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Towards a budget approach to Pleistocene terraces: Preliminary studies using the River Exe in South West England, UK

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ABSTRACT

This paper presents a first approach to using a sediment budget methodology for paired terrace staircase sediments in SW England. Although a budget approach has become firmly established in Holocene fluvial studies, it has not been used in Pleistocene sequences due to the problems of temporal resolution, catchment changes and downstream loss from the system. However, this paper uses a budget approach in a paired non-glaciated basin, primarily as a method of interrogating the terrace record concerning the degree of reworking and new sediment input required to produce the reconstructed terrace sequences. In order to apply a budget approach a number of assumptions have to be made and these are justified in the paper. The results suggest that the Exe system can most parsimoniously be explained principally by the reworking of a Middle Pleistocene floodplain system with relatively little input of new resistant clasts required and a cascade-type model in geomorphological terms. Whilst this maybe partially a result of the specific geology of the catchment, it is likely to be representative of many Pleistocene terrace systems in NW Europe due to their litho-tectonic similarities. This cascade-type model of terrace formation has archaeological implications and sets the context for the Palaeolithic terrace record in the UK. Future work will involve the testing of this and similar budget models using a combination of landscape modelling and chronometric dating.

1. Introduction

It has been accepted for many years that Holocene fluvial sequences preserved as valley fills can be studied within a sediment budget framework (Dietrich and Dunne, 1978; Trimble, 1983; Brown and Barber, 1985; Passmore and Macklin, 2000; Brown et al., 2009a,b). This involves the collection of data on rates of accumulation including breaks in sedimentation, erosion and sediment provenance. This approach has not been taken with Pleistocene terraces, although they are former floodplains, for two principal reasons. Firstly, there is a belief that without high-resolution chronometric dating, rates of accumulation cannot be estimated, and secondly, that subsequent erosion is unquantifiable, so that budgets would always be incomplete particularly where catchment boundaries have changed. However, these considerations have not deterred the use of terrace surfaces as proxies of uplift rates (Westaway et al., 2006) or as archives of fluvial events (Bridgland, 2000). Also the problem of loss of sediment from the catchment outlet is probably greater for Holocene fine-sediment dominated systems than for predominantly cold-stage Pleistocene rivers. The terrace record is predominantly a record of bedload transport and deposition with fines (fine sand, silt and clay) being deposited off the continental shelf at sea level lowstands (Blum and Straffin, 2001). The erosion problem also includes erosion into terraces, creating accommodation space and the formation of both inset (cut-and fill) and compound terraces (stacked units). However, these problems are fundamentally the same for Holocene coarse and mixed-load systems, and it is only the temporal scale that is different. In practice some Pleistocene gravel terrace systems have an advantage in that the varied durability of catchment lithologies allows the ready distinction of inherited versus locally eroded bedrock. Paired terraces also have the advantage that terrace levels are easier to reconstruct, terrace widths are preserved and the lateral component of bedrock is limited in comparison to the case of uniclinal shifting (sensu Bridgland, 1985).

The use of catchments outside glacial limits with paired terrace systems, along with models of rapidly deposited gravel units separated by hiatuses, sometimes of great magnitude (Bridgland, in press), allows them to be conceptualised as sediment slugs from bounded areas driven by a combination of partially coupled ground

