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Coastal evolution in south-west England, United Kingdom: An enhanced reconstruction using geophysical surveys

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Abstract

The coastline of south Devon, south-west England, is believed to be subsiding faster than any area in the United Kingdom (UK). Current estimates are based however on very limited Holocene relative sea level (RSL) and lithostratigraphic data. There is, therefore, an urgent need for more information to improve our understanding of coastal evolution in the region. Sediment coring from Slapton Sands and Blackpool Sands in south-east Devon provides material for interpreting land- and sea-level changes. Further stratigraphic mapping was carried out using 2D Electrical Resistivity Tomography (ERT) of the near-surface. This method of geophysical survey, ground-truthed with borehole data, has rarely been used for palaeoenvironmental reconstruction but provided useful results here. Models of Holocene coastline evolution, based on those from the Eastern USA, show that sea level in Start Bay was ~17 m below present RSL ca. 9000 cal. yr BP. A barrier–lagoon system was forced landward by seas rising at ~5 m/ka across substrates comprised of weathered slate and shale. Thick deposits of minerogenic fines (~10 m at Slapton Sands) were identified in cores and mapped using the ERT survey method. Barrier-lagoons became choked by sediment when RSL was ~5 m below present at ca. 4400 cal. yr BP and reached their current configuration during the late Holocene. ERT results show that the Slapton Sands modern-day barrier complex is a uniform ~9 m thick for a longshore distance of at least 1.5 km.
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1. Introduction

Few coastal lithostratigraphic studies have been published from south-west England in comparison to the rest of the United Kingdom (Waller and Long, 2003). This is extraordinary given Shennan and Horton's (2002) estimate that the region's coast is the fastest subsiding shoreline in the UK. In addition, the region was also peripheral to the British Ice Sheet at the Last Glacial Maximum (Peltier, 1998) and is therefore a favourable location for the testing of geophysical models (Lambeck, 1995, 1997; Peltier et al., 2002) and forebulge theory (Wingfield, 1995). Holocene sea-level index points (SLIPs) are scarce (Heyworth and Kidson, 1982; Haslett et al., 1997; Waller and Long,

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2003) and few models based on coastal sedimentary surveys exist to explain coastline evolution in the region (Massey, 2004; Chadwick et al., 2005).

Back-barrier sediments along the Channel coast of south-west England contain valuable information about its post-glacial land- and sea-level recovery history (Carr and Blackley, 1973, 1974; Healy, 1993, 1995; Edwards, 2001). A few lithostratigraphic studies from south-east Devon (Fig. 1) have contributed to the regional geological archive (Clarke, 1970; Hails, 1975a,b; Morey, 1976, 1983a,b) but it is clear that there is a lack of high-quality, well-constrained data from the region. For example, Shennan and Horton's (2002) estimate of land subsidence for south Devon (1.23 ± 0.18 mm yr^{-1}) is based on only 5 index points from sediments poorly linked to the reference tide level (Haslett et al., 1997, 1998). There is a need, therefore, for coring projects and other subsurface surveys that provide insight into the nature of south Devon's palaeoenvironments (Massey, 2004) both to improve our local understanding of coastline evolution, and on a larger scale to understand sea-level change and its drivers (Waller and Long, 2003).

Back-barrier sediments may contain fossils indicative of former intertidal environments from which the height of SLIPs can be quantified (Massey et al., 2006a). Suitable material for radiocarbon dating can also be obtained from lithofacies identified in cores thus providing temporal constraints on coastline positions (Heyworth and Kidson, 1982). However, coring in itself is a limited method of data collection for improving our understanding of coastline changes (Massey et al., 2006c). Geophysical surveys, on the other hand, allow greater geographic coverage and should, when coupled with ground-truth data from cores, identify valuable sequences without the need for further extensive, expensive, and time-consuming coring. Electrical resistivity surveying began about 100 yr ago for prospecting purposes in Sweden (Petersson, 1907; Bergström, 1913) and a little later in the USA (Schlumberger, 1920), and there are now several methods available to the surveyor (Dahlin, 2001). For example, 2D Electrical Resistivity Tomography (ERT) of the near-surface is one such method that has been used to good effect in engineering and environmental projects but, until recently (Massey, 2004; Massey et al., 2006c; this project), not in the field of coastline evolution.

The direct current (DC) resistivity field method is based on measuring the potentials between a pair of electrodes while transmitting DC between another electrode pair (Overmeeren and van Ritsema, 1988; Robinson and Coruh, 1988; Dahlin, 2001). Typically, for operational reasons, a low (<10 Hz) frequency alternating current (AC) is substituted for DC. Depth of penetration along the survey run is proportional to electrode spacing in homogenous strata (Bernstone and Dahlin, 1996) thus varying the electrode spacing will provide more or less detail about subsurface stratigraphy (Gish and Rooney, 1925). An interpretation of the field data (the apparent resistivity is the measured quantity of the field survey) (Johansen, 1977) provides a physical model after which the resulting physical parameters can be interpreted geologically (Dahlin, 2001). Two-dimensional electrical resistivity imaging or tomography (ERT) of subsurface sediments is ideally suited to complex surveys (Griffiths and Barker, 1993; Dahlin and Loke, 1998) because it employs computer-controlled multi-electrode data acquisition systems to make significant time-savings during fieldwork. Nonetheless, back-barrier marshes remain challenging environments for any type of resistivity survey method because of the complex interaction of three primary factors: porosity, water saturation, and pore fluid salinity, which together control the measured resistivities (Hallenburg, 1984). Subsurface mapping projects involving the use of ERT must therefore be verified via ground-truth data from cores strategically located along the surveyed profile, to interpret the physical parameters of the resistivity model.

The aim of this paper is, through the provision of additional resistivity survey data from Slapton Sands and Blackpool Sands (Massey et al., 2006c), to further evaluate our understanding of the method for research into coastal evolution. Index points obtained from cores used in the ground-truthing method also provide insight into local Holocene sea-level changes. Finally, models of coastal change, based on those of Kraft and Chrzastowski (1985) originally developed along the eastern seaboard of the USA, are used to further elucidate the Holocene barrier–lagoon history of south-east Devon.

2. Regional setting and study sites

The rias, or drowned river valleys, of south Devon's submerging coastline were fronted by gravel barriers during the early to middle Holocene (Hails, 1975a,b; Morey, 1976; Waller and Long, 2003). Lithofacies and their fossil contents indicative of former barrier–lagoon systems can be found at several sites (Clarke, 1970; Massey, 2004; Chadwick et al., 2005). The back-barrier sediments should ideally record distinctly different electrical resistivities (Massey et al., 2006c) for differing lithofacies. Two coastal back-barrier systems selected here (Fig. 1) comprise variable thicknesses of minerogenic-peat, fines and gravel sediments overlying a hard substrate (Fig. 2). The underlying solid geology is

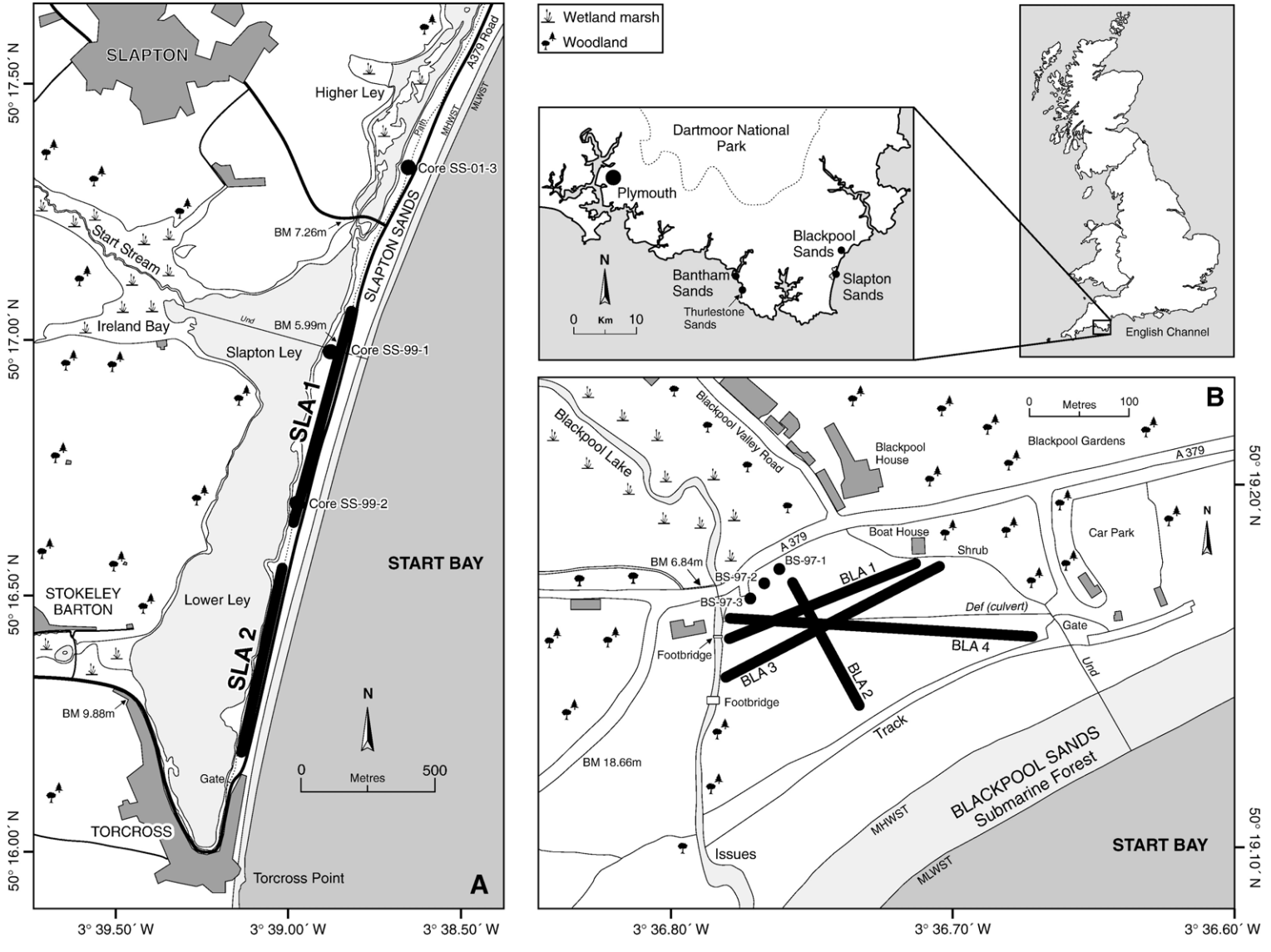


Fig. 1. Coastal back-barrier sites in south-east Devon showing positions of electrical resistivity survey lines and boreholes. Slapton Sands (A); Blackpool Sands (B). ©Crown Copyright/Database right 2006. An Ordnance Survey/EDINA supplied service. Coordinates are Ordnance Survey of Great Britain National Grid System and Latitude and Longitude.

