Accepted Manuscript

Journal of the Geological Society

Indicative meanings of geological sea-level indicators in the Solent region and Sussex coast (south coast of England) and implications for uplift rates

Rebecca M. Briant, Martin R. Bates, Jenni Robertson, Jean-Luc Schwenninger & John E. Whittaker

DOI: https://doi.org/10.1144/jgs2023-120

To access the most recent version of this article, please click the DOI URL in the line above. When citing this article please include the above DOI.

Received 21 July 2023

Revised 1 February 2024

Accepted 26 March 2024

Supplementary material at https://doi.org/10.6084/m9.figshare.c.7172532

Indicative meanings of geological sea-level indicators in the Solent region and Sussex coast (south coast of England) and implications for uplift rates

Rebecca M. Briant[1]*, Martin R. Bates[2], Jenni Robertson[3], Jean-Luc Schwenninger[4] and John E. Whittaker[5].

[1]Department of Geography, Birkbeck, University of London, Malet Street, London, WC1E 7HX, UK.
[2]School of Archaeology, History and Anthropology, University of Wales Trinity Saint David, Lampeter Campus, Ceredigion, SA48 7ED, Wales.
[3]Department of Earth and Planetary Sciences, Birkbeck, University of London, Malet Street, London, WC1E 7HX, UK.
[4]Research Laboratory for Archaeology and the History of Art, Dyson Perrins Building, South Parks Road, Oxford, OX1 3QY, UK.
[5]Palaeontology Department, Natural History Museum, Cromwell Road, London, SW7 5BD, UK, deceased.

*Correspondence: b.briant@bbk.ac.uk

Abbreviated title: Sea-level change and uplift in southern England

Abstract

The Solent Region and Sussex coastal plain in southern England have preserved palaeo- sea-level indicators from multiple interglacial periods, with a particularly complete record of deposition throughout the last interglacial. However, as yet, none of the research on these indicators have fully addressed the relationship of the different types of deposits preserved to mean sea-level. In this paper we apply recent approaches to estimating past relative sea-levels based on applying modern analogues to understand the indicative meaning of these indicators. We also apply a synchronous correlation model previously developed on rapidly uplifting coastlines to assess uplift rates. The uplift rates required to match the elevations of sequences suggest a significant decrease in uplift rates between the Late Wolstonian Substage and Ipswichian Stage – i.e. the c. 240 ka and c. 125 ka sea-level highstands, broadly equivalent to Marine Isotope Stages (MIS) 7 and 5e. This coincides in time with the final opening of the Straits of Dover.

Introduction

Geomorphological sea-level indicators play an important role in constraining Quaternary global sea-level estimates (e.g. Kopp et al., 2009; Cohen et al., 2022). This is particularly because they are often found in 'near-field' locations, adjacent to the ice sheets whose fluctuations drive eustatic change. Long et al. (2015) show clearly that near-field locations, due to gravitational effects, experience a very different trajectory of sea-level transgression and regression than far-field locations such as coral terraces. However, the complexity of natural systems and tidal regimes means that the elevation in a landscape where a feature is preserved may not represent mean sea-level. Therefore, elevations need to be corrected to give an 'indicative meaning' of former relative sea-levels (palaeo-RSL) (Rovere et al., 2016). This is particularly important where tidal ranges are high, as in southern England. This paper presents indicative meanings from the Solent region and Sussex coast in southern England, based on modern analogues from the same regions to provide more accurate values for future studies. Recently, various palaeo-RSL values from this region were calculated as part of the World Atlas of Last Interglacial Shorelines (WALIS) project (Cohen et al., 2022, Table 1), but no uplift modelling undertaken. Whilst modern analogue data is preferred to calculate palaeo-RSL values (Rovere et al., 2016), there was none available from this region at that time. Thus all the WALIS palaeo-RSL values shown in Table 1 were corrected using a first-order approximation using the methodology of Lorscheid and Rovere (2019). This uses global wave and tide datasets and a series of hydro- and morphodynamic equations to calculate indicative meaning for a range of RSL indicators. Our study therefore provides an opportunity to refine these palaeo-RSL values using modern analogue data.

These relative sea-level indicators can also be used to estimate uplift rates if they have robust age control, which is present along the Sussex coast due to a large programme of optically-stimulated luminescence (OSL) dating in this region (e.g. Briant et al., 2006; Bates et al., 2010, Table 2). Previous uplift modelling (Westaway et al., 2006) suggested a rate of 0.134 mm/yr since the formation of the Boxgrove beach mentioned below, chosen because this fitted the observed tie-points best. However, it is clear from Table 1 that the tie-points used do not represent geomorphologically meaningful features because they represent the upper surface of the deposit, which may have been modified later by erosion or the addition of overlying slope deposits or both.

The uplift modelling method applied here is synchronous correlation (Houghton et al., 2003; Roberts et al., 2009; Roberts et al., 2013; Pedoja et al., 2018; Meschis et al., 2018, Robertson et al., 2019). This approach uses global sea-level curve data and measured palaeoshoreline elevations to determine where within the landscape globally identified sea-level highstands would be expected under various uplift scenarios (either constant or changing over time). Synchronous correlation modelling identifies a 'best fit' uplift rate for the geomorphological data in a particular location through an iterative approach where at least one palaeoshoreline is correlated to a sea-level highstand using an absolute age control. This modelling is designed to use the inner edge of a marine terrace (WALIS terminology – Cohen et al., 2022) as a value representative of mean sea-level at the peak of the sea-level transgression. The assumption is that the carving of the platform is done during transgression prior to the highstand, then at the eustatic peak of the highstand the upper shoreline angle is formed and preserved and any deposits on the terrace are then regressive. It should be noted that the global sea-level data used are a composite of various sea-level estimates, with the timing of highstands variable between reconstructions, thus multiple curves were compared to show the sensitivity of the uplift modelling to the curve chosen.

Using this uplift modelling on newly developed relative sea-level values corrected for the indicative meanings of successive sea-level indicators will give the most robust estimates of uplift rates in this region to date. Our uplift modelling shows that it is only with a significant decrease of uplift rates between the c. 240/200 ka and c. 125 ka highstands (i.e. in the Late Wolstonian and Ipswichian Stages, broadly equivalent to marine isotope stages (MIS) 7 and

5e) that the geomorphological sea-level indicators along the Sussex coast can be fitted into global sea-level curves.

Regional setting

The Solent region and Sussex coastal plain (Figure 1) lie on the northern side of the English Channel, within the Hampshire Basin where the bedrock geology consists of Eocene and Cretaceous rocks (Melville and Freshney, 1982) conducive to preserving a wide range of palaeoenvironmental indicators. Chalk forms the South Downs to the north and an east-west ridge bisecting the Isle of Wight as well as elements of the coastal plain while Eocene sediments of the Lambeth, Thames, Bracklesham, Barton and Solent Groups (mainly shallow marine clays, silts and sands) rest in a series of individually subsiding basins. The two regions can be treated together structurally because all the structural features formed during the same period of compression in the Paleozoic basement rocks (Plint, 1982) and are no longer active (Hopson, 2009).

Modern coastal geomorphology

The present-day coast of the Solent region and Sussex coastal plain splits into three parts. In the furthest west, the Solent seaway and Southampton Water flow within poorly consolidated Eocene sediments and are flanked by low gravel cliffs of the erstwhile Solent river system (Figure 1, e.g. Briant et al., 2006). Tidal range is smaller than further east, with the mean spring tidal range varying from 4.05m in Southampton Water to 3.9m at Calshot (east of Stone Point), 2.3m at Lymington and 2.0m at Hurst Point (New Forest District Council, 2017). Neap tides are about half the range of spring tides. Sediment movement is dominated by estuarine and tidal flow, with some longshore drift (Figure 2). The dominant onshore wind is from the southwest.

From Portsmouth to Selsey Bill, a low coastline with three extensive harbours is cut into Eocene (Bracklesham Group) sandstones and clays (Figure 2). A very low gravel cliff is present on both western and eastern sides of Selsey Bill, comprising sediments of the Selsey ridge, but otherwise the area is low lying. Offshore, bathymetric data show a series of offshore bars and banks, including the Medmerry Bank and Kirk Arrow Spit to the west (New Forest District Council, 2017) and the Inner Owers to the east (New Forest District Council, 2017). These banks are an important source of sediment at the present day, as are Portsmouth, Langstone and Chichester Harbours and are the ancestors of various offshore barrier systems that developed since c. 8000 BP, stabilising only in 1960 (Bates et al., 2019). The tidal range is 4.9m (springs) and 2.7m (neaps) at Pagham Harbour mouth and at the entrance to Chichester Harbour, with the ebb phase shorter than the flood (New Forest District Council, 2017). Offshore, most waves come from the south and south-west, although the east and west facing coastlines on either side of Selsey Bill complicate this and parts of Bracklesham Bay (west of Selsey Bill) are partially sheltered by the Isle of Wight. Southern and eastern waves are more prevalent on the eastern side of Selsey Bill. Bracklesham Bay is therefore a swash aligned shoreline, whereas Selsey Bill to Pagham Harbour is a drift aligned shoreline (New Forest District Council, 2017).

The third area runs from Pagham Harbour to Beachy Head (in Eastbourne) in East Sussex. This section of coast is mostly underlain by Cretaceous chalk (Figure 1). It comprises mainly lower lying areas with significant height chalk cliffs only developing to the east of Brighton. River estuaries of the Arun, Adur, Ouse and Cuckmere cross the region at 90 degrees to the coastline, but there are no natural harbours (Figure 2). Between Brighton and Newhaven the chalk cliffs are mostly protected by coastal defences and associated with some gravel beaches overlying shore platforms. Between Seaford Head and Beachy Head, the shore platforms are exposed chalk with scattered rocks and rock fall sediments. The mean spring tidal range increases from west to east from 5.3m to 6.4m. Flow is eastwards on the flood tide, westwards on the ebb (New Forest District Council, 2017). The coastline is open to relatively high energy waves from the south-east, south and south-west as well as Atlantic swell waves propagating up the Channel from the west that become diffracted around the Isle of Wight. Maximum wave energy is experienced along the shoreline between Seaford and Beachy Head (New Forest District Council, 2017). Beaches are dominated by gravel. Sand is sometimes present in the foreshore, but not where shoreline platforms occupy most of the inter-tidal zone. The dominant transport of coarse sediment is west to east (New Forest District Council, 2017, Figure 2).

Pleistocene sea-level indicators

During the Pleistocene the region was dominated by two major geomorphological systems consisting of the Solent River system to the west draining large parts of the Hampshire Basin (Allen and Gibbard, 1993; Westaway et al., 2006; Briant et al., 2006) and the English Channel/Manche coastline to the east (Bates et al., 2003). Transformation of a Manche embayment into an open seaway during the Middle Pleistocene (Gibbard, 1988; Gibbard, 1995) allowed transfer of marine waters from the southern North Sea into the English Channel from the Anglian / Elsterian Stage onwards during periods of sea-level highstand. This occurred due to overflow of an ice-dammed lake and was completed during a second phase of lake formation at the very end of the Wolstonian / Saalian Stage (Gupta et al., 2007; Busschers et al., 2008). A number of palaeo-sea-level indicators are preserved in the area. These are described below, using the categories in the WALIS database (Cohen et al., 2022).

The chronostratigraphic sequence of the British Isles (Bowen, 1999) identifies only one stage (the Wolstonian Stage) between the Hoxnian and Ipswichian Stage interglacials. However, it has been shown, through a dual process of biostratigraphic refinement and comparison of terrestrial records with the more complete global marine record, that it is likely that the Wolstonian Stage encompasses multiple climatic cycles. Because this scheme does not have enough formally specified Stages to capture all of the complexity now recognised in the British terrestrial record, previous authors have sought to establish the age of sea-level highstand sequences in the Sussex coastal plain by direct reference to marine isotope stages. This can be problematic, because the global ice volume changes recognised in the composite marine stratigraphy do not correspond directly to terrestrial climatic events, particularly because the signal is dominated by the Laurentide ice sheet, which does not seem to have expanded in sync with ice sheets in the British Isles and northwest Europe (Gibbard and Hughes, 2021). It is less problematic for sea-level than ice volume changes, since this signal is more globally synchronised, but even these have some regional variability. Therefore, in this paper we primarily apply a terrestrial stratigraphy using the newly suggested subdivision of the

Wolstonian Stage into Early, Middle and Late Substages (Gibson et al., 2022). The Early Wolstonian Substage comprises a glacial period immediately following the Hoxnian interglacial, whereas the Middle and Late Wolstonian Substages each encompass a full climatic cycle (both glacial and interglacial). Where appropriate, to aid comparison with work by previous authors, dated highstand events are noted as is likely equivalence with marine isotope stages.

Marine terraces

The oldest marine terrace feature is developed in Cretaceous chalk and underlies deposits of the Goodwood-Slindon Formation (Figure 1). It is best developed at Boxgrove, where the inner margin of the marine terrace has a value of 39 ± 1.5 m O.D. (Ordnance Datum, i.e. mean sea-level) (Figures 3B and 4, Table 2). This is overlain by successively finer deposits which were laid down in a back barrier setting (Roberts and Parfitt, 1999) with a total sequence thickness of 10-15 m. These deposits are argued to date from the end of the Cromerian Stage, equivalent to MIS 13 (i.e. 478 – 524 ka) on the basis of biostratigraphy (Roberts and Parfitt, 1999). It therefore likely relates to the c. 485 ka highstand seen in multiple global sea-level compilations (e.g. Grant et al., 2014). The coastline during deposition of this Formation and prior to the formation of the Straits of Dover was a sheltered embayment (Bates et al., 2010).

