The role of geomorphology in the Quaternary

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Abstract: The advances in understanding of Quaternary geomorphology in the latter half of the twentieth century were closely linked with the improved knowledge of Quaternary climatic fluctuation, principally derived from isotopic evidence from ocean and ice cores. An important goal was finding terrestrial sedimentary records that can be correlated with the globally applicable isotopic sequence. From a geomorphological viewpoint, river terraces are paramount, particularly since they can provide semi-continuous sequences that record palaeoclimate and landscape evolution throughout the Quaternary, as well as the interaction of rivers with glaciation, sea-level change and notable geomorphological events. In coastal areas, shoreline terraces and raised beaches can provide similar sequences. The chapter discusses the progress made in understanding these archives and, in particular, the various mechanisms for dating and correlation, as well as touching upon contributions from other environments, namely slopes and karstic systems, as well as the role of soils in deciphering geomorphological evidence.

This chapter is dedicated to the memory of Rob Westaway, whose untimely death occurred while it was in the final stages of revision. With expertise in crustal processes and computer modelling, Rob made a major contribution to the understanding of Quaternary landscape evolution, one that is perhaps yet to be fully appreciated.

Irrespective of whether human impact justifies separation of most recent Earth history under a new Anthropocene classification (Goudie 2021, this volume), the Quaternary remains the broader division of geological time in which we live, having begun 2.6 myr ago. The term describes the time interval as well as the rocks and sediments emplaced during that period. Landforms shaped from such materials, as well as by erosional processes, also represent part of the Quaternary archive and their study contributes to understanding of the period. As is well known, the Quaternary has been characterized by periodic expansion and retreat of continental ice sheets, reflecting climatic changes that can be explained by the Croll–Milankovitch astronomical cycles. This has provided the means of division of the period into alternating glacial and interglacial episodes, defined as named stages but also classified as numbered oxygen isotope stages, the latter initially established from studies of ocean-sediment cores and subsequently recognized within ice cores (for an excellent summary, see Imbrie and Imbrie 1979). During the years represented in this volume has come realization that there is considerable complexity within the broad concept of glacial–interglacial cyclicity, a topic explored already in the previous volume (Grove 2008). This complexity mostly belongs within the Pleistocene, the epoch that accounts for nearly 98% of the Quaternary, the last 11.7 kyr being separately classified as the Holocene; the latter is essentially the most recent in the sequence of interglacials, remarkable only for the profound influence of humanity, especially during its latter half.

The role of geomorphology in the Quaternary, as in the chapter title, reflects aspects of landform study that are of value in understanding that period. The one that will spring to mind immediately is glacial geomorphology, given the defining importance of ice in the Pleistocene, but this is a topic covered elsewhere in this and earlier editions and so will not figure particularly prominently here. Its continued significance in this chapter revolves around the persistent debate about the number of different glaciations and which stage of the Pleistocene each represents: fundamental knowledge that remains, in part, elusive, not least because distinction of the products of different glaciations continues to be highly challenging, as is the definitive dating of glacial sediments (and, indeed, all forms of geomorphology). The difficulty in doing justice to this topic in a single chapter means that its content is inevitably biased towards the experience and interests of the author, who has attempted, nonetheless, to concentrate on those divisions of geomorphology of greatest value in understanding Quaternary stratigraphy, environmental change and landscape evolution.

In the late twentieth century, support for research advancement in ‘Quaternary geomorphology’ (it could also be called ‘historical geomorphology’) was enhanced by the growth of organizations with interests in the topic. For example, having been founded in 1928, the International Union for Quaternary Research (INQUA) expanded its activities in the latter half of the century with post-war congresses in Italy (No. 4 in 1953), Spain, Poland, the USA, France, New Zealand, the UK and the USSR, and then the final four ‘modern’ twentieth-century congresses, with multiple parallel sessions: Ottawa (1987), Beijing (1991), Berlin (1995) and Durban (1999). INQUA existed before the national Quaternary societies, the oldest of which include the Association française pour l’étude du Quaternaire (AFEQ: 1962), the UK’s Quaternary Research Association (QRA from 1968; 1964 as the Quaternary Field Studies Group), AMQUA (1970) and CANQUA (1975). These have made important contributions, despite not having the antiquity of learned societies like the Geological Society of London and the Geologists’ Association, both with an early interest in Quaternary topics, as reflected in their long-established journals. In the late twentieth century, several international and high-impact specialist Quaternary journals were established, further adding to the prominence and widespread dissemination of the topic. These include *Quaternary Research* (1970), *Boreas* (1972), *Quaternary Science Reviews* (1982) and *Journal of Quaternary Science* (1986), with several primarily geomorphological titles also publishing Quaternary-facing material, notably *Earth Surface Processes and Landforms* (1976) and *Geomorphology* (1987).

Improved understanding of the palaeoclimate record

Palynology had been the method of choice in Europe to provide a biostratigraphical framework for the ages of Quaternary events and landforms, since it had been used to characterize the interglacials that were identified between the glacials, the latter (at least to start with) being the four Alpine glaciations identified by Penck and Bruckner (1909) as the impetus for a paradigm shift from monoglacialism. These were widely applied in the Gunz–Mindel–Riss–Würm sequences recognized by Zeuner (1945, 1959), although there were separate

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definitions in different parts of the world, notably the North American Nebraskan, Kansan, Illinoian and Wisconsin glaciations, separated by the Aftonian, Yarmouthian and Sangamonian interglacials (Richmond and Fullerton 1986). In NW Europe, the climatic template into which the terrestrial sequence was fitted evolved separately from the Alpine nomenclature, although it was also driven by geomorphological recognition of the products of multiple glaciations, in this case ice-sheet advances into lowland Germany (Keilhack 1926; cf. Kukla 1977). Starting with the one episode named from Britain, the Cromerian interglacial, it recognized Elsterian (glacial), Holsteinian (warm), Saalian (g), Eemian (w) and Weichselian (g) episodes, with the present warm period termed 'Flandrian' before it was raised in status and the name 'Holocene' mandated.

Later recognition of a more complex climatic template would require these named stages to be subdivided or redefined, but while they remained valid, during the mid-twentieth century, the importance of pollen was maintained (West 1961, 1963, 1968; Zagwijn 1973, 1985, 1989; De Jong 1988). That was despite murmurings of discontent, in particular from the mammalian camp (Sutcliffe 1964) as well as pioneering work on insects (Coope 1961, 1970; Coope *et al.* 1961) that showed them to be more sensitive to climatic change. Eventually, the improvement in understanding of the long-timescale palaeoclimatic record, in particular the recognition of its greater complexity in the oxygen-isotope record from oceanic sediments (Shackleton and Opdyke 1973; CLIMAP 1976), became an unsurmountable challenge to the supremacy of pollen. By the 1980s, most of those working on longer-timescale Quaternary interests realized that their most urgent task was correlation between the isotope stages, soon to be recognized additionally from ice cores (Greenland Ice-Core Project (GRIP) Members 1993), and the more fragmentary terrestrial record. Palynology, although it had outlived its primacy for the identification of particular episodes, remained a valuable means for charting the waxing and waning of warm climatic events, based on the well-established zonation scheme (Turner and West 1968; Turner 1970; Thomas 2001), and assuming sufficient continuity of sequences. There is an argument that the value of palynology is dependent on geomorphological setting, with lacustrine basins, and especially large, subsiding ones, providing optimal records (Tzedakis 1994; Thomas 2001; Tzedakis *et al.* 2001; Diehl and Sirocko 2007). There is a link with glaciation here, since glaciers and ice sheets have formed lacustrine basins, from kettle holes to overdeepened valleys, explaining why the interglacials following glaciation have optimal representation from high-resolution lacustrine palynological archives (Mangerud 1991).

Determining the number of Quaternary glaciations

The first half of the twentieth century saw the replacement of monoglacialism with the acceptance that there had been multiple advances of ice sheets into lowland regions, but in the second half the determination of how many such ice sheets there had been, and where and when their advances took place, remained a consistent challenge, one that remains largely unresolved at the present day, despite much attention being paid to it (e.g. Šibrava 1986; Ehlers and Gibbard 2004). Penck and Bruckner's (1909) Alpine glaciations were based on outwash from each feeding into different river terraces, whereas the parallel northern European scheme arose from the mapping of moraines and glacial limits (e.g. Keilhack 1926; Woldstedt 1954). Extension and correlation often relied on the recognition of tills attributable to particular glaciations, with differentiation variously based on lithological composition or degree of weathering and/or dissection (Clayton 1957). In the mid-twentieth century, it was thought that the North American glacial record was broadly comparable with Penck and Bruckner's Alpine scheme, but later work revealed a much longer history of ice advances, notably with reverse-magnetized tills of Late Pliocene–Early Pleistocene age (Boelstorff 1978; Easterbrook and Boelstorff 1984; Fullerton 1986; Richmond and Fullerton 1986). Parallel advances revealed similar characteristics in the Quaternary record of South America, where some of the most important archives of glaciation are to be found (Clapperton 1993).

Geomorphology points to greater palaeoclimatic complexity

Within the new early-twentieth-century paradigm of multiple climatic cycles, Zeuner (1945, 1959) recognized river terraces as important evidence for potential correlation with these episodes. The terraces in question are in general formed from sedimentary sequences, providing various combinations of sedimentological, palaeontological and archaeological evidence, overlying erosional surfaces cut into bedrock. Zeuner (1959, 1961) used the term 'benches' for the latter and attempted to correlate them with the astronomical cycles, as linked to the variations in ocean-water temperate determined by Emiliani (1955). Zeuner (1959) differentiated two types of fluvial terrace: climatic and thalassostatic, the latter generally confined to the lower parts of valleys, since they were attributed to aggradation in response to rises in sea level. In upstream reaches, beyond the influence of sea-level change, Zeuner saw aggradation as a response to colder climate and its effect on fluvial energy and sediment supply, thus forming climatic terraces. Given that sea-level changes during the Pleistocene, away from the influence of glacio-isostasy, have been driven by the climate cycles, the likely linkage between the two types of terrace is clear.

