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Terrace reconstruction and long profile projection: a case study from the Solent river system near Southampton, England.

Short title: Terrace reconstruction and long profiles

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ABSTRACT (up to 200 words)

River terrace sequences are important frameworks for archaeological evidence and as such it is important to produce robust correlations between what are often fragmentary remnants of ancient terraces. This paper examines both conceptual and practical issues related to such correlations, using a case study from the eastern part of the former Solent River system near Southampton, England. In this region two recent terrace schemes have been constructed using different data to describe the terrace deposits: one based mainly on terrace surfaces; the other on gravel thicknesses, often not recording the terrace surface itself. The utility of each of these types of data in terrace correlation is discussed in relation to the complexity of the record, the probability of post-depositional alteration of surface sediments and comparison of straight-line projections with modern river long profiles. Correlation using age estimates is also discussed, in relation to optically-stimulated luminescence dating of sand lenses within terrace gravels in this region during the PASHCC project. It is concluded that the need for replication at single sites means that this approach has limited use for correlative purposes, although dating of sediments is important for understanding wider landscape evolution and patterns of human occupation.

KEYWORDS (up to five): long profiles, optically-stimulated luminescence (OSL) dating, fluvial records, terrace deposit

Introduction:

Understanding the long-term evolution of river systems is a matter of considerable stratigraphic importance, since river deposits comprise much of the Quaternary record globally (e.g. Westaway et al., 2009; Bridgland, 2010). River terraces are particularly important in providing a framework for understanding the Palaeolithic archaeological record and associated patterns of human occupation of the landscape. However, where the deposits preserved within river catchments form terrace features rather than sediment stacks within a subsiding basin, they are often fragmentary and very similar in lithological and biological composition, making them hard to correlate with confidence.

Where there are lithological changes over time, these can be used to correlate river terrace fragments (e.g. the Thames-Medway in eastern Essex – Bridgland, 2003 and references contained therein; the Kesgrave Thames in Suffolk – Whiteman, 1992; Whiteman and Rose, 1992). River terrace fragments can also be correlated using stratigraphic markers associated with volcanic activity (e.g. Veldkamp et al., 2007) or geochemical fingerprinting of sands (e.g. Veldkamp and Kroonenberg, 1993a; Bateman and Rose, 1994). Another way in which terrace deposits can be differentiated is by the development of different numbers of palaeosols within overlying loess sequences, as in the Somme (e.g. Antoine, 1994). However, more typically, none of these additional lines of evidence are present and geochemical and clast lithological assemblages change very little in successive terrace deposits. Where this is the case, the main method usually used in correlation is downstream projection of approximately straight or slightly concave upward terrace gradients. This approach is simple to apply, but study of modern rivers shows the significant complexity of many river long profiles.

The long profile of a modern river system can be measured at the base of the channel (e.g. Harmar and Clifford, 2007), the estimated high water level (e.g. Rice and Church, 2001) or the surface of the surrounding floodplain as when Digital Elevation Models are used (e.g. Phillips and Lutz, 2008). The floodplain surface is the most useful measure for comparing with ancient river deposits, since this is the only feature that is non-varying over longer time scales. It also reflects the sedimentary evidence on which terrace deposit correlations are based, thus increasing comparability. However, floodplain surfaces have significant topography on a small scale, sloping from the back to the front of the terrace and preserving empty or partially filled palaeochannels up to 5 m deep (e.g. at Brampford Speke in the Exe - Bennett et al., 2011). On larger scales, recent work shows that even a concave-upward profile from source to mouth is too simplistic and that many irregularities occur, for example relating to changes in underlying bedrock geology, changes in discharge or median grain size following confluence with a tributary (e.g. Harmar and Clifford, 2007; Phillips and Lutz, 2008), or tectonic features. Similar complexity and different reach-scale behaviour is seen in modelling of Late Quaternary longitudinal profile development in the Meuse (Tebbens et al., 2000). The implication is therefore that we should expect complexity in ancient terrace deposits since modern terrace deposits are complex. This complexity will then be compounded by post-depositional addition to or alteration of surface sediments and

spatially variable preservation of deposits within the terrace. Additionally, modern long profile gradients are affected by proximity to base level (usually sea level). The location of base level in relation to terrace fragments is often uncertain since they are mainly deposited during periods of low sea level. However Veldkamp and Tebbens (2001) suggest that sea level influence, although spatially extensive, is usually restricted to the area downstream of the hinge zone, characterised by sediments deposited in a subsiding basin.

Alternatively, it is potentially possible to correlate between adjacent terrace deposits on the basis of age rather than altitude. In this approach, you would use relative or absolute age determinations from the river sediments, or failing this, biostratigraphic evidence or archaeological artefacts. To constrain the correlation effectively, however, you would need such evidence from the majority of the terrace fragments, which is unlikely in the context of fairly low preservation / find rates for biological and archaeological material. It is theoretically more likely to find such evidence for age estimations, particularly optically-stimulated luminescence (OSL) dating, but even with this technique, suitable material (sand) is not always exposed, nor is it always financially possible to undertake as many dates as would be required to make robust correlations. There is also some concern about the reliability of this technique for providing dates on fluvial sediments. However Bailey and Arnold (2006) have shown that incomplete bleaching, although problematic for younger samples (less than c. 10 ka), is not important for older deposits, because of the small size of any residual dose preserved. Ongoing technical developments are increasing the robustness of this technique and recommendations for best practice are discussed below.

The eastern part of the former Solent river system near Southampton Water in south-east England is illustrative of many of these problems, and representative of many river systems. Firstly, it is likely that clast lithological assemblages change very little in successive terrace deposits, as to the west of Southampton Water (Allen, 1991; Allen and Gibbard, 1993). This means that all terrace correlations have to be based on either altitudinal correlations or age attributions. Secondly, there may be some base level effects. It is likely that the c. 350 km distance to the shelf break and glacial-period coastline means that the largely cold-stage deposits may have been unaffected by sea level changes. However the proximity to the modern coast has led to significant reworking of these deposits as they have been dissected by numerous perpendicular tributary valleys, most of which have patches of Quaternary gravels on their flanks. Finally, there is limited age control. There is no biological material preserved from within the river gravels and whilst some workers (e.g. White, 1998) have claimed that certain types of archaeological material can be age-diagnostic, this has been disputed (e.g. Briant et al., 2009; Ashton and Hosfield, 2009) and such material from this region is sparse. OSL dating is possible on these deposits, but as this paper will show, has proved problematic due to difficulties in exposing suitable deposits.

A further reason for using this part of the Solent river system as a case study to explore terrace projection is that two terrace stratigraphical schemes have recently been proposed for this region by Westaway et al. (2006) and an English Heritage funded project on the 'Palaeolithic Archaeology of the Sussex / Hampshire Coastal Corridor' (PASHCC - Bates et al., 2004; 2007; Bates and Briant, 2009). These two schemes therefore differ considerably in the data on which they are based. As will be shown later, they also differ in some key correlations. It is suggested that the different data

used account for these different conclusions. It should also be noted that there is ongoing work in this region which will have implications for both these schemes (Harding et al., in review; Hatch, 2011).