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cover conditions (including soils) and climate. Each gravel terrace, or part thereof, can be regarded as a volume transported by excess stream power during a period of high river discharge and deposited within a channel zone which in the case of braided systems can occupy most, if not all, of the floodplain. Additionally where terraces are paired, in at least part of a basin or reach, then the original edges of the floodplain can be demarcated and assuming there has been no erosional inversion this can be used to calculate palaeo-floodplain width. Erosional inversion would occur if a bedrock outlier (or knoll) had existed but had subsequently been eroded away. This is generally unlikely as slope erosion may cause slope decline or retreat but rarely causes inversion due to a tendency to decrease entropy (Kirkby and Carson, 1972; Dietrich and Perron, 2006). A further and more problematic assumption is that the river has not re-excavated or exhumed an earlier gravel-filled buried valley. This occurrence is known from sections of some valleys such as the Nene in eastern England which crosses and at points has re-excavated easterly flowing pre-Anglian valleys (Horton, 1970; Belshaw et al., 2004; Westaway, 2008) but, as in this the Nene case, it is probably the result of glacial erosion and so less likely in non-glaciated basins. Downstream buried valleys are known from the lower Exe but they are associated with the lower Late Pleistocene terraces grading to low relative sea-levels (Durrance, 1969, 1980) and there is no indication of any deeper or older buried valleys. So making these assumptions, and within these limitations, strath gravel-terraces can be treated as flood-plains for the purpose of volumetric modelling with the aim of raising important questions concerning sediment influx–outflux, reworking and archaeological residuality. Although chronometric dating of the Exe system is underway, it is not essential for this approach as each terrace can be regarded as a chronostratigraphic unit in a relative chronological sequence. This approach is complimentary to models of terrace formation driven by Milankovitch forced quasi-cyclic variations in climate with erosional down cutting occurring principally during cold periods, relative stability in glacials, interglacials and interstadials and deposition during transitional phases particularly from cold-to-warm transitions (Bridgland, 2000, 2001, 2006; Westaway et al., 2006) and at cooling transitions (Bridgland and Westaway, 2007a). The additional element to this fundamentally 1D model recently proposed by Brown et al. (in press) and used here, is the lateral component of both erosion and deposition – the balance between which is a major component of staircase morphology through terrace width and thickness. Whilst regional uplift maybe required to create staircases through incision (Blum, 2007) – although modelling suggests that climatic cyclicity can achieve the same result alone (Hancock and Anderson, 2002), the lateral erosion of both bedrock and terrace gravels determines both morphology and the input of eroded bedrock and previously deposited gravels to the floodplain system. Where the upstream or higher level clast lithologies differ from the underlying bedrock this component can be assessed through its contribution to both local and downstream gravels. This is clearly highly dependant upon the differential resistance to erosion and form of erosion of both bedrock, and terrace, lithologies. Although only tangential to the argument of this paper there is an apparent contradiction between the numerous and indeed classic studies which show terrace formation without uplift (Schumm, 1977), and particularly caused by mining (Gilbert, 1917), and the Quaternary fluvial record which strongly suggests that uplift is necessary for long-term terrace staircase formation (Bridgland and Westaway, 2007b). Indeed recent work in a headwater of the Exe has revealed a 4 m high terrace almost certainly formed as a result of Roman iron-mining (Brown et al., 2009a,b). The answer lies probably in both the supply of sediment and the lack of reworking associated with uplifting systems. Although a component of the local slope and a small orographic meteorological effects the direct influence of uplift to catchment sediment flux is almost certainly small in comparison to sediment climatically controlled supply and transport.

