The stratigraphy and chronology of the fluvial sediments at Warsash, UK: implications for the Palaeolithic archaeology of the River Test.

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ABSTRACT

This paper reports new fieldwork at Warsash which clarifies the terrace stratigraphic framework of the Palaeolithic archaeology of the region. Sections were recorded in former gravel pits and at coastal locations, supplemented by the use of ground penetrating radar and luminescence dating techniques. The region's extensive borehole archive was also analysed to produce a revised terrace stratigraphy at Warsash and for the Test valley as a whole. At Warsash, some of the sediments previously identified as the Mottisfont/Lower Warsash Terrace are reassigned to the Hamble, Belbin/Upper Warsash and Ganger Wood/Mallards Moor Terraces. A luminescence dating programme, using test procedures not utilised in earlier dating studies in the region, yielded age estimates for the Hamble and Mottisfont/Lower Warsash Terraces at Warsash and also highlighted the complicated nature of the fluvial sediments of the River Test, suggesting that published luminescence ages for these deposits should be treated with some caution. This study indicates that the data used to construct terrace stratigraphies also requires careful assessment. The use of bedrock height and sediment thickness data produces more coherent long profile correlations than those produced by terrace surface data alone. The revised terrace stratigraphy provides the framework for the Palaeolithic archaeology at Warsash and clarifies correlations within and between archaeologically important sediments of the Test Valley, enabling it to contribute to discussions on the Lower-Middle Pleistocene settlement history of southern Britain.

Keywords: Lower–Middle Pleistocene, Warsash, Solent, River terrace stratigraphy, Long profiles, Luminescence dating (IRSL, OSL).

1. Introduction

The Solent region of southern England, including the River Test valley, contains an important Lower and Middle Palaeolithic record. Stratigraphic uncertainties have prevented this region from fully contributing to central themes of recent Palaeolithic and Quaternary research, such as understanding hominin population dynamics, regional settlement histories and technology/technological change during the Pleistocene in Britain. Studies have been concerned with the effects of climate and changing environments and landscapes, as these are seen as primary influences on hominin colonisation and population dynamics (e.g. Gamble 1992; Roebroeks *et al*. 1992; White & Schreve 2000; Ashton & Lewis 2002; Ashton & Hosfield 2010; Parfitt *et al*. 2010). The southerly position of the Solent region, and the likelihood that Pleistocene hominins accessed the area via the Channel rather than the North Sea basin route that led into the Thames and East Anglia regions, provides the potential for the examination of regional signatures in the archaeological record. Pleistocene fluvial terraces provide a fundamental resource for examining such questions of hominin occupation because they can produce coarse-resolution, time averaged records of hominin presence (e.g. Wymer 1968, 1999; Bridgland 1994, 2000, 2001; Bridgland *et al*. 2004, 2006; Hosfield 1999; Ashton & Lewis 2002; Mishra *et al*. 2007; Brown 2008; Ashton & Hosfield 2010; Ashton *et al.* 2011; Briant *et al*. 2012). The fluvial archive of the Solent River is therefore important as both the major source of Palaeolithic archaeological material in the region and as a framework for contextualising that material.

Remnant fluvial gravels of the Pleistocene River Test, a north-bank tributary of the Palaeo Solent River first recognised by Darwin-Fox (1862), survive alongside the modern course of the Test, recognisable from north of the confluence with the River Dun at Dunbridge downstream to Southampton Water (Figure 1). The substantial archaeological resource found in these terraces has been the focus of renewed interest (Davis 2013; Hatch 2014; Davis *et al*. 2016), in order to better understand its characteristics and chronology. The context of this record has until recently been unclear in two significant respects, firstly the lack of accurate location information for many artefact and assemblage find-spots (Davis 2013; Davis *et al*. 2016) and secondly deficiencies in the broader terrace stratigraphic framework, due to a lack of preserved biological material, poor chronological control, and the absence of a correlative model of terrace sediments from Bournemouth through to the Test valley. The most recent reviews of the terrace stratigraphy of the River Test (the Palaeolithic Archaeology of the Sussex/Hampshire Coastal Corridor project (PASHCC, Bates *et al*. 2004, 2007; Bates and Briant 2009; Briant *et al*. 2012) and Harding *et al*. 2012) have produced very different interpretive models, due partly to contrasting approaches to the construction of long profile projections of terrace sediments and landforms, and also to their differing interpretations of the stratigraphic and topographic data. The same issues are apparent when comparing recent reviews of the terrace stratigraphy in the wider Solent River system by Allen and Gibbard (1993) and Westaway *et al*. (2006) (Hatch 2014). Many questions remained unresolved, including the age of much of the sequence and the correlation of terraces both within and between key parts of the Solent system. Fundamental to building a robust contextual framework for the wider Solent is a better understanding of the terrace stratigraphy of archaeologically important regions such as the River Test and how they relate to other parts of the system.

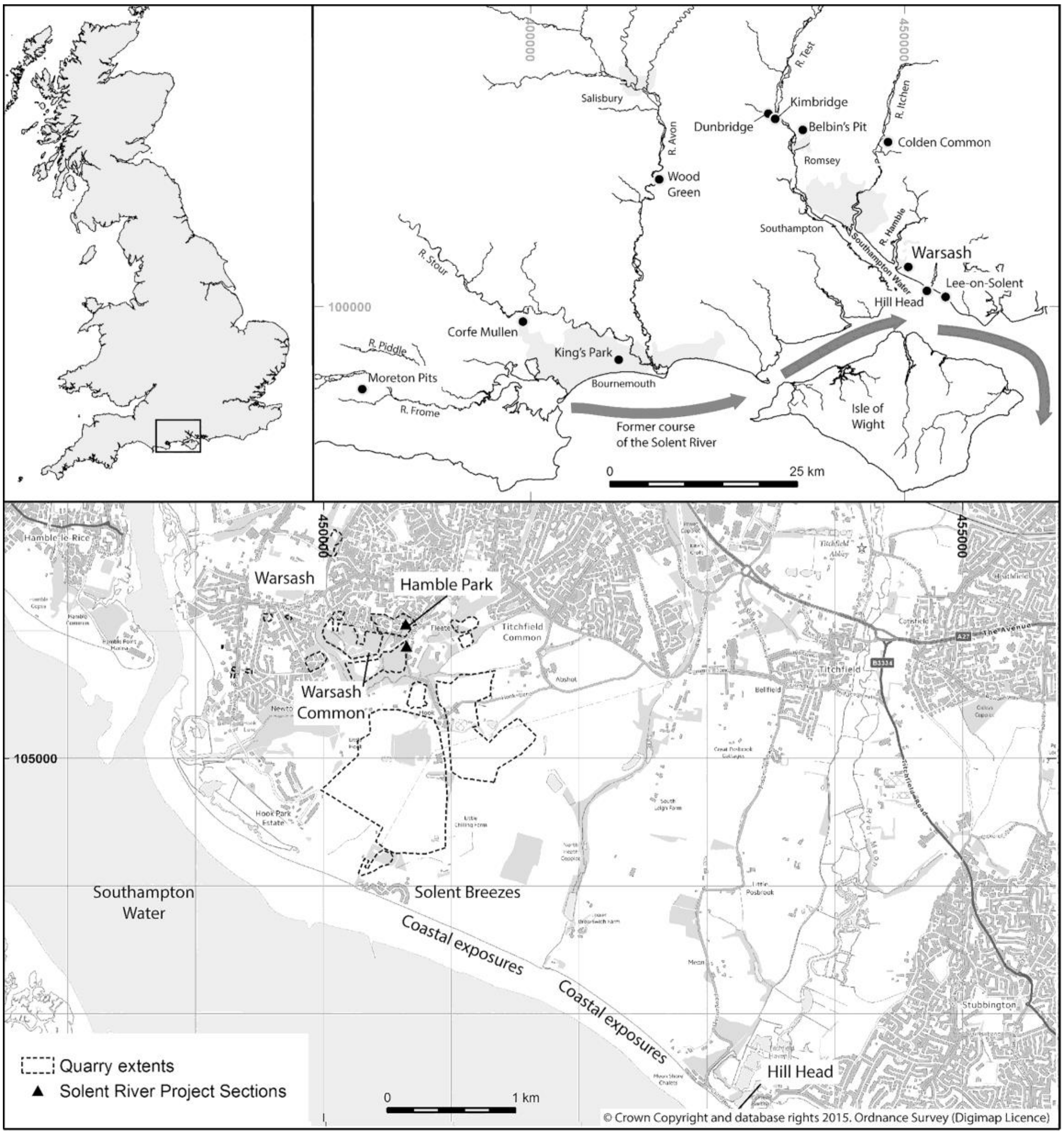

Figure 1. Location map of the Solent River region (top) and the Warsash study area (bottom).

Warsash, located near the former confluence of the River Test and River Hamble to the south-east of Southampton (Hampshire) (Figure 1), is one of the most important Palaeolithic sites in the region. The area was quarried extensively during the 20th century, and soon became recognised as a rich source of Palaeolithic artefacts (e.g. Burkitt *et al* 1939). Unfortunately the majority of the material collected at Warsash was not accompanied by detailed stratigraphic or contextual detail. However, a recent review of historic mapping and museum archives and collections enabled the locations of the key Palaeo-producing pits to be identified (Davis *et al*. 2016). Furthermore, correlating the timing of artefact collection and the history of gravel extraction in the Warsash area allowed a significant proportion of artefacts with a 'general' provenance to be assigned to the Mottisfont/Lower Warsash Terrace. The Warsash record consists of approximately 500 handaxes and 30 Levallois artefacts (Roe 1968, 1981; Wessex Archaeology 1993), which is significant in a region characterised by a scarcity of Middle Palaeolithic material (Ashton and Hosfield 2010). The handaxe assemblage includes ficrons, cleavers and plano-convex handaxes, elements that may be temporally significant (e.g. Roe 1981, 2001; Wenban-

Smith 2004; Bridgland and White 2014; White 2015). The stratigraphic relationship between the handaxe assemblage and the smaller Levallois assemblage at Warsash is significant in understanding the nature of early Middle Palaeolithic occupation, both in the Solent region and in Britain in general (Ashton and Hosfield 2010; Ashton *et al.* 2011; Pettitt & White 2012; Ashton *et al.* 2015; Davis *et al*. 2016).

2. Previous research

Burkitt *et al.* (1939) provided brief notes on the geology at Warsash as seen in a section at Newbury's Pit (Figure 2). They describe a 3.65 m sequence of fluvial deposits covering Barton Sand, which rises in hummocks. Above this lies a thin coarse brown gravel conglomerate showing evidence of solifluction. Above this lies ~1.8 to 2.4 m of coarse, loose, dark coloured ferruginous gravel, described as the source of large bifaces, sometimes heavily rolled. The unit contains a lens of non-ferruginous, grey, clayey sand with a basal gravel layer. The sand is overlain by a finer gravel than that below, less brown in colour and contorted by solifluction. This gravel was eroded and is disconformably overlain by a fine, bedded, gravelly sand with occasional sand lenses. Above this lies ~0.3 m of fine angular gravel, contorted and then covered by a buff, stony loam. The uppermost deposits are a black pebbly sand with a thin basal layer of angular gravel. Burkitt *et al.* note that Levallois flakes had been recovered in the nearby Park's Pit below a blue clay, not seen at Newbury's Pit but possibly equivalent to the buff, stony loam there.

Eleven River Test terraces are recognised in the British Geological Survey (BGS) Southampton sheet (Sheet 315) according to the mapping scheme of Edwards and Freshney (1987). The BGS Winchester sheet (Sheet 299) recognises eight upstream River Test terrace levels (Booth 2002) (Table 1). The two sheets were mapped with independent numbering schemes, which makes upstream/downstream terrace correlation of often fragmentary deposits difficult. This is particularly significant with regard to how the archaeologically important Dunbridge deposits, where over 1000 handaxes and at least four Levallois artefacts have been recovered (Roe 1968, 1981; Wessex Archaeology 1993; Harding *et al*. 2012; Davis 2013), fit into the broader downstream Test sequence. There is some agreement in the two BGS schemes as Terraces 1 and 4 persist across both sheets, while Terraces 2 and 3 cease north of Romsey and do not appear in the south of sheet 299. At Dunbridge, however, Booth (2002) recognises two intermediate terrace levels between Terraces 1 and 4 without differentiating between them, attributing them to a 'Terrace 2/3' level. This makes understanding the relationship between the assemblages at Dunbridge and Warsash difficult, in particular in determining if they are contemporaneous. The immediate Warsash area was mapped largely as Terrace 3, with Terrace 2 to the southwest, outcrops of Terrace 4 downstream, and more extensive spreads of Terrace 5 and Terrace 6 to the northeast and north respectively (Figure 2). Archaeological material has been recovered from Terraces 2 and 3 around Warsash, although contextual information was often lacking as discussed in 2.1 below. The correlation between the two BGS sheets is therefore significant for both the terrace stratigraphy of the River Test as a whole and for understanding the region's Palaeolithic archaeology.

Westaway *et al*. (2006) reinterpreted the Test stratigraphy, identifying 13 terrace levels, with the most significant alterations to the Edwards and Freshney (1987) and Booth (2002) schemes appearing above Terrace 8. Westaway *et al*. (2006) noted the first appearance of Levallois in the Test Valley occurring in or on their equivalent of Terrace 4 upstream at Dunbridge and in or on Terrace 3 downstream at Warsash. This scheme produced a revised correlation between the River Test deposits in BGS sheets 299 and 315, proposing that Terrace 4 in the Dunbridge area correlates with Terrace 3 in the Warsash area. Their Belbin/Warsash Terrace resulted in the archaeological sites at Warsash being revised to Terrace 4, rather than Terrace 3, which fits their age model for the first appearance of Levallois (around the MIS 9-8 transition). However the long profile projection of the Test sequence produced by Westaway *et al*. (2006) erroneously placed the archaeologically important gravel pits in Terrace 3 at Warsash at ~25 m OD, around 10 m too high (Ashton and Hosfield 2010; Hatch 2011; Harding *et al*. 2012). This issue was addressed by Harding *et al*. (2012), who proposed a Test terrace stratigraphy with revised correlations to those of Westaway *et al*. (2006). Harding *et al*. (2012) adjusted the attribution of the terraces at Warsash, identifying an 'upper' and 'lower' terrace with an intervening degraded bluff between ~15 and ~20 m OD, and correlated them upstream with the Belbin and Mottisfont Terraces respectively (Table 1). The Levallois artefact-bearing quarries at Warsash, located in the lower terrace, were reassigned to the Mottisfont/Lower Warsash Terrace of Harding *et al*. (2012). This interpretation was based on data obtained during a geoarchaeological watching brief carried out at Kimbridge Farm quarry (SU 321 255) between 1991 and 2007. In contrast, the PASHCC scheme correlated Booth's (2002) Terraces 2/3 at Dunbridge with Edwards and Freshney's (1987) Terraces 4 and 5.

This mismatch may partly result from the use of different datasets for correlation (Briant *et al*. 2012). The work of Westaway *et al*. (2006) and Harding *et al*. (2012) beyond the Dunbridge area was based on 140 surface elevations, plotted by relating outcrop information from Edwards and Freshney (1987) and BGS (1987; 1998) to the topography shown at 5 m contours and spot heights (to the nearest 1 m) on 1:25,000 scale topographic maps. In contrast, the PASHCC project was based on observations in 12 test pits, optically stimulated luminescence (OSL) dating, published data (Bridgland and Harding 1987) and 96 BGS boreholes, using the full gravel thickness.