Terrace mapping by the British Geological Survey

Gravels on the eastern side of Southampton Water and the lower part of the Test Valley were mapped by Edwards and Freshney (1987). They recognised up to 11 terrace levels at various heights trending north-west / south-east up the Test Valley between Romsey and Portsmouth (Figure 1) and a further three submerged terrace levels offshore, the lowest of which is infilled with various Holocene sediments. Deposits mapped as Terrace 2 are more extensive in the east, covering the entire area from Fareham to the coast, but sparse in the Romsey area and absent north of the town. Terrace levels 3 to 6 are common between Southampton and Fareham, but more limited north of Romsey and south of Portsdown. Terraces 7 to 11 are fragmentary and found only on high ground (Edwards and Freshney, 1987). Edwards and Freshney (1987) also mapped deposits relating to four significant tributary valleys cutting across fluvial deposits in the Eastern Solent region - the Itchen, Hamble, Meon and Wallingford rivers. Of these, only the Itchen has extensive terrace deposits, but all significantly disrupt the main spreads of gravel alongside Southampton Water (Figure 1).

North of Romsey, the Test Valley has been mapped by Booth (2002) using a different terrace numbering scheme that recognises only 8 terrace aggradations rather than the 11 of Edwards and Freshney (1987). These deposits are best developed near confluences such as with the river Dun near Dunbridge. Booth's (2002) terraces initially correlate well with those on Sheet 315, with a hiatus between Terraces 1 and 4 and no terraces higher than 8. However, correlation is more difficult in Dunbridge and further north. The main difference between the two mapping approaches is the recognition of a further low terrace level in the Dunbridge area. The gravels at Kimbridge and Dunbridge have long been known to occur at two altitudinally distinct levels (Dale, 1912; White, 1912). Bridgland and Harding (1987) suggested that these distinct levels were of different ages and yielded different types of artefacts, with the Dunbridge material older than that recovered from Kimbridge. Past mapping of sheet 299 (BGS, 1975) did not differentiate these gravels but new mapping recognises this difference and attributes this low terrace level to Terrace 2-3 (Booth, 2002), although it does not define the two deposits separately. Whilst this is internally consistent for Sheet 299, it raises problems when correlating with deposits further downstream, since Terraces 2 and 3 of the main Eastern Solent / Test Valley are mapped separately on Sheet 315 and do not seem to persist north of Romsey. The correlation between Sheets 299 and 315 is one of the main areas of difference between the two more recent schemes discussed below.

Comparison of the Westaway et al. (2006) and PASHCC (Bates et al., 2004; Bates and Briant, 2009) terrace long profile projections

The Westaway et al. (2006) scheme is a combination of desk study data and numerical uplift modelling. In this region (though not in others), the data points used for terrace projection are 140 surface altitudes plotted by relating outcrop information from Edwards and Freshney (1987) and BGS (1998) to topography at a 1:25,000 scale. This is because there is no published borehole data from Mineral Assessment Reports from this region. The nature of the projection onto a downstream axis and the software

package used do not seem to be stated. The PASHCC scheme correlates gravel thicknesses and therefore often does not include information on terrace surfaces, at least where overburden thicknesses are considerable. The data used are 96 British Geological Survey (BGS) boreholes, Bridgland and Harding's (1987) test pits at Dunbridge and 12 PASHCC project test-pits, 7 of which were dated using optically-stimulated luminescence (OSL). The projections were undertaken using Rockworks software, using a multi-log profile (Bates et al., 2004) in which the distance between logs is determined by their perpendicular projection onto the profile line and their exact visual location therefore dependent on the details of the profile line chosen.

Westaway et al.'s (2006, Figure 2) terrace scheme is similar to that of Edwards and Freshney (1987), with Terraces 1 to 7 broadly corresponding to their Broadlands Farm to Bitterne terraces and thus also showing the patterns described above. They do however suggest that deposits mapped as Terrace 3 in the Warsash area correlate instead with their Belbin terrace (equivalent to Terrace 4) upstream. In addition Terrace 5 is named Gangers Wood upstream and Mallards Moor downstream. Above Edwards and Freshney's (1987) Terrace 7 (where deposits become more fragmentary), terrace fragments are correlated differently and a greater number of terrace levels is proposed. The result is a series of sub-parallel terrace levels (Figure 3a), with deviations from parallel attributed to localised higher uplift rates near Chilworth (halfway between Southampton and Romsey). In relation to correlation across BGS mapped sheets, the Westaway et al. (2006) long profiles (Figure 3a) include the lower part of Sheet 299 and the key archaeological site at Dunbridge, but their map (Figure 2) is confined to Sheet 315 of Edwards and Freshney (1987) – i.e. south of Romsey to just west of Fareham.

The PASHCC terrace scheme requires further description, since the details of the approach are listed in a hard-to-access English Heritage project report (Bates et al., 2004) with only an overview presented in Bates and Briant (2009). As stated above, terrace long profiles in this project were constructed using gravel thicknesses. It is clear from Figure 3b that there is considerable variation in altitude and thickness between borehole records attributed to different terrace deposits using the Edwards and Freshney (1987) mapping. This may reflect differences in altitude between the back and front of a terrace deposit that are masked when projecting perpendicularly onto a profile line. However, it was judged by Bates et al. (2004) that there was a relatively clear separation of deposits where boreholes broadly overlapped with each other and not with those assigned to different terrace groups (although Terraces 4 and 5 and 7 and 8 are harder to separate). For this reason, the PASHCC scheme mostly retained the earlier Edwards and Freshney (1987) stratigraphy in the area covered by BGS Sheet 315, though recognised fewer of the higher terraces. The envelope plotted for Terrace 1 in Figure 3b contains a wider range of altitudes than the other Terrace deposits. It is likely that it is a composite feature of two or three poorly separated gravel bodies deposited in different phases of the last glacial period, as is common in many lowland rivers (e.g. Gao and Boreham, 2010).

There were, however, practical considerations to assigning terrace attributions to boreholes, given the inaccuracies involved in mapping the edge of terrace deposits at the 1:50,000 scale. Indeed 29 of the 96 boreholes shown on Figure 3b were near the edge of or on the boundary between mapped units and their terrace attribution had to be decided by the project members (Bates et al., 2004). This suggests that it is harder to determine to which gravel body a record belongs when it is at the margins of a terrace deposit.

This difficulty may be a function of the variation in gravel thickness in this region (Edwards and Freshney, 1987) or the significant size of the tributary valleys that dissect the Test gravels. It is also possible that there has been some movement of gravels downslope at terrace edges. A further 2 boreholes were assigned to Terrace 10 because it did not seem possible to differentiate between Terraces 10 and 11 on altitudinal grounds and 3 boreholes in the Locks Heath area (SU 50 08 to SU 51 06) reassigned from Terrace 6 to 5 because they occurred at a height more consistent with that of Terrace 5. For presentation in this paper, a further 3 boreholes were removed from the eastern parts of Terrace 1 compared with the sequence presented in Bates and Briant (2009) because they represented submerged deposits whose depositional origin was not reliably known.