2. Regional variation on terrace systems

As already highlighted the budget approach is dependant on a number of assumptions, the most important of which is that the total area of the catchment has not altered under the period of erosion and sediment deposition. The second is that the valley gravels are separable into morphologically distinct units allowing volumetric estimates to be made, and thirdly that there is at least an order of magnitude similarity between the rates of accumulation of terrace gravels. The first two of these criteria are controlled at the regional scale by the Pleistocene glaciation of the British Isles and resultant catchment changes and to a lesser extent variations in uplift history (Bridgland, in press). There is considerable variation across the British Isles in terrace form and the number of identifiable levels (Fig. 1) from stacked "single" terrace sequences (cf. Ruegg, 1994) such as the river Axe, to inset or cut and fill forms (the attitudinally lowest 1–4 terraces of several rivers) and finally altitudinally separated terrace (ASTs) staircases (e.g. Thames, Solent, Exe). These terraces are both morphological forms and sedimentary units or members, which can be multiple (or composite) and sit on a strath the base of which is higher than the surface of the next terrace down the staircase, hence altitudinally separated. They are in a formal geological sense morpho-sedimentary units. This variation in the number of terrace surfaces or morpho-sedimentary units identified during geological mapping is of course partly due to historical factors relating to mapping approaches and conventions and produces part of the regional variation in the number of terrace levels mapped by the British Geological Survey as mapped in Fig. 1. This figure is only a first approximation and it has not been possible, and may never be, to be entirely consistent as to the division of ctachments into sub-catchments. It is only possible to use the BGS mapping and memoirs to plot the AST's of the main valleys which have been surveyed or resurveyed. Due to drainage changes associated largely with the Anglian glaciation (MIS 12) many catchments have changed and this also complicated any synchronic representation. However, the BGS re-mapping of many areas has been underpinned by a more systematic and unified approach with the 'splitting' rather than the 'lumping' of terrace levels. This along with reconciliation of adjacent map sheets has allowed a countrywide comparison for the first time. Fig. 1 shows that unsurprisingly all the systems with over 8 ASTs lie south of the extent of the maximum glaciation of Britain (MIS 12). On geomorphological grounds and modelling a relationship might be expected between catchment size and terrace number (Veld- Q1 kamp and van Dijke, 2000), however, this is not simple. Large systems do generally have more ASTs (e.g. Thames and Severn) but smaller catchments do not necessarily have a low number of ASTs (e.g. Upper Solent catchments). Indeed most striking is the correspondence of the valleys with the highest numbers of terraces (i.e. 8 or over) with catchments draining Palaeogene-Neogene basins which still have uplands with a residual cover of gravels, or clay-with-flints including the Thames, Exe and Solent Systems. Also of note are anomalous juxtapositions of catchments with high and low ASTs (e.g. Exe/Axe in SW England) even outside of the maximum glacial limit. Whilst it is possible that in some cases this is due to local neotectonic factors (Westaway et al., 2006) in others it is not and this suggests that elements of catchment change (e.g. capture) may still be present in the terraces record as has been recently argued for the Axe in SW England (Gallois, 2006). Due to the conservative nature of terrace depth (and less so width) this spatial variation also implies a spatial variation in the Pleistocene sediment flux across the British Isles.

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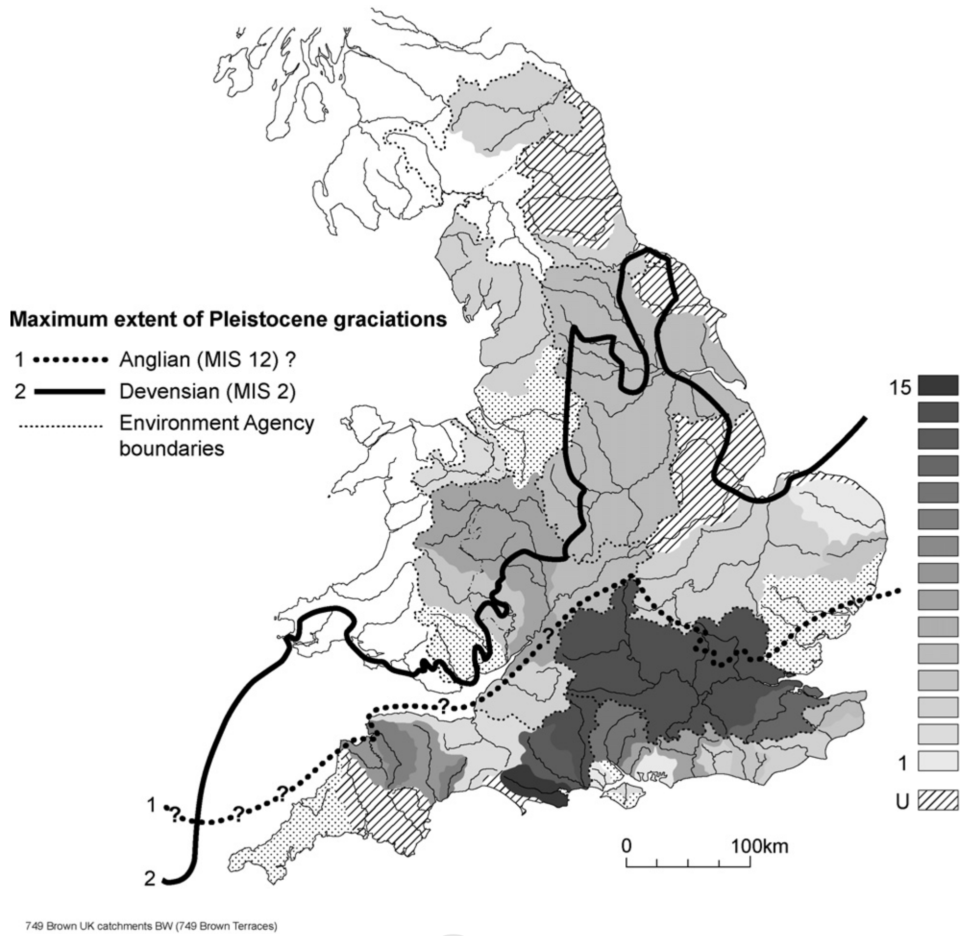

Fig. 1. A map of terrace numbers per modern catchment of England and parts of Wales. Data derived from mapping by the British Geological Survey and supplementary sources. The divisions are in single ALT steps. See text for further explanation.