A further lower marine terrace is also developed within the Cretaceous chalk. This is overlain by beach gravels, some beach sands and several metres of clay-rich solifluction deposits. The two best exposures of this sequence of deposits, termed the Brighton-Norton Formation (Figure 3B), are at Norton Farm (Figures 1 and 4, Bates et al., 2010) and Black Rock, Brighton (Briant et al., early view 2022), but only at Norton Farm are there elevation measurements or age estimates. At Norton Farm, the inner edge of the marine terrace has a value of 7.2 ± 1.5 m O.D. (Table 3), formed in Cretaceous chalk, but transitioning to sands and clays of the Lambeth and Thames Groups within 50 m offshore. Microfossils suggest that the sands are marine and include cold water indicators (Bates et al. 2010) that are overlain by regressive units (Figure 3). The overlying silts are terrestrial, being rich in freshwater molluscs. The OSL age from the borehole closest to the inner edge (BH16) is 238 ± 27 ka, at the start of the Late Wolstonian Substage. It was attributed to the earlier part of MIS 7 by Bates et al. (2010) which might suggest deposition during the c. 240 ka global highstand (Grant et al., 2014). Alternatively, the cold-water microfossils and the small horse / mammoth fauna found at Westhampnett, Norton Farm and Black Rock (Bates et al., 2010), suggesting late-interglacial conditions, possibly relate to the global highstand at c. 200 ka. This later highstand, however, has approximately the same elevation as the 240 ka highstand relative to today (e.g. Grant et al., 2014, Bates et al., 2014). The Brighton-Norton Formation is the earliest evidence for a more open coastline in the region (Figure 1, Bates et al., 2010).

A marine terrace is also formed further west within the more erodible Bembridge Limestone at Bembridge on the Isle of Wight (Figure 1). The exact location of the inner edge is less clear because the angle of the former cliff is less steep than those formed in chalk but is measured to c. 6 ± 2 m O.D. (Figure 5). The terrace is overlain by a thick sequence of marine gravels rising to 18 m O.D. (Tables 2, 3 and 4, Figures 3 and 5, Preece et al., 1990). Sand and gravel near to, but not directly overlying, the inner edge of this marine terrace was dated to the Ipswichian Stage , i.e. the c. 125 ka highstand (Table 2, Wenban-Smith et al., 2005).

Beach deposit / Beach rock

Beach gravels attributed to the Aldingbourne Formation (intermediate in elevation between the Goodwood-Slindon and Brighton-Norton Formations, Figure 1B) are the youngest sediments associated with the 'embayed coastline phase' identified by Bates et al. (2010) and included in the WALIS database (Table 1). Where investigated, the base of these deposits is found at c. 18-20 m O.D. (Bates et al., 2010). The thickness of these deposits is c. 3 m. Despite their position on the edge of the chalk, they are mostly decalcified, making palaeoenvironmental interpretations and biostratigraphic age assignment hard. It is possible that these deposits are of mixed age because a variety of marine, brackish, freshwater and terrestrial sequences have been recovered between Fontwell and Tangmere. The Aldingbourne Formation deposits fall within the Wolstonian Stage. They were assigned to MIS 7 / Late Wolstonian Substage by Bates et al. (2010) on the basis of OSL ages ranging from 182-265 ka from Norton Farm and younger OSL ages from Pear Tree Knap of c. 90-190 ka, thought to be too young because of the altitude of these deposits and the saturation of the signal (Bates et al., 2010). It should be noted that c. 250 ka is close to the age at which quartz OSL signals saturate at the relatively low dose rates common in England (Rixhon et al., 2017).

The lowest elevation palaeo-sea-level indicators (Table 1) in the Sussex coastal plain (Pagham Formation) are also beach deposits, occurring closest to the present-day coastline (Figure 1b), located between Chichester and Worthing, and typically, but not exclusively, with lowest contacts below 5 m O.D. (Figure 3). These sequences are not associated with a preserved marine terrace and occur at a range of altitudes. They comprise both gravels and sands and contain well preserved and diverse ostracod and foraminifera assemblages. These marine sequences are assigned to the Ipswichian Stage on the basis of OSL dating (Table 3, Figure 3A). The most distinctive deposit of this type is the Selsey ridge (Bates et al., 2009a). This is a ridge of sand and rounded gravels currently exposed at the coast at Selsey Bill and forming a low cliff (c. 5 m O.D. top surface) where the deposits are truncated by the modern coastline (Figure 2A). The ridge has been interpreted as an offshore bar by Bates et al. (2010). This is the most exposed part of the Solent estuary with the greatest fetch from the Channel, so the development of such bars would be expected at this location, as is seen in the modern coastal system (Figure 2). Whilst none of the ostracod and foraminifera assemblages yield evidence of specific water depths, some show transgression, e.g. at the Pagham Water Treatment Works (PWTW) where small numbers of *Elphidium williamsonii* at the base of the sequence are replaced upwards by an ornate form of *A. batavus* argued by Bates *et al.* (2010) to be indicative of high energy environments, as would be likely during transgression. In addition, some sequences show regression, e.g. in parts of the sequences at Warblington, Woodhorn Farm, Mill Farm Caravan Park and North Street, Worthing. Regression here is suggested by elements suggesting colder water conditions, e.g. *Cassidulina reniformis* and *Elphidium clavatum* at Warblington and Woodhorn Farm and dwarfed versions of *A. batavus and Elphidium fichtellianum* Warblington, Woodhorn Farm and at Mill Farm Caravan Park (Bates et al., 2010). The regressive / transgressive tendencies are shown on Figure 3 and all these sites were included in the WALIS database (Table 1). The sequences of the Pagham Formation were interpreted by Bates et al. (2010) to represent a harboured coastline phase where the offshore bar of the Selsey Ridge formed a protected coastal plain behind which shallow ‘harbours’ developed despite the full opening of the Straits of Dover by this time (Busschers et al., 2007).

Salt marsh / estuary deposits

An estuarine sequence of Ipswichian age, also listed in the WALIS database (Table 1) is preserved at Stone Point (Figure 1), originally studied by West and Sparks (1960), Brown et al. (1975) and Briant et al. (2009). Briant et al. (2019) extended the interglacial sequence to -9 m O.D (borehole 16, Figure 3A). Their unit 2 records the transition from freshwater (units 2a to 2c) to estuarine deposits (unit 2d). This latter is a stiff grey clay with shells, interbedded with thin discontinuous beds of compressed wood-peat, especially in the upper parts of the profile and extending in depth from -8.5 to 1 m O.D. (Briant et al., 2019). The pollen from unit 2d suggests mixed-oak woodland (Ipswichian pollen zone Ip IIa grading upwards into Ip Iib). The estuarine deposits grade upstream Into silts at the nearby site of Pennington Marshes (c. 17 km upstream). Here, Ipswichian Stage deposits with freshwater affinities occur at –3.9 to –5.3 m O.D. depth and yield pollen suggestive of a transition from the pre-temperate (Ip I) to early-temperate (Ip II) zones (Allen et al., 1996). In addition, at St Leonards Farm c. 5 km upstream of Stone Point, decalcification and poor fossil preservation means that silts from c. 0.1 – 1.8 m O.D. cannot be attributed to either freshwater or estuarine deposits. The pollen records a transition from oak-dominated assemblages typical of the Early-temperate zone (Ip II) to a birch-pine-alder assemblage which may be Late-temperate (Ip III), although pollen preservation in this part of the sequence is very low (Briant et al., 2013).

Further saltmarsh deposits are preserved on the Isle of Wight. Somewhat enigmatic and truncated deposits of the Steyne Wood Clay occur at c. 40 m elevation and may be coeval with the Goodwood-Slindon Formation (Briant et al., early view 2022). A more complete sequence is associated with the lower Bembridge marine terrace. Here at Bembridge Foreland is an Ipswichian age saltmarsh sequence used as a sea-level index point in the WALIS database (Table 1, Figure 3). At the top of this sequence (Table 4), pollen records document saltmarsh conditions giving way to freshwater marsh up-profile, a locally regressive trend during the early to late temperate vegetation transition (Ip II/III). These fossil bearing deposits are at c. 5 – 6 m O.D., overlying the thinner, northeastern end of the thick sequence of gravels overlying the marine terrace (Preece et al., 1990; Wenban-Smith et al., 2005).

Materials and Methods

Field description and sampling

The sequences studied were retrieved from a mixture of open sections, test pits and boreholes. Field description and sampling were followed by sieving and analysis of fossils, using methods described in Bates et al. (2004). Where fossils were previously published, the original references are cited in the text. Table S1 contains fossil data from sites that have not previously been published.

Geochronology

Age control on MIS 5e deposits from the Solent and Sussex coastal plain is provided primarily by OSL (Briant et al., 2006; Bates et al., 2010; Wenban-Smith et al., 2005) (Table 2, Figures 2 and 3). Amino acid racemisation (AAR) was less successful because of the lack of freshwater molluscs for analysis (Bates et al., 2004; Briant et al., 2006). Dating is based on both direct dating of marine sands and indirect dating of bracketing cold stage fluvial deposits (Table 2).

Determining indicative meaning from palaeo-sea-level indicators

A robust way of assessing how palaeo-sea-level indicators relate to past mean sea-levels is to use the indicative meaning approach of Rovere et al. (2016). This approach takes into account the exact local relationships between modern analogues for a preserved geological sea-level indicator and mean sea-level – e.g. is the inner edge of a marine terrace formed at the present-day mean sea-level or instead formed above or below? This is called the reference water level (RWL) for this feature and the error on this estimate the indicative range (IR). The relative sea-level (RSL) and associated error (δRSL) are then estimated by adjusting measured present-day elevationsI) of features using the RWL and IR. Indicative meanings were calculated both for marine terraces for use in uplift modelling and also for Pagham Formation beach deposits to compare with the estimate from Kopp et al. (2009). The features used to determine palaeo- RSL values are different from those used by Cohen et al. (2022), who only calculate these for beach deposits of the Aldingbourne Formation and the saltmarsh sequences at Bembridge and Stone Point (Table 1).

The modern analogue used to assess the indicative meaning of the two modelling tie-points at Boxgrove and Norton Farm comes from Seaford Head, which is the closest marine terrace to the sites that was developed in Cretaceous chalk and not directly affected by coastal protection structures (Figure 2). Several LIDAR profiles to the east of Seaford Head were used to assess the upper and lower limits of the inner edge of the modern marine terrace. These were chosen on the basis of completeness of data and clarity of the junction between the cliff face and the marine terrace. The final values used are an average value from all the cliff profiles used (Figure 4) and the adjusted relative sea-level shown in Table 3.

The modern analogue used to assess the indicative meaning of the modelling tie-point at Bembridge comes from Hamstead cliffs on the north-east coast of the Isle of Wight near Yarmouth because the Bembridge Limestone is obscured by the Pleistocene sequence at Bembridge itself and other locations have significant beach thicknesses. Even here, the Bembridge Limestone is exposed only at the base of the cliff (Gale, 2019). However, since the transition to the overlying Hamstead Member is above the cliff-terrace junction, the inner edge of the marine terrace is still adequately preserved in Bembridge Limestone. LIDAR profiles along the full length of the cliffs were used to assess the maximum and minimum levels of the inner edge of the modern marine terrace. The final values used are an average value from all the cliff profiles used (Figure 5) and the adjusted relative sea-level shown in Table 3.

Indicative meanings of the beach deposits from the Pagham Formation can be calculated but are known less precisely because of the lack of a marine terrace and because beach elevations vary significantly seasonally. In addition, modern coastal deposits use the top of the deposit as an elevation tie-point, but the elevation of the top of the palaeo-sea-level indicators is not necessarily comparable because the deposit may have been truncated since deposition. To address this issue, larger error bars were given where the Pagham Formation deposits were visibly truncated (3 m), smaller where they were visibly not truncated (1 m) and intermediate otherwise (2 m). The modern analogue used here was a beach profile from West Street Selsey, qualitatively sense-checked by comparison with bathymetric data shown in Figure 2 to assess the relative elevation of offshore banks and bars. The final elevations used incorporate a significant error (Figure 6) and the adjusted relative sea-levels are given in Table 3.

Synchronous correlation uplift modelling

Where age controls are available within a marine terrace sequence, the synchronous correlation approach tests whether the elevations of undated marine terraces can be explained by the uplift rates implied by the elevations of dated marine terraces. In doing so synchronous correlation can be used to 'predict' the elevations of marine terraces that may not be observable in the landscape. The non-linear temporal spacing of sea-level highstands results in marine terraces and their associated marine terraces that are not evenly spaced in elevation (Houghton et al., 2003; Roberts et al., 2009; Grant et al., 2014). Indeed, highstand variation over time combined with tectonic uplift may result in the destruction of older marine terraces by younger marine highstands, particularly, as here, where uplift rates are low (e.g. Westaway et al., 2000; Roberts et al., 2009; Jara-Munoz and Melnick, 2015; Pedoja et al., 2014, 2018; Normand et al., 2019). The synchronous correlation method therefore recognises that not all marine terraces in a profile will sequentially represent all sea-level highstands (e.g., Robertson et al., 2019; De Santis et al., 2023).

Specifically, the synchronous correlation approach uses dated marine terraces as 'tie-points' to constrain the uplift rate at the highstand associated with the age control (e.g., Roberts et al., 2009). Initially, these absolute age constraints are used to drive the simplest hypothesis of a constant uplift rate through time, but more complex uplift scenarios are tested if a constant uplift rate cannot be successfully applied to explain the marine terrace elevations within the entire sequence.

The tie-points used in this study were the adjusted relative sea-levels shown in Table 3 associated with marine terrace inner edges at 37.5 ± 1.7 m O.D. at Boxgrove for the 485 ka highstand (Roberts and Parfitt, 1999) and 5.3 ± 2 m O.D. at Bembridge at the 125 ka highstand (Preece et al., 1990; Wenban-Smith et al., 2005). The tie-point at Norton Farm of 5.7 ± 1.8 m O.D. was not used because of the uncertainty over which highstand (200 or 240 ka) it related to. The uplift rates were iterated until the predicted marine terrace elevations matched those associated with the observed, dated marine terraces. The resultant uplift rate was applied to the marine terrace inner edge sequence, the outcome of which is a set of predicted marine terrace elevations that were matched to elevation observations to enable correlation between undated marine terrace inner edges and sea-level highstands. Herein, we use eustatic sea-level highstand timing and elevation data from Grant et al. (2014) which is the global sea-level curve which shows the most detail (Table 5).