The PASHCC scheme also suggested correlations between Sheets 315 (Edwards and Freshney, 1987) and 299 (Booth, 2002). These were based on projection of gradients upstream to PASHCC field sites near Mottisfont (north of Dunbridge). Correlations were made between mapped Sheet 299 gravel bodies at Mottisfont and the Sheet 315 scheme. All deposits with the same terrace number according to Booth (2002) were then reassigned accordingly. There were no BGS boreholes in this section of the sequence, but 3 PASHCC field events in Terrace 2-3 were assigned to Terrace 5; 5 in Terrace 4 to Terrace 7 and 5 in Terrace 5-6 to Terrace 8. Similar projections of terrace locations were also made to the southeast of Sheet 315 and are shown in Figures 1 and 3b. It should be noted that the original PASHCC terrace scheme was presented with straight line projections (Bates and Briant, 2009). These have been removed for this paper and 'envelopes' drawn around each terrace deposit (Figure 3b) instead to more accurately reflect the complexity involved in correlating terrace fragments from such data. Increased complexity when the full thickness of sediment is used to define terrace bodies was also observed by Whiteman (1992) and Veldkamp and Kroonenberg (1993b).

Table 3 shows a comparison of the Westaway et al. and PASHCC stratigraphic schemes. There are three key differences between them. Firstly, the archaeologically significant sites at Dunbridge and Kimbridge that have yielded many artefacts over the years, including Levallois (Bridgland and Harding, 1987; Westaway et al., 2006) have been differently attributed. Because of the two levels within this gravel spread, the stratigraphic position of these finds has always been open to dispute. The PASHCC terrace stratigraphy places the Dunbridge (higher) deposits in Terrace 5, whereas Westaway et al. (2006) correlate them with their Belbins terrace (Terrace 4). This difference is partly due to the different gradients used in the two studies, because of the different altitudinal tie-points used in this region (terrace surfaces in Westaway et al., 2006; gravel thicknesses in the PASHCC study – Figure 3). Since there is often significant overburden (e.g. up to 2 m of brickearth in the Warsash area – see CHILL03 TP1 in Figure 4), these two sets of data are not directly comparable and you would expect the projected gradients based on them to differ. Whilst the use of gravel thicknesses is not a perfect solution because of spatial variability in the thickness of gravel deposition across the braidplain, the use of terrace surfaces to define river terrace bodies seems more problematic. This is because geomorphological activity does not cease when the river ceases to deposit a particular terrace gravel. Ongoing processes include periglacial slope processes, stream erosion, gullying and various forms of bedrock collapse. These processes will mean that 'remains of its original uppermost

surface will be modified, or in the older examples, lost completely' (Lewin and Gibbard, 2010, p. 304). The terrace surface could be either lowered due to erosional processes or raised if it is covered by later slope deposits such as the brickearth seen in CHILL03 TP1 and the sand yielding a very young OSL age from SPW03-01 (Figures 4 and 5). Post-depositional alteration of river terrace surfaces seems particularly likely in this region due to the extensive perpendicular dissection of the deposits (Figures 1 and 2). The use of surface altitudes in long profile projection does however have the advantage of greater spatial coverage, not being restricted to areas where borehole records occur. Since borehole records are usually clustered in lower terraces and urban areas this could be a particular advantage if reconstructing terrace sequences from less developed regions or countries. The difference in the terrace attribution of the key sites at Dunbridge is also a function of the difference in height within the gravel spread mapped as Terrace 2-3 by Booth (2002). The PASHCC reattribution of Terraces 2-3 in this region to Terrace 5 is based on test pitting within this mapped deposit a little way north of Dunbridge, at Mottisfont Field (Figures 1, 4, Table 3). At this location, the terrace surface occurs between 44 and 49 m O.D. (Bates et al., 2004). The Westaway et al. (2006) attribution is based on terrace surfaces shown as being around 48 m O.D. (TT5-13,14 on Figure 3a). Sections recorded in 1986 from Dunbridge (Bridgland and Harding, 1987; Figure 3b) have terrace surfaces at approximately 38 m O.D. The separation between Terraces 4 and 5 is obviously not clear at this location (Figure 3b). Further data from Dunbridge in Harding et al. (in revision) and borehole work in the region by Hatch (e.g. 2011) should help to clarify this issue.

Secondly, as noted above, Westaway et al. (2006) correlate Terrace 3 in the Warsash area with their Belbins terrace upstream (equivalent to Terrace 4). This makes the archaeological interpretation easier, since Levallois is then present in deposits associated with a single terrace (see discussion below). This difference is mainly due to a significant range of heights in Edwards and Freshney's (1987) Terrace 3 near Warsash. This includes deposits with their top surfaces between c. 25 m O.D. and c. 15 m O.D. and may reflect a difference in height between the front and back of the terrace or different thicknesses of brickearth overburden, which is a significant feature here (Figure 4). Figure 3 shows that Westaway et al. (2006) used a value of 25 m O.D. for their projection and PASHCC (Bates and Briant, 2009; Figure 4) a gravel deposit with an upper level nearer to a surface level of 15 m O.D. (the PASHCC methodology does not use actual surface heights). Hatch's (2011) reinvestigation of this area should clarify the relationships between deposits in the Warsash area and elsewhere.

Thirdly and finally in the higher terraces the Westaway et al. (2006) scheme recognises many more terrace levels than the PASHCC stratigraphy (Table 1, Figure 3). Many of these differences are not archaeologically relevant. However, the important site at Midanbury Hill (Wymer, 1993) is part of Terrace 8, which has been subdivided by Westaway et al. (2006), but not by PASHCC. They place it into a terrace called the Midanbury terrace (Figure 2, 3), which is separated from their Terrace 7 equivalent (Bitterne) by a further Rownhams Farm terrace that contains some Terrace 7 deposits. Such subdivisions were not made in the PASHCC terrace stratigraphy because of the limited borehole records and the associated lack of secure evidence for new correlations.

Both schemes show a gradual steepening of gradients with decreased altitude with steeper gradients for the lower terraces. Westaway et al. (2006) attribute this to localised

deformation on the Portsdown Anticline. Bates and Briant (2009) attribute their more abrupt gradient change to a change in catchment area following the breaching of the chalk barrier between the Isle of Wight and the Isle of Portland, after which the Test was isolated from the Avon-Stour and Frome-Piddle further west (Velegrakis et al., 1999). It should be noted that Terrace 1 in the PASHCC scheme has a shallower gradient in the projection presented here (Figure 3b) than in that presented by Bates and Briant (2009) because of the removal of three poorly-provenanced submerged gravel records in the eastern part of the region. This decreases the difference between the gradients in the two schemes.

There are therefore two reasons for the differences seen between the two terrace stratigraphic schemes. Firstly, the use of different actual data points (e.g. at Warsash and Dunbridge) has significant implications for the correlations proposed for larger areas of which these data points are assumed to be representative. Some progress can be made in addressing this by increasing the number of data points used, for example in the use of terrace surface data by Westaway et al. (2006). However the issue of trying to represent three-dimensional bodies of sediment by isolated x,y,z data points (even if they include gravel thickness data) remains. Ideally, three-dimensional sediment bodies would be represented by three-dimensional datasets, but these are complex and time-consuming to collect and interpret.

