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The contribution of Rob Westaway to the study of fluvial archives

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ABSTRACT

Robert Westaway was a structural and hard-rock geologist who turned his attention to the study of Late Cenozoic fluvial archives, believing that the preservation of staircases of river terraces, particularly representing the Middle and Late Pleistocene, could only be explained in terms of crustal activity in response to surface processes, the latter affected by climatic change. His entry into this research area coincided with the realisation that such terrace sequences required surface or crustal uplift to have taken place over the time interval represented. Workers were unable to explain the observed amounts of uplift in terms of erosional isostasy, a process that could potentially have explained such one-way crustal movement. Westaway envisaged a mechanism by which mobile lower crust migrated to beneath uplifting areas, maintaining and reinforcing their uplift. The mechanism requires complex mathematics to explain it, as well as lending itself to mathematical modelling of the process, based on varying crustal properties and changes in the rates of surface processes in response to climatic fluctuation. Essentially the lower-crustal effect can be envisaged as a positive-feedback enhancement of erosional isostasy.

It became apparent that Westaway's theories could explain geomorphological and sedimentary fluvial archives that were otherwise difficult to elucidate. Mantle-based erosional isostasy could not explain terrace staircases, for example. Many of these occur in regions that are tectonically inactive, and so cannot be attributed to neotectonic activity. A game-changer in terms of persuading the wider community came from the recognition of crustally ultrastable regions in which progressive long-timescale uplift has not occurred: Archaean cratons. Westaway's envisaged lower-crustal flow would not be expected in such regions, which have cold, brittle and immobile crust to its full depth. Ancient fluvial deposits are found close to modern valley-floor levels in such areas. Regions of younger Precambrian crust (Proterozoic) showing intermediate situations were subsequently identified. Other dilemmas could be resolved, such as the 'back-tilting' of the early-Middle Pleistocene Bytham River in the English Midlands, caused by its drainage crossing crustal blocks with different properties that have accordingly experienced differential uplift. Although glacio-isostasy, mostly seen in the effects of rebound since the Last Glacial Maximum (LGM), is largely accommodated in the mantle, and thus is reversed as a response to glacial loading and unloading, in areas of suitable crustal type there is evidently a small lower-crustal component that is less readily reversible.

Westaway's important contribution has yet to be fully integrated into received wisdom in geomorphological and Quaternary circles, although much of it is now widely accepted and more will be explored and published in due course.

1. Introduction

Robert William Charles Westaway was born in Cornwall but brought up in the English East Midlands. His first degree was in physics, with mathematics, geology and material science, at Cambridge (1981), where he stayed to undertake doctoral research in geophysics, on the topic of earthquake seismology (Westaway and Jackson, 1984; Westaway, 1985), becoming a structural geologist. Unsuccessful in obtaining a permanent teaching appointment, he held temporary lectureships at Reading, Liverpool and Durham, before joining the Open University as an Associate Lecturer and Regional Tutor in 1999. That role was shared, from 2012, with a part-time position as Senior Research Fellow in the School of Engineering (Energy Engineering Group) at the University of Glasgow, working with Paul Younger and, latterly, with Gioia Falcone. From 1995 Rob also operated his own consultancy company.

Westaway's interest in fluvial archives stemmed from the application of his understanding of crustal processes to unexplained aspects of river-terrace records, casting new light on drainage and wider landscape

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evolution. His activity remained broad; he continued to be involved the study of volcanism (Arger et al., 2000; Yurtmen et al., 2002; Westaway et al., 2009a, 2011; Seyrek et al., 2008a, 2008b; Harley et al., 2017), tectonic activity (Westaway, 1990a, 1993, 1994a, 2003, 2004a; Mitchell and Westaway, 1999; Westaway et al., 2006a, 2008; Westaway and Arger, 2001) and engineering geology, with recent publications on fracking and geothermal data (Green et al., 2013; Westaway and Younger, 2013; Westaway, 2016).

Rob's contribution to the study of fluvial archives arose from his realisation that some of the poorly understood features of riverine records could be explained in relation to crustal processes and the properties of the underlying continental crust. He had previously worked extensively in the Mediterranean region, studying in particular the tectonic activity there (Westaway, 1993, 1994a, 2002a, 2011; Westaway and Arger, 1996), from which experience he had an excellent understanding of the highly dynamic nature of the crust in much of that area. He had alluded to river terraces in some of his earliest publications, predominantly in respect of their potential for measuring tectonic movements, including fault offsets (Westaway et al., 1989; Westaway, 1990b), about a decade before he considered the potential of such landforms as a measure of epeirogenic uplift.

2. Context of the Westaway contribution: the uplift paradigm

At the time when Westaway began his collaboration with members of the Quaternary and Fluvial Archives communities, both (although there was an overlap of personnel between the two) were engaged in debate of what might be called ‘the uplift paradigm’. This marked the realisation by a growing proportion of these communities that common features in the landscape, of Quaternary age or a little older and with important sedimentary components, pointed to progressive uplift of the land surface. Fluvial archives provide a large proportion of such features, notably river terrace systems and gorges, both indicative of vertical incision by rivers, with uplift seen as the driver for this down-cutting (Veldkamp and Van den Berg, 1993; Van den Berg, 1994; Bridgland, 1994, 2000; Maddy, 1997; Antoine et al., 2000), although it had previously been attributed to falling sea level from the late Tertiary and through the Pleistocene (e.g., Zeuner, 1945, 1961; Woldstedt, 1952; Evans, 1971). The same uplift is implicated in the formation of marine terraces and raised beaches. In England an early pointer was the recognition that the ~40 m Goodwood–Slindon raised beach at Boxgrove, West Sussex (Roberts, 1986; Roberts and Parfitt, 1999), and sediments on the Isle of White from a comparable raised shoreline level (Preece et al., 1990), date from the late Cromerian Complex, ~0.5 Ma. More than half the world's land-based ice would need to be added to ocean water to raise modern sea level to the elevation of these deposits, implying, since there is little evidence for such ice-sheet depletion at that time, that their current altitude is the result of uplift (Westaway et al., 2006b).

The idea of uplift was not new; it had been a fundamental component of the erosion cycles of W.M. Davis (1899). An alternative view of river-valley evolution had held sway during much of the 20th Century, however, one of intrinsic headwater deepening in response to upstream propagation of base-level lowering events, taking the form of landward-migrating knickpoints that had generally formed at the coast at times of falling sea-level (e.g., Zeuner, 1945, 1959, 1961); this stemmed partly from the concept that erosion cycles could be reset by ‘rejuvenation’, an idea that is arguably attributable to W. Penck's (1924) addition of crustal movement to the Davisian cycle (cf. Simons, 1962). Some have preferred to attribute river-terrace formation to mechanisms of this sort, seemingly considering that this could occur in the absence of uplift, with the primal role of climatic fluctuation (via its effect on sea level) emphasized by many (e.g., Törnqvist and Blum, 1998; Hancock and Anderson, 2002; Gibbard and Lewin, 2009), a view in common with those who saw climatic fluctuation as the triggering mechanism for uplift-enabled terrace formation, including Westaway (e.g., Westaway et al., 2002; Westaway, 2006; Bridgland and Westaway, 2008a, 2008b). Towards the turn of the century, the evidence from river-terrace sequences was increasingly interpreted in terms of progressive uplift, particularly by participants in the Fluvial Archives Group (FLAG), instigator of this present themed issue; such uplift was envisaged as a regional (epeirogenic) effect seen in many parts of the world (Veldkamp and Van den Berg, 1993; Antoine, 1994; Van den Berg, 1994; Bridgland, 1994, 2000; Maddy, 1997; Antoine et al., 2000; Westaway et al., 2003, 2006b, 2009b; Bridgland and Westaway, 2008a, 2008b) rather than the result of tectonic activity, the latter being seen only in in the vicinity of plate-boundary areas or in active fault zones (cf. Krzyszkowski and Biernat, 1998; Krzyszkowski et al., 1998, 2000; Abou Romieh et al., 2009). Based on the above progression of theory, it has generally been inferred that fluvial incision has been a direct response to crustal uplift and can thus provide an approximate measure of that uplift (Van den Berg, 1994; Maddy, 1997; Maddy et al., 2000).

Another alternative mechanism for terrace formation, albeit one that can have operated in partnership with surface uplift, has already been mentioned: climatic forcing, the direct and indirect effect of climate change on fluvial systems. A large body of data exists supporting the importance of this effect (Bull, 1991; Vandenberghe, 1995, 2002, 2003; Hancock and Anderson, 2002; Bridgland, 2000; Starkel, 2003). Abundant data come from the temperate latitudes of Eurasia, where typical fluvial evolution during the late Cenozoic involved the formation of terrace staircases, excepting in areas of cratonic crust and subsiding basinal areas (controlled by tectonic activity or sediment accumulation). Flights of aggradational river staircases can be shown to have formed in response to climatic forcing, often in the form of alternating incision and sedimentation in close synchrony with glacial–interglacial cycles (Tyràček, 1983; Bridgland, 1994, 2000). This climatic triggering produced terraces only in areas where it was superimposed upon a background of progressive regional (epeirogenic) uplift (Bridgland, 1994, 2000; Maddy, 1997; Antoine et al., 2000; Maddy et al., 2000). The match with Milankovitch climatic fluctuation means that terrace sequences can provide a framework for modelling Quaternary landscape evolution in such uplifting regions (Veldkamp and Van Dijke, 1998, 2000; Bridgland and Westaway, 2008a, 2008b, 2012, 2014).