3. The Exe terrace staircase

The terraces of the lower Exe at its confluence with the Culm and Creedy in and around the Netherexe Basin are paired and well preserved (Edwards and Scrivener, 1999). Re-mapping by BGS revealed a staircase of eight terrace levels in the middle-lower sections of the River Exe and this has allowed a cross-sectional model for a transect across this area illustrated in Fig. 2 and shown in planform in Fig. 3. This planform has been created using the highest surviving fragments of the terrace surface and extrapolating those levels across the valley to bedrock. Fig. 2 is based on recent data, although the gravel texture is generalized and simplified, a more detailed description of which can be found in Brown et al. (in press). This study has also provided a provisional chronology has been erected and stratigraphic, ground survey and environmental information data sets for this sequence have been collected as part of the Palaeolithic Rivers of Southwest Britain (PRoSWEB) project. This is an ideal study-area as it has was re-mapped by the British Geological Survey in the 1980s to early 1990s and published in 1995 (Edwards et al., 1995). The geological maps and cross-section show how the area covered by floodplain has reduced in width through every major deposition/erosion cycle and as this has happened the floodplains have become more confined and differentiated as the confluences became incised. The dominant fluvial process is the incision and lateral erosion of channels which created accommodation space with simultaneous reworking of the former floodplain gravels into which the channel erodes. In this model there does not have to be a time differential between incision and deposition since as accommodation space is created it is filled by reworked gravels. A simple test of this hypothesis is presented in this paper below. An important factor in this test is the differential erodibility of the local bedrock and the terrace gravels. The Netherexe Basin is developed in a transgressive sequence of the Exeter Group of Permo-Triassic rocks. Lithologies include breccia (Cadbury Breccia) and weakly cemented sandstones (Thorverton, Shute and Dawlish Sandstones). Sandstones make up the majority of the valley sides in the Netherexe Basin. The Netherexe terraces complex starts upstream of the basin in the Upper Carboniferous Culm Measures (greywackes, sandstones and shaly mudstones), which also form the constricted reach at Bickleigh to the north. The Dawlish Sandstones are weakly cemented sandstones, mainly cross-bedded with intercalated thin lenses of claystone, clayey siltstone and fine-grained breccia which weather predominantly to sand, clay and silt (Edwards and Scrivener, 1999). The Thorverton Sandstone is predominantly a reddish-brown fine- to very fine-grained weakly or uncemented sandstone with thin beds and partings of reddish-brown clay which weathers easily to sand, silt and clay. From the lithology of these rocks and their weathering products (predominantly sand) it can be seen that they form only the matrix component of the terrace gravels which are predominantly clast-supported medium to coarse gravels (Hosfield et al., 2007; Brown et al., in press). The Exeter-Group derived weathered sandstone along with upstream Carboniferous and Devonian derived sand, and fragments of shattered and weathered mudstones (locally called shillet) makes up the gravel matrix of the middle and lower terraces in the Netherexe Basin. The vast majority of the terrace gravels (in volume) which are composed on Culm measures sandstones, vein quartz, quartzite, chert, flint and occasional volcanics (Edwards and Scrivener, 1999; Brown et al.,