Secondly, the use of conceptually different types of data has given rise to different gradients and therefore different correlations between the fragments of terrace deposits that have been preserved (Figure 3). The use of terrace surface data does give greater spatial coverage. It is also more comparable with the gradient of the modern floodplain, which, as discussed above, is the most useful modern long profile measure for comparing with ancient river deposits. However, it may give an overly optimistic impression of certainty about the proposed correlations since geomorphological activity will continue to modify terrace surfaces for many thousands of years after deposition. Indeed, the degree of modification will increase with increasing age. This makes the proliferation of proposed terraces at higher levels in the Westaway et al. (2006) scheme problematic. It is possible that they merely represent different fragments of reworked material from a single terrace deposit, although given their antiquity it is hard to make robust statements about these.

In contrast, use of gravel thicknesses as data points makes the researcher dependent on the density of borehole coverage and location of exposure which is spatially variable. Borehole records are particularly sparse in rural areas and outside the developed world. Exposures are often concentrated in the thickest parts of a deposit because that is where quarrying is most cost-effective. Such deposits may represent unusually thick sequences, for example as preserved within gully-fills. Nonetheless we would argue that the use of gravel thicknesses gives a more robust dataset than terrace surface data, reflecting as they do a wider range of uncertainty in the data. Recognition of this uncertainty is reflected in the use of 'envelopes' rather than straight lines to constrain the data in Figure 3b. An ideal dataset for terrace reconstruction would have a greater three dimensional element still.

Despite this increased representation of the uncertainty in the data, the PASHCC stratigraphy, in common with all terrace stratigraphic schemes, remains subject to larger conceptual uncertainties relating to our understanding of river long profile development.

Not only do modern long profiles not conform to a standard concave shape, it seems unlikely that any river long profile ever reaches 'equilibrium', since the controlling factors (discharge, sediment supply, base level, erodibility of the substrate) are likely always to change before the system has managed to adjust fully (Dade and Friend, 1998). Indeed 'the time required to produce a profile without significant convexities (>1.3 Ma) is long compared to the typical timescale of environmental change' (Phillips and Lutz, 2008, p. 565).

We therefore propose that to ensure the maximum robustness, all terrace long profile reconstructions should use data that captures as much of the three-dimensional variability within the deposits as possible. Nonetheless, all terrace correlations should be treated with some caution, given the fragmentary nature of the record, the likelihood of post-depositional alteration of the sediments and the near certainty that none of the former long profiles preserved were in an equilibrium state when they were abandoned.

Terrace correlation in relation to age estimates

A further possible way of creating correlation between terrace fragments could be the use of age estimates. Biostratigraphic approaches to correlation are not possible in the eastern Solent region because there is a general lack of biological evidence within the sequences, with only some fossiliferous clays of unknown age underlying terrace gravels near Lee-on-Solent (Lake et al., 1985). Archaeological artefacts are more widespread within the region and Westaway et al.'s (2006) age model uses Palaeolithic artefact types as tie-points, supplemented by uplift modelling at key locations. Use of Palaeolithic artefacts as tie-points is based on present ideas on the earliest occupation of southern England in MIS 13 and the development in this region of (a) twisted ovate-dominant assemblages in MIS 11 (White, 1998) and (b) Levalloisian technology in late MIS 9/early MIS 8 (Bridgland, 1996). In the eastern Solent sequence, the key artefact type that aids the suggested chronology is the Levallois technique, which is present in Terrace 4 at Belbin's Pit, Terrace 3 near Warsash, and also possibly Terrace 2 near Warsash. Age estimation is based on the Warsash sequence where they appear to be located in superficial deposits. Their underlying Belbins Terrace (a composite of PASHCC Terrace 3 downstream and Terrace 4 upstream) is then assigned to MIS 10. Westaway et al. (2006) also note the presence of Levallois artefacts at Kimbridge and Dunbridge, shown on their long profile as correlating with their Belbins Terrace. However, this age model has recently been challenged by Ashton and Hosfield (2009) on two grounds. Firstly, the age used for first occupation of southern Britain is based on a reinterpretation of the age of deposits at Pakefield that Ashton and Hosfield (2009) believe to be erroneous. Secondly, Ashton and Hosfield (2009) argue that the low number and insecure provenance of Levallois artefacts in the Solent region make this an insecure tie-point to use in dating these sequences. New work at both Dunbridge (Harding et al., in revision) and Warsash (Hatch, 2011) will hopefully shed light on the exact location of the Levallois material and its stratigraphic implications.

The only numerical age estimation technique that might be possible to use to correlate these sequences is OSL dating, since most terrace gravels contain sand. This technique has been used with significant success in other similar sequences (e.g. Törnqvist et al., 2000; Toms et al., 2005). In the eastern Solent however, prior to the work of the PASHCC project the only luminescence date was a thermoluminescence (TL) date of

15.8 ± 1.5 ka from brickearth overlying Terrace 3 at Chilling Copse at SU 515 042 (Parks, 1990; Parks and Rendell, 1992).

During the PASHCC project, test pits were dug in as many terrace deposits as were accessible, in four key locations (Figure 1). The Warsash area was chosen because of the previously-recorded abundant Palaeolithic artefacts (e.g. Shackley, 1970). The archaeology of the Romsey area is also prolific, and PASHCC field investigation included sites where artefacts had previously been recorded such as in Terrace 6 at Ridge and Terrace 4 at Belbins Pit (Wymer, 1993). The investigations at Mottisfont, north of Dunbridge, allowed a more detailed focus on higher terrace deposits to provide tie-points for suggesting new correlations (Figure 3b). Investigations were also undertaken at Cams Hall in an unsuccessful attempt to trace relationships between terrace deposits and adjacent raised beach deposits of the West Sussex Coastal Plain. Figures 1 and 4 show that only some of these test pits yielded material suitable for OSL dating. In addition, only the site at Solent Breezes had sufficient exposure to allow multiple samples to be taken for replication.

The sections were recorded using a combination of vertical sediment logs, drawings and photographs. The exact location of luminescence samples was recorded to show their relative stratigraphic positions (Figure 4). Sand samples for optically-stimulated luminescence (OSL) dating were taken in opaque plastic tubing and stored in light-tight bags until processed. Sample locations were chosen to maximise the likelihood of zeroing before deposition and were usually clean, well-sorted sand beds. Preparation to quartz involved treatment with hydrochloric and hydrofluoric acids, removal of heavy minerals using sodium polytungstate and separation of the modal size fraction by wet sieving (Bates et al., 2004). Sample purity was tested using infra-red (IR) light stimulation, and those samples with feldspar contamination subjected to further treatment in fluorosilicic acid. Palaeodose was determined in the Research Laboratory for Archaeology and the History of Art, Oxford, using automated Risø measurement systems with both blue diodes and green halogen light. The Single Aliquot Regenerative (SAR) protocol of Murray and Wintle (2000) was used, with the addition of a post-IR blue OSL procedure (Banerjee et al., 2001) to further minimise feldspar contributions. Luminescence measurements were made at 125°C, with a preheat 1 (PH₁) value of 260°C for 10 s, preheat 2 (PH₂) of 220°C for 10 s and up to 6 regeneration dose points. Equivalent dose (D_e) is a weighted mean of between 6 and 12 aliquots. Luminescence behaviour was good, with low IRSL values observed for most samples, in addition to low aliquot rejection rates, good recycling ratios and low thermal transfer (Bates et al., 2004; Schwenninger et al., 2006, 2007).

