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Mid- to late-Holocene relative sea-level change in southwest Britain and the influence of sediment compaction

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Abstract: Relative sea-level changes in southwest Britain are poorly constrained because of limitations in the quality and quantity of existing geological data. As a consequence, in contrast to most other regions in the UK, it is not possible to reliably infer rates of land and sea-level change during the last few thousand years. Furthermore, geologically based sea-level reconstructions from this area display significant misfits with relative sea-level predictions based on a recent global model of the glacio-isostatic adjustment process. This paper presents a new record of relative sea-level change for the last 4000 years derived from radiocarbon-dated sea-level index points. In addition to providing information concerning the pattern and rates of late Holocene sea-level change, these data are used to evaluate the suggestion that the apparent misfits between model predictions and geological reconstructions can be satisfactorily explained as a consequence of the lowering of sea-level index points by sediment compaction. The results indicate that a simple, first-order method of decompaction based on the stratigraphic position of sea-level index points, can eliminate much of the misfit between reconstructions and predictions, and substantially reduce vertical scatter in geological data. They also suggest that the influence of compaction on sea-level data from this region may be larger than previously thought. The simple addition of reliable stratigraphic data, in combination with targeted sampling, has the potential to improve our understanding of the compaction process, and increase the utility of existing data. This is increasingly important as the partnership between geophysical modelling and geological investigation becomes more commonplace in sea-level studies around the world.

Key words: Relative sea level, sediment compaction, glacio-isostasy adjustment, southwest Britain, Holocene.

Introduction

Coastal change as a consequence of future sea-level rise is one of the major challenges facing policy makers and environmental managers. The latest consensus projections detailed in the Third Assessment Report of the Intergovernmental Panel on Climate Change, suggest a globally averaged rise of up to 88 cm by AD 2100. Such predictions are of limited utility however, since the relative sea-level (RSL) variations experienced at the coast may differ markedly from the global average, both in terms of their magnitude and direction of change. In regions close to former ice sheets, such as the British Isles, the dominant cause of this spatial variability is the vertical movement of the land surface, which occurs as part of the glacial isostatic adjustment (GIA) process. A firm understanding of the local impacts of GIA is a prerequisite for interpreting tide gauge data and establishing rates of sea-level change.

The British Isles is an ideal testing ground for global models seeking to quantify the GIA process (Lambeck, 1993a,b, 1995; Lambeck *et al.*, 1996; Peltier *et al.*, 2002; Shennan *et al.*, 2002). As a consequence of the comparatively small size of its local ice sheet, resulting histories of RSL change are particularly sensitive to shallow earth structure (Lambeck, 1995; Peltier *et al.*, 2002). The large body of geologically based RSL data available from around the coast can be used to validate model predictions, thereby testing and refining the parameters associated with these global models. Discrepancies between model predictions and geological reconstructions may arise as a consequence of limitations in the model, or because of problems associated with the sea-level data. It is important that the cause of any misfit is correctly identified to ensure that model parameters are tuned in a reliable manner.

Peltier *et al.* (2002) tested their ICE-4G (VM2) global model of the isostatic adjustment process against a data base of over

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900 sea-level index points (SLIs) from around the UK. After modification of Earth and ice parameters, the resulting fits between prediction and reconstruction demonstrated that the model captured the dominant patterns of change observed throughout the Holocene (Peltier *et al.*, 2002; Shennan *et al.*, 2002). At certain locations and time intervals however, significant misfits between predictions and reconstructions occur. One of these areas is along the coastline of Wales, where existing reconstructions consistently place mean sea-level at lower altitudes than model predictions for much of the Holocene.

In the latest synthesis of sea-level data from Great Britain, Shennan and Horton (2002) estimate rates of RSL change for the last 4000 years from around the coast. In contrast with many other parts of the UK, a lack of data from South Wales prevented them from inferring a rate of RSL rise for this region. Where good data coverage does exist, Shennan and Horton (2002) note a tendency for model predictions to lie in the upper part of the scatter of SLIs. The lowering of sea-level index points by sediment compaction has been suggested as an explanation for observed discrepancies between model estimates and geological reconstructions (Shennan *et al.*, 2000; Shennan and Horton, 2002). Shennan *et al.* (2002) suggest that many of the misfits between modelled and reconstructed change may be removed if the influence of this process is accounted for.

This paper presents new radiocarbon-dated sea-level index points from the Loughor Estuary, West Glamorgan, Wales, covering the last 4500 years. These data begin to redress the paucity of reliable sea-level information from this area and time period that prevented Shennan and Horton (2002) from inferring a rate of RSL rise for the region. Furthermore, these new data are used to investigate the suggestion that the misfits between sea-level reconstructions and model predictions can be satisfactorily explained by accounting for sediment compaction.

Existing sea-level data

Predictions for the Welsh coastline produced by the ICE-4G (VM2) GIA model (Peltier *et al.*, 2002) suggest that RSL attained an altitude equal to, or greater than, present by around 4000 BP. In North Wales, a RSL highstand of around 3 m above modern sea-level is predicted, and this decreases in altitude with increasing distance south. In contrast to the model predictions, the geological evidence collected to date shows no evidence of Holocene RSL higher than today along the coast of Wales. No raised beaches of appropriate age are reported from North Wales, and the sea-level index points from further south suggest continued RSL rise to the present day with no evidence that modern levels were attained by 4000 BP.

Whilst a corpus of radiocarbon dates is available for the study region (Kidson and Heyworth, 1973, 1976, 1978; Heyworth and Kidson, 1982) many of these are from contexts with ambiguous vertical relationships to sea-level. Figure 1 shows a smaller body of sea-level index points that all posses quantified vertical relationships between the palaeoenvironment in which they formed and a contemporaneous palaeotide level (termed the indicative meaning (Preuss, 1979; van de Plassche, 1986)). These data are subdivided into three geographical groups (see Figure 2a) on the basis of the tidal parameters used to derive their indicative meanings.

With the exception of a clear outlier (index point 12), these data form a broad band of mean sea-level (MSL) rising from -6 m OD at *c.* 5000 BP to around -2 m OD by 2000 BP. The bulk of these data, which come from the Bristol Channel area, cluster in the time interval between 3000 and 4500 BP and exhibit a vertical scatter of around 4 m. No distinctive pattern is discernible between the geographical groupings, suggesting that the scatter does not primarily reflect systematic differences in tidal regime or geological conditions across