3. The Westaway hypothesis: forcing/feedback resulting from lower-crustal flow

Westaway expanded upon the ‘uplift paradigm’, taking it from an acceptance of progressive Quaternary uplift to the modelling of fluctuating vertical movement, which he believed to have been modulated by mobility of the lower crust, and showing there to be a probable coupling between the effect of climatic change on Earth-surface processes and the rate of uplift, via a positive-feedback mechanism that has enhanced erosional isostasy (Westaway, 2002a, 2002b, 2002c, 2007a). The notion of a mobile lower crust was a pre-existing idea; in his early references to it, Westaway cited Wernicke (1990) and Kruse et al. (1991), although he attributed its origination to Sir John Herschel in a letter (1836) to Charles Lyell, published in edited form by Babbage (1837). In an idea he had explored prior to developing his interest in fluvial archives (cf. Westaway, 1994b, 1994c), Westaway envisaged mobile lower crustal material flowing from areas under load and into adjacent areas, causing the latter to rise and thickening their crust from its base and so maintaining their increased elevation; the impetus was loading caused by rising sea levels, accumulating sediment or glacial ice (e.g., Westaway et al., 2002). Rob's belief that fluctuations in such uplift were coupled with palaeoclimate came from observations that the greater severity of the Quaternary glacials since the Mid-Pleistocene Transition (MPT), when 100 ka climate cycles began (Pisias and Moore, 1981; Imbrie et al., 1993; McClymont et al., 2008), has led to accelerated surface processes and, therefore, more rapid uplift, albeit with a time-lag that varies with crustal properties. He developed a mathematical computer model that matched the patterns of uplift recorded by staircases of river terraces and raised beaches to palaeoclimatic records. The power of these ideas is their ability to explain features of the Quaternary record that cannot otherwise be understood: in particular, why river-terrace staircases have formed in tectonically quiescent areas and why the spacing of these terraces (and the depth of valleys) has shown a marked increase since the MPT (see Fig. 1). An implication of these ideas is that important characteristics of the modern landscape, over and above the features resulting directly from glaciation, are seen to be inexorable products of Quaternary climatic fluctuation.

An earlier pulse of increased uplift in the latest Pliocene was associated by Westaway with climatic cooling following the mid-Pliocene warm period (in many ways this was the precursor to the Quaternary glaciations). The effects of this earlier cooling can only be seen in the longer fluvial records, being evident in the terrace sequences of the Maas (Netherlands), which is one of the world's longest (Van den Berg, 1994; Van den Berg and van Hoof, 2001; Westaway, 2001, 2002c; Westaway et al., 2009b; Fig. 1), and Euphrates (Demir et al., 2007, 2008, 2012; Bridgland and Westaway, 2014). Westaway (2007b) also pointed to this effect in the long North American fluvial sequences of the Rivers Ohio and Susquehanna. On his visit to Brazil in 2003, as part of a FLAG-affiliated- IGCP meeting, he recognized the likely effects of this same Late Pliocene cooling in the area immediately west of the Amazon Craton, where the Rivers Acre and Purus have incised into pre-Quaternary basin-fill sediments (the Solimões Group) and have left terraces up to 70 m above current river level (Latrubesse et al., 1997), in marked contrast to the absence of evidence for systematic Pleistocene incision in the area of the Craton (Westaway, 2006). This is one of numerous examples of 'basin inversion' (the switch from sediment accumulation to incision) that can be shown to have occurred at about this time, others including the Selendi Basin in western Turkey, where the earliest part of the incision record includes rare examples of terraces formed by the River Gediz in response to pre MPT obliquity-driven climate cycles (Maddy et al., 2005, 2008, 2012; Westaway et al., 2006c; Fig. 2).

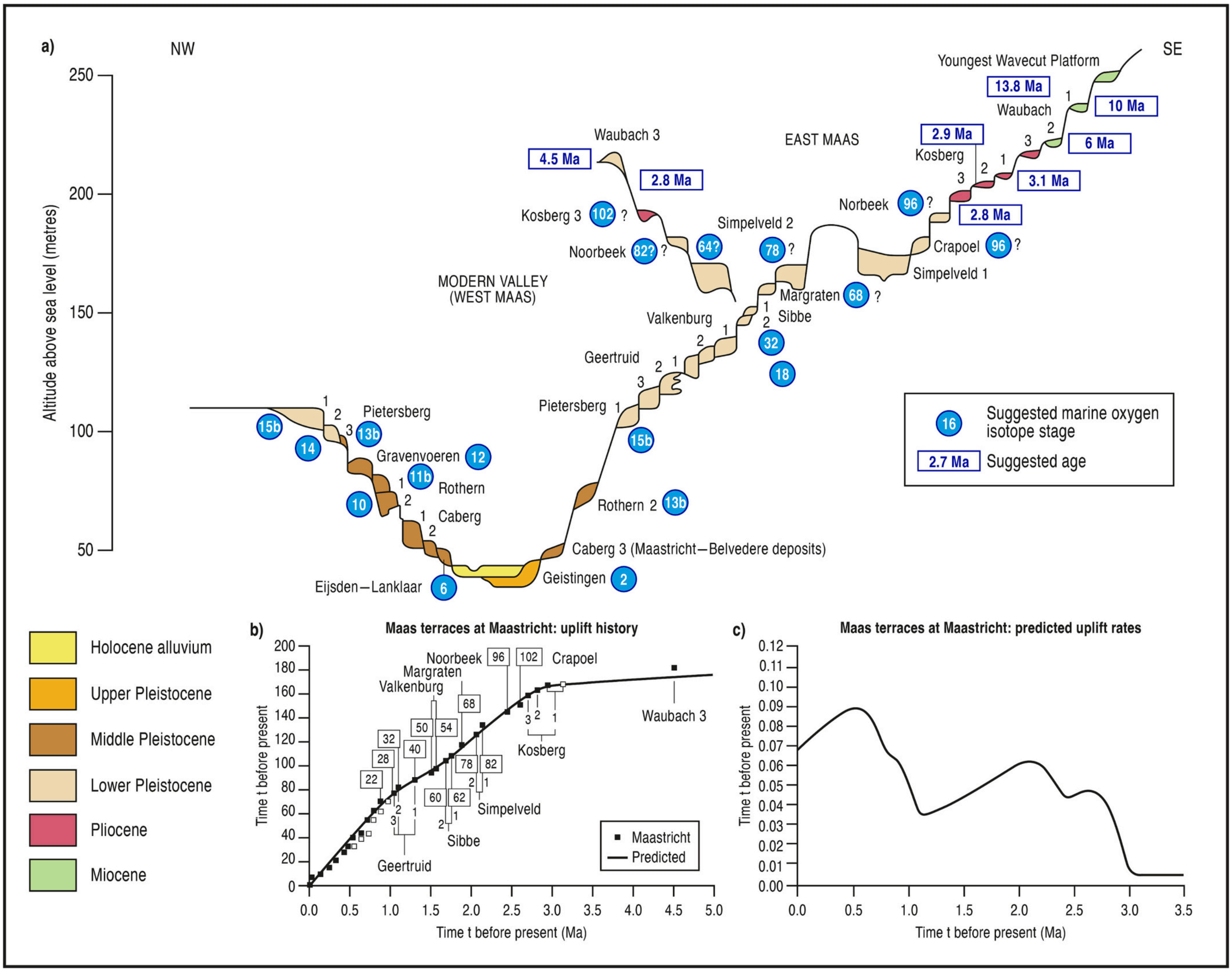

Fig. 1. The terraces of the River Maas, in the region of Maastricht, Netherlands. The main illustration (a) is an idealized cross section through the terrace sequence (modified from Bridgland and Westaway, 2014; data from Van den Berg, 1994; Westaway, 2002b, 2002c). Numbers in roundels show suggested correlation with marine oxygen isotope stages. Inset b is a graphic representation of Westaway's (2002c) modelling of uplift at Maastricht over the past 5 Ma, based on the tops of river terraces (open symbols are alternative correlations, with the closed symbols the preferred options). Numbers in boxes show suggested correlation with marine oxygen isotope stages. Inset c is a representation of varying uplift rate at Maastricht over the past 3.5 Ma derived from this modelling, showing increases in response to Late Pliocene cooling and the Mid-Pleistocene Transition (from Westaway, 2002c).

