Chapter 1 The Pleistocene of the Thames

The Quaternary record of the River Thames

Few rivers of so modest a size have had so much attention devoted to their deposits and geological history as the Thames. The present size of the river belies its importance to British Quaternary geology, however, since Thames sediments provide a framework for this the latest part of the geological record in Britain. Indeed, there is abundant evidence to show that the modern Thames is a mere shadow of its Pleistocene forebear. Not only did it once flow from the London Basin out across East Anglia to north Norfolk, but there are indications that its headwaters may once have drained a large part of the West Midlands and even North Wales (Figure 1.1). During Middle and Late Pleistocene cold episodes, when sea level was much lower and Britain was joined to the continent, the river extended for many kilometres over areas that now lie offshore; during these episodes it was a tributary of the Rhine system. Thus Thames deposits provide a potential means for correlation between the London Basin and other areas of Britain, as well as with the North Sea Basin and surrounding parts of the European continent.

The river has undergone a number of significant changes during the Pleistocene, some as a result of glaciation. It appears initially to have been a 'consequent stream', flowing along the approximate centre of the London syncline and receiving tributaries from the north and south. Many of the latter would have been of even greater antiquity, having originated on the newly formed Weald and Chiltern uplands and draining into the sea that covered the London Basin during the Palaeogene. The central drainage of the western end of the London Basin is the province of the River Kennet, the Thames upstream from Reading probably having originated as an early river flowing southwards into the basin down the northern limb of the syncline. The presence of quartz pebbles in the Palaeocene deposits of Buckinghamshire suggests that a fluvial route through the Chilterns, tapping pre-Cretaceous strata beyond, was in existence by that time (see Chapter 3, Part 1). The relative lowering of sea level that brought about marine regression in the late Neogene was responsible for the initiation of the Middle and Lower Thames as the main drainage line along the emergent sea-floor.

It appears that, by the Early Pleistocene, the Thames had acquired a much more extensive catchment, with Midlands and Welsh detrital material being brought into the London Basin via the Upper Thames system. There is still controversy as to whether the Thames once drained these areas directly, or whether glacial transport carried this 'exotic' material into its catchment during the Early Pleistocene. It is apparent that this supply ended by the Middle Pleistocene and that the Upper Thames was at that time confined to the south-east of the Cotswold escarpment (see Chapter 2).

The Thames terrace system

Research on the Thames terrace system first began over a hundred years ago, although there was relatively little progress until the early years of this century. The description by Trimmer (1853) of a gravel terrace 150 ft (46 m) above tidal level at Dartford is one of the earliest such records from the Thames. But the 'type area' for the Thames terrace sequence was established at about the turn of the century as the region in the Middle Thames around Maidenhead, Slough and Beaconsfield, where the lower parts of the succession were recognized and defined by officers of the Geological Survey (see Chapter 3, Part 3). The Survey applied this scheme throughout the Middle and Lower Thames valleys, classifying the terrace gravels as Boyn Hill, Taplow or Floodplain Gravel. These names replaced what had become a confusion of terms based on height above river level, relative elevation (High, Middle and Low terraces) or numerical schemes (First, Second etc. terraces) in which numbering from high to low or vice versa was employed by different authors (for summary, see Gibbard, 1985).

The system of named terraces accounted only for the 'valley gravels', which extend up to *c.* 40 m above the modern floodplain. Deposits above this level were generally mapped as 'Glacial Gravel' or, higher still, 'Pebble Gravel', the latter being regarded by most authors as marine rather than fluviatile (see Chapter 3). The view that many of these high-level deposits are the remains of older terraces of the Thames was already in existence by the turn of the century and has progressively gained widespread acceptance, although there is still a degree of controversy over whether the highest gravels may be marginal marine deposits (see Chapter 3, Parts 1 and 2). The full terrace sequence, as recognized at present, has been built up over the last sixty years by additions to the original Geological Survey scheme, the most important work being by S.W. Wooldridge, F.K. Hare, R.W. Hey and P.L. Gibbard (see Chapter 3). Prior to the 1960s, work on the Middle Thames was generally based on geomorphological mapping, which led to the recognition of further terraces both between and above those of the original scheme. These were (in stratigraphical order) the Harefield, Rassler, Winter Hill and Black Park Terraces, all above the Boyn Hill, and the Lynch Hill Terrace, between the Boyn Hill and the Taplow (Hare, 1947; Sealy and Sealy, 1956; see below and (Figure 3.2)). Additional, less well-developed terrace features have been described at various times, but their existence as products of fluvial aggradation has not been confirmed.

Later studies have concentrated on the aggradational deposits themselves, rather than the terrace 'flats' formed by their upper surfaces. The latter are geomorphological features and thus may be recognized independently from the sediment bodies underlying them, which formed as a result of aggradation by the river from an earlier, lower base level to the level of the terrace surface. The study of gravel remnants, as opposed to terrace geomorphology, allowed several earlier Thames aggradations to be recognized, despite the fact that the deposits laid down during these events are now highly degraded and fragmentary. Thus the highest and earliest elements of the sequence, the Nettlebed, Stoke Row, Westland Green, Satwell, Beaconsfield and Gerrards Cross Gravels, have all been defined in recent years (see Chapter 3). A refined classification of terrace deposits, based on lithostratigraphy, was pioneered in East Anglia (Rose *et al.,* 1976; Rose and Allen, 1977) and has been applied to the sequences in the Middle Thames (Gibbard, 1985; Chapter 3), in the Lower Thames (Bridgland, 1988a; Gibbard et al*,* 1988; Chapter 4) and in Essex (Bridgland, 1988a; Chapter 5).

Work in the Upper Thames basin (see Chapter 2) has generally been carried out entirely in isolation from that downstream of the Chiltern escarpment. The Upper Thames represents an important link between the London Basin and the Midlands, both of which have complex Quaternary sequences. Correlation of Pleistocene deposits between these areas has been hampered by the difficulty in tracing terrace aggradations between the Upper and Middle Thames valleys through the constriction of the Goring Gap, where terrace preservation is minimal. Biostratigraphical evidence from fos-siliferous sites in the Upper Thames valley has provided some grounds for correlation, but the interpretation of all the key localities has been the subject of controversy (see Chapter 2). An important marker within the Upper Thames sequence is provided by the first appearance of glacially derived material, mainly fresh flint, which was introduced through gaps in the Cotswolds escarpment. The glaciation that carried flint to the Cotswolds has been attributed to the Wolstonian (Saalian) Stage (Shotton, 1973a). However, recent work in the Midlands has raised important questions about the established chronology in that area, suggesting in particular that the glaciation of the Cotswolds occurred during the Anglian Stage (see below; (Table 1.1); Chapter 2).

Several important review articles have described the Thames sequence, from different viewpoints, in recent years. The most significant and useful of these are by Evans (1971), Brown (1975), Hey (1976a), Clayton (1977), Green and McGregor (1980) and Gibbard (1983). Several major works have described and discussed the formation of the Thames terraces (Wooldridge and Linton, 1939, 1955; Zeuner, 1945, 1959; Wymer, 1968; Gibbard, 1985).

The diversion of the Thames

The suggestion that the Thames formerly flowed to the north of London, through the Vale of St Albans, dates back to the turn of the century, when this old drainage route was recognized by Salter (1905). Sherlock and Noble (1912) considered that glaciation of the Vale of St Albans ended Thames drainage by this northern route. Wooldridge (1938, 1960), however, recognized two previous courses of the Thames, the first being that recognized by Salter and the second an intermediate route through the Finchley area (see Chapter 3, Part 2). He suggested that separate glacial advances were responsible for the demise of both routes, the first as a result of a 'Chiltern Drift' ice advance and the second in response to the main 'Chalky Boulder Clay' (Anglian Stage) glaciation. Recent workers have found little evidence to support the existence of a pre-Anglian glaciation in the London Basin (Moffat and Catt, 1982; Avery and Catt, 1983; Green and McGregor, 1983), but have determined that the Thames flowed through the Vale of St Albans until blocked by ice during the Anglian Stage (Gibbard, 1977; Green and McGregor, 1978a; Cheshire, 1986a; see Chapter 3, Part 2). In addition, Gibbard (1979) has demonstrated that the Thames was diverted from the Vale of St Albans directly into its modern valley without using Wooldridge's intermediate route, which in fact represents the pre-Anglian valley of the Mole–Wey tributary (see Chapter 3).

Gibbard (1977) showed that the Anglian glacial deposits of the Vale of St Albans provide a stratigraphical marker that enables correlation of the Thames terrace sequence with the established British Pleistocene chronology. He demonstrated that the Winter Hill Gravel of the Middle Thames was accumulating at the time of the glacial advance, thus implying an Anglian age for that formation. The next terrace aggradation (topographically lower) in the sequence, the Black Park Gravel, is also regarded as contemporaneous with the occupation of the Vale of St Albans by ice, but this formation has been traced into the modern Thames valley through London, whereas the Winter Hill Formation can be traced downstream into the Westmill Lower Gravel of the Vale of St Albans, which underlies Anglian glacial deposits. This indicates that the diversion of the Thames occurred between the aggradation of the Winter Hill and Black Park Terrace deposits, at the time of the Anglian glacial maximum (see Chapter 3, Part 2).

The continuation of the Thames into Essex

The first evidence for the route of the pre-diversion Thames downstream from the Vale of St Albans was derived from sub-drift contour mapping by Wooldridge and Henderson (1955), who recognized in their 'Mid Essex Depression' a buried valley system extending eastwards from Ware to Bishops Stortford, Chelmsford and Colchester. Detailed sub-drift mapping of parts of this area was subsequently published in various Geological Survey (Mineral Assessment Unit) reports, which include exhaustive borehole records but no regional interpretation. Green *et al.* (1982) suggested correlations of isolated gravel samples from this area with the Middle Thames sequence on the basis of 'clast-lithological analysis' (which is the identification of the clasts that make up a deposit and the calculation of their relative proportions — see Bridgland, 1986a), but their work lacked the added control of geological mapping. The first attempt to combine both types of evidence and to trace terrace aggradations through this area by reconstructing their downstream profiles has recently been made by Whiteman (1990; see below and Chapter 5).

Confirmation of the extension of the pre-diversion Thames system into East Anglia came with the recognition of early Thames gravels in Essex, Suffolk and Norfolk, important early contributions to this work being made by S.H. Warren, R.W. Hey, J. Rose and P. Allen (see Chapter 5). The distribution of these various aggradations, which make up the Kesgrave Sands and Gravels (Rose *et al.,* 1976), reflects a progressive southward migration of the pre-diversion Thames valley (see Chapter 5, Part 1). This migration culminated in a course through Chelmsford and Colchester, recognized in the lowest part of the 'Mid Essex Depression'. Gravel representing this final pre-diversion floodplain has been traced to the Clacton area, where it forms the lowest of a sequence of Kesgrave Group formations and is in close juxtaposition with post-diversion Thames deposits (Bridgland, 1988a; see Chapter 5, Part 1). The distinction in this area between pre- and post-diversion gravels is based on differences in their clast composition, assisted by the recognition of an influx of distal outwash from the Anglian glaciation at the end of the last pre-diversion aggradational phase. Using the stratigraphical evidence for the glaciation and the diversion of the Thames, the sequence in the Clacton area can be correlated directly with that in the Middle Thames and the Vale of St Albans (Bridgland, 1988a; see Chapter 5).

The post-diversion terrace formations of the Lower Thames continue into eastern Essex, where they make up the Low-level East Essex Gravel Subgroup (Bridgland, 1988a). These formations extend northwards from the Southend district, running approximately parallel to the coast (see Chapter 5, Part 2), but only the oldest (immediately post-dating the diversion) reaches the Clacton area. Earlier terrace deposits are preserved in south-eastern Essex, however, representing formations within a High-level East Essex Gravel Subgroup, but these are products of the River Medway that pre-date the diversion of the Thames. The sequence in eastern Essex therefore indicates that the Medway formerly flowed northwards across this area, towards its confluence with the pre-diversion Thames. This early Medway valley was never glaciated and continued to operate throughout the Anglian glaciation. It is apparent that the newly diverted Thames took over the former Medway route between Southend and Clacton, where it rejoined its former valley (Bridgland, 1988a). In the southern North Sea, Anglian (Elsterian) ice is thought to have ponded the waters of the Thames-Medway and the continental Rhine system, forming a huge proglacial lake (see Gibbard, 1988a). This lake eventually spilled over the watershed that then existed between North Sea drainage and English Channel drainage, to form a through valley, flowing southwestwards, in the position of the present-day Straits of Dover. After the Anglian Stage it appears that, during phases of low sea level, the Rhine and Thames united in the area of the southern North Sea and flowed south-westwards through the English Channel to the Atlantic Ocean (Gibbard, 1988a).

Later onshore terrace formations record the continued southward migration of the Thames. This migration culminated in the valley system, submerged by the Holocene transgression, that has been mapped beneath modern marine sediments on the floor of the southern North Sea using seismic techniques (D'Olier, 1975; Bridgland and D'Olier, 1989). Following the diversion, and as the Thames migrated southwards, the modern drainage system of Essex became established, rivers such as the Blackwater and Crouch being initiated as left-bank tributaries of the Thames. Later Pleistocene deposits in the areas of northern, central and eastern Essex formerly drained by the Thames are invariably the products of these tributary rivers (see Chapter 5, Part 3).

Classification of Thames terraces and deposits

Two types of classification are used in parallel in this volume; one for the series of morphological features, the terrace surfaces, and the other for the deposits that the Thames and its tributaries have laid down during the Pleistocene. The terrace surfaces are geomorphological features formed by alternating periods of fluvial aggradation and downcutting, the surfaces representing former floodplains that were abandoned as a result of rejuvenation. Terrace surfaces can also be formed by erosion, but features of this type are almost entirely unrepresented in the Thames system. Thus, wherever morphological terrace features are recognized in the Thames valley, the parallel geological classification of the deposits can also be applied. In contrast, remnants of fluvial deposits can be recognized in areas where severe post-depositional modification, such as erosion or burial by later sediments, prevents the recognition of original terrace surfaces. Consequently, the geological (lithostratigraphical) method of classification is generally more useful.