Briant *et al*. (2012) highlight a number of issues that can lead to contrasting interpretations of terrace stratigraphies depending on the conceptual and methodological approaches taken. These approaches could include what data are used to describe or define terrace deposits, such as the modern terrace (i.e. ground) surface (e.g. Westaway *et* al. 2006; Harding *et al*. 2012) or the thickness of the underlying sedimentary deposit (e.g. Bates *et al*. 2004, 2007; Bates and Briant 2009; Briant *et al*. 2012). The potential for post-depositional modification from solifluction/addition of overburden, or reworking by stream erosion etc, will complicate the former approach. The latter approach may be affected by topographical variation in the palaeo-floodplain due to channelling or changing terrace thickness between the front and back of the outcrop. The choice of data used will also affect the volume of data available; terrace surfaces may be readily obtained from mapping data and provide more extensive geographical coverage while sedimentary data will be limited by the number of borehole records or fieldwork locations available.

The schemes of the PASHCC project and Westaway *et al*. (2006; cf. Harding *et al*. 2012) differ in the projection of long profiles of terrace fragments between Sheets 299 and 315, while the latter scheme also reassigns some downstream terrace deposits in Sheet 315 in the process (Table 1). For clarity this study has correlated the numbered

Test terrace deposits with the Harding *et al*. (2012) named terrace scheme, with modifications as discussed below.

Table 1. Terrace correlations between BGS sheets 299 (Winchester) and 315 (Southampton) as proposed by Harding *et al*. (2012) and the PASHCC project (Bates *et al*. 2004, 2007; Bates and Briant 2009; Briant *et al*. 2012). Terraces 9 – 11 do not appear in BGS sheet 299.

Booth 2002	PASHCC	Westaway *et al*. 2006	Harding *et al*. 2012	Edwards and Freshney 1987
BGS sheet 299	*BGS sheet 299*	*Upstream*	*Downstream*	*BGS sheet 315*
Terrace 1	Terrace 1	Broadlands Farm	Broadlands Farm	Terrace 1
	Terrace 2	Hamble	Hamble	Terrace 2
	Terrace 3			
Terrace 2/3	Terrace 4	Mottisfont	Lower Warsash	Terrace 3
	Terrace 5	Belbin	Upper Warsash	Terrace 4
Terrace 4	Terrace 6	Ganger Wood	Mallards Moor	Terrace 5
	Terrace 7			
Terrace 5/6	Terrace 8	Nursling	Nursling	Terrace 6
		Bitterne	Bitterne	Terrace 7
		Midanbury	Rownham's Farm	Terrace 8

The PASHCC project has also contributed a substantial OSL dating programme (Bates *et al*. 2004, 2010; Briant *et al*. 2006, 2009a and 2009b; Schwenninger *et al*. 2006, 2007; Briant *et al*. 2012), but confidence is limited in those dates produced above Terrace 2 of the Test (Bates and Briant 2009). The PASHCC project dated five terraces in the Test sequence, Terraces 1 (at Timsbury), 2 (at Solent Breezes), 5 (at Hook), 6 (at Ridge) and 8 (at Yewtree Cottage), and a brickearth deposit overlying Terrace 3 (at Chilling Copse) (Bates *et al*. 2004, 2010; Briant *et al*. 2012). The lowest terraces dated in the Test sequence produced ages that were judged to be the most reliable; Terrace 1 (69 ±5 ka; MIS 5a-4) and Terrace 2 (217 ±22 ka weighted mean; MIS 7) (Bates and Briant 2009; Briant *et al*. 2012). The remaining ages were problematic; the brickearth overlying Terrace 3 (29 ±2.3 ka; MIS 3) was a later slope deposit, Terrace 8 only yielded a minimum age (>200 ka; >MIS 7), and Terraces 5 (292 ±20 ka and 233 ±27 ka; MIS 9-8 and 8-7a) and 6 (280 ±19 ka and 413 ±26 ka; MIS 8 and 12-11) produced varying ages from two replicated samples at each site. Time restrictions meant that the number of aliquots measured was low, up to a maximum of 12. The methods applied by the PASHCC project, while rigorous in their analysis of the ages produced by samples, were less comprehensive in attempting to detect potential issues that are not identified during the standard SAR protocol. The same preheat temperatures of 260° C (Preheat 1) and 220° C (Preheat 2) were used for each sample, with no prior assessment (i.e. a preheat test (PHT)) of which thermal pre-treatment would remove the unstable signal component in the signal. Recycling ratios were all between ±10% and thermal transfer was low, but dose recovery tests (DRT) were not conducted. A DRT would indicate whether the applied preheat temperatures in the SAR protocol resulted in accurate recovery of a given dose. Finally, the equivalent dose (D_e) was calculated as the weighted mean of between only 5 and 12 aliquots per sample. The Harding *et al*. (2012) OSL dating programme followed a similar protocol. The anticipated antiquity of the terraces of the Solent region, and reported issues encountered during the PASHCC project, led to the development of a rigorous programme of tests in order to assess the luminescence ages produced during this study.

2.1 Brief history of archaeological research at Warsash

The majority of the Palaeolithic material collected at Warsash was recovered from gravel pits by collectors between the mid-1920s and 1950s. As with many sites of this type, the precise number of artefacts discovered is unknown. The Southern Rivers Palaeolithic Project database lists a total of 609 artefacts, including 478 handaxes and 24 Levallois artefacts, from 15 separate locations (Wessex Archaeology 1993). The majority of these (475 artefacts including 366 handaxes and 11 Levallois artefacts) are listed as a 'general' entry for the Warsash area. This reflects the frequent absence of associated contextual information and the fact that most collectors did not record the name of the pits from which the material had been recovered. A recent review of Warsash material in museum collections produced revised totals of 499 handaxes and 34 Levallois artefacts (Davis 2013; Davis *et al.* 2016).

The largest collection of Warsash palaeoliths was assembled by Mr C. J. Mogridge of Winchester Museum. His collection formed the basis of Burkitt *et al.* (1939), one of the few papers to deal directly with aspects of the Warsash Palaeolithic record prior to the current work, the others being Myra Shackley's (1974, 1978) work on site formation processes in fluvial contexts, for which Warsash was a case study. The Mogridge Collection was recovered from four pits - Dyke's Pit, New Pit, Park's Pit and Newbury's Pit - which Burkitt *et al.* describe as being located between Warsash and Hook. Burkitt *et al.* describe four series of artefacts from these sites which they define on the basis of typology, technology and condition: an Early Acheulean series consisting of crude handaxes, a Middle Acheulean series consisting of ovates, points, cleavers and hand-choppers, a Late Acheulean series that included elegant plano-convex handaxes and a Levalloisian series. The presence at Warsash of cleavers in combination with ficrons (Roe 2001) and plano-convex handaxes is notable in light of suggestions that these handaxe types are characteristic of some handaxe assemblages manufactured between MIS 10-8 (Bridgland & White 2014; Pettitt & White 2012; Roe 2001; Wenban-Smith 2004). Burkitt *et al.* indicated that their Early and Middle Acheulean series was recovered from basal gravels, while some of the Levallois material was recovered from beneath a blue clay at Park's Pit, which they suggest might be equivalent to the stony loam that overlies the terrace deposits at Newbury's Pit.

The most recent work on the Warsash Palaeolithic material is that of Davis (2013; Davis *et al.* 2016), who has been able to resolve some of the uncertainty over the provenance of the Warsash material. This has been achieved through a combination of historic map regression and the study of museum collections and archives, which has enabled Mogridge's pits to be located and identified on historic maps (Figure 2). Historic map regression revealed the expansion of quarrying in the Warsash area from north to south through time, which, when correlated with the date of recovery of the artefacts, provided a further means of estimating likely origins for much of the archaeological material. The presence at Warsash of small numbers of ficrons (2.4% of total handaxe assemblage) and cleavers (4.7%), plus a number of handaxes with full or partial plano-convex profiles (11.5%) has been confirmed. There is also an important contrast in condition between the handaxes and Levallois artefacts at Warsash. While the former are typically rolled and stained, the Levallois material is much fresher and typically patinated. This and the observations of Burkitt *et al.* (1939) support Ashton and Hosfield's (2010) assertion that the Warsash Levallois material is likely to have been recovered from sediments overlying the terrace gravels, and therefore post-date terrace aggradation.

3. Methods and materials

3.1 Sedimentology and stratigraphy

Stratigraphic data were collected at four locations in the Warsash area: Hamble Park, Warsash Common, Solent Breezes and Brownwich Lane. At Hamble Park and Warsash Common sections were exposed in old gravel pits. At Solent Breezes and Brownwich Lane, which are coastal locations, stratigraphic data were collected using a Topcon Imaging Station (IS). Sections were scanned by means of automated reflectorless surveys, where user-defined areas of a vertical surface are measured by the IS laser. Sections were between 20 m and 110 m in length, dependent on where vegetation cover or sediment slumping obscured sedimentary detail. Scanning was conducted by continuous horizontal measurement at 10 cm vertical steps. A representative vertical log was also recorded where access was possible. Sedimentary description and interpretation follow Miall's (1977, 1996) lithofacies analysis approach as modified by Briant (2002).

3.2 Boreholes

The borehole archive for the River Test was also assessed for inclusion in this study, accessed via the online BGS Geoindex resource (http://mapapps2.bgs.ac.uk/geoindex/home.html). Records that contained sands and gravels of likely fluvial origin (determined from the borehole descriptions) and provided location, ground level and bedrock contact data were included. In total, 280 borehole records from the River Test valley were utilised in assessing the fluvial terraces as discussed in Sections 6 and 8 below. This significant archive contributed to determining the location of fieldwork sites, interpretation of mapped terrace extents, the construction of terrace long profiles and cross-sections, and terrace upstream/downstream correlations within the Test Valley. Twenty one borehole records in the vicinity of Warsash were used, along with new field data, to reassess the terrace stratigraphy in this area.

3.3 Ground penetrating radar

Ground penetrating radar (GPR) was used to determine bedrock elevation and terrace deposit thickness in key areas that lacked borehole coverage. Principles of the method can be found in Bristow & Jol (2003), Moorman *et al*. (2003), Neal (2004) and Annan (2009). The survey was designed to investigate the extent and form of terrace features over transects, up to ~900 m in length at Warsash. Surveys focused on areas containing sequences of multiple terrace levels (including intervening bluffs) in order to aid stratigraphic differentiation in those areas or at locations where they could contribute to addressing specific research questions. Surveys were carried out using a Sensors and Software pulseEKKO PRO with 50 MHz antenna, in order to provide sufficient depth penetration to reach bedrock contact. The transmitting and receiving antenna are fixed (at 1 m separation) on a wheeled cart. Topographic data were collected by means of differential GPS or through surveying with a total station. GPR surveys were processed using a figure of 0.11 m ns^{-1} for radar velocity as recommended by Sensors and Software (2006) and also determined by a common mid-point test conducted at Dunbridge, which produced a velocity of 0.1091 m ns^{-1}. This value is consistent with studies which show the electromagnetic-wave velocity through unsaturated sand and gravel to vary between 0.09-0.13 m ns^{-1} (Neal and Roberts 2000). The GPR results were ground-truthed, where possible, against boreholes or sections located on or near the GPR transects. At Solent Breezes for example (see Section 5 below) the proximity of coastal sections to the GPR transects enabled comparison of GPR and geological data. Depth to bedrock within the BRW08 section logs ranges between 5.37 m and 7.38 m, comparable to the interpreted bedrock contact in GPR transects CHC A-H of 5.96 m to 6.46 m.

The GPR and IS data is summarised as representative 'synthetic borehole logs' (SBH) (Hatch 2014), which enable the large volume of linear altitudinal data generated during fieldwork to be integrated with the borehole data and be included in the generation of long profile projections. SBH logs consist of ground level and bedrock surface heights (in m OD) from which terrace deposit thickness could also be calculated

3.4 Luminescence dating

3.4.1 Sample collection and preparation

Sediment samples for luminescence dating were taken within opaque plastic tubing, sealed at the outer end and driven into cleaned section faces. Upon removal from the section, tubes were sealed at the other end to prevent light penetration and stored and transported in lightproof bags. Further (non light-sensitive) samples were then taken from a 30 cm diameter surrounding the sampled sediment for water-content and isotope analysis to measure concentrations of uranium (U) and thorium (Th) (by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)) and potassium (K) (by Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES)), carried out at the Scottish Universities Environmental Research Centre (SUERC). Luminescence samples were then taken to the luminescence lab at Queen Mary University of London for analysis. In addition to samples obtained through fieldwork at Warsash, samples that had previously been collected from the Hamble Terrace of the River Test at Brownwich Lane were also available for dating.

Samples were prepared to isolate quartz components for OSL and K-rich feldspar for Infrared Stimulated Luminescence (IRSL). Chemical preparation of samples was carried out according to standard laboratory procedures, using HCl and H_2O_2 in order to remove carbonates and organic material. Quartz and feldspar separates were isolated from heavy minerals in the sample, and then from each other, using sodium polytungstate with densities of 2.70g cm^{-3} and 2.58g cm^{-3} respectively (Mejdahl 1985). Quartz samples for OSL dating were further treated with 40% hydrofluoric acid (HF) in order to remove any feldspar component remaining (Mauz and Lang 2004). No feldspar contamination was detected in any quartz sample. Grain fractions used were 212-250 µm (HAP10-02Qz, HAP10-03Qz and BRW08-02Qz) and 180-212 µm (WAC10-03Fs).

3.4.2 Test procedures

Rigorous quality control on the single aliquot regenerative dose (SAR) protocol (Murray and Wintle 2000, 2003; Wintle and Murray 2006) was utilised in order to calculate the amount of laboratory-induced radiation that was equivalent to the dose that the sample received while buried (the equivalent dose (D_e), measured in Gy (Gray)). All luminescence measurements were conducted using a Risø TL/OSL-20 reader with an in-built 90Sr/90Y beta source. Quartz samples were stimulated with blue LEDs emitting at a wavelength of 470 ±30 nm and an intensity of 37 mW cm^{-2}. Signal readout was at 125° C for 60 s. Feldspar samples were stimulated with infrared LEDs emitting at a wavelength of 870 nm, an intensity of 117 mW cm^{-2}, and readout was at 50° C for 300 s.

Prior to the application of the SAR protocol a number of test sequences were applied to each luminescence sample in order to determine how well the sample behaved using this protocol. The dose recovery test (DRT) (Roberts *et al*. 1999; Wallinga *et al*. 2000; Murray and Wintle 2003) aims to demonstrate that the SAR protocol is able to recover a known laboratory-induced dose. The preheat test (PHT) aims to determine the appropriate preheat temperature to apply to a sample in order to remove the thermally unstable signal components in an artificially induced signal (Aitken 1985). The thermal transfer test (TTT) aims to investigate whether electrons are being transferred from thermally unstable to light-sensitive traps (Rhodes and Pownall 1994; Rhodes and Bailey 1997; Rhodes 2000), an effect that has been observed in similar depositional settings and results in erroneous D_e during the SAR protocol.

3.4.3 D_e determination and age calculation

The equivalent dose used for age calculation was based on a central age model (Galbraith *et al*. 1999), using D_e values from each aliquot that passed the test procedures. It is expected that individual grains from samples rarely receive exactly the same dose of natural radiation over time, due to sediment mixing and beta-dose heterogeneity post-burial as well as pre-burial incomplete bleaching (Galbraith and Roberts 2012).. To account for the resulting ‘overdispersion’ of D_e values a central age model is appropriate for calculating the equivalent dose used for the production of final age estimates (Galbraith and Roberts 2012). The calculations required to produce age determinations for samples were carried out in ADELE (G. Kuhlig, University of Freiberg); this program takes into account cosmic ray concentrations based on latitude and longitude, buffering due to sediment overburden and assumes a standard internal dose component provided by 13% of K in K-rich feldspar samples. Further details of the input for D_e and dose-rate determination can be found in Lukas *et al*. (2012).