Building on Zeuner's ideas, Evans (1971) developed a pioneering model for chronostratigraphical correlation of the terraces of the River Thames with the deep-sea record. He envisaged that cycles of fluvial aggradation and downcutting were superimposed onto a progressive decline in relative sea level since the Pliocene, as indicated by the increasing height with age of interglacial raised beaches and shorelines, both in Britain and further afield. Evans's model had limited impact, perhaps because most workers doubted the implicit progressive decline in eustatic sea level through the Quaternary (a view that had been promoted by Woldstedt 1952*a*, *b*), but the greater complexity he envisaged was vindicated by work towards the end of the century in which the cumulative lowering of base level seen in many parts of the world was attributed to uplift (Bridgland 1994, 2000; Maddy 1997). Such responses to base-level change at a Quaternary timescale should not be confused with the interpretation of paired and unpaired fluvial terraces in Holocene settings, some of them very recent in origin and clearly recording localized intrinsic process-based effects on rivers (e.g. meander migration), land-use changes, particular climatic events and even glacio-isostatic rebound (e.g. Womack and Schumm 1977; Boardman 1997; Taylor and Macklin 1997; Merrett and Macklin 1999; Howard *et al.* 2000; cf. Bridgland *et al.* 2010). Such short-term effects became better understood through work in such diverse research fields as flume simulations (Schumm and Parker 1973) and geo-archaeological recording, the latter of value for dating geomorphological changes and relating them to anthropogenic activity (Needham and Macklin 1992; Macklin *et al.* 2006).

The recognition that progressive Quaternary uplift had affected many parts of the world, including regions long regarded as tectonically stable such as NW Europe, owed much to the improved understanding and geochronology of raised beaches, which record relative sea level during Pleistocene interglacials (Sommé *et al.* 1978; Keen *et al.* 1981; Bowen *et al.* 1985; Davies and Keen 1985; Miller and Mangerud 1985; Mottershead *et al.* 1987; Bowen and Sykes 1988; Balescu *et al.* 1991; Proctor and Smart 1991; Keen 1995). Indeed, the dating of the Boxgrove raised beach, West Sussex, to *c.* 500 ka (Roberts 1986; Roberts and Parfitt 1999) had important ramifications in respect of the now well-founded 'uplift paradigm'. For eustatic relative sea level to have been at the height of the Boxgrove beach, *c.* 40 m above the modern shoreline, at that time would require a substantial proportion of the polar ice sheets to have been missing, with little evidence from other proxies for that to be plausible; thus, differential tectonic movement or progressive regional uplift must be invoked (Preece *et al.* 1990; Westaway *et al.* 2006). Bridgland (1994) suggested erosional isostasy as a likely driver for this progressive uplift, although an important positive-feedback enhancement mechanism, one that has responded to the increase in surface-process activity caused by greater Pleistocene climatic severity, was added to the mix by Westaway (1994): lower crustal flow.

Arguments about whether the aggradational phases represented within river-terrace sequences occurred during cold- or warm-climate episodes continued through the latter half of the twentieth century, often slanted towards evidence from prominent sites within the region most familiar to the worker(s) concerned. Woldstedt (1952*b*) summarized this in a wider overview, noting that the Boyn Hill Terrace of the Thames was attributed to warm-climate aggradation. Although he did not name the site, this was undoubtedly based on the celebrated fossiliferous and Palaeolithic locality at Swanscombe (Ovey 1964), shown soon afterwards to be unrepresentative of the terrace as a whole, the latter being mostly represented by cold-climate deposits (e.g. Gibbard 1985; Bridgland 1994). The modern association of terrace-gravel aggradation with cold (periglacial) episodes, firmly established by the end of the century, rendered Evans's sea-level-based scheme for the Thames effectively obsolete, although the broad correlation between Emiliani's climate cycles and the terrace sequences that he proposed, essentially one of counting backwards through time, was noted to compare quite closely with later interpretations, including his own, by Bridgland (1994).

Along with the advocacy for a key role for regional uplift, the late twentieth century saw another paradigm shift in the understanding of morphostratigraphic sequences such as river terraces and raised beaches, arising from the delayed realization that there were sufficient glacial–interglacial cycles during the Quaternary for a meaningful match with such archives. The new and expanded geochronological framework is of such fundamental significance that it has featured prominently above, although it will be explained in more detail here. Also highlighted already have been the oceanic climate cycles promoted by Emiliani (1955, 1957). Indeed, the provision of a new chronostratigraphic framework with which the morphostratigraphy can be matched (a task that continues to the present day) relied not on geomorphologists or conventional stratigraphers, but on geochemical analysis of continuous records, starting with the sediments that have accumulated in the deep oceans. Pleistocene climatic fluctuations have been recorded in these sediments by variations in the ratio between the oxygen isotopes ^{16}O and ^{18}O in the calcareous tests of foraminifera, which can be presumed to represent the relative proportions of these isotopes in seawater when those micro-organisms were alive. As the lighter isotope (^{16}O) is preferentially represented in water evaporated from the oceans as part of the hydrological cycle, when, during cold episodes, that cycle is somewhat interrupted by increasing amounts of water becoming locked up in long-term ice accumulation, seawater becomes enriched in the heavy isotope (^{18}O). The fluctuation of the ratio between these two isotopes can be plotted against time, thus producing oxygen isotope curves from particular oceanic coring sites, these curves being records of global ice volume and, indirectly, of palaeoclimate and thus eustatic sea level (Fig. 1). In a change from the notation used by Emiliani, the curve was divided into alternating warm and cold stages numbered in reverse stratigraphical sequence from Stage 1, the Holocene (Shackleton 1969, 1987; Shackleton and Opdyke 1973; Hays *et al.* 1976), such that even-numbered stages represent cold episodes and odd-numbered stages equate with warm intervals (Fig. 1).

The importance of Quaternary climatic fluctuation in the formation of river and coastal terraces provides an explanation for the prominence of this type of geomorphological evidence in the temperate climatic zone. Indeed, a view emerged in the late twentieth century, following Büdel's (1977, 1982) work on climatic geomorphology, that river terraces were absent from the tropics, since the climatic oscillations have not been experienced to as great an extent in such areas. Although the latter fact clearly limits the potential for tropical river terrace formation, Bridgland and Westaway (2008) noted examples that disprove the general rule and that many of the tropical regions upon which Büdel's views were based coincide with ultra-stable cratons, where Westaway's key mechanism of lower-crustal flow (see above) does not operate, explaining the absence of evidence for progressive Quaternary uplift in such areas.

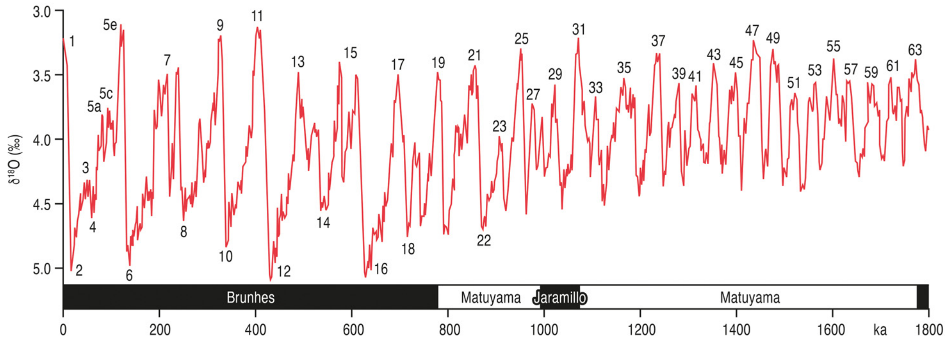

Fig. 1. Updated marine oxygen isotope record, representing knowledge at the end of the twentieth century. Based on the LR04 benthic $\delta^{18}O$ stack constructed by Lisiecki and Raymo (2005) by the graphic correlation of 57 globally distributed benthic records. Note the change from shorter *c.* 40 kyr to longer *c.* 100 kyr cycles (the 'Mid-Pleistocene Revolution') at around the transition from the Early to the Middle Pleistocene. That boundary, which lies within MIS 19, coincides with the Matuyama–Bruhnes magnetic reversal, as depicted in the palaeomagnetic polarity record, shown below the curve. Reproduced from Bridgland and Westaway (2014) with permission from the Geologists' Association.

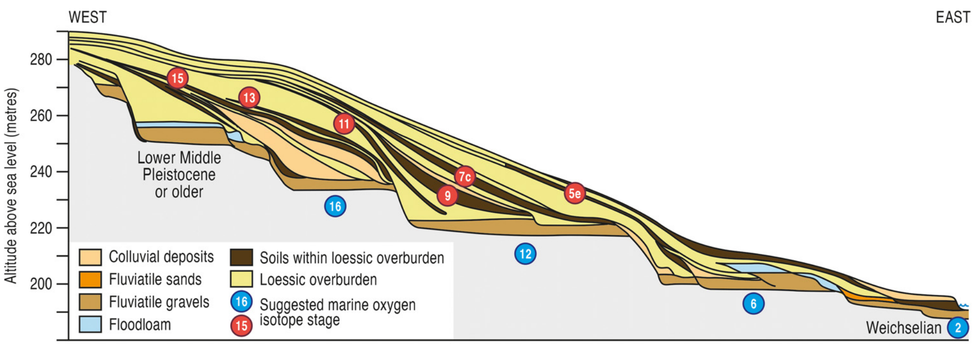

Fig. 2. Transverse profiles illustrating the classic 'Red Hill' sequence at Brno, SE Czechia, showing the terrace staircase of the River Svratka (left-bank tributary of the Danube) with loess–palaeosols in the overburden, used as an age constraint for the terrace sequence. Suggested MIS correlation is shown, with red for warm episodes and blue for cold (adapted from Kukla 1975; reproduced, with modifications, from Bridgland and Westaway 2008).