It should be noted that because of the time required to irradiate samples of this age the number of aliquots measured for each sample was quite low. With such old samples it is sometimes hard to plot a meaningful equivalent dose frequency distribution and to choose a representative mean value for age estimation. To mitigate this problem, small aliquots were measured, in line with the recommendations of Olley et al. (1999). In large aliquots using the full 1 cm diameter of the disc c. 1000 grains are measured from each aliquot (grain size of 150 µm – Wallinga, 2002). In contrast, in this study grains occupied only a 2 mm diameter section of the disc and thus yielded c. 200 grains per aliquot. The use of large aliquots can mask inter-grain variability due to averaging across the aliquot. This might lead to greater age agreement between aliquots and give a

false impression of homogeneity. In comparison the signal measured from small aliquots comes from fewer grains. Thus, averaging within an aliquot is less, each aliquot is more likely to give an extreme value and true variability within the population is more likely to be detected despite limited aliquot numbers (cf. Olley et al., 1998, 1999). Single grain measurements were not deemed practicable in this case and are difficult to interpret.

Environmental dose rates were calculated by combining the results of Neutron Activation Analysis (NAA) or ICP-MS and in situ gamma spectroscopy measurements, where the latter was feasible (see Table 2). Cosmic dose rates were calculated using the equation of Prescott and Hutton (1994) and it was assumed that sediments had been buried to depth immediately after deposition. The water content used to attenuate dose rates was field moisture content (percentage dry weight of sample) with a 5% error. The results of the OSL measurements, water content values and dosimetry data are shown in Table 2.

It is clear from Figures 4 and 5 that the OSL dates undertaken during the PASHCC project are insufficiently numerous to comprehensively correlate individual terrace fragments. Whilst there were financial constraints on the amount of test pits undertaken, this sparseness also reflects the decreased likelihood of recovering suitable samples where test pitting is the main way of accessing sediments. The maximum number of samples available from a single test pit is usually two (paired replicates from the same context). If only a single test pit is undertaken from a gravel member, there is therefore a danger as in this study that some members will not have a tie-point date associated with them. Indeed, even 3-4 test pits per unit may not guarantee sampling success (e.g. at Cams Hall or Mottisfont Field – Bates et al., 2004).

Nonetheless, if reliable, these age estimates could be of some use with terrace correlation. In general, the OSL-dates in the lower parts of the eastern Solent sequence seem more reliable (Tables 2, 3; Figure 5). For example, sediments within Terrace 1 at Timsbury (HUF03-01) yield an age of c. 69 ka in the Early Devensian Stage (MIS 4), which seems plausible given that this appears to be the most recent phase of cold stage deposition within the system. This differs slightly from the Westaway et al. (2006) age model that suggests this Broadlands Farm terrace was deposited during MIS 2. However, as discussed above, this could reflect complexity of deposition within the last glacial period, where many lowland river systems show multiple poorly-separated terrace levels (e.g. Gao and Boreham, 2010).

The reliability of the dates within Terrace 2 at Solent Breezes is enhanced by replication, because it was possible to take multiple samples in a cliff exposure. These dates largely agree within errors (Table 1, Figure 5). The midpoints of all these dates place aggradation of this unit into MIS 7 (Table 2, Figure 5). This contrasts with the Westaway et al. (2006) age model that suggests this Hamble terrace was deposited during MIS 6. MIS 7 is usually associated with interglacial conditions, but considerable climatic fluctuations did occur. Therefore it is suggested that Terrace 2 relates to a colder phase within MIS 7, possibly relating to a low sea level event between the deposition of the Aldingbourne and Brighton-Norton raised beaches to the east (Bates et al., 2010). Fluvial deposition is not unknown from MIS 7, with formations in both the Somme and Yonne sequences in France (also tributaries of the low-stand Channel

River) dated to this time period (Antoine et al., 2007). It is interesting to note the hiatus between this and the age for Terrace 1, which occurs at the same time as the change in gradient discussed above. This suggests that there may have been additional phases of deposition between these two terrace levels. These may be preserved offshore as one of the three submerged terrace levels recognised by Edwards and Freshney (1987).

Age estimates from the higher terraces are harder to interpret and probably less reliable, largely because the exposure in these terraces is much less extensive. All the OSL samples were taken from smaller sections accessed through test pitting or cleaning up of remnant quarry faces (at Ridge in Terrace 6). This has two significant implications. Firstly, it was not possible to choose the best sand beds for sampling, because samples were taken only when a sand bed is present and located at a depth shallow enough to allow for safe sampling. This matters because sedimentary facies can have a noticeable effect on the scatter between aliquots (e.g. Thrasher et al., 2009) and therefore the consistency between palaeodose estimates from replicate samples, particularly when the number of aliquots measured per sample is low, as in this study. Briant et al. (2006) noticed such an effect in the western Solent terraces, with thick sand channel-fills at Stanswood Bay corresponding to tightly clustered OSL age estimates. This contrasted with samples from the Tom's Down Gravel at Badminton Farm and the Lepe Gravel at Lepe where sand lenses sampled were thinner and more discontinuous and there was less agreement between age estimates. Similar patterns have also been seen in the Fenland Basin (Briant, 2002). This probably reflects the fact that systems characterised by shallower channels are also characterised by more flashy regimes and less low-stage reworking, increasing the likelihood of deposition without sufficient prior bleaching and potentially further increasing scatter between aliquots.

None of the samples from higher terraces were taken from thick sand beds (Figure 4, HOOK03, RIDGE03, YTC03, SPW03) and so all could have been subject to this effect. At both Hook and Ridge, two samples have been measured and at neither location do the age estimates from them overlap, which is also seen in the replicate samples from the western Solent system at Badminton Farm and Lepe discussed above. Increased scatter is particularly problematic when palaeodose estimation is on the flatter section of an exponential growth curve. This increases the likelihood of difference between samples because small differences in measured luminescence equate to large differences in palaeodose. By analogy with Badminton Farm (Briant et al., 2006) the greater difference in ages between the samples from Ridge may be due to this effect. The lack of overlap between age estimates could also be argued to reflect the different methods used to determine dose rate. There is some indication that NAA analysis underestimates the true potassium content and thus the total dose rate (Schwenninger et al., 2007). However, the dose rate differences in Table 2 are small and thus unlikely to cause the difference in age estimates seen.

Secondly, when exposure is poor it is not always possible to be certain that the sample is being taken from the fluvial deposit itself. This is the case with sample SPW03-01 (X1735) which yielded an age of c. 11 ka, despite falling within the highest mapped deposit. Since the luminescence behaviour of this sample is good it seems likely that this sample records a later disturbance of the terrace deposit, or a sand body deposited overlying it, perhaps during the widespread deposition of windblown sediments recorded in the Late-glacial period (e.g. Bateman, 1995). This sample also provides

evidence for the post-depositional alteration of terrace surfaces, suggesting that caution should be used when basing terrace stratigraphies on surface altitudes.