4. Stratigraphy and sedimentology at Hamble Park, Warsash Common, Solent Breezes and Brownwich Lane

Warsash is located on River Test gravels predominantly mapped as the Mottisfont/Lower Warsash Terrace, with areas of the Hamble Terrace to the south (Edwards and Freshney 1987) (Figure 2). To the east there are spreads of Belbin/Upper Warsash and Ganger Wood/Mallards Moor terrace deposits and to the north the Nursling Terrace. The Pleistocene Test flowed to the south-east, and the orientation of the terrace landforms shows a north-east to south-west trending migration. In the Warsash area, access to *in situ* fluvial deposits was provided at the perimeter of two disused gravel quarries, which in turn provided samples suitable for luminescence dating. GPR surveys were also carried out along with examination of the borehole archive of the region (see below).

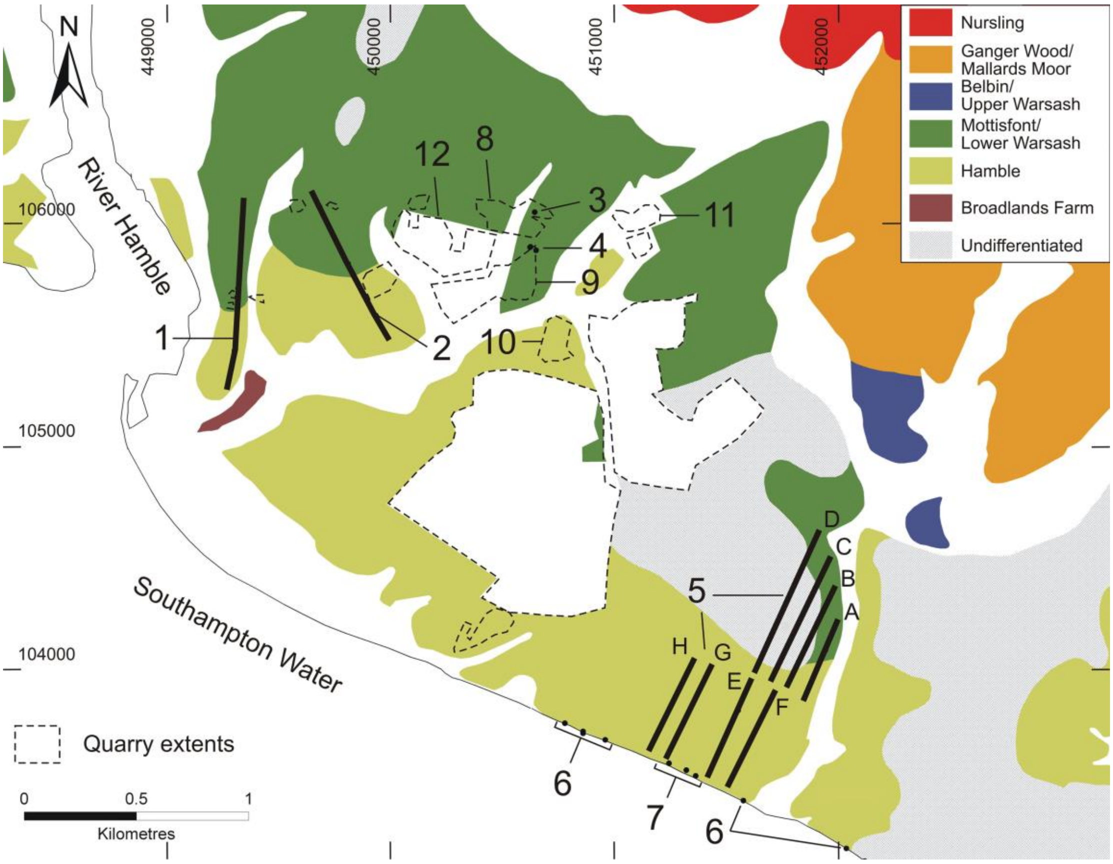

Figure 2. Location map of fieldwork sites and terrace attributions (Edwards and Freshney 1987) in the Warsash area. Fieldwork sites are numbered: 1. Newtown Road (GPR). 2. Church Road (GPR). 3. Hamble Park (excavation of quarry section HAP10 S1 and OSL/IRSL). 4. Warsash Common (excavation of quarry section WAC10 S1 and OSL/IRSL). 5. Chilling Copse (GPR lines A-H). 6. Solent Breezes (coastal section recording at SOB10 S1-5 and SOB L2). 7. Brownwich Lane (coastal section recording at BRW08 L1-3 and OSL/IRSL). 8. Park's Pit. 9. Dyke's Pit. 10. Newbury's Pit. 11. Fleet End Pit. 12. New Pit. Quarry extents from Davis *et al*. 2016.

4.1 Hamble Park and Warsash Common

Sections were recorded at Hamble Park (SU 506 060) (HAP10 S1) and Warsash Common (SU 506 058) (WAC10 S1), sites of the former Park's Pit and Dyke's Pit respectively (Figure 2). The section recorded in Hamble Park (Figure 3; Table 2) has three identifiable sedimentary units above Barton Sand bedrock. The lowest deposit comprises a horizontally bedded, clast supported, flint-dominated gravel, with sub-angular to sub-rounded clasts in a medium to coarse slightly silty sand. The unit is concreted, with an iron-pan layer 5 to 10 cm below the top of the deposit. The lower bounding surface with bedrock was not reached in the section but bedrock was located by use of a hand-auger. The next deposit comprises two sand beds: the lower bed is a moderately compact fine sand with a slightly clayey band and patches, displaying sub-parallel bedding aligned with the lower boundary, while the upper bed is a friable medium sand with some horizontal bedding, slightly gravelly in the right of the section. The sands fill a channel or scour cut into the lowest gravels, the extent of which could not be determined due to the limited exposure. The upper deposits consist of a sequence of gravelly and sandy bedform accumulation, possibly representing stacked gravel bars. The gravels are clast-supported with some crude horizontal bedding, with flint-dominated sub-angular to sub-rounded clasts. The intervening sand beds are medium-coarse with some horizontal bedding.

The restricted width of the section recorded at Warsash Common (Figure 3; Table 2) combined with a lack of diagnostic features made detailed description of the deposits difficult, although its lithological characteristics appear similar to HAP10 S1. The deposits overlie Barton Sand above an erosional unconformity and consist of a sequence of gravelly and sandy bedform elements, possibly representing stacked gravel bars. The lower gravel units are clast supported with very fine to coarse clasts, coarsening upwards from the base of the section. The upper 1.4 m of gravels consist of fine to medium clasts, generally fining upwards. The basal gravel is concreted with an iron-pan layer at the top of the deposit, similar to the basal gravel bed at Hamble Park quarry. The gravel units are separated by medium to coarse sandy bedforms with some horizontal bedding, again possibly indicative of bar-tops. Each of the gravels recorded were dominated by flint clasts.

Neither of these sites revealed the extensive buff, stony loam or 'localised' blue clay that overlies the Mottisfont/Lower Warsash Terrace (Burkitt *et al.* 1939). In addition to Park's Pit and Dyke's Pit, two further locations in the Warsash area which could potentially retain *in situ* deposits around the perimeter of former quarries Newbury's Pit and Fleet End Pit were identified (Davis 2013). However, the footprint of Newbury's Pit has since been filled-in and restored to agricultural use. Fleet End Pit was located and a small scale hand-auger survey was undertaken but the brickearth was not found.

4.2 Solent Breezes and Brownwich Lane

Solent Breezes (SU 5077 0377) is located on the eastern shore of Southampton Water, is situated around 2 km south of Warsash (Figure 2). The deposits exposed in coastal sections are of the Hamble Terrace, with the transition to the Mottisfont/Lower Warsash Terrace occurring around Chilling Copse, some 500 m inland (see below). A reconnaissance survey of undeveloped coastal areas between Solent Breezes and Lee-on-Solent identified several locations with potentially *in situ* fluvial deposits exposed. Table 2 summarises the stratigraphy of the coastal sections.

The fluvial sands and gravels seen in the coastal section at Solent Breezes are out of reach from the modern beach level. The only access to the deposits was afforded by a slumped section face near the second IS section recorded, due to modern erosion of the coast. Sedimentary log SOB10 L2 (Figure 3; Table 2) was recorded in as much detail as was possible with limited access. Six sedimentary units were identified below the topsoil level, although only the bedrock and basal fluvial sandy gravel was easily accessible. Bedrock consists of fine to medium Barton Sand, overlain by an iron-stained fine to coarse, moderately sorted gravel of sub-angular to sub-rounded clasts in a fine/fine to medium sand matrix. A sequence of sands and sandy gravels overlies the basal sandy gravel unit; the sands consist of slightly clayey fine to medium sand with no apparent bedding, while the sandy gravel units appear to consist of fine to coarse, poorly sorted gravel with sub-angular to sub-rounded clasts in a medium sand matrix.

Table 2 also shows ground level, gravel terrace thickness and bedrock height data generated from Imaging Station recording of five coastal sections at Solent Breezes. Synthetic boreholes SOB10 SBH 1 to 5 summarise the stratigraphy of the coastal sections SOB10 S1 to 5 respectively. The first three IS sections (SOB10 S1 to S3; Figure 2) provide around 270 m of near-continuous stratigraphic data in the coastal section. Sections SOB10 S4 and S5 (Figure 2) were recorded 300 to 400 m further downstream. The five coastal sections extend over ~1.4 km of exposures of sands and gravels of the Hamble Terrace at Solent Breezes. The vertical range of bedrock heights recorded along that distance, and in particular the range seen in each individual section, highlight the variety present in bedrock surface topography.

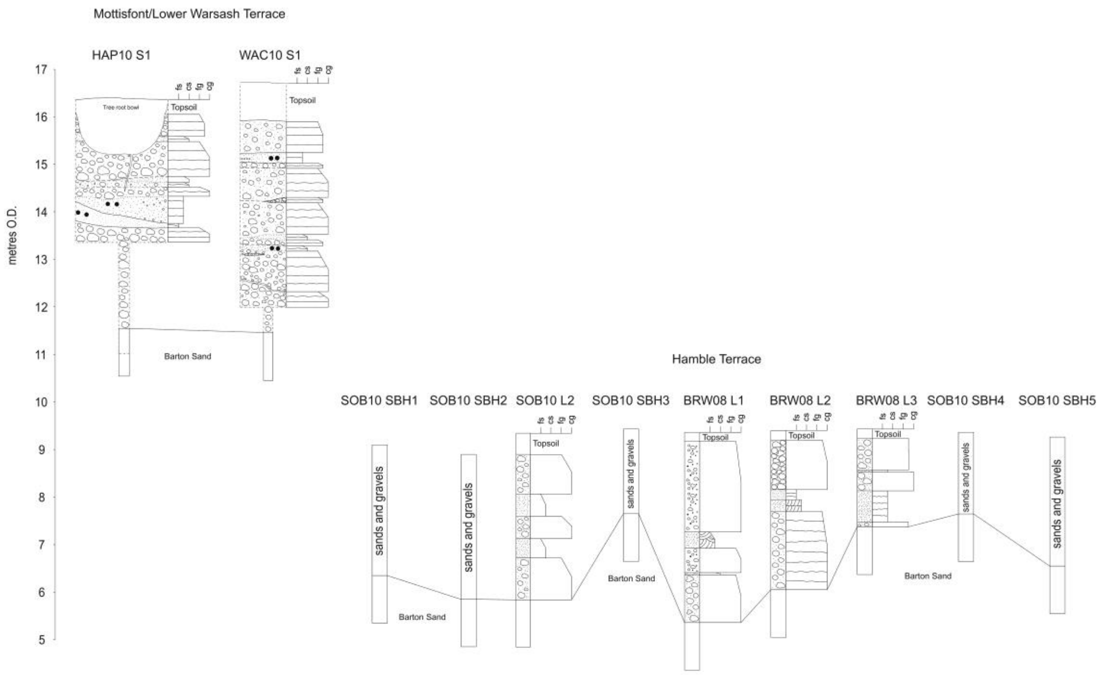

Figure 3. Quarry sections and coastal section logs recorded at Hamble Park (HAP10 S1), Warsash Common (WAC10 S1), Solent Breezes (SOB10 SBH1 to 5 and L2) and Brownwich Lane (BRW08 L1 to 3). Black circles denote luminescence sampling locations.

Three sedimentary logs, BRW08 L1 to 3, were also recorded at Brownwich Lane and samples were taken for luminescence dating (Figure 3, Table 2). Here up to 4 m of terrace deposits rest on Barton Sand bedrock, consisting of medium to coarse massive sandy gravels, overlain by a medium to coarse trough cross-stratified sand unit, which is in turn overlain by massive medium to coarse clast supported flint gravel.

Table 2. Synthetic borehole data from logs and IS sections at Hamble Park, Warsash Common, Solent Breezes and Brownwich Lane, GPR transects in the Warsash area, and BGS borehole data in the Warsash area as discussed in the text. The terrace attributions of Edwards and Freshney (1987) and Harding *et al*. (2012) are shown. The final column shows the revised terrace scheme proposed here, with terrace attributions changed from either previous scheme highlighted in **bold**. Terrace nomenclature key: Mott./LW: Mottisfont/Lower Warsash; UW: Upper Warsash; GW/MM: Ganger Wood/Mallards Moor.