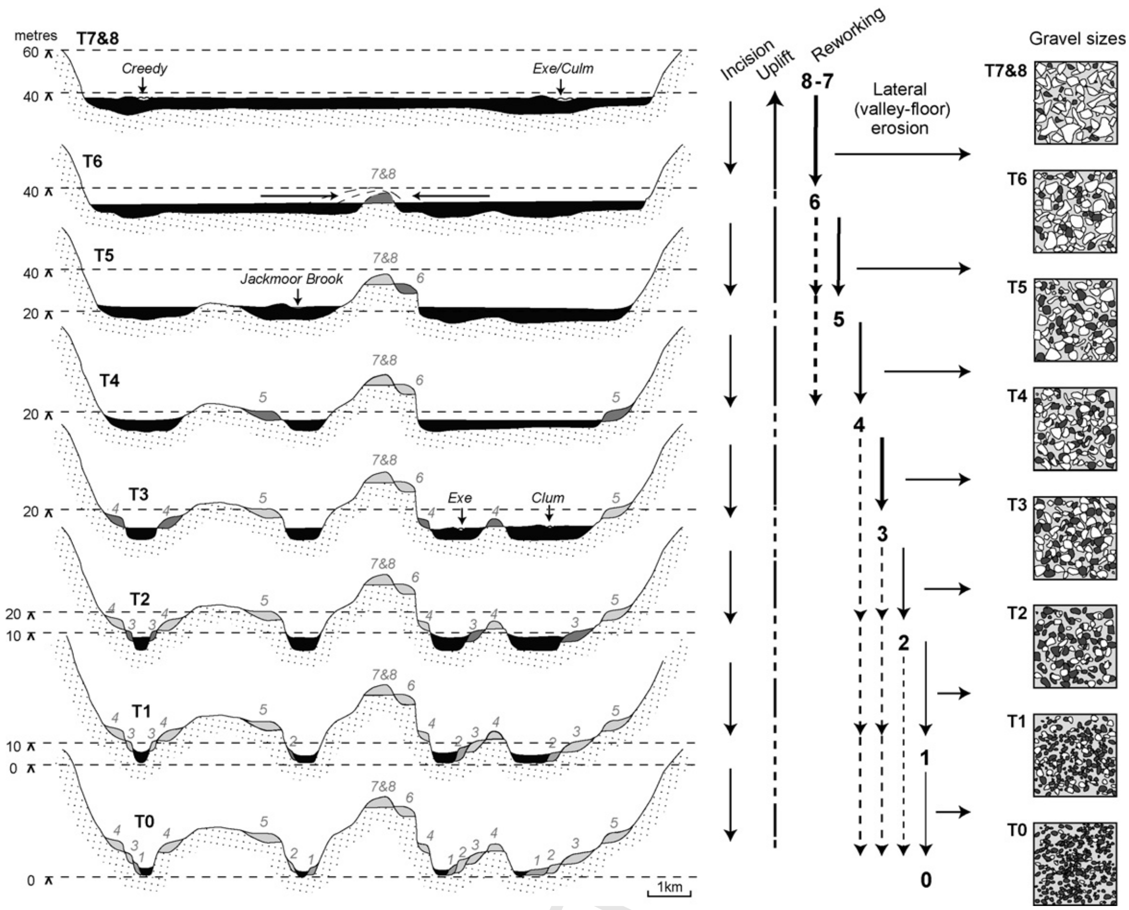

Fig. 2. A cross-sectional model of the Middle Exe terrace staircase in the Nether Exe Basin with a depiction of forcing factors (uplift and incision) and typical resultant sediment fabric and texture.

in press) are therefore not derived from the local bedrock and bedrock erosion makes up a minor terrace component with the majority probably having been transported out of the basin.

4. Methodology

The methodology used is similar to that employed by Hosfield (1999) but critically it uses volume rather than terrace area. The reason is that differences in floodplain width can easily be offset by the variable thickness of terrace units. Fig. 4 shows a simplified valley reach with terrace dimensional notation and three terraces where for the sake of simplicity the incision depth equals the terrace thickness. This allows the calculation (1) of the total deposited mass in T_1, the eroded mass from the reach only in $T_1 - T_2$, the deposited mass in T_2 and so on.

$$Tq_s = w \cdot h \cdot x \quad (1)$$

where Tq_s is the equivalent sediment discharge contained within terrace a T, w is alluvial plain width, h is terrace thickness and x is the reach length. If after incision into this highest (original or

Q12 **Fig. 3.** A map of the reconstructed lateral extent of terrace 7 of the Exe (green) using terrace fragments in the Exe-Culm confluence zone as mapped by BGS and investigated as part of the PRoSWEB project (red).