Geomorphological classification

The system of naming terraces after type localities is favoured here, rather than numbering or other alternatives (see above). The established sequence of Thames terrace features is as follows (see also (Figure 3.2)):

Terrace	**Underlying lithostratigraphical formation**
9. Lower Floodplain	Shepperton Gravel
8. Upper Floodplain	Kempton Park Gravel
7. Taplow	Taplow Gravel
6. Lynch Hill	Lynch Hill Gravel
5. Boyn Hill	Boyn Hill Gravel
4. Black Park	Black Park Gravel
3. Winter Hill	Winter Hill Gravel
2. Rassler	Rassler Gravel
1. Harefield	Gerrards Cross Gravel

Lithostratigraphical classification

Formal lithostratigraphical classification was first applied to the type-sequence of Middle Thames terrace deposits by Gibbard (1983, 1985), although a number of earlier workers had classified the sediments rather than the terrace surfaces, particularly when describing older, dissected aggradations (Wooldridge, 1938; Hey, 1965). Gibbard adopted the scheme for lithostratigraphical nomenclature recommended by the stratigraphical guides (Hedberg, 1976; Holland *et al.,* 1978), in which the following hierarchical divisions are applied:

Group	Two or more formations
Formation	The primary unit, into which the entire stratigraphical column is divided
Member	Named unit within a formation
Bed	Named distinctive layer within a formation or member

Gibbard considered individual terrace aggradations to be of member status and grouped these into a 'Middle Thames Valley Gravel Formation'. He sought to differentiate between his various members on the basis of clast-lithological differences, applying techniques of statistical evaluation (Gibbard, 1985, 1986). A similar method was adopted by McGregor and Green (1986), who also regarded the study of clast lithology as a lithostratigraphical method but did not advocate formal nomenclature. Hey (1986) adopted the Gibbard model in subdividing the Northern Drift of the Upper Thames (see Chapter 2), again on the basis of clast-lithological differences. However, Bridgland (1988b, 1990a), citing the various stratigraphical guides, observed that lithostratigraphical classification should be based on gross lithological properties rather than on laboratory techniques such as clast–lithological analysis. The former properties may include major breaks in sedimentary continuity (unconformities), such as occur at the base and top of each individual terrace aggradation. These allow the individual aggradations to be separated using basic techniques of geological mapping (including geomorphological mapping), thus making them primary units. For this reason Bridgland proposed that individual terrace aggradations should be classified as formations, rather than members. In some cases several of these can be collected together to form a group, for which no single type locality is necessary, although other lithostratigraphical units must be defined at a type locality. Members and beds may be defined within some of the primary units: for example, the Swanscombe Lower Gravel and other Swanscombe units (see Chapter 4) are members or beds within the Boyn Hill/Orsett Heath Gravel Formation, since they fall within the body of sediment that can be mapped as the Boyn Hill/Orsett Heath Gravel (see Chapter 4).

Although the Middle Thames is regarded as the type area for the Thames sequence, recent work in Essex has revealed that there are a number of terrace formations in that area for which no Middle Thames equivalent is recognized (Bridgland, 1988a; Whiteman, 1990; see Chapter 5). It is therefore necessary to refer to type localities outside the Thames valley to define these formations. In fact, separate nomenclature has been established in recent years for the Lower Thames, Essex and southern East Anglia and has been in existence since the earliest research in the Upper Thames (where the nomenclature used in the London Basin has never been applied). The overriding reason for this proliferation of names is that correlation between these various areas has been problematic, usually because of breaks in the continuity of recognizable terrace remnants. The most important breaks of this type coincide with the Goring Gap, central London and the Essex till sheet; in the first of these there has been little preservation of terrace deposits because of the constriction of the valley, whereas in the other two the evidence is preserved but largely inaccessible. Once correlation is on a sounder footing, however, it would be desirable to suppress synonyms and use a single nomenclature, probably that established in the Middle Thames (see (Table 1.1)).

The stratigraphical framework: Pleistocene chronostratigraphy and correlation

The interpretation of the floral and faunal content of temperate deposits, taken together with geological evidence for the deposition of other sediments under intensely cold or even glacial conditions, has been used as a basis for 'climato-stratigraphical subdivision of Pleistocene time. During the middle part of this century a scheme for climato-stratigraphical (relative) dating of the British Pleistocene succession was established using palynology (West, 1963, 1968). This scheme, which is still in use, distinguishes different interglacial episodes on the basis of their distinctive patterns of vegetational development, as determined by the analysis of pollen assemblages from successive horizons within depositional sequences. Moreover, climatic fluctuation has been accepted as a guide for the division of Pleistocene time (Shotton, 1973b), so that time periods corresponding with interglacials and glacials have been defined as chronostratigraphical stages. Thus palynological analyses allowed pollen-bearing sequences to be allocated to particular stages, enabling a chronostratigraphy for the British Pleistocene to be developed, as summarized by Mitchell *et* al. (1973). The following stages were recognized by these authors in the sequence post-dating the marine crags of East Anglia (in stratigraphical order):

Holocene = Flandrian (warm)

Devensian (cold)

Ipswichian (warm)

Wolstonian (cold)

Hoxnian (warm)

Anglian (cold)

Cromerian (warm)

Beestonian (cold)

Pastonian (warm)

Baventian (cold)*

* most recent stage within the Norwich Crag, the youngest marine crag.

Mitchell *et al.* recognized two interglacials between the Anglian Stage and the Holocene. These correspond with the Hoxnian Stage (type locality at Hoxne in Suffolk) and the Ipswichian Stage (type locality at Bobbitshole, near Ipswich, Suffolk). The Ipswichian and the Holocene were separated by the last glaciation, within the Devensian Stage. The time interval between the Hoxnian and Ipswichian Stages was ascribed by Mitchell *et al.* (1973) to the Wolstonian Stage, which replaced the Gipping Stage of West (1963). This stage, regarded by Mitchell *et al.* as a cold episode, was defined at Wolston, Warwickshire, where a detailed sequence of gravels, sands, clay and till occurs, entirely ascribed to the Wolstonian (Shotton, 1973a, 1973b). The absence of earlier or later sediments at Wolston underlines the acknowledged difficulties in relating the type-Wolstonian deposits to the local Pleistocene sequence, let alone the British climatostratigraphical scheme (Bowen, 1978). In recent years it has been suggested that the glacial sequence at Wolston is in fact equivalent to the Anglian Stage deposits of East Anglia, therefore invalidating the term Wolstonian (Perrin *et al.,* 1979; Sumbler, 1983a, 1983b; Rose, 1987, 1988, 1989, 1991). Furthermore, there is mounting evidence from other research that more than a single climatic cycle separates the Hoxnian and Ipswichian interglacials (see below and (Table 1.1)). As no redefinition of this time interval has been forthcoming, the corresponding continental term, Saalian, is used in this volume. This is not without some problems, as the definition and subdivision of the European Saalian Stage is also under scrutiny at present. It is widely accepted, however, that this stage incorporates a series of climatic fluctuations separating the continental equivalents of the Hoxnian and Ipswichian, the Holsteinian and Eemian Stages respectively (Zagwijn, 1985, 1986; Bowen *et al.,* 1986b; Sibrava, 1986a, 1986b; de Jong, 1988; see below). Whatever the result of any review of the continental Saalian, the term is used in this volume for the time interval between the Swanscombe interglacial (Hoxnian *sensu* Swanscombe) and the Ipswichian *sensu* Trafalgar Square (for definitions of these, see below and (Table 1.1)).

The pollen-based 'climato-stratigraphical' model has formed the basis for British Pleistocene studies since its inception, other biostratigraphical evidence generally being related to the palynological sequence. Within the Thames system, well-documented interglacial sites at Swanscombe and Trafalgar Square have been attributed to the Hoxnian and Ipswichian respectively, providing a biostratigraphical framework for Thames terrace stratigraphy that continues to be used. However, the relative dating of various sites within the Lower Thames terrace sequence at intermediate heights between Swanscombe (23–30 m O.D.) and Trafalgar Square (around Ordnance Datum) has proved controversial (see Chapter 4). Misgivings have been expressed about the above model on the basis of discrepancies between the palynological record and the evidence from Pleistocene mammals (Sutcliffe, 1964, 1975, 1976, 1985; Shotton, 1983; Green *et al.,* 1984). At several sites, including examples in the Lower Thames (see Chapter 4, Aveley), different mammalian faunas have been found in deposits that appeared, from their palynology, to represent the Ipswichian Stage. This led to the suggestion, first made by A.J. Sutcliffe, that there had been two separate interglacials since the Hoxnian. These had similar patterns of vegetational development and are therefore indistinguishable on the basis of palynology. The morphological separation of apparent Ipswichian sites in the Lower Thames within different terraces has been cited in support of this suggestion (see Chapter 4). Corroboration has come from radiometric dating of bone and travertine (Szabo and Collins, 1975; Green *et al.,* 1984), from studies of molluscan palaeontology (Allen, 1977; see Chapter 4, Purfleet) and from the analysis of the amino acid content of these same fossils (Miller *et al.,* 1979; Bowen *et al.,* 1989; see below). Stratigraphical evidence from the Warwickshire Avon (Bridgland *et al.,* 1989; Maddy, 1989; Maddy *et al.,* 1991a) goes even further, in suggesting that two additional climatic cycles occurred between the Anglian and Ipswichian

Stages.

With the current uncertainty about the chronological significance of the palynological framework, although pollen analyses remain critically important in the study of Quaternary sites, the search for an alternative scheme has occupied many workers in the past few years. An obvious basis for a stratigraphical standard is the record provided by ocean-bed sediments, since these are from environments where sedimentation during the Pleistocene is presumed to have been uninterrupted. The pattern of climatic fluctuations during the Pleistocene has been recognized in these sediments from the study of oxygen isotopes (^{16}O and ^{18}O) in the remains of foraminifera (Emiliani, 1955, 1957; Shackleton, 1969; Shackleton and Opdyke, 1973). Changes in the relative frequencies of the isotopes reflect parallel changes in the isotopic composition of seawater in direct response to fluctuations of global climate through time. The lighter isotope (^{16}O) is relatively common in water evaporated from the oceans, so during cold episodes, when much of this water goes to form long-term accumulations of ice, the sea water becomes enriched in the heavy isotope (^{18}O). Fluctuations in the relative frequencies of these two isotopes have been plotted against time, as represented by the oceanic sedimentary record, to provide a graphic representation of climatic change through the Pleistocene, the 'oxygen isotope curve' (Figure 1.2). The climatic fluctuations observed in this curve also form the basis for 'oxygen isotope stratigraphy', in which a scheme of 'oxygen isotope stages' is recognized. These stages represent alternate cold and warm episodes and are numbered in reverse stratigraphical sequence from Stage 1, the equivalent of the Holocene ((Figure 1.2) and (Table 1.1); see Bowen, 1978, for explanation). Thus even-numbered ^{18}O stages represent cold episodes and odd-numbered stages represent warm intervals. It must be emphasized that the oxygen isotope record can only indicate an episode of ice-cap depletion and gives no direct indication of global climate or vegetational development. Nevertheless, the oceanic record affords a truly global framework for Pleistocene chronology, since the same sequence can be recognized in oceans throughout the world. More problematic, however, is the correlation of the deep-sea record with discontinuous terrestrial sequences, for which radiometric dating methods are rarely available. On land, relative dating methods are generally used, relying on land-based fauna and/or flora that cannot be related directly to the oceanic stratigraphy.

One approach to this problem that has been pursued in recent years is an attempt to establish a stratigraphy based on a relative dating method in which the progressive alteration of amino acids in mollusc shells is measured. The amino acid L-isoleucine epimerizes to form D-alloisoleucine progressively through time, although the rate of change is dependent on temperature. During life only L-isoleucine is present in a shell, but after death and incorporation in sediments, progressive epimerization causes increasing amounts of D-alloisoleucine to be present, until an equilibrium level is reached. Therefore the ratio between these two amino acids gives an indication of relative age, which can be calibrated using radiometric dating where available (Wehmiller, 1982; Bowen *et al.,* 1985, 1989). This method has been applied to shells from a number of important sites in the Thames system (Miller *et al.,* 1979; Bowen *et al.,* 1989).

The desirability of relating terrestrial sequences such as that of the Thames terraces to the oxygen isotope record is obvious. However, apart from a general consensus that the Ipswichian interglacial represents Oxygen Isotope Substage 5e (Gascoyne *et al.,* 1981; Shotton, 1983; Bowen *et al.,* 1985; Stringer *et al.,* 1986; Bowen and Sykes, 1988; Campbell and Bowen, 1989), there has been little agreement about correlation between the British and European sequences and the deep-sea cores. Of critical importance is the position, in relation to the oxygen isotope record, of the Anglian Stage, which is well-established in the British stratigraphy and particularly important within the Thames sequence. The Anglian Stage has generally been correlated with Oxygen Isotope Stage 12, primarily because this appears to represent one of the most severe cold episodes within the Middle Pleistocene deep-sea record (Shackleton and Opdyke, 1973; Shackleton, 1987; Bowen *et al.,* 1986a, 1986b; Bowen and Sykes, 1988; Campbell and Bowen, 1989). Support for this view is provided in this volume from the number of post-diversion (post-Anglian) climatic fluctuations recognized within the Lower Thames sequence (see Chapter 4).

Evidence from amino acid ratios suggests that the Hoxnian Stage interglacial, as represented at Swanscombe and Clacton (see respective site descriptions), equates with Oxygen Isotope Stage 11 (Bowen *et al.,* 1986a, 1989; (Table 1.1)), but similar evidence from Hoxne suggests correlation with Stage 9 (Bowen *et al.,* 1989). If these ratios provide an accurate indication of age, the Thames sites that have traditionally been regarded as Hoxnian may prove to belong to a hitherto undefined temperate episode that followed immediately after the Anglian glaciation, whereas later temperate deposits within the Thames sequence might be true equivalents of the sequence at Hoxne (see Chapter 4). However, the type-Hoxnian sequence has been interpreted as a kettlehole infill, formed immediately following deglaciation late in the

Anglian Stage (West, 1956). Thus, if the Anglian equates with Stage 12, it is difficult to envisage the type-Hoxnian sediments post-dating Stage 11. For the deposits at Swanscombe and Clacton, which unequivocally post-date the diversion of the Thames, to equate with Stage 11 and those at Hoxne with Stage 9, the till underlying the latter would have to post-date the glaciation that effected the diversion. As the East Anglian glacial deposits have been attributed to a single pre-Hoxnian glaciation (since the post-Hoxnian Gipping glaciation was disproved — see Chapter 5), there is a clear conflict between the interpretation of the Hoxne sequence as a kettlehole infill and the amino acid ratios from the site (see, however, below and Chapter 2 for discussion of the possibility that a post-Stage 12 glaciation is represented in the Cotswolds). It is perhaps appropriate to question whether the origin of the lake-beds at Hoxne in a kettle-hole can be demonstrated unequivocally. Lake basins have been formed in East Anglia in other ways, as is indicated by the occurrence of several large closed depressions containing modern lakes and/or substantial infills of Holocene sediments. The formation of these features, the 'meres' of central East Anglia, is attributed to solution of bedrock Chalk beneath the cover of Anglian till (Bennett *et al.*, 1991).

It is possible that the amino acid ratios obtained from Hoxne are misleading and that the type-Hoxnian sequence equates with Oxygen Isotope Stage 11 (and is therefore the same age as the Swanscombe deposits). Correlation of the British Hoxnian and continental Holsteinian sequences on the basis of palynology is considered by many workers to be highly convincing, it being possible to match important aspects of vegetational evolution in both (Turner, 1975). If the Hoxnian is taken to equate with Oxygen Isotope Stage 11, Stage 9 remains to be identified within the British terrestrial succession, falling within the interval called Volstonian' by Mitchell *et al.* (1973), and here referred to as the Saalian Stage. The Stage 9 temperate episode is believed to be represented by deposits in the Upper and Lower Thames sequences and in eastern Essex (Table 1.1). It is notable that shells from sediments at Grays and Purfleet in the Lower Thames, considered from stratigraphical evidence to represent Stage 9, have produced amino acid ratios suggestive of greater antiquity (see Chapter 4). This may indicate that amino acid analyses of shells from deposits older than 200,000 years in the Lower Thames are as yet problematic, although these ratios do provide important evidence in support of the pre-Ipswichian age of the Grays and Purfleet sediments, which remains a subject of some controversy. Shells from a site a few kilometres upstream from Purfleet, at Belhus Park (see Chapter 4, Purfleet), have recently yielded amino acid ratios consistent with a Stage 9 age (Bowen, 1991).