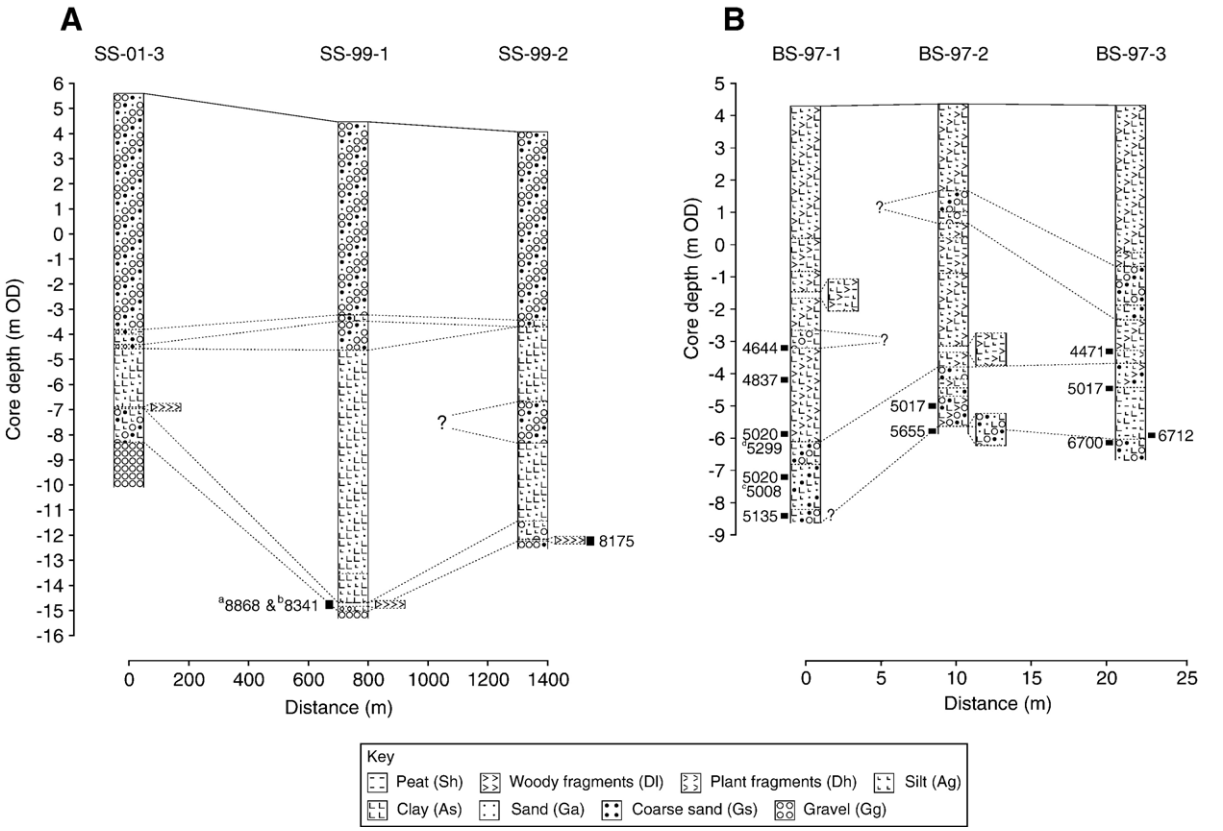


Fig. 2. Lithostratigraphical records from south-east Devon. Slapton Sands (A); Blackpool Sands (B). Linking lines show lithofacies connections where easily observable in core section. Significant units too small (normally <0.25 m) to be shown in section are expanded alongside cores. AMS ^{14}C median ages (of the $\pm 2\sigma$ cal. yr BP range) are shown alongside sample layers. [a]Minerogenic sample; [b]charcoal sample; [c,d]check age determinations (see Table 2 for detailed results).

predominantly Lower Devonian slate and shale (Ussher, 1904). Periglacial material, sand, river gravel and alluvium of the Quaternary are also found in south Devon. The tidal range is ~4.3 m (Hydrographic Office, 2002).

Coring projects carried out in 1997 and 1999 established the potential for a local sea-level study (Massey, 2004). For example, coring at North Sands (50° 13.77′ N, 03° 46.93′ W) and Bantham Sands (50° 16.60′ N, 03° 52.51′ W) revealed bedrock overlain by basal peat, minerogenic fines and freshwater peat deposits. Subsequent electrical resistivity surveys produced encouraging results for mapping the extent of subsurface lithofacies identified in cores (Massey et al., 2006c). Additional data are provided here for Slapton Sands (50° 16.96′ N, 03° 38.80′ W) and Blackpool Sands (50° 19.17′ N, 03° 36.78′ W) (Fig. 1).

Slapton Sands is a 5 km long gravel barrier separating two basins from Start Bay (Fig. 1A). The Higher Ley is a reed swamp and the Lower Ley a shallow freshwater lake. These were formed by the damming of several pre-Holocene valleys (Morey, 1983a) and the site is a wetland National Nature Reserve of 116 ha. The underlying geology consists of slates with some Permian breccia, sandstone and igneous rocks (Ussher, 1904). Boreholes and ERT surveys are situated about 100 m inland from mean high water of spring tides (MHWST), above +4.10 m Ordnance Datum (OD at Newlyn, Cornwall). Mean tide level (MTL) at Slapton Sands is 0.12 m above OD.

Blackpool Sands is a 700 m long extension of the Slapton Sands gravel barrier (Hails, 1975a,b). Grassland, low scrub, and a wooded wetland valley cover a back-barrier area of 2 ha (Fig. 1B). This was the location of a lake during the mid-Holocene but the basin is now filled with organic silts and muds. The local geology comprises slates and grit of the Meadfoot Group, quartzite beds and some igneous rocks (Orme, 1960; Dineley, 1961). Boreholes are situated about 150 m inland from MHWST, around +4.3 m OD. MTL at Blackpool Sands is 0.11 m above OD.

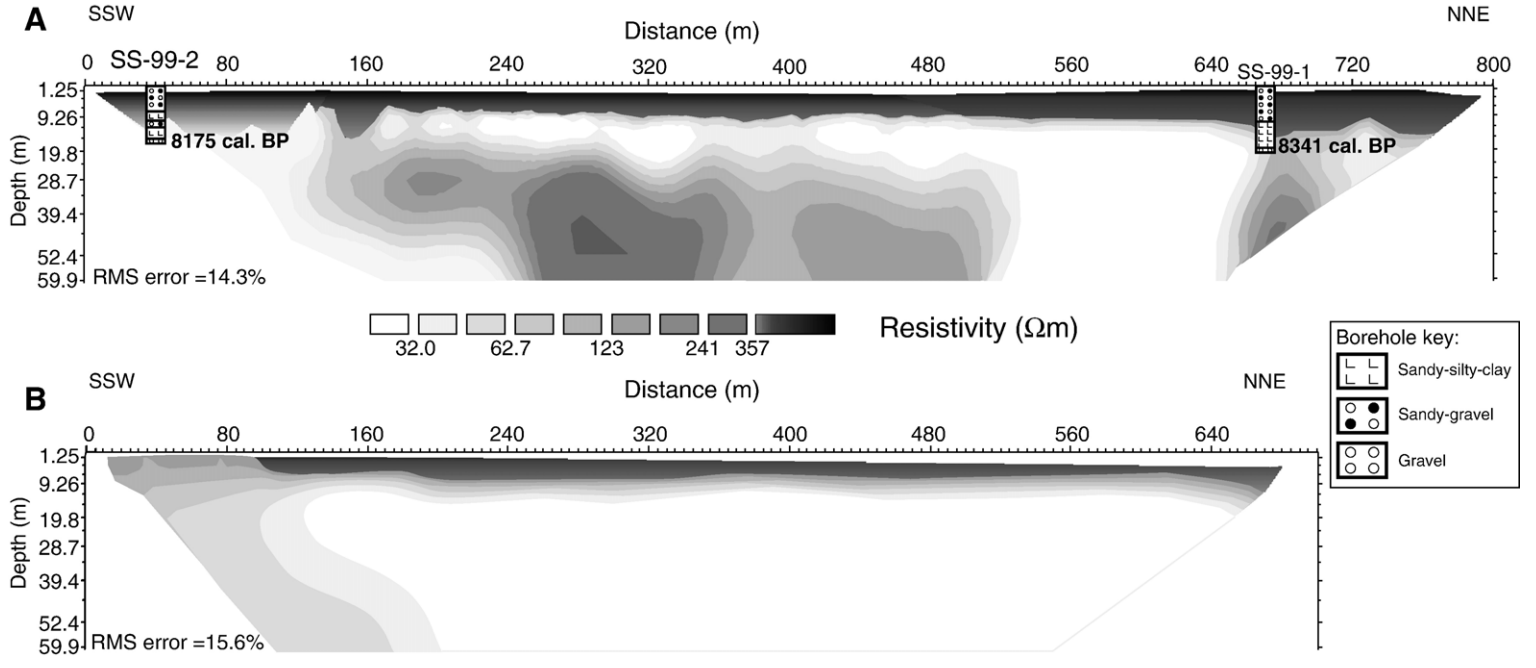


Fig. 3. Electrical resistivity tomography profiles from Slapton Sands. A. Shore-parallel survey (SLA 1) (modified from Massey et al., 2006c). B. Shore-parallel survey (SLA 2).

3. Methods

3.1. Electrical resistivity surveying

Roll-along resistivity surveying was carried out using the multi-electrode method with an ABEM LUND Imaging System. A multi-core cable array was attached to a terrameter and laptop PC (Overmeeren and van Ritsema, 1988; Dahlin, 2001). Total cable runs in this study ranged from 65 m to 800 m (see Figs. 3 and 5). Two shore-parallel, one shore-normal and one shore-diagonal survey were carried out at Blackpool Sands and two shore-parallel surveys at Slapton Sands (Fig. 1). Electrodes were spaced at 5 m intervals along each cable. The centre of the cable spread is usually located over the maximum depth of investigation (~30 m at Slapton Sands) but this is also a function of sediment electrical resistivity (Bernstone and Dahlin, 1996). For example, coastal marshes are highly conductive sites that can reduce the depth of investigation. The laptop PC was used to control the system and record data in the field. Erigraph (ABEM supplied software) and RES2DINV were used to complete on-site data inversion and visualisation of profiles (Loke and Barker, 1996). This proved useful in terms of quality control. Further detailed interpretation of profiles was based on ground-truthing with core records (Massey et al., 2006c).

3.2. Coring and sediment analysis

Core sediments were recovered in 1 m × 76 or 94 mm hard plastic tubes using a non-rotary percussion drilling rig. Partial recovery is common to this type of drilling method (Emery and Dietz, 1941; Richards and Keller, 1961; Rees, 1999) but this did not significantly hinder lithofacies interpretation or the ground-truthing process. A sediment catcher was attached to the base of each section to prevent sediment loss during extraction from the borehole. Compaction of minerogenic fines and peat, and core loss due to sediment de-watering was measured in the field. Some uppermost core sections were not retrieved because they were not crucial to the wider project (Massey, 2004). These sections were described in the field. Cores were placed in cold storage then later opened horizontally to avoid vertical movement of sediment in the tube. Sediments were classified according to Troels-Smith (1955) and lithofacies simplified with TSPPlus (Waller et al., 1995) before plotting onto resistivity profiles.