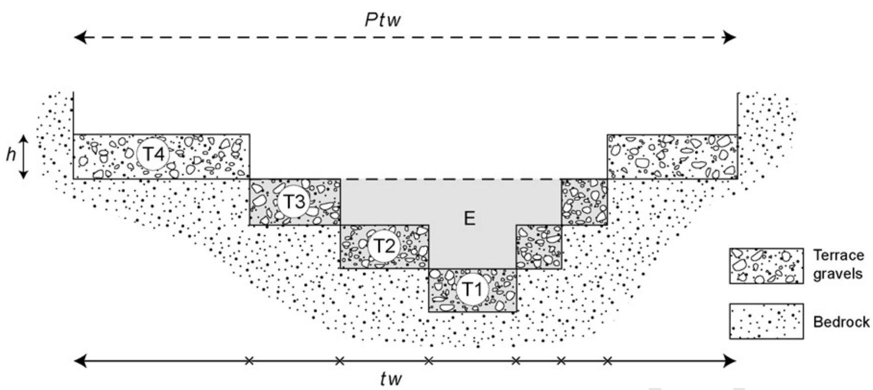

Fig. 4. The geometric methodology used for the estimation of terrace volumes. The equal separation of terrace unit heights has been used just for clarity.

palaeo) terrace ($PT1_{qs}$) the eroded mass from $PT1$ is simply redistributed within the basin (when there is no loss form the reach, i.e. $\nabla \cdot Tq_s = 0$) then the system can be defined by:

$$PT1_{qs} = T1_{qs} + T2_{qs} + T3_{qs} + T4_{qs} \tag{2}$$

and in the case of a valley where scour had been equal to terrace thickness then bedrock erosion in the reach (B_{qs}) is approximated by:

$$B_{qs} = T2 + 2T3 + 3T4 \tag{3}$$

For the Hancock and Anderson (2002) model x becomes downstream distance:

$$\frac{\partial h}{\partial t} = \frac{1}{w} \cdot \frac{\partial q_s}{\partial x} \tag{4}$$

and the changes in q_s are the fundamental cause of downcutting. As a preliminary test of comparable mass and in the absence of sufficiently reliable dating, a modified version of Eq. (2) has been applied to the Netherexe reach on the River Exe in SW England. As discussed previously this is reasonable as the bedrock of the reach is predominantly erodable sandstones and marls, which only contribute to the matrix of these predominantly clast-supported gravels and might be expected to favour high terrace creation and preservation (Bridgland, 1985). The depths of the terraces were averaged from boreholes (45 in total), coring, exposures and trenching within the reach (Hosfield et al., 2007; Brown et al., in press). Stratigraphic drawings, locational and sedimentological data on the five sites in this reach can be found in Brown et al. (in press). Unfortunately due to a lack of sufficient preservation and borehole records volumes could only be reconstructed for BGS terraces 6-1. Given the relatively low data volumes available for this area (45 boreholes and 5 areas of exposure or trenches) it is not possible to estimate a meaningful comparative error term for each terrace, however, there is no reason to believe that the areal and thickness estimate errors would not be approximately normally distributed suggesting that as a first approximation the estimates are useful. This approach is dependant upon a high density of borehole or geophysical data giving accurate estimates of gravel body thicknesses. However, given the economic importance of aggregates in the UK and other industrialized regions this data is often available for larger river valleys having been collected by national resource mapping programmes undertaken by governmental agencies such as the British Geological Survey, or from the Q3 aggregate industry (Brown, 2009). This will be most limited in areas where aggregates cannot be exploited, such as National Parks, and in urban areas.

The composite nature (multiple members) of many morphosedimentary units, is not necessarily as large a problem as it might seen, as we might expect periods of significant bedrock incision to be of approximate time-equivalence as per climatic models of terrace formation (Bridgland, 2000, 2006) consigning the multiple episodes of terrace aggradation to time windows between these periods of incision. Hence whilst they will not necessarily equate to individual marine isotope stages (or glacials) and hence the problem with 'counting back-chronologies' they should represent broadly equivalent time periods over which the flux of gravels has occurred.