It has been shown that different late Quaternary sea-level curves reveal variations in the timing and elevations of past sea-level highstands which may affect highstand to marine terrace inner edge correlations and uplift rate determinations (e.g. Caputo, 2007; Robertson et al., 2019; de Gelder et al., 2020). Consequently, we also tested how the results of our synchronous modelling using the sea-level data of Grant et al. (2014) varied when sea-level curves of Bintanja et al. (2005), Bates et al. (2014) and Spratt and Lisiecki (2016) were employed. These sea-level curves were selected as representative of a range of possible values because they extend back to the assumed age of the Boxgrove tie-point and have been constructed using differing approaches (i.e. hydraulic modelling – Grant et al. (2014); principal component statistical analyses using numerous sea-level datasets – Spratt and Lisiecki (2016); ice-sheet-ocean-temperature models from oxygen isotope ratios in benthic foraminifera – Bintanja et al. (2005); and transfer functions associated with 10 marine sediment cores – Bates et al. (2014)).

Results

Indicative meanings and relative sea-level estimates

Figures 4, 5 and 6 and Table 3 show the relative sea-levels of the three marine terraces in the region at Boxgrove, Norton Farm and Bembridge and the various Ipswichian Stage beach deposits of the Pagham Formation. Comparing Figures 4 and 5 with Figure 6, it is clear that it is possible to estimate indicative meaning more precisely for marine terraces (1.84 m indicative range at Seaford Head and 0.89 m at Hamstead) than for beach deposits (7.74 m indicative range). This is because it is not possible to say from the beach sequences preserved what type of beach is represented, nor how far inland or offshore it is. It is probably for this reason that Cohen et al. (2022) list these as marine limiting datapoints (Table 1) rather than sea-level indicators. In all cases the relative water level is above mean sea-level, meaning that the relative sea-level estimate from the sites is lower in elevation than the actual feature.

Synchronous correlation uplift modelling

Given the uncertainty over the age of the Norton Farm tie-point, initial uplift rate iterations used only the two tie-points with indicative meanings of 37.5 m (Boxgrove – 485 ka) and 5.3 m (Bembridge – 125 ka). It proved impossible to fit these tie-points with a single uplift rate, but a rate change between the 200 ka and 125 ka highstands allowed all dated tie-points to be correctly placed (Figure 7, Table 5). This model solution suggests that the Norton Farm tie-point is more likely to relate to the 240 ka in the Late Wolstonian Substage (c. MIS 7e) highstand and that the Aldingbourne Formation may date from the 335 ka highstand in the Middle Wolstonian Substage (c. MIS 9). The former agrees with OSL dating, but not biostratigraphy and the latter conflicts with published OSL dating though not unpublished data (see discussion below). The latter is older than multiple adjacent OSL ages deemed to be reliable by Bates et al. (2010) and requires further investigation. An uplift rate change at 140 ka fits the data best. This is approximately coeval with a sea-level lowstand adjacent to Termination 2 in the marine record (Lisiecki and Raymo, 2005), also termed the 'Penultimate Glacial Maximum' (Gibbard and Hughes, 2021). Using Grant et al. (2014) models that until c. 140 ka the uplift rate was c. 0.164 mm/yr reducing to 0.005 mm/yr from c. 140 ka to the present day with a propagated error of 0.13 mm/yr. It is possible, however, that this change occurred gradually between the 240 ka and 125 ka highstands rather than at a single point in time, or closer to c. 160 ka when ice extents in NW Europe were at their maximum during the Moreton and Drenthe Stadials (Gibbard et al., 2022; Gibson et al., 2022). Whilst a 160 ka rate change results in an acceptable fit between the measured and predicted elevations in our modelling within its uncertainties, we prefer to employ a rate change at 140 ka because we observe a better match between the measured elevations and those predicted in the modelling. The uncertainties are high compared to the uplift rates themselves but this is an inevitable function of the errors on global sea-level curves that can be in the order of c. 12 m (e.g., Siddall et al, 2003; Bintanja et al., 2005; Grant et al., 2014; Rohling et al., 2014). However, we note that the sea-level elevations close to or above present day may be better defined (e.g. those at MIS 1, 5e, 9e and –1c - Past Interglacials Working Group, 2016). We also note that similar propagated errors occurred in the study by Pedoja et al. (2018) in their study of slow coastal uplift on the Cotentin Peninsula, France.

Comparing the outcome of using different sets of sea-level curve data in our uplift modelling (Bintanja et al., 2005; Bates et al., 2014; Spratt and Lisiecki, 2016) to the results using Grant et al. (2014) shows a similar temporal pattern, although different values (Table 5). This is because in many of these reconstructions a younger highstand has a sea-level elevation higher than the 485 ka which would mean the 485 ka is destroyed by the 340 ka or 410 ka, for instance. However, it would be extremely surprising if the exact uplift rates were the same given the different datasets on which the various sea-level curves are based. Table 5 clearly shows that a similar temporal pattern is maintained regardless of which sea-level curve is used in which the rate from 485 ka to 140 ka is between 0.07-0.2 mm/yr, dropping after 140 ka to 0-0.005 mm/yr (with the exception of Spratt and Lisiecki, 2016, which drops to 0.1 mm/yr).

Discussion

Refining relative sea-level estimates for the Sussex Coastal Plain using indicative meanings from modern analogues

This study has produced three new detailed palaeo-RSLs for marine terraces based on modern analogues (Table 3). These are reliable geomorphological landforms because they have the narrowest elevation range in relation to mean sea-level in the modern coastal setting. They are also the geomorphological indicators for which the synchronous correlation modelling approach has been developed. The use of modern analogues is the preferred approach of Rovere et al. (2016) for determining palaeo-RSLs. All these palaeo-RSL values have been estimated at lower elevations (37.5 m at Boxgrove, 5.7 m at Norton Farm and 5.3 m at Bembridge) than the previous tie-points used for modelling by Westaway et al. (2006). This difference stems partly from the fact the inner edge of the marine terrace in both modern analogues is higher than mean sea-level, but is exacerbated by the use by Westaway et al. (2006) of uncorrected values for the top surface of the overlying deposit, not the inner edge of the marine terrace (Table 1), so that the two elevations are not comparing the same feature. In the case of the WALIS database, none of the datapoints included are comparable with the marine terrace values in this study because there are no marine terrace datapoints listed in this region and the database focusses on last interglacial (Ipswichian Stage) sequences. In addition the WALIS elevation value from the Brighton-Norton Formation at Norton Farm was taken from the overlying sands and therefore defined as marine limiting rather than a palaeo-RSL value (Table 1, Cohen et al., 2022). The WALIS database also only lists a palaeo-RSL from the saltmarsh deposits at Bembridge, not the marine terrace.

New palaeo-RSL values have also been estimated from beach deposits from the MIS 5e Pagham Formation (Table 3), again using the preferred method of modern analogues. This yielded a much wider range of possible palaeo-RSL values (0.3 to 9.3 m) because of the wide range of elevations at which beach deposits form in the modern coastal system. They overlap with the Kopp et al. (2009) estimate of 9.13 m (Table 1), but this latter has an 8 m uncertainty, even larger than the c. 4 m uncertainty applied here (Table 3). Again, these cannot be compared with the WALIS database (Cohen et al., 2022) because the Pagham Formation deposits are assigned marine limiting status and palaeo-RSL values are not calculated. Whilst palaeo-RSL values were calculated by WALIS from the Aldingbourne Formation (Table 1), we chose not to do so in this study, given the eroded and dissected nature of these sands and the associated difficulty of direct comparison with modern analogues. It is clear that beach deposits are problematic to use as palaeo-RSL indicators, at least in regions such as southern England with a wide tidal range where modern deposits form over a significant elevation range.

In the WALIS database, sea-level indicators were also calculated from estuarine / saltmarsh sediments at Bembridge and Stone Point on the basis of foraminiferal assemblages interpreted as representing different saltmarsh environments, which are associated with specific elevations (Table 1, Cohen et al., 2022). In contrast, we chose not to calculate sea-level indicators from these sequences. This was partly because of the lack of modern analogues in the region at the present day – there are very few salt marshes and those that exist have not been studied in detail. In addition, the sequences from Bembridge and Stone Point are incomplete and it was difficult to assess whether they represented salt marsh deposition at the edge of an estuary or deeper estuarine channel deposition (although the peat beds present at Stone Point may suggest an estuary-edge location). Furthermore, at Stone Point, different fossil groups suggested different salinity levels, presumably due to tidal transport within the estuary (Briant et al., 2019).

We suggest, on the basis of the size of the error margins calculated, that the most reliable palaeo-RSL indicators from the Solent and Sussex coastal plain are those where a marine terrace is preserved, because this has the clearest relationship to local modern analogues, with the smallest error margins. It is hard to compare these new palaeo-RSL values with previous studies because the methodologies used are very different (Kopp et al., 2009; Westaway et al., 2006) and the reliability of the different types of indicators have been assessed differently in the WALIS database (Cohen et al., 2022), where the salt marsh sequences and beach sequence from the Aldingbourne Formation are designated as sea-level indicators and no marine terraces are included.

Uplift rates

The uplift rates modelled from this study are relatively low, which is not surprising given the lack of evidence for significant tectonic activity since the Miocene (Hopson, 2009). Westaway et al. (2006) attributed uplift to lower crustal flow from adjacent subsiding areas receiving the erosional products of large river systems such as the Solent into areas from which sediments had been removed. They calculated a range of possible uplift rates, but their favoured solution, based on age estimates for the same tie-points at the same ages as in this study, gave a rate of 0.134 mm/yr. This is only slightly less than the higher uplift rate of 0.164 mm/yr modelled from 485 ka to c. 140 ka in this study and slightly more than a weighted average of the two uplift rates used in this study (c. 0.11 mm/yr). It is also very similar to an average uplift value for passive margins globally calculated by Pedoja et al. (2011) of 0.13 mm/yr, although Pedoja et al. (2014) revised this down to 0.06 mm/yr by including only those datapoints whose elevation falls within the eustatic range of global sea-level compilations. Pedoja et al. (2011) and Pedoja et al. (2014) both ascribe uplift at passive margins to a gradual increase in the mean compression of the lithosphere inducing deformation and associated uplift. A specific case study of this uplift at passive margins in the Cotentin peninsula by Pedoja et al. (2018) suggested uplift rates of either 0.06 mm/yr or 0.01 mm/yr using the synchronous correlation method, depending on the age of the four marine terraces observed. Since only the lowest (MIS 5e) terrace is reliably dated in Cotentin, it was not possible to determine uplift rates more precisely. However, for the purposes of comparison, it should be noted that Pedoja et al. (2018)'s higher uplift rate coincided with the age model that is most similar to that of the Sussex marine terraces in this study. A sequence of marine terraces is also observed in Jersey (Renouf and James, 2011). Elevations cover wide ranges, attributed to the tidal range in Jersey of c. 12 m, and absolute age estimates are limited, but uplift rates are tentatively suggested to fall from 0.09 mm/yr at c. 500 ka to 0.02 mm/yr at the present day. Neither the Cotentin nor Jersey studies corrected terrace elevations for local indicative meanings, but nonetheless, uplift rates are similarly low.

The key difference between this study and previous similar studies is that the greater age constraint on the Sussex sequence due to biostratigraphic age estimates from the Goodwood-Slindon Formation at Boxgrove (Roberts and Parfitt, 1999) enables non-uniform uplift rates to be estimated. This may allow the short-term effects of isostatic responses to start to be detected (although not to be fully disentangled from the long-term uplift of the south coastal region without complex ice-sheet and crustal modelling). Generalised compressive uplift could be counteracted quite significantly by glacioisostatic adjustment (GIA)-related subsidence, given that this reaches up to c. 1.6 mm/yr, for example in south-west England between 0 and 6 ka (Lambeck, 1996; Shennan and Horton, 2002). Using global positioning system (GPS) corrected modelling, Bradley et al. (2009) estimate current (post-Devensian) subsidence in the Sussex / Solent region at c. 1.2 mm/yr. Whilst it is likely that there was considerable variability in uplift rates over the last 485 ka due to GIA of different magnitudes associated with various ice advances, our modelling suggests that the largest change occurred at c. 140 ka (or possibly 160 ka), i.e. towards the end of the Late Wolstonian Substage.

A difficulty with estimating subsidence rates for interglacials before the Holocene is that there is insufficient precision in both sea-level estimates and dating of these to determine the location and extent of the forebulge in front of the ice sheet, which is the area which will experience the most subsidence after ice retreat. Busschers et al. (2008) suggest that the most extensive Saalian Stage forebulge (i.e. that of the Drenthe Stadial, c. 180-160 ka) may have been located between Rotterdam and Amsterdam, further south than Vink et al. (2007) place the Weichselian Stage forebulge (Hijma et al., 2012). Alternatively, Hijma et al. (2012) and Gibson et al. (2022) show Saalian Stage (Drenthe Stadial) and Wolstonian Stage (Moreton Stadial) ice limits a similar distance from Sussex (c. 200 km) as the Devensian / Weichselian Stage limits. Thus similar subsidence rates to those at the present day might have been experienced relating to the Moreton Stadial glacial advance, offsetting compressional uplift associated with a passive margin and leading to the very low uplift rates modelled in this study since c. 140 ka. It should be noted, however, that the impact on ground surface level at the time of the associated sea level transgressions will differ, since the Moreton Stadial advance predates the Ipswichian sea-level highstand by c. 40ka, but the Devensian advance only by c. 20 ka. In the absence of more detailed modelling it is at the moment only possible to state that subsidence may have occurred due to forebulge collapse during the penultimate glacial advance in addition to the Devensian advance. This might account for the observed reduced uplift rates in Sussex since c. 140 ka (or maybe c. 160 ka) by counteracting the underlying long-term uplift rates. Previous work (Bates, 2001) has shown that there is a general decrease in numbers of mapped terraces in the river systems from west to east across the region from the Solent to the Adur. This may relate to different glacioisostatic effects causing formation of composite terraces in river systems further east. However, in the absence of absolute age estimates from the Arun and Adur river systems, this cannot be stated with certainty.