An undefined interglacial, palynologically similar to the type-Ipswichian, is now well-established from several sites in southern and Midland England as representing Oxygen Isotope Stage 7 (Shotton, 1983; Bowen *et al.,* 1989). Many deposits formerly attributed to the Ipswichian may represent this earlier interglacial, which (like the Stage 9 temperate episode) falls within the Saalian (Wolstonian) Stage. Deposits now attributed to Stage 7 include those previously distinguished from Ipswichian sediments on the basis of mammals (Sutcliffe, 1975, 1976, 1985; Green *et al.,* 1984). Separation may also be possible using molluscs (see Chapter 2, Stanton Harcourt and Magdalen Grove). The age of Oxygen Isotope Stage 7 has been estimated at 245,000–186,000 years (Martinson *et al.,* 1987), largely on the basis of dating by the uranium-series method at a number of important sites. Worthy of mention in this respect is Pontnewydd Cave, North Wales, where a range of uranium-series dates, with corroboration using the thermoluminescence dating technique, suggests an age of 225,000–160,000 years for the fossiliferous Lower Breccia (Green, 1984; Campbell and Bowen, 1989). At Marsworth, Buckinghamshire, travertine clasts containing leaf-impressions from interglacial tree species have provided three dates, pointing to an age between 200,000 and 140,000 years (Green et al*,* 1984). Other uranium-series dates attributed to Stage 7 are from Stoke Goldington, Buckinghamshire, where an age of 200,000–180,000 years is suggested (Green *et al.,* in Bridgland *et al.,* 1989). These dates contrast with indications, again using the uranium-series technique, of an age of 130,000–100,000 years for Ipswichian deposits at Victoria Cave, Settle, North Yorkshire (Gascoyne *et al.,* 1981) and in Minchin Hole and Bacon Hole caves, South Wales (Bowen *et al.,* 1985; Stringer *et al.,* 1986; Bowen and Sykes, 1988; Campbell and Bowen, 1989). A 'marine stratotype' for Oxygen Isotope Stage 7 has been proposed at Minchin Hole (Bowen *et al.,* 1985). At this site, raised beach deposits that are attributed to Stage 7 underlie cold-climate cave deposits. The last-mentioned are in turn overlain by further raised beach sediments from which uranium-series dates indicative of the Ipswichian Stage have been obtained (see above). Temperate-climate sediments attributed to Stage 7 are recognized at several sites within the Thames system (see Chapter 2, Stanton Harcourt and Magdalen Grove; Chapter 4, Lion Pit, Aveley and Baker's Hole). There is support for a Stage 7 age for Thames deposits at Aveley, Crayford and Stanton Harcourt, and for their separation from sites representing the Ipswichian Stage (Substage 5e), from amino acid geochronology (Bowen *et al.,* 1989).

This complex stratigraphical scheme, in which four separate interglacials are recognized be tween the glaciations of the Anglian and Devensian Stages, receives considerable support from some of the more complete Pleistocene sequences on the continent. There is a long-standing correlation of the British Ipswichian and the continental Eemian Stages and of the British Hoxnian and continental Holsteinian Stages (Mitchell *et al.,* 1973). In recent years 'climato-stratigraphical' schemes in a number of European countries have been claimed to include one or more additional temperate episodes between the Holsteinian and Eemian. This interval is classified on the continent as the Saalian, which is the equivalent of the Wolstonian Stage as defined by Mitchell *et al.* (1973). The Saalian succession, named after the River Saale in north Germany, comprises the deposits of two glaciations, the Drenthe and Warthe (for English summaries, see Evans (1971), Bowen (1978), Sibrava (1986a, 1986b) and Gibbard (1988a)). Many German authors have regarded these as separate advances within a single glacial episode (Duphörn *et al.,* 1973; Ehlers, 1981), the only early suggestions to the contrary being based on equivocal geomorphological evidence such as the relative 'freshness' of depositional features (moraines) related to the two ice sheets (Bowen, 1978). There have, however, been recent claims that an intra-Saalian interglacial cycle separated these glaciations, on the basis of evidence from biostratigraphy, sea levels and cycles of soil formation in thick loess sequences (Wiegank, 1972; Kukla, 1975, 1977; Turner, 1975; Brunnacker, 1986; Cepek, 1986; Grube *et al.,* 1986; Sarnthein *et al.,* 1986; Sibrava, 1986a, 1986b). Kukla (1975), Sarnthein *et al.* (1986) and Sibrava (1986a, 1986b) have also presented arguments for a second additional temperate episode between the Holsteinian and Eemian Stages.

Intra-Saalian temperate episodes have been recognized in several areas of northern Europe, predominantly on the grounds of biostratigraphy or from the study of soil horizons within loess sequences. Evidence for a single additional climatic cycle between the Holsteinian and Eemian has been described in Germany, from the Middle Rhine valley and from the type area of the Holsteinian Stage in Schleswig-Holstein (Brunnacker *et al.,* 1982; Brunnacker, 1986; Sarnthein *et al.,* 1986). However, a significant number of areas have now produced evidence for two intra-Saalian temperate episodes. Kukla (1975, 1977) based his recognition of two post-Holsteinian but pre-Eemian interglacials on soils within the loess sequence of central Europe. A similar sequence of palaeosols has been described from Normandy, where four temperate-climate soils are recognized within a thick loess succession at St-Pierre-les-Elbeuf. The lowest of these is correlated with the Holsteinian and the highest with the Eemian (Lautridou *et al.,* 1974, 1983; Lautridou, 1982; Sarnthein *et al.,* 1986). Evidence for two intra-Saalian temperate half-cycles is also recognized in east Germany (Cepek and Erd, 1982; Cepek, 1986; Sarnthein *et al.,* 1986). In their summary of Pleistocene correlation in Europe, Bowen *et al* (1986b) also recognized three post-Elsterian and pre-Eemian interglacials in Poland, Russia and the Carpathians. The names that have been most commonly applied to the two additional temperate episodes are 'Domnitz' or 'blacken' for the earlier and 'Treene' for the later interval (Bowen *et al*., 1986b).

In northern Holland, palynological studies have revealed two temperate episodes within the Saalian sequence, both pre-dating the Drenthe glaciation. These have been named the Hoogeveen and Bantega Interstadials (Zagwijn, 1973, 1986; de Jong, 1988). In the south, at a site near Maastricht, a fully temperate molluscan fauna was described by Meijer (1985), who ascribed it to an intra-Saalian interglacial episode. Although classifying the Hoogeveen and Bantega episodes as interstadials, de Jong (1988) admitted that the former has many of the features of a full interglacial and is difficult to distinguish from the Holsteinian when incomplete fragments of vegetational sequences are studied using palynology. This implies that the fauna described by Meijer might relate to this same episode. Zagwijn (1973) had previously suggested a correlation between the Hoogeveen Interstadial and the 'Wacken Warmzeit' as recognized in Schleswig-Holstein.

The same problems in correlating the terrestrial stratigraphy with the oxygen isotope chronology apply on the continent as in Britain; the absence of reliable dating methods and the frequency of gaps within the sequences on land mean that all correlation schemes of this type are tentative at present. Notwithstanding these reservations, it has been widely agreed that the Eemian Stage and Oxygen Isotope Substage 5e are equivalent (see, for example, Sibrava, 1986b; de Jong, 1988), supporting correlation with the British Ipswichian. However, there is consider able doubt about the oceanic equivalent to the Holsteinian, with stages 7, 9, 11 and 13 all being contenders (Kukla, 1975, 1977; Bowen, 1978; Zagwijn, 1978; Linke *et al.,* 1985; Sarnthein *et al.,* 1986 (provides summary); de Jong, 1988; Gran *et al.,* 1988; Schwarcz and Gran, 1988). De Jong (1988) favoured correlation of the Holsteinian with Stage 9 in a tentative scheme in which he linked the Elsterian glaciation to Stage 10. He considered both the Hoogeveen and Bantega temperate intervals to fall within Oxygen Isotope Stage 7. However, Sarnthein *et al*. (1986) argued from biostratigraphical evidence, supported by geochronometric dating, for a correlation between the Holsteinian Stage of northwest Europe and Oxygen Isotope Stage 11. This is more easily reconciled with the evidence from central Europe, Germany and Normandy, where two full climatic cycles appear to separate the Holsteinian and Eemian. The Dutch record could also be accommodated within such a scheme if the Hoogeveen and Bantega episodes were separately correlated with Stages 9 and 7 respectively. The attribution of the type■ Holsteinian to Stage 11 has been questioned, however, by Schwarcz and Gran (1988), who favoured correlation with Stage 7.

The British sequence can be accommodated readily in the scheme of Sarnthein *et al.* (1986). The Anglian Stage, which is generally regarded as the equivalent of the Elsterian, has been equated by most authorities with Stage 12 (Wymer, 1985a; Bowen *et al.,* 1986a, 1986b). This would imply a Stage 11 age for the Holsteinian, which follows the Elsterian, and for the Hoxnian, which is regarded as being immediately post-Anglian in age (Turner, 1973). Thus the correlation of the Hoxnian-dated Thames sites at Clacton and Swanscombe with the Holsteinian is confirmed; these have been ascribed on stratigraphical grounds to Stage 11 (see Chapter 4). However, doubts remain about the Hoxnian type locality. If suggestions that this represents Stage 9 are correct (see above), correlation of the Hoxnian *sensu* Hoxne with a post-Holsteinian temperate episode in Europe, such as the Wacken (Domnitz) Warmzeit', might be implied. Because of this uncertainty, subsequent references to the Hoxnian in this volume will distinguish, where appropriate, between Hoxnian *sensu* Hoxne and Hoxnian *sensu* Swanscombe, the latter equating with Oxygen Isotope Stage 11 and the former of uncertain age.

Some discussion of the pre-Anglian sequence is also required here, as it is now clear that the earliest Thames deposits date back to the Early Pleistocene or even the Pliocene, although biostratigraphical evidence for precise dating is extremely limited. Recent research, particularly on the Norwich Crag Formation, has led to considerable revision of the pre-Anglian stratigraphical scheme of Mitchell *et al.* (1973). West (1980) added a series of climatic cycles to the scheme, under the names Pre-Pastonian a–d. From comparisons with the continental record it has become apparent that the British succession, which is effectively confined to East Anglia, contains several important hiatuses. The following revised scheme was outlined in the latest summary of the East Anglian sequence by Zalasiewicz and Gibbard (1988), with an additional modification from Gibbard *et al.* (1991):

Anglian

Cromerian

HIATUS

Beestonian

HIATUS (added by Gibbard *et al.,* 1991)

Pastonian

Pre-Pastonian d Substage

Pre-Pastonian c Substage

Pre-Pastonian b Substage

HIATUS

Pre-Pastonian a

HIATUS

Baventian

A number of workers have argued in recent years that the British sequence includes evidence for a further climatic cycle between the type-Cromerian and the Anglian (Bishop, 1982; Currant, *in* Roberts, 1986). This is based on a single but important difference in the mammalian faunas from some sites that would otherwise be classified as Cromerian. Most Cromerian small-mammal assemblages, including those from the stratotype and from sites within the Thames system at Sugworth and Little Oakley, contain the extinct water vole *Mimomys savini* (Hinton). Sites at Ostend, Norfolk (Stuart and West, 1976; Stuart, 1982a), Boxgrove, Sussex (Roberts, 1986), and Westbury-sub-Mendip, Somerset (Bishop, 1982), have yielded similar faunas, but with the vole *Arvicola cantiana* (Hinton) instead of *M. savini.* The former species has been interpreted as the evolutionary descendant of the latter (von Koenigswald, 1973; Sutcliffe and Kowalski, 1976; Stuart, 1982a, 1988). Not all authors accept this faunal change as evidence for an additional climatic cycle, however. An alternative explanation that has been proposed is that the sites with *A. cantiana* represent the later part of the Cromerian *sensu* West Runton, whereas the assemblages with *M. savini* date from the early part of the same temperate episode (Stuart and West, 1976; Stuart, 1982a, 1988).

The same controversy exists on the continent, where mammalian assemblages of Cromerian aspect containing both *M. savini* and *A. cantiana* occur. For example, freshwater deposits beneath Elsterian till at Voigstedt, Germany, have yielded an assemblage of small mammals remarkably similar to that of the West Runton freshwater bed, including *M. savini* (Kahlke, 1965; Stuart, 1981). Pollen spectra from overlying clays suggest that the Voigtstedt mammalian assemblage may relate to Cromerian pollen biozones CrII or early CrIII. *Mimomys savini* also occurs in the sparse fauna of small mammals from the upper part of a sequence capped by Elsterian till at Silssenborn, Germany (Kahlke, 1969). The rich assemblage of large mammals from this locality probably dates partly from the Cromerian and partly from the previous cold episode (Stuart, 1982a, p. 118). Early Middle Pleistocene sites yielding faunas with *A. cantiana* include Mosbach (Germany), Vertesszollos (Hungary) and Stranska Skala (Czechoslovakia) (Kahlke, 1975; Janossy, 1975, 1987).

Comparison with the lower Middle Pleistocene sequence in The Netherlands (Zagwijn *et al.,* 1971; Zagwijn, 1985, 1986; de Jong, 1988), which is more complete than that in Britain, indicates that the hiatus between the Cromerian and Beestonian Stages corresponds to several climatic cycles. It has been suggested that the British Beestonian and Anglian Stages correlate with the Dutch Menapian and Elsterian Stages respectively (Zalasiewicz and Gibbard, 1988). Further reappraisal of correlation between The Netherlands and Britain has recently indicated that the Beestonian is much older than hitherto believed; an age of over 1.5 million years has been suggested (Gibbard *et al.,* 1991). Dutch geologists currently recognize a sequence of at least six interglacial and five cold oscillations between the Menapian and Elsterian (Zagwijn, 1986; de Jong, 1988), as follows:

Elsterian Stage	
	Interglacial IV (Noordbergum)
	Glacial C
	Interglacial III (Rosmalen)
'Cromerian Complex'	Glacial B
	Interglacial II (Westerhoven)
	Glacial A
	Interglacial I (Waardenburg)
	Dorst Glacial
'Bavelian Complex'	Leerdam Interglacial
	Linge Glacial Bavel Interglacial
Menapian Stage (upper boundary *c.* 1,000,000 years BP)	

The four interglacials of the 'Cromerian Complex' are defined on palynology alone. However, evidence from palaeomagnetism enables the first of these to be separated from the remainder of the complex, since the Matuyama–Brunhes magnetic reversal roughly coincides with the transition from Interglacial I to Glacial A (de Jong, 1988). Deposits from the Waardenburg interglacial are therefore the most recent sediments to show a reversed geomagnetic polarity. The Matuyama–Brunhes magnetic boundary, dated at around 780,000 years BP (Shackleton *et al.,* 1990), has been suggested as the base of the Middle Pleistocene (Richmond and Fullerton, 1986), which would therefore fall within the 'Cromerian Complex'.