An alternative explanation for the seemingly anomalously young ages could be that there is some sort of systematic offset when dating quartz using the SAR protocol that has yet to be identified fully. There is some suggestion of this in sites of last interglacial age, where ages are often c. 10% too young compared with independent age control (Murray et al., 2007). However Murray et al. (2008) found no evidence for this effect in quartz SAR OSL age estimates from earlier time periods, so it may not affect the dates presented here. It would seem sensible in future dating programmes to date both the feldspar and quartz fractions, now that progress is being made in addressing anomalous fading in feldspars (e.g. Jain and Ankjærgaard, 2011). It should be noted that incomplete bleaching can be problematic for young fluvial samples, yielding ages that are older than expected. However, modelling work by Bailey and Arnold (2006) suggests that older fluvial dose distributions are likely to be less affected than young fluvial samples because of the relatively small size of the residual dose. In addition, the dates in this region are younger than expected, which cannot be attributed to incomplete bleaching.

The most likely explanation for the young and scattered dates from the higher terraces in this region is that all these samples are nearing saturation. When the natural signal is close to the saturation level (the maximum signal that can be achieved, when all the trapping sites are full), aliquots with higher natural signals are often preferentially rejected because the natural signal plots above the regenerated growth curve and the D_e cannot be reliably calculated by interpolation between dose points. This can give anomalously young age estimates because only those aliquots with lower values of D_e (perhaps due to microdosimetric effects on a grain to grain scale) remain in the distribution. It is for this reason that the age estimate from YTC03-01 (X1734) is quoted as a minimum age estimate only.

Whilst there are a number of technical reasons why the dates from the higher terraces may be less reliable the main problem in this region is the lack of age estimates, as discussed above, which makes it harder to assess the robustness of age estimates. We therefore propose that good practice when using OSL dating to assess terrace ages will aim for replication of samples, targeting of thicker sand beds and use of both quartz and feldspar fractions. Where further choices have to be made, replicate samples from a single sequence are likely to yield more robust and interpretable results than single samples from multiple sequences.

Conclusion

The fragmentary nature of river terrace deposits makes it harder to construct stratigraphic schemes than for river deposits in subsiding basins. Nonetheless, it is essential because of the archaeological significance of these deposits. There are two main reasons for this difficulty. Firstly, there are intransigent conceptual issues about the nature of the 'equilibrium' long profile. Indeed there is a significant likelihood that the length of time taken for river systems to adjust is so much longer than the timescale of environmental changes during the Quaternary that this is never achieved. This means that neither a straight line nor a downstream concave profile is an adequate approximation to former long profiles. Furthermore, the relative position of any location

within a river valley to former base level is also subject to uncertainty. Secondly, there are practical procedural issues about which data is the most robust for basing projections on. Whilst use of terrace surfaces can increase the spatial coverage of a dataset, they may not represent the actual sediment bodies being correlated. The use of ‘envelopes’ surrounding records gravel thicknesses provides a more complete picture of the uncertainty associated with any single terrace sequence. However, these records can be spatially limited to more populated regions and anomalously thick sequences targeted for gravel extraction. Future work would benefit from greater use of three-dimensional datasets, given the three-dimensional nature of the sediment bodies being correlated. All terrace correlations should however be treated with caution, given the likelihood that both post-depositional alteration of the sediments has occurred and straight-line approximations are unlikely to adequately reflect former long profiles.

Whilst it is appealing to circumvent these problems by correlating deposits using age estimates, specifically sand-based OSL dating, this too is problematic. There are both financial and practical constraints that mean that it is unlikely that any project can ever generate enough age estimates to successfully correlate every terrace fragment. This is exacerbated by the need to replicate samples at single locations to ensure robustness, and the decreased likelihood of yielding suitable material when sediments are poorly exposed. Nonetheless, age estimates are important for understanding wider landscape evolution and patterns of human occupation. This can be done by the use of ‘tie-points’ within sequences established using the most robust long profile projections possible. Good practice for these ‘tie-points’ should aim for replication of samples from fewer sequences, targeting of thicker sand beds and use of both quartz and feldspar fractions.

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Field code	Laboratory code	Field moisture (%)	Basis of dose rate estimate	Total dose rate (Gy/ka)	Mean D _e (Gy)	Age estimate (ka)
SPW03-01	X1735	5.1	NAA	1.19±0.12	7.9±0.2	11.1±1.7
YTC03-01	X1734	13.6	NAA	1.61±0.14	332.8±14.2	>200
RIDGE03-01	X1575	13.4	NAA+ γ -spec	0.82±0.03	337.1±16.3	413±26
RIDGE03-02	X1576	13.0	ICP-MS+ γ -spec	0.88±0.04	246.0±12.8	280±19
HOOK03-05	X1646	15.7	NAA	1.05±0.07	245.1±35.7	233±37
HOOK03-06	X1647	16.0	ICP-MS	1.09±0.07	318.9±8.1	292±20
CHILL03-01	X1648	18.2	NAA	2.31±0.16	66.5±2.8	29±2.3
SB03-03	X1481	11.0	NAA+ γ -spec	0.89±0.05	189.7±19.8	212±25
SB03-04	X1482	9.4	NAA+ γ -spec	0.83±0.04	168.0±11.8	204±17
SB03-05	X1483	13.5	NAA+ γ -spec	0.81±0.04	188.3±16.9	231±24
SB03-06	X1484	1.3	NAA+ γ -spec	0.82±0.04	182.0±13.5	221±20
HUF03-01	X1577	8.0	NAA+ γ -spec	0.82±0.03	56.3±3.8	69±5

Table 1: OSL dosimetry, equivalent dose and age estimates for samples from the Eastern Solent and Isle of Wight. Gy = Grays, ka = thousands of years. NAA shows that a single NAA value was used to calculate dose rate; ICP-MS was used on some later samples, and gamma spectroscopy (γ -spec) at some locations. Samples from SB03 and HUF03 have previously been published in Bates *et al.* (2010).

Site & stratigraphy	Field code	Lab code	OSL date	MIS attribution
Yewtree Cottage (T8, Test Valley)	YTC03-01	X1734	> 200 ka	Older than MIS 7
Spearywell Woods (T8, Test Valley)	SPW03-01	X1735	11.1 ± 1.7 ka	MIS 1
Ridge (T6, Test Valley)	RIDGE03-01	X1575	413 ± 26 ka	MIS 12 / 11
	RIDGE03-02	X1576	280 ± 19 ka	MIS 8
Hook (T5, Eastern Solent)	HOOK03-05	X1646	233 ± 37 ka	Early MIS 7
	HOOK03-06	X1647	292 ± 20 ka	MIS 9 / 8
Chilling (brickearth overlying T3, Eastern Solent)	CHILL03-01	X1648	29 ± 2.3 ka	MIS 3
Solent Breezes (T2, Eastern Solent)	SB03-03	X1481	212 ± 25 ka	Mid MIS 7
	SB03-04	X1482	204 ± 17 ka	Late MIS 7
	SB03-05	X1483	231 ± 24 ka	Early MIS 7

	SB03-06	X1484	221 ± 20 ka	Mid MIS 7
Timsbury (T1, Test Valley)	HUF03-01	X1577	69 ± 5 ka	Early MIS 4

Table 2: OSL dates from the Eastern Solent and Isle of Wight, showing stratigraphic position and approximate MIS attribution. MIS boundaries are taken from Imbrie *et al.* (1984). Samples from SB03 and HUF03 have previously been published in Bates *et al.* (2010).