Whilst similar subsidence might also have occurred during the Hoxnian / Holsteinian Stage , following the Elsterian / Anglian glaciation, which reached to within c. 100 km of Sussex (Hijma et al., 2012), this is harder to determine. This is due to the lack of age constraints in this upper part of the sequence and the presence of only a single marine deposit between the Goodwood-Slindon and Brighton-Norton Formations, despite two known global highstand events in this time period.

Overprinting of sea-level events in the landscape

The modelling in Table 5 suggests that the 485 ka (Cromerian Stage / MIS 13) and 405 ka (Hoxnian Stage / MIS 11) highstand events should be seen at the same elevation in the landscape. Recent research has shown that high Hoxnian Stage sea-levels are related to late melting of the Greenland ice sheet (Tzedakis et al., 2022), validating the projected elevation estimates in our study. However, there is only solid evidence for one sea-level highstand event at c. 38 m, at Boxgrove, where excavations were undertaken in enough detail that evidence from two different events would likely have been seen if it were present. Recent ESR dating of quartz grains from the Slindon Sand at the Valdoe gave mean dates falling within the Hoxnian Stage and the Early Wolstonian Substage (ages coeval with MIS stages 11 and 10), suggesting presence of younger material at Boxgrove, but there are large error margins associated with these dates meaning that they also overlap with the later part of the Cromerian Stage / MIS 13 (Voinchet et al., 2015). In addition, the mammalian biostratigraphic age estimate from Boxgrove is based on the presence of a number of species such as the shrews *Sorex runtonensis* and *Sorex savini*, the cave bear *Ursus deningeri* and the giant deer *Megaloceros dawkinsi* and *M.* cf. *verticornis*, all of which became extinct during the Anglian Stage, c. MIS 12 (Roberts and Parfitt, 1999).

The lack of evidence of Hoxnian Stage marine sequences may be due to limited quarrying south of the Goodwood-Slindon Formation. Alternatively, their preservation potential may have been low due to the continuing presence of a closed embayment (Bates et al., 2010), forming within clays and silts of the Lambeth and Thames Groups (Figure 1a). Hoxnian Stage deposits would only have been preserved within the embayment, because outside were erosional chalk cliffs, as seen west of Havant and east of the Arun. Preservation potential within the embayment was also likely to be low because the Lambeth and Thames Groups south of the Goodwood-Slindon cliffline in the Cretaceous chalk would not readily preserve a marine terrace form because they are significantly erodible. Furthermore, the area to the south of the Goodwood-Slindon Formation would have seen considerable reworking of solifluction deposits overlying the Goodwood-Slindon Formation, which might have also eroded any Hoxnian Stage sands that were deposited.

The Aldingbourne Formation was attributed to MIS 7 (Late Wolstonian Substage) by Bates et al. (2010) based on several OSL ages that agree well with each other. However, evidence from unpublished excavations further west, with a very different fauna and independent age estimates, seems more in line with the Middle Wolstonian Substage (c. 335 ka highstand / MIS 9) age proposed by the uplift modelling. At present, therefore, the Aldingbourne Formation remains an enigma which requires further investigation but may contain deposits of various ages, including the Middle Wolstonian Substage.

Global sea-level curves place the two Late Wolstonian Substage highstands at 200 ka and 240 ka at a very similar elevation (Grant et al., 2014, Table 5), although assuming constant uplift between these times means that we do not model them at the same elevation in the Sussex sequence. Neither is projected at a significantly higher elevation than the 125 ka highstand, presumably partly because global sea-levels were not particularly high. As discussed above, there is some uncertainty over which highstand is represented in the Brighton-Norton Formation. The key site of Norton Farm has an OSL age from marine sands of c. 240 ka but the mammalian biostratigraphy suggests a c. 200 ka age (Bates et al., 2000). The OSL age from the marine sands of c. 240 ka (Bates et al., 2010) has large error bars of c. 30 ka which may reflect either inclusion of older sediments and associated incomplete bleaching of the sample or insufficiently detailed dose rate determination because the sample was taken from a borehole. The horse found in marine sands and overlying terrestrial silts at Norton Farm is a particularly small form of *Equus ferus,* previously only seen in deposits attributed to late MIS 7 and the early part of MIS 6, i.e. within the Late Wolstonian Substage (Parfitt, 1998). Candy and Schreve (2007) later refined the dating of this small horse to early in the Late Wolstonian Substage glacial period (c. MIS 6) at Marsworth, where it was recorded in slope deposits overlying precisely dated tufa deposits within an underlying channel which contained full-size horse remains (Murton et al., 2001). Bates et al. (2010) conclude that the dating evidence is insufficient to differentiate between these two highstands at this site.

This age uncertainty raises the possibility that the Brighton-Norton Formation at Norton Farm is a composite sequence, forming during both 240 ka and 200 ka highstand events. The modelling results in this study suggest that the marine terrace itself was most likely formed at the 240 ka highstand, but it is possible that the sedimentary sequence overlying it may date at least partially from 200 ka. The original investigation of the Brighton-Norton Formation at Norton Farm showed that it represented a period of marine regression, grading upwards from marine sands into terrestrial silts (Figure 4) with pollen and molluscs suggesting a cool or cold climate throughout. Foraminiferal and ostracod data show marine elements throughout, whereas the molluscs contain more freshwater elements (Bates et al., 2000). The terrestrial elements seen in this sequence and related sequences at Tangmere and Portfield Pit (Bates et al., 2010) might corroborate the slightly lower modelled sea-level for the 200 ka highstand in this study. It therefore seems likely that at c. 240 ka a shallow terrace formed both in Cretaceous chalk and in the Thames and Lambeth Group rocks southward of the Brighton-Norton cliffline on which a range of marine sediments were deposited during the 200 ka highstand near Norton Farm and then again during the 125 ka highstand further south.

Controls on preservation of robust relative sea-level indicators

It is striking that marine terraces have only been preserved in more competent rocks – Cretaceous chalk at Boxgrove and Norton Farm and Bembridge Limestone at Bembridge. The presence of more erodible Eocene rocks of the Thames and Lambeth Groups interspersed with chalk on the Sussex coastal plain has led to a gap in the record of sea-level change for the Hoxnian Stage (see above), a patchy record of the Aldingbourne Formation, tentatively assigned by modelling in this study to the Middle Wolstonian Substage (c. 335 ka highstand) and a wide range of elevation estimates for past sea-level during the Ipswichian Stage from the Pagham Formation.

Whilst at Bembridge, a clear marine terrace formed in Bembridge Limestone during the Ipswichian Stage, this was not the case further east. In Sussex, the lack of a clear cliffline associated with the Pagham Formation is exacerbated by both the similarity of the highstand elevation to that of the 240 ka and 200 ka highstands and a change in bedrock lithology. At the start of the Ipswichian Stage, the geomorphology of the Sussex coastline likely comprised a relict marine terrace formed in Cretaceous chalk to the north, with 5-10 m of slope deposits overlying marine sands, transitioning southwards into a terrace formed in the Thames and Lambeth Groups. It is plausible that the 125 ka highstand transgressed over this platform, depositing the beach sediments known as the Pagham Formation, but was unable to form a new preservable marine terrace due to a lack of suitable rocks to erode. The Ipswichian Stage beach deposits likely abutted directly onto slope deposits, as seen at Portelet and Belcroute in Jersey and also in the Cotentin Peninsula of northern France (Renouf and James, 2011), although such direct relationships have not been seen in Sussex.

This marks a significant shift in coastal configuration during the Ipswichian Stage. A relatively stable coastline position persisted from the Cromerian Stage to the Middle Wolstonian Substage (c. MIS 13 to MIS 9), backed by the Cretaceous chalk ridge (with the single large Goodwood-Slindon bay). This would have altered significantly when the coastline shifted southwards onto the Eocene deposits. Coupled with lower rates of uplift this shift in bedrock types created the opportunity for the development of the harboured coastline postulated by Bates et al (2010) where packages of sediments from both the Ipswichian Stage and Late Wolstonian Substages (c. MIS 5e and 7 / 125 ka, 200 ka and 240 ka highstands) seem to occupy similar elevations in the landscape. The different distributions of the softer Eocene and harder chalk bedrocks across this coastal plain likely further enhanced this complexity by responding differently to periglacial activity during cold periods, creating shallow water bodies during cold stages, subsequently exploited by the sea during the following highstand episode. This led to dissection of the Pagham Formation and replacement with a series of cold stage and Holocene silts, for example at Warblington (Figure 3b, Bates et al., 2009b; Bates et al., 2010).

Interactions with the fluvial systems of the Lavant to the west and Arun to the east also reduce the preservation potential of Pagham Formation sequences. Whilst the most significant evidence of Lavant activity is in the Chichester Fan Gravels on which the town of Chichester has been built (Figure 1b), the interglacial channels around Selsey Bill also appear to be associated with channels emerging from the Lavant Valley. These channels were likely cut during one or more cold stages and then filled during various interglacial transgressions. Sequences are thought to become progressively younger from west to east from Earnley to West Wittering, West Street Selsey and the Lifeboat station channel to the east of Selsey Bill (Briant et al., early view 2022). To the east, the Arun channel cuts fully across the marine terrace, with likely further dissection from tributary valleys running east-west as at the present day. Pagham Formation marine deposits were therefore deposited across a marine terrace which was dissected by river channels as well as differential periglacial wasting of different bedrock types, significantly reducing their preservation potential.

Conclusions

This study provides three new robust palaeo-RSL datapoints from marine terraces for the Solent and Sussex region in southern England, based on correction for indicative meanings from modern analogues. Palaeo-RSL values were also calculated from beach deposits of the Pagham Formation, but these are not reliable enough to use to determine past sea-level. The new palaeo-RSL datapoints in this study are different from, but not directly comparable to, previous palaeo-RSL estimates from this region.

The marine terrace palaeo-RSL values are:

- Goodwood-Slindon Formation at Boxgrove: 37.5 m ± 1.7 m (age of late Cromerian Stage based on biostratigraphy, c. MIS 13 / 485 ka highstand)
- Brighton-Norton Formation at Norton Farm: 5.7m ± 1.8 m (age of Late Wolstonian Substage / MIS 7 – either 200 ka or 240 ka highstand – OSL and biostratigraphy conflict)
- Bembridge: 5.3 m ± 2 m (age of Ipswichian Stage, c MIS 5e / 125 ka based on OSL)

Modelling uplift based on the two palaeo-RSL datapoints with the most reliable age estimates (Boxgrove and Bembridge) suggests the following conclusions:

- Uplift rates are low, and comparable with those found in other passive margin settings (i.e. noticeably below 0.2 mm/yr).
- Uplift rates are modelled to have changed at c. 140 ka, modelled at 0.164 mm/yr between 485 and 140 ka and 0.005 mm/yr afterwards. It is suggested that the reduction in uplift rate might be due to compressive uplift being offset by GIA subsidence, although this cannot be confirmed without more detailed crustal and GIA modelling.
- The 405 ka highstand of the Hoxnian Stage (c. MIS 11) is modelled to be coincident with that of the earlier 485 ka highstand, but no evidence is found in the landscape of this event, possibly because of the thick covering of slope deposits above the Goodwood-Slindon Formation or the geomorphological setting.
- The Aldingbourne Formation at an elevation of c. 21 m O.D. (uncorrected) coincides with a modelled highstand at c. 335 ka, during the Middle Wolstonian Substage. If accurate, this would place it earlier in time than previously suggested by OSL dating.
- The Brighton-Norton Formation marine terrace at Norton Farm deposited within the Late Wolstonian Substage is modelled to c. 240 ka, suggesting that the overlying sediments whose age has been suggested as late MIS 7 (i.e. similar to the 200 ka highstand) might have been emplaced on a pre-existing geomorphological feature.

- The only marine terrace preserved from the Ipswichian Stage (c. 125 ka highstand) is at Bembridge on the Isle of Wight. It is suggested that this is due to the underlying bedrock being stronger than the bedrock underlying the Pagham Formation in Sussex. Preservation potential of the Pagham Formation has been further reduced by differential periglacial wasting of different bedrock types and fluvial dissection.

Acknowledgements

Research described in this paper was funded from multiple sources, including archaeological consultancy work and an English Heritage funded Aggregate Levy Sustainability Fund project (*Palaeolithic Archaeology of the Sussex / Hampshire Coastal Corridor* Phases I and II) that covered much of the field and laboratory costs incurred in elements of the project. We would also like to thank all the landowners on whose land we have drilled, dug and investigated. We are grateful to Kevin Pedoja and an anonymous reviewer whose comments on an earlier draft of this paper greatly improved it. A CC BY or equivalent licence is applied to the authors accepted manuscript (AAM) arising from this submission.

References

Allen, L.G. and Gibbard, P.L. 1993. Pleistocene evolution of the Solent River of southern England. Quaternary Science Reviews **12**, 503–528.

Allen, L.G., Gibbard, P.L., Pettit, M.E., Preece, R.C. and Robinson, J.E. 1996. Late Pleistocene interglacial deposits at Pennington Marshes, Lymington, Hampshire, southern England. Proceedings of the Geologists' Association **107**, 39–50.

Bates, M.R. 2001. The Meeting of the Waters: raised beaches and river gravels of the Sussex Coastal Plain/Hampshire Basin. In: Wenban-Smith, F.F. and Hosfield, R. (eds.) Palaeolithic archaeology of the Solent River, Lithic Studies Society Occasional Paper 7. Lithic Studies Society: London, 27 – 45.

Bates, M.R., Bates, C.R., Gibbard, P.L., Macphail, R.I., Owen, F.J., Parfitt, S.A., Preece, R.C., Roberts, M.B., Robinson, J.E., Whittaker, J.E. and Wilkinson, K.N. 2000. Late Middle Pleistocene deposits at Norton Farm on the West Sussex coastal plain, southern England. Journal of Quaternary Science, **15**, 61-89.