Method and Reference	Easting	Northing	Ground level (m OD)	Gravel thickness (m)	Bedrock height (m OD)	Terrace E. & F. (1987)	Terrace Harding *et al*. (2012)	Revised terrace scheme
Logs and IS								
SOB10 SBH1	450775	103775	9.08	2.46	6.36	Terrace 2	Hamble	Hamble
SOB10 SBH2	450856	103738	8.90	2.80	5.85	Terrace 2	Hamble	Hamble
SOB10 SBH3	450955	103701	9.43	1.54	7.66	Terrace 2	Hamble	Hamble
SOB10 SBH4	451570	103430	9.37	1.43	7.64	Terrace 2	Hamble	Hamble
SOB10 SBH5	452110	103160	9.27	2.37	6.55	Terrace 2	Hamble	Hamble
SOB10 L2	450856	103730	9.34	3.07	5.84	Terrace 2	Hamble	Hamble
BRW08 L1	451358	103540	9.37	3.80	5.37	Terrace 2	Hamble	Hamble
BRW08 L2	451316	103566	9.40	3.15	6.05	Terrace 2	Hamble	Hamble
BRW08 L3	451239	103596	9.43	1.85	7.38	Terrace 2	Hamble	Hamble
HAP10 S1	450641	106051	16.27	4.39	11.47	Terrace 3	Mott./LW	Mott./LW
WAC10 S1	450647	105881	16.56	4.26	11.56	Terrace 3	Mott./LW	Mott./LW
GPR								
NTRD SBH 1	449340	106030	16.10	3.19	12.91	Terrace 3	Mott./LW	Mott./LW
NTRD SBH 2	449320	105711	14.32	3.89	10.43	Terrace 3	Mott./LW	Mott./LW
NTRD SBH 3	449304	105434	11.94	4.22	7.72	Terrace 2	Hamble	Hamble
CHRD SBH 1	449684	106073	16.35	4.34	12.01	Terrace 3	Mott./LW	Mott./LW
CHRD SBH 2	449810	105821	15.81	5.39	10.42	Terrace 3	Mott./LW	Mott./LW
CHRD SBH 3	449933	105591	15.36	5.94	9.42	Terrace 2	Hamble	**Mott./LW**
CHC SBH 1	451935	104101	12.14	4.40	7.74	Terrace 3	Mott./LW	**Hamble**
CHC SBH 2	451900	104145	15.04	3.95	11.09	Terrace 3	Mott./LW	Mott./LW
CHC SBH 3	451880	104167	15.55	3.60	11.95	Terrace 3	Mott./LW	Mott./LW
CHC SBH 4	451761	104210	15.74	3.61	12.13	Terrace 3	Mott./LW	Mott./LW
CHC SBH 5	451546	103832	10.82	4.67	6.15	Terrace 2	Hamble	Hamble
CHC SBH 6	451569	103825	10.50	4.54	5.96	Terrace 2	Hamble	Hamble
CHC SBH 7	451500	103840	10.90	4.44	6.46	Terrace 2	Hamble	Hamble
CHC SBH 8	451485	103844	10.92	4.60	6.32	Terrace 2	Hamble	Hamble
BGS boreholes								
SU50NW207	449340	106030	16.22	2.50	13.52	Terrace 3	Mott./LW	Mott./LW
SU50NW214	449320	105711	28.66	1.80	25.86	Terrace 3	Belbin/UW	**GW/MM**
SU50NW323	449304	105434	20.24	4.40	15.84	Terrace 3	Mott./LW	**Belbin/UW**
SU50NW324	449684	106073	20.24	3.10	16.94	Terrace 3	Mott./LW	**Belbin/UW**
SU50NW325	449810	105821	20.38	3.00	17.08	Terrace 3	Mott./LW	**Belbin/UW**
SU50NW326	449933	105591	20.79	2.50	18.29	Terrace 3	Mott./LW	**Belbin/UW**
SU50NW327	451935	104101	21.59	2.40	18.19	Terrace 3	Belbin/UW	**Belbin/UW**
SU50NW328	451900	104145	22.17	2.50	19.67	Terrace 3	Belbin/UW	**Belbin/UW**
SU50NW329	451880	104167	22.99	1.80	21.19	Terrace 3	Belbin/UW	**Belbin/UW**
SU50NW331	451761	104210	25.42	3.70	19.72	Terrace 3	Belbin/UW	**Belbin/UW**
SU50NW332	451546	103832	23.74	2.80	19.34	Terrace 3	Belbin/UW	**Belbin/UW**
SU50NW333	451569	103825	23.51	1.68	19.03	Terrace 3	Belbin/UW	**Belbin/UW**
SU50NW334	451500	103840	24.10	3.20	19.20	Terrace 3	Belbin/UW	**Belbin/UW**
SU50NW335	451485	103844	22.90	5.80	16.90	Terrace 3	Belbin/UW	**Belbin/UW**
SU50NW336	449340	106030	22.27	5.20	16.77	Terrace 3	Belbin/UW	**Belbin/UW**
SU50NW343	449320	105711	22.00	1.40	18.60	Terrace 3	Mott./LW	**Belbin/UW**
SU50SW16	449304	105434	11.55	2.10	8.25	Terrace 3	Mott./LW	**Hamble**
SU50SW21	449684	106073	13.40	2.10	10.90	Terrace 2	Hamble	**Mott./LW**

Method and Reference	Easting	Northing	Ground level (m OD)	Gravel thickness (m)	Bedrock height (m OD)	Terrace E. & F. (1987)	Terrace Harding *et al.* (2012)	Revised terrace scheme
SU50SW23	449810	105821	8.40	1.95	6.20	Terrace 2	Hamble	Hamble
SU50SW26	449933	105591	13.00	5.00	8.00	Terrace 2	Hamble	**Mott./LW**
SU50SW27	451935	104101	10.67	4.27	5.49	Terrace 2	Hamble	Hamble

5. Ground penetrating radar at Warsash, Chilling Copse and Solent Breezes

GPR surveys were carried out along Newtown Road and Church Road in Warsash itself and between Solent Breezes and Chilling Copse to the south-east of the town (Figure 2). Both areas contained the Hamble and Mottisfont/Lower Warsash terraces. Representative synthetic borehole (SBH) logs were derived from the GPR data for the three locations (Table 2).

The GPR transect at Newtown Road (SU 4934 0603) (Figure 4; Table 2) shows two bluff features in the ground level with corresponding breaks of slope in the bedrock. Surface height along the first 310 m of the transect is at around 16 m OD, with the bedrock surface at around 12.9 m OD. From around 350 m to 600 m along the transect ground level is around 14.3 m OD with bedrock between 10 and 11 m OD. At 600 m the last break in profile sees ground level at 12 m OD with bedrock at 7.7 m OD. Ground level then drops into a stream valley from 825 m along the transect.

The topography of the second transect at Church Road (SU 4968 0607), east of Newtown Road, shows a similar profile for the first 600 m, with a single gentle break of slope at around 250 m (Figure 5; Table 2). Ground level differed by less than two metres (16.62 m to 14.95 m OD) over a consistent gradient along the length of the transect, while the corresponding bedrock surface ranges from 12.79 m to 8.75 m OD. The second break of bedrock profile present at Newtown Road is not seen at Church Road; rather there appears to be a gently sloping bedrock surface towards the front edge of the Mottisfont/Lower Warsash Terrace. The breaks in profile seen at Newtown Road are however comparable to those seen in the Hamble and Mottisfont/Lower Warsash Terrace borehole logs at Warsash (see Figure 7 below).

A further GPR survey was carried out in the area between Chilling Copse (SU 5176 0420) and Solent Breezes (Figure 2), both to locate the transition between the Mottisfont/Lower Warsash and Hamble Terraces and also to provide a larger dataset of the Hamble Terrace bedrock topography and terrace thickness. Eight transects (A-H) were carried out. A similar profile was seen in each transect, lines D and E are representative of the profile produced from the Mottisfont/Lower Warsash Terrace to the Hamble Terrace (Figure 6; Table 2).

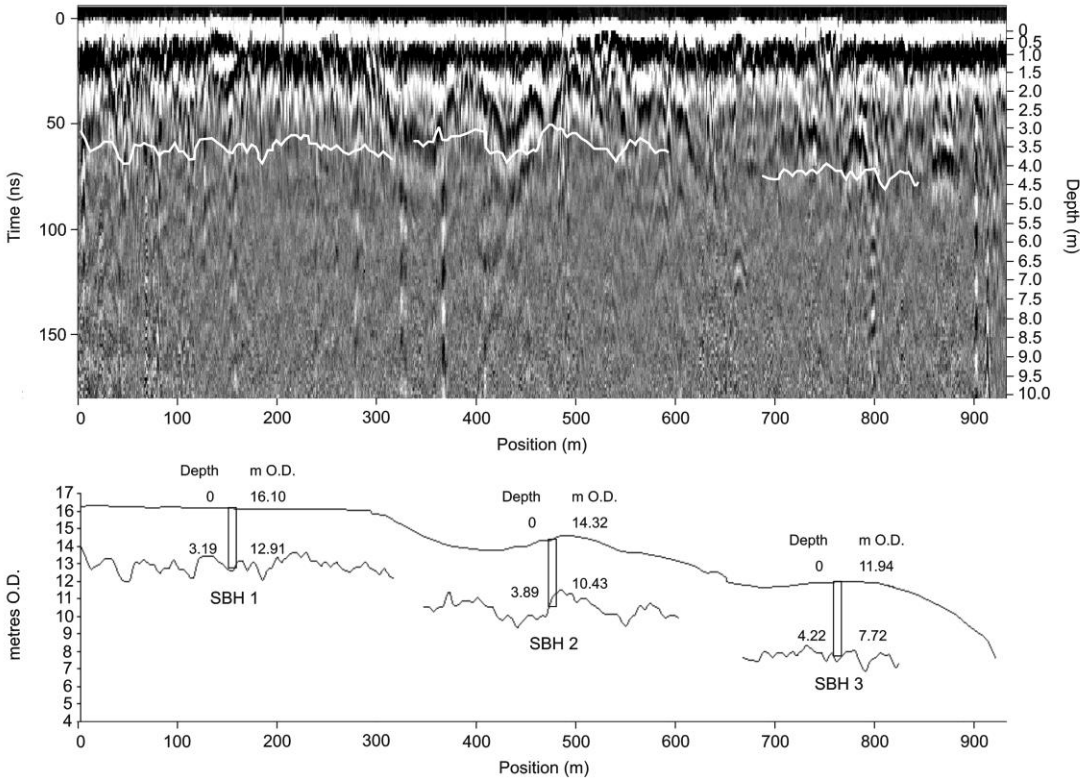

Figure 4. North to south GPR trace output of Newtown Road with interpretation of bedrock contact (top). Bottom image is a profile of the GPR transect with synthetic boreholes NTRD SBH 1, 2 and 3 locations.

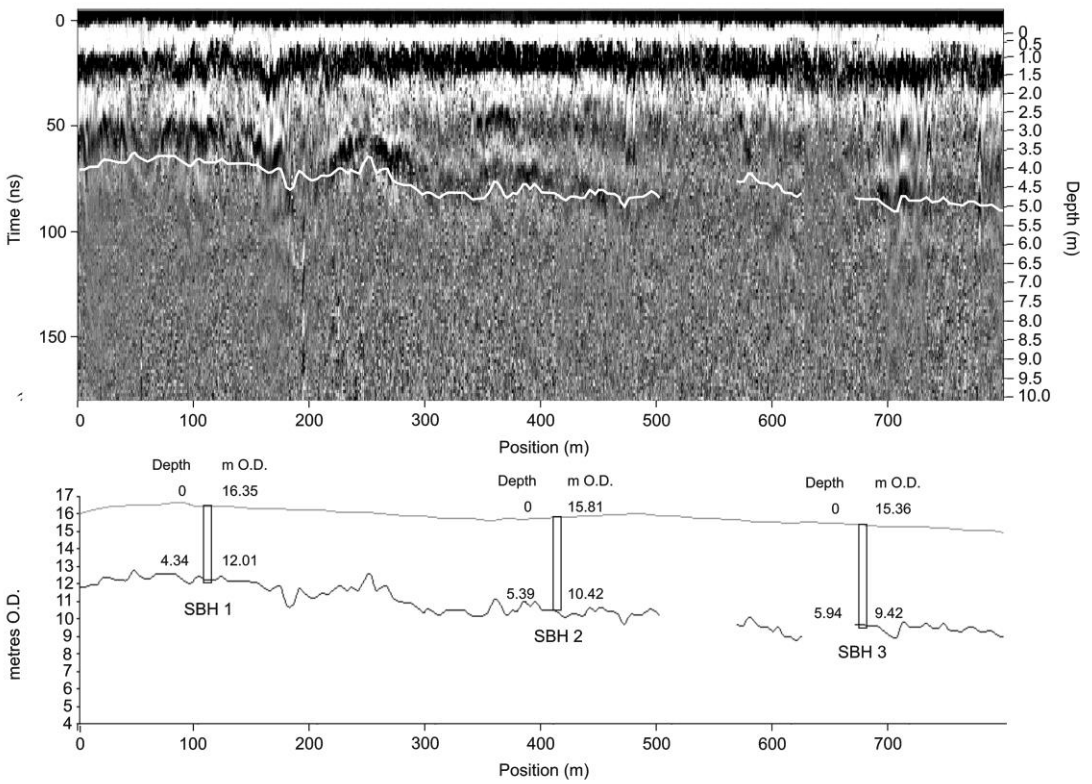

Figure 5. North to south GPR trace output of Church Road with interpretation of bedrock contact (top). Bottom image is a profile of the GPR transect with synthetic boreholes CHRD SBH 1, 2 and 3 locations.

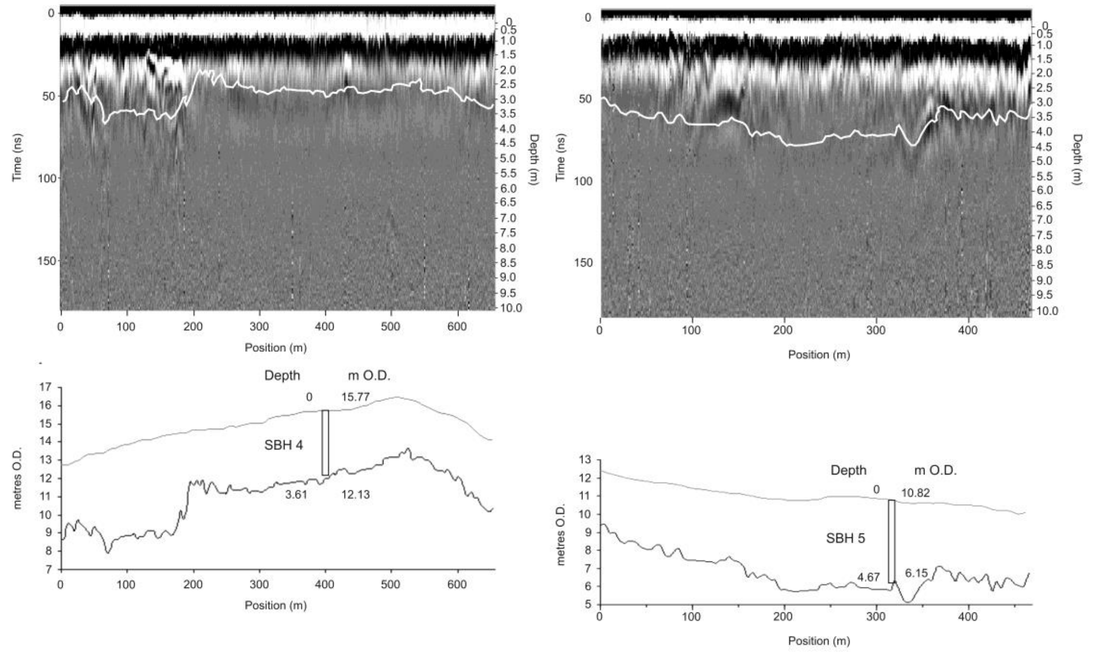

Figure 6. Northeast to southwest GPR trace outputs of Chilling Copse Lines D and E with interpretation of bedrock contact (top). Bottom image is a profile of the GPR transect with synthetic boreholes CHC SBH 4 and 5 locations and heights shown.

6. The terrace stratigraphy of the Warsash region

The integration of the new data from fieldwork around Warsash with existing borehole data (Figure 7, section A-A'; Hatch 2011) indicates that the current terrace classification is incorrect (Figure 7b) and that more than one terrace level is present in the area assigned to the Mottisfont/Lower Warsash Terrace (Figure 7c). To the north of Warsash, a series of fourteen boreholes (SU50NW323 to 329, 331 to 336 and 343) form a previously unrecognised higher terrace level and are reassigned to the Belbin/Upper Warsash Terrace (Tables 2 and 9; Figure 7c). The GPR survey at Church Road (CHRD SBH 3) revealed a continuation of the Mottisfont/Lower Warsash Terrace where Edwards and Freshney (1987) place the transition to the Hamble Terrace (Figure 7a). Boreholes SU50SW21 and SU50SW26 similarly show the Mottisfont/Lower Warsash and Hamble Terrace transition to be slightly further south-west, supported by GPR results at Chilling Copse. These re-attributions affect the area to the south/south-west of Warsash Common previously assigned to the Hamble Terrace. Here ground level is at ~15 m and, in light of the changes to the Mottisfont/Lower Warsash Terrace discussed above, these outcrops are reassigned to the Mottisfont/Lower Warsash Terrace (Figure 7a).