A geotechnical correction was carried out on two cores from Blackpool Sands using the Paul and Barras (1998) model. Standard techniques (e.g., Terzaghi et al., 1996) were used to calculate autocompaction, i.e. the compression of a sediment sequence by the weight of overlying sediments, to improve the quality of SLIPs (Massey et al., 2006b). Basal sediments are defined as those resting directly on hard rock substrate and are therefore not subject to autocompaction. Lithofacies interpretation was aided by biostratigraphical and chronological analyses (Massey, 2004).

3.3. Surveying

All boreholes and cable arrays were levelled to UK OD from nearby Ordnance Survey (OS) benchmarks using an Electronic Distance Measurer (EDM). Measurements were recorded to the nearest millimetre or 0.001 of a degree, and then used to locate boreholes and resistivity profiles on large-scale OS maps. Positions were confirmed with a hand-held Global Positioning System (GPS). Topographic surveys of the cable runs assisted in the positioning of boreholes onto resistivity profiles. The height of each electrode location was measured on very undulating ground, every 10 m on ground with height changes in the order of ±0.10 m, and at mid-points and cable ends on level ground.

3.4. Foraminiferal analysis

Sampling and analysis of foraminifera follows Scott and Medioli (1980a,b) and Gehrels (2002). Sediment samples of 5 ml were extracted at core intervals of 2–5 cm and 300 foraminifera per 1/8th sample were counted where possible. Sampling was increased to 1 or 2 cm intervals when whole samples contained <50 foraminifera across index point horizons. Foraminiferal taxonomy and generic names follow Murray (1979) and Loeblich and Tappan (1987). Sample indicative meaning, i.e. the height at which a sea-level indicator was deposited in relation to a reference tide level (Shennan, 1983), was calculated with a transfer function that reconstructs palaeowater depths with a precision of ±0.29 m (Massey et al., 2006a).

3.5. Radiocarbon dating

Sampling of cored sediments was carried out according to Gehrels (1999). Detrital plant macrofossils, the preferred material for radiocarbon dating, were not present in most cores so bulk sediment or wood fragments were dated instead. Samples were prepared to graphite at the Natural Environmental Research Council (NERC) Radiocarbon Laboratory in East Kilbride, Scotland, UK. AMS ^{14}C analyses were carried out at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory at the University of California.

Table 1
Electrical resistivity ranges and median values of coastal sediments from south-east Devon (units in Ω m)

Electrical resistivity (Ω m)				
Survey	Basal gravel	Minerogenic fines	Gravel infill	Gravel barrier
BLA 1	50–250	≤79	~50	No data
BLA 2	55–100	≤55	<78	No data
BLA 3	50–160	≤79	<160	No data
BLA 4	50–160	≤79	<160	No data
SLA 1	≤32	≤100	No data	46–1500
SLA 2	79–320	≤79	No data	50–320
Range (Ω m)	<320	≤100	<160	46–1500
Median value (Ω m)	160	50	80	727

Basal gravel is local weathered bedrock. Minerogenic fines are sand, silt and clay. Gravel infill includes gravel, sand and mud. Gravel barrier data is the >2 mm fraction from Slapton Sands only. Surveys BLA 1 and SLA 1 are based on the ground-truthing method. Surveys BLA 2, BLA 3, BLA 4 and SLA 2 are interpolated from nearby borehole records.

Calibrations follow Stuiver et al. (1998) using standard Calib 4.2 (c.f. Stuiver and Reimer, 1993). Median ages are shown alongside cores.

4. Results

While we are aware that temporal disturbances in groundwater conditions can and do cause significant variation in resistivity surveys the results reported herein were acquired during a two year long campaign during which five sites were studied and we found remarkably little variation except under extreme surface conditions. Our main concerns at the outset of the study were the potential that saline invasion may have had on our depth of investigation and the ability to discriminate between rock and sediment but both fears proved groundless. At one site we have conducted surveys over a five year period at various seasons, although not high summer, and have found the results to be remarkably consistent.

4.1. Slapton Sands

4.1.1. Lithostratigraphy

Slate bedrock reaches about −8 m OD in the Higher Ley (core SS-01-3) and varies between −15 and −12 m OD in the Lower Ley (Fig. 2A). A thin basal wood-peat rests on top of the underlying fractured slates. Basal lithofacies in the Higher Ley also contains red silty-sandy clay and gravel to −7 m OD. The minerogenic phase is dominated by clay to −4 m OD but very coarse gravel units occur between −8.5 and −4.5 m OD. The gravel barrier sequence begins around −3.5 m OD and is covered by a very thin layer of herbaceous peat and topsoil.

4.1.2. Electrical resistivity surveys

SLA 1 (Fig. 3A) is situated to the east of Ireland Bay, extending 800 m along the Lower Ley shore (Fig. 1A). Cores SS-99-1 and SS-99-2 are located 41 and 5.5 m west of SLA 1, respectively. The depth to the bedrock surface is uncertain, with deeper resistivities showing wide variation (<32 to >1500 Ω m) and masked by a large anomaly of uncertain origin (220–1500 Ω m) beginning at 160 m. In the upper part of the section resistivity values >68 Ω m along the length of the profile coincide with a gravel facies in core SS-99-2. Near-surface tomography of the modern gravel barrier is very clear (>63 Ω m above −5 m OD/9 m in the section). No ERT survey was carried out in the Higher Ley but core SS-01-3 shows the barrier to be of continuous thickness and the bedrock surface to have risen around 7 m (Fig. 2A).

SLA 2 (Fig. 3B) extends 700 m from Torcross along the Lower Ley shore (Fig. 1A). It is ~180 m SSW of SLA 1 and barrier ground surface height falls by 0.6 m. The bedrock surface is again unclear, and must correspond to very low resistivity values, perhaps as a result of saline water intrusion. The modern gravel barrier is again a very distinct layer of ~7–8 m thickness (−3 m OD) with resistivities >63 Ω m (Table 1). This coincides with the contact between barrier gravel and minerogenic fines in core SS-99-2. Marked undulations in this well defined layer on both profiles may reflect former channels or breaks in the barrier itself, e.g., at 150 m on SLA 1 (Fig. 3A).

4.1.3. Foraminifera and palaeoenvironments

Basal sediments from core SS-99-1 contain a few calcareous foraminifera. Agglutinated foraminifera dominate overlying sediments (Fig. 4A). Significant numbers occur above 19.25 m (SLIPs 14 and 15) (Table 2) above which agglutinated species decline and calcareous foraminifera increase. Low numbers of agglutinated foraminifera occur at 16.25 m in core SS-99-2 (SLIP 16) (Table 2) above which calcareous foraminifera increase in dominance (Fig. 4B). Assemblages from Slapton Sands basal lithofacies suggest a gradual change from salt marsh to mudflat conditions.

4.1.4. Chronology of lithofacies

Basal lithofacies along SLA 1 date to 9000–8000 cal. yr BP (Fig. 3A). Basal minerogenic sediment from core SS-99-1 is ca. 8850 cal. yr old and charcoal extracted from the same sample is ca. 8350 cal. yr old (Table 2). Basal sediments from core SS-01-3 were not dated.

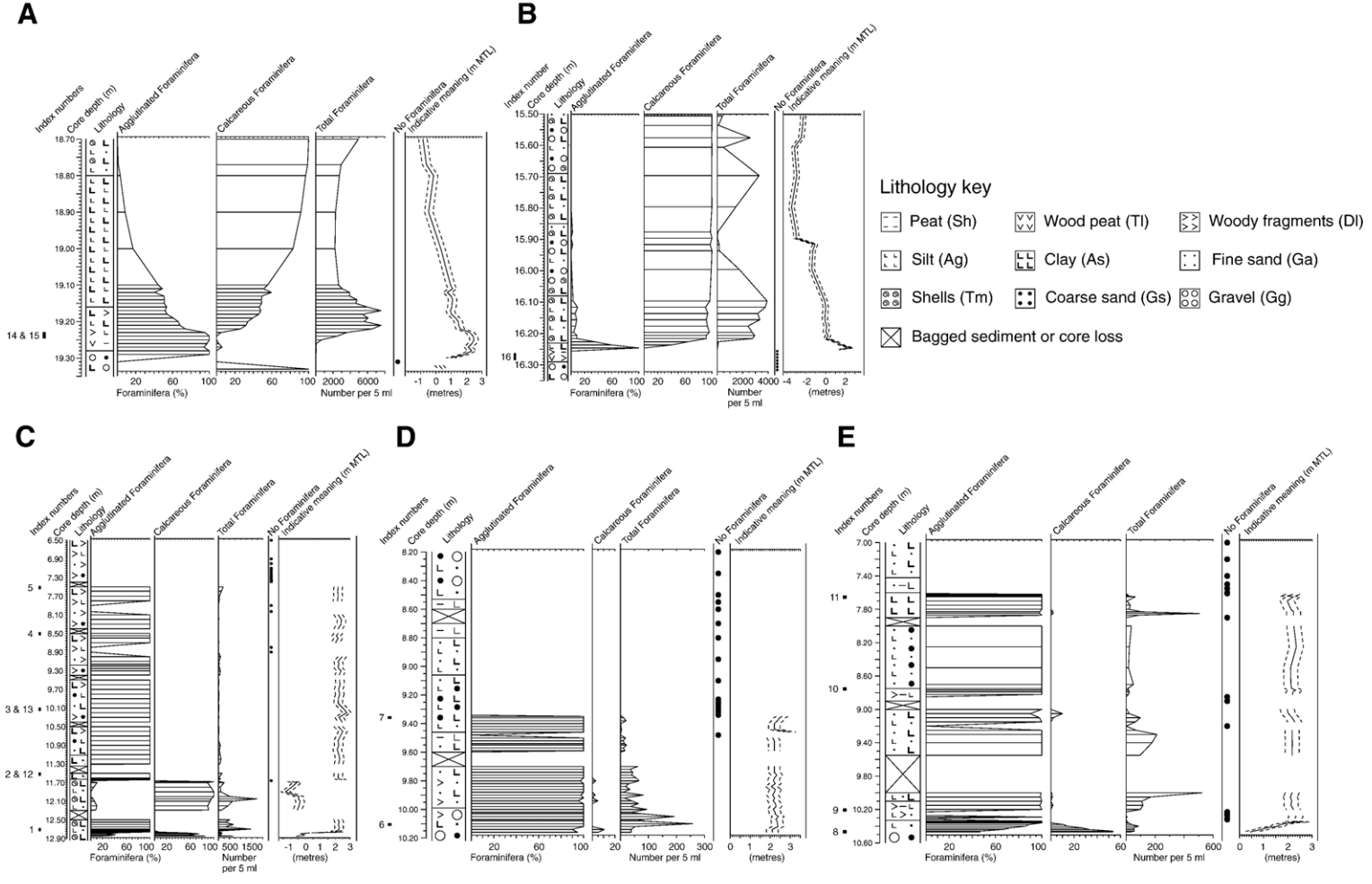


Fig. 4. Foraminifera totals and indicative meaning from Slapton Sands core SS-99-1 (A); core SS-99-2 (B); and Blackpool Sands core BS-97-1 (C); core BS-97-2 (D); core BS-97-3 (E).