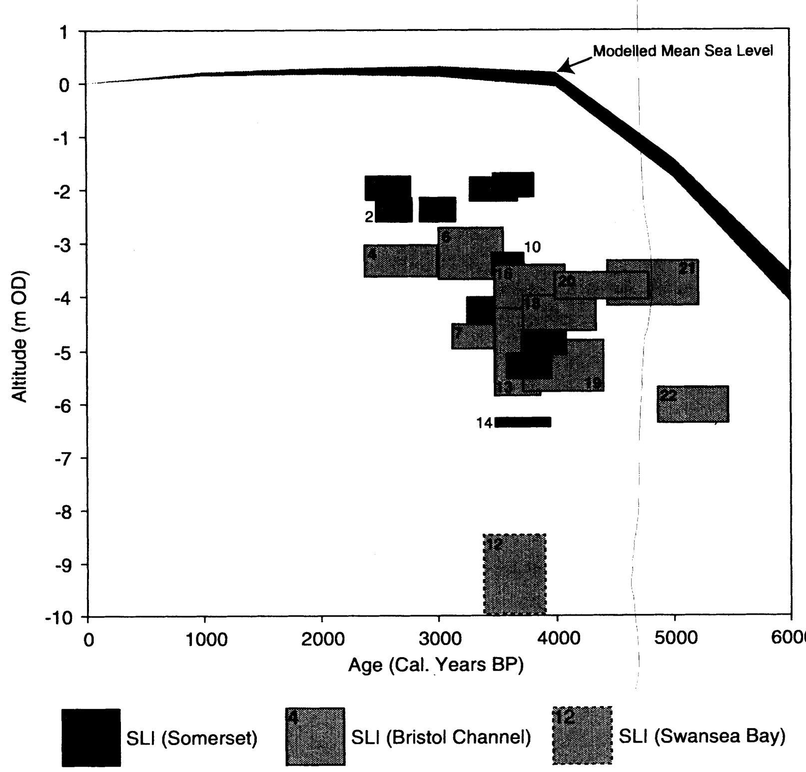

Figure 1 Sea-level index points for three areas in southwest Britain showing the altitude of palaeo-mean sea-level. The solid curve shows modelled mean sea-levels for this region (West Glamorgan, Pembroke, Bristol Channel) derived from ICE-4G (VM2) GIA model (from Peltier *et al.*, 2002)

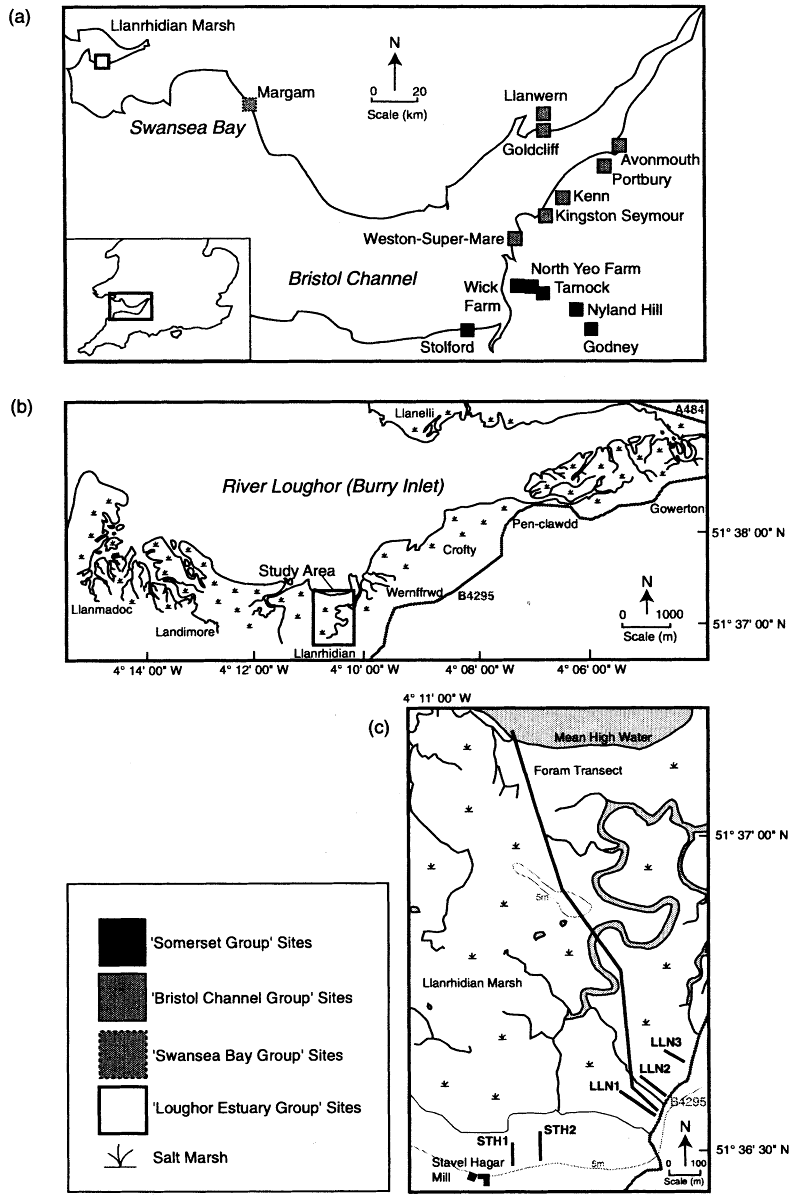

Figure 2 Location maps showing: (a) the sites with existing sea-level index points referred to in the text; (b) the study area; (c) the positions of the borehole and surface foraminiferal transects

the region. The absence of significant differential crustal movement is also predicted by the ICE-4G (VM2) model, and estimated MSL for the region (West Glamorgan to Bristol Channel), is plotted on Figure 1 as a band of change. The model consistently predicts higher RSLs than are suggested by the sea-level data, with altitudes ranging between 2 and 6 m above reconstructions. The scatter in the SLIs, coupled with the absence of index points from the last 2000 years, precludes a comparison between the general patterns of RSL change estimated by geological and modelling methods.

Study area

Site selection was directed by the need to minimize potential problems associated with local-scale processes such as changes in tidal range or sediment compaction (Shennan *et al.*, 2000). The Llanrhidian marshes, situated within the Loughor Estuary (Burry Inlet), West Glamorgan, were chosen on the basis that this area has an open connection with the sea and accumulations of fine-grained (low energy), dateable organic deposits (Figure 2b).

The estuary covers an area of around 45 km^2 and is macrotidal, with a range of 7.1 m on spring tides and 3.3 m on neap tides (Admiralty Tide Tables). The tidal prism exceeds river discharge by several orders of magnitude, resulting in well-mixed waters with salinities ranging from 29‰ to 33‰ (Moore, 1976). As a consequence, the potential influence of changes in river discharge is minimized.

Sediments within the Loughor Estuary are primarily composed of reworked fluvioglacial outwash that was mobilized and moved onshore by rising Holocene sea-level (Bridges, 1977). The sea-bed deposits consist of very well sorted fine sand and the only coarser material comes from whole and fragmented shells (Elliott and Gardiner, 1981).

Whilst no sea-level index points are available for this estuary, Plummer (1960) investigated the lithostratigraphy of saltmarshes around Llanelli, on the northern shore of the inlet. The sequences contained evidence of two humified peat beds, one below −2.5 m OD resting upon 'firm clay', and the other around 0 m OD intercalated between silts and clays. The remaining sequence was dominated by silts and clays but with some organic intercalations. Carling (1978) recovered two cores from Llanrhidian Marsh to seaward of the area investigated in this study. The sequence revealed a single 'Flandrian peat' *c.* 2 m thick, centred around 0 m OD and intercalated between minerogenic sediments. On the basis of its pollen content, this was interpreted as having formed in an open, fresh to brackish environment. This sequence is similar to the record from the northern shore reported by Plummer (1960) although Carling (1978) suggested that the 'higher peats' of the Llanelli shore were absent at Llanrhidian.

Materials and methods

Extensive reconnaissance coring was undertaken throughout the estuary to locate thin sedimentary sequences that contained peat deposits overlying bedrock or sediments with low potential for compaction (eg, sand or gravel). Surveys were conducted from Llanelli on the north shore, Gowerton at the eastern edge of the inlet, through Pen-clawdd, Crofty and Wernffrwd on the south shore to Landimore and Llanmadoc toward the west (Figure 2b). On the basis of this reconnaissance, two sites in the area around Llanrhidian were selected for further study (Figure 2c).