At Noordbergum, the most recent of the 'Cromerian Complex' interglacials (IV) has yielded the vole *A. cantiana,* suggesting that it post-dates the type-Cromerian of West Runton (van Kolfschoten, 1988). On the other hand, Bridgland *et al.* (1990) have presented a palynological argument against correlating the West Runton and Little Oakley sites with the three earliest interglacials from the Dutch 'Cromerian Complex'. If the suggestion (above) that faunas with *A. cantiana* represent a later temperate episode than the type-Cromerian is correct, there would appear to be no equivalent of the West Runton interglacial yet recognized in The Netherlands, implying that the Dutch sequence is also incomplete (Bridgland *et al.,* 1990).

Pre-Cromerian (*sensu* West Runton) interglacials may be represented within the Kesgrave Group at Ardleigh (Chapter 5) and Broomfield, both in Essex, and these may equate with one or more of the post-Menapian temperate episodes recognized in The Netherlands (Gibbard, 1988b).

Terrace formation

There has been considerable debate about the possible correlation between the formation of river terraces and climatic fluctuation during the Pleistocene (Zeuner, 1945, 1959; Wymer, 1968; Clayton, 1977; Rose, 1979; Green and McGregor, 1980, 1987). Zeuner (1945, 1959) considered depositional fluviatile terraces to fall into two groups, climatic and thallassostatic. In the lower reaches of rivers, he believed that thallassostatic terraces were predominant, formed by aggradation in response to rises in sea level. In the higher and middle reaches of rivers, remote from the effects of sea-level change, he envisaged aggradation in response to climatic deterioration (and its effect on river energy and sediment supply), forming climatic terraces. Since sea-level changes during the Pleistocene were climatically controlled, both types of terrace formation are potentially related to climatic fluctuation. Recognizing these two types of terrace, many authors have regarded terrace aggradations in the higher reaches of river valleys as the product of cold-climate environments, whereas those in the lower reaches have frequently been attributed to aggradation in response to relative rises in sea level during interglacials (see, for example, Evans, 1971). Direct correlation between these two types of terrace in the lower and higher reaches of river valleys should not be possible, although interdigitation of the two sets of deposits would be expected, especially as the cold-climate aggradations were laid down when sea level was much lower, so that the present lower reaches of rivers would then have been a considerable distance inland from the contemporary coast.

Zeuner believed that the major downcutting events (rejuvenations) in all parts of river valleys occurred in response to falls in sea level. In the case of the Thames, he recognized a series of erosional 'benches', overlain by sheets of cold-climate gravel, that he attempted to correlate with phases of low sea level. The mechanism of rejuvenation is poorly understood, however. Investigations in the North Sea have indicated that fluvially formed valley floors and terraces continue offshore beneath Holocene marine deposits (D'Olier, 1975; Bridgland and D'Olier, 1987, 1989). It is apparent that the Holocene sea-level rise brought about a considerable accumulation of estuarine and marine alluvium in the lower reaches and estuaries of rivers such as the Thames; presumably a return to a low sea level similar to that of the Devensian Stage would cause these deposits to be dissected as the rivers returned to their pre-Holocene flood-plain levels. However, there is no reason why a fall in sea level should cause rivers to cut down to a lower level than they have previously occupied, as has happened at each 'rejuvenation' between different terraces of the Thames. Instead, their valleys would merely be extended further and further beyond the interglacial coastline with the progressive decline in eustatic sea level during the onset of 'glacial' conditions, reoccupying the channels (like those beneath the southern North Sea) that were submerged at the end of the previous cold episode.

Evans (1971) presented a model for the chronostratigraphical interpretation of the Thames terrace sequence, in an early attempt at correlation with the deep-sea record. In Evans' scheme, cycles of river aggradation and rejuvenation were superimposed against the background of a progressive decline in relative sea level since the Pliocene, which is indicated by evidence for successive interglacial sea levels from raised beaches and shorelines both in Britain and abroad. Despite doubts in recent years about the marine origin of some of the high-level features used by Evans to formulate his views, it remains clear that fluvial base levels in most areas have been progressively lowered during the Pleistocene, irrespective of cycles of river aggradation and rejuvenation. This may reflect a gentle tectonic (isostatic) adjustment to the redistribution of material by rivers over this period; an uplift of terrestrial areas in response to erosion and a downwarping of marine areas under the weight of fluvially derived sediment. The reconstruction of Early Pleistocene floodplain levels of the Thames indicates that a vast amount of material has been removed from the land area of Britain since that time. Since land masses can be shown to rise over thousands of years following the removal, by deglaciation, of the weight of ice sheets (isostatic rebound), it is clear that the removal of solid rock over hundreds of thousands of years must result in a similar, if more gradual, tectonic adjustment.

This process of tectonic adjustment provides a possible explanation for the progressive lowering of fluvial base levels that is required for the formation of a terrace sequence. Given this progressive uplift of land areas, the initiation of a cycle of aggradation and downcutting, either in response to climatic or thallassostatic factors, would bring about terrace formation. The evidence from the Thames allows some insight into this process. Firstly, it is clear that during cold episodes the river was a considerably more active agent of both deposition and erosion than during temperate intervals, such as the present interglacial (the Holocene). This is partly because (1) there would have been a greater discharge during the spring melt season than would have occurred under temperate conditions and (2) the paucity of vegetation during cold intervals would have allowed more ready transfer of sediment to river channels. Secondly, it is apparent from the common preservation of temperate sediments in the Upper Thames that aggradation during interglacials was not restricted to the lower reaches of the valley. In all parts of the Thames system the preservation of interglacial sediments seems to be restricted to minor channel-fills or lenses within much larger bodies of cold-climate sand and gravel. In the Lower Thames, more extensive sheets of interglacial sediment appear to have accumulated under estuarine conditions, providing the only evidence in support of the theory of thallasso-static terrace formation. In fact, rises in relative sea level during interglacials appear to have drowned the lower reaches of river valleys, leading to accumulations of predominantly fine-grained estuarine sediment, such as those preserved within the Lower Thames sequence (see Chapter 4).

It is also apparent, from the stratigraphical position of many of the occasional sedimentary remnants from temperate episodes that occur within terrace aggradations, that more than one cold-climate episode is often represented by a single aggradational sequence. Even when interglacial sediments occur close to the base of a sequence, they are usually underlain by a basal gravel that is suggestive of a colder climate (examples are the basal gravels at Swanscombe and Clacton and the basal gravels of buried channels in eastern Essex (Bridgland, 1988a)). It is therefore possible to suggest a modified climatic model for terrace formation, which may be directly related to the climatic cycles recorded in the oxygen isotope curve:

Phase 1 Downcutting by rivers during a time of high discharge, under cold climatic conditions. The limits of this rejuvenation would be controlled by base level.

Phase 2 Aggradation of sand and gravel and the formation of floodplains at the new level; energy levels remain high, but sedimentation now exceeds erosion, leading to a vertical accumulation of sediment (final part of cold half cycle).

Phase 3 Limited deposition by less powerful rivers under temperate conditions (interglacial). This usually takes place in single-thread channels covering only small areas of floodplains, although overbank deposits may be more extensive. Estuarine sediments accumulate above phase. .2 deposits (often overlapping these) in the lower reaches of valleys.

Phase 4 Climatic deterioration results in increases in discharge coupled with enhanced sediment supplies, brought about by the decline of interglacial vegetation and increases in erosion and mechanical weathering. This causes the removal and/or reworking of existing floodplain deposits and the renewed aggradation of sand and gravel.

Then Discharge exceeds sediment supply, causing renewed downcutting (repeat of phase 1).

In the above model, the aggradation of sands and gravels occurs both at the beginning (phase 4) and end (phase 2) of cold climatic episodes. Of these, the latter is probably the principal aggradational phase, represented by most of the classic terrace gravel accumulations within the Thames system. Deposits from the three depositional phases may occur in superposition, but are likely also to be variously represented in different parts of former floodplains, so that later deposits may be banked laterally against earlier ones. The gravels of phases 2 and 4 are, however, indistinguishable without the recognition of interglacial sediments (phase 3) within the system. This presents an important stratigraphical problem, because these two phases would have been separated by an entire warm climatic half-cycle and are of different geochronological ages, yet they are represented beneath a single terrace surface, often at identical elevations. This makes it particularly important to fully assess the complex aggradational sequences that underlie terrace surfaces, as previously emphasized by Green and McGregor (1980, 1987) and Gibbard (1985).

The above model resembles the scheme for climatic terrace formation outlined by Zeuner (1945, 1959), although Zeuner considered that downcutting, once initiated in cold episodes by a fall in sea level, continued to work upstream during the subsequent temperate period. He therefore attributed downcutting in the higher reaches of valleys to interglacials. Similar climatic terrace models have been proposed by Wymer (1968) and Green and McGregor (1980, 1987). Wymer followed Zeuner in linking downcutting phases to falls in sea level, whereas Green and McGregor considered that both downcutting and aggradation may be triggered by hydrological changes as well as changes in base level.

Most of the depositional sequences within the Thames system can be interpreted according to the model outlined above. The main exceptions occur where sediments from more than a single interglacial episode are recorded from a particular terrace aggradation (for example, the Summertown-Radley sequence of the Upper Thames — see Chapter 2). In these cases rejuvenation appears not to have occurred between the two temperate episodes represented. No temperate deposits have yet been found within the Winter Hill or Black Park aggradations (excepting, perhaps, the Sugworth deposits — see below). These aggradations are correlated with the glaciation (Anglian Stage) of parts of the Thames catchment and the rejuvenation that separated them appears to have directly resulted from the diversion of the river (see Chapter 3, Part 2).

The stratigraphy of the Thames sequence

The earliest stratigraphical scheme for the interpretation of the Thames terraces, in which a complex sequence of climatic fluctuations was envisaged, was proposed by King and Oakley (1936). Evidence from biostratigraphy and Palaeolithic artefact assemblages formed the principal bases for this scheme, in which numerous alternating phases of downcutting and aggradation by the river were recognized, far greater in number than the mapped terraces. Phases of downslope movement of soliflucted colluvium, which is locally interbedded with the Thames terrace deposits, were also used as an indication of periglacial episodes. Considerable complexity was necessary in order to reconcile similarities between the archaeological and fossil content of deposits within different terraces, as well as the occurrence of different Palaeolithic industries within single terraces. The scheme therefore reflected what at that time was regarded as a progressive typological evolution of Palaeolithic implements through the Middle and Late Pleistocene. It also sought to correlate the Thames sequence with the limited Pleistocene chronology then recognized. The great complexity of King and Oakley's scheme offered little prospect for extending the stratigraphy from areas in which both interglacial and artefact-bearing deposits are commonly preserved, such as the Lower Thames (where the scheme was established), to other less informative parts of the catchment.

Repeated rejuvenation and aggradation without a progressive lowering of base level, as envisaged by King and Oakley, is necessary to accommodate the post-Anglian Thames sequence within the Pleistocene climato-stratigraphical scheme of Mitchell *et al.* (1973), since the latter recognizes fewer climatic cycles than the number of post-diversion Thames terraces. Perhaps because of this, King and Oakley's scheme remained in favour until quite recently. However, the realization that there is little basis for the Palaeolithic typological succession favoured in the middle part of this century has coincided with the recognition, from the oceanic record, that a greater number of climatic fluctuations has occurred since the Anglian Stage. Furthermore, a stratigraphical reappraisal of the terrace system suggests that the sequence can be reconstructed satisfactorily using a new, simpler model that relates downcutting and aggradation to palaeoclimatic fluctuations and which can be correlated with the oxygen isotope record.

The only previous attempt to relate the Thames sequence to the oceanic record was by Evans (1971), who based his correlation on estimates for successive interglacial sea levels, many of which were extrapolated from terrace projections. Evans assumed that each major terrace aggradation could be correlated with a particular interglacial sea level, the successive fall in fluviatile terrace levels corresponding to a parallel decline in sea level maxima during the Pleistocene. He attempted to correlate this sequence of levels with the warm cycles of the oxygen isotope curve. Despite the fact that the Thames gravel aggradations are now recognized as the products of cold-climate episodes, and the demonstrable invalidity of his conclusions regarding sea level, the correlations of interglacial sites with the oceanic record suggested by Evans show remarkable similarities with those outlined below. This fact suggests that there is a clear correlation between terrace formation and climatic fluctuation, so that simply counting backwards from the present interglacial and river level provides at least an approximate means for correlation.

It has been shown in recent years that the Anglian glaciation and the resultant diversion of the river provides an important stratigraphical marker within the Thames succession, both in the form of changes in sediment constituents (the addition of glacial 'erratics') and in the obvious change in drainage routes (Gibbard, 1977; Bridgland, 1980, 1988a; Cheshire, 1986a). Biostratigraphical evidence, derived from the occasional preservation of fossiliferous sediments within the terrace sequence, has proved valuable for relative dating with reference to the standard British Pleistocene stratigraphy (see above). Important early interglacial remnants have come to light in recent years at Sugworth, in the Upper Thames (see Chapter 2), at Nettlebed on the Chiltern dip slope (see Chapter 3, Part 1) and at a number of sites within the Kes-grave Sands and Gravels of Essex (see Chapter 5, Part 1). Post-Anglian Stage interglacial sites are more numerous, occurring in the Upper Thames (see Chapter 2), Lower Thames (see Chapter 4) and in Essex (see Chapter 5, Parts 2 and 3).

In the present volume, suggested correlations of the post-diversion Thames sequence with the oxygen isotope curve (see (Table 1.1)) are based on a number of lines of evidence. Firstly, the sequence of cold-climate terrace aggradations has been traced throughout the Thames system, primarily by reconstructing the three-dimensional form of the now-dissected sediment bodies, particularly their downstream profiles (Figure 1.3). Biostratigraphical evidence provides important support for this scheme, which is described in detail below. Secondly, interglacial sediments (representing phase 3 of the terrace model described above) preserved within the primarily cold-climate gravel sequences provide evidence of climatic events that can be related to the standard British Pleistocene chronology. Correlation with the oxygen isotope record can then be attempted with reference to climato-stratigraphical markers, such as the presumed equivalence of (1) the Anglian Stage and Oxygen Isotope Stage 12 and (2) the Ipswichian Stage with Oxygen Isotope Substage 5e. Interglacial deposits at Aveley and Stanton Harcourt, widely accepted as correlating with Stage 7 (see Chapters 2 and 4, respectively), provide important evidence for correlation between different parts of the Thames valley and between the terrace system and the oxygen isotope record. Four post-diversion (post-Anglian) temperate episodes are recognized within the Thames sequence (see (Table 1.1))

Many of the deposits ascribed here to Oxygen Isotope Stage 7 have previously been attributed to the Ipswichian Stage. For this reason, when reference is made in this volume to Substage 5e, the term Ipswichian (*sensu* Trafalgar Square)' will be used. Similarly, there is some doubt whether the Hoxne type sequence and deposits in the Thames system at Swanscombe and Clacton, attributed to the Hoxnian Stage, are of equivalent age (see above). As the deposits at Swanscombe and Clacton are considered here to represent Oxygen Isotope Stage 11, the term 'Hoxnian (*sensu* Swanscombe)' will be applied in this volume to that stage. The term 'Swanscombe interglacial' (Bowen *et al.,* 1989) will also be used. If the indications, from amino acid stratigraphy, that the type-Hoxnian correlates with Oxygen Isotope Stage 9 were to be confirmed (Bowen *et al.,* 1989), the implication would be that the Swanscombe and Clacton sediments are pre-Hoxnian (*sensu* Hoxne) and that the true correlatives of the Hoxne sediments within the Thames system are the deposits at Wolvercote, Purfleet and Grays (see (Table 1.1)). Although the Wolvercote and Grays deposits have been claimed to be Hoxnian by some authors (see Chapters 2 and 4), their age has remained controversial.