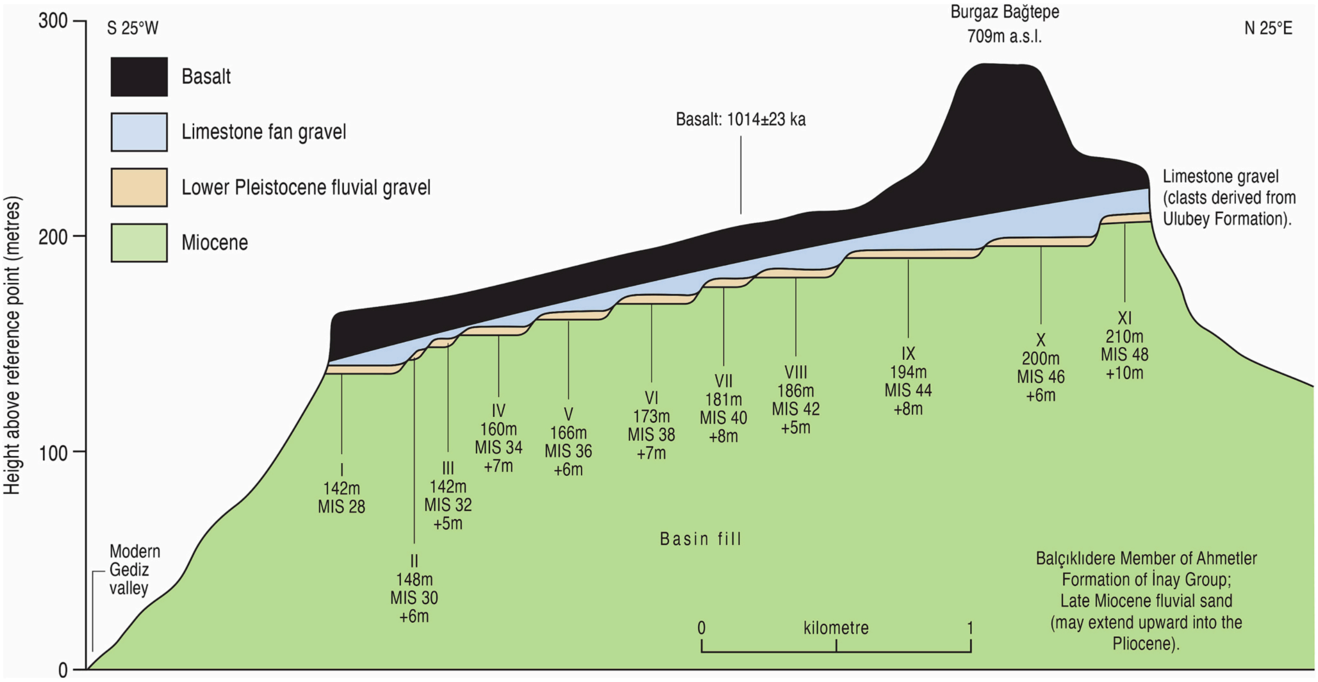

Fig. 2. Transverse profile through the Early Pleistocene terrace staircase as preserved beneath dated basalt capping the Burgaz Plateau, near Kula, Turkey (from Bridgland and Westaway, 2014; see also Maddy et al., 2008; Aytaç et al., 2023).

4. Testing the hypothesis in relation to evidence from fluvial archives

4.1. *River terrace staircases: presence or absence*

Westaway's contribution to the understanding of long-timescale fluvial archives thus coincided with a growing consensus that river terrace sequences have formed in response to uplift, with the fluctuating riverine processes (alternating deposition and erosion) driven by climatic fluctuation, often in synchrony with glacial–interglacial cycles (Maddy, 1997; Bridgland, 2000; Maddy et al., 2001.; Westaway et al., 2002; Bridgland and Westaway, 2008a, 2008b, 2012, 2014; Westaway et al., 2009b). Other interpretations, excluding the imperative for progressive uplift, have persisted, however (Hancock and Anderson, 2002; Gibbard and Lewin, 2009), with a prolonged adherence to the textbook explanation of terrace formation as a response to base-level (sea-level) change (Törnqvist and Blum, 1998; Martins et al., 2010), often through the mechanism of knick-point recession (Rosenbloom and Anderson, 1994; Tucker and Whipple, 2002; Crosby and Whipple, 2006; Bishop, 2007; Roberts and White, 2010; see below). While it is evident that sea-level fluctuation can be an important driver for both incision and sedimentation in the lower reaches of rivers in areas where the continental shelf is narrow, such as the Atlantic-margin of Iberia (Martins et al., 2010; Viveen et al., 2012, 2013), it is generally considered that the effect of base-level change does not extend more than a few hundred km inland (e.g., Leopold and Bull, 1979; Schumm, 1993).

The evidence that uplift has been an important and widespread factor in terrace formation is essentially empirical. There are, for example, clear differences between areas that can be shown to be subsiding under sedimentary load and those thought to have experienced long-term and progressive uplift; fluvial archives in the latter take the form of the familiar river-terrace staircases, whereas in the former there is generally a subdued plain beneath which, as revealed by boreholes, sediments (including fluvial deposits) have accumulated in conventional stratigraphical mode, oldest at the base and most recent just beneath the modern land surface. Examples of subsiding fluvial basin-fill deposits that have continued to accumulate to the present day can be seen in Eurasia, such as the Danube and Tizza deposits beneath the Great Hungarian Plain (Ruszkiczay-Rüdiger et al., 2005; Gábris and Nádor, 2007) and the lowermost Rhine sediments beneath the Netherlands (Caston, 1977; Brunnacker et al., 1982; Ruegg, 1994; Fig. 3). An Asian example of particularly large scale is the Himalayan foreland region, beneath which >4 km of sediments laid down by the Ganges system have accumulated in places (Sinha et al., 2007).

Even more compelling evidence in support of uplift as a crucial factor in river-terrace generation comes from areas that have Quaternary or longer Late Cenozoic records indicative neither of progressive uplift nor subsidence. Generally underlain by ancient, ultra-stable ‘basement’, Precambrian ‘shield’ rocks or Archaean cratons, the rivers in such areas can often be seen to flow at levels similar to those of their early Quaternary or even pre-Quaternary valley-floors (Bishop and Brown, 1992; Gale, 1992; Westaway et al., 2003, 2009b; cf. de Broekert and Sandiford, 2005; Belton et al., 2004). This pattern is evident from observations from earlier FLAG activity, notably IGCP 449, with key data coming from Kaapvaal Craton of South Africa (Helgren, 1977, 1978; cf. Ballard and Pollack, 1987), peninsular India (Mishra et al., 1995; Mishra and Rajaguru, 1996; cf. Westaway et al., 2011) and the Ukrainian Shield (Matoshko et al., 2004), all showing early Middle Pleistocene or older fluvial sediments at or close to modern river level (Westaway et al., 2003; Bridgland and Westaway, 2014; Fig. 4).

4.2. *Rates of uplift and patterns of change*

Westaway's modelling produced estimates of the rate of uplift at particular times during the Quaternary and, in some cases, the pre-Quaternary. He used published data on crustal properties, such as heat flow, as a guide but, irrespective of the mathematical calculations, the plausibility of the output and of his interpretation was often readily apparent from the convincing match between the timing of recognizable forcing factors and features in the physical archive. He used dated levels within river-terrace sequences, for example, to calibrate the modelling. An example has already been illustrated in Fig. 1 (b and c) showing his modelling of the uplift of the Maastricht region of the Netherlands, based on the fluvial archive of the River Maas. Two further examples are