The lithostratigraphy of each site was investigated via a series of gouge augered transects. Sediments were described in the field using the Troels-Smith scheme of stratigraphic notation (Troels-Smith, 1955), and full descriptions are tabulated in Edwards (1998). A Leica TC 1010 total station was used to level the ground surface altitude of all cores to the closest Ordnance Survey benchmark. Possible sources of altitudinal error have been considered in detail by Shennan (1980, 1982, 1986). Errors in the measurement of stratigraphic contacts are considered to be no more than ± 0.02 m OD, and levelling to the benchmark was closed to within ± 0.02 m OD, giving a combined local altitudinal error of ± 0.04 m OD.

Sea-level index points

Sea-level index points are established on the basis of combined lithostratigraphic, biostratigraphic and chronostratigraphic data as formalized in the IGCP Project 61 (Preuss, 1979; van de Plassche, 1986; Shennan, 1983, 1987, 1989a,b). Selected cores were recovered for foraminiferal analysis and radiocarbon dating. Material was removed using a Russian-type coring device and checked in the field for contamination before being placed in plastic tubing and sealed in polythene. On return to the laboratory, all cores were stored below 4°C to retard biological and chemical processes.

The ages of the index points were determined by AMS radiocarbon dating. Samples were prepared to graphite at East Kilbride and analysed at the Centre for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory for C^{14} analysis. All radiocarbon ages are converted to calibrated years before present (cal. yr BP, where present corresponds to AD 1950) using the OxCal program (ver. 3.5; Bronk Ramsey, 1995, 2001).

Foraminiferal samples were washed through 500 μm and 63 μm mesh sieves in accordance with the methods described by Scott and Medioli (1980). Samples were counted wet under a binocular microscope and follow the taxonomy employed in Horton *et al.* (1999) and Horton and Edwards (2006). Contemporary samples were stained with Rose Bengal at the time of collection to distinguish life and death assemblages. Quantitative foraminifera-based sea-level reconstructions in the UK use death rather than life or total assemblages, since their composition is less variable in time and space and more reliably reflects the material that is incorporated into the subsurface sediments (Horton, 1997, 1999; Murray, 2000; Horton and Edwards, 2003).

The indicative meaning of each dated sample was established using a foraminiferal transfer function for tide level (Horton *et al.*, 1999, 2000). This transfer function quantifies the modern vertical distribution of intertidal foraminifera using weighted averaged partial least squares regression (WA-PLS). These modelled relationships between species and environment are then used to predict the elevation above mean tide level at which a sediment sample formed on the basis of its foraminiferal content. Unlike indicative meanings developed from classic stratigraphic analysis, the foraminiferal transfer function accounts for intersite differences in tidal range within its error estimates (Horton *et al.*, 2000).

A survey of the modern foraminifera at Llanrhidian Marsh was conducted to characterize their vertical distribution across the marsh. These local data were added to the UK training set that has been successfully employed by Horton *et al.* (1999, 2000) and expanded by Horton and Edwards (2006). The addition of data from other sites improves the reliability of reconstructions by increasing the range of environmental conditions represented in the modern training set (Horton and Edwards, 2005). Summary details of the modified transfer function are presented in Table 1, and full details concerning the development and application of foraminiferal transfer functions for tide level can be found in Horton *et al.* (1999, 2000) and Horton and Edwards (2006).

Table 1 Summary description and performance of the foraminiferal transfer function for tide level

No. sites	No. samples	r^2	RMSE	Vertical error in MSL prediction for Loughor Estuary (m)
14	209	0.71	8.6	0.64

r^2, coefficient of correlation; RMSE, root mean squared error. The vertical error term, which is related to the root mean squared error of prediction, is given in metres for the Loughor Estuary. This value will vary with tidal range (see Horton *et al.*, 1999 for details).

Results

Contemporary foraminifera at Llanrhidian Marsh

A summary of the modern foraminiferal distribution at Llanrhidian Marsh, based on death assemblages, is shown in Figure 3 along with a profile of the saltmarsh surface. The distribution exhibits the classic bipartite division between low marsh assemblages with relatively high abundances of calcareous taxa (most notably *Haynesina germanica* and *Quinqueloculina* species), and a high marsh assemblage dominated by agglutinated species (especially *Jadammina macrescens*). The large tidal range in this area, coupled with an uneven surface topography has resulted in a number of characteristic subtidal taxa being advected onto the marsh platform and deposited at station 7. These predominantly calcareous species are readily dissolved in the more acidic higher marsh environments, and it is likely that they were freshly deposited at the time of collection (sampling was conducted on a falling spring tide). Conditions appear to be particularly harsh in the high marshes of this region as a consequence of the prolonged periods of subaerial exposure associated with areas of high tidal range. This results in a relatively high abundance of *J. macrescens*

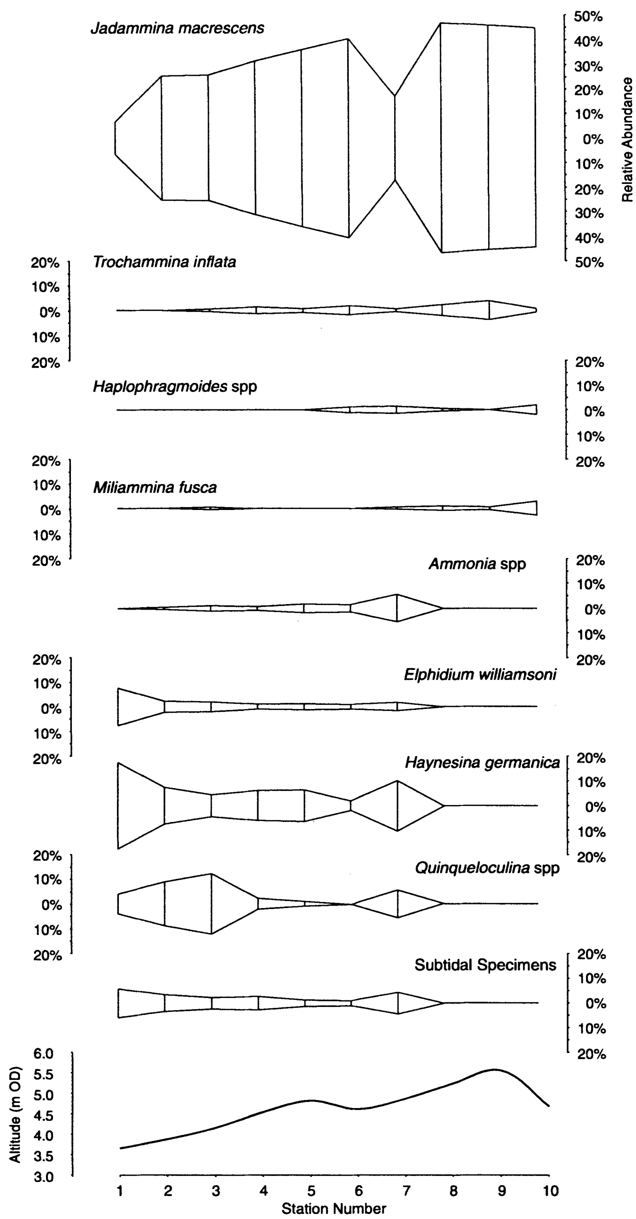

Figure 3 Summary diagram of the modern foraminiferal death assemblage distribution across Llanrhidian Marsh. The relative abundance of key species is plotted by station, and the corresponding marsh surface altitude is shown in the lower graph

across much of the marsh platform, and the generally poor preservation of material in the sedimentary sequences. Similar patterns have been noted in studies from neighbouring marshes in the Bristol Channel and Taf Estuary (Charman *et al.*, 1998; Haslett *et al.*, 2001a).