A further borehole record located in the Mottisfont/Lower Warsash Terrace as previously mapped required reassessment of its terrace attribution. Borehole SU50NW214 (Tables 2 and 9) is one of four logs from the north and east of Warsash that indicate a previously unmapped extension of the spread of the Ganger Wood/Mallards Moor Terrace in the area. SU50NW214 projects to a higher level than the Warsash boreholes reassigned to the Belbin/Upper Warsash Terrace in the locality, and is interpreted as representing the front edge of the terrace seen in boreholes SU50NW177, 178 and 186. SU50NW214 is reassigned from the Mottisfont/Lower Warsash Terrace to the Ganger Wood/Mallards Moor Terrace to reflect this terrace level, with corresponding adjustments made to the mapped extent of the Ganger Wood/Mallards Moor Terrace (see Figures 7 and 12).

The fieldwork and borehole data indicates that the Hamble, Mottisfont/Lower Warsash, Belbin/Upper Warsash and Ganger Wood/Mallards Moor Terraces can be identified in an area previously mapped as the Mottisfont/Lower Warsash Terrace (Table 2). Depth to bedrock under the Ganger Wood/Mallards Moor Terrace is at ~30.0 m with ground level at ~33.3 m OD. Bedrock contact under the re-assigned Belbin/Upper Warsash Terrace at Warsash averages ~18.3 m with ground level at ~22.3 m OD. The bedrock contact height below the revised Mottisfont/Lower Warsash Terrace averages ~11.2 m with ground level at ~15.4 m OD and the bedrock contact below the revised Hamble Terrace is at average ~6.6 m with ground level ~10.1 m OD. The relationship of the revised terrace stratigraphy at Warsash to the Test terraces as a whole is discussed further below.

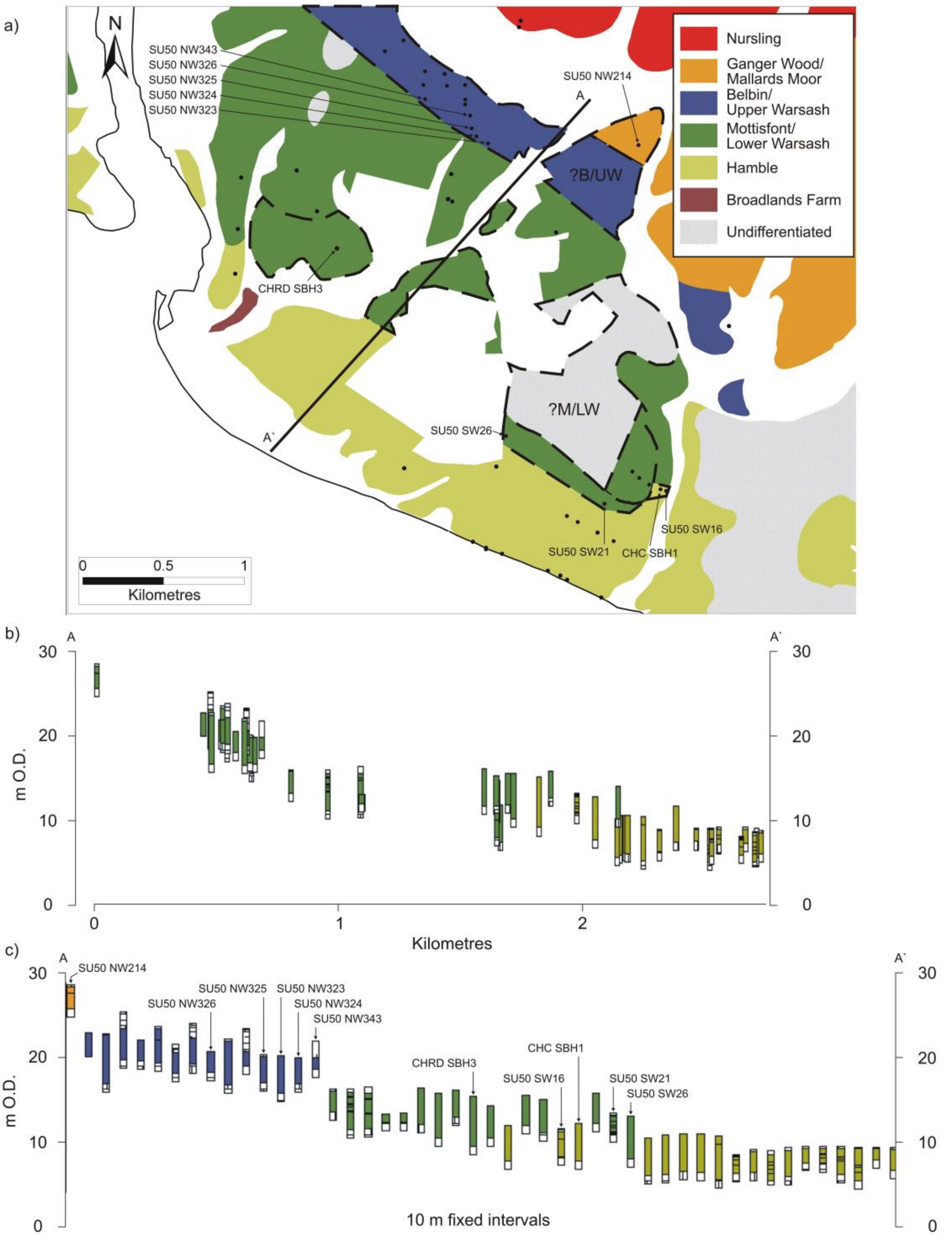

Figure 7. Section profiles of the borehole and fieldwork record at Warsash (after Hatch 2011). a) Location map with the revised terrace attributions of this study in dashed lines (cf. figure 2); b) as plotted in section (A – A´) with original terrace attributions; c) The same section plotted at fixed distances, shown with revised attributions.

7. Luminescence dating at Hamble Park, Warsash Common and Brownwich Lane: Results and discussion

The primary aim of the geochronological element to this study was to produce chronological tie-points for key terraces of the Warsash sequence. Specific geochronological objectives for the study were i) to establish the age of the archaeologically important Mottisfont/Lower Warsash Terrace, a key terrace lacking chronological data, ii) to strengthen the age attribution of the Hamble Terrace. A further element was iii) that these would enable comparison with other parts of the Test sequence, notably Dunbridge, and with the main Solent River. Such correlations further contextualise the archaeological signal of the region.

7.1 Sample context

Figure 8 shows details of the sedimentary logs recorded at the sample locations HAP10-02, HAP10-03, WAC10-03 and BRW08-02. It provides the sedimentological context for the interpretation of D_es and issues encountered with dose rate determination (see below). Table 3 provides a summary of sedimentary information at luminescence sample locations.

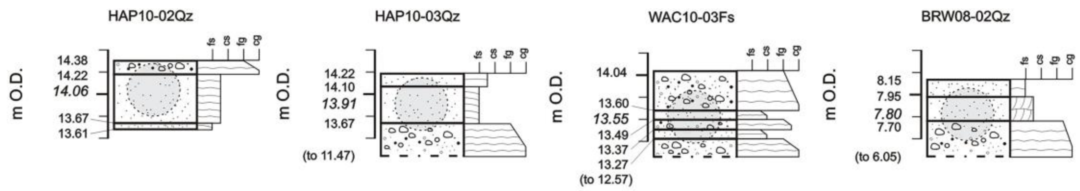

Figure 8. Sedimentary logs of luminescence sample locations HAP10-02Qz, HAP10-03Qz, WAC10-03Fs and BRW08-02Qz. Sample location altitude (m O.D.) in italics. The 60 cm field around each sample location which may contribute to the dose rate is indicated.

Table 3. Summary of sedimentary information at luminescence sample locations.

	Sample			
	HAP10-02Qz	HAP10-03Qz	BRW08-02Qz	WAC10-03Fs
Sample depth below ground surface	2.21 m	2.36 m	1.60 m	3.01 m
Sample bed sediment	Medium sand, some Fe staining, slightly gravelly in right of bed; some horizontal bedding	Fine sand, with slightly clayey grey band and patches; some Fe staining; sub-parallel bedding aligned with lower boundary	Sand. Medium grained; planar cross-stratified; yellow; pebbly in places (to left of section)	Sand, medium to coarse; some horizontal bedding; some Fe staining
Unit thickness	0.55 m	0.36 m	0.25 m	0.17 m
Overlying sediments	Sandy fine to coarse gravel with occasional cobbles; medium matrix; some crude horizontal bedding	Medium sand, some Fe staining, slightly gravelly in right of bed; some horizontal bedding	Sand. Fine grained ripples in places	Sandy, very fine to coarse gravel; medium to coarse matrix; some crude horizontal bedding
Underlying sediments	Fine sand, with slightly clayey grey band and patches; some Fe staining; sub-parallel bedding aligned with lower boundary	Sandy fine to coarse gravel with occasional cobbles; compact; ; horizontally bedded; Fe pan layer 5 to 10 cm from top of strata; Fe stained	Gravel. Crude sub-horizontal bedding; flint, medium to coarse	Sandy, very fine to medium gravel; fining upwards; horizontally bedded
Sample depth to bedrock	2.59 m	2.44 m	1.72 m	1.99 m
Bedrock	Clay, slightly silty	Clay, slightly silty	Sand	Clay, slightly silty

7.2 Test procedures

Section 2 critiqued previously published OSL dates for the Solent region. The studies reviewed there did not carry out performance tests on the reported samples to the degree conducted in this study, and that have become customary in recent luminescence studies (section 3.4.2; Wintle and Murray 2006). Therefore, these previous Solent studies would not have detected the issues that arose here which caused so many samples and aliquots to be rejected. The objective of the tests conducted here was to ascertain whether the SAR protocol was applicable to each individual sample and to find the most suitable preheat temperature that could be applied in the SAR protocol. The outcome of the testing procedure resulted in the rejection of more than half of the samples processed. This was entirely due to those samples not fulfilling any of the tests applied, for example being unable to recover known doses with no apparent systematic over- or underestimation of given doses, or show a lack of sensitivity changes to increases in preheat.

Four of the ten samples from Brownwich Lane, Hamble Park and Warsash Common (BRW08-02Qz, HAP10-02Qz, HAP10-03Qz and WAC10-03Fs) passed all three tests and were deemed suitable for the application of the SAR protocol in order to calculate luminescence ages (Table 4). The dose recovery tests showed robust SAR behaviour in only 50% of cases, as five of the ten samples failed to recover the given dose accurately. This is very low compared to most other studies, even in more problematic glaciofluvial settings (e.g. Klasen *et al.* 2006). The remaining samples showed a varied response to the dose recovery test, indicating accurate recovery at some temperature ranges but not others. More than half the samples failed to produce clear plateaux in preheat temperatures during the preheat tests. The majority of samples performed well in the thermal transfer tests, showing no increase in apparent palaeodose as the applied preheat temperature increased, demonstrating that thermal transfer is the only problem sometimes experienced elsewhere (e.g. Rhodes, 2000) that is not a problem in the samples reported here. However, some samples showed a signal transfer from light-insensitive (but heat-sensitive) to light-sensitive traps. Samples HAP10-02Qz and WAC10-03Fs indicated minor thermal transfer at and above specific temperatures which informed the preheat temperature chosen for the SAR protocol (270°C and 230°C, respectively).

Table 4. Results of the test procedures applied to samples in the study. The Dose Recovery Test (DRT) indicates preheat temperatures in the test SAR applied that resulted in accurate recovery of a given dose (preheat range 230° – 310° C); The Preheat Test (PHT) indicates the thermal pre-treatment that removes the unstable signal component in an artificially induced signal; The Thermal Transfer Test (TTT) detects thermal transfer of electrons from light-insensitive to light-sensitive traps. The final column indicates the suitability of a sample for age calculation and the appropriate preheat temperature to be used in the SAR protocol for that sample.

Sample code	DRT (°C)	PHT (°C)	TTT	Status
HAP10-02Fs	None	None	Increasing with PHT	Unsuitable
HAP10-02Qz	270° C	270° C	Some thermal transfer at 290° C	Measure at 270° C
HAP10-03Fs	250°, 270° C	None	Increasing with PHT	Unsuitable
HAP10-03Qz	270° C	270° C	No thermal transfer	Measure at 270° C
WAC10-03Fs	230-290° C	230-250° C	Some thermal transfer increasing with PHT	Measure at 230° C
WAC10-03Qz	None	None	No thermal transfer	Unsuitable
BRW08-02Fs	None	None	Some thermal transfer at 290° C	Unsuitable
BRW08-02Qz	270°, 290° C	270-290° C	No thermal transfer	Measure at 270° C

Sample code	DRT (°C)	PHT (°C)	TTT	Status
BRW08-03Fs	None	None	No thermal transfer	Unsuitable
BRW08-03Qz	230° C (weak)	None	No thermal transfer	Unsuitable

For each of the samples that passed these tests, aliquots were then screened for recycling and recuperation to check for good correction of sensitivity change and the amount of thermally transferred signal induced by the preheat stage of the SAR sequence after the application of a zero Gy regenerative dose. Table 5 shows the performance of the quartz samples HAP10-02, HAP10-03 and BRW08-02 are generally good, with mean recycling ratios of 1.02, 1.01 and 0.99 respectively showing reliable performance of the SAR. Recuperation, expressed as mean thermal transfer, is present but minimal (1.09 to 1.98%), well within the 5% maximum value of the natural signal put forward by Murray and Wintle (2000). The feldspar sample WAC10-03 similarly indicates reasonable recycling but with more thermal transfer present. Recycling ratios of 0.97 for the sample is well within the suggested limit of ±10% (Murray and Wintle 2000). The general good performance of the luminescence properties of the samples that were taken forward for dating indicates that the test procedures applied successfully isolated the well-behaved parts of the samples. The final column of Table 5 shows the number of aliquots rejected during the application of the SAR protocol as discussed in section 7.3.

Table 5. Summary of the luminescence characteristics of samples.

Field Code	Sequence number	Mean recycling ratio	Mean thermal transfer (%)	Rejected aliquots (%)
HAP10-02Qz	0006	1.01 ± 0.08	1.09 ± 0.91	34/48 (70.83)
HAP10-03Qz	0008	0.99 ± 0.07	1.98 ± 2.18	25/48 (52.08)
BRW08-02Qz	0010	1.02 ± 0.07	1.42 ± 1.08	32/48 (66.67)
WAC10-03Fs	0028	0.97 ± 0.07	4.08 ± 2.25	12/24 (50.00)

7.3 D_e determination

The performance of each aliquot measured was assessed relative to a number of criteria before they could be considered to contribute to the determination of a sample's D_e (Table 6). Firstly aliquots which produced a recycling ratio of greater than ±15% were rejected, with 65% (110 of 168) meeting the criteria for acceptance. The ±15% cut off point exceeds that of ±10% suggested by Murray and Wintle (2000). However, as there was found to be no correlation between the D_e and the recycling ratios of aliquots in each sample, a higher recycling ratio cut off point does not introduce any systemic bias. It was therefore considered reasonable to use a higher recycling ratio cut-off point. It was also deemed reasonable to increase the threshold due to the large amount of rejected samples due to poor performance generally encountered during this study. Overall 51 of the 65 aliquots (78%) used in the final age calculations (below) met the ±10% threshold. The remaining 14 aliquots were in the ±15% range.

Curve fitting was carried out using exponential or exponential and linear fits, with preference given to the method which produced the lower average error in the fit. Curve fitting was generally unproblematic, with only 11 of 110 aliquots (10%) that passed the recycling ratio criteria rejected on the criterion of producing a viable regeneration curve. Issues primarily related to apparent saturation of electron traps within grains, where the latent luminescence signal reached the point of filling all available traps over time, in effect ceasing accumulation of a signal and therefore not recording depositional time. This assessment was done visually, i.e. by assuming that any asymmetric, supralinear components of the growth curve resembled samples in saturation rather than assessing 2D0-values mathematically (cf. Lowick *et al*. 2015).