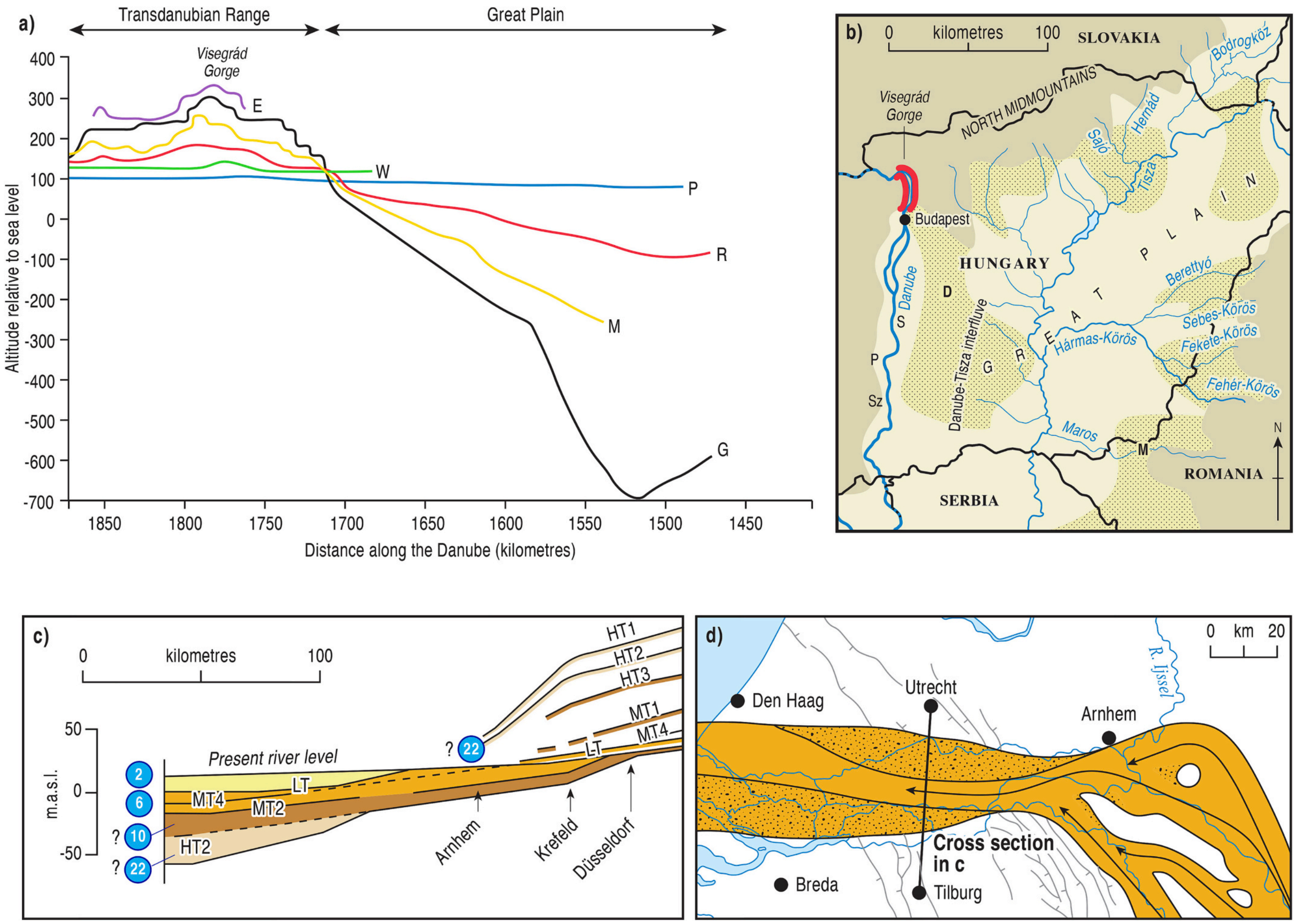

Fig. 3. Rivers with reaches in both uplifting and subsiding regions: the Danube in Hungary and the Rhine in the Netherlands. The longitudinal profile of the Danube (a) shows terraces in NW Hungary and stacked sediments beneath the Great Plain (locations shown in b). After Gábris and Nádor (2007). The longitudinal profile of the Rhine (c; after Bridgland and Westaway, 2008b) shows terraces in the Netherlands–Germany border area giving way to stacked sedimentation in the lowermost coastal reach (d; after Busschers et al., 2007). In c, numbers in roundels show suggested correlation with marine oxygen isotope stages. Images reproduced, with modification, from Bridgland et al. (2020).

provided in Figs. 5 and 6, these again being rivers beyond the reach of frequent Quaternary glaciation and therefore having long-timescale records, extending back to the pre-Quaternary. The first is the Allier, France, an important left-bank tributary of the Loire that drains the Massif Central and has interacted with the Neogene and Quaternary volcanism of that region, which has provided a means for accurate dating of its fluvial archive, using K–Ar and Ar–Ar geochronology (Pastre, 2004; Westaway, 2004b; Fig. 5). Comparison of Figs. 1 and 5 shows that the Allier valley has uplifted slightly less than the Maas at Maastricht during the Pliocene–Quaternary (~150 m as compared to ~175) but both show clear evidence of an increased uplift rate following the Late Pliocene cooling and the MPT. Both are in similar crustal provinces, of Caledonian–Variscan type (see Demir et al., 2018). The third example is from a different crustal type, however. It is the River Don, at Voronezh, Russia, which flows over Early Proterozoic crust (~2300–1900 Ma) of the Lipetsk–Losev crustal domain. Crust of this type has a narrow mobile lower layer, the result of a thick 'root' of mafic material at its base, and so shows a degree of stability, albeit less than the ultrastable Archaean cratons (compare with Fig. 4). The Don sequence records a series of reversals in vertical crustal motion, alternations between uplift and subsidence, over timescales of several hundred thousand years (Fig. 6), a pattern that has been identified in comparable Late Cenozoic fluvial archives in many parts of the world, as summarized in detail by Westaway and Bridgland (2014). Such archives differ from those on ultrastable Archaean crust and from the progressive uplift seen widely in other regions, and can be regarded as intermediate between those contrasting patterns.

5. Evidence from caves

Westaway was able to extend his modelling of the progressive crustal uplift revealed by commensurate downcutting of river systems by using data from associated subterranean drainage systems, as represented by karstic speleothem archives (e.g., Westaway, 2007b, 2009a, 2010, 2020; Westaway et al., 2015). He identified two considerable advantages of this extension. First, more reliable geochronology is available for the critical Middle Pleistocene interval from the dating of karstic speleothem precipitates, using uranium-series methodologies, than for subaerial fluviatile sediments, with biostratigraphical data also more widely present in caves. Second, caves and their contained archives have generally survived the occupation of their parent valleys by glacial ice, whereas pre-glacial superficial sedimentary archives are rarely preserved in glaciated valleys.

Incorporating such data can thus be highly beneficial to the understanding of valley and landscape evolution in karstic regions, although it requires familiarity with a largely separate branch of literature, Westaway being one of the few to have made the connection. A prime example of such an application is the Peak District of the English East

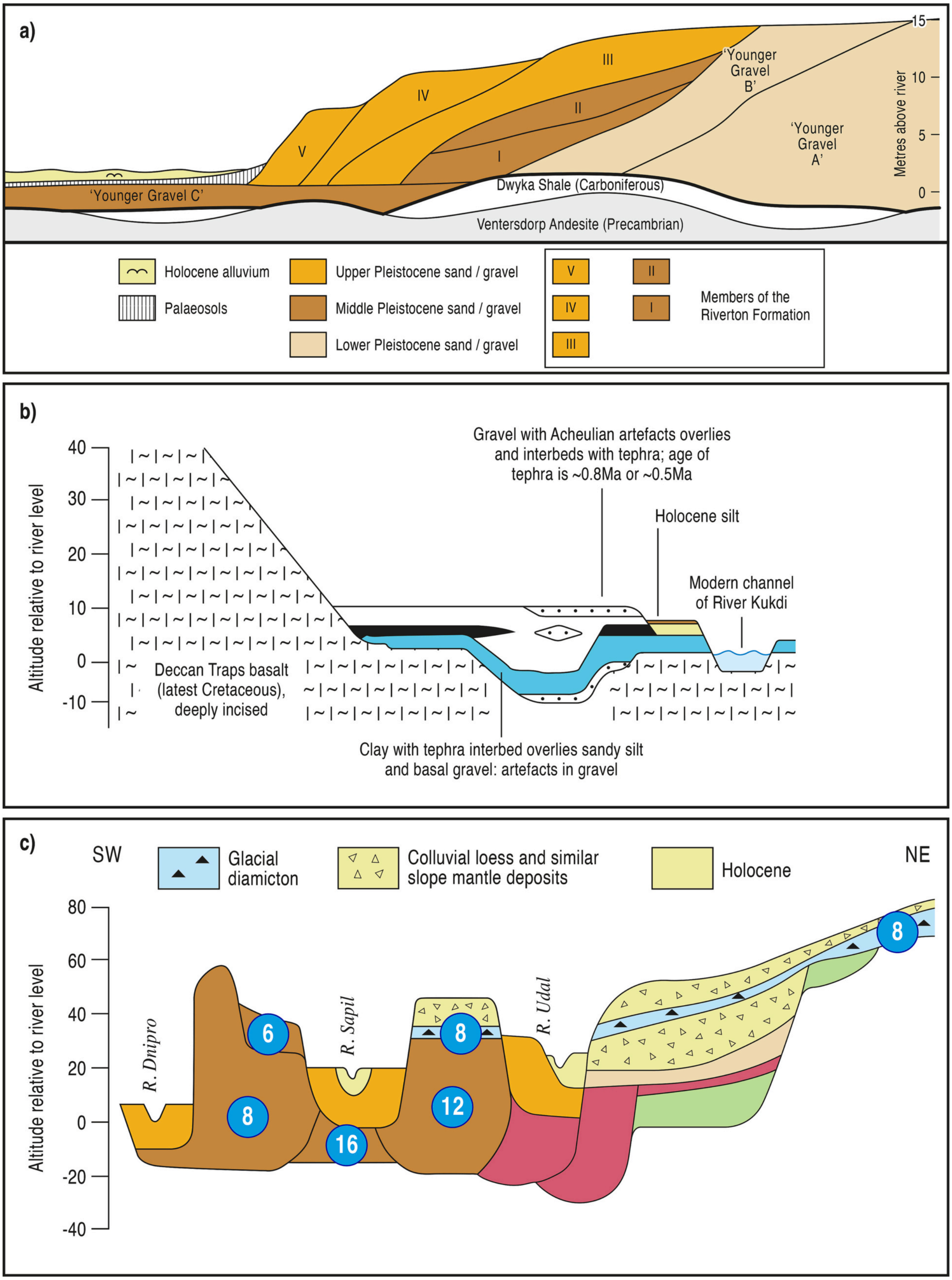

Fig. 4. Example fluvial archives from cratonic regions, showing little or no net uplift during the Quaternary: a. transverse profile through the Vaal sequence at Riverton, South Africa (reproduced from Bridgland and Westaway, 2014, after Helgren, 1978); b. the River Kukdi sequence at Bori, India (modified from Westaway et al., 2003; original drawing by RW); c. transverse profile, ~240 km long, across the Middle Dnipro basin, ~100 km downstream of Kyiv, Ukraine (reproduced from Bridgland and Westaway, 2014, based on data from Matoshko et al., 2004). Numbers in roundels show suggested correlation with marine oxygen isotope stages.