The most convincing attempt at correlation between terrestrial morphostratigraphical sequences and the oceanic record in the 1970s was that by Kukla (1975, 1977), based on the directly comparable cyclicity of aeolian loess accumulation and soil formation in central Europe, which allows age calibration of underlying river terrace systems, including those of the Dniester (Ukraine), the Danube (Austria) and, perhaps the most celebrated, the Svratka at Brno, Czechia (Fig. 2). Kukla's interpretations, regarded with scepticism at the time (although see Bowen 1978), are remarkably close to contemporary views (cf. Bridgland and Westaway 2008). Within two decades of Kukla's pioneering work, schemes were proposed for correlation of river-terrace staircases near the Atlantic margin of Europe with the marine record; here each climate cycle is generally registered within the sequences, in contrast with central Europe. A similar approach to Kukla's, making use of loess–palaeosol cyclicity within overburden, was used in the Somme and other rivers in northern France, where there is supporting evidence from biostratigraphy and Palaeolithic archaeology (Antoine 1994; Antoine *et al.* 2000, 2007) (Fig. 3).

Biostratigraphy was the main line of evidence applied to the terraces of the Lower Thames, where local chalk bedrock (by providing calcareous groundwater) has enhanced the preservation of vertebrate and molluscan fossils (Bridgland 1994) (Fig. 4). In eastern Europe, meanwhile, workers were building comparable knowledge of the extensive sequences of terraces in rivers beyond the reach of Quaternary glaciations, most notable amongst which is that of the Dniester, which has a classic staircase with abundant biostratigraphical dating control (Alexeeva 1977; Bukatchuk *et al.* 1983; Adamenko *et al.* 1986; Michailesku and Markova 1992; Tchepalyga 1997), as summarized in English by Matoshko *et al.* (2004).

Mention should be made of an alternative approach to the study of river-terrace sequences and associated landscape evolution developed towards the end of the century, using process-based mathematical modelling and attempting to relate knick points in fluvial long profiles to former sea-level falls (Rosenbloom and Anderson 1994; Whipple and Tucker 1999). Paying little attention to the regular sea-level changes during the Quaternary, or to evidence from the fluvial sedimentary and palaeontological record with which it is often at odds (cf. Bridgland and Westaway 2012), this approach has generated an entirely separate body of literature, with attempts at reconciliation between the two approaches coming only recently (e.g. Demoulin *et al.* 2017; Martins *et al.* 2017).

Catastrophism

In the latter half of the last century, the long-standing catastrophism v. uniformitarianism argument largely subsided in Quaternary circles, with the recognition of the greater contribution

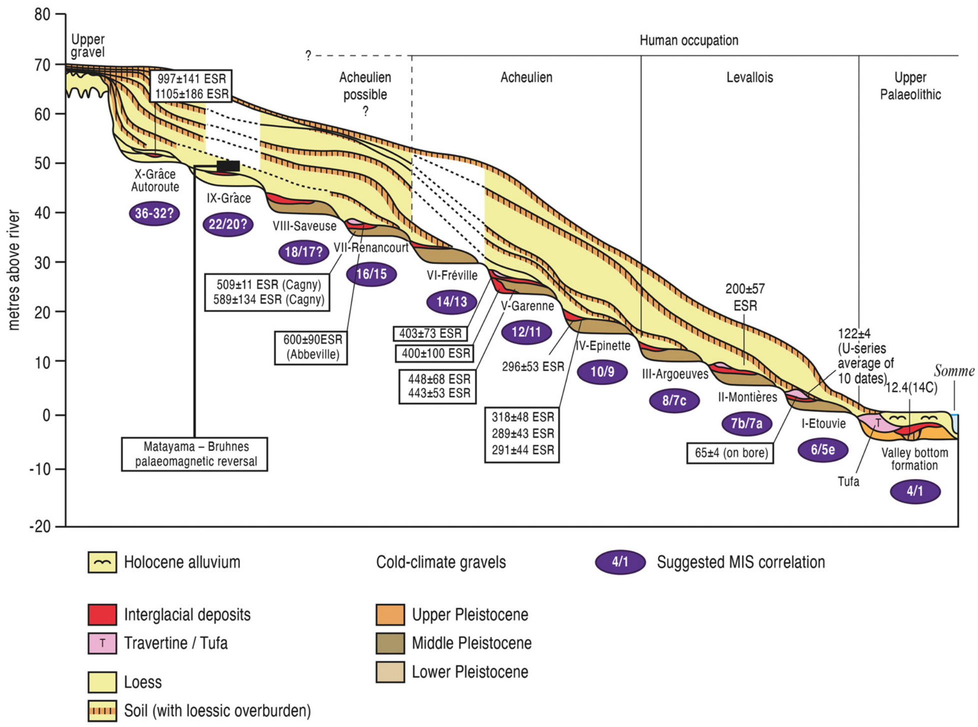

Fig. 3. Idealized transverse section through the terraces of the River Somme, showing fluvial deposits, loess–palaeosol overburden, the range of archaeological content and geochronological data (suggested MIS correlations are shown). After Antoine *et al.* (2007); reproduced, with modifications, from Bridgland and Westaway (2014), with permission from the Geologists' Association.

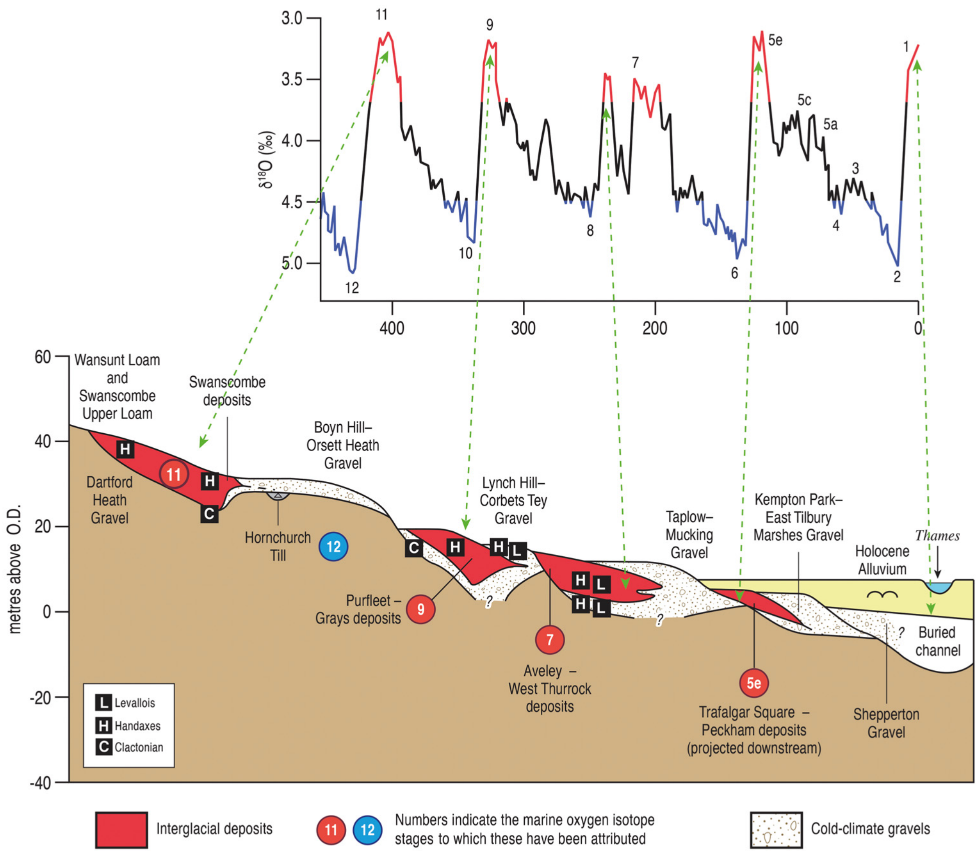

Fig. 4. Idealized transverse sequence through the terraces of the Lower Thames, east of London, showing stratigraphic positions of interglacial deposits and of major archaeological assemblages (suggested MIS correlations are shown). Modified from Bridgland (2006), with permission from the Geologists' Association, with the addition of the LR04 benthic $\delta^{18}O$ stack (see Fig. 1).

of enhanced geomorphic processes during episodes of greater climatic severity and, in particular, the heightened discharge resulting from melting, both annually, during spring, and with climatic amelioration and deglaciation. Events of catastrophic dimensions remained influential, such as the rapid drainage of Glacial Lake Missoula in the Mid-West USA (Bretz 1969; Baker 1973); comparison of the channelled 'scabland' left from this example with the floor of the English Channel led to the suggestion that the Dover Strait was formed by catastrophic drainage of a North Sea glacial lake (Smith 1989; Gibbard 1995), an event of profound regional geomorphological importance in that it was the foundation of Britain's island status.

Slopes

Although of great significance in terms of medium-scale landscape evolution, as well as civil engineering and hazard mitigation, the geomorphology of slopes has little obvious relevance to the understanding of longer-timescale Quaternary evolution. There are, however, detailed archives of recent slope-failure and accumulation events, generally restricted in terms of preservation to the last climate cycle. Furthermore, in some regions river terraces are closely linked with contemporaneous valley-side slope development, with former valley floors represented by terraces grading upwards into hillside slopes or piedmonts. Sometimes used as part of a systematic classification of sloping surfaces linked to stages in valley evolution is the French term 'glacis', which has been subdivided into 'glacis rocheux', developed on bedrock, 'glacis d'érosion', developed on softer material (including slope deposits) and 'glacis alluvial' (for which the equivalent term 'bajada' exists): a slope comprising coalesced alluvial fans. Linkage between fans from multiple episodes and terrace deposits of ephemeral rivers represent valuable Quaternary geomorphological archives in North Africa, as in the Souss Valley, Morocco (Bhiry and Occhietti 2004; Chakir *et al.* 2014). Glacis were recognized in mid- to late-twentieth-century geomorphological mapping of river-terrace systems in the Near East by French workers, generally motivated by studies of Lower–Middle Palaeolithic occupation. Thus river-terrace sediments and associated glacis, the latter generally formed on slope deposits, were mapped and classified in the Kebir and Orontes rivers in Syria according to a standard notational scheme in which Middle–Late Pleistocene levels (terraces and associated glacis) were designated QfIV to QfI, approximately equivalent to the four main Alpine glaciations (Besançon *et al.* 1978; Copeland and Hours 1978; Sanlaville 1979; Besançon and Sanlaville 1993). This mapping, although detailed and highly valuable, has been found to have simplified the true complexity of the sequences (e.g. Bridgland *et al.* 2012), the work predating widespread acceptance of the global template from the deep oceans (see above). Areas where archives of long-timescale slope features form important parts of the Quaternary record are generally beyond the reach of the Quaternary glaciations and, indeed, of widespread periglacial activity during cold stages. This is presumably a requirement for preservation, alongside relative aridity, another characteristic of the examples cited above, to which can be added the Sierra de Albarracín, eastern Iberia, where stratified 'old screes' have been suggested to represent high-level remnants of valley-side slopes related to late Middle Pleistocene river terraces (Peña Monné and Jiménez 1993).