As a final measure of the success of the SAR protocol to determine the D_e of a sample, the response of each aliquot to a fixed test dose (*T*) was examined. This response shows sensitivity changes that may have been present during the measurement of the main luminescence signal (*L*) within a regenerative dose procedure such as the SAR protocol. Studies have shown that sensitivity changes can reach a factor of two when sedimentary grains are heated (Wintle and Murray 2000). To reduce the possible impact of sensitivity change an arbitrary limit of ±50% was employed, with aliquots showing more than 50% change being rejected. Under this criterion 65 of the remaining 99 aliquots (65.6%) were accepted. The cumulative effect of the performance criteria applied to aliquots resulted in a pass rate of 38.7% (65 of 168). This outcome calls into question the results of luminescence dating procedures which rely on small numbers of aliquots and/or do not apply rigorous test protocols.

It was hoped that the samples processed would each yield, after the three test stages applied, a minimum of 24 aliquots suitable for producing luminescence ages for each sample. This did not occur. Table 6 details the success rate of aliquots during the SAR protocol in regard to their recycling ratio, curve fitting and sensitivity correction. This highlights the poor performance of samples taken from the Test Valley, which is out of line with luminescence studies in other regions where a similarly rigorous testing programme has been carried out (e.g. Wallinga 2002). Figure 9 shows the distribution of D_es from the accepted aliquots which were deemed to have passed the SAR-performance tests.

Table 6. Number (and percentage) of aliquots which passed an assessment of the recycling test, curve fitting and sensitivity change within a regenerative cycle test for each sample.

Sample code	Total aliquots measured	Passed recycling test	% of total aliquots	Passed curve fitting	% of total aliquots	Passed sensitivity correction/ Final sample size	% of total aliquots
HAP10-02Qz	48	28	58.33	24	50.00	14	29.17
HAP10-03Qz	48	37	77.08	32	66.67	23	47.92
BRW08-02Qz	48	32	66.67	30	62.50	16	33.33
WAC10-03Fs	24	13	54.17	13	54.17	12	50.00

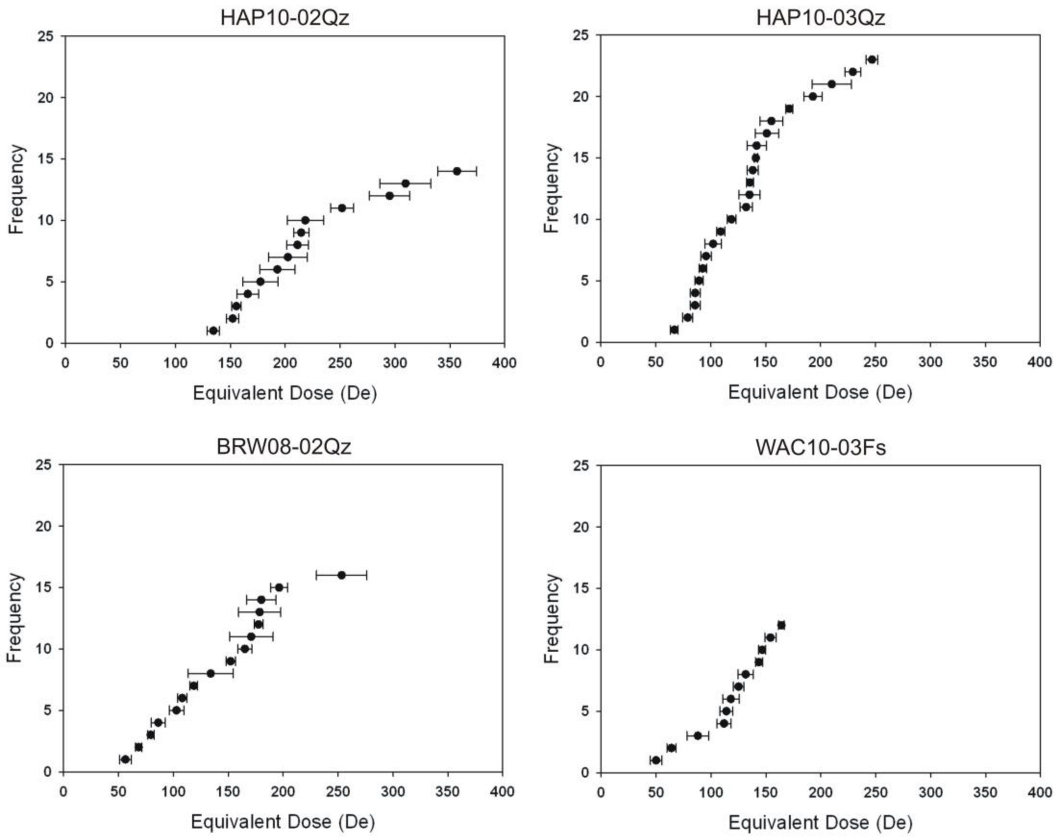

Figure 9. D_e distribution of aliquots that passed the recycling, curve fitting and sensitivity correction test stages.

The D_e distributions shown in Figure 9 display a degree of scatter. Samples BRW08-02Qz, HAP10-02Qz and HAP10-03Qz in particular exhibit a positively-skewed distribution potentially indicative of incompletely-bleached samples (Preusser *et al*. 2008). The expected antiquity of the sediments dated meant that partial bleaching was not considered to represent a significant issue; if a signal of a few thousand years did remain in incompletely bleached samples, the effect on the ages produced (>120 ka) would not be great (cf. Bailey and Arnold 2006).

7.4 Age calculation and discussion

The D_e values produced by samples BRW08-02Qz, HAP10-02Qz, HAP10-03Qz and WAC10-03Fs were used to produce age calculations (Table 7). Table 2 showed the overall good performance of the quartz samples HAP10-02, HAP10-03 and BRW08-02, while WAC10-03Fs indicated more thermal transfer present but within the 5% tolerance.

Table 7. Summary of luminescence age calculations produced using K, U and Th concentrations determined by inductively-coupled-plasma mass spectrometry (ICP-MS). n = number of aliquots used. Water content error margin ranges used in calculations: [1] 7 to zero; [2] 9.5 to zero; [3] 8.3 to zero. MIS chronology from Lisiecki and Raymo (2005). Test dose sizes: 75.40 Gy (BRW08-02Qz); 75.45 Gy (HAP10-02 & -03Qz) and 75.65 Gy (WAC10-03Fs). Regeneration dose sizes: 151.1, 302.2 and 453.3 Gy (BRW08-02Qz); 151.2, 302.4 and 453.6 Gy (HAP10-02 & -03Qz) and 151.6, 303.2 and 454.8 Gy (WAC10-03Fs). Preheat temperatures: Quartz samples 270°C for 10s; Feldspar samples 230°C for 10s.

Terrace	Sample ID	n	K (%)	U (ppm)	Th (ppm)	Water Content (%)	D (Gy ka^{-1})	D_e (Gy)	Age (ka)	MIS
Hamble	BRW08-02Qz	16	0.38 ±0.03	0.21 ± 0.01	1.18 ± 0.02	2±5 [1]	0.64 ± 0.06	127.94 ±8.68	200 ±22.8	7-6
Belbin/UW	HAP10-02Qz	14	1.27 ±0.03	0.76 ± 0.01	5.08 ± 0.02	6.4±5	1.75 ± 0.11	208.36 ±13.51	119 ±10.7	5e – 5d
Belbin/UW	HAP10-03Qz	23	0.28 ±0.01	0.25 ±0.002	1.62 ± 0.01	4.5±5 [2]	0.56 ± 0.04	127.26 ±9.79	229 ±23.7	8-7
Belbin/UW	WAC10-03Fs	12	0.67 ±0.01	0.52 ± 0.01	4.24 ±0.03	3.3±5 [3]	2.05 ± 0.12	114.1 ± 8.93	55 ±5.4	4-3

The sand bed that yielded sample WAC10-03 (Figure 8) was notably thin at just 17 cm, potentially leading to an underestimation of contributing external gamma sources from the gravels above and below (Table 3) that could include high-emitters such as flints or gravels eroded from zircon-rich source rocks. The beds that yielded BRW08-02 and HAP10-03, at 25 cm and 36 cm respectively, were also somewhat thinner than the 60 cm gamma field that may contribute to the received dose rate. The sand bed sampled for HAP10-02 reached 55 cm in thickness, and the sample location was targeted to minimise the inclusion of any visible clasts in the unit.

The use of isotope concentration data obtained by ICP-MS is also not without problems. The method analyses a subsample of sediment recovered from the location of luminescence samples taken in a sedimentary unit. Subsamples of 30-50 g were sent for analysis, from which 10g was processed, with 0.1 g subsequently dissolved and analysed by ICP-MS. It is therefore difficult to assess how representative the sample analysed is in terms of the sediment body as a whole.

A further complication arises from the inability of ICP-MS to differentiate between the different uranium decay series ^{238}U and ^{235}U. An assumption is often made during luminescence dating that the decay products of these isotopes are in equilibrium; however environmental conditions, particularly the movement of water through a sediment, can preferentially remove ^{238}U from the ^{238}U – ^{210}Pb-decay chain causing the dose rate received by that sediment to vary over time (Olley *et al*. 1996). A more homogeneous sample (e.g. dune sand or loess) would not present the same issue, nor would a chemically-closed depositional environment after burial (Olley *et al*. 1996). The effect on dose rate disequilibrium will typically be <3%, however past changes to precipitation and ground water movement can influence that effect (Olley *et al*. 1996). Given that the sediments were deposited in a fluvial environment and probably buried in a near-saturated state on the floodplain until incision caused this floodplain to be abandoned as a terrace, the water content determined in the laboratory after sampling in a wind and sun-dried exposure face is an absolute minimum value to be applied. Water content significantly lowers the dose rate a sample receives (Preusser *et al*. 2008; Lowick *et al*. 2012; Lukas *et al*. 2012); however, it is impossible to determine in retrospect whether this effect was pronounced enough in the present situations to have a notable effect, and it is merely noted that this further complication exists. Due to the issues reported above, it is also noted that sample WAC10-03Fs could suffer from anomalous fading; however, given the problems faced, no fading tests were carried out as part of this study. In summary, the age calculations presented above should only be regarded as indicative and likely represent minimum ages.

8. The terrace stratigraphy of the River Test

A dataset of 280 borehole records has been used to reassess the terrace stratigraphy of the River Test (Table 8). This dataset, consisting of surface elevation and bedrock surface elevation (m OD) and sediment body thickness, has been enhanced for a number of key locations in the study area by 30 synthetic borehole logs generated by this study and a further 41 records from other work (Bates *et al*. 2004, 2007; Bates and Briant 2009; Bridgland and Harding 1987; Harding *et al*. 2012). Each record in the dataset was assigned to a terrace level as defined by the schemes of the BGS (Edwards and Freshney 1987; Booth 2002) and Harding *et al.* (2012), with alternative attribution by PASHCC highlighted as necessary. The resulting long profile projection (Figure 10) reveals considerable variation in altitudinal range of a number of terraces. The revised long profile projection of the terrace stratigraphies of the River Test, after the interrogation and integration of data presented in this paper, is presented in Figure 11 and removes the anomalies noted in previous mapping schemes (cf. Figure 10).

Table 8. Distribution of the 280 borehole records from the Test Valley region used in the study. Terrace attributions as mapped by the BGS (Edwards and Freshney 1987; Booth 2002) and Harding *et al*. (2012).

Scheme	T1	T2	T2/3	T3	T4	T5	T6	T6/7	T7	T8	T9	T10	T11	T12	Total
BGS	64	65	1	40	35	9	28	1	5	4	22	4	2	-	280
H. *et al*.	62	64	-	18	54	16	28	1	5	12	-	-	15	5	280

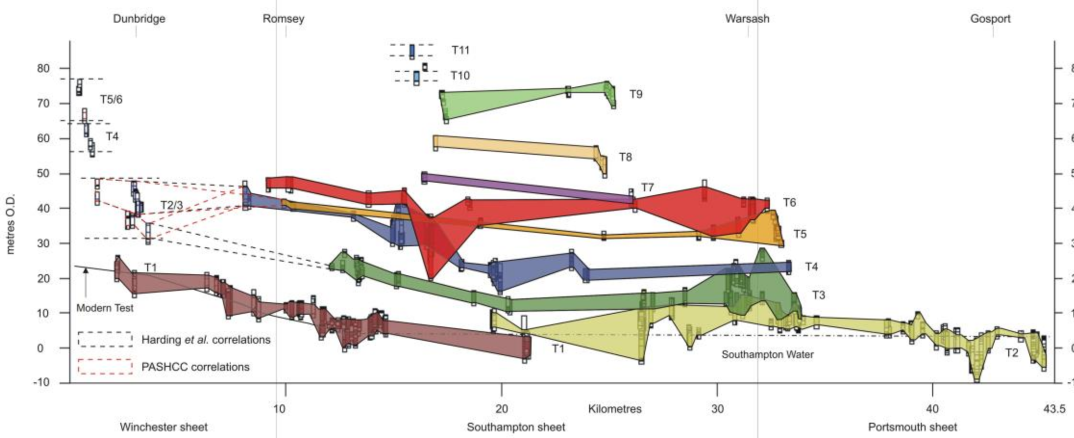

Figure 10. The terrace stratigraphy of the Test Valley using borehole and fieldwork data collated during this study. Mapping nomenclature is that of Edwards and Freshney (1987) (Southampton sheet) and Booth (2002) (Winchester sheet). Alternative terrace attributions of the Westaway *et al*. (2006) scheme around Warsash and in the higher Test terraces are set out in the text. Profile projected along N135°E with distance measured from zero at SU 31595 29000.

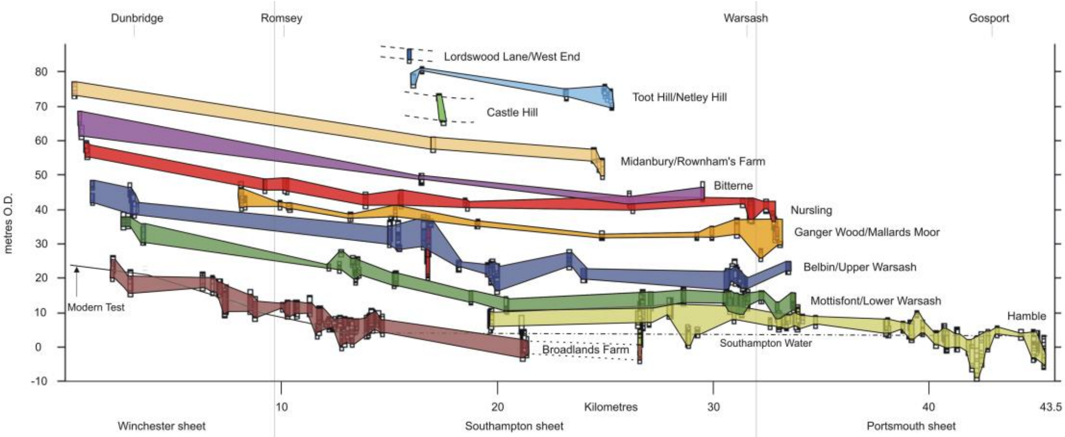

Figure 11. The terrace stratigraphy of the River Test in the Test Valley region as assigned by this study. Suggested upstream correlation between deposits in BGS map sheets 315 (Southampton) and 299 (Winchester) are shown as discussed in the text. Profile projected along N135°E with distance measured from zero at SU 31595 29000.