Bates, M.R., Wenban-Smith, F.F., Briant, R.M. and Marshall, G. 2004. Palaeolithic Archaeology of the Sussex/Hampshire Coastal Corridor. English Heritage Archive Report (Project No. 3279).

Bates, M.R., Bates, C.R., Gibbard, P.L., Keen, D.H., Parfitt, S.A., Peglar, S.M., Schwenninger, J-L., Wenban-Smith, F.F. and Whittaker, J.E. 2009a. West Street, Selsey. In: Briant, R.M., Bates, M.R., Hosfield, R.T. and Wenban-Smith, F.F. (eds.) The Quaternary of the Solent Basin and West Sussex Raised Beaches. Field Guide. Quaternary Research Association: London, 73-95.

Bates, M.R., Bates, C.R., Bates, S., Jones, S., Schwenninger, J-L., Walker, M.J.C. and Whittaker, J.E. 2009b. Cold stage deposits of the West Sussex Coastal Plain: the evidence from Warblington, Hampshire. In: Briant, R.M., Bates, M.R., Hosfield, R.T. and Wenban-Smith, F.F.

(eds.) The Quaternary of the Solent Basin and West Sussex Raised Beaches. Field Guide. Quaternary Research Association: London, 60 – 72.

Bates, M.R., Briant, R.M., Rhodes, E.J., Schwenninger, J.L. and Whittaker, J.E. 2010. A new chronological framework for Middle and Upper Pleistocene landscape evolution in the Sussex/Hampshire Coastal Corridor. Proceedings of the Geologists' Association **121**, 369 – 392.

Bates, M.R., Bates, C.R., Toms, P., Krawiec, K. and Pope, M. 2019. Medmerry and the Manhood Peninsula in it's Quaternary context. In: Stephenson. P. and Krawiec, K. (eds). A View from the Edge: Archaeological Investigation on the Manhood Peninsula, Selsey for the Medmerry Managed Realignment Scheme. SpoilHeap publications, University College London, London, 15 – 27.

Bates, S.L., Siddall, M. and Waelbroeck, C., 2014. Hydrographic variations in deep ocean temperature over the mid-Pleistocene transition. Quaternary Science Reviews, **88**, 147-158

Bintanja, R., Van De Wal, R.S. and Oerlemans, J., 2005. Modelled atmospheric temperatures and global sea levels over the past million years. Nature, **437**, 125-128.

Bowen, D Q., 1999. A revised correlation of Quaternary deposits in the British Isles. Geological Society Special Report **23**.

Bradley, S.L., Milne, G.A., Teferle, F.N., Bingley, R.M. and Orliac, E.J. 2009. Glacial isostatic adjustment of the British Isles: new constraints from GPS measurements of crustal motion. Geophysical Journal International **178**, 14-22.

Briant, R.M., Bates, M.R., Schwenninger, J-L. and Wenban-Smith, F.F. 2006. A long optically-stimulated luminescence dated Middle to Late Pleistocene fluvial sequence from the western Solent Basin, southern England. Journal of Quaternary Science **21**, 507–523.

Briant, R.M., Bates, M.R., Boreham, S, Cameron, N.G., Coope, G.R., Field, M.H., Keen, D.H., Simons, R.M.J., Schwenninger, J-L., Wenban-Smith, F.F. and Whittaker, J.E. 2009 Gravels and interglacial sediments at Stone Point Site of Special Scientific Interest, Lepe Country Park, Hampshire. In: Briant, R.M., Bates, M.R., Hosfield, R.T. and Wenban-Smith, F.F. (eds.) The Quaternary of the Solent Basin and West Sussex Raised Beaches. Field Guide. Quaternary Research Association: London, 171-188.

Briant, R.M., Bates, M.R., Boreham, S., Coope, G.R., De Schepper, S., Field, M.H., Wenban-Smith, F.F. and Whittaker, J.E. 2013 Palaeoenvironmental reconstruction from a decalcified interglacial sequence in the former Solent rivers system at St Leonard's Farm, Hampshire, England. Quaternary Newsletter **130**, 23-40.

Briant, R.M., Bates, M.R., Boreham, S., Cameron, N.G., Coope, G.R., Field, M.H., Hatch, B.M., Holmes, J.A., Keen, D.H., Kilfeather, A.A. and Penkman, K.E. 2019. Early Ipswichian (last interglacial) sea level rise in the channel region: Stone Point Site of Special Scientific Interest, Hampshire, England. Proceedings of the Geologists' Association, **130**, 1-26.

Briant, R.M., Haggart, B.A., Schreve, D.C. and Whiteman, C.A. early view 2022. Quaternary sea level landforms and sediments in southern England: description of geological conservation review sites. Proceedings of the Geologists' Association.

Brown, R.C., Gilbertson, D.D., Green, C.P. and Keen, D.H. 1975. Stratigraphy and environmental significance of Pleistocene deposits at Stone, Hampshire. Proceedings of the Geologists' Association **86**, 349–363.

Busschers, F.S., Kasse, C., Van Balen, R.T., Vandenberghe, J., Cohen, K.M., Weerts, H.J.T., Wallinga, J., Johns, C., Cleveringa, P. and Bunnik, F.P.M. 2008. Late Pleistocene evolution of the Rhine-Meuse system in the southern North Sea basin: imprints of climate change, sea-level oscillation and glacio-isostacy. Quaternary Science Reviews, **26**, 3216-3248.

Caputo R. 2007. Sea-level curves: perplexities of an end-user in morphotectonic applications. Global and Planetary Change, **57**, 417-423.

Candy, I. and Schreve, D. 2007. Land–sea correlation of Middle Pleistocene temperate sub-stages using high-precision uranium-series dating of tufa deposits from southern England. Quaternary Science Reviews, **26**, 1223-1235.

Channel Coast Observatory (2021). Data available from: https://coastalmonitoring.org/cco/ [last accessed 31/7/2021].

Cohen, K.M., Cartelle, V., Barnett, R., Busschers, F.S. and Barlow, N.L. 2022. Last Interglacial sea-level data points from Northwest Europe. Earth System Science Data, **14**, 2895-2937.

De Gelder, G., Jara-Muñoz, J., Melnick, D., Fernández-Blanco, D., Rouby, H., Pedoja, K., Husson, L., Armijo, R. and Lacassin, R. 2020. How do sea-level curves influence modelled marine terrace sequences? Quaternary Science Reviews, **229**, 106132.

De Santis, V., Scardino, G., Scicchitano, G., Meschis, M., Montagna, P., Pons-Branchu, E., … and Caldara, M. 2023. Middle-late Pleistocene chronology of palaeoshorelines and uplift history in the low-rising to stable Apulian foreland: Overprinting and reoccupation. Geomorphology, **421**, 108530.

Gale, A., 2019. The Isle of Wight. Geologists' Association Field Guide No. 60.

Gibbard, P.L., 1988. The history of the great northwest European rivers during the past three million years. Philosophical Transactions of the Royal Society of London. B, Biological Sciences, **318**, 559-602.

Gibbard, P.L., 1995. The formation of the Strait of Dover. Geological Society, London, Special Publications, **96**, 15-26.

Gibbard, P.L. and Hughes, P.D., 2021. Terrestrial stratigraphical division in the Quaternary and its correlation. Journal of the Geological Society **178**, jgs2020-134.

Gibbard, P.L., Hughes, P.D., Clark, C.D., Glasser, N.F. and Tomkins, M.D. 2021. Britain and Ireland: glacial landforms prior to the Last Glacial Maximum. In: Palacios, D., Hughes, P.D., Garcia-Ruiz, J.M., de Andrés, N. (eds). European Glacial Landscapes. Elsevier, Amsterdam, 245-253.

Gibson, S.M., Bateman, M.D., Murton, J.B., Barrows, T.T., Fifield, L.K. and Gibbard, P.L., 2022. Timing and dynamics of Late Wolstonian Substage 'Moreton Stadial' (MIS 6) glaciation in the English West Midlands, UK. Royal Society Open Science, **9**, 220312.

Grant, K.M., Rohling, E.J., Ramsey, C.B., Cheng, H., Edwards, R.L., Florindo, F., Heslop, D., Marra, F., Roberts, A.P., Tamisiea, M.E. and Williams, F., 2014. Sea-level variability over five glacial cycles. Nature Communications, 5.

Gupta, S., Collier J.S., Palmer-Felgate, A. and Potter, G. 2007 Catastrophic flooding origin of shelf valley systems in the English Channel Nature, **448**, 342-345.

Hijma, M.P., Cohen, K.M., Roebroeks, W., Westerhoff, W.E. and Busschers, F.S. 2012. Pleistocene Rhine–Thames landscapes: geological background for hominin occupation of the southern North Sea region. Journal of Quaternary Science, **27**, 17-39.

Hopson, P.M. 2009. The geological setting of the coastal fringes of West Sussex, Hampshire and the Isle of Wight. In: Briant, R.M., Bates, M.R., Hosfield, R.T. and Wenban-Smith, F.F. (eds.) The Quaternary of the Solent Basin and West Sussex Raised Beaches. Field Guide. Quaternary Research Association: London, 1-20.

Houghton, S.L., Roberts, G.P., Papanikolaou, I.D., McArthur, J.M. and Gilmour, M.A. 2003. New 234U-230Th coral dates from the western Gulf of Corinth: Implications for extensional tectonics. Geophysical Research Letters, 30, 19.

Jara-Muñoz, J. and Melnick, D. 2015. Unraveling sea-level variations and tectonic uplift in wave-built marine terraces, Santa María Island, Chile. Quaternary Research, **83**, 216-228.

Kopp, R.E., Simons, F.J., Mitrovica J.X., Maloof, A.C. and Oppenheimer, M. 2009. Probabilistic assessment of sea-level during the last interglacial stage. Nature, **462**, 863-867.

Lambeck, K. 1996. Glaciation and sea-level change for Ireland and the Irish Sea since Late Devensian/Midlandian time. Journal of the Geological Society, **153**, 853-872.

Lorscheid, T. and Rovere, A. 2019. The indicative meaning calculator – quantification of paleo sea-level relationships by using global wave and tide datasets. Open Geospatial Data, Software and Standards **4,** 10. doi: 10.1186/s40965-019-0069-8.

Long, A.J., Barlow, N.L., Busschers, F.S., Cohen, K.M., Gehrels, W.R. and Wake, L.M. 2015. Near-field sea-level variability in northwest Europe and ice sheet stability during the last interglacial. Quaternary Science Reviews **126**, 26-40.

Melville, R.V. and Freshney, E.C. 1982 The Hampshire Basin and adjoining area. 4th Edition. HMSO: London.

Meschis, M., Roberts, G.P., Robertson, J. and Briant, R.M. 2018. The Relationships Between Regional Quaternary Uplift, Deformation Across Active Normal Faults, and Historical Seismicity in the Upper Plate of Subduction Zones: The Capo D'Orlando Fault, NE Sicily. Tectonics, **37**, 1231-1255.

Murton, J.B., Baker, A., Bowen, D.Q., Caseldine, C.J., Coope, G.R., Currant, A.P., Evans, J.G., Field, M.H., Green, C.P., Hatton, J. and Ito, M. 2001. A late Middle Pleistocene temperate–periglacial–temperate sequence (Oxygen Isotope Stages 7–5e) near Marsworth, Buckinghamshire, UK. Quaternary Science Reviews, **20**, 1787-1825.

New Forest District Council (2017). 2012 Update of Carter, D., Bray, M., and Hooke, J., 2004 SCOPAC Sediment Transport Study, www.scopac.org.uk/sts [accessed 30/11/2022].

Normand, R., Simpson, G., Herman, F., Biswas, R.H., Bahroudi, A. and Schneider, B. 2019. Dating and morpho-stratigraphy of uplifted marine terraces in the Makran subduction zone (Iran). Earth Surface Dynamics, **7**, 321-344.

Past Interglacials Working Group of PAGES, 2016. Interglacials of the last 800,000 years. Reviews of Geophysics, **54**, 162-219.

Parfitt, S.A. 1998. Pleistocene vertebrates of the West Sussex Coastal Plain: their stratigraphic and palaeoenvironmental significance. In: Murton, J.B., Whiteman, C.A., Bates, M.R., Bridgland, D.R., Long, A.J. Roberts, M.B. and Waller, M.P. (Eds.), The Quaternary of Kent and Sussex. Field Guide. Quaternary Research Association, London, 121–135.

Pedoja, K., Husson, L., Regard, V., Cobbold, P.R., Ostanciaux, E., Johnson, M.E., Kershaw, S., Saillard, M., Martinod, J., Furgerot, L. and Weill, P. 2011. Relative sea-level fall since the last interglacial stage: are coasts uplifting worldwide? Earth-Science Reviews, **108**, 1-15.

Pedoja, K., Husson, L., Johnson, M.E., Melnick, D., Witt, C., Pochat, S., Nexer, M., Delcaillau, B., Pinegina, T., Poprawski, Y. and Authemayou, C. 2014. Coastal staircase sequences reflecting sea-level oscillations and tectonic uplift during the Quaternary and Neogene. Earth-Science Reviews, **132**, 13-38.

Pedoja, K., Jara-Muñoz, J., De Gelder, G., Robertson, J., Meschis, M., Fernández-Blanco, D., Nexer, M., Poprawski, Y., Dugué, O., Delcaillau, B. and Bessin, P. 2018. Neogene-Quaternary slow coastal uplift of Western Europe through the perspective of sequences of strandlines from the Cotentin Peninsula (Normandy, France). Geomorphology, **303**, 338-356.

Plint, A.G. 1982. Eocene sedimentation and tectonics in the Hampshire Basin. Journal of the Geological Society, **139**, 249-254.

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

Renouf, J. and James, L. 2011. High level shore features of Jersey (Channel Islands) and adjacent areas. Quaternary International, **231**, 62-77.