The greater activity of slope processes in more humid and, especially, colder regions can be assumed to have prevented such slope features from surviving into the longer-timescale record. Nonetheless, important archives from latest Quaternary slope activity were recognized during the late twentieth century, assisted by improvements in biostratigraphical understanding and in geochronology. Important work in the chalklands of southern England was undertaken by Kerney (1963), who pioneered the examination of sediments associated with the geomorphological features of the escarpments as a means for constraining the time of formation of the latter, using biostratigraphy (primarily from molluscs) and radiocarbon dating. Although fruitful in enhancing understanding of recent geomorphological evolution, this approach proved to be of limited value in addressing long-standing questions about possible origins in relation to former through-flowing drainage and river capture (Wooldridge and Linton 1955; Worssam 1973), since the surviving sediments in chalkland valleys and scarp-face hollows ('coombes') were invariably found to date from the Lateglacial and Holocene, presumably because these features were flushed out and/or (re)excavated during the Last Glacial (Kerney *et al.* 1964, 1980; Preece and Bridgland 1998).

The building of the Channel Tunnel provided important insight into such issues, since it allowed the study of temporary exposures in the lower slopes and floor of a scarp-face valley in the North Downs, Holywell Coombe, near Folkestone, Kent. This provided unprecedented access to buried sediment bodies related to solifluction fans, land-slipped masses and patches of temporary wetland ponded by the emplacement of these, as well as tufa-forming springs (Preece and Bridgland 1998, 1999). The evidence from Holywell Coombe points to episodes of valley erosion there during the Last Glacial (MIS 2) and extending into the Lateglacial, especially the Younger Dryas (Loch Lomond Stadial), with slope stability during the optimum of the Allerod interstadial and throughout the Holocene aided presumably by vegetation; the main period of landslipping was at the end of the Last Glacial, dated with reference to organic sediments that had accumulated 12–13 kyr ago in wetland hollows created in front of the foundered masses (Preece and Bridgland 1998). Valley-side erosion by solifluction processes during the Younger Dryas stadial had also been demonstrated from stratigraphical evidence at Brook, near Ashford, in a scarp-face valley in the North Downs (Kerney *et al.* 1964), and on the Lower Greensand escarpment near Sevenoaks (Skempton and Weeks 1976), respectively *c.* 16 and *c.* 75 km to the NW of Holywell Coombe.

The instability of the scarp-face and coombe-edge slopes is heightened by the superposition of porous Chalk above impervious and Gault Clay, as exemplified a few kilometres from Holywell Coombe, at Folkestone Warren, infamous for the frequency and scale of slope failures in the modern era, greatly affecting the Folkestone–Dover railway (Smart *et al.* 1966). Rotational failures of Gault Clay are believed to have been initiated here by the Holocene marine transgression and resultant coastal erosion, and greatly exceed similar features on the French side of the Dover Strait because of the greater thickness of Gault Clay (Hutchinson 1969; Hutchinson *et al.* 1980).

Karst

Karstic features, including caves, represent distinct divisions of geomorphology and Quaternary studies, of particular importance because associated calcareous precipitates (speleothems) are readily datable using uranium-series methodology (e.g. Rowe *et al.* 1989; Smart 1991), thus providing chronological constraint within both disciplines. The large bodies of karstic research and literature lie largely beyond the scope of this chapter, but linkages with its other themes are worthy of attention. First, dated speleothem levels in caves provide records of the depth of fluvial incision in adjacent valleys (e.g. Waltham *et al.* 1997; Granger *et al.* 2001), of great value in regions where subaerial evidence has been removed by glacial erosion, such as the English Peak District (Westaway 2009). In addition, dolines and larger karstic depressions such as poljes can be repositories for sedimentary and archaeological archives (Sampson 1978; Mihevc and Zupan Hajna 1996; White *et al.* 1999); an important example is the Ioannina Basin in Greece, a polje from which a long-timescale record of Quaternary lacustrine sediment has been much studied (Tzedakis *et al.* 1997; Wilson *et al.* 2021). The formation of subaerial tufas and travertines during interglacials has also provided means for U-series dating of river-terrace sequences (Figs 3 & 5) and has preserved rare glimpses of preserved Pleistocene land surfaces on which hominins lived, as represented by the preservation of hearths within such deposits at sites such as Bilzingsleben (Mania 1991), Weimar–Ehringsdorf (Vlček 1993) and Taubach (Bratlund 1999), all in Germany, and West Stow, in Suffolk, England (Preece *et al.* 2006).

Soils

The role of soils and palaeosols (fossil/buried soils) in the Quaternary is of great importance in some regions, providing a primary means of correlation and chronostratigraphy in areas of China and central Europe where loess cover occurs, as was

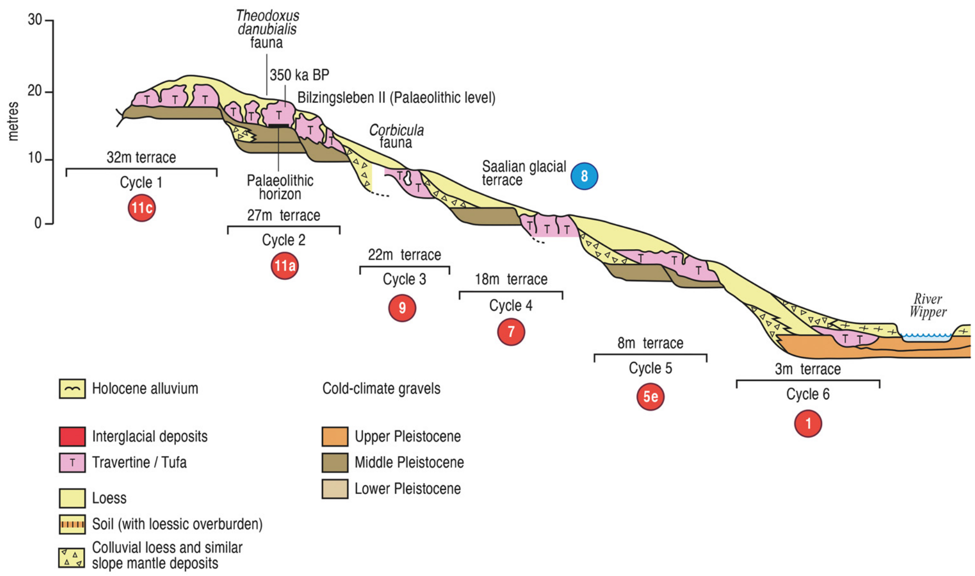

Fig. 5. Transverse sequence through the terraces of the River Wipper, Thuringia, Germany: non-idealized cross-section of a meander core at Bilzingsleben. The subaerial travertine deposits are representative of interglacials (suggested MIS correlations are shown). Modified from Mania (1995) and reproduced from Bridgland and Westaway (2014) with permission from the Geologists' Association.

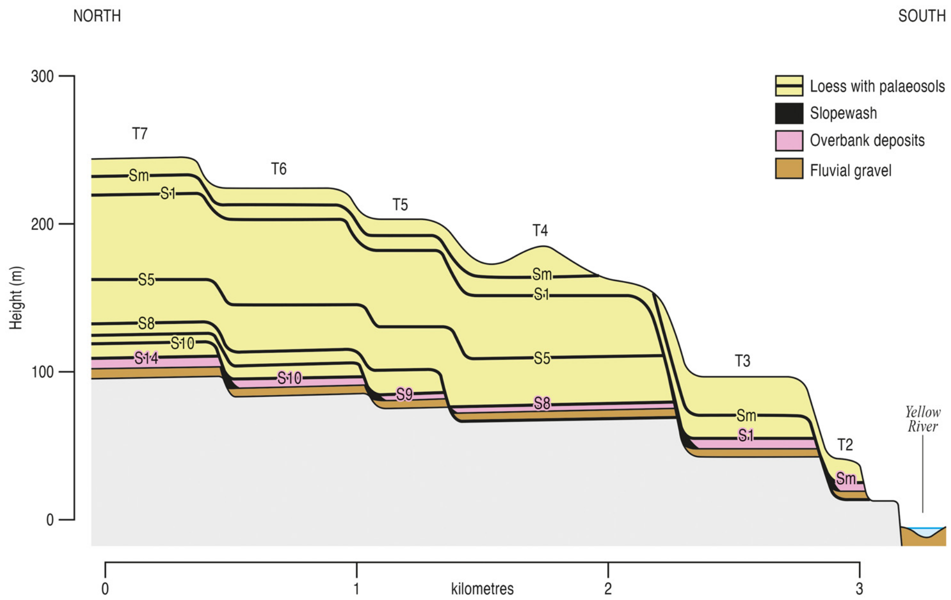

Fig. 6. Part of the Chinese loess–palaeosol sequence around Lanzhou, Ganshu Province, overlying the terraces of the Yellow River, for which it provides key dating evidence (modified from Pan *et al.* 2009).

noted already, particularly with reference to the great advances made by Kukla (1975, 1977) (Fig. 2). Indeed, Kukla (1987; Kukla and An 1989) (Fig. 6) was involved in correlation of the stacked palaeosol sequences of the Chinese loess plateau with the marine climatic record, along with Bronger and Heinkele (1989), Ding *et al.* (1994), Vandenberghe *et al.* (1997) and Lu *et al.* (1999).