The uppermost (barrier contact) lithofacies was not dated but Morey (1976, 1983a) estimates the contact to be ca. 3200–2850 cal. yr old.

4.2. Blackpool Sands

4.2.1. Lithostratigraphy

Basal sediments comprise fractured slate, fines and gravel below −6 m OD (Fig. 2B). Remnants of a basal minerogenic wood-peat are present in cores BS-97-2 and BS-97-3 but core BS-97-1 contains blue-grey fines, shells and some wood fragments at its base. The overlying minerogenic sediment is predominantly sandy-clayey-silt and coarse gravel. Fine and gravel lithofacies contain thin layers of humified wood-peat. No pure organic phase is present; instead lithofacies from around OD are mostly infill (glass shard at +1.1 m OD in core BS-97-2) of sandy-silty-clay and gravel to roughly +4.3 m OD. Sediments at ground level are peat and topsoil.

Autocompaction in core BS-97-2 increases from 0.02 m at 10.10 m core depth to 0.21 m at 9.36 m core depth (SLIPs 6 and 7) (Table 2). Sediments overlying those at the base of core BS-97-3 have been displaced 0.04–0.08 m but values increase significantly to 0.35 m at 8.76 m core depth and 0.49 m at 7.66 m core depth (SLIPs 8–11). Autocompaction was not calculated in core BS-97-1 because some sedimentary units may have been reworked (Massey, 2004; Massey et al., 2006b). Index points 1–5, 12 and 13 (Table 2) should therefore plot higher than their current position (Fig. 8).

4.2.2. Electrical resistivity surveys

BLA 1 (shore-parallel survey) (Fig. 5A) is 105 m long and positioned about 25 m SE of the boreholes (Fig. 1B). Cores were extracted about 10 m south of the A379 road in a physically restricted part (<100 m width) of the back-barrier, and hence this limited the depth of investigation of the ERT survey. Cores are therefore positioned relative to BLA 1 (Fig. 5A). Basal gravel in core BS-97-3 corresponds to relatively high resistivity (~130–160 Ω m). The survey profiles a basin low in which core BS-97-1 is located and basal fines and gravel have resistivities of 100–250 Ω m. Basal fines and organics in core BS-97-2 correspond to resistivities of 79–160 Ω m while the overlying fines and gravel have values of 50–160 Ω m. Minerogenic-peat facies are ≤79 Ω m (Table 1).

BLA 2 (shore-normal survey) (Fig. 5B) is 65 m long between the barrier track and core BS-97-1 (Fig. 1B). The bedrock surface, as imaged electrically (>100 Ω m), slopes seaward. The maximum depth of investigation (around −4 m OD) occurs prior to a possible rock lip (a rise in bedrock topography located at the 0 m distance point along the profile). This lies below a thick sequence of probable minerogenic-peat (≤55 Ω m) and gravel infill (<78 Ω m). BLA 2 was hampered by the available distance between the barrier and a road but near-surface tomography is very clear in the centre of the profile.

BLA 3 (shore-parallel survey) (Fig. 5C) extends 125 m from Blackpool Lake to an area restricted by low shrubs (Fig. 1B). The bedrock surface has resistivity values of ~160 Ω m and is most likely overlain by minerogenic-peat and gravel (50–160 Ω m). A thick layer of probable minerogenic-peat (≤79 Ω m) is overlain by gravel infill recording up to 160 Ω m at ground level (Table 1). This gravel infill is well-imaged extending from the car park entrance diagonally across the back-barrier surface.

BLA 4 (shore-diagonal survey) (Fig. 5D) extends 125 m from Blackpool Lake to a car park entrance (Fig. 1B). The bedrock surface (~160 Ω m) and gravel lithofacies (<50 Ω m) slope eastward from Blackpool Lake. A possible rock lip (<100 Ω m) is situated below the gravel barrier about 20 m east along the profile (Fig. 5D). The overlying minerogenic-peat (≤79 Ω m) is covered by gravel infill (<160 Ω m) at the eastern end of the profile (which, here, is actually modern aggregate laid down at the entrance to a car park).

4.2.3. Foraminifera and palaeoenvironments

Calcareous foraminifera dominate basal sediments in core BS-97-1 (Index point 1) (Table 2). Agglutinated species dominate above 12.77 m (Fig. 4C). A sudden change to a primarily calcareous assemblage at 12.30 m is followed by a further abrupt change to an agglutinated assemblage at 11.65 m and continues to 7.50 m (Index points 2–5, 12 and 13) (Fig. 4C). Basal sediments in core BS-97-2 are dominated almost entirely by agglutinated foraminifera (SLIPs 6 and 7) (Table 2). No foraminifera are present above 9.35 m (Fig. 4D). A change from calcareous (SLIP 8) to agglutinated assemblages (SLIPs 9–11) occurs at the base of core BS-97-3 and continues to 7.60 m (Fig. 4E). In general, assemblages from Blackpool Sands core sediments suggest short lived basal mudflat or low marsh conditions and well-established overlying salt-marsh environments.

4.2.4. Chronology of lithofacies

Basal lithofacies along BLA 1 date to 6800–5000 cal. yr BP (Fig. 5A). The uppermost intertidal sediments are 5300–4400 cal. yr old (Fig. 2B). Above and below the gravelly unit in core BS-97-1 (~−7 to −6 m OD) samples are separated by 1.4 m of sediment but ages are identical (5020 cal. yr BP) (Table 2). Later analyses

Table 2
Radiocarbon and associated lithofacies data from coastal back-barriers in south-east Devon

Index number	Lithofacies description (Troels-Smith, 1955)	Material dated	Radiocarbon laboratory number	^{14}C age (yr BP±1σ range)	Cal. age (yr BP±2σ range)			Sample height (m OD)	Numbers of Foraminifera		Indicative meaning (±0.29 m MTL)	Geotechnical correction for autocompaction (m) (Type)	Altitude (±0.29 m RSL)
					Max	(Median)	Min		Agglutinated	Calcareous			
1	As2, Ag1, Ga1, Gs++, Gg++, Dh+, Dl+, Dg+	Wood	CAMS-75520	4510±40	5310	(5135)	4980	−8.42	1452	0	+2.25	No data (B)	−10.78
2	Ga2, Ag1, As1, Gs++, Dl++, Gg++, Dh+	Wood	CAMS-75521	4410±40	5274	(5020)	4864	−7.23	162	0	+2.21	No data (I)	−9.55
3	Ag2, Ga1, As1, Gs++, Gg++, Dh++, Dl++, Dg++	Wood	CAMS-75522	4410±40	5274	(5020)	4864	−5.84	26	0	+2.52	No data (I)	−8.46
4	As2, Ag2, Ga++, Dh++, Dl++, Dg++, Th++	Wood	CAMS-75523	4270±40	4869	(4837)	4664	−4.22	4	0	+2.20	No data (I)	−6.53
5	Ag2, As2, Ga++, Gs++, Dl++, Dh+	Minerogenic	CAMS-75524	4140±40	4828	(4644)	4526	−3.23	212	0	+2.20	No data (I)	−5.54
6	Gg2, Ga1, Gs1, As++, Ag++, Dl+, Dh+	Wood	CAMS-75525	4940±40	5834	(5655)	5595	−5.74	258	0	+2.36	0.02 (B)	−8.19
7	Gg2, Ag1, As1, Gs++, Ga++, Sh++, Dh++, Dl++	Minerogenic	CAMS-75526	4420±40	5278	(5017)	4866	−5.00	4	0	+2.46	0.21 (I)	−7.36
8	Gg2, Gs1, Ga1, As++, Ag++	Wood	CAMS-75527	5880±40	6795	(6700)	6571	−6.15	26	30	+0.51	0.00 (B)	−6.77
9	Ag2, As1, Sh1, Ga++, Dh++, Dl++, Dg++, Tl++, Gg+, Gs+	Minerogenic	CAMS-75528	5850±40	6776	(6712)	6549	−5.89	98	0	+2.23	0.08 (I)	−8.15
10	Gs2, Ga1, Ag1, As++, Dh++, Dl++, Gg+	Wood	CAMS-75529	4420±40	5278	(5017)	4866	−4.44	12	0	+2.16	0.35 (I)	−6.35
11	Ag2, As2, Ga++, Dh+, Sh+	Minerogenic	CAMS-75530	4020±40	4775	(4471)	4412	−3.34	64	0	+2.22	0.49 (I)	−5.18
12	Ga2, Ag1, As1, Gs++, Dl++, Gg++, Dh+	Wood	AA-54118	[c]4438±42	5286	(5008)	4868	−7.23	162	0	+2.21	No data (I)	−9.55
13	Ag2, Ga1, As1, Gs++, Gg++, Dh++, Dl++, Dg++	Wood	AA-54119	[d]4556±43	5441	(5299)	5047	−5.84	26	0	+2.52	No data (I)	−8.46
14	As2, Ag2, Dl++, Gg++, Dg+, Gs+	[a]Minerogenic	CAMS-72401	7980±50	9011	(8868)	8613	−14.77	2464	0	+2.43	0.00 (B)	−17.31
15	As2, Ag2, Dl++, Gg++, Dg+, Gs+	[b]Charcoal	CAMS-72402	7500±40	8387	(8341)	8183	−14.77	2464	0	+2.43	0.00 (B)	−17.31
16	Gg3, Ag1, Gs++, Ga++, Dl++, Dh+	Wood (*Alnus*)	CAMS-75531	7370±40	8325	(8175)	8036	−12.21	10	0	+2.45	0.00 (B)	−14.78
17	Submerged forest	Wood	SRR-318	2541±67	2776	(2729)	2358	+1 to −1	Wood		No data	No data (I)	−3.06±0.75
18	Top of peat facies	Plant (*Carex*)	SRR-492	1813±40	1864	(1716)	1613	−0.19	Pollen		No data	No data (I)	−2.16±0.56
19	Base of peat facies	Plant (*Carex*)	SRR-493	2889±50	3207	(2996)	2868	−1.79	Pollen		No data	No data (I)	−4.06±0.27

Index numbers 1–13: Blackpool Sands (50° 19.17′ N, 03° 36.78′ W); index numbers 14–16: Slapton Sands (50° 16.96′ N, 03° 38.80′ W); minerogenic samples are bulk sediment; [a]minerogenic fines and [b]charcoal separated from the same sample; [c]check age determination for index number 2; [d]check age determination for index number 3; type: B = basal; I = in-core; RSL: Relative Sea Level. Altitude (m RSL) is calculated according to Gehrels (1999). Data for index points 17–19 were obtained from Morey (1974, 1976, 1980, 1983a).

produced ages that overlap at 2σ (Massey, 2004) suggesting that this deposit is the result of rapid sediment accumulation in one or more short lived events.