Considerable advances have been made in recent years in the dating of pre-diversion Thames deposits. The first evidence for the climato-stratigraphical dating of such deposits came from southern East Anglia, where the gravels of the Kesgrave Group were recognized as products of the pre-Anglian Thames (Rose *et al.,* 1976; Rose and Allen, 1977; see Chapter 5). The upper levels of the Kesgrave Group sands and gravels were shown to have been subjected to pedogenesis during both warm and cold episodes, before burial by Anglian Stage glacial sediments. These processes resulted in the formation of the Valley Farm Soil, a temperate-climate palaeosol, superimposed upon which was the Barham Soil, formed under intensely cold conditions. Rose and Allen concluded that the Kesgrave Group gravels were laid down during the Beestonian (at that time considered to immediately pre-date the Cromerian) and that the temperate Valley Farm Soil was developed during the Cromerian Stage.

This interpretation has since been shown to be oversimplified. Subsequent work has allowed the subdivision of the Kesgrave Group (Hey, 1980; Allen, 1983, 1984; Bowen *et al.,* 1986a; Bridgland, 1988a; Whiteman, 1990), which is now regarded as a series of individual formations dating from numerous periglacial episodes within the Early and early Middle Pleistocene (Bowen *et al.,* 1986a; Zalasiewicz and Gibbard, 1988). Studies of the Valley Farm Soil have shown that at many sites it is highly complex, with evidence for repeated climatic fluctuation, particularly where developed on higher and older formations within the Kesgrave Group (Kemp, 1985a, 1987a, 1987b; Zalasiewicz and Gibbard, 1988). A discussion of the current stratigraphical scheme for the pre-Anglian Thames sequence appears below.

Hey (1980) correlated early Kesgrave Group deposits in Norfolk with the 'Pre-Pastonian a' Stage, as defined by West (1980; see above), on the basis of the first appearance in the East Anglian marine sequence of a clast assemblage including quartzites from the Midlands and Greensand chert from the Weald, which he considered to have been introduced by the Kesgrave Thames. This is of considerable significance, as the recent reappraisal of the correlation between the East Anglian and Dutch stratigraphies suggests that the Pastonian Stage, hitherto placed near the end of the Early Pleistocene, is in fact equivalent to the European Tiglian C5–6 (Gibbard *et al.,* 1991). Since this part of the Tiglian has an estimated age of over 1,600,000 years, considerable antiquity is implied for the earliest formations of the Kesgrave Group. Hey classified the deposits in question as Westland Green Gravels, which he differentiated from lower-level Kesgrave Group formations on the basis of clast lithology. Allen (1983, 1984) recognized two divisions of this high-level gravel in Suffolk, which he termed Baylham Common Gravel and Westland Green Gravels (in stratigraphical sequence).

Allen (1983, 1984) found that a lower formation, below the Westland Green Gravels, could be distinguished within the Kesgrave Group in south-eastern Suffolk, on the basis of clast lithology and mapping. He named this the Waldringfield Gravels. Bridgland (1988a) described three lower formations within the Kesgrave Group on the Tendring Plateau, northern Essex (see Chapter 5, Part 1). Therefore the full sequence of formations within the Kesgrave Group of pre-diversion Thames deposits (and equivalent Thames-Medway deposits, marked *) is as follows:

St Osyth/Holland* Gravel Wivenhoe/Cooks Green* Gravel Ardleigh/Oakley* Gravel Waldringfield Gravel	Low-level Kesgrave Subgroup
Westland Green Gravels (*sensu* Allen) Baylham Common Gravels	High-level Kesgrave Subgroup

As shown, this group of six formations can be divided, on the basis of clast lithology and geo-morphological criteria, into two subgroups (see Chapter 5, Part 1). The lowest formation, the St Osyth/Holland Gravel, has been correlated (Bridgland, 1988a) with the (Anglian Stage) Winter Hill/Westmill Gravel of the Vale of St Albans, on the grounds that it is overlain by deposits representing an unglaciated Medway, formed while the Thames was blocked by Anglian ice (see Chapter 5, St Osyth and Holland-on-Sea). In north-eastern Essex, interglacial sediments are interbedded with gravels of the Ardleigh/Oakley and Wivenhoe/Cooks Green Formations (Bridgland *et al.,* 1988; Chapter 5, Part 1). Assessment of biostratigraphical evidence from these suggests that the two formations were laid down in the interval between the Beestonian and Anglian Stages, which is otherwise poorly represented in Britain (see above).

Recent re-evaluation of the correlation of pre-diversion Thames gravels between the Middle Thames and Essex by Whiteman (1990; see also Chapters 3 and 5) has major stratigraphical implications. By collating all available borehole information, Whiteman compiled a three-dimensional picture of the various Thames gravels buried beneath the Anglian till sheet of central Essex. He found that these deposits could be divided into several well-preserved terrace formations and that these could be traced both upstream to the Vale of St Albans and Middle Thames and downstream to the areas around Colchester and Ipswich, where the subdivisions of Allen (1983, 1984) had already been established. Whiteman found that the unit classified as Westland Green Gravels in Suffolk is, in fact, a continuation of the Gerrards Cross Gravel of the Middle Thames, the youngest pre-Winter Hill formation according to Gibbard (1983, 1985). From Whiteman's evidence, the Baylham Common Gravel of Suffolk appears to equate with the Beaconsfield Gravel, leaving older formations in the Middle Thames without equivalents in East Anglia. Therefore only formations within the older High-level Kesgrave Subgroup would appear to have equivalents upstream, with the exception of the St Osyth/ Holland Gravel (see above). The name Westland Green Gravels, as used in Suffolk and Norfolk, is invalidated by this reappraisal, which implies that the gravels correlated by Hey with the 'Pre-Pastonian a' Stage are equivalents of the Gerrards Cross or

Beaconsfield Formations. This has major implications for the ages of higher parts of the Middle Thames sequence (see Chapter 3).

Whiteman has argued that the older High-level Kesgrave Subgroup formations, and their upstream equivalents, reflect the maximum extent of the Thames catchment, when the river drained a considerable region beyond the Cotswolds. In contrast, the Low-level Kesgrave Subgroup represents a series of aggradations reflecting a much reduced catchment, a change that gave rise to the differences in composition between the two subgroups, effectively a reduction in far-travelled material. In the Middle Thames the absence of any significant gravel formations (with the possible exception of the Rassler Formation — see below) in the interval between the Gerrards Cross Gravel and the Winter Hill Gravel (in effect, a hiatus in the sequence in that area), implies that, between the 'Pre-Pastonian a' and Anglian stages, terrace generation was restricted to southern East Anglia. The sequence of just four formations representing this interval in the latter area, one of which is of Anglian age, is clearly fewer than the corresponding number of climatic cycles now recognized. Thus the climatic model for terrace formation breaks down during this interval. It may be that the beheaded river, with a much reduced discharge and flowing in an oversized valley, was less effective at both erosion and aggradation, so that rejuvenations affected only its lower reaches. This would explain the selective preservation in Essex of aggradation products representing the interval between the 'Pre-Pastonian a' and the Anglian. Only after its diversion by Anglian ice into a new course did the river resume the aggradation of terraces in all parts of its basin. The severity of climatic fluctuation during the post-Anglian period, as opposed to the earlier part of the Pleistocene, may have had an important influence on terrace formation, as climatic change is seen as the driving force in the model for terrace generation outlined above.

Whiteman's reinterpretation of the sequence in East Anglia has major implications throughout the Thames catchment. The most important of these is that the Gerrards Cross Gravel and all earlier formations are very much older than was hitherto believed. They are all Early Pleistocene or older and so, therefore, are their upstream equivalents recognized by Hey (1986) within the 'Northern Drift' of the Upper Thames (see Chapter 2). Prior to Whiteman's work, the Gerrards Cross Gravel was held to be of early Anglian age or only slightly older (Gibbard, 1983, 1985). This posed difficulties in reconciling Hey's interpretation of the 'Northern Drift' with the recently revised Middle Pleistocene sequence in the Midlands proposed by Sumbler (1983a, 19836) and Rose (1987, 1989). Rose's work, in particular, suggests that a major eastward-draining valley existed in the area north of the Cotswolds for an unknown interval of time leading up to the Anglian. This is the proto-Soar valley first recognized by Shotton (1953), containing the Baginton Gravel and Baginton Sand of the type 'Wolstonian' sequence, originally defined in the Coventry area. Rose concluded that the Wolston sequence represents the Anglian Stage rather than equating with the continental Saalian, as envisaged by Shotton (1953, 1973b). It was difficult to see how the 'Severn-Thames', the river considered to have deposited the 'Northern Drift', could have co-existed with the 'proto-Soar' in the immediate pre-Anglian and early Anglian period. According to Rose (1987, 1989), the 'proto-Soar' deposited gravel and sand in the Stratford-upon-Avon district to an elevation of *c.* 100 m O.D. at this time. This is approximately 60 m lower than an upstream projection of the Freeland Formation (the lowest division of the 'Northern Drift' — see below) would allow a contemporary Severn-Thames valley floor to have traversed the area of the modern Avon valley. By erecting a scheme in which the Thames ceased to flow from the Midlands before the Middle Pleistocene, Whiteman appears to have resolved these difficulties. It is still evident (from their gradients in the Upper Evenlode) that the earlier Middle Pleistocene formations in the Evenlode valley reflect a larger Thames catchment than at present, but the Thames may have been beheaded by the proto-Soar well before the deposition of the Freeland Formation. A comparable upstream projection of the Gerrards Cross Gravel, the lowest Thames formation considered by Whiteman to reflect a catchment beyond the Cotswolds, crosses the Stratford area only slightly higher than the projection of the Freeland Formation, largely because there is no indication for a marked upstream steepening of the older formation (perhaps because of the scarcity of data points) as there is with the Freeland. The considerable early Middle Pleistocene erosion by the proto-Soar that must have occurred between Gerrards Cross Gravel and Anglian times (if the reinterpretation of the Wolston sequence as Anglian is correct) appears to have coincided with a relative quiescence of the Thames, as described above. Further consideration of the important evidence for correlation between the Midlands and the Thames basin through the area of the Evenlode headwaters is given in Chapter 2.

Evidence from Palaeolithic artefacts in Thames deposits

Support for the revised chronostratigraphical interpretation of the Thames sequence outlined in this chapter is derived from the distribution of Palaeolithic artefacts within the sequence, although the role of archaeology in this scheme is very much reduced in comparison with many earlier models. The occurrence of Lower Palaeolithic artefacts in the lower terraces of the Thames sequence (within the Black Park Gravel and all later formations) is extremely well documented, most material of this type being collected, before mechanization, by gravel diggers in commercial pits. For this reason large collections of Palaeolithic tools were assembled, but there is little information available about their exact provenance. Much has been learned, however, from the few sites that have been systematically excavated in recent years. These include the type site of the Clactonian Industry (see Chapter 5), itself part of the Thames story, and Swanscombe (see Chapter 4), the only site in England to have produced Lower Palaeolithic human remains.

Assemblages of Lower Palaeolithic artefacts are broadly divisible into industries with formal tools (hand-axes) and those in which only flaking from cores was carried out. Early assemblages comprising only cores and flakes are assigned to the Clactonian Industry, in which flaking was simplistic, involving minimal prior shaping of the core, which might also have been serviceable as a crude 'chopper'. More advanced flake-core industries appear later in the sequence; these involved the use of a more advanced flint knapping method, known as the Levallois technique, in which cores were carefully prepared in order to yield flakes of a desired size and shape. Although some assemblages showing evidence of the Levallois flaking technique lack hand-axes, many include large numbers of such implements.

Hand-axe industries, both with or without evidence for the use of the Levallois technique, are collectively termed Acheulian. Until recently the Acheulian Industry was subdivided using a scheme in which collections of cruder implements were regarded as being earlier than assemblages showing more skilful or painstaking workmanship. This industry was also held to make its first appearance later in the British stratigraphical record than the Clactonian, largely on the basis of the evidence from Swanscombe (Wymer, 1968, 1974). The recent discovery at Boxgrove, West Sussex, of skilfully made hand-axes in conjunction with a late Cromerian fauna (Roberts, 1986) has led to the realization that typological subdivisions within the Acheulian Industry, and other hand-axe classifications such as the 'Abbevillian' and 'Chellean', have no chronological significance. On biostratigraphical grounds, the Boxgrove industry is now widely believed to pre-date the Clactonian assemblages from Clacton and Swanscombe. However, a flake/core industry from High Lodge, Suffolk, regarded as Clactonian (J. McNabb, pers. comm.), may be of similar antiquity. The evidence from Boxgrove and High Lodge would appear to indicate that both the Clactonian and Acheulian industries were in operation in Britain before the Anglian Stage glaciation. Wymer (1988) regarded both the Boxgrove and High Lodge industries as pre-Anglian and included more controversial collections from Kent's Cavern, Devon, and Westbury-sub-Mendip, Somerset, in the same category.

Some doubt remains about the age of the Boxgrove artefacts. They are associated with a 'late Cromerian' mammalian fauna (Roberts, 1986; see above), but amino acid ratios from marine shells from the site suggest a post-Anglian age, in Oxygen Isotope Stage 11 (Bowen and Sykes, 1988; Bowen, 1991).

The Palaeolithic content of the Thames terrace deposits continues to yield important stratigraphical information, however, in that the first appearance of artefacts in the sequence of gravels provides a marker. The first appearance in the terrace sequence of artefacts showing the Levallois flaking technique is also stratigraphically significant. Evidence from the Lower Thames suggests that this technique was first being used on a large scale during Oxygen Isotope Stage 8, since it appears in the uppermost levels of the Corbets Tey Formation. It is also well-represented in the basal deposits of the Mucking Formation, also attributed to Stage 8 (see (Table 1.1)). Deposition of the latter formation continued into the Stage 7 temperate episode (see Chapter 4, Lion Pit). It is interesting to note that the Levallois technique is recognized in the Palaeolithic assemblage from Pontnewydd Cave, North Wales, in deposits that have recently been ascribed to Stage 7 (Green, 1984; Campbell and Bowen, 1989).