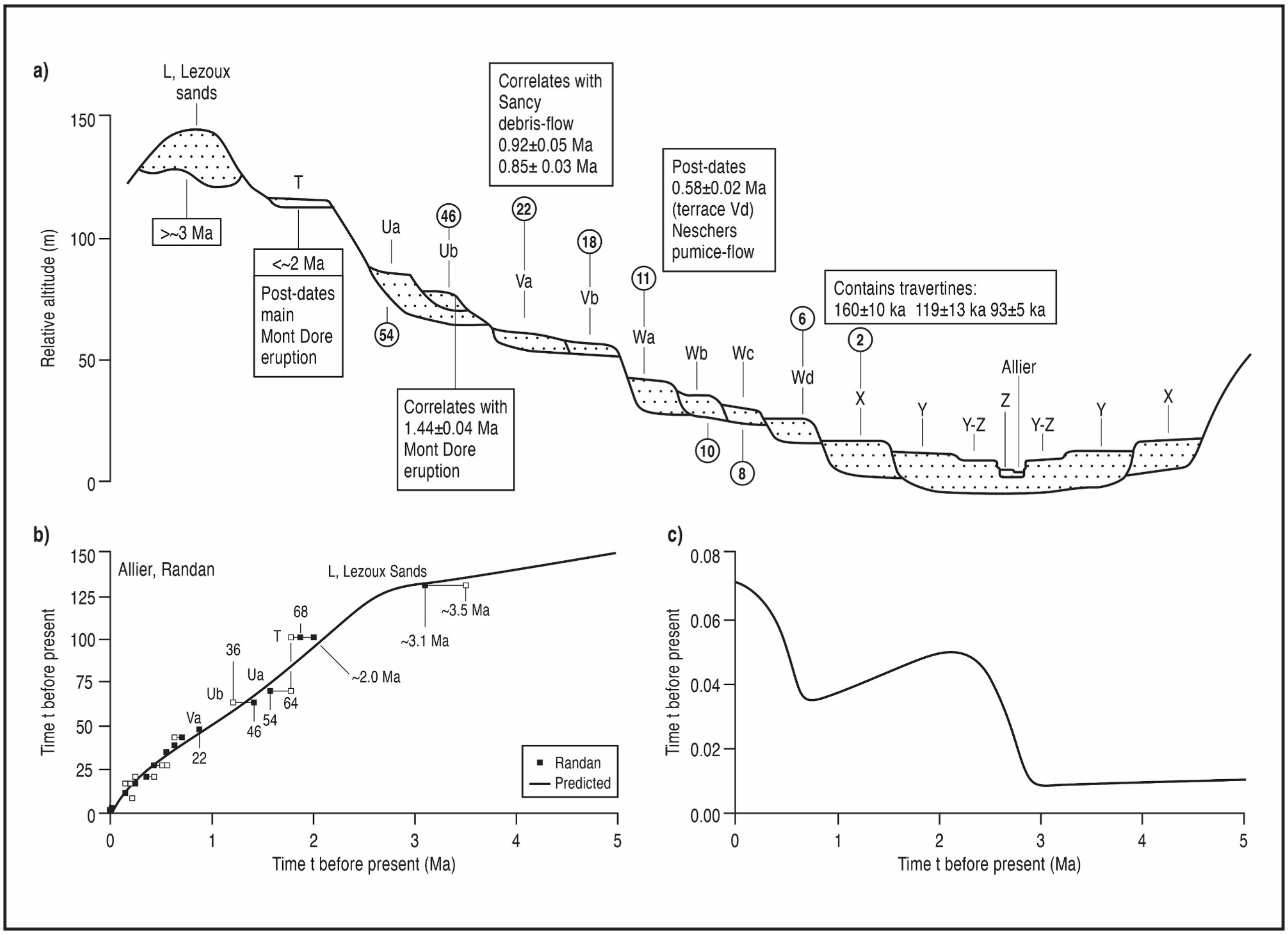

Fig. 5. Computer modelling of uplift at Randan, France, based on the terrace record of the River Allier, as illustrated in 'a'. The observed and predicted uplift histories are illustrated in 'b' and a summary of fluctuating uplift rate over the last 5 Ma in 'c'. Numbers (in roundels in 'a') show suggested correlation with marine oxygen isotope stages. Reproduced from Bridgland and Westaway (2008b), from which further details can be obtained.

Midlands, where the fluvial archive of the River Derwent, an important north-bank tributary of the Trent, is greatly enhanced by its subterranean karstic component (Bridgland et al., 2014; Westaway et al., 2015; Westaway, 2020; Fig. 7). Indeed, the Derwent has been shown to predate its parent river, having been inherited by the Trent from the pre-Anglian Bytham River (Bridgland et al., 2014, 2015; cf. Brandon, 1995). Westaway (2020) managed to integrate karstic, fluvial and glacial datasets from the Peak District, from which he quantified its uplift history (as well as that of a wider surrounding region), inferring >100 m of uplift since the Mid-Pleistocene Transition and ~300–400 m since the Miocene.

It is worth noting some comparative studies. For example, Proctor and Smart (1991) linked dated speleothems in coastal caves on the English south coast, near Torquay, with a local sequence of raised beaches and associated erosional platforms, representative of the last few climate cycles; they interpreted their results in terms of sea-level change, without recognition of any effects from vertical crustal movement. In contrast, Wagner et al. (2011) used cave speleothems as part of a dataset spanning ~4 Ma that also included river terraces and planation surfaces near the eastern margin of the Alps, associated with the River Mur. They considered tectonic activity to be the chief driver of landscape evolution here, unsurprising given the proximity to Alpine orogenesis; it is perhaps pertinent that they detected decreased incision around the Pliocene–-Pleistocene transition, the opposite to Westaway's envisaged climatically accelerated uplift in response to Late Pliocene cooling (see above). Farrant et al. (1995) had measured progressive uplift using dated speleothems in the limestone caves of Sarawak, Malaysia; they regarded this uplift as epeirogenic. Farrant et al. (2015) have recently used dated speleothems in 'gull' crevices (i.e., resulting from cambering) in the Cotswolds as a measure of landscape evolution, encompassing both uplift and scarp retreat of the cuesta.

6. Other perplexing phenomena explained

The importance has already been noted of Westaway's realisation that surface uplift was influenced by crustal type, something he predicted within his envisaged mechanism for the enhancement of uplift instigated by erosional isostasy by the inflow to uplifting areas of mobile lower crust. This mechanism explains the ultra-stability and general absence of Quaternary uplift in regions of ancient crust, where there is no mobile basal lower that can react to the isostatic forcing. This same mechanism has provided an explanation for a phenomenon that had impeded the reconstruction of early Middle Pleistocene drainage in the English East Midlands: the reversed gradient (longitudinal) profile of the Bytham River between Leicester and the Jurassic escarpment ~35 km to the east (Fig. 9).

The Bytham was first recognized as a pre-Anglian drainage system of greater size than any existing British river by Rose (1987, 1989, 1994), although its upstream part had been described as a 'proto-Soar' by Shotton (1953) and its downstream component, in central East Anglia, had been noted by Hey (1980) and named after the village of Ingham (Suffolk; cf. Westaway, 2009b) by Clarke and Auton (1984). The extension of quartzitic 'proto-Soar' gravels through the Leicester area and along the Wreake valley (Fig. 9) had been observed by Rice (1965,