An example of late-twentieth-century advancement of Quaternary understanding based on palaeosol evidence stems from the recognition of superimposed warm- and cold-climate soils beneath the Anglian (MIS 12) till in East Anglia, which led to the realization that much of the underlying gravel, formerly classified as glacial, represents ancient terraces of the River Thames (Rose *et al.* 1976; Rose and Allen 1977). These superimposed soils were named the Valley Farm Rubified Sol Lessivé and the Barham Arctic Structure Soil, the former characterized by reddening and evidence for clay translocation, and the latter by periglacial disruption structures, both macro- (e.g. ice-wedge pseudomorphs and patterned ground) and micro-scale, the latter determined from micromorphological analysis of thin sections (Kemp 1987). The geomorphological relevance of these is in their contribution to new thinking on landscape evolution in SE Britain, confirming the glacial diversion of the Thames first suggested by Salter (1905) and promoted on the basis of gravel composition by Hey (1967, 1980). This event had a geomorphological impact on a regional scale, moving the main axis of eastward drainage significantly southwards; without it, the UK's primary river would not flow through the present location of its capital city. In East Anglia, the pedogenic and geomorphological components of this event-stratigraphical marker proved to have been oversimplified at first, envisaging a single sheet of Thames gravel emplacement during the Beestonian Stage, followed by the formation of the Valley Farm Soil in the Cromerian and the Barham Soil in the early Anglian, before the arrival of the ice sheet. Later work refined the story to fit better with the greater complexity of Quaternary climatic fluctuation that was becoming established, such that the gravels were seen to represent a broad flight of terraces, spanning the late Early and early Middle Pleistocene, with progressively more complex soils developed on the higher and older ones, reflecting alternating periods of interglacial and periglacial climate (Kemp 1987) (Fig. 7).

Soil formation has also had a role in morphostratigraphy, in the somewhat imprecise relative dating of landforms based on the degree of soil development on the surfaces of landforms, particularly moraines (Harden 1982; Harden and Taylor 1983; Berry 1994; Evans 1999), but also fluvial and marine terraces (Muhs 1982; Bull 1990; Markewich and Pavich 1991; Smith and Boardman 1994; Bockheim *et al.* 1996; Leigh 1996).

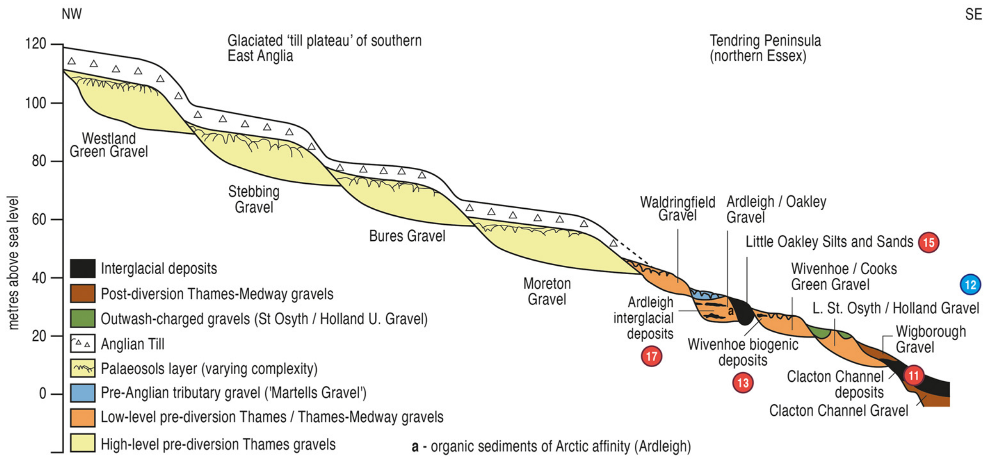

Fig. 7. Idealized transverse section though the terrace sequence of the River Thames in southern East Anglia, showing the development of overlying palaeosol complexes. In part derived from Bridgland *et al.* (1988) with permission from the Geologists' Association.

Summary and conclusion

Priority has been given to river-terrace and raised-beach sequences in this chapter, justifiable in that these provide frameworks for the understanding of the Quaternary and for unravelling the records of other Pleistocene geomorphological records, such as multiple glacial advances of different ages. Significant advances in understanding the relation between these geomorphological features and their Quaternary context were made during the late twentieth century. In addition, the geomorphology of slopes has been found valuable in that the processes involved have produced archives of fossil features and sediments that record Quaternary landscape evolution. Karstic studies have an overlapping relevance to both geomorphology and Quaternary science, particularly in the dating of calcareous precipitates and the accommodation space for substantial sedimentary archives provided by karstic depressions.

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References

Adamenko, O.M., Alexandrova, L.P. and Anisutkin, N.K. 1986. *Antropogen i paleolit Moldavskogo Pridnestoviya*. Shtiintsa, Chishinau, Moldova.

Alexeeva, L.I. 1977. *Teriofauna rannego antropogena Vostochnoi Evropy*. Trudy Geologicheskogo Instituta Akademii Nauk SSSR, 300.

Antoine, P. 1994. The Somme valley terrace system (northern France); a model of river response to Quaternary climatic variations since 800 000 BP. *Terra Nova*, **6**, 453–464, https://doi.org/10.1111/j.1365-3121.1994.tb00889.x

Antoine, P., Lautridou, J.-P. and Laurent, M. 2000. Long-term fluvial archives in NW France: response of the Seine and Somme rivers to tectonic movements, climate variations and sea-level changes. *Geomorphology*, **33**, 183–207, https://doi.org/10.1016/S0169-555X(99)00122-1

Antoine, P., Limondin-Lozouet, N. *et al*. 2007. Pleistocene fluvial terraces from northern France (Seine, Yonne, Somme): synthesis, and new results from interglacial deposits. *Quaternary Science Reviews*, **26**, 2701–2723, https://doi.org/10.1016/j.quascirev.2006.01.036

Baker, V.R. 1973. *Paleohydrology and Sedimentology of Lake Missoula Flooding in Eastern Washington*. Geological Society of America Special Papers, **144**, https://doi.org/10.1130/SPE144

Balescu, S., Packman, S.C. and Wlntle, A.G. 1991. Chronological separation of interglacial raised beaches from northwestern Europe using thermoluminescence. *Quaternary Research*, **35**, 91–102, https://doi.org/10.1016/0033-5894(91)90097-O

Berry, M.E. 1994. Soil-geomorphic analysis of late Pleistocene glacial sequences in the McGee, Pine and Bishop Creek drainages, east-central Sierra Nevada, California. *Quaternary Research*, **41**, 160–175, https://doi.org/10.1006/qres.1994.1018

Besançon, J. and Sanlaville, P. 1993. La vallée de l'Oronte entre Rastane et Aacharné. *British Archaeological Reports International Series*, **587**, 13–39.

Besançon, J., Copeland, L., Hours, F. and Sanlaville, P. 1978. The palaeolithic sequence in Quaternary formations of the Orontes River Valley, northern Syria: A preliminary report. *Bulletin of the Institute of Archaeology, London*, **15**, 149–170.

Bhiry, N. and Occhietti, S. 2004. Fluvial sedimentation in a semi-arid region: the fan and interfan system of the Middle Souss Valley, Morocco. *Proceedings of the Geologists' Association*, **115**, 313–324, https://doi.org/10.1016/S0016-7878(04)80011-7

Boardman, J. 1997. *Geomorphology of the Lake District: A Field Guide*. British Geomorphological Research Group, Oxford, UK.

Bockheim, J.G., Marshall, J.G. and Kelsey, H.M. 1996. Soil-forming processes and rates on uplifted marine terrace in southwestern Oregon, USA. *Geoderma*, **73**, 39–62, https://doi.org/10.1016/0016-7061(96)00017-1

Boelstorff, J. 1978. A need for redefinition of North American Pleistocene stages. *Transactions of the Gulf Coast Association of Geological Societies*, **28**, 65–74.

Bowen, D.Q. 1978. *Quaternary Geology: A Stratigraphic Framework for Multidisciplinary Work*. Pergamon Press, Oxford.

Bowen, D.Q. and Sykes, G.A. 1988. Correlation of marine events and glaciations on the northeast Atlantic margin. *Philosophical Transactions of the Royal Society of London*, **B318**, 619–635.

Bowen, D.Q., Sykes, G.A., Reeves, A., Miller, G.H., Andrews, J.T., Brew, J.S. and Hare, P.E. 1985. Amino acid geochronology of raised beaches in south west Britain. *Quaternary Science Reviews*, **5**, 299–340, https://doi.org/10.1016/0277-3791(85)90003-4

Bratlund, B. 1999. Taubach revisited. *Jahrbuch des Römisch-Germanischen Zentralmuseums Mainz*, **46**, 61–174.

Bretz, J.H. 1969. The lake Missoula floods of the channelled scablands. *Journal of Geology*, **77**, 505–543, https://doi.org/10.1086/627452

Bridgland, D.R. 1994. *Quaternary of the Thames*. Geological Conservation Review Series, **7**. Chapman and Hall, London.

Bridgland, D.R. 2000. River terrace systems in north-west Europe: an archive of environmental change, uplift, and early human occupation. *Quaternary Science Reviews*, **19**, 1293–1303, https://doi.org/10.1016/S0277-3791(99)00095-5

Bridgland, D.R. 2006. The Middle and Upper Pleistocene sequence in the Lower Thames; a record of Milankovitch climatic fluctuation and early human occupation of southern Britain: Henry Stopes Memorial Lecture. *Proceedings of the Geologists' Association*, **117**, 281–305, https://doi.org/10.1016/S0016-7878(06)80036-2

Bridgland, D.R. and Westaway, R. 2008. Preservation patterns of late Cenozoic fluvial deposits and their implications: Results from IGCP 449. *Quaternary International*, **189**, 5–38, https://doi.org/10.1016/j.quaint.2007.08.036

Bridgland, D.R. and Westaway, R. 2012. The use of fluvial archives in reconstructing landscape evolution: the value of sedimentary and morphostratigraphical evidence. *Netherlands Journal of Geoscience*, **91**, 5–24, https://doi.org/10.1017/S0016774600000536

Bridgland, D.R. and Westaway, R. 2014. Quaternary fluvial archives and landscape evolution: a global synthesis. *Proceedings of the Geologists' Association*, **125**, 600–629, https://doi.org/10.1016/j.pgeola.2014.10.009

Bridgland, D.R., Allen, P. *et al*. 1988. Report of the Geologists' Association Field Meeting in north-east Essex, May 22nd–24th, 1987. *Proceedings of the Geologists' Association*, **99**, 315–333, https://doi.org/10.1016/S0016-7878(88)80056-7

Bridgland, D.R., Westaway, R. *et al*. 2010. The role of glacio-isostasy in the formation of post-glacial river terraces in relation to the MIS 2 ice limit: evidence from northern England. *Proceedings of the Geologists' Association*, **121**, 113–127, https://doi.org/10.1016/j.pgeola.2009.11.004

Bridgland, D.R., Westaway, R. *et al*. 2012. The River Orontes in Syria and Turkey: downstream variation of fluvial archives in different crustal blocks. *Geomorphology*, **165–166**, 25–49, https://doi.org/10.1016/j.geomorph.2012.01.011

Bronger, A. and Heinkele, T. 1989. Micromorphology and genesis of paleosols in the Luochuan loess section, China: pedostratigraphic and environmental implications. *Geoderma*, **45**, 123–143, https://doi.org/10.1016/0016-7061(89)90046-3

Büdel, J. 1977. *Klima-Geomorphologie*. Gebrüder Borntraeger, Berlin.