Correlation of Thames terraces

The last systematic attempt at correlation between the terraces of the different parts of the Thames catchment was that by Evans (1971). Gibbard (1985) traced individual terrace formations in detail within the Middle Thames valley and suggested correlations with both the Upper and Lower Thames, but he failed to provide a comparison of his data for different terraces by plotting all the information on a single long-profile diagram. Without this comparison the degree of separation of terraces and differences in their downstream gradient are difficult to assess.

The long-profile diagram provided here (Figure 1.3) forms an important part of the evidence for correlating terraces across the principal zones of demarcation that separate the various parts of the Thames basin; namely, the Goring Gap, the urban area of London and the till sheet of Essex. The main problems in providing a composite long-profile diagram of this type arise from differences in the courses followed by different formations. In particular, the later gravels appear to follow markedly more sinuous courses, although this may be a reflection of the fact that they are better preserved and it is therefore possible to reconstruct their routes in greater detail. In general it is possible to overcome this problem by plotting gravel heights against a simplified Thames course, but this has the effect of greatly shortening the more sinuous parts of some formations, causing apparent increases in gradient that are artefacts of the cartographic technique (see (Figure 3.3)).

The Middle Thames terrace sequence as plotted in (Figure 1.3) and (Figure 3.3) differs from that outlined by Gibbard (1985) in a number of important ways. The first of these concerns the important Winter Hill Gravel Formation, which represents the final phase of aggradation by the Thames prior to its diversion. The Winter Hill Gravel can be traced downstream into the Westmill Lower Gravel of the Vale of St Albans, which is overlain by Anglian glacial deposits (see Chapter 3, Part 2). Sealy and Sealy (1956) recognized upper and lower divisions of the Winter Hill Terrace, an elevation in status of two facets of the terrace previously mapped by Hare (1947). Gibbard (1983, 1985) reinterpreted this double terrace feature in the area north of Slough as the dissected remnants of a sequence, formerly in superposition, of fluvial deposits (Winter Hill Lower Gravel) overlain by deltaic deposits (Winter Hill Upper Gravel). He believed the deltaic gravels to be restricted to this area and to have prograded into an ice-dammed lake that formed in the Vale of St Albans when the Thames route north of London was blocked by the Anglian glaciation (see Chapter 3, Part 2).

Upstream from the Marlow area, the Winter Hill Formation is poorly preserved, except in the region of the 'Ancient Channel', which represents an abandoned course of the Thames last used during the aggradation of the Black Park Gravel (see Chapter 3, Highlands Farm Pit). Gibbard (1985), in his reconstruction of the Winter Hill (Lower) Gravel, included in this formation deposits to the north and south of the 'Ancient Channel' that had been attributed by Sealy and Sealy (1956) to their Rassler Terrace. This correlation requires a marked steepening of the gradient of the formation upstream from Winter Hill.

However, an alternative interpretation can be presented. The Sealys mapped the gravel flooring the 'Ancient Channel', now correlated with the Black Park Gravel, as Lower Winter Hill Terrace, but also recognized a few small remnants of an additional terrace formation, intermediate between this and the Rassler Terrace. The two most significant remnants of this additional formation, which the Sealys classified as their Upper Winter Hill Terrace, are at Bellehatch Park [SU 748 803] and Crowsley Park [SU 725 804], at 86.5 and 88 m O.D. respectively. If the Winter Hill/Westmill Gravel of the Slough–Watford area is projected upstream to the vicinity of the 'Ancient Channel', its elevation conforms closely to that of the Sealys' Upper Winter Hill Terrace remnants. This suggests that the latter are in fact part of the Winter Hill Formation, whereas the higher gravel correlated by Gibbard with this unit represents a separate, earlier formation. As the Rassler Wood type locality [SU 822 854] of the Rassler Terrace is included in that earlier formation, the name Rassler Gravel is here given to this previously undefined unit (see (Figure 1.3) and (Table 1.1)).

This reinterpretation of the Winter Hill Gravel and adjacent deposits in the Reading area is not based solely on the longitudinal projection of formation levels. There are stratigraphical arguments, based on the correlation of the Middle and Upper Thames terraces (see (Figure 1.3)), in support of the revised stratigraphy outlined immediately above. The steep gradient of the Winter Hill Gravel implied in Gibbard's reconstruction requires the contemporaneous floodplain level in the Upper Thames valley to have been in excess of 110 m O.D., apparently converging upstream with the Gerrards Cross Gravel (see (Figure 3.3)). This is problematic, since the Sugworth Channel interglacial deposits, ascribed by most authors to the Cromerian Stage, occupy a lower altitudinal position within the Upper Thames terrace 'staircase' than this. The interglacial sediments at Sugworth lie at under 90 m O.D. and are overlain by a decalcified gravel attributed to the Freeland Formation, which has been correlated with the late Anglian Black Park Gravel (see Chapter 2, Sugworth; (Figure 1.3)). According to Gibbard's reconstruction, the earlier of the two Anglian Stage formations, the Winter Hill Gravel, forms a higher terrace than the late Anglian Freeland Formation. This interpretation would appear to imply that the Winter Hill Gravel is also older than the (Cromerian) Sugworth channel-fill, which underlies the Freeland Formation. Such a conclusion is clearly untenable. The revised interpretation outlined above, in contrast, suggests that the Winter Hill aggradation and the (lower) Black Park Gravel converge upstream and that both can be correlated with the Freeland Formation (Figure 1.3). This allows a more satisfactory interpretation of the sequence at Sugworth, with decalcified Anglian Stage gravel overlying Cromerian deposits. The convergence of the Winter Hill and Black Park formations can also be readily explained. It has already been noted that the rejuvenation that occurred between the deposition of these two units was the direct consequence of the diversion of the Thames. The Black Park Gravel was laid down while ice still occupied the Vale of St Albans (see Chapter 3, Part 2). The two gravels are therefore closely associated and the time interval between them was short.

The second important difference between the scheme presented here and that of Gibbard (1985) is that the latter author recognized an additional aggradation between the Taplow Gravel and the Kempton Park Gravel in the Reading area, his Reading Town Gravel. Reassessment of the altitudinal distribution of gravel remnants in the Middle Thames associated with the Taplow aggradation (see Chapter 3, Fern House Pit) suggests a rather different interpretation, however. Projection of the Taplow Gravel upstream from the type area indicates that the Reading Town Gravel of Gibbard (1985) is the true upstream continuation of the Taplow Formation (confirming the geomorphological interpretation of Sealy and Sealy (1956)). It is suggested in Chapter 3 that interglacial sediments underlying the Taplow (Reading Town) Gravel at Redlands Pit, Reading, ascribed by Gibbard (1985) to the Ipswichian Stage, may instead be correlatives of an intra-Saalian interglacial correlated with Oxygen Isotope Stage 7 (see Chapter 3, Fern House Pit).

This re-evaluation of the terrace stratigraphy in the Reading area has major repercussions for correlation with the Upper Thames. Gibbard (1985) correlated the Summertown-Radley aggradation of the Upper Thames, which he considered to have continued until the early Devensian, with his Reading Town Gravel; this correlation appears highly plausible on altitudinal grounds. However, the Summertown-Radley aggradation is seen by many workers to be a highly complex succession of temperate-and cold-climate deposits, the main part of which was deposited during the latter part of the Saalian Stage. At Stanton Harcourt the main cold-climate gravel of the Summertown-Radley aggradation overlies a temperate channel-fill that has been claimed as representative of Oxygen Isotope Stage 7 (Shotton, 1983; Chapter 2, Stanton Harcourt and Magdalen Grove), although other workers, including Gibbard (1985), have regarded it as Ipswichian. The Stage 7 age is supported by amino acid ratios (Bowen *et al.,* 1989) and correlations based on mammalian faunas (Shotton, 1983).

Correlations based on this revised terrace stratigraphy have implications for the dating of another important site upstream from the Reading area, but this time in the tributary Kennet valley, at Brimpton (see Chapter 3, Part 3). At Brimpton a sequence of gravels incorporates fossiliferous silt and clay lenses at several stratigraphical levels. These have been attributed, on biostratigraphical grounds, to a series of interstadial episodes within the Devensian Stage (Bryant *et al.,* 1983). However, projection of the Middle Thames terrace formations up the Kennet valley, even allowing for the probable increased gradient in the tributary, strongly indicates correlation of the Brimpton deposits with the Taplow Gravel (see (Figure 3.3)). This would appear to imply a pre-Devensian age, as the deposition of the Taplow Formation in the Slough area is considered here to have occurred between Oxygen Isotope Stages 8 and 6 (Table 1.1). In the Middle Thames the main post-interglacial phase of aggradation (phase 4 of the climatic terrace model) of the Taplow Formation is therefore ascribed to early Stage 6. In the Summertown-Radley Formation of the Upper Thames, which is also correlated with the Taplow Gravel, the main Stage 6 gravel aggradation is overlain by sediments attributed to the Ipswichian (*sensu* Trafalgar Square) and, probably, the early part of the Devensian (see Chapter 2). This unusually long sequence is believed to be repeated in the Reading area (see Chapter 3, Fern House Pit). This is thought to indicate that the Stage 6 rejuvenation (phase 1 of the terrace model) only occurred in the Thames valley below Reading. It is therefore possible for the Taplow Formation above Reading to include sediments ranging in age from late in Oxygen Isotope Stage 8 to the mid-Devensian Stage ((Table 1.1); see Chapter 3, Part 3).

The results of the correlation between the Upper and Middle Thames described above have considerable significance for the correlation of glacial events between the London Basin and the Midlands. As has been noted, the Thames was diverted, between the Winter Hill and Black Park aggradational phases, by a glacial advance into Hertfordshire during the Anglian (see Chapter 3, Part 2). This stage is widely regarded as the equivalent of Oxygen Isotope Stage 12 of the deep-sea record (see above). Glacial deposits also impinge on the sequence in the headwaters of the Upper Thames around Moreton-in-Marsh, reputedly overlying deposits correlated with the Hanborough Gravel and supplying outwash material to the Wolvercote Gravel (Arkell, 1947a, 1947b; Briggs and Gilbertson, 1974; Chapter 2). The correlation scheme between the Upper and Middle Thames shows that the Hanborough Gravel is an upstream equivalent of the Boyn Hill Gravel and the Wolvercote of the Lynch Hill Gravel. It is suggested (see Chapter 2) that the glacial input into the Wolvercote Gravel may have occurred during the pre-interglacial aggradational phase (phase 2 in the scheme for terrace formation outlined earlier in this chapter) of the Wolvercote/Lynch Hill aggradation. The combination of terrace correlation and climato-stratigraphy suggests that the interglacial represented within the Wolvercote/Lynch Hill aggradation, as seen in the Wolvercote Channel, equates with Oxygen Isotope Stage 9 (see Chapter 2). The Hanborough/Boyn Hill Formation is believed to include remnants of deposits laid down during Oxygen Isotope Stage 11 (Hoxnian *sensu* Swanscombe), although in the Upper Thames this interglacial is represented only by derived mammalian remains in the dominant post-interglacial (phase 4) aggradation. The Hanborough/Boyn Hill Formation clearly post-dates the diversion of the Thames and, therefore, the Anglian (Oxygen Isotope Stage 12) glaciation of Hertfordshire. The glaciation of the Cotswolds thus appears to post-date the phase 4 aggradation of the Hanborough Gravel, which, according to the terrace model outlined above, occurred earlier in the same cold episode as the phase 2 aggradation of the Wolvercote Gravel. The glaciation must have taken place during this same cold episode, since it fed outwash material into the Wolvercote Gravel. The implication of the correlations proposed here is that this cold episode is equivalent to Oxygen Isotope Stage 10 and not Stage 12 (see Chapter 2).

This is of great significance, because it implies that glacial deposits that have been ascribed to the Anglian may in fact be the products of two separate glacial episodes (equivalent to Oxygen Isotope Stages 12 and 10). This interpretation relies heavily, however, on Arkell's account of the stratigraphy of the Moreton-in-Marsh area and on the recognition of a glacial input into the Wolvercote Gravel. In a recent review of the stratigraphical significance of glacially derived flint in the Wolvercote Terrace deposits, Maddy *et al.* (1991b) have challenged the notion that such material appears for the first time in this formation (see Chapter 2). It is interesting to note that Arkell (1943, 1947b) was initially inclined to correlate the Moreton glaciation with his Freeland Terrace, which would allow correlation with both Stage 12 Anglian terrace formations in the London Basin, the Winter Hill and the Black Park Gravels (see (Figure 1.3) and (Table 1.1)). He rejected this correlation following his assessment of the stratigraphy in the watershed area between the Evenlode and Stour valleys. Kellaway *et al.* (1971) recorded high-level quartzite-rich sands and gravels at Sarsden, well above the level of the Hanborough Gravel (Figure 2.1) and (Figure 2.3), which they interpreted as outwash of the 'Northern Drift' glaciation. Although they reported that flint was absent from these deposits, Tomlinson (1929) had previously described a gravel at a similar height (Figure 2.3) on the opposite side of the Evenlode valley, at Milton-under-Wychwood (*c.* [SP 264 182]; (Figure 2.1)), in which flint was present. Tomlinson suggested that this might represent an upstream continuation of the Hanborough Terrace, but it occurs in association with Northern Drift (mapped as till) and was mapped as 'Glacial Gravel' on the Geological Survey map (Sheet 236). Both the Sarsden and Milton gravels are at elevations that could suggest correlation with the Freeland Formation (Figure 2.3), providing a possible link between that deposit and the glaciation of the Cotswolds. However, Briggs (1973) described gravels, which he attributed to glacial outwash, overlying the Hanborough Formation in the Upper Evenlode, thus supporting Arkell's later interpretation.

It is worth noting that there are breaks in the downstream continuity of all the Evenlode gravels and miscorrelation between the lower and upper parts of the valley cannot be ruled out. This could mean that the gravels underlying the Moreton glacial deposits, the 'Bledlington Terrace' of Arkell (1947b), are older than the Hanborough Formation. The limestone content of these deposits would seem to preclude correlation with any pre-Hanborough formation, but burial by till could have effected the preservation of calcareous clasts in an older deposit. If the longitudinal profile of the Freeland Formation downstream from the type area in the Lower Evenlode was to be continued upstream at the same gradient, instead of at the increased gradient needed to take it up to the level of the Sarsden and Milton deposits described above (see Figure 1.3) and (Figure 2.3), it would pass through the Moreton-in-Marsh area at exactly the altitude of the Bledlington gravels. Thus the Bledlington and Paxford gravels (see (Figure 2.3)) could be upstream equivalents of the Freeland Formation rather than the Hanborough Formation, which would allow correlation of the Cotswolds and Vale of St Albans glaciations. The steepness of the floodplain gradient in the Upper Evenlode during Freeland Formation times is dependent to a large extent on the size of the catchment at that time. The older Northern Drift formations are believed to have shallow gradients throughout the area, reflecting a catchment that extended well beyond the present Stour–Evenlode watershed, whereas the later Evenlode terraces are much steeper, being confined to the modern catchment (Figure 2.3). The obvious importance of the interpretation of the Upper Thames terraces and their relation to the glacial deposits of the Moreton-in-Marsh area, both for studies of the Thames sequence and for British glacial and interglacial stratigraphy in general, indicates that a reappraisal of the evidence in the Evenlode valley is urgently required.