5. Interpretation and discussion

This project has contributed valuable further subsurface information to the coastal geological archive of south-west England, a region currently in need of more data to reconstruct land- and sea-level movements (Shennan, 1989; Shennan and Horton, 2002; Waller and Long, 2003; Massey et al., 2006b). Previously, Clarke (1970), Hails (1975a,b), and Morey (1976, 1983a,b) were amongst very few early contributors of coastal sedimentary core records to the region's geological database but coastal projects often tend to rely on only a few cores (e.g., Crabtree and Round, 1967; Gehrels and Massey, 2004) to reconstruct past coastline shape and form. The remaining subsurface geometry is usually therefore interpolated by correlation between lithofacies, a method that is clearly subject to some error (e.g., Fig. 2A). Geophysical survey methods such as ERT of near-surface sediments can help remedy this problem (e.g., Figs. 3 and 5).

Results from ERT surveys of back-barrier marsh sites can be exceptionally useful despite variation in controlling factors such as water saturation and porosity (Hallenburg, 1984; Massey et al., 2006c). For example, an enlarged end-view of a shore-normal ERT profile taken at Bantham Sands (50° 16.60′ N, 03° 52.51′ W) (Fig. 1) in south-west Devon shows an increasing resistivity from ground level to basal strata (Fig. 6) (Massey, 2004). Weathered basal gravel have values of 50–63 Ω m (lithified rock is therefore >63 Ω m), minerogenic fines are generally <63 Ω m and peat is ≤40 Ω m. An interesting feature identified by near-surface tomography of the site is an 'intrusion' (in the range ~32–50 Ω m) which corresponds to a sand and gravel layer below peat and above fines in the upper core record (~0 m OD), stretching >100 m from Bantham sand dunes into the back-barrier marsh (Fig. 6). This feature reveals the possible extent of a middle- to late Holocene sand and gravel overwash fan. Such features have been mapped by Morey (1983a) at Slapton Ley, showing that overtopping of barriers was widespread along south Devon's coastline at that time.

5.1. Slapton Sands

The narrow, ~5 km long, Slapton Sands barrier presented a considerable challenge to ERT surveying because of factors identified by Massey et al. (2006c), specifically (i) high porosity, (ii) permeability, and (iii) unsaturated near-surface sediments. For example, SLA 2 has produced similar anomalies to SLA 1 (Fig. 3) and high salinity levels in sediments may have influenced results (Hallenburg, 1984) at the time of survey. Resistivity patterns from other local back-barrier sites that contained surface streams and drainage channels showed similar interference in cross-section (Massey et al., 2006c) but basal strata and basin shape were generally clearly discernible from the surrounding 'noise'. In contrast, ground-truthing of SLA 1 showed this not to be the case (Fig. 3A). However, Slapton Sands differs from its neighbouring coastal systems because it comprises a ~9 m thick porous gravel barrier, overlying large sections of porous bedrock (e.g., >1 m weathered basal section in core SS-01-3) (Fig. 2A), and separates an extensive back-barrier freshwater lake from the open sea (Fig. 1A). The interplay of these geographical factors is therefore likely to play an important role in the quality of results achievable with this type of survey. It is possible that a faulty electrode contact affected the quality of results at the time of survey (Massey et al., 2006c) but SLA 1 and SLA 2 were completed at different times so environmental factors discussed above cannot be ignored.

The contact between basal gravels (<320 Ω m) (Table 1) and minerogenic fines (<100 Ω m) is not easy to distinguish because of the basal anomalies along SLA 1 and 2 (Fig. 3) but similar ages to this event (ca. 9000–8000 cal. yr BP) (Table 2) have been recorded in other cores from Start Bay (e.g., Clarke, 1970; Hails, 1975a). In field examples from Dahlin (1996), Auken and Christiansen (2004), and Christiansen and Auken (2004) pre-inversion filtering of raw data was used to eradicate near-surface heterogeneities and identify more clearly the accumulated thickness of clay layers for hydrogeological investigations. Given the occurrence of thick layers of minerogenic fines identified at Slapton Sands a similar method of 'noise' reduction is deemed useful in future studies (see Ritz et al., 1999). Some surveys have also benefited from ground-truthing with a considerably greater number of cores than used in this study e.g., 10 cores along a 250 m transect (Christiansen and Auken, 2004), a technique that more reliably identifies the best model to use from different inversion methods. Despite the 'noise' apparent in this survey, the contact between minerogenic fines and the gravel barrier at ~4 m OD (~100 Ω m) is a precise match with core records (Fig. 2) and results show the gravel barrier (≤1500 Ω m) to be an almost uniform 8–9 m depth along 1500 m of the survey profile (Fig. 3). SLA 2 therefore confirms that, whilst bedrock depth has not been reliably identified, the 1500 m ERT survey has successfully corroborated the depth and profile of the gravel barrier.

5.2. Blackpool Sands

Results from the back-barrier system at Blackpool Sands (Fig. 5) are in complete contrast to those at Slapton Sands. The considerably smaller system has been infilled with organic silts and mud since ca. 4400 cal. yr BP and is no longer dominated by near-surface waterlogged sediments of variable nature, multiple fluvial channels or a back-barrier freshwater lake. This has resulted in ERT surveys of greater clarity, although lithofacies from cores BS-97-1, 2 and 3 are more complex than those recovered from Slapton Sands (Fig. 2). The weathered basal slates and shales of Blackpool Sands (6800–5000 cal. yr BP) are in the range 50–250 Ω m (Table 1), and are more variable but nonetheless lower resistivity than the solid Pleistocene geology of the site (Fig. 5A), a finding in agreement with that of Dahlin et al. (1996) in Sweden. Distinguishing between the resistivity of thinner overlying and intercalated lithofacies is more challenging at Blackpool Sands. For example, a known limitation of 2D smooth inversion, e.g., RES2DINV (Loke and Barker, 1996), is its inability to differentiate sharp layer interfaces (Wisén et al., 2005). This problem has been resolved to some extent by the approach of Auken and Christiansen (2004), in which they used laterally constrained inversion (LCI) and 2D smooth inversion

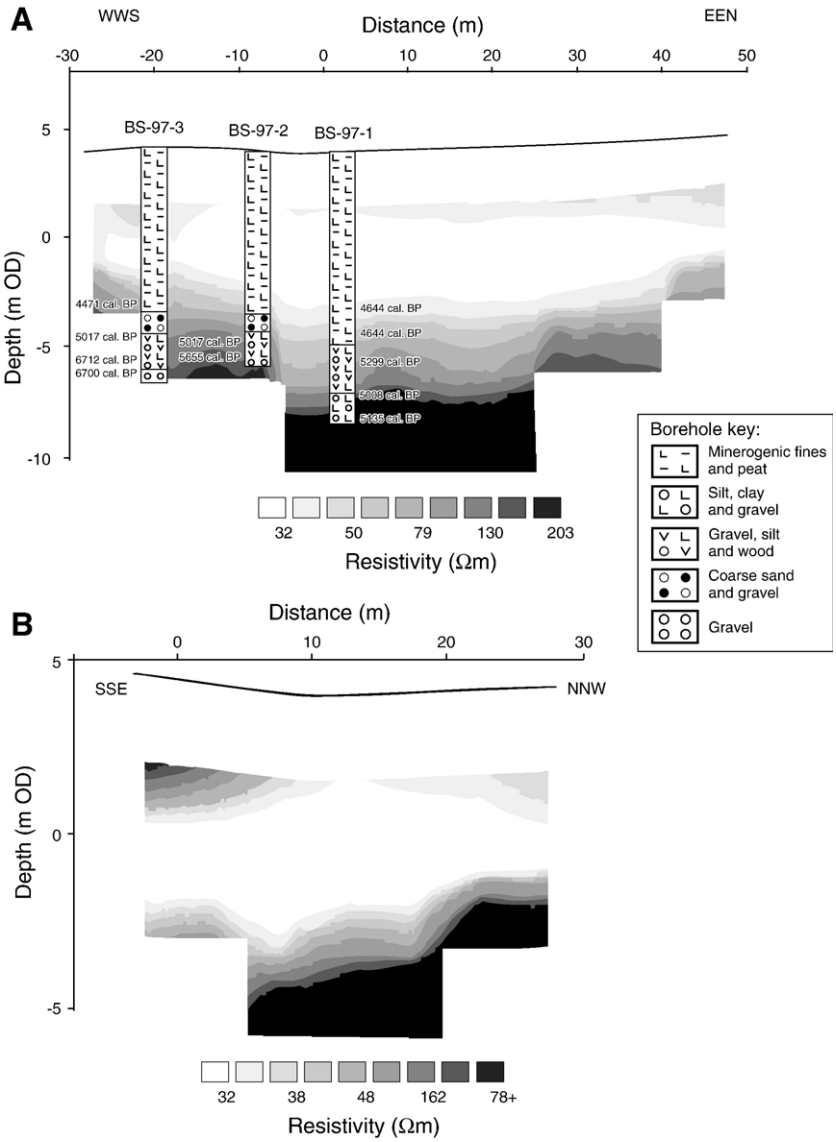


Fig. 5. Electrical resistivity tomography profiles from Blackpool Sands. A. Shore-parallel survey (BLA 1*). B. Shore-normal survey (BLA 2*). C. Shore-parallel survey (BLA 3). D. Shore-diagonal survey (BLA 4) (* modified from Massey et al., 2006c).