Lithostratigraphy

Three transects comprising 27 boreholes were recovered from Llanrhidian Marsh. Figure 4a shows the simplified summary lithostratigraphy adapted from the Troels-Smith descriptions recorded in the field. The resulting diagrams emphasize the interchange between minerogenic and organic sedimentation. Most cores terminate in a grey, frequently iron-stained, consolidated clay with large sand clasts, found between 2 m OD and 4 m OD. This deposit is interpreted as the weathered pre-Holocene surface and in places is penetrated by woody roots. A well-humified peat containing abundant detrital wood fragments overlays this surface. This peat, which approaches 2 m in thickness in the seaward cores, progressively thins and pinches out toward the rear of the marsh. In the more westerly transects LLN-2 and LLN-3, this unit becomes increasingly silty and devoid of wood in the landward cores. In the seaward cores, the peat also exhibits intervals with elevated silt and clay components that occasionally contains charcoal fragments.

Organic deposition terminates at around 4 m OD across the entire site. In transect LLN-2 and LLN-3, the contact between the peat and the overlying iron-stained silts and clays is abrupt and may be associated with erosion in some of the cores. An exception to this is core LLN1–96–66 where the upper contact is gradational and material was selected for radiocarbon analysis on this basis.

A further two transects comprising 20 boreholes were recovered from a field in the grounds of Stavel Hagar Mill, approximately 0.5 km west of the Llanrhidian Marsh site. The lithostratigraphy is summarized in Figure 4b, and reveals a similar general pattern of sedimentation to that of the previous locality. A basal well-humified peat with wood fragments rests upon a compact, iron-stained sandy silt that is commonly penetrated by woody roots. Once again, the peat unit is around 2 m in thickness in the most seaward cores and progressively thins and pinches out to the south. Similarly, it also terminates abruptly at around 4 m OD across the site. The peat unit is more variable and complex at Stavel Hagar Mill, however, and contains a widespread minerogenic horizon between about 2.2 and 3.0 m OD. These silts and clays contain some plant and detrital wood fragments in the seaward cores, and increasing amounts of *Phragmites* toward the rear of the site. A second layer dominated by silty clay and also containing *Phragmites* is found between 3.5 and 3.8 m OD, although the stratigraphy becomes increasingly complex in the western transect.

New sea-level index points

Five sea-level index points are established at the contacts between terrestrial peat and organic-rich silts and clays (Table 2). The presence of foraminifera identifies the onset or removal of marine conditions, and the UK foraminiferal transfer function is used to reconstruct palaeomarsh surface elevations. All samples are characterized by almost monospecific assemblages of *J. macrescens* indicative of deposition at the upper limit of marine influence, and the transfer function predicts elevations equivalent to *c.* 40 cm above mean high water of spring tides (MHWST). The resulting SLIs are plotted in Figure 5 alongside the existing SLIs from the region and the modelled MSL curve. The larger vertical uncertainties associated with the new SLIs reflect the large tidal range of the study area. It is likely that the limits assigned to the traditional index points, which were originally developed for an area with a much smaller tidal range, are in reality at least as large as those reported for the new SLIs at this site (see Horton *et al.*, 2000).

The new SLIs plot above the existing data and index points 23 and 25 fill an important temporal gap in the record. Whilst index points 25, 26, and 27 still plot below the ICE-4G predictions, index points 23 and 24 rest on the modelled MSL curve. It should be noted that the new SLIs do not plot above the existing data as a result of using the transfer function to determine their indicative meaning. If indicative meanings are assigned using the classic lithostratigraphic method, four of the five index points will be fixed at or below MHWST resulting in an underestimate of palaeomarsh-surface elevation. The result of this is to raise the index points between 0.4 and 0.6 m, placing them closer to the model predictions and further above the existing data. The exception to this is index point 26, which is assigned an elevation (relative to MSL) of +4.35 m on the

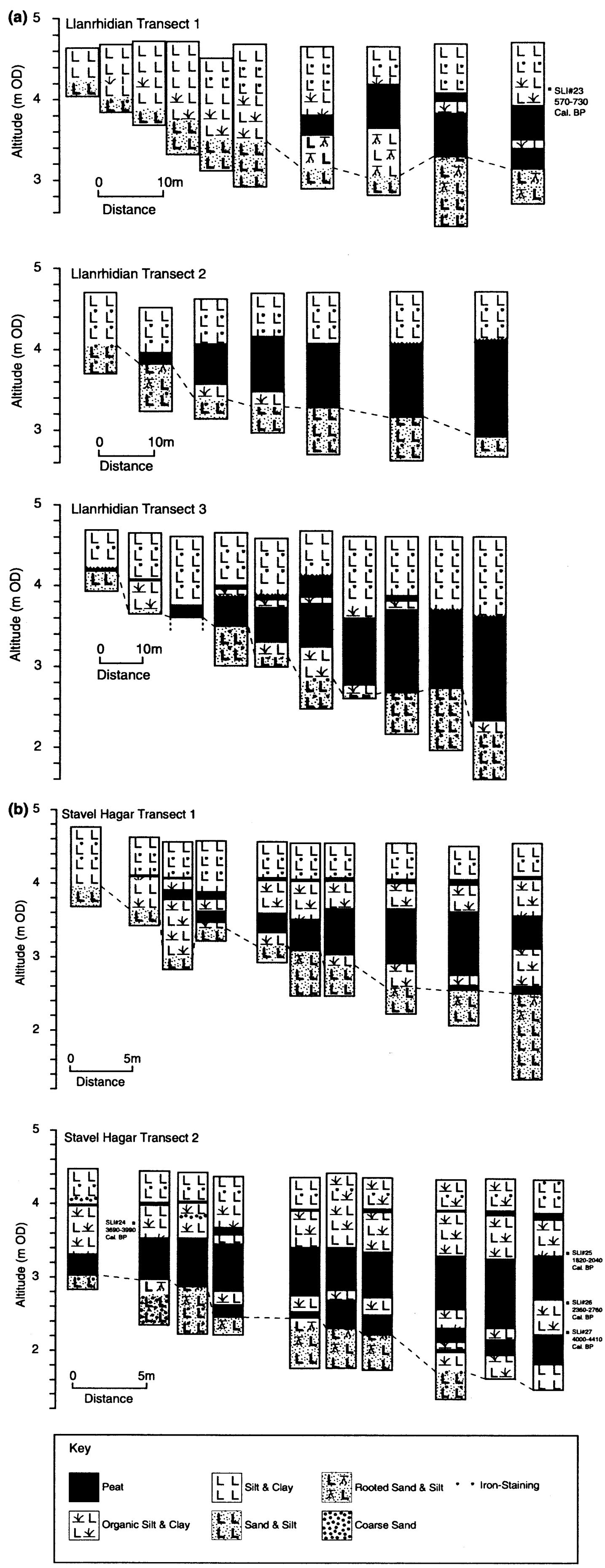

Figure 4 Summary lithostratigraphic diagram for: (a) transects LLN1–LLN3, at Llanrhidian Marsh; (b) transects STH1 and STH2, at Stavel Hagar Mill. See Figure 2 for transect locations

Table 2 Details of the sea-level index points used in this study, including source publications