Büdel, J. 1982. *Climatic Geomorphology* [English translation by Fischer, L. and Busche, D.]. Princeton University Press, Princeton, NJ.

Bukatchuk, P.D., Gozhik, P.F. and Bilinkis, G.M. 1983. O korrelyatsii alluvial'nyh otlozheniy Dnestra, Pruta i Nizhnego Dunaya. *In*: *Geologiya chetvertichnyh otlozheniy Moldavii*. Shtiintsa, Chishinau, Moldova, 35–70.

Bull, W.B. 1990. Stream-terrace genesis: implications for soil development. *Geomorphology*, **3**, 351–367, https://doi.org/10.1016/0169-555X(90)90011-E

Chakir, L., Aït Hssaine, A. and Bridgland, D.R. 2014. Morphogenesis and morphometry of alluvial fans in the High Atlas, Morocco: A geomorphological model of the fans of the Wadi Beni Mhammed, Souss valley. *International Journal of Environment*, **3**, 294–311, https://doi.org/10.3126/ije.v3i3.11090

Clapperton, C. 1993. *Quaternary Geology and Geomorphology of South America*. Elsevier, Amsterdam.

Clayton, K.M. 1957. Some aspects of the glacial deposits of Essex. *Proceedings of the Geologists' Association*, **68**, 1–19, https://doi.org/10.1016/S0016-7878(57)80013-3

CLIMAP Project Members 1976. The surface of the ice-age Earth. *Science*, **191**, 1131–1144, https://doi.org/10.1126/science.191.4232.1131

Coope, G.R. 1961. On the study of glacial and interglacial insect faunas. *Proceedings of the Linnean Society of London*, **172**, 62–65, https://doi.org/10.1111/j.1095-8312.1961.tb00868.x

Coope, G.R. 1970. Interpretations of Quaternary insect fossils. *Annual Review of Entomology*, **15**, 97–120, https://doi.org/10.1146/annurev.en.15.010170.000525

Coope, G.R., Shotton, F.W. and Strachan, I. 1961. A late Pleistocene fauna and flora from Upton Warren, Worcestershire. *Philosophical Transactions of the Royal Society, London*, **B224**, 379–417.

Copeland, L. and Hours, F. 1978. La séquence Acheuléenne du Nahr el Kebir, région septentrionale du littoral Syrien. *Paléorient*, **4**, 5–31, https://doi.org/10.3406/paleo.1978.4211

Davies, K.H. and Keen, D.H. 1985. The age of the Pleistocene marine deposits at Portland, Dorset. *Proceedings of the Geologists' Association*, **96**, 217–225, https://doi.org/10.1016/S0016-7878(85)80004-3

De Jong, J. 1988. Climatic variability during the past three million years, as indicated by vegetational evolution in northwest Europe and with emphasis on data from The Netherlands. *Philosophical Transactions of the Royal Society of London*, **B318**, 603–617.

Demoulin, A, Mather, A. and Whittaker, A. 2017. Fluvial archives, a valuable record of vertical crustal deformation. *Quaternary Science Reviews*, **166**, 10–37, https://doi.org/10.1016/j.quascirev.2016.11.011

Diehl, M. and Sirocko, F . 2007. A new Holsteinian pollen record from the dry maar at Döttingen (Eifel). *Developments in Quaternary Science*, **7**, 397–416, https://doi.org/10.1016/S1571-0866(07)80052-2

Ding, Z.L., Yu, Z.W., Rutter, N.W. and Liu, T.S. 1994. Towards an orbital time scale for Chinese loess deposits. *Quaternary Science Reviews*, **13**, 39–70, https://doi.org/10.1016/0277-3791(94)90124-4

Easterbrook, D.J. and Boelstorff, J. 1984. Paleomagnetism and chronology of Early Pleistocene tills in the central United States. *In*: Mahaney, W.C. (ed.) *Correlation of Quaternary Chronologies*. GeoBooks, Norwich, UK, 73–90.

Ehlers, J. and Gibbard, P.L. 2004. *Quaternary Glaciations – Extent and Chronology*. Developments in Quaternary Science, **2**, Elsevier, Amsterdam.

Emiliani, C. 1955. Pleistocene temperatures. *Journal of Geology*, **63**, 538–578, https://doi.org/10.1086/626295

Emiliani, C. 1957. Temperature and age analysis of deep-sea cores. *Science*, **125**, 383–387, https://doi.org/10.1126/science.125.3244.383

Evans, D.J.A. 1999. A soil chronosequence from Neoglacial moraines in western Norway. *Geografiska Annaler*, **81A**, 47–62, https://doi.org/10.1111/j.0435-3676.1999.00048.x

Evans, P. 1971. Part 2: Towards a Pleistocene timescale. *Geological Society, London, Special Publications*, **5**, 123–356, https://doi.org/10.1144/GSL.SP.1971.005.01.08

Fullerton, D.S. 1986. Stratigraphy and correlation of glacial deposits from Indiana to New York and New Jersey. *Quaternary Science Reviews*, **5**, 23–37.

Gibbard, P.L. 1985. *The Pleistocene History of the Middle Thames*. Cambridge University Press, Cambridge, UK.

Gibbard, P.L. 1995. The formation of the Strait of Dover. *Geological Society, London, Special Publications*, **96**, 15–26, https://doi.org/10.1144/GSL.SP.1995.096.01.03

Goudie, A.S. 2021. The impacts of humans on geomorphology. *Geological Society, London, Memoirs*, **58**, https://doi.org/10.1144/M58-2020-24

Granger, D.E., Fabel, D. and Palmer, A.N. 2001. Pliocene–Pleistocene incision of the Green River, Kentucky, determined from radioactive decay of cosmogenic ^{26}Al and ^{10}Be in Mammoth Cave sediments. *Geological Society of America Bulletin*, **113**, 825–836, https://doi.org/10.1130/0016-7606(2001)113<0825:PPIOTG>2.0.CO;2

Greenland Ice-Core Project (GRIP) Members. 1993. Climate instability during the last interglacial period recorded in the GRIP ice core. *Nature*, **364**, 203–207, https://doi.org/10.1038/364203a0

Grove, A.T. 2008. The revolution in palaeoclimatology around 1970. *In*: Burt, T.P., Chorley, R.J., Brunsden, D., Cox, N.J. and Goudie, A.S. (eds) *The History of the Study of Landforms, Volume 4: Quaternary and Recent Processes and Forms (1890–1965) and the Mid-Century Revolutions*. Geological Society, London, 961–1004.

Harden, J.W. 1982. A quantitative index of soil development from field descriptions – examples from a chronosequence in central California. *Geoderma*, **28**, 1–28, https://doi.org/10.1016/0016-7061(82)90037-4

Harden, J.W. and Taylor, E.M. 1983. A quantitative comparison of soil development in four climatic regimes. *Quaternary Research*, **20**, 342–359, https://doi.org/10.1016/0033-5894(83)90017-0

Hays, J.D., Imbrie, J. and Shackleton, N.J. 1976. Variations in the Earth's orbit: Pacemaker of the ice ages. *Science*, **194**, 1121–1132, https://doi.org/10.1126/science.194.4270.1121

Hey, R.W. 1967. The Westleton Beds reconsidered. *Proceedings of the Geologists' Association*, **78**, 427–445, https://doi.org/10.1016/S0016-7878(67)80008-7

Hey, R.W. 1980. Equivalents of the Westland Green Gravels in Essex and East Anglia. *Proceedings of the Geologists' Association*, **91**, 279–290, https://doi.org/10.1016/S0016-7878(80)80023-X

Howard, A.J., Macklin, M.G., Black, S. and Hudson-Edwards, K. 2000. Holocene river development and environmental change in upper Wharfedale, Yorkshire Dales, England. *Journal of Quaternary Science*, **15**, 239–252, https://doi.org/10.1002/(SICI)1099-1417(200003)15:3<239::AID-JQS480>3.0.CO;2-W

Hutchinson, J.N. 1969. A reconsideration of the coastal landslides at Folkestone Warren, Kent. *Geotechnique*, **19**, 6–38, https://doi.org/10.1680/geot.1969.19.1.6

Hutchinson, J.N., Bromehead, E.N. and Lupini, J.F. 1980. Additional observations on the Folkestone Warren landslides. *Quarterly Journal of Engineering Geology*, **13**, 1–31, https://doi.org/10.1144/GSL.QJEG.1980.013.01.01

Imbrie, J. and Imbrie, K. 1979. *Ice Ages: Solving the Mystery*. Macmillan, London.

Keen, D.H. 1995. Raised beaches and sea-levels in the English channel in the Middle and Late Pleistocene: problems of interpretation and implications for the isolation of the British Isles.

Geological Society, London, Special Publications, **96**, 63–74, https://doi.org/10.1144/GSL.SP.1995.096.01.06

Keen, D.H., Harmon, R.S. and Andrews, J.T. 1981. U-series and amino-acid dates from Jersey. *Nature*, **289**, 162–164, https://doi.org/10.1038/289162a0

Keilhack, K. 1926. *Das Quartär in Grundzüge der Geologie, II*. W. Salomon, Stuttgart, Germany.