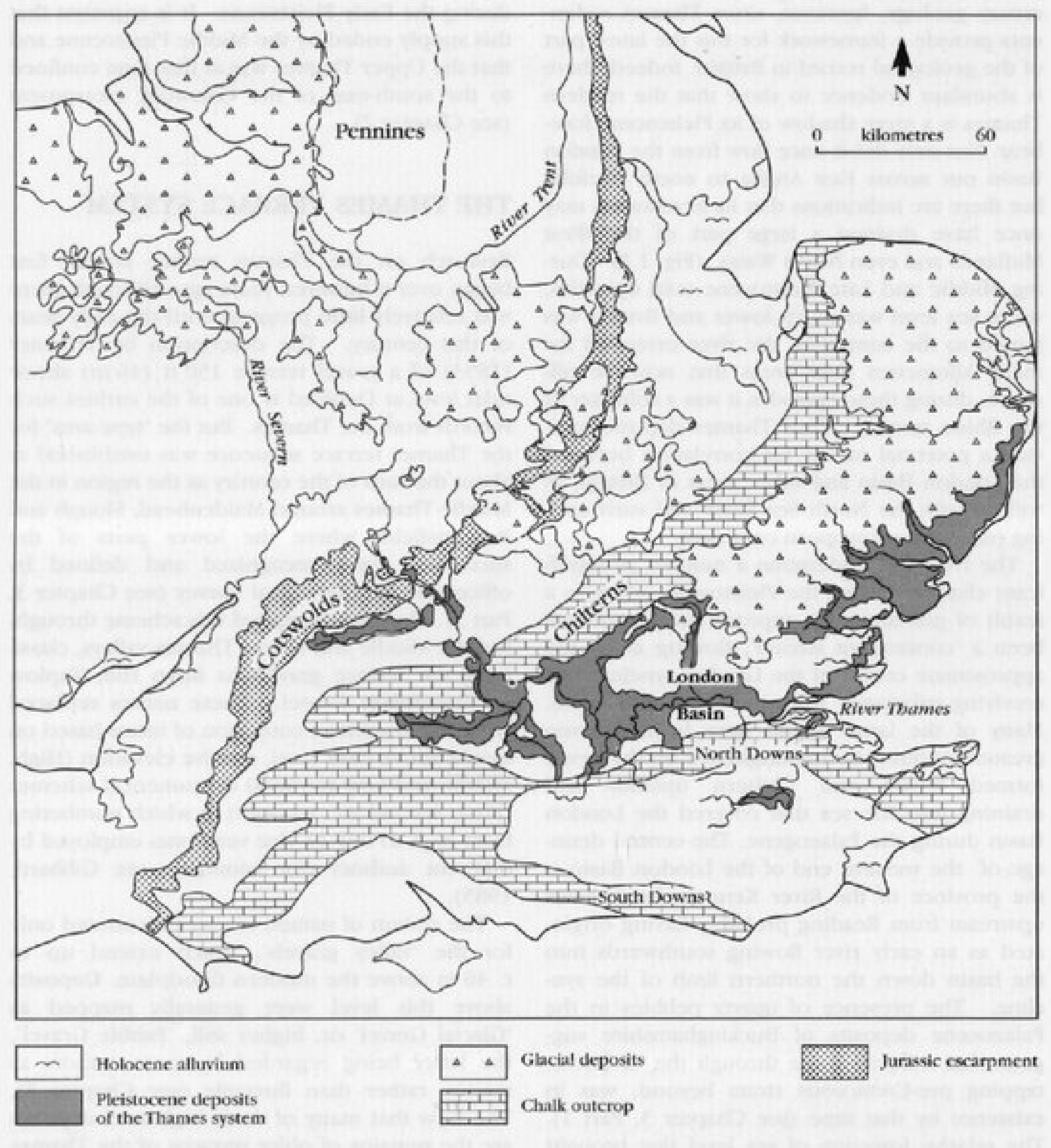
Conclusions

In this volume a radically new scheme for terrace stratigraphy in the Thames basin is proposed. This results from the incorporation of the latest evidence for Pleistocene chronostratigraphy and geochronology in a critical review of the evidence from which the Thames sequence has been reconstructed. Although much of the latter derives from previously published work spanning more than a century, new investigations, carried out as part of the GCR project, are described here for the first time.

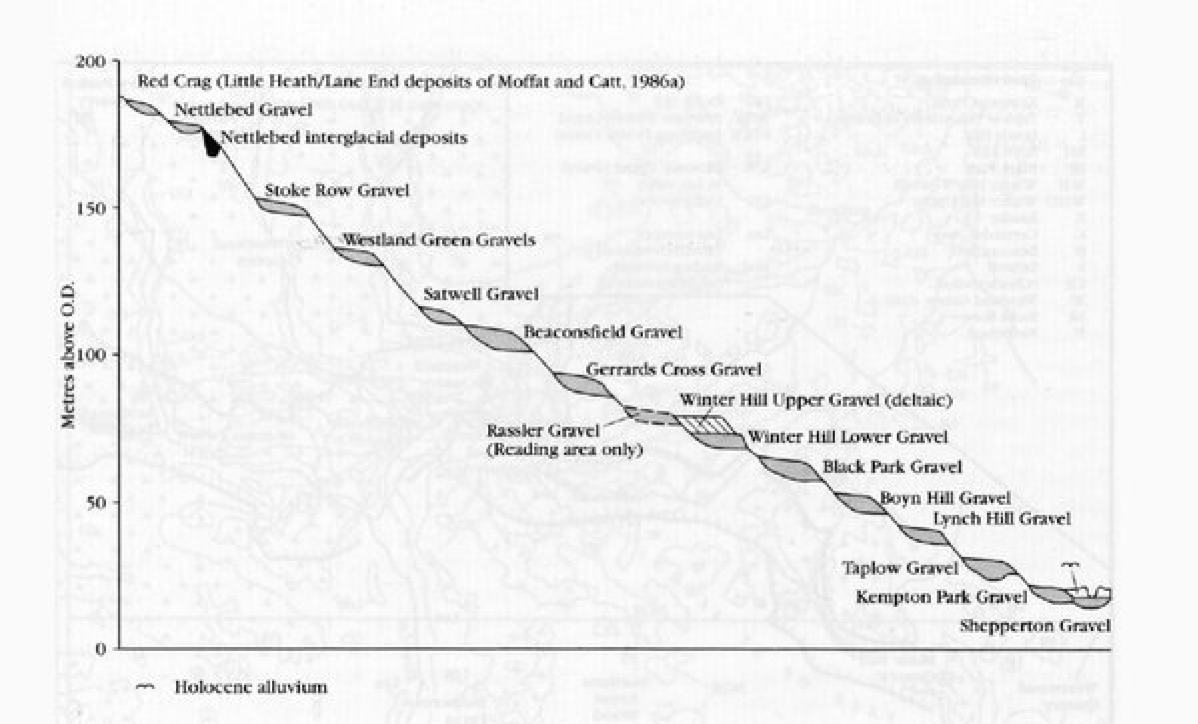
The proposed new scheme for Thames terrace stratigraphy attempts to correlate this fragmentary, but complex, terrestrial sequence with the more continuous sedimentary and climatic record from deep-sea cores. This is based on biostratigraphical evidence, with support from amino acid geochronology, and on assumptions about the correlation between cycles of terrace formation, as represented in the Thames sequence, and climatic fluctuation during the Pleistocene. Although many of the new interpretations based on these premises will be regarded as controversial, the task of correlating the Thames sequence with the oceanic record should have the highest priority, as it promises to improve greatly the resolution of Pleistocene terrestrial stratigraphy in Britain. The terrace sequence of the Thames is particularly suited to this type of approach, since the terraces themselves provide a range of deposits that extend from the Early Pleistocene to the last glaciation. This can be regarded as a genuine 'long sequence' of the type needed to provide a land-based framework for correlating with the global deep-sea record. Although it is punctuated with numerous gaps (rejuvenations between different terrace levels), the Thames sequence benefits from the continuity of its formative agent, the river itself. With King and Oakley's (1936) model involving repeated occupation of similar terrace levels now considered obsolete, and with many more climatic cycles now recognized than the chronology of Mitchell *et al.* (1973) allowed, there is a real possibility that the terrace sequence matches closely the sequence of climatic fluctuations recognized in the oxygen isotope record.

In the remaining chapters the various GCR sites (Figure 1.4) are described in detail, with further consideration given, where relevant, to wider issues such as correlation with the oceanic record.

References



(Figure 1.1) Map of southern and central England, showing the division into the catchments of the modern Thames, Severn and Trent rivers. As is described in the text, the area to the north-west of the Cotswolds escarpment was probably drained by the Thames in the Early Pleistocene. In the early Middle Pleistocene it was drained by the Trent system (the proto-Soar of Shotton, 1953).

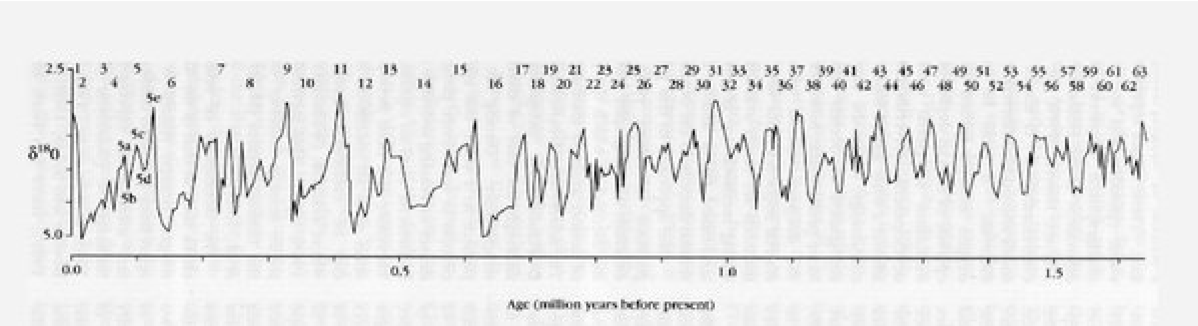


(Figure 3.2) Idealized transverse section through the classic Middle Thames sequence of the Slough-Beaconsfield area. The stratigraphical position of the Rassler Gravel, not preserved in this area, is shown.

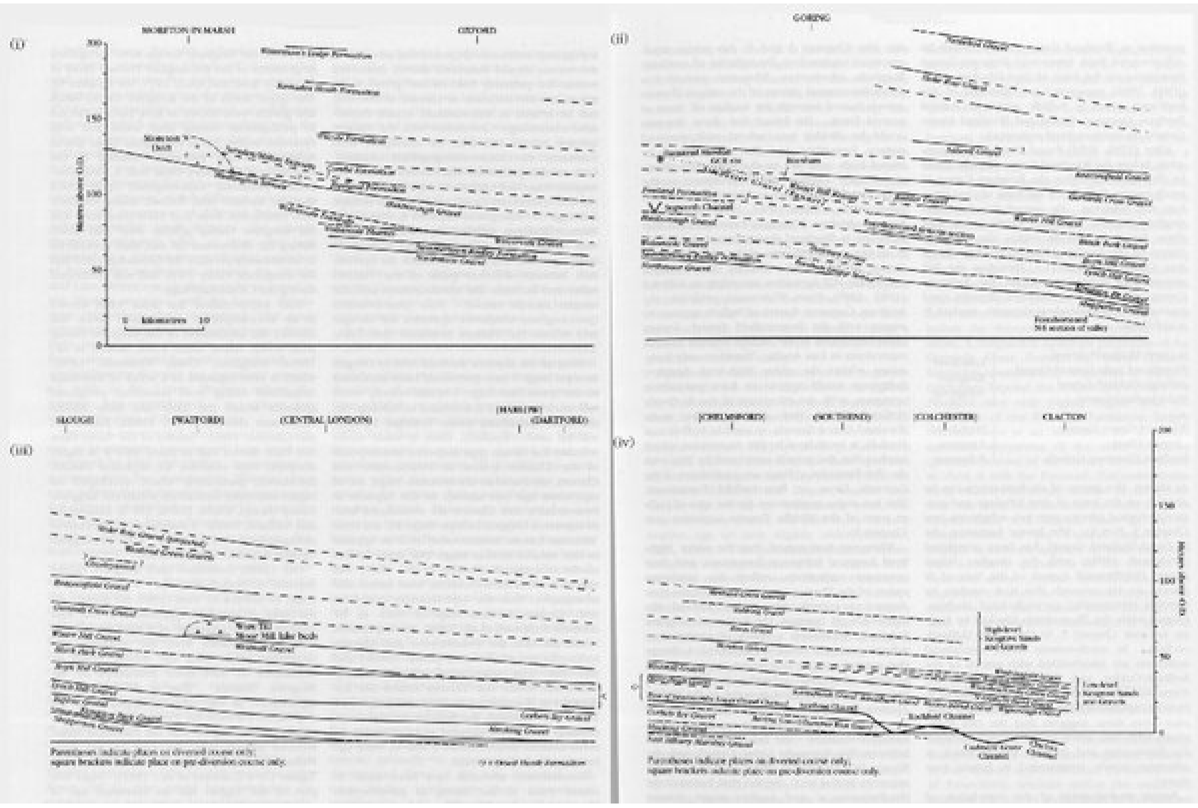
Age (in thousands of years)	Upper Thames	Middle Thames	Lower Thames	Essex	Stage	^{18}O
	Recent floodplain and channel deposits: Holocene alluvium of floodplain and coast				Holocene	1
10						
	Northmoor Gravel	Shepperton Gravel	Submerged	Submerged	late Devensian	2-4
	Rejuvenation event					
71						
		Temperate climate deposits at South Kensington (Ismaili centre), Isleworth and Kempton Park	Submerged	Submerged	early/mid Devensian? interstadial(s)	5a &/or 5c?
?						
	Cold climate gravels above Eynsham Gravel	**Reading area** U. levels of Taplow Gravel; **Slough area** Kempton Park Gravel	East Tilbury Marshes Gravel	Submerged	early-mid Devensian	5d-2
122						
	Eynsham Gravel	Reading area: Within Taplow Formation; Slough area: Trafalgar Square and Brentford deposits	Below floodplain	Submerged	Ipswichian (sensu Trafalgar Square)	5e
128						
	Stanton Harcourt Gravel	Reading area: Taplow Gravel; Slough area: Basal Kempton Pk Gravel - incl. Spring Gardens Gravel of Gibbard (1985)	Basal East Tilbury Marshes Gravel	Submerged	late Saalian	6
		Rejuvenation event				
		Taplow Gravel	Mucking Gravel			
186						
	Stanton Harcourt Channel Deposits, interglacial Magdalen Grove, Summertown etc	Interglacial deposits at Redlands Pit, Reading	Interglacial deposits at Aveley, Ilford (Uphall Pit), West Thurrock, Crayford and Northfleet	Submerged	Intra-Saalian temperate episode	7
245						
	Basal Summertown-Radley Formation at some sites?	Basal Taplow Gravel?	Basal Mucking Gravel	Submerged		
	Rejuvenation event				mid-Saalian	8
	Wolvercote Gravel at some sites?	Lynch Hill Gravel	Corbets Tey Gravel	Barling Gravel		
303						
	Wolvercote Channel Deposits		Interglacial deposits at Ilford (Cauliflower Pit), Belhus Park, Purfleet and Grays	Shoeburyness Channel interglacial deposits	Intra-Saalian temperate episode	9
339						
	Basal Wolvercote Gravel	Basal Lynch Hill Gravel?	Basal Corbets Tey Gravel	Shoeburyness Channel - basal gravel		
	Rejuvenation event				early Saalian	10
	¹Moreton Drift (Arkell, 1947a)					
	Hanborough Gravel	Boyn Hill Gravel	Orsett Heath Gravel	Southchurch/Asheldham/Mersea Island/Wigborough Gravel		
?						
	Reworked mammalian fauna in Hanborough Gravel		Swanscombe deposits	Southend/Asheldham/Cudmore Grove/Clacton Channel Deposits	Hoxnian (sensu Swanscombe)	11
423						
	Basal Hanborough Gravel?	Basal Boyn Hill Gravel?	Basal Orsett Heath Gravel (incl. Basal Gravel at Swanscombe)	Southend/Asheldham/Cudmore Grove/Clacton Channel - basal gravel		
	Rejuvenation event					
	Freeland Formation	Black Park gravel				
	Moreton Drift?	Anglian glacial deposits	Hornchurch Till	U. St Osyth/U. Holland Gravel	Anglian	12
	Freeland Formation	Winter Hill/Westmill Gravel	Valley did not exist as a Thames course prior to this	St Osyth/Holland Formation		
478						
	Sugworth Channel Deposits	Rassler Gravel?		Wivenhoe/Cooks Green Fm Ardleigh/St Osyth Formation Waldringfield Gravel	Cromerian Complex	21-13
?						
	Combe Formation	Gerrards Cross Gravel		Bures Gravel*	Early Pleistocene	pre 21
	Higher divisions of the Northern Drift Group	Beaconsfield Gravel, Satwell Gravel, Gravel at Chorleywood, Westland Green Gravels, Stoke Row Gravel, Nettlebed Gravel, Nettlebed interglacial deposits		Moreton Gravel*, Stebbing Gravel*		