Rixhon, G., Briant, R.M., Cordier, S., Duval, M., Jones, A. and Scholz, D. 2017. Revealing the pace of river landscape evolution during the Quaternary: recent developments in numerical dating methods. Quaternary Science Reviews, **166**, 91-113.

Roberts, M.B and Parfitt, S.A. 1999. Boxgrove. A Middle Pleistocene hominid site at Eartham Quarry, Boxgrove, West Sussex. English Heritage Archaeological Report 17. English Heritage: London.

Roberts, G.P., Houghton, S.L., Underwood, C., Papanikolaou, I., Cowie, P.A., Van Calsteren, P., Wigley, T., Cooper, F.J. and McArthur, J.M. 2009. Localization of Quaternary slip rates in an active rift in 105 years: an example from central Greece constrained by 234Ue230Th coral dates from uplifted paleoshorelines. Journal of Geophysical Research **114**, B10406. http://dx.doi.org/10.1029/2008JB005818.

Roberts, G.P., Meschis, M., Houghton, S., Underwood, C and Briant, R.M. 2013. The implications of revised Quaternary paleoshoreline chronologies for the rates of active extension and uplift in the upper plate of subduction zones. Quaternary Science Reviews **78**, 169-187.

Robertson, J., Meschis, M., Roberts, G.P., Ganas, A. and Gheorghiu, D.M. 2019. Temporally constant Quaternary uplift rates and their relationship with extensional upper-plate faults in south Crete (Greece), constrained with 36Cl cosmogenic exposure dating. Tectonics, **38**, 1189-1222.

Rohling, E.J., Foster, G.L., Grant, K.M., Marino, G., Roberts, A.P., Tamisiea, M.E. and Williams, F. 2014. Sea-level and deep-sea-temperature variability over the past 5.3 million years. Nature, **508**, 477-482.

Rovere, A., Raymo, M.E., Vacchi, M., Lorscheid, T., Stocchi, P., Gomez-Pujol, L., Harris, D.L., Casella, E., O'Leary, M.J. and Hearty, P.J. 2016. The analysis of Last Interglacial (MIS 5e) relative sea-level indicators: Reconstructing sea-level in a warmer world. Earth-Science Reviews, **159**, 404-427.

Shennan, I. and Horton, B. 2002. Holocene land-and sea-level changes in Great Britain. Journal of Quaternary Science **17**, 511-526.

Siddall, M., Rohling, E.J., Almogi-Labin, A., Hemleben, C., Meischner, D., Schmelzer, I. and Smeed, D.A. 2003. Sea-level fluctuations during the last glacial cycle. Nature, **423**, 853-858.

Spratt, R.M. and Lisiecki, L.E. 2016. A Late Pleistocene sea level stack. Climates of the Past, **12**, 1079-1092.

Tzedakis, P.C., Hodell, D.A., Nehrbass-Ahles, C., Mitsui, T. and Wolff, E.W., 2022. Marine isotope stage 11c: An unusual interglacial. Quaternary Science Reviews **284**, 107493.

Vink, A., Steffen, H., Reinhardt, L. and Kaufmann, G. 2007. Holocene relative sea-level change, isostatic subsidence and the radial viscosity structure of the mantle of northwest Europe (Belgium, the Netherlands, Germany, southern North Sea). Quaternary Science Reviews, **26**, 3249-3275.

Voinchet, P., Moreno, D., Bahain, J.J., Tissoux, H., Tombret, O., Falguères, C., Moncel, M.H., Schreve, D., Candy, I., Antoine, P. and Ashton, N. 2015. New chronological data (ESR and ESR/U-series) for the earliest Acheulian sites of north-western Europe. Journal of Quaternary Science, **30**, 610-622.

Wenban-Smith, F.F., Schwenninger, J-L. and Scaife, R. 2005. New OSL dates and pollen records from the Bembridge Raised Beach sequence, Isle of Wight (UK). Quaternary Newsletter **107**, 1–19.

West, R.G. and Sparks, B.W. 1960. Coastal interglacial deposits of the English Channel. Philosophical Transactions of the Royal Society of London **243**, 95–133.

Westaway, R.W.C., Bridgland, D.R. and White, M. 2006. The Quaternary uplift history of central southern England: evidence from the terraces of the Solent River system and nearby raised beaches. Quaternary Science Reviews **25**, 2212–2250.

List of Figures.

Figure 1. Map of the Solent region and Sussex coast, showing location of sites mentioned in the text, Figures 3-6 and Tables 1-4.

Figure 2. Geomorphological setting of the Solent region and Sussex coast showing offshore bathymetry (Channel Coast Observatory, 2021), dominant sediment movements from New Forest District Council (2017) and the modern analogue locations used to calculate indicative meanings for relative sea-level estimates.

Figure 3. a) Lithological profiles and optically stimulated luminescence (OSL) dates (see also Table 3) through selected MIS 5e sites from the Solent region and the Sussex coast. ML = sites used as marine limiting data; SLIP = sites used as sea-level index points, both in the WALIS database - Cohen et al. (2022). f = freshwater sequence, ↑ = transgressive sequence (contains reworked warm elements and foram *Ammonia batavus* (ornate)), ↓ = regressive sequence (contains shallow-water foram species *Elphidium williamsonii* and freshwater ostracods). Sequences are described fully in Allen et al., 1996; Briant et al., 2006, 2013, early view 2022; Bates et al., 2010; Wenban-Smith et al., 2005 or previously unpublished (Butlins, Bognor and North Street, Worthing, Table S1). b) schematic profile through raised marine sediments of the SHCC, showing which groups of sediments are associated with marine terraces.

Figure 4. Calculation of indicative sea-level meaning of the raised clifflines at Boxgrove and Norton Farm, using the methodology of Rovere et al. (2016). The Boxgrove sequence shown is from Quarry 2 (Figure 31, Briant et al., early view 2022) and the Norton Farm sequence is shown in Figure 6 of Bates et al. (2010). The modern analogue of a cliffline developed in Cretaceous Chalk is Seaford Head (location c on Figure 2). The 2018 LIDAR profiles across Seaford Head come from data available from the Channel Coast Observatory (2021).

Figure 5. Calculation of indicative sea-level meaning of the raised cliffline at Bembridge, using the methodology of Rovere et al. (2016). The Bembridge sequence shown is from Figure 12 of Briant et al. (early view 2022). The modern analogue used of a cliffline developed in Bembridge Limestone is Hamstead Cliffs (location a on Figure 2). The 2008 LIDAR profiles across Hamstead Cliffs come from data available from the Channel Coast Observatory (2021).

Figure 6. Calculation of indicative sea-level meaning of the Pagham Formation marine sediment sequences on the West Sussex coastal plain as shown on Figure 3, using the methodology of Rovere et al. (2016). The modern analogue used is Selsey Bill (location b on Figure 2). The beach profile across Selsey Bill comes from data available from the Channel Coast Observatory (2021).

Figure 7. Synchronous correlation modelling results using the sea-level curve of Grant et al. (2014).

List of Tables

Table 1. Previous palaeo-sea-level estimates from Westaway et al. (2006), Kopp et al. (2009) and Cohen et al. (2022). Indicative meaning from Cohen et al. (2022) follow the methodology of Rovere et al. (2016). U_1 (L_1) = upper (lower) range of landform in modern analogue in relation to mean sea-level; IR = indicative range = U_1-L_1; RWL = reference water level = (U_1+L_1)/2; E = Elevation of palaeo-sea-level indicator above MSL, with error (E_e); RSL = palaeo-relative sea-level = E-RWL; δRSL = error on RSL = Sqrt $((IR/2)^2 + (E_e/2)^2)$. Note that other estimates are listed in the WALIS database (https://zenodo.org/record/7944196#.ZGSlck_MKUl) reported by Cohen et al. (2022), with a representative sample (excluding all terrestrial limiting points) given below.

Table 2. OSL age estimates from various sequences within the Sussex / Hampshire Coastal Corridor containing sea level indicators which are listed in Table 1 and / or shown in Figure 3. .

Table 3. Indicative meaning of palaeo-sea-level indicators at Boxgrove, Norton Farm, Bembridge and various sites within the Pagham Formation on the Sussex Coastal Plain, using modern analogues at Seaford Head, Hamstead Cliffs and Selsey Bill and the methodology of Rovere et al. (2016). U_1 (L_1) = upper (lower) range of landform in modern analogue in relation to mean sea-level; IR = indicative range = U_1-L_1; RWL = reference water level = (U_1+L_1)/2; E = Elevation of palaeo-sea-level indicator above MSL, with error (E_e); RSL = palaeo-relative sea-level = E-RWL; δRSL = error on RSL = Sqrt $((IR/2)^2 + (E_e/2)^2)$. Modern analogues are shown in Figures 4 to 6 and locations shown on Figure 2.

Table 4. Details of the Bembridge Foreland sequence, Isle of Wight. Descriptions are a summary of work presented by Preece et al. (1990) and Wenban-Smith et al. (2005). Full OSL age details for key samples given in Table 2.

Table 5. Best-fit modelling results for Grant et al. (2014) and various comparator sea-level curves chosen to represent different types of reconstruction (i.e. hydraulic modelling -– Grant et al. (2014); principal component statistical analyses using numerous sea-level datasets -– Spratt and Lisiecki (2016); ice-sheet-ocean-temperature models from oxygen isotope ratios in benthic foraminifera -– Bintanja et al. (2005); and transfer functions associated with 10 marine sediment cores -– Bates et al. (2014)). . Stratigraphic comparisons follow the schemes of Gibbard and Hughes (2021) and Gibson et al (2022).

Supplementary Material

Table S1. Microfossil range chart: Butlins Bognor, Test Pit 3 and North Street, Worthing. o - one specimen; x - a few specimens; xx – common. Previously unpublished.

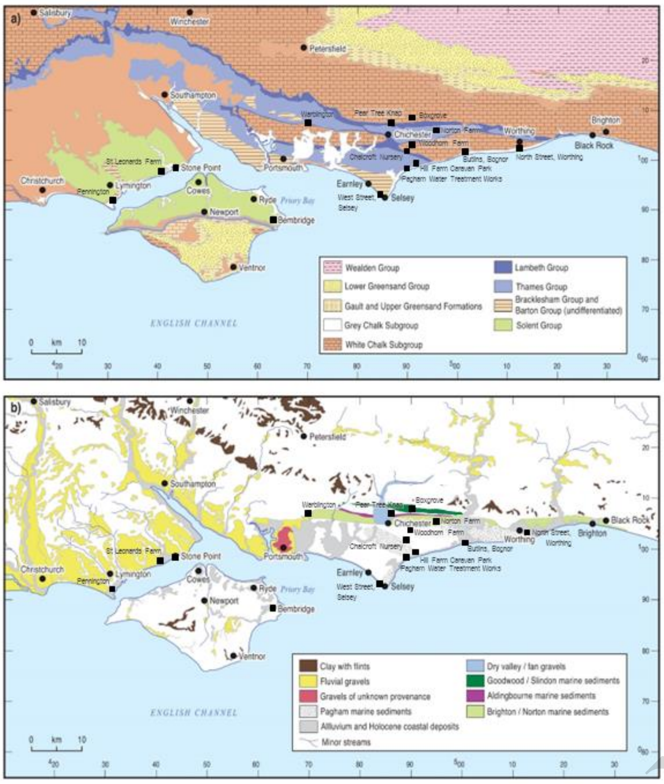


Figure 1


Hydrographic legend
Elevation (meters OD)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-1.16
-2.5
-4.76
-7.19
-9.61
-12.04
-14.39
-16.73
-21.67
-26.36
-31.21
-36.07
-42.1
-47.96
-53.9
-60
chalk cliffs
estuarine transport
tidal transport
long shore and onshore transport
Locations of modern analogues: a Hamstead cliffs; b Selsey Bill; c Seaford Head
Portsmouth Harbour
Langstone Harbour
Chichester Harbour
Pagham Harbour
Medmerry Bank
Kirk Arrow Spit
Inner Owers
a
b
c
Isle of Wight
Wight-Barfleur Reef Special Area of Conservation
Southampton
Portsmouth
Brighton
Winchester
20 km

Figure 2

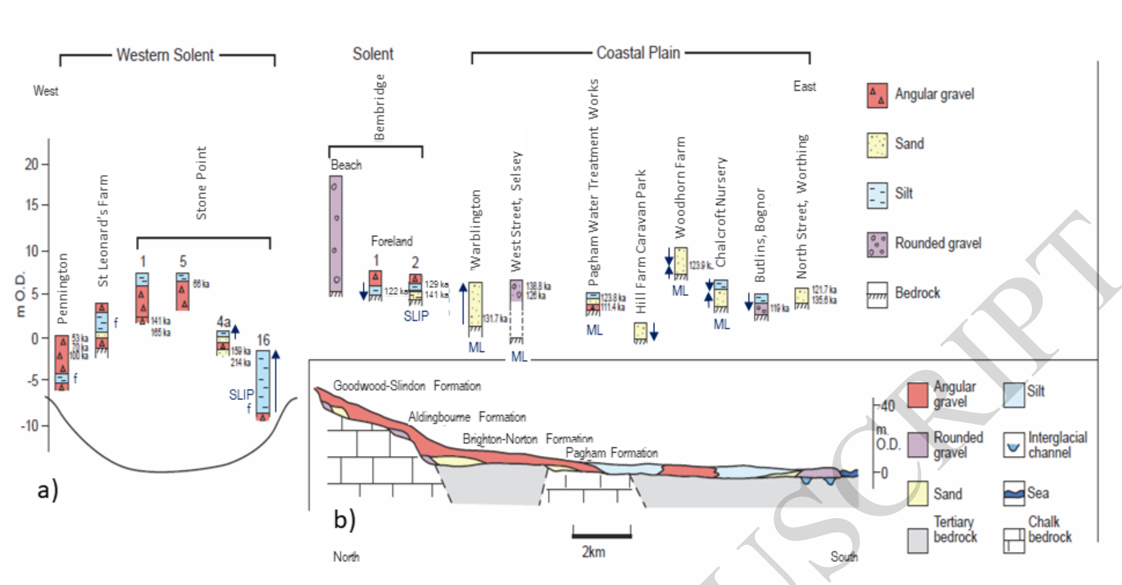

Western Solent
Solent
Coastal Plain
West
East
Bembridge
Beach
Foreland
Pennington
St Leonard's Farm
Stone Point
Warblington
West Street, Selsey
Pagham Water Treatment Works
Hill Farm Caravan Park
Woodhorn Farm
Chalcroft Nursery
Butlins, Bognor
North Street, Worthing
m O.D.
SLIP
ML
Angular gravel
Sand
Silt
Rounded gravel
Bedrock
a)
Goodwood-Slindon Formation
Aldingbourne Formation
Brighton-Norton Formation
Pagham Formation
m O.D.
Interglacial channel
Sea
Tertiary bedrock
Chalk bedrock
2km
North
South
b)