5. Results and implications

The results (Fig. 5) show an approximate constancy in mass, with the decreasing width of alluvial terrace being offset by an increase in thickness. Fig. 5 shows the estimated sediment volumes for the 18 km reach that existed within each terrace when it had just been formed. From this has been calculated the volume associated with each terrace fragment by subtraction. As can be seen from Fig. 5, the volumes, which are in effect a Pleistocene flux rate, are approximately constant with the exception of terrace 4. The reason for this is that whilst the reduction in width from terrace 5 to 4 is minimal (300 m reduction) probably due to a prolonged period or high rate of incising lateral erosion, the mean depth of terrace 4 (1.8 m) is less than that of all the other terraces so there is less mass in terrace 4 than is predicted by the erosion of terrace 5 (difference between grey and black bar) suggesting that at this point in the evolution of the terraces there was a net loss of terrace gravel. In contrast there is an increase in the volume deposited in terrace 3 above that which could be supplied by terrace 4 – so a net gain from terraces 5, 6 and the upper catchment. The total of terraces below terrace 6 is 244 M m^3 in comparison with the reconstructed volume for terrace 6 of 267 M m^3 or 91%. Indeed the same pattern holds for each terrace down the staircase

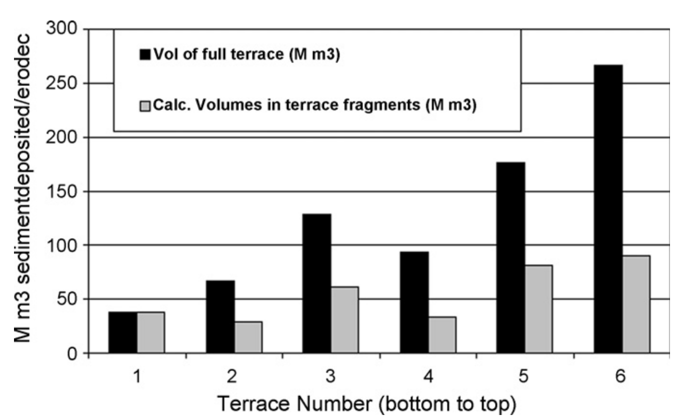

Fig. 5. Estimated sediment volumes for the Nether Exe Basin reach.

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– making it in mass terms a cascading-type system (Chorley and Kennedy, 1971; Kondolf and Piégay, 2003). This pattern agrees with observations of the terrace clast composition, which is dominated by resistant lithologies with local sandstone and marl only making up a minor proportion of the matrix. Local bedrock erosion would have generated sand-sized sediment which has largely lost from the reach with the vast bulk of the terrace mass being simply reworked from the previous terrace gravels and possibly higher level gravels now not preserved around the basin (Cullingford, 1982; Gallois, in press). It is also in agreement with observations by Maddy et al. (2000) on rivers in southern England suggesting an earlier mid-Pleistocene state of broad palaeo-valleys into which the main staircase has been developed.

However, one of the problems with this type of analysis is choosing a starting point. It is possible that above the highest surviving remnants of gravels terraces there existed earlier in the Pleistocene higher terraces which have been entirely eroded leaving only benches, nickpoints, erosion surfaces, erratics or high-level flats. There is some evidence, which supports this including very isolated gravels such as at Black Hill in East Devon (Gallois, in press) and observations of higher levels by Kidson (1962) and the distribution of sarsens which are erratics in this area. These have been found up to 3 m in long axis in clusters within the interfluve area between the Exe and Creedy below the level of terrace 7/8, but not on higher slopes (Scrivener et al., forthcoming). The relatively low relief of the surfaces above the higher terraces and the common draped nature of the upper terrace remnants (Edwards and Scrivener, 1999) suggests that a different geomorphic system was in operation with less pronounced erosional-depositional cyclicity at least prior to the incision which created the terrace staircase. This has been interpreted as a change in the regional uplift rate (Westaway, 2002; Westaway et al., 2006) but at present the data supporting this hypothesis are derived from the terrace relative altitudes. A second frequently cited cause of a mid-Pleistocene change in fluvial activity is the shift from the 41 K dominated astronomical forcing cyclicity to the dominant 100 K cycle at c.1 Ma – the so-called Mid-Pleistocene Revolution or MRP (Kukla, 1975; Mudelsee and Schulz, 1997; Westaway et al., 2006).