Edwards and Freshney (1987) stratigraphy	Westaway et al. (2006) revised stratigraphy	Westaway et al. (2006) age model (MIS)
Terrace 1	Broadlands Farm Gravel	2
		3-5d
		5e
Terrace 2	Hamble Gravel	6
		7
Terrace 3	Mottisfont Gravel (not recognised in the Warsash area)	8
		9
Terrace 4	Belbin Gravel (includes terrace 3 in the Warsash area)	10
		11
Terrace 5	Mallards Moor Gravel downstream (includes some T 6 deposits) Ganger Wood Gravel upstream	12
Terrace 6	Nursling Gravel	13b
Terrace 7	Bitterne Gravel	14
Terrace 8	Rownhams Farm Gravel (includes some T 7 deposits)	15b
	Midanbury Gravel	16
		17
	Castle Hill Gravel	18
		19-21
Terrace 9	Toot Hill / Netley Hill Gravels (includes T 9 and 10 gravels)	22
Terrace 10		23-25
Terrace 11	Lordswood Lane / West End Gravels (includes T 9, 10 and 11 gravels)	26
		27-35
	Chilworth Gravel	36

Table 3. Comparison of the Edwards and Freshney (1987) stratigraphy, endorsed and expanded to Sheet 299 by the PASHCC project (Bates *et al.*, 2004), with the stratigraphy of Westaway *et al.* (2006). OSL dating during the PASHCC project is reliable only from Terraces 1 and 2 and is discussed in the text.

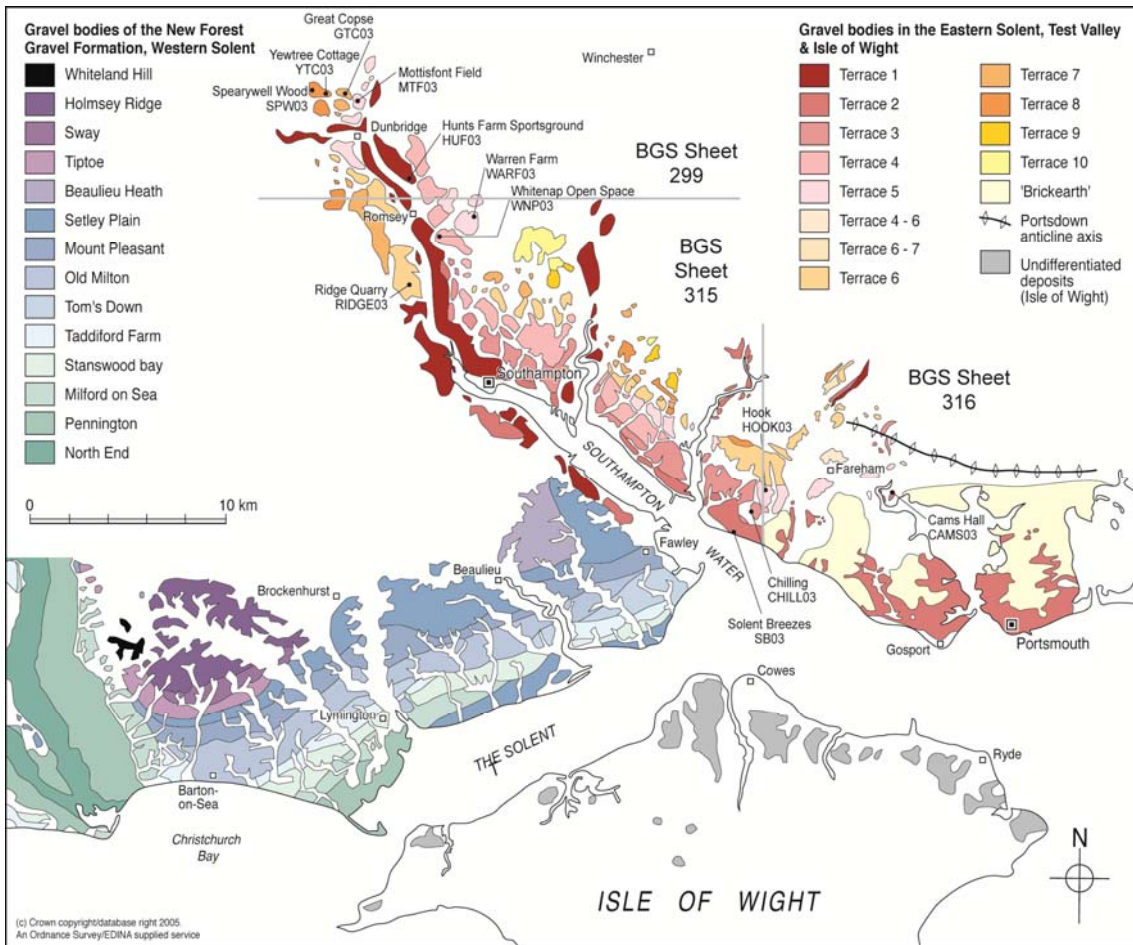
Figure 1. Location of study sites, showing fluvial deposits of the former Solent River east and west of Southampton Water and location of OSL-dated sites (filled circles) and PASHCC project sites used for terrace attribution (open circles, Figure 3). Mapped gravel members of the New Forest Gravel Formation to the west of Southampton Water follow the nomenclature of Allen (1991). Gravel bodies assigned terrace numbers follow the terminology of Edwards and Freshney (1987) with a number of changes and extended north to Sheet 299 as discussed in the text (Figure 3b). Deposits higher than Terrace 1 in the valley of the Itchen are not shown. Terrace 10 on Sheet 315 includes deposits attributed by Edwards and Freshney (1987) to Terrace 11, because it was not possible to distinguish these on altitudinal grounds. On Sheet 299, deposits mapped as Terrace 2-3 by Booth (2002) have been reassigned to Terrace 5 on altitudinal grounds based on test pits at MTF03. Deposits north of Dunbridge mapped as Terrace 4 by Booth (2002) have been reassigned to Terrace 7 on altitudinal grounds based on test pits at GTC03. Deposits north of Romsey and south of Dunbridge mapped as Terrace 5-6 by Booth (2002) have been reassigned to Terrace 6 because they are continuous with Terrace 6 deposits mapped by Edwards and Freshney (1987). Deposits north of Dunbridge mapped as Terrace 5-6 by Booth (2002) have been reassigned to terrace 8 on altitudinal grounds based on test pits at YTC03 and SPW03.

