanical (nivation) weathering compared with chemical weathering for the rate of landscape dissection and lowering. Moreover, it emphasizes the role of forest vegetation in stabilizing the landscape surface and reducing surface runoff, even though precipitation was apparently greater throughout much of the Tertiary than during the Quaternary (e.g. Daley 1972).

Conclusions

(1) The major drainage systems developed at least as early as the land emerged from beneath the sea during the Late Cretaceous and were well-established by the early Paleocene. Destruction of the extensive Chalk cover followed under a tropical climate, with virtually the entire cover being removed over uplifting axes (e.g. the Weald–Artois Anticline, the Channel High). Paleocene and early Eocene sediments were deposited on an evolving 'Sub-Paleogene Surface'.

(2) Evidence of high-relief erosional episodes is found locally, but rather than an alternation of uplift and relief-reduction phases, it seems that uplift and erosion proceeded simultaneously (if episodically) to maintain an overall low-relief landscape in southern and eastern Britain.

(3) A striking point is the long-term stability of the fluvial system, the major elements being initiated in the late Paleocene. It is unequivocally demonstrated that the major elements, the Thames, Solent, Irish Sea river and possibly an early Trent, existed almost throughout the Cenozoic. This conclusion must be seen against a backdrop of significant, continual crustal deformation and upwarping throughout the period, which continues today. The persistent tectonic regime is the overriding control on the long-term stability of the drainage system.

(4) The rivers, although maintaining their general courses throughout the era, markedly extended and reduced them in response to external changes including tectonic activity and sea-level fluctuations. A comparable pattern is also seen in neighbouring regions of western Europe.

(5) The constancy is also seen in river form, as meandering streams predominate throughout the period. Although their form certainly varied depending on materials in transport, discharge variability and variations in slope, the overall stability is striking. This appears to relate to the subdued relief, the stability of the regolith resulting from dense forest vegetation cover, and the predominance of fine particulate materials in transport.

(6) Coarser accumulations dominated by gravels (conglomerates) are extremely rare in the record. Except in local situations, chemically stable lithologies dominate the clastic component throughout.

(7) The fluvial responses to sea-level changes appear to parallel closely the reactions seen later in Pleistocene river systems.

(8) Low-relief land surfaces dominated the southern British and adjacent regions until the Pleistocene. It is apparent therefore that the deeply incised river valleys seen today are the product of high, predominantly coarse to very coarse sediment yields, encouraged by the substantial, rapid climate changes that characterize the Pleistocene. This highlights the role of vegetation cover for stabilizing the land surface and mitigating flood events. It also emphasizes the significance of mechanical (principally frost-weathering) compared with chemical weathering for the rate of landscape dissection and lowering. Moreover, it also demonstrates that climate, and not tectonic uplift, is the primary drive on fluvial incision in the Pleistocene. It is likely that the extensive valley networks (currently largely dry) on permeable lithologies were also added in this period.

(9) When viewed from the Tertiary perspective, the Pleistocene evolution represents the most recent ramification of a pattern that has repeated throughout the Cenozoic, albeit modified by glaciation, frost-climate weathering, altered and rapidly changing climates, and sea levels. It is reasonable to conclude that the overall pattern of major drainage lines will continue for as long as the current tectonic regime affects the British region.

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