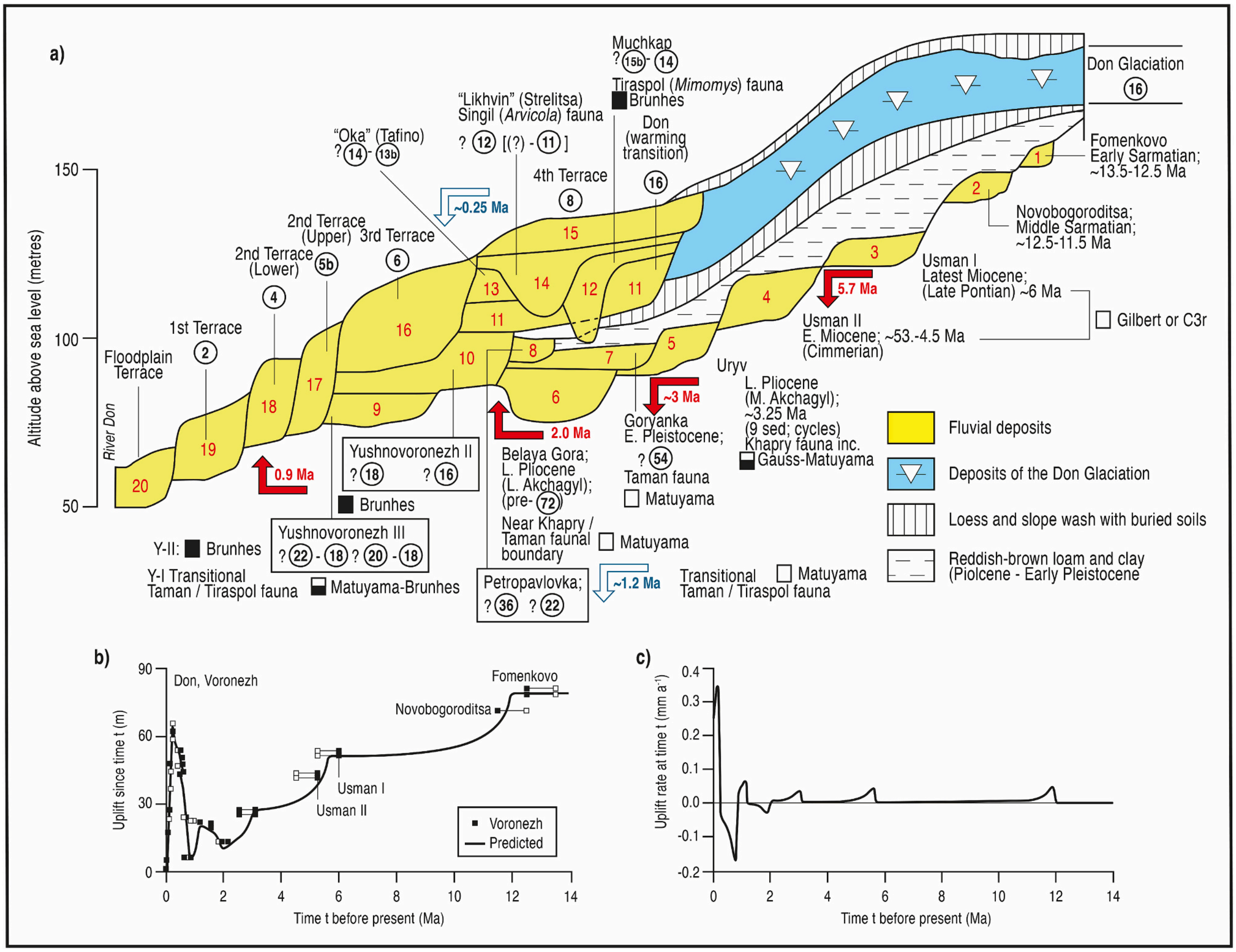

Fig. 6. Computer modelling of uplift at Voronezh, Russia, based on the fluvial archive of the River Don, as illustrated in 'a' (modified from Westaway and Bridgland, 2014; after Matoshko et al., 2004); numbers in roundels show suggested correlation with marine oxygen isotope stages, with fluvial deposits also numbered in sequence of emplacement. The observed and predicted vertical movements over the last 14 Ma are illustrated in 'b' and a summary of fluctuating rates of movement over the same interval in 'c'; both reproduced from Bridgland and Westaway (2008b), from which further details can be obtained.

1968, 1981, 1991), although he was reluctant to conclude that a river had flowed eastward along the Wreake valley because of the westward-declining gradient of the subjacent 'Thurmaston Sand and Gravel' sediment body. That reluctance continued after Rose (1987, 1989, 1994) had reconstructed his Bytham River via the Wreake, incorporating the Thurmaston Sand and Gravel, and despite the acknowledged western derivation of the clast lithologies and palaeocurrent evidence for eastward flow (Rice, 1991).

This dilemma was resolved by the Westaway explanation of crustal uplift in relation to the mobility of its lowermost part. In the context of the realisation, largely since Rice's work was undertaken, that much of the land area has been significantly uplifted during the Quaternary (see above; Bridgland and Westaway, 2008a, 2008b), the east-to-west gradient of the Thurmaston–Bytham Gravel in the Wreake valley can now be explained in terms of differentially low uplift of the Leicester area in comparison with areas further downstream, causing a 'back-tilting' effect (Bridgland et al., 2014; Fig. 9). This relates to the less dynamic nature of the Precambrian crust of the Charnwood Forest inlier around Leicester, which has experienced ~20 m less uplift in the past 0.5 Ma (since the deposition of the Thurmaston–Bytham Gravel) in comparison with the Nottingham area, a decrease of approximately 50 % (Westaway, in Bridgland et al., 2014).

The paucity (if not lack) of uplift of ancient crustal provinces, as explained by the application of Westaway's ideas, also solved a dilemma for Sheila Mishra in her studies of the fluvial Lower Palaeolithic record on the Deccan plateau, India. Here, on Archaean basement covered with the celebrated Cretaceous–Palaeogene Deccan Traps lava stack, are river gravels little above floodplain level that contain Acheulian (Lower Palaeolithic) archaeology and so are regarded as Middle Pleistocene or older; some at a similar level, overlying several metres of weathered basalt, are potentially even older (Mishra and Rajaguru, 1993; Mishra, 1995; Mishra et al., 1999). The Archaean basement beneath the region, with absence of a mobile lower crust, provides an explanation for the occurrence of such deposits at a level little above the modern floodplain, as elucidated in a paper co-authored with Mishra (Westaway et al., 2003; see Fig. 4b).

7. Dismissal of alternative hypotheses

This paper is intended as an appreciation and celebration of Rob Westaway's contribution to the subject under discussion, so little space will be devoted to topics and approaches that were targets of his displeasure. He was sometimes outspoken in opposition to alternative approaches to the reconstruction of drainage and landscape evolution. These included the modelling of isostatic uplift based only on accommodation within the mantle, which is the mainstream approach to modelling post-LGM glacio-isostatic vertical displacement (e.g., Lambeck, 1993; Peltier, 1998). In Westaway's view (in Bridgland et al.,

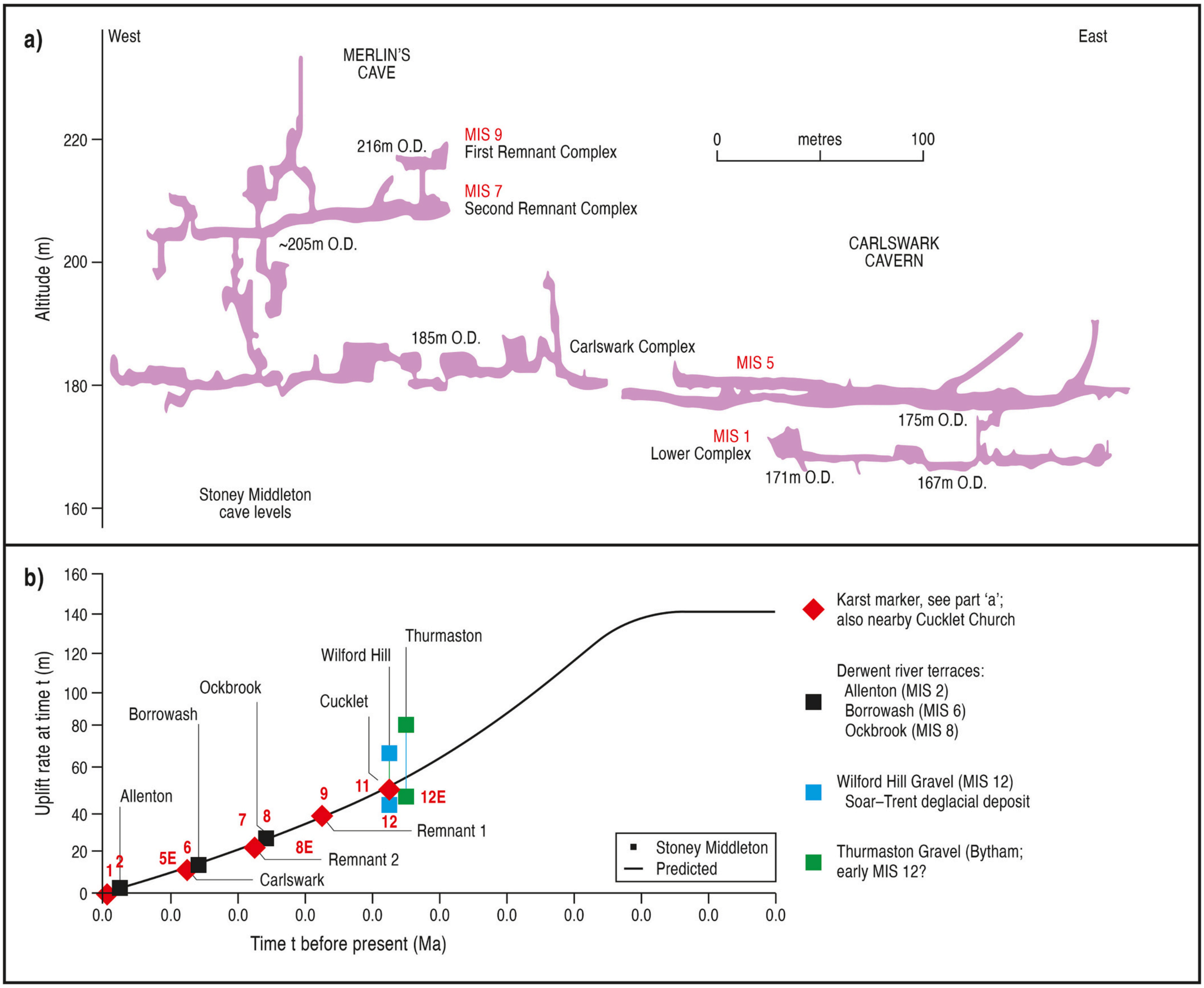

Fig. 7. Westaway's use of cave evidence to enhance the record of uplift in the River Derwent, Peak District, Derbyshire. Upper (a): Cross-sections through the superimposed cave levels at Stoney Middleton. Lower (b): Model prediction for uplift history at Stoney Middleton. Numbers refer to suggested correlation with marine oxygen isotope stages. Both are modified from Westaway (2020), who used data from Waltham et al. (1997). For location see Fig. 8.

2010), such an approach is appropriate only in cratonic regions, in which no crustal accommodation is possible because of the lack of mobile lower crust. The neglect of any crustal component in such modelling perhaps explains the documented difficulty in matching predictions to empirical data in areas of younger and more dynamic crust (cf. Peltier et al., 2002; Shennan et al., 2006).

Another mantle-based approach that received criticism from Westaway was the hypothesis that mantle plumes, or 'hot blobs' within the mantle, are causative of patterns of uplift (e.g., Goes et al., 1999; Garcia-Castellanos et al., 2000; Moucha et al., 2009; Robert et al., 2011), given that this mechanism cannot explain the match between palaeoclimate and pulses of uplift (cf. Bridgland and Westaway, 2008b). He acknowledged, however, the importance of mantle plumes in causing magmatic underplating of the crust, bringing about a restricted thickness of the mobile basal layer and thus restricting vertical crustal motion rather than promoting it (cf. Bridgland and Westaway, 2014); for a recent review, revisiting the potential influence of the Iceland mantle plume on the British Isles during the Cenozoic, see Lovell (2023).