SLI	Site	Code	C^{14} yr	Error (1σ)	Cal. BP (2σ)	Mean sea-level (m OD)	Error (m)	Publication
1	Godney Island Somerset Levels	Q2459	2550	50	2384–2764	−1.97	0.22	Housley (1988)
2	Godney Island Somerset Levels	GU3247	2560	50	2469–2770	−2.38	0.21	Somerset County Council (1992)
3	Godney Island Somerset Levels	GU3246	2590	50	2483–2787	−2.38	0.21	Somerset County Council (1992)
4	Llanwern Monmouth	Q691	2660	110	2364–2998	−3.33	0.27	Godwin and Willis (1961)
5	Godney Island Somerset Levels	Q2458	2860	50	2848–3159	−2.38	0.22	Housley (1988)
6	Avonmouth Bristol Channel	IGS27	3110	100	3003–3554	−3.19	0.47	Heyworth and Kidson (1982)
7	Goldcliff 1	CAR644	3130	70	3116–3543	−4.75	0.21	Smith and Morgan (1989)
8	Tarnock Somerset	Be142352	3190	70	3245–3625	−4.25	0.23	Haslett *et al.* (2001b)
9	Nyland Hill 12 Somerset	Be101742	3250	80	3272–3684	−1.99	0.21	Haslett *et al.* (1998)
10	Nyland Hill 11 Somerset	Be101741	3380	60	3460–3730	−3.38	0.21	Haslett *et al.* (1998)
11	Nyland Hill 4 Somerset	Be101740	3370	60	3465–3820	−1.92	0.21	Haslett *et al.* (1998)
12	Margam Glamorgan	Q265	3402	108	3382–3905	−9.23	0.75	Godwin and Willis (1961)
13	Goldcliff 1	CAR645	3440	70	3479–3868	−5.04	0.80	Smith and Morgan (1989)
14	Stolford Somerset	NPL146	3460	90	3477–3959	−6.37	0.07	Heyworth and Kidson (1982)
15	Wick Farm Somerset	Be142354	3500	70	3586–3969	−5.29	0.23	Haslett *et al.* (2001b)
16	Kenn Pier Somerset	IGS36	3510	100	3485–4081	−3.91	0.50	Heyworth and Kidson (1982)
17	North Yeo Farm Somerset	Be142350	3600	70	3701–4087	−4.87	0.23	Haslett *et al.* (2001b)
18	Weston-S-M Somerset	IGS40	3675	100	3716–4342	−4.3	0.32	Heyworth and Kidson (1982)
19	Kingston Seymour	I4846	3690	110	3719–4400	−5.3	0.47	Heyworth and Kidson (1982)
20	Avonmouth Bristol Channel	IGS28	3905	100	3988–4784	−3.8	0.25	Heyworth and Kidson (1982)
21	Portbury Bristol Channel	I4842	4240	105	4441–5211	−3.75	0.41	Heyworth and Kidson (1982)
22	Weston-S-M Somerset	IGS41	4530	105	4869–5463	−6.03	0.32	Heyworth and Kidson (1982)
23	Llanrhidian	CAMS-41307	740	50	570–730	−0.08	0.64	This paper
24	Stavel Hagar	CAMS-40114	3560	60	3690–3990	−0.54	0.64	This paper
25	Stavel Hagar	CAMS-41310	1990	50	1820–2040	−0.83	0.64	This paper
26	Stavel Hagar	CAMS-41309	2540	60	2360–2760	−1.47	0.64	This paper
27	Stavel Hagar	CAMS-41308	3840	60	4000–4410	−1.87	0.64	This paper

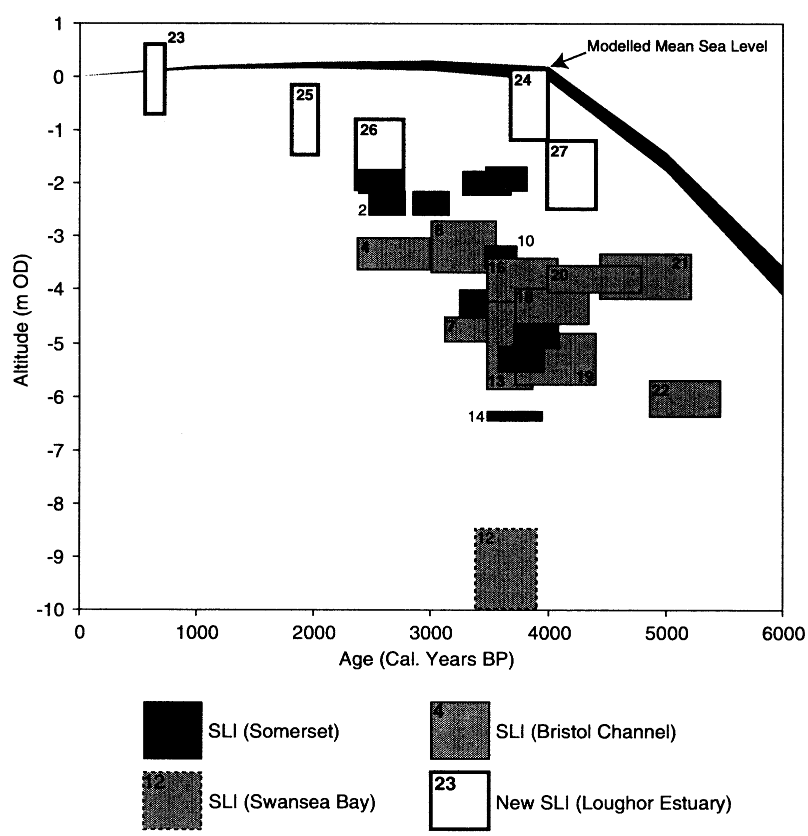

Figure 5 New sea-level index points derived from the foraminiferal transfer function for tide level plotted alongside the existing data from the region, and the modelled mean sea-level estimated by the ICE-4G (VM2) GIA model for the same areas (from Peltier *et al.*, 2002)

basis of its lithostratigraphic context, compared with the transfer function prediction of +4.34 m.

Index point 24 plots out of sequence in terms of age and altitude. One explanation is that this sample may record the early attainment of modern RSL around 3700–4000 BP predicted by the GIA model. An erosive horizon is evident in the adjacent core accompanied by a thin layer of coarse sand (Figure 4b), and it is possible that index point 24, which comes from the very rear of the marsh, escaped the erosion that removed contemporaneous sediments from the more seaward cores. This sample has a very low carbon content however and, given the general similarity in the stratigraphy across the site, it is more likely that contamination by old carbon introduced from groundwater draining onto the rear of the marsh has produced an erroneously old age estimate.

Discussion

Changes in depositional environment

On the basis of the lithostratigraphic and chronostratigraphic data from Llanrhidian and Stavel Hagar Mill, a general sequence of environmental change can be inferred. The first occurrence of marine conditions is associated with the inundation of the seaward cores at Stavel Hagar Mill after *c.* 4400 BP. Whilst considerable scatter exists in the age–altitude data, the general trend in both SLIs and model predictions suggests RSL was rising at this time. This rise in RSL, coupled with the input of freshwater springs in the marsh hinterland, appears to have elevated the water-table in this area, producing localized brackish to fresh standing water. This is evident in the sequence at Stavel Hagar Mill, where silts and clays devoid of foraminifera and associated with *Phragmites* remains and thecamoebians are present.

Index points 26 and 27, coupled with the general cluster of SLIs 1–6, 9 and 11, suggest that the rate of RSL rise decreased markedly after 4000 BP and may well have stabilized or fallen slightly until *c.* 2800 BP. If index point 24 is considered reliable, RSL attains an altitude equivalent to modern levels around 4000 BP before falling slightly. Irrespective of the precise pattern of change, there is little evidence at the study sites of significant RSL movement until 2000 BP. During this interval, the well-developed peat accumulated in the seaward cores.