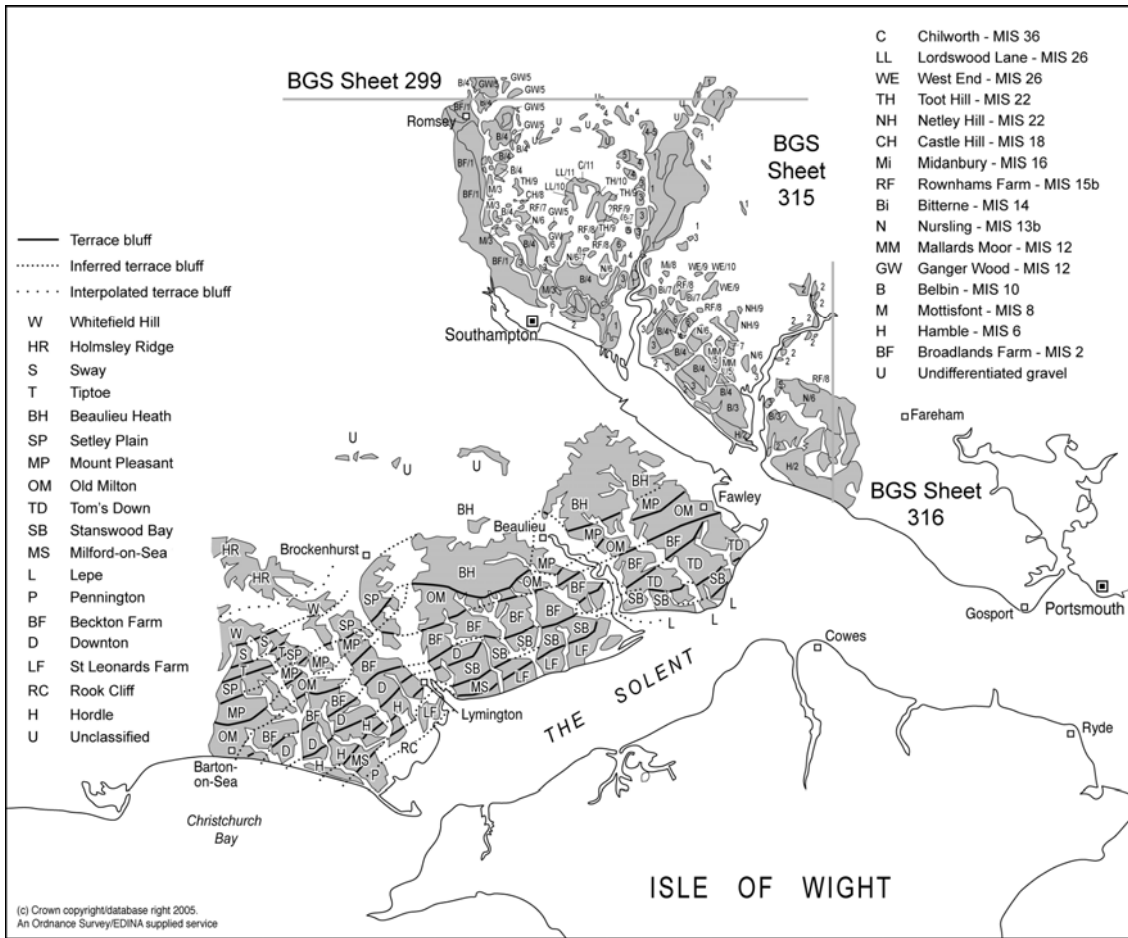
Figure 2. Distribution of gravel bodies around Southampton Water and the western end of the West Sussex Coastal Plain, after Westaway *et al.* (2006).

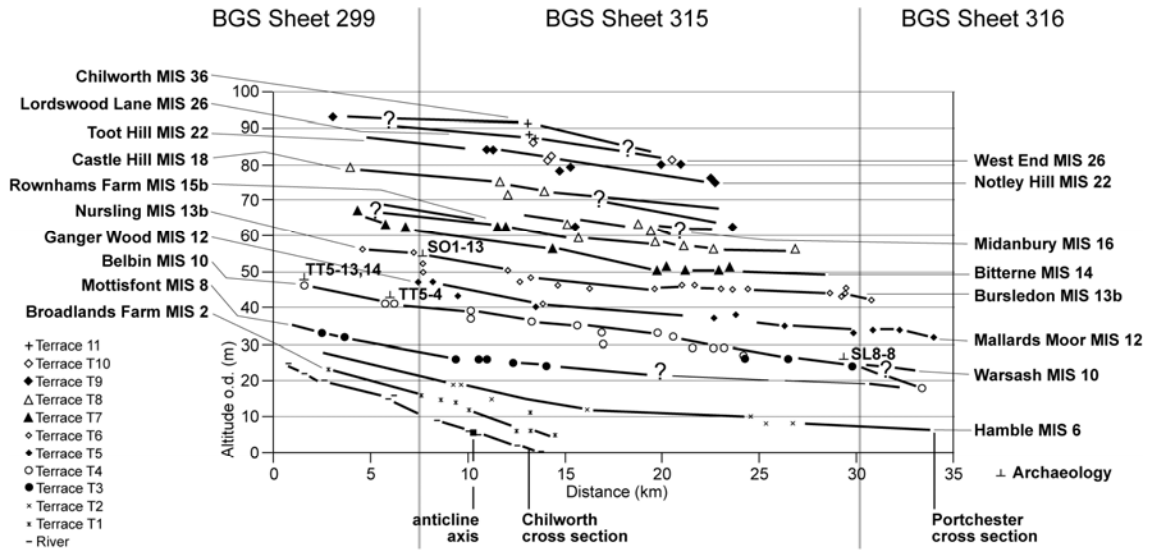
Figure 3. Long profiles of the Eastern Solent terraces using a) the Westaway *et al.* (2006) scheme based on terrace surfaces (redrawn from their Figure 17) and b) the PASHCC (Bates *et al.*, 2004; Bates and Briant, 2009) scheme based on borehole records from the British Geological Survey, PASHCC test pits and Bridgland and Harding's (1987) test pits at Dunbridge. PASHCC sites that have been OSL-dated are shown as filled rectangles. Redrawn from Bates and Briant (2009) – envelopes have been placed around groups of deposits in place of the previously presented straight line projections to reflect the true uncertainty in the projections. Also, three submerged gravel deposits have been removed from the eastern part of the region, which has decreased the steep angle previously reported for Terrace 1.

Figure 4. Sedimentary logs from OSL-dated sites within the eastern Solent, after Bates *et al.* (2004). Key is as shown.

Figure 5. Summary diagram showing OSL age estimates from the eastern Solent terraces in relation to the Marine Isotope stratigraphy, after Imbrie *et al.* (1984). Samples shown as circles have dose rates determined by both gamma spectroscopy and NAA, those as diamonds by NAA or ICP-MS only (see Table 2 for details). Samples with open circles / diamonds and dotted error bar lines are thought to be less reliable (see discussion in text). Samples from Terraces 1 and 2 have previously been published in Bates *et al.* (2010) and other dates in Bates *et al.* (2004; 2007); Bates and Briant (2009).







Archaeological sites:

- TT5-13,14 Dunbridge
- TT5-4 Belbins gravel pit
- SO1-13 Pauncefoot Hill, Romsey
- SL8-8 Warsash