Westaway was frustrated that other workers were reluctant to acknowledge a distinction between crustal movements resulting from plate tectonic motions and fault activity, for which he deemed the adjective 'tectonic' appropriate, and uplift and subsidence related to isostasy and epeirogenesis, for which he favoured the term 'atectonic' (Westaway, 2002c; cf. Maddy et al., 2000). The latter term should be applied to the crustal movements responsible for the formation of fluvial and marine terraces in areas distant from plate boundaries.

Also disparaged by Westaway has been the 'Stream Power Law approach' (cf. Bridgland and Westaway, 2012) to the understanding and reconstruction of river-system evolution, and in particular the derivation of fluvial history from the study of longitudinal (gradient) profiles, as seen in a considerable body of literature (e.g., Whipple and Tucker, 1999; Snyder et al., 2000; Kirby and Whipple, 2001; Tucker and Whipple, 2002; Pritchard et al., 2009; Roberts and White, 2010; Hartley et al., 2011; see above), largely from workers in the process-based theoretical branch of the wider subject, as opposed to those studying fluvial archives. Indeed, these two contrasting approaches have rarely been combined, although Demoulin et al. (2017) attempted exactly that, in a review of recent developments in the understanding of vertical crustal motions, while Martins et al. (2017) had the same objective in using studies of longitudinal stream profiles in tributary valleys of the Portuguese Tagus, a river already well understood from its Quaternary terrace record (e.g., Cunha et al., 2017).

Implicit in the notion that knickpoints propagate upstream as river valleys are lowered in a headward direction is that downstream from a knickpoint the valley-floor level from upstream is continued as a terrace. According to this principle, upstream from each knickpoint the number of terraces decreases by one. Reconstruction of terrace systems in that way has been relatively uncommon, although two British examples are of note, both now regarded as obsolete. The first is a depiction of the terraces of the Great Stour in Kent by Wooldridge and Kirkaldy (1936),

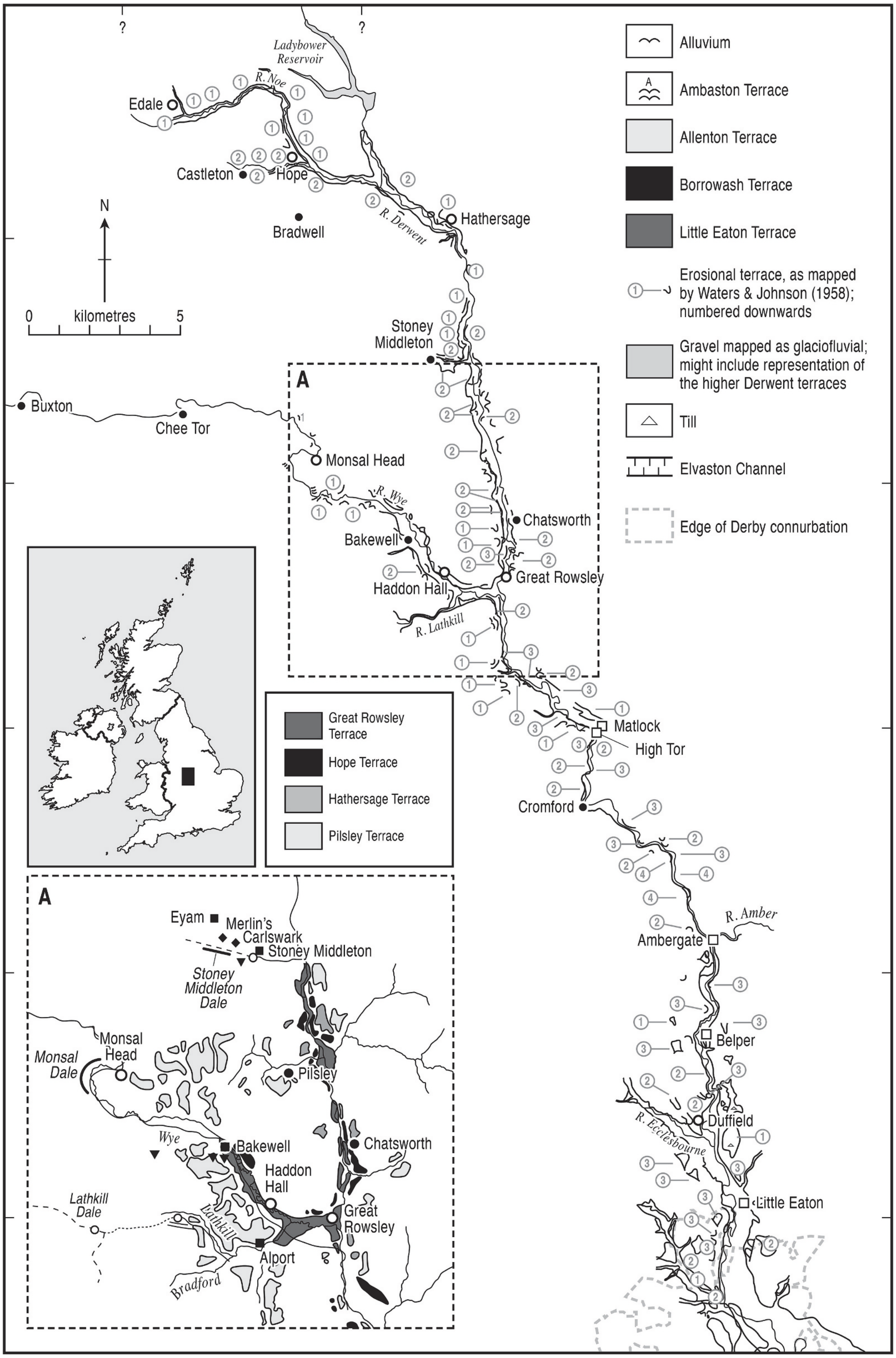

Fig. 8. Depositional and rock-cut terraces in the Derwent valley, Derbyshire, UK. This combines data from Waters and Johnson (1958), Straw (1968) and British Geological Survey mapping (from BGS DiGMap). A. Inset showing part of the Middle Derwent. This shows, near its northern edge, the location of the Peak District cave systems illustrated in Fig. 7.
Modified from Bridgland et al. (2014).

part of a study founded in the early–mid 20th century concept of ‘denudation chronology’ (e.g., Green, 1941, 1946, 1947, 1949; King, 1950, 1953; Brunsden, 1963; cf. Twidale, 1992); that river is currently being studied by a doctoral student, so it will be judicious to move to the second example, which is the River Derwent of Derbyshire, already mentioned in respect of its longer pedigree than its parent river, the Trent (see above; Fig. 8). The terraces of the Derwent, many of them erosional (bedrock straths), were reconstructed by Waters and Johnson (1958) in a scheme that envisaged subhorizontal remnants with low downstream gradients, each converging upstream with the steeper modern valley floor at one of several knickpoints (Fig. 10). The implication was that each knickpoint had propagated upstream to its current location, with no net valley deepening further upstream since emplacement of the associated terrace deposits. This is contradicted by more recent geological survey mapping of the Trent terrace system (e.g., Brandon and Sumbler, 1988, 1991) and by the even more recent reappraisal of the Derwent record, carried out as part of the ‘Trent Valley Palaeolithic Project’ (Bridgland et al., 2014), in which Westaway was involved. This envisages terraces that are approximately parallel with the modern Derwent valley floor (Fig. 10). It was these terraces that Westaway used to supplement his modelling of uplift from the dated Peak District karstic evidence (see above).

The jury remains out about whether river-valley incision takes place approximately synchronously in different reaches of a system or by upstream propagation of knickpoints or, indeed, by a mixture of the two. There is evidence from recent geochronological research that the ages of sediments forming particular terraces become progressively younger upstream or in tributaries: for example, in the Meuse system in the Ardennes (Rixhon et al., 2011), in the upper Main system in northern Bavaria (Kolb et al., 2016) and in the lower Chippewa River, part of the upper Mississippi system, Wisconsin, USA (Faulkner et al., 2016). The last of these is, however, a short-timescale, post-LGM record. There is some support for upstream knickpoint propagation from the familiar terrace record of the Thames, despite that record being reconstructed as a subparallel system; there are examples of convergence of Thames terraces upstream, notably the Taplow (MIS 8–7–6) and the Kempton Park (MIS 6–2), which converge around Marlow in the Middle Thames, above which the deposits of the combined terrace (the Summertown–Radley Terrace of the Upper Thames) represent two Croll–Milankovitch climate cycles (Briggs et al., 1985; Bridgland, 1994; Bridgland and Schreve, 2009). Westaway's (2020) final word on the matter was to suggest that knickpoints that are not fixed and maintained by valleys crossing resistant bands of rocks will be rapidly dissipated after a brief period of headward propagation, generally within a single 100 ka Croll–Milankovitch cycle; he alluded to evidence from eastern Scotland reported by Bishop et al. (2005), who noted that landward propagation of a knickpoint generated by Lateglacial (~14 ka) sea-level fall in response to glacio-isostatic subsidence had reached ~2 km inland, with its amplitude decreasing from an original ~30 m (seen in an associated raised coastal platform) to only ~5 m.