Figure 12 shows the location of reassigned logs, around Warsash as discussed above and in the wider Test as discussed below, and the corresponding terrace mapping revisions that resulted. Data records that have been reassigned are numbered as in Table 9.

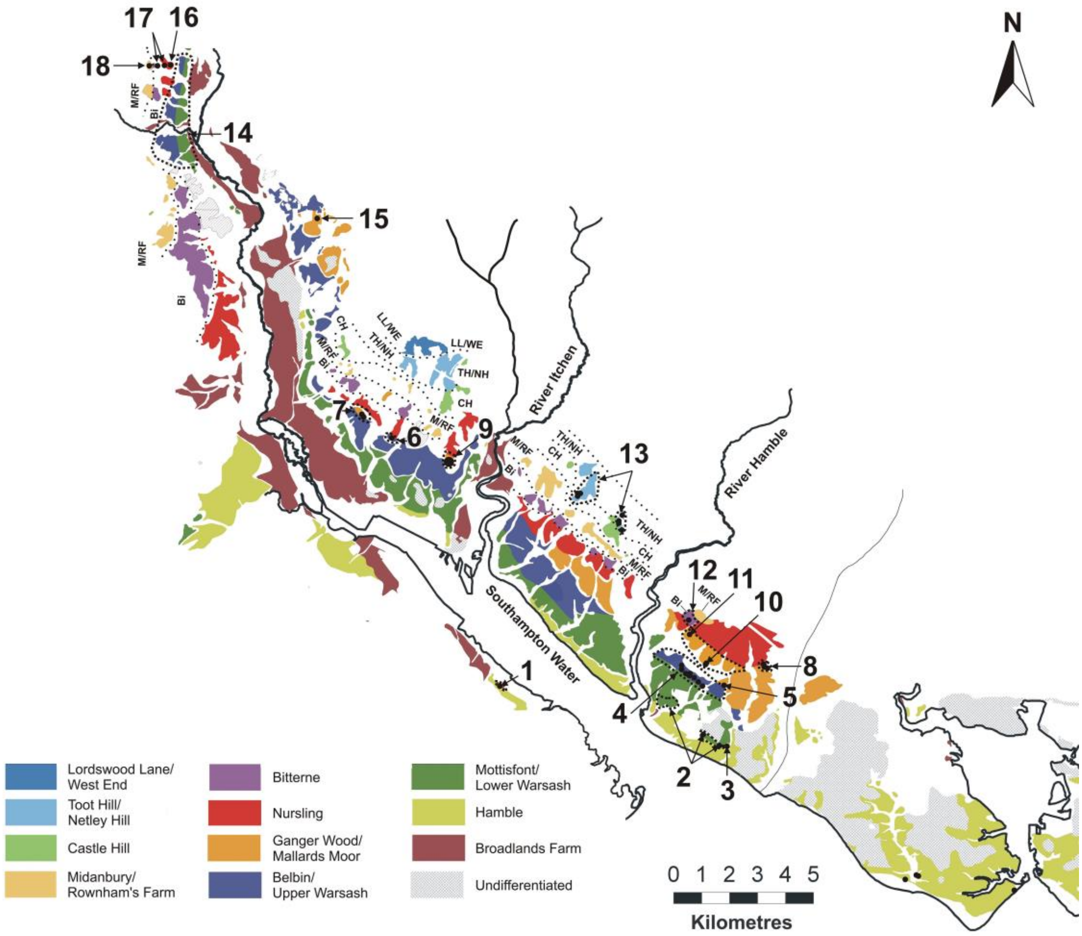

Figure 12. Mapping of the terrace stratigraphy of the River Test in the Test Valley region as reassigned by this study. Numbers show locations of borehole records and fieldwork data reassigned as in Table 9 and discussed in the text. Dashed lines show extent of mapping alterations. The fragmentary deposits of the higher terraces are labelled: Bi: Bitterne; M/RF: Midanbury/Rownham's Farm; CH: Castle Hill; TH/NH: Toot Hill/Netley Hill; LL/WE: Lordswood Lane/West End differentiated by dotted lines.

Table 9. Adjustments made to terrace correlations and borehole data points in the Test Valley region record. Columns 3, 4 and 5 show the mapping schemes of Edwards and Freshney (1987)/Booth (2002), Westaway *et al.* (2006)/Harding *et al.* (2012) and PASHCC (Bates *et al.* 2004, 2007; Bates and Briant 2009; Briant *et al.* 2012) respectively. Columns 6 and 7 show the revised attribution and rationale.

		Previous mapping				
Fig. Note	Reference	BGS	Harding et al.	PASHCC	Revised terrace	Rationale
1	SU40NW86 & 87	Terrace 2	Hamble	Terrace 2	Broadlands Farm	Altitudinally more consistent with B. Farm in the locality
2	SU50SW21 & 26; CHRD SBH3	Terrace 2	Hamble	Terrace 2	Mottisfont/ L. Warsash	Altitudinally more consistent with Mott./LW in the locality
3	SU50SW16	Terrace 3	Mottisfont/ L. Warsash	Terrace 3	Hamble	Altitudinally more consistent with Hamble in the locality
4	North Warsash boreholes (see text)	Terrace 3	Belbin/ U. Warsash	Terrace 3	Belbin/ U. Warsash	Long profile shows two terraces at Warsash; mapped as Terrace 3 by the BGS
5	SU50NW214	Terrace 3	Belbin/ U. Warsash	Terrace 3	G. Wood/ M. Moor	Altitudinally more consistent with GW/MM in the locality
6	SU31SE263, 264, 346, 347, 348 and 349	Terrace 6	Nursling	Terrace 6	Belbin/ U. Warsash	Altitudinally more consistent with Belbin/U. Warsash in the locality
7	SU31NE371D, E and G	Terrace 4	Belbin/ U. Warsash	Terrace 4	G. Wood/ M. Moor	Altitudinally more consistent with GW/MM in the locality

8	SU50NW467, 469, 470 and 471	Terrace 5	G. Wood/ M. Moor	Terrace 5	Nursling	Altitudinally more consistent with Nursling in the locality
9	SU41SW476 & 477	Terrace 6	Nursling	Terrace 6	G. Wood/ M. Moor	Altitudinally more consistent with GW/MM in the locality.
10	SU50NW177 & 178	Terrace 6	Nursling	Terrace 6	G. Wood/ M. Moor	Altitudinally more consistent with GW/MM in the locality; could be edge of terrace
11	SU50NW186	Terrace 6	Nursling	Terrace 6	G. Wood/ M. Moor	Altitudinally more consistent with GW/MM in the locality
12	SU50NW353	Terrace 6	Nursling	Terrace 6	Bitterne	Altitudinally more consistent with Bitterne in the locality.
13	SU41SE301, 303, 306, 317, 322, 324, 368-69, 371	Terrace 9	Toot Hill/ Netley Hill	Terrace 9	Toot Hill/ Netley Hill	Altitudinally more consistent with Toot Hill/ Netley Hill
14	Dunbridge area (see text)	Terrace 2/3	Mottisfont/ L. Warsash Belbin/ U. Warsash	Terrace 4 Terrace 5	Mottisfont/ L. Warsash Belbin/ U. Warsash	Altitudinally discernable into M/LW and B/UW; fits revised long profile projection of Test terraces
15	SU32 SE96, 98	Terrace 4	Belbin/ U. Warsash	Terrace 4	G. Wood/ M. Moor	Altitudinally more consistent with GW/MM in the locality.
16	GTC03 TP1, 2, 3, 4	Terrace 4	Not specified	Terrace 7	Nursling	Altitudinally more consistent with Nursling in the locality.
17	YTC03 TP1 YTC03 TP4	Terrace 4 Terrace 5/6	Bitterne	Terrace 7 Terrace 8	Bitterne	Altitudinally more consistent with Bitterne in the locality.
18	SPW03 TP1, 2, 3, 4	Terrace 5/6	Midanbury/ R. Farm	Terrace 8	Midanbury/ R. Farm	Altitudinally more consistent with M/R.F in the locality.

In order to tackle the mapping issues in the region, areas of agreed attribution of terrace extent were used to provide a foundation for re-interpretation. The Broadlands Farm Terrace of the Test consists of extensive fluvial landforms and sediments that form a coherent, identifiable terrace body. The Hamble Terrace also survives in extensive spreads of fluvial gravels at the downstream end of the course of the Test, and projects upstream at a higher level than the Broadlands Farm Terrace. As such the Broadlands Farm and Hamble Terraces formed the foundation for constructing the remainder of the Test terrace sequence.

The extent of the Broadlands Farm Terrace as assessed by this study remains largely unchanged from previous schemes, possibly with an additional recognition of the terrace at Fawley. Borehole records show two possible terrace levels (Hamble and Broadlands Farm) with a degraded surface between them, making it difficult to attribute the location of the bluff or transition between the two levels. Examining the long profile projection downstream from the Broadlands Farm Terrace (Figure 11) appears to support a Broadlands Farm Terrace attribution for the lower gravels at Fawley on altitudinal grounds, which would extend the extent of the terrace in the area (Figure 12; Table 9, note 1). The extent of the Hamble Terrace as assessed by this study similarly remained largely unchanged to previous schemes, with only minor adjustments necessary.

The upstream extent of the Mottisfont/Lower Warsash Terrace in BGS sheet 315 is unchanged, while at its downstream end around Warsash the Hamble, Belbin/Upper Warsash and Ganger Wood/Mallards Moor Terraces are recognised in deposits previously mapped as the Mottisfont/Lower Warsash Terrace as described above (Figure 12; Table 9, notes 2, 3, 4 and 5). The upstream projection of the Lower

Warsash Terrace into the Winchester map sheet (299) is consistent with correlation with the lower terrace level at Dunbridge, the Mottisfont terrace of Harding *et al*. (2012). This interpretation contrasts with the PASHCC scheme correlation of Terrace 3 in BGS sheet 315 with Terrace 4 in sheet 299 (see Table 1).

Boreholes in the Nursling Terrace at Southampton General Hospital record bedrock altitude more consistent with the Belbin/Upper Warsash Terrace locally and in long profile (Figure 12; Table 9, note 6). The mapping of the Belbin/Upper Warsash Terrace here is extended further northeast to incorporate this data. The Belbin/Upper Warsash Terrace shows variation in bedrock height and gravel thickness around Nursling (just upstream of Southampton) suggesting that the Ganger Wood/Mallards Moor Terrace is present (Figure 12; Table 9, note 7). Boreholes SU31NE371D, E and G more easily project downstream to the Ganger Wood/Mallards Moor Terrace and are reassigned accordingly. The upstream projection of the Upper Warsash Terrace into the Winchester map sheet (299) is consistent with correlation with the higher terrace level at Dunbridge, the Belbin terrace of Harding *et al*. (2012). This interpretation contrasts with the PASHCC scheme, which correlates Terrace 4 (sheet 315) with Terrace 5 (sheet 299) (see Table 1).

The Ganger Wood/Mallards Moor Terrace is extended between the Belbin/Upper Warsash Terrace and Nursling Terrace north of Warsash as discussed above. Elsewhere, minor adjustments to the extent of the Ganger Wood/Mallards Moor Terrace are made at Titchfield Park (Figure 12; Table 9, note 8), Westwood Park (Figure 12; Table 9, note 9) and Locks Heath (Figure 12; Table 9, notes 10 and 11). The upstream projection of the Ganger Wood/Mallards Moor Terrace into the Winchester BGS map sheet incorporates two boreholes at Abbotswood, mapped as the Belbin/Upper Warsash Terrace but immediately north of a spread of the Ganger Wood/Mallards Moor Terrace. These boreholes are reassigned to Ganger Wood/Mallards Moor here (Figure 12; Table 9, note 15). The Ganger Wood/Mallards Moor Terrace then seems to project further upstream above the higher terrace level at Dunbridge (interpreted here as Belbin/Upper Warsash) but below the next highest terrace level recorded at Great Copse to the north. The Ganger Wood/Mallards Moor Terrace therefore appears to be absent from the northern extent of the Test long profile projection. The reach of the Nursling Terrace in the sequence remains as previously mapped. A number of re-attributions downstream refine the lateral extent of the terrace however, such as at Southampton General Hospital mentioned above, reducing the apparent elevation discrepancies seen in long profile projection (Figure 10). The upstream projection of the Nursling Terrace into the Winchester BGS map sheet is consistent with correlation with PASHCC test pits GTC03 TP1 to 4, previously mapped (Booth 2002) as Terrace 4 (Figure 12; Table 9, note 16).

The Bitterne to Lordswood Lane/West End Terraces are poorly represented in the borehole archive. The only available data upstream in BGS sheet 299 (Winchester) are six PASHCC logs. Apart from the adjustments mentioned above, the remainder of the sequence remains largely as originally attributed by BGS mapping. The exceptions are a minor extension to the Bitterne Terrace (Figure 12; Table 9, note 12) and a group of boreholes that are mapped as the Castle Hill Terrace. When plotted in the Test long profile the latter group project to a level above Terrace 9 further upstream, indicating that at least the northeast portion of the terrace body in which they are located is more likely attributable to the Toot Hill/Netley Hill Terrace (Figure

12; Table 9, note 13). Generally the limited number of borehole records available does not provide enough detail to be sure of the attribution of the Bitterne to Lordswood Lane/West End Terraces; instead they indicate plausible height ranges and correlations only. The upstream projection of the Bitterne Terrace into the Winchester BGS map sheet seems consistent with correlation with PASHCC test pits YTC03 TP1 and 4, previously mapped (Booth 2002) as Terrace 4 (TP1) and 5/6 (TP 4) (Figure 12; Table 9, note 17). The Midanbury/Rownham's Farm Terrace projects upstream to PASHCC test pits SPW03 TP1 to 4, also previously mapped (Booth 2002) as Terrace 5/6 (Figure 12; Table 9, note 18). However these correlations can be stated with less confidence than with those of the lower terraces in the Test sequence.

9. Discussion

9.1 The stratigraphy and chronology of the Pleistocene sediments at Warsash

The terrace stratigraphy of the River Test at Warsash has been reassessed as described above, with revised attributions to the Hamble, Mottisfont/Lower Warsash, Belbin/Upper Warsash and Ganger Wood/Mallards Farm Terraces in the area (Figures 8 and 11). The new stratigraphic detail has provided a more robust framework for the spatial and temporal distribution of the Palaeolithic record. These changes are significant for understanding the characteristics of the archaeology of the Warsash region as discussed in section 9.2. The revisions have also allowed a broader reassessment of the Palaeolithic archaeology of Warsash and its place in the Lower-Middle Pleistocene settlement history of southern Britain (Davis *et al*. 2016).

Two of the luminescence ages produced here are consistent with previous age determinations and stratigraphy. Samples HAP10-03Qz (Mottisfont/Lower Warsash Terrace) and BRW08-02Qz (Hamble Terrace) are stratigraphically consistent, although uncertainties overlap. BRW08-02Qz is comparable to the youngest age already reported for the Hamble Terrace in the Test region of 203 ±17.7 ka (MIS 7c-6) (Bates *et al*. 2004), although one of the Mottisfont/Lower Warsash Terrace age calculations (HAP10-03Qz) also falls within the PASHCC study's range of MIS 8-6 for the Hamble Terrace (with a weighted mean of 217 ±22 ka (MIS 7)). BRW08-02Qz and the PASHCC results indicate a MIS 7 age for the deposition of the Hamble Terrace. The age estimate for HAP10-03Qz is comparable to the attribution of MIS 9-8 for the Mottisfont terrace at Dunbridge, based on OSL-dates (Harding *et al*. 2012). The Mottisfont Terrace appears correlative to the Lower Warsash Terrace based on luminescence dating and the long profile presented above (Figure 11). The results produced here suggest aggradation of the Mottisfont/Lower Warsash Terrace during MIS 8 followed by the Hamble Terrace during MIS 7. An age estimate of MIS 8 for the aggradation of the Mottisfont/Lower Warsash Terrace may suggest that the Warsash handaxe assemblage derives from MIS 9 or earlier. It is noted that further dating studies are required to address the methodological issues identified above; therefore, any correlations attempted here are tentative and have to be treated with caution.