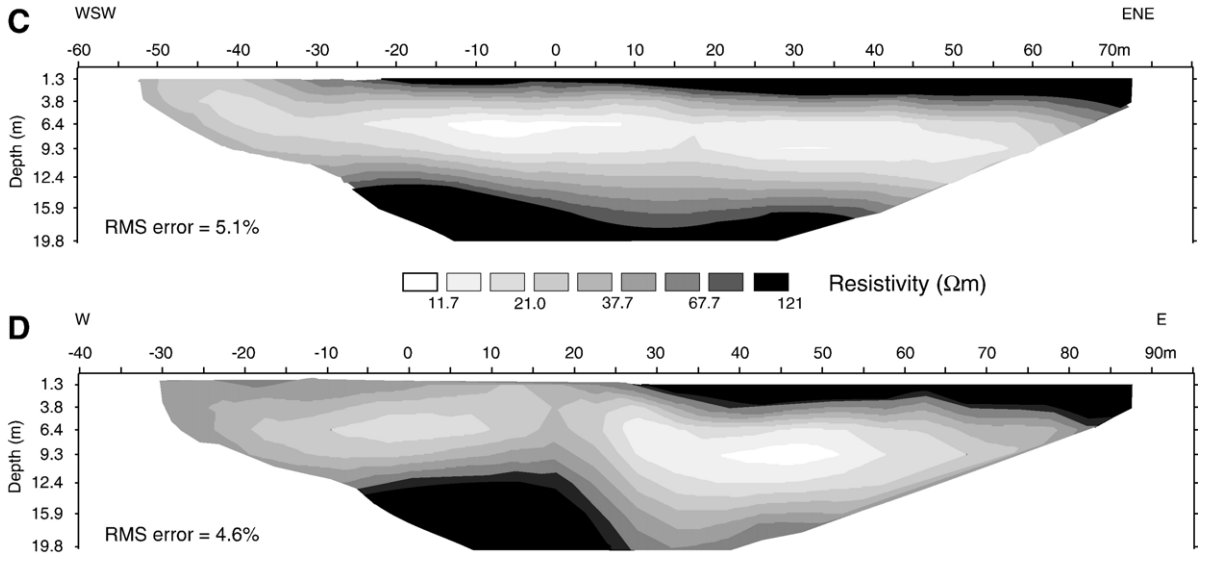


Fig. 5 (*continued*).

with ground-truthing from borehole data to good effect (Wisén et al., 2005). Given the complicated nature of subsurface sediments found at coastal sites around south Devon (Massey et al., 2006b) this approach is recommended for future back-barrier ERT surveys in this area.

Surveys at Blackpool Sands were successful in differentiating between the layers of surface aggregate, including infill (e.g., track across the barrier and car park) (Fig. 1B), underlying fines and basal strata (Fig. 5B–D). These findings may also provide further evidence that differentiating subsurface sharp layer interfaces along Slapton Sands was hindered by high porosity and conductive saline layers not present in the Blackpool Sands sediments. Furthermore, although overwash events have occurred at Blackpool Sands (Morey, 1974, 1976) such layers are not clearly represented in ERT of the near-surface (e.g., Fig. 5B). Overwash fans may be resting on or above weathered basal gravel and therefore indistinguishable from the resistivity of minerogenic fines. Further surveys along and normal to the barrier should resolve this issue.

5.3. Coastline and sea-level changes in south-east Devon

Coastal palaeochannels acted as tidal inlets for the Slapton Sands early Holocene barrier–lagoon system

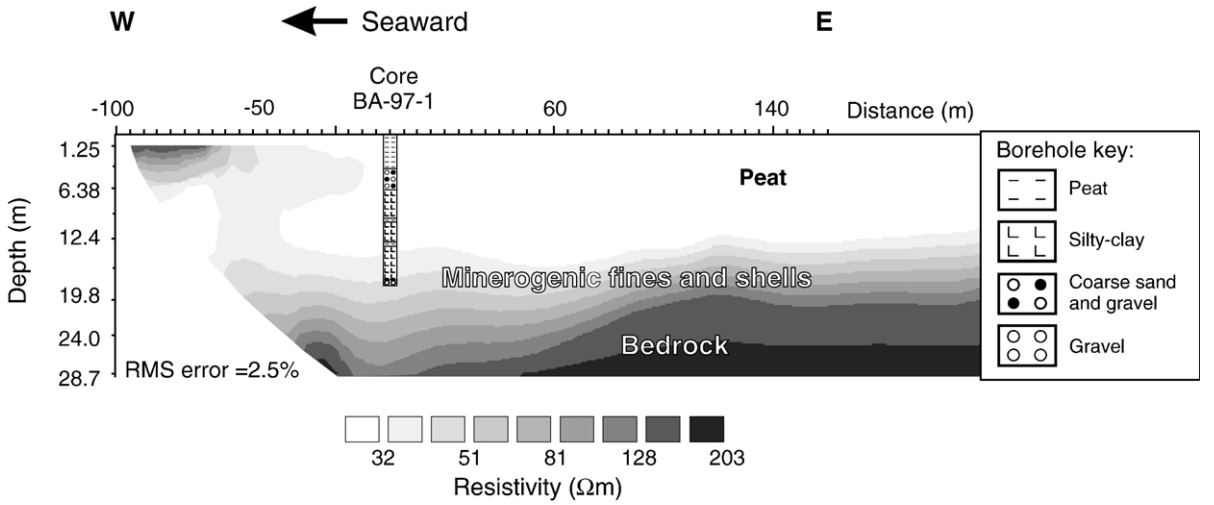


Fig. 6. Enlarged view of a shore-normal ERT survey (end section) carried out at Bantham Sands in south-west Devon (50° 16.60′ N, 03° 52.51′ W) (Fig. 1).

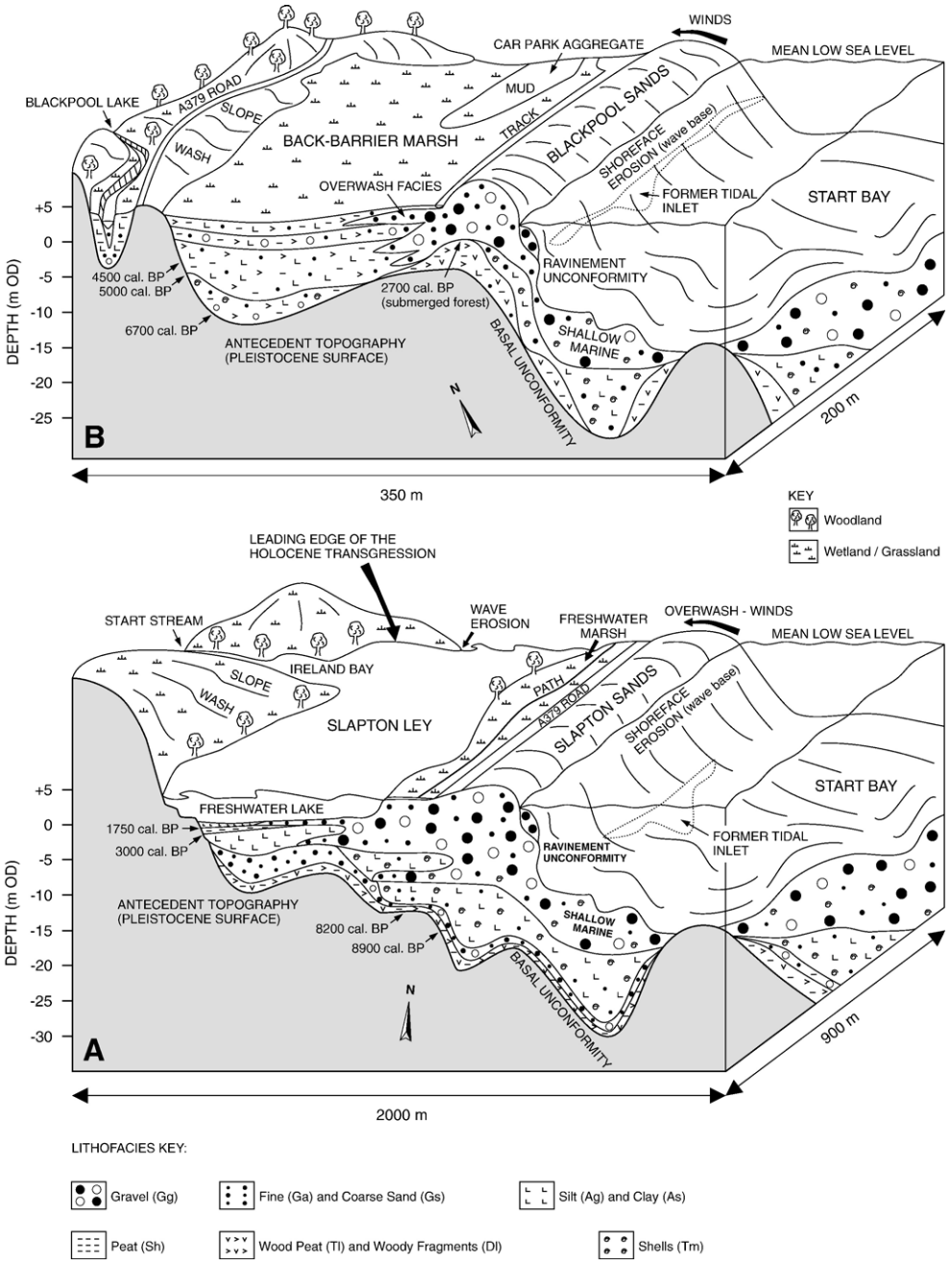


Fig. 7. Illustrations of tentative coastal depositional histories in south-east Devon. Slapton Sands (A); Blackpool Sands (B). Back-barrier lithofacies interpreted from borehole and ERT survey results. Selected AMS ^{14}C ages are positioned approximately. Radiocarbon age of submerged forest (Morey, 1974) and Slapton Ley sediments (Morey, 1976, 1983a) are discussed in the text. Lithofacies key follows Troels-Smith (1955).

(Clarke, 1970; Hails 1975a,b; Kelland, 1975) (Fig. 7). Basal lithofacies reveal a marginally marine coastline at −14.8 m OD (−17.3 m RSL) ca. 9000–8200 cal. yr BP (Figs. 4A, 7A and 8) and a fully intertidal one at −12.2 m OD (−14.8 m RSL) by ca. 8300 cal. yr BP (Fig. 4B) (Table 2). The marine transgression had reached Blackpool Sands at −6.2 m OD by 6800 cal. yr BP (Figs. 4E, 7B and 8). However, ERT surveys reveal deeper minerogenic sequences that may be earlier intertidal lithofacies. Furthermore, Clarke (1970) dated similar offshore basal facies from Torbay ca. 9500 yr BP at −25.2 m RSL and also mapped submerged cliffs at −40.2 m MSL, the approximate depth of a similar Late Quaternary/early Holocene feature identified in Start Bay by Hails

(1975a,b) and Kelland (1975). This is evidence of a still-stand in sea-level rise that was followed by rapidly rising RSL (~5 m/ka) regimes in the early Holocene causing dramatic changes in (barrier) shoreline position (Healy, 1995).

The early Holocene marine transgression of south-east Devon is best described in terms of models developed for the eastern coast of USA where the preservation of back-barrier sediments was controlled by the antecedent topography and depth of shoreface erosion (e.g., Belknap and Kraft, 1981; Kraft and Chrzastowski, 1985; Belknap, 1991; Barnhardt et al., 1997). The ravinement unconformity moves landward and upward, thereby destroying the top of the back-barrier sequence. The best preservation of coastal back-barrier sediments is usually found in palaeo-channels but some basal sediment reworking occurred while the ravinement unconformity formed under rising sea level and landward barrier movement (Massey, 2004; Massey et al., 2006b), and at the edge of the back-barrier tidal marsh (Figs. 4C and 7A).