Figure 3

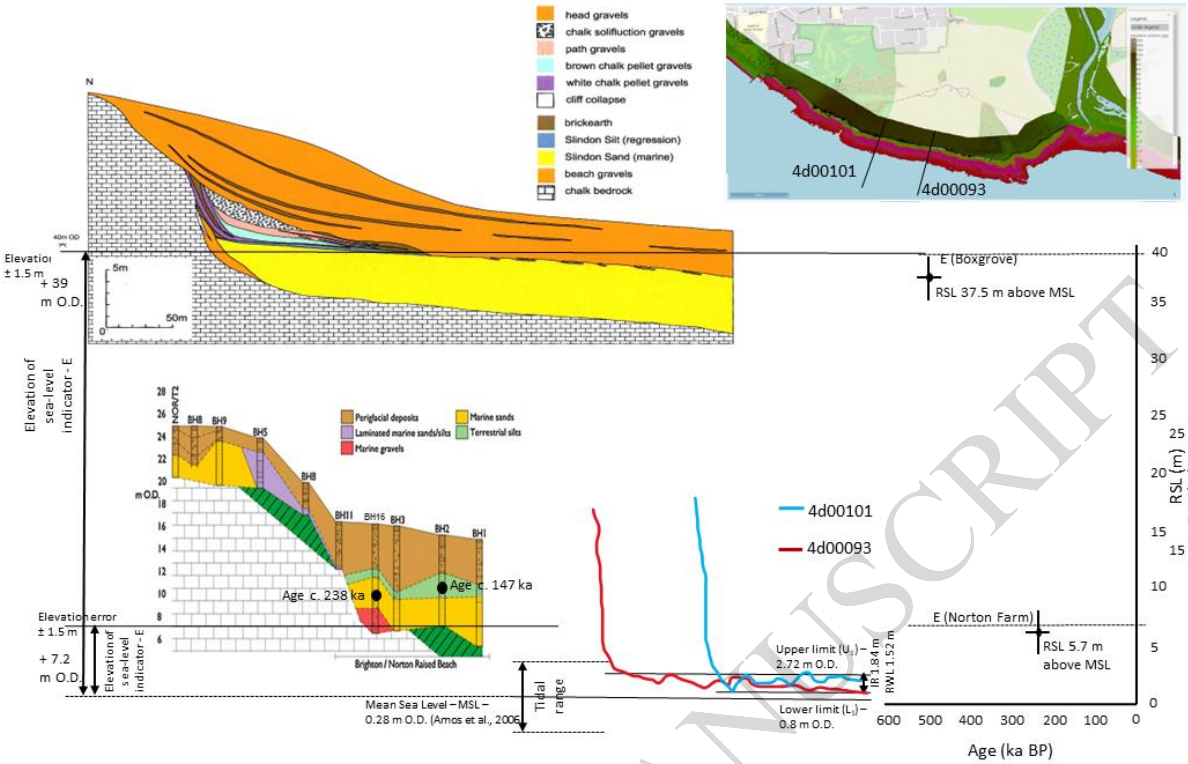
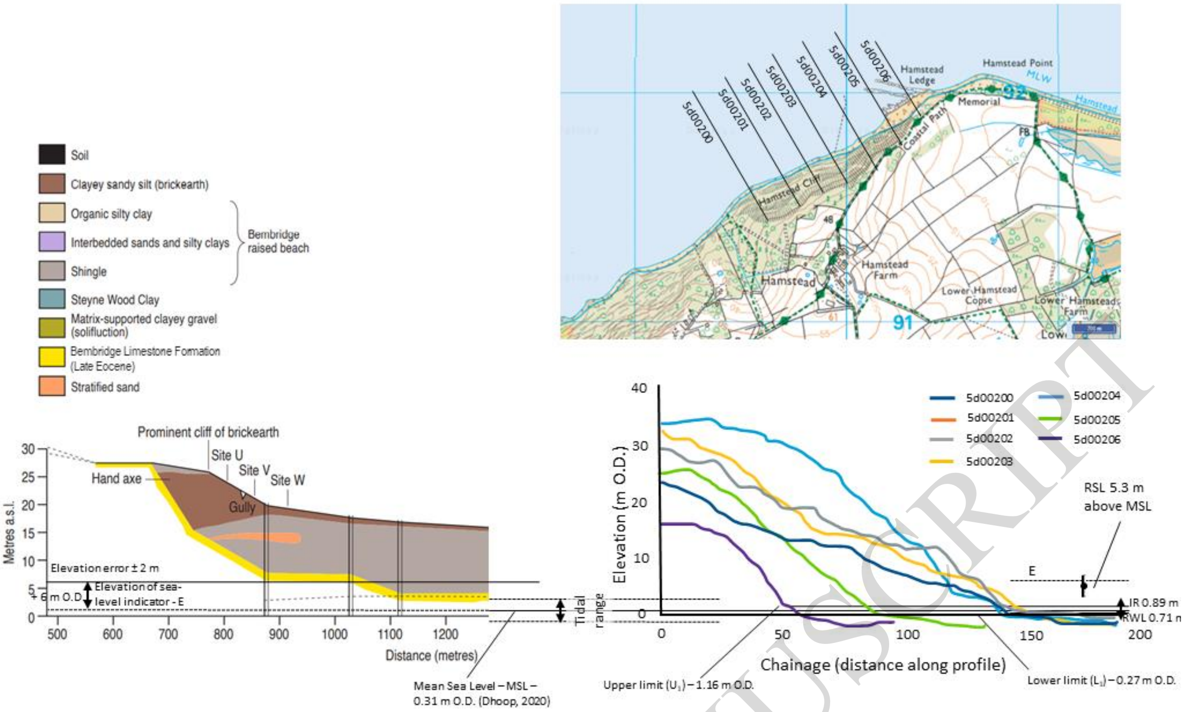

head gravels
chalk solifluction gravels
path gravels
brown chalk pellet gravels
white chalk pellet gravels
cliff collapse
brickearth
Slindon Silt (regression)
Slindon Sand (marine)
beach gravels
chalk bedrock
4d00101
4d00093
Elevation error ± 1.5 m
+ 39 m O.D.
Elevation of sea-level indicator - E
E (Boxgrove)
RSL 37.5 m above MSL
Perigiacial deposits
Laminated marine sands/silts
Marine gravels
Marine sands
Terrestrial silts
Age c. 238 ka
Age c. 147 ka
Brighton / Norton Raised Beach
Elevation error ± 1.5 m
+ 7.2 m O.D.
Mean Sea Level – MSL – 0.28 m O.D. (Amos et al., 2006)
Tidal range
Upper limit (U) – 2.72 m O.D.
Lower limit (L) – 0.8 m O.D.
IR 1.84 m
RWL 1.52 m
E (Norton Farm)
RSL 5.7 m above MSL
RSL (m)
Age (ka BP)

Figure 4



Soil
Clayey sandy silt (brickearth)
Organic silty clay
Interbedded sands and silty clays
Shingle
Bembridge raised beach
Steyne Wood Clay
Matrix-supported clayey gravel (solifluction)
Bembridge Limestone Formation (Late Eocene)
Stratified sand
Prominent cliff of brickearth
Site U
Site V
Site W
Hand axe
Gully
Metres a.s.l.
Elevation error ± 2 m
6 m O.D.
Elevation of sea-level indicator - E
Distance (metres)
Tidal range
Mean Sea Level – MSL – 0.31 m O.D. (Dhoop, 2020)
5d00200
5d00201
5d00202
5d00203
5d00204
5d00205
5d00206
Hamstead Ledge
Hamstead Point
MLW
Memorial
Coastal Path
Hamstead Cliff
Hamstead
Hamstead Farm
Lower Hamstead Copse
Lower Hamstead Farm
91
92
Elevation (m O.D.)
Chainage (distance along profile)
RSL 5.3 m above MSL
E
IR 0.89 m
RWL 0.71 m
Upper limit (U$_L$) – 1.16 m O.D.
Lower limit (L$_L$) – 0.27 m O.D.

Figure 5

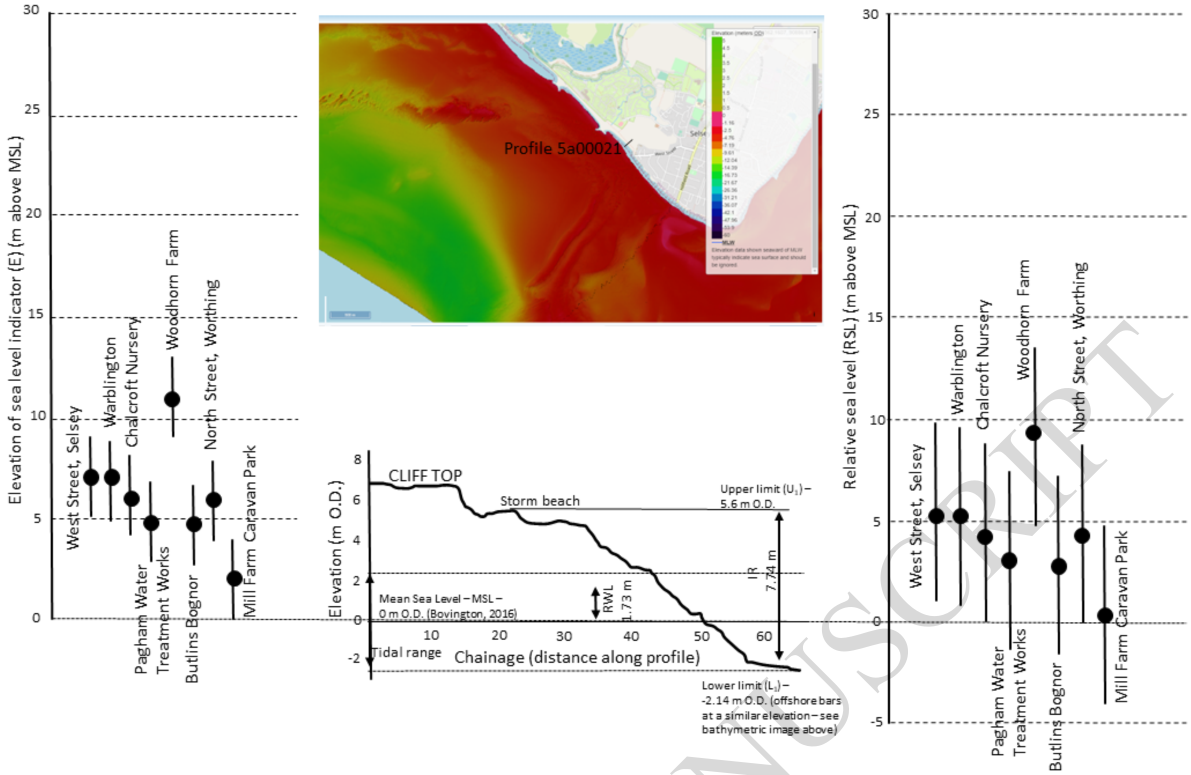
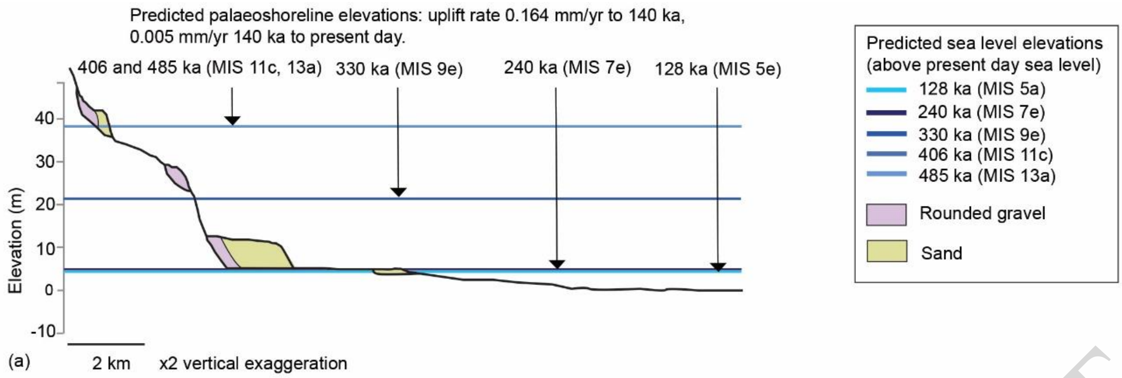

Elevation of sea level indicator (E) (m above MSL)
30
25
20
15
10
5
0
West Street, Selsey
Warblington
Chalcroft Nursery
Pagham Water Treatment Works
Woodhorn Farm
Butlins Bognor
North Street, Worthing
Mill Farm Caravan Park
Profile 5a00021
CLIFF TOP
Storm beach
Upper limit (U$_I$) – 5.6 m O.D.
Elevation (m O.D.)
8
6
4
2
0
-2
Mean Sea Level – MSL – 0 m O.D. (Bovington, 2016)
RWL 1.73 m
IR 7.74 m
Tidal range
Chainage (distance along profile)
10
20
30
40
50
60
Lower limit (L$_I$) – -2.14 m O.D. (offshore bars at a similar elevation – see bathymetric image above)
Relative sea level (RSL) (m above MSL)
30
25
20
15
10
5
0
-5
West Street, Selsey
Warblington
Chalcroft Nursery
Pagham Water Treatment Works
Woodhorn Farm
Butlins Bognor
North Street, Worthing
Mill Farm Caravan Park

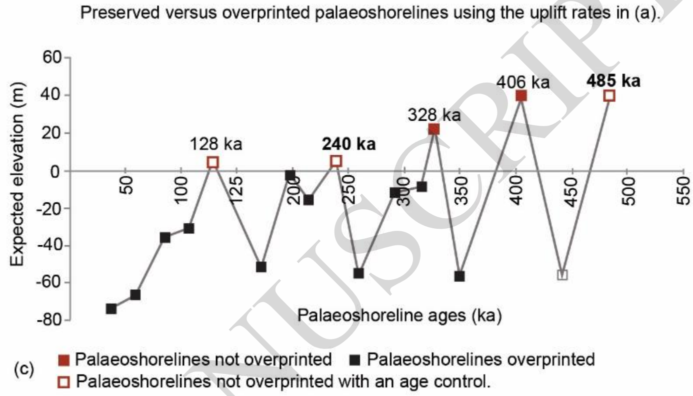
Figure 6



(a)

Uplift rate (mm/yr)	Highstand age (y), [relative sea level (m)]	Predicted elevation (m)	Measured elevation (m)
0.005	37000 [-72]	-72	
0.005	58000 [-66]	-65	
0.005	85000 [-35]	-35	
0.005	107000 [-31]	-30	
0.005	**128000 [5]**	**5**	**5.3**
0.164	172000 [-56]	-51	
0.164	197000 [-12]	-2	
0.164	214000 [-28]	-15	
0.164	**240000 [-12]**	**6**	**5.7**
0.164	292000 [-37]	-11	
0.164	315000 [-38]	-8.2	
0.164	330000 [-10]	-21	
0.164	406000 [-6]	38	
0.164	**485000 [-19]**	38	**37.5**

(b)



(c)

Figure 7

Table 1.