Finally, the quartz sample HAP10-02Qz and feldspar sample WAC10-03Fs both appear too young. Both derive from the same fluvial terrace as HAP10-03Qz, located in neighbouring gravel pits at Warsash at similar altitude, yet HAP10-02Qz produced an indicative age of 119 ±10.7 ka (MIS 5e-5d) and WAC10-03Fs an age of 55 ±5.4 ka

(MIS 4-3). This may be due to inhomogeneity of samples not detected by ICP-MS analysis or other problems that are inherent in the bedrock geology of the catchment. The dose rates calculated for HAP10-02Qz and WAC10-03Fs are higher than those calculated in the PASCHH studies (Schwenninger *et al.* 2006, 2007), which reported rates of 0.81-1.19 (Gy ka^{-1}) for the majority (10) of Test samples; they are also around 3 to 4 times those of BRW08-02Qz and HAP10-03Qz (Table 7). The PASCHH project did produce two samples with higher rates of 1.61 and 2.31 (Gy ka^{-1}), comparable to those for samples HAP10-02Qz and WAC10-03Fs, but these were based on Neutron Activation Analysis (NAA) rather than *in situ* gamma spectrometry. For sample HAP10-02Qz, applying a dose rate towards the lower range measured by PASHCC (~0.81-0.90 Gy ka^{-1}) would produce an age estimate similar to HAP10-03Qz of around 230-250 ka. For sample WAC10-03Fs a lower dose rate of ~0.45-0.50 Gy ka^{-1} would be required.

Each of the three recent attempts to date terraces in the Test sequence, PASHCC, Harding *et al*. (2012) and this study, have encountered issues with the results obtained. This study acquired likely minimum ages of 229 ±23.7 (MIS 8-7) for the Mottisfont/Lower Warsash Terrace and 200 ±22.8 (MIS 7-6) for the Hamble Terrace, comparable with results from the PASHCC project. Two rejected ages appear to have unrealistically high dose rates. The PASHCC ages are acknowledged to be problematic above the lowest terraces sampled (Bates and Briant 2009; Briant *et al*. 2012), In calculating the slightly later attribution of MIS 9-8 for the Mottisfont/Lower Warsash Terrace at Dunbridge, Harding *et al*. (2012) excluded four ages ranging from 456 ±101 ka to 393 ±62 ka as being unreliable. The remaining four ages ranged from 335 ±45 ka to 262 ±43 ka (MIS 11-7) and were not stratigraphically consistent. The methods applied here indicate a high rejection rate of samples and aliquots within samples which would not have been detected in the PASHCC and Harding *et al*. (2012) studies. Further work is needed to investigate why so many problems have been encountered in attempts to use luminescence dating in the Test Valley.

Understanding the chronology of the Test sequence remains problematic above the Mottisfont/Lower Warsash Terrace. Previous work by Bates *et al*. (2004; cf. Westaway *et al*. 2006) has proposed a correlation between the Nursling Terrace of the River Test and a cold-stage before or after the MIS 13 Goodwood/Slindon Raised Beach (Roberts and Parfitt 1999) (i.e. MIS 14 or 12). In such a scenario it is likely that at least the Bitterne Terrace and above of the Test sequence were deposited prior to MIS 13. More chronological tie-points above the Mottisfont/Lower Warsash Terrace are required to construct a robust stratigraphic sequence for the Test.

9.2 Implications for the terrace stratigraphy and Palaeolithic archaeology of the River Test

The terrace stratigraphy of the River Test has been reassessed as described above, with revised correlations of terrace levels between BGS sheets 299 (Winchester) and 315 (Southampton) (Figure 11). The results suggest agreement with the correlation of Lower and Upper Terraces at Warsash with the Mottisfont and Belbin Terraces upstream as per Harding *et al*. (2012) (cf. the PASHCC model). The Hamble and Ganger Wood/Mallards Moor Terraces downstream are not recognised in the Dunbridge area. Correlations have also been proposed for the Nursling, Bitterne and

Midanbury/Rownham's Farm Terraces while recognising that the latter two terraces are poorly represented in the dataset.

Table 10 shows the revision of terrace attribution for some significant Palaeolithic archaeological sites located at Warsash, Dunbridge and elsewhere in the Test region. The revisions proposed by this study have a number of implications for the understanding and interpretation of the archaeological record. Two implications in particularly are of consequence: the relationship of terraces of the River Test upstream at Dunbridge and downstream at Warsash; and the terrace attributions of individual assemblages in the Warsash area.

The earliest archaeological evidence in the Test region, and potentially the Solent region as a whole, is the three handaxes found at Towns Pit, Southampton Common (Davis 2015; Table 10), which retains its attribution to the Midanbury/Rownham's Farm Terrace here. The upstream correlation of River Test terraces between the Southampton BGS map sheet and the Winchester sheet favoured here results in a reattribution of the Great Copse, Mottisfont artefacts (Table 10) from the Bitterne Terrace (Terrace 7 of PASHCC) to the Nursling Terrace. Two major sites at Romsey remain in the Belbin/Upper Warsash Terrace in the revised terrace scheme (Table 10). The important sites at Dunbridge and Kimbridge are attributed to Belbin/Upper Warsash and Mottisfont/Lower Warsash respectively (Table 10), and downstream sites at Warsash remain in the Mottisfont/Lower Warsash and Hamble Terraces (Table 10) as in previous schemes (Edwards and Freshney 1987; Westaway *et al*. 2006).

The revisions to the terrace mapping in and around Warsash enable some of the Warsash archaeological material to be assigned to specific terraces. As discussed previously, the majority of the Warsash record lacks locality data, with just a small amount that has a specific pit recorded. Davis's (2013; Davis *et al.* 2016) recent review has established that the four gravel pits discussed by Burkitt *et al.* (1939) are all located in areas of the Mottisfont/Lower Warsash Terrace (Figure 2). Therefore, all of the Mogridge Collection that can be demonstrated to have been collected prior to 1939 can be assigned to the Mottisfont/Lower Warsash Terrace. Further, all gravel pits in the Warsash area prior to 1945 were restricted to areas of the Mottisfont/Lower Warsash Terrace (Davis *et al.* 2016). So any artefacts collected prior to 1945 can be assigned to Mottisfont/Lower Warsash. After 1945, quarrying in the region exploited gravels of the Hamble and Mottisfont/Lower Warsash Terraces. Therefore artefacts with only a general Warsash provenance recovered after 1945 cannot be assigned to a specific terrace. On this basis, 254 handaxes and 30 Levallois artefacts can be associated with the Mottisfont/Lower Warsash Terrace, 51 handaxes with the Hamble Terrace, while 194 handaxes and 4 Levallois artefacts cannot be assigned to a specific terrace.

It is therefore likely that the Levallois material from Warsash is exclusively associated with the Mottisfont/Lower Warsash Terrace. It is also clear from the condition of the artefacts – the majority of the Levallois material is fresh and patinated, contrasting the typically rolled and stained handaxes – that the Levallois assemblage has a different taphonomic history to the handaxes associated with the same terrace (Ashton & Hosfield 2010; Davis *et al.* 2016). The high degree of rolling and staining among the Mottisfont/Lower Warsash Terrace handaxes strongly suggests that they originated within terrace gravels, an assertion that is supported by the observations of Burkitt *et al.* (1939), who stated that two of their three series of handaxes were recovered from the basal gravels. If an MIS 8 age for the Mottisfont/Lower Warsash Terrace is accepted, these are likely to have been reworked from earlier deposits of at least MIS 9 age.

With regards to the Levallois material, Burkitt *et al.* suggest that at least some of it originated in fine-grained deposits overlying the terrace gravels and therefore post-dates terrace formation. The fresh condition of the artefacts fits with this interpretation. A similar situation is found at several sites of the Middle Thames, such as Creffield Road and Yiewsley (Scott *et al.* 2011). There, fresh Levallois artefacts have been observed to rest on, or in sediments that overlie, Lynch Hill gravels that contain rolled handaxes (Brown 1889, 1895). Ashton *et al.* (2003) argue that the Levallois material was either discarded on the margins of the floodplain prior to downcutting during late MIS 8, or discarded post-downcutting on the terrace surface adjacent to the new floodplain during MIS 7. If a parallel situation is found at Warsash, then the fresh Levallois material may date to late MIS 8 or MIS 7.

Table 10. Major Palaeolithic artefact site locations as assigned in previous schemes and the revised terrace stratigraphy of the River Test. Site location precision key: [A] Accurate; [E] Estimated; [G] General. Artefact numbers key: H Handaxes; L Levallois; O Other. Previous terrace scheme and previous MIS model key: [1] Edwards & Freshney 1987); [2] Westaway *et al.* (2006); [3] PASHCC (Bates *et al.* 2004, 2007; Bates and Briant 2009); [4] Harding *et al.* (2012). Westaway *et al.* (2006)/ Harding *et al.* (2012) terrace nomenclature: Mottisfont/LW: Mottisfont/Lower Warsash; Belbin/UW: Belbin/Upper Warsash. Attributions in **bold** indicate revised terrace correlations and/or MIS age modelling as discussed in the text. Site location and artefact data from Davis (2013).

Site location [Precision]	Artefacts H	L	O	Previous terrace schemes	Harding *et al.* MIS model	Revised terrace scheme	Probable MI Stage [Range]
Town Pits, [A] Southampton Common	3	0	0	Terrace 8 [1] Rownham's Farm [4]	14 [4]	Midanbury/ Rownham's Farm	?16-15 [>13]
Great Copse, Mottisfont [A]	1	0	3	Terrace 7 [3] Not specified [4]	-	**Nursling**	?14-12
Chivers Gravel Pit, Romsey Extra [A]	100	3	18	Terrace 4 [1] Belbin/UW [2, 4]	9b [4]	Belbin/ Upper Warsash	?9 [12-9]
Belbin's Pit, Romsey Extra [A]	200	3	9	Terrace 4 [1] Belbin/UW [2, 4]	9b [4]	Belbin/ Upper Warsash	?9 [12-9]
Dunbridge:				Belbin/UW [2, 4] Terrace 5 [3]	9b [4]	**Belbin/ Upper Warsash**	?9 [12-9]
Dunbridge Hill [A]	1000	5	0				
Hatt Hill [E]	1	0	0				
RMC Gravel Pit [A]	0	0	5				
Kimbridge, Mottisfont [A]	77	0	9	Mottisfont/LW [2, 4] Terrace 4 [3]	8 [4]	**Mottisfont/ Lower Warsash**	8 [8-7]
Warsash:				Terrace 3 [1, 3] Mottisfont/LW [4]	8 [4]	Mottisfont/ Lower Warsash	8 [8-7]
Fleet End Pit [A]	20	13	2				
New Pit [A]	15	4	0				
Park's Pit [A]	10	0	0				
Button's Pit [E]	0	0	1				
Dyke's Pit [A]	2	0	0				
Hook Lane [G]	1	0	0				
Newbury's Pit [A]	6	0	1	Terrace 2 [1, 3] Hamble [2, 4]	6 [4]	**Mottisfont/ Lower Warsash**	**8 [8-7]**
Warsash: General	200	13	43	Terrace 2 or 3 [1, 3] Hamble or Mottisfont/ LW [4]	6 or 8 [4]	**Mottisfont/ Lower Warsash**	**8 [8-7]**

Site location [Precision]	Artefacts H	L	O	Previous terrace schemes	Harding *et al*. MIS model	Revised terrace scheme	Probable MI Stage [Range]
Warsash: General	194	4	34	Terrace 2 or 3 [1, 3] Hamble or Mottisfont/ LW [4]	6 or 8 [4]	? Hamble or Mottisfont/ Lower Warsash	7 [7-6] or 8 [8-7]

9.3 Methodological approaches to constructing long profile projections and correlations

In regions where diagnostic lithological, biostratigraphical or chronological data are scarce, whether due to minimal variations in clast input into the fluvial system over time, preservation issues, or the availability of sedimentary exposures or datasets, terrace remnants may be correlated by means of altitudinal position along the river's palaeo-course alone (Briant *et al*. 2012). Such long profile correlations of terrace bodies are usually based on downstream projections of approximately straight or slightly concave upward gradients (Gibbard 1985; Briant *et al*. 2012). This has been the case in the Test Valley, where interpretation of the terrace stratigraphy and important downstream correlations of often fragmentary terrace units has been reliant on limited, and methodologically different, datasets as discussed above. Two recent terrace stratigraphies have been constructed for the River Test using contrasting data to describe the terrace deposits. Post-depositional modification may affect methods based on modern terrace 'surfaces' (i.e. ground level), which may not be representative of former terrace aggradations. Methods based on the thickness of underlying sedimentary deposits need to account for topographical variation in the palaeo-floodplain or changing terrace thickness between the front and back of an outcrop. Where datasets are sufficiently large, an assessment can be made on the representative nature of each sedimentary record in relation to the framework as a whole. Comparison of Figures 10 and 11 shows that a more robust terrace stratigraphy can be constructed by use of sedimentary data (in this case bedrock elevation and terrace deposit thickness) rather than ground surface data. Such an approach is dependent on sufficient data-coverage and it has been demonstrated that the use of GPR can be an effective method to close larger data gaps. The method is time efficient and allows extensive data capture. Synthetic boreholes (Hatch 2014) can be used to summarise linear datasets and enable integration with other data types, such as borehole records and sedimentary logs.

10. Conclusions

This study has produced revised terrace stratigraphies for the Warsash area and the wider River Test based upon an extensive and robust set of data. Geomorphological subdivision of the terrace sequence has been carried out after careful assessment of long profiles of stratigraphic data collected from boreholes, new fieldwork and previous studies in the region. The new stratigraphic detail at Warsash has produced a more robust framework for the spatial and temporal distribution of the Palaeolithic record, enabling closer interrogation of technological and typological patterning. The revised stratigraphy of the wider region has also clarified correlations between archaeologically important sediments of the Test Valley and proposed upstream correlations between fragmentary deposits on two BGS map sheets. The stratigraphic framework produced has provided the foundation for reassessment of the characteristics and chronology of the Palaeolithic record of the region, and enabled it to contribute more fully to understanding the Lower-Middle Pleistocene settlement history of southern Britain.

Finally the study has highlighted broader methodological issues that remain in both the use of luminescence methods in the River Test region and in the construction of long profile projections of terraces generally. The comprehensive suite of tests applied during the dating programme of this study demonstrated the complicated luminescence properties of the fluvial sediments of the River Test. Where rigorous test procedures have not been applied in previous studies the ages produced should be treated with some caution. Similarly, the construction of stratigraphic frameworks requires careful assessment of the data. Where the use of geomorphological methods are necessary, such as in the Solent region, it has been shown that the data used to define and correlate terraces will impact the resulting stratigraphic model. Uncertainties may be mitigated, to a degree, by the availability of sufficient closely-spaced data to enable confidence in the representative nature of data-points within a terrace landform.

Important detail has been added to the terrace stratigraphy of the Warsash area and broader Test Valley, enabling a more rigorous interrogation of Middle-Late Pleistocene hominin settlement history and technology of the region. However, more chronological control is still required in order to further refine the stratigraphic model presented here for the evolution of the River Test and the archaeological record it contains.

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