Infilling of tidal inlets and back-barrier lakes began during the middle Holocene slow-down of sea-level rise (~1 m/ka) (Figs. 4C–E, 7 and 8). Saline lagoons rapidly changed to freshwater systems (Fig. 2A) (Hails, 1975a,b) but back-barrier minerogenic salt marsh existed at Blackpool Sands prior to barrier closure (between −6 and −5 m RSL) (Massey, 2004). The Slapton Sands barrier–lagoon system was probably discontinuous until ca. 3000 cal. yr BP (Morey, 1976) by which time many of the Quaternary valley mouths were dammed by shingle and subsequently filled with fines and muds, e.g., Blackpool Sands (Morey, 1976, 1983b) (Figs. 2 and 5). The transition from open to closed (saline to freshwater) barrier–lagoon coastline is a critical phase in the evolution of Slapton Sands (Chadwick et al., 2005). This probably occurred when the average rate of sea-level rise slowed to <3 m/ka. Freshwater lagoon deposits (e.g., *gyttja*) and terrestrial sediments found in upper lithofacies from Slapton Sands confirm this. Furthermore, overwash fans (Figs. 2A and 6) indicate some cross-barrier sediment transfer (Morey, 1983b) and net shoreface erosion probably resulted in the formation of a headland beach (e.g., Kraft, 1979; Kraft and Chrzastowski, 1985) at some sites in south Devon. Barrier closure at Blackpool Sands appears to have occurred at least 1400 yr earlier than Slapton Sands (Morey, 1976, 1983b; Massey, 2004; Chadwick et al., 2005).

The rate of sea-level rise continued to decline during the late Holocene (Massey, 2004). Data from Morey (1974, 1976, 1983a), however, suggest a slight increase to ~1.3 m/ka (Fig. 8) (Table 2). Index points from submerged forests and lake sediments may provide an upper limit for sea level at the time but numbers 17–19 (Table 2) have no brackish or marine provenance; thus, their link with former sea levels is tenuous (Haslett et al., 1997, 1998). Potential late Holocene intertidal samples have been obtained locally. Taylor (unpublished data) found salt-marsh foraminifera at ~1.45 m core depth (~+0.45 m OD) in undisturbed back-barrier sediments at Thurlestone Sands (Fig. 1), but radiocarbon dating was not carried out in the study. Therefore, south Devon's back-barrier marshes may provide valuable additional late Holocene SLIPs for the region. As local smaller

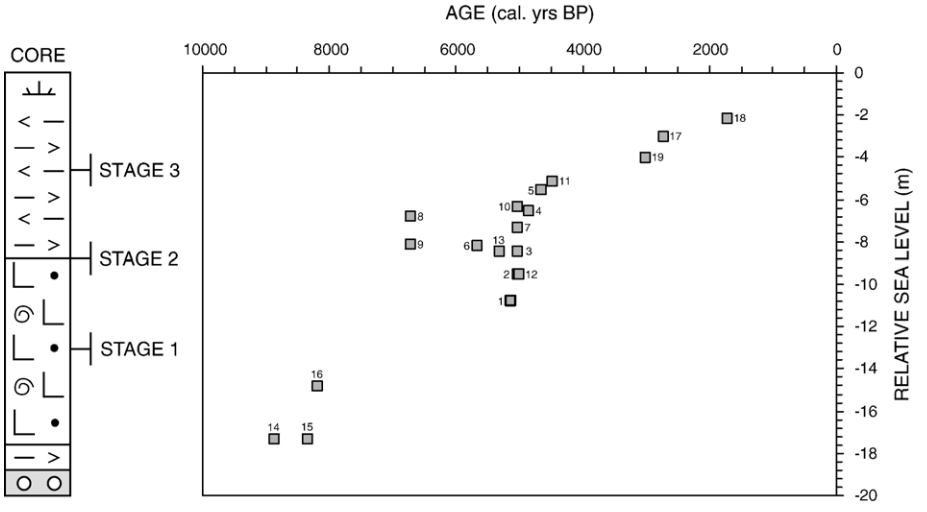


Fig. 8. Sea-level history of coastal sites in south-east Devon. Numbering of SLIPs matches Table 2. Core depicts typical lithofacies represented during a 3-stage model of coastal evolution (Massey, 2004). Core symbols follow Troels-Smith (1955). Stage 1: Early Holocene rapid rise of sea level produces discontinuous barrier system. Stage 2: Middle Holocene slow-down of sea-level rise leads to barrier closure. Stage 3: Back-barrier basins are filled in with sediment during the late Holocene slow rise of sea level.

freshwater lagoons filled in with peat or minerogenic sediments (e.g., Blackpool Sands) (Fig. 7B) larger systems remained at the lacustrine stage (e.g., the Lower Ley) (Fig. 7A). The Higher Ley at Slapton is now in an advanced state of terrestrialisation (Massey et al., 2006c) (Figs. 1 and 2A). The entire system will stabilise once the barrier is pinned between the Pleistocene bedrock surface and local Ipswichian cliff base, and any tidal inlets have been completely choked under slowly rising sea levels in the late Holocene. Potentially rapid future sea-level rise ($\sim \geq 3$ m/ka) will likely return the system to an open coastal barrier-lagoon.

6. Conclusions

Electrical resistivity tomography (ERT) of the near-surface contributes much needed data to the stratigraphic archive of south-west England. Weathered basal slate and shale has a resistivity of $\sim 160\ \Omega$ m, minerogenic fines $\sim 50\ \Omega$ m, intercalated coarse sand and gravel $\sim 60\ \Omega$ m, near-surface gravel infill $\sim 80\ \Omega$ m, and barrier gravel $\sim 730\ \Omega$ m. A possible washover sand and gravel facies recorded ~ 32–$50\ \Omega$ m at Bantham Sands. High porosity, permeability, unsaturated near-surface sediments, and high salinity levels can produce significant interference with this method of electrical resistivity survey. Similarly, the proximity of fresh and saline water-bodies and height of ground level relative to the tidal frame are also factors that may influence the quality of results achievable with 2D ERT survey. However, groundwater levels at our sites varied little during two years of research, except under extreme surface conditions. Furthermore, concerns that saline invasion may have influenced the depth of investigation and our ability to discriminate rock from sediment proved unjustified. In general, results have been very consistent and the method can be used for determining depth to the weathered rock strata and the thicknesses of finer sediments and the overlying gravel barrier. At sites where interference is minimal, determination of thinner lenses (e.g., washover lithofacies) is possible.

A complex barrier–lagoon system existed offshore of the present-day coast of south-east Devon, UK, during pre- and early Holocene times. Weathered basal slate and shale were covered by peat and fines as a result of the early Holocene rise (~ 5 m/ka) in relative sea level. Minerogenic sediment filled river channels and marshland bordered shallow marine lagoons in coastal barrier–lagoon settings that dominated ca. 9000–6800 cal. yr BP (-12.2 to -6.2 m OD). Intertidal conditions existed at Blackpool Sands until at least 4400 cal. yr BP and ca. 1400 yr later at Slapton Sands when sea-level rise slowed to ~ 1 m/ka. As barriers choked with sediment, closing off lagoons from the open sea, freshwater lake and marsh environments developed behind Slapton Sands and Blackpool Sands. Smaller basins filled in with organic silts, clays and mud by ca. 3000 cal. yr BP. Slapton Sands Lower Ley coastal section is presently in the Lacustrine Stage (2) of the Holocene transgressive model of barrier development (adapted from Kraft and Chrzastowski, 1985 and others) whilst Blackpool Sands has reached the Terrestrialised Stage (3). Potentially rapid sea-level rise ($\sim \geq 3$ m/ka) will likely return this system to Stage 1 (an open coastal barrier-lagoon system). The identification of back-barrier environments from lithofacies here contributes significantly to findings from coastal models developed elsewhere in the Northern Hemisphere.

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References

Auken, E., Christiansen, A.V., 2004. Layered and laterally constrained 2D inversion of resistivity data. Geophys. 69, 752–761.

Barnhardt, W.A., Belknap, D.F., Kelley, J.T., 1997. Stratigraphic evolution of the inner continental shelf in response to late Quaternary relative sea-level change, northwestern Gulf of Maine. Geol. Soc. Amer. Bull. 109, 612–630.

Belknap, D.F., 1991. Preservation potential of the Delaware Atlantic coast barrier — backbarrier system. In: Kraus, N.C., Gingerich, K.J., Kriebel, D.L. (Eds.), Coast. Sed. '91. Vol. II: Proceedings of a Specialty Conference on Quantitative Approaches to Coastal Sediment Processes, Seattle, Washington. Am. Soc. Civ. Eng., New York, pp. 1269–1283.

Belknap, D.F., Kraft, J.C., 1981. Preservation potential of transgressive coastal lithosomes on the U.S. Atlantic shelf. Mar. Geol. 42, 429–442.

Bergström, G., 1913. Försök med elektrisk malmletning. Sver. Geol. Unders. Årsb. Stock. 7, 1–10.

Bernstone, C., Dahlin, T., 1996. 2D resistivity surveying of old landfills. Proc. Eur. Environ. Eng. Geophys. Meet. France, Nantes, pp. 188–191.

Carr, A.P., Blackley, M.W.L., 1973. Investigations bearing on the age and development of Chesil Beach, Dorset, and the associated area. Trans. Inst. Br. Geogr. 58, 99–111.

Carr, A.P., Blackley, M.W.L., 1974. Ideas on the origin and development of Chesil Beach, Dorset. Proc. Dorset Nat. Hist. Archaeol. Soc. 95, 9–17.

Chadwick, A.J., Karunarathna, H., Gehrels, W.R., Massey, A.C., O'Brien, D., Dales, D., 2005. A new analysis of the Slapton barrier beach system, UK. Marit. Eng. 158, 147–161.

Christiansen, A.V., Auken, E., 2004. Optimizing a layered constrained 2D inversion of resistivity data using Broyden's update and 1D derivatives. J. Appl. Geophys. 56, 247–261.

Clarke, R.H., 1970. Quaternary sediments off south-east Devon. Q. J. Geol. Soc. Lond. 125, 277–381.

Crabtree, K., Round, F.E., 1967. Analysis of a core from Slapton Ley. New Phytol. 66, 255–270.

Dahlin, T., 1996. 2D resistivity surveying for environmental and engineering applications. First Break 14, 275–283.

Dahlin, T., 2001. The development of DC resistivity imaging techniques. Comput. Geosci. 27, 1019–1029.

Dahlin, T., Loke, M.H., 1998. Resolution of 2D Wenner resistivity imaging as assessed by numerical modelling. J. Appl. Geophys. 38, 237–249.

Dahlin, T., Bjelm, L., Svensson, C., 1996. Resistivity pre-investigations for the railway tunnel through Hallandsås, Sweden. Proc. 2nd Eur. Environ. Eng. Geophys. Meet. France, Nantes, pp. 109–112.

Dineley, D.L., 1961. The Devonian system in south Devonshire. Field Stud. 1, 121–140.

Edwards, R.J., 2001. Mid- to late Holocene relative sea-level change in Poole Harbour, southern England. J. Quat. Sci. 16, 221–235.

Emery, K.O., Dietz, R.S., 1941. Gravity coring instrument and mechanics of sediments coring. Bull. Geol. Soc. Am. 52, 1685–1714.