Kemp, R.A. 1987. Genesis and environmental significance of a buried Middle Pleistocene soil in eastern England. *Geoderma*, **41**, 49–77, https://doi.org/10.1016/0016-7061(87)90028-0

Kerney, M.P. 1963. Late-glacial deposits on the Chalk of south-east England. *Philosophical Transactions of the Royal Society of London*, **B246**, 203–254.

Kerney, M.P., Brown, E.H. and Chandler, T.J. 1964. The late-glacial and post-glacial history of the Chalk escarpment near Brook, Kent. *Philosophical Transactions of the Royal Society of London*, **B248**, 135–204.

Kerney, M.P., Preece, R.C. and Turner, C. 1980. Molluscan and plant biostratigraphy of some Late Devensian and Flandrian deposits in Kent. *Philosophical Transactions of the Royal Society of London*, **B291**, 1–43.

Kukla, G.J. 1975. Loess stratigraphy of Central Europe. *In*: Butzer, K.W. and Isaac, G.L. (eds) *After the Australopithecines: Stratigraphy, Ecology and Culture Change in the Middle Pleistocene*. Mouton, The Hague, The Netherlands, 99–188.

Kukla, G.J. 1977. Pleistocene land–sea correlations. I. Europe. *Earth-Science Reviews*, **13**, 307–374, https://doi.org/10.1016/0012-8252(77)90125-8

Kukla, G.J. 1987. Loess stratigraphy in Central China and correlation with an extended oxygen isotope stage scale. *Quaternary Science Reviews*, **6**, 191–220, https://doi.org/10.1016/0277-3791(87)90004-7

Kukla, G.J. and An, Z. 1989. Loess stratigraphy in Central China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **72**, 203–225, https://doi.org/10.1016/0031-0182(89)90143-0

Leigh, D.S. 1996. Soil chronosequence of Brasstown Creek, Blue Ridge Mountains, USA. *Catena*, **26**, 99–114, https://doi.org/10.1016/0341-8162(95)00040-2

Lisiecki, L.E. and Raymo, M.E. 2005. A Pliocene–Pleistocene stack of 57 globally distributed benthic δ^{18}O records. *Paleoceanography*, **20**, PA1003, https://doi.org/10.1029/2004PA001071

Lu, H., Liu, X., Zhang, H., An, Z. and Dodson, J. 1999. Astronomical calibration of loess–paleosol deposits at Luochuan, central Chinese Loess Plateau. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **154**, 237–246, https://doi.org/10.1016/S0031-0182(99)00113-3

Macklin, M.G., Benito, G. *et al*. 2006. Past hydrological events in the Holocene fluvial record of Europe. *Catena*, **66**, 145–154, https://doi.org/10.1016/j.catena.2005.07.015

Maddy, D. 1997. Uplift-driven valley incision and river terrace formation in southern England. *Journal of Quaternary Science*, **12**, 539–545, https://doi.org/10.1002/(SICI)1099-1417(199711/12)12:6<539::AID-JQS350>3.0.CO;2-T

Mangerud, J. 1991. The last interglacial/glacial cycle in northern Europe. *In*: Shane, L.C.K. and Cushing, E.J. (eds) *Quaternary Landscapes*. Bellhaven Press, London, 38–75.

Mania, D. 1991. The zonal division of the Lower Palaeolithic open-air site Bilzingsleben. *Anthropologie*, **29**, 17–24.

Mania, D. 1995. The earliest occupation of Europe: the Elbe-Saale region (Germany). *In*: Roebroeks, W. and Van Kolfschoten, T. (eds) *The Earliest Occupation of Europe*. University of Leiden, Leiden, The Netherlands, 85–100.

Markewich, H.W. and Pavich, M.J. 1991. Soil chronosequence studies in temperate to subtropical, low-latitude, low-relief terrain with data from the eastern United States. *Geoderma*, **51**, 213–239, https://doi.org/10.1016/0016-7061(91)90072-2

Martins, A.A., Cabral, J., Cunha, P.P., Stokes, M., Borges, J., Caldeira, B. and Martins, A.C. 2017. Tectonic and lithological controls on fluvial landscape development in central-eastern Portugal: Insights from long profile tributary stream analyses. *Geomorphology*, **276**, 144–163, https://doi.org/10.1016/j.geomorph.2016.10.012

Matoshko, A., Gozhik, P. and Danukalova, G. 2004. Key late Cenozoic fluvial archives of eastern Europe: the Dniester, Dnieper, Don and Volga. *Proceedings of the Geologists' Association*, **115**, 141–173, https://doi.org/10.1016/S0016-7878(04)80024-5

Merrett, S.P. and Macklin, M.G. 1999. Historic river response to extreme flooding in the Yorkshire Dales, northern England. *In*: Brown, A.G. and Quine, T.M. (eds) *Fluvial Processes and Environmental Change*. Wiley, Chichester, UK, 521–532.

Michailesku, K.D. and Markova, A.K. 1992. *Paleogeographicheskie etapy razvitiya fauny Moldovy v Antropogene*. Shtiintsa, Chishinau, Moldova.

Mihevc, A. and Zupan Hajna, N. 1996. Clastic sediments from dolines and caves found during the construction of the motorway near Divača, on the classical Karst. *Acta carsologica*, **25**, 169–191.

Miller, G.H. and Mangerud, J. 1985. Aminostratigraphy of European marine interglacial deposits. *Quaternary Science Reviews*, **4**, 215–278, https://doi.org/10.1016/0277-3791(85)90002-2

Mottershead, D.M., Gilbertson, D.D. and Keen, D.H. 1987. The raised beaches and shore platforms of Torbay: a re-appraisal. *Proceedings of the Geologists' Association*, **98**, 241–257, https://doi.org/10.1016/S0016-7878(87)80042-1

Muhs, D.R. 1982. A soil chronosequence on Quaternary marine terraces, San Clemente Island, California. *Geoderma*, **28**, 257–283, https://doi.org/10.1016/0016-7061(82)90006-4

Needham, S. and Macklin, M.G. (eds) 1992 *Alluvial Archaeology in Britain*. Oxbow Monographs in Archaeology, **27**. Oxbow, Oxford, UK.

Ovey, C.D. (ed.) 1964. *The Swanscombe Skull: a Survey of Research on a Pleistocene Site*. Royal Anthropological Institute, Occasional Paper No. 20.

Pan, B., Su, H., Hu, Z., Hu, X., Gao, H., Li, J. and Kirby, E. 2009. Evaluating the role of climate and tectonics during non-steady incision of the Yellow River: evidence from a 1.24 Ma terrace record near Lanzhou, China. *Quaternary Science Reviews*, **28**, 3281–3290, https://doi.org/10.1016/j.quascirev.2009.09.003

Peña Monné, J.L. and Jiménez, A. 1993. El modelado de laderas en el curso medio del río Guadalaviar (Sierra de Albarracín), prov. de Teruel). *El Cuaternario en España y Portugal*, **1**, 129–134.

Penck, A. and Bruckner, E. 1909. *Die Alpen im Eiszeitalter*. 3 vols. Tauchmitz, Leipzig, Germany.

Preece, R.C. and Bridgland, D.R. 1998. *Late Quaternary Environmental Change in North-West Europe: Excavations at Holywell Coombe, South-East England*. Chapman and Hall, London.

Preece, R.C. and Bridgland, D.R. 1999. Holywell Coombe, Folkestone: a 13 000 year history of an English Chalkland Valley. *Quaternary Science Reviews*, **18**, 1075–1125, https://doi.org/10.1016/S0277-3791(98)00066-3

Preece, R.C., Scourse, J.D., Houghton, S.D., Knudsen, K.L. and Penney, D.N. 1990. The Pleistocene sea-level and neotectonic history of the eastern Solent, southern England. *Philosophical Transactions of the Royal Society*, **B328**, 425–477.

Preece, R.C., Gowlett, J.A.J., Parfitt, S.A., Bridgland, D.R. and Lewis, S.G. 2006. Humans in the Hoxnian: habitat, context and fire use at Beeches Pit, West Stow, Suffolk, UK. *Journal of Quaternary Science*, **21**, 485–496, https://doi.org/10.1002/jqs.1043

Proctor, C.J. and Smart, P.L. 1991. A dated cave sediment record of Pleistocene transgressions on Berry Head, Southwest England. *Journal of Quaternary Science*, **6**, 233–244, https://doi.org/10.1002/jqs.3390060306

Richmond, G.M. and Fullerton, D.S. 1986. Summation of Quaternary glaciations in the United States of America. *Quaternary Science Reviews*, **5**, 183–196, https://doi.org/10.1016/S0277-3791(86)80018-X

Roberts, M.B. 1986. Excavation of the Lower Palaeolithic site at Amey's Eartham Pit, Boxgrove, West Sussex: a preliminary report. *Proceedings of the Prehistoric Society*, **52**, 215–245, https://doi.org/10.1017/S0079497X00006666

Roberts, M.B. and Parfitt, S.A. 1999. *Boxgrove: A Middle Palaeolithic Pleistocene Hominid Site at Eartham Quarry, Boxgrove, West Sussex*. English Heritage, London.

Rose, J. and Allen, P. 1977. Middle Pleistocene stratigraphy in south-east Suffolk. *Journal of the Geological Society, London*, **133**, 83–102, https://doi.org/10.1144/gsjgs.133.1.0083

Rose, J., Allen, P. and Hey, R.W. 1976. Middle Pleistocene stratigraphy in southern East Anglia. *Nature*, **263**, 492–494, https://doi.org/10.1038/263492a0

Rosenbloom, N.A. and Anderson, R.S. 1994. Evolution of the marine terraced landscape, Santa Cruz, California. *Journal of Geophysical Research: Solid Earth*, **99**, 14 013–14 030, https://doi.org/10.1029/94JB00048

Rowe, P., Austin, T. and Atkinson, T. 1989. The Quaternary evolution of the South Pennines. *Cave Science*, **16**, 117–121.