	Westaway et al. (2006)		Kopp et al. (2009)		World Atlas of Last Interglacial Shorelines (WALIS) - Cohen et al. (2022)		
Sequence	**Correction applied**	**Elevation quoted (grid references for locations not given)**	**Correction applied**	**Elevations quoted (grid references for locations not given)**	**Correction applied (using Lorscheid and Rovere, 2019)**	**Type of datapoint**	**Elevations quoted (grid references given in WALIS database)**
Marine terraces (various ages)							
Goodwood-Slindon Formation at Boxgrove	None (upper surface of deposit)	42 m O.D. (MIS 13a)					
Brighton-Norton Formation at Norton Farm	None (upper surface of deposit)	10 m (late MIS 7)				Marine limiting	Elevation: 11.25 ± 1.5 m
Beach deposits (various ages)							
Aldingbourne Formation at Norton Farm	None (upper surface of deposit)	25 m O.D. (MIS 9)			Beach deposit: IR = 3.81 RWL = 0.36	Sea level indicator	Elevation: 21.4 ± 1.5 m 21.6 ± 1.5 m 22 ± 1.5 m Paleo RSL: 21.04 ± 2.42 m 21.24 ± 2.42 m 21.64 ± 2.42 m
Aldingbourne Formation at Pear Tree Knap					Beach deposit: IR = 3.81 RWL = 0.36	Sea level indicator	Elevation: 21.6 ± 1.5 m 22.4 ± 1.5 m 22.6 ± 1.5 m Paleo RSL:

							21.24 ± 2.42 m 22.04 ± 2.42 m 22.24 ± 2.42 m
Pagham Formation (PF): West Street, Selsey		4 m O.D. (MIS 5e)	Not clear from paper	Elevation: 4 m O.D. ± 1 m Paleo RSL: 9.13 ± 8 m	N/A	Marine limiting	Elevation: 6.1 ± 1 m
PF: Pagham Water Treatment Works					N/A	Marine limiting	Elevation: 3 ± 1 m
PF: Chalcroft Nurseries					N/A	Marine limiting	Elevation: 6 ± 1 m; 5.5 ± 1 m; 5 ± 1 m; 4.5 ± 1 m; 3.5 ± 1 m
PF: Warblington					N/A	Marine limiting	Elevation: 1.2 ± 1 m
PF: Woodhorn Farm					N/A	Marine limiting	Elevation: 5.2 ± 1 m; 6.2 ± 1 m
Salt marsh / estuary deposits (Ipswichian, equivalent to MIS 5e)							
Bembridge Foreland					Saltmarsh (undifferentiated): IR = 2 RWL = 0.98	Sea level indicator	Elevation: 5 ± 1 m Paleo RSL: 4.02 ± 1.41 m
Stone Point base of estuarine unit 2d in borehole 16					Tidal (brackish) mudflat: IR = 1.9 RWL = 1.05	Sea level indicator	Elevation: -8.3 ± 0.5 m Paleo RSL: -8.5 ± 2.25 m
Stone Point top of estuarine unit 2d in test pit 7					Low saltmarsh environment: IR = 4.4 RWL = 0.2	Sea level indicator	Elevation: -1.5 ± 0.5 m Paleo RSL: -2.55 ± 1.07 m

Table 2.

Site	Stratigraphic unit	Sample code	Lab code	OSL dates (ka)	Original reference
Marine terraces					
Norton Farm	Brighton-Norton Formation	BH16 6.1–6.55 BH2 3.86–3.89	X1736 X1850	232.8±27.4 147.6±11.4	Bates et al. (2010)
Bembridge	Storm beach - see Table 4	3 - beach		121.9±10.4	Wenban-Smith et al. (2005)
Beach deposits					
Pear Tree Knap	Aldingbourne Formation (Sands III)	PTK06-1 PTK06-2 PTK06-3 PTK06-4	X2822 X2823 X2824 X2825	143.8±15.3 135.2±11.2 103.6±18.4 119.8±17.7	Bates et al. (2010)
	Aldingbourne Formation (Silts VI)	PTK06-5 PTK06-6 PTK06-9 PTK06-10	X2826 X2827 X2830 X2831	180.8±17 124±26 104.9±15.9 152.2±22.7	Bates et al. (2010)
Selsey West Street	Pagham Formation	SEL01-1 SEL01-2	X549 X550	138.8 ± 11 126 ± 10.1	Bates et al. (2010)
Pagham Water Treatment Plant	Pagham Formation	PWT06-01	X2796 X2797	123.8 ±8.7 117.4± 19.7	Bates et al. (2010)

Warblington	Pagham Formation	WAB, BH1, 6-7m	X2875	131.7±12.4	Bates et al. (2010)
Chalcroft Nursery	Pagham Formation	CHCN BH3, 2.6m CHCN BH 3 3.3m CHCN BH 3 3.8m CHCN BH 2 3.95m CHCN BH 24.15m	X2821 X2819 X2820 X3042 X3043	195.9±26.1 231.3±19.7 582.4±75.6 233.0±21.1 104.4±17.3	Bates et al. (2010)
Woodhorn Farm	Pagham Formation	WHF05 BH1 4.48–4.54m	X2876	123.9±9.6	Bates et al. (2010)
Butlins, Bognor	Pagham Formation	BUT 11, OSL 1	X5283	119.01±12.52	Previously unpublished
North Street, Worthing	Pagham Formation	OSL 1 OSL 2		121.75± 21.07 135.64 ± 8.84	Previously unpublished
Estuarine / salt-marsh deposits					
Bembridge Foreland	See Table 2	4 – salt marsh 5 - estuary		129.1±8.1 141.3±14.4	Wenban-Smith et al. (2005)
Stone Point (bracket estuarine Ipswichian deposits)	Lepe Upper Gravel (FG)	LEPE03-05	X1729	57 ± 6	Briant et al. (2006)
	Lepe Lower Gravel (FG)	LEPE03-01 LEPE03-02 LEPE03-03	X1725 X1726 X1727	198 ± 15 146 ± 10 141 ± 11	Briant et al. (2006)

		LEPE03-04	X1728	165 ± 14	
Terrestrial deposits (terrestrial limiting)					
Pennington (overlie freshwater Ipswichian deposits)	Pennington Gravel – upper facies (FG)	PENN03-06	X1733	48 ± 5	Briant et al. (2006)
	Pennington Gravel – lower facies (FG)	PENN03-01 PENN03-03	X1638 X1640	66 ± 7 94 ± 11	Briant et al. (2006)

Table 3.

	Elevation (m)	Error (m)	Relative Water Level (RWL) (m)	Indicative Range (IR) (m)	Relative Sea level (RSL) (m)	Error (δRSL) (m)	Comments on sequence
Marine terraces – elevation of inner edge of shore platform							
Boxgrove (Goodwood-Slindon Formation)	39	1.5	1.52	1.84	37.5	1.7	
Norton Farm (Brighton-Norton Formation)	7.2	1.5	1.52	1.84	5.7	1.8	
Bembridge (Ipswichian age, equivalent to Pagham Formation)	6	2	0.71	0.89	5.3	2	
Beach deposits – elevation of top of deposit within Pagham Formation							
West Street Selsey	7	1	1.73	7.74	5.3	4.0	Not truncated
Warblington	7	2	1.73	7.74	5.3	4.4	Not clear if truncated
Chalcroft Nurseries	6	1	1.73	7.74	4.3	4.0	Overlain by silt. Probably not truncated
Pagham Water Treatment Works	4.8	1	1.73	7.74	3.1	4.0	Overlain by silt. Probably not truncated
Woodhorn Farm	11	2	1.73	7.74	9.3	4.4	Not clear if truncated
Butlins Bognor	4.5	2	1.73	7.74	2.8	4.4	Not clear if truncated
North Street Worthing	6	2	1.73	7.74	4.3	4.4	Not clear if truncated
Mill Farm Caravan Park	2	2	1.73	7.74	0.3	4.4	Not clear if truncated

Table 4.

Southwestern sedimentary sequence (palaeocliffline) and elevation	Interpretation	Chronological control	North-eastern sedimentary sequence (Bembridge Foreland) and elevation
Brickearth up to 10 m thick adjacent to palaeocliffline, 15-27 m OD	Possibly aeolian	TL c. 18 & 24 ka (Parks and Rendell, 1992)	Thin brickearth, above Bembridge Foreland pollen sequence, c. 7-8 m OD
Thin layer of clayey gravel, c. 18 m OD	Colluvial / solifluction	OSL 1,2, 8, c. 82, 103 & 116 ka (Wenban-Smith et al., 2005)	Thick layer of clayey gravel, with some sand at base, c. 6-7 m OD
	Salt marsh sediments adjacent to main beach (Preece et al., 1990), freshening upwards (W-S et al., 2005)	OSL 4, c. 129 ka (Wenban-Smith et al., 2005) Early to Late-temperate pollen assemblages	Bembridge Foreland pollen sequence: pollen bearing humic silt c. 5-6 m OD
	Estuarine sediments	OSL 5 & 6, c. 141 & 157 ka (Wenban-Smith et al., 2005)	Clay-silt, fine sand, c.4-5 m OD
Sand and gravel, c. 4-18m OD, next to palaeocliffline	Cuspate foreland storm beach (Preece et al., 1990)	TL c. 104 & 115 ka (Preece et al., 1990 Appx B) OSL 3 & 7, c. 122 & 183 ka (Wenban-Smith et al., 2005)	Sand and gravel, c. 4-5m OD

Table 5.

British Stage or Substage		NW European Stage	Equivalent marine isotope stage (MIS)	Sussex marine terrace tie-points	Grant et al. (2014) 0.164 mm/yr 485 to 140 ka 0.005 mm/yr 140 ka →		Spratt and Lisiecki (2016) 0.13 mm/yr 485 to 140 ka 0.015 mm/yr 140 ka →		Bintanja et al. (2005) 0.164 mm/yr 485 to 140 ka 0.005 mm/yr 140 ka →		Bates et al. (2014) 0.164 mm/yr 485 to 140 ka 0.005 mm/yr 140 ka →	
				Corrected relative sea level (m)	Highstand date	Predicted back point elevation (m)	Highstand date	Predicted back point elevation (m)	Highstand date	Predicted back point elevation (m)	Highstand date	Predicted back point elevation (m)
Devensian		Weichselian	MIS 5d-2		37000	-72.0						
					58000	-65.2	53000	-61.2	50000	-77.5	55000	-50.0
					84875	-34.8	82000	-25.8	80000	-34.6	80000	-12.0
					106500	-30.0	102000	-14.5	98000	-31.1	100000	-8.0
Ipswichian		Eemian	MIS 5e	Pagham Fm / Bembridge beach: 5.3 ± 2	127750	5.3	120000	5.8	123000	5.7	125000	8.0
Wolstonian	Late	Saalian	MIS 6		171500	-50.6	168000	-49.3	172000	-65.0	175000	-44.8
			MIS 7d-a		196875	-2.0	198000	-2.4	198000	-6.2	200000	-2.9
					213900	-15.4	225000	4.2	215000	-2.2	210000	-1.7
			MIS 7e	Brighton-Norton Fm: 5.7 ± 1.8	239750	5.5	236000	4.6	238000	4.0	240000	6.9
	Middle		MIS 8		258875	-54.2						
					291750	-11.1	284000	-13.2	285000	-8.4	280000	4.7
			MIS 9	Aldingbrn Fm?	315375	-8.2			307000	14.6		
	Early		MIS 10		328000	21.1	330000	23.8	340000	45.6	325000	24.0
			MIS 11b		350000	-54.8	383000	13.7				
Hoxnian		Holsteinian	MIS 11c		405625	38.2	404000	46.4	410000	53.3	410000	34.1

Anglian	Elsterian	MIS 12		442375	-54.9						
Cromerian	'Cromerian complex' Interglacial IV	MIS 13	Goodwood-Slindon Formation: 37.5 ± 1.7	485000	38.2	485000	37.0	488000	37.5	495000	37.2