* Nomenclature for High-level Kesgrave Subgroup in Essex follows Whiteman (1990).

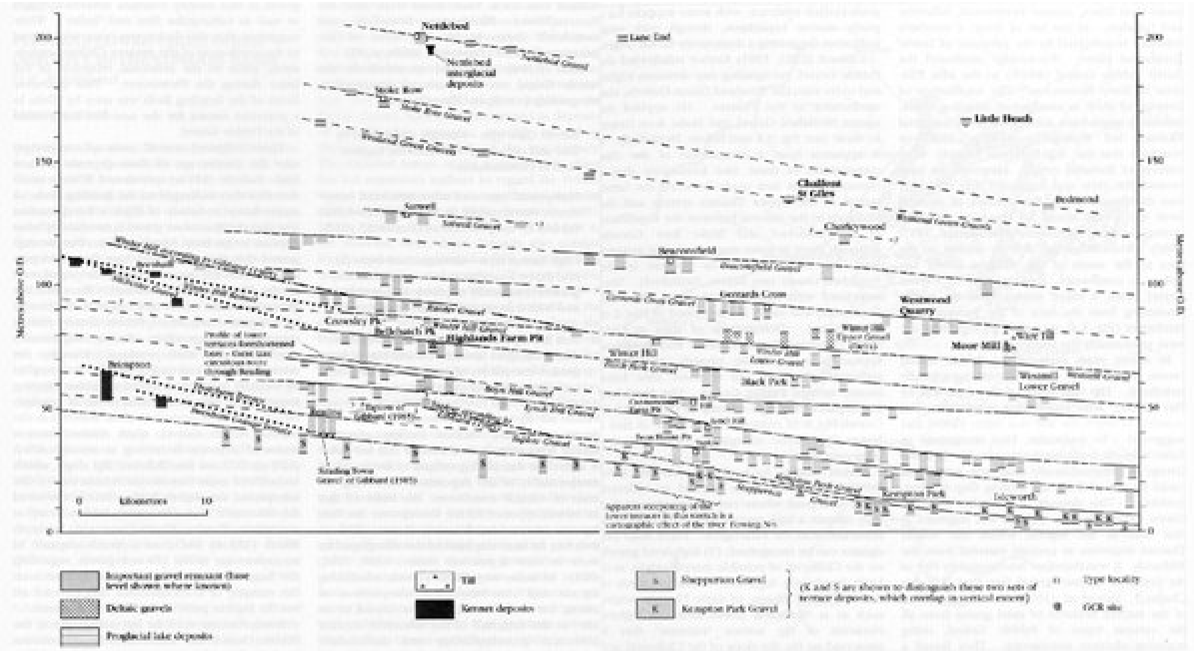
(Table 1.1) Correlation of Quaternary deposits within the Thames system. Rejuvenations that have occurred since the Anglian glaciation are indicated.



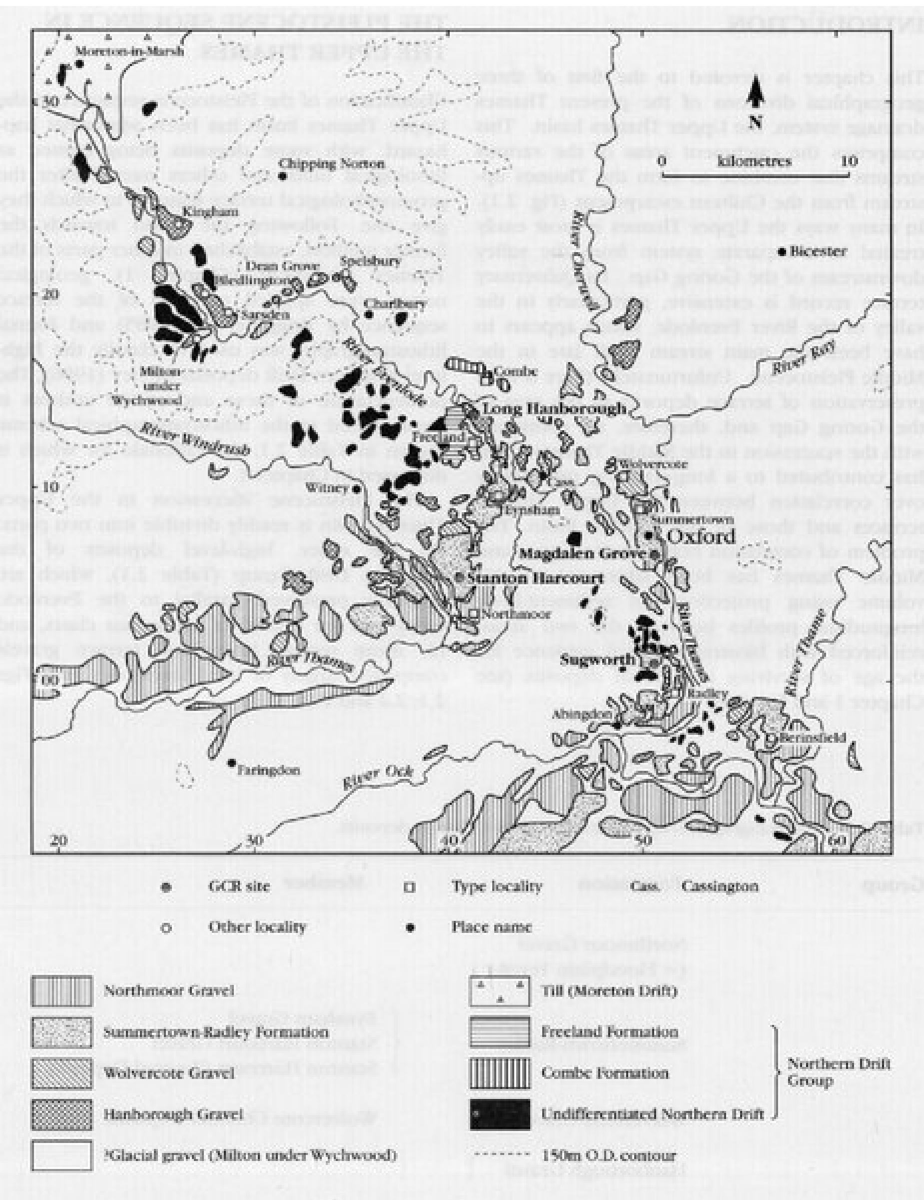
(Figure 1.2) The oxygen isotope record, as represented in a borehole (Site 607) in the mid-Atlantic at latitude c. 41°N. Numbered stages are shown at the top; even-numbered ones are relatively cold (more ice) and odd-numbered ones relatively warm (less ice). Note that the amplitude and wavelength of the curve increases at around 0.7 million years ago (the $\delta^{18}O$ scale is a ratio obtained by comparing the proportion of ^{18}O to ^{16}O in samples to that in a mean sea-water standard). Compiled from data published by Ruddiman et al. (1989).



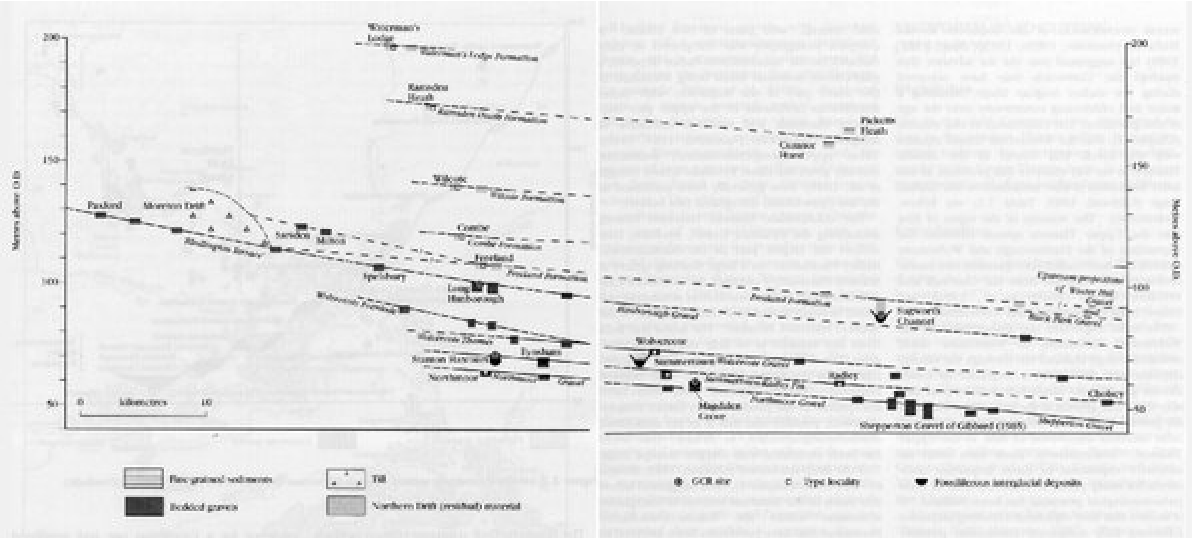
(Figure 1.3) Longitudinal profiles of Thames terrace surfaces throughout the area covered by the present volume. The main sources of information used in the compilation of this diagram are as follows: Arkell (1947a, 1947b), Briggs and Gilbertson (1973), Briggs et al. (1985), Evans (1971) and Sandford (1924, 1926) for the Upper Thames; Gibbard (1985) and Sealy and Sealy (1956) for the Middle Thames; Bridgland (1983a, 1988a) and Bridgland et al. (1993) for the Lower Thames and eastern Essex; Whiteman (1990) for central Essex.



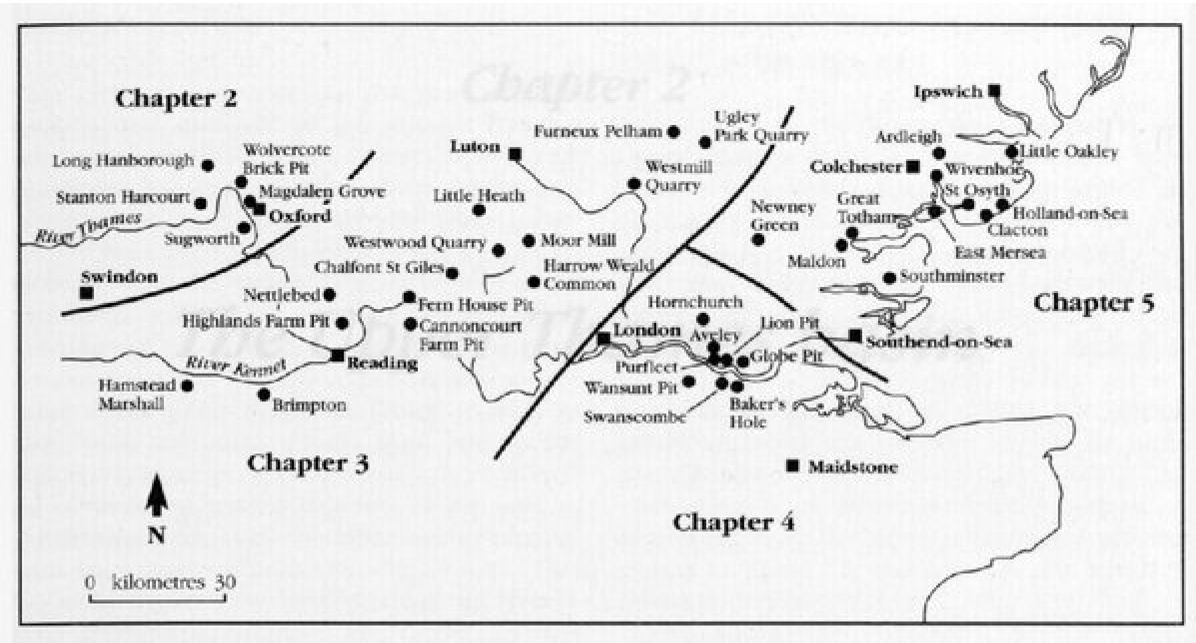
(Figure 3.3) Long-profiles of terrace formations in the Middle Thames. Compiled predominantly from data provided by Gibbard (1985), with subordinate information from Sealy and Sealy (1956) and Thomas (1961). Modifications to the source information are described in the text.



(Figure 2.1) The gravels of the Upper Thames catchment.



(Figure 2.3) Longitudinal profiles of the Upper Thames terrace deposits. Compiled from the following sources: Arkell (1947a, 1947b); Bishop (1958); Briggs and Gilbertson (1973); Briggs et al. (1985); Evans (1971); Kellaway et al. (1971); Sandford (1924, 1926); Tomlinson (1929).



(Figure 1.4) Map showing the locations of the GCR sites described in this volume.