Salter, A.E. 1905. On the superficial deposits of central and parts of southern England. *Proceedings of the Geologists' Association*, **19**, 1–56, https://doi.org/10.1016/S0016-7878(05)80062-8

Sampson, C.G. (ed.) 1978. *Paleoecology and Archaeology of an Acheulian Site at Caddington, England*. Southern Methodist University, Dallas, TX, 29–38.

Sanlaville, P. 1979. Étude géomorphologique de la basse-vallée du Nahr el Kébir. *In*: Sanlaville, P. (ed.) *Quaternaire et préhistoire du Nahr el Kébir septentrional. Les débuts de l'occupation humaine dans la Syrie du nord et au Levant. Collection de la Maison de l'Orient Méditerranéan no. 9, Série Géographique et Préhistorique no. 1*. CNRS, Paris, 7–28.

Schumm, S.A. and Parker, R. 1973. Implications of complex response of drainage systems for Quaternary alluvial stratigraphy. *Nature Physical Science*, **243**, 99–100, https://doi.org/10.1038/physci243099a0

Shackleton, N.J. 1969. The last interglacial in the marine and terrestrial records. *Proceedings of the Royal Society of London*, **B174**, 135–154.

Shackleton, N.J. 1987. Oxygen isotopes, ice volume and sea level. *Quaternary Science Reviews*, **6**, 1835–1890, https://doi.org/10.1016/0277-3791(87)90003-5

Shackleton, N.J. and Opdyke, N.D. 1973. Oxygen isotope and palaeomagnetic stratigraphy of Equatorial Pacific Core V28-238: oxygen isotope temperatures and ice volumes on a 10^5 year and 10^6 year scale. *Quaternary Research*, **3**, 39–55, https://doi.org/10.1016/0033-5894(73)90052-5

Šibrava, V. 1986. Correlations of European glaciations and their relation to the deep-sea record. *Quaternary Science Reviews*, **5**, 433–442, https://doi.org/10.1016/0277-3791(86)90209-X

Skempton, A.W. and Weeks, A.G. 1976. The Quaternary history of the Lower Greensand escarpment and Weald Clay vale near Sevenoaks, Kent. *Philosophical Transactions of the Royal Society of London*, **A283**, 493–526.

Smart, J.G.O., Bisson, G. and Worssam, B.C. 1966. *Geology of the Country Around Canterbury and Folkestone*. Memoir of the Geological Survey of Great Britain. HMSO, London.

Smart, P.L. 1991. Uranium series dating. *In*: Smart, P.L. and Frances, P.D. (eds) *Quaternary Dating Methods – A User's Guide*. Quaternary Research Association Technical Guide, **4**. Quaternary Research Association, London, 45–83.

Smith, A.J. 1989. The English Channel – by geological design or catastrophic accident? *Proceedings of the Geologists' Association*, **100**, 325–337, https://doi.org/10.1016/S0016-7878(89)80052-5

Smith, R.F. and Boardman, J. 1994. Soils in Mosedale. *In*: Boardman, J. and Walden, J. (eds) *Cumbria Field Guide*. Quaternary Research Association, London, 173–177.

Sommé, J., Paepe, R. *et al*. 1978. La Formation de Herzeele: un nouveau stratotype du Pléistocène moyen marin de la Mer du Nord. *Bulletin de l'Association Française pour l'Étude du Quaternaire*, **54–56**, 81–149, https://doi.org/10.3406/quate.1978.1334

Sutcliffe, A.J. 1964. The mammalian fauna. *In*: Ovey, C.D. (ed.) *The Swanscombe Skull: A Survey of Research on a Pleistocene Site*. Royal Anthropological Institute Occasional Paper, **20**, 85–111.

Taylor, M.P. and Macklin, M.G. 1997. Holocene alluvial sedimentation and valley floor development: the River Swale, Catterick, North Yorkshire. *Proceedings of the Yorkshire Geological Society*, **51**, 317–327, https://doi.org/10.1144/pygs.51.4.317

Tchepalyga, A.L. 1997. Detalnaya stratigrafiya sobytiy pleistotsena Chernogo morya. *In*: Alekseev, M.N. and Khoreva, I.M. (eds) *Quaternary Geology and Palaeogeography of Russia*. Geos Press, Moscow, 196–201.

Thomas, G.N. 2001. Late Middle Pleistocene pollen biostratigraphy in Britain: pitfalls and possibilities in the separation of interglacial sequences. *Quaternary Science Reviews*, **20**, 1621–1630, https://doi.org/10.1016/S0277-3791(01)00026-9

Turner, C. 1970. The Middle Pleistocene deposits at Marks Tey, Essex. *Philosophical Transactions of the Royal Society of London*, **B257**, 373–440.

Turner, C. and West, R.G. 1968. The subdivision and zonation of interglacial periods. *Eiszeitalter und Gegenwart*, **19**, 93–101.

Tzedakis, P.C. 1994. Vegetation change through glacial–interglacial cycles: A long pollen sequence perspective. *Philosophical Transactions of the Royal Society, London*, **B345**, 403–432.

Tzedakis, P.C., Andrieu, V. *et al*. 1997. Comparison of terrestrial and marine records of changing climate of the last 500,000 years. *Earth and Planetary Science Letters*, **150**, 171–176.

Tzedakis, P.C., Andrieu, V. *et al*. 2001. Establishing a terrestrial chronological framework as a basis for biostratigraphical comparisons. *Quaternary Science Reviews*, **20**, 1583–1592, https://doi.org/10.1016/S0277-3791(01)00025-7

Vandenberghe, J., An, Z., Nugteren, G., Lu, H. and Van Huissteden, J. 1997. New absolute time scale for the Quaternary climate in the Chinese loess region by grain-size analysis. *Geology*, **25**, 35–38, https://doi.org/10.1130/0091-7613(1997)025<0035:NATSFT>2.3.CO;2

Vlček, E. (ed.) 1993. *Fossile Menschenfunde von Weimar-Ehringsdorf*. Weimarer Monographien zur Ur- und Frühgeschichte, **30**.

Waltham, A.C., Simms, M.J., Farrant, A.J. and Goldie, H.S. 1997. *Karst and Caves of Great Britain*. Geological Conservation Review Series, **12**. Chapman & Hall, London.

West, R.G. 1961. Interglacial and interstadial vegetation in England. *Proceedings of the Linnean Society, London*, **172**, 81–89, https://doi.org/10.1111/j.1095-8312.1961.tb00871.x

West, R.G. 1963. Problems of the British Quaternary. *Proceedings of the Geologists' Association*, **74**, 147–186, https://doi.org/10.1016/S0016-7878(63)80031-0

West, R.G. 1968. *Pleistocene Geology and Biology*. Longman, London.

Westaway, R. 1994. Evidence for dynamic coupling of surface processes with isostatic compensation in the lower crust during active extension of western Turkey. *Journal of Geophysical Research: Solid Earth*, **99**, 203–220, https://doi.org/10.1029/94JB01054

Westaway, R. 2009. Quaternary uplift of northern England. *Global and Planetary Change*, **68**, 357–382, https://doi.org/10.1016/j.gloplacha.2009.03.005

Westaway, R., Bridgland, D.R. and White, M.J. 2006. The Quaternary uplift history of central southern England: evidence from the terraces of the Solent River system and nearby raised beaches. *Quaternary Science Reviews*, **25**, 2212–2250, https://doi.org/10.1016/j.quascirev.2005.06.005

Whipple, K.X. and Tucker, G.E. 1999. Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales and research needs. *Journal of Geophysical Research*, **104**, 17 661–17 674, https://doi.org/10.1029/1999JB900120

White, M.J., Lewis, S.G. and McNabb, J. 1999. Excavations at the Lower Palaeolithic site of Whipsnade, Bedfordshire 1992–4. *Proceedings of the Geologists' Association*, **110**, 241–255, https://doi.org/10.1016/S0016-7878(99)80074-1

Wilson, G.P., Frogley, M.R. *et al*. 2021. Persistent millennial-scale climate variability in Southern Europe during Marine Isotope Stage 6. *Quaternary Science Advances*, **3**, 100016, https://doi.org/10.1016/j.qsa.2020.100016

Woldstedt, P. 1952*a*. Interglaziale Meereshochstände in Nordwesteuropa als Bezugsflächen für tektonische und isostatische Bewegungen. *Eiszeitalter und Gegenwart*, **2**, 5–12.

Woldstedt, P. 1952*b*. Probleme der Terrassenbildung. *Eiszeitalter und Gegenwart*, **2**, 36–44.

Woldstedt, P. 1954. Saaleeiszeit, Warthestadium und Weichseleiszeit im Norddeutschland. *Eiszeitalter und Gegenwart*, **415**, 34–48.

Womack, W.R. and Schumm, S.A . 1977. An example of episodic erosion. *Geology*, **5**, 72–76, https://doi.org/10.1130/0091-7613(1977)5<72:TODCNC>2.0.CO;2

Wooldridge, S.W. and Linton, D.L. 1955. *Structure, Surface and Drainage in Southeast England*. 2nd edn. G. Phillip, London.

Worssam, B.C. 1973. *A New Look at River Capture and at the Denudation of the Weald*. Institute of Geological Sciences Report **73/17**.

Zagwijn, W.H. 1973. Pollenanalytical studies of Holsteinian and Saalian Beds in the Northern Netherlands. *Mededelingen Rijks Geologische Dienst, Nieuwe Serie*, **24**, 139–156.

Zagwijn, W.H. 1985. An outline of the Quaternary stratigraphy of the Netherlands. *Geologie en Mijnbouw*, **64**, 17–24.

Zagwijn, W.H. 1989. The Netherlands during the Tertiary and the Quaternary: case history of Coastal Lowland evolution. *Geologie en Mijnbouw*, **68**, 107–120.

Zeuner, F.E. 1945. *The Pleistocene Period: Its Climate, Chronology and Faunal Succession*. 1st edn. Ray Society, London.

Zeuner, F.E. 1959. *The Pleistocene Period: its Climate, Chronology and Faunal Successions*. 2nd edn. Hutchinson, London.

Zeuner, F.E. 1961. The sequence of terraces of the Lower Thames and the radiation chronology. *Annals of the New York Academy of Sciences*, **95**, 377–381, https://doi.org/10.1111/j.1749-6632.1961.tb50045.x