After *c.* 1900 cal. BP there is evidence of another increase in marine influence in the seaward cores at Stavel Hagar. Once again, the back marsh environment appears to have responded to a rising water-table by a freshening of the environment, and the lithostratigraphy suggests an extensive *Phragmites* reed bed developed during this period. There is a progressive increase in organic content of the seaward cores and the limited biostratigraphic evidence suggests that the thin peat bed centred around 4.2 m OD and dated to *c.* 600–700 cal. BP, is of freshwater origin. These subtle changes in marine influence may indicate small variations in RSL or simply changes in local sedimentary processes as the salt-marsh system developed under relatively stable RSL. Whichever is the case, both SLIs and model predictions suggest that RSL in this area has changed by less than 2 m in the last 2000 years, and is likely to have attained levels close to those observed today by as early as 4000 BP.

Sediment compaction

Sediment compaction is highly complex, involving a variety of processes that alter the arrangement, composition and physical properties of an accumulating sedimentary body. In geotechnical studies, it is common to distinguish post-depositional compression caused by the overlying sediment burden, from sediment consolidation arising from the expulsion of pore-water over time. In the wider literature, considerable variability exists in the use of the terms compaction, auto-compaction and consolidation. Here, the term compaction is used in a general sense and simply refers to the overall reduction of a sediment's volume after its deposition.

Irrespective of the detailed processes involved, the significance of compaction for sea-level studies is that it serves to lower the altitude of sediments used to establish sea-level index points. This, in turn, causes the underestimation of former sea-level altitudes and an overestimation of the long-term rate of relative sea-level rise. Whilst the potential influence of compaction on Holocene RSL records is long established and widely acknowledged (eg, Jelgersma, 1961; Terzaghi and Peck, 1967; Greensmith and Tucker, 1971a,b, 1973; Tooley, 1978; Heyworth and Kidson, 1982; Allen 1996; Shennan, 1986; Haslett *et al.*, 1998; Shennan *et al.*, 2000), it has commonly been set aside because of the lack of a formal means for correcting for its influence (Allen, 2000; Shennan and Horton, 2002). Whilst a small number of detailed, site-specific studies have been undertaken (eg, Paul and Barras, 1998; Shaw and Ceman, 1999), the general absence of geotechnical data, and the inability to quantify factors such as past sediment and water loading histories, means that the precise decompaction of existing SLIs is beyond our grasp.

In a study of SLIs from the eastern coast of England, Shennan *et al.* (2000) examined the potential influence of sediment compaction by comparing the altitude and stratigraphic context of SLIs with the predicted altitude of RSL generated by the GIA model of Lambeck (1995). They noted that the differences between reconstructed and modelled altitudes were correlated with the thicknesses of sediment beneath the index points and the thicknesses of the sediment overburden above them. This indicates that much of the misfit between modelled and reconstructed sea-level altitude may be explained as the differential local response of compaction. In addition, these results suggest that, whilst variables such as sediment composition, water content and loading history will influence the precise degree of compaction, a first-order estimate based on stratigraphic position may be possible for the types of sequence commonly used to furnish sea-level data.

The SLIs from southwest Britain are used to examine this idea and the related suggestion that misfits between model predictions and geological reconstructions can largely be attributed to the influence of compaction (eg, Shennan *et al.*, 2002). Eight of the existing SLIs (all of which come from the Somerset group) possess detailed information on the thicknesses of underlying and overlying sediment. These data are combined with the five new SLIs presented in this study and compared with the modelled mean sea-levels of Peltier *et al.* (2002). Linear regressions of the stratigraphic variables and the differences between modelled and reconstructed mean sea-levels reveal that both the thickness of the underlying sediment and the sediment overburden are correlated with these residuals (Table 3, Figure 6). The strongest correlation exists for sediment overburden ($r^2 = 0.8$), but correlations for both variables are significant (> 1% level) and the results are unaffected by the inclusion or removal of the potentially erroneous SLI 24. Whilst the data set is of limited size, these results, in combination with those of Shennan *et al.* (2000), are consistent with the suggestion that differential sediment compaction produces vertical scatter in age–altitude diagrams of reconstructed RSL and introduces variable misfits with modelled mean sea-levels.

On this basis, it is possible to use stratigraphic data in combination with the regression coefficients to attempt a first-order 'decompaction' of the SLIs. The results of three

Table 3 Sea-level index points with associated stratigraphic contexts used to develop the decompaction operations

SLI	Site	Code	Underlying sediment (m)	Overlying sediment (m)	Reconstructed MSL (m OD)	Predicted MSL (m OD)	Residual (m)
1	Godney Island Somerset Levels	Q2459	3.5	0.4	−1.97	0.17	−2.14
5	Godney Island Somerset Levels	Q2458	3.3	0.6	−2.38	0.16	−2.54
8	Tarnock Somerset	Be142352	6.3	4.3	−4.25	0.13	−4.38
9	Nyland Hill 12 Somerset	Be101742	1.1	2.1	−1.99	0.12	−2.11
10	Nyland Hill 11 Somerset	Be101741	1.5	3.16	−3.38	0.02	−3.4
11	Nyland Hill 4 Somerset	Be101740	1.6	2.4	−1.92	0	−1.92
15	Wick Farm Somerset	Be142354	10.8	5.2	−5.29	−0.12	−5.17
17	North Yeo Farm Somerset	Be142350	10.7	4.6	−4.87	−0.13	−4.74
23	Llanrhidian	CAMS-41307	1	0.5	−0.08	0.12	−0.20
24	Stavel Hagar	CAMS-40114	0.8	0.8	−0.54	0.28	−0.82
25	Stavel Hagar	CAMS-41310	1.8	1	−0.83	0.29	−1.12
26	Stavel Hagar	CAMS-41309	1.2	1.7	−1.47	0.2	−1.67
27	Stavel Hagar	CAMS-41308	0.8	2	−1.87	−0.15	−1.72

The residuals show the altitude difference between the modelled mean sea-level predictions and geological reconstructions.

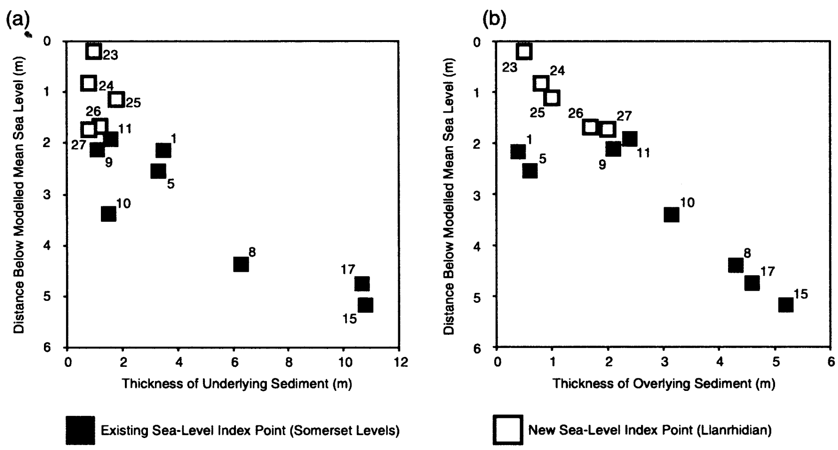

Figure 6 Scatter plots showing the relationships between the residuals (modelled mean sea-level minus reconstructed mean sea-level) for each index point and (a) the thickness of sediment beneath it; (b) the thickness of sediment overlying it. See Table 3 for details

'decompaction operations' are presented in Table 4 and illustrated in Figure 7 alongside the raw SLI data. Figure 7a and 7b show the changes in SLI altitude resulting from corrections based on the thickness of underlying sediment, and the thickness of sediment overburden respectively. Decompaction operations will, by their very nature, elevate the SLIs and move the lower points into closer agreement with the modelled curve. Instead, the significant feature is the extent to which each operation reduces the vertical scatter in the SLIs.

Prior to decompaction, vertical scatter in the data is around 5 m if the potentially erroneous SLI 24 is included, or around 4 m if it is removed (Figure 7a). Decompaction based on the thickness of underlying sediment (Figure 7a) reduces the scatter to around 3.5 m. Index point 10 plots as an outlier, indicating that the decompaction operation fails to account for its low altitude. This SLI rests on a layer of peat, but this is thin in comparison with the thickness of the overlying sediment. On this basis, it is likely that the sediment overburden is a more significant factor in controlling the degree of its compaction.

Table 4 Vertical corrections resulting from the three decompaction operations (see text for details)

SLI	Site	Correction A (m): underlying sediment	Correction B (m): overlying sediment	Correction C (m): both (weighted)
1	Godney Island Somerset Levels	1.90	0.52	1.76
5	Godney Island Somerset Levels	1.79	0.71	1.63
8	Tarnock Somerset	3.42	4.26	3.76
9	Nyland Hill 12 Somerset	0.60	2.15	1.62
10	Nyland Hill 11 Somerset	0.81	3.16	2.41
11	Nyland Hill 4 Somerset	0.87	2.44	1.81
15	Wick Farm Somerset	5.87	5.12	5.62
17	North Yeo Farm Somerset	5.81	4.54	5.43
23	Llanrhidian	0.54	0.62	0.57
24	Stavel Hagar	0.43	0.91	0.67
25	Stavel Hagar	0.98	1.10	1.02
26	Stavel Hagar	0.65	1.77	1.31
27	Stavel Hagar	0.43	2.05	1.59

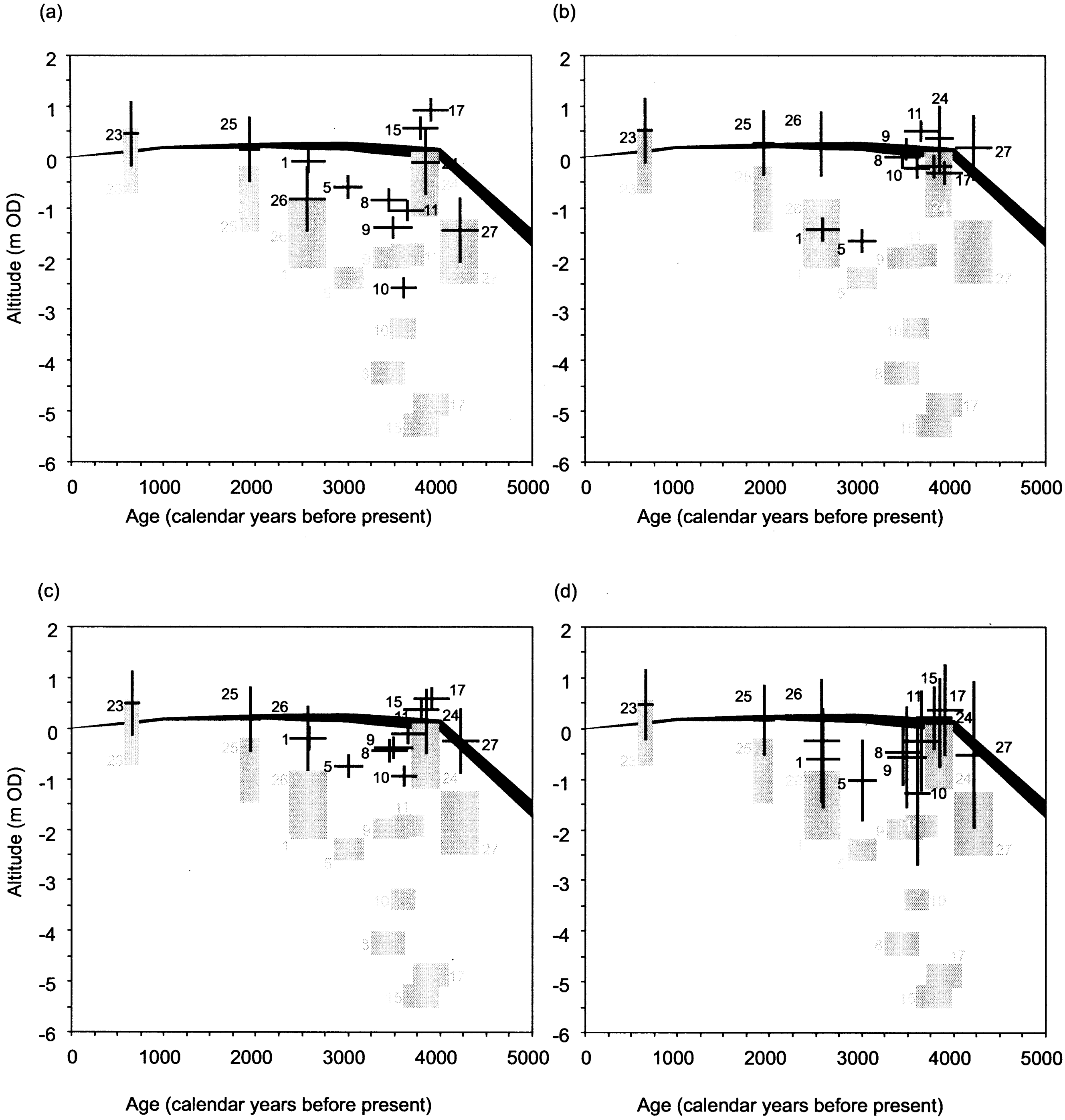

Figure 7 Sea-level index points (SLIs) with reliable stratigraphic data plotted against modelled mean sea-level estimated by the ICE-4G (VM2) GIA model. Grey boxes indicate the positions of each SLI before correction. Crosses indicate the corrected altitude of each SLI based on: (a) underlying sediment thickness; (b) sediment overburden; (c) both underlying sediment thickness and sediment overburden (weighted); (d) consensus (mean) of the previous methods. See text for details

The decompaction operation based on sediment overburden (Figure 7b) supports this idea, elevating index point 10 into agreement with a tight cluster of other index points. Overall, this operation performs slightly better, reducing vertical scatter to around 2 m. In this instance, index points 1 and 5 plot as outliers, but both of these points have very small overburdens compared with the thicknesses of underlying sediment.

Clearly the decompaction operations perform least well when the variable under consideration constitutes a small proportion of the overall sediment thickness. In order to address this, a third decompaction operation is presented in Figure 7c, which applies both regression coefficients weighted by the relative proportion of the sequence above or below the index point. This operation results in the tightest clustering of all SLIs (around 1.5 m), with no obvious outliers.

From Figure 7 it is clear that a range of possible 'corrected altitudes' can be derived depending on which decompaction operation is selected. In light of the limited number of index points, and the fact that additional complicating factors such as lithology are not considered, it is inappropriate to comment on the relative merits of the variables used, or to place much significance on the precise values of the regression coefficients employed. Instead, it is sufficient to observe that both underlying and overlying sediment thickness are correlated with the degree of compaction experienced by a SLI, and that consideration of either or both of these variables reduces vertical scatter in palaeo-MSL reconstructions. In order to represent some of the variability between decompaction operations, Figure 7d shows a consensus decompaction based on the mean of the previous operations. Vertical errors are assigned to each index point on the basis of their original uncertainties (Table 2) plus a one-sigma error derived from the differences in the decompaction operation estimates. The study of Haslett *et al.* (1998), in which three index points are decompacted on the basis of local stratigraphy and radiocarbon dates, provides an opportunity to independently evaluate this first-order decompaction approach. These data (index points 9, 10 and 11), when decompacted using the site-specific information from Haslett *et al.* (1998) place mean sea-level at -1.13 m OD. This altitude lies toward the lower end of the error range of all three of the SLIs after correction using the consensus decompaction operation (Figure 7d).

Implications for land and sea-level changes in SW Britain

Patterns of late-Holocene relative sea-level change

There has been considerable debate concerning the nature of RSL changes in southwest Britain. Kidson and Heyworth (1978) suggested that the region was tectonically stable, and hence a local RSL curve could be indicative of eustatic change. They went on to suggest that RSL in this area reached its current altitude at about 4000 BP (Heyworth and Kidson, 1982). Later workers highlighted problems with some of these data (eg, absence of indicative meaning), suggesting that RSL continued to rise after the Roman period (*c.* 2000 BP) and was perhaps associated with an oscillation in sea-level (Allen, 1991; Haslett *et al.*, 1998).

The general pattern of RSL change shown in Figure 7 is replicated irrespective of which decompaction operation is selected. The corrected index points indicate the early attainment of modern sea-levels at around 4000 BP, but suggest RSL fell after this to a low around 3000 BP, before rising back to modern levels by *c.* 2000 BP. This general pattern of change would seem to reconcile some of the differing interpretations presented above and indicates that, whilst RSL was not stable during the last 4000 years, it has remained close to its present value. These results are also consistent with the model predictions for this region, since geophysical models are not capable of resolving submillennial-scale RSL oscillations. Finally, this sequence of change, derived from regional data, is consistent with the local variations in stratigraphy at Llanrhidian and Stavel Hagar Mill, and the RSL changes inferred from them.

Rates of late-Holocene relative sea-level change

The new SLIs collected as part of this study mean that it is now possible to estimate the long-term rate of RSL rise for the last 4000 years, and compare this with the other UK data presented by Shennan and Horton (2002). Considering the new SLIs in isolation, and not correcting for compaction, an average rate of RSL rise of 0.4 mm/yr is produced for W Glamorgan. This value is slightly lower than 0.5–1.0 mm/yr expected on the basis of the general pattern of Holocene change presented by Shennan and Horton (2002). It is also at the lower end of the range inferred by Haslett *et al.* (1998) for the Somerset Levels, who suggest rates between 0.4 and 0.8 mm/yr. If pre-existing data are considered, the general rate of RSL rise for South Wales and the Bristol Channel is *c.* 1.1 mm/yr. This reduces to 0.8 mm/yr if only data with good stratigraphic control are used. Both these higher values are at the upper end of the rates inferred by Haslett *et al.* (1998) and Shennan and Horton (2002).

In their assessment of relative sea-level changes in the UK, Shennan and Horton (2002) analysed over 1000 index points and, by comparing intercalated and basal SLIs, suggested that on average, compaction increased the apparent rate of RSL rise by *c.* 0.2 mm/yr. However, they noted that in the southeast of England, the effect on SLIs from large estuaries is much greater, increasing rates by 0.5–1.1 mm/yr. Correction of SLIs using the decompaction operations presented in Figure 7 results in estimated rates of RSL rise for the last 4000 years that range from around 0 mm/yr to 0.7 mm/yr, with a best-fit estimate of around 0.1 mm/yr. This value, if correct, suggests that compaction may have increased apparent rates of RSL rise in this region by 0.7–1.0 mm/yr. This is similar to the increase noted by Shennan and Horton (2002) in southeast England, and suggests that this larger value is also appropriate for the large estuarine systems of southwest Britain.

Instrumental records

Geological estimates of long-term rates of RSL change such as those described in the previous section are necessary for the reliable interpretation of trends in sea-level data from tide-gauges (Woodworth, 1990). The large amount of interannual variability in tide gauge records means that long time series are required before reliable secular trends can be discerned (Douglas, 1991; Shennan and Woodworth 1992). In the UK, Woodworth *et al.* (1999) identify five such sites with records longer than 50 years, and use geological reconstructions of RSL change from neighbouring regions to examine evidence for recent accelerations in the rate of sea-level rise.

One of these records, generated by the tide gauge at Newlyn, has a long-term submergence rate derived from SLIs from southwest Britain (which includes some of the data considered in this paper). In their analysis, Woodworth *et al.* (1999) note that, in contrast to the other four regions of the UK, the Newlyn record does not appear to indicate a recent increase in that rate of RSL rise. This discrepancy suggests that existing geological data from the region may overestimate the actual long-term rate of RSL rise by around 0.7 mm/yr (Woodworth *et al.*, 1999). The results presented here support this suggestion and indicate that this discrepancy is reasonably explained as the consequence of a failure to satisfactorily account for index point lowering resulting from sediment compaction.

Conclusion

The combination of new and existing sea-level index points from southwest Britain, suggests that relative sea-level attained its modern altitude by around 4000 BP. Whilst RSL may have oscillated around 3000 BP, new data from the last 2000 years indicates that, within the resolution of the indicators, RSL has remained largely constant during this time. Previous studies have identified significant discrepancies between the altitudes of past RSL inferred from geological reconstructions, and those predicted by geophysical models. The sea-level data presented here support the suggestion that, in southwest Britain, these apparent misfits are primarily due to the influence of sediment compaction. Simple first-order approximations of the amount of lowering resulting from compaction can be inferred given the thickness of sediment resting upon, and underlying an index point. Correction for this variable influence reduces vertical scatter in sea-level reconstructions, and decreases the apparent long-term rate of RSL rise for this region. These results suggest that sediment compaction in the large estuarine systems of southwest Britain can increase the apparent rate of RSL rise over the last 4000 years by between

0.7 and 1.0 mm/yr. This enhancement is similar to results presented by Shennan and Horton (2002) for comparable estuarine systems in southeast Britain, and suggests that the influence of compaction has been underestimated in previous studies.

The combination of geological reconstructions and geophysical predictions of Holocene RSL change is becoming increasingly commonplace as people seek to quantify a range of issues such as the timing and magnitude of eustatic sea-level changes, meltwater sources, Earth structure, coastal evolution and secular sea-level trends. The results presented here demonstrate that the validation process must focus on correcting sea-level data for compaction as well as tuning ice and earth model parameters. Geomorphological, sedimentological and logistical factors mean that compaction-free data (eg, from isolation basins, encrusting organisms, basal peat) will be spatially and temporally restricted. Recent developments in high-resolution sea-level reconstruction, such as the use of foraminiferal transfer functions to 'monitor' elevation changes throughout a core, mean that it is no longer possible, or desirable, to restrict the collection of RSL data to an extremely limited subset of stratigraphic contexts. Consequently, approaches that simply attempt to avoid the problem of compaction are becoming increasingly untenable.

The results presented here suggest that, whilst the processes involved in sediment compaction are complex, first-order estimates of its influence are possible providing the stratigraphic context of an index point is quantified. The combination of compaction-free data with other SLIs and model predictions has the potential to dramatically improve our understanding of the compaction process. As more data become available, these first-order estimates may be refined through the inclusion of other parameters that are routinely recorded in sea-level investigations, such as variations in lithology. Consequently, whilst intercalated sequences need not be avoided, it is important that lithostratigraphic details accompany SLIs to maximize the utility of these data. Further work is now required to evaluate this simple decompaction approach in other regions with larger data sets and more detailed sea-level records.

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