8. Discussion and conclusions

The outstanding contribution made by Rob Westaway to the study of fluvial archives has been his provision of a viable mechanism for the formation of flights of river terraces in tectonically stable regions, essentially achieved by establishing a positive feedback mechanism for the erosional isostatic uplift of river catchments. As a biproduct, the Westaway approach also provides a tentative dating mechanism for fluvial sequences in regions where other dating proxies are scarce, based on the modelling of the uplift and resultant valley incision represented by terrace elevations. This is most effective when there are occasional dating markers within sequences, such as within the terrace staircase of the erstwhile River Solent, for which uplift modelling was combined with Upper Pleistocene palaeontological remains in low terraces and distinctive Palaeolithic artefact assemblages at various Middle and Late Pleistocene levels (Westaway et al., 2006b). The archaeological evidence was regarded at the time as controversial, although subsequent research has consolidated that approach in application to other fluvial sequences (Bridgland and White, 2014, 2015; White et al., 2018) and the almost simultaneous application of optically stimulated luminescence (OSL) dating to the Solent terraces (Briant et al., 2006) produced similar results (cf. Harding et al., 2012). The expansion and greater reliability of luminescence dating since the Solent work, with routine application of feldspar-based IRSL techniques (e.g., Cunha et al., 2017; Rixhon et al., 2017; cf. Colarossi et al., 2015), means that a geochronological dataset can invariably be used in conjunction with uplift modelling in future, provided that funding is available for the former.

Westaway's mechanism for uplift-facilitated terrace formation also explains the different patterns of terrace generation in areas of different crustal types, from the rapid progressive uplift on young dynamic crust to the ultra-stability of the Archaean cratons (Westaway et al., 2003;

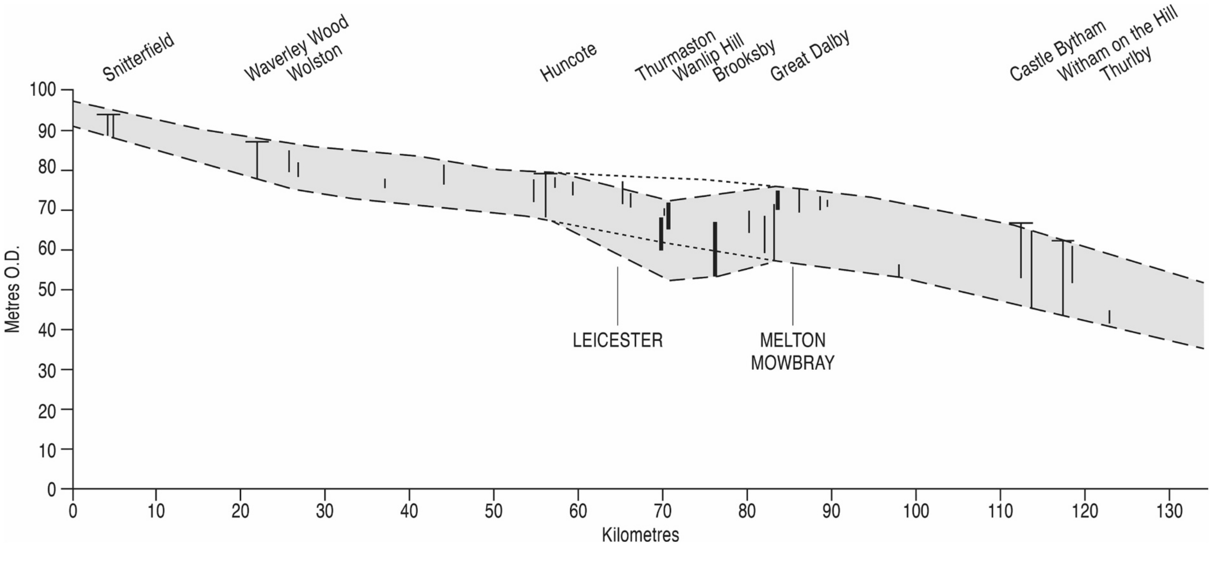

Fig. 9. Back-tilting of the Bytham Formation resulting from differential crustal properties in Midland England, which have led to less uplift in the area between Leicester and Melton Mowbray. Reproduced (with modifications) from Bridgland and Westaway (2014), who modified the Bytham longitudinal profile from Rose (1994). Key boreholes are emboldened.

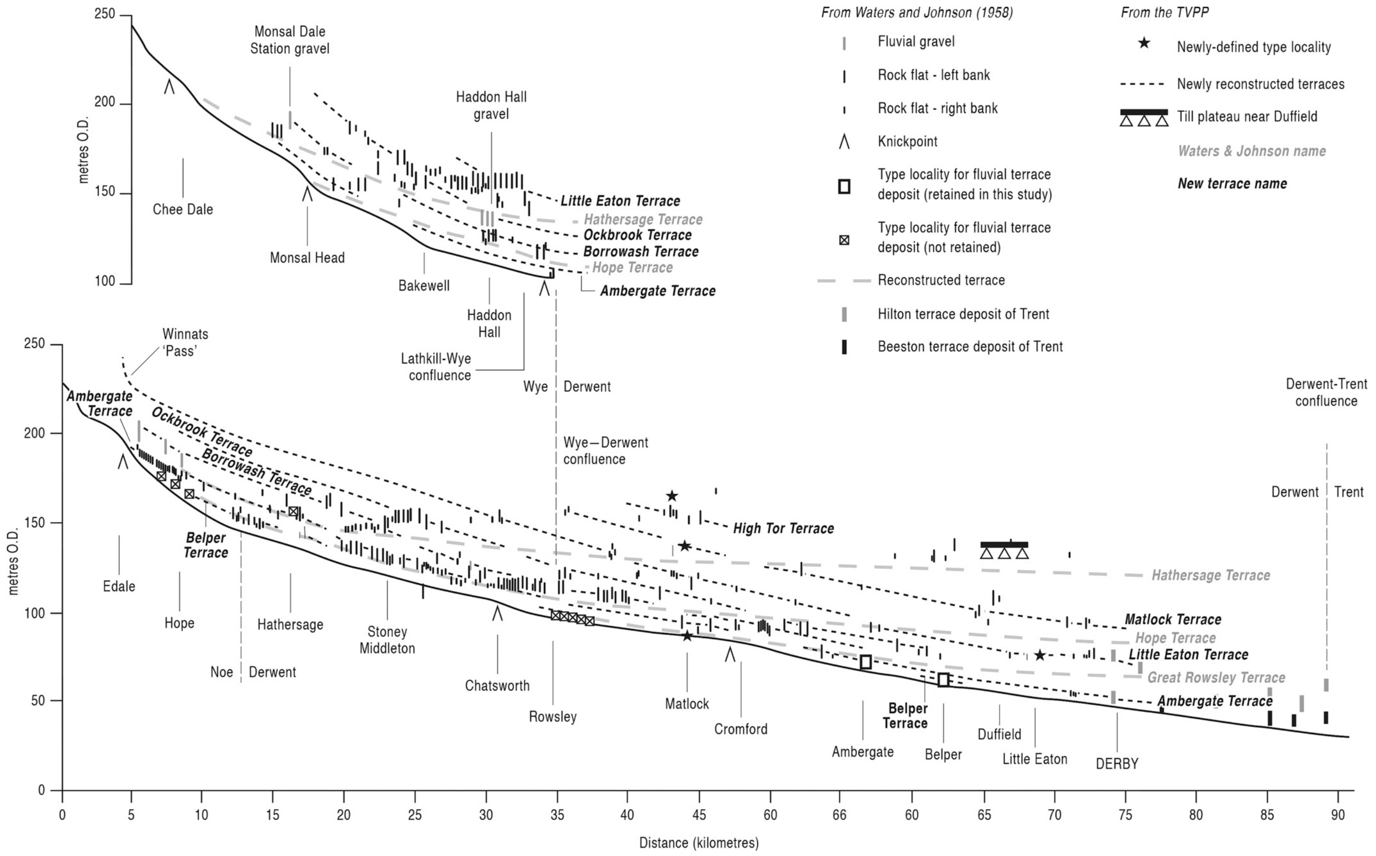

Fig. 10. Contrasting reconstructions of longitudinal profiles of terraces of the River Derwent system (Derbyshire), according to Waters and Johnson (1958), who related them to knickpoints, and the Trent Valley Palaeolithic Project. After Bridgland et al. (2014).

Fig. 4), with the intermediate later Precambrian and underplated crustal provinces showing alternation of uplift and subsidence (Westaway and Bridgland, 2014; Fig. 6): patterns that were scarcely observed, let alone explained prior to the Westaway contribution. Also important is that the uplift modelling approach allows karstic evidence from limestone uplands adjacent to valley gorge reaches to be included in the database, with added bonuses from the high level of precision available from U-series dating of speleothems and the survival of such evidence within caves despite submergence beneath glacial ice, as in the English Peak District (see above).

Westaway's important contribution has yet to be fully tested, a requirement before it can be adopted as received wisdom in terms of Late Cenozoic landscape evolution. Work is in progress, nonetheless, to explore the possibility that something similar to his hypothesized linkage between climatic change and uplift/incision, via the influence of the former on Earth-surface processes, can be seen in records from deeper geological time. Meanwhile aspects of the Westaway hypotheses are now widely accepted and more will be explored and published in due course. This paper can perhaps provide impetus for such evaluation and synthesis.

CRediT authorship contribution statement

D.R. Bridgland: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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