Gehrels, W.R., 1999. Middle and Late Holocene sea-level changes in eastern Maine reconstructed from foraminiferal saltmarsh stratigraphy and AMS ^{14}C dates on basal peat. J. Quat. Res. 52, 350–359.

Gehrels, W.R., 2002. Intertidal foraminifera as palaeoenvironmental indicators. In: Haslett, S.K. (Ed.), Quaternary Environmental Micropalaeontology. Arnold Publishers, pp. 91–114. Ch.5.

Gehrels, W.R., Massey, A.C., 2004. Slapton Line Coast Protection: Impact of Sea-Level Rise. In: Scott Wilson Consultants (Ed.), A379 Slapton Sands Main Study. A Report Prepared for English Nature. Devon County Council, Exeter, Devon, UK.

Gish, O.H., Rooney, W.J., 1925. Measurement of resistivity of large masses of undisturbed earth. Terr. Magn. Atmos. Electr. 30, 161–188.

Griffiths, D.H., Barker, R.D., 1993. Two-dimensional resistivity imaging and modelling in areas of complex geology. J. Appl. Geophys. 29, 211–226.

Hails, J.R., 1975a. Sediment distribution and Quaternary history of Start Bay, Devon. J. Geol. Soc. (Lond.) 131, 19–35.

Hails, J.R., 1975b. Some aspects of the Quaternary history of Start Bay, Devon. Field Stud. 4, 207–222.

Hallenburg, J.K., 1984. Geophysical logging for mineral and engineering applications. PennWell Books. PennWell Publishing, Tulsa, Oklahoma, USA, pp. 18–41. Ch.4.

Haslett, S.K., Davies, P., Strawbridge, F., 1997. Reconstructing Holocene sea-level change in the Severn Estuary and Somerset Levels: the foraminifera connection. Archaeol. Sev. Estuary 8, 29–40.

Haslett, S.K., Davies, P., Curr, R.H.F., Davies, C.F.C., Kennington, K., King, C.P., Margetts, A.J., 1998. Evaluating late Holocene relative sea-level change in the Somerset Levels, southwest Britain. Holocene 8, 197–207.

Healy, M.G., 1993. Coastal evolution and relative sea-level change in west Cornwall, U.K. Ph.D. Thesis, The National University of Ireland, University College Cork, Cork, Ireland.

Healy, M.G., 1995. The lithostratigraphy and biostratigraphy of a Holocene coastal sediment sequence in Marazion Marsh, west Cornwall, U.K. with reference to relative sea-level movements. Mar. Geol. 124, 237–252.

Heyworth, A., Kidson, C., 1982. Sea-level changes in southwest England and Wales. Proc. Geol. Assoc. 93, 91–111.

Hydrographic Office, 2002. Admiralty tide tables: United Kingdom and Ireland including European and Channel ports. Hydrographer of the Navy, vol. 1. Somerset, Taunton, pp. 1–364.

Johansen, H.K., 1977. A man computer interpretation system for resistivity soundings over a horizontally stratified earth. Geophys. Prospect. 25, 667–691.

Kelland, N.C., 1975. Submarine geology of Start Bay determined by continuous seismic profiling and core sampling. J. Geol. Soc. (Lond.) 131, 19–35.

Kraft, J.C., 1979. Processes and morphologic evolution of an estuarine and coastal barrier system. In: Leatherman, S.P. (Ed.), Barrier Islands from the Gulf of St. Lawrence to the Gulf of Mexico. Academic Press, New York, pp. 149–183.

Kraft, J.C., Chrzastowski, M.J., 1985. Coastal stratigraphic sequences. In: Davis Jr., R.A. (Ed.), Coastal Sedimentary Environments. Springer-Verlag, New York, pp. 625–663. Ch.9.

Lambeck, K., 1995. Late Devensian and Holocene shorelines of the British Isles and North Sea from models of glacio-hydro-isostatic rebound. J. Geol. Soc. (Lond.) 152, 437–448.

Lambeck, K., 1997. Sea-level change along the French Atlantic and Channel coasts since the time of the Last Glacial Maximum. Palaeogeogr. Palaeoclimatol. Palaeoecol. 129, 1–22.

Loeblich, A.R., Tappan, H., 1987. Foraminiferal genera and their classification. Van Nostrand Reinhold Company, New York, vols. 1, 970 p., and 2 pls., 212 p., and 847 pls.

Loke, M.H., Barker, R.D., 1996. Rapid least-squares inversion of apparent resistivity pseudosections using a quasi-Newton method. Geophys. Prospect. 44, 131–152.

Massey, A.C., 2004. Holocene Sea-level Changes along the Channel Coast of South-west England. Ph.D. Thesis, University of Plymouth, Plymouth, Devon, UK. 330 pp.

Massey, A.C., Gehrels, W.R., Charman, D.J., White, S.V., 2006a. An intertidal foraminifera-based transfer function for reconstructing Holocene sea-level change in southwest England. J. Foraminiferal Res. 36, 215–232.

Massey, A.C., Paul, M.A., Gehrels, W.R., Charman, D.J., 2006b. Autocompaction in Holocene coastal back-barrier sediments from south Devon, southwest England, UK. Mar. Geol. 226, 225–241.

Massey, A.C., Taylor, G.K., Gehrels, W.R., Charman, D.J., 2006c. Electrical resistivity of coastal back-barrier sediments from south Devon, south-west England, UK. J. Coast. Res. 22, 1179–1191.

Morey, C.R., 1974. Visit to South Hams. Proc. 101st Conf. Inst. Munic. Eng. Torbay, June 1974, vol. 32, p. 41.

Morey, C.R., 1976. The natural history of Slapton Ley Nature Reserve IX: the morphology and history of the lake basins. Field Stud. 4, 353–368.

Morey, C.R., 1980. The Origin and Development of a Coastal Lagoon System, Start Bay. M.Phil. Thesis, C. N. A. A.

Morey, C.R., 1983a. The evolution of a barrier-lagoon system — a case study from Start Bay. Proc. Ussher Soc. 5, 454–459.

Morey, C.R., 1983b. Barrier stability. Quat. Newsl. 40, 23–27.

Murray, J.W., 1979. British nearshore foraminiferids: keys and notes for the identification of the species. In: Kermack, D.M., Barnes,

R.S.K. (Eds.), Synopses of the British Fauna (New Series), vol. 16. Academic Press, London, pp. 1–68 (Linn. Soc. Lond. Estuar. Brackishwater Sci. Assoc.).

Orme, A.R., 1960. The raised beaches and strandlines of south Devon. Field Stud. 1, 109–130.

Overmeeren, R.A., van Ritsema, I.L., 1988. Continuous vertical electrical sounding. First Break 6, 313–324.

Paul, M.A., Barras, B.F., 1998. A geotechnical correction for post-depositional sediment compression: examples from the Forth Valley, Scotland. J. Quat. Sci. 13, 171–176.

Peltier, W.R., 1998. Postglacial variations in the level of the sea: implications for climate dynamics and solid-Earth geophysics. Rev. Geophys. 36, 603–689.

Peltier, W.R., Shennan, I., Drummond, R., Horton, B.P., 2002. On the post-glacial isostatic adjustment of the British Isles and the shallow visco-elastic structure of the Earth. Geophys. J. Int. 148, 443–475.

Petersson, W., 1907. Om malmsökande medelst elektricitet. J. Kontor. Ann. 2-3, 153–171.

Rees, J.G., 1999. LOEPS logging protocol. Coastal Geology Group BGS Report, Keyworth. Nottinghamshire, UK. 4 pp.

Richards, A.F., Keller, G.H., 1961. A plastic-barrel sediment corer. Deep-Sea Res. 8, 306–312.

Ritz, M., Robain, H., Pervago, E., Albouy, Y., Camerlynck, C., Descloitres, M., Mariko, A., 1999. Improvement to resistivity pseudosection modelling by removal of near-surface inhomogeneity effects: application to a soil system in south Cameroon. Geophys. Prospect. 47, 85–101.

Robinson, E.S., Coruh, C., 1988. Basic Exploration Geophysics. Wiley, New York. 562 pp.

Schlumberger, C., 1920. Étude sur la Prospection Électrique du Sous-sol, Gaultier-Villars et Cie. France, Paris. 94 pp.

Scott, D.B., Medioli, F.S., 1980a. Living vs. total populations: their relative usefulness in palaeoecology. J. Palaeontol. 54, 814–831.

Scott, D.B., Medioli, F.S., 1980b. Quantitative studies of marsh foraminiferal distributions in Nova Scotia: implications for sea-level studies. Cushman Found. Foraminifer. Res. Spec. Publ., vol. 17. 57 pp.

Shennan, I., 1983. Flandrian and Late Devensian sea-level changes and crustal movements in England and Wales. In: Smith, D.E., Dawson, A.G. (Eds.), Shorelines and Isostasy: Inst. Br. Geogr. Spec. Publ., vol. 16. Academic Press Inc., London, pp. 255–283. Ch. 11.

Shennan, I., 1989. Holocene crustal movements and sea-level changes in Great Britain. J. Quat. Sci. 4, 77–89.

Shennan, I., Horton, B., 2002. Holocene land- and sea-level changes in Great Britain. J. Quat. Sci. 17, 511–526.

Stuiver, M., Reimer, P.J., 1993. Extended ^{14}C data base and revised CALIB. 3.0 ^{14}C age calibration program. Radiocarbon 35, 215–230.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, G., van der Plicht, J., Spurk, M., 1998. INTCAL98 radiocarbon age calibration, 24,000–0 cal BP. Radiocarbon 40, 1041–1083.

Terzaghi, K., Peck, R.B., Mesri, G., 1996. Soil Mechanics in Engineering Practice, 3rd ed. John Wiley and Sons Inc., Chichester. 549 pp.

Troels-Smith, J., 1955. Karakterising af lose jordater (Characterisation of unconsolidated sediments). Dan. Geol. Unders., 4. række 3, 1–73.

Ussher, W.A.E., 1904. The Geology of the Country Around Kingsbridge and Salcombe (Explanation of Sheets 355 and 356). Mem. Geol. Surv. Engl., Wales. 79 pp.

Waller, M.P., Long, A.J., 2003. Holocene coastal evolution and sea-level change on the southern coast of England: a review. J. Quat. Sci. 18, 351–359.

Waller, M.P., Entwistle, J.A., Duller, G.A.T., 1995. TSPPlus — a menu driven program for the display of stratigraphic data. Quat. Newsl. 77, 32–39.

Wingfield, R.T.R., 1995. A model of sea-levels in the Irish and Celtic seas during the end-Pleistocene to Holocene transition. In: Preece, R.C. (Ed.), Island Britain: a Quaternary Perspective. Geol. Soc. Spec. Publ., vol. 96, pp. 209–242.

Wisén, R., Esben, A., Dahlin, T., 2005. Combination of 1D laterally constrained inversion and 2D smooth inversion of resistivity data with *a priori* data from boreholes. Near Surf. Geophys. 3, 71–79.