Although this is a crude and preliminary approach it is a first approximation, and it does confirm a conservatism in the mass balance of the system suggesting that during the later Pleistocene the loss of coarse material from the system has been limited with bedrock erosion predominantly into the most erodable lithologies allowing the creation of the basin-length paired terrace staircases and presumably off-shore stacked sequences of fine sediments. It also helps explain the earlier observation of the correspondence of high numbers of terrace levels in the softer sediments of the Palaeogene-Neogene basins where there is both a high supply of high-level gravels (predominantly of flint and chert) and easily eroded bedrock facilitating the lateral reworking of terrace gravels (Allen and Gibbard, 1993; Westaway et al., 2006). Luminescence dating is underway and increased precision in the measurement of terrace volumes (using remote sensing) combined sediment budget modelling could provide us with long-term sediment budgets linked to landscape evolution, climate and uplift. Such a model of terrace evolution has important implications for Palaeolithic archaeology. Firstly the relative relief and ruggedness (sensu King and Bailey, 2006) of these environments have changed with each Milankovitch cycle as has the resource set contained within the valley as opposed to the surrounding uplands. This maybe important for not only resource procurement but also route-finding and the symbolization or even cognitive understanding of the environment by highly mobile hominins (Pope et al., 2006). Secondly, the slightly to moderately abraded state of many Palaeolithic artefacts from terrace gravels from so-called secondary contexts implies that they were transported as bedload but possibly only from the adjacent eroded terrace with inputs of new material during habitable periods. In this model lateral input is far more important than downstream or long-distance reworking of artefacts. This is supported by sites where admixtures occur of unabraded and abraded lithics in the same sedimentary unit (Hosfield and Chambers, 2002, 2004). It is possible that lithics maybe reworked down several terrace levels, however, they may not have moved any great distance downstream supporting Wymer and Singer's (1993) view that dense concentrations of palaeoliths have not traveled far from their "place of discard" (Wymer and Singer, 1993).

6. Conclusions

This study has built on recent work in the Exe catchment, which has generated data on the geometry, lithological composition and chronology of the staircase in the Netherexe Basin. It has presented a test of a conceptual model of terrace evolution, which highlights the role of lateral erosion and simultaneous reworking of previous floodplains in the evolution of terrace staircases. From this test there three conclusions are derived:

(a) The relative proportion of input and output to the total terrace mass is relatively small, in mass terms the system is a semi-closed (or conservative) cascading-type system.
(b) On budget calculation criteria alone, the majority of non-matrix clasts in the lower terraces are likely to have been reworked from higher terrace levels, and have not traveled far within the reach. In theory this is testable using clast lithology as it might be expected that through reworking the original terrace units the lower terrace gravels would become progressively enriched in the more resistant clast components. However, there are two problems in the case of the Exe and probably many other European rivers. Firstly if the highest or ancestral terrace is composed of a very resistant lithology derived from an earlier Cretaceous cover such as flint and chert, then the result would then be the inverse as some local and softer lithologies would enter the system over time even if the gravels were largely reworked – a dilution effect. Secondly there will always be some local input although it may be restricted in its downstream persistence.
(c) The occurrence of anomalously large non-matrix clasts, such as sarsens, in and above the higher level terraces is the result of selective erosion of smaller more mobile clasts. This also explains the slight fining seen down the terrace staircase (Brown et al., in press).

Whilst these conclusions are preliminary, and proposed in order to be further tested, they have implications for the Quaternary history of the Exe and other similar terrace staircases. The study implies, along with recent luminescence dating by the PRoSWEB Project, that there was a major change in the depositional and erosional regime sometime in the mid Pleistocene which converted a river system dominated by lateral aggradation into one characterised by increasingly confined incision-deposition cycles that lead to progressive terrace reworking. Whilst this may have been the product of the changing intensity of Milankovitch cycles alone it may also have operated through variations in the erosional-unloading component of regional uplift (Maddy et al., 2001; Westaway et al., 2006; Lane et al., 2008). There are also significant archaeological implications concerning both changes in the environment of early Hominins through increased landscape relief and ruggedness, and for the distribution and pattern of reworked or residual lithics within terrace gravels.

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Q6 Bridgland (1995) and Westaway (in press).

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