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Relative sea-level change and postglacial isostatic adjustment along the coast of south Devon, United Kingdom

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ABSTRACT: Previous sea-level studies suggest that southwest Britain has the fastest subsiding coastline in the United Kingdom, but tide-gauge data, GPS and gravity measurements and geophysical models show little evidence of anomalous subsidence in this region. In this paper we present 15 new sea-level index points from four coastal barrier systems in south Devon. Eight are from compaction-free basal sediments and others were corrected for autocompaction. Our data suggest that relative sea level along the south Devon coastline has risen by 21 ± 4 m during the past 9000 years. Sea-level rise slowed during the middle and late Holocene and a rise of 8 ± 1 m has occurred since ca. 7000 cal. yr BP. Anomalous ages for many rejected points are attributed to sediment reworking during barrier transgression. The relative sea-level history during the early and middle Holocene shows a good fit with geophysical model predictions, but the geological and modelled data diverge in the later Holocene. Unlike the geophysical models, sea-level index points cannot differentiate between late Holocene relative sea-level histories of south Devon and southwest Cornwall. It is suggested that this discrepancy can be resolved by obtaining additional high-quality sea-level index points covering the past 4000 years. Copyright © 2008 John Wiley & Sons, Ltd.

KEYWORDS: isostasy; sea-level change; Holocene; foraminifera; England.

Introduction

The British Isles are of interest to the study of postglacial isostatic adjustment and relative sea-level (RSL) change, given their position marginal to the Scandinavian and British Isles ice sheets at the Last Glacial Maximum (LGM). The southwest of England was ice-free during the LGM; its postglacial relative sea-level history has implications for understanding of proglacial forebulge dynamics, a flexing of the lithosphere near the ice margin that migrates and eventually collapses as the land-based ice retreats (e.g., Walcott, 1970; Peltier, 1974). The British Isles have been a traditional testing ground for geophysical modellers (e.g., Lambeck, 1993a,b, 1995; Peltier, 1998; Peltier *et al.*, 2002; Milne *et al.*, 2006; Shennan *et al.*, 2006) and new relative sea-level data are useful to develop and test models of ice retreat and Earth rheology.

Postglacial sea-level studies around the British Isles were summarised by Shennan (1989). In an update of this work, Shennan and Horton (2002) determined that the coastline of southwest England is currently undergoing relative subsidence at a faster rate than other coasts in Britain (~0.9–1.4 mm yr^{-1}). Recent GPS measurements indicate absolute subsidence rates of 0.0 ± 0.5 mm yr^{-1}, while subsidence determined by gravity measurements is 0.9 ± 0.9 mm yr^{-1} (Teferle *et al.*, 2006). The sea-level rise measured by the tide gauge at Newlyn, Cornwall, since 1916 is not indicative of anomalous subsidence in southwest England, as the rate of rise (~1.6 mm yr^{-1}) does not differ significantly from the global average (Woodworth *et al.*, 1999).

The Channel coasts of Devon and Cornwall have produced only 18 scattered sea-level index points (SLIPs) (Shennan and Horton, 2002; Waller and Long, 2003; Massey, 2004). Information on the indicative meaning of these points is often lacking in detail and many data points cannot be precisely related to a former tide level (Haslett *et al.*, 1997; Massey *et al.*, 2006a). Only four of the available sea-level index points were used by Shennan and Horton (2002) in their analysis of regional

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subsidence: two for Cornwall and two for Devon. Their findings are in disagreement with those of Waller and Long (2003), who concluded, based on an analysis of almost the same dataset, that southeast England may have subsided relative to southwest England. The discrepancy between these two, seemingly opposite, conclusions can be explained by sediment consolidation (or 'autocompaction', i.e. the compression of a sediment sequence by the weight of the overlying sediments). This process may have affected as many as 14 sea-level index points from Devon and Cornwall and most index points in southern England and Wales (Waller and Long, 2003; Edwards, 2006). The most reliable sea-level index points are obtained from the base of Holocene sediments where they overlie a hard substrate. Only four basal index points have been obtained from southwest Cornwall (Healy, 1995) and none from south Devon.

There is no commonly accepted methodology that is used to correct sea-level index points for autocompaction (e.g., Pizzuto and Schwendt, 1997; Paul and Barras, 1998; Rybczyk *et al.*, 1998; Tovey and Paul, 2002; Williams, 2003; Bird *et al.*, 2004; Massey *et al.*, 2006b; Edwards, 2006). This is in part due to the lack of geotechnical models capable of dealing with the complex stratigraphies found in coastal sediments (Allen, 1999; Massey *et al.*, 2006b; Shennan *et al.*, 2006). However, samples from thick unconsolidated Holocene sediments are likely to have experienced significant post-depositional lowering (Allen, 1995, 2000; Shennan and Horton, 2002) and more so those from organic-rich sediments, thereby affecting rates of relative sea-level change calculated from sea-level index points (Massey *et al.*, 2006b). Sea-level histories corrected for autocompaction are likely to change estimates of late Holocene relative land movement (Shennan and Horton, 2002).

The quantification of vertical errors attached to sea-level index points is fundamental to the precise determination and comparison of sea-level histories. To date no quantitative studies have been produced in southwest England to assess indicative meaning (the height at which a sea-level indicator was deposited relative to a reference tide level; Shennan, 1983). In this study this is achieved using an intertidal foraminifera-based transfer function (Massey *et al.*, 2006a).

Study sites

Four coastal back-barrier systems were selected during a pilot study in 1997 based on the presence of basal organic units (Fig. 1). The barrier at Bantham Sands (50° 16.60′ N; 03° 52.51′ W) (Fig. 1(A)) is part of a dune system reaching +15 m OD that separates a back-barrier freshwater marsh from the sea. The back-barrier marsh at North Sands (50° 13.77′ N; 03° 46.93′ W) (Fig. 1(B)) is located at the mouth of the Salcombe–Kingsbridge Estuary, a submerged valley that was fronted by a barrier ('The Bar') (Fig. 1(E)) when sea level was lower in the early Holocene. Slapton Sands (50° 16.96′ N; 03° 38.80′ W) (Fig. 1(C)) is a shingle barrier that separates a reed swamp and shallow freshwater lake from Start Bay. Blackpool Sands (50° 19.17′ N; 03° 36.78′ W) (Fig. 1(D)) is an extension of Slapton Sands to the north (Hails, 1975a, 1975b), and protects a reclaimed back-barrier marsh from Start Bay. The regional underlying solid geology is primarily Lower Devonian slate and shale (Ussher, 1904). The tidal range in our study area varies from 4.6 m in southwest Devon to 4.3 m in the southeast (Hydrographic Office, 2002) (Table 1).

Methods

Coring and surveying

Coring was carried out in 1997 and 1999 using a percussion drilling rig to extract 1 m sections in hard plastic tubes. Partial recovery in some tubes was attributed to the settling of fine waterlogged sand following removal above the water table (Rees, 1999). Core loss was recorded at the base of these sections. Core compaction was measured in the field. A sediment catcher was attached to the base of each tube to prevent sediment loss upon extraction and 'captured' sediment was retained in a bag. Twelve boreholes were surveyed to UK Ordnance Datum (Newlyn) using an electronic distance measurer (EDM) and local Ordnance Survey (OS) benchmarks. Borehole positions were determined with a hand-held global positioning system (GPS) (Fig. 1). Core sections were stored at +4°C. All cores were logged in detail using the Troels-Smith (1955) classification scheme, but stratigraphy is generalised in this paper for clarity of presentation. Additional information on subsurface stratigraphy is provided in Massey *et al.* (2006c).

Geotechnical correction

Autocompaction was calculated in two cores from North Sands and two cores from Blackpool Sands using the Paul and Barras (1998) model. Methods and classifications are based on standard techniques (e.g. Terzaghi, 1925; Terzaghi *et al.*, 1996). Plastic and liquid limits (Atterberg, 1911) were calculated at 1 m intervals to determine sediment compressibility (British Standard 4691, 1974; British Standard 1377, 1975). Particle size analysis (PSA) of the <2 mm fraction was carried out using a Laser Mastersizer autosampling system and the >2 mm fraction using a Camsizer (particle size and shape analyser). PSA served as a check for the Atterberg (1911) limits and did not form part of the model input. Sections were sampled every 20 cm for water content and bulk sediment density, the methods conforming generally to British Standard 1377 (1975) using a sediment moisture sampler. Further details are reported in a separate paper (Massey *et al.*, 2006b).

Foraminiferal analysis

Standard techniques were used to sample and analyse foraminifera (Scott and Medioli, 1980a,b; Gehrels, 2002). Foraminifera were identified in 5 mL sediment samples at 2–5 cm intervals in the cores. A minimum of 300 foraminifera per sample were counted where possible. The sampling resolution was increased to 1 or 2 cm intervals when whole samples contained <50 foraminifera at crucial levels (e.g. sample horizons selected for dating and reconstructing palaeoenvironments).

Foraminiferal taxonomy is based on Murray (1979), Scott and Medioli (1980b), Loeblich and Tappan (1987) and de Rijk (1995). Some species were classified to a single generic level for ease of description, e.g. *Elphidium* spp. include *E. earlandi*, *E. gerthi* and *E. incertum*, and *Quinqueloculina* spp. include *Q. dimidiata*, *Q. cliarensis*, *Q. oblonga* and *Q. seminulum*. Generic names are in accordance with Loeblich and Tappan (1987). Agglutinated juveniles deemed unclassifiable due to

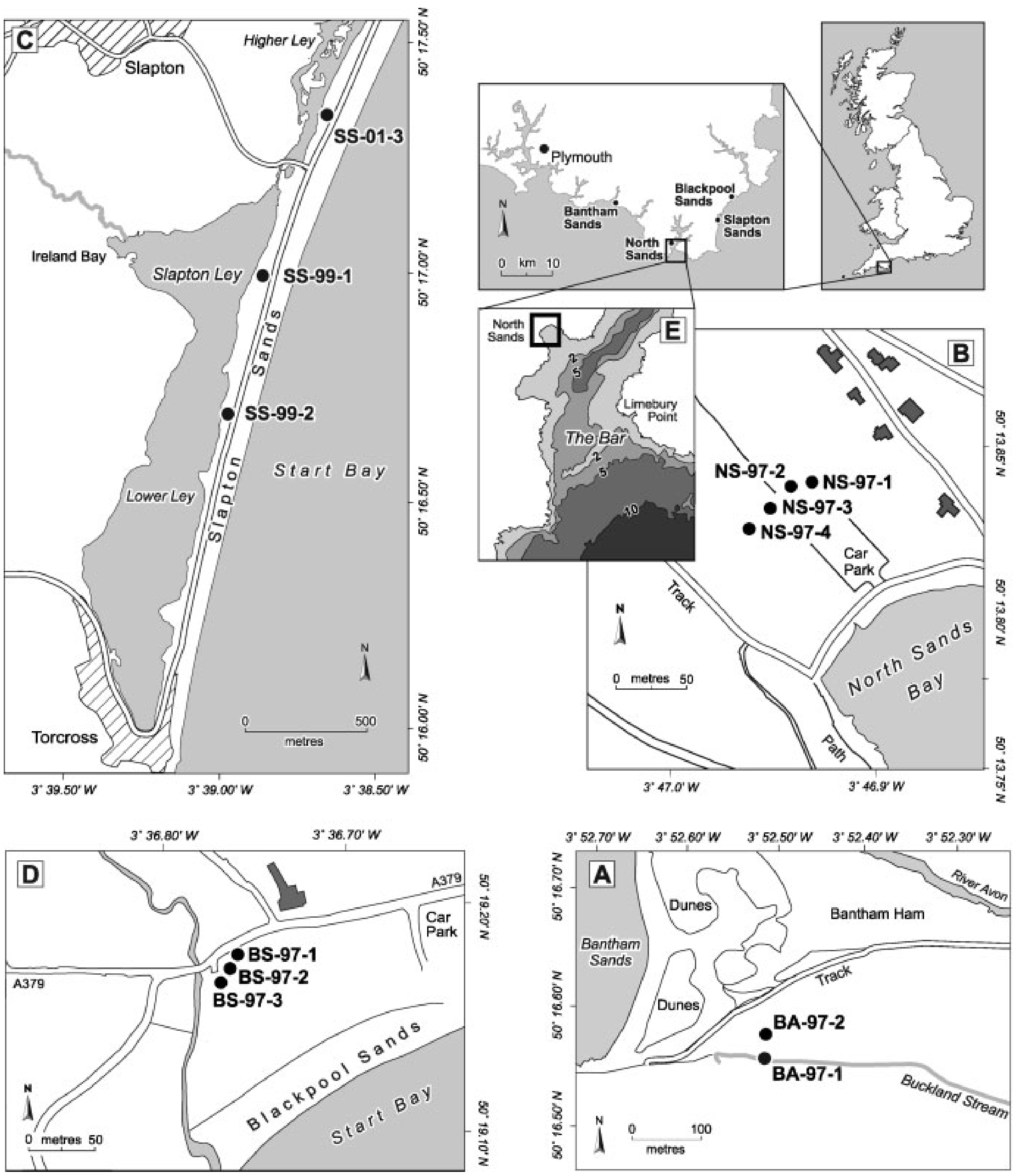

Figure 1 Location of boreholes at Bantham Sands (A), North Sands (B), Slapton Sands (C) and Blackpool Sands (D), south Devon. Also shown is 'The Bar' (E), a subtidal feature which probably represents a former barrier fronting the palaeovalley of the Salcombe–Kingsbridge Estuary. © Crown Copyright/Database right 2006. An Ordnance Survey/EDINA supplied service. Reproduced with the permission of Ordnance Survey/EDINA supplied service

their simple test form were recorded as 'unidentified'. A few partially dissolved calcareous specimens were easily identified by their test lining (Edwards and Horton, 2000).

The indicative meaning for each sample was calculated using a regional transfer function to reconstruct palaeowater levels from fossil core records based on 113 modern intertidal samples (Massey *et al.*, 2006a). The C^2 programme (Juggins, 2003) was used to estimate palaeoelevation from a weighted averaging–partial least squares model and the root mean squared error of prediction (±0.29 m) (Massey *et al.*, 2006a).

Table 1 Tidal heights interpolated from nearest tidal stations

Tidal station/site	Latitude N	Longitude W	MHWST (m)	MLWST (m)	Tidal range (m)	Chart datum (m)	MTL (m)
Bantham Sands (River Avon entrance)	50° 17′	3° 53′	2.29	−2.35	4.64	−3.05	0.11
North Sands (Salcombe Harbour entrance)	50° 13′	3° 47′	2.25	−2.35	4.60	−3.05	0.09
Slapton Sands (Start Bay)	50° 17′	3° 38′	2.28	−2.06	4.34	−2.98	0.12
Blackpool Sands (Start Bay)	50° 19′	3° 36′	2.25	−2.07	4.32	−2.95	0.11

Heights are relative to the UK Ordnance Datum.
MHWST, mean high water of spring tides; MLWST, mean low water of spring tides; MTL, mean tide level.
Source: Hydrographic Office (2002).

Radiocarbon dating

Basal units in cores were dated to provide compaction-free sea-level index points. Other levels of the core, in sections containing salt-marsh foraminifera, were also dated to provide additional index points. In most cores detrital plant macrofossils, the preferred material for dating, were not well preserved in sediments and bulk sediment samples or small wood fragments were used instead. Samples were prepared to graphite at the Natural Environment Research Council (NERC) Radiocarbon Laboratory in East Kilbride, Scotland. Accelerator mass spectrometry (AMS) ^{14}C analyses were carried out at the National Science Foundation–AMS Facility, University of Arizona (North Sands), and the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory at the University of California (Bantham, Slapton and Blackpool Sands). Calibrations follow Stuiver *et al.* (1998) using the Calib 4.2 program (cf. Stuiver and Reimer, 1993) (Table 2).

Pollen analysis

Following radiocarbon dating, pollen analysis was used as a further age check on ^{14}C age determinations, to evaluate continuity of the sediments and a possible hiatus in one core from North Sands. Pollen was sampled, prepared and analysed according to Moore *et al.* (1991). Sediment samples of 2 mL were initially selected adjacent to ^{14}C horizons then increased to ~5 cm intervals throughout for a detailed reconstruction of pollen zones. A target of 300 total land pollen grains per sample was set but this was difficult to achieve for some basal samples (counts <80) and the majority of slides analysed from other sections (counts 100–200). These samples also contained a significant number of damaged grains. Identification followed Andrews (1984) and Moore *et al.* (1991) and nomenclature follows Stace (1991) and Bennett *et al.* (1994).

Sea-level index points

The altitude of sea-level index points (SLIPs) is calculated according to Gehrels (1999):

$$\text{SLIP (m MTL)} = H - D - I + A + C$$

where H = height of the ground surface in metres above or below MTL; D = sample depth below ground level in metres; I = indicative meaning of the sample in metres above or below MTL as calculated from counts of fossil foraminifera by a transfer function (Massey *et al.*, 2006a); A = autocompaction of the sediment as determined by geotechnical correction; and C = core compaction resulting from drilling as determined by measuring the length of retrieved sediment in each 1 m core tube. The vertical precision of our sea-level estimate is ±0.35 m, a value based on our transfer function analyses (Massey *et al.*, 2006a) and levelling errors (Gehrels *et al.*, 1996; Shennan and Horton, 2002). Full details of sea-level index points are reported in Table 2 and foraminiferal counts associated with the points are shown in Table 3. The stratigraphic context and chronology are described below, followed by an evaluation of the validity of some data points.

Results

Bantham Sands

Basal sediments at Bantham Sands comprise fractured slates below −12.50 m OD (Fig. 2(A)). The overlying sequence, to about −7.0 m OD, consists predominantly of clay and silt. A fine silty-sand sequence was found from about −7.0 to −2.0 m OD. Wood and peat dominate the uppermost sediments, but in core BA-97-2 fine sand, blown in from the adjacent dune field, caps the sequence.

The basal sediments in core BA-97-1 contain no or very few foraminifera (Fig. 3(A)). The core section between 16.0 and 15.7 m is dominated by agglutinated foraminifera, in particular the salt-marsh species *Jadammina macrescens* and *Trochammina inflata*. Above this, species indicative of low salt-marsh and tidal mudflat, e.g. *Haynesina germanica* and *Ammonia beccarii*, increase to 60–80%. The first occurrence of high numbers of agglutinated foraminifera at 15.91 m provides SLIP 1 on bulk sediment, with a median age of ca. 8390 cal. yr BP and an indicative meaning of ca. +2.5 m MTL (Tables 2 and 3).

The foraminiferal assemblages are similar throughout the base of core BA-97-2 (Fig. 3(B)). High numbers of mixed agglutinated and calcareous species occur within 5 cm of the base and provide an indicative meaning of +0.4 m MTL. A date on a wood fragment at 17.12 m (ca. 7885 cal. yr BP) provides SLIP 2 (Table 2).

North Sands

Fractured slates, sand and gravel are found below the unconsolidated basal sediments at North Sands (Fig. 2(B)). Basal organic units are identified in all four cores. Silty-clay sediments occur up to ~−7 m OD in the longer cores NS-97-1 and NS-97-2. Wood peat caps the sequence at North Sands above ~−7 m OD.

The basal 30 cm of sediments in core NS-97-1 contains no foraminifera but there are significant numbers (up to 800 tests per 5 mL) of calcareous foraminifera (mostly *H. germanica*) in the sediments above this (Fig. 4(A)). Bulk sediment at 16.54 m has an indicative meaning of ca. −0.9 m MTL (Table 3) and provides SLIP 3, dated to ca. 7900 cal. yr BP (Table 2).

There are low but countable numbers of foraminifera in the base of core NS-97-2 (Fig. 4(B)). The basal portion of the core is dominated by *J. macrescens*, providing SLIP 4 at 15.85 m with an indicative meaning of ca. +2.2 m MTL and dated to ca. 8180 cal. yr BP. At 15.42 m, agglutinated species dominate the total assemblage and provide SLIP 5 (ca. 8200 cal. yr BP, indicative meaning ca. +1.8 m MTL) (Tables 2 and 3). Both dated samples are bulk sediment.

Core NS-97-3 contains a sequence of alternating foraminiferal assemblages dominated by either agglutinated or calcareous species. Large variations in abundance occur between 11.15 and 9.39 m depth. We have divided the foraminiferal stratigraphy into assemblage zones based on cluster analysis (Grimm, 1987) (Fig. 4(C)). Eleven AMS ^{14}C ages on bulk sediment provide the chronology for core NS-97-3 (index points 6–16) (Table 2) but significant age reversals occur in the two lowermost core sections (Fig. 2(B) and Table 2). These are assessed in the Discussion.

Foraminifera are present in some of the basal samples in core NS-97-4 (Fig. 4(D)), with significant numbers of calcareous species between 6.97 and 6.95 m. A date on a minerogenic

Table 2 New south Devon sea-level index points with associated details

Index no.	Core	^{14}C laboratory number	Sample	^{14}C age (years BP ±1σ)	Cal. age BP (±2σ range) max. (median) min.	Carbon content (% by weight)	δ^{13}C ± 0.1 (‰)	Core height (m MTL)	Depth in core (m)	Core consolidation (m)	Indicative meaning (±0.29 m MTL)	Geotechnical correction for autocompaction (m)	SLIP (±0.35 m MTL)	Type	Reject/ Accept
1	BA-97-1	CAMS-75518	Bulk (m)	7600 ± 40	8424 (8390) 8349	1.1	−25.60	3.86	15.908	0.000	2.509	0.00	−14.557	B	Accept
2	BA-97-2	CAMS-75519	Wood	7120 ± 30	8005 (7885) 7865	60	−29.00	4.55	17.118	0.000	0.409	0.00	−12.977	B	Accept
3	NS-97-1	AA-38822	Bulk (m)	7119 ± 63	8108 (7885) 7791	6.1	−28.60	2.78	16.535	0.005	−0.905	0.00	−12.850	B	Accept
4	NS-97-2	AA-38823	Bulk (m)	7408 ± 59	8355 (8183) 8038	3.2	−28.40	2.65	15.845	0.120	2.186	0.07	−15.191	B	Accept
5	NS-97-2	AA-38824	Bulk (m-p)	7359 ± 59	8333 (8172) 8014	1.8	−28.10	2.65	15.545	0.120	1.816	0.15	−14.441	I	Accept
6	NS-97-3	AA-38825	Bulk (m)	7835 ± 61	8977 (8597) 8434	0.05	−24.50[a]	2.62	11.305	0.740	0.572	0.04	−8.477	B	Reject
7	NS-97-3	AA-38826	Bulk (m)	9741 ± 73	11234 (11173) 10793	0.1	−24.50	2.62	11.185	0.740	2.329	0.05	−10.104	I	Reject
8	NS-97-3	AA-38827	Bulk (m)	9277 ± 79	10687 (10441) 10237	0.3	−24.70	2.62	11.005	0.740	2.200	0.07	−9.775	I	Reject
9	NS-97-3	AA-38828	Bulk (m)	7597 ± 54	8451 (8389) 8222	0.4	−25.20	2.62	10.855	0.740	2.200	0.09	−9.605	I	Reject
10	NS-97-3	AA-38829	Bulk (m)	7770 ± 61	8645 (8582) 8410	0.3	−24.90	2.62	10.805	0.740	0.840	0.09	−8.195	I	Reject
11	NS-97-3	AA-38830	Bulk (m)	6824 ± 53	7785 (7667) 7574	0.5	−25.40	2.62	10.655	0.740	−0.846	0.11	−6.339	I	Reject
12	NS-97-3	AA-38831	Bulk (m)	8063 ± 56	9236 (9008) 8773	0.4	−24.60	2.62	10.445	0.240	2.200	0.13	−9.655	I	Reject
13	NS-97-3	AA-38832	Bulk (m)	8443 ± 63	9538 (9481) 9298	0.3	−24.80	2.62	10.325	0.240	2.200	0.14	−9.525	I	Reject
14	NS-97-3	AA-38833	Bulk (m)	6989 ± 58	7940 (7814) 7673	0.6	−25.30	2.62	10.085	0.240	−0.864	0.14	−6.221	I	Reject
15	NS-97-3	AA-38834	Bulk (m)	6323 ± 50	7412 (7252) 7097	2.9	−26.30	2.62	9.785	0.240	−0.688	0.15	−6.087	I	Reject
16	NS-97-3	AA-38835	Bulk (m)	6442 ± 65	7461 (7369) 7250	4.8	−27.20	2.62	9.395	0.000	−0.809	0.16	−5.806	I	Reject
17	NS-97-4	AA-38836	Bulk (m-p)	4129 ± 59	4833 (4615) 4443	44	−29.30	2.66	7.235	0.270	−1.359	0.00	−2.946	B	Accept
18	SS-99-1	CAMS-72401	Bulk (m)	7980 ± 50	9011 (8868) 8613	1.2	−29.10	4.35	19.238	0.000	2.427	0.00	−17.314	B	Accept
19	SS-99-1	CAMS-72402	Bulk (c)	7500 ± 40	8387 (8341) 8183	37	−26.70	4.35	19.238	0.000	2.427	0.00	−17.314	B	Accept
20	SS-99-2	CAMS-75531	Wood	7370 ± 40	8325 (8175) 8036	54	−29.70	3.95	16.280	0.000	2.450	0.00	−14.780	B	Accept
21	BS-97-1	CAMS-75520	Wood	4510 ± 40	5310 (5135) 4980	52	−29.90	4.18	12.708	0.000	2.250	0.00	−10.778	B	Reject
22	BS-97-1	CAMS-75521	Wood	4410 ± 40	5274 (5020) 4864	50	−29.20	4.18	11.518	0.000	2.212	0.00	−9.550	I	Reject
23	BS-97-1	CAMS-75522	Wood	4410 ± 40	5274 (5020) 4864	54	−26.60	4.18	10.125	0.000	2.519	0.00	−8.464	I	Reject
24	BS-97-1	CAMS-75523	Wood	4270 ± 40	4869 (4837) 4664	54	−28.30	4.18	8.505	0.000	2.200	0.00	−6.525	I	Reject
25	BS-97-1	CAMS-75524	Bulk (m)	4140 ± 40	4828 (4644) 4526	6.8	−28.80	4.18	7.515	0.000	2.200	0.00	−5.535	I	Reject
26	BS-97-2	CAMS-75525	Wood	4940 ± 40	5834 (5655) 5595	52	−28.10	4.25	10.100	0.000	2.357	0.02	−8.187	B	Accept
27	BS-97-2	CAMS-75526	Bulk (m)	4420 ± 40	5278 (5017) 4866	2.8	−28.60	4.25	9.358	0.000	2.461	0.21	−7.359	I	Accept
28	BS-97-3	CAMS-75527	Wood	5880 ± 40	6795 (6700) 6571	46	−29.10	4.21	10.465	0.000	0.513	0.00	−6.768	B	Accept
29	BS-97-3	CAMS-75528	Bulk (m)	5850 ± 40	6776 (6712) 6549	6.2	−26.80	4.21	10.205	0.000	2.232	0.08	−8.147	I	Accept
30	BS-97-3	CAMS-75529	Wood	4420 ± 40	5278 (5017) 4866	55	−28.70	4.21	8.755	0.000	2.157	0.35	−6.352	I	Accept
31	BS-97-3	CAMS-75530	Bulk (m)	4020 ± 40	4775 (4471) 4412	4.1	−29.00	4.21	7.655	0.000	2.224	0.49	−5.179	I	Accept
32	BS-97-1	AA-54118	Wood	4438 ± 42	5286 (5008) 4868	44	−29.00	4.18	11.518	0.000	2.212	0.00	−9.550	I	Reject
33	BS-97-1	AA-54119	Wood	4556 ± 43	5441 (5299) 5047	53	−26.60	4.18	10.125	0.000	2.519	0.00	−8.464	I	Reject

[a] Estimated δ^{13}C value (insufficient sample material for an independent δ^{13}C measurement).
m, minerogenic sample; m-p, minerogenic-peat sample; c, charcoal sample.
Type: B, basal; I, intercalated.

Table 3 Foraminiferal counts associated with sea-level index points

Index no.	Core	^{14}C laboratory no.	*M.f.*	*E.s.*	*H.* spp.	*P.i.*	*T.i.*	*T.o.*	*J.m.*	*B.* spp.	*E.* spp.	*E.o.*	*E.g.*	*E.w.*	*H.g.*	*A.b.*	*A.m.*	UC	Environment	Indicative meaning (±0.29 m MTL)
1	BA-97-1	CAMS-75518	8	0	0	2	90	0	174	0	0	0	0	0	0	10	0	0	Salt marsh	2.509
2	BA-97-2	CAMS-75519	0	0	0	0	96	0	216	0	0	0	136	16	512	1824	0	0	Low salt marsh	0.409
3	NS-97-1	AA-38822	0	0	0	0	0	0	0	0	0	0	0	1	13	2	0	0	Mudflat	−0.905
4	NS-97-2	AA-38823	0	0	1	0	0	0	38	0	0	0	0	0	0	1	0	0	Salt marsh	2.186
5	NS-97-2	AA-38824	8	0	0	0	5	0	15	0	0	0	0	0	3	0	0	0	Salt marsh	1.816
6	NS-97-3	AA-38825	0	2	0	0	0	0	1	0	1	0	0	0	1	0	0	0	Low salt marsh	0.572
7	NS-97-3	AA-38826	1	0	0	0	2	0	4	0	0	0	0	0	0	0	0	0	Salt marsh	2.329
8	NS-97-3	AA-38827	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	Salt marsh	2.200
9	NS-97-3	AA-38828	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	Salt marsh	2.200
10	NS-97-3	AA-38829	0	0	0	0	0	0	0	0	2	0	0	0	1	0	0	0	Low salt marsh	0.840
11	NS-97-3	AA-38830	0	0	0	0	0	0	0	3	8	2	0	2	26	4	2	0	Mudflat	−0.846
12	NS-97-3	AA-38831	8	0	0	0	5	0	177	0	0	0	0	0	0	0	0	0	Salt marsh	2.200
13	NS-97-3	AA-38832	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	Salt marsh	2.200
14	NS-97-3	AA-38833	0	0	0	0	0	0	2	5	8	0	0	2	104	5	0	0	Mudflat	−0.864
15	NS-97-3	AA-38834	0	0	0	0	0	2	5	1	0	0	0	0	56	18	0	0	Mudflat	−0.688
16	NS-97-3	AA-38835	0	0	0	0	0	0	5	0	0	0	0	0	32	0	0	0	Mudflat	−0.809
17	NS-97-4	AA-38836	0	0	0	0	0	0	0	4	0	0	0	0	6	3	0	2	Mudflat	−1.359
18	SS-99-1	CAMS-72401	16	0	0	32	552	72	1792	0	0	0	0	0	0	0	0	0	Salt marsh	2.427
19	SS-99-1	CAMS-72402	16	0	0	32	552	72	1792	0	0	0	0	0	0	0	0	0	Salt marsh	2.427
20	SS-99-2	CAMS-75531	0	0	0	0	4	0	6	0	0	0	0	0	0	0	0	0	Salt marsh	2.450
21	BS-97-1	CAMS-75520	28	0	0	0	116	0	1308	0	0	0	0	0	0	0	0	0	Salt marsh	2.250
22	BS-97-1	CAMS-75521	4	0	0	0	6	0	152	0	0	0	0	0	0	0	0	0	Salt marsh	2.212
23	BS-97-1	CAMS-75522	4	0	0	0	14	0	8	0	0	0	0	0	0	0	0	0	Salt marsh	2.519
24	BS-97-1	CAMS-75523	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	Salt marsh	2.200
25	BS-97-1	CAMS-75524	0	0	0	0	0	0	212	0	0	0	0	0	0	0	0	0	Salt marsh	2.200
26	BS-97-2	CAMS-75525	24	0	0	2	48	0	184	0	0	0	0	0	0	0	0	0	Salt marsh	2.357
27	BS-97-2	CAMS-75526	0	0	0	0	2	0	2	0	0	0	0	0	0	0	0	0	Salt marsh	2.461
28	BS-97-3	CAMS-75527	2	0	0	0	2	4	18	0	0	0	0	2	18	10	0	0	Low salt marsh	0.513
29	BS-97-3	CAMS-75528	0	0	0	0	4	0	94	0	0	0	0	0	0	0	0	0	Salt marsh	2.232
30	BS-97-3	CAMS-75529	2	0	2	0	2	0	6	0	0	0	0	0	0	0	0	0	Salt marsh	2.157
31	BS-97-3	CAMS-75530	0	0	0	0	2	0	62	0	0	0	0	0	0	0	0	0	Salt marsh	2.224
32	BS-97-1	AA-54118	4	0	0	0	6	0	152	0	0	0	0	0	0	0	0	0	Salt marsh	2.212
33	BS-97-1	AA-54119	4	0	0	0	14	0	8	0	0	0	0	0	0	0	0	0	Salt marsh	2.519

M.f., Miliammina fusca; E.s., Eggerella scabra; H. spp., Haplophragmoides spp.; P.i., Polysaccammina ipohalina; T.i., Trochammina inflata; T.o., Trochammina ochracea; J.m., Jadammina macrescens; B. spp., Brizalina spp.; E. spp., Elphidium spp.; E.o., Elphidium oceanensis; E.g., Elphidium gerthi; E.w., Elphidium williamsoni; H.g., Haynesina germanica; A.b., Ammonia beccarii; A.m., Asterigerinata mamilla; UC, unidentified calcareous species.

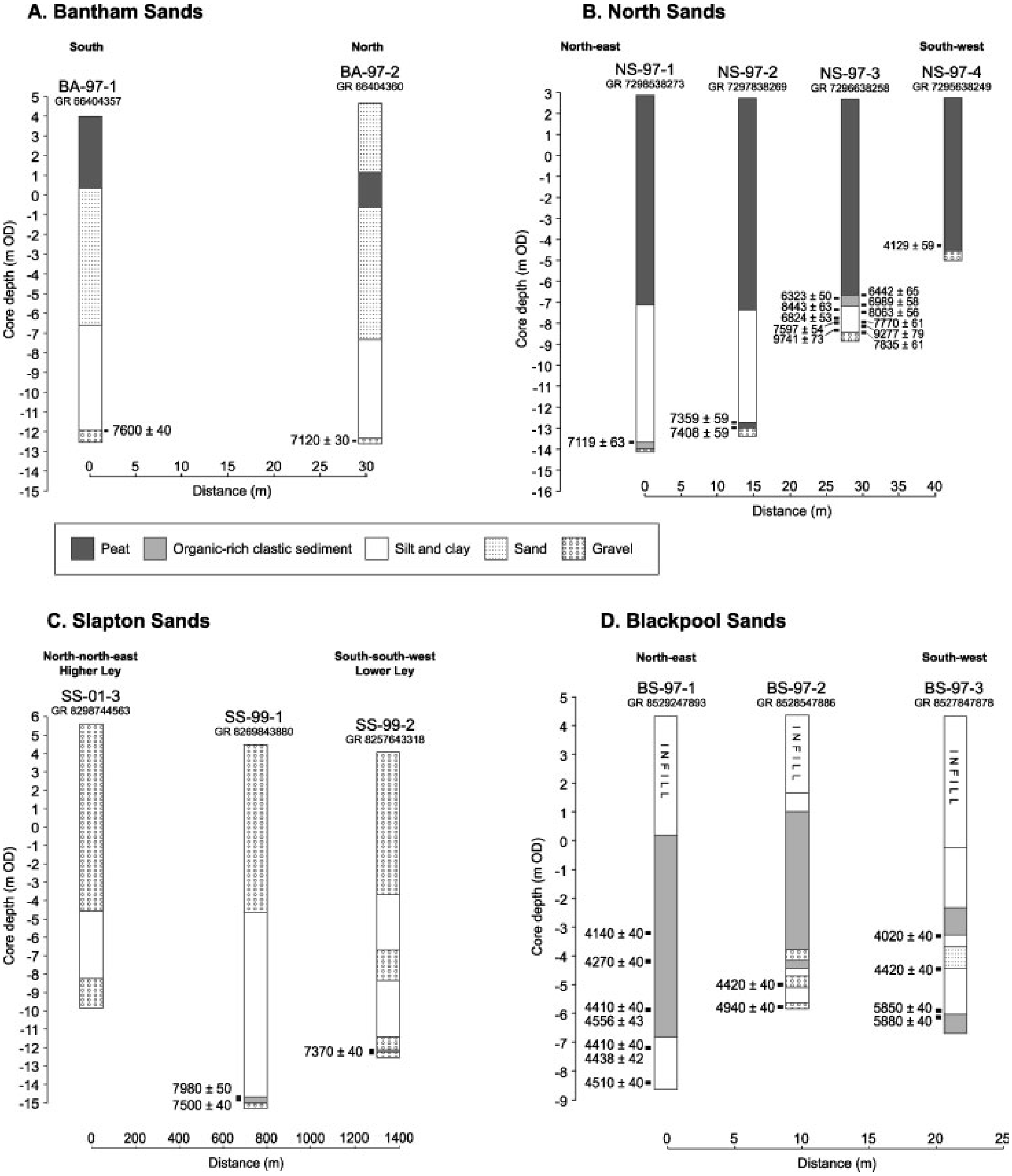

Figure 2 Coastal sediment stratigraphy at Bantham Sands (A), North Sands (B), Slapton Sands (C) and Blackpool Sands (D), south Devon. Core heights are relative to UK Ordnance Datum (Newlyn, Cornwall). Index numbers listed alongside cores correspond to sea-level index points in Table 2. Lithology follows key in Fig. 2

peat sample provides index point 17 at 7.24 m, dated to ca. 4800–4400 cal. yr BP with an indicative meaning of ca. −1.4 m (Table 3).

Slapton Sands

At Slapton Sands, a broken and weathered slate substrate is found around −15 m to −8 m OD (Fig. 2(C)). Organic remains are preserved at the base of the two deepest cores (Fig. 5). A thick sequence of silts and clays is found between −14 and −3 m OD. This is broken by units of coarse gravel in core SS-99-2 between −8.5 and −4.5 m OD. Alternating beds of gravel and silts/clays occur from around −3.8 to −3.2 m OD and the sequence is capped by barrier gravels up to 10 m in thickness.

Biostratigraphical analyses were carried out on cores SS-99-1 and SS-99-2. The base of core SS-99-1 contains the agglutinated salt-marsh foraminifera *J. macrescens*, *T. inflata* and *M. fusca* (Fig. 5(A)), providing SLIPs 18 and 19, with an indicative meaning of ca. +2.4 m MTL (Tables 2 and 3). Bulk sediments (SLIP 18; ca. 8870 cal. yr BP) and charcoal from the same sample were dated separately (SLIP 19; ca. 8340 cal. yr BP). Above this, there is a gradual decline in agglutinated species and an increase in *A. beccarii* and *H. germanica*, indicating a gradual drowning of a salt-marsh environment and a transition to tidal mudflat conditions.

At the base of core SS-99-2, *Phragmites* and large alder fragments (~16.30 m) are present in peat (16.33–16.26 m) but there are no foraminifera (Fig. 5(B)). Above this level, the

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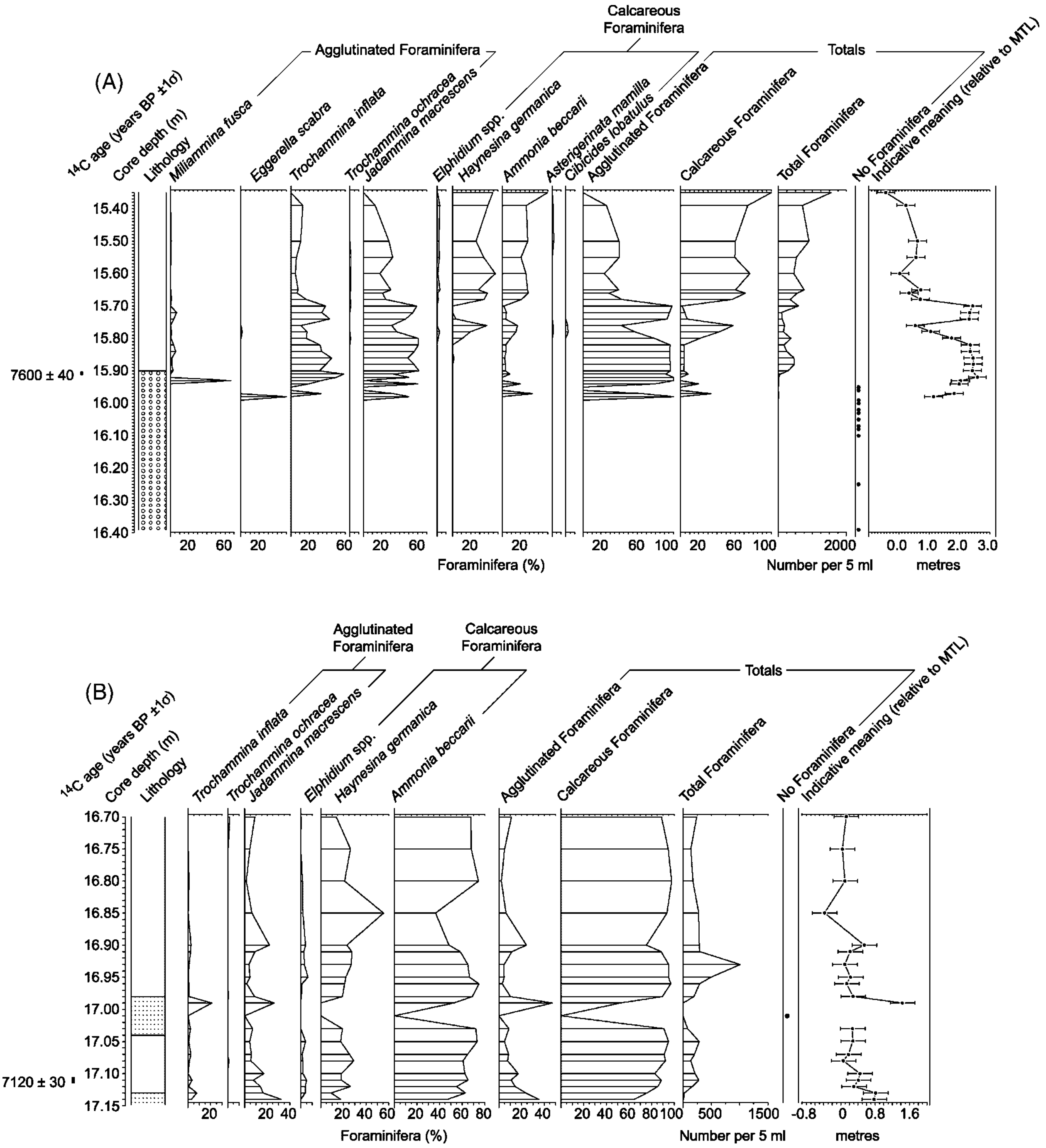

Figure 3 Foraminiferal stratigraphy of Bantham Sands cores BA-97-1 (A) and BA-97-2 (B)

foraminiferal assemblage initially consists of 100% salt-marsh foraminifera (*J. macrescens* and *T. inflata*), falling to 35% within 2 cm. A 2 cm long chunk of alder, found at 16.28 m, provided a date of ca. 8175 cal. yr BP (SLIP 20; indicative meaning ca. +2.5 m MTL) (Tables 2 and 3). Above this, calcareous species dominate most of the core and the total numbers increase. The most dominant species are *A. beccarii* and, in the upper part of the section, *Elphidium margaritaceum*. The latter is a nearshore (deeper water) species and signifies a change to subtidal conditions (Murray, 1979).

Blackpool Sands

Basal sediments at Blackpool Sands below −6 m OD are fractured slates, sandy and clayey silts and gravel (Fig. 2(D)). A thick sequence of alternating clastic and organic-rich sediments occurs throughout most of the cores. Above ca. 0 m OD sediments are artificial infill.

The foraminiferal stratigraphy at Blackpool Sands consists mostly of salt-marsh species, but abrupt changes to calcareous assemblages are present. The base of core BS-97-1 from 12.90 to 7.50 m (Fig. 6(A)) is dominated by *H. germanica* and *A. beccarii*, abruptly succeeded by *J. macrescens* above 12.74 m. Above a section where core loss occurred, the assemblage consists of 90–100% calcareous foraminifera. Another abrupt change, to low counts of agglutinated salt-marsh species, mostly *J. macrescens*, *T. inflata* and *M. fusca*, occurs at 11.63 m. This assemblage is found up to 7.50 m. Higher in the core section foraminifera are absent. The chronology of core BS-97-1 spans ca. 5300–4525 cal. yr BP (SLIPs 21–25, 32 and 33) (Table 2) but the close spread of ages suggests possible sediment reworking. This issue is assessed in the next section.

Agglutinated foraminifera dominate the base of core BS-97-2 between 10.17 and 9.35 m, mostly *J. macrescens*, *T. inflata* and *M. fusca* (Fig. 6(B)). No foraminifera were found above this level. The top and bottom of this section provide SLIPs 26 and 27 suggesting salt-marsh conditions ca. 5835–4865 cal. yr BP (indicative meaning ca. +2.4 m MTL) (Tables 2 and 3).

Foraminifera are present in core BS-97-3 from between 10.48 and 7.62 m (Fig. 6(C)). At the base there is a transition from calcareous to agglutinated assemblages and the latter persist throughout the examined sections. No foraminifera were found above 7.60 m. SLIP 28 (10.47 m) was collected from tidal mudflat sediments dated at ca. 6700 cal. yr BP (indicative meaning ca. +0.5 m MTL), while SLIPs 29–31 contained salt-marsh foraminifera (indicative meaning ca. +2.2 m MTL) (Tables 2 and 3).

Discussion

Evaluation of anomalous data

Thirty-three possible sea-level index points were obtained from coastal back-barrier sites in south Devon (Table 2, Fig. 8). Results show that index points from cores NS-97-3 and BS-97-1 are potentially subject to irreconcilable age or height errors.

In core NS-97-3 reversals occur in the chronology (Table 2). Index points 7 and 8 are ca. 2000 yr older than index point 6, and index points 12 and 13 are ca. 1000 yr older than index points 9, 10 and 11. All dates are on bulk sediment. We evaluate these age reversals using pollen stratigraphy (Fig. 7).

Pollen analyses show that the sediments in core NS-97-3 contain a fairly mixed assemblage of predominantly *Quercus*, *Corylus* and *Alnus* pollen. Lower sediments have a greater proportion of *Quercus* pollen and less *Ulmus* (Fig. 7). The presence of *Alnus* suggests that the sediments must post-date ca. 8000–7500 cal. yr BP (Birks, 1989) and upper sediments with *Ulmus* must pre-date the elm decline at ca. 5300 ^{14}C yr BP (Parker *et al.*, 2002). Four index points (7, 8, 12 and 13) are in direct conflict with the pollen stratigraphy, as the sediment contains alder pollen and their ages are 11200–8700 cal. yr BP (Fig. 7).

We interpret core NS-97-3 to have sampled a section of reworked sediments containing old carbon. On the basis of pollen stratigraphy alone it is not possible to determine whether the ages of some of the younger index points are accurate, but we consider it likely that the entire section has been affected by reworking to some degree. We therefore choose to err on the side of caution and reject all dates from this core as SLIPs.

In core BS-97-1 all dates from a 5 m section of core are within a 500-year range. Four of these are obtained from wood fragments and one date is on bulk sediment. The foraminifera are mostly indicative of a salt-marsh environment and high sedimentation rates (on the order of a metre per century) can therefore be ruled out. The core also contains abrupt changes between agglutinated and calcareous assemblages, which points to discontinuous sedimentation. We conclude that this entire section is also reworked and possibly represents the infilling of a creek by eroded salt-marsh deposits. This mechanism is not implausible given the setting of the site in a narrow and steep palaeovalley. We reject all dates from core BS-97-1 for our sea-level reconstructions.

The basal index point 17 from core NS-97-4 is a critical constraint on RSL change between 7000 and 4000 cal. yr BP. It plots higher than four new index points of similar age (26, 27, 30, 31) (Fig. 8(A)), which have been corrected for vertical displacement by compaction. It is possible that the indicative meaning of index point 17 (−1.4 m MTL), which is based on low counts of calcareous foraminifera, is too deep. At the base of core NS-97-4, the lithostratigraphy (minerogenic peat) and biostratigraphy (calcareous foraminifera) are in disagreement and if the date is assigned a salt-marsh indicative meaning, for example, the point would place ca. 3 m lower in the sea-level plot. Alternatively, it is possible that the geotechnical correction for the four index points (26, 27, 30, 31) has underestimated their true vertical displacement (Massey *et al.*, 2006b). Published data points 34 and 35, which seem to agree with points 26, 27, 30 and 31, are intercalated points and may also have been affected by compaction. When we consider all available data we are unable to resolve this issue and uncertainty of the sea-level changes between 7000 and 4000 cal. yr BP therefore remains relatively large (Fig. 8).

Due to a chronic lack of available plant macrofossils in the sediments we dated many small wood fragments. Wood fragments are not ideal dating material as they are prone to post-depositional transport. Perhaps fortuitously, a closer inspection of the accepted wood dates (index points 2, 20, 26, 28, 30) does not reveal any anomalous ages.

In the discussion below we elaborate further on possible mechanisms for the reworking of sediments. It will also be shown that the samples from cores NS-97-3 and BS-97-1 are anomalous, in terms of height and age, in comparison with sea-level index points from other cores. The rejection of index points from the two cores leaves us with 15 validated new SLIPs for south Devon.

Holocene relative sea-level history of south Devon

Of 15 new sea-level index points that can be used to reconstruct the Holocene relative sea-level history of south Devon, eight are basal SLIPs between ca. 9000 and 6000 cal. yr BP. The other seven (intercalated) points have been corrected for autocompaction (Table 2). In Fig. 8(A) we have drawn an envelope based on the validated sea-level index points for south Devon. The data reveal an overall rise in RSL of 21 ± 4 m since ca. 9000 cal. yr BP. Since ca. 7000 cal. yr BP, sea level has risen by 8 ± 1 m (Fig. 8).

The slowdown of relative sea-level rise to $\sim$1 m ka^{-1} at ca. 7000 cal. yr BP is in agreement with estimates from other regions in southern England and Wales (Heyworth and Kidson, 1982; Healy, 1995; Shennan and Horton, 2002; Waller and Long, 2003; Edwards, 2006). Two index points older than 7000 cal. yr BP have previously been published for south Devon and Cornwall (39, 40). These are limiting dates obtained from freshwater sediments (Clarke, 1970; Hails, 1975b) (Table 4). These index points and two (34, 35) from Hails (1975a) are in line with our new data (Fig. 8(A)).

Our study does not contribute any new sea-level index points younger than 4000 years. Three previously published data points exist (Hails, 1975a, 1975b; Morey, 1976) (Table 4). However, one of these index points is from a tree stump (36), while the others are from intercalated freshwater coastal fen peat (37, 38). They are limiting dates (i.e. sea level must be below the points), so that they appear to have been vertically displaced by compaction. Their indicative meaning is only constrained by pollen and should not be considered as valid sea-level index points (as discussed in detail by Gehrels, 2006). The average rate of relative sea-level rise in the late Holocene

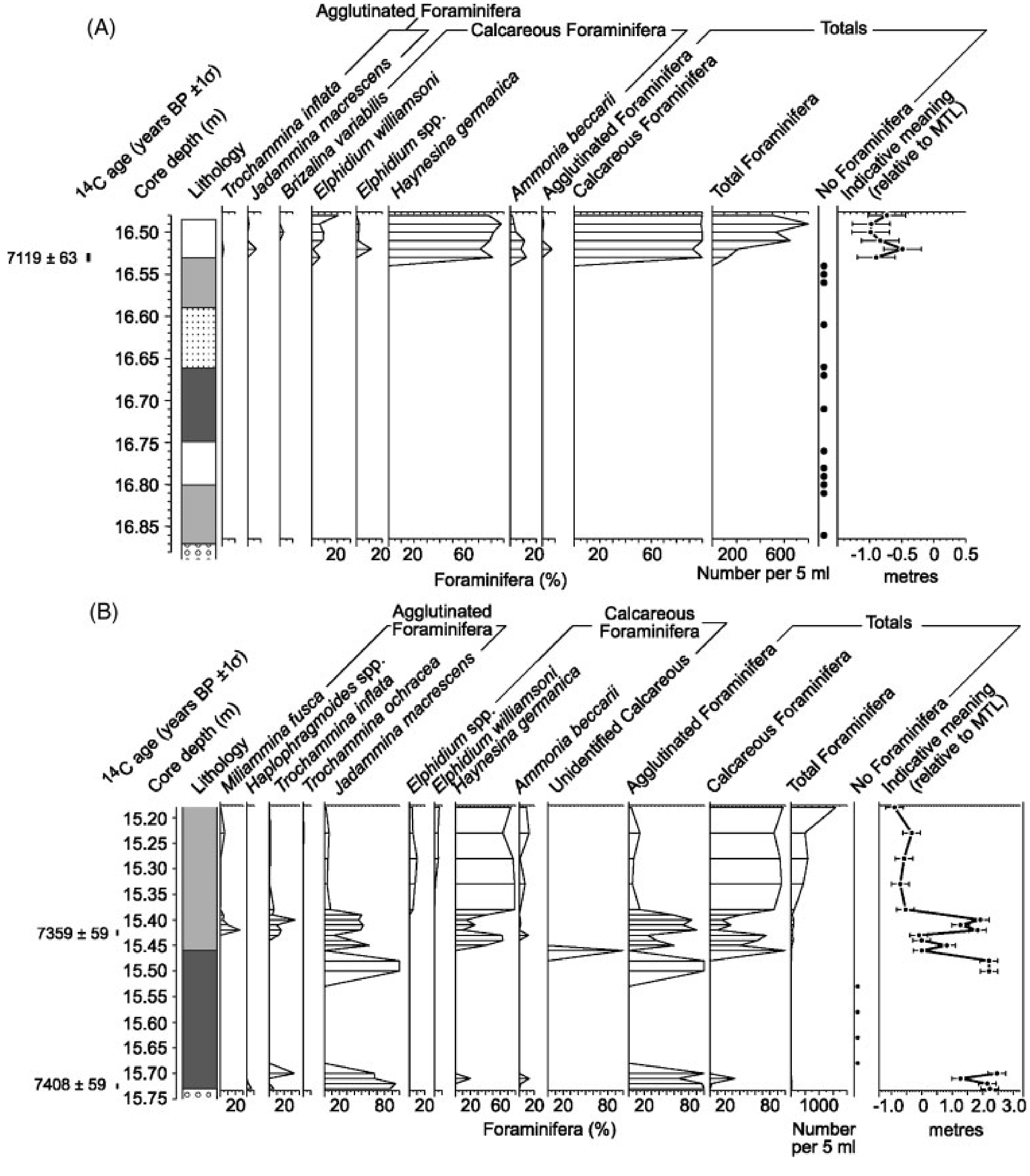

Figure 4 Foraminiferal stratigraphy of North Sands cores NS-97-1 (A), NS-97-2 (B), NS-97-3 (C), and NS-97-4 (D). Zonation in (C) is based on CONISS (Grimm, 1987)

calculated by Shennan and Horton (2002) was based on the two youngest of these dates (36, 37).

Postglacial isostatic adjustment along the coast of south Devon

In an initial assessment, Shennan (1989) calculated rates of 0.1–1.4 m ka^{-1} relative subsidence in southwest England using Mörner's (1984) sea-level curve for the Kattegat area in Sweden as a 'eustatic' regional baseline curve from which regional curves around the British Isles were subtracted. As the concept of 'regional eustasy' is not widely accepted (e.g. Gehrels *et al.*, 2006), Shennan and Horton (2002) undertook a reanalysis, adding many sea-level index points to the UK dataset and making corrections for tidal range along the UK east coast. They also evaluated problems of autocompaction and in their sea-level age–altitude graphs selected the points towards the higher end of the error envelopes for their analysis. This resulted in a reduced rate of relative subsidence for south-eastern England compared to the previous estimates of Shennan (1989). For Devon, Shennan and Horton (2002) used index points 36 and 37 to calculate 1.23 ± 0.18 m ka^{-1} of relative land subsidence. They used index points 42 and 45 to determine 1.12 ± 0.21 m ka^{-1} of relative subsidence for Cornwall. Unlike Waller and Long (2003), they did not consider the data from the Isles of Scilly (Ratcliffe and Straker, 1996). Shennan and Horton's (2002) method of calculating relative land movements also differed from Shennan (1989), by assuming that since ca. 5000–4000 cal. yr BP the long-term eustatic contribution of ice sheets has been zero and that any relative sea-level signal since that time is primarily a function of isostatic crustal movement. It should be noted, therefore, that

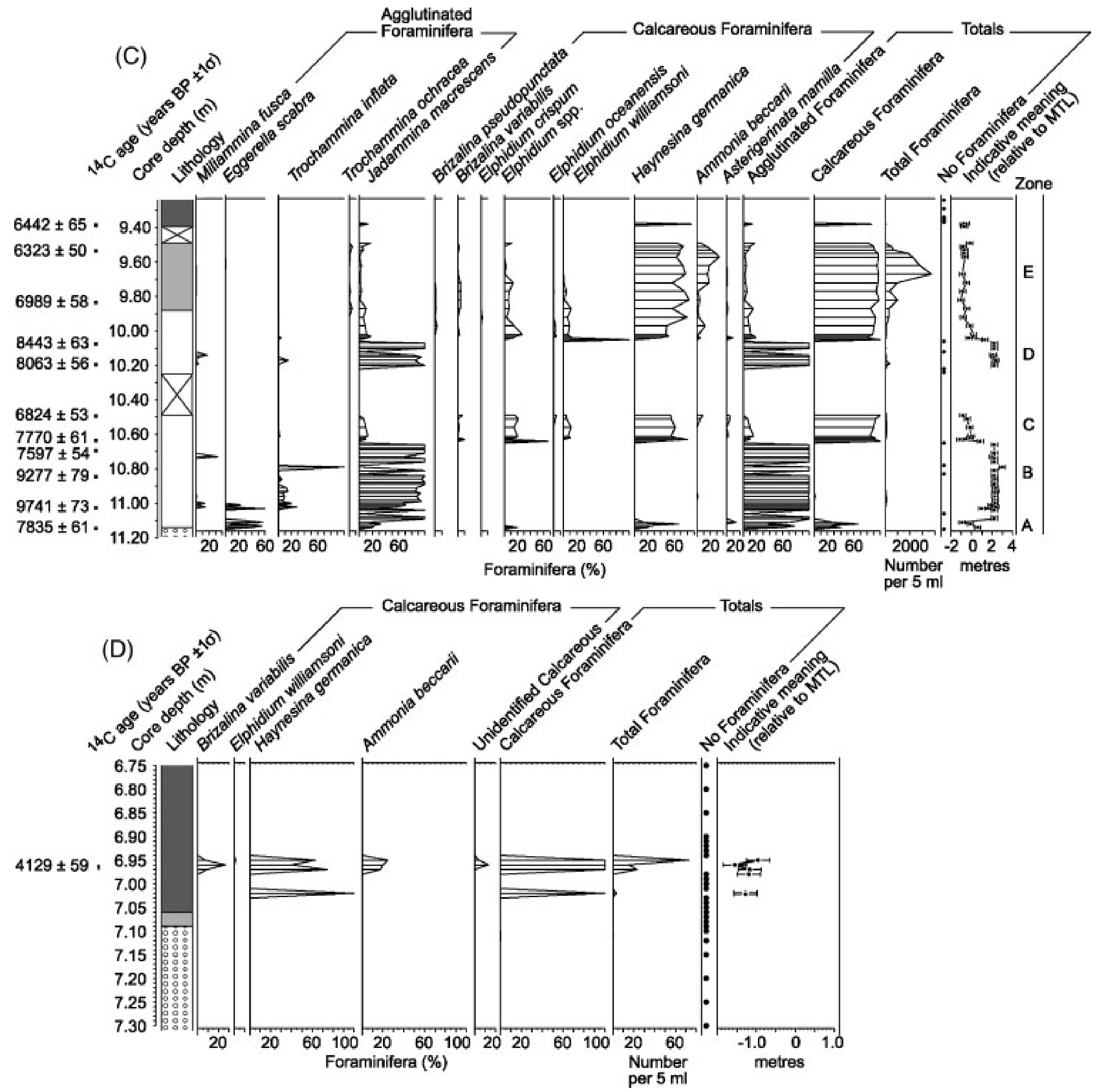

Figure 4 (*Continued*)

subsidence rates would be lower if global deglaciation continued after ca. 4000 cal. yr BP. Estimates of cessation of global ice melt are frequently revised with respect to the growing body of empirical evidence used to test models (e.g., Peltier, 1994). If we account for global sea-level rise during the past century, the rate of land subsidence in south Devon is reduced by 0.1 m ka^{-1}. Shennan and Horton (2002) used a linear fit to the sea-level index points to estimate relative land movements. A more realistic approach (on geophysical grounds) is a curvilinear fit which would produce an even lower estimate of relative subsidence.

Differential crustal movements in southwest England

The relative sea-level history for south Devon can be compared with sea-level data from Cornwall to evaluate differential isostatic movements in southwest England. Healy (1995) provided four basal sea-level index points and three points from intercalated peat units from Marazion Marsh in south-western Cornwall. Waller and Long (2003) discussed four index points collected from peat outcrops on beaches in the Isles of Scilly (Ratcliffe and Straker, 1996) (Table 4). Vertical errors applied to these sea-level index points do not include an estimate of autocompaction.

In Fig. 8(B) we have plotted the sea-level envelope from south Devon, and sea-level index points from Cornwall and the Isles of Scilly in one diagram. The points from Cornwall and the Isles of Scilly span a time period that is poorly covered by the south Devon data. The Isles of Scilly points appear to be positioned within the south Devon envelope, and above the rejected published south Devon index points (36–38). Given the poor constraints on indicative meaning, and the possibility that published index points have been affected by compaction, it is not possible to differentiate between sea-level index points from south Devon, west Cornwall and the Isles of Scilly.

Geophysical model predictions

This study has added 15 new data points to test geophysical Earth models (e.g., Lambeck, 1993a,b, 1995, 1997; Peltier,

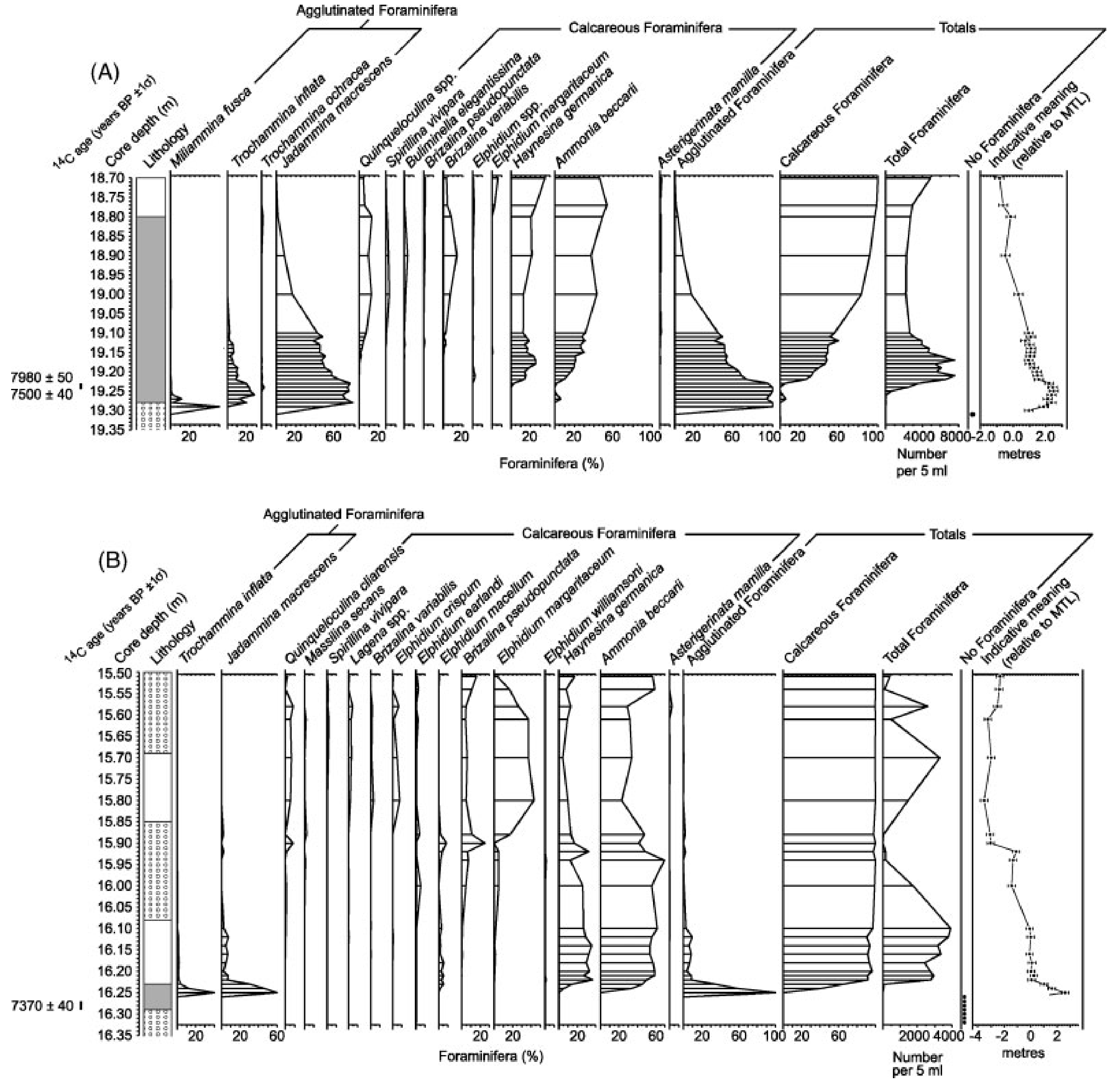

Figure 5 Foraminiferal stratigraphy of Slapton Sands cores SS-99-1 (A) and SS-99-2 (B)

1998; Peltier *et al.*, 2002; Milne *et al.*, 2006; Shennan *et al.*, 2006). Here, we compare our data with the updated GB-3 model of Lambeck (1995) and ICE-5G (VM2) of Peltier (2004) (Fig. 8(A)). We also use predictions by the model of Shennan *et al.* (2006).

Models differ in their components of the palaeotopography of ice sheets (e.g., ice-equivalent eustatic sea-level rise or the 'eustatic function') and Earth rheology (e.g. see Plag *et al.*, 1998), resulting in different predictions for the timing and altitude of Holocene sea levels along the south Devon coast (Fig. 8(A)). An in-depth comparison between the three models is provided by Shennan *et al.* (2006). The RSL response from ICE-5G is curvilinear and GB-3 is more rectangular in profile. The Shennan *et al.* (2006) model prediction is intermediate between the two. The shapes of the curves and the positions of inflection points are a reflection of the 'eustatic function' of the models, i.e. the built-in history of meltwater that is added to the world's oceans. Of the three models, Lambeck's GB-3 generally predicts lower sea-level heights, except between ca. 7000 and 5000 cal. yr BP when GB-3 sea levels are as much as 3 m higher than those from ICE-5G. The three models are in reasonable agreement with the sea-level data older than ca. 6000 cal. yr BP, but ICE-5G provides the best fit with our sea-level envelope.

The middle to late Holocene south Devon data points plot below the predictions of all three models. Over-prediction of sea-level positions by the models can be resolved by assuming increased melting in the Earth models after ca. 6000 cal. yr BP, but these adjustments have a global effect and would produce misfits in other locations. A more regional solution would be to increase ice loads over the British Isles (Shennan *et al.*, 2002) to amplify the 'forebulge effect'. This is an issue that is frequently revised with respect to field evidence, e.g. the height of trim-lines in the Scottish Highlands (Watts, 1977; Ballantyne, 1984; Sutherland, 1991), and is likely to affect rates of crustal movement in the south (Shennan and Horton, 2002). Interestingly, the three model predictions are very close to index point 17. Comparison with the models shows that additional sea-level data between 4000 and 2000 cal. yr BP would be useful, as the models diverge during this time period.

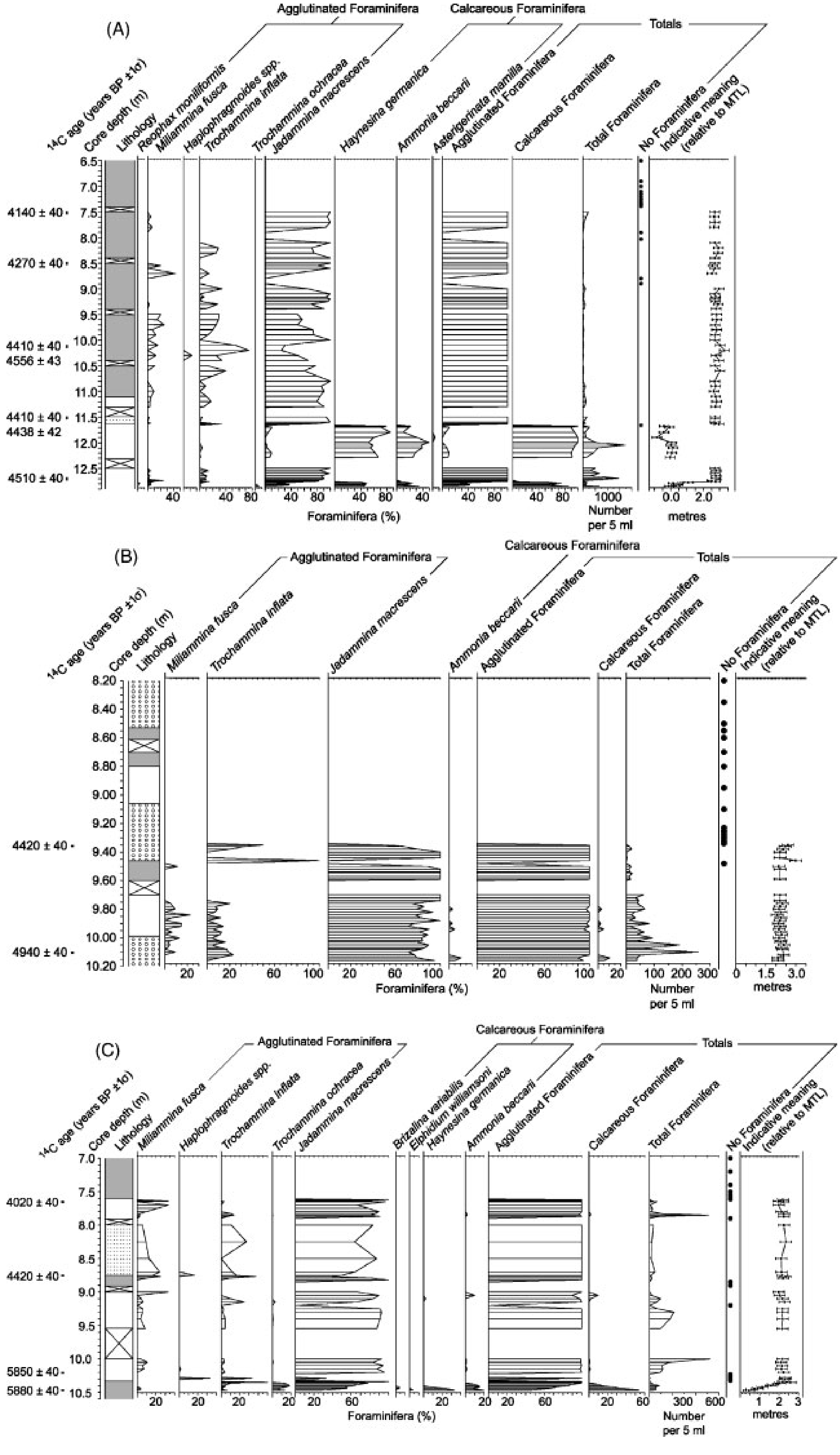

Figure 6 Foraminiferal stratigraphy of Blackpool Sands cores BS-97-1 (A), BS-97-2 (B) and BS-97-3 (C)

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In Fig. 8(B) we compare the south Devon sea-level envelope with index points from west Cornwall and the Isles of Scilly and with predictions for west Cornwall based on the models by Shennan *et al.* (2006) and ICE-5G by Peltier (2004). Both models place the Cornwall predicted sea-level curves below the Devon predicted curves, with a similar offset (compare Figs 8(A) and 8(B)). The Shennan *et al.* (2006) model is closer to the late Holocene index points (Fig. 8(B)), whereas the Peltier model shows a slightly better fit with the early to middle Holocene data. Nine of eleven data points, however, plot below the predicted heights. This highlights the need for additional modelling work and the collection of new, high-quality sea-level index points.

An important advantage of geophysical models is that they can separate land motion from other processes that contribute to relative sea-level changes. The model by Shennan *et al.* (2006) predicts that present-day crustal subsidence is 0.85 mm yr^{-1} in south Devon and 1.04 mm yr^{-1} in west Cornwall. Rates determined by GPS (0.0 ± 0.5 mm yr^{-1}) and gravity measurements (0.9 ± 0.9 mm yr^{-1}) contain large uncertainties (Teferle *et al.*, 2006) and longer records are required to make fair comparisons with the geophysical model data. The rate for west Cornwall appears high when compared with the Newlyn tide-gauge data ($\sim$1.6 mm yr^{-1}; Woodworth *et al.*, 1999), even when a long-term late Holocene sea-level fall of $\sim$0.3 mm yr^{-1} resulting from 'ocean syphoning' is taken into account (Mitrovica and Peltier, 1991; Mitrovica and Milne, 2002). The model-predicted rates of relative sea-level rise are somewhat lower than the estimates of Shennan and Horton (2002). It is clear, however, that the misfit between model predictions and sea-level index points requires further study and a priority should be the collection of basal sea-level index points covering the late Holocene (i.e. the past $\sim$4000 yr).

Coastal dynamic processes and implications for sea-level studies

The sea-level history at Marazion, in southwestern Cornwall, was reconstructed by Healy (1995) (Table 4) from back-barrier sediments and therefore provides interesting comparative material for our work. Healy (1995) concluded that the Marazion water-level history was not only controlled by relative sea-level movements, but also by significant morphodynamical and sedimentary processes. We find a scatter in our sea-level index points which suggests that the back-barrier systems in south Devon have also been affected by processes that complicate the reconstruction of sea-level changes. One such process is the reworking of sediment, for which there is evidence in the stratigraphy of North Sands and Blackpool Sands. The biostratigraphy at these sites is characterised by abrupt changes in foraminiferal populations, whereas foraminiferal changes at Slapton Sands and Bantham Sands are more gradual. This may suggest that the pattern of biostratigraphical changes revealed by foraminifera is a good indicator for the integrity of back-barrier sediments. On this basis we cannot rule out that some of our 'accepted' index points are also

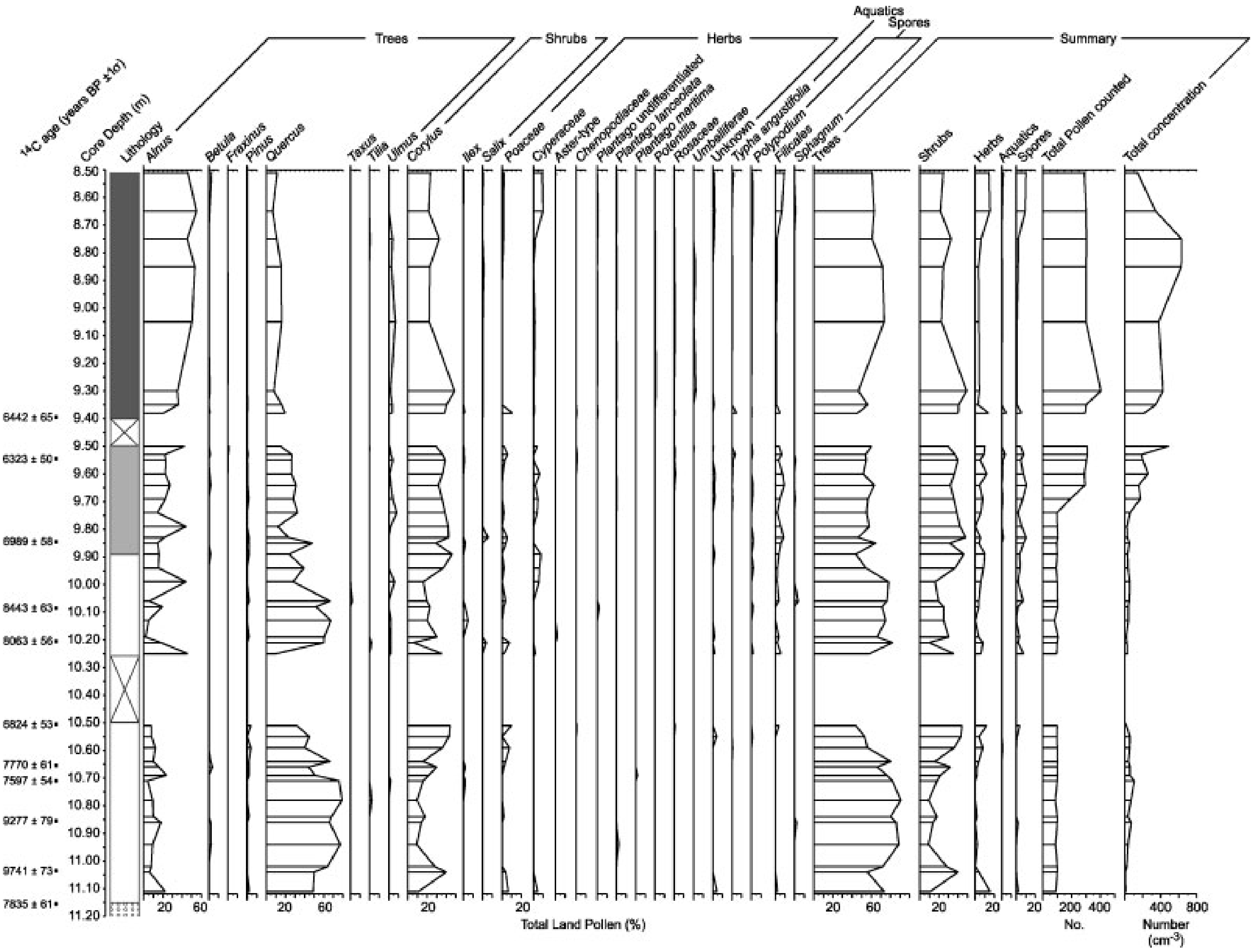

Figure 7 Pollen stratigraphy of core NS-97-3 from North Sands

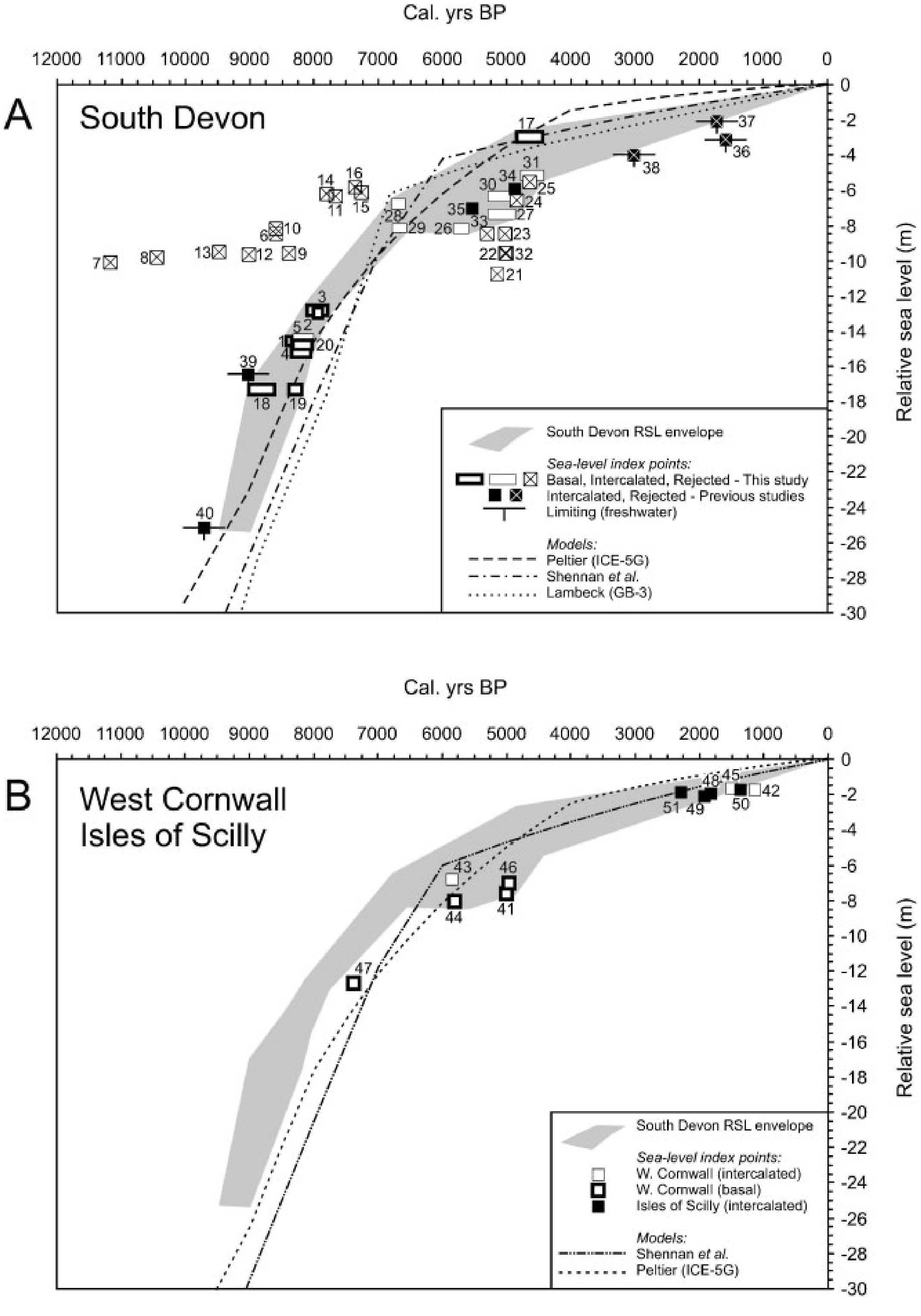

Figure 8 (A) Sea-level index points from south Devon compared with three sea-level curves predicted by geophysical models. The envelope of relative sea-level change encompasses the accepted data points. Index points from this study were corrected for vertical displacement by autocompaction. No corrections were applied to previously published data points. See Table 4 for references of previous studies. Index numbers correspond to Table 2. (B) Sea-level index points for western Cornwall (Healy, 1995) and the Isles of Scilly (Ratcliffe and Straker, 1996) compared with south Devon relative sea-level envelope and model prediction. Index numbers correspond with Table 2. No corrections were applied for possible compaction

affected by sediment reworking. The cluster of index points from Blackpool Sands (26, 27, 30, 31; Fig. 8(A)), for example, appears to be young compared to index points 28 and 29 from the same site, which can be explained by channel bank erosion and redeposition of marsh sediments on the channel floor. A recommendation for future studies from similar environments is that sea-level index points should be obtained, whenever possible, from sedimentary sequences that have been examined for stratigraphical continuity using microfossils.

It is likely that onshore barrier migration during the Holocene rise in sea level was accompanied by reworking and redeposition of sediment as the barriers 'rolled' over the marsh and lagoon deposits behind them. Evidence for this process is

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Table 4 Published sea-level index points from south Devon, west Cornwall and the Isles of Scilly

Index number	^{14}C lab. no.	Location (lat./long.)	^{14}C age (years BP ±1σ)	Cal. age BP (±2σ range) max (median) min.	Height (m OD)	SLIP (m RSL)	Type	Reference
34	SRR164	Beesands (50° 15.24′ N; 03° 39.15′ W)	4302 ± 45	5034 (4870) 4729	−4.32	−5.99 ± 0.73	I	Hails (1975a); Shennan and Horton (2002)
35	SRR165	Beesands (50° 15.24′ N; 03° 39.15′ W)	4767 ± 45	5594 (5512) 5328	−4.62	−7.09 ± 0.29	I	Hails (1975a); Shennan and Horton (2002)
36	SRR317	North Hallsands (50° 14.15′ N; 03° 39.28′ W)	1683 ± 45	1709 (1592) 1422	−1.00	−3.17 ± 0.66	I	Hails (1975a); Shennan and Horton (2002)
37	SRR492	Slapton Ley (50° 16.58′ N; 03° 39.08′ W)	1813 ± 40	1864 (1753) 1621	−0.19	−2.16 ± 0.56	I	Morey (1976); Shennan and Horton (2002)
38	SRR493	Slapton Ley (50° 16.58′ N; 03° 39.08′ W)	2889 ± 50	3206 (3028) 2876	−1.79	−4.06 ± 0.27	I	Morey (1976); Shennan and Horton (2002)
39	SRR237	Start Bay (50° 20′ N; 03° 35′ W)	8108 ± 60	9265 (9056) 8779	−16 to −17	−16.5 ± 1.0	L	Hails (1975a, 1975b); Heyworth and Kidson (1982); Shennan and Horton (2002)
40	NPL86	Teignmouth (50° 31.30′ N; 03° 25.00′ W)	8580 ± 800	11956 (9692) 7835	−23.80	−25.20 ± 1.66	L	Clarke (1970); Hawkins (1971); Shennan and Horton (2002)
41	Q2774	Marazion (50° 07.44′ N; 05° 28.54′ W)	4395 ± 60	5280 (4987) 4848	−5.28	−7.63 ± 0.21	B	Healy (1995); Shennan and Horton (2002)
42	Q2775	Marazion (50° 07.44′ N; 05° 28.54′ W)	1210 ± 40	1263 (1137) 1014	+0.80	−1.75 ± 0.70	I	Healy (1995); Shennan and Horton (2002)
43	Q2776	Marazion (50° 07.54′ N; 05° 28.50′ W)	5100 ± 65	5988 (5826) 5662	−4.46	−6.81 ± 0.21	I	Healy (1995); Shennan and Horton (2002)
44	Q2777	Marazion (50° 07.54′ N; 05° 28.50′ W)	5050 ± 80	5931 (5796) 5610	−5.71	−8.06 ± 0.21	B	Healy (1995); Shennan and Horton (2002)
45	Q2778	Marazion (50° 07.40′ N; 05° 29.04′ W)	1610 ± 40	1601 (1488) 1403	+0.88	−1.67 ± 0.70	I	Healy (1995); Shennan and Horton (2002)
46	Q2780	Marazion (50° 07.41′ N; 05° 28.59′ W)	4380 ± 55	5274 (4959) 4842	−4.71	−7.06 ± 0.21	B	Healy (1995), Shennan and Horton (2002)
47	Q2781	Trewornan (50° 32.33′ N; 04° 49.43′ W)	6460 ± 80	7559 (7371) 7183	−9.40	−12.70 ± 0.40	B	Healy (1993), Shennan and Horton (2002)
48	GU-5056	Tresco, Isles of Scilly (49° 56′ N; 06° 20′ W)	1880 ± 100	2044 (1816) 1560	+1.22	−1.97 ± 0.50[a]	I	Ratcliffe and Straker (1996); Waller and Long (2003)
49	GU-5057	Tresco, Isles of Scilly (49° 56′ N; 06° 20′ W)	1980 ± 80	2178 (1938) 1730	+1.03	−2.16 ± 0.50[a]	I	Ratcliffe and Straker (1996); Waller and Long (2003)
50	GU-5058	Tresco, Isles of Scilly (49° 56′ N; 06° 20′ W)	1480 ± 80	1541 (1384) 1274	+1.39	−1.80 ± 0.50[a]	I	Ratcliffe and Straker (1996); Waller and Long (2003)
51	GU-5059	Tresco, Isles of Scilly (49° 56′ N; 06° 20′ W)	2180 ± 100	2356 (2178) 1903	+1.30	−1.89 ± 0.50[a]	I	Ratcliffe and Straker (1996); Waller and Long (2003)

Index numbers correspond to Fig. 8.

[a] Vertical error estimates by Massey (2004). Other vertical errors by Shennan and Horton (2002) and Horton (pers. comm.). They use ±0.20 m for indicative meaning, ±0.05 m for coring compaction, ±0.05 m tidal correction, ±0.05–0.20 m survey (levelling) error and ±0.01 m vertical error per 1 cm sample thickness. No vertical correction is applied for autocompaction.

Type: L, limiting; B, basal; I, intercalated.

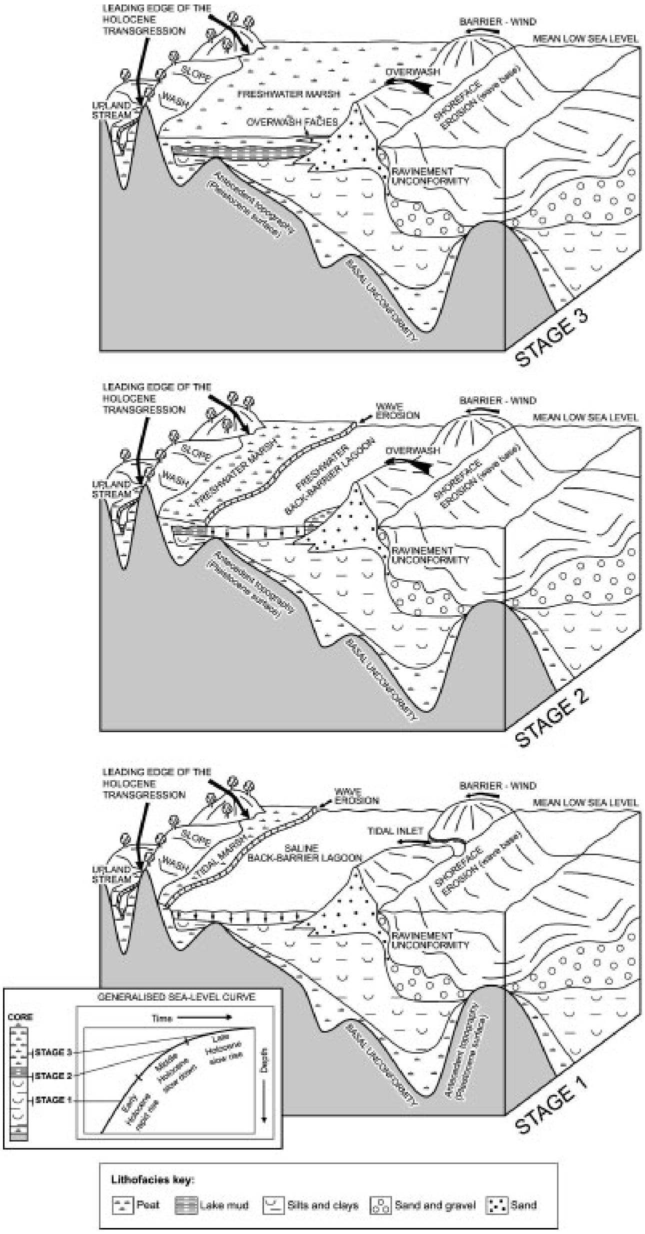

Figure 9 A transgressive model of barrier system development for south Devon. Partly based on Kraft and Chrzastowski (1985). Stage 1: rapid relative sea-level rise during the early Holocene forces barrier-lagoon system landward. Stage 2: barrier system closes under decelerating relative sea-level rise during the middle Holocene. Stage 3: infilling of back-barrier system under slow relative sea-level rise during the late Holocene. Inset shows the generalised sea-level curve for south Devon and related schematic lithostratigraphy

found offshore of Slapton Sands and Blackpool Sands where fossil salt-marsh deposits outcrop on the seabed of Start Bay (Hails, 1975a,b). The mouth of the Salcombe–Kingsbridge Estuary, where North Sands is located, is obstructed by a subtidal bar ('The Bar'; Fig. 1(E)), which during low sea levels must have blocked the valley from marine incursions. Several bar-fronted valleys still exist along the coast of south Devon (e.g., at Bantham Sands) and these are filled with freshwater peat deposits. The overtopping of 'The Bar' may have been responsible for the erosion of peat deposits in the Salcombe–Kingsbridge Estuary palaeovalley, introducing significant quantities of 'old' carbon into the sediments.

In all our sites we find thick minerogenic sequences containing marine microfossils, indicating that barrier systems contained tidal inlets and lagoons before they closed in the later Holocene. Kraft (1971), Kraft and Chrzastowski (1985) and Belknap and Kraft (1977, 1981, 1985) describe a transgressive model of landward barrier movement which can be applied to the back-barrier systems of south Devon (Fig. 9). In this model, the preservation of back-barrier sediments is controlled by the antecedent topography and depth of shoreface erosion. A 'ravinement unconformity' is formed by shoreface erosion which moves landward and upward, thereby destroying the top of the back-barrier sequence. The erosion of old back-barrier peat, as found in North Sands, takes place while the ravinement unconformity moves landward under rapidly rising sea level. Internal reworking occurs in the back-barrier lagoon at the edge of the tidal marsh by wave erosion and within the marsh by creek meandering. The latter processes can explain the 'young' ages at Blackpool Sands.

Conclusions

Fifteen new sea-level index points provide an early to middle Holocene relative sea-level history for the south Devon coast. These data, combined with four previously published index points, show that sea level has risen by 13 ± 5 m between ca. 9000 and 7000 cal. yr BP and 8 ± 1 m in the past 7000 years. The overall RSL rise since 9000 cal. yr BP has been 21 ± 4 m. Anomalous ages of rejected samples are explained by a transgressive model of barrier movement, which includes shoreface erosion during barrier migration and reworking of sediments within back-barrier marsh/lagoon systems. Reliable sea-level index points are best obtained from sedimentary sequences where microfossil analyses show evidence of stratigraphical integrity and continuity.

Geophysical model predictions are in good agreement with sea-level index points between 9000 and 6000 cal. yr BP, but the later part of the Holocene is poorly covered by geological observations. Previous estimates of relative land subsidence based on low-quality late Holocene sea-level data need to be reconciled with geophysical model predictions, the Newlyn tide-gauge data and measurements by GPS and gravity methods. Obtaining new late Holocene sea-level data, covering the past 4000 years, is a priority for future sea-level investigations